Nuclear physics and technology – inside the atom

How research into the atomic nucleus is improving our lives and helping the planet
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The uncovering of the structure of atoms – the basic units of matter – as composed of clouds of electrons surrounding a central nucleus is one of the landmark 20th-century discoveries, underpinning modern healthcare, advanced materials and information technology. However, while the chemical and physical characteristics of atomic electrons have been studied thoroughly, and have been successfully exploited to make pharmaceuticals, plastics and electronic devices, for example, the nucleus is less well understood.

The forces binding together the components of the nucleus are extremely strong, and so require the input of high energies, using large accelerator facilities, to probe and manipulate their structure and behaviour. Furthermore, the strong interactions involved are extremely complex and difficult to unravel both theoretically and experimentally.

THE IMPORTANCE OF NUCLEAR PHYSICS AND TECHNOLOGY

Over the past decades, studies of the nucleus have led to many major developments that have transformed our lives. One of the most significant has been in medicine: in developing nuclear methods to treat cancer safely, to analyse biological processes and diagnose disease using medical isotopes, and to image the body non-invasively. The application of nuclear-based analytical techniques continues to revolutionise the chemical and life sciences, and plays an increasing role in monitoring environmental change, as well as providing new portable devices used to aid national security.

A prominent application of nuclear research is in developing the long-term means of securing our energy needs within a low-carbon economy. Tapping into the powerful forces within the nucleus to generate power is a major goal of nuclear scientists and engineers. Revolutionary designs of fission reactors, some using novel fuel sources, are already being tested, while various approaches to nuclear fusion – the ideal environmentally-friendly solution to our energy needs – are being developed on an international scale. Nuclear transmutation is also being investigated as a means of destroying nuclear waste safely.

Studies of the nucleus are also extending our understanding of the basic laws of nature and how the universe evolved. Much of nuclear physics research involves exploring the forces and particles characterising everyday matter, as well as more exotic phenomena found in stars and the early universe. One of the most exciting areas of research is the investigation of stellar processes by which all the elements are created, which involve unusual, unstable nuclear species. It is this kind of research that attracts students into physics.

This report describes the research carried out in nuclear physics and technology, and shows how the discoveries made are leading to a growing range of applications in medicine, power generation, as well as environmental and security monitoring.

Dr Robert Kirby-Harris
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THE UK ROLE

The atomic nucleus was discovered at the University of Manchester, and much of the early, seminal research into nuclear structure was carried out in the UK. Today, vibrant nuclear physics research programmes continue across Europe, including at expanding international facilities in Germany and France. The EU recognises the economic importance of these centres through its support of the European Roadmap for Research Infrastructures (ESFRI).

Nuclear research in the UK is funded primarily by two members of the UK research councils family, The Engineering and Physical Sciences Research Council (EPSRC) funds nuclear engineering and also leads the UK Energy Research Programme. The Science and Technology Facilities Council (STFC) funds nuclear physics and also manages facilities which are used for a broad range of research, including some for nuclear physics and engineering challenges.
Introduction

The complex heart of matter

Studies of the atomic nucleus are offering profound insights into the nature of matter, how it was made, and how to unlock its power

All the matter we see around us is composed of different types of atoms characterising the elements. Deep in the heart of each atom is the nucleus, which is composed of yet smaller particles, protons and neutrons (nucleons). How they behave is controlled by three fundamental forces of nature – the strong force, together with the weak and electromagnetic forces. These forces combine to generate highly complex nuclear structures that are challenging to study and understand.

Nuclear physics research focuses on several important scientific questions:
• how are the nucleons arranged in nuclei?
• how many kinds of nuclei are possible and what affects their stability?
• how are the building blocks of nucleons – quarks – bound together?
• how did quarks first form nucleons, and how did the nucleons then build up into the elements?
• how can we exploit the properties and behaviour of nuclei?

A QUANTUM SYSTEM IN MINIATURE
Like all atomic and subatomic particles, the nucleus obeys the laws of quantum mechanics, the theory of how matter behaves at a very small scale (million-billionths of a metre for nuclei). Many phenomena seen in nuclei mirror those in larger-scale quantum systems, so the nucleus offers an ideal microscopic laboratory for probing quantum behaviour.

POWER FOR THE PEOPLE
The existence of the atomic nucleus has been known since the beginning of the 20th century, and for the past 50 years the energy within it has been exploited to provide a reliable supply of electricity throughout the world. Nuclear energy is a low-carbon option so it offers a viable way of helping to mitigate climate change. Nuclear power generation involves the controlled fission of uranium in a reactor, and efficient reactors are being built that extract more energy from the uranium fuel. Furthermore, nuclear physics studies are already pointing the way to different types of nuclear power, some of which utilise other elements.

THE ORIGIN OF THE ELEMENTS
One fascinating aspect is understanding how nuclei, and thus the elements, are cooked up in the fiery cauldrons of stars. Nuclear physicists design experiments to study particular nuclear reactions which may be key to this process of nucleosynthesis. Many of them involve nuclei with unusual ratios of protons and neutrons, which can be made in the laboratory.
Atoms consist of a positively charged nucleus with a concentrated mass, surrounded by lightweight negative electrons. The electrons are responsible for the chemical binding of atoms into molecules, and for conducting electricity. Nuclei consist of positively charged protons and neutral neutrons. Together, they are responsible for the mass of the element. The number of protons gives the element’s atomic number. The lightest element, hydrogen, has one proton in its nucleus; helium has two protons and usually two neutrons. The heaviest naturally-occurring element, uranium, has 92 protons. Elements can have varying numbers of neutrons, which are essential for stability, giving rise to isotopes with different masses. Some isotopes are unstable, spitting out alpha particles (helium nuclei), electrons (beta-radiation) or positrons (the positive, antimatter version of electrons), together with high-energy electromagnetic radiation (gamma-rays). They are then transmuted into other elements. Many radioactive isotopes exist naturally on Earth and in stars, but they are also made in the laboratory.

Protons and neutrons each consist of three fundamental particles called quarks. They are combinations of the two lightest quarks; there are also four, heavier quarks that form unstable nuclear particles. Quarks can also bind in nuclear pairs called mesons, some of which played a significant role in the universe’s evolution.

Lung function can be assessed by breathing in a gas containing radioisotopes of xenon or krypton.

The seminal work that led to the discovery of the atomic nucleus was carried out a century ago by the father of nuclear physics, Ernest Rutherford, at the University of Manchester.
Exploring the nucleus

Nuclear physics increases our understanding of nature at a fundamental level

Scientists who study atomic nuclei tackle a wide range of questions that provide deep insights into the origin and behaviour of the material world.

How are the protons and neutrons arranged in a nucleus?
The nucleons sit in ‘shells’ with discrete quantum energies to form a diverse range of structures (just as electrons are arranged in shells in atoms). So-called magic nuclei, with spherical shells of protons and neutrons, are very stable. However, some heavier nuclei can adopt more unusual shapes, with different shell arrangements. Very light nuclei sometimes behave like clusters of nucleons, while very heavy species are described as liquid drops of nuclear matter that can rotate and deform. Theorists and experimentalists work together to test these concepts.

How many nuclei can exist?
About 7000 different combinations of protons and neutrons in nuclei are thought possible (see the nuclear landscape, above right), most of which are short-lived. Researchers explore the outer edges of stability where nuclei with extreme ratios of neutrons or protons can behave in exotic ways. In very neutron-rich nuclei, for example, the neutrons may form extended ‘halos’ around a dense core. ‘Superheavy’ nuclei are of great interest because theorists predict that some of them, which do not exist naturally, could be quite stable.

How are nuclei and thus elements made in the universe?
Extreme nuclei are important because they are thought to form the transient stepping stones in the nuclear reactions by which the heavier elements are built up in stellar processes, particularly supernova explosions. The elements then spread out into space, to form the construction materials for subsequent generations of new stars and planets – and eventually life.

How do the forces binding nuclei work, and where does the mass and spin of the nucleus come from?
The forces holding nuclei together operate in an extremely complex way that is still not well understood. For example, the constituent quarks of a proton account for only one-fiftieth of its mass, with the rest arising from strong force interactions.

How does nuclear matter behave across the wide range of conditions that exist – or have existed – in the universe?
Before the first stars formed, about 14 billion years ago, the temperature and pressure in the universe were high enough for the quarks to be free of their nuclear prisons. Scientists are trying to understand how quarks became confined in protons and neutrons, as well as how they behave in the cooler but unbelievably high-pressure environment of a neutron star.

Understanding the huge variety of nuclei, and the forces holding them together, not only helps scientists to understand the evolution of the universe and the conditions leading to life, but also provides the underpinning knowledge needed to exploit nuclear properties in new technologies.
**EXPERIMENTS**

Experiments to understand nuclei require large-scale equipment that can accelerate to high energies beams of subatomic particles and charged ions (atoms stripped of most of their electrons). These projectile nuclei are then directed onto a target. The principle is to make new nuclear species, either by fusion of the projectile nuclei with those in the target, or by fragmenting the nuclei. The masses, lifetimes and energies of the particles and the radiation (gamma-rays) emitted are measured. One aim is to make new magic nuclei and study their structure. Often, the nuclei are generated in high-energy states with unusual shapes, and may be set spinning fast. The gamma-rays emitted, as the nuclei lose energy, provide information about nuclear structure and behaviour. To understand the binding forces better, nuclei may also be prepared where the proportions of protons and neutrons have been interchanged – to create ‘mirror’ nuclei. Additional experimental approaches include smashing together beams of heavy nuclei at high energies, with the aim of breaking them up into the constituent quarks; high-energy lasers and electron beams are used to probe the structure of target nuclei; and very high-energy lasers can induce nuclear reactions such as fission and fusion.

**NUCLEAR PHYSICS IN THE UK**

The existence of the atomic nucleus was uncovered in experiments at the University of Manchester a century ago. Today, UK nuclear physicists continue their studies at facilities around the world: in Europe, the US, Canada, Japan, South Africa and Australia. The core community includes groups from the Universities of Birmingham, Brighton, Edinburgh, Glasgow, Liverpool, Manchester, Surrey, the West of Scotland and York, as well as the STFC Daresbury Laboratory in Cheshire. They collaborate in international teams to develop new experimental set-ups, in particular, dedicated devices such as detectors (p14). Increasingly, nuclear physics and its applications are becoming multidisciplinary, involving astrophysicists, and atomic, laser, medical and particle physicists, as well as materials scientists and engineers.

The UK is contributing to an experiment called NuSTAR (Nuclear Structure, Astrophysics and Reactions) at a major new European facility based in Darmstadt, Germany – the Facility for Antiproton and Ion Research (FAIR). It will comprise a large accelerator complex for generating intense beams of a wide range of nuclei, of which many are unstable and very rare. They will be used in experiments to investigate all of the questions on p6. Beams of antiprotons (the antimatter version of protons) will also be generated to investigate quark interactions. At CERN in Geneva, Switzerland, the UK is already involved in ALICE, an experiment using the Large Hadron Collider (LHC) to study how quarks first interacted in the early universe. European physicists are also considering a future facility, EURISOL, to produce even more intense beams of exotic nuclei.

**LOW-ENERGY EXPERIMENTS**

Nuclear studies include experiments investigating very rare radioactive decays of certain nuclei in highly controlled environments. The measurements aim to shed light on the behaviour of matter and energy at the most fundamental level. Experiments involving the binding of antimatter particles into, for example, antihydrogen, offer another avenue of investigation.
Nuclear physics in medicine

Nuclear physics research has contributed significantly to improving the health of the nation.

The behaviour of particular nuclei, both stable and unstable, can be manipulated and monitored to diagnose and cure disease.

Basic research into nuclear structure and reactions is essential in characterising and evaluating new isotopes for medical use, as well as developing improved methods of making and detecting them. This may mean designing more efficient accelerators, targets and detectors. A more sensitive detector enables the dose of radioactive tracer to be lowered. University groups such as those at Birmingham, Glasgow, Liverpool, Manchester and Surrey have applied medical physics research programmes.

Because most isotopes used do not survive for long, they need to be made close to the clinic. While some large hospitals have their own accelerator facilities for isotope production, physicists are investigating smaller, cheaper accelerators and alternative methods of production, in response to the growing demand. The Universities of Strathclyde and the West of Scotland recently achieved a first in using high-power lasers to generate medical isotopes.

MEDICAL ISOTOPEs

Scientists and clinicians have long realised that the radiation emitted by short-lived isotopes offers a highly sensitive tool for diagnosing illnesses and studying disease. The most commonly employed radioisotope, technetium-99, is used in at least 30 million hospital diagnoses a year, worldwide. It emits readily detectable, low-energy gamma-rays and has a half-life of a few hours.

The isotope is obtained from the decay of molybdenum-99, which is made in dedicated nuclear reactors in which a target is irradiated with neutrons. Specific isotopes such as iodine-131 are often bound to bioactive compounds, which, when taken in by the body, concentrate in specific organs and so can be used as tracers to follow metabolic processes linked to disease.

RADIATION THERAPIES

As well as providing sensitive imaging techniques, carefully directed doses of nuclear radiation can be targeted to kill cancer cells, which are more sensitive to radiation than normal tissue. Around one in six of the UK population will receive radiotherapy at some point in their lives. The simplest approach is to insert an implant containing a small amount of a radioisotope close to the tumour – a technique called brachytherapy. This is used to treat prostate cancer, for example. A more experimental therapy, boron neutron capture therapy (BCNT), being tested at the University of Birmingham, exploits...
IMAGING

Because the radiation emitted by isotopes is penetrating, it can be traced back to its origin, thus accurately pinpointing locations in tissues, and so offering opportunities for imaging inside the body. A technique called single photon emission computed tomography (SPECT) involves detecting gamma-rays emitted from radioactive tracers at all angles to construct a three-dimensional image, for example, of blood flow in the heart and brain. A team at the University of Liverpool and the Daresbury Laboratory is developing a new type of gamma camera that accurately pinpoints the origin of the gamma-rays using new position-sensitive semiconductor components.

The use of an even more sensitive technique has expanded rapidly in the past two decades. This relies on short-lived isotopes (fluorine-18, carbon-11 and oxygen-15) which emit positively charged electrons (positrons). When these antimatter particles interact with ordinary matter, they annihilate releasing pairs of gamma-rays that are then detected by a gamma camera. Again, the gamma-rays can be traced back to their origin, and a 3-D map of tissues reconstructed using computer analysis. Positron emission tomography (PET) has proved to be a powerful analytical technique, and is frequently employed to image brain function using a sugar compound labelled with a positron-emitting tracer.

Current PET scanners can detect only a small percentage of the emitted gamma-rays, which may also be scattered, and so do not give a clean image. Researchers from Liverpool and the Daresbury Laboratory are now developing an improved new imaging system called SmartPET. This is based on ultra-pure germanium detectors (p14), which when combined with fast digital electronics, enable the gamma-ray paths, and thus the image, to be reconstructed accurately.

PET imaging is increasingly being combined with other imaging techniques such as computerised X-ray tomography (3-D X-ray scanning) to obtain detailed views of organs as they move inside the body. An important part of the process is the use of realistic anatomical computer models, or ‘phantoms’, to calibrate the images. Researchers at the University of Surrey have developed a phantom based on research into the characterisation of electron beams and gamma-rays in accelerator-based experiments.

**Beams of nuclear particles such as protons and carbon-12 ions can selectively kill cancer tumours that are normally difficult to treat**
Harnessing the nucleus for power

The forces binding protons and neutrons in a nucleus represent a highly condensed energy source that could provide a long-term answer to sustainable living

Climate change, greater energy security and limited fossil-fuel reserves are powerful reasons for the much wider adoption of nuclear energy, with its near-zero carbon-dioxide emissions, as a major source of power in the medium and long term. Nuclear physicists have a pivotal role to play in not only developing improved energy-generation schemes but also in exploring the basic science that may lead to novel methods of harnessing the powerful forces locked inside the nucleus. Experiments at international nuclear physics research facilities provide the necessary data needed to develop improved nuclear energy schemes.

University nuclear physics groups around the UK are actively collaborating with colleagues in other disciplines – engineers, materials scientists, particle and accelerator physicists, plasma and laser physicists, and computer experts, as well as those in the energy industry – in preparing for a sustainable future supported by a nuclear power option that is safe, economic and reliable. The Dalton Nuclear Institute at the University of Manchester, for example, brings together expertise in nuclear structure and reactions, and also reactor and waste-disposal technologies.

GREENER NUCLEAR REACTORS
Reactor design has improved radically since the first generations of nuclear power stations were built. In some reactors in Europe, fuel efficiency is increased, and the costs of enrichment and plutonium inventory reduced, by the use of mixed oxide fuel (MOX), from re-processing. The latest advanced reactors being planned around the world have a simpler, more robust design, making them easier to operate reliably over a long lifetime (about 60 years). They are also cheaper and quicker to build, have inbuilt, passive-safety features, are more efficient, and produce considerably less waste, with the potential for running proliferation-resistant fuel cycles.

Further ahead, six more efficient ‘Generation IV’ prototypes are in the concept phase. They include high-temperature designs, also capable of generating hydrogen for fuel as well as low-cost electricity, and fast-neutron breeder reactors, which can generate more fuel that is then used onsite in a closed cycle. These systems can achieve a 50 to 60-fold increase in the energy extracted per tonne of natural uranium ore when compared with current thermal reactors.

Most of these designs are unlikely to be constructed before 2030, apart from one high-temperature reactor. A favoured cost-competitive version of this is the pebble bed modular reactor. Invented in Germany, it is now being developed in the US, South Africa and China. The uranium fuel is encapsulated in meltdown-proof graphite ‘billiard balls’, which provide a pre-packaged system for long-term disposal. This design also offers the possibility of small, mass-produced reactors that might even power vehicles or local facilities such as desalination plants.

About one-fifth of the UK’s electricity supply is generated using nuclear energy. The civil nuclear industry operates around 440 reactors in dozens of countries round the world, providing about one-sixth of the planet’s electricity needs, with virtually no carbon-dioxide emissions.
NUCLEAR ENERGY FROM THORIUM

Reactor schemes utilising another fuel source, thorium, are gaining increasing attention. Thorium-232 – three times more abundant in the Earth’s crust than uranium ore – absorbs a neutron to produce uranium-233, which then undergoes fission. India is already building a test reactor based on the thorium fuel cycle, in which some plutonium is required to provide the neutron balance.

UK teams are also exploring schemes based on thorium. One ingenious approach, developed at CERN, is to control the fission at a sub-critical level using a beam of neutrons generated in an accelerator complex. A new type of inexpensive, compact machine, the fixed-field alternating gradient accelerator, being developed by a UK consortium of universities, could provide the driving system. The fuel would not need enriching, as limited waste is produced and a lower potential for proliferation exists. Researchers at the University of Manchester are adapting the idea to create a novel design in which thorium-loaded fuel rods irradiated with a neutron beam could be introduced into existing nuclear power stations.

FUSION SCHEMES

The other major option for future nuclear power relies on fusing the isotopes of hydrogen – deuterium and tritium – to produce helium and energetic neutrons. The advantages are that the fuel is plentiful and could be obtained from seawater, the main reaction product is harmless with low radioactivity generated in surrounding structural materials, and the process can easily be turned off. However, creating and managing the conditions for fusion are challenging. The fuel must be heated to 100 million degrees (hotter than the Sun’s core) so that the nuclei collide with each other at sufficient energy to fuse. At these temperatures, the fuel is in the form of a gas of charged particles – a plasma.

Magnetic confinement

The hot plasma can be confined by magnetic fields, as happens in a doughnut-shaped device called a tokamak. The UK’s Culham Science Centre near Oxford has been host to the Joint European Torus (JET) for nearly 30 years, and is the world’s largest tokamak in operation. The complex plasma characteristics and energy transport (which also underlie nuclear processes in stars, p6) are being studied at Culham with the collaboration of many universities both in the UK and overseas. This is in preparation for the global test experiment, ITER, being constructed in southern France. Also of great interest is the testing, at Culham, of a compact, spherical tokamak design, MAST.

Inertial confinement

Another approach to fusion is to heat and compress simultaneously a pinhead-sized pellet containing the fuel, via the shock induced by a very high power laser pulse (inertially confined fusion, ICF). Teams from UK universities and the STFC Rutherford Appleton Laboratory (RAL) near Oxford are using the Vulcan Petawatt laser at RAL to explore ICF, in preparation for the proposed European High Power Laser Energy Research Facility (HiPER), which will investigate laser-driven fusion as a future energy source. HiPER may be located in the UK. Another version of ICF being studied employs a laser to release a beam of protons or heavy ions from a target, which then trigger fusion.

DESTROYING NUCLEAR WASTE

Waste management is a key challenge that nuclear physicists are addressing. Instead of storing long-lived radioactive waste, a potential alternative is to transmute the heavy elements which fission into isotopes that decay quickly, whilst also generating energy.

One method proposed in the US is to use a fusion reactor like the UK’s MAST to produce high-energy neutrons that would then slam into a blanket of nuclear waste (from normal fission-power generation) surrounding the reactor, thereby transmuting the waste.

Accelerator-driven thorium reactors can also incorporate waste for transmutation, and such a system is under development in Europe. In the UK, researchers at the University of Strathclyde and RAL are investigating laser-driven approaches to nuclear transmutation. Although experiments have required the large Vulcan laser, smaller, high-intensity lasers are becoming available.
A powerful analytical tool

High-energy acceleration techniques, reactions and detection methods derived from nuclear physics provide an indispensable set of analytical tools for research, manufacturing and environmental monitoring.

The high-energy beams of particles produced in nuclear studies such as ions, neutrons and positrons are used as analytical probes in industry and academic research. Many of the ion-beam methods were first developed by physicists at the AEA Harwell Laboratory and the University of Oxford in the 1980s. The company, Oxford Microbeams Ltd, now manufactures and supplies the necessary equipment for these techniques, which is exported around the world. The University of Surrey hosts the UK’s national ion beam facility, providing highly focused ion beams which can scan a sample down to the nanometre scale, while the Daresbury Laboratory provides a medium energy ion beam facility to study the surfaces of materials.

Particle probes

NEUTRONS
Like X-rays, neutron beams are employed to analyse the structure and behaviour of advanced materials for energy generation and information technology, and increasingly to study biological processes at the molecular level. The UK is a leader in the field, having constructed the world’s first spallation neutron facility, ISIS, which is based at RAL. Neutrons are generated by firing a beam of protons, produced in an accelerator, at a uranium target. UK researchers also participate in the reactor-based Institut Laue-Langevin neutron facility in Grenoble, France.

Neutrons can also probe the elemental composition of materials by inducing signature nuclear reactions. Portable neutron emitters using, for example, an artificial neutron-emitting isotope such as californium-252, are employed in prospecting, or in detecting terrorist weapons and chemical waste.

POSITRONS
The nuclear physics group at the University of Birmingham has adapted the medical technique PET (p9) to study flow in engineering systems. Early work included studying lubrication in engines and gearboxes and observing the flow of liquids and gases through fractured rock – important for establishing the safe underground storage of radioactive waste. A variant, positron emission particle tracking (PEPT), reveals the behaviour of granular materials by tracking single, fast-moving particles labelled with a tracer, and has been extensively used in the food and bioengineering industries, for example.

The nutrition and health of African children has been evaluated at the University of Surrey with the nuclear technique of neutron activation analysis which determined the concentrations of key elements in hair samples.

RADIOACTIVE ION BEAMS
Beams of unstable nuclei, produced for astrophysics and nuclear-structure experiments, are also used to probe materials, since their pattern of decay is perturbed by the immediate sample environment. Ion beams produced at FAIR will be employed to simulate and evaluate the effects of radiation on both materials and living tissue.

Left: the motion of individual particles during pharmaceutical processing as visualised with positron emission particle tracking (PEPT); right: the time-averaged motion of a grinding bead inside a mill used for minerals processing.
Applications of radiation detection

Research in nuclear physics has led to better methods for detecting radiation from both natural and anthropogenic sources, which is increasingly important for maintaining national security and monitoring environmental change.

SECURITY
The PORGAMRAYS project
UK researchers are collaborating with industrial partners to develop a portable radiation sensor and imager, based on AGATA gamma-ray tracking technology (p14), and using room-temperature CZT sensors (p14), aimed at detecting radioactive waste and ‘dirty bombs’.

Other radioisotopes such as carbon-14, which are produced by cosmic-rays, offer methods of dating over short timescales. A sample is often converted into an ion beam to allow single ions to be detected (accelerator mass spectrometry, AMS). Carbon-14 dating has become a particularly significant technique because it can be applied to biological materials.

The DISTINGUISH project
A consortium (Universities of Lancaster, Liverpool and Manchester) is building a system using neutron activation, which is based on high-purity germanium detectors and digital pulse-shape processing (p14), to screen cargo and baggage in transit for explosives.

ENVIRONMENT
Small concentrations of radioisotopes are used to track pollutants such as acid rain or the effects of climate change. The Scottish Universities Environmental Research Centre (SUERC), operated jointly by the Universities of Edinburgh and Glasgow, carries out studies on both natural and anthropogenic environmental radioactivity.

The decay of certain long-lived radioactive isotopes, such as those of uranium, provide a set of crucial tracers and dating tools for analysing geological processes such as erosion, and studying planetary evolution. The accuracy of the data may depend on understanding how the isotopes were first formed in stars, which nuclear astrophysics experiments can probe.

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ARCHAEOLOGY AND ART
Radiocarbon dating covers the past 50,000 years, making it ideal for studying human activities from prehistoric times. The first dedicated radiocarbon dating centre, the Oxford Radiocarbon Accelerator Unit, has famously dated the Turin Shroud, and the 4500 years-old ‘Iceman’ found high in the Alps.

Nuclear techniques are used to analyse the element composition of ancient artefacts and art objects to determine their provenance and authenticity. The relatively new technique of neutron radiography, which works like X-ray radiography, provides extraordinary images of the interiors of otherwise impenetrable fossils and archaeological specimens.

Fossilised leaves in a rock can be imaged using neutron radiography
Technology transfer and training

New technologies

Much of the new technology developed for nuclear physics finds use in other fields

Nuclear physics experiments are demanding. They require high-energy particle accelerators and advanced detectors, combined with fast data-acquisition and processing software.

ACCELERATOR TECHNOLOGY

New methods of accelerating nuclear particles, including compact machines and laser acceleration, are already being developed, which can then be applied in other fields. The SCAPA project set up by the Scottish Universities Physics Alliance (SUPA) is developing a laser facility to accelerate ion beams for cancer treatment (p9).

DETECTORS

Experiments involve detecting rare, highly unstable isotopes (p7) via the gamma-rays, protons and neutrons they emit when they lose energy or decay. Most UK nuclear physics groups are involved in developing new, more sensitive detectors, which are then tailored for other applications (p13). Segmented arrays of semiconducting materials such as silicon are used to register charged particles and high-energy radiation. Researchers at the University of Edinburgh and RAL have developed advanced silicon strip devices, originally for nuclear astrophysics experiments (p6), that also incorporate the necessary microelectronics. They work closely with industry; silicon-strip technology is found in medical X-ray machines used for mammography.

Gamma-ray tracking

Ultra-pure germanium is the material of choice for detecting gamma-rays. A germanium-based detector, AGATA, involves novel detection methods developed in the UK that can disentangle how a gamma-ray interacts in the detector. The trajectory can then be tracked, the total energy measured accurately and the event producing it determined. The technology is already being applied in medical (p9) and security detectors (p13).

Digital pulse-shape processing

An important ingredient in extracting the gamma-ray data is to characterise the intensity of the signal recorded over time – the pulse shape. This helps to determine the precise location of each interaction within the detector volume.

Room-temperature detectors

Germanium detectors must be cooled to liquid-nitrogen temperatures, but alternative detector materials based on cadmium, zinc and tellurium (CZT) work at room temperature. A UK university collaboration, HEXITEC, is applying the technology in mobile X-ray and gamma-ray cameras for analytical, medical and space-science applications. In addition, the Universities of Surrey and York are working with the company, Diamond Detectors Ltd, on radiation-hard devices using synthetic diamond for monitoring environmental radiation.

Neutron detectors

Neutrons emitted from nuclear reactions are more difficult to detect, because they do not respond to electric fields. A new neutron detector being developed at the University of York for astrophysics experiments combines a liquid scintillator with digital pulse-shape technology, and could be used for radiation monitoring in nuclear power stations.
As well as driving advances in a broad range of sectors, nuclear physics and technology train people who work in associated industries such as nuclear medicine. Nuclear physics plays a role in inspiring students to take up science, supplying science graduates with technical skills that are vital to a modern economy.

**UNiversities and Industry**
Concerns about climate change and the potential of the nuclear power option, together with a growing recognition of the value of nuclear methods in providing good healthcare and vital national security, has led the government to evaluate how to improve core competencies in the nuclear sectors. All the main UK academic nuclear physics groups now have strong, interdisciplinary collaborative programmes to ensure that there is a transfer of knowledge and skills from basic research into fields such as power generation and radiological science.

**Active Targets**
Many nuclei, created in reactions in a target, exist transiently in minute quantities that are difficult to detect. Physicists at the Daresbury Laboratory, and the Universities of Glasgow, Liverpool and York are working on a new detection system in which the target – a gas of hydrogen or helium nuclei – also acts as the detector. The gas is ionised by nuclear particles, releasing electrons that then produce a signal.

**Schools and Outreach**
Surveys have shown that nuclear physics, along with particle physics and astronomy, attracts school students into science. The STFC, which funds nuclear physics research, encourages researchers to engage in activities that enable children and the general public to appreciate and understand what nuclear physics is about. David Jenkins, a nuclear physicist at the University of York, was for two years an STFC Science in Society Fellow, providing material for teachers’ continuing development programmes and events for schoolchildren. Jim Al-Khalili, a nuclear theorist at the University of Surrey and EPSRC Senior Media Fellow, is well-known for his books and broadcasts on the subatomic world.

Details on all UK nuclear courses can be found at www.nuclearliaison.com and www.world-nuclear-university.org
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