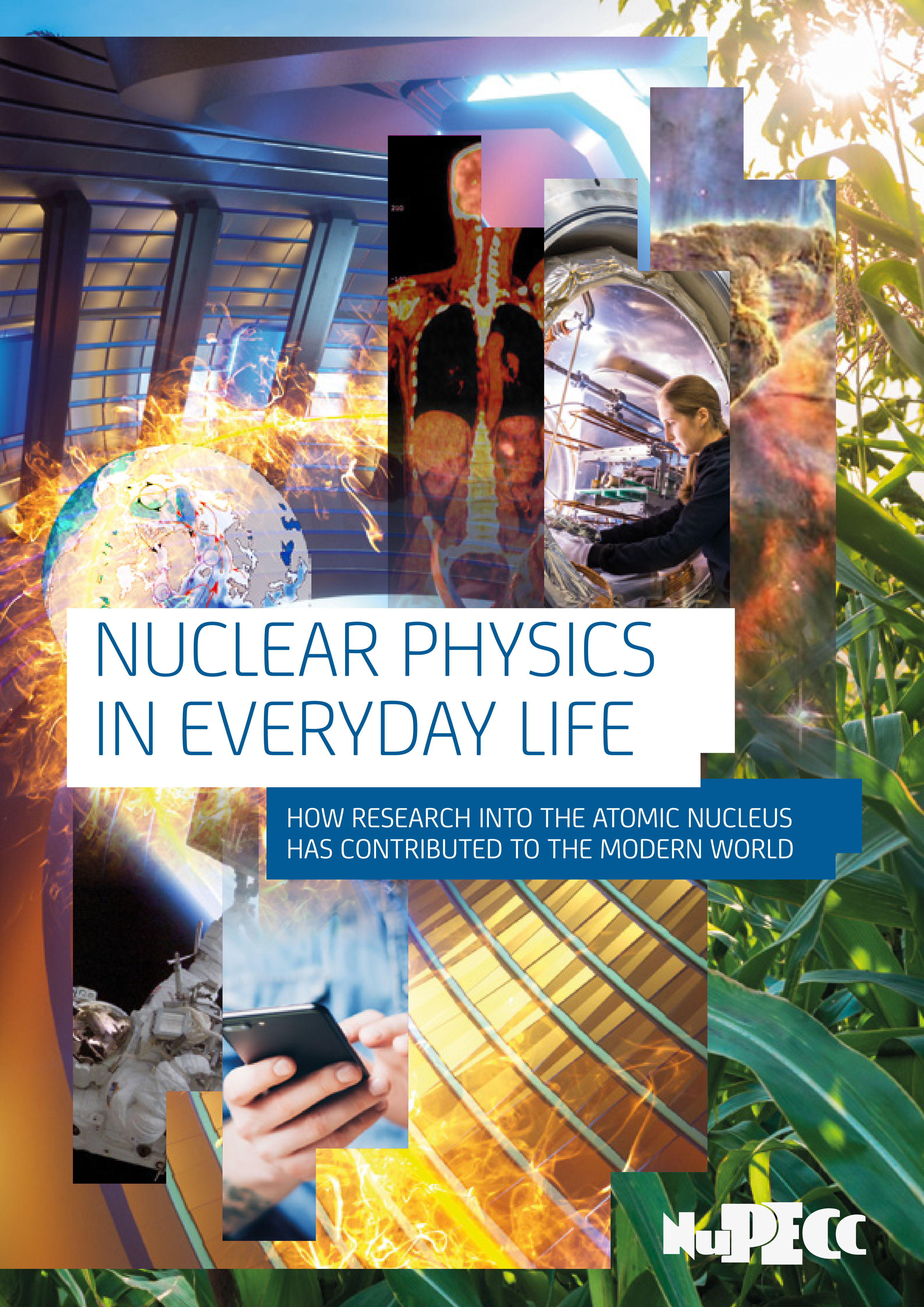


NUCLEAR PHYSICS IN EVERYDAY LIFE

HOW RESEARCH INTO THE ATOMIC NUCLEUS HAS CONTRIBUTED TO THE MODERN WORLD

NuPECC

NUCLEAR PHYSICS EUROPEAN COLLABORATION COMMITTEE
NUPECC

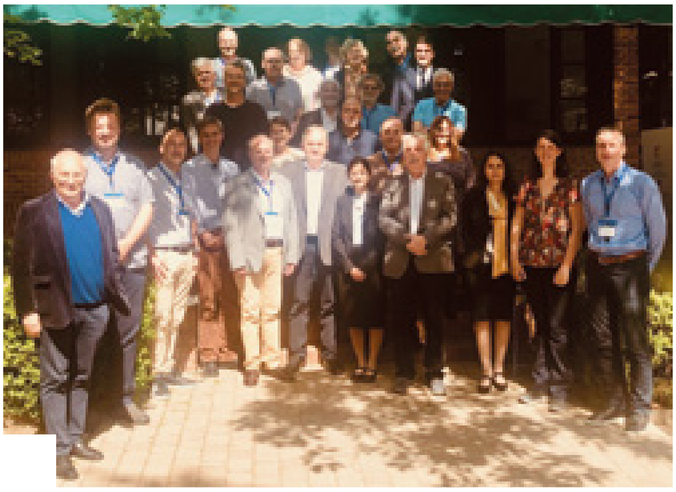
NuPECC is an Expert Committee hosted by the European Science Foundation (ESF).

THE OBJECTIVE OF NUPECC IS TO:

- develop the strategy for European collaboration in nuclear science by supporting collaborative ventures between research groups within Europe, and
- promote nuclear physics and its trans-disciplinary use in applications for societal benefit.

In pursuing this objective the Committee shall:

- **provide advice** and make strategic recommendations to funding agencies and decision-making bodies;
- **define a network** of complementary facilities within Europe and encourage optimisation of their usage;
- **provide a forum** for the discussion of the provision of future facilities and instrumentation;
- **contribute to public** education and awareness.



NuPECC regularly arranges scientific meetings where scientists can come together to discuss ongoing nuclear physics research and its applications, and how to optimise potential benefits to society so as to improve lives around the world.

NUCLEAR PHYSICS IN EVERYDAY LIFE IS EDITED BY:

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* Chapters 7 & 8

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FOREWORD

In today's uncertain world, progress in science and technology is becoming ever more important in finding solutions to challenging problems that affect our world, whether it is in mitigating climate change and seeking a sustainable future, or preparing for the next pandemic. Food and energy security are a particular global concern, as is meeting the health needs of increasingly longer-lived populations.

One area of science that is making substantial strides in improving lives while protecting the environment is nuclear physics – the study of the atomic nucleus. The chemical elements, which constitute the world around us and ourselves, are defined by their distinctive nuclei and their properties. By studying the nature and behaviour of the many possible kinds of nuclei, we can learn how they were first created in the stars, how they influenced the evolution of the Universe, the history of our extraordinary and beautiful planet – and even determined the development of life itself.

This underpinning knowledge of nuclear behaviour has led to some remarkable applications – particularly in 'greener' nuclear energy production, as well as in safer cancer treatment and in finding out the causes of disease. Precise analytical techniques based in nuclear physics provide essential tools in many significant fields that affect everyday life: environmental research, crime prevention and the preservation of cultural heritage. Nuclear physics technologies help make food production more efficient and safe – especially in the developing world – while enabling improvements in industrial manufacturing and processing, leading to considerable economic benefits.

This report, which is written by experts in all these areas, aims to describe in an accessible way how modern applications of nuclear physics enhance our everyday lives. As well as describing the widespread terrestrial uses – whose extent you might find surprising – the report also reveals how nuclear technology provides the gateway to space exploration and maybe one day even colonisation.

The NuPECC Committee, who compiled this report, hopes that you enjoy reading how research in nuclear physics and the resulting applications benefit us all.

Professor Marek Lewitowicz NuPECC Chair

CONTENTS

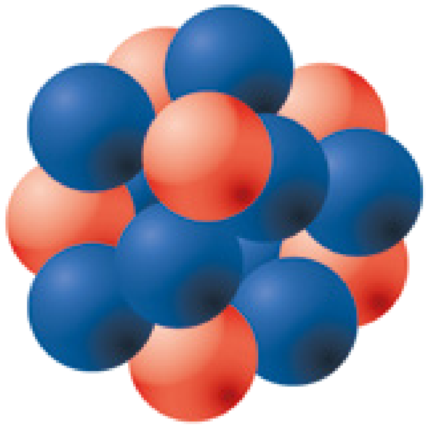
CHAPTER 1:
INTRODUCTION

Nuclear physics has many applications but they depend on basic knowledge gained from experiments in large-scale nuclear research facilities. **[Credit GSI].**

NUCLEAR PHYSICS IS THE STUDY OF THE ATOMIC NUCLEUS, ITS STRUCTURE AND BEHAVIOUR. IT IS A KEY BASIC SCIENTIFIC FIELD THAT INVESTIGATES THE PROPERTIES OF MATTER AT THE SUBATOMIC LEVEL. OVER THE PAST CENTURY, SUCH RESEARCH HAS LED TO A VAST RANGE OF APPLICATIONS AND TECHNOLOGIES, MANY OF THEM EXPLOITING NUCLEAR REACTIONS AND THE HIGH-ENERGY RADIATION EMITTED. IN THIS WAY, NUCLEAR SCIENCE AND TECHNOLOGIES HAVE CONTRIBUTED NOT ONLY TO HEALTH, ECONOMIC DEVELOPMENT AND SECURITY IN COUNTRIES ACROSS THE WORLD BUT ALSO MORE GENERALLY TO HUMAN PROGRESS, CULTURE AND A DEEPER UNDERSTANDING OF OUR FRAGILE ENVIRONMENT.

The word ‘nuclear’ is often associated with something that is powerful, dangerous and difficult to control. It may first bring to mind images related to the atomic bomb explosions of the 1940s and 1950s – and more recently, the press coverage of the environmental damage caused by the accidents at the Chernobyl and Fukushima nuclear power plants in Ukraine and Japan.
In the past, the words ‘nuclear’ and ‘atomic’ were popularly used somewhat interchangeably, after the discovery in the first half of the 20th century that usable energy could be released from the atomic nucleus – a process then loosely described by the press as ‘splitting the atom’.

In fact, what had been discovered was that atoms, previously identified as the basic constituents of all matter on Earth including ourselves, had an internal structure consisting of a central, very dense spherical nucleus that was positively charged, and was surrounded by clouds of negative electrons. The nucleus itself was composed of further particles, positive protons and neutral neutrons (collectively known as nucleons). Nuclear scientists soon realised that the atomic nucleus had a complex structure held together by a powerful force. Just as chemically bound atoms and combinations of atoms – molecules – separate, react, and re-form, driven by the fundamental force of electromagnetism, so nuclei can undergo analogous reactions driven by nuclear forces. So the nuclear reactions involved in ‘splitting the atom’ really refer to splitting the nucleus.



The structure of a typical atomic nucleus with protons (red) and neutrons (blue) bound by the strong force.

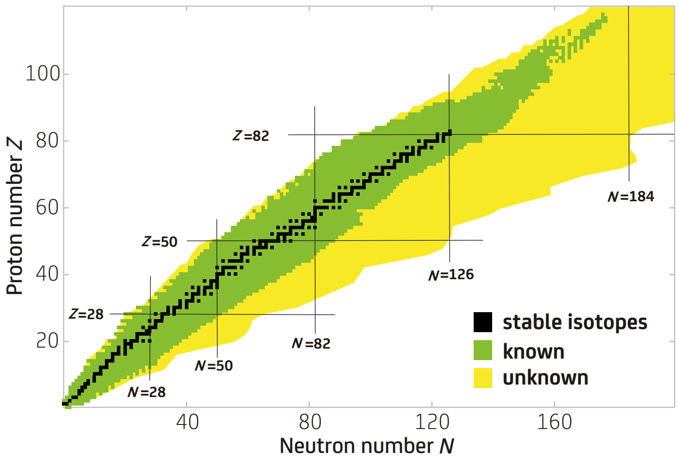
Although the first nuclear reaction to be given extensive publicity was the fission of uranium, the heaviest natural element, as a potential source of vast amounts of energy, nuclei can undergo many kinds of reactions. The study of nuclear structure and reactions is known as nuclear physics.

Nuclear physics is an incredibly important and diverse field of research and development. It plays a significant role in probing the fundamental properties of matter and the evolution of the Universe, while providing a vast range of remarkable tools for improving our quality of life – from energy generation, advanced medical procedures, improved agricultural and environmental practices to analytical techniques used in industry, heritage studies and space exploration. The following chapters will show just how diverse nuclear physics applications are in everyday life.

WHY IS NUCLEAR PHYSICS IMPORTANT?

It is useful first to reflect on what we now know about the world and the Universe beyond in terms of their constituent building blocks – and where nuclear physics fits in.

Ancient Greek philosophers suspected that all matter was made of fundamental tiny units they called atoms that accounted for the characteristics and behaviour of everyday matter. It was not until the early 19th century, however, that scientists re-discovered the concept of the atom and started to build up a picture of how different kinds of atoms were related via the Periodic Table of elements (Chapter 3). The subsequent decades up until the present day have been momentous in terms of uncovering and understanding the fundamental components of the material world at the level of the atom, and deeper at much smaller scales.

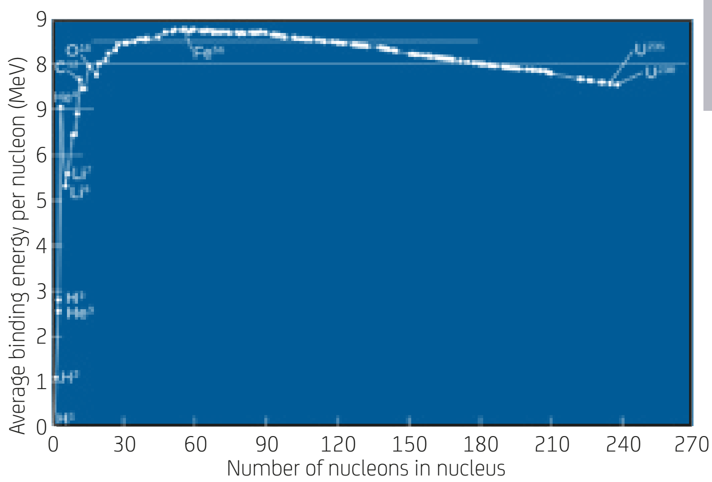


The nuclear 'landscape' of possible isotopes according to the numbers (and thus proportions) of protons and neutrons they contain. The black jagged area represents nuclei that are stable. The green area represents known unstable nuclei that undergo certain types of decay, as indicated in Chapter 2 on radioactivity (page 14), and the yellow area represents nuclei with certain proportions of protons and neutrons that could exist but are unknown.

Studies in nuclear physics have now explained that the elements of the Periodic Table are defined by their atomic nuclei, that is, the number of protons therein (the atomic number). For example, the hydrogen atom has just one proton while carbon has six protons – atomic number 6; uranium has 92. Each element includes a number of nuclear variations with differing numbers of neutrons, known as isotopes of the element. For example, hydrogen has two heavier isotopes, deuterium, which has an extra neutron, and tritium, which has two neutrons. In general, as we go up the Periodic Table of elements with increasing numbers of protons, ever more neutrons are needed to stabilise the nucleus, and the number of possible isotopes thus also increases. Nuclei can contain any number of nucleons from one to close to 300. All in all, nuclear physicists have calculated that up to 7000 isotopes are possible, although most would not be stable.

The force that binds protons and neutrons together, and ultimately determines the stability of nuclei, is a fundamental interaction called the strong nuclear force (see below). The associated 'binding energy' is defined as the minimum amount of energy that must be applied to overcome this fiercely attractive force – and so disassemble a nucleus into its individual nucleons.

The mass of a nucleus is less than the sum of the individual masses of the free constituent protons and neutrons. This difference in mass is equivalent to the binding energy as given by the famous Einstein equation, $E = mc^2$, where E is the nuclear binding energy, c is the speed of light, and m is the difference in mass. The nuclear binding energy is not the same for all nuclei; it depends on the number of nucleons in a nucleus. This concept of the nuclear binding energy is essential to understand nuclear stability and how different nuclei behave.

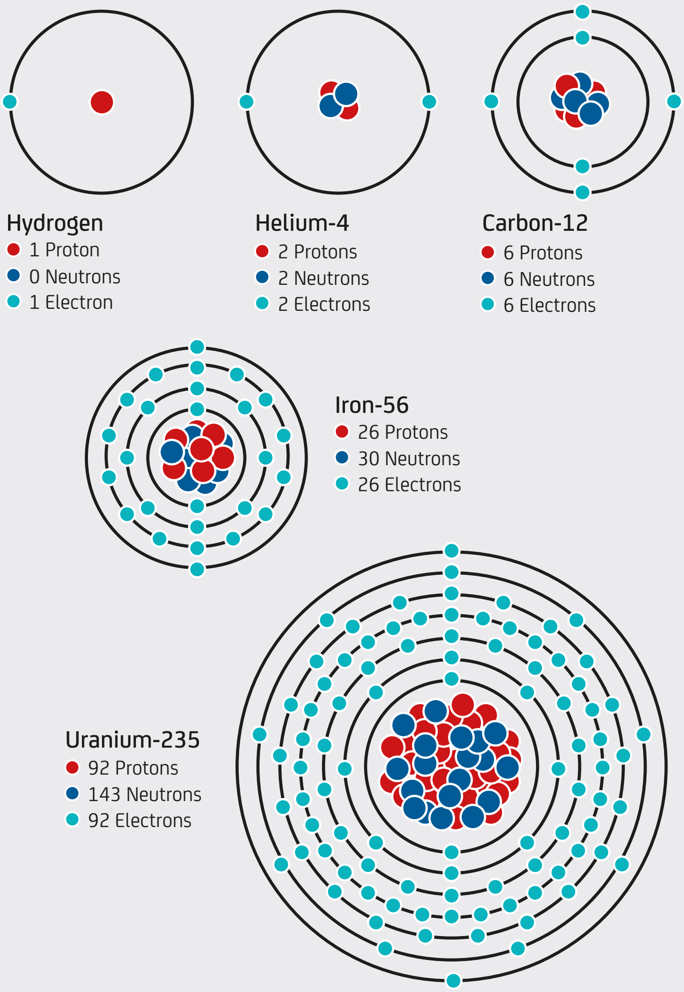


The graph shows the nuclear binding energy for some common isotopes – from hydrogen (one proton), through helium, lithium, carbon, oxygen and iron, to the heavy isotopes of uranium.

THE STRUCTURE OF THE ATOM

All neutral atoms consist of a massive positive nucleus around which an equal number of electrons orbit. Almost all of the mass of an atom (more than 99 per cent) is located within the nucleus, with only a small contribution from the surrounding electron cloud. The diameter of the nucleus is in the range of 1.7×10^{-15} metres for a hydrogen nucleus (the diameter of a single proton) to about 11.7×10^{-15} metres for a uranium nucleus. That means we are talking about a scale in the million-millionth of a millimetre range. The nucleus is close to 15,000 times smaller than the size of the whole atom.

The electrons themselves are spread out into defined orbitals arranged in shells. Their exact configuration in an atom depends upon the element and – along with its mass – endows individual elements with their characteristic physical and chemical properties. For example, some elements have atoms with loosely-bound outer electrons that are mobile, allowing for the conduction of electricity, and also give them their typical metallic look; others like carbon can form a diversity of strong, directional chemical bonds that allow for the formation of extremely complex molecular entities like DNA.



Simple graphical representations of the atomic structures of hydrogen, helium-4, carbon-12, iron-56 and uranium-235. The sizes here are not to scale but uranium is about five times the size of hydrogen; note that the helium-4 atom is smaller than hydrogen with a single proton, because the increased charge due to the second proton pulls the electrons closer to the nucleus.

THE FUNDAMENTAL UNITS OF NATURE

Since the 1960s, researchers have uncovered a yet deeper structure to matter beyond that of atoms and nuclei, and that is that the protons and neutrons themselves consist of particles known as quarks. The behaviour of these fundamental particles is largely governed by the previously mentioned strong force. This force is approximately 10^{38} (100 million million million million million million) times stronger than the force of gravity! It acts only within a very short distance of 10^{-15} metres (that is, at one-thousand million millionth of a metre). The strong force acts so as to bind tightly together three quarks to form a proton or a neutron, and to overcome the electrostatic repulsion between the positive charges of protons to combine protons and neutrons to form nuclei.

Studies of Nature at this most fundamental level is known as particle physics, but there is a large overlap between nuclear and particle physics research in the many experiments carried out and the theories they test. As a result, we now have a good working description of the basic building blocks of matter and the fundamental forces that govern their behaviour. This is built on the most successful theory in modern physics: quantum mechanics.

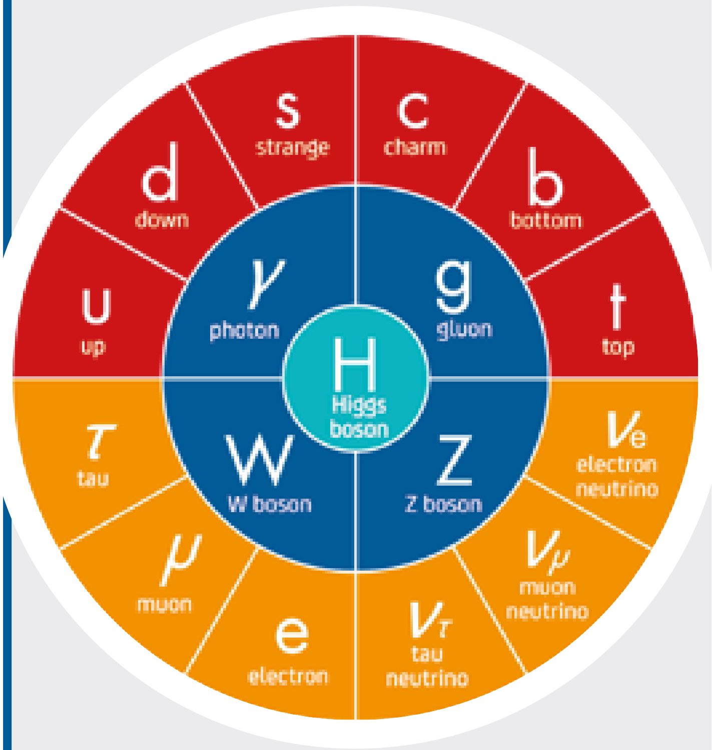
In this theoretical model, matter particles are divided into two kinds: quarks and leptons, of which there are six 'flavours' for each kind. They are divided into three generations of increasing mass (see the Box opposite). Only the two lightest quarks – 'up' and 'down' – form our everyday world, being the particles that make up the proton and neutron. (The proton contains two up quarks and one down quark, and the neutron, two down quarks and one up quark).

The lightest lepton is the familiar electron, followed by the heavier muon and tau particle, which are both unstable. Accompanying these particles are the more mysterious neutral neutrinos which have virtually no mass but are very significant in the evolution of the Universe and the production of energy in the Sun, as well as in various nuclear reactions such as radioactive decay. All the mass particles have an antimatter partner with an opposite charge; for instance, the antimatter partner of the negative electron is the positively charged positron.

There are four fundamental forces governing matter: the strong nuclear force, the weak nuclear force, electromagnetism, and gravity. According to quantum theory, they are each mediated by a quantum particle, although the very much weaker gravitational force does not yet fit well into the overall picture. Physicists are attempting to bring together their theoretical descriptions of the four forces into one unified model; as a first step, the electromagnetic force and the weak nuclear force have now been combined into a single, electro-weak force.

THE STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model of fundamental particles and forces is based on the theoretical predictions of quantum physics, which have then been confirmed by experiment. It consists of three 'generations' of quarks and leptons, together with particles associated with the electromagnetic force, and the strong and weak nuclear forces. Quarks are responsible for the massive nature of matter; the leptons are much lighter. The lightest generation of quarks, called up and down, combine in threes to make up protons and neutrons. There are two, increasingly heavier generations: charm and strange, and top and bottom, seen only at high energies. The three generations of leptons of increasing mass start with the electron and its partner neutrino, followed by the muon and tau and their neutrinos. The electromagnetic force is mediated by the photon, the strong force by the gluon and the weak force by the W and Z bosons. In addition, the so-called Higgs boson endows all the particle with mass.



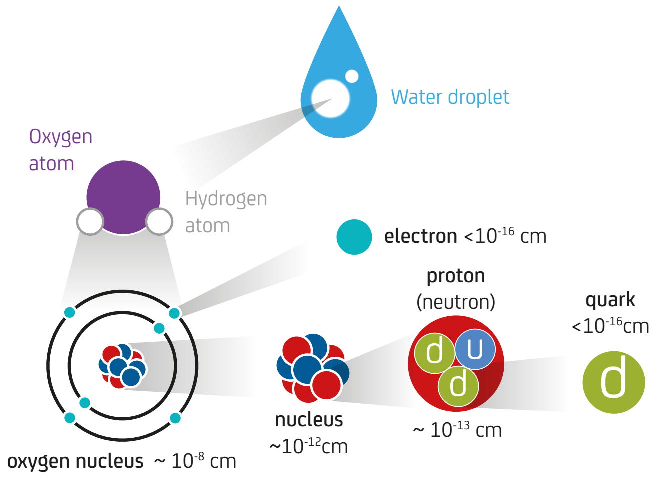
Matter particles

- Quarks
- Leptons
- Force carriers
- Higgs boson

The Standard Model is continually tested in experiments and is proven to work well. However, the fundamental force of gravity, which is very much weaker than the other forces, does not yet fit well into the quantum description. Theorists are looking for a deeper, more unifying description that includes gravity. Nuclear physics experiments can provide probes for testing theories going beyond the Standard Model.

THE HIERARCHICAL NATURE OF MATTER

We now have a clear understanding of the hierarchical structure of matter. For example, water, which is essential for life, is composed of molecules consisting of two hydrogen atoms (each a single proton) bound an oxygen atom, which has a nucleus with eight protons and eight neutrons in its most common form. Each nucleon consists of three quarks – the most fundamental level of Nature that we know of.

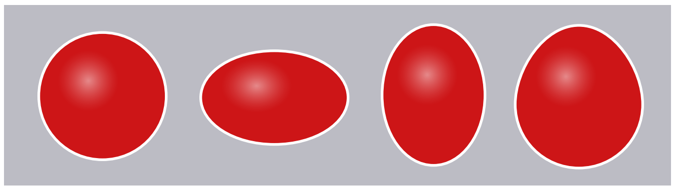


Zooming into the heart of matter.

THE ROLE OF NUCLEAR PHYSICS IN NATURE

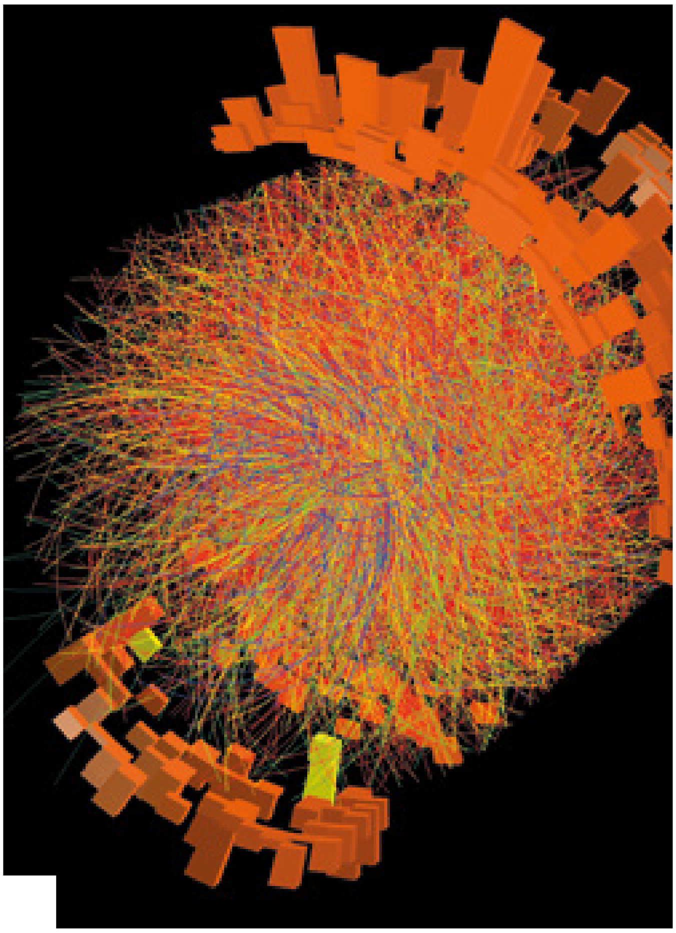
Nuclear physics plays a hugely important role in these fundamental studies, in particular in understanding how the strong force works in binding nucleons together. Nuclear physicists investigate and compare the diverse internal structures and behaviour of many different nuclei. In lighter nuclei, the nucleons are described as being arranged in shells, rather as electrons are arranged in shells in atoms; in heavier nuclei, the nuclei seem to behave to some extent more collectively, like particles in a liquid drop.

One of the ways of testing such nuclear descriptions is to subject a nucleus to extreme energy conditions, for example by making it spin very fast or giving it a hard knock with another nucleus. Another approach is to create versions of nuclei with extreme ratios of neutrons to protons such that they are on the edge of stability. Some of these more unusual nuclei may adopt extreme shapes such as that of a rugby ball or even be pear-shaped.



Heavy nuclei are not necessarily spherical; they can adopt a rugby-ball or even a pear shape.

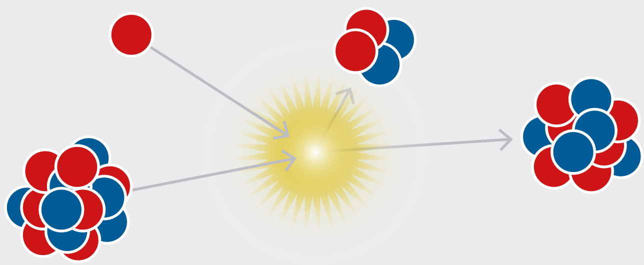
One of the key aims of nuclear physicists is to make and study a huge variety of nuclei – some very exotic – with differing proportions of protons and neutrons. This is not just to test theoretical models, but also to investigate the evolution of matter from the extreme high-energy conditions of the early Universe to the beautiful cosmological configurations of stars and their host galaxies we see now. One type of cosmologically significant experiment is to create nuclei at very high temperatures, such that the quarks making up the nucleons start to uncouple and form what is called a quark–gluon plasma. This is the primordial state of matter that pervaded the Universe just after the Big Bang.



The Large Hadron Collider at the CERN laboratory in Geneva collides heavy ions (lead) to recreate the quark–gluon plasma that formed just after the Big Bang. **[Credit CERN/ALICE Collaboration].**

THE EXPERIMENTS

Because the strong nuclear force is so powerful, nuclear studies must generally be carried out at high energies – high enough to induce nuclear reactions; the results of the reactions are then studied. To achieve these energies, large machines accelerate beams of subatomic particles such as protons, neutrons and selected heavier nuclei using electromagnetic devices. They may be aimed at a target in which nuclear reactions then happen, or two beams may be collided. Nuclei can undergo a range of reactions such as fusion or fragmentation to form new nuclei. A nucleus may capture a neutron, which transforms into a proton (a down quark changes to an up quark) to create an isotope of the element with one atomic number higher. High-energy lasers are also used to excite nuclei so that their structure can be studied. During all these reactions, gamma-rays of characteristic energies are emitted, together with particles such as electrons or positrons (known as beta particles) and helium nuclei (alpha particles), plus neutrinos. By analysing the radiation emitted, nuclear physicists can determine the details of the reactions and other nuclear information.



Nuclear studies often involve colliding subatomic particles at high energies to trigger a reaction, and then detecting and measuring the energies of the products.

OUR STELLAR ORIGINS

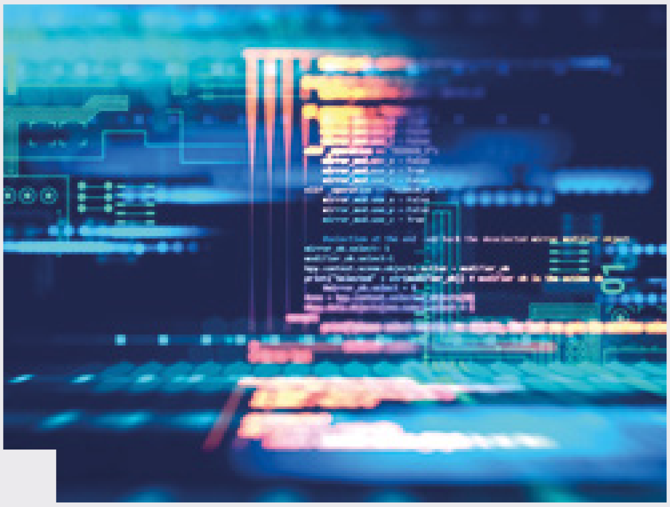
Another important field of study is to make and examine nuclei thought to play a part in the nuclear reaction pathways by which the elements are made in stars. Some of these nuclei may be those with unusual proportions of protons or neutrons. These reaction pathways drive the evolution of stars, and, as explained in Chapter 3 on the origin of the elements, are responsible for the elemental abundances found in our world and reflected in our own biological composition. While the very lightest elements – hydrogen, helium and lithium – were created after the quark–gluon plasma condensed into protons and neutrons, the very heaviest elements are thought to form in extremely violent cosmic environments that can exist at the end of a star's life – those of supernovae, neutron stars and black holes. The result is that the everyday elements we know about have gradually built up from the lightest primordial elements, hydrogen and helium, over the entire history of the Universe, via generations of stars that have died spreading their contents across their host galaxies as swirling dust clouds. These active nebulae, often driven by radiation emitted from the vicinity of supermassive black holes found at the centres of galaxies, give birth to new stars like our Sun with its accompanying planetary system. Investigating the underlying nuclear physics of all these processes helps us to understand the composition of the Earth in terms of the elements and how life came to be.

Nuclear physics studies thus involve investigating matter at all scales, from the very smallest – that of quarks and gluons – through planets like the Earth and the elements they are composed of, to the largest possible scales, that of stars, galaxies and the Universe itself.

This is the Hubble Space Telescope's Deep Field view of the Universe in which each distant object observed is a galaxy composed of billions of stars. The elements are continually built up across the Cosmos through star-birth and death. **[Credit NASA/ESA/STScI].**

COLLECTING NUCLEAR DATA

The many nuclear experiments carried out generate a huge amount of data that are not only useful for theoretical studies in nuclear physics such as those on nuclear structure, but also provide important quantitative information for nuclear applications. These include the lifetimes and decay modes of unstable but useful isotopes, including the energy spectra of the emitted radiation. Also of importance is measuring how probable is it that a certain nuclear reaction, say, the collision between two particles (two nuclei or a nucleus and a neutron, for example), would happen. This probability is called the reaction's 'cross section'. Measuring reaction cross-sections is particularly important in understanding the likelihood of various nuclear transformations in stars, but is also an essential ingredient in a wide range of terrestrial applications that involve nuclear interactions.



Nuclear experiments involve collecting large amounts of data that require the huge computing capacity available at large facilities. **[Credit CERN].**

The data collected are employed in all the sectors described in the following chapters. Radioactive isotopes find use in many fields, and accurate information about their behaviour is vital in developing their commercial production, in applications such as medical diagnostics and radiotherapy, and in the use of radioisotopes as tracers in geology, environmental protection and heritage studies. Both radioactive decay and reaction cross-section data are particularly important in the design and operation of nuclear power plants. They are used in computer simulations of nuclear reactor operation, and for evaluating radiation damage in reactor materials and neutron shielding, as well as in the management of nuclear waste.

NUCLEAR PHYSICS AND PEOPLE

A RADIOACTIVE WORLD

One of the most important sets of experiments in nuclear physics is that of creating new isotopes that have a practical use. Many of the chapters give examples and show how they are used. The majority of these isotopes are not stable, meaning they are radioactive, and it is this property that allows them to be exploited practically. Chapter 2 explains the kinds of radioactive decay possible and their significance for us. Much of the radioactivity we experience every day is natural and comes from the Earth itself, but some also comes from space in the form of charged particles. We also benefit from the effects of artificially generated radioactivity, delivered in shielded environments such as during hospital radiotherapy. Exposure to such radiation is strictly controlled; however, exposure to natural radioactivity is inescapable.

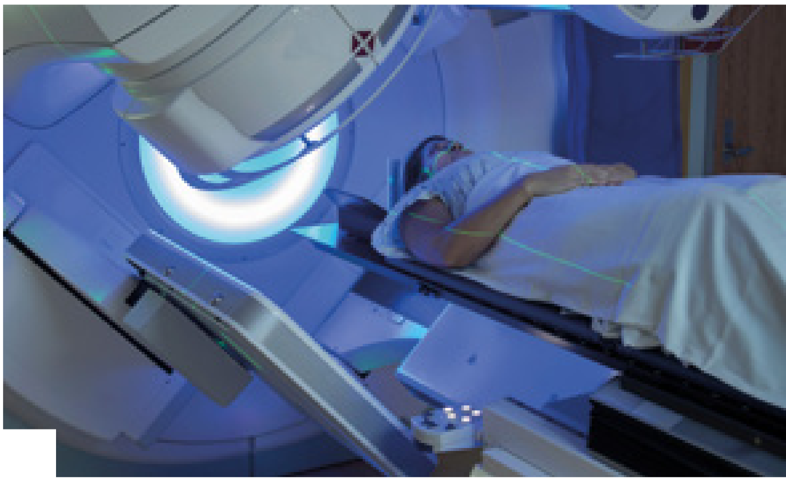
We and the rest of the living world rely on the warmth generated by the Earth's natural radioactivity for survival, as well as, of course, the radiation from the stellar nuclear reactor that shines on us every day. Solar activity affects both climate and weather. Chapter 4 describes how climate and weather are driven by these sources of energy. The evolution of the Earth and life can be investigated by studying isotopes found in geological formations, the oceans and in fossils. The concentrations of both stable and radioactive isotopes provide information about past climates, including ice ages, temperatures and carbon-dioxide levels, giving us a clearer understanding of the conditions that control significant climate change. We really do live in a nuclear world.

A GREENER FUTURE FOR NUCLEAR POWER

The most well-known application of nuclear physics is certainly the harnessing of nuclear energy for power. Exploiting the strong nuclear force, via the nuclear fission of uranium, in theory, seemed the obvious answer to the World's increasing energy needs when it was first discovered. Accidents at nuclear power plants, and problems surrounding the removal of radioactive waste have led some countries to be cautious in advocating the expansion of nuclear energy. Chapter 5 explains the processes underpinning nuclear power generation and the development of modern power plants. There are now a number of advanced designs based on various modified fuel cycles that are safer and more efficient than those of early power plants. Nuclear physicists and engineers are developing methods of destroying nuclear waste as well as alternative power generation sources such as nuclear fusion. With increasing concerns about climate change, nuclear power is now seen, in many countries, as one of the main options for future energy generation.

BETTER HEALTH THROUGH NUCLEAR SCIENCE

Many people may experience the benefits of radioactivity personally, through hospital medical procedures, as described in Chapter 6. A large number of selected radioactive isotopes are now used to diagnose and treat cancer, as well as to image parts of the body such as the brain and heart in order to examine their function. To provide gentler, more effective treatments, isotopes are being chemically bound to suitable antibodies, and there is also now a trend to combine diagnosis and therapeutic procedures using isotopes of the same element. In addition, carefully tailored beams of subatomic particles including nuclei are becoming effective options for killing hard-to-reach cancerous tumours.



The various types of radiotherapy now on offer have radically improved the outcomes for cancer patients.

Nuclear physics is also providing many of the analytical tools that enable research scientists to elucidate the chemical structure of complex organic molecules of biological significance and the way they behave in living tissue. This is leading to the development of not only new drugs but also more personalised treatments, some of which may help to treat so-far incurable diseases like dementia.

TOOLS FOR INDUSTRY AND AGRICULTURE

Irradiation techniques and analytical methods derived from nuclear processes play some part in almost every human activity that benefits from technology, including many areas of industry. Radioactive isotopes are employed in a number of ways, providing high-energy radiation that can be exploited to modify materials during their manufacture, or to sterilise biological and agricultural systems, including killing pests, as described in Chapter 7. One of the main uses of radioactive tracers is in industry and construction, and in relevant environmental monitoring. This may involve scanning the interiors of engineering structures and equipment with various types of radiation, and providing gauge systems that rely on radiation to measure wear and corrosion, or monitor different stages in industrial processing. In effect, nuclear methods help safeguard the quality of products we use, while improving manufacturing efficiency, commercial efficacy and protecting the environment.

The use of nuclear power contributes to the security of carbon-free electricity supplies in today's world of uncertainties.

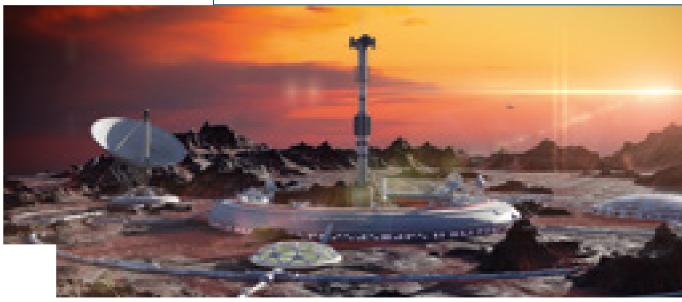
NUCLEAR DETECTIVES

You might be surprised to learn that nuclear analytical techniques are applied in criminal investigations, and in the world of art and heritage studies, as shown in Chapter 8. They provide crucial tools in the fight against large-scale crime including counterfeiting and smuggling dangerous or illegal goods across borders. These techniques can identify even tiny amounts of individual elements and compounds, for example, of metals or nitrogen-containing explosives, as well as radioactive materials. Perhaps even more fascinating is the way nuclear-based methods can be exploited in the conservation of ancient artefacts and paintings, or to find out where they originated, how they were made, and – very important – when they were made. In this way, we learn about our own heritage and culture right back from the earliest times in human evolution. While some methods used in the field, for example at an airport, exploit radiation provided by isotopes, other methods involve firing beams of ions (nuclei) at samples in a dedicated laboratory setting. Many nuclear methods can be carried out only at large-scale nuclear facilities, as Chapter 10 explains.

Carbon-14 dating is used to detect forgeries. For example, this supposedly 19th-century American 'primitive' painting was shown to be painted post-1950. **[Credit Laura Hendriks *et al.*, PNAS, June 3, 2019; https://doi.org/10.1073/pnas.1901540116, James Hamm (Buffalo State College, The State University of New York, Buffalo, NY, US)].**

THROUGH NUCLEAR TO THE STARS

We know that, beyond the Earth, space is not empty but teems with radiation with a nuclear origin, that is, from the Sun and violent cosmic events across our Galaxy. As explained in Chapter 9, our understanding of these events has helped space agencies to prepare both spacecraft and astronauts for the hazards of space travel. Laboratories housing nuclear facilities are able to test special radiation-hardened electronic devices for satellite systems. As space missions venture further towards the farthest reaches of the Solar System, they will rely ever more on some form of nuclear energy, either from radioactive sources or from a nuclear reactor. If humans do ever settle elsewhere in the Solar System, the primary source of energy needed will most certainly be nuclear.



A colony on Mars would depend on nuclear energy.

NUCLEAR ANALYTICAL TECHNIQUES

One of the most important contributions of nuclear physics is in the development of a host of analytical techniques that find application across all the areas described in the chapters. These include radioactive tracers deployed widely to gain information about environments that are difficult to access, such as oceans and geological formations, the body's internal organs and large-scale industrial processes. Various types of radiation are used to create images of the interior of objects and determine accurate and quantitative data on composition at an atomic level. During the past decades, nuclear physics research, particularly at large-scale facilities (Chapter 10) has led to many kinds of novel chemical and physical analyses that allow researchers in every scientific field to explore the structure and behaviour of a vast range of materials that play significant roles in modern life. It is, indeed, hard to evaluate all the benefits of nuclear physics as an enabling science.

NUCLEAR PHYSICS AND CIVILISATION

The various types of radiation generated by nuclear reactions are increasingly employed to change materials in a beneficial way, whether it is to kill pathogens or malignant tumour cells, or to induce chemical reactions of industrial importance. And, of course, nuclear energy is likely to become a major source of power that will be needed in underpin human progress in an increasingly challenging and complex environment.

NUCLEAR PHYSICS AND CULTURE

Finally, nuclear physics also offers the means by which we can understand better the Universe and our own place in it – the evolution of stars and planets including the Earth, and how life came to be. It has provided many of the tools needed to explore our past and cultural heritage, and may well provide some of the solutions to ensure the long-term future of humankind, whether here on Earth or even beyond in space.

The following chapters provide a more detailed account of the role that nuclear physics plays in the world around us, and in the many applications and technologies that enhance our lives.

FURTHER INFORMATION

Nucleus: A Trip Into the Heart of Matter, Ray Mackintosh, Jim Al-Khalili, Björn Jonson and M.T. Pena, Johns Hopkins University Press, second edition, 31 December, 2011, ISBN-13: 978-1421403519.

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CHAPTER 2:

RADIOACTIVITY

RADIOACTIVITY IS A FUNDAMENTAL PHENOMENON THAT HAS SHAPED THE UNIVERSE AND IS AN INTEGRAL AND INEVITABLE PART OF OUR WORLD. IT HELPED TO FORM THE TERRESTRIAL ENVIRONMENT AND PROBABLY PLAYED A PART IN THE EVOLUTION OF LIFE. TODAY, WE HAVE LEARNT TO EXPLOIT THE BENEFICIAL EFFECTS OF RADIOACTIVE MATERIALS AND BEHAVIOUR WHILE OPTIMISING THE MEANS OF PROTECTION FROM ITS MORE EXTREME EFFECTS.

Ascribing the term 'radioactive' to any material or object tends to fill many people with some alarm. They associate radioactivity with the potentially harmful biological effects caused by (very rare) leaks from nuclear power stations or the long-term emissions from nuclear waste, regarded as difficult to manage. Furthermore, the secure transport and use of radioactive materials is often mentioned as a concern. The result is that many developed countries have become extremely cautious about investing in and applying new technologies that exploit nuclear science because the associated phenomena generally involve some kind of radioactivity.

We are all bathed in radiation from the Sun and from the Earth itself.

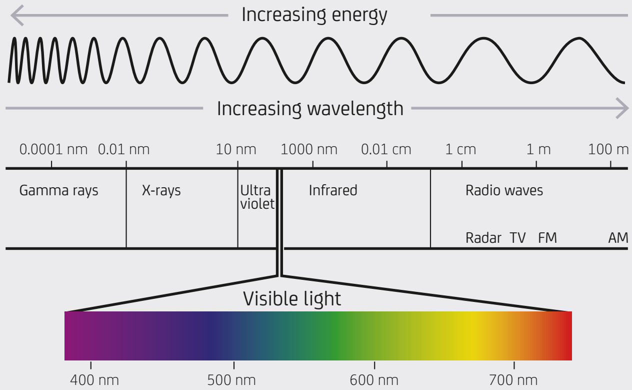
However, as the following chapters in this report will show, the understanding and application of diverse radioactive effects can be hugely beneficial. New technologies are allowing them to be controlled and manipulated, not only to provide carbon-free power sources but also as analytical tools, and – most important – to improve human health.

WHAT IS RADIOACTIVITY?

Radioactivity refers to the general phenomenon of the emission of radiation by atomic nuclei that are inherently unstable. As explained in the Introduction, some 7000 different types of nuclei can theoretically exist, defined by the proportions of protons and neutrons they contain. They are held together by the strong nuclear force, which gathers them into complex arrangements of varying stability. In general, if a nucleus has too high a proportion of neutrons or protons for its mass, it undergoes some kind of disintegration, transmuting to a lower-mass nucleus with the emission of high-energy particles, or radiation. If the 'daughter' nucleus that forms is also unstable, then further decay occurs accompanied by radiation emissions, sometimes leading to a chain of nuclear transmutations before a stable and lighter atomic nucleus is reached.

WHAT DO WE MEAN BY RADIATION?

Radiation refers to any form of energy or matter that is directly transmitted across space. It is mostly in the form of waves but can also be as beams of atomic and nuclear particles (which according to quantum theory also behave as waves). We are continually bathed in radiation of one kind or another – from the Sun and distant space, from the Earth itself and all the objects around us including ourselves. The most common form of radiation are electromagnetic waves, visible light being an everyday example. Electromagnetic wavelengths cover a huge range from radio waves kilometres long, through millimetre wavelengths (at which mobile phones operate), microwaves (as in ovens), to the infrared red, visible light and ultraviolet regions. Beyond are the much shorter wavelengths of the X-ray region, and finally gamma-rays with the shortest wavelengths – in the range from nanometres (billionths of a metre) to picometres (million millionths of a metre). As the wavelength becomes shorter so the energy carried by the radiation increases and the more penetrating it becomes. In general, it is only the shortest wavelength radiation – far-ultraviolet wavelengths, X-rays and gamma-rays – that is energetic enough to penetrate and damage biological tissue. Indeed, gamma-rays are emitted only in nuclear reactions, which are effectively governed by the nuclear forces, and is why they are so energetic. Gamma-rays are a significant component of radioactivity.



The electromagnetic spectrum.

There are other types of radiation, which are composed of subatomic particles. They include electrons, positrons (antimatter versions of electrons), protons, neutrons, atomic nuclei and more exotic subatomic particles such as pions, muons and neutrinos. Some are produced during radioactive decay (see below). Others are also produced artificially in the laboratory through nuclear reactions, and also in natural astrophysical processes.

TYPES OF RADIOACTIVE DECAY

Unstable nuclei can undergo several types of decay or disintegration, the most common producing radiations designated by the first three letters of the Greek alphabet: alpha (α), beta (β) and gamma (γ).

Alpha radiation is composed of helium nuclei, that is two protons and two neutrons. The emission of alpha particles from a nucleus results in its transmutation into the nucleus of an element with an atomic number 2 lower and an atomic mass of 4 lower. For example, polonium-210, with atomic number 84 (84 protons and 126 neutrons), decays to stable lead-206 with atomic number 82 (82 protons and 124 neutrons). Alpha radiation is mostly emitted by radioactive isotopes of the heavier elements at the bottom of the Periodic Table, such as radium, polonium and uranium.

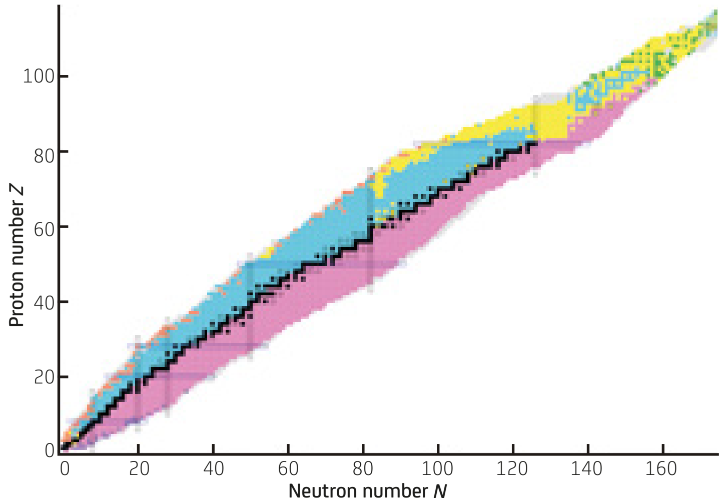
Beta radiation consists of negatively charged electrons or positively charged positrons (the positively charged, antimatter version of the electron). In the first case, electrons are released by a process by which one of the electrically neutral neutrons in the nucleus is transformed into a positively charged proton. At the same time, a neutral electron-antineutrino is also emitted. (Neutrinos and their antimatter versions are almost massless neutral particles that pass through matter without interacting with it, so play no part in the effects of radioactivity.) Beta decay results in the transmutation of a nucleus into one with a higher atomic number but the same mass (protons and neutrons have the same mass). For example, strontium-90, with 38 protons and 52 neutrons, undergoes beta emission to yttrium-90 with 39 protons and 51 neutrons.

The other variety of beta decay happens in unstable, proton-rich nuclei when a proton transforms into a neutron, resulting in the emission of a positron, together with an electron-neutrino. This time, the resulting nucleus is thus one atomic number lower. Fluorine-18 is a typical positron emitter and is used in a type of medical imaging – positron emission tomography, or PET, (Chapter 6).

The final common form of radiation are gamma-rays, which are frequently emitted by a nucleus undergoing a nuclear reaction such as radioactive decay. The resulting new nuclei may lose excess energy via the emission of gamma-rays. These have an energy and wavelength that relates to the characteristic energy levels of the nuclei involved and therefore their structure. Analysing the gamma radiation thus tells us something about the nature of the nuclei and the reactions that have occurred.

Other types of radioactivity are possible. Nuclei with very high proportions of neutrons can eject one or several neutrons after beta-decay. Nuclei with a very large excess of protons can spontaneously emit one or two protons or even heavier nuclei like carbon-14 (six protons and eight neutrons). Of course, it is well understood that some heavy, neutron-rich nuclei such as uranium-235 can fission into smaller nuclei (sometimes spontaneously) when bombarded by neutrons, with the emission of neutrons and gamma-rays, leading to a self-sustaining nuclear reaction under the right conditions (Chapter 5).

There are also more subtle radioactive decay modes. Nuclear physicists study these modes, often using accelerated particle beams to induce various nuclear reactions and create new isotopes. These experiments enable them to build up a detailed understanding of nuclear structure and behaviour that both benefit our understanding of matter at a fundamental level, and create a knowledge base for nuclear technologies and applications.



RADIOACTIVE DECAY MODES	NUCLEAR SOURCE
Stable, no decay	Low-to-medium mass nuclei with more equal numbers of protons and neutrons (though the relative proportion of neutrons slowly increases with nuclear mass)
Alpha (helium nuclei)	High-mass nuclei
Beta minus (electrons)	More neutron-rich nuclei
Proton	Lower-to-medium mass, proton-rich nuclei
Neutron	Lower-mass, neutron-rich nuclei
Spontaneous fission	Very-high-mass nuclei
Unknown decay mode	Nuclei with very extreme proportions of neutrons or protons

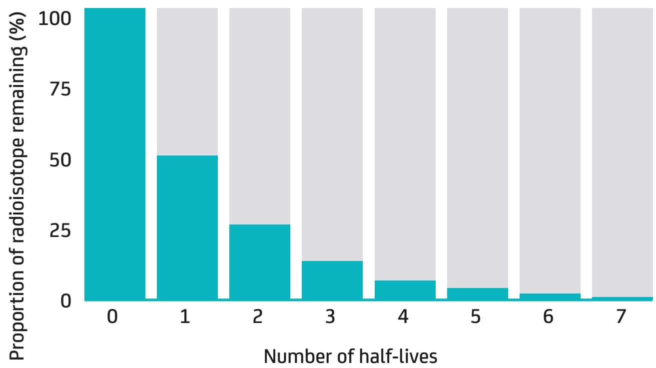
Note that gamma-rays are emitted during most radioactive decay processes.

The nuclear chart, as in Chapter 1, but showing the different decay modes undergone by nuclei, depending upon their mass and proportions of protons and neutrons they contain.

RADIOACTIVE HALF-LIVES AND RADIOACTIVITY MEASUREMENTS

The stability of a nucleus is indicated by its half-life, which is the amount of time taken for half the nuclei in a sample to decay. The decay process is entirely random, so the half-life provides a way of quantifying the 50-per-cent probability of a nuclear decay happening within a given time. This overall rate is unaffected by external influences such as temperature, pressure and chemical environment. Half-lives can vary hugely from a fraction of a second to the age of the Universe. For example, the half-life of iodine-131 is about 8 days, while potassium-40 – one of the main sources of radioactivity in our bodies – has a half-life of 1.42 billion years. The isotopes commonly used in industry and medicine generally have half-lives from a few hours to a few days or months. Generally, the shorter the half-life the more intense is the radioactivity of a sample.

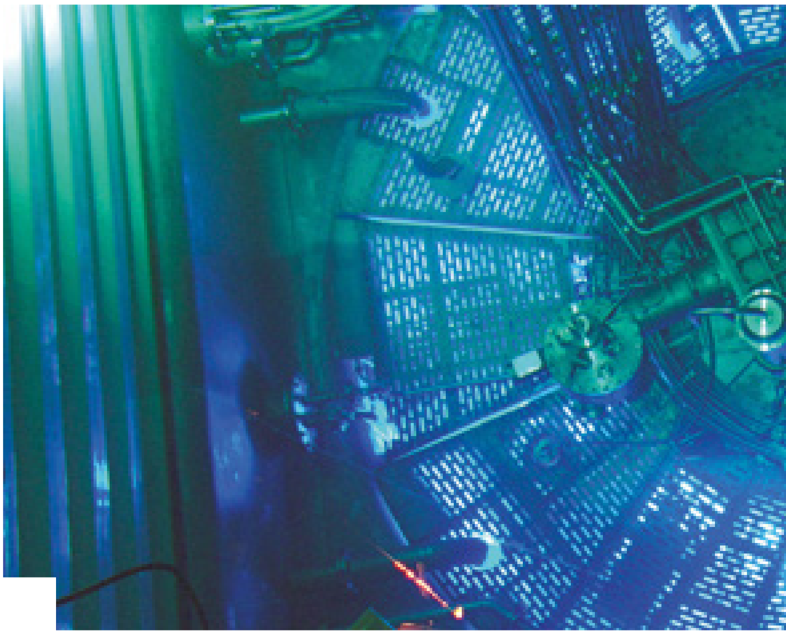
THE RATE OF RADIOACTIVE DECAY



The first method of measuring the intensity of radioactivity was based on the amount of radioactive decays in one gramme of radium (the first radioactive material to be discovered by Marie Skłodowska-Curie and Pierre Curie at the turn of the 20th century) in one second, and was called the curie (Ci). Today, the standard way of measuring radioactivity is by counting the number of single nuclear disintegrations per second. This is denoted by the international unit, the becquerel (Bq), after the physicist Henri Becquerel who first observed radiation emitted from uranium salts. One curie is equivalent to 37 billion (3.7×10^{10}) disintegrations per second, or 37 billion becquerels. The typical natural radioactivity emitted by human body is 8000 becquerels (8 kBq). Significantly, for technology and medicine, radioactivity has other several units associated with it that measure its effects on the environment and on people.

EFFECTS OF RADIOACTIVITY ON MATTER

The various types of high-energy radiation associated with radioactivity penetrate and interact strongly with matter. When they impinge upon a material, they may cause electrons in the material's atoms to be excited to a higher quantum energy level, such that when the electrons then fall back to a lower energy state they emit light with a characteristic wavelength – this effect was exploited in the vintage wristwatches that had numerals painted in radioactive paint (containing alpha-emitting radium-226) so that they could glow in the dark.



UNITS THAT MEASURE THE EFFECTS OF RADIOACTIVITY

EXPOSURE

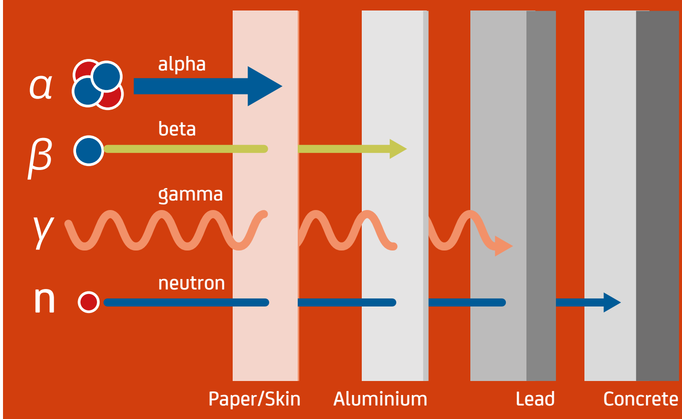
This refers to the amount of ionisation caused by radiation in a given volume and mass of air, and so measures initial exposure.
Units: the coulomb/kilogramme (C/kg, the official international unit) or the roentgen (R, US unit).

ABSORBED DOSE

This describes the amount of radiation absorbed by an object or organism.
Units: the gray (Gy, international unit) or the rad (still used in the US). One gray is equal to 100 rads.

EFFECTIVE DOSE

This measures the biological effects of radiation on an organism subject to exposure (depending on its nature and the organs exposed) and is generally expressed as ‘equivalent dose’ or ‘effective dose’.
Units: the sievert (Sv, international unit) or the rem (US unit). (A typical adult chest X-ray gives a dose of 0.1 mSv.)



TYPES OF RADIATION AND THEIR ABILITY TO PENETRATE PAPER, AN ALUMINIUM SHEET, AND THICK LEAD OR CONCRETE.
ALPHA PARTICLES (helium nuclei) have very little penetration in air; a single sheet of paper is enough to stop them.
BETA PARTICLES (electrons) have a range of a few metres in air, and an aluminium sheet a few millimetres thick will stop them.
GAMMA-RAYS have deeper penetration depending on their energy, with a range of several hundred metres in air; thick lead or concrete shielding is needed to stop them.
For NEUTRONS, their penetration also depends on their energy, but they will be blocked by a thick concrete, water or paraffin barrier.

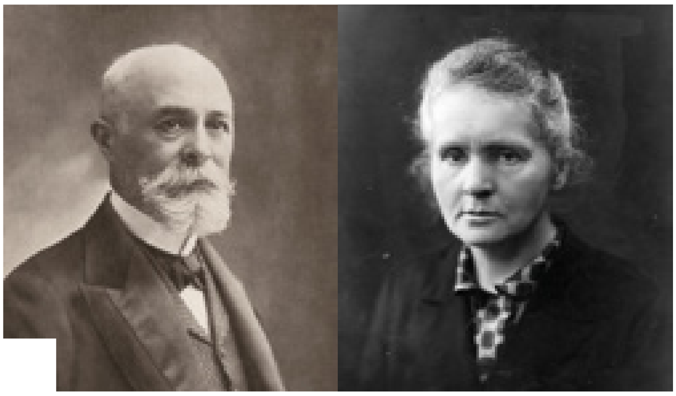
Atomic electrons may be completely knocked out by radiation, resulting in ionisation (the formation of charged atoms, or ions) and the breaking of chemical bonds in molecules, causing affected materials to degrade. Ionising radiation can have a particularly devastating effect on biological matter, by damaging or breaking up biomolecules such as DNA, thus causing genetic mutations or killing cells. This effect is, however, very successfully employed in radiation and particle therapy to destroy cancer tumours (Chapter 6).

Of the main kinds of radioactivity, alpha particles have the least penetrating power and will hardly pass through a piece of paper, beta particles are more penetrating to a depth of few millimetres in light metals like aluminium, while gamma radiation is the most penetrating and requires thick lead shielding to block it. However, it is worth noting that beta radiation can cause secondary gamma-rays and X-rays (also penetrating and ionising) to be emitted in materials they pass through. In the swimming-pool-size cooling tanks of nuclear reactors, you can also see a glow of blue light called Cherenkov radiation, which is triggered by beta rays from the radioactive isotopes in the spent fuel, as they pass through the water in the pool. However, the neutrinos, also emitted in beta radiation, have virtually no mass and are neutral, so pass straight through matter with no discernible effect. Neutrons are also penetrating and can be exploited, like X-rays, in analysing and imaging material samples. In terms of the severity of ionisation effects, the order is reversed, and is the reason why alpha-emitting isotopes are only toxic when ingested. However, although not directly ionising, neutrons can interact with matter to give rise to secondary radiation (alpha, beta, gamma-rays, X-rays) which then causes ionisation.

The cooling tanks of a nuclear reactor illuminated by the blue Cherenkov radiation emitted. **[Credit Institut Laue-Langevin].**

LIVING WITH RADIOACTIVITY

It was at the end of the 19th century that scientists became aware of the phenomenon of radioactivity. They soon realised that elements could exist in several versions and that some of these isotopes were unstable. Those studies ultimately led to our modern understanding of the building blocks of matter and their behaviour at the most fundamental level. Their painstaking work underpins the modern world.



The French scientist Henri Becquerel (left) and Marie Skłodowska Curie, together with her husband Pierre Curie, carried out the pioneering work on radioactivity for which they won the Nobel Prize for Physics in 1903.

NATURAL RADIATION SOURCES

Today, we know of 28 elements with radioisotopes that have existed naturally on Earth since primordial times. More have come into existence during its lifespan, either through natural radioactive processes in the Earth – from the decay of geological uranium-235 and 238 and thorium-232. An example is the radioactive gas radon-222. Radioactive isotopes like carbon-14 are created in the atmosphere by the impact of high-energy radiation from space. Ongoing radioactivity is thus a natural part of our everyday environment.

RADIATION FROM SPACE

In fact, our planet receives large amounts of high-energy radiation, particularly from the Sun which emits particles like protons. The Earth is also constantly being bombarded by very energetic particles coming from the furthest reaches of our Galaxy and even beyond. These cosmic rays include protons, alpha particles and heavier nuclei. They can have extremely high energies, having been created in a variety of exotic ways – from the spectacular explosions of massive stars (supernovae), supermassive galactic black holes and neutron star/black-hole collisions. When these primary cosmic rays collide with the atomic nuclei of atmospheric gases like those of oxygen and nitrogen, they give rise to a shower of secondary particles both charged and neutral. They include pions and muons, and other exotic particles. While the Earth's magnetic field deflects most of these particles, many do reach the ground, where the flux is about 240 per square metre per second. The result is that, inevitably, hundreds of these particles pass through our bodies every second. In addition, 65 billion neutrinos sail through a square centimetre of our skin every second, as if we were transparent. In fact, neutrinos interact so little, that among the 100,000 billion neutrinos emitted by the Sun and passing through the Earth, one – or less than one – interacts with terrestrial matter.

Since the Earth's magnetic field attenuates with altitude, the cosmic particle flux also increases with altitude such that radiation levels rise to double at 1500 metres above sea level. Furthermore, as the atmosphere becomes thinner, the fewer air molecules there are to interact with radiation from space. This means that we are exposed to more cosmic radiation during air travel. A return flight across the Atlantic results in an exposure of about 0.1 millisieverts, equivalent to five chest X-rays. Even without getting on a plane, we are still exposed to radiation. People living high up in the Andes or the Himalayas are exposed to four times as much cosmic radiation as the inhabitants of Paris, London or New York. The annual exposure to cosmic radiation at sea level is roughly 0.27 millisieverts, a figure that takes into account the protection offered by buildings. The average dose absorbed in this way by an individual is extremely hard to calculate, given the large number of factors involved. In France, for example, this figure has been calculated to be around 0.30 millisieverts a year.

Frequent air travel increases exposure to cosmic radiation.

RADIOACTIVITY AND THE EARTH

You might be surprised to learn that naturally occurring radioactive isotopes, such as uranium-238, within the Earth itself have played and continue to play the major role in the evolution of the Earth (Chapter 4). The energy liberated by radioactivity is one of the driving forces behind geological activity such as the movement of tectonic plates, mountain-building and so on, and thus creating a dynamic environment that affects global water flows and geochemistry. Furthermore, radioactivity in the Earth's crust is responsible for generating a significant proportion of the heat that keeps the Earth habitable for us.

There is one naturally occurring radioactive isotope, radon-222, that affects us more than others. This gas is the end-product of a decay-chain starting with uranium-238, which first transmutes into radium-226. It escapes from granite rock, which contains small amounts of uranium. Studies in Norway have shown that levels in domestic and workplace environments there can reach 400 becquerels per square centimetre, and miners can suffer even greater exposure. Since it is known that inhaling radon and its decay products is a leading cause of lung cancer (after tobacco smoking), precautions are taken in granite-based areas to prevent radon from seeping into houses. In general, amounts are not high enough to cause harm.

Radon can seep into houses built on granite, as in Cornwall in the UK.

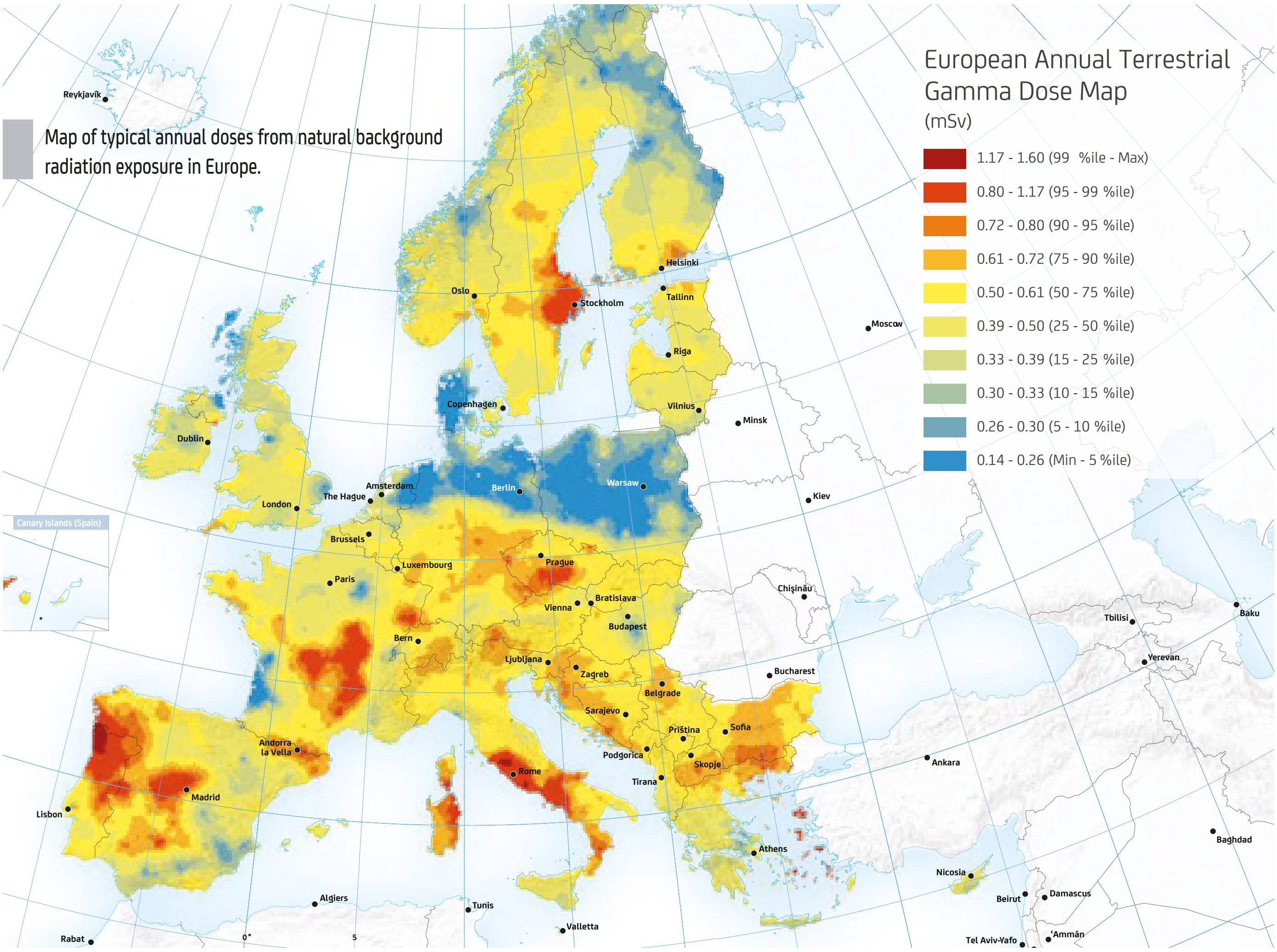
Natural radioactivity is still the principal source of radiation exposure. For example, in France, the exposure dose is 2.4 millisieverts per person per year, as opposed to 1 millisieverts from medical examinations. This is, of course, an average, and location and lifestyle play equal roles in determining the level of exposure. Where you live, travel, and even whether or not you use air-conditioning are all important factors. The food we eat and the air we breathe contain radioactive elements. There is absolutely no way to escape from them: even we are radioactive! Typically, 8000 atoms of natural potassium-40 and carbon-14 disintegrate in our bodies every second! In general, natural radioactivity does us little harm. It is an integral part of life.

INDUCED RADIOACTIVITY

For almost a century, humanity has been exposed to radiation sources other than those occurring naturally. These new sources, except of course those related to nuclear weapons, are almost all for our benefit, with a large number of medical advances resulting in higher levels of exposure. The most common form of radiation in medicine is of course X-rays, which are not in this context generated by nuclear reactions but from interactions within the electronic shells of atoms. Despite their differing origins, X-rays and alpha/beta/gamma rays all have similar effects on living tissue. As a result, they are often grouped together when discussing protection from overexposure.

Of the 3 millisieverts originating from non-natural sources in the world (6.24 millisieverts in the US), the non-medical contribution is estimated to be 0.050 millisieverts. This dose comes from such diverse sources as computer screens, televisions, smoke detectors and illuminated dials. Contrary to urban myths, nuclear power stations and the remnants from atomic bomb tests amount to less than 0.020 millisieverts – that is, 1 or 2 per cent of the total dose. This low figure is a result of the great precautions taken at the heart of nuclear reactors to isolate all radioactive material present. People living close to nuclear reactors receive, over a whole year, just one-third of the radiation experienced on a single transatlantic flight.

Even with all our new inventions, naturally occurring radiation still remains the primary source of exposure.



Map of typical annual doses from natural background radiation exposure in Europe.

RADIOACTIVITY AND HUMAN HEALTH

Large doses of radioactivity can be deadly and thousands of people died from radiation as a result of the nuclear bombs dropped on Japan in 1945. More recently, in 1986, 28 people were killed by radiation when the Chernobyl nuclear power plant in the Ukraine blew up. There were also considerable health problems in the surrounding population afterwards.

The amounts of radiation that are known to damage health are far greater than the background radiation from cosmic rays, rocks and so on. Any of our cells that might be damaged by these sources can repair themselves, because only a few will be affected. In the case of bigger doses of radiation, a large number of cells are damaged beyond repair, which is why it can be dangerous. We know that plants and animals have been living and evolving with radioactivity for billions of years. So, whether radioactivity is dangerous depends on how much we receive. Even too much common salt can kill us, which is why people adrift on the ocean can die of thirst! As they say, too much of anything is a bad thing.

RADIATION PROTECTION

Over the years, as more was learned, scientists became increasingly concerned about the potentially damaging effects of exposure to large doses of radiation. The need to regulate exposure to radiation prompted the formation of a number of expert bodies to consider what is needed to be done. In 1928, an independent non-governmental body of experts in the field, the International X-ray and Radium Protection Committee, was established. It later was renamed the International Commission on Radiological Protection (ICRP). Its purpose is to establish basic principles for, and to issue recommendations on, radiation protection. These principles and recommendations form the basis for national regulations governing the exposure of radiation workers and members of the public. The standards are used worldwide to ensure safety and radiation protection of radiation workers and the general public.

Basic approaches to radiation protection are consistent all over the world. The ICRP recommends that any exposure above the natural background radiation should be kept as low as reasonably achievable, but below the individual dose limits. The individual dose limit for radiation workers averaged over 5 years is 100 millisieverts, and for members of the general public, is 1 millisievert per year. These dose limits have been established based on a prudent approach by assuming that there is no threshold dose below which there would be no effect. It means that any additional dose will cause a proportional increase in the chance of a health effect. This relationship has not yet been established in the low-dose range where the dose limits have been set.

BENEFITS AND RISKS

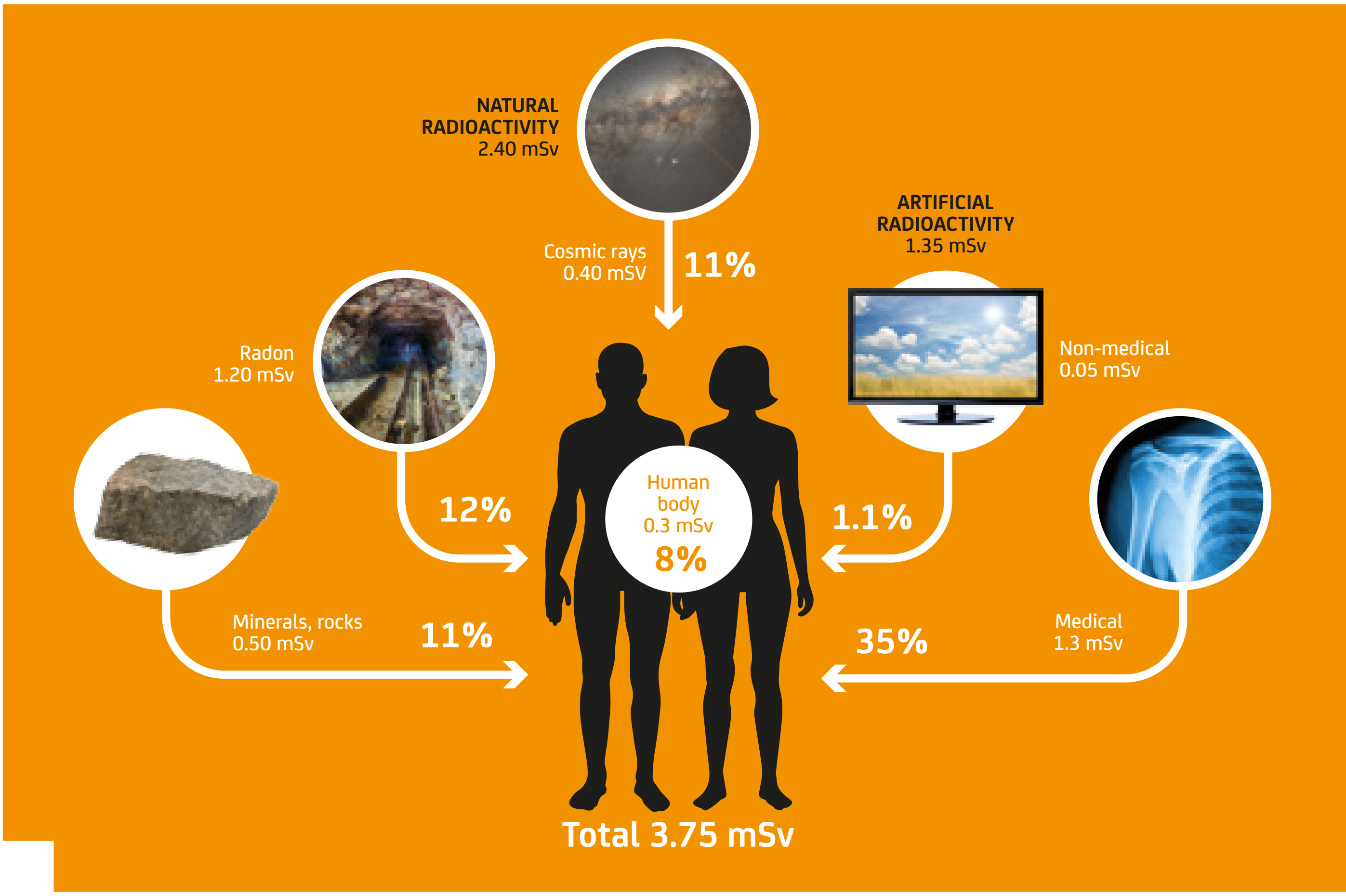
The energy we receive from the Sun comes from one comparatively simple reaction: the fusion of two hydrogen nuclei into another, heavier nucleus. This reaction, involving the same forces as those responsible for radioactivity, is what has allowed elements other than hydrogen to be generated. Without it, the great matter factories of the stars would not be able to build the heavier elements that make up our Universe (see Chapter 3).

Without radioactivity, our planet would have frozen over long ago and life on Earth would be impossible. Radioactive processes in the Earth's core slowly release the heat essential for our survival, constantly maintaining the temperate climate we take for granted (see Chapter 4). All life has developed in a constant shower of radiations, adapting to it and occasionally using it for its own benefit.

Radioactivity from the Earth's core helps keep our planet habitable.

Radioactivity is an omnipresent, inescapable feature of our lives. Whether we go on mountain-climbing expeditions, go down to the cellar to get a bottle of wine, or get aboard a plane, we will always be exposed to it. Even our bodies are radioactive, containing as they do millions of atoms of radioactive substances such as potassium-40.

Apart from the countless natural sources of exposure, the harnessing of radiation by humanity has led to a multitude of applications that we use every day. Even though the main artificially generated exposure comes from medical examinations and treatments, we also use radioactive substances and radiations to sterilise food, so prolonging its shelf-life. We must not forget, however, that all these common sources of radiation, whether natural or artificial, remain virtually harmless.



Sources of radiation contributing to an adult average annual dose in Europe (mSv).

We all face risks in everyday life. It is impossible to eliminate them all, but it is possible to reduce them. The use of nuclear energy for electricity production (Chapter 5), for example, is associated with some sort of risk to health, however small. In general, society accepts the associated risk in order to derive the relevant benefits. Exposure to carcinogenic pollutants will carry some risk of getting cancer for an individual. Strenuous attempts are made in nuclear medicine and industry to reduce such risks to as lower level as is reasonably achievable.

The use of radiation and nuclear techniques in medicine, industry, agriculture, energy and other scientific and technological fields has brought tremendous benefits to society. The benefits in medicine for diagnosis and treatment in terms of human lives saved are enormous (Chapter 6). Radiation is a key tool in the treatment of certain kinds of cancer. Three out of every four patients hospitalised in developed countries benefit from some form of nuclear medicine. The beneficial impacts in other fields are similar.

No human activity or practice is totally devoid of associated risks. Radiation should be viewed from the perspective that its benefits are much greater than any negative effects. Indeed, the effects of radiation and radioactivity are considerably less harmful than those from many other agents affecting our lives.

FURTHER INFORMATION

https://www.radioactivity.eu.com
http://nupex.eu
https://www.iaea.org/Publications/Factsheets/English/radlife#types

CHAPTER 3:

THE ORIGIN OF THE ELEMENTS

Our home galaxy, the Milky Way, contains between 100 billion and 400 billion stars, and also black holes and dust clouds. This is where the elements are made. **[Credit ESO/Yuri Beletsky].**

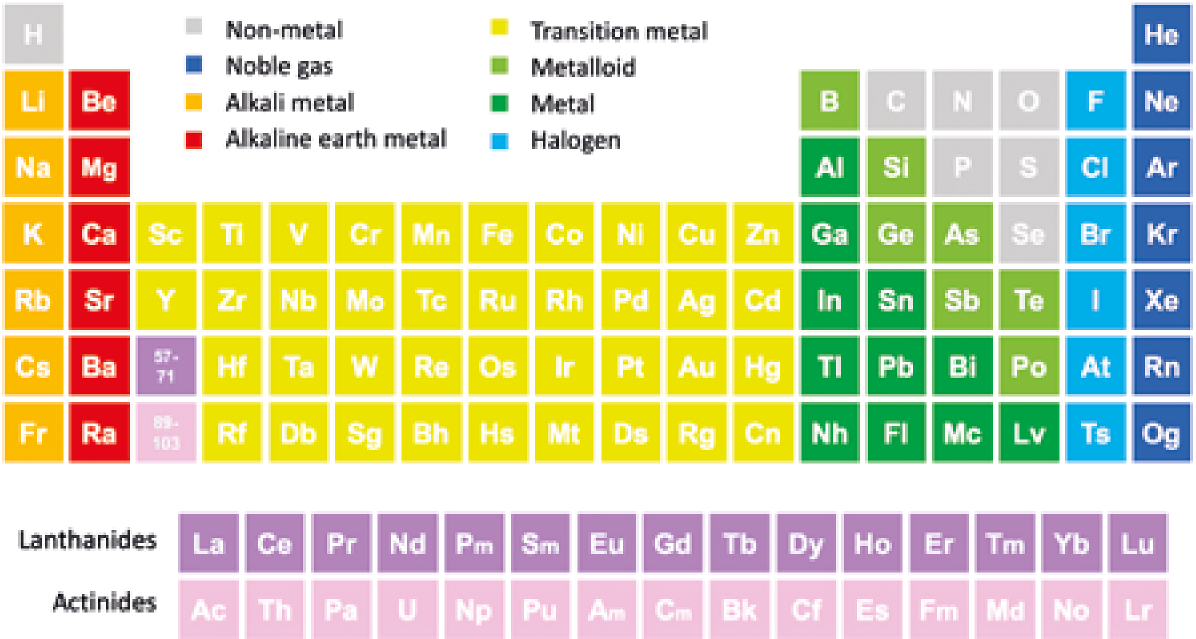
THE CONNECTION BETWEEN PEOPLE, EVERYDAY LIFE AND NUCLEAR PHYSICS COULD NOT BE MADE CLEARER THAN THROUGH EXPLORING THE NUCLEAR PROCESSES BY WHICH THE ELEMENTS WERE MADE IN THE STARS.

During the past 200 years, we have built up a remarkably clear and fascinating picture of our everyday world at the most fundamental level. We know that the huge diversity we see in the materials and objects around us, including ourselves, is the result of what seems an almost infinite number of chemical combinations of basic building blocks known as elements. From the 17th century onwards, European scientists masterfully studied the physical and chemical properties of a wide range of substances, identifying various elements and looking for patterns within their reactivity and behaviour. The result was the all-encompassing Periodic Table of elements, first formulated by the Russian chemist Dmitri Mendeleev in 1871. It was a remarkable story of scientific detective work; it has furnished an incredible framework of knowledge about these building blocks upon which modern technology is based.

In the late 19th and early 20th centuries, the Periodic Table was shown to consist of 92 elements – most found naturally on Earth – of gradually increasing mass, ranging from the lightest elements hydrogen and helium to uranium, then the heaviest identified (though trace amounts of heavier elements plutonium and neptunium were also discovered later in the Earth).

This knowledge provided the gateway to a much deeper understanding of Nature's building blocks. As explained in Chapter 1, it became clear that the type of atom characterising each element was composed of further subatomic units – electrons orbiting an atomic nucleus consisting of positive protons and neutral neutrons. Most significantly, each element was defined according to the number of protons in its atoms, with the number of neutrons varying to generate more than one version, or isotope of an element.

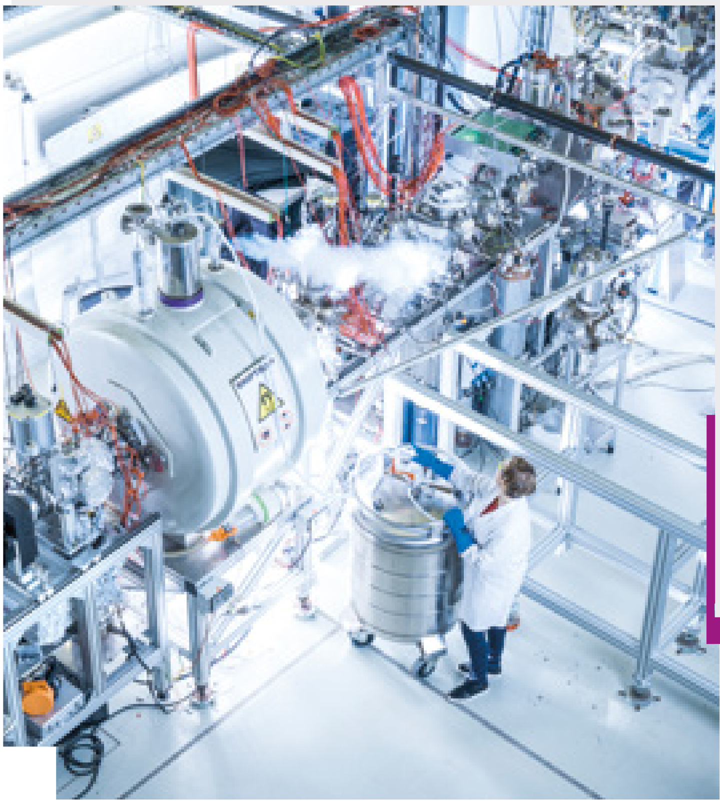
Our modern understanding of the origin and abundance of the elements and their isotopes comes from the detailed study of reactions between nuclei that occur in the ultimate cosmic sources of the elements – the stars.



The Periodic Table of Elements.

NEW ELEMENTS OF THE PERIODIC TABLE

There were still two gaps in the Periodic Table, even as recently as the 1940s when technetium and promethium (atomic numbers 43 and 61) were isolated from the products of uranium fission. They were the first elements to be made artificially. All the isotopes of both elements are unstable and therefore radioactive. Thus, only the minutest quantities have been found on Earth, formed by the radioactive decay of uranium isotopes (Chapter 3).



Today, an increasing number of new, much heavier elements have been added to the Periodic Table. They have been created in the laboratory using nuclear reactors or particle accelerators, reaching up to atomic number 118. Examples are the synthetic elements, americium (atomic number 95), and curium (atomic number 96). All elements beyond uranium are radioactive, generally with increasingly shorter half-lives that mostly range from minutes to milliseconds (see Chapter 2). This means most of the transuranium elements (apart from plutonium, see Chapter 5) currently have little practical use – although americium has been utilised in smoke detectors, and both americium and curium find use as nuclear fuel sources for space applications (Chapter 9). Nuclear physicists still investigate the so-called superheavy elements in order to understand better the fundamental forces that bind nucleons together. In fact, theoretical models describing the formation of nuclei have predicted there should be a group of very long-lived superheavy elements starting at around atomic number 114 and going up to 120. Several laboratories around the world – in Germany, the US, Russia and Japan – have managed to make a few atoms of each of these elements but none has proved to be even remotely stable so far.

Superheavy elements that do not exist in Nature are made in collisions between heavy nuclei in laboratories such as the GSI Helmholtz Centre for Heavy Ion Research in Germany. **[Credit GSI].**

THE ELEMENTS AND CIVILISATION

In the case of the more common stable elements found on Earth, their discovery and use have shaped the progress of humanity. The first elements isolated were metals – with copper (atomic number 29) most probably mined and used as long ago as 9000 BC. Indeed, the period of technical and cultural advancement that represented the first step-jump in human progress, the Bronze Age from about 3300 to 1200 BC, is characterised by the extensive use of copper to make the bronze alloy. Gold (atomic number 79) would have also been discovered early in human history because its lack of reactivity, which means it can exist on the surface of the Earth in its elemental form. Its reflective beauty, relative rarity and malleable nature have meant that gold has always been highly prized for decoration. Indeed, its high value has been the basis for trade and national economies for millennia, and still is today.

Las Médulas mining site in Spain, where the Romans carried out open-pit gold mining. **[Credit Rafael Ibáñez Fernández].**

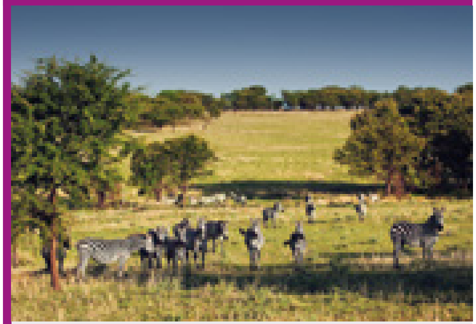
The later discovery of iron (atomic number 26), most likely first in meteorites, and the ability to smelt iron ore, marked the start of the Iron Age, from about 1500 BC, which of course had a huge effect on civilisations that learnt to craft and shape the metal. In more modern times, the Industrial Revolution of the 19th century, and all the mass production technologies that developed as a result, are unimaginable without iron.

Today, the world economy is increasingly controlled by another element, silicon (atomic number 14). Extremely abundant in the Earth's crust, its electronic properties have meant that it has become the workhorse of the information technology age. The discovery and isolation of many other elements throughout human history have had dramatic effects on its course and continue to influence global economies. They include the identification of the lightest metal, lithium (atomic number 3), now used in batteries, and boron (atomic number 5), to the much heavier trace elements such as europium, terbium, gadolinium and dysprosium (atomic numbers 63 to 66) that now find their way into electronic devices such as your smart phone.

WHERE DO THE ELEMENTS COME FROM?

Human progress is clearly tied to the extensive use of particular elements, which is thus also linked to their availability and their relative abundance. On Earth, elements (usually chemically bound) like hydrogen, carbon, nitrogen, oxygen, aluminium, silicon and iron, are extremely common, being major constituents of the Earth's lithosphere, oceans and atmosphere. Many of the heavier elements are extremely rare – in fact, the heaviest are known as 'rare earths'. The rarest element found on Earth is astatine (atomic number 85) with only a few grams in existence. All its isotopes are radioactive and are created by the decay of other radioactive elements in the Earth's crust (see Chapter 4). Although predicted to exist (there was a gap in the Periodic Table for it), it was actually discovered via a nuclear reaction in the 1940s, in which an isotope of bismuth was bombarded with alpha particles (helium nuclei) in a particle accelerator, before being later discovered in Nature.

THE ELEMENTS OF LIFE



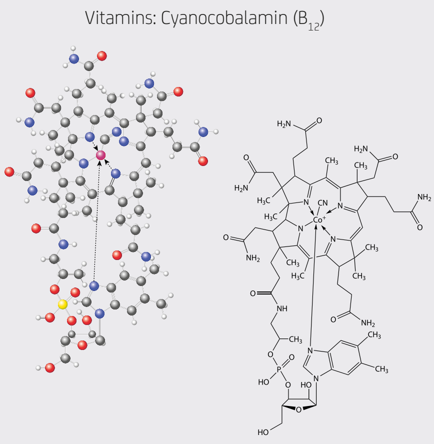
Perhaps the most rewarding aspect of studying nucleosynthesis in the stars is that it reveals the deep connection with ourselves and our natural world. Life on Earth is built from complex chemical units based on carbon's versatile ability to bond with other common elements – in particular, hydrogen, oxygen and nitrogen.

Hydrogen is most common element in Universe, being the starting fuel for making the elements. It is, of course, a component of water without which there would be no life. Particularly important in living processes is the subtle behaviour of single hydrogen atoms (protons) in mediating the essential behaviour of large biological molecules such as proteins in living processes.

Carbon, nitrogen and oxygen were created in large quantities in stellar processes. Carbon is the fifth most abundant element in the Universe, and certain types of red giants accumulated large amounts of carbon. What is extraordinary is that the starting reaction for making carbon – the triple-alpha reaction – depends on just one particular nuclear energy state of carbon. If that had not existed, you and I would not exist either. Nitrogen is the seventh most abundant in the Universe and oxygen is the third most abundant, both created via fusion reactions in most stars.

A huge variety of other common elements are essential for life, including sodium, potassium and chlorine involved in nerve transmission, sulfur in various proteins, phosphorus in cell membranes, calcium in bones and iron in haemoglobin. In plants, magnesium is needed for chlorophyll in photosynthesis, and boron (made by cosmic-ray interactions) to build cell walls.

Less known is the fact that there are a huge variety of heavier trace elements that play a vital role in living processes. They include zinc found in certain proteins, cobalt in vitamin B12, and molybdenum used by certain microbes to fix nitrogen from the air and so improve soil fertility. Bacteria, in particular, are amazing chemical factories able to utilise many of the less common elements in unusual ways. It is extraordinary all these possibilities for the vast variety of life on Earth depend on the availability of elements made in the stars.



Vitamin B12 (made by gut bacteria in herbivores but not in humans) is essential for many metabolic functions in animals. The complex molecule contains a cobalt atom (red) as well as the familiar lighter elements associated with life.

It is clear that the abundances of the elements are linked to how they came into existence. To appreciate their origins means looking beyond the Earth to the Cosmos. As early as the beginning of the 1800s, scientists noted that the rainbow spectrum associated with Sun's light had dark lines cutting across it. They realised that this feature was due to the absorption of particular wavelengths of light, which were characteristic of the particular elements present in the outer layers of the Sun. In fact, the second heaviest element helium was discovered via its solar spectral absorption line. This very lightweight gas is relatively rare on Earth because it is chemically inert and not found in a bound state, and so would have long leaked away. The small amount of helium found in the Earth's atmosphere today comes from radioactive decay of thorium and uranium (see Chapter 4).

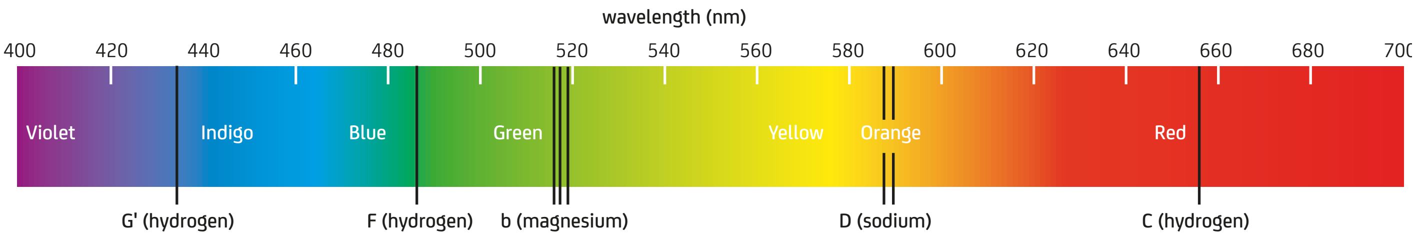
THE BIG BANG ELEMENTS

Through spectroscopy, we now know that the stars, as well as the space between the stars, contain the same elements as constitute the Earth. Over the past century or so, astronomical studies have revealed the relative abundances of the elements across the Universe. Hydrogen followed by helium are by far the most abundant. Today, we believe that hydrogen and helium, as the simplest atomic nuclei, were largely produced just minutes after the Big Bang, some 13.8 billion years ago, when all the basic building blocks of matter and energy came into existence. Protons, which are basically hydrogen nuclei, together with neutrons that also formed, would have fused into helium (two protons and two neutrons). Soon after the Big Bang, this primordial matter was pulled together by gravity to create the first large, luminous stars. The exact proportion of these elements we see in these stars is in perfect agreement with predictions of Big Bang theory, thus confirming this idea. There is just one snag remaining, however: the associated Big Bang nuclear physics also predicts that a small amount of lithium, the next lightest element after helium with three protons, (and possibly some beryllium with four protons) would have been generated too. Astronomical observations indicate that the primordial abundance of the lithium isotope that formed, lithium-7 (with four neutrons), is only a one-third of that predicted by the Big Bang model, and this is still one of the greatest enigmas of astrophysics.

STELLAR NUCLEOSYNTHESIS

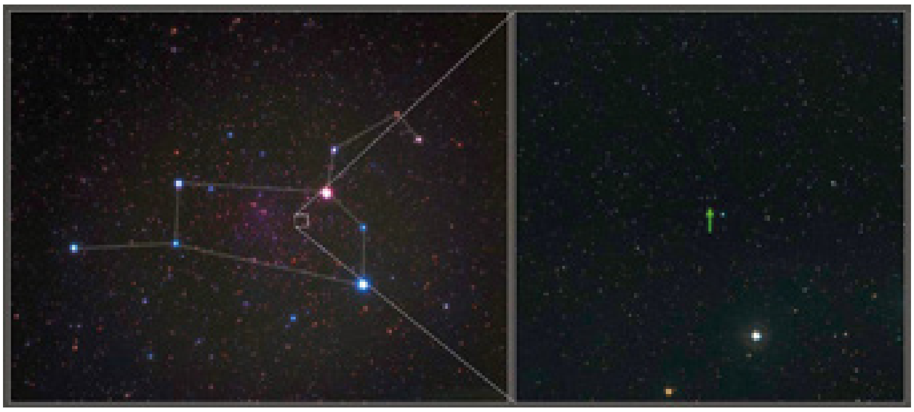
Nevertheless, despite some remaining anomalies and quite a few uncertainties, nuclear physicists who study the origin of the elements have developed some elegant descriptions of how the rest of the elements in the Periodic Table were created, and in doing so account for their abundances. Stars are giant, energy-generating nuclear cauldrons of matter tightly confined by the force of gravity. They are prevented from collapsing in on themselves by the outward pressure of energy released by the fusion of hydrogen into helium, followed by a series of nuclear reactions that lead to the formation of nuclei of increasingly heavy elements. This process is called nucleosynthesis. The heaviest elements are thought to be produced in some of the most violent astrophysical phenomena in the Universe, those associated with spectacular events in the later lives of stars.

The first stars were thus composed mostly of primordial hydrogen and helium, as observed in a star labelled as SDSS J102915+172927, and known as Caffau's Star. Located 4500 light years away in the constellation of the Lion, it is 13 billion years old, and has only one-millionth of the amount of the heavier elements observed in the spectrum of our much



The solar spectrum: the dark lines seen here are the result of elements absorbing light at characteristic wavelengths that depend on their atomic structure, and so provide 'fingerprints' of the elements present in the Sun.

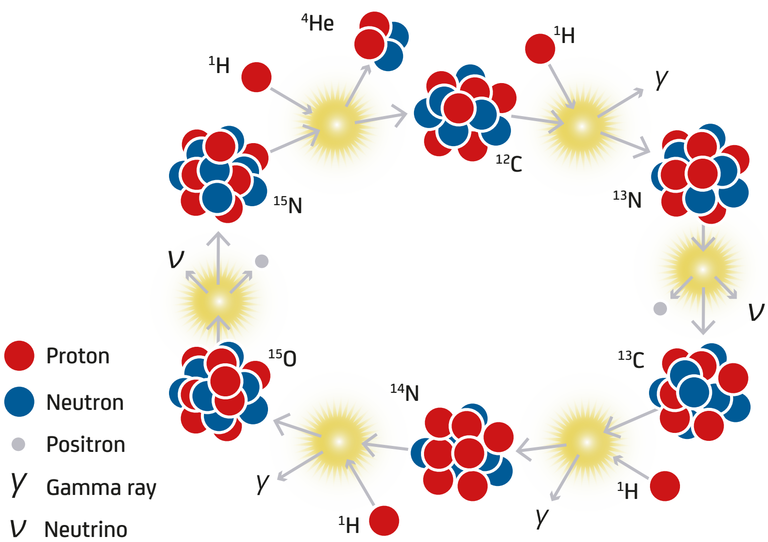
younger Sun (5 billion years old). Since then, as old stars died and new generations of stars formed from their dispersed remnants, the heavier elements created would have been incorporated into the new stars at birth, enriching their composition and modifying the kinds of nucleosynthesis undergone. In general, the main nucleosynthesis pathway peaks when it reaches iron. Indeed, a way to determine the age of a star is to measure its ratio of iron to hydrogen; the higher the ratio, the younger the star.



The faint star shown here, Caffau's Star, is one of the earliest stars so far observed, being 13 billion years old. It is composed mostly of hydrogen and helium. **[Credit ESO].**

HOW THE ELEMENTS ARE MADE

Stellar nucleosynthesis starts with the fusion of hydrogen into helium and is responsible for most of the energy generated in our Sun (see Chapter 4 for a description). In slightly more massive stars, it is thought that the carbon, nitrogen and oxygen nuclei (atomic numbers 6, 7 and 8) already present catalyse the formation of helium via a slightly different reaction, called the CNO cycle.



The CNO cycle also converts hydrogen into helium, with carbon, nitrogen and oxygen nuclei acting as catalysts.

How do we get to these heavier elements in the first place? To make a carbon nucleus requires bringing six protons together. It not possible to envisage a chain-like process built on simply adding one proton at a time, because nuclear physics studies show that any nucleus with five protons is extremely unstable and would decay almost instantly. To overcome this blockage, astrophysicists Edwin Ernest Salpeter and Fred Hoyle, in 1952, suggested a reaction called 'triple alpha capture'. This is the simultaneous fusion of three helium-4 nuclei to build a bridge to carbon-12, via a very subtle energy resonance called the 'Hoyle state' – a unique nuclear process that virtually bypasses the formation of lithium, beryllium and boron. It is a marvel of precision that was quickly confirmed experimentally.

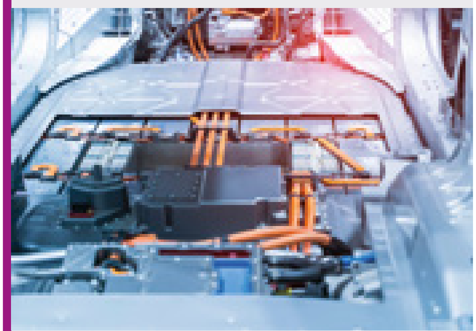
PRACTICAL APPLICATIONS OF ELEMENTS OF INTEREST IN NUCLEOSYNTHESIS

Hydrogen and helium

Made in the Big Bang, hydrogen is used extensively in the chemical industry. For example, it is chemically combined with nitrogen to make ammonia for use as fertiliser. Hydrogen is also being employed in combustion technologies as a clean alternative to fossil fuels, while both hydrogen and helium could be a future energy source if thermonuclear fusion becomes practical.

Lithium

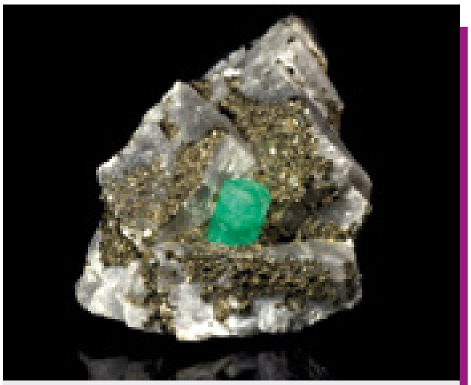
The mystery of when, where and how much lithium was made in the Universe – via primordial fusion, in stars, or in space via cosmic-ray spallation – continues to intrigue nuclear physicists who think there should be much more around. It exists in only moderate quantities on Earth, but its use is rising dramatically with the demand for lithium batteries for electric vehicles.



Lithium is ideal for car batteries because it is so light and has a high charge density.

Beryllium and boron

These elements largely being made by cosmic-ray spallation in space are thus two of the less abundant materials on Earth and in the Universe as a whole. Astronomers have observed that the older the star is, the less beryllium and boron it contains indicating that hardly any, or none at all, was made in those first fusion reactions just after the Big Bang. Beryllium is mainly used as a hardening agent in certain alloys, while boron when combined with carbon or nitrogen produces an ultra-hard engineering material. Boron is a constituent of glass fibre and heat-resistant glass, and is also used in portable neutron sources (see Chapter 7, page 74). Both elements are used as neutron reflectors or moderators in nuclear reactors, and beryllium acts as a complementary source of neutrons in the ITER fusion test reactor (see Chapter 5).

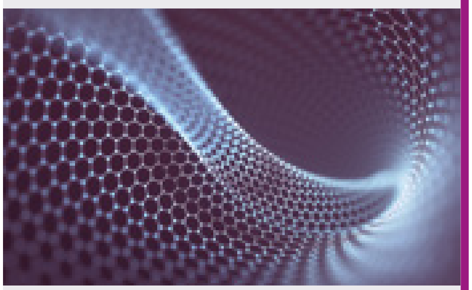


The highly prized emerald gemstone is a beryllium aluminium silicate, though its vivid green colour comes from traces of chromium or vanadium. **[Credit @MNHN Paris/François Farges].**

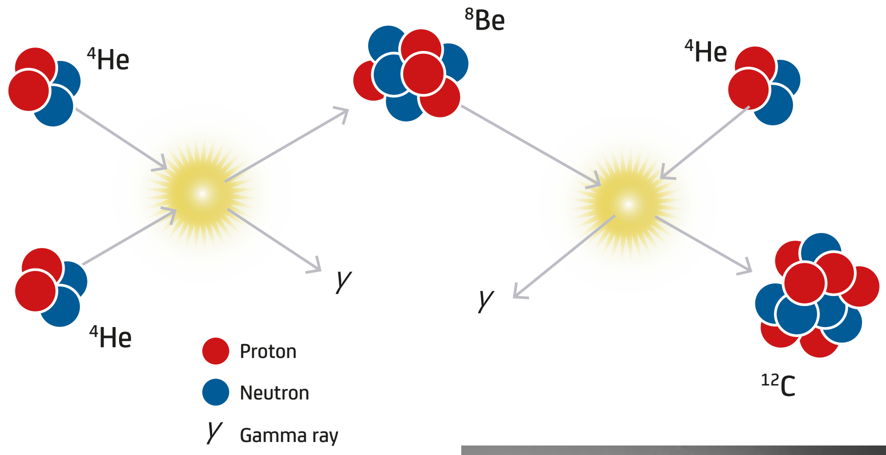
Intriguingly, a boron isotope, boron-11, is a possible fuel for a novel nuclear energy source called aneutronic fusion, which could be safer than uranium fission because it does not produce penetrating neutrons and can be controlled.

Carbon

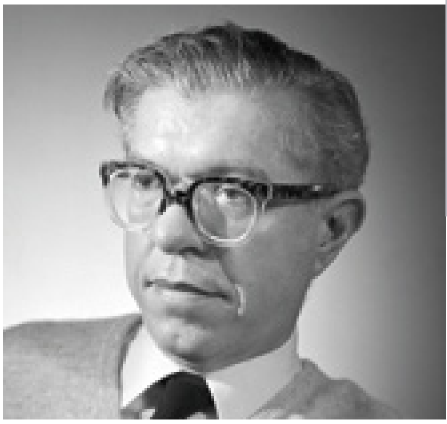
We have seen that carbon is one of the most common materials in the Universe, thanks to that triple-alpha process. On Earth, it is often combined with oxygen – both in the ground and the atmosphere. Its most stable crystalline elemental form, graphite, is used as a lubricant, while in its hardest crystalline state, diamond, is prized for its visual beauty and inertness. Diamond also has many industrial uses. Carbon comes in several other structural forms. The remarkable and versatile properties of the most recent carbon material made, graphene, which is an atomic-scale layer of hexagonally-arranged carbon atoms, could have a huge impact on the electronics industry.



Graphene – a single sheet of carbon atoms – is very much the material of the moment, as its intriguing electronic properties could be exploited in a number of advanced technologies.

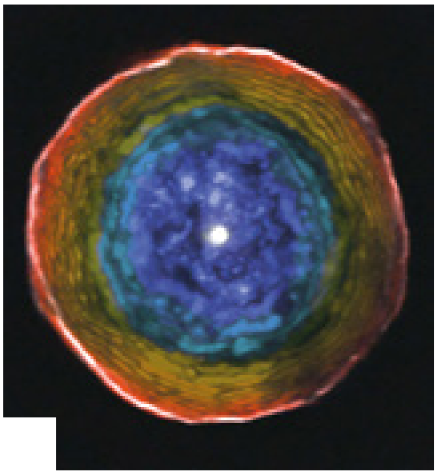


Above is the 'triple alpha' process by which carbon is built in stars from helium via a transient beryllium-8 nucleus, which must rapidly bind with another helium nucleus to form an excited state of carbon called the Hoyle state. It is named after the astrophysicist Sir Fred Hoyle (right) who proposed its existence. The process is chancy, but the fact that the energy of the beryllium–helium fusion matches the energy of the Hoyle state means that it is more likely to happen. Without the Hoyle resonant condition, the creation of the elements would stall and we would not exist.

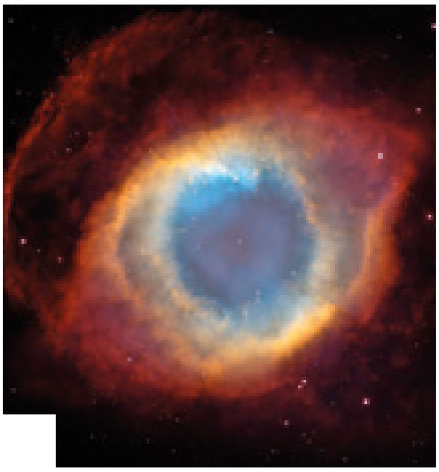


Sir Fred Hoyle. **[Credit The Lotte Meitner-Graf Archive].**

This extraordinary reaction happens when the hydrogen is used up. As the helium is converted to carbon (and oxygen via the fusion of carbon-12 and helium-4 to oxygen-16) and the energy produced starts to run out, the outer layers of stars like our Sun first expand to form a cool red-giant star, while the core shrinks under the force of gravity, eventually forming a white dwarf star. Carbon is ejected from the core as the outer atmosphere is blown off to create a so-called planetary nebula (though nothing to do with the formation of planets!). In this way, the formation of carbon controls the evolution of stars and its abundance in the Universe.



Some red giant-type stars such as U.Antilae can contain large amounts of carbon in their outer layers; It has been dredged up from the star's core. **[Credit ALMA (ESO/NAOJ/NRAO)/ F. Kerschbaum].**



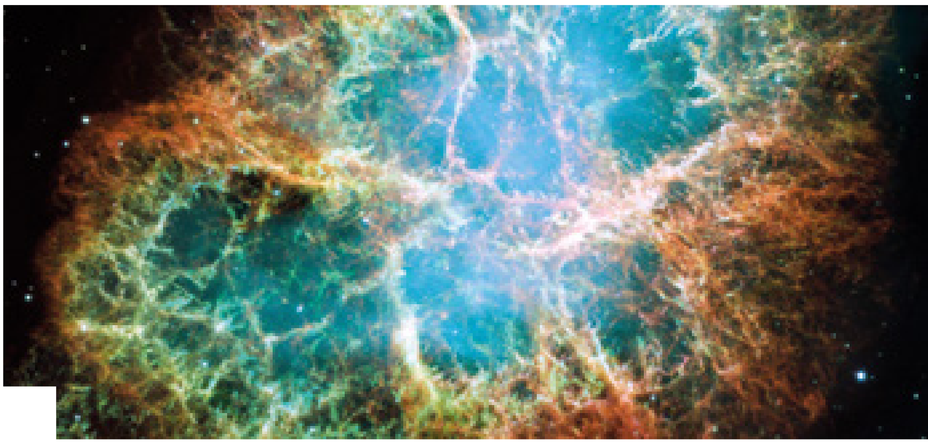
A planetary nebula like this one (the Helix Nebula) is the end-stage of stars like our Sun. **[Credit NASA/ESA/C. R. O'Dell (Vanderbilt University)/M. Meixner, P. McCullough and G. Bacon (STSI)].**

For stars much more massive than the Sun, further fusion reactions continue between light nuclei. For example, carbon nuclei fuse (called 'carbon burning') to create elements, neon, sodium and magnesium (atomic numbers 10, 11 and 12). Eventually, nucleosynthesis reaches very stable iron (atomic number 26). Seeded by iron nuclei and a good source of neutrons from fusion reactions – for example, between carbon-13 and helium-4 to create oxygen-16 – heavier elements are built up via a stepwise process in which a nucleus captures a stray neutron. This then decays into a proton, with the emission of an electron, to create a nucleus of higher atomic number. This is called the slow process, or *s*-process, because successive neutron captures take thousands of years. A few links in this chain are extremely slow because the nuclei that form have structures that are especially stable – so-called magic nuclei – and this is thought to control the relative abundances. Some 30 elements heavier than iron going up to lead (atomic number 82) are formed in this way in red giants.

One particular element, technetium (atomic number 43), has provided unambiguous proof that this kind of nucleosynthesis occurs in stars. The most stable isotope, technetium-98, has a half-life of 4.2 million years. This means that on a cosmological scale it does not last long; the tiny amount identified on Earth would have been generated by ongoing radioactive decay, not in stars. Nevertheless, it has been detected at the surface of some red giants, having been 'dredged up' from core layers. Its instability means that it must have been made during the life-cycle of that particular star.

VIOLENT BIRTHS

To reach the heaviest elements, another version of neutron capture happens that is so blindingly fast that large numbers of neutrons are able to stick on to nuclei at a rate faster than the new nuclei can decay. This rapid process or *r*-process, which lasts just seconds, happens only in the most catastrophic circumstances. One event that was always thought to be responsible is a supernova explosion (specifically called a type II supernova). This happens when a star with at least eight times the mass of the Sun has used up its nuclear fuel and collapses under gravity. In these stars, the explosive process starts because the transmutation of iron and nickel (the most tightly bound of all nuclei) into heavier nuclei requires an input of energy (unlike the fusion of the lighter elements which generate energy). The consequent energy expenditure causes the star to cool, allowing gravity to take over, causing the star's core to collapse. There is then a 'bounce' of collapsing matter on the stellar core's surface, which generates a shockwave that rushes outwards, triggering rapid nuclear reactions in the process and violently spewing out a massive bubble of matter out into the surrounding space. Such supernova events occur in our Galaxy on average once a century. When it happens, the star becomes 100 billion times brighter for a short time, eventually leaving behind a massive nebula of both old and newly minted elements surrounding a compact neutron core - a neutron star.



In 1058, a Chinese astronomer observed a supernova and today the remains of the dead star are visible in the form of magnificent gas trails ejected at very high speed; this is the Crab Nebula. At the centre of the nebula, there is an ultra-compact star of the size of a large city but with the mass of our Sun, being composed mainly of neutrons. **[Credits] NASA, ESA, J. Hester and A. Loll (Arizona State University)**

Neon

We are all familiar with the bright red glow of neon signs. This element is synthesised in abundance in the stars by the fusion of helium and oxygen nuclei. However, like helium, being chemically inert and a volatile gas, it is relatively rare on Earth and can be extracted only from the air.

Silicon

Silicon is produced by the fusion of oxygen nuclei. It is the eighth most common element in the Universe and more than 90 per cent of the Earth's crust is composed of chemically combined silicon, so we are literally supported by this element. Although not as chemically versatile as carbon, it nevertheless forms a wide range of useful compounds especially with oxygen. Being a semiconductor, it is the workhorse of the electronics industry and also has an increasing role in generating 'green energy' via photovoltaic panels.

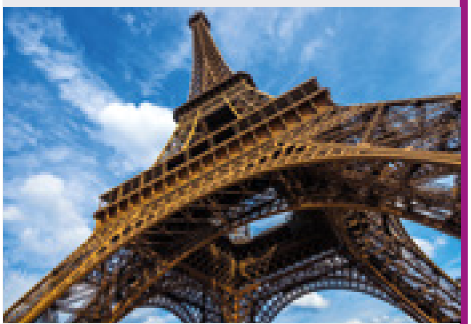
Optical fibres made from silica have made broadband possible.

Molybdenum

With five atoms out of 100 million in the Universe being molybdenum, it is a relatively rare element, and so it is 100 times more expensive than iron. Molybdenum is mainly used in metallurgy and as a chemical catalyst. The annual production is approximately 300 million tonnes.

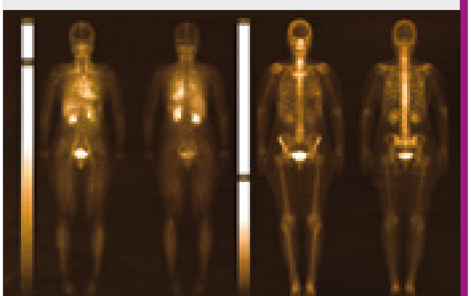
Essential food legumes like soy bean plants host bacteria that can fix atmospheric nitrogen using an enzyme called nitrogenase, which contains iron and molybdenum.

Iron
Although six times less abundant than carbon, it is one of the most common elements in the Universe. Iron is produced in large quantities in a type II supernova by the explosive fusion of oxygen and silicon but is not actually released during the explosion, remaining in the compacted core left behind! The large amounts of iron found on Earth were produced and released in type II supernova. It is interesting to note that without the Earth's protective magnetic field generated by its iron core, complex life-forms might never have evolved. Iron is one of the most common elements used by humanity for thousands of years.



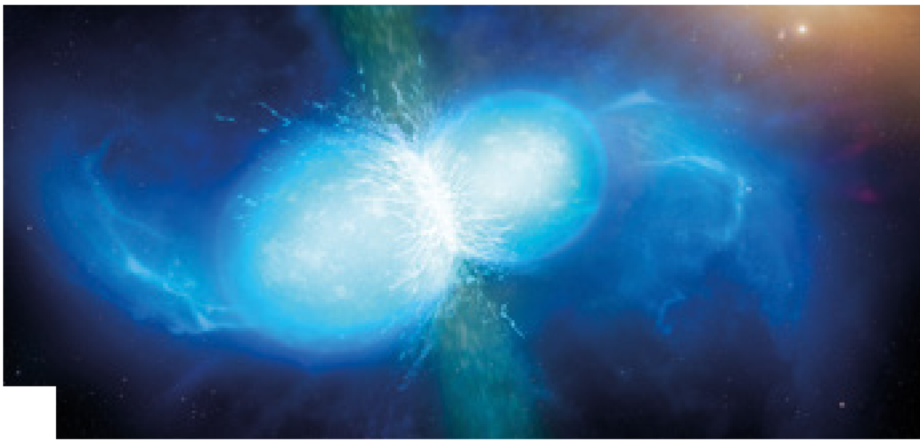
The Eiffel Tower is a magnificent symbol of the role of iron in human progress.

Technetium
As explained, this very rare element does not possess a stable form. Early evidence for its existence was found in the spectra of stars. Nevertheless, it has an important use. An isotope of technetium existing in an excited state – technetium-99m – is the radioisotope most used in medicine. It is made in a nuclear reactor via the decay of one of the fission products, molybdenum-99. Technetium-99m releases gamma-rays (half-life for this emission is six hours) which provide a diagnostic tool similar to X-rays (see Chapter 6).



Technetium-99m is an important gamma-emitting isotope used in medical scanning. The bone scans shown here are obtained after administering the radioactive isotope to the patient.

It has long been thought that gold and half of the elements heavier than iron were produced in this way, but no indisputable proof has ever been found. However, some researchers proposed a rather different astrophysical scenario – but without being able to prove it: the collision of two neutron stars. In this case, a fragment of the neutron star is expelled and transformed by *r*-process reactions and nuclear decays into a vast cloud of material made up of all kinds of nuclei – possibly even including superheavy elements. In 2017, three giant instruments designed to detect the faint tremors of distant, powerful gravitational waves spotted signals thought to be associated with neutron-star mergers. The accompanying spectroscopic measurements made in observatories around the world revealed the telling presence of gold and other heavy elements like barium and lanthanum in the surrounding ejected matter. The neutron-star merger as a source of the heaviest elements was therefore confirmed. There is still a lot more to learn, however: we do not yet know the proportion of gold and heavier elements that would have been produced in these cataclysmic events.



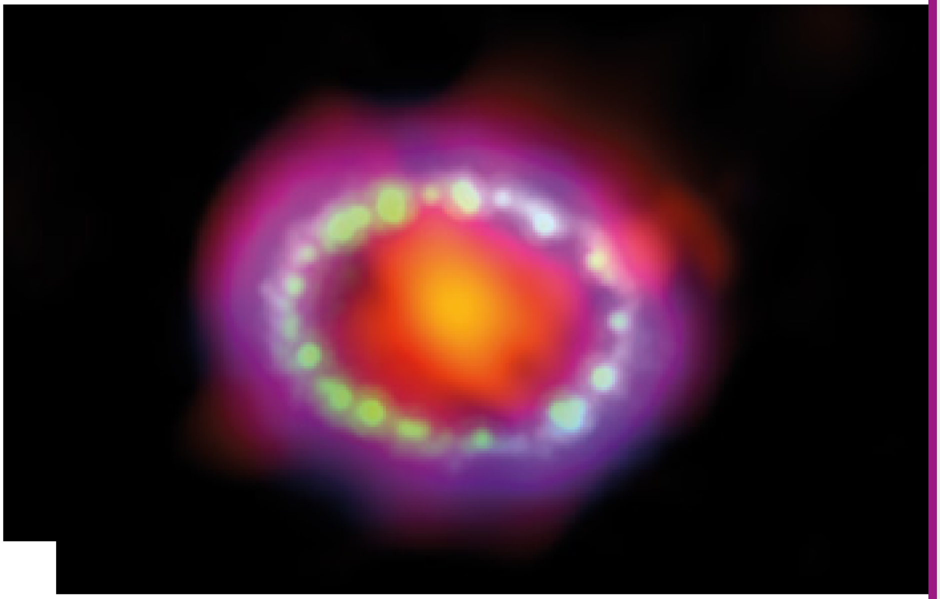
An artist's impression of two neutron stars merging. The massive explosion would create gravitational tremors that spread across the Universe. The heaviest elements like gold and platinum can be detected in these cataclysmic events. **[Credit ESO/University of Warwick/Mark Garlick].**

Another type of supernova explosion (type Ia) also results in rapid nucleosynthesis. The source is a much more common white dwarf star, composed mainly of carbon and oxygen, to which matter is added, little by little, usually from another companion star. When the total mass of the star reaches a certain limit, the star explodes, and all the oxygen and carbon is transformed into heavier elements, typically up to iron. Indeed, most the Earth's iron is the result of vast amounts of iron being expelled rapidly from the star.

Tycho's supernova: in 1572, a 'new star' observed in the constellation of Cassiopeia and recorded by the Danish astronomer Tycho Brahe, was, in fact a type Ia supernova, whose dusty spherical remnant can be seen today. It contains many elements including silicon and iron.
[Credit NASA/CHANDRA/NuSTAR/HST] .

Sometimes, the different isotopes of an element are produced at different sites in the Universe depending on the number of neutrons they have. This is the case with molybdenum, for example (atomic number 42). The isotope containing 58 neutrons was probably produced at the same explosive sites as gold. But those isotopes with fewer neutrons – 53 to 56 – were made essentially in the same site as lead atoms, in red giants. The astrophysical origin of isotopes with only 50 and 52 neutrons is still very controversial. They are relatively poor in neutrons and are thought to be ejected into space, like oxygen, in type II supernova explosions – but unlike oxygen, they are produced essentially during the explosion. They are thought to be synthesised from pre-existing elements that are heated to several billion degrees during the explosion. The intense gamma-rays generated would cause nuclei to fragment. In effect, the temperature would be so high and the radiation so violent, that protons, neutrons and helium nuclei would be ejected or evaporated from the stable nuclei to produce other stable isotopes. In a way, these molybdenum isotopes would have been synthesised in a kind of super-microwave oven.

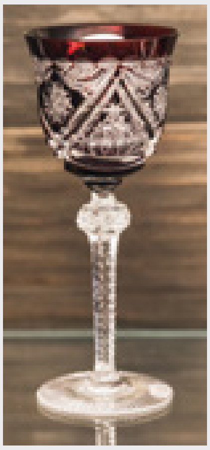
Not all the elements are produced in stellar processes, but in the interstellar medium. In the 1970s, studies showed that certain light elements – helium-3, lithium, beryllium and boron – were mainly produced by high-speed collisions between atomic nuclei. Such collisions occur between highly accelerated hydrogen or helium nuclei (cosmic rays) and carbon or oxygen nuclei present in interstellar gas clouds. This results in their fragmentation to these lighter elements – a process known as spallation.

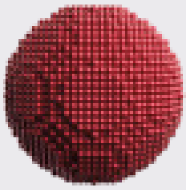


This is a combined multi-wavelength image of the ring of gas and the shockwave generated by the supernova SN1987A that leads to the spreading out of elements in space from which the next generation of stars and planets are made. **[Credit X-ray: NASA/CXC/SAO/PSU/D. Burrows et al.; optical: NASA/STScI; millimetre: NRAO/AUI/NSF)].**

Gold and lead

Alchemists dreamed of turning lead into gold but not even the stars can accomplish that. Lead is made in red giants by the *s*-process, whereas gold is generated in the explosive *r*-process associated with supernovae and neutron-star mergers. Both elements are rare in the Universe because they are produced in the later or end phases of star life. Gold is three times less abundant than lead but 3000 times more expensive. Although mostly recognised for its intrinsic value and beauty, gold is put to work in the form of nanoparticles (around 30 nanometres across). These are being used as drug-delivery vehicles and biosensors, for example. Lead finds use in many important applications: batteries for accumulators, ammunition, nuclear radiation protection devices, roofs, glass, ceramic glazes and balancing weights.





(Left) A stunning cut lead-crystal goblet; lead crystal must contain a minimum of 25 per cent of lead oxide. (Right) A single gold nanoparticle: solutions of these nanoparticles are not golden in colour but shades of red, blue or purple depending on the particle size. This is because the optical properties of gold are different at the nanoscale. Such nanoparticles are used in many technologies, including cancer treatment.

FINDING THE EVIDENCE

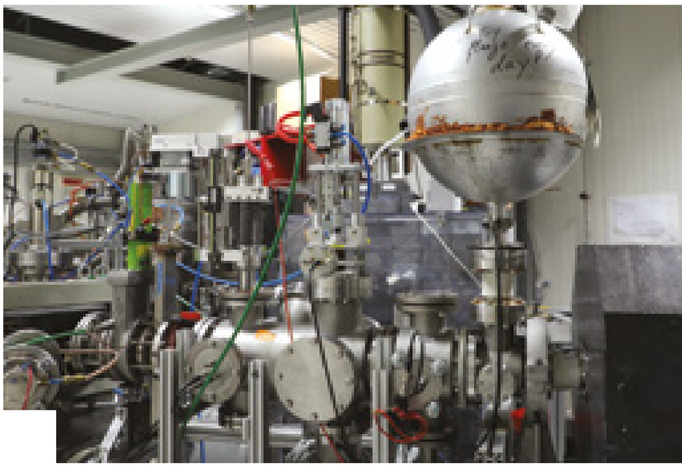
The study of the origin of the elements is an extremely active area of research, with nuclear physicists trying to untangle the various types of reactions that could occur during a star's life and in space. Ideas constantly change as more information comes to light. Measuring the abundances of elements in stars, stellar remnants, dusty nebulae and the interstellar medium via spectroscopic observations at various wavelengths, as well as abundances on Earth, provide important clues.

Thirty-five years ago, a large type II supernova occurred in the Large Magellanic Cloud galaxy, SN1987A, and the evolution of its remnant has been followed ever since. Spectroscopic measurements made over a range of wavelengths from gamma-rays and X-rays to millimetres have detected many elements, including cobalt-56, iron-56 and more recently titanium-44 created in the explosion.

Closer to home, certain types of microscopic grains taken from meteorites landing on Earth are thought to have originated in the atmospheres of red giants before the Sun was born. They also provide clues. Their pre-solar origin is revealed because the ratios of isotopes of particular elements identified are different from those measured in Solar System material.

Of crucial importance are laboratory experiments to test various reactions thought to be components of nucleosynthesis. They are combined with theoretical predictions of the nature and energies of those reactions. In astrophysics, nuclear reactions involve interactions that are quite unlikely to happen – that is, with very low probabilities (some of the major element-building pathways happen over millions of years).

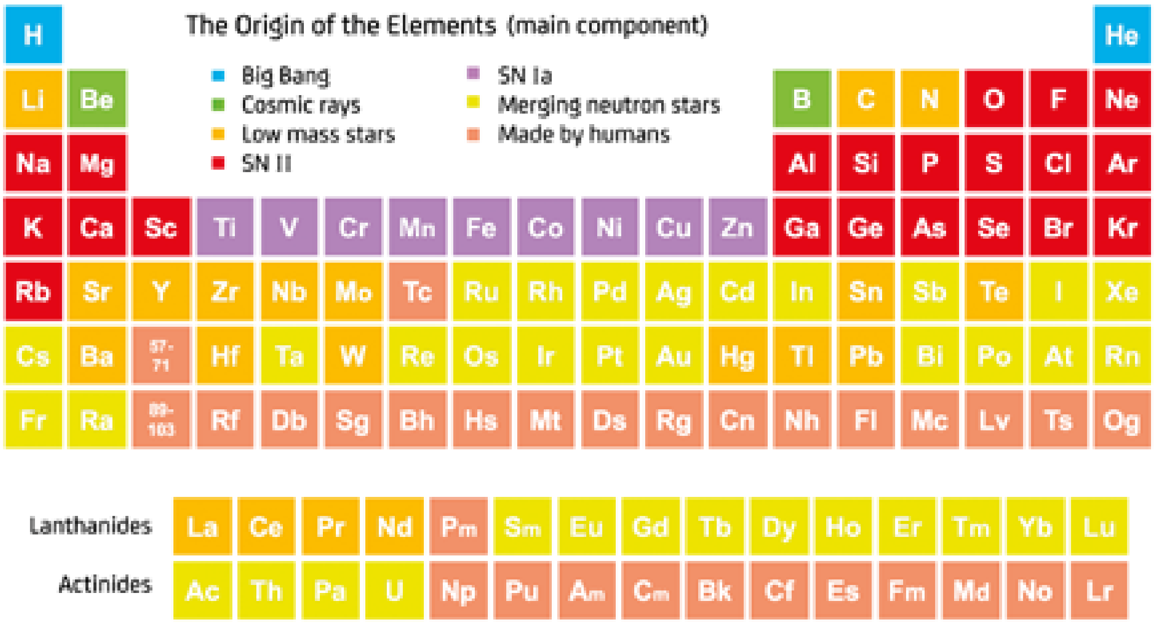
Nuclear astrophysicists have built experiments to measure the crucial astrophysical process by which carbon 'burns' to oxygen, by carrying them out at stellar energies using a particle accelerator. For example, the LUNA underground laboratory, located in Gran Sasso Italy, is one of the best laboratories able to measure the reaction probabilities. It is situated underground so as to shield experiments from external disturbances such as cosmic rays that might interfere with the delicate interactions.



The LUNA laboratory in Italy is dedicated to experiments that explore the nuclear fusion cycles in stars like the Sun. **[Credit: The LUNA collaboration].**

stars, collisions with cosmic rays, the death of low-mass stars, the explosion of white dwarf stars and the merging of neutron stars. Many types of nuclear processes are involved, which we are still investigating, such as fusion, neutron capture, proton capture and fission and spallation.

The Periodic Table of Elements indicating the origins or sites of their manufacture.



THE NEW MENDELEYEV TABLE

With an increased understanding of nucleosynthesis, researchers can now start to design a new Mendeleyev table – one that shows the astrophysical origins of the chemical elements.

In truth, this table should be three-dimensional – a cube, because each isotope of each element has a different story to tell. The origins and proportions are not yet precisely known – this is the work of researchers today – but the astrophysical scenarios are becoming clearer. We now believe that the elements are made in six major astrophysical scenarios. In order of appearance, they are: primordial nucleosynthesis, the evolution and explosion of massive

It is extraordinary to think that our everyday world and ourselves exist only because of this fascinating nuclear evolution of the Universe and the stars in it.

FURTHER INFORMATION

https://www.youtube.com: *Astronuclear Nibbles*, Jordi José.

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CHAPTER 4:

CLIMATE AND ENVIRONMENT

The Earth's complex weather and climate systems are driven by the Sun's energy and also the Earth's own radioactivity.

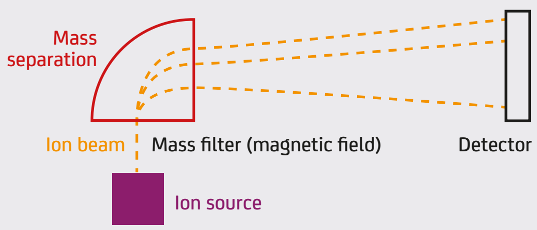
CLIMATE CHANGE IS POSSIBLY THE MOST IMPORTANT ISSUE FOR HUMANITY IN THE 21ST CENTURY. NUCLEAR PHYSICS AND ITS TECHNIQUES ARE PROVIDING CRUCIAL KNOWLEDGE AND TOOLS TO UNDERSTAND, PREDICT AND MITIGATE THE CONSEQUENCES.

People might be surprised to know how much nuclear processes control our everyday lives in terms of influencing the Earth's weather and climate. The Sun, which provides the main source of energy to the Earth, is a giant nuclear reactor. The radiation it emits not only heats the surface of the Earth, but also drives the complex dynamics of the climate and controls the weather – thus shaping our daily environment. This is because the heating is uneven across the Earth, and it is redistributed between the Equator and higher latitudes by atmospheric and ocean currents. However, the Sun is not the only source of energy on Earth, geothermal energy and vulcanism are also sources of heat and power. This energy source originates from the initial formation of the Solar System and from the radioactive decay of elements in the Earth's interior.

One method of studying Earth's complex climate and systems is carried out using isotopic tracers, both radioactive and stable. Isotopes of various elements, because of their chemical and physical properties, can record the interactions between the different subsystems of the climate system. There are a variety of nuclear isotopes that serve as tracers, and in some cases, due to their low abundance in the environment, special measuring techniques are required. One of these is accelerator mass spectrometry, AMS, (see Box opposite) a cutting-edge technology that is used to detect tiny amounts of long-lived radioactive isotopes that act as tracers of climate and environment.

MEASURING ISOTOPIC RATIOS BY MASS SPECTROMETRY

The measurement of isotopic ratios is mostly done by mass spectrometry. This is an analytical technique used in many scientific fields, and relies on measuring the ratio of mass to electric charge of an ion (a charged particle such as an atom or molecule). The sample is first ionised and a stream of the charged particles at the same velocity is then subjected to an applied magnetic field, which causes their trajectories to bend into a circle. The radius of each trajectory is proportional to the ratio of their mass to charge. This means that isotopes of the same element will follow different trajectories because they have different masses. Appropriately placed detectors can then measure the relative amounts of each isotope in a sample.



The basic principle of a mass spectrometer. Charged particles follow circular trajectories when they move through a perpendicular magnetic field. The radius of each trajectory depends on the mass and charge of the ion.

A version of mass spectrometry taking advantage of a particle accelerator to accelerate the sample ions to high energies – accelerator mass spectrometry (AMS) – is used to select and determine radioisotopes that are in very low concentrations with respect to their stable isotopes and which have a long half-life (that makes them very difficult to detect by techniques counting radioactive decays).

PREDICTING THE WEATHER

The person in the street may have an image of meteorology as the work of the TV weather-person – apparently making educated guesses about tomorrow's weather based on the input of thermometers, barometers and satellite images. The reality is that weather and climate studies require sophisticated computer models encapsulating the extraordinarily complex behaviour of the atmosphere, continents and oceans at a global level. Nuclear physics plays a relevant role in this modelling, since isotopic measurements are used as tracers of atmosphere and oceans, as well as irradiation tests to ensure the proper functioning of satellites and meteorological sensors.

ANALYSING CLIMATE CHANGE

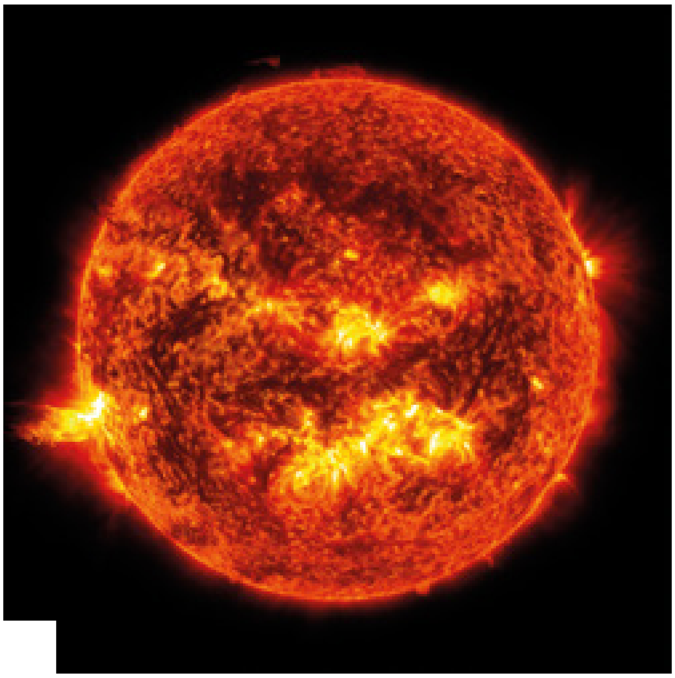
Palaeoclimate records based on several natural tracers are helping to unravel significant climate variations in the past – which strongly informs our evaluation of current climate change. By providing the means by which changes in the atmosphere, the oceans and on land, together with their biospheres, can be followed, nuclear physics plays a significant role in understanding both past and present interactions.

Understanding the factors that influence weather and climate has become increasingly essential as it becomes ever clearer that effects of human activities is a significant component. This means probing in detail not only changes in weather patterns, and thus climate, but also seeking a deeper understanding of the primary sources of energy driving them – that is, the Sun and the Earth itself.

In this chapter, we outline the role that nuclear physics plays in this cross-disciplinary effort to analyse both Sun–Earth interactions and the Earth's evolution, with the ultimate goal of understanding and perhaps mitigating the severest effects of current and future climate change.

THE ROLE OF THE SUN

Most people consider the Sun as a steady source of heat – the ultimate driver behind our weather and climate. However, it is in fact a hugely dynamical body whose behaviour is dominated by the complex interaction of nuclear, convective and magnetic forces. The resulting activity varies considerably over a range of timescales from millennia to minutes. A deeper understanding of this behaviour is needed to understand fully its effect on past, present and future climates, and to mitigate the disrupting effects of explosive events such as solar flares on communication systems and the functioning of meteorological satellites.



Variations in solar activity such as solar flares have huge effects on weather and climate, which scientists are trying to understand more fully. **[Credit NASA/SDO].**

A proper understanding of the Sun requires it to be considered as a huge gaseous ball of electrically charged particles – a plasma – consisting largely of positively charged hydrogen (protons), helium and other light nuclei, together with subatomic particles such as electrons, neutrons and neutrinos. It is constrained into a spherical shape by gravity, which creates enough pressure to cause the hydrogen and helium nuclei to undergo fusion reactions, releasing massive amounts of energy.

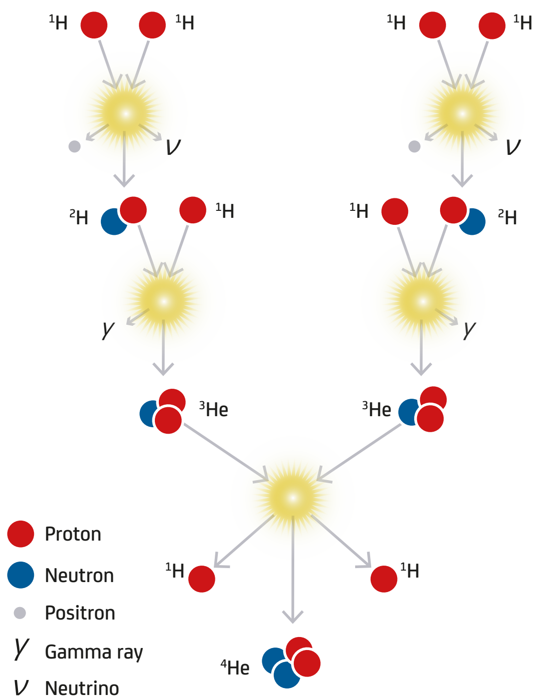
AMS provides two important features: first, interfering molecules in the sample are destroyed in an accelerator stripper; secondly, the use of high energies enables nuclear properties to be exploited to provide stopping power enabling the isotope of interest to be separated from other masses that arrive at the final detector. These two characteristics make AMS an extremely sensitive technique.

The accelerator mass spectrometer used at the Centro Nacional de Aceleradores, In Seville, Spain.

Traditionally, AMS has been applied to carbon-14 (for dating) beryllium-10, aluminium-16, chlorine-36, iodine-29 and plutonium isotopes. In the past few years, other isotopes as calcium-41, uranium-236 and neptunium-237 can also be reasonably detected by AMS. As a result, the technique can be applied in many fields such as, nuclear physics, geology, geochronology, paleoclimatology, materials science, (Chapter 7), archaeology (Chapter 8), environmental studies and medicine. Its high sensitivity allows difficult problems to be solved, as it requires only small samples and short measuring times.

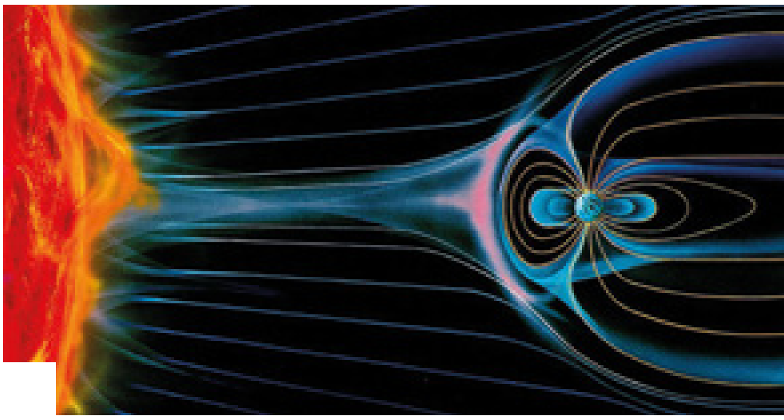
HOW THE NUCLEAR SUN AFFECTS THE EARTH

A range of fusion reactions is possible in stars (see Chapter 3), but for our Sun, the main reaction is the fusion of two hydrogen nuclei (protons) into helium. As the protons fuse, one of them is converted into a neutron with the emission of a positron and a neutrino to create another hydrogen isotope, deuterium (one proton and one neutron). The positron annihilates with an electron to release gamma-rays. The deuterium nucleus then fuses with another proton to create a helium-3 nucleus with two protons and one neutron, with more energy released. Two helium-3 nuclei then fuse to form a helium-4 nucleus with the release of two further protons and more energy. These reactions are surprisingly slow, happening over millions of years. Other nuclear reactions also occur to a lesser degree. Some of the electromagnetic radiation released in all these reactions in the Sun's core eventually reaches the solar surface (the photosphere) and is emitted, a small proportion reaching the Earth to illuminate and heat it, and thus provide the conditions for life.



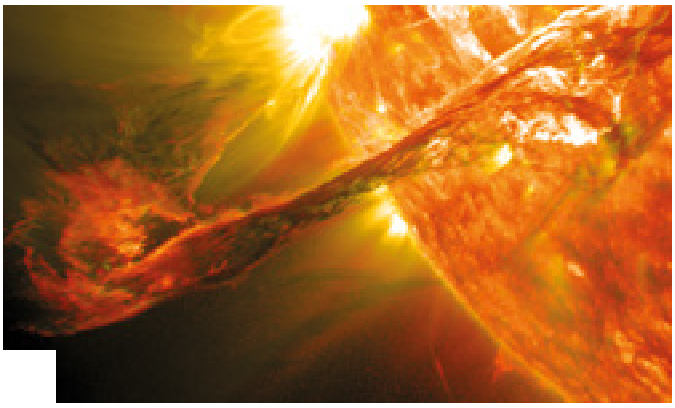
The proton–proton cycle that leads to the formation of helium from hydrogen. This is the fusion reaction that powers our Sun.

Also emitted are streams of charged particles such as protons called the solar wind. This high-energy radiation envelops our planet but fortunately is diverted by the Earth's magnetic field, with particles entering the atmosphere only at the magnetic poles. These produce the magnificent aurorae resulting from interactions with atmospheric oxygen and nitrogen molecules.



An illustration of the electromagnetic interaction between the solar wind and the Earth's magnetosphere. **[Credit ESO/K. Endo].**

There are solar phenomena that have more serious effects on human activities and the environment. Because the Sun is composed of an electrically charged plasma, it generates a powerful magnetic field. Furthermore, the interactive (nuclear-driven) dynamics both within the Sun's interior and at its surface result in complex magnetic structures forming in the outer layers of the Sun. They are manifested as cell-like structures of rapidly churning matter (visible in telescopes), and dark regions of dense magnetic field lines called sunspots. These sunspots have provided an obvious visual measure of the Sun's activity which can be seen to vary over an 11-year cycle. Associated with the magnetic activity are solar flares – outbursts of matter into space. Sometimes very massive amounts of matter are ejected called coronal mass ejections (CMEs). If these reach the Earth, they can endanger human life by interfering with the electronics in high-tech systems such as satellites and power grids, causing blackouts and disrupting satellite communications and GPS systems.



The start of a massive coronal mass ejection in 2012. **[Credit NASA/GFSC].**

STUDIES OF THE SUN AND CLIMATE

A deeper understanding of the Sun's activity and its fluctuations is required to develop technologies and policies that enable the effects of events such as CMEs to be countered. It is also needed to study their effects on past, present and future climates – particularly to help unpick and highlight anthropogenic influences on climate change. These need to be separated from ongoing changes in solar activity and the consequent variations in the total level of solar irradiance at the top of the atmosphere (in addition to global effects of any volcanic activity).

Nevertheless, a proper evaluation of solar effects on climate has to start with an understanding of the underlying nuclear fusion processes. The reactions are studied by simulating them in nuclear physics laboratories using particle accelerators (for example, the nuclear physics experiments carried out at the Gran Sasso National Laboratory in Italy, as mentioned in Chapter 3). Recent space missions such as the European Space Agency's SOHO and Cluster missions have improved our understanding of how so-called space weather in the Earth's near-space regions is controlled by varying solar activity and the solar cycle. It should be noted that changes in solar activity cannot explain the rapid increase in the air global average temperature at the Earth's surface, observed since the 1980s. It is thus crucial to consider anthopogenic effects.

Solar flares and CMEs are the most powerful energy-release events in the Solar System. What drives them is the subject of intense laboratory study. In the hours or days preceding a solar flare, the energy appears to be stored in the stressed magnetic field of the solar corona. During a flare, a large fraction of magnetic energy is converted into kinetic energy of energetic particles, which results in the emission of large amounts of visible light, X-rays and gamma-rays when they hit the lower solar atmosphere, the chromosphere. The mechanism of the particle acceleration in solar flares and CMEs – or even where they come from – is still not clear. The conversion of magnetic energy into accelerated particles can be accomplished by several processes, probably more than one taking place at the same time. Certainly, the complex and turbulent plasma interactions within the Sun generate powerful magnetic waves that drive the particles. Studies of plasma dynamics in the laboratory, though challenging, can test various models of these interactions.

Studies of terrestrial radioisotopes have also provided insights. Although sunspot activity, and the resulting magnetic fields on the Sun have been observed only for the past 400 years, radioisotopes such as carbon-14, produced by the influx of solar particles, which then undergo nuclear reactions in the atmosphere, provide insights.

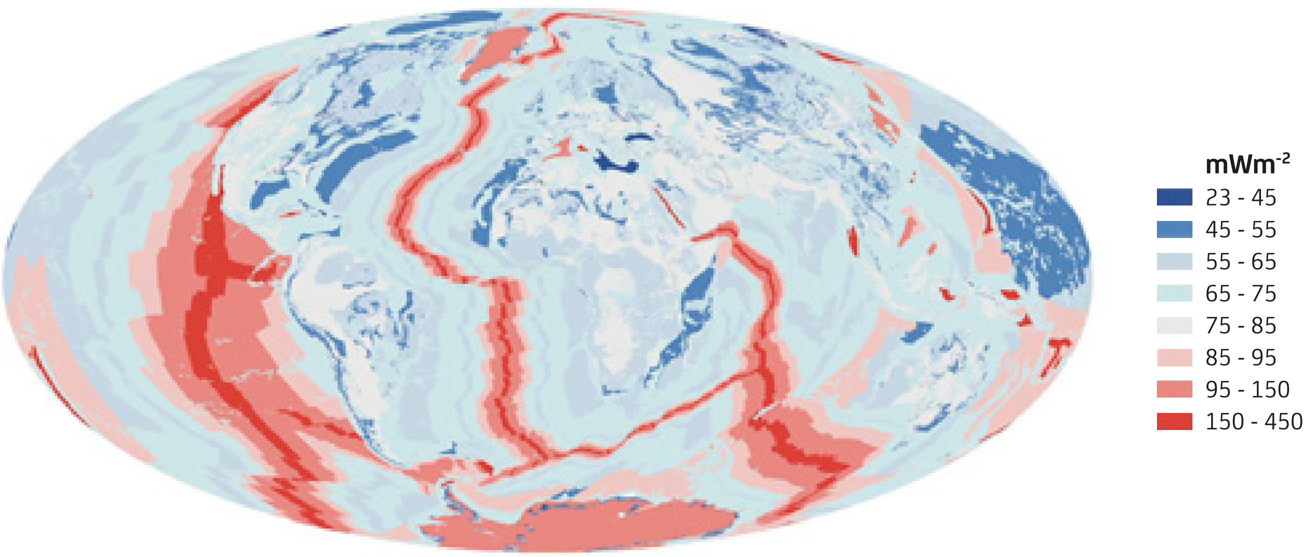
These radioisotopes are preserved in ancient tree rings or ice cores, and serve as proxies for solar activity extending back thousands of years. The lower the amount of carbon-14 in a tree ring, then the higher solar activity was during that period of tree growth, because a more powerful solar magnetic field associated with increased activity reduces the number of cosmic rays reaching Earth.

Studies of carbon-14 in the atmosphere also offer a method of linking the use of fossil fuels directly to climate change. It acts as a tracer of the greenhouse gas, carbon dioxide, specifically emitted in the burning of fossil fuels. These organic materials, laid down from living plants millions of years ago, should contain no carbon-14 because it should have all decayed away (see carbon-dating, Chapter 8). By measuring the ratio of carbon isotopes in the air, the proportion of carbon dioxide now coming from burning fossil fuels can be ascertained.

Carbon dating of ancient tree rings has provided a clearer understanding of the carbon cycle and extended measurements of climate change over thousands of years.

THE ROLE OF GEOTHERMAL ENERGY

After the Sun, geothermal energy is the second most abundant source of energy on Earth. It provides, on average 44.2 terawatts of power, which, when distributed over the surface of the Earth, corresponds to an average flux of energy of 0.0866 watts per square metre. This amount is indeed small compared with the flux of energy coming from the Sun (1361 watts per square metre). However, geothermal energy is not always liberated gently and large amounts can reach the Earth's surface rather suddenly in very localised places, giving rise to earthquakes and volcanic eruptions.



A map of heat output from the Earth's interior to the surface. The largest amounts coincide with the mid-ocean ridges.
[Credit J. H. Davies and D. R. Davies].

Although the residual heat from the Earth's formation accounts for much of the geothermal energy, nuclear processes also contribute to its generation (and helps slow down the cooling of the Earth). It comes from the decay of long-lived radioisotopes of uranium and thorium, as well as potassium-40, that have been in existence since the formation of the Earth (see Chapter 3). Until recently, it was difficult to separate the contributions of the radioactive components from the residual heat. However, radioactivity generates neutrinos, and these elusive particles can be detected by dedicated instruments such as those at the Kamioka Observatory in Japan. These measurements indicate that approximately half of the geothermal energy comes from radioactivity. Thus, we should be aware that, not only is our Sun a nuclear reactor, but our Earth is also a mildly radioactive ball! Indeed, it is the large volume of the Earth that shields us from the harmful effects of this radioactivity, so that it is mostly only heat and non-damaging neutrinos that reach its surface and affect us.

RADON AND EARTHQUAKE FORECASTING

Since the interior of the Earth contains primordial radioisotopes, the radon gas emitted in the decay of uranium and thorium deep in the Earth's crust can reach its surface. The lifetimes of the different naturally occurring radon isotopes differ widely. Radon-222 is one of the most commonly observed, since it has the longest half-life (3.8 days). It can be found in significant concentrations in groundwaters, soils, caves and the lowest floors of buildings in contact with the ground, and it becomes a natural hazard when exceeding certain levels. Usually, national agencies are in charge of mapping and monitoring radon concentration in the air and water with regard to health and safety (see Chapter 2).

Interestingly, radon emission can be a precursor of earthquakes – one of the natural catastrophes causing the greatest damage to human life. People have tried to forecast earthquakes over the centuries, often through noting changes in animal behaviour, ground-water levels and other phenomena. However, a step-change in our knowledge of earthquake precursors occurred in 1966, in connection with the earthquake in Tashkent, Uzbekistan, where increased levels of radon were observed before the earthquake. Subsequently, in many locations in China, Japan and India, anomalies in radon concentration – often a substantial increase – have been detected and reported prior to earthquakes. A well-known example is the Kobe (Japan) earthquake of 1995, where radon was measured continuously, following similar measurements performed as part of the Kamiokande experiment in Japan, mainly to detect cosmic neutrinos passing through a large cylinder of water. The radon concentration started to increase slowly a year before the earthquake, approaching three times the normal level a month beforehand. A sudden and pronounced increase was observed 10 days before the incident, followed by a steep drop in concentration 7 days before. The content of other chemicals in the water also revealed changes.

Large increases in local radon concentration were detected before the massive earthquake near Kobe, Japan in 1995.

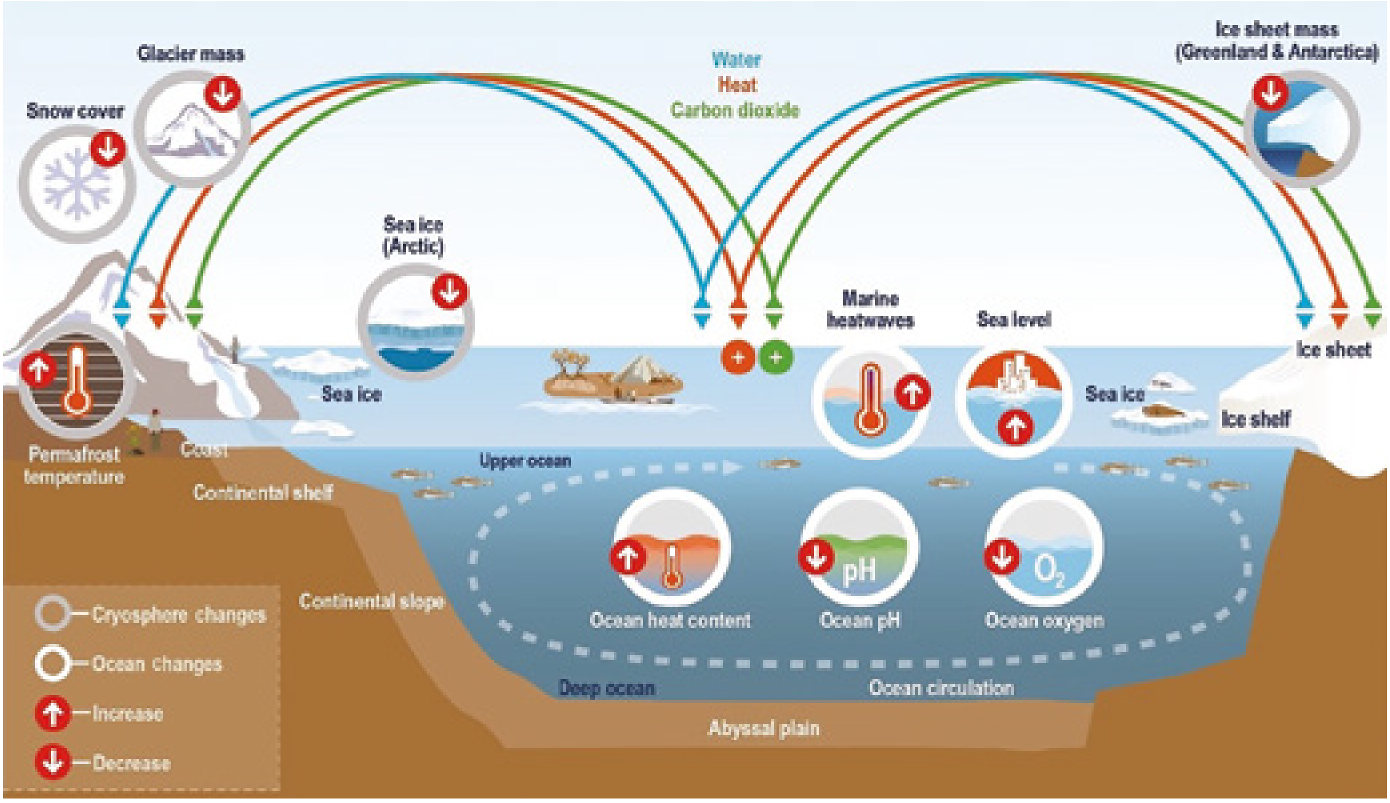
There are several theories that account for the increase in radon emission. Tectonic movements and increased pressure can, for example, cause a multitude of small cracks in deep layers of the Earth's crust. These, in turn, enable the radon gas to escape, which otherwise would be trapped in the rock material. The transport of radon to the surface of the Earth is a highly complex process and assumed to happen by advection, in which water or gases like CO_2, and methane act as carriers.

Given that some very large cities are in real danger from destruction by earthquakes, why have radon measurements not become the standard approach for predicting earthquakes? To make a prediction, one would like to know the location, the timing, and the magnitude of the earthquake. There are essentially two problems associated with radon as a precursor for earthquake prediction. Changes in radon concentration have been observed in locations far from the earthquake's epicentre. There are certain deep-lying aquifers where radon is measured constantly and where changes have been observed at distances of more than 1000 kilometres away. Since radon cannot be transported over such large distances, other explanations of these phenomena are required. It is assumed that changes in geological stress are transmitted over those distances and in turn are responsible for the release of radon. The second problem is that changes in radon concentration can be initiated by many effects such as changes in air pressure, temperature, humidity and ground-water flow – and are not necessarily connected to changes in the stress of the Earth's outer crust.

Nevertheless, nuclear physics could therefore also contribute to changing the paradigm of earthquake forecasting. Whereas there exist several radon monitoring networks worldwide, there is no large-scale network measuring radon emissions in real time in earthquake-prone areas. This would be a challenging project for a multidisciplinary team of nuclear physicists, geophysicists, hydrologists, seismologists and computer scientists that would provide us with significant new knowledge of our environment.

THE OCEANS AND CLIMATE CHANGE

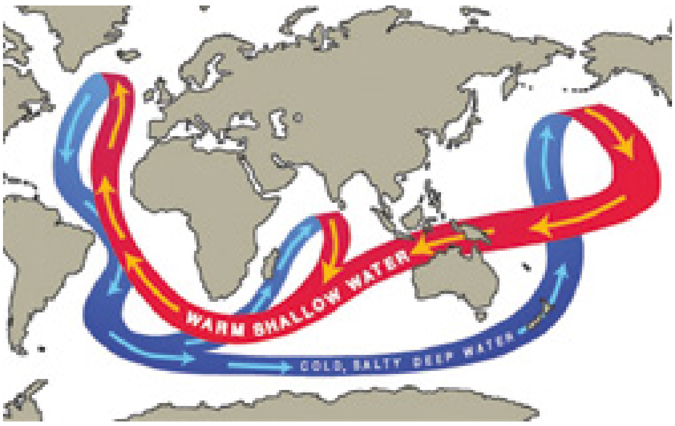
We depend directly or indirectly on the oceans and cryosphere (the areas where water is frozen). They contain 97 per cent of the world's water and play a crucial role in regulating the climate. They store and transport large amounts of energy and carbon, and interact with the atmosphere by transporting heat from lower to higher latitudes. This transport of heat could ultimately be disrupted or changed due to either natural or anthropogenic forcing. transport heat, carbon and nutrients, thereby supporting primary productivity and ecosystems. The link between northward and southward waters is achieved through heat loss to the atmosphere and associated water-mass transformation that transports waters from the surface to the ocean interior.



The effects of climate change on oceans and cryosphere.
[Credit IPCC Special Report on the ocean and cryosphere in a changing climate].

Despite the utmost importance of oceans in regulating the Earth's climate, they are still poorly understood and their spatial variability remains largely unknown. To improve global climate projections, we need to answer some fundamental questions regarding water mass-transport, pathways, mixing regimes and circulation timescales. One way of studying these circulation processes and their changing trends due to climate change, is by means of radioisotope tracers.

The ocean currents are not in a steady state; there is a large-scale circulation, named the thermo-haline circulation, which is driven mainly by density differences due to a combination of temperature (thermo) and salinity (haline) differences. It acts as a great ocean conveyor belt that transports low-density upper waters to higher-density intermediate and deep waters, and returns them back to the upper ocean. In the figure opposite, we can observe how the Gulf Stream (surface waters driven by wind and originating in the Gulf of Mexico) circulates from lower to higher latitudes, transporting warmth to western Europe. This results in a warm and mild climate in cities like Barcelona, Rome and Lisbon, whereas New York is frequently faced with strong blizzards during the winter, despite being in the same latitude band as the European cities. As the surface waters circulate to the polar and subpolar areas, they



The great ocean conveyor belt in which circulation is driven by differences in salt concentrations and temperature.
[Credit Lamont-Doherty Earth Observatory].

The Arctic Ocean and the Subpolar North Atlantic therefore play a crucial role as one of the world's most important ocean refrigerators, contributing to the formation of deep waters in the North Atlantic. This component of ocean currents is called the Atlantic Meridional Overturning Circulation (AMOC).

Climate change is triggering profound changes in the marine environment such as sea-level rise, increasing ocean heat content and marine heat waves, as well as increasing ocean oxygen loss and acidification. Changes in the cryosphere include the decline in the extent of Arctic sea-ice, loss of the Antarctic and Greenland ice-sheets and glaciers, thawing of permafrost, and decreasing extent of snow cover. In particular, because of global warming, temperatures in the Arctic Ocean are increasing twice as fast as the global average. We can already observe the direct consequences through the reduction of sea-ice. In September 2020, the Arctic sea-ice minimum reached the second lowest on record, reinforcing the long-term downward trend of almost 13 per cent per decade (1979–2019). There are two main reasons for most of sea-ice mass loss in the Arctic Ocean: the increase of northward atmospheric heat transport and the warming of Atlantic water inflows to the Arctic. If current trends continue, this region may soon be transferred from an Arctic to an Atlantic type of climate with 'unknown consequences', not only for the ocean circulation, but also for the wider ecosystem and commercial fishing.

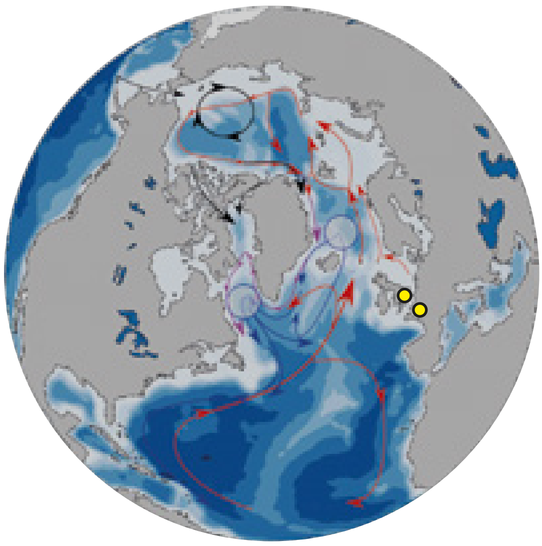
In the subpolar North Atlantic, observations indicate that the AMOC has weakened relative to the period between 1850 and 1900, and this trend will continue in the 21st century. Any substantial weakening of the AMOC is projected to cause a decrease in marine productivity in the North Atlantic, more storms in Northern Europe, a reduced number of tropical cyclones in the Atlantic and an increase in the regional sea level along the northeast coast of North America.

STUDYING OCEAN CIRCULATION WITH NUCLEAR-WASTE TRACERS

Nuclear physics is thus an important tool in understanding the ocean circulation. The first description of ocean currents and circulation – the ocean great conveyor belt – was made possible by the radiocarbon (carbon-14) measurements in one of the first ocean global surveys in the 1970s: the Geochemical Ocean Sections Study (GEOSECS). Carbon-14 is produced naturally in the upper atmosphere and enters the ocean via gas exchange. There is no further carbon-14 production in the ocean, and only its radioactive decay (with a half-life of 5730 years) reduces its concentration over time. Therefore, carbon-14 has been used as a clock to understand the timescales of vertical water-mass circulation (or ventilation) from the surface to the ocean interior. Since then, chemical tracers have become a pivotal variable in understanding ocean circulation processes.

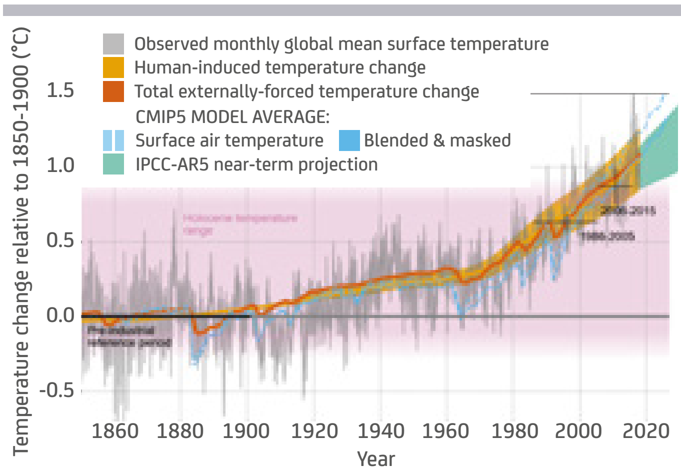
Besides the naturally produced carbon-14, humankind's activities have resulted in the release of a number of globally distributed substances into the environment. These enter the oceans and travel following the pathways of the global conveyor belt, 'tracing' the biological, chemical and physical pathways of the ocean. We refer to these substances in the ocean as 'transient tracers' because their distributions are not yet in a steady state but rather still evolving in time. Notorious examples are the set of radioactive substances – for example, tritium (the radioactive isotope of hydrogen), caesium-137, strontium-90, and so on – that entered the surface of the oceans during the atmospheric nuclear weapons tests in the 1950s and 1960s (along with the chemicals chlorofluorocarbons, or CFCs, and sulfur hexafluoride used as industrial coolants and in the electrical industry, respectively). These globally dispersed tracers are excellent markers that imprint the ocean surface with time-dependent signatures before being injected into the ocean interior and transported away from their sources.

On a more local scale, and as point-like sources, artificial radioisotopes have also been introduced into the marine environment as a result of controlled releases over decades from the two European nuclear reprocessing plants of Sellafield in UK and La Hague in France (yellow dots in the figure below). These two facilities have been labelling Atlantic waters since the 1960s with a unique set of radioisotopes that can be traced from the Eastern North Atlantic (North Sea) northwards into the Arctic Ocean, or recirculating to the Subpolar North Atlantic and beyond. These tracers of nuclear origin have been highly valuable to oceanographers for understanding circulation pathways between the source region and downstream location in different basins in the Arctic Ocean, Nordic Seas and the Subpolar North Atlantic

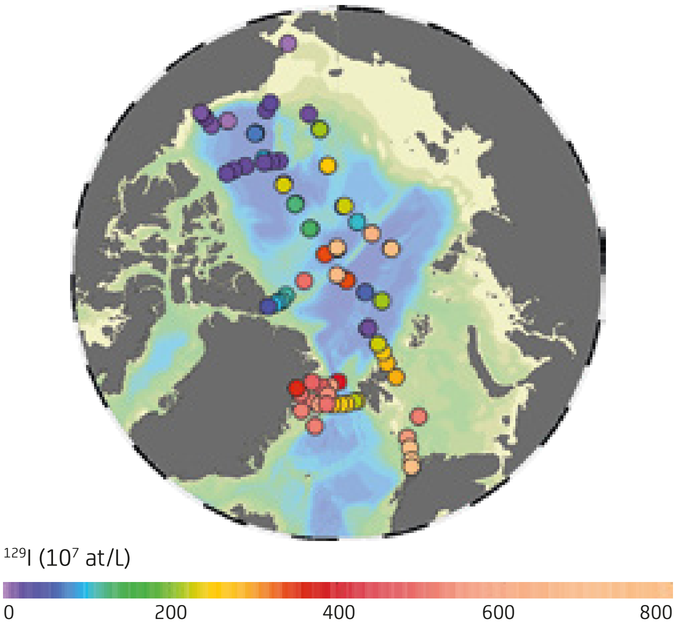


A schematic representation of the main water mass circulation in the Arctic and Atlantic oceans as part of the ocean great conveyor belt (and AMOC). The red arrows represent the warm surface ocean currents and blue arrows the deep circulation. The yellow dots represent the two European reprocessing plants of Sellafield (SF) and La Hague (LH), where radioisotopes of artificial origin have been discharged and subsequently used to trace circulation of waters in this particular domain.

One of the most well-known examples is the long-lived isotope, iodine-129. This artificial radioisotope has been released since the 1980s from Sellafield and La Hague, and its signal was observed only a few years later in the Arctic Ocean, allowing for the estimation of circulation times of waters from the North Sea to the North Pole. Today, the distribution of this isotope in the surface of the Arctic Ocean (see the figure opposite) reflects the transport pathways



of tracer-labelled waters during their journey through the polar ocean and its penetration to the subpolar North Atlantic Ocean via the western side of the Fram Strait. If we compare the circulation pathways in the figure left and the concentrations of iodine-129 in the figure below, we will realise that the initial high concentrations of iodine-129 entering the Arctic Ocean, mostly from the Barents Sea opening, decrease while being transported across the different basins. Iodine-129 concentrations are low in the Amerasian Basin, due to the mixing of Atlantic tracer-labelled waters, with the Pacific being almost-tracer-free waters. This radioisotope therefore provides a powerful tool for understanding the pathways of waters carrying its signal into the Arctic Ocean, as well as their transport timescales and the dilution with other water masses.



Concentrations of iodine-29 observed in the Arctic Ocean and Fram Strait between years 2012 and 2016 at the water surface (10 to 60 metres). The distribution of iodine-29 tells us about the circulation pathways of Atlantic waters in the Arctic Ocean.

The use of the artificial long-lived anthropogenic radionuclides such as iodine-129, and others such as uranium-236 and neptunium-237, from nuclear reprocessing-plant discharges, emerged with the advances on accelerator mass spectrometry (AMS), see page 30. Once more, nuclear physics has proved to be in our everyday life by providing with the tool to understand the climate and our environment.

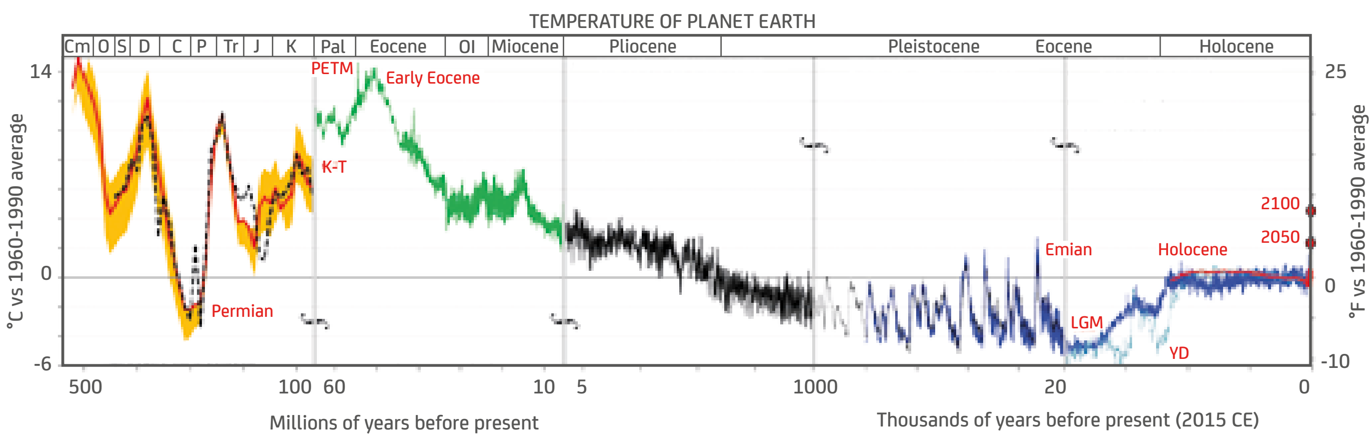
ISOTOPIC TRACERS OF PAST CLIMATE

To understand fully the nature and consequences of climate change, we need to build climate models – and that requires investigating past changes in climate. However, direct observations are available only for the past 200 years, and this is not sufficient to validate climate models aimed at spanning thousands of years of the Earth's geological history. To go further back in time, we need to extract the information from the traces that the climate has stored in different natural archives, such as trees, ice, lake and marine sediments, as well as mineral deposits in caves such as stalactites. These are known as proxy data, which need to be properly calibrated to extract climate information from them. A key component of these proxy data is the abundance of nuclear isotopes, both stable and radioactive.

STABLE ISOTOPES AND ARCHIVES OF PAST CLIMATE

Many common elements found on Earth have several stable isotopes. They demonstrate the same overall chemistry – but having different atomic masses (because of the varying numbers of neutrons), chemical reaction rates can differ – as can their molecular spectral fingerprints used for identification during chemical analysis. These differences allow them to be used as tracers of processes that may change the ratios of the isotopes with respect to the average values found on Earth. This ratio is denoted by the term *delta* – for example, *delta* 0-18 (δ^{18}O) is a measure of the ratio of stable isotopes oxygen-18 and oxygen-16. The isotopic ratio is preserved once the relevant material (shells, ice, sediments, and so on) has been formed, so the environmental variables in the past can be reconstructed (temperature, pH, biological activity). The isotopes of three elements particularly relevant in the study of past climates are oxygen-18 relative to standard oxygen-16, deuterium (the heavier hydrogen isotope) relative to hydrogen – δ^2H, and carbon-13 relative to everyday carbon-12 – δ^{13}C. These isotope ratios allow us to study the Earth's water and carbon cycles.

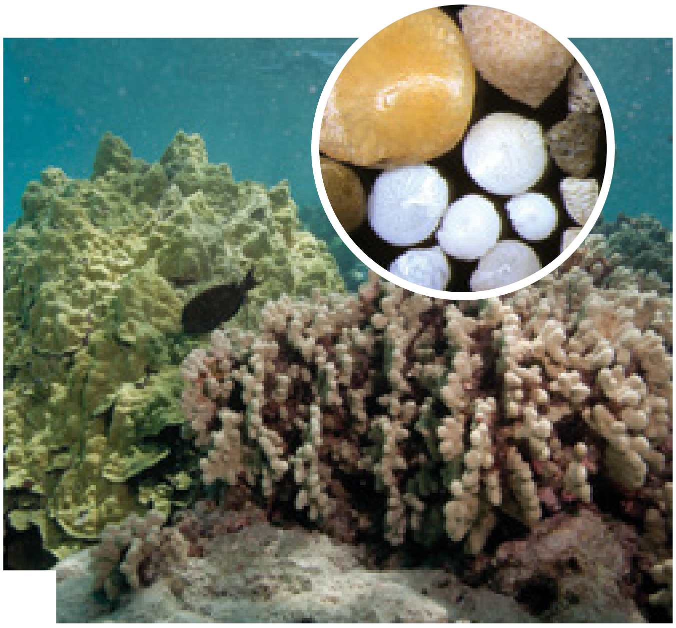
The evolution of global average surface air temperature in the past 540 million years: (right) obtained from the δ^{18}O excess in marine sediments (between 540 and one million years ago), Antarctic ice (one million to 20,000 years ago), and Greenland ice (20,000 years ago until now); and (left) over the recent period of instrumental observation (1850-2021). **[Credits (a)IPCC and (b) Glen Fergus https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons].**



As an example of how measurements of these ratios are useful, the isotopic delta ratios for hydrogen and oxygen in water (H_2O) change during evaporation and condensation processes, and this is linked to temperature and humidity. Water molecules formed by lighter isotopes evaporate more quickly than those formed by heavier isotopes. Thus, negative values of $\delta^{18}O$ and $\delta^{2}H$ are produced in water vapour, cloud droplets and ice cores. However, evaporation enriches the water remaining in plants in the heaver isotopes, producing positive values of $\delta^{18}O$ and $\delta^{2}H$ in the organic residues. Rainfall determines the isotopic composition of shallow waters.

From the measurements of the isotopic ratio of oxygen in marine sediments and in Antarctic ice cores, the average Earth temperature 540 million years ago has been reconstructed (see figure on page 37). It is well known that the weather was much warmer than it is today (+12°C) at the beginning of the Eocene period), and also much cooler (-6°C) in the last glacial period. In the current era, the Holocene, the average temperature has stayed fairly constant – yet the constant temperature rise since 1950s is now disrupting this stability.

The measurements of $\delta^{18}O$ in shells of planktonic *Foraminiferae* or in porite corals tell us about the local conditions in temperature and salinity on the two sides of the tropical Pacific Ocean. By analysing the difference in sea surface temperatures between the eastern and western parts, information can be obtained on whether conditions such as *El Niño* have occurred and their variability in the past. *El Niño* is the oceanic component of the '*El Niño*/Southern Oscillation'. This phenomenon is characterised by the fluctuations in sea surface temperature between the eastern and central part of the tropical Pacific, associated with atmospheric changes. It affects the climatic conditions of various parts of the world and is responsible for violent storms and persistent draughts in the Pacific coasts.



Isotope measurements of fossil plankton and corals reveal differences in sea surface temperatures in ancient climates. **[Credit Lindsey Kramer/ USFWS].**

Another powerful tracer of the past climate is the carbon isotopic ratio, $\delta^{13}C$. For most inorganic processes, both isotopes have the same chemical behaviour. However, some organic processes such as photosynthesis reduce the amount of carbon-13 relative to carbon-12. Also, at different stages of evolution, and in different climatic conditions, plants build up carbon from photosynthesis via two different biochemical pathways, C_3 and C_4, which result in a different $\delta^{13}C$. When plants are in benevolent conditions (moderate temperatures, high light intensity, plenty of CO_2), the C_3 path dominates, and $\delta^{13}C$ is small. However, in harsh conditions, the C_4 photosynthesis path dominates, and the $\delta^{13}C$ is higher. A study of the isotopic ratios of oxygen and carbon in the sediments of the Himalayas has indicated a change in the vegetation of the region between 10.5 and 6 million years ago, from the C_3 type to the C_4 type. This change is associated with a change in rainfall. The monsoon pattern was more intense than it is today, favouring C_3 plants. Since then, C_4 plants have appeared, adapted to reduced rainfall.

Therefore, accurate measurements of $\delta^{13}C$ in carbonate strata are indicators of biological activity, and can identify when a mass extinction has occurred. It is fascinating that counting the neutrons found in the nuclei of carbonate strata (seven for carbon-13, six for carbon-12) can give so much information about the past life on Earth.

THE ROLE OF RADIOACTIVE ISOTOPES

The radioactive versions of isotopes are also valuable tracers for the study of past climate. For example, protoactinium-231 and thorium-230 are produced by the decay of the primordial radioisotopes uranium-235 and uranium-238 respectively. These isotopes have different chemical behaviour in the ocean, with protoactinium-231 being more soluble than thorium-230, which is deposited in the marine sediments. Thus, the ratio of these two radioactive isotopes can be used to study changes of oceanic circulation in the past. Different ratios are found in the central Atlantic and in the Austral Oceans, indicating a predominant southward transport of the more soluble protoactinium-231 compared to thorium-230. Indeed, there is evidence that, after the last glacial period, there were huge icebergs that broke out from the North Atlantic ice shell, and eventually melted in the Atlantic Ocean, releasing sediments which could not be carried by the usual marine currents. Measurements of the isotopic ratios associated to those events indicated a significant weakening of the thermohaline currents, which was associated to a cooling of the northern hemisphere during that period.

Other natural radioisotopes are used for dating past geological events. The most well-known is carbon-14. It is constantly produced by the interaction of cosmic rays with the nitrogen atoms in the atmosphere. Once produced, it is incorporated into the carbon cycle, and it is absorbed by living organisms, which preserve the same ratio of carbon-14 to naturally occurring carbon-12 in their bodies as in the atmosphere. Once the organisms die, the exchange of carbon with the atmosphere ceases, and the content of carbon-14 reduces at a constant decay rate that is determined by its half-life (5730 years). Thus, a measurement of the ratio in a dead organism tells us when the organism stopped exchanging carbon with the atmosphere. Indeed, once the amount of carbon-14 gets below the detection limits, the age cannot be determined, and this limits the validity of radiocarbon dating to 40,000 years. Variations of carbon-14 in the atmosphere are taken into account by calibrating the radiocarbon date with other more accurate proxies such as tree rings and corals.

Other radioisotopes produced by cosmic-ray interactions, such as beryllium-10, aluminium-26 and chlorine-36 (with half-lives of 1.39, 0.72 and 0.30 million years respectively) can also be used for dating. They are produced both in the atmosphere and at the surfaces of rocks (*in-situ* production). Thus, we can extract information about the last time the rock was exposed to cosmic rays and not covered by ice. This allows us to estimate the extent of glaciers, and the speed of their recession. As examples, beryllium-10 has been used to investigate the flows and retreat of ice in Europe and Greenland, 11,000 years ago, which were associated which a minimum of solar activity. The extension of ice in the Antarctic during the last glacial maximum (20,000 years ago) was investigated through AMS measurements of these isotopes. The rate at which Antarctic ice was melting, and the contribution to the rise in sea level was determined during a period between 10,000 and 4000 years ago. AMS measurements of beryllium and aluminium radioisotopes in Greenland have allowed the percentage of time that rocks were covered by ice during the past million years to be determined.

Studies of the Greenland ice sheet and the Antarctic ice cap using radioisotopes provide clues about climate change in the past. **[Credit British Antarctic Survey].**

Past climate is indeed the only benchmark that climate science has in order to predict climate change reliably. Nuclear physics, through the measurements of stable and radioactive nuclei, provides a glimpse into the past climate, which tells us what happened and when. Past situations in which temperatures increased, CO_2 levels changed, glaciers and ice shells melted, ocean levels rose, and ocean circulation was modified, are indeed of the utmost interest in the current climate situation.

TRACERS OF A 'SNOWBALL EARTH'

Geologists and paleo-climatologists use the term 'snowball Earth' to describe extreme glacial events in which the entire Earth was frozen as far down as the equator. Because ice reflects much more sunlight than the liquid water, the albedo (total reflected light) of the Earth increased, such that a large amount of solar energy was reflected away from the Earth's surface, and average global temperatures settled down to those of present-day Antarctica.

A depiction of the Earth covered in snow and ice more than 2 billion years ago.

One such event is believed to have happened during the Huronian glaciation (2.4 to 2.1 billion years ago) in the Paleoproterozoic era. This event is associated to the appearance of cyanobacteria (blue-green algae), which managed to use solar light to decompose water via photosynthesis, producing large amounts of gaseous oxygen. The oxygen then reacted with the methane – then dominant in the atmosphere – to produce CO_2 and water. Methane is a very effective greenhouse gas, so that when it was depleted and substituted by CO_2, the greenhouse effect decreased, and a rapid glaciation occurred, converting the Earth to a 'snowball'. In this situation, life was reduced to a minimum, and a mass extinction of the previous anaerobic life occurred. The way out from this snowball Earth is thought to have been due to the contribution of CO_2 from the volcanic activity. Over time, the relatively modest contribution of CO_2 from volcanoes accumulated in the atmosphere, increasing the greenhouse effect, eventually melting the oceans and allowing the development of new life, tolerant of the large amount of oxygen produced by the cyanobacteria.

Another snowball Earth did occur later, in the Cryogenian period of the Neoproterozoic era (720 to 635 million years ago). Again, a mass extinction occurred, as indicated by the carbon-13 records, and CO_2 from the volcanoes came to the rescue, allowing the Earth to become a more friendly environment for the kind of life-forms from which we ultimately descended.

This fascinating story indicates how our mildly radioactive Earth had energy resources, coming in part from radioactivity, that released greenhouse gases into the atmosphere and so avoided a permanent, Mars-like snowball state. It also indicates how the extensive use of energy resources by some living species (cyanobacteria in the Huronian glaciation, and *Homo sapiens* in the modern Holocene) can alter the climate system, and carry it beyond a tipping point that could produce a mass extinction. Earth will recover, but individual species may not.

FURTHER INFORMATION

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.; https://www.ipcc.ch/report/ar5/wg1

CHAPTER 5:

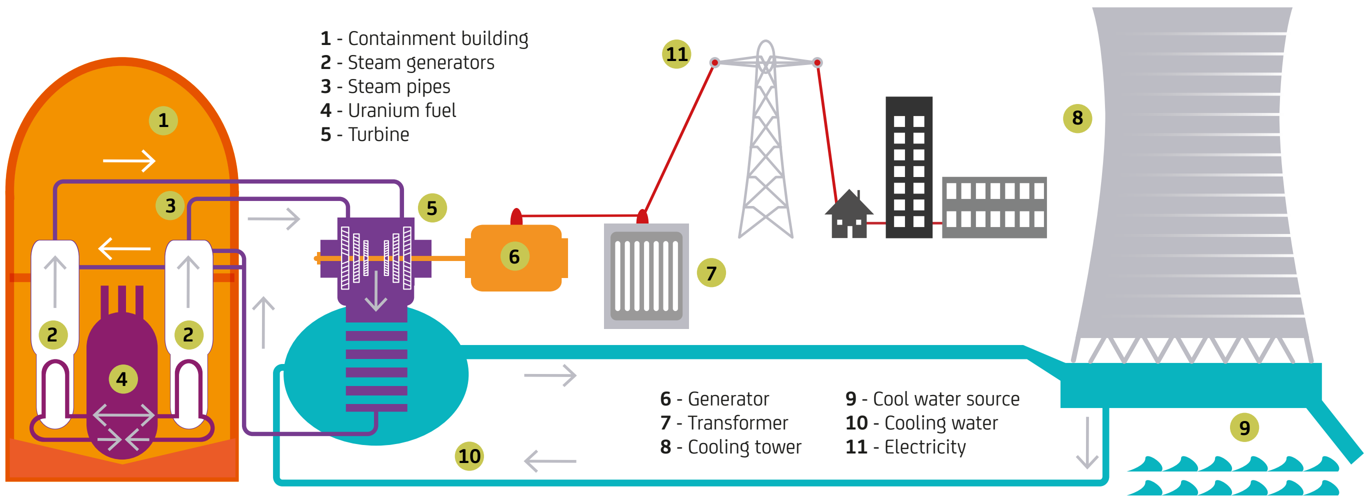
ENERGY

The Temelin nuclear power plant in the Czech Republic.
[Credit CEZ Group].

NUCLEAR ENERGY IS NOW RECOGNISED AS ONE OF THE KEY RESOURCES IN SATISFYING GLOBAL DEMANDS FOR POWER PRODUCTION WHILE MITIGATING CLIMATE CHANGE. THE MOST ADVANCED NUCLEAR REACTOR DESIGNS ARE EFFICIENT, SAFE TO OPERATE, AND HAVE THE POTENTIAL TO GENERATE VERY LITTLE WASTE. HOWEVER, THEIR SUCCESSFUL EXPLOITATION REQUIRES A CONTINUOUS AND EXPANDING COMMITMENT TO INVESTMENT IN NUCLEAR RESEARCH, TECHNOLOGY AND EDUCATION.

Most informed people – scientists, politicians and the educated public – now recognise that one of the greatest threats to the natural world and human progress is uncontrolled climate change caused by large emissions of greenhouse gases from the use of fossil fuels. While the further development of various energy sources with low greenhouse-gas emissions – solar, wind, wave, geothermal and hydro power – will help satisfy our ever-more hungry energy demands, nuclear energy stands out as a significant resource in protecting the environmental future of our planet. Nuclear physicists and engineers are developing ever more efficient and safe nuclear energy plants, along with underlying technologies, for electricity production.

Layout of a typical nuclear power plant.



Over past decades, many environmentalists have been against the use of nuclear power, quoting opinions based on information often relating to outmoded nuclear energy generation from more than half a century ago; the perceived problematic disposal of long-lived nuclear waste and the (rare) nuclear accidents that have happened are frequently quoted as reasons for not investing in nuclear power. However, in this chapter, we will describe the progress that has been made in developing nuclear energy production as a safe and efficient resource to help address climate change. Just as humanity's earliest use of energy, chemical combustion (fire), was wasteful, polluting, and actually a difficult-to-control chain reaction, it has since been tamed to be a mostly safe energy source, so nuclear energy is becoming ever safer and more efficient via developments made through advanced nuclear physics studies and engineering.

WHAT IS NUCLEAR ENERGY?

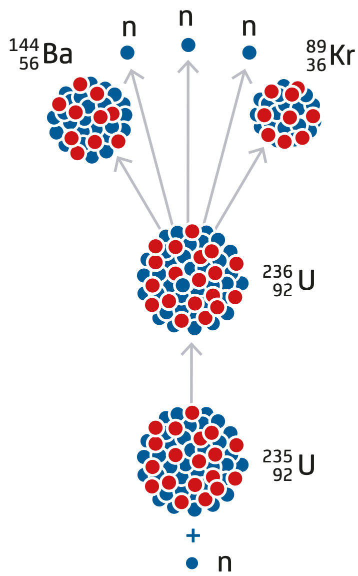
As described in Chapter 1, there are four fundamental forces in the Universe, electromagnetism (the force responsible for chemistry and electricity), gravity (exploited in hydroelectric power), and the strong and weak nuclear forces, which govern how atomic nuclei behave. It is the strong force that really lives up to its name, in binding together in an incredibly tight grip the quarks, which make up the protons and neutrons (nucleons) in the nucleus. It represents the most concentrated form of energy in existence, so it is not surprising that physicists have looked at methods of exploiting this force by finding ways of triggering nuclear reactions that result in the release of energy.

There are two possible ways to produce energy by means of nuclear reactions. The first involves the breaking apart of a heavy nucleus (nuclear fission), and the second is when or two lighter nuclei fuse (nuclear fusion). In nuclear fission or fusion, some of the energy needed to bind the nucleons in a nucleus is converted into the kinetic energy of the nuclei produced and subatomic particles such as neutrons. This can then be converted into heat and harnessed to produce electricity. High-energy electromagnetic radiation (gamma-rays) is also emitted. In all nuclear reactions, the law of the conservation of mass and energy applies according to Einstein's famous $E = mc^2$ equation.

Both nuclear fission and nuclear fusion reactions are candidates for power production, but so far only nuclear fission has been utilised successfully, though extensive work is being carried out on a global level to develop a practical reactor based on nuclear fusion.

FISSION SYSTEMS

Nuclear fission was discovered just before World War II. In the 1930s, researchers in Europe and the US working in the embryonic science of nuclear physics soon realised that if a very heavy nucleus like that of uranium-235 (92 protons and 143 neutrons) was bombarded with slow-moving neutrons, then it would capture a further neutron, become unstable and break into two or more smaller fragments (for example, barium-141 and krypton-92). A further two or three neutrons would be released, and under the right conditions, would trigger and sustain a growing chain reaction. Uranium, the heaviest element then known in Nature, has a proportionately much higher number of neutrons to protons in its nucleus, which must be thrown out when the lighter nuclei with proportionately fewer neutrons form. The fission fragments are mostly radioactive, so also contribute to the energy production by decaying further. As well as fissioning, neutrons are also captured by uranium nuclei to create, via beta decay, elements with atomic numbers higher than uranium, such as plutonium (with two more protons), some of which are fissile. The resulting amount of energy released per unit mass of fuel is vastly more than can be achieved using chemical fuel sources such as coal. It is worth remembering that at this time, the neutron had only just been discovered, in 1932!



Uranium fission to produce lighter nuclei and neutrons.

A FISSION REACTOR

Harnessing nuclear energy in a dedicated reactor to generate power is challenging. The neutrons released have too higher energy to be easily captured by another uranium-235 nucleus and cause fission, so they have to be slowed down to increase the probability of capture. In standard reactors, this is achieved by means of collisions with lighter nuclei – such as those of graphite (carbon), 'light' or normal water, or so-called heavy water containing the heavier hydrogen isotope deuterium. Such a process is called neutron moderation.

When engineering a fission reactor, the conditions in the reactor core must be maintained so that the course of the fission chain reaction is stable. This stability is extremely sensitive to the number of fissions and generated neutrons, so the composition of the reactor core and the proportion of the fissile material therein must be tuned and strictly defined. The ratio between the number of neutrons in the next generation of neutron capture and fission to that of the previous one in the chain reaction – the multiplication factor – must be equal to one in order to achieve a sustainable, controlled chain reaction. We call such a nuclear fission system 'critical'. The transition between different power levels of such a reactor can be altered by very small deviations of the multiplication factor from one. If it is a little lower, the power decreases, if it is a little higher, the power increases.

STABLE REACTOR CONTROL

Nuclear engineers employ various methods to control the operation of a nuclear reactor, but they predominantly involve exploiting the differing rates of neutron absorption by materials such as boron or cadmium. These are most often in the form of rods, which are of three types. The first are the control rods that regulate the reactor power by absorbing more neutrons when pushed in, and fewer when pulled out. During the reactor operation, as fuel is consumed, strongly neutron-absorbing transuranium elements, as well as the fission products, are created, so that the conditions for maintaining the fission chain reaction deteriorate. Compensation rods are used to ensure that the fuel does not have to be changed too often. These are fully inserted into the reactor when fresh fuel is introduced. They are then gradually extracted to compensate for the decrease in available fuel and increase in neutron absorbers in the core. When they are fully extracted, some of the fuel is changed. The third type are safety rods, which immediately slide into the reactor core in the event of any fault, and stop the fission chain reaction.

A nuclear fuel assembly **[Credit Framatome].**

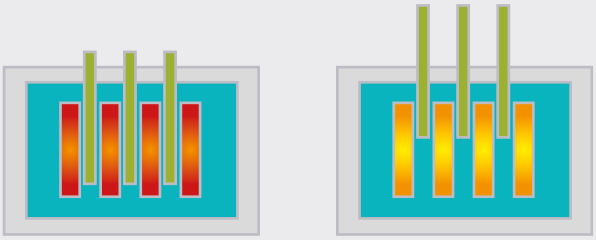
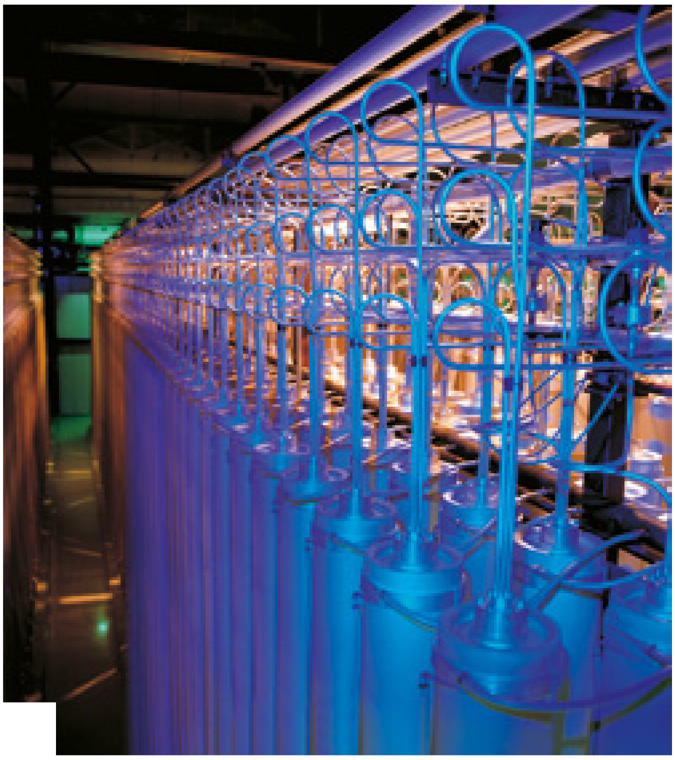


Diagram of how the control rods in a reactor assembly work.

The uranium fuel itself also presents technical challenges. Nuclei with an odd number of neutrons have a lower binding energy than those with an even number. Fission is thus much more likely if a heavy nucleus with an odd number of neutrons captures a neutron, since it will be less stable. In fact, uranium-235 is the only uranium isotope in natural uranium ore that is fissile using low-energy neutrons. The uranium-oxide ore found in the Earth's crust contains only 0.72 per cent of uranium-235, the rest being non-fissile uranium-238, with a minute trace of uranium-234. The first reactors employed natural uranium either as the metal or as an oxide. However, reactors using light water as a moderator require some enrichment of uranium-235 in the fuel. This is because the (normal) water absorbs too many neutrons to reach a critical condition; in fact, most modern reactors require some enrichment to achieve necessary concentrations of around 4 per cent of uranium-235. Enrichment is difficult to achieve because the chemical properties of the two uranium isotopes are identical, and so the slight mass difference (of three neutrons) must be exploited. To achieve enrichment, the uranium is converted into a gaseous form, uranium hexafluoride, and the two isotopes are separated by the differential diffusion, or by using a centrifuge – or more recently using advanced laser methods.



Centrifuges are used to separate uranium 235 from uranium-238. **[Credit Urenco].**

FAST-BREEDER TECHNOLOGY

As well as the problem of limited supplies of uranium-235, another concern is the amount of radioactive waste to be disposed of from conventional, moderated nuclear reactors. Instead of fissioning, uranium may capture neutrons and via beta decay to form plutonium-239 (94 protons and 145 neutrons), and other heavier isotopes such as those of neptunium and americium. These are also radioactive and some of them may have very long half-lives of thousands or millions of years.

One answer is to utilise a variant of the fuel cycle that does not involve slowing down the neutrons with a moderator. In this case, it is possible to design the active core of the reactor such that the major component of natural uranium, uranium-238, when exposed to fast, unmoderated neutrons, is very likely to absorb a neutron to form uranium-239. This undergoes radioactive decay to neptunium-239 and then to plutonium-239. Like uranium-235, plutonium-239 fissions to release more fast neutrons – more than are produced from uranium-235. The result is that more fissile material is created than is destroyed. The advantage of this 'fast-breeder' technology is that all the uranium ore can be utilised, not just a small proportion. Furthermore, fast breeder reactors can destroy the long-lasting radioactive waste-products present after conventional nuclear fission, because they become part of the fuel cycle.

In fact, the very first nuclear reactor to generate electricity was a fast reactor cooled with liquid metal. In 1951, the Experimental Breeder Reactor 1 (EBR 1) in Idaho, US, was switched on, success being demonstrated by the turning on of four light bulbs! EBR 1 then went on to deliver 200 kilowatts of electric power. In later years, a number of fast reactors were developed around the world, the first one being in the UK in 1962. However, by the second millennium, most had been shut down as a result of anti-nuclear fears and the fact that uranium ore became cheaper. Currently, only Russia operates breeder reactors commercially. However, as nuclear technology has developed, there is today renewed interest in exploiting breeder fuel cycles, as described in this chapter.

The Experimental Breeder Reactor EBR1 turned on four light bulbs when it was first switched on in 1951.

A NATURAL REACTOR IN OKLO

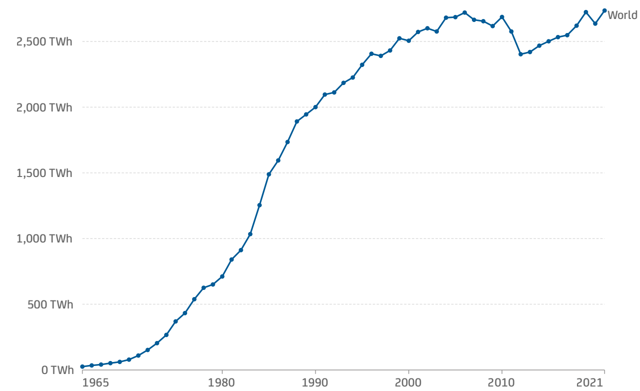
You might be intrigued to learn that nuclear fission reactors are not always artificial. The Oklo uranium site in Gabon has detected the presence of radioisotopes that are formed only in nuclear reactors. The proportions of various such radioisotopes confirm that a natural reactor must have been running there about two billion years ago. At that time, the proportion of uranium-235 in uranium ore would have been much higher and would have reached the level found in current conventional reactors. At the same time, the uranium ore was flooded with water, which acted as a moderator, effectively forming a natural nuclear reactor. Today, this site offers a valuable source of information on how the transuranium elements, as well as fission products, have spread in the environment over many thousands of years without any artificial barrier. This information is very important in preparing repositories for the long-term storage of nuclear waste.

The strange case of an ancient natural nuclear reactor on the site of uranium mines in Gabon. **[Credit CEA].**

THE GROWTH OF NUCLEAR ENERGY GENERATION

The first nuclear power plant to supply electricity commercially came into operation in 1954 in Obninsk, Russia. Electricity production from nuclear power plants then grew rapidly, especially in the 1970s and 1980s, mainly in the US. At the end of the 1980s, the share of electricity production from nuclear sources exceeded 16 per cent and remained at this level until the beginning of this century. The number of reactors then dropped and today, the proportion is at just over 10 per cent. The maximum electricity production achieved has exceeded 2600 terawatt-hours (TWh); this was in 2006 and was reached again in 2019. Currently, there are more than 440 reactors in the world with a total output of almost 400 gigawatts of electrical power (GWe). More than 50 reactors are under construction and a further 100 or so are planned. A number of European states, such as the Czech Republic, Slovakia, Finland, France, Poland and the UK, expect to expand their use of nuclear power. However, the nuclear reactor fleet is ageing, so in the near future it is important not only to replace these reactors but also to develop nuclear energy in developing countries to satisfy their emerging energy needs. It is further interesting to note that while around 70 per cent of France's electricity comes from nuclear power, Germany has been phasing out its limited nuclear power use – despite emitting around 10 times as much carbon dioxide per kilowatt hour of electricity as France. Opposition to nuclear power is hardly the green option if attempting to limit climate change!

a



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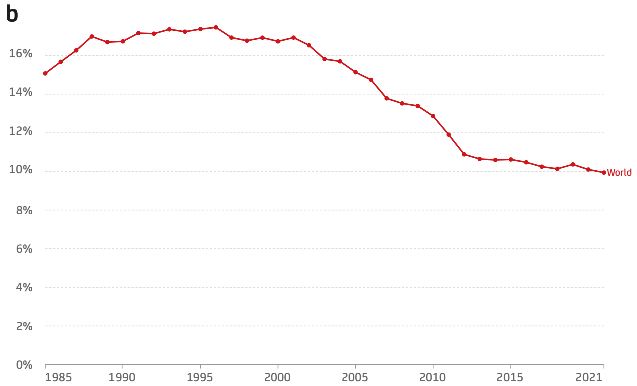


The growth of nuclear power production (a) and the percentage of electricity production that is nuclear across the world (b). **[Credit OurWorldinData.org.energy].**

TOWARDS THE MODERN NUCLEAR REACTOR

As the use of nuclear energy has grown during the past 70 years, a wide variety of reactors designs have been commercialised, and work continues in developing improved nuclear technology. These designs have been divided into generations. The first generation includes the earliest nuclear units, which tested the possibility of obtaining electricity production from nuclear reactions. None of them is currently in operation. The dominant part of the current fleet of nuclear power plants consists of so-called Generation II reactors, which began operation over a period from the late 1960s to 1990s.

During the past two decades, the first Generation III reactors have been built and operated. The experience gained through these 'first of a kind' nuclear power plants should ensure the efficient serial construction of new reactors. Generation III reactors should have a service lifetime of more than 60 years and have a very high safety level. They also have improved economic characteristics, better use of fuel and reduced nuclear waste, so are competitive with other energy sources. The most commonly used nuclear power units are water-cooled reactors. The leading kind are pressurised-water reactors, followed by boiling-water reactors. At present, seven types of Generation III reactors are in operation.

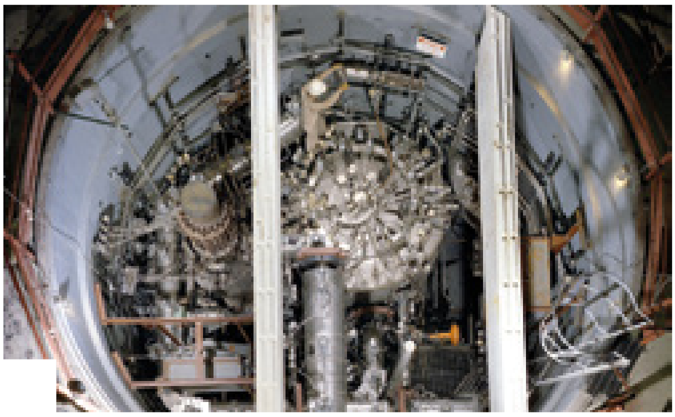
One concern has always been the production of plutonium in the reactor. About 1 per cent of the spent fuel consists of plutonium isotopes, some of which are fissile. An important approach to increasing efficiency and reducing radioactive waste is to recover the plutonium, mix it with depleted uranium as a mixed oxide (MOX), and then add this to the nuclear fuel. In this way, the efficiency of the fuel cycle is increased.

Economy of scale has meant that Generation III reactors have a high-power capacity (GWe and more). However, the economics of commercialisation can be complex. As the size of the plant grows, the ratio of construction and operating costs to the power output, and thus the cost per unit of electricity produced, decreases. However, the total investment costs and risks are higher. The importance of these factors – limited returns on investment and, in some regions of the world, long construction times due to the complexity of the nuclear power plant – has been increasing in recent decades. At least in western countries, this has hampered the further development of nuclear power.

The Olkiluoto 3 European Pressurised Water Reactor in Finland. **[Credit TVO].**

THORIUM REACTORS

Uranium and plutonium are not the only fuels that can be used to generate energy. Thorium-232 (90 protons, 122 neutrons) is what is called a fertile material. Like uranium-238, it too can absorb neutrons, converting first to thorium-233 via neutron capture, and then decaying to uranium-233. This isotope is fissile and can start a chain reaction. Thorium can be used in a breeder set-up using moderated neutrons. The thorium fuel cycle has an advantage in that it produces lower levels of the transuranium elements than the uranium fuel cycle, and thus less waste. There is more than three times more thorium than uranium in the Earth's crust, though it is harder to extract. The technical feasibility of using thorium in reactors was explored from the 1960s onwards in various reactor types, particularly in the US and India (which has sizeable thorium deposits), and current advanced reactor concepts do include utilising thorium as a fuel.

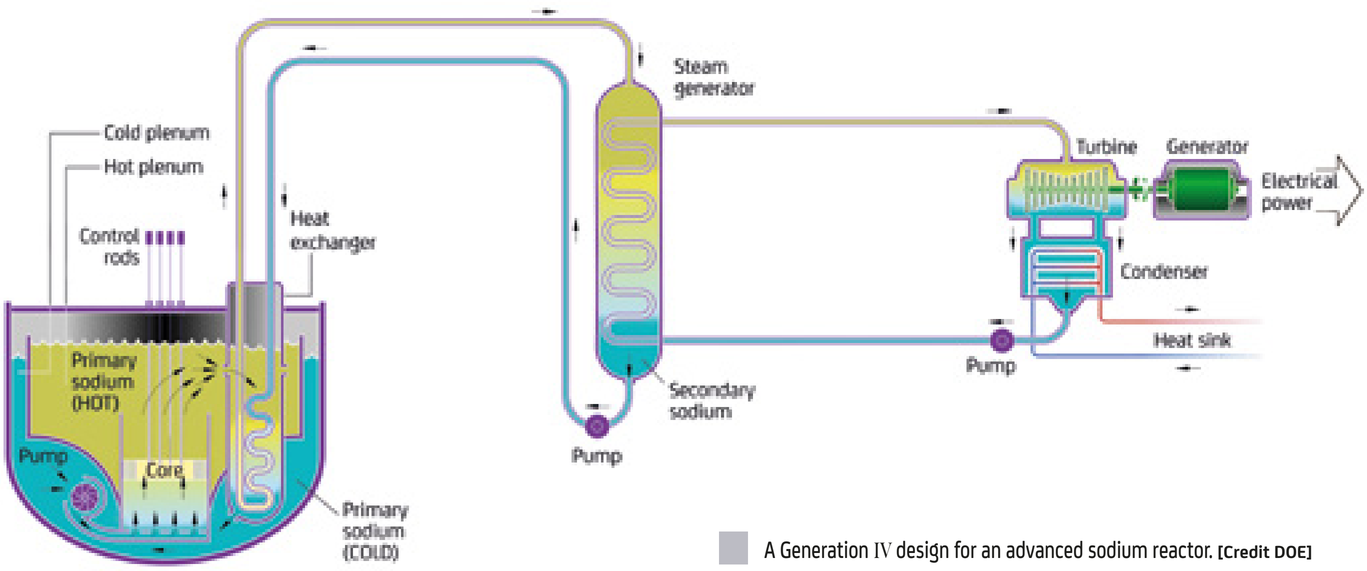


The molten salt reactor using thorium at Oak Ridge National Laboratory in the 1960s. Thorium is again being studied as a fuel for nuclear power. **[Credit ORNL].**

ADVANCED REACTORS

Countries around the world are now developing a fourth generation of reactors that very much focuses on being efficient, safe and clean. As previously explained, conventional thermal reactors make only limited use of the bulk of uranium available, uranium-238. Advanced nuclear fast breeder systems are now being developed that allow the conversion of uranium-238, or thorium-232, to fissile materials by efficient neutron capture. In these designs, the recycling of spent nuclear fuel would be used even more intensively to create a closed fuel cycle in order to reduce the volume of high-level radioactive waste. Four of the six Generation IV reactor concepts are such fast reactors. At present, the most advanced of them is a reactor cooled by liquid sodium; two such reactors already supply electricity at the Beloyarsk nuclear power plant in Russia. Others are liquid lead-cooled and gas-cooled reactors.

One rather exotic concept uses liquid fuel in the form of molten salts, which has the advantage of allowing the continuous separation of radioisotopes from the fuel. It offers a relatively efficient tool for burning transuranium elements from spent fuel. Some Generation IV reactor concepts – supercritical water-cooled reactors and high-temperature gas-cooled reactors – would very efficiently enable the production of electricity and industrial heat at medium to very high temperatures, even as high as 1000 °C. The development of an advanced high-temperature gas-cooled reactor (HTGR) has also made considerable progress, and two first units of small modular HTGRs entered into operation in 2022 in China.



A Generation IV design for an advanced sodium reactor. **[Credit DOE]**

SMALL MODULAR REACTORS

The high investment costs associated with ever larger nuclear power stations have encouraged many countries to consider the development of novel, small modular reactors (SMRs) with an output of less than 300 MWe. These would be small, factory-fabricated power units that are cheaper and quicker to build and could be used to generate power on small industrial sites. SMRs are also particularly suitable for remote regions, and non-electricity-producing applications like hydrogen generation and water desalination. In addition, they can be integrated with renewable energy sources. The modular concept should mean that they are safer (smaller radioactive inventory and less fall-out from an unlikely leak or accident), so should make it possible to simplify the licensing and exploit nuclear energy for decentralised energy production.

Some reactor set-ups would work a bit like changing a battery. The reactor module would be brought on a truck to its requested location, and at the end of a fuel cycle, it would be replaced by another unit. Fuel would not be changed at the place of use. Intensive work is also being done on completely new small reactor concepts, which would make it possible to extend the cycle between fuel changes up to decades. Although several SMR projects are being developed, only a few are in commercial operation. They include six prototype marine ice-breakers, and a floating two-module nuclear power plant, Akademik Lomonosov, in far-east Russia, which was connected to the grid in 2020.

Rolls Royce is developing a small modular reactor that could be transported by an HGV or even a barge. **[Credit Rolls Royce]** .

Russia's first floating nuclear power station, Akademik Lomonosov. **[Credit Rosatom].**

SMALL REACTORS FOR NUCLEAR PROPULSION

Over the past 70 years, several countries have built fleets of ships and submarines for military purposes that are propelled by compact nuclear reactors used in conjunction with a steam turbine. Today, serious consideration is to be given to employing nuclear power more generally in commercial shipping, which would allow marine vessels to operate for many years without re-fuelling. Marine shipping using fossil fuels currently accounts for 3 to 4 per cent of global greenhouse emissions.

Both the US and Russia have in the past developed nuclear propulsion systems for space satellites, and they are now being considered for manned spaceflight to Mars (see Chapter 9). In one design, liquid hydrogen is pumped through the reactor where it is converted to a gas by the heat from uranium fission. The gas expands through a nozzle to generate thrust. Such systems based on nuclear reactors are much more efficient than those based on chemical propulsion.

ACCELERATOR-DRIVEN FISSION SYSTEMS

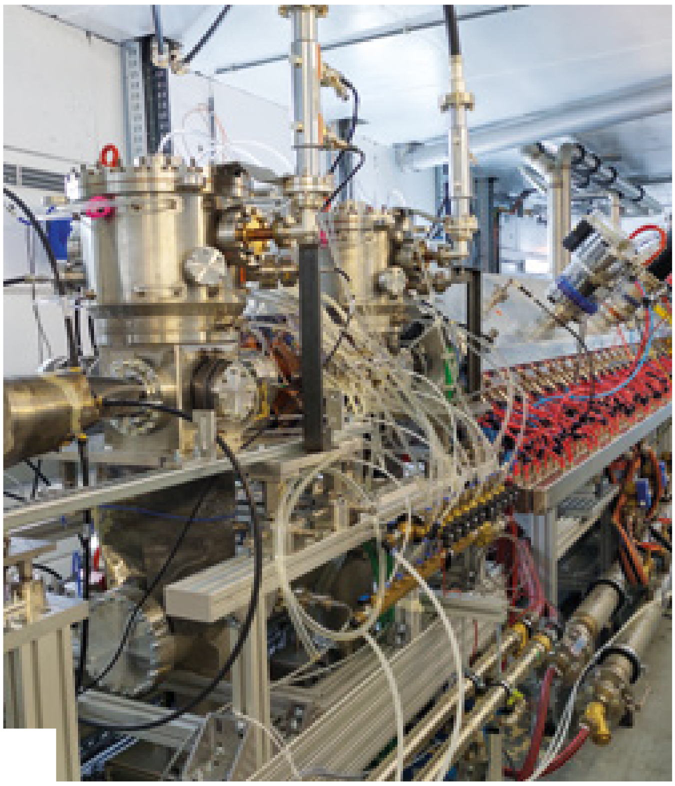
As we know, two of the main objections to nuclear fission as a power source has been the perceived danger of runaway nuclear reactions causing explosive leaks and the generation of long-lived radioactive waste. There is another approach to nuclear fission that is more controllable and also has the potential to burn nuclear waste in a dedicated setup. This is to carry out fission at a subcritical level such that it can be 'turned-off' as needed. It requires an additional external source of neutrons to keep the fission going; when this neutron source is removed, the chain reaction stops. Such systems would be much safer and so are creating a great deal of interest.

To generate the neutron source requires a high-energy accelerator, which is why they are called accelerator-driven systems (ADS). An intense beam of neutrons is created by firing a beam of accelerated protons at a neutron-rich metal target such as lead, tungsten or uranium. The high-energy protons knock out neutrons from the target material – a process called spallation. The underlying technology of building proton accelerators (used in many applications including medical treatments) is well established – although they would need to deliver more intense beams than have so far been available. There has been a proton-driven spallation source in the UK for four decades, and a very intense spallation source, the European Spallation Source, is now being constructed in Sweden. Both are designed to exploit neutrons, rather like X-rays, in studies of technological and biological materials and processes (see Chapters 6, 7 and 8).

The MYRRHA reactor being built in Belgium will test accelerator-driven nuclear fission.

An ADS would thus consist of a spallation neutron source, in which the target would be surrounded by a blanket assembly of fissile or fertile materials. Such a system is far less sensitive to fuel composition, and can make use of fuel with a high content of plutonium and transuranium elements from spent nuclear fuel. To avoid capturing more neutrons than the system can handle during the neutron irradiation of the reactor core, isotopes that are stable, short-lived or suitable as a fuel for conventional reactors can be separated continuously. As described for the Generation IV molten salt reactor using fuel in a liquid form, the radioisotopes do not accumulate and so the problem of removing the damaging excess heat generated during radioactive decay disappears. When working as a power plant, the conversion of heat to electricity will be the same as for conventional reactors. Part of the electricity generated would be used to operate the accelerator and other equipment; the rest would be sent to the electricity grid.

Of particular interest is the use of thorium as a fuel. As explained earlier, a source of neutrons converts thorium-232 into fissile uranium-233. The reaction is subcritical, meaning it will not keep going unless there are additional neutrons available, either from being enriched with a material like plutonium, which produces a lot of neutrons, or from a spallation source. In either case, the system would burn up the minor radioactive isotopes normally produced in uranium fission, making energy production much cleaner. In the early 1990s, Carlo Rubbia, the then Director of CERN (the European Laboratory for Nuclear Research) in Geneva, proposed a concept that he called the Energy Amplifier which combined a proton accelerator with a thorium reactor. The accelerator-driven thorium reactor is now being taken forward by India and also the UK.

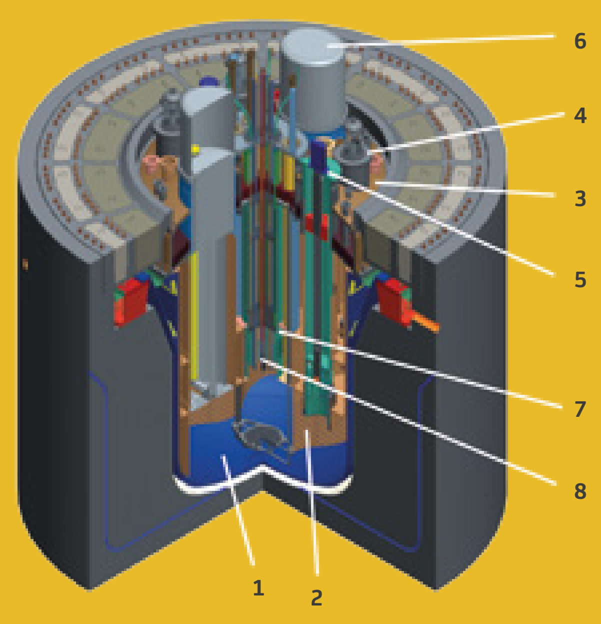


Myrrha's proton injector system.

TRANSMUTATION OF NUCLEAR WASTE

Of immediate interest is the significant development of accelerator-driven systems for the transmutation of spent nuclear fuel from conventional reactors. This idea represents the first step in testing and utilising ADS technology. An intense neutron source would allow spent fuel containing transuranium elements to be transmuted efficiently into less harmful elements by the resulting successive neutron captures and decays.

The experimental reactor MYRRHA (Multi-purpose hybrid Research Reactor for High-tech Applications) being built at the Belgian Nuclear Research Centre – SCK CEN – in Mol, Belgium will test the capabilities of accelerator-driven transmutation systems. It consists of a small fast reactor (7 metres by 4.4 metres) that can operate in both critical and subcritical modes. In the case of subcritical operation, the external source of neutrons will be a proton accelerator providing protons with a kinetic energy of 600 mega-electronvolts (MeV). Protons would hit a liquid lead–bismuth target. Fuel assemblies using MOX fuel enriched with plutonium up to 30 per cent will be used, and the reactor core will also be cooled by a liquid bismuth–lead mixture. The resulting thermal output of the reactor will be between 50 and 100 megawatts. In September 2018, the financing of the first phases of this project was approved by the Belgium Government and MYRRHA is expected to be commissioned by 2033.



1. Reactor vessel
2. Diaphragm
3. Reactor cover
4. Primary heat exchanger
5. Primary pump
6. In-vessel fuel handling machine
7. Core barrel
8. Reactor core

A graphic of the layout of the accelerator-driven system. **[Credit SCK-CEN].**

Other research facilities testing the capabilities of accelerator-driven transmutation technologies are being developed elsewhere in the world. China, for example, is working on the Accelerator Driven AdvaNced Energy System (ADANES), which would include an Accelerator Driven System Burner (ADB) to burn transuranium elements and an Accelerator-Driven Recycle Used Fuel (ADRUF) to recycle spent fuel from conventional nuclear units.

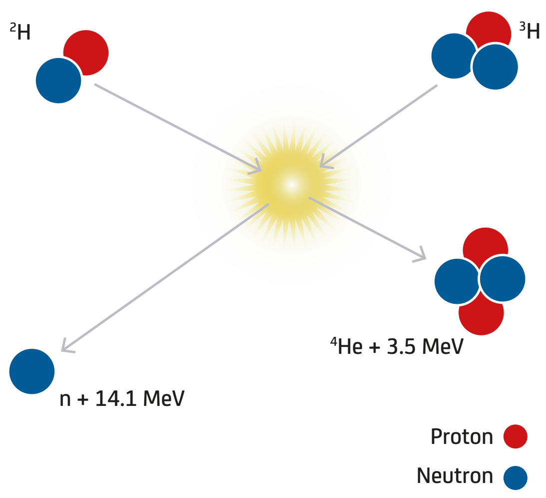
FUSION ENERGY SYSTEMS

In addition to fission, nuclear energy can be generated from fusion reactions, that is, when two light atomic nuclei combine to form a single heavier one, releasing energy in the process. This is how the Sun produces its energy output, by the fusion of hydrogen nuclei (protons) to form helium. The concept of nuclear fusion has been around for a century when it was realised that such a process would release energy. As explained in Chapter 3 on nucleosynthesis in stars, this energy release applies only to the fusion of the lighter elements.

Mimicking the same processes in the terrestrial environment, however, presents considerable challenges. As well as neutral neutrons, nuclei contain protons, which are positively charged. The repulsive force between them creates an electrostatic energy barrier which must be overcome before the nuclei can be pulled together and bound by the powerful strong nuclear force. In the classical case, fusion requires that nuclei are heated to very high temperatures in the order of 100 to 1000 million degrees when the kinetic energy of the particles is high enough to overcome the electrostatic repulsion. In fact, so much energy is required that fusion is achieved only because quantum mechanics allows the particles to 'tunnel' through the energy barrier. Fusion can also happen at lower energies by pushing the nuclei close enough together to overcome the electrostatic repulsion, so that the strong force takes over and the nuclei fuse. However, the reaction is less likely to happen.

CANDIDATE FUSION REACTIONS FOR ENERGY PRODUCTION

Several fusion reactions of the lightest nuclei could be used for energy production. The most likely reaction that can be achieved at realistic temperatures is that between the nuclei of hydrogen isotopes, deuterium (one proton and one neutron) and tritium (with two neutrons), to form helium-4 (two protons and two neutrons) plus an energy-carrying neutron. One of the reasons that there has been so much enthusiasm for nuclear fusion is that a much lower level of radioactive waste would be produced than from fission, and the fact that deuterium is relatively common in the sea water. Tritium is radioactive with a half-life of 12.3 years, and is generated naturally by the interaction of cosmic rays with nuclei in the atmosphere. It is also produced in fission reactors, especially those that are cooled and moderated by heavy water. However, the most efficient method for making tritium is by bombarding either lithium-6 (three protons and three neutrons) or lithium-7 (with a further neutron) with neutrons to make tritium and helium-4 (and an additional neutron in the case of lithium-7). The reaction with lithium-6 is the most energy efficient but naturally occurring lithium is mostly composed of the heavier isotope (92.5 per cent lithium-7 and 7.5 per cent of lithium-6).



The fusion of deuterium and tritium to helium-4.

A second possible reaction is the fusion of deuterium and helium-3. This would require an even higher temperature, and the rate at which reaction would happen is far lower. Helium-3 is stable, but the problem is obtaining it. It is thought that it could occur as trapped solar wind particles on the surface of the Moon. Pure deuterium fusion is another possibility but is much less efficient than that with tritium, and needs much higher temperatures.

A more exotic reaction is that of boron-11 (five protons and six neutrons) and a proton to form three helium-4 nuclei (sometimes called aneutronic fusion). Boron-11 forms 80 per cent of natural boron sources and is in plentiful supply. The disadvantage is that very extreme temperatures are needed, as is the case in other fusion variants involving light nuclei.

HOW TO ACHIEVE FUSION

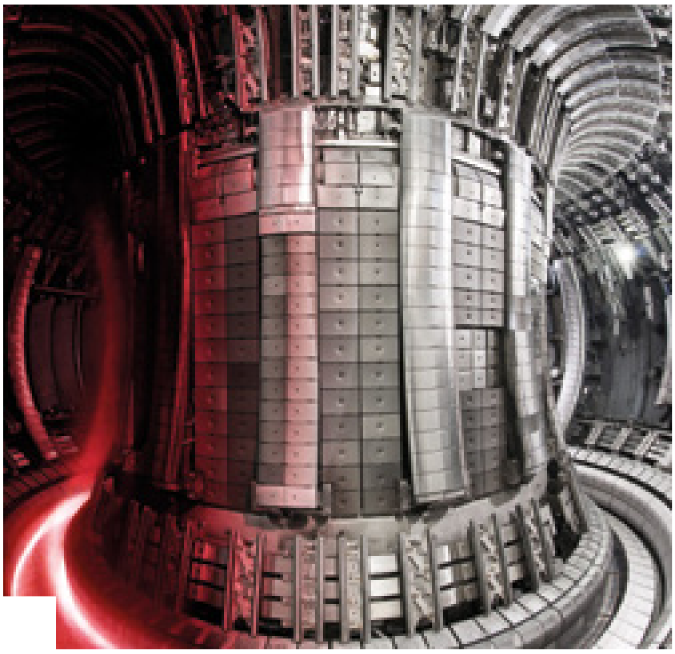
At the high temperatures required for fusion, the nuclei in the hydrogen fuel have lost their attendant electrons to form an electrically charged ‘plasma’ of very rapidly moving charged particles. For fusion to happen, such a high-energy form of matter has to be confined to a given volume for a given time in some way. It cannot touch the walls of the containment vessel and must be kept under vacuum conditions. It is not surprising that overcoming the technical problems of creating and controlling such a plasma is the major factor in the development of fusion as a power source.

The three main parameters to be considered in achieving fusion are the plasma temperature, density and confinement time. They control the probability of fusion and the total energy produced per unit volume. It is thus possible to calculate the ideal combination of parameters to ensure that fusion becomes worthwhile, which is when it delivers more energy than is consumed by heating the plasma – so-called ignition breakeven.

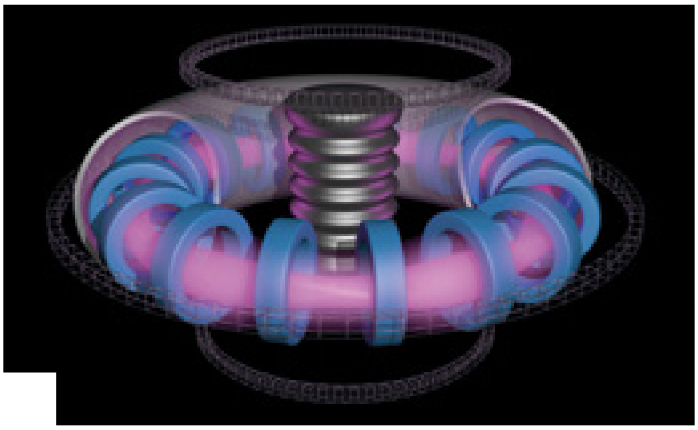
There are two main approaches to creating and confining a plasma. The first approach involves generating a low-density plasma confined for a long period in a magnetic trap – magnetic confinement. The second method is inertial confinement in which a very high-density plasma is maintained for a very short time. Both approaches are being developed, although magnetic confinement seems at present to be the most promising.

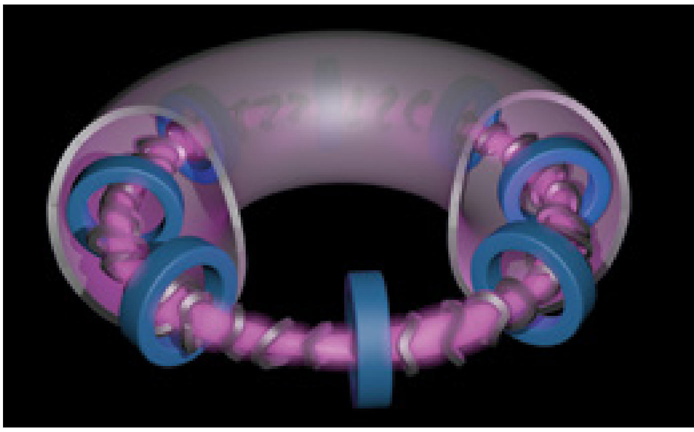
MAGNETIC CONFINEMENT

Because a plasma is electrically conducting, it is sensitive to magnetic fields, which can then be imposed and structured to hold the plasma in place. The earliest systems were tubular employing magnetic mirrors at the open ends, but they suffered significant leaks. The problem was solved by bending the setup into a torus to create a closed system in a vacuum vessel. Plasma densities of up to between 10^{19} and 10^{20} particles per cubic metre can be achieved, with a confinement time in the tens of seconds.

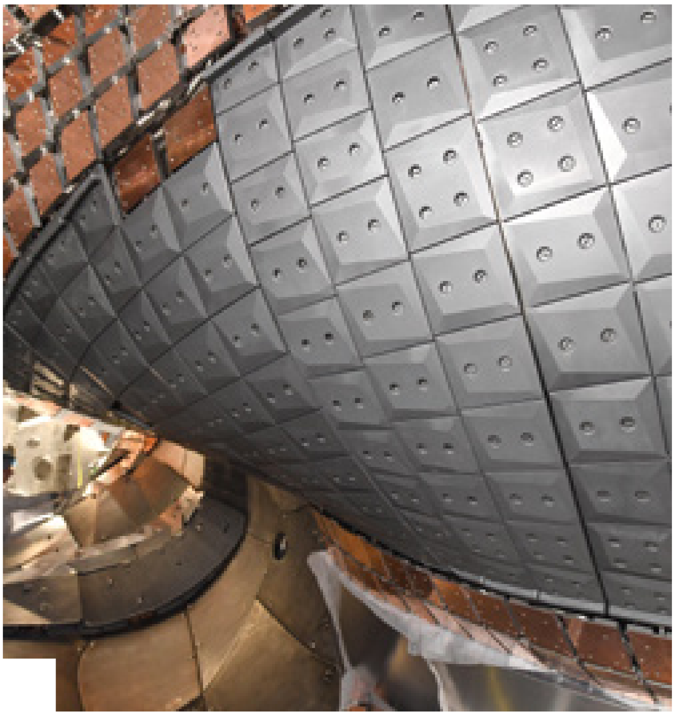


The Joint European Torus (JET) in the UK recently sustained fusion for more than five seconds to deliver an average output of 11 megawatts (59 megajoules). **[Credit Eurofusion].**





The tokamac (left) and the stellarator employ slightly different approaches to confine a fusion plasma magnetically.



The Wendelstein 7-X stellarator with its twisted magnetic coils, at the Max Planck Institute for Plasma Physics (IPP) in Germany, is being tested; this design could require less energy input than a tokamac to achieve fusion.

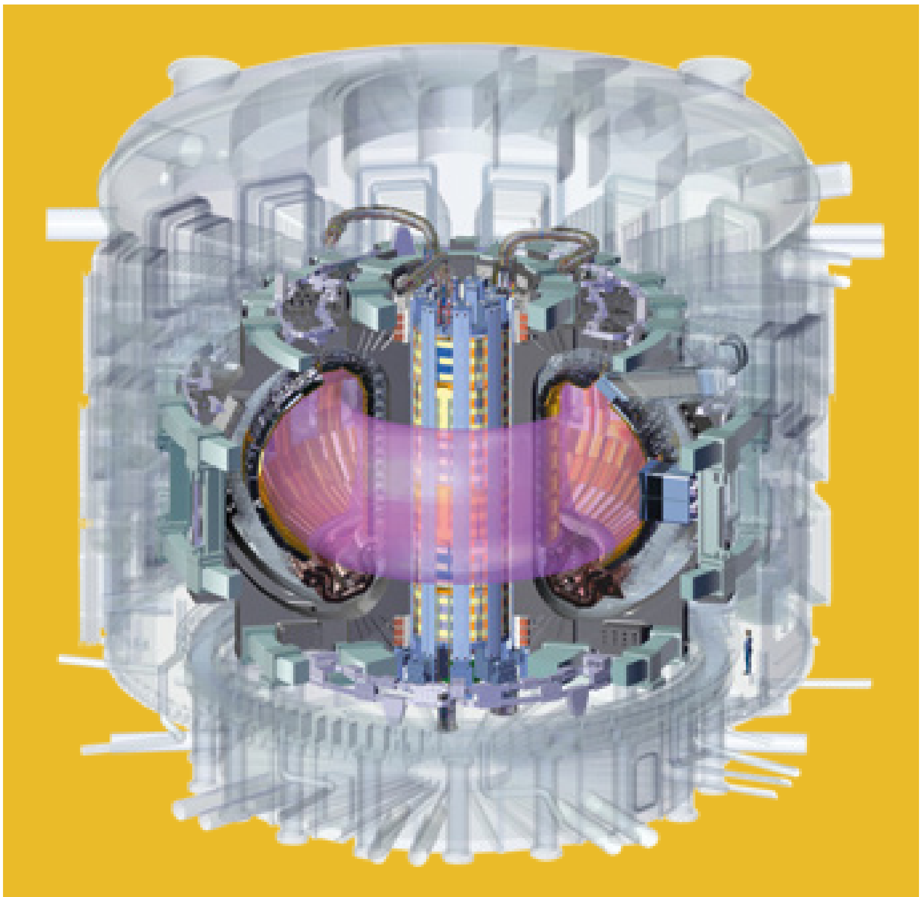
The most successful concepts for magnetic confinement fusion are the tokamak and the stellarator. The tokamak is a Russian concept from the early 1950s. The vacuum chamber is located around the transformer, which generates an electric current in the plasma to create a poloidal magnetic field. At the same time, electromagnets create a toroidal magnetic field. The combination of these two fields results in a helical magnetic field that ensures a closed path of movement for the plasma particles. The plasma is thus captured and retained inside the doughnut-shaped vacuum vessel. The current generated in the plasma heats the plasma itself.

Another design, the stellarator, does not use a plasma current to create a magnetic field and therefore it does not need a transformer. The confinement of the path of the plasma particles is achieved purely by external electromagnets. The structure of the electromagnetic coils and of their magnetic field is more complicated, and the toroidal geometry of the vessel is twisted into a rather more complex shape.

ADVANCED FUSION REACTORS

Several advanced tokamak concepts have been built around the world in recent years, including some with superconducting magnets. The largest project taking fusion to the next stage is ITER, an international tokamak, which started construction in 2013 in southern France by 35 partner countries. It will aim to reach ignition point, so producing more energy than is needed to heat the plasma. It is the world's largest scientific experimental facility. The vacuum vessel's main radius is 6.2 metres and the plasma volume will be 840 cubic metres. The total weight of the equipment will be 23,000 tonnes. The intensity of the magnetic field will be 5.3 tesla and the energy output should be 500 megawatts. The plasma confinement time should be 300 seconds and its temperature 150 million degrees. The ratio between the power obtained from the fusion and that supplied for the heating should reach a value of 10.

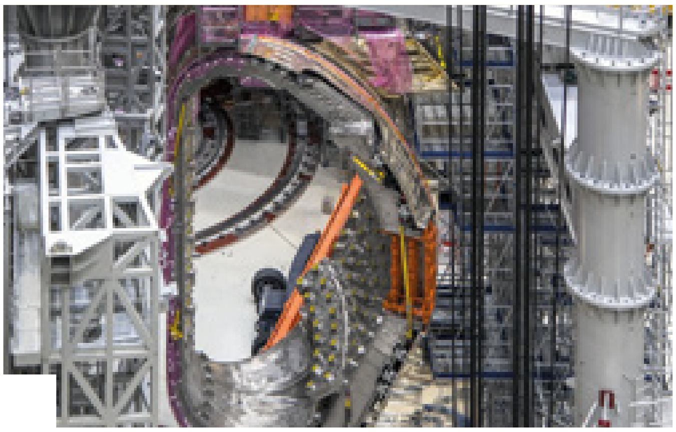
ITER's first experiments are scheduled to begin at the end of 2025. For the first few years, tritium will not be used while the plasma properties are studied because of the radioactivity induced in structural components. The tokamak should be fully operational, with experiments on the fusion of deuterium and tritium, by 2035. Because of the limited supply of tritium, a key component will be experimenting with lithium blankets to breed tritium using neutrons (as described above) from the plasma. It must be said that we know from the experience of its predecessors that the construction of the ITER tokamak is a great challenge – but the facility will work. It is ITER's large size that will enable it to demonstrate that nuclear fusion can produce enough energy, and its operation will be a key step towards the harnessing of fusion.



A graphic of the ITER design.

The next step is projected to be the DEMO thermonuclear power plants. While planning is underway, key lessons are awaited that ITER will provide. The beginning of its construction will probably be after 2040. However, it should be noted that it will be a prototype device, which will most likely not be economically competitive.

Although the biggest challenges lie in the study of plasma behaviour, the knowledge of the interaction of very intense neutron fluxes with materials, and the probability and course of several key nuclear reactions, are also of importance. Fusion and fission energy production have a number of common problems and technologies. In both cases, they are thermal power plants with a similar system of conversion of thermal energy into electricity. In fission and fusion devices, we encounter very intense neutron fluxes that require the use of materials resistant to radiation damage. At the same time, they are very stressed by very high temperatures. Furthermore, as within nuclear fission reactors, high levels of radioactivity will have to be managed in fusion reactors. However, there will be no long-lived fission or transuranium products.



Part of ITER's vacuum vessel with two toroidal field coils and thermal shield segments awaiting assembly. **[Credit ITER].**

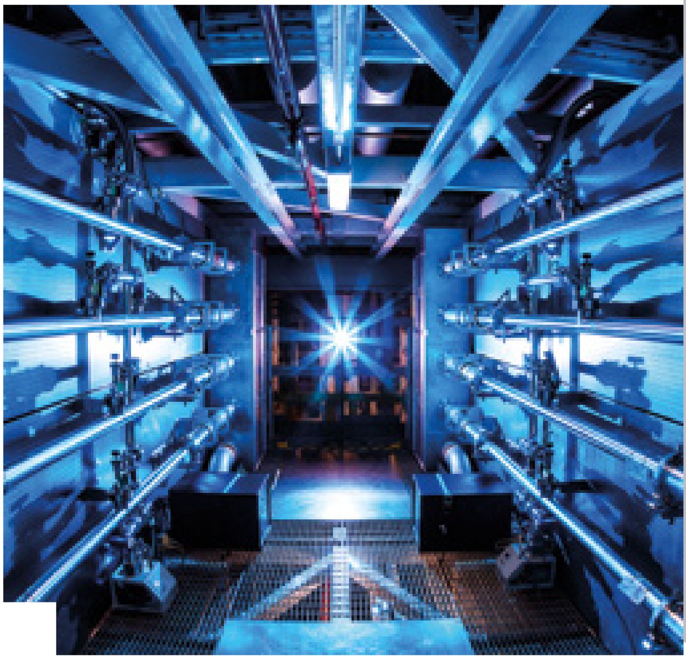
HYBRID SYSTEMS

Fission and fusion systems could be combined if, in addition to lithium, transuranium elements from spent nuclear fuel, or uranium-238 or thorium-232, are placed in the blanket around the fusion vacuum vessel. We would then have a subcritical fission system driven by the plasma neutrons. This would also contribute to increasing energy production. However, its main advantage would be that it would make it possible to use and incinerate nuclear waste for energy production as described above.

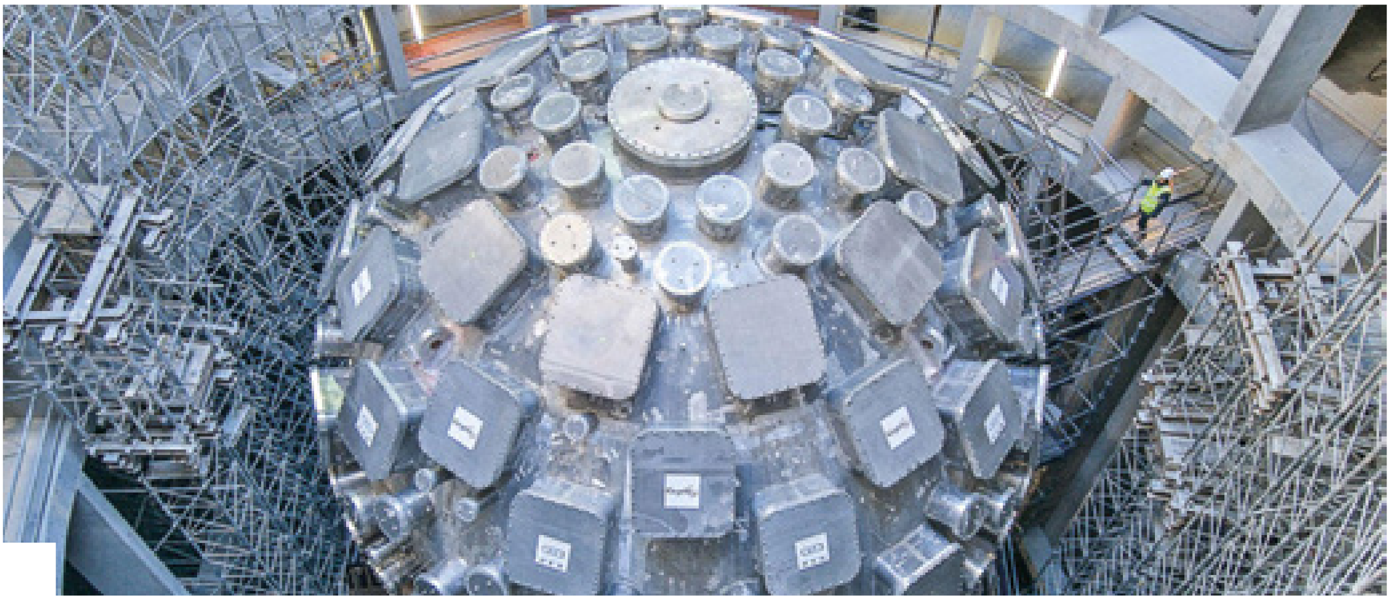
INERTIAL CONFINEMENT FUSION

Another route to fusion is to compress and heat a small pellet containing deuterium and tritium using powerful beams of laser light. The rapid heating causes the outer shell of the pellet to explode sending a shock wave that compresses the pellet interior and further heats the fuel. The plasma created is confined by its own inertia to create the conditions for fusion ignition, so it is called inertial confinement fusion, ICF. The overall concept is that a reactor would depend on a series of laser pulses to provide a continuous output of fusion energy.

The scheme is being investigated at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the US. In an indirect approach being studied, an outer gold cylinder is first irradiated with a laser shot to produce X-rays which then create a higher pressure and smoother implosion. Like magnetic confinement fusion, the technical challenges are formidable. Nevertheless, NIF recently announced that it had achieved a 70 per cent conversion of the laser power to fusion energy, bringing the experiment closer to ignition point.



In 2021, a NIF experiment achieved a fusion yield of more than 1.3 megajoules, close to the threshold of fusion ignition.



The heart of the Laser Mégajoule ICF facility, seen here during construction.
[Credit University of Bordeaux].

Meanwhile, in Europe, an important ICF device called Laser Mégajoule has been operating (for defence applications) since 2015 near Bordeaux in France. In 2017, it was coupled to a high-power laser called PETAL and is now available for a range of research experiments. A further project called the Extreme Light Infrastructure (ELI), which comprises laboratories located in three EU countries, has begun to study the possibilities of lasers delivering up to 10 petawatts – power levels that would be crucial for ICF.

NUCLEAR SAFETY

The disposal of nuclear waste and the safe operation of nuclear plants has always been of major concern to both governments and the general public. Today, the intensive studies within both academia and the nuclear industry are finding, and have found, solutions that make nuclear power one of the safest industrial production sectors.

NUCLEAR WASTE

The major, oft-quoted objection to nuclear energy is dealing with spent nuclear fuel. As explained earlier in this chapter, one solution is to recycle, transmute and incinerate the most hazardous waste in advanced nuclear systems. However, if the spent fuel is not recycled, it must be stored safely. Either way, it is not allowed to enter the general environment. Much of the spent fuel from standard reactors is stored until it can be re-used in fast-breeder reactors, as described page 42. Otherwise, long-lived nuclear waste must be placed in a permanent underground repository within a stable geological formation. To ensure its safety for the thousands of years required, we need to know how the composition and properties of nuclear waste change gradually. This requires detailed nuclear physics studies and the precise nuclear data. Different nuclear methods can be used to monitor the properties of different geological structures in which permanent repositories will be built. Important knowledge is also gained by examining the remains of the Oklo natural reactor mentioned on page 43.

The first underground permanent repository of nuclear waste is being completed in Onkalo, Finland. Others are being prepared, for example, in Sweden and France. There are also several underground laboratories where methods of nuclear waste disposal and its long-term behaviour are studied. The Waste Isolation Pilot Plant (WIPP) in the US also provides important knowledge. This deep geological repository is licensed to store transuranic radioactive waste for thousands of years, though only from research reactors and from the production of US nuclear weapons.

The Posiva spent-fuel disposal facility at Onkalo Finland. **[Credit Posiva].**

NUCLEAR ACCIDENTS

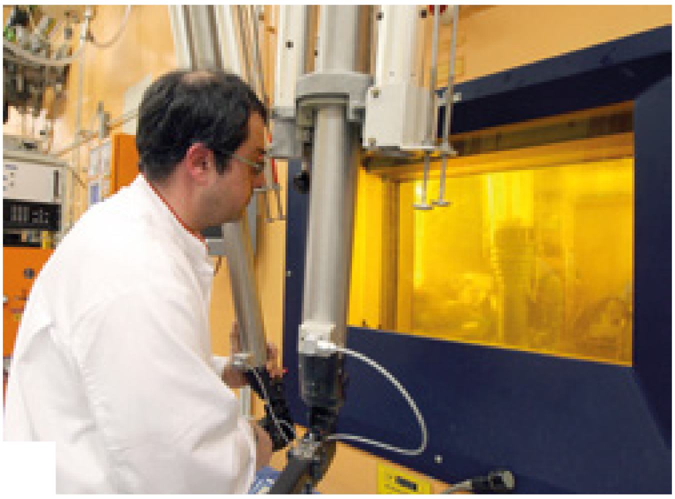
Three major nuclear accidents have occurred within the lifetime of the nuclear power industry. The first was the partial meltdown of the second unit of the Three Mile Island nuclear power plant in Pennsylvania, US, on 28 March, 1979. The accident destroyed the reactor but did not result in any casualties. The reactor's containment limited the release of radioactivity, and the impacts on the environment were minimal. Indeed, the consequences of the accident have already been completely eliminated. Recently, the operation of the first unit also ended and work is underway to decommission the entire power plant.

The biggest catastrophe in nuclear energy production occurred at the Chernobyl nuclear power plant in Ukraine. On 26 April 1986, an explosion occurred at the fourth unit of this power plant. The accident was caused by operator errors and also errors in the construction of the reactor. The RBMK reactor had no containment, resulting in the partial expulsion of the molten core and a massive escape of the radioactivity. The number of direct victims – mainly as a result of radiation sickness – did not exceed 100. The estimated number of later victims of lower radiation doses was probably between 4000 to 20,000 for the entire life expectancy of the affected population. In 2017, a new arch-shaped sarcophagus was completed that ensured full protection of the destroyed reactor. Thus, the regeneration of the most affected, and so far closed, areas around the affected power plant could begin.

The Chernobyl sarcophagus.

The last major accident happened in Japan, after one of the largest earthquakes and accompanying tsunami, which hit the Tohoku area on 11 March 2011. The tsunami flooded the power plant, and especially the diesel generators. The power outage eventually led to the melting of three reactor cores. Thanks to the containments, the release of radioactivity was limited, but it still affected a wide area. There were no direct casualties, but large areas were evacuated. Decontamination and regeneration of the affected areas are intensive. Residents are already returning to much of the evacuated area, though decontamination of the hardest hit areas is still ongoing. The complete disposal of destroyed reactors will take decades.

All three accidents have led to a dramatic improvement in the safety parameters of all nuclear facilities such that these accidents could not happen today. The likelihood of radioactivity leakage events has decreased dramatically, and the huge emphasis on safety in nuclear installations has led to the industry having the highest level of safety. Indeed, It is worth remembering that other types of energy production have had their fair share of catastrophic



Nuclear fuel rods are being analysed here using a 'hot cell' at the Institute for Transuranium Elements in Karlsruhe, Germany. [Credit Uli Deck].

accidents. For example, the Vaiont hydroelectric dam in Italy in 1966 led to around 2000 direct casualties, while the catastrophic rupture of a cascade of dams in Henan, China in 1975 resulted in the deaths of at least 26,000 people and possibly many thousands more. In 1989, the explosion of a gas pipeline near the Russian city of Ufa in the Chelyabinsk region killed 575 people. Indeed, there is a prevailing distorted public opinion on the comparative safety within the energy sector. In fact, the number of casualties per unit of energy produced is very low for nuclear sources and comparable to those for photovoltaic and wind sources. In the case of fossil fuels or even bio-gas, they are orders of magnitude higher.

OPERATIONAL SAFETY

Nevertheless, ensuring the operational safety of a currently ageing fleet of nuclear reactors is an important task for today's nuclear power industry. Some have been operating for as long as 50 years, and many have already received extended licensing for 60 or even 80 years of operation. So far, there is no operational experience for these extended lifetimes. While a substantial proportion of a plant can be replaced, this does not apply to the reactor vessel. The study of long-term behaviour, and especially the effects of long-term exposure to intense neutron fluxes, relies on use of nuclear methods and nuclear physics.

NUCLEAR PHYSICS STUDIES TO SUPPORT NUCLEAR ENERGY

Nuclear physics studies enable the acquisition of the necessary nuclear data, and nuclear methods to study and modify the properties of materials needed for nuclear technologies. This should allow for the safe operation of existing nuclear power plants as well as ensure the safe disposal and/or incineration of nuclear waste. The development of advanced reactor designs also requires precise data on relevant nuclear reactions (neutron emission and capture, and the radioactive decay of a large range of radioisotopes). This not only applies to the behaviour of reactor fuels, but also interactions with reactor materials (which become 'activated'). In particular, data are gathered on the relative likelihoods of various reactions happening, and the energies of the emitted electromagnetic radiation and particles such as neutrons (see Chapter 1). Very intense neutron levels are expected during the operation of both advanced fission and fusion reactors. Generation IV reactors, accelerator-driven systems, small modular reactors and fusion technologies also experience high temperatures exceeding 1000°C, and so it is vital to know precisely the properties of materials used in nuclear reactor technologies to ensure they have the necessary radiation, heat and mechanical resistance.

Nuclear behaviour, as well as the propagation of heat released from nuclear reactions in various locations in a nuclear facility, can be simulated on a computer. This requires a good understanding of nuclear physics and the development of accurate computer codes to ensure the reliability of nuclear databases used. Their verification can be performed through measurements on simple nuclear assemblies that simulate the properties of advanced nuclear technologies. Benchmarking codes using such measurements represent a significant area of nuclear physics research.

Of vital importance are the studies of neutron reactions, their probabilities and their energies. Neutrons are relatively heavy particles that, when moving at speed, can damage the structure of materials used in a plant. Fortunately, there are international research facilities hosting nuclear reactors and spallation neutron sources that produce tailored neutron beams specifically for research, including that into nuclear reactions involving neutrons and their interactions with relevant materials.

CONCLUSION

Energy is essential for sustainable economic growth and improved human welfare, but carbon dioxide emissions and consequent global warming are huge challenges for humanity, and the use of all low-carbon emission technologies needs urgent consideration. Nuclear power sources are currently one of the most important energy sources associated with extremely low greenhouse gas emission. Because of their concentrated energy production, their ecological impact can be reduced very effectively. They provide access to clean, reliable and affordable energy, while mitigating the negative impacts of climate change.

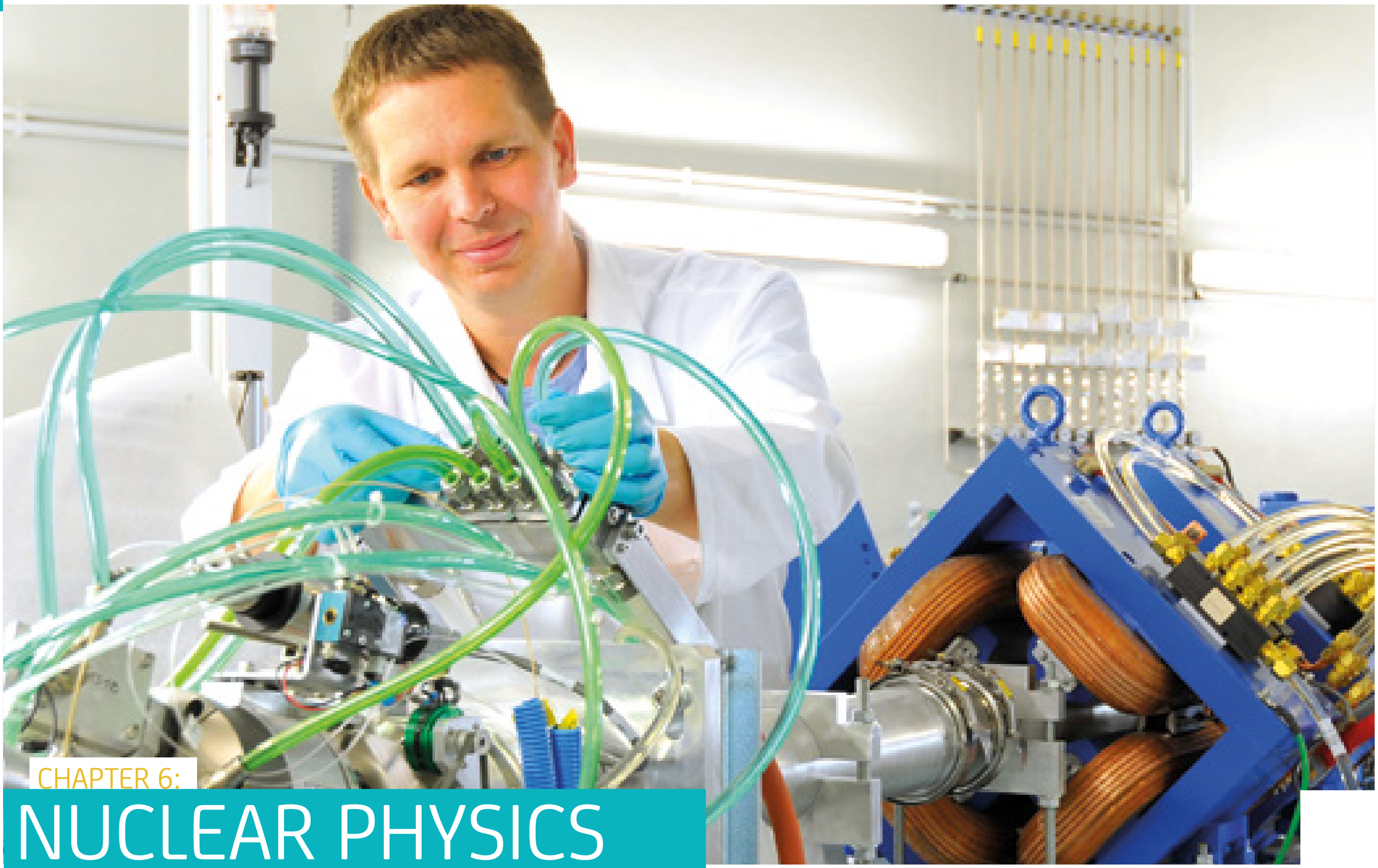
Today, most nations understand the threat that climate change presents, and there are a number of countries now planning nuclear power expansion to address it. There are others which assume they can transition to low-emission energy systems without nuclear power. Nevertheless, it is a significant part of the global energy mix and its use is expected to grow in the coming decades. One serious consideration is that building nuclear energy sources is technologically demanding, and needs a high level of education and technical know-how. However, many developing countries do not yet have the skills, knowledge and experience to support a nuclear power programme. It is therefore important that those countries with a developed nuclear power industry offer expertise and resources to help expand the use of nuclear power worldwide.

FURTHER INFORMATION

https://www.world-nuclear.org

https://www.iaea.org

Nuclear Energy in the 21st Century, Ian Hore-Lacy, World Nuclear Association, 4th Revised edition, 2018, ISBN 978-0993101939.



CHAPTER 6:

NUCLEAR PHYSICS AND HEALTH

Cyclotron accelerators like this one are used to make radioisotopes for medical research and applications in the clinic.
[Credit Center for Radiopharmaceutical Tumor Research Helmholtz-Zentrum Dresden-Rossendorf, Germany].

NUCLEAR PHYSICS HAS CONTRIBUTED HUGELY TO IMPROVING HUMAN HEALTH, PROVIDING UNIQUE TOOLS FOR DIAGNOSIS AND TREATMENT, AS WELL AS EXTRAORDINARILY SOPHISTICATED ANALYTICAL METHODS FOR BIOMEDICAL RESEARCH.

Many people may not realise how much nuclear physics has contributed to improving the human health worldwide. The radiation (subatomic particles and gamma-rays) emitted by many unstable nuclei is employed to image the internal parts of the body, to follow biological processes in living tissue, to treat significant diseases like cancer, and for pain relief. To identify and make the radioactive isotopes that are useful in the clinic or in medical research requires a detailed understanding of nuclear reactions, nuclear structure – and crucially how radioisotopes (see Chapter 2) interact with biological molecules like proteins (enzymes and antibodies, for example), lipids in cell membranes, and of course DNA.

Scanning techniques based on nuclear physics play a crucial role in clinical diagnosis and research.

Furthermore, beams of high-energy particles generated by nuclear interactions are increasingly being exploited in cancer therapies, as well as to probe biological structure and behaviour at the molecular level. The development of new drugs and vaccines to treat challenging conditions, for example, dementia and viral infections (such as Covid-19) very much depends on advanced analytical techniques that have their basis in nuclear physics.

The development of the many nuclear methods that are now essential components of medical research and therapeutic treatments requires facilities hosting complex instrumentation that can deliver high-energy particle beams, handle radioactive materials and generate powerful magnetic fields. It is not surprising, therefore, that many of these facilities are internationally supported by high-energy and nuclear physics laboratories, and that much of the frontier, exploratory research pertinent to the medical application of radioisotopes and particle beams is carried out in these centres (see Chapter 10).

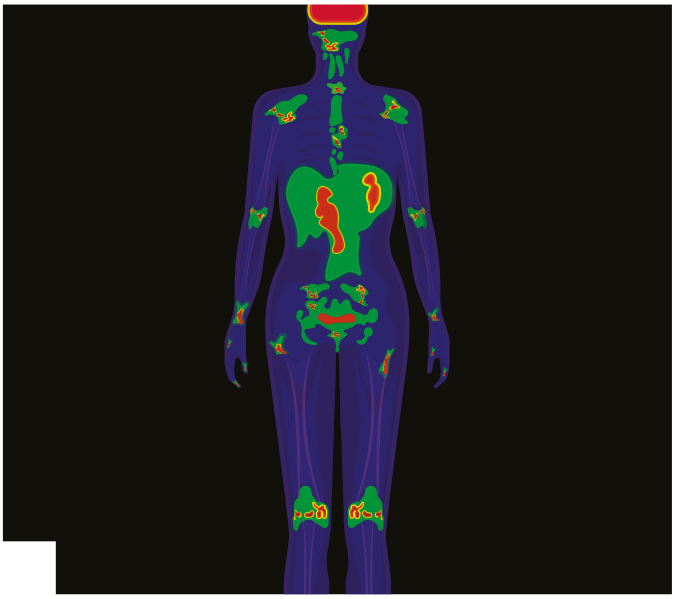
Radioisotopes, especially, have long been used in the clinic, and today, many millions of medical procedures based on radioisotopes are carried out annually at more than 10,000 hospitals across the world. Some tens of thousands of these procedures employ accelerated nuclear particles (ions and gamma-rays) designed to understand, diagnose and cure cancer, thus becoming an irreplaceably vital component of critical life-saving healthcare.

In this chapter, we show how nuclear physics and nuclear-based methods have crucially contributed to improved life-saving diagnoses and therapies.

MEDICAL RADIOISOTOPES

Nuclear physicists recognised the potential of radioisotopes for applications to human health not long after the discovery, in the 1930s, that radioactivity could be induced in certain heavy elements by bombarding them with neutrons. It was soon realised that the resulting artificial radioisotopes had immense potential for medical use because they emitted high-energy radiation or particles (alpha, beta and gamma-rays) that could selectively kill living tissue, in particular cancer cells. The first applications of such radioisotopes were at the Oak Ridge National Laboratory in the US, in 1946. In the same year, the success of radioactive iodine-131 (which emits beta and gamma radiation) in treating a patient with advanced thyroid cancer was reported in the Journal of the American Medical Association.

Since then, the range of medical radioisotopes has grown considerably. There are now many dozens of isotopes employed, some of them familiar elements like oxygen, sodium, and phosphorus, while others are isotopes of rarer, much heavier elements. They may be used to diagnose disease by tracing selected metabolic functions in the body or by imaging organs; others may act as therapeutic agents enabling the treatment of specific cancers. They are most frequently chemically attached to a drug or biological molecule that can home in on particular tissues – a radiopharmaceutical. In general, isotopes are increasingly selected for a specific procedure according to both their radiological and also their biochemical properties. Iodine-131 is now widely used not only to treat thyroid cancer (iodine is essential for thyroid function so is very compatible), but also in the diagnosis of abnormalities in the liver, kidneys, blood circulation and the urinary tract. Technetium-99m has become the most common agent for imaging all parts of the body including the heart and brain. (The 'm' refers to the fact that the technetium-99 nucleus is in a particular 'excited' energy state.) Fluorine-18, which emits positrons, is one of the most significant isotopes for imaging and detecting malignant tumours via a technique called positron emission tomography, or PET (see page 58). Lutetium-177 has become an increasingly important gamma and beta emitter that can both image and treat late-stage prostate cancer, the second most common type of cancer in men.



Iodine-131 has been used since the 1940s to diagnose metabolic function.

SELECTING THE RIGHT ISOTOPE

To be suitable for medical procedures, the isotope should have a half-life that is just long enough to be delivered, but short enough not to cause unnecessary radiation exposure for the patient or present problems of waste disposal. If the isotope is to be used for imaging, then the radiation emitted must have a suitable range and energy to reach outside the patient's body and be readily detected. The energy should not be so powerful that excessive radiation shielding or isolation protocols are needed. For therapy, the isotope needs to emit short-range radiation (for example, beta or alpha particles) that can deposit the maximum amount of energy in a specific location in the target tissue. It also must have the right chemical properties so that it can seek out target tissues, or be coupled to molecules that preferentially bind to specific cell-types. It is of course important that the isotope is expelled from the body reasonably quickly after it has done its job. The chemical behaviour of the associated element should be such that it is well-tolerated by the body.

Of considerable importance is the ease of manufacturing the isotope (see page 56), and the amount that can be made economically. The manufacturing site may also be significant. In a few cases, it may need to be fairly close to the treatment clinic if the half-life of the isotope is relatively short. The larger hospitals may well have their own particle accelerator in which the isotopes are produced as required, or may be associated with a nuclear physics facility nearby (see Chapter 10). If the half-life of the isotope is very short, then it might be stored in the form of a longer-lived progenitor isotope called a generator.

GENERATORS

Generator systems provide a convenient way of delivering isotopes to the clinic. A longer-lived 'parent' isotope is prepared in a reactor or accelerator; the isotope then decays to the required, much shorter-lived 'daughter' isotope. Depending on the ratio of their half-lives (the half-life of parent radioisotope might be about 10 to 100 times that of the daughter), an equilibrium between the two exists. The generator system is supplied from the reactor or accelerator facility in a lead-shielded glass container to a hospital or centralised radio-pharmacy. There, the differences in chemical properties of daughter and parent allow for the regular separation of the daughter isotope via a suitable chromatography column containing an absorbent material such as alumina (aluminium oxide). This is set up so as to ensure that the parent isotope is retained on the column while the daughter is eluted from it at a rate such that its availability for use matches the decay rate of the parent.

By far the most widely used generator isotope is for the preparation of the technetium-99m. It is mainly produced in nuclear reactors. Molybdenum-99 has a half-life of 66 hours, compared with the half-life of its daughter of just over 6 hours.

A second important generator is germanium-68; it decays to positron-emitting gallium-68 (by electron capture, see Box opposite), and has a half-life of 275 days. Another widely used generator is strontium-82 with a half-life of 25.5 days which can deliver rubidium-82 (used for cardiac PET imaging, see page 58) every 10 minutes for almost one month via an appropriate radiopharmaceutical kit.

SHORTAGES OF RADIOISOTOPES

Although tens of millions of medical procedures using radioisotopes are carried out every year (at least 10 million in Europe alone), the demand is increasing all around the world. In recent years, shortages of medical isotopes have been identified and have become a cause for concern. As ageing research reactors have been closed down, key radioisotopes such as technetium-99m have threatened to be in short supply. Fortunately, new, dedicated reactors are now being built, and thanks to nuclear physics research into key nuclear reactions, more isotopes can now be produced in upgraded cyclotrons and other accelerators. Furthermore, new, compact accelerator designs, combined with novel high-energy physics and engineering concepts, as well as improved isotope processing, are also coming to the rescue.

APPLICATIONS

Radioisotopes offer two main applications:

- When taken into a patient's body, the low-energy gamma-rays that are emitted and then detected allow clinicians to evaluate the appearance and function of selected organs, and so make a diagnosis.
- Therapeutic medical protocols can be designed around specific radioisotopes that emit higher-energy radiation and are able to kill cancer cells (therapy) or pathogenic microbes (sterilisation of medical equipment as described in Chapter 7).

To ensure the correct selectivity, both procedures usually require that the isotope is attached to a biologically active molecule. It is not surprising, therefore, that designing effective delivery systems and procedures – right from the nuclear facility into the clinic – requires collaboration not only between accelerator engineers, nuclear physicists and clinicians, but also with chemists and life-scientists.

DIAGNOSIS

Diagnostic procedures account for more than 90 per cent of radioisotope applications. They rely on the fact that various chemical compounds will accumulate in specific organs. For example, the thyroid gland selectively takes up compounds containing iodine, while the brain makes use of glucose; potassium concentrates in muscle and phosphorus in bones. Even heavy metals like cobalt – the essential metal in vitamin B12, and copper – another metal key to many biological functions, provide diagnostic methodologies. In this way, pharmaceuticals labelled with radioisotopes can scrutinise the function of vital organs like the brain, heart, lungs or liver, follow blood flow and how bones are growing. They can identify physical abnormalities, and confirm other types of diagnoses and procedures.

MAKING RADIOISOTOPES

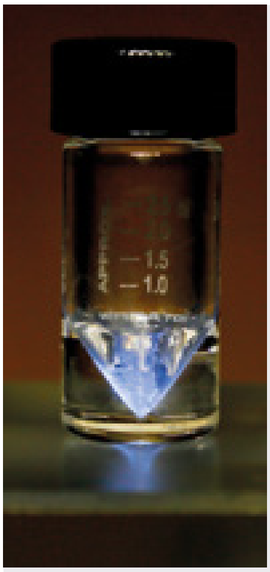
The High Flux Reactor at Patten in the Netherlands, which produces a range of medical isotopes such as molybdenum-99. **[Credit NRG].**

There are several approaches to radioisotope production, but they all are based on nuclear reactions caused when particles, for example neutrons or an accelerated beam of protons, hit a target. This is usually a metallic foil or gas containing atoms of a suitable stable isotope. The required radioisotopes then have to be separated from other reaction products and purified using physico-chemical methods, such as chromatography.

Isotope production at the Patten HFR research reactor. **[Credit NRG].**

TYPICAL NUCLEAR REACTIONS TO GENERATE MEDICAL RADIOISOTOPES

- A beam of protons reacts with oxygen-18 to generate the PET imaging isotope, fluorine-18, plus a neutron.
- A gamma-ray disintegrates a radium-226 nucleus to produce radium-225 plus a neutron. Radium-225 subsequently decays to the therapeutic isotope, actinium-225, by emitting beta particles. Actinium-225 is used to treat prostate cancer.
- The neutron-induced fission of uranium-235 results in the production of two lighter nuclei – that is, xenon-136 and the radioisotope molybdenum-99, which transmutes to technetium-99m, the most used radioisotope in nuclear medicine.



A capsule of actinium-225. [Credit ORNL].

Such radioisotopes are made in facilities employing either a nuclear reactor or a (usually dedicated) accelerator. The type of equipment employed depends on the properties of the isotope and the nature of the nuclear reaction needed. Short-lived isotopes (half-lives between hours and days) tend to be generated with accelerators, while longer-lived ones, typically requiring long irradiations lasting days to weeks, are produced in nuclear reactors.

THE USE OF NUCLEAR REACTORS

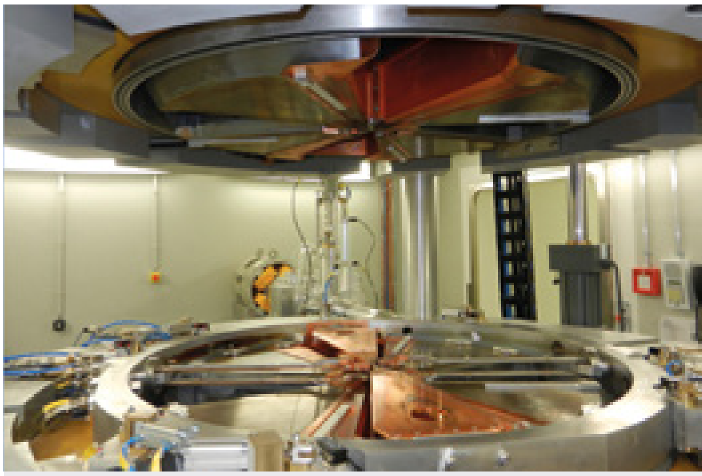
As well as providing energy (see Chapter 5), small, dedicated nuclear reactors based on uranium fission, and often attached to laboratories, are employed in scientific research, in particular to provide neutrons as nuclear probes of a wide range of materials (see page 74). In addition, neutrons from a reactor core can also be exploited to induce nuclear reactions in target materials that generate radioisotopes. The reaction could be the capture of a neutron to create a heavier radioisotope of the same element – for example, lutetium-177 is made from lutetium-176 – or the impinging neutron, if of the right energy, might kick out a proton from the nucleus being bombarded to create an isotope of an element with an atomic number that is one lower, as happens in the production of beta-emitting phosphorus-32 from sulfur-32. Phosphorus-32 is widely used to detect and treat eye and skin cancers.

THE USE OF ACCELERATORS

CYCLOTRONS

The most common type of particle accelerator employed in radioisotope production is the cyclotron. Some hospitals have their own cyclotron to deliver often short-lived isotopes directly to the clinic. It is a long-established design in which light, positively charged particles such as protons or deuterons (deuterium nuclei) are repeatedly accelerated around a circular machine by a radio-frequency voltage, while being guided along the circular path by a system of powerful electromagnets. Usually, the new nuclei produced have an extra proton, so giving the atoms an extra positive charge, which creates an instability.

This extra charge can then lead to two scenarios depending on the size of the new atoms. In the case of heavy atoms with many (negatively charged) electron shells, the strong positive charge of the large nucleus holds the innermost electron orbitals very tightly, allowing a proton to absorb one of these electrons, so converting to a (neutral) neutron. This 'electron capture' thus results in the formation of an extra neutron in the nucleus and the accompanying emission of useful gamma-rays. In light atoms with nuclei containing less than about 30 protons, the atoms can divest themselves of their positive charge by just emitting a positively charged positron instead when the proton converts to a neutron. Both gamma-rays and positrons generated in these two ways from a wide variety of isotopes are utilised in two powerful imaging techniques as described below (page 58).

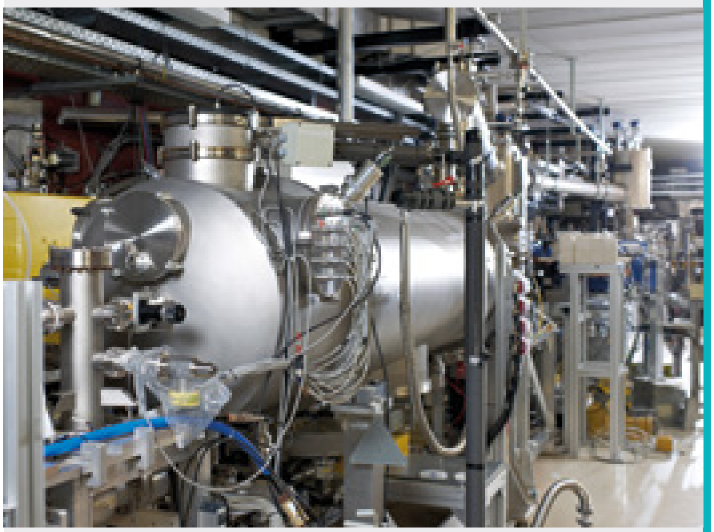


Inside the cyclotron used to make medical radioisotopes at the University of Bern Hospital in Switzerland.

LINACS

In addition to relatively inexpensive and compact cyclotrons, high-energy linear accelerators or linacs, can be used to produce many radioisotopes that cannot be harvested with cyclotrons. They are rather complex and expensive machines and so are typically housed in large national laboratories. A range of medical radioisotopes such as cobalt-55, copper-64 and iodine-122 are created with linacs accelerating protons.

High-energy electrons accelerated in a linac can also induce nuclear reactions by first releasing high-energy electromagnetic radiation in target atoms, which then knock out a proton or neutron from their nuclei. Such reactions can be the most efficient way to produce life-saving isotopes including copper-67, scandium-47 and actinium-225.

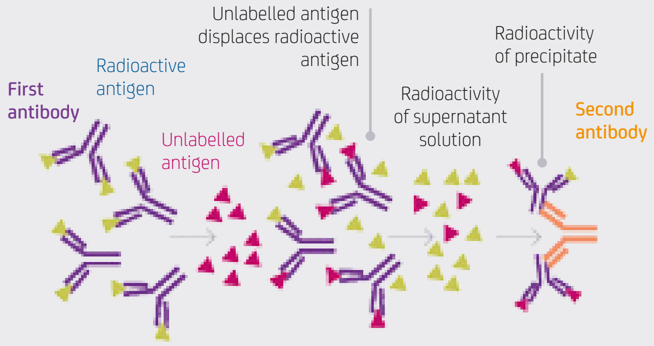


The ELBE superconducting electron accelerator at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) has recently successfully tested the production of molybdenum-99 using an intense electron beam. [Credit HZDR].

In recent years, commercial companies making accelerators have been developing more convenient compact systems that provide electron beams for the production of medical radioisotopes. There is also growing interest in making isotopes using highly intense lasers as accelerator systems.

RADIOIMMUNOASSAY

Radioimmunoassay (RIA) is an extremely sensitive and specific test to measure the amount of antigens (molecules such as allergens, vaccines and hormones that recognise and respond to a specific antibody) in a patient sample.



In the RIA test, a measured amount of the antigen is labelled with a gamma-emitting isotope, usually iodine-125, and mixed with a known amount of the particular antibody it responds to, so that they can bind. Then, a sample of, say, the patient's blood serum containing the unknown quantity of the same but unlabelled antigen is added, so that it gradually displaces the radio-labelled version bound to the antibodies, so reducing the ratio of the bound radio-labelled antigen to the unbound radio-labelled antigen in the sample. The bound antigens are then separated from the unbound ones, and the radioactivity of the free antigen remaining in the supernatant liquid is measured. The bound antigen–antibody complexes are precipitated by further binding with a second antibody and their radioactivity level is detected. The percentage of antibody-bound radio-labelled antigen is then compared with standard samples of unlabelled antigen to obtain the concentration of antigen in the patient sample. Although it sounds complicated, RIA is cheap and easy to use.

RIA was developed through a collaboration between a New York doctor, Solomon Berson, and a nuclear physicist, Rosalyn Yalow. Yalow alone won the Nobel Prize for Medicine in 1977 for the work – unfortunately after Berson had died. The first use of RIA was in research into diabetes, using the hormone insulin bound to iodine-131. Since then, RIA has been used to screen for hepatitis B, in studies of thyroid disease, and to detect illicit drugs in samples of human hair.

IMAGING

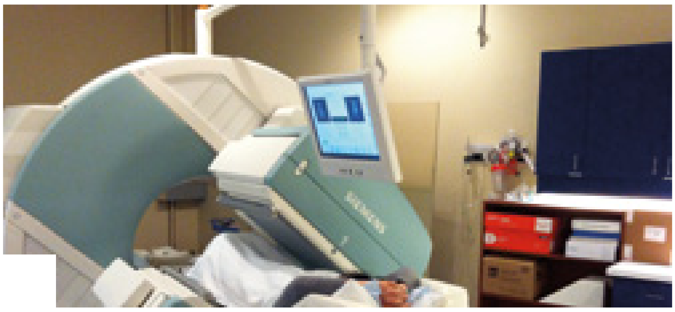
Diagnosis is most often achieved through computerised imaging based on detecting gamma-ray emission after administration of the radioisotope. The amount of radiopharmaceutical given must be just enough to obtain the information needed before the short-lived isotope decays. The dose will be low enough to have no harmful effects on the patient before the radioisotope with its carrier drug is excreted relatively quickly. This diagnostic approach is thus effectively non-invasive. A patient either receives an injection, ingests or inhales the radio-compound. A special camera then detects the gamma radiation, and a two-dimensional image is reconstructed on a computer. A series of images may be taken from different angles, and in 'slices' through an organ. A reconstruction algorithm then generates a three-dimensional graphical representation in a technique called tomography. A clinician can then detect any abnormalities or monitor relevant dynamic physiological processes.

The gamma radiation is generated via two kinds of nuclear processes. In the first, the radioisotope decays to release a single low-energy gamma-ray. The resulting imaging technique is called single-photon computerised tomography (SPECT). The other relies on the emission of a positron (an 'antimatter' electron), which, when it comes into contact with a 'normal' electron in the surrounding biological tissue, annihilates to release two gamma-rays. This is known as positron emission tomography (PET). The gamma-rays are emitted simultaneously in opposite directions along a straight line to be detected by cameras on opposite sides of the patient. From this detected line, the point of origin of the gamma-ray pair can be calculated and an image reconstructed.

SPECT

SPECT is the major scanning technique employed today – together with technetium-99m, which has ideal properties for SPECT. Its short half-life of 6 hours is just the right length of time to allow it to be delivered from the radiopharmaceutical supplier, be injected and then reach the intended organ. The emitted gamma radiation is low, so that the dose to the patient is minimised. The gamma-rays emitted easily escape the body and are of suitable energy to be clearly detected by a gamma camera to create the required multiple images.

The chemistry of technetium is versatile enough for it to be incorporated into a wide range of biologically active compounds, including significant biomolecules such as peptides and enzyme inhibitors that enable it to be concentrated in many different tissues or organs. For example, it can form positively charged complexes used for imaging the heart and negatively charged complexes to evaluate kidney function. Almost any human organ can be imaged using a technetium-99m compound supplied in the form of a commercially available kit, as described above. It is thus not surprising that 80 per cent of all such procedures involve this isotope. Other isotopes commonly used include iodine-123, iodine-131, thallium-201, gallium-67 and indium-111. Due to its long half-life of 2.8 days, indium-111 is useful for imaging of slower biological processes. Antibodies labelled with indium-111 are the most important tracers of solid tumours as scanned with SPECT.



A SPECT scanner.

PET

Positron emission tomography is a more recently developed imaging technique but its use is slowly increasing. Although not used as widely as SPECT, it is twice as sensitive and provides higher-resolution images. PET is particularly effective at imaging less-defined cancerous tissue, and mapping the brain, where it can visualise physical changes associated with neurological disorders. The demand for positron-emitting radioisotopes for PET is growing rapidly.

The positron-emitting isotope mostly commonly and successfully used is fluorine-18 combined with a glucose derivative, fluoro-deoxy glucose (FDG), which is easily distributed in the body. Because it has a short half-life of just under two hours, the radiation dose is low. The FDG is readily incorporated into a living cell without being broken down, and so is a good indicator of cell metabolism.

Other common positron emitters include carbon-11, oxygen-15 and nitrogen-13. These isotopes can follow metabolic changes associated with naturally occurring compounds found in the body, such as water (H_2O), ammonia (NH_3) and all biological molecules containing carbon atoms. Though not normally found in biological systems, fluorine has become major player in PET radio-pharmacy because it is almost identical in size to the hydrogen atom.

More novel positron emitters such as copper-64, yttrium-86 and iodine-124 are becoming available, some of them very short-lived and accessible in the clinic via longer-lived generator systems. Rubidium-82, which is a promising agent for studying the blood flow in heart muscle, has a half-life of only 75 seconds. It is generated from strontium-82, which is made only in the larger accelerators based in nuclear physics centres. However, to meet rising demand, new dedicated machines are now coming online, including a new generation of small, compact cyclotrons. Such machines can also make the long-lived generator isotope, germanium-68 for the PET isotope, gallium-68. This can be attached via binding complexes called chelators to a large variety of molecules that are cancer markers to produce successful PET scans.

The need is also growing for imaging biological processes over longer periods. This may require detection periods lasting several hours and possibly days. For instance, in order to visualise and follow up the fate of antibodies or tumour shrinkage would require radio-pharmaceuticals where the half-life is between 1 and 3 days. Examples include copper-64 with a half-life of 12.7 hours, yttrium-86 half-life 14.7 hours, zirconium-89 half-life 3.25 days, and iodine-124 with a half-life 4.2 days.

COMBINING WITH OTHER IMAGING TECHNIQUES

Today, SPECT or PET are generally combined with X-ray computerised tomography (commonly called CT scanning) in order to provide background structural information that renders a more quantitatively accurate image. To obtain even more valuable complementary information, another imaging method – also with its origin in nuclear physics – magnetic resonance imaging (MRI) would be preferable (see Box opposite). However, the high magnetic fields associated with MRI present challenges for traditional PET and SPECT instrumentation – which is being addressed through the development of a new generation of detectors.

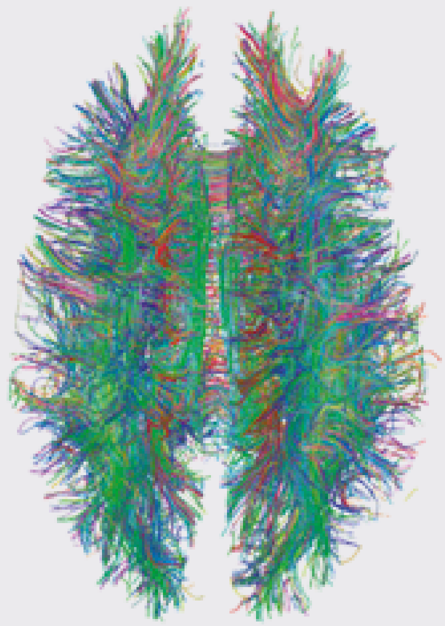
A PET–CT scan of the human body.

MAGNETIC RESONANCE IMAGING

One of the most powerful analytical techniques rooted in nuclear physics is magnetic resonance imaging (MRI). It was developed in the 1970s by British physicist Sir Peter Mansfield and American chemist Paul Lauterbur, as a spin-off from nuclear magnetic resonance, NMR (see page 64). NMR exploits the effects of magnetic fields and radio-frequency radiation on the quantum spin states of nuclei that have intrinsic spin, such as hydrogen nuclei. It was realised that the distribution of water molecules (which of course contain hydrogen) in the body could be detected via their NMR signals. By introducing gradients in the applied magnetic field in different directions, the spatial position of the nuclei could be mapped and a three-dimensional image generated. This allows significant organs such as the heart, brain, spine and liver to be scanned. Since the applied magnetic fields and radio-frequencies are not harmful to living tissue, a patient can be placed in a whole-body MRI scanner to obtain the images. MRI imaging has become a routine hospital procedure, and today, there are more than 25,000 scanners in operation worldwide. It is used to diagnose disease in every part of the body.

Like other imaging techniques mentioned, MRI continues to develop via collaborations between physicists, chemists and clinicians. Better image contrast can be obtained by manipulating the radio-frequency pulses and magnetic fields so as to spread out the time taken for the hydrogen nuclei in different tissues to relax back to their initial spin state. Chemical contrast agents such as gadolinium complexes may be injected to highlight target structures. MRI has become extremely sensitive and can offer image resolution, for example, of veins down to the sub-millimetre scale.

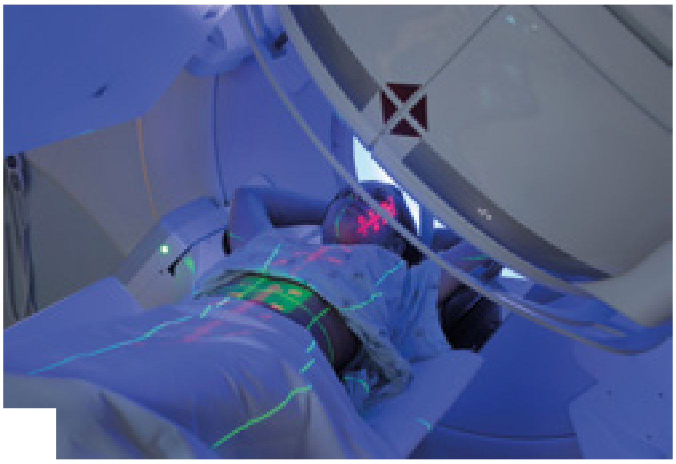
One developing area is to utilise MRI to study physiological changes in real time, for example, brain activity. Chemical changes during brain metabolism can be studied directly by detecting signals from glucose labelled with the nucleus that has spin, carbon-13. Helium gas prepared in a highly polarised (aligned) nuclear state can be employed to image lungs, which contain little water.



MRI has become an incredibly sensitive technique. In one version called diffusion MRI tractography, connections in the human brain can be mapped in extraordinary detail. **[Credit X. Gigandet *et al.*, PLOS, 2008, Dec. 23].**

RADIOTHERAPY

One of the most effective ways of treating cancers is with high-energy radiation, often used in combination with surgery and chemotherapy. Painful inflammatory conditions such as arthritis are also increasingly being treated with radiotherapy. Radiotherapy carried out in two ways. The first is via external irradiation with X-rays or gamma-rays – teletherapy – which is the most common form of radiotherapy, or by placing radioactive sources inside a patient – brachytherapy. The latter approach has the advantage that the radiation is localised, so reducing the risk of tissue damage due to the radiation itself.



A patient being treated for cancer using radiotherapy.

TELETHERAPY

The most common form of nuclear teletherapy relies on radioactive cobalt-60 as a source of high-energy gamma-rays. The cobalt unit is positioned about a metre away from the patient so as to allow the radiation to reach deep-seated tumours if required. The most modern set-ups enable the radiation dose to be 'sculpted' such that it reaches and affects only the target tumour. This may require irradiation from different angles. This approach limits the harmful effects of the radiation to healthy tissues and spares vital organs.

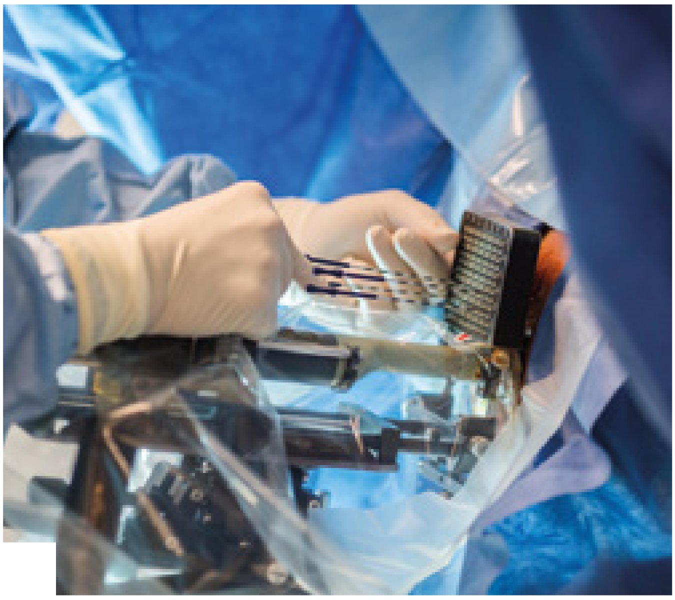
BRACHYTHERAPY

The candidate radioisotopes for brachytherapy are those emitting either beta particles or alpha particles. Because the particles have mass, they are more easily stopped on impact with tissues than are gamma-rays (which just pass through). They then disseminate their kinetic energy to the surrounding cell environment, thus disrupting its function. If the radioisotope is concentrated in a selected location such as a tumour by combining it with a molecule that specifically targets the tumour cell-type, then the surrounding healthy tissues remain largely unaffected.

Most therapeutic radio-pharmaceuticals are labelled with beta-emitting isotopes that can penetrate tissues up to just a few millimetres. The commonly used beta emitters include lutetium-177 (tissue penetration: 0.5 to 2 millimetres) and yttrium-90 (tissue penetration: 2.5 to 11 millimetres).

Alpha particles, being considerably more massive and with a double positive charge, are stopped more quickly in tissues, so cannot penetrate so easily, but they generate more lethal energy over a short range. Well-known alpha emitters include radium-223 to alleviate bone pain, actinium-225 to treat prostate cancer and bismuth-213 for neuroendocrine tumour therapy. The type of radioisotope chosen depends on how it is to be used. As for diagnostic isotopes, the availability from nuclear facilities, the half-life, the delivery method and biocompatibility are all significant factors. A great deal of research goes into identifying the most suitable radioisotope and attached bioactive agent in this kind of targeted radiotherapy.

The radiopharmaceutical may be delivered in several ways, by implanting a device such as a wire introduced via a catheter into a tumour, or via tiny seeds injected into the blood stream; more radioactive isotopes may be inserted directly into the tumour via a needle. The dosage and the duration of the localised radiation exposure is carefully controlled to provide the lowest effective dose.

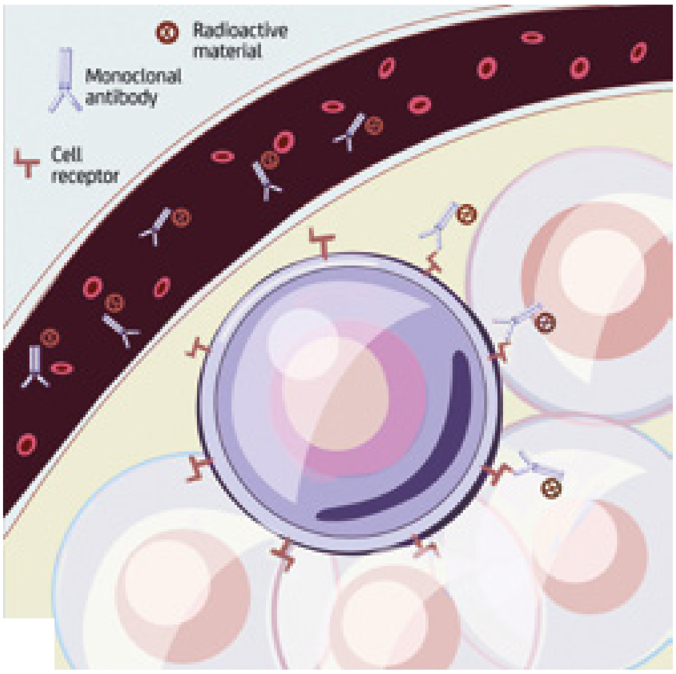


Prostate cancer can be treated using brachytherapy.

RADIOIMMUNOTHERAPY

The most difficult conditions to treat are those where the cancerous cells have spread around the body. A novel and effective biological approach to treat such metastases is to introduce into the body antibodies (so-called monoclonal antibodies, or MABs, prepared in the laboratory). They act as though they are part of the body's natural immune system, and their job in this case is to seek out the cancer cells and bind to specific antigens that collect on their membranes. This encourages the body to make its own antibodies to identify, then destroy or weaken these cells. The approach is even more effective if a radioisotope is attached to the MAB, so it can then deliver lethal radiation straight into the cell. The treatment time is much shorter than for traditional chemotherapy with fewer toxic effects for the patient. Trials have been carried out with a number of radioisotope-antibody pairs, and are ongoing. Therapies recently approved include those with iodine-131 and yttrium-90 attached to MABs, tositumomab and ibritumomab tiuxetan respectively. They are used to treat non-Hodgkin's lymphoma, in which the cancerous white blood cells spread throughout the body.

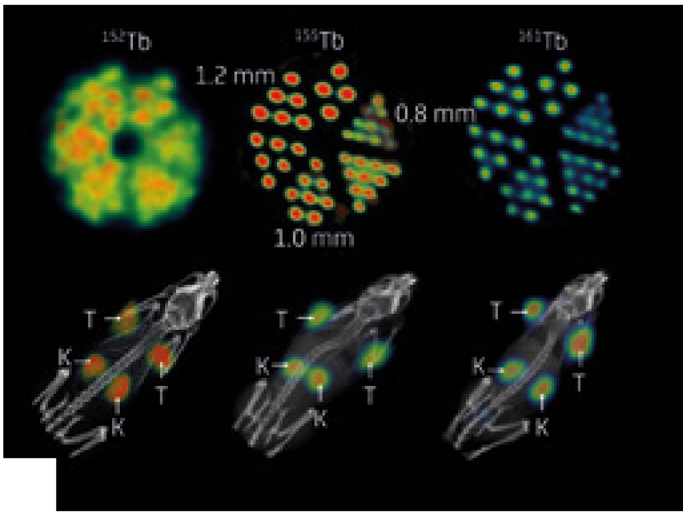
Other metastases are effectively treated with more powerful alpha-emitting isotopes attached to a MAB. They include bismuth-213, which has a half-life of 46 minutes and is produced by the decay of actinium-225 whose half-life is 10 days. This is thus delivered as a generator system similar to the one for technetium-99m (see p55).



A schematic representation of the radioimmunotherapy in which cancer-destroying radioactive isotopes are attached to monoclonal antibodies that target cancer cells.

THERANOSTICS

Another approach of growing interest is to combine diagnostic imaging and therapy into a single procedure – theranostics – by using just one radiopharmaceutical that does both. This can be achieved in two ways. The first involves attaching to the targeting biomolecule just one isotope that delivers two kinds of radiation – one for imaging (for example, gamma-rays in SPECT) and one for therapy (beta radiation). Iodine-131 and lutetium-177 both emit gamma and beta radiation, so can be employed in this way. Copper-64 is gaining interest because it emits both positrons and beta particles suitable for PET imaging and therapy respectively. The second approach is to combine two isotopes of the same element but with different types of radioactive decay. So-called matched pairs of isotopes used in theranostics include iodine-123 as the gamma-emitter and iodine-131 as the therapeutic agent – and more recently developed, the matched pair yttrium-86 (positron-emitting) and yttrium-90 (beta-emitting). Nuclear physicists have even identified and generated an interesting 'matched quartet' of the element terbium: terbium-152 (positron emitter), terbium-155 (gamma emitter), terbium-149 (alpha emitter) and terbium-161 (beta emitter).



PET/CT images after the injection of terbium-152 (PET), 155 (SPECT), and 161 (therapy). Combining imaging and therapy offers a more efficient treatment procedure. **[Credit ISOLDE CERN/ILL/PSI].**

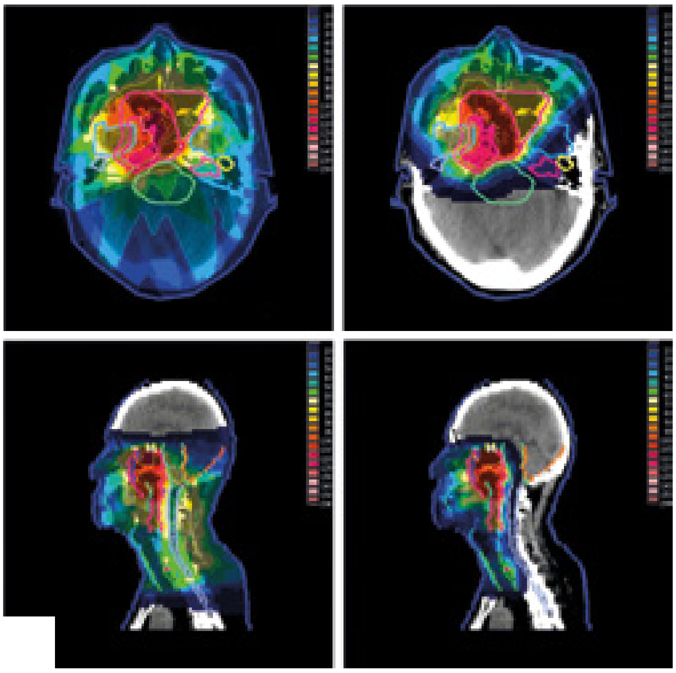
Theranostics has a number of advantages. It is quicker, safer and potentially less expensive to implement – and, increasingly important, enables the oncologist to design the therapeutic procedure that is optimised for the patient.

BORON–NEUTRON CAPTURE THERAPY (BNCT)

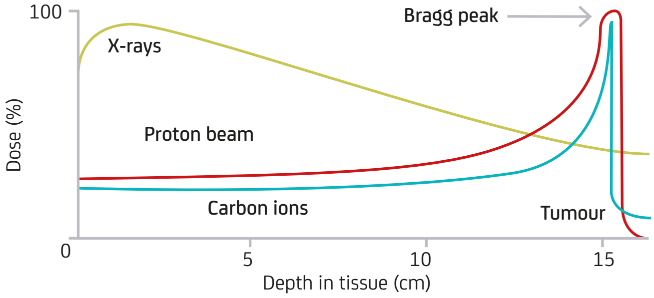
Another rather novel and still experimental therapy employs a stable isotope of boron, boron-10. This isotope is again incorporated into a drug that localises in cancer cells. But in this case, after being injected, a low-energy beam of neutrons is aimed at the patient. The boron-10 then undergoes a nuclear reaction, capturing a neutron to form boron-11. This isotope decays with the emission of high-energy alpha particles. Boron–neutron capture therapy is now being developed in various centres in the world. It is particularly suitable for treating brain tumours, liver cancer and malignant melanomas.

HADRON THERAPY

An exciting alternative to X-ray and gamma-ray radiotherapy is the use of precisely-tailored beams of hadrons (that is, nuclear particles composed of quarks, such as protons and other atomic nuclei, see Chapter 1). They can more accurately target a malignant tumour without harming surrounding tissues. Hadron therapy involves directly aiming thin pencil-like beams of protons – or increasingly of carbon-12 ions – at the tumour. Because these highly-penetrating guided missiles have mass and speed, they charge straight through normal tissue without harming it. However, their energy profile is designed so that the hadrons come to rest at a precise distance within the tumour volume where they deposit all their destructive energy. This is powerful enough to break up DNA in the tumour cells so killing them outright, not easily achieved with conventional radiotherapy. Furthermore, there is little scattering of the energy outside the target location, so that the surrounding tissue is spared. The extreme precision and guided lethality of hadron therapy is therefore ideally suited to treating cancerous lesions that are resistant to other therapies, or are located in difficult-to-reach, highly sensitive locations such as the head and neck.



Proton therapy (right) is more accurate that X-rays (left) in delivering the optimum therapeutic radiation dose.



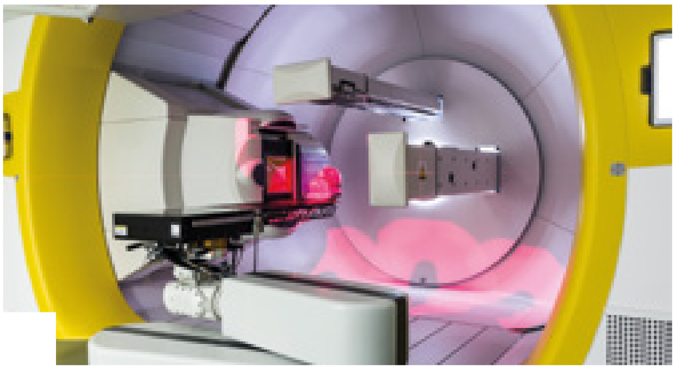
For both proton and carbon beams, all their energies are deposited at a given location (*ie* in the tumour) and are not scattered as in the case of X-rays. Lower levels of energy are needed.

THE SET-UP

The set-up requires an accelerator that delivers beams to the patient lying in front of a gantry that can be rotated to accommodate various beam orientations. The tumour and the surrounding tissues are first scanned to give a three-dimensional image (via X-ray CT, MRI or PET scanning), and the correct radiation dose and how it is to be delivered is calculated on a computer. The particle beam is then 'painted' like a fine brush across the target volume in layers at different depths. The effects are monitored via imaging so as to achieve the desired outcome through as fewer treatments as possible; this is beneficial for the patient and keeps costs down. This optimised approach is thus highly personalised and so very effective.

Hadron therapy has expanded rapidly in recent years and is employed to treat a wide range of cancers. There are now more than 20 proton therapy centres in Europe (the number is predicted to grow to well over 40 by 2023), and over 90 throughout the world. There is growing interest in therapy employing the heavier carbon ions, which provide more intense radiation doses and is highly effective on the most resistant tumours. Currently, there are 13 carbon-ion therapy centres in clinical operation.

Research into improving treatment-planning and monitoring, types of ions used, and dose delivery continue to be very active areas of hadron-therapy research. As in other areas of nuclear medicine, it requires interdisciplinary cooperation – between nuclear physicists, accelerator engineers, radio-biologists and clinicians.



Proton therapy with a movable gantry at the Institute of Nuclear Physics in Kraków Poland.

IMPROVED TREATMENTS

One issue being studied is how to compensate for the natural motion of tumours and organs, for example, breathing, which will keep changing the exact outline of lung and breast tumours. This problem is being solved in several ways. The target can be first scanned several times to average out the motion, or the beam can be stopped and started so its exact position coincides with a pre-defined position of the target. Another option is to track the motion of the organ continuously using simultaneous imaging with PET, to guide the beam.

Other light atoms are also candidates for hadron therapy. Helium has a similar biological effectiveness to protons, but there is less lateral scattering of the dose deposited. Helium ion beams might offer a lower-dose, better-targeted treatment than protons for young cancer sufferers. Oxygen-16 is being studied as a more effective ion beam for treating hypoxic tumours such as those characterising pancreatic cancer, which are very radiation-resistant, and for which the therapeutic outcomes are still rather poor. The drawback of this ion is its potential toxicity to normal tissue.

Neutron beams have been extensively applied in hadron therapy since the 1930s, but their use has been overtaken by other forms of radiation therapy including protons, because neutrons are less easy to deliver, requiring more complex guidance systems. More exotic particles such as pions (a light, highly unstable hadron produced in some nuclear reactions) and antiprotons (the antimatter version of a proton) have been considered for therapy since they would deliver additional energy via their decay or annihilation. However, creating and handling them would be technologically demanding and costly, so they are not likely to find routine clinical use. Of more interest is the radioactive ion, carbon-11, which emits positrons. Carbon-11 is already used as a radioactive label to study biological molecules of interest and as a PET imager. Nuclear physics facilities are investigating whether carbon-11 could replace stable carbon-12 in carbon-ion treatments such that imaging and therapy could be encapsulated in just one particle beam, and work rather like the theranostic treatments mentioned on page 61. The PET imaging could guide the incident beam and monitor the therapeutic treatment in real time.

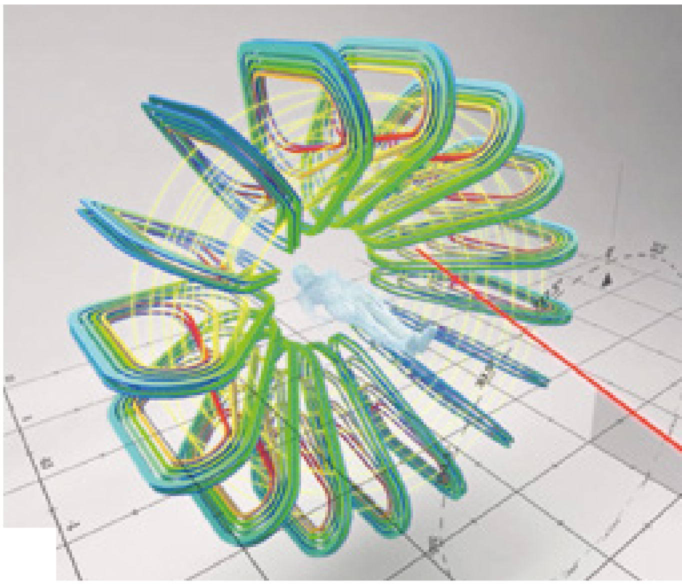
NEW TECHNOLOGY

The potential efficacy and fast growth of hadron therapy has stimulated developments in accelerator technology. Proton and helium beams can be prepared using large-scale cyclotrons, synchrotrons (a larger ring-shaped accelerator) or linacs. Carbon-ion production generally requires the use of a synchrotron, which can be more complex to operate than a cyclotron. The delivery gantry for carbon ions is huge and heavy (hundreds of tonnes) because large magnets are needed to guide the energetic charged particles. The complex and massive set-up makes treatment expensive and is an obstacle to further expansion.

The massive gantry used to deliver ground-breaking carbon-ion therapy at the Heidelberg Ion Therapy Centre in Germany. More compact designs are now being developed. **[Credit HIT].**

To meet demand, reduce costs and increase efficiency, new generations of accelerators of novel design are being developed – primarily for medical use but also for other applications. One compact design is the fixed-field alternating gradient accelerator, which is a hybrid of a cyclotron and a synchrotron. High-energy cyclotrons and linacs are also being developed including ones that can be rotated around a patient. Modern magnets are to be reduced in size and cost because they take advantage of advanced superconducting (conduction without resistance) technology, which generate much higher magnetic fields than normal electromagnets. Increasingly, proposals are coming forward to bring the accelerator and gantry together as one unit. Other completely novel accelerator systems are also being considered, including those in which the charged particles are accelerated by a powerful electromagnetic wave generated, for example, by a laser.

Treatment costs and efficacy will also be lowered by delivering more intense doses of radiation such that a treatment dose can be delivered during a patient's single breath hold, for example. Another aim is to give larger and fewer doses in a short amount of time in order to increase patient throughput. Therapy normally involves several sessions over weeks.



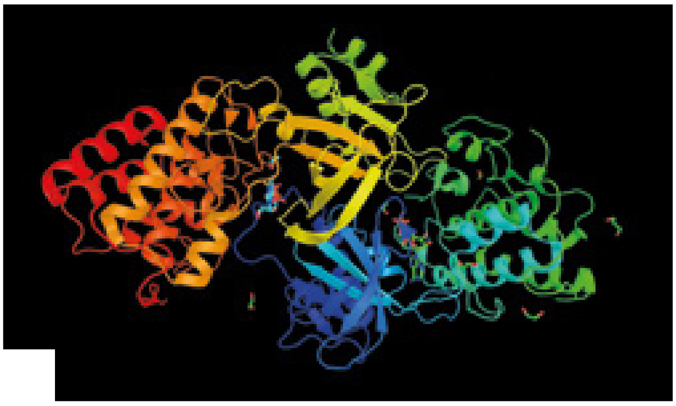
CERN is developing a new compact non-rotating gantry design for hadron therapy that can rotate the beam around the patient and reach tumours from different angles. It uses superconducting toroidal magnets. **[Credit Daniel Dominguez/CERN].**

NUCLEAR PHYSICS, BIOLOGY AND DRUG DEVELOPMENT

Today, our understanding of living processes and the consequent development of new drugs and medical procedures depend on analytical studies of living processes at the molecular level. The most well-known analytical technique is X-ray diffraction, usually referred to as X-ray crystallography. When X-rays pass through a sample in crystalline form, they are reflected, or scattered, by the regular array of atoms in the crystal. The scattered X-ray waves interfere with each other either cancelling or enhancing each other (diffraction) to give an interference pattern, when recorded on a detector, that is characteristic of the molecular structure. During the past 100 years, X-ray diffraction has been used to study many substances but the most significant have been materials with essential biological functions. Indeed, the double-helix structure of DNA was discovered in this way in the 1950s, which ultimately led to the genetic revolution.

Another set of important biomolecules, intensely studied by X-rays, are proteins. These large, long-chain molecules do much of the work in cells. For example, as enzymes they catalyse chemical reactions, and as receptors embedded in cell membranes they control what molecules or atoms enter or leave the cell. Drug molecules are often designed to block the actions of such proteins, for example, those associated with immune responses or infectious agents such as pathogenic bacteria and viruses. An important aspect significant to good health, is the recognition that proteins are folded into specific three-dimensional shapes that allow them to carry out their job. If they become misfolded, then they can no longer function correctly. Misfolding is associated with neuro-degenerative conditions like Alzheimer's and Huntington's disease, so understanding the interactions between three-dimensional proteins and relevant drug molecules is an important goal in improving human health.

X-ray studies are not the only analytical tool available to medical researchers; two other methods, which are based in nuclear physics, are growing in use: nuclear magnetic resonance (NMR) and neutron scattering. The latter is analogous to X-ray analysis mentioned above and is often employed in conjunction with it. The former is one of the most important laboratory techniques for analysing the chemical structure of organic molecules such as potential pharmaceuticals, or natural products like steroids and enzymes.



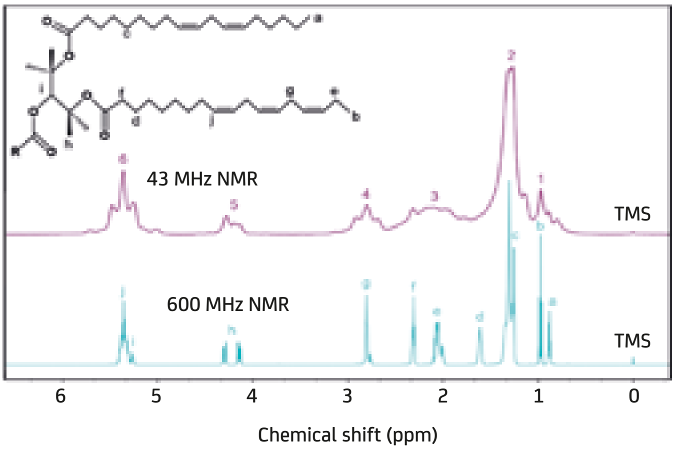
A typical protein, which is a large molecule composed of a long chain of amino acids folded into a series of characteristic 3D shapes. X-ray, NMR and neutron scattering are all used to study on how the protein's structure affects its function.

NUCLEAR MAGNETIC RESONANCE

Nuclear magnetic resonance (NMR) exploits a quantum property of nuclei known as spin. It endows the constituent neutrons and protons with a magnetic moment. In some nuclei, the spins cancel out so they have no magnetic moment, but in others they add up to give an overall characteristic spin and magnetic moment. Nuclei with spins include hydrogen (proton), carbon-13 and phosphorus-31.

As with electronic spins in a standard magnetic material, nuclear spins align when an exterior magnetic field is applied. In the 1930s and 1940s, nuclear physicists noted that if an oscillating electromagnetic field was applied in the form of radio waves, then each type of magnetic nucleus absorbed the radiation at a particular frequency. This causes the nuclear spin to tilt and then relax back into its previous alignment with the same frequency (resonance). However, each resonant signal is affected by its immediate electronic and thus molecular environment, which tends to shield it from the external magnetic field experienced. The resonant radio-frequency signal detected is then shifted in energy to some degree. A complex molecule containing many magnetic nuclei will thus generate a whole spectrum of NMR signals demonstrating an array of shifts that reflect in some detail its overall chemical structure.

The most common form of NMR spectroscopy exploits protons, although many other isotopes with spin are also used as chemical probes. Organic molecules generally contain many hydrogen atoms bonded to a carbon backbone as well as other atoms such as nitrogen and oxygen. Proton NMR can analyse not only the chemical bonding structure but even how the bonds are angled in relation to each other. Such information is extremely important in studies of biological molecules where three-dimensional structure is relevant to correct function.



A typical NMR spectrum of an organic molecule. Today, NMR can also be used to study much more complex biological molecules like proteins.

With the advent of ever more powerful magnetic fields delivered by superconducting magnets, NMR has now developed into an arsenal of highly sophisticated, high-resolution techniques that can probe the structure and behaviour of large molecules like proteins, and may provide information not always available with X-ray crystallography. To unpick the thousands of signals in the protein NMR fingerprint, specific parts of the molecule may be labelled with other magnetic nuclei as such as nitrogen-15. Increasingly, the motions of biomolecules can be followed. NMR is normally carried out on samples in solution. If the solvent is labelled with the hydrogen isotope, deuterium, which behaves chemically like hydrogen but has a different and much weaker NMR signal, the deuterium atoms may exchange with accessible hydrogen atoms in the biomolecule. It is now possible to follow the unfolding of a protein by monitoring the changing rate of exchange between the deuterium in the solvent and the hydrogens in the protein. The more deeply buried hydrogen atoms in the protein's 3D structure will exchange more slowly.

NEUTRON SCATTERING METHODS

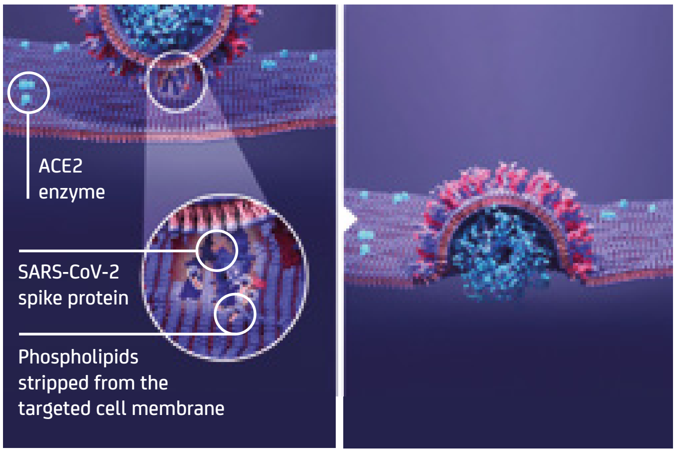
Intense beams of neutrons provide an extremely powerful analytical tool for studying the detailed structure of many biomolecules and structures, including proteins and their interactions with potential therapeutic agents, and also the behaviour of cell membranes – all at the molecular or atomic scale. Because neutrons are quantum particles, they have a characteristic wavelength depending on their energy. Indeed, when interacting with matter, including biological materials, they can be diffracted or scattered like X-rays, and so reveal structural details. The big difference between neutrons and X-rays is that while X-rays interact with the electrons in an atom, neutrons are scattered by the nucleus, so they give a different kind of signal offering different information, which is considered complementary to that from X-ray studies.

Neutron beams are particularly suitable for molecular studies related to health. Their wavelengths and energies are appropriate for probing a wide range of biological structures, from the small, long-chain lipids that make up cell membranes to very large proteins and the complex molecular assemblies that control how cells function. Being electrically neutral, neutrons can travel deep into materials without destroying their internal arrangement.

The beams are prepared at dedicated nuclear facilities hosting either a small reactor, or a so-called spallation source. In the latter case, an accelerator aims a beam of protons at a neutron-rich target and knocks out neutrons from the target material (often tungsten). Specialised instrumentation guides and modifies the neutron beams generated from the neutron source, and steers them to experimental areas designed for specific neutron analytical methods.

A particular advantage of neutrons in medical research is that they interact quite strongly with hydrogen nuclei, which X-rays cannot 'see' very clearly. Biological structures contain vast numbers of bound hydrogen atoms whose exact locations and orientations can dominate a physiological process. Even more significant is that molecules like proteins can be studied in their natural watery surroundings, rather than just in a prepared crystalline form, to give a truer understanding of their function. Because water also contains hydrogen, relevant molecular interactions involving water can also be studied. This is aided by a special technique in which some of the hydrogen atoms may be substituted by deuterium. This hydrogen isotope gives a different scattering signal from hydrogen, so deuterium substitution allows different parts of a complex molecule to be selectively highlighted. Furthermore, if some of the water surrounding the molecule is deuterated such that its scattering signal matches that of selected parts of the molecule, those parts are rendered invisible against the aqueous background, so that only the remaining molecular components can be distinctly seen. This is particularly useful when investigating large molecular assemblies.

Another technique – reflectometry – is to bounce neutrons off the surfaces of cell membranes. These consist of layers of lipids hosting different molecules such as proteins. Understanding their behaviour is significant in many studies such as those of neurological diseases and infection mechanisms including the Covid-19 virus.



Neutrons offer a unique way of investigating not only structure but also dynamic behaviour at the molecular level. Membranes, proteins and other biomolecules are not stiff structures but are 'floppy', and studying their motions is key to understanding their function. Neutrons provide a unique tool to probe the dynamics. When a neutron beam is reflected from a sample of flexible molecules, some of beam's kinetic energy will be taken up by the molecules' internal motions in a characteristic way. This can be analysed by measuring the changes in neutron energy after the beam has been scattered by a sample.

THE FUTURE

Over the past century, life expectancy and quality of life has increased, especially in developed countries. This is due to improved living conditions including sanitation, plentiful food supplies and increased mobility – and of course improved healthcare. However, new major health issues have emerged, often related to extended periods of old age for many. These include multiple cancers, inflammatory diseases, heart disease and various forms of dementia. Diabetes related to inappropriate nutrition is on the rise in many wealthy countries, and increased travel means that viral agents spread and mutate faster. Furthermore, the demands and expectations associated with often stressful modern life are resulting in poor mental health for some. Increased pollution and exposure to a vast of new chemicals seem to be relevant to unexpected and pathological immune and allergic responses.

While the battle against many cancers has been successful, thanks partly to the kind of radiological therapies described in this chapter, diabetes, dementia and many other life-threatening illnesses pose huge challenges and remain difficult to treat. Tackling these challenges requires a detailed understanding of the body's metabolic and neurological pathways on the most detailed atomic and molecular scales, so that the causes of disease can be properly identified and appropriate treatments developed. One of the aims is to make treatments more personalised to achieve better outcomes. Nuclear physics studies will continue to provide and expand the tool-box of advanced radiological and instrumental methods needed to achieve these goals – not only in diagnosis and therapy, but also in the underpinning biomedical research, so helping to improve human health in the 21st century.

Neutron reflectometry can probe how the spike protein of the Covid-19 virus (SARS-Cov-2) interacts with the cell membrane receptor (ACE2), stripping away lipids from the membrane so it can enter the cell.
[Credit: Institut Laue-Langevin]

FURTHER INFORMATION

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CHAPTER 7:

PRODUCTS AND FOOD

Nuclear science plays a part in the manufacture of everyday goods, like cars, food and packaging and smart phones, and in maintaining food supplies across the world.

RADIOACTIVE ISOTOPES, PARTICLE BEAMS AND THE EXPLOITATION OF NUCLEAR PROPERTIES PLAY A SIGNIFICANT ROLE IN THE PRODUCTION OF FOOD, AND THE MATERIALS AND GOODS WE RELY ON.

Lifestyles in the modern world very much rely on the ready availability of a vast array of products and devices made from advanced and often complex materials. We expect them to be dependable and efficient. At home, they include 'soft goods' often made from long-chain molecules – polymers (for example, plastics, textiles and detergents), and 'white goods' usually constructed using metallic alloys and composites, and including sophisticated electronics. Mining, construction, industrial processing and transport also rely on materials and advanced engineering that meet specified requirements. The same applies to the efficient production of food, which also needs to be safe and sustainable.

Industry and agriculture employ many analytical and monitoring methods to ensure we have the products we need or desire to improve our lives. Many of them employ techniques based on nuclear physics. Radiation is also employed in a positive, transformative way in manufacturing. As Chapter 6 has demonstrated, medicine is being radically improved through the use of radioisotopes and particle beams generated from nuclear reactions. However, of equal importance to our health and wellbeing is not only food security but also a well-cared-for environment that helps to conserve resources for the future. Again, nuclear methods are playing a significant part in agriculture and environmental protection.

In this chapter, we describe some of the many ways in which nuclear physics contributes to the material world.

RADIATION FROM NUCLEAR PHYSICS

Nuclear methods employed in industry ultimately depend up on the delivery of various types of high-energy radiation generated from an atomic nucleus – via the decay of radioactive isotopes, reactions between nuclei, or induced nuclear excitations. These include gamma-rays, beta particles, neutrons, alpha particles, positrons, muons and accelerated radioactive ions. The types of radiation most employed by industry are gamma radiation and neutrons. The techniques exploiting them are often employed in conjunction with, or as an alternative to, X-rays and accelerated electron beams generated by atomic rather than nuclear processes (that is, involving the electron orbitals in an atom). All of these processes generally involve the generation of high energies, using for example particle accelerators, so the underlying technology is often similar. Thus, both nuclear and atomic physics methods are often developed and applied in the same or closely allied research institutions.

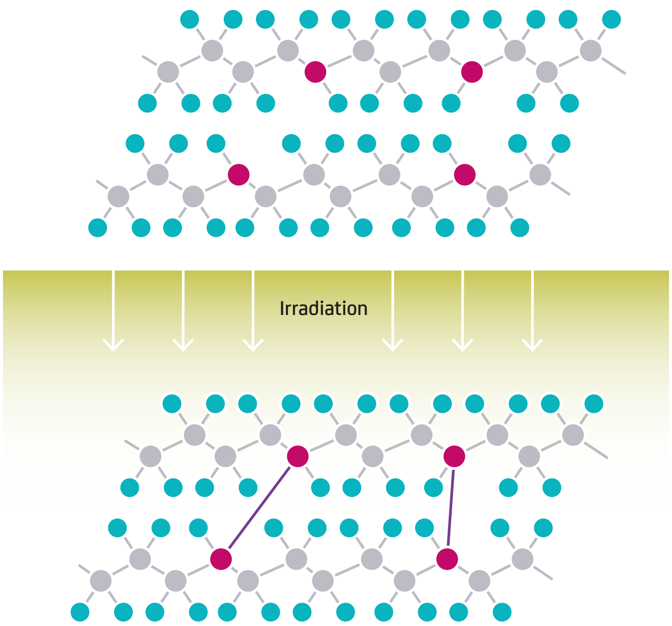
THE ROLE OF RADIOACTIVE ISOTOPES

As explained in previous chapters, radioactive isotopes offer one of the main sources of useful radiation. They are created either via accelerators or in nuclear reactors for specific purposes. The high-energy radiation they produce offers a simple and quick way of producing and modifying materials during manufacture, or killing pathogens to increase the efficiency of agricultural and food production. Radioisotopes can be used as tracers in industrial and environmental processes (to follow the flow of sewage for instance), in scanning or imaging goods for quality control, and in many kinds of sensors and measuring devices.

IRRADIATION

CHEMICAL MODIFICATION

High-energy radiation such as gamma-rays is ionising: that is, it strips out electrons in atoms to create electrically charged ions. This may cause chemical bonds in compounds (including those in biological materials) to break or re-arrange, resulting in decomposition or the formation of new chemical bonds. Ionising radiation can generate a particularly chemically active species of atoms or molecules called radicals. These have a single unpaired electron that very rapidly forms new chemical bonds, often initiating a molecular chain reaction. Many plastics and rubbers are made via such a reaction, in which small molecules rapidly bind to create a polymer chain. The advantages of radiation-induced polymerisation is that it is ideal for making polymers not easily achieved by conventional chemical means, or if the chemical reaction involves toxic compounds. The process can be carried out on solid starting materials, and there is no need for the removal of unwanted side-products afterwards.



The polymer cross-linking process initiated by irradiation is used to produce heat-resistant polythene cables for electrical equipment.

One of the main applications of this kind of irradiation, using radioactive sources emitting gamma radiation or electron accelerators, is to introduce chemical cross-links between polymer chains, such that it hardens the material and increases its melting point, thus improving its mechanical behaviour. Such plastics are used as insulation for electrical wiring and cables, and to make car tyres, or natural rubber latex for medical items such as gloves. Other commercial applications are heat-shrinkable tubing, food wraps and self-regulating heaters. Cross-linked water-soluble polymers, also known as hydrogels, are commercialised for wound dressing, specifically for burn wounds and diabetic ulcers. Recently, irradiation has been used to form polymethacrylates. These polymers readily absorb toxic metals such as chromium and lead ions, and so are used for water purification.

RADIATION PROCESSING ENABLES SMALL BUSINESSES TO ENTER GLOBAL VALUE CHAINS IN MALAYSIA

Cable manufacturing is essential to the automotive industry, which has always played one of the major roles in the industrialisation of economies. Cables used in hot vehicle engines need to be insulated with a heat-resistant and fire-retardant polymer coating to ensure they do not catch on fire. To improve the heat resistance, the required starting polymer is cross-linked. Irradiation is the preferred method since it optimises operating costs and provides a more environmentally-friendly process than the chemical approach. Malaysia's nuclear agency, Nuklear Malaysia, is helping small and medium-sized businesses by irradiating their cable products.

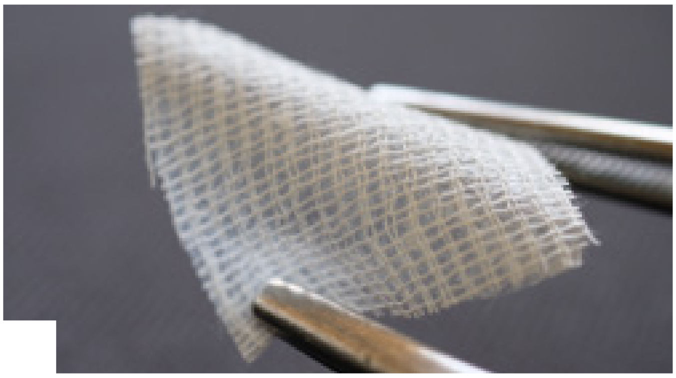
Cables being irradiated in Malaysia to improve their resistance and longevity. **[Credit IAEA].**

STERILISATION

Another useful form of modification by irradiation is to induce irreversible changes at the molecular level in living tissue such that an organism dies. When applied to harmful microorganisms, such as pathogenic bacteria, viruses and fungal spores, it is known as sterilisation. Radiation sterilisation of medical equipment and products has been in use for more than 60 years. Many medical products are now sterilised via gamma or electron-beam irradiation, rather than with heat treatment. It is most suitable for sterilising heat-sensitive materials such as medicines in the form of powders, creams or liquids. It is also used to sterilise many single-use products such as syringes, and personal protective equipment (PPE) such as surgical masks and gloves, which has recently been in high demand. The process can be deployed on sealed packaged items such that the items therein retain an almost indefinite shelf-life. Smaller gamma irradiators based on gamma-emitting caesium-137 sources, or low-energy electron accelerators, are also utilised in treating blood for transfusions.

Radiation sterilisation is particularly effective for single-use products such as surgical gloves.

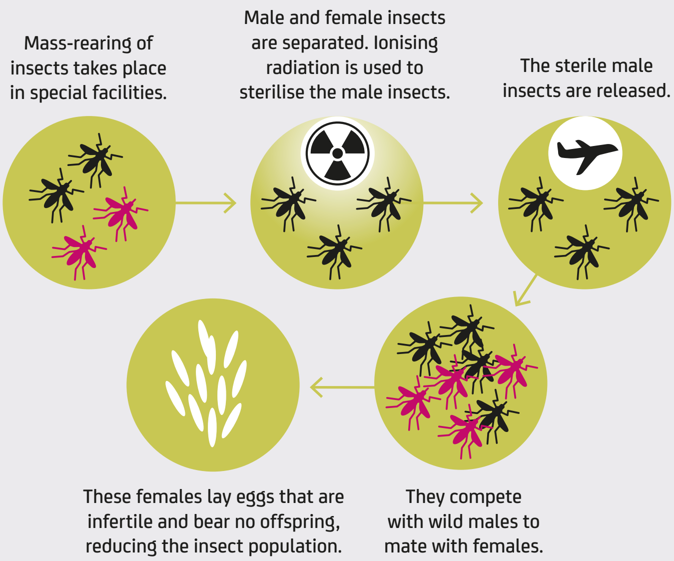
Another area where sterilisation is essential is in regenerative medicine. This is an emerging field that focuses on the restoration of damaged and failing tissue and organs in the body. Its applications include the growth of new bone, skin, cartilage, and muscle. Synthetic biomaterials may be introduced consisting of plastic scaffolds on which new tissues can be grown. Radiation offers the most suitable method for sterilising such biological materials, and so is playing a key role in supporting the development of the growing area of tissue engineering.



Irradiation provides the optimum method for sterilising medical equipment and bio-engineered tissues.

COMBATTING INSECT-BORNE DISEASE

An interesting application of gamma irradiation is in tackling mosquitos, which are vectors for disease in tropical countries. The sterile insect technique (SIT) involves the rearing of mosquitos in special facilities. The male mosquitos are separated from the females and are sterilised with gamma radiation. They are then released over towns and cities, where they mate with wild females which then lay infertile eggs, so reducing the overall mosquito population. The most recent high-profile application of SIT has been in the fight against mosquitos carrying the deadly Zika virus in Brazil and the broader Latin America and Caribbean region.

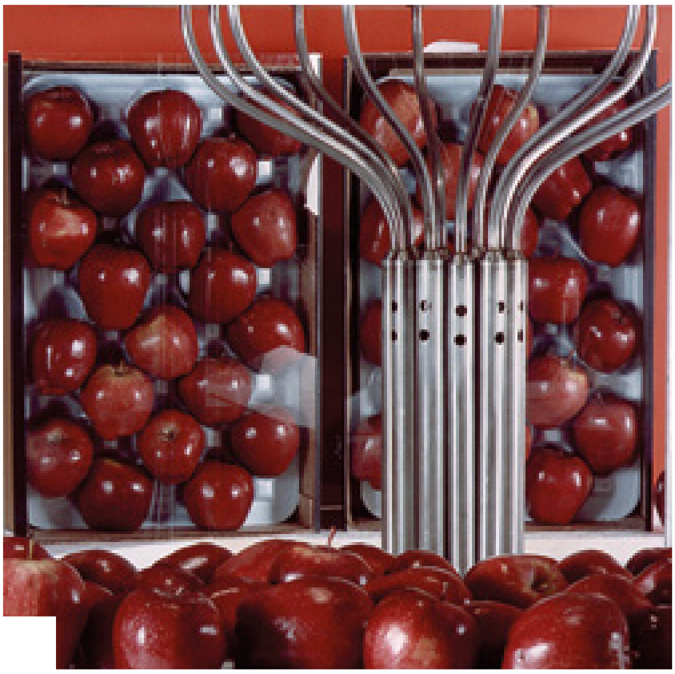


The Sterile Insect Technique to combat the Aedes mosquito, which carries the Zika virus.

FOOD IRRADIATION TO ENSURE FOOD SECURITY AND PROTECT THE ENVIRONMENT

Irradiating food provides some of the same benefits as heating, refrigerating, freezing or adding preservatives, but without changing the temperature or leaving residues. Irradiation controls spoilage, destroying food-borne pathogenic micro-organisms that cause food poisoning, or insect pests, without significantly affecting the food's taste or smell. Its two main advantages are that ionising radiation is penetrating and the fact that it does not involve heat, which may cause damage. Pre-packaged food will thus remain protected from contamination or infestation post-irradiation, and the temperature of food during irradiation does not significantly change. The latter is important for food quality. For example, dried herbs and spices will retain their volatile components which give them their unique flavours, appearance and smell; fresh fruits and vegetables do not degrade because of heat. Chilled or frozen products such as seafoods can be irradiated as well, and the process is known as cold pasteurisation.

International standards specify that gamma-rays (from cobalt-60 or caesium-137 radioactive sources), electron beams or X-rays can be used to irradiate food. There are a small number of facilities that specialise in irradiating food, but the treatment is generally carried out at multipurpose irradiation centres where many different commodities, both food and non-food, can be treated.



The irradiation of fruit using cobalt-60.

RADIOISOTOPES AND AGRICULTURE

In 2019, the United Nations Food and Agriculture Organisation estimated that as many as one in 10 people in the world suffers from malnutrition. However, employing radioisotopes and radiation in food production can help to reduce this number. Nuclear methods are an important aid in protecting land fertility and water resources – as well as controlling pests, and crop and animal diseases, so increasing crop production and improving animal health. In addition, irradiation techniques are being employed in plant-breeding programmes to develop more productive crops.

A BETTER ENVIRONMENT FOR AGRICULTURE

Nuclear analysis techniques are highly suitable for testing soil quality, detecting the presence of contaminants and tracking water movements. Neutron activation analysis (see page 75) can detect up to 40 elements in a single sample of soil that are significant to plant growth and thus help to evaluate shortages of key minerals. For example, wilt in cotton plants is associated with a lack of manganese. Once identified, the mineral can be added to the soil. Pollution can significantly affect crops such as cotton. In regions around the heavily polluted Aral Sea in central Asia, studies revealed that soils were considerably contaminated with sodium chloride (salt) as well as toxic metals such as mercury and arsenic and sewage.

Nitrogen is important for plant health. Labelling techniques using stable nitrogen-15 can follow its microbial fixation in plants and the uptake of nitrogen-containing fertilisers. A significant aim is to minimise the use of fertilisers, which reduces farmers' costs while maintaining soil health. During the past decade, nitrogen-labelling studies in Benin in Africa enabled farmers to optimise their use of fertilisers and quadruple their yields of soya beans. Similarly, labelling water supplies with stable oxygen-18 and deuterium helps to improve irrigation practices without water degradation.

CONTROLLING PESTS

Insect pests can cause huge damage to both agricultural plants and animals resulting in significant economic losses. The sterile insect technique, SIT, using gamma-rays, mentioned opposite, has been extremely successful in eradicating agricultural pests such as the Mediterranean fruit fly and preventing them from spreading. It is a much more environmentally friendly approach than deploying pesticides. SIT is now applied across the world to tackle various species of fruit fly. It has also been used to eradicate screwworms in Central America where they lay eggs in the flesh of mammals such as cattle, eventually killing them. In Africa, the tsetse fly, which carries a parasite that causes trypanosomiasis (sleeping sickness) and nagana (cattle disease), has prevented profitable livestock farming in almost two-thirds of sub-Saharan Africa, resulting in economic losses of $4 billion a year. However, the use of SIT has made an impact. Zanzibar was declared tsetse-free more than 20 years ago; Ethiopia has now established the largest tsetse fly mass-rearing facility for SIT in the world.

PLANT BREEDING AND GENETICS

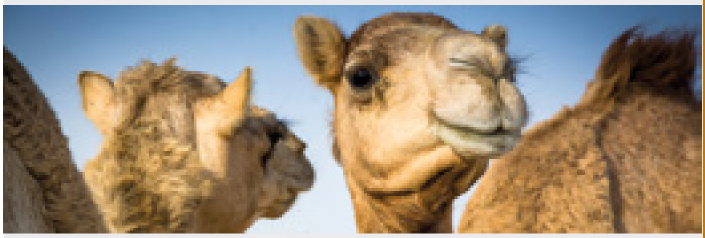
Nuclear irradiation is not always employed to sterilise or kill organisms, but instead to induce genetic mutations that are beneficial to plant breeding. Genetic changes mostly happen naturally as a result of cross-pollination, resulting in seedlings with new attributes that may be selected to create new varieties of crops. However, this process can be speeded up by irradiating with gamma-rays, X-rays, neutrons, and ion or electron beams to initiate genetic changes. This creates a greater diversity of attributes such as resistance to drought, a saline environment or heat – and of course diseases. The technology is cost-effective and safe, and more than 3000 new crop varieties have been introduced in this way. Developing countries in Africa and South America have particularly benefited: drought-resistant varieties of groundnut developed in Sudan have resulted in a yield more than a quarter higher. Gamma-induced mutations in the very valuable Arabica coffee plant, *Coffea arabica*, is also being studied to widen its rather narrow genetic base, and to counter a very destructive leaf rust that has wiped out large swathes of coffee production in Africa and the Americas. Even more important, is that this technology can efficiently prepare the world's agriculture for the effects of climate change.

Leaf rust has decimated coffee-growing in Africa and South and Central America. Gamma-induced mutations could produce more resistant varieties.

ANIMAL HEALTH

Managing the health of livestock benefits considerably from radioactive labelling. Radioisotopes such as carbon-14 are used to follow digestion and metabolism in dairy herds, so that commercial feeds can be optimally adjusted for improved milk production while maintaining animal health. Protein synthesis can be followed using phosphorus and sulfur isotopes, while a range of radio-labelled minerals can identify mineral imbalances in farm animals. Even, methane – a powerful greenhouse gas – emitted by ruminants can be estimated by isotope dilution using either tritium (hydrogen-3) or carbon-14 labelled methane. The technique of radioimmunoassay (explained in Chapter 6) has been used to measure hormones in milk, blood and other body fluids. It has even been developed as a mobile test kit to improve the outcomes of bovine artificial insemination and detect pregnancy at an early stage.

Livestock breeding is substantially benefitting from the preparation of complete genome maps. So-called radiation hybrid mapping provides a powerful high-resolution approach. It relies on radiation to induce fragmentation in the genome so as to find the position of selected genetic markers in the map. It is called hybrid because the chopped-up chromosomes of interest are implanted in rodent cells. An entire high-resolution genome radiation hybrid map has been completed for goats and is now being generated for camels using cobalt-60 sources.



Camel breeding has been enhanced by using cobalt-60 in a radiation-based technique to map the camel genome.

Until the early 2000s, the majority of irradiated foods world-wide tended to be high-value products. The objective was not to sterilise the food completely, but to minimise the risk of contamination with organisms such as *Escherichi coli*, *Staphylococcus aureus*, *Listeria monocytogenes* and *Campylobacter jejuni*. Because irradiation slows down food spoilage, shelf-life is extended, as well as ensuring food safety. In some special applications, packaged ready-meals are irradiated to high doses, for example, specially prepared hospital foods to ensure that they are completely sterile, emergency rations, and also those for manned space exploration.

FRESHER FRUIT AND VEGETABLES THROUGH IRRADIATION

A quarter of food harvested is lost as a result of spoilage, particularly in hot and humid countries. As a result, more than 60 countries worldwide have introduced regulations allowing the use of irradiation for products such as grain, fruit, vegetables and spices. As well as eliminating pests, irradiation also helps to reduce the loss of fresh fruit and vegetables through premature ripening, germination or sprouting. In some countries, it is employed on a commercial scale to prevent the sprouting of fresh produce like potatoes, ginger and garlic. For example, built as part of a common facility for the collection, storage and shipment of potatoes, the Shihoro Irradiation Centre in Hokkaido, Japan has for many years been irradiating potatoes on a commercial scale as a chemical-free method to inhibit sprouting.

Today, irradiating fresh fruit and vegetables has become one of the fastest growing commercial methods to prevent the spread of regulated plant pests (fruit fly, mites and weevils) through trade in fresh commodities. Ensuring that produce is free of certain pests is a prerequisite for global trade in fresh produce. The detection of a single Mediterranean fruit fly in a produce container, for example, can lead to immediate import bans and devastating financial consequences for the exporting country. Vietnam has several irradiation facilities employing low-dose gamma rays, as well as electron beams or X-rays, to secure exports worth $20 million a year to the US alone, and new markets to Australia are opening up. Other major fruit exporting countries, such as India, Mexico, South Africa and Thailand, are trading irradiated fruits and vegetables, while countries such as the US, Australia and New Zealand rely on the method to ensure the safety of imported produce. More than 60 countries worldwide have introduced regulations allowing the use of irradiation for food products.

Products being irradiated in Vietnam before export. **[Credit IAEA]**

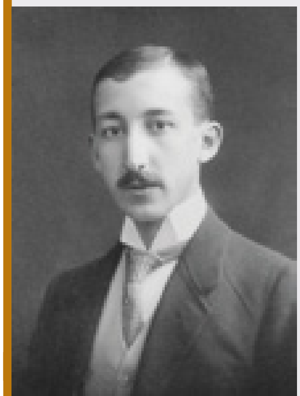
TRACING, INSPECTING AND ANALYSING

RADIOACTIVE TRACERS

One of the first uses of radioactive isotopes was as tracers. They can be incorporated into objects or devices of interest to detect any physical or dynamic changes. Today, radioactive tracers are applied extensively in industry as they offer a sensitive, simple and inexpensive method to monitor the efficacy and efficiency of industrial processes, which may involve complex pathways that might otherwise be inaccessible. Very small amounts of tracers are needed to detect the flow rates of liquids, powders and gases, how well they mix, what happens when they are filtered and whether any sediments are blocking pipes. One of the most important applications is in tracing leaks, especially if they result in harmful materials entering the environment – as in the case of oil spills or sewage and liquid waste escapes. Leaks in underground pipelines are best detected using beta radiation, which has enough energy to detect the leak but not escape the pipe walls. Radioactive tracers such as rubidium-86 are also used in engine studies to optimise design and to identify leaks.

A LANDLADY CAUGHT OUT

The Hungarian nuclear scientist George de Hevesy was the first person to make use of radioactive tracers – in 1911 after moving to work in Ernest Rutherford's laboratory in Manchester, UK. (Rutherford discovered the atomic nucleus.) De Hevesy had suspected that his landlady was serving him meals made from rather old leftovers of previous meals (no domestic freezers then!). When challenged, she denied it, so one day, he put a tiny amount of radioactive material on the food remains from his meal. Sure enough, using a simple radiation detector called a gold-leaf electroscope, he was able detect radioactivity in a stew served days later, thus revealing the landlady's unsavoury practice. De Hevesy went on to win the 1943 Chemistry Nobel Prize for his work on radioactive tracers.



George de Hevesy was the first scientist to use radioactive tracers.

OIL PIPELINES

Radioactive tracing is also traditionally used in environmental monitoring to follow water flow and erosion (see Chapter 4), as well as in the oil industry and mining to evaluate the extent and stability of oil fields and mineral deposits. A fluid carrying a gamma-emitting isotope may be pumped into a borehole in order to determine permeability and fractures in the oil well walls, and thus the likelihood of water flooding in. The efficiency of an oil well may be ascertained by injecting a radioactive tracer at a point upstream of output; a drop in the level of radioactive tracer downstream would indicate that oil is being lost. Flow rates can also be measured between one injection point and another.

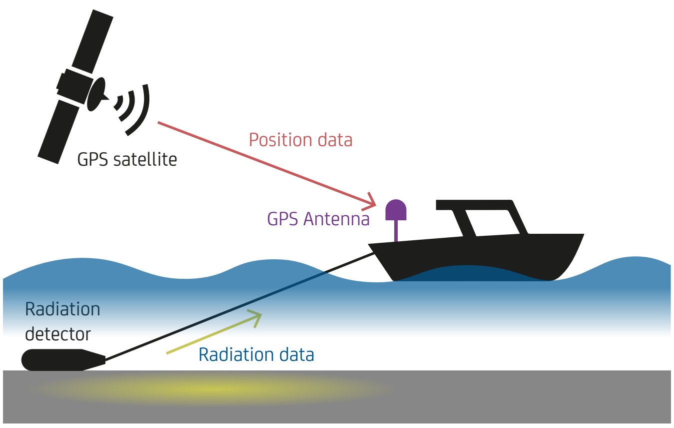
Flow rates in oil wells may be measured using radioactive tracers.

SHORELINE CONSTRUCTION AND PROTECTION

Construction projects also employ radioactive tracing to evaluate shorelines in coastal areas, rivers and lakes, or sea beds. Of particular significance is the robustness of coastal sediments – that is, whether coastal erosion or deposition is occurring. Radioactive tracers are more sensitive than conventional methods when investigating sediment dynamics, in providing better quantitative parameters for designing, optimising and maintaining civil engineering structures. They offer by far the most suitable tool for the study of sediment transport by furnishing information on the density of sediments deposited in a navigation channel, for example, as well as on the concentration of sediments circulating in suspension.

A knowledge of sediment transport behaviour in seas and rivers is also important for shore protection and management. The main causes for erosion in beaches include storms and anthropogenic activities such as the construction of seawalls, jetties and the dredging of river mouths, which disrupt the natural flow of sand. To ensure there is a sufficient depth of water at ports and harbours to accommodate ships, navigation channels are often dredged. Radio-tracing can help in the selection of suitable dumping sites for the dredged material, to ensure that it does not find its way back into the channels.

The figure below illustrates a typical bed-load sediment transport using radio-tracers injected on the sea bottom surface.



A sketch of the data-acquisition system for sediment transport and pollutant-tracing studies in coastal areas.

INDUSTRIAL USES OF SOME RADIOACTIVE ISOTOPES

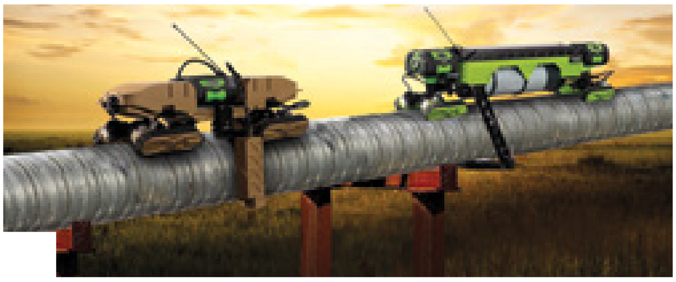
Isotope	Application
Technetium-99m	Study of sewage and liquid waste movements Sand movement in river beds and ocean floors
Hydrogen-3 (in tritiated water)	Study of sewage and liquid wastes
Gold-198	Study of coastal erosion
Chromium-51	Study of coastal erosion
Manganese-54	Prediction of the behaviour of heavy metals in waste water from mining
Zinc-65	Prediction of the behaviour of heavy metals in waste water from mining
Caesium-137	Identification of sources of soil erosion and deposition Density and fill-height detectors Low-intensity gamma sterilisation
Cobalt-60	Gamma sterilisation Industrial radiography Density and fill-height detectors
Iridium-192	Gamma radiography to locate flaws in metal components
Americium-241	Backscatter gauges Fill-height detectors Measuring the ash content of coal
Krypton-85	Industrial gauging
Nickel-63	Light sensors in cameras and plasma displays Thickness gauges Long-life beta-voltaic batteries
Selenium-75	Gamma radiography Non-destructive testing
Strontium-90	Industrial gauging
Thallium-204	Industrial gauging
Ytterbium-169	Gamma radiography Non-destructive testing

INDUSTRIAL RADIOGRAPHY

GAMMA SCANNING

Gamma-rays can be used just like X-rays to obtain an image of the structure and internal workings of industrial equipment. Gamma scanning offers a method of non-destructive inspection that can reveal any hidden cracks in pipe walls or machine parts, blockages, and damage due to corrosion and wear – and so diagnose any production problems. It has an advantage over X-rays in being more penetrating. The gamma source is more portable, being a small pellet of radioactive material (typically iridium-192 or cobalt-60) in a sealed metal capsule, and does not require a power supply. The gamma scanner is placed on one side of the object under test. The impinging radiation passing through is characteristically attenuated by the object's internal structure (denser material absorbs more of the radiation). The gamma-rays emerging on the other side are then detected either using a photographic film or more likely an electronic sensor.

The technique is extensively employed in the oil and chemical industries to check welds in vessels and pipes. A gamma-sensitive film might, for instance, be taped around a weld in a pipe, and then a so-called pipe crawler containing the shielded radioactive source finds the weld, where the radioactive source is then exposed so that radiographic image can be taken. A similar approach is also be employed to monitor and evaluate the operation of a distillation column by following with a gamma source changes in the densities of the vapour and condensing fluid along the column.

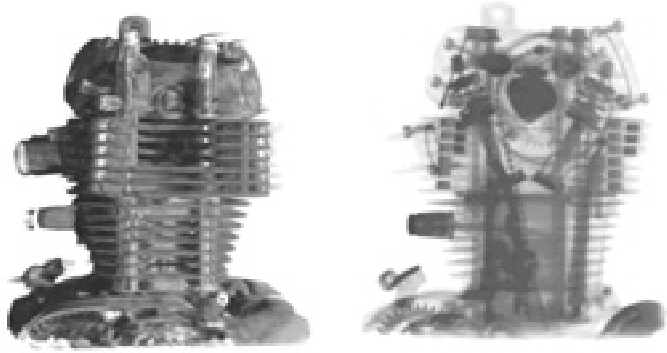


Radiographic-testing crawlers to detect corrosion and oil flow in pipelines. **[Credit Mistras].**

Radiography is also used to inspect the integrity of high-performance ceramics used in the aerospace industry, and even the damage to concrete buildings after a natural disaster such as the devastating 2015 earthquake in Nepal.

NEUTRON RADIOGRAPHY

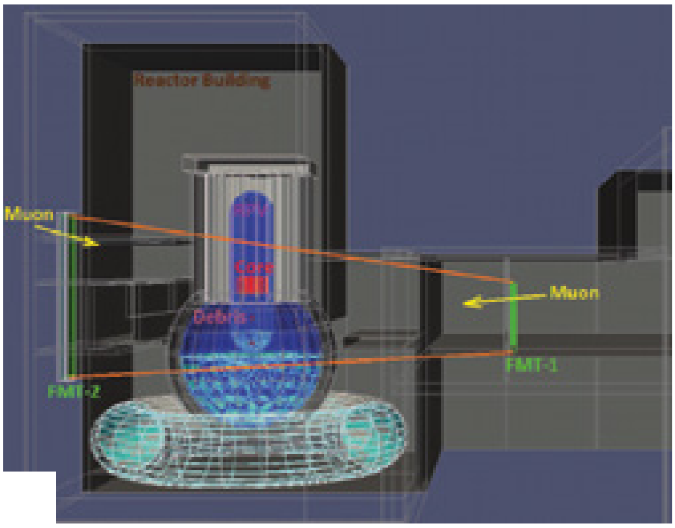
Neutron radiography is a relatively new technique that is developing fast. It works in a similar way to X-ray and gamma radiography to produce a three-dimensional tomographic image. Because neutrons are heavy nuclear particles that interact strongly with atomic nuclei, neutron radiography reveals slightly different and complementary information from that obtained with X-rays. Unlike X-rays, neutrons are absorbed by light elements like hydrogen and carbon, so can image cracks, flaws in advanced composite materials and ceramic objects. Neutrons are also more penetrating, which means that they can scan bulky objects such as engines and turbine blades, distinguishing between components and, for example, the movement of fluids such as lubricants. A recent development is the remarkable real-time neutron imaging of engines while they are actually running.



The neutron image of a working motorcycle engine. **[Credit Paul Scherrer Institut].**

MUON RADIOGRAPHY

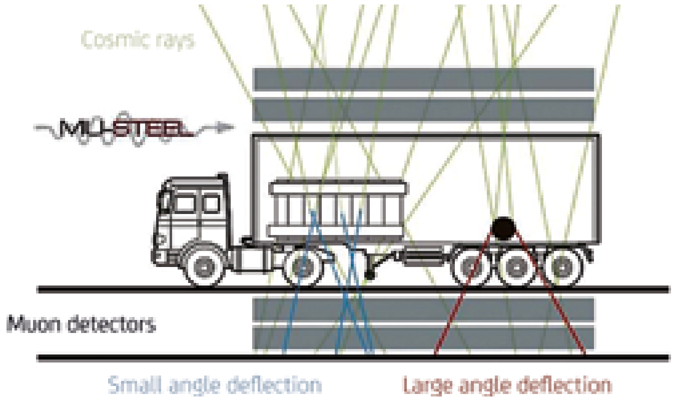
Muons are unstable, heavier versions of electrons produced on Earth in particle accelerators (see Chapter 1). However, they also rain down on Earth at a rate of 10,000 per square metre a minute, as the products of interactions of cosmic rays with molecules comprising the Earth's atmosphere. Remarkably, that is enough to be of practical value in generating radiographs of large-volume objects that they pass through, whether underground sites or buildings. Muons have the advantage that they are more penetrating than X-rays, while doing little damage (they decay into electrons and harmless neutrinos) – and of course they are free! The first use of muon radiography was in archaeology to image the interior of pyramids, as described in Chapter 8, but increasingly, muography, as it is sometimes called, is being exploited to image all kinds of underground structures such as volcanos, tunnels, mining areas and nuclear-waste depositories. One recent, significant application was to examine one of the Fukushima nuclear reactors after it was shattered in 2011 by an earthquake and tsunami. The site was extremely radioactive and could not have been examined easily in any other way.

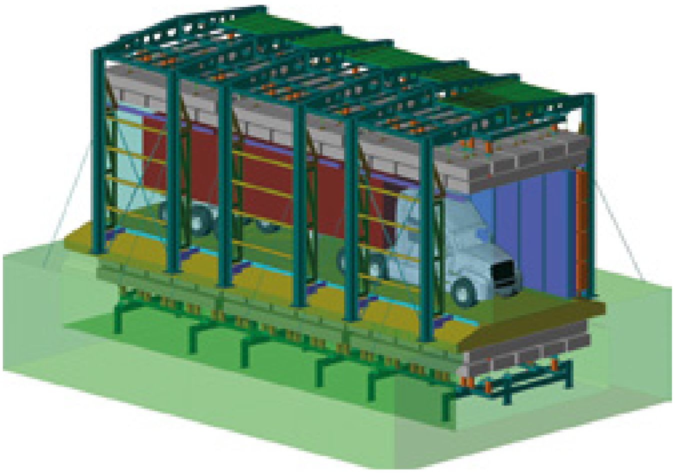


Cosmic muons were used to study the FMT-2 reactor core after the Fukushima nuclear power plant was damaged. Muon-imaging has high sensitivity for detecting uranium fuel and debris even through thick concrete walls and a reactor pressure vessel. **[Credit Haruo Miyadera *et al., AIP Advances*, 3, 052133 (2013)].**

MUON SCATTERING TOMOGRAPHY

Muon radiography, by which muons are simply absorbed by an object depending on its density and thickness, has recently been extended to a more high-resolution imaging method that relies on detecting the muons that are scattered multiple times within a given volume. Muon trackers are located in positions before and after they have passed through the volume under study, and their trajectories are reconstructed. Muons are deflected most by dense materials containing elements with a high atomic number such as uranium or iron, so the technology is suitable for use as nuclear cargo scanners, and inspecting spent nuclear fuel deposits and the inner structure of blast furnaces.



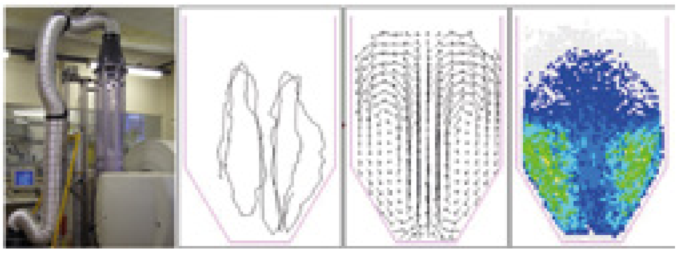


A muon scanner to detect radioactive materials in scrap metal containers. **[Credit The Mu-steel EU project].**

POSITRON EMISSION TOMOGRAPHY (PET)

Once exclusively used in medicine as an imaging technique (see Chapter 6), PET is increasingly being taken up by industry to obtain three-dimensional images of the flow and distribution of fluids inside process units – even those with steel walls several centimetres thick. Similarly, the spread of lubricant in engines can be followed. In the chemical industry, the changes in a water-based, detergent-bearing phase in a water-in-oil emulsion, labelled say with gallium-66, can be followed during processing.

A particular variant of PET called positron emission particle tracking (PEPT) involves tracking and mapping the movement of a single radio-labelled particle. The technique is suitable for studying high-speed flows in granular material (by labelling and tracking a single grain) or viscous fluid flow (using a buoyant tracer particle).

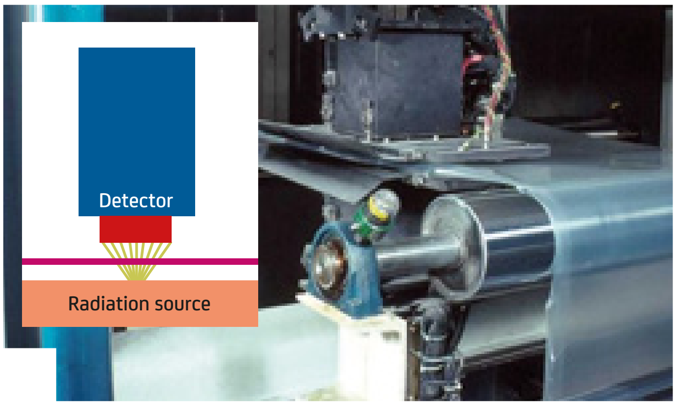


Particle motion in a fluidised bed followed by PEPT. **[Credit Positron Imaging Centre, University of Birmingham].**

MEASURING SYSTEMS USING RADIOACTIVE SOURCES

In addition to radiography, manufacturing and heavy industries usually need to take ongoing detailed measurements during processing to ensure the quality of its products and to optimise processes, while saving time and energy. Measuring instruments incorporating radiation sources are ideal as control devices where direct contact with the product is not possible, for example, if the process involves extreme heat and pressure, or corrosive materials such as molten glass and metal. Because they acquire data quickly, such gauges are also suitable for monitoring high-speed processes. They are usually fixed in position, require little maintenance, and often pay for themselves within a few months of installation due to savings in inspection times. It is not surprising that several hundred thousand of such systems are operating in industry worldwide.

The gauge system may operate either by detecting the intensity of radiation transmitted through a material or that scattered back towards the radiation source. In this way, the density or thickness can be measured. A gauge based on beta radiation from krypton-85 can continuously monitor the thickness of plastic films and paper sheets produced – in some cases, at speeds of up to 400 metres per second! The back-scattering method is particularly effective when monitoring the thickness of coatings. Automated density gauges are similarly employed to check the correct mixing in the manufacture of detergent powders and liquids. Gauges can also be used measure levels. For example, in the coal industry, the coal fill level in a hopper can be checked by placing gamma sources at various heights on one side of the container and detecting the radiation passing through to the other. Gauges may also be portable for applications in construction and civil engineering – for instance to determine the degree of soil compaction on agricultural land, or the density of an asphalt mix to be applied to a road surface.



A beta-emitter krypton-85 used in the paper or plastics industry for the quality control of thickness. **[Credit IAEA].**

The backscattering approach is also applied in gauges employing a portable neutron source. This consists of a combination of an alpha emitter, americium-241, and an element of low atomic number, beryllium-9 (in pellet form in a sealed and shielded container). The light isotope absorbs the alpha particles, which results in the release of copious amounts of fast-moving neutrons. These can travel hundreds of metres before being slowed down and reflected back by bulk materials containing high amounts of hydrogen, such as organic materials or water (neutrons interact strongly with hydrogen nuclei). The neutron energy lost depends on the hydrogen content of the material and its density, and so a neutron detector can be calibrated to measure moisture in, for example, foods during processing.

Freshly laid asphalt being measured with a density gauge based on a gamma-emitting isotope like caesium-137.

Radioactive isotopes are commonly used to measure wear and corrosion in materials such as ceramics and metals. The principle is to introduce them directly into the test material by irradiating it with neutrons or lightweight charged particles so as to create radioactive species in the surface layers. The loss of material due to wear is determined by measuring the decrease in radioactivity after a given time of use. A better method is to implant radioisotopes, by irradiating the material via a beam of radioactive ions (see page 96), for example, of beryllium-7, which has a half-life of 52 days. Such radioactive tracers are applicable for wear diagnostics of machine parts. The accompanying increase in the radioactivity of the lubricant used provides a complementary reading.

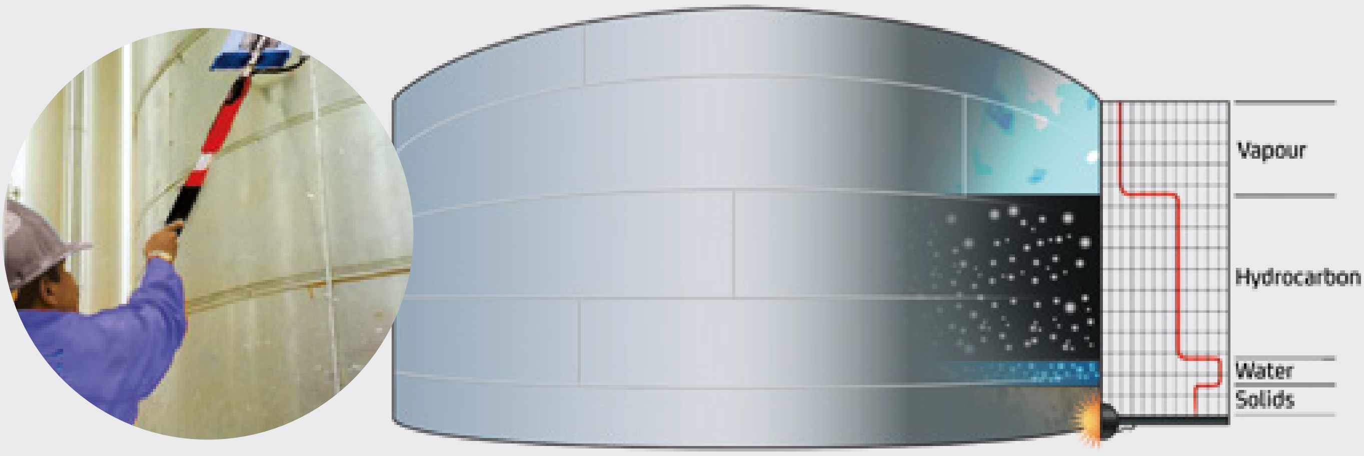
MATERIALS ANALYSIS

In addition to the nuclear screening and testing of materials and commercial goods, analytical methods based on nuclear physics are vital in the development of new materials, some key to combatting climate change. These include photovoltaic materials for solar power, catalysts for 'green' chemical manufacture, more efficient car batteries, improved recyclable plastics, and the next generation of ever-smaller electronic devices. Therefore, the materials-science research community relies on a large variety of techniques to control and optimise their processing steps.

Neutrons are particularly useful in determining the composition as well as the behaviour of many modern materials at the atomic and molecular level.

NEUTRON GAUGE MEASUREMENT IN OIL STORAGE TANKS TO EVALUATE SLUDGE-WATER-OIL-GAS INTERFACES

Neutron backscattering has been widely utilised for more than 40 years to measure the amounts of sludge, water and oil in the large tanks storing bulk hydrocarbon feedstocks. The tank contents separate out into phases of differing densities, and a neutron-based level gauge can detect the interfaces between them to an accuracy of a few centimetres. The technique works by remotely sweeping the outside of the vessel, which can be almost any diameter. It is applicable to any process feedstock – whether toxic, corrosive, or viscous, and at any temperature or pressure – without affecting the relevant process. It is reliable and accurate enough to measure foam levels, and to calibrate installed level-gauges quickly and easily.



Levels and interfaces in feedstocks in storage tanks can be evaluated using a neutron gauge. **[Credit Scantech Nuscan].**

NEUTRON ACTIVATION ANALYSIS (NAA)

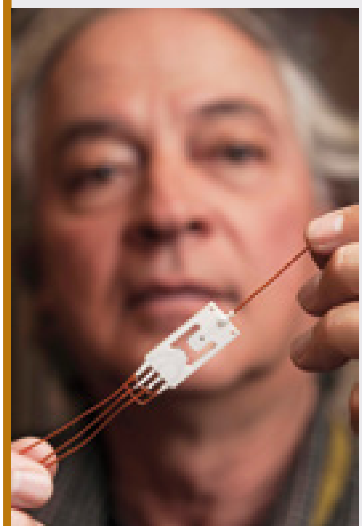
Even only minor traces of many elements can be detected and analysed in a sample by irradiating it with a neutrons. In NAA, a neutron interacts with a target nucleus, leading to a compound nucleus and prompt (immediate) emission of radiation such as a gamma-ray or alpha radiation. The new radioactive nucleus that has formed then decays, with the emission of a delayed gamma-ray and other particles. The prompt and delayed radiation can both be used to identify the target nucleus and quantify how much of each element is present in a sample – with a sensitivity down to one part per billion in favourable cases. Because neutrons penetrate deeply in most samples, NAA is a true bulk technique, capable of measuring samples that weigh from a few microgrammes up to tens of kilogrammes. It thus finds use in many fields including medicine and geology.

Because NAA is rather sensitive, it can be taken out of the laboratory and into the field to analyse the elemental composition of a wide range of materials including useful ores. Californium-252 (half-life 2.6 years) provides a powerful portable neutron source.

NOVEL NEUTRON GENERATORS – FUSION ON A CHIP

While radioactive isotopes such as californium-252 provide portable sources of neutrons, there is another approach using nuclear fusion. A small ion accelerator assembly can be placed in a sealed tube, which enables isotopes of hydrogen to fuse to release neutrons. The neutron flux is higher than from a fissile isotope, and such devices can be employed in many of the applications mentioned in this Report; however, they are expensive.

Sandia National Laboratories in the US is one of the companies which has developed a novel design that could be game-changer. It places a mini-accelerator on a chip, and relies just on (stable) deuterium fusion to generate neutrons. Deuterium ions are accelerated under a voltage and they bombard a target containing deuterium in the form of metal hydrides. This approach would be safer (can be easily switched off) and less wasteful of materials. The technology has the potential to be miniaturised to the same scale as modern electronic devices, so the applications in everyday life could be extensive.



Sandia's 'neutristor', which exploits deuterium fusion to generate neutrons. [Credit Sandia National Laboratories].

NEUTRON SCATTERING

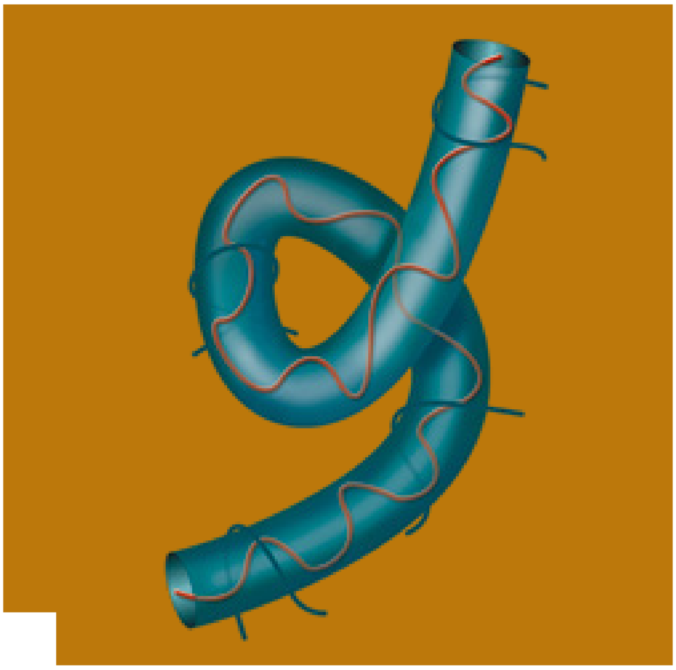
As explained in Chapter 6, beams of neutrons created via nuclear reactions are essential analytical tools in elucidating structure and behaviour at the microscopic level. The neutron diffraction technique, which probes interference patterns created when a neutron beam passes through a crystalline material (a regular array of atoms or molecules), can provide measurements of the distances between atoms in the crystal lattice. This allows any strains or stresses in mechanical components, for example, of a car engine to be mapped. Machining, heat treatment or welding can introduce residual tensile stresses which may lead to cracks, while compressive stresses introduced by hammering can produce beneficial hardening of a material's surface.

Measuring residual stress in welds in an aircraft wing rib using neutron diffraction which acts as a strain gauge. [Credit STFC ISIS Neutron and Muon Source/ENGIN-X].

Increasingly advanced materials have complex structures at the nano-level, often fabricated as thin films and coatings or as multilayers. The behaviour of surfaces and interfaces between layers can be studied using a form of diffraction in which a neutron beam is reflected from a two-dimensional boundary layer.

A unique property of neutrons used as probes is that they have a spin, or a magnetic moment. This means that they are ideal for studying novel magnetic materials that have the potential to provide the next generation of electronic devices, for example magnetic memories and storage. A special instrument is sometimes used to polarise the neutrons, that is, to align all their spins, before they pass through a sample, and then the changes in alignment are measured afterwards.

Neutrons are particularly sensitive to hydrogen, and so one of the most important neutron applications is in the study, at the nano-level, of complex molecular assemblies composed of carbon and hydrogen. These materials are referred to as 'soft matter', and include many household items such as detergents, cosmetic creams and lotions, plastics, car-tyre rubber, paints and foods. Many of these products contain polymers, and it is the dynamic behaviour of these long-chain carbon molecules that is significant to their physical behaviour, especially during processing – the tangled chains wriggle about. This can be studied using a remarkable technique called neutron spin echo, which can follow slow molecular motions in detail. In this technique, a magnetic field first polarises the incident neutron beam, so that the spins align and precess like a wobbling spinning top. After passing through the sample, a second magnetic field winds the spins back to their original orientations. If some of the neutrons have lost or gained energy by interacting with the motions of sample molecules, they will not all end up with the same spin polarisation. Measuring the changes in polarisation thus provides a way of measuring the tiny energy changes associated with slow movements of a polymer chain.



Neutron studies show that polymer chains in a polymer melt move in a snake-like way. **[Credit Institut Laue-Langevin].**

SPECTROSCOPY

NUCLEAR MAGNETIC RESONANCE (NMR) SPECTROSCOPY

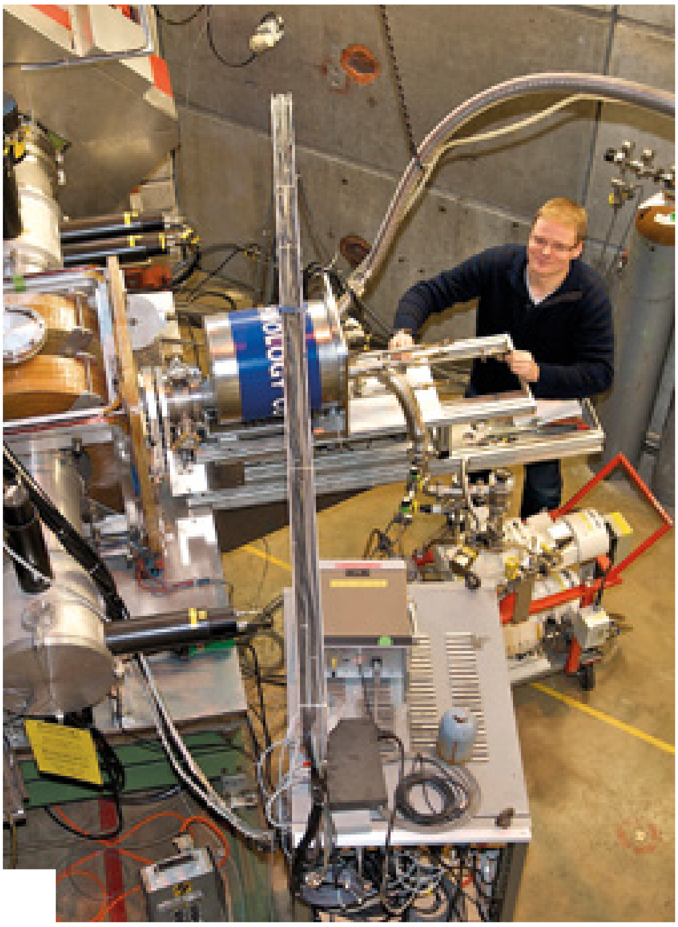
The development and characterisation of advanced materials benefit from several spectroscopic techniques derived from nuclear physics. The best known technique is nuclear magnetic resonance (NMR), which, as described in Chapter 6, exploits the signature response of the spin of a nucleus – usually hydrogen - in its particular local chemical environment in the presence of radio-frequency and magnetic fields. The NMR spectrum of a particular compound reveals the bonding involving hydrogen including the direction of individual bonds, and is most useful in determining the chemical structure of synthesised organic compounds in solution. However, NMR can also be applied to solid materials such as minerals using other nuclei with a quantum spin, for example lithium-7 (used in battery research), carbon-13 (used in the coal and oil industries), and aluminium-27 plus silicon-29 (used in the development of environmentally friendly aluminosilicate catalysts for oil-processing).

MUON SPIN RESONANCE (μSR) SPECTROSCOPY

Exotic particle beams are also used in spectroscopy. As well as being generated from cosmic rays by nuclear reactions in the atmosphere, muons are also made in the laboratory (by firing a proton beam at a low-mass target, see page 84) to be used as analytical probes. The muons are positively charged and exit from the target perfectly spin-polarised. When implanted in a material, detected changes in the spin behaviour due to the immediate atomic or molecular environment provide chemical and physical information about the material – in much the same way as in the NMR technique. The muon lasts only a short time before decaying into a positron which preferentially emerges in the direction of the muon spin. Any changes in spin are extremely sensitive to local magnetic fields in a material, so are well suited to studies of new magnetic and superconducting materials. The positive muon can also be thought as a very light proton, since when implanted in a material it can bind with an electron to form 'muonium', a lightweight analogue of the hydrogen atom. The muonium atoms that form act as a probe to study the behaviour of hydrogen impurities in semiconductors (used in computer chips), in hydrogen-storage materials and in chemical reactions.

SOME MATERIALS AND PRODUCTS STUDIED WITH NEUTRON SCATTERING

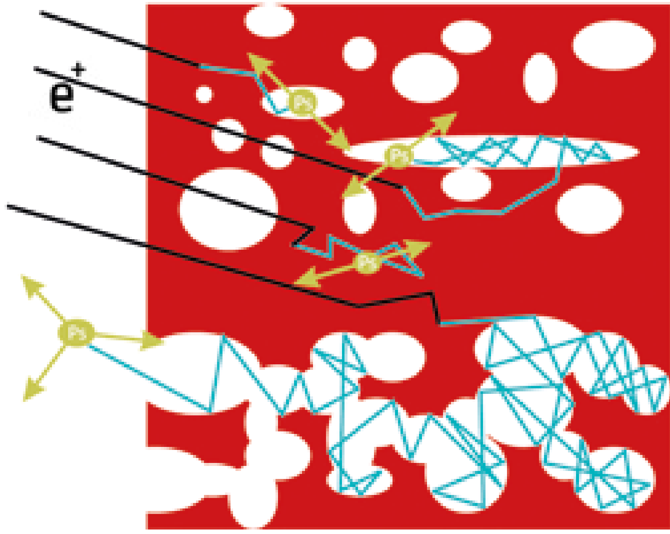
Engineering:	the behaviour of mechanical components, railway-track welds, and new ceramic alloys for aerospace
Electronics:	materials for advanced magnetic and electronic transistors, memories and sensors, quantum computer development
Green energy:	superconducting materials for resistance-free power transmission, hydrogen-fuel storage, solar cells, batteries and fuel-cell technology
Green chemical manufacturing:	advanced catalysts and other complex materials
Soft materials:	rubbers, plastics, complex fluids and gels used in cosmetics, foods and cleaning products
Nanotechnology:	nanoparticles, micelles and ultra-thin multilayers found in high-performance materials, or for drug delivery



The muon source at the Paul Scherrer Institut in Switzerland used in experiments to study advanced materials. **[Credit Paul Scherrer Institut/ Markus Fischer].**

POSITRON ANNIHILATION LIFETIME SPECTROSCOPY (PALS)

As described above for PET imaging (see Chapter 6), positrons annihilate with electrons in a sample with the emission of two gamma-rays, which fly off in opposite directions and can be picked up by detectors. This annihilation can also reveal micro-structural information about materials. Using positron-emitting neon-22, which is an inert gas, the time taken to annihilate can reveal tiny atomic irregularities in a material – voids, pores and defects. This is because these sites will contain fewer electrons for the positrons to annihilate with, so the positrons last longer and the gamma emission is delayed in these locations.



Positrons last longer in the form of positronium in tiny pores or defects in materials, so reveal their location and nature.

Positrons also behave differently in metals and insulators. Metals have high densities of electrons (that is what makes them conducting) so the positron lifetimes are very short, measured in picoseconds. In insulators, the electrons are mostly tightly bound in atoms and less accessible to a positron. Instead, the positron may form a new kind of atom with the electron (like the muon mentioned above) called positronium. This may have a mean lifetime measured in nanoseconds. PALS is an important technique for studying advanced materials – from semiconductors, which often contain crystalline defects, to porous solids like aluminosilicate zeolites used as catalysts and for water desalination. Using slow positron beams that penetrate to a given depth also allow thin films and layers in advanced material to be profiled.

CONCLUSION

This chapter has revealed the huge extent to which radiation and particles generated in nuclear processes are employed in many manufacturing and production sectors that deliver the items and standards of living we expect. Nuclear physics also helps in ensuring that products and services are delivered safely and efficiently while enhancing environmental protection. Industry and academia also employ highly-sophisticated nuclear techniques to develop the next generation of advanced materials, products and devices for everyday use.

FURTHER INFORMATION

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CHAPTER 8:

FORENSICS AND HERITAGE

What do art forgeries and fake designer goods have in common? Apart from being criminal activities, they can be identified or traced through nuclear analytical techniques. **[Credit English Heritage].**

DETECTIVE WORK OF THE SCIENTIFIC KIND IS ESSENTIAL IN CATCHING WRONGDOERS, WHETHER INVOLVED IN VIOLENCE, OR CRIMINAL ACTIVITIES SUCH AS THEFT, FORGERY AND THE ILLEGAL DRUG TRADE. SCIENTIFIC ANALYSIS IS ALSO A KEY COMPONENT IN UNCOVERING PAST CULTURES, IN PARTICULAR THE ORIGIN AND NATURE OF ANCIENT ART AND ARCHAEOLOGICAL OBJECTS. ANALYTICAL METHODS WHOSE BASIS AND OPERATION DEPEND ON NUCLEAR PROCESSES PLAY A SIGNIFICANT ROLE IN BOTH FORENSIC SCIENCE AND IN CULTURAL HERITAGE STUDIES.

What comes to mind when forensic science is mentioned? You may have seen TV series or movies where crime-scene investigators reveal fingerprints, collect blood samples for DNA analysis, bullets and broken glass fragments of evidence – and in the end, the detectives unfailingly send the criminals to jail... In fact, forensic science is much more than that: it is the application of scientific principles and techniques to matters of criminal, as well as civil and regulatory law. For instance, determining whether a signature or a stamp was put to paper, before or after some other text has been placed, may be crucial in investigating forged commercial or private documents such as contracts or wills. Counterfeit medicine and foodstuffs have a huge economic impact worldwide – not to mention the potentially negative effects on people's health. And even though an activity like supplying counterfeit animal feed may be a simple regulatory offence in many countries, it is, nevertheless, a crime, and may have huge negative effects on an economy, on animal health, and indirectly on human health.

And what about cultural heritage? When you go to a museum to view and appreciate precious objects from our collective past – from prehistorical artefacts to contemporary art – have you wondered whether the objects are what they seem to be? Paintings by the most famous artists fetch astronomical prices, and this inevitably attracts forgers. Many fakes have found their way into museums and private collections, and it is quite common that, once identified as such, they are removed from public view. But perhaps, the most fascinating aspect of cultural heritage is in establishing where an ancient artefact came from, where its component materials originated and how the object was made. Such information tells us a great deal about past civilisations.

As previous chapters have described, nuclear science offers a set of powerful analytical techniques based on nuclear reactions, and many of these are applicable to both forensic science and cultural heritage studies. The main goal is identification: in forensic science, the key questions could be: "is this metal fragment from a bullet made by a specific manufacturer? And was it shot from one particular gun?" In the area of cultural heritage, they could be: "Is this statue from the Renaissance period? And is it by Michelangelo, or by one of his many students?" These are the kind of questions that nuclear science can help to answer.

Cultural heritage has one further dimension: using high-energy radiation in the preservation and conservation of artefacts for future generations. As explained in Chapter 7, it can have a profound effect on the biological or chemical properties of materials. This effect can be used to disinfest ancient artefacts and help restore them. Unlike chemical or other physical methods, such radiation does not leave any trace on these objects.

IDENTIFICATION: CLASSIFICATION AND INDIVIDUALISATION

The French criminologist Edmond Locard formulated the basic principle of forensic science: "Every contact leaves a trace." Criminals leave traces of their passage at the crime scene, often from their body or clothes. Forensic scientists employ a range of highly sophisticated analytical techniques to identify these traces.

The word 'identification' involves two steps in forensic science. The first is 'classification', which is assigning some trace evidence to a given class – for instance, that a metal particle comes from a bullet. The second is 'individualisation', which is to distinguish one object or trace from all objects or traces considered – for instance, that the metal particle comes from one specific gun or specific gun manufacturer. The ultimate aim of all forensic science is to establish individuality, or to approach to it as closely as the present state of the science allows. Criminology is the science of individualisation.

A similar approach is often used in cultural heritage to verify the authenticity of a given object or to establish connections between objects. For instance, it may be possible to trace back ceramics found at one historical site to a site where the pottery was fabricated hundreds or thousands of kilometres away, thus uncovering trade patterns and relationships between cultures that are far away from each other. Nuclear analytical techniques, however, can be utilised to find out other information: for instance, neutron imaging can, in a non-destructive way, help reveal ancient technologies that were employed to create historical artefacts.

PRESERVATION, CONSERVATION, RESTORATION

Ancient artefacts form an important part of a country's cultural heritage, and preserving them can pose a serious challenge since many factors can adversely affect their condition, including natural weathering of archaeological sites, improper storage conditions, climate change or local adversities such as flooding. All these may lead to the deterioration or even total loss of an object or site of historical importance.

Irradiation techniques (see Chapter 7) have been used for many years to preserve a variety of cultural heritage artefacts. Several national and international research programmes have been set up to develop harmonised methodologies for radiation treatment, which in turn has led to the acceptance of this conservation approach.

NUCLEAR ANALYTICAL TECHNIQUES

The forensic techniques we hear about most are fingerprint collection and analysis, the use of the chemiluminescent compound luminol to detect blood, DNA analysis and ballistics. In cultural heritage, analysis of artistic style and technique, together with visual examination using infrared, ultraviolet, radiography, and even examination with an optical microscope, are the most common methods to identify objects, as well as the techniques of analytical chemistry to identify materials such as paints.

However, in both forensic science and cultural heritage studies, nuclear analytical techniques also contribute significantly to discovering "who did it?" – whether it is a criminal, a master potter, or a modern-day painter. They rely on nuclear processes to obtain information on the composition and structure of samples, sometimes in 2D and even 3D. The techniques are extremely powerful, often non-destructive, and in many cases usually require only minuscule samples of material from often unique or precious objects.

Today, a wide range of nuclear techniques is available, many of them explained in previous chapters. They all rely on radiation (consisting of beams of subatomic or nuclear particles, or high-energy electromagnetic radiation generated by nuclear processes) to probe samples. The interactions within the sample may also involve some kind of nuclear reaction, leading to a characteristic effect that can be detected and measured. In this way, specific elements and their position in a sample can be identified and thus the composition of a sample or object evaluated. The data obtained can then indicate their geographical and cultural provenance or commercial source, method of manufacture as well as age.

ION-BEAM BASED TECHNIQUES

Ion beam analysis (IBA) refers to a group of techniques which exploits beams of ions. They are used in biomedical studies, materials science and the development of various devices, as well as in forensic work. However, it is in heritage studies where IBA comes to the fore. In all the IBA methods, the ions are first generated in an ion source and then accelerated to energies that are high enough to cause an interaction with the atoms of a sample such that it provides a signature characteristic of the sample. This can then be used to identify and measure the concentrations and distribution of the constituent elements present. Ions typically employed include those of hydrogen (protons), helium, oxygen and nitrogen, although heavier ions are also utilised.

In the basement of the Louvre in Paris is a new accelerator, New AGLAÉ, devoted to the study of heritage objects using IBA methods, such as this bronze statuette from the Bavay ancient forum in France. **[Credit Christophe Hargoues/C2RMF/CNRS Photothèque].**

IBA can identify all elements, in concentrations typically between one part per thousand and one part per million, and sometimes even lower concentrations can be detected. Because the regular positioning of atoms can be pinpointed by some techniques, the crystalline structure of materials can also be determined.

When the ion beam interacts with the atoms and nuclei in samples, it provides information about composition, starting from the first layers of atoms and going into deeper layers as they pass into the sample. The beam may be focused into a narrow spot, around 1 micrometre across (called a microbeam), and scanned over the sample. This maps the element concentration in 2D. Special techniques can also provide 3D concentration maps. Some methods can probe to a depth of a fraction of a millimetre so providing depth information – that is, they can distinguish between different layers in a material. This is often an advantage, because many materials are layered – for instance, vehicle window glass, which may offer trace evidence in scenarios involving car accidents, are complex multi-layered materials. The same is true for the layers of paint in paintings, and for the surface layers of artefacts that have suffered centuries of exposure to air.

IBA techniques thus provide a powerful analytical arsenal in the fields of art and archaeology, but they have been less used in forensic work. Examples can be cited however, such as the analysis of gunshot residue, explosives, ink and fingerprints, and interest in the application of IBA to forensic science has been steadily growing in the 21st century as a result of advances in the various techniques.

THE MAIN IBA TECHNIQUES INCLUDE THE FOLLOWING:

RUTHERFORD BACKSCATTERING SPECTROSCOPY (RBS)

In this technique, the incident ions hit the nuclei of the target sample material and are 'backscattered'. The back-scattered ions are then detected and their energies – which depend on the type of the scattering nuclei and how deep they are in the sample – are measured. The data collected then provide the information to identify the element responsible for the backscattering and in which layer it is.

PARTICLE-INDUCED X-RAY ANALYSIS (PIXE)

In this method, the ion beam leads to the emission of X-rays from the sample, which are detected. These have an energy that is characteristic of the sample atoms. PIXE is used to detect heavier elements.

PARTICLE-INDUCED GAMMA-RAY ANALYSIS (PIGE)

In this case, the beam interacts directly with the target nuclei, either losing energy to the nuclei when scattered off them or causing a nuclear reaction. In either case, gamma rays are emitted from the excited nuclei. It is ideal for identifying specific isotopes of lighter elements.

NUCLEAR REACTION ANALYSIS (NRA)

NRA is particularly useful for detecting light elements which are not easily analysed by RBS and PIXE. Low-mass ions such as hydrogen or helium nuclei are fired at a thin-film sample to induce nuclear reactions. The particles or gamma radiation emitted identify the concentrations of elements in the sample.

CERN and the Italian National Institute for Nuclear Physics (INFN) are developing a new transportable accelerator, MACHINA, to be used to analyse works of art like the one here at the laboratories of the Opificio delle Pietre Dure in Florence. It will also be used for radiotherapy (see Chapter 6).
[Credits] INFN and CERN

ELASTIC RECOIL DETECTION ANALYSIS (ERDA)

This technique involves analysing the forward-travelling particles emitted from a sample (as opposed to the backscattered ones as in RBS).

ACCELERATOR MASS SPECTROMETRY (AMS)

Accelerator mass spectrometry is another important accelerator-based analytical technique. It is explained in detail in Chapter 4 on climate and the environment. The technique is, indeed, employed – both as a research tool and commercially – in diverse fields, particularly where dating is important or where the detection of small amounts of isotopes is useful. AMS finds use in in many aspects of astrophysics research (Chapter 3), in studies of geological formations and historical climate change (Chapter 4), in nuclear reactor accidents and radioactive contamination assessments (Chapter 5), in medical research and drug development (Chapter 6), and in studies of fuels and foodstuffs (Chapter 7).

Mass spectrometry is itself a standard analytical technique in which beams of ions generated from a sample are separated using magnetic and electric fields according to their mass and electric charge. In AMS, the ions are accelerated to high energies, separated and detected using nuclear physics methods such that the different isotopes of an element can be detected.

APPLICATION OF PIXE AND RBS: THE VIDIGUEIRA TREASURE

Left: The pax of the Vidigueira treasure; right: The pax being analysed with a proton beam. 1: X-ray detector; 2: camera; 3: beam exit nozzle; 4: particle detector; 5: lasers **[Credit The Centre for Nuclear Sciences and Technologies, Instituto Superior Técnico, Portugal)].**

André Coutinho was the first Catholic priest ordained in China, having taken his vows in Macau in the late 1570s. After nearly four decades in the Orient, he returned to his country, Portugal, bringing back a set of religious silverware. He willed it to the Carmo Convent in Vidigueira on his death in 1597. With time, the objects of what came to be known as the 'Vidigueira treasure' were scattered, and the trail of many of them could not be followed.

In 1883, the three remaining objects, a missal lectern, a pax and a reliquary, were incorporated into the collections of the Portugese National Academy of Arts and then of the National Museum of Ancient Art. In the 2010s, the Museum asked the scientific community to conduct extensive research on this treasure. The ion-beam accelerator of the Instituto Superior Técnico was used to conduct PIXE and RBS analysis with its external microbeam.

The analysis contributed to knowledge about the influence of European religious orders on Far-East trade routes involving India, China and Japan, and how in turn these influenced European religious art. Various Catholic orders such as the Jesuits and Franciscans, which were established in those countries, used the local established industries and craftspeople for the production of Christian devotional objects. These were circulated within Asia, from one seat of a religious order to another, and also sent to Europe.

In particular, silver is not always silver. Modern-day production methods can control its purity up to 99.9999 per cent. Analysis of the impurities in historical silver can help to establish its identity and provenance. PIXE was used to analyse various sections of the three remaining objects, which led to the identification of components that were not original, since the composition and impurities of the silver were very different. These parts came from previous restorations, which the museum curators had been unable to identify because the original style and appearance had been perfectly reproduced by the restorers of centuries past.

The microbeam was also used in selected areas of the objects, to create 2D concentration maps. These helped to understand the technique used to gild the relics. Portuguese craftsmen of the time used, among other techniques, mercury fire gilding, and the combination of PIXE and RBS analyses carried out on religious objects made in Portugal in the 16th century had revealed the presence of mercury in them. However, mercury was absent in the Vidigueira Treasure, providing evidence of the different technique used in India, namely the application of gold leaf in the crown (in the pax). This identification of the method used in the different pieces to obtain gilded surfaces is of great importance for the conservation work.

One of the most important analytical tools in analysing the history of a carbon-based artefact is radiocarbon dating using an AMS setup. As explained in Chapter 4, radioactive carbon-14 is constantly formed by the interaction of cosmic rays in the atmosphere and becomes incorporated into plants, via photosynthesis, and thus enters the biosphere. When an organism dies, no more carbon is taken up. The amount of carbon-14, relative to the remaining stable carbon-12, starts to decrease over time and so provides a measure of the age of a material derived from an organic source. AMS is now the preferred technique for dating objects from very small amounts of material – a famous example is the determination of the age of the Shroud of Turin.

AMS has been used to solve many outstanding questions about the cultural heritage of humanity. It is also employed in forensics, for instance to uncover forgeries of paintings or other precious objects, to establish the age of ivory (in some countries, only old ivory can be sold), and even to date human remains in murder cases.

AN APPLICATION OF AMS: THE CAPITOLINE SHE-WOLF – A SYMBOL OF ROME

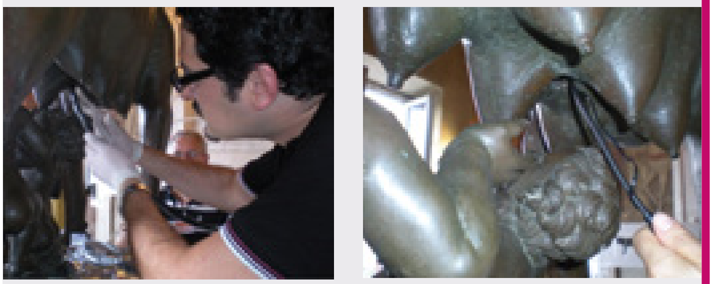
Legend has it that Rome was founded in the 8th century BC by the brothers Romulus and Remus, who after being abandoned at birth were nursed and fed by a she-wolf. The Capitoline She-Wolf is a bronze statue that depicts the wolf suckling the twins, and is perhaps the most important symbol of the city of Rome, the centre of the Roman Empire in ancient times.

It was long believed that the statue of the wolf had been made in the Etruscan era, in the 5th century BC, well before the advent of the Roman Empire. The Romulus and Remus figures were known to have been added in the 15th century. However, during restoration works done recently at the turn of this century, the interior of the statue was observed, revealing details of the casting technique used. Based on this information, Anna Maria Carruba, an experienced conservator of metals, stated in 2006 that the statue had to be of medieval origin, that is, around 15 centuries younger than previously thought: the statue had been cast in one piece, with a technique first deployed in the early Middle Ages.

This discovery represented a radical departure from the traditional belief – and from the knowledge derived from stylistic analysis and years (even centuries) of scholar consensus. The debate that followed was, to say the least, very lively, and led to further scientific analysis of the She-Wolf.

Crucially, the interior of the statue contains many materials that come from the casting process, including clay and organic materials. Some of these materials had been retrieved during the restoration through a hole existing in the bottom side of the statue, and more materials were obtained for the ensuing analyses.

Researchers carried out carbon-dating using AMS at the University of Salento on different organic materials collected from the She-Wolf. The results from 34 samples were all consistent, enabling the statue to be dated to the 11th/12th centuries, in a range from 1020 to 1152 AD. With this, the argument about dating was solved, which allowed the historians and archaeologists to concentrate on other questions: what is the origin of the statue? Is it a reproduction of an older statue mentioned in ancient texts? Who ordered it done and why?



Gianluca Quarta of the University of Salento in Lecce, Italy takes samples from the Capitoline Wolf statue for radiocarbon dating. **[Credit University of Salento]**

ANALYSIS USING NEUTRONS

NEUTRON SCATTERING

Neutrons are excellent analytical probes of materials as described in Chapters 6 and 7. Carefully prepared beams of specific energies can be generated by dedicated nuclear fission reactors or by neutron spallation. They are then deployed to analyse or image structures at the molecular and atomic scale via methods similar to those in X-ray studies.

Neutrons are particularly useful in studying structures containing a lot of hydrogen, for example, biological materials, plastics, and those containing water, because they readily interact with the nuclei of light elements, which are not easily detected by X-rays. Because neutrons are both penetrating and non-destructive, they are ideal for studying items of both forensic and cultural heritage interest. The materials that can be analysed by neutrons are extensive. They include ceramics, textiles and mummified biological materials, and can also detect defects or welding patterns in ancient weapons and armoury by examining their microstructure.

A neutron diffraction technique called small-angle neutron scattering (SANS) is ideal for studying large molecules and nano-particles. Here, an ancient Gallo-Roman barge is being preserved using a solution of nanoparticles whose effectiveness in the treatment has been verified by SANS. **[Credit Institut Laue-Langevin/arc-nucleart.fr].**

NEUTRON RADIOGRAPHY

One neutron technique is particularly useful in cultural heritage studies, and that is neutron imaging (described in Chapter 7). Neutron radiography is complementary to traditional X-ray radiography because neutrons are more sensitive to light elements, which make up many interesting artefacts. They can easily pass through most metals, unlike X-rays. Neutron tomography, in which two-dimensional images are taken as 'slices' through an object, provide particularly detailed information on its composition and fabrication. Neutron radiography thus offers a unique and fascinating method for 'seeing' inside an ancient artefact while leaving it intact – often giving clues about the technology used in its manufacture that could not be obtained in any other way.

NEUTRON ACTIVATION ANALYSIS (NAA)

The neutron technique most used in forensic science has been neutron activation analysis (NAA), described in Chapter 7. This is a non-destructive technique that can identify many elements of forensic interest with high accuracy and at relatively low limits of detection. NAA has been used in hundreds of homicide cases by the FBI to examine bullet fragments and gunshot residues. It is also deployed in many other forensic-science applications such as cases of poisoning, hair analyses, forgeries, explosives, and illicit drugs.

These same capabilities also make NAA invaluable in cultural heritage studies including archaeometry, for the identification of artefacts, the study of trade routes, and even the detection of fake and forged art – an area where art-history studies and forensics join to become 'art forensics'. For example, NAA was used to determine whether the French Emperor Napoleon, or Tycho Brahe the Danish nobleman and astronomer, were poisoned by arsenic and mercury respectively.

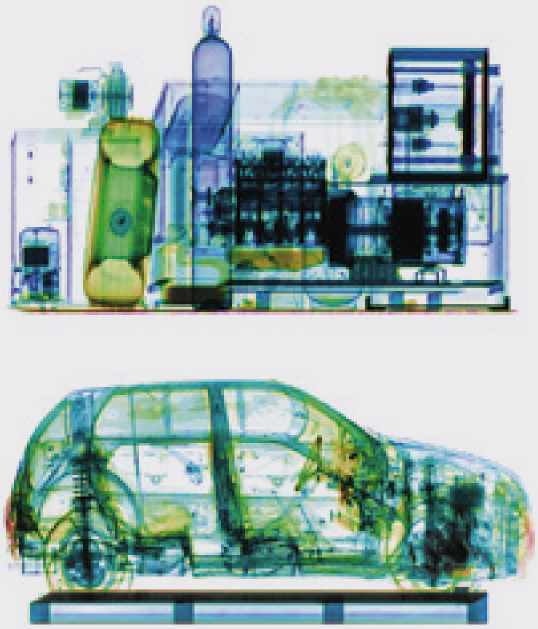
Portable neutron generators using radioactive isotopes, in particular californium-252, which provides an intense source of neutrons, are employed in the field to identify and prevent criminal uses of chemical warfare agents, to scan airline luggage for hidden explosives and to detect land mines.

WHAT'S IN A CARGO? COMBINED LARGE-SCALE NEUTRON AND X-RAY IMAGING CAN TELL

When thinking about international organised crime, illegal drugs, and arms trafficking may come to mind. In fact, the transnational crime with highest estimated annual value is none of these: it is counterfeiting, worth around one trillion US dollars annually. That is one million million dollars, a staggering number – more than 1 per cent of the entire world's GDP, and more than that of most countries, including Switzerland, Thailand, Norway or Argentina. The reason is simple: the profit is immense, and the penalties are much smaller than for getting caught trafficking drugs, people, arms or human organs.

One of the significant components of counterfeiting is the moving of products around the world, and the concept of contraband becomes increasingly important. With the immense volume of legal goods being traded, the inspection of cargo has to be quick, and there is no time to open all the containers to see what is inside. Large-scale industrial X-ray systems have been employed for some decades. A vertical X-ray beam produces a line image, which can be several metres high. An object such as a cargo container or pallet is moved along it, resulting in an image of the entire object, line by line.

The challenge is that air cargo is typically composed of densely packed materials with varying compositions and densities. The X-ray images obtained can be difficult to interpret, and when time is short this may lead to contraband getting through the system. Neutrons, however, are extremely sensitive to hydrogen and other light elements not so easily detected by X-rays, and so it is possible to have the best of both worlds by combining X-rays and neutrons in the same industrial scanner. The resulting images are easier to interpret and can assist customs and other law enforcing agencies worldwide to better control what exactly is being transported.



X-ray and neutron radiography can now be combined in one scanner to search for illicit drugs and explosives in containers and vehicles. **[Credit Brian Sowerby/CSIRO].**

AN APPLICATION OF NAA: THE ASSASSINATION OF JOHN F. KENNEDY

US President John F. Kennedy was murdered on 22 November 1963 when travelling in a car in Dallas, Texas. Lee Harvey Oswald was arrested and charged but was in turn assassinated before he could go to trial.

Fragments of bullets were recovered from the car, from President Kennedy himself, and from Governor John Connally who was also in the car. Different hypotheses emerged regarding the number and origin of the bullets, with suspicions that more than one shooter might have been involved. In 1977, several fragments were analysed with NAA by Vincent Guinn, an analytical chemist at the forefront of forensic evidence in the US. His conclusion was that at least two bullets, but unlikely more than two, were responsible for all fragments found. Crucially, it supported the conclusion that all of the fragments had the same origin, Oswald's rifle.

More recently, in the first decade of the 21st century, the interpretation of Guinn's NAA results was questioned. Analysis of many bullets from by the same manufacturer and period seemed to show lack of homogeneity within bullets. Also, it was claimed that their silver and mercury content, which had been assessed by Guinn, was not sufficient for individualisation. Some technical aspects such as the uncertainties of the 1977 analysis were also questioned. The debate continues, centred on the interpretation of the results more than on the nuclear science itself, which is only one component of this case.

NAA has played an important part in determining how many bullets were involved in Kennedy's assassination.

A RECENT APPLICATION OF NAA: THE CASE OF THE STOLEN BEACH

In a case that made international news, a pristine beach on Jamaica's north Caribbean coast was stolen, allegedly to supply white sand to nearby tourist resorts. An estimated 500 truckloads of beach sand from the Coral Springs Beach, Trelawny in Jamaica were removed within a few days in July of 2008. Believe it or not, this is not an uncommon case, where sand is a precious commodity for the tourism and construction industries.

After several months with no arrests or headway made in the case, the Jamaican Forensic Science Laboratory approached the International Centre for Environmental and Nuclear Sciences (ICENS) to see whether NAA could provide the discriminatory power that other techniques could not. The sample, being sand of which there was plenty available, provided bulk evidence, making it ideal for NAA.

The chain-of-custody protocols included the Director General signing a chain-of-custody form, and also maintaining the security of the samples by making them inaccessible to members of staff, who were not directly involved in the analysis. The data resulting from the analysis of the sand samples by NAA, and evaluated using various statistical operations, were able to discriminate correctly between the donor beach, potential donor beaches, alibi samples and the potential receptor beaches.

Despite this evidence, the case was not pursued in court when the main complainant decided not to give evidence in the matter. This shows that scientific results alone do not solve crimes or win court cases: the interpretation of results within the context of a specific case is essential, and it is only one of many contributions to the investigation and trial. In any case, all these years later, the sand at Coral Spring Beach was replenished and the white sandy beach with crystalline waters was reborn.

Sand stolen from Coral Spring Beach in Jamaica was investigated using neutron activation analysis. **[Credit Jamaica Gleaner].**

OTHER NUCLEAR TECHNIQUES

MUONS

Muons are subatomic particles, similar in nature to electrons but 207 times heavier and with a lifetime of only 2.2 microseconds. Beams of muons are created at research facilities when an accelerated beam of protons hits a light-element target such as carbon. Heavier particles called pions are generated which decay into muons. They can be either positively or negatively charged, and they have the curious property that they can act either as negative electrons in forming so-called muonic atoms, or as positive protons that can replace hydrogen atoms in molecules to form muonium molecules. Both species are employed as analytical tools.

Muons are increasingly being used to study heritage objects at European muon facilities. For example at ISIS in the UK, negative muons are implanted into a sample forming muonic atoms which then emit X-rays characteristic of particular elements. In this way, a detailed three-dimensional map of the sample's chemical composition is built up. The technique has been used to study a variety of metal objects including Roman coins and Japanese swords.

The composition of a gold Roman coin was analysed using negative muons. **[Credit STFC].**

POSITRONS

Positron emission tomography (PET) is a well-established imaging method, as described in Chapter 6, and is often used to study the brain. More recently, some researchers have suggested that PET brain scans could even provide forensic evidence that links changes in the brain resulting from injury or a tumour to criminal behaviour in a defendant.

ISOTOPE ANALYSIS

Carbon dating is not the only isotope-based method used to uncover the age of artefacts, their origin and, in doing so, uncover fakes. Various radioisotope 'parent–daughter' decays are used to measure the ages of materials, particularly those of geological origin (see Chapter 4). One such dating method probes isotope ratios in the decays of uranium-238 to thorium-230, which then decays further to stable lead. The rates at which the isotopes decay reach an equilibrium; however, any changes in this equilibrium due to preferential removal or absorption of one of the isotopes – for example, uranium dissolves in water while thorium does not – will re-start the equilibrium process, and so this change can date when this happened. Because thorium-230 has a half-life of 76,000 years, it can date samples up to half a million years old.

This method has been used date ancient, fossilised bones, which will contain much higher levels of uranium than modern bones, because, due to their porous nature, they will have soaked up uranium dissolved in groundwater. It can also date calcium carbonate that has precipitated from ground water in caves. An intriguing example of uranium–thorium method is the dating of Neanderthal cave art in Spain, which had become covered with a layer of limestone. The research team could date samples of the carbonate from before and after the paintings were done and thus establish the age range for this earliest of art – at 65,000 years ago. That is 20,000 years before modern humans arrived.

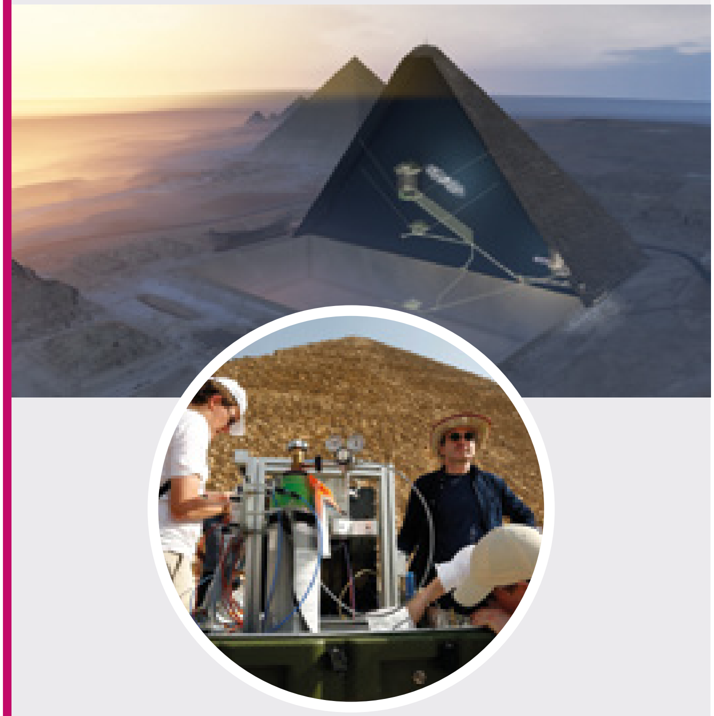
A LOOK INSIDE THE GREAT PYRAMID WITH MUONS

Muon radiography, as described in Chapter 7, is now an established technique for scanning non-invasively the interiors of large constructions that otherwise are not easily accessible. It exploits the showers of muons produced when cosmic rays collide with molecules in the atmosphere. These transient particles, travelling close to the speed of light, traverse through a site or building of interest. They are then detected, and, as with X-rays, used to construct a three-dimensional image.

A fascinating example of muon radiography has been in the study of the Great Pyramid of Cheops at Giza in Egypt. The Great Pyramid was built during the reign of the Pharaoh Cheops 4500 years ago. This massive structure is known to have many internal chambers, including the King's Chamber, the Queen's Chamber and the Grand Gallery, but nobody is sure how it was built.

Recently, an international research collaboration, ScanPyramids, set about learning more, using muon radiography to image the Cheops Pyramid's internal structure. The data were collected over several months using three kinds of detector including compact nuclear emulsion films that detect muons. Three-dimensional analysis revealed a large, previously unknown void, 30 metres across, above the Grand Gallery. It could be there just as part of the construction method employed or it could be another burial chamber.

Muon radiography was first used in 1971 by the physicist Luis Alvarez to investigate the second largest pyramid, that of Cheops' son Chephren, but that was shown to contain only a small chamber, the Belzoni Chamber, and no large void. Ancient mines and tunnels of archaeological interest have also successfully been investigated using muons, by creating a computer simulation of the site and comparing it with the muon data obtained.



A telescope designed to detect cosmic muons passing through the Great Pyramid of Giza identified a previously unknown large void. [Credit ScanPyramids]

The uranium–thorium dating of perforated and pigmented sea shells in a cave in south-east Spain, thought to be once occupied by Neanderthals, reveals them to be around 115,000 to 120,000 years old, long before similar cultural evidence was found relating to modern humans. **[Credit J. Zilhão *et al., SCIENCE ADVANCES,* 2018, 4, 22 Feb; DOI: 10.1126/sciadv.aar5255].**

Another uranium–thorium method can distinguish when ancient gold objects were made and so uncover forgeries, which are difficult to spot from their appearance. In this case, what is measured is the amount of accumulated helium-4 (alpha particles) produced in the decay of small amounts of uranium and thorium in gold. These are released when the gold is melted prior to fabrication, and are measured with a mass spectrometer, along with that of the uranium and thorium.

FISSION TRACK DATING

The natural fission of uranium-238 found in some minerals and glasses etches minute trails of damage and the number of tracks gives a guide to their age. The technique has been combined with PIXE to study archaeological sites and obsidian artefacts in South America. The obsidians could be dated by comparing the natural fission tracks with freshly made tracks in obsidian samples, caused by irradiating the obsidian with neutrons, so as to induce uranium fission and thus new tracks. In this way the ageing of the tracks over time could be evaluated. Fission track dating has also been applied to dating flints found in caves from the Palaeolithic Era.

LEAD AND STRONTIUM ISOTOPE STUDIES

The stable isotopes of both lead and strontium are ubiquitous on Earth. Both metals have four stable isotopes, (lead-204, 206, 207, and 208, and strontium-84, 86, 87 and 88). In the case of lead, only one isotope is primordial (lead-204) while the others are end-products of radioactive decay chains. In the case of strontium, only one has been produced through radioactive decay – strontium-87. The result in that the ratios of these isotopes can vary according to the rocks in which they are found, and so can be used to establish the geographical origin of artefacts containing these elements. Analysing lead isotope ratios via mass spectrometry in lead piping, glass and pigments, for example, can indicate which mine the lead came from.

Both lead and strontium are used to determine the migration and animal herding patterns of Neolithic populations. By excavating human and animal bone or teeth from archaeological sites, researchers can determine whether the population stayed local or had come from elsewhere.

NUCLEAR ANALYSIS

The subtle intrinsic behaviour of nuclei is also exploited in the analysis of materials – their detailed chemical structure, bonding and behaviour. Applications inevitably include studying items of heritage and archaeological interest. Nuclear physicists have developed two such analytical approaches: one based on the nuclear recoil-less emission of gamma-rays, Mössbauer spectroscopy; the other on the precession of its spin, nuclear magnetic resonance (NMR). Both methods are non-invasive and so suitable for studying heritage objects. Both come in portable forms.

MÖSSBAUER SPECTROSCOPY

An atomic nucleus is excited by the absorption of a gamma-ray of a specific energy. It de-excites by re-emitting the gamma ray, which is of slightly lower energy because some of the energy released goes into the recoil of the nucleus (like a fired gun). If the host atoms are part of a crystal structure and held in place, this recoil is reduced considerably because it is taken up by the whole crystal. If the recoil effect is completely removed, the gamma-rays can be reabsorbed and further emitted by another nucleus (nuclear resonance), giving a clear but very fine single absorption signal. This is called the Mössbauer effect. In practice, recoilless, resonant emission is achieved by moving the gamma-emitting source in relation to the absorbing source such that the energy of the gamma-ray is shifted by the Doppler effect (the observed change in wavelength due to the relative movement) to meet the resonance condition. Small energy changes due to interactions between a sample nucleus and its chemical environment will affect the Doppler shift to meet resonance condition, and so provides a very subtle chemical and physical probe – Mössbauer spectroscopy.

The Mössbauer effect shows up in a large number of isotopes but the most prominent one is iron-57, and so is most used as a source to analyse iron-containing materials, for example the raw materials used to make early pottery, and ancient Middle-Eastern documents employing iron-containing inks. Portable Mössbauer spectrometers enable the various coloured iron-oxide pigments found in rock paintings in Brazil to be analysed *in-situ* without destroying them.

Ancient cave paintings in the Chapada Diamantina National Park in Brazil.

NUCLEAR MAGNETIC RESONANCE (NMR)

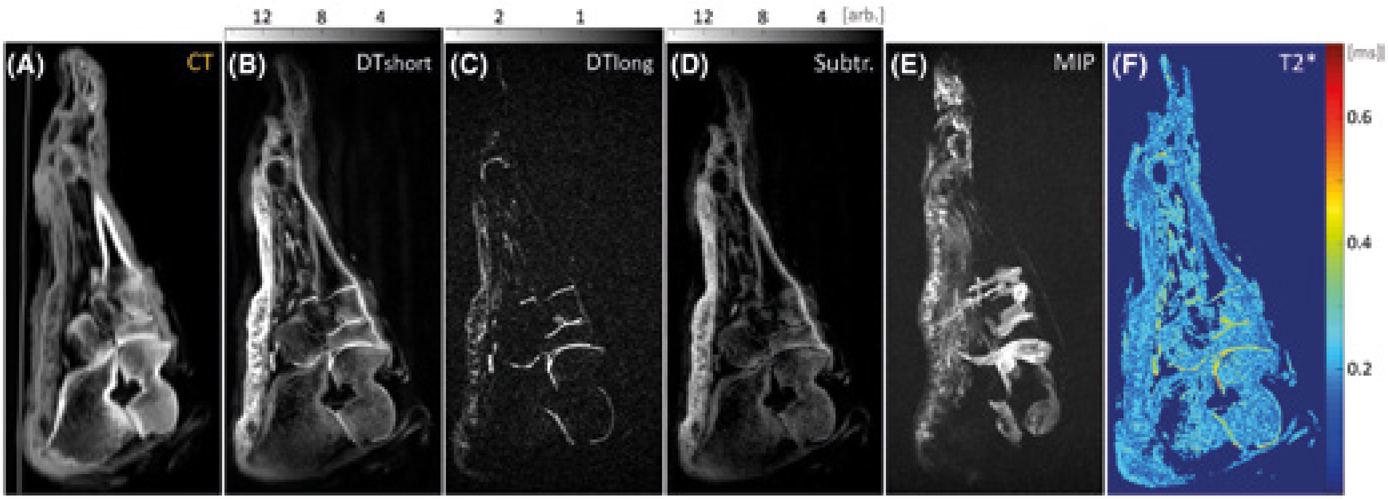
As described in Chapters 6 and 7, NMR is one of the most successful chemical analytical techniques that is based on inherent nuclear behaviour. In the field of cultural heritage, the development of specialised mobile NMR instruments has enabled the technique to be used to investigate a wide range of objects, for example, the moisture content of murals, varnishes and the wood from Stradivarius violins, and the preservation state of Egyptian mummies. As well as being a powerful tool in conservation, it also helps in identifying art forgeries. Magnetic resonance imaging (MRI) has also been used extensively to study mummies and mummified tissues.

OTHER TECHNIQUES

Many of the methods described here are employed in combination with those relying on X-rays. They are emitted when the innermost electrons of atoms are excited so do not directly involve nuclear behaviour. X-rays are used extensively in many research areas, particularly molecular biology and materials science. Many X-ray techniques are employed in a similar way to the neutron techniques above, in particular, diffraction to analyse crystal structure and chemical composition, for example to study pigment layers in paintings.

The production of X-rays increasingly relies on the same kind of technology as that for neutrons and other subatomic particles – that is a high-energy particle accelerator. Europe hosts several international X-ray facilities in which electrons are accelerated in large circular machines, synchrotrons, and are guided and manipulated by complex magnetic systems. As the electrons change direction when travelling down a circular tube, they emit intense X-rays, known as synchrotron radiation over a range of wavelengths. X-rays of selected wavelengths and energies are siphoned off to be used for a huge range of experiments, particularly in molecular biology and materials science, and including those in the fields of archaeology and palaeontology.

All in all, high-energy analytical techniques provide an arsenal of non-invasive methods to study the past as well as crimes of the present.



Advanced high-resolution MRI, combined with CT scanning, has been successfully used to investigate ancient Egyptian mummification processes. **[Credit E. Baadsvik et al., *Magnetic Resonance in Medicine*, 03 October 2020; https://doi.org/10.1002/mrm.28530].**

FURTHER INFORMATION

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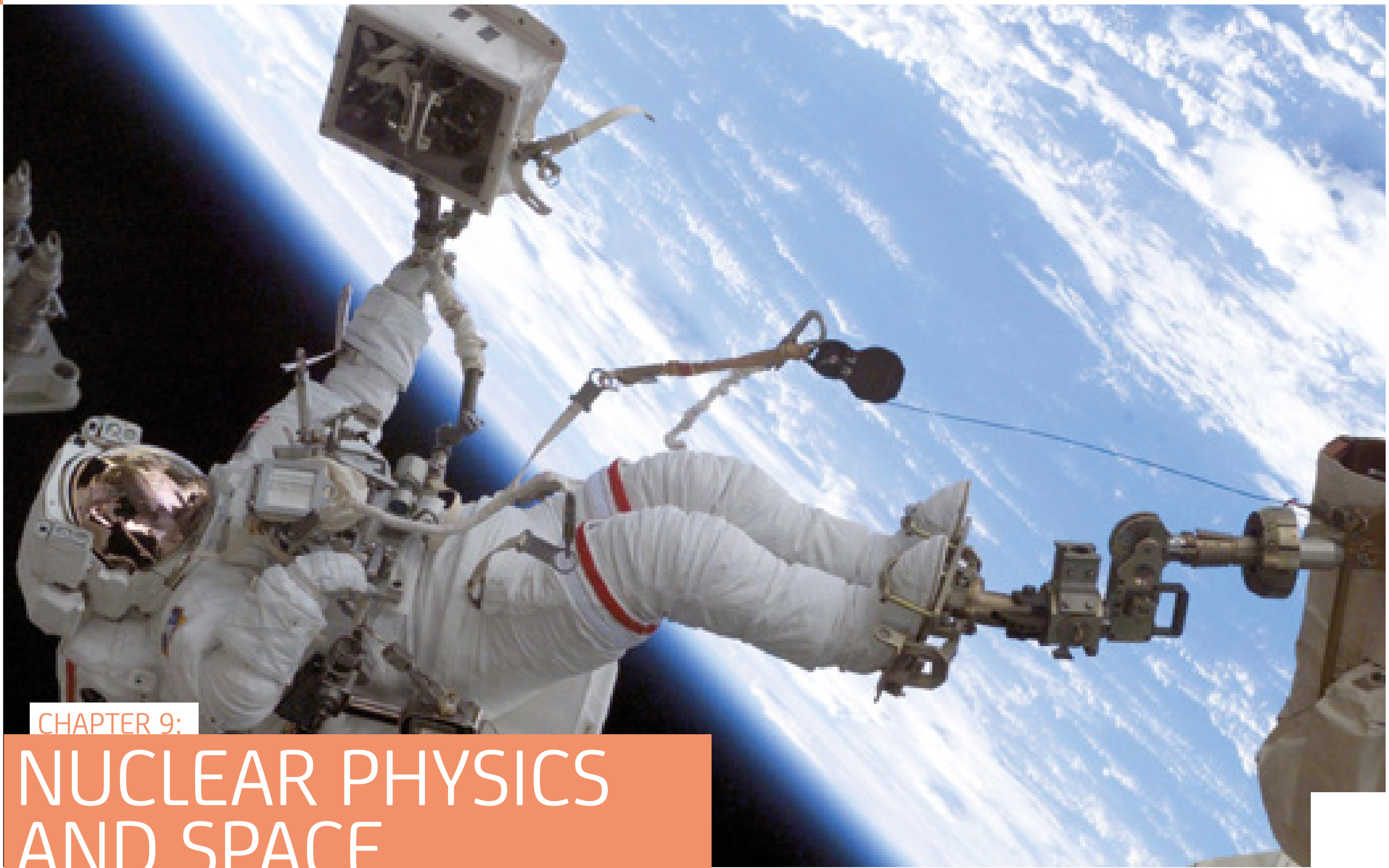


CHAPTER 9:

NUCLEAR PHYSICS AND SPACE

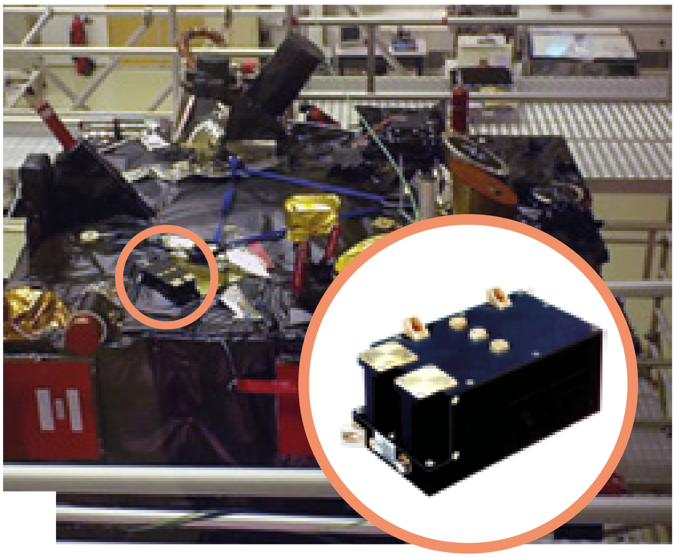
Space radiation can be a serious hazard to astronauts. **[Credit NASA].**

INVESTIGATING NUCLEAR PROCESSES RELEVANT TO THE HARMFUL EFFECTS OF COSMIC RADIATION PLAYS A SIGNIFICANT ROLE IN DEVELOPING THE ROBUST TECHNOLOGY NEEDED FOR SATELLITE-BASED COMMUNICATIONS AND SPACE EXPLORATION. ASTRONAUTS ALSO NEED TO BE PROTECTED FROM HIGH-ENERGY RADIATION, ESPECIALLY IN DEEP SPACE. THE DEVELOPMENT OF ADVANCED SOURCES OF NUCLEAR ENERGY WILL BE ESSENTIAL FOR DEEP-SPACE EXPLORATION AND FOR THE EXCITING PROSPECT OF COLONISING THE MOON AND MARS.

RADIATION HAZARDS OF SPACE

Space beyond our planet is not empty, but teeming with fast-moving, high-energy subatomic particles and electromagnetic radiation including X-rays and gamma-rays. These cosmic rays are released in immensely powerful and catastrophic processes such as supernova explosions and black-hole collisions across our Galaxy, and – most significantly for many space-related human activities – from our nearest star, the Sun. Like all stars, the Sun is a nuclear furnace emitting vast amounts of energy in the form of light and heat that drive life on our planet (see Chapter 4). However, solar nuclear processes also result in the release of a continual stream of energetic electrically charged particles, the solar wind.

The galactic cosmic rays consist of 85 per cent of protons (hydrogen nuclei), 12 per cent alpha particles, approximately 1 per cent of heavier nuclei with atomic numbers up to 92 (uranium) and 2 per cent of electrons. Solar cosmic radiation is composed predominately of protons, with a minor component of about 10 per cent of helium ions, and an even smaller contribution from heavy ions and electrons of about 1 per cent. Atomic nuclei, whether light or heavy, are highly ionising forms of radiation and can damage both biological tissue and sensitive electronic materials such as semiconductors.



The European Space Agency (ESA) has flown a shoebox-sized instrument called the Standard Radiation Environment Monitor (SREM) on several of its missions to monitor galactic cosmic rays (protons and heavy nuclei) from supernovae and other violent events that could cause damage to spacecraft components – as well as living tissue. **[Credit ESA].**

The amount and type of these particles depends on location. In deep space far from the Sun, the flux of galactic cosmic rays is much higher than in near-Earth regions, where, for example, the International Space Station orbits. Nevertheless, space radiation remains a serious hazard for low-orbit satellites. Fortunately for us, the Earth's magnetic field prevents much of the radiation from reaching the ground. However, space radiation – in particular when the Sun is very active (see Box opposite) – can impinge on everyday life – for example, on air travel and telecommunications.

EFFECTS OF SOLAR 'SPACE WEATHER'

The Sun's surface is far from quiet; it occasionally spews out massive amounts of plasma material and radiation, which may reach near-Earth space. These solar storms not only pose a significant health hazard to astronauts, but can also cause considerable damage to orbiting satellites and space missions – whether employed in studying the Universe and planetary exploration, or in communications, GPS and Earth observation. They can even disrupt power supplies and communications at ground level. **[Credit ESA].**

SATELLITES AND TELECOMMUNICATIONS

According to the World Economic Forum, there are currently about 5000 active satellites orbiting the Earth, with about 2200 used for communications (in 2021). This number is set to grow rapidly – at least tripling in the next five years – so it becomes increasingly important to study how space radiation impacts on electronic satellite systems and instruments. Countering the negative effects is a huge challenge in the design of spacecraft and satellites, both for civil and military applications.

Networks of satellites covering the globe are essential components of modern telecommunications. The new Spacebus Neo was launched in 2020 to improve broadband services in Europe and Africa. **[Credit Thales Alenia Space].**

RADIATION EFFECTS ON ELECTRONIC DEVICES

A single, high-energy charged particle such as a proton passing through an electronic device can cause serious damage to the constituent semiconductor materials. It can release avalanches of electrons, resulting in electronic noise and voltage spikes that destroy the signal. 'Single-event upsets' can be triggered by ionising particles generated in nuclear interactions with cosmic radiation, or in the decay of residual radioactive material in integrated circuit packages. The trend towards the miniaturisation of electronic and optoelectronic devices has made standard commercial integrated circuits ever more susceptible to such incidents.

The French space agency, Centre National d'Études Spatiales, reports observing, in a fleet of 16 low-earth-orbit satellites, one minor radiation-induced anomaly a week, and one major one every month. This accounts for 90 per cent of all operation problems.

EFFECTS OF COSMIC RADIATION ON OUR LIVES

It is not just in space where cosmic radiation can have a deleterious effect. It may be significant in the critical operation of the growing range of increasingly elaborate and ever smaller electronic systems found in, for example, mobile phones, vehicle-control systems and medical devices such as pacemakers. Years ago, cosmic radiation was not considered an issue for the safe operation of the then simpler versions of these devices. Today, however, not only do we want more advanced technology but we also expect it to have higher levels of reliability and safety – particularly significant in, for instance, self-drive cars. The automotive industry is embedding ever more complex electronic devices to control wheel direction or braking, for example. The aerospace sector also employs automated avionic control systems.

The reliability of electronics is also significant for activities in ground-based high-radiation environments such as nuclear reactors and particle accelerators, and many safety-critical everyday-life applications. Indeed, in the short and medium term, the evaluation of radiation effects will become as important as thermal or mechanical constraints. It has been a must for the space industry for many years, and is now being considered by the aviation industry. Tomorrow, it will be required by the automotive industry, the medical device industry and other manufacturing sectors where reliability is of the essence.

Examples of how issues of radiation reliability are addressed are:

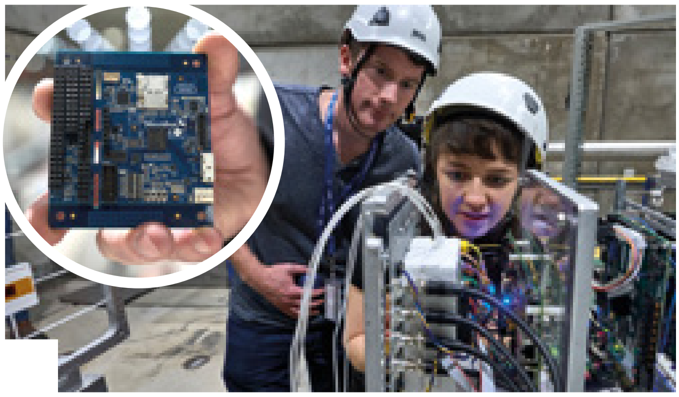
- For satellite and avionic control systems, more than 30 per cent of the computational power available is applied to ensure fault tolerance; a specific challenge (for example, for Airbus) is to avoid increasing this percentage further as more integrated and complex (and possibly more radiation-sensitive) electronic components are used in avionic equipment
- For the most critical functionalities, safety is ensured by employing a high level of redundancy (based on dissimilar hardware and software). This will clearly not be possible for cars, whose ever more sophisticated operation is likely to be affected by radiation (for example, in smart power applications).

RADIATION HARDENING

The most valuable way of protecting electronic components and circuits is via a process called radiation hardening, in which they are rendered resistant to damage or malfunction caused by high levels of ionising radiation.

Most semiconductor components are susceptible to radiation damage, so engineers design radiation-hardened components that are operationally equivalent to their non-hardened versions by introducing design and manufacturing features that reduce the susceptibility to radiation damage. Hardened chips are often manufactured on insulating substrates instead of the usual semiconductor wafers. While normal commercial-grade chips can withstand radiation doses of between 50 and 100 gray (5 and 10 krad), a space-grade chip on insulating substrates must survive doses many orders of magnitude greater.

Before such electronic components can be sent into space, they have to be qualified on Earth. Radiation-hardened products are typically evaluated using one or more radiation-hardness assurance tests, including measurements of the total ionising dose, enhanced low dose-rate effects, single-event effects and damage to the semiconductor crystal structure caused by an incoming particle. These tests are usually done using a low-energy gamma-ray source (for total dose effects) or using high-energy particles generated at low and mid-energy accelerator facilities. Recently, several European facilities involved in testing electronic components have initiated efforts to optimise their services for industry and research in the framework of the EU-funded RADNEXT project.



ESA's AI chip, Myriad 2, about to be tested for the effects of space radiation using the proton beam from CERN's SPS accelerator.
[Credit Maximilien Brice/CERN].

HEALTH RISKS OF SPACE TRAVEL

The health risks of space radiation are arguably the most serious challenge to human space exploration, possibly even preventing these missions due to safety concerns, or by increasing costs to amounts beyond what would be acceptable. As mentioned earlier, radiation in deep space is substantially different from that in near-Earth regions: high-energy and charged particles provide the main contribution to the equivalent dose in deep space, whereas gamma-rays and low-energy alpha particles are major contributors around Earth, where its magnetic field offers some protection.

Beyond the Earth's neighbourhood, space radiation can induce radiation sickness, and substantially increase risks for cancer, neurological damage and other degenerative diseases. Although heavy ions account for less than 1 per cent of the galactic cosmic-ray particle fluxes, they contribute significantly to the total radiation dose received by individual biological cells. This is because the dose received by a cell is proportional to the square of the particle's energy-dependent effective charge.

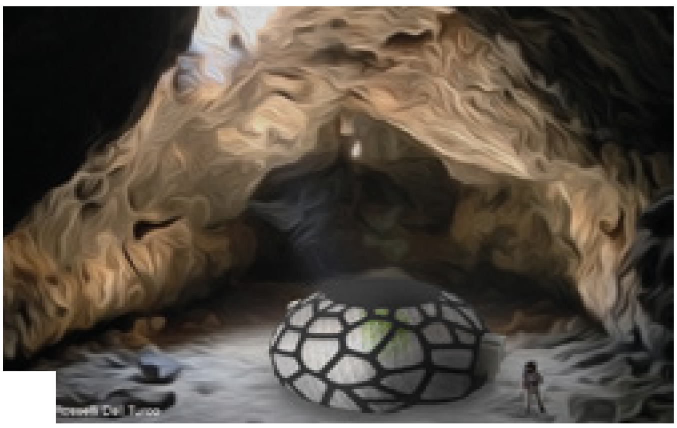
The radiation health risk due to these particles is difficult to estimate and so makes protection via the provision of external shielding challenging. The very high energy of cosmic rays and the severe mass constraints in spaceflight represent a serious hindrance to its effectiveness. Passive shielding can be effective for solar particle events; however, it is limited for galactic cosmic rays. Any active shielding system would have to overcome difficult technical hurdles to protect against them. Improved risk assessment, and genetic and biomedical approaches are a significant component in finding solutions to radiation protection in space.

EXPLORING THE MOON AND MARS SAFELY

The Moon has no atmosphere so experiences the same levels of radiation as found in space. The more distant Red Planet has a thin atmosphere but no magnetic field to deflect incoming, though weaker solar radiation. Furthermore, when galactic heavy-ion particles hit the Martian atmosphere, they undergo nuclear reactions to create showers of secondary, lighter particles including neutrons, resulting in a higher level of radiation exposure than on the lunar surface.

Digging through the loose surface material to shield planetary habitats with take-along equipment is one approach considered. Certainly, exposures could be reduced substantially if a habitat were covered by several metres of regolith. However, lengthy periods spent inside such habitats would likely reduce the science objectives of such missions. The Moon is known to contain lava tubes as well as craters that could provide some shielding from space radiation, and Mars has similar geographical features to increase habitat shielding. Hydrogen generated *in-situ*, and perhaps boron transported from Earth, could be used to create regolith shielding bricks; however, they will require new manufacturing approaches on planetary surfaces.

A lunar pit like this one could lead to a lava tube with extensive connected tunnels that is suitable for habitation. **[Credit NASA/Lunar Reconnaissance Orbiter/SETI Institute/Mars Institute/Pascal Lee].**



A habitat concept for living in a lunar lava tube shielded from space radiation. **[Credit ESA/Emilia Rosselli del Turco].**

NUCLEAR ENERGY FOR SPACE MISSIONS

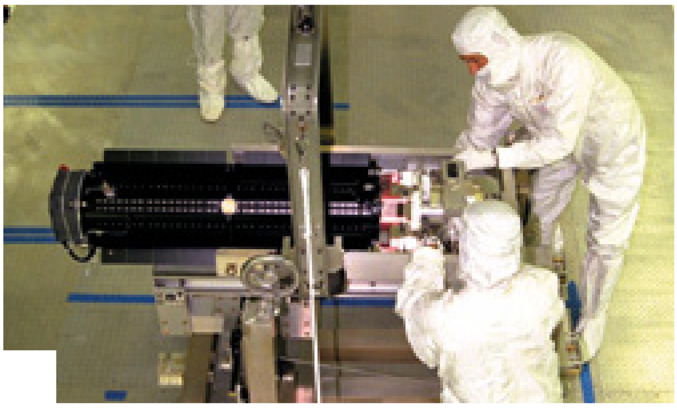
Space agencies launching spacecraft to study the farthest, darkest reaches of the Solar System cannot rely on the Sun to provide energy for manoeuvring and operation. The photovoltaic panels that you see spread out from the main body of a spacecraft will not operate effectively when travelling far away from the Sun to Jupiter and the other outer planets. Even instruments and remote-controlled rovers operating on the surface of the Moon or Mars would not receive enough sunlight to operate continuously. The lunar night lasts about two weeks, and a combination of the long Martian winter and dust storms means that sunshine is very limited on the Red Planet. Certainly, if humans intend to explore or settle on the Moon or Mars, they will need another source of energy, and the obvious candidate is the most energy-dense source we have – that generated by nuclear reactions. Nuclear power sources are thus needed both as a space drive, and to produce electricity for general use, as well as enough heat to keep devices and machines – and people – at a temperature at which they can operate efficiently.

The DeLorean DMC-12 car that was used in the *Back to the Future* film trilogy, with the plutonium box used for power and the hoverboard. **[Credit Rijinatwiki, CC BY-SA 4.0].**

So far, two types of nuclear energy sources have been deployed in space. In the first, the energy harnessed is that released when radioactive nuclei decay (see Chapter 2), and in the second, it is the energy generated from nuclear fission (see Chapter 5).

NUCLEAR BATTERIES

Nuclear batteries, or radioisotope thermoelectric generators, RTGs, which rely on radioactive isotopes to supply power, have been used in space exploration for several decades to carry unmanned spacecraft to distant planets. They are incredibly reliable, being able to withstand the extreme conditions of outer space. They can provide energy for far longer periods than chemical batteries whose energy density is too low and whose weight is prohibitive for long missions. Solar energy does not work much beyond Mars and only in line-of-sight with the Sun.



The Cassini-Huygens mission to Saturn relied on a nuclear battery (RTG) for energy, seen here being checked before installation on the spacecraft **[Credit NASA].**

In these devices, the kinetic energy of particles released by a radioisotope is transformed into heat, which may be utilised directly or converted into electricity. They mostly exploit the thermoelectric effect by which a temperature gradient in a conducting material generates an electrical current. Another process being considered to convert nuclear energy into electricity is thermionic emission in which electrons are emitted from a hot electrode onto a colder one. Less direct processes involve the conversion first into mechanical energy using a Stirling (heat) engine or a gas turbine.

It is possible to identify radioisotopes with a suitable half-life that is long enough for the RTG to operate for the length of the space mission. However, the half-life must not be so long as to compromise the level of activity needed to provide adequate power. For this reason plutonium-238, which has a half-life of 88 years, is the favoured radioisotope for such generators. It is produced by irradiating neptunium-237 (the next element after uranium in the Periodic Table) with neutrons in dedicated reactors. Neptunium-237 is abundant in spent nuclear fuel and has very long half-life of 2.14 million years. (Other long-lived isotopes of this element are neptunium-236 and 235, with half-lives of 154,000 years and 396 days respectively; all other isotopes have a half-life of not more than a few days and decay too quickly to be of use.) After chemical separation, large reserves of relatively isotopically pure neptunium-237 can be obtained.

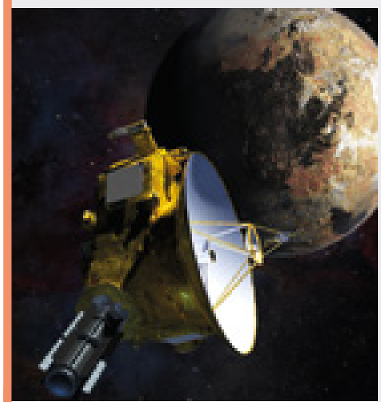
In the past, nuclear reactors generating a high flux of neutrons, which were built to produce plutonium for military purposes, were used to irradiate neptunium-237. These were all decommissioned in the 1980s and 1990s. Since then, reserves of pure plutonium-238 have declined dramatically. In recent years, NASA has been trying to resume production using research reactors. However, only a very small and insufficient amount of plutonium can be produced for nuclear batteries in this way. This is why the European Space Agency (ESA) has decided to switch to americium-241 (half-life of 432 years). This isotope is the result of the decay of plutonium-241 and reasonably plentiful supplies can be obtained from the spent nuclear fuel after extraction by chemical separation.

Both plutonium-238 and americium-241 have their advantages and disadvantages. The main advantage of plutonium-238 is that its half-life of 88 years is long enough for most planned missions. However, this is about five times shorter than that of americium-241. This means that for a given amount of plutonium-238, five times more americium-241 is needed to provide the same power output. Another advantage is that, unlike americium-241, plutonium-238 has almost no gamma activity and so avoids the need for gamma-radiation shielding. The main advantage of americium-241 is that it is easier to recover from spent nuclear fuel, without the need for irradiation in a special reactor, and is therefore cheaper to produce.

TO BOLDLY GO...

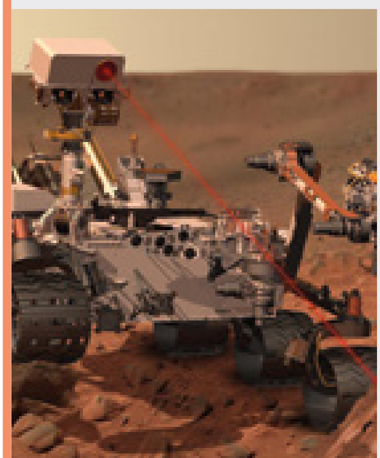
The remarkable Voyager 2 spacecraft, launched 45 years ago to study the outer planets, is powered by three radioisotope thermoelectric generators using plutonium-238. Its long half-life has enabled the spacecraft to continue onwards and leave the Solar System; it is now more than 19 billion kilometres from Earth. The spacecraft, Galileo and Cassini, which were sent to explore Jupiter and Saturn respectively, also employed nuclear batteries to power their heavy payloads including a sophisticated array of instruments (and a lander in the case of Cassini).

More recently, at the beginning of 2019, the nuclear-powered NASA New Horizons spacecraft flew by the most distant object ever observed up close - Arrokoth, far beyond Pluto, in the region called the Kuiper Belt, outside the Solar System proper. It will continue on into the outermost region of the Solar System, the Oort Cloud, which hosts the remains of the primordial nebula from which the Sun and planets formed, before it exits our Solar System completely.



New Horizons needed nuclear power to fly past Pluto and beyond. **Credit] NASA**

The most recent and spectacular use of nuclear power is in the Mars Perseverance rover which successfully landed in the Jezero crater in February 2021. Perseverance requires a nuclear battery because at certain times of the Martian year (which is twice as long as an Earth year) there is not enough energy in the light from the Sun. The rover needs the 110 watts from the nuclear power pack to carry out a range of experiments with electrically powered instruments. It should last for about 14 years.



None of these space missions could have been carried out without nuclear energy.

The Mars Perseverance rover requires a nuclear battery to operate. **[Credit NASA/JPL-Caltech].**

FISSION REACTORS

The second option for energy generation in space is the use of fission reactors (Chapter 6). Even in the 1960s and 1970s, such reactors were being developed for use in space. The reason is that they offer the lowest possible weight per unit of power required, especially if reactors with high fuel-enrichment are used. In the 1960s, the US developed a nuclear reactor designed for space and sent it into orbit. In the former Soviet Union, developments in this area were far more intense. Reactors were used to power the radar on RORSAT (radar ocean reconnaissance satellite) satellites, which tracked NATO and US military submarines.

The most modern model of the space reactor was the TOPAZ, which was developed by the USSR mainly in the 1970s. It was launched into Earth orbit in 1987. TOPAZ was cooled by liquid metal (an alloy of sodium and potassium), so its operating temperature could be as high as 610°C. This well-designed reactor employed 12 kilogrammes of highly enriched uranium (90 per cent) in the form of uranium dioxide. The total weight of the reactor was 320 kilogrammes with the heat output of 150 kilowatts. To achieve maximum efficiency, a beryllium reflector was used that reflected the neutrons generated by fission back into the reactor core. The design involved rotating cylinders, consisting partly of beryllium to reflect neutrons and partly of neutron-absorbing material, which were placed around the core. This arrangement ensured safe control and enabled the reactor to be switched on and off. In this reactor, the thermionic conversion approach was chosen to generate electricity. It offered an efficiency of up to about 5 per cent, an electrical output of 5 to 10 kilowatts, and a planned operating time of 12 months.

Future habitats on Mars would rely on nuclear power like the fission system shown here. **[Credit NASA].**

FUTURE MANNED SPACE MISSIONS

Work is currently underway to return humans to the Moon and also to travel to Mars. However, these activities cannot happen without the use of nuclear power sources. In 2014, NASA began developing a reactor called Kilopower. The goal is to prepare a prototype power source in the coming years, that would supply electrical power of 1 to 10 kilowatts for at least 10 years. The reactor uses highly enriched uranium in a metallic form as an alloy with molybdenum. It has a beryllium reflector and one control rod made from neutron-absorbing boron carbide. Its total weight is comparable to the previous Russian TOPAZ reactor. Heat is removed from the reactor by means of hot water tubes filled with liquid sodium, which then transfer the heat to Stirling engines. Waste heat is removed via a lightweight carbon-composite radiator. NASA is planning several configurations of varying size and performance. The largest, with an output of 10 kilowatts, should weigh 1800 kilogrammes. Thus, the specific power will be about 5.5 watts per kilogramme. The reactor could provide enough power to support a crew of four to six astronauts. It was successfully tested in 2018.

The prototype NASA nuclear reactor, Kilopower, designed for space travel. **[Credit NASA].**

SPACE COLONISATION

For future manned space missions, especially for establishing colonies on the Moon or Mars, new energy systems are needed to power large ground-based facilities as well as spacecraft. Human off-world settlements will require kilowatt and megawatt power systems for life support, the propulsion of large payloads, and off-world industry. While solar energy might work well in many locations for small loads, energy from a nuclear reactor would be necessary for large loads in locations far from the Sun or in locations like the Moon which experiences long periods of darkness. More recently, NASA ground-tested a tiny nuclear reactor that is perfect for powering a colony on the Moon or Mars, or operating a mining operation in the asteroid belt – or even fuelling a large spacecraft to a distant star.

The new reactors are designed to provide 1 to 10 kilowatts of electrical power, and can be set up in coordinated modules, which could be used for more science instruments, to power electric propulsion systems, or to support human exploration or colonies on another planet. It would provide higher data-rate communications via a small antenna, something that is more important than might be thought.

Until recently, putting a payload into orbit around the Earth was incredibly expensive. Any object orbiting the Earth was worth its weight in 14-carat gold. But the situation is changing rapidly and the cost of space missions has decreased significantly. For fission-power systems, this is game-changing. In the past, the launch cost was simply too high to achieve the critical mass requirements necessary for colonisation.

So the gateway to space is now open, and nuclear energy is the power that will get humanity through that gate. When humans are ready to live and work in space, a safe and efficient nuclear power source must be ready as well.

FURTHER INFORMATION

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CHAPTER 10:

THE ROLE OF LARGE RESEARCH FACILITIES IN NUCLEAR SCIENCE

MANY APPLICATIONS OF NUCLEAR PHYSICS SUCH AS THOSE EMPLOYING LESS COMMON RADIOISOTOPES DEPEND UPON FACILITIES AVAILABLE ONLY AT LARGE-SCALE NUCLEAR RESEARCH CENTRES. NEVERTHELESS, RESEARCH IS BEING CARRIED OUT TO TRANSFER THE NECESSARY TECHNOLOGY TO SMALLER, DEDICATED FACILITIES, AND TO MAKE NEW ENGINEERING DEVELOPMENTS AT THESE CENTRES MORE WIDELY AVAILABLE TO INDUSTRY FOR A WIDE RANGE OF USES.

The study of the atomic nucleus requires large-scale research infrastructures hosting one or more particle accelerators, plus extensive engineering and computing facilities. Accelerators are generally large machines that employ huge magnets and accelerating devices, fixed along tubular linear or circular structures down which subatomic and atomic particles are directed. In this way, beams of particles such as protons and neutrons, and various nuclei in the form of ions – that is, positively charged atoms created by stripping away some of their electrons – can be accelerated to high energies. As explained in the Introduction, the accelerated ions can then be employed in a wide variety of nuclear physics experiments. The energies available at large-scale facilities can exceed by several orders of magnitude those available in hospital cyclotrons, for example. This allows rather more exotic radioisotopes to be created and studied.

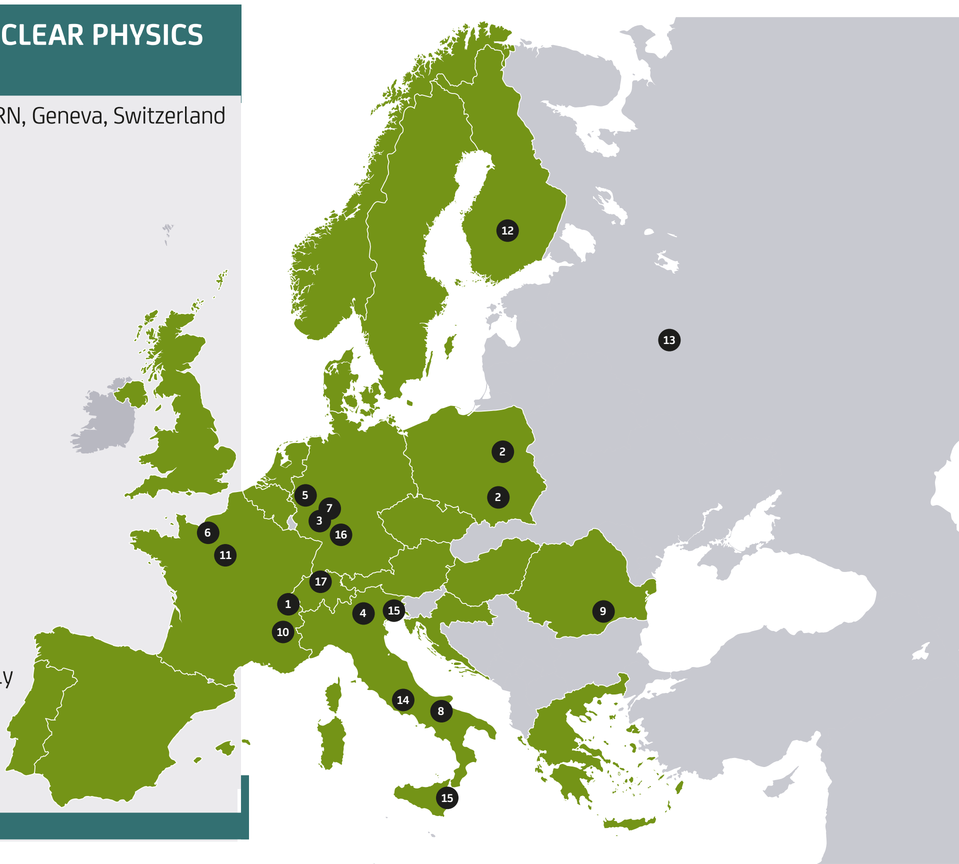
Large nuclear research facilities such as GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany play an essential role in not only providing radioactive ion beams for basic research in nuclear physics but also for investigations in materials science and medical applications.

WORLD-CLASS EUROPEAN NUCLEAR PHYSICS FACILITIES

A diverse range of large research facilities exists throughout Europe, as shown on the map opposite, which carries out research at the forefront of fundamental nuclear science. These European nuclear physics facilities are world-class and excel in comparison with those elsewhere in the world. Their primary goal concerns investigating the structure of the nucleus and the arrangement of protons and neutrons within. In this way, we can learn how the nuclear forces arising from the interaction between the building blocks of neutrons and protons manifest themselves in the rich structure of atomic nuclei, as described in Chapter 1, and how different isotopes of elements are synthesised in primaeval processes in stars (see Chapter 3). More than 3000 different isotopes have been made in these facilities.

A MAP SHOWING THE MAJOR NUCLEAR PHYSICS FACILITIES ACROSS EUROPE

1 - **ALICE, ELENA, ISOLDE and nTof** at CERN, Geneva, Switzerland
2 - **NLC,** Warsaw and Kraków, Poland
3 - **ELSA** Bonn, Germany
4 - **ECT*** Trento, Italy
5 - **COSY,** Jülich, Germany
6 - **GANIL-SPIRAL2,** Caen, France
7 - **GSI-FAIR, Darmstadt,** Germany
8 - **LUNA-LNGS,** Grand Sasso, Italy
9 - **ELI-NP, IFIN-HH,** Magurele, Romania
10 - **ILL, Grenoble,** France
11 - **ALTO, Orsay,** France
12 - **JYFL, Jyväskylä,** Finland
13 - **JINR, Dubna,** Russia
14 - **LNF, Frascati,** Italy
15 - **LNL and LNS,** Legnaro and Catania, Italy
16 - **MAMI, Mainz,** Germany
17 - **PSI, Villigen,** Switzerland



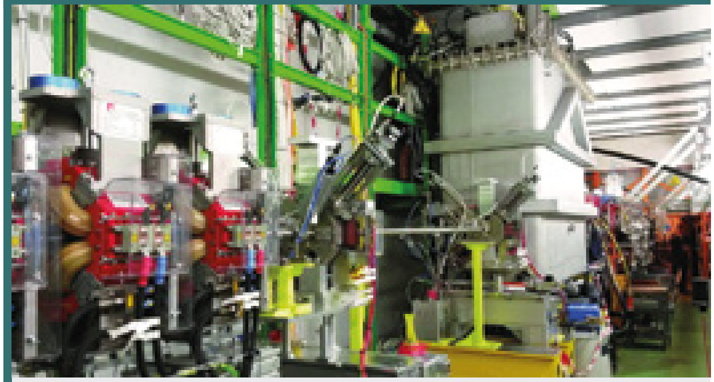
This is part of a new linac, SPIRAL2, at the one of Europe's major nuclear physics facilities, GANIL (Grand Accélérateur National d'Ions Lourds) in Caen, France. The accelerator uses an advanced superconducting accelerating system to create beams of a wide variety nuclei for nuclear physics experiments.

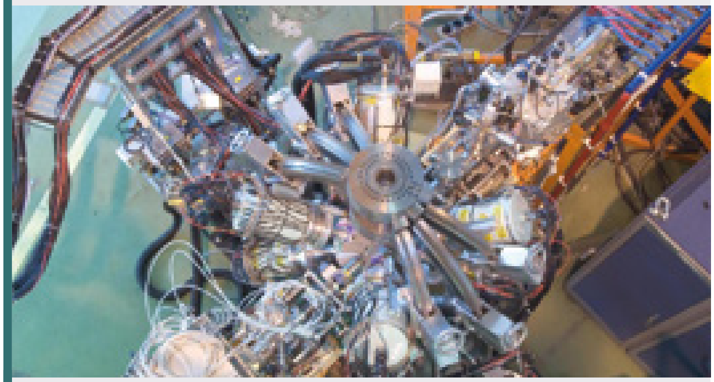
Nuclear science, however, also has a long tradition of applying state-of-the-art developments in nuclear instrumentation to other research fields (for example, archaeology in Chapter 8) and for the benefit of humanity (for example, medical imaging in Chapter 6). The experience gained – particularly in delivering isotopes for nuclear physics experiments – has also led to spin-off activities that apply the knowledge acquired and the technology developed to scientific programmes in the domains of medicine, materials science, biophysics and the latest quantum technologies.

The most successful transfer of this expertise from research laboratory to daily life has undoubtedly been in the area of medicine. Ever since the discovery of X-rays, developments in modern physics have enabled improvements in healthcare (see Chapter 5), and this continues today – not only in diagnosis and imaging, but also in therapy. Cancer will affect 30 per cent of the adult population at some stage in their lives, and effective treatment very much relies on techniques that have emerged directly from nuclear physics.

However, it is not only in the field of medicine where expertise from pure nuclear physics research can be applied. The production of electronics adapted for harsh environments, such as outer space (see Chapter 9), requires techniques originally developed to create ion beams for nuclear physics research. In addition, research currently taking place in the areas of materials science and biophysics at large-scale facilities across Europe promises to have a direct effect on daily life in the years to come. The precision, sensitivity and microscopic-level information regarding a material's composition and behaviour, which is enabled by the use of radioisotopes, is being applied to next-generation, energy-efficient electronic materials, as well as to complex biological systems.

RADIOACTIVE ION BEAMS





CERN's ISOLDE facility creates the more unusual radioisotopes for studies in both fundamental nuclear physics and increasingly in a wide range of applications such as the exploration of advanced materials and medical applications.

One of the central activities of large nuclear physics laboratories is the creation of radioisotopes, some of them quite heavy nuclei. Many of the isotopes are extremely exotic in the proportions of neutrons to protons they possess, and their structure and shapes. Some may be relatively stable while others last just fractions of a second. Although most studies focus on understanding the nucleus and its interactions, multidisciplinary applications are growing. Researchers in a variety of scientific disciplines working on new technologies are finding use for radioactive isotopes as has been explained in the previous chapters.

Radioactive isotopes can be created in dedicated research nuclear reactors; but increasingly accelerator facilities are being built around the world to generate energetic beams of radioactive nuclei both for basic research purposes and a wide variety of applications. Special techniques have been developed to separate and purify the isotopes.

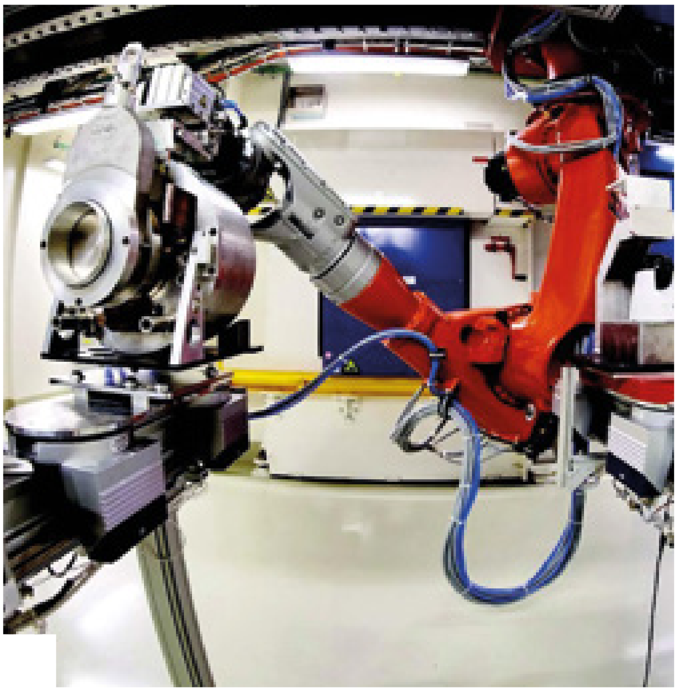
Europe has a number of radioactive ion beam facilities. They include the ISOLDE facility at CERN in Geneva, GSI in Darmstadt, the SPIRAL2 facility at GANIL in Caen, SCK-CEN in Mol (Belgium), ALTO CNRS in Paris, and two INFN laboratories – LNL in Legnaro and LNS in Catana.

As well providing new isotopes for medical use and as environmental tracers, for example, experiments are being carried out in which individual radioactive ions can be introduced into samples of advanced electronic or biological materials, where they act as probes, able to provide detailed information about structure and behaviour at the atomic scale.

MEDICAL ISOTOPES: EXPLORING FUTURE POSSIBILITIES FOR DIAGNOSIS AND THERAPY

As has been shown in Chapter 6, nuclear physics research has directly led to many of the main approaches to diagnosing and treating cancer. However, the standard isotopes used in hospitals have become so as a consequence of the limited capabilities of the small-scale accelerators that hospitals have access to and other logistical concerns. Other isotopes may be more attractive for theranostics (see Chapter 6, page 61), for example, not only in terms of efficacy but also for biological reasons: they cause less damage to tissues surrounding the target tumour, and may exit the body quicker due to their shorter half-lives.

Considerable effort into utilising other isotopes for cancer treatment is being undertaken at large-scale facilities around the world. As these facilities can produce isotopes of almost all elements, researchers can look into the properties of isotopes otherwise out of reach using more standard hospital-based accelerators. In recent years, such research has led to the rapid pathway for lutetium-177 to be accepted in nuclear medicine (see page 55). An example of current research involves the study of terbium isotopes for theranostics. There are four terbium isotopes that can be applied to both imaging and therapy. Of particular interest is the alpha-emitting isotope terbium-149, which has the potential to treat tumours with more efficiency than other isotopes such as lutetium-177 and actinium-225. Initial trials with these isotopes are ongoing and are very promising. However, at the moment, isotopes such as terbium-149 can be produced only at large-scale nuclear research laboratories. This means that research into its use is primarily taking place within the ISOLDE and the dedicated MEDICIS facilities at CERN. Similar research is also planned at the ISOLPharm facility at Italy's INFN facility in Legnaro. To improve clinical access, as well as to evaluate the biological aspects, close collaboration with industrial partners is essential, so that production methods can be adapted for smaller accelerator facilities used by hospitals.



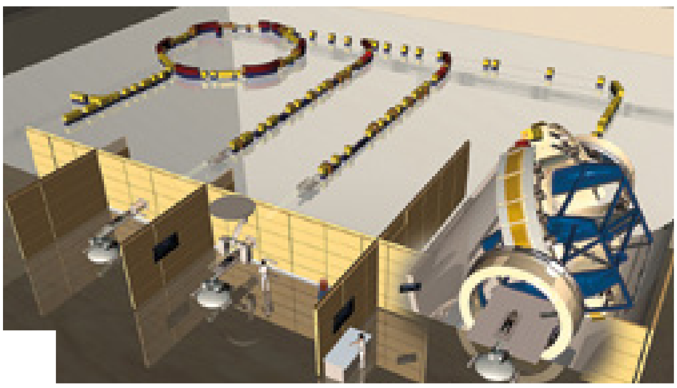
The robot manipulator for handling radioactive materials at the CERN-MEDICIS facility. **[Credit CERN].**

The newly built ISOLPharm radioactive ion beam facility in Legnaro, Italy specialises in making specialised medical radioisotopes. It employs a compact cyclotron. **[Credit INFN LNL].**

FROM ACCELERATOR TO CANCER THERAPY

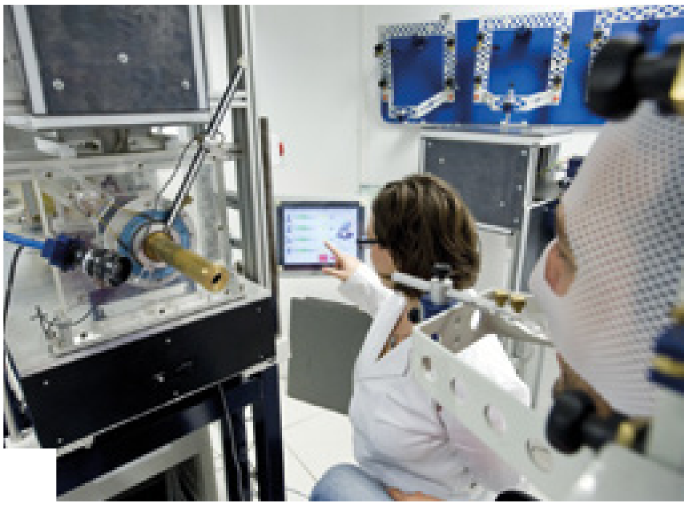
A particle accelerator is fundamental to a nuclear physics laboratory. Beams of protons or electrons are typically accelerated and directed towards a target from which radioisotopes are produced. As facilities have developed over the years, the knowledge gained in producing increasingly complex machines for research has been passed to other areas, and in particular to the development of dedicated accelerators for the treatment of cancer. Chapter 6 has described in detail some of these accelerators. Both GSI in Darmstadt, Germany and the INFN LNS facility in Catana, Italy offer examples of this kind of transfer.

At GSI, the development of carbon-ion beams for cancer treatment (see page 61) was the result of many years of research in conjunction with physicians and accelerator physicists. Therapy with ion beams is precise, highly effective and gentle for the patients. Subsequent monitoring of these patients over a five-year period revealed that the growth of the irradiated tumours was halted in 75 to 90 per cent of the patients, depending on the type of tumour. Side-effects requiring treatment occurred only in very few cases. Since 2009, this type of cancer therapy has been in routine clinical use at the Heidelberg Ion Beam Therapy Center (HIT) where up to 1000 patients can be treated annually. The accelerator facility and the technique for irradiation at HIT were developed and built by GSI scientists and technicians.



The accelerator setup at HIT in Heidelberg, Germany, where cancer patients can be treated with carbon ions via a massive gantry (at the right) built by GSI engineers. **[Credit HIT].**

At LNS, the first proton therapy clinic in Italy has been installed, again a direct result of the expertise in proton accelerators gained in producing beams for nuclear physics research. This leading centre is now used to treat aggressive eye melanomas in addition to investigating irradiation effects in biological systems.



The proton therapy centre in Catana, Italy for treating cancer of the eye. **[Credit INFN LNS].**

ACCELERATORS FOR SPACE EXPLORATION

As mentioned in Chapter 9, the testing of electronics before they are sent into the harsh environment of outer space is vital to ensure their correct operation and reliability for the duration of a specific mission. The only way to simulate the space radiation environment on a terrestrial level, and thus to test the radiation hardness of satellite electronics cost-effectively, is to employ a facility such as the RADEF (Radiation Effects Facility) laboratory at Jyväskylä in Finland, where electronic components are subjected to environments similar to those to be encountered in space.

RADEF is currently the only place in Europe where heavy-ion tests at sufficiently high energy can be carried out. The combination of a versatile ion source and the cyclotron accelerator allows for so-called cocktail beams containing a mixture of ions with similar properties to be produced. RADEF is used by ESA (European Space Agency), NASA and many other leading space organisations.

The cyclotron at RADEF in Finland, which is used to test the radiation hardness of electronics to be used in space.

REVEALING THE NANOSCOPIC

The materials that provide the basis for current technologies such as information technology, lighting and energy production are the result of many years of intense research. Understanding the complex physics and chemistry responsible depends on a variety of techniques to unravel the electronic processes that can be harnessed in modern devices. The application of nuclear physics to the study of materials is very attractive, because unique information can be obtained from the interaction of radioactive isotopes within a material. As we saw in Chapter 2, radioactive decay results in the emission of gamma-rays, electrons or alpha particles. These secondary particles can interact with the crystal lattice characterising the structure of these materials, and reveal the origin of their often exotic and novel electronic and magnetic properties.

MATERIALS SCIENCE

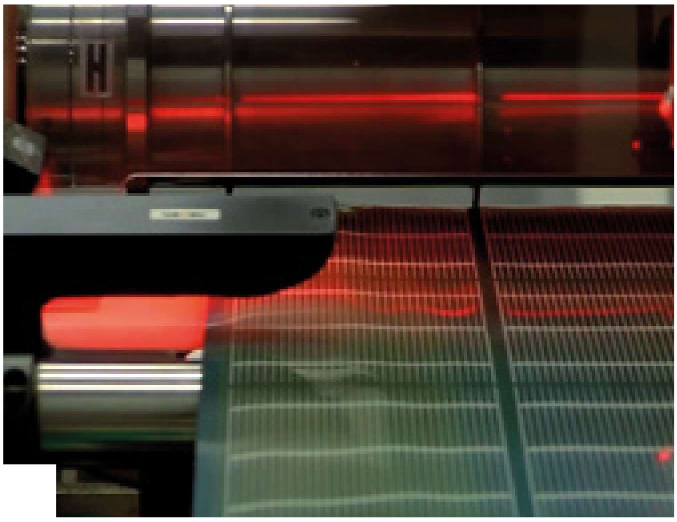
IMPROVED LIGHTING

An example is the semiconductor, gallium nitride. It first appeared on the scene in the 1990s as the first blue light-emitting diode (LED) material. Its use has since expanded considerably because it is very hard and stable, and conducts electrons more efficiently than the main semiconductor used in electronic devices, silicon. Gallium nitride can be 'doped', meaning additional metal atoms, such as magnesium, can be included in its crystalline lattice such that the electronic properties are tuned to emit light at a selected wavelength. Gallium-nitride-based LEDs are now ubiquitous – being the basis of lighting in the workplace, at home and for the automobile industry. Gallium nitride is also being employed widely in the defence, healthcare and detector sector. However, the long-term stability of gallium-nitride devices has been a problem because of a lack of precise knowledge on the behaviour of some of the key dopant materials.

Work at the ISOLDE facility, using radioactive isotopes of magnesium, has allowed the locations of the magnesium atoms in the gallium-nitride lattice to be pinpointed precisely, and so enable researchers evaluate the efficiency and stability of the doped devices. These experiments are currently possible only at large-scale nuclear physics facilities where such isotopes can be made available.

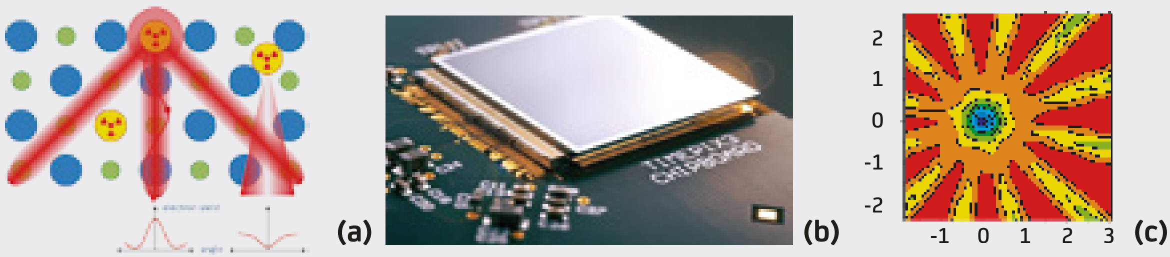
EFFICIENT CAPTURE AND STORAGE OF ENERGY

The development of novel electronic, magnetic, thermal and optical materials with highly sophisticated properties and behaviour is an exciting and rapidly growing field of research. For example, over the past few decades, physicists have identified a range of mixed metal oxides called perovskites with surprising (and energy-saving) properties – for example, superconductivity (electrical conduction without resistance) at relatively high temperatures. More recently, focus has turned to a different set of perovskites for converting sunlight into electricity. The solar panels you might currently install on your roof are based on silicon, which has a limited conversion efficiency, so the hunt is on for more efficient materials, and perovskites might be an option. In addition, a related class of materials called multiferroics, which exhibit a mixture of electric and magnetic properties, offer the prospect for highly efficient energy-storage devices.



Thin-film perovskite solar cells now being developed are expected to overtake silicon cells in efficiency. Research teams across Europe and the world are racing to produce the first practical devices.
[Credit Stanford Energy]

PINPOINTING IONS IN ADVANCED ELECTRONIC MATERIALS WITH RADIATION



In order to understand how incorporating different ions into a semiconductor material (doping) can 'tune' its electronic properties, radioactive versions of the ions can be implanted in the semiconductor's crystal lattice, and their exact positions obtained via a technique called emission channelling. The radiation, in this case beta particles, is emitted – shown in red in (a) – and detected in a position-sensitive detector. Because the escaping particles are charged, their paths are either guided or 'channelled' by the charged ions of the lattice along certain directions resulting in a strong signal in the detector, or they may be blocked and dispersed to give a low signal. The pattern of emission obtained is characteristic of the position occupied by the dopant ion in the crystal lattice.

The photo (b) shows an example of the two-dimensional detector used to detect this radiation, and (c) is an example of the emission pattern, after channelling along a particular direction, of a gallium nitride crystal that has been implanted with radioactive magnesium. Blue signifies a strong signal and red a low one.

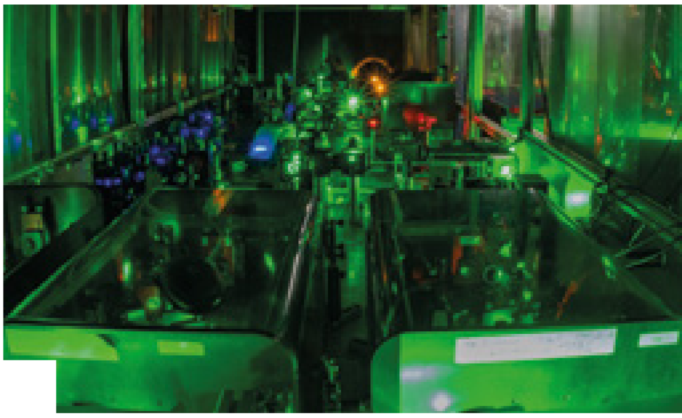
Increasingly, interest is growing in developing such technologically important materials as very thin films (nanomaterials). Radioactive ion implantation provides a fast and efficient way of both modifying their properties and unravelling the complex interplay of subsequent electronic and magnetic interactions. There are available nuclear analytical techniques that employ implanted radioactive ions to characterise such materials. One subtle and highly sensitive technique called time-dependent perturbed angular correlation (TPAC) probes electronic/magnetic behaviour in a sample using an implanted radioactive ion as a kind of microscopic detective. As the radioactive probe interacts with its local environment, the emission of gamma rays is perturbed by the local electrical and magnetic environment of the material into which it has been implanted, for example, a crystal.

BIOPHYSICS: REVEALING BIOLOGICAL PROCESSES WITH UNPRECEDENTED SENSITIVITY

A growing trend at large-scale nuclear facilities is applying nuclear methods – often initially developed for studying materials – to biological systems.

You might find it surprising that radioactive ion beams can be applied to the study of biological molecules. One of the traditional methods of studying the structure and dynamics of large biomolecules such as proteins and nucleic acids (DNA and RNA) is using nuclear magnetic resonance; NMR can be used to follow the folding of a protein, for example, as described in Chapter 6 on page 64. Of particular interest are biomolecules containing a metal atom, which usually have a specific and essential function such as energy transfer. For example, magnesium, zinc and copper are involved in mediating the folding of nucleic acids and in the function of catalytic RNA. However, the precise details are unknown, and these metal ions exist in a chemical state that does not allow for a measurable NMR signal.

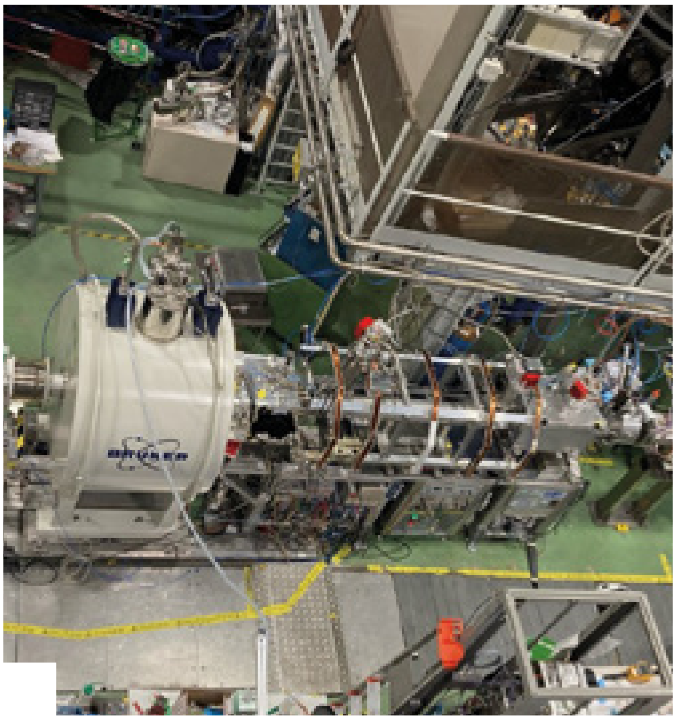
Radioactive versions of these ions that emit beta particles (electrons) offer a way of increasing NMR sensitivity by an astonishing billion-fold! The so-called beta NMR technique involves polarising a radioactive ion beam so that the spins align in a certain direction. This is achieved using a laser that 'forces' the ion beam into a particular orientation; this polarisation then decreases after a certain time. The polarisation causes subtle changes in the magnetic behaviour of the radioactive ions such that the beta emission is asymmetric. When combined with the NMR method of using magnetic and radiofrequency fields, an enhanced resonance signal can be measured by detecting the decrease in beta-emission asymmetry as the polarised ions relax back to their initial state. Again, the signal depends on the ion's electronic/chemical environment.



Laser techniques are widely used in fundamental nuclear physics, where they are employed in the ionisation of isotopes, for the study of the nucleus itself and also for the production of polarised ion beams.
[Credit CERN].

Beta-NMR is a common technique for studying materials at large-scale facilities. Until recently however, the prospect of applying it to biology was considered impossible, but it is now being realised due to improvements in the handling of biological samples – which are often liquids – in the high-vacuum environment required at ion beam facilities. This research has required the development of several new handling techniques. The project is at an early stage but shows great promise in studying the role of metals in biology.

An example of folding in DNA G-quadruplexes which is currently being investigated using radioactive ion beams.



An example of the beamline currently in use to study these quadruplexes.

QUANTUM TECHNOLOGY

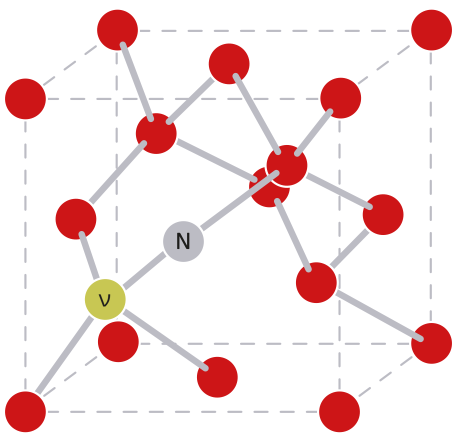
One of the most exciting scientific developments in recent years is the exploitation of the mysterious behaviour of particles (subatomic particles, atoms and molecules) as described by quantum theory, which proposes that such particles can be in two different quantum states simultaneously (called quantum superposition), and that the quantum states of separate particles can be 'entangled' so that they affect each other in some significant way. In computing, for example, these properties mean that very much more information can be processed quickly and communicated. Today, there is a huge drive to build the first quantum computer and communication network.

This new quantum technology also promises to revolutionise many other aspects of daily life including sensing and metrology. Research into this area is being generously supported by policy-makers, and Europe is no exception – with quantum technology currently being the basis of the 10-year European flagship project.

Large-scale nuclear facilities are also involved in this research, exploiting some of their unique experimental possibilities – in particular, in the areas of quantum information and the realisation of a nuclear clock.

QUANTUM INFORMATION

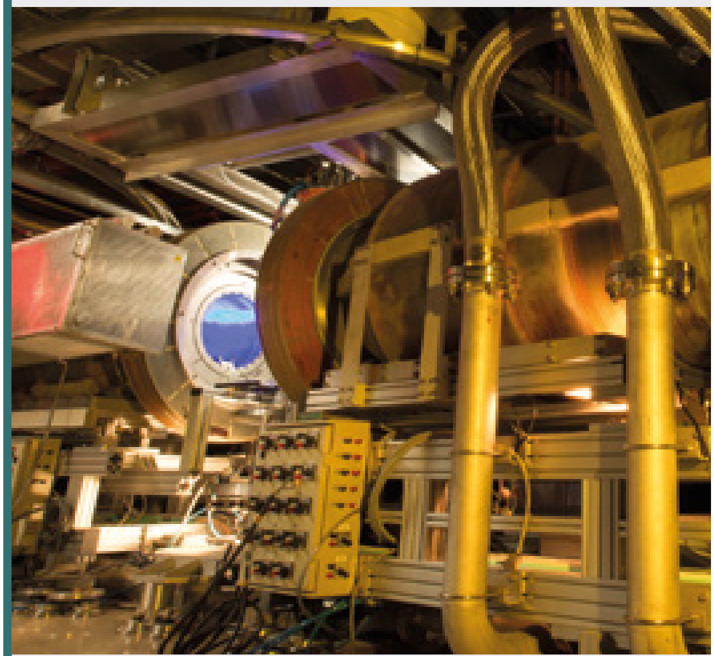
Quantum information processors exploit a new kind of 'bit' called a quantum bit or qubit, in which the bit is held in a quantum superposition of states. Amongst the most promising candidate qubits are atom-sized 'centres' in a diamond crystal lattice. They typically feature an impurity atom like nitrogen coupled with a nearby vacancy (where an atom is missing in the crystal lattice). The qubit is characterised by the centre's possible quantum spin states. If these centres are stable enough and have the appropriate characteristics, they could become the standard qubit in quantum devices. However, many candidates still require an understanding of their stability within a crystal. Since they are created via implantation and irradiation, the structural and electronic properties of the centres can be probed to a very precise limit, in same way as for magnesium dopants in gallium nitride described above. Indeed, systems where a nitrogen atom replaces a carbon atom in a diamond lattice coupled to a vacancy, and one based on tin and two vacancies, are now being studied using radioactive probes.



A nitrogen–vacancy qubit in a diamond crystal lattice.

NEUTRON BEAMS AT LARGE-SCALE FACILITIES

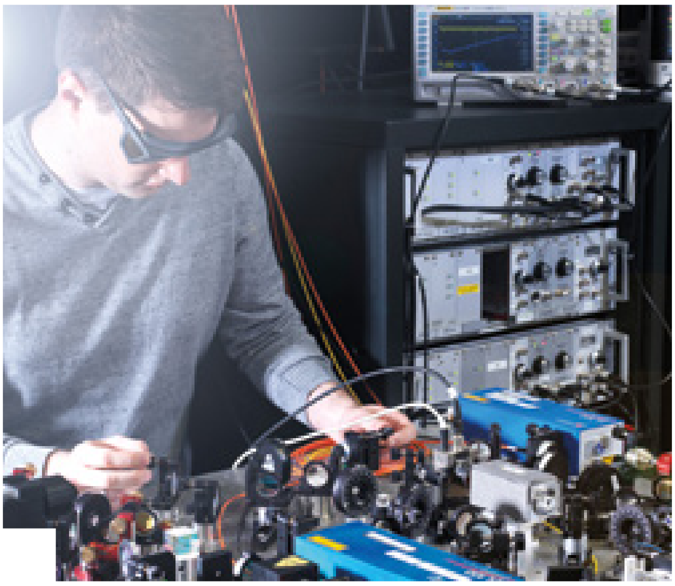
As described in previous chapters, beams of neutrons are used extensively to study novel chemical, electronic and magnetic structures at the molecular level, as well as biological molecules and assemblies. The production of suitable neutron beams also requires large-scale facilities housing either a particle accelerator or a nuclear reactor. The Institut Laue–Langevin (ILL) in Grenoble, which has a research reactor, carries out a wide range of neutron experiments probing various materials, but also produces radioactive isotopes. Some of the work on terbium isotopes mentioned earlier was carried out at the ILL. The beta-emitting isotope, terbium-161, was first produced at the ILL and also at another major nuclear facility, the Paul Scherrer Institut in Villigen, Switzerland, using neutron beams. Both laboratories have been developing routine methods for making terbium-161, and other important radioisotopes such as lutetium-177, for cancer treatments.



One of the instruments (IN15) at the international ILL facility that utilises an intense neutron beam supplied from its nuclear reactor, and which is tailored for specific experiments in materials science. **[Credit Institut Laue-Langevin].**

A NUCLEAR CLOCK

At present, the precision of timekeeping is determined using atomic clocks. These use as a frequency standard the precise difference between quantum energy levels that electrons occupy in atoms such as rubidium or caesium when excited to a defined higher energy state. However, clocks based upon excitations in nuclei offer the promise to increase the precision in time-keeping by a factor of at least 100. This would have a significant impact on many aspects of life from metrology to GPS. Of all the nuclear isotopes known, only one appears to offer the prospect of realising a nuclear clock – thorium-229. This isotope has a very low-level excited quantum state that can potentially be pumped using laser systems. However, the precise level of this excited state is still unknown to sufficient accuracy. Research at numerous facilities across Europe is being carried out to pinpoint the excited level using, for example, the unique production of actinium-229 (which beta-decays to thorium-229) available at laboratories such as ISOLDE, CERN. In this way, the excited level is expected to emit energy that can be detected, and would allow for the most accurate measurement of this level to date.



Measuring the nuclear properties of thorium-229, to be used as nuclear clock. **[Credit PTB, Germany].**

Most of the applications of nuclear physics mentioned in these chapters originated in fundamental research at large nuclear facilities. This includes the development of methods to make radioactive isotopes, now used as tracers, detectors, in imaging, and in treating various pathologies and pathological organisms. The profound understanding of nuclear structure and behaviour, plus all the data collected on nuclear reactions, which are achieved through major nuclear physics experimental programmes, also underpin progress in developing advanced forms of nuclear energy.

New accelerator concepts usually emerge at large facilities, which have access to international engineering expertise. The knowledge and technologies developed can then be transferred to industry – for example, through the commercialisation of compact accelerators and isotope manufacture.

NEW LARGE-SCALE FACILITIES

Europe has a variety of large facilities where applied nuclear science is carried out. Some are national, while others involve international partners like CERN and the ILL. A new major nuclear facility is being built at GSI, the Facility for Antiproton and Ion Research (FAIR), which will expand research not only into fundamental physics but also in materials and the life sciences. In parallel, a new international neutron facility is being constructed in Lund in Sweden – the European Spallation Source, which will provide neutron beams up to 100 times more intense than are currently available. Both facilities expect be ready by around 2027.

The test facility for FAIR, a major new nuclear physics laboratory complex being built in Darmstadt, Germany. **[Credit GSI].**

Furthermore, large-scale facilities provide training for generations of nuclear scientists and engineers for industries that employ nuclear science and technology in the many applications that affect our everyday life.

FURTHER INFORMATION

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VIDEOS

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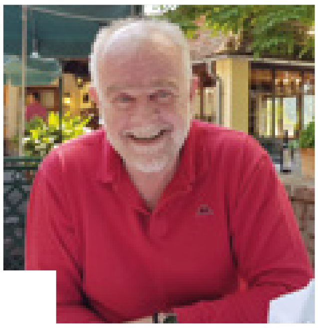

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