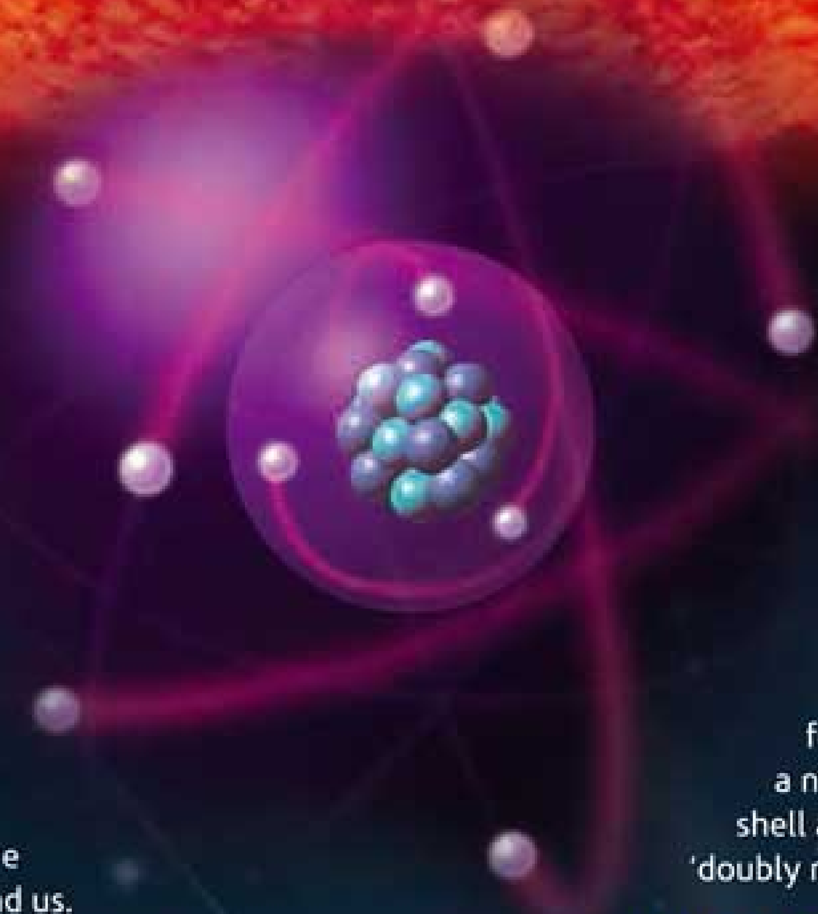
Inside the atom

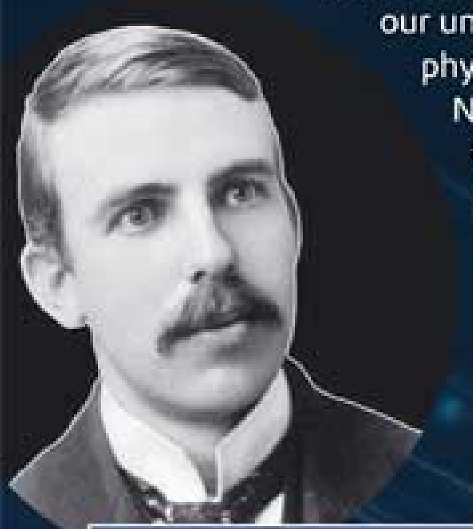
Nuclear activity in the UK



The nucleus: well that is a different matter

The idea of the indivisible atom, held since the time of the ancient Greeks, was smashed just over 100 years ago. Ernest Rutherford and his team of scientists in the UK discovered that atoms have a very dense and extremely small central nucleus that contains more than 99.9% of the mass of an atom and is ten thousand times smaller than an atom.

Nuclear physics is the study of the properties and behaviour of this atomic nucleus and is central to our understanding of the physical world around us. Nuclear physics describes how the Sun generates the energy we need for life on Earth, how almost all the elements in your body were made in stars and what happens in stars when they die. Nuclear physics really is a matter of life and death!



PARTICLE	RELATIVE MASS	ELECTRIC CHARGE
PROTON	1	+1
NEUTRON	1	0
ELECTRON	1/1840	-1

At the heart of the atom

The atomic nucleus is made up of nucleons – protons and neutrons – that are surrounded by a cloud of electrons (table above). An atom is classified by the number of protons and neutrons in its nucleus: the proton or atomic number, Z, determines the chemical element of the atom, and the neutron number, N, determines the isotope of the element. For example, the most common form of carbon found in nature is carbon-12 which has Z=6 and N=6, while one of the radioactive isotopes of carbon – carbon-14 has Z=6 and N=8.

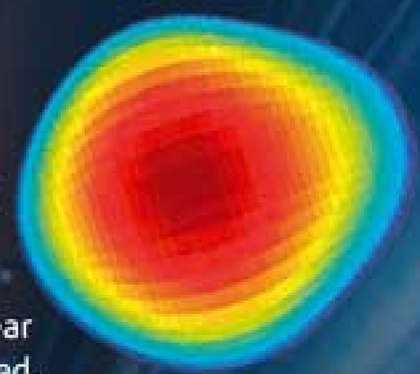
$^{14}_{6}C_{8}$

Magic nuclei

Nucleons in the nucleus sit in energy 'shells', just as electrons in an atom are arranged into shells around the nucleus. Elements with a full electron shell, the noble gases, are particularly unreactive, while a nucleus with the right 'magic' number of protons or neutrons to fill a shell are more stable. Nuclei with full proton and neutron shells are called 'doubly magic'.

It's all gone pear-shaped

Many nuclei have a spherical or rugby ball shape, but some can adopt more unusual shapes. Discovering the exact shape of certain nuclei is an important test of the theories that describe the building blocks of the Universe. Experiments carried out at CERN by UK nuclear physicists indicate some nuclei may even be pear shaped.



FURTHER INFORMATION

If you would like to know more about nuclear physics, try the following links:

Websites

www.stfc.ac.uk/NuclearPhysicsForYou
www.iop.org/education/teacher/resources
http://ph.qmul.ac.uk/engagement/physics-kits
www2.lbl.gov/abc
http://ed.ted.com/lessons/just-how-small-is-an-atom
www.stfc.ac.uk/nuclearphysics

UK Nuclear Physics Groups

University of Birmingham
www.np.ph.bham.ac.uk

University of Brighton
http://about.brighton.ac.uk/nprg

STFC Daresbury Laboratory
www.stfc.ac.uk/npg/

University of Edinburgh
www2.ph.ed.ac.uk/nuclear

University of Glasgow
http://nuclear.gla.ac.uk

University of Liverpool
www.liv.ac.uk/physics/research/nuclear-physics

University of Manchester
www.nuclear.manchester.ac.uk

University of Surrey
www.surrey.ac.uk/physics/cnrp/

University of the West of Scotland
www.uws.ac.uk/nuclearphysics

University of York
http://npg.york.ac.uk

Acknowledgements

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Science & Technology Facilities Council

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The Council's Public Engagement team offers a wide range of support for teachers, scientists and communicators to facilitate greater engagement with STFC science which includes astronomy, space science, particle physics and nuclear physics:

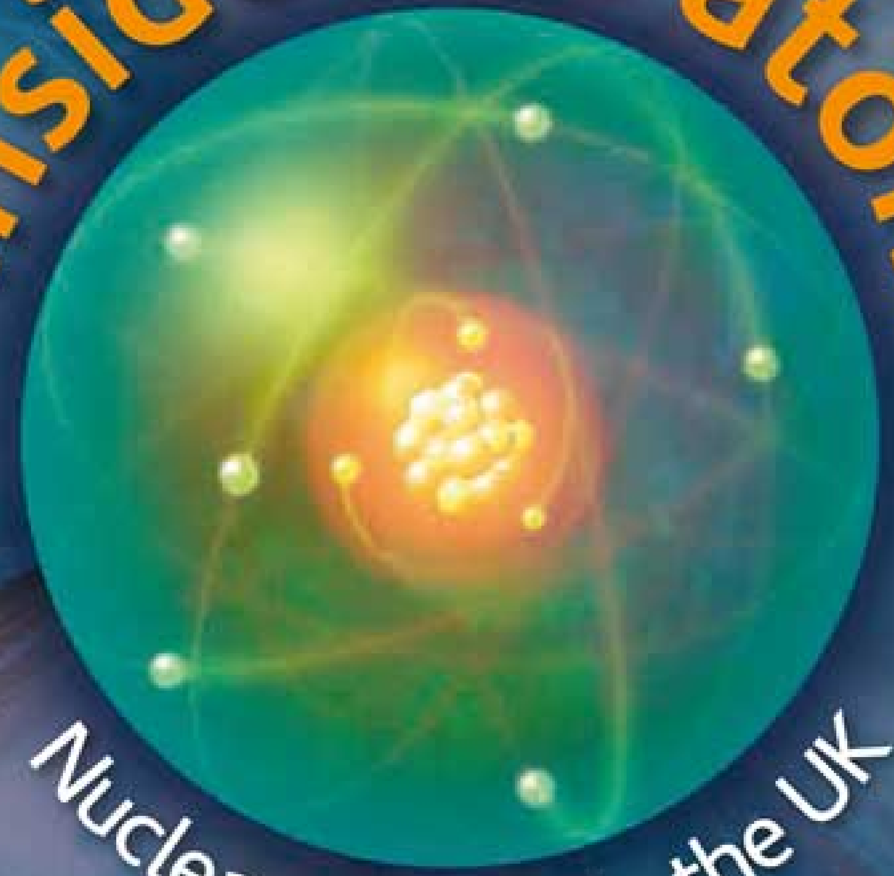
For Schools

- Free resource guides suitable for teaching ages 10-18. www.stfc.ac.uk/teachers
- STFC educational publications dealing with many aspects of fundamental physics. www.stfc.ac.uk/pepublications
- Funding schemes for projects and school visits. www.stfc.ac.uk/pefunding
- A Moon rock and meteorite loan scheme. www.stfc.ac.uk/moonrocks

For Scientists

Communication and media training courses, funding schemes and fellowships for public engagement. Go to www.stfc.ac.uk/pefunding

For further information contact the STFC Particle and Nuclear Physics Outreach Officer:
Elizabeth.Cunningham@stfc.ac.uk



Science & Technology Facilities Council

Limits of existence

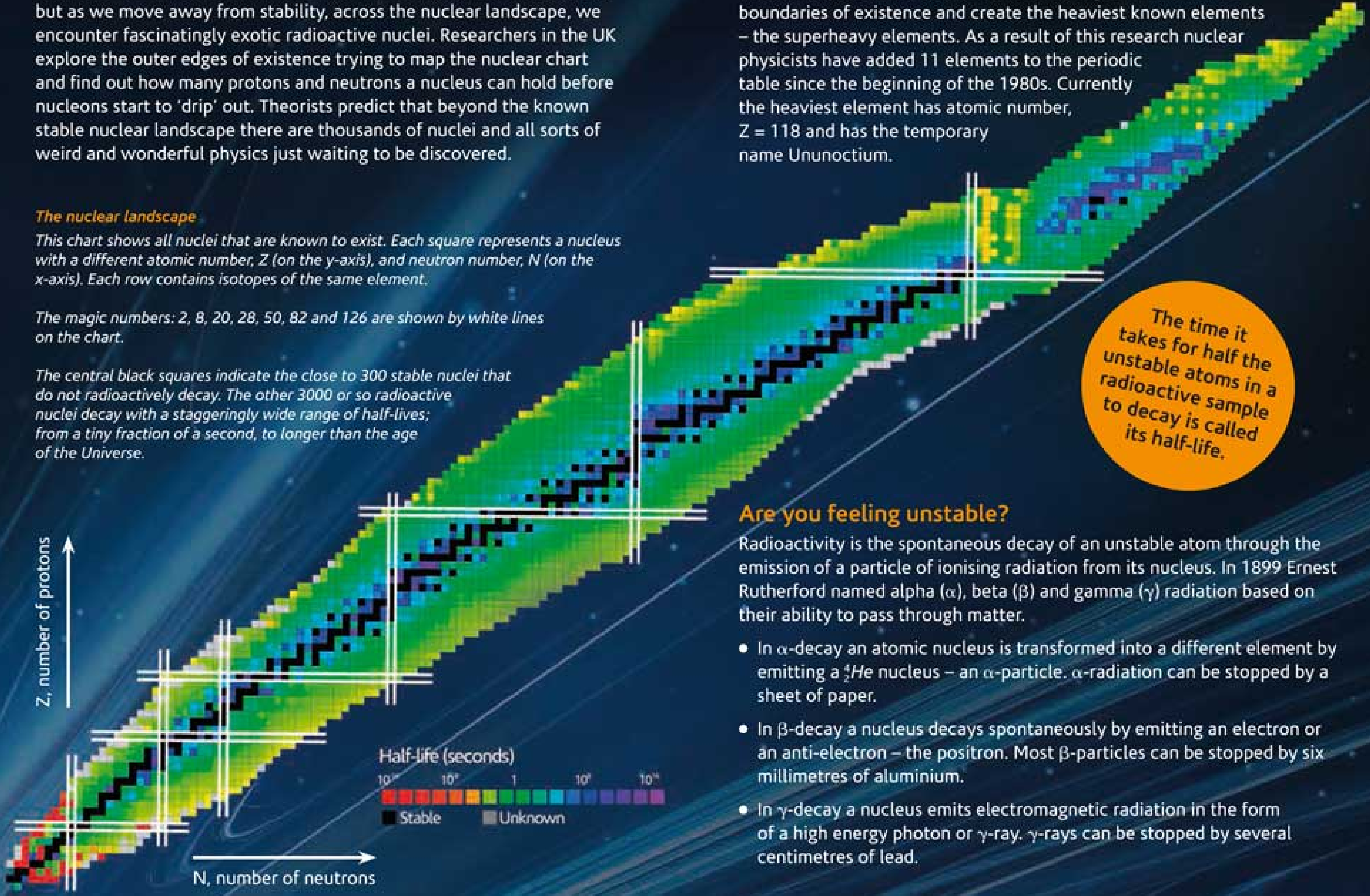
Stable isotopes make up the majority of the everyday world around us, but as we move away from stability, across the nuclear landscape, we encounter fascinatingly exotic radioactive nuclei. Researchers in the UK explore the outer edges of existence trying to map the nuclear chart and find out how many protons and neutrons a nucleus can hold before nucleons start to 'drip' out. Theorists predict that beyond the known stable nuclear landscape there are thousands of nuclei and all sorts of weird and wonderful physics just waiting to be discovered.

The nuclear landscape

This chart shows all nuclei that are known to exist. Each square represents a nucleus with a different atomic number, Z (on the y-axis), and neutron number, N (on the x-axis). Each row contains isotopes of the same element.

The magic numbers: 2, 8, 20, 28, 50, 82 and 126 are shown by white lines on the chart.

The central black squares indicate the close to 300 stable nuclei that do not radioactively decay. The other 3000 or so radioactive nuclei decay with a staggeringly wide range of half-lives; from a tiny fraction of a second, to longer than the age of the Universe.



Superheavy elements

Nuclear physicists across the world work together to push the boundaries of existence and create the heaviest known elements – the superheavy elements. As a result of this research nuclear physicists have added 11 elements to the periodic table since the beginning of the 1980s. Currently the heaviest element has atomic number, Z = 118 and has the temporary name Ununoctium.

The time it takes for half the unstable atoms in a radioactive sample to decay is called its half-life.

Are you feeling unstable?

Radioactivity is the spontaneous decay of an unstable atom through the emission of a particle of ionising radiation from its nucleus. In 1899 Ernest Rutherford named alpha (α), beta (β) and gamma (γ) radiation based on their ability to pass through matter.

- In α-decay an atomic nucleus is transformed into a different element by emitting a $^{4}_{2}He$ nucleus – an α-particle. α-radiation can be stopped by a sheet of paper.
- In β-decay a nucleus decays spontaneously by emitting an electron or an anti-electron – the positron. Most β-particles can be stopped by six millimetres of aluminium.
- In γ-decay a nucleus emits electromagnetic radiation in the form of a high energy photon or γ-ray. γ-rays can be stopped by several centimetres of lead.

Elementary particles

Until the 1960s protons and neutrons were believed to be elementary particles that could not be broken down into smaller parts. We now know that nucleons are composite particles made up of quarks. Quarks are bound together by a force known as the strong interaction, which is mediated by the exchange of particles called gluons. Quarks and gluons are now considered to be elementary particles.

The first nucleons

A few millionths of a second after the Big Bang, the Universe was too dense and too hot for protons and neutrons to exist. In these conditions, scientists believe that quarks and gluons would be free in a new state of matter called quark-gluon plasma (QGP). Experiments like ALICE at the LHC at CERN aim to study the transition between QGP and normal nuclear matter to help us answer these important fundamental questions:

1. What is the mechanism that causes quarks to be confined? No quark has ever been observed by itself, they are always found confined within particles like nucleons.
2. Where does nucleon mass come from? For protons and neutrons, only about 1% of their mass arises from the quarks themselves, the strong force is somehow responsible for the rest.

Birth... Life... Death...

Nuclear processes are involved at every stage of a star's life: from birth, when hydrogen fusion begins in its core – to death, when the nuclear fuel in its core runs out. Stars spend most of their lives fusing hydrogen nuclei into helium nuclei, but it is when a star dies that much more dramatic nuclear reactions can occur. The death of a star may hold the key to understanding how most of the elements needed for life on Earth – like carbon and oxygen – were created.

We are made of star stuff

How a star dies depends on how massive it is. Stars less than eight times the mass of our Sun become unstable when the fuel in their centre runs out. Their outer layers blow away leaving behind a dense hot core called a white dwarf star. Stars with more than eight solar masses collapse under their own gravity and then explode as a supernova. The Crab Nebula (pictured below) shows a beautiful example of a supernova remnant. In the violent environments found in a supernova, nuclear processes lead to the 'nucleosynthesis' of the elements. Nuclear astrophysicists in the UK work to use their knowledge of atomic nuclei to explain the processes involved in nucleosynthesis.

INSIDE THE ATOM: nuclear activity in the UK

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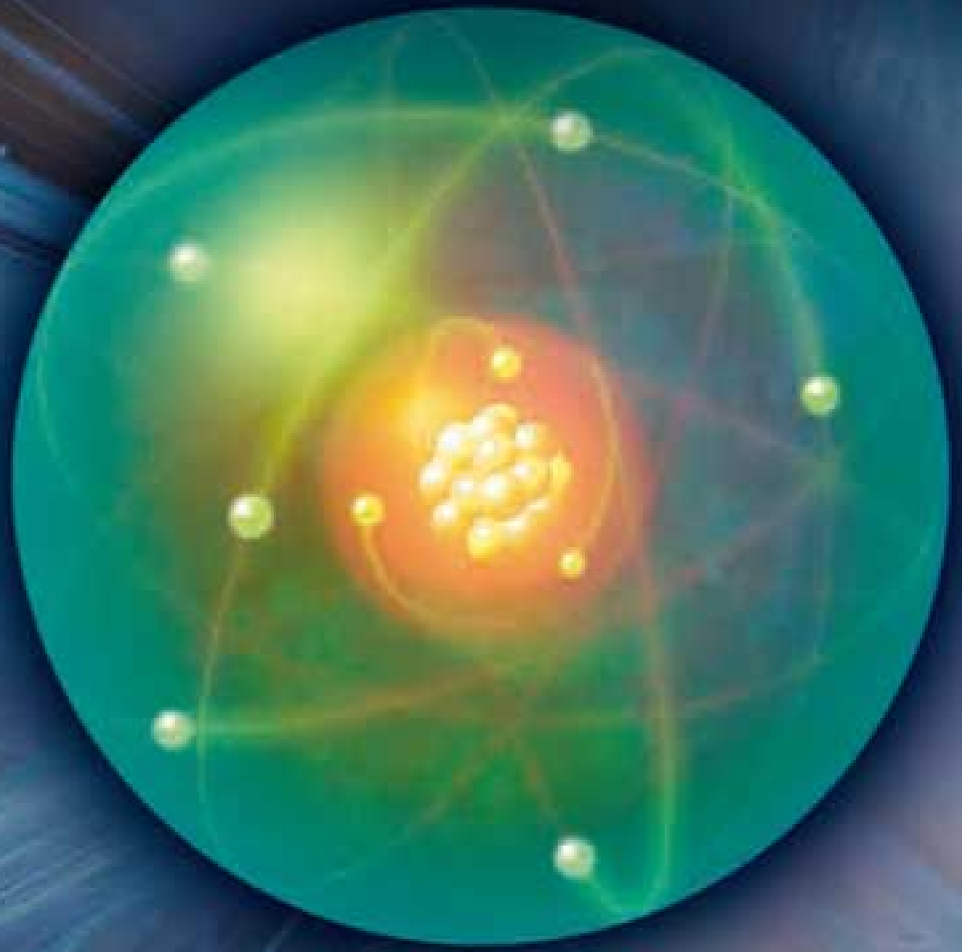


Security and the environment

In order to answer the big questions in nuclear physics, researchers continually have to develop new and innovative ways to detect and measure radiation. The advanced detectors developed for this fundamental research can also be tailored for other fields and wider applications. Of particular interest is the development of portable radiation sensors and imagers that can quickly and accurately identify materials. This type of detector would have a wide range of important applications: from decontamination and clean-up of radioactive waste, to screening cargo and baggage in transit.

Radiometric dating

Using nuclear techniques to identify the different amounts of stable and radioactive isotopes in a sample, along with the knowledge of how they decay, enables scientists to determine the age of an object. This technique has been used to date meteorites, historical artefacts and even our own solar system. As there are a large number of different radioactive isotopes that decay at different rates, multiple dating measurements can be taken from a sample to date it reliably. One of the most well-known forms of radioactive dating is carbon, Z=6, dating.

The half-life of carbon-14 is 5700 years, so it can be used to date material up to about 60,000 years old. Isotopes with extremely long half-lives, such as uranium-238 with a half-life of 4.5 billion years, enable us to date much older objects. By looking at the proportion of uranium isotopes in meteorites, compared with the elements created when they decay, the age of the Earth has been determined to be 4.54 billion years.

Nuclear power

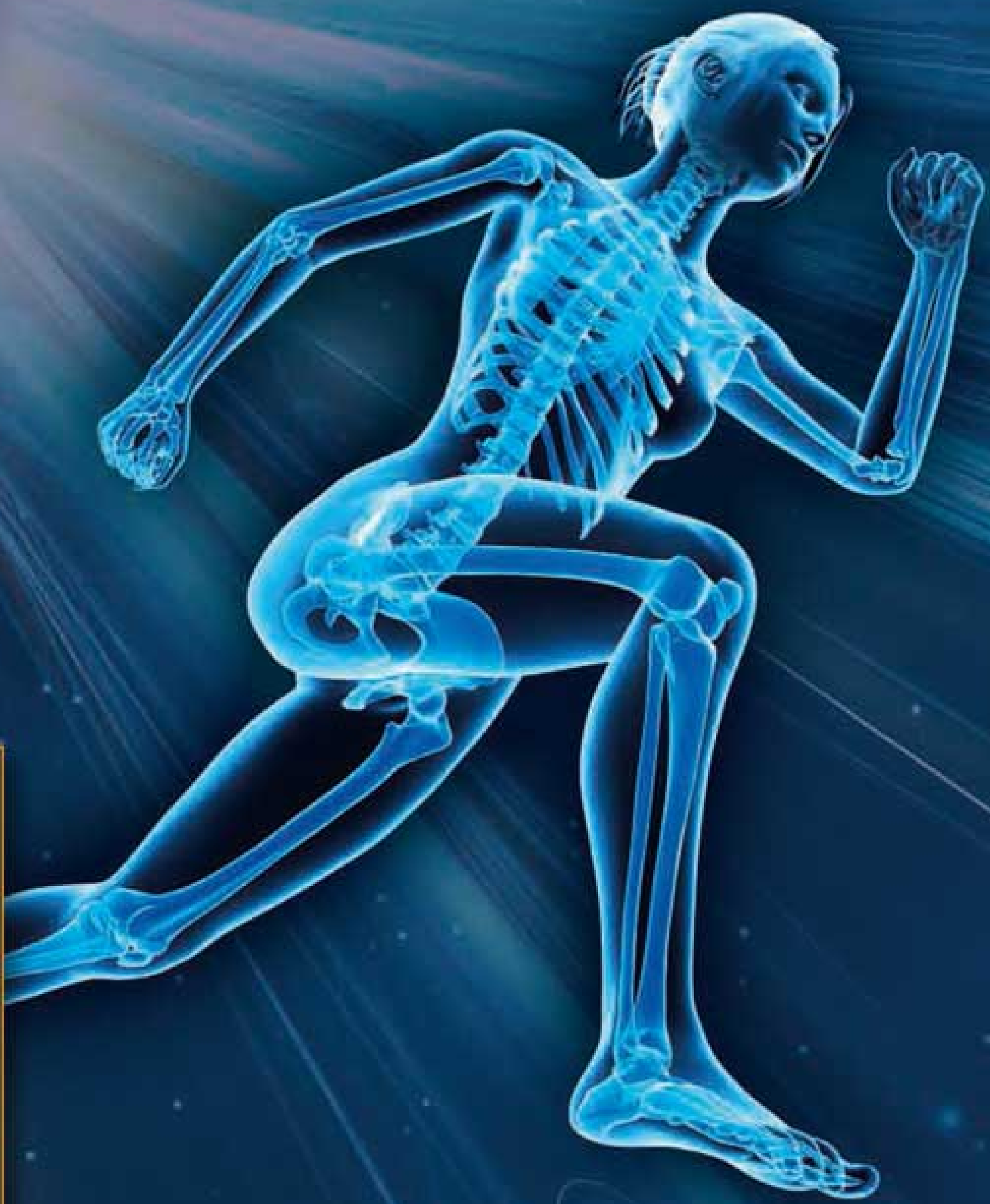
Nuclear power stations generate energy through nuclear fission, the splitting apart of heavy atomic nuclei. When elements like uranium, Z=92, fission, the large nucleus splits into smaller 'daughter' nuclei releasing a lot of energy, which can be harnessed to produce electricity. There are 16 operational nuclear reactors in the UK and they generate about 18% of the UK's electricity. By 2023 13 of these nuclear reactors will be due for decommissioning. Scientists are using ISIS at RAL to investigate how materials in the reactors behave after long term irradiation. This will help to determine if the lifetimes of these power stations can be safely extended to help keep 'the UK's lights on' while new reactors are built.

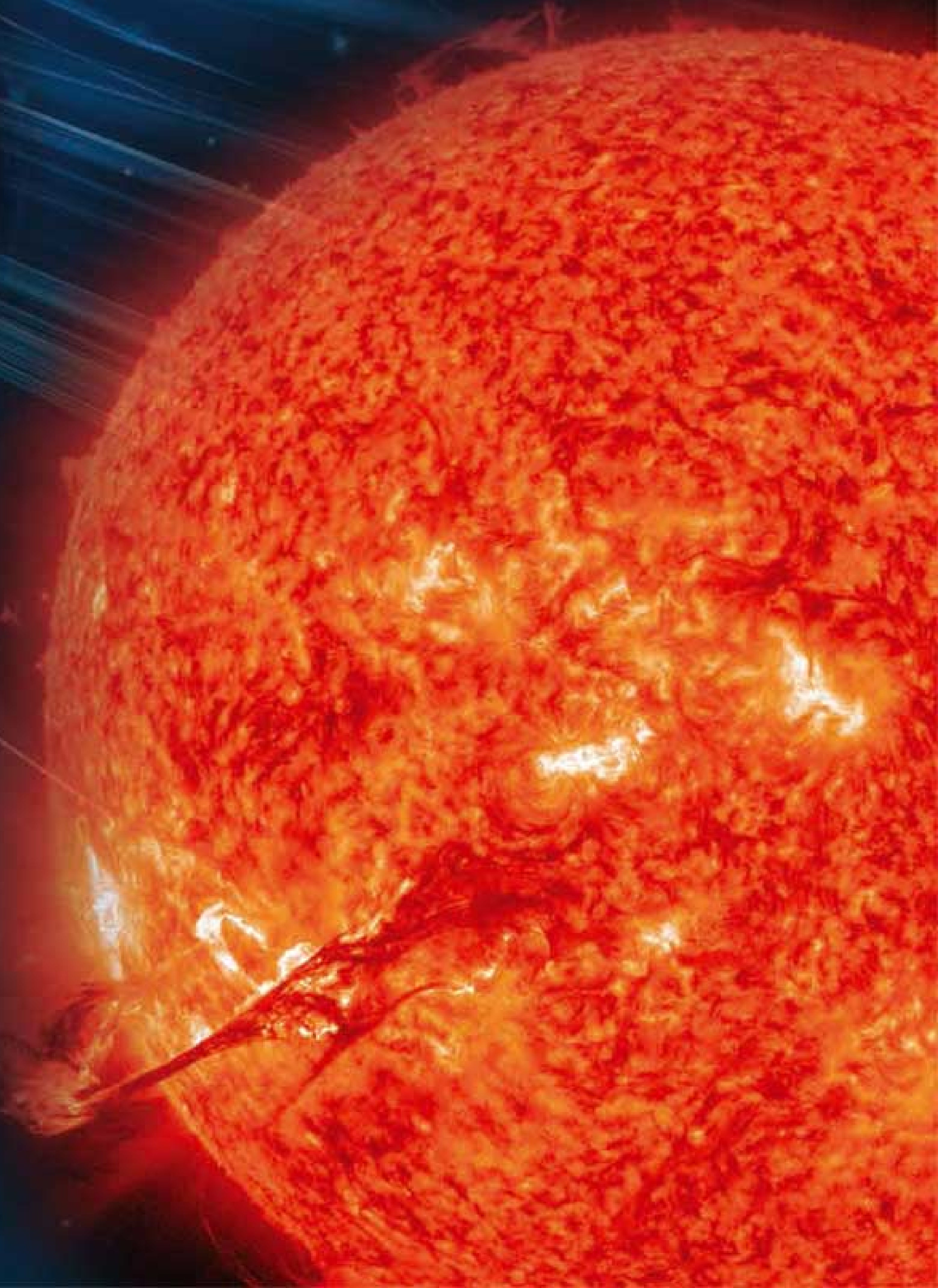
Nuclear fusion

Harnessing the nuclear fusion reactions that power the Sun could provide a clean and inexhaustible supply of energy to help meet the world's needs. To generate energy from fusion on Earth gases of two types of hydrogen isotopes – deuterium and tritium – have to be heated to 100 million degrees Celsius to ignite the fusion reaction. To help develop materials that can withstand these temperatures, and the radiation generated by the fusion reaction, nuclear physicists in the UK are studying the properties of the nuclear reactions likely to occur in these materials.

Nuclear applications

Research into nuclear physics has enabled the development of science and technology that directly benefits us. Whether it is saving lives through nuclear medicine or investigating a long dead civilization using radiometric dating, nuclear physics really is a matter of life and death! Here are just a few examples of how nuclear processes and ionising radiation are being used to improve our lives and address the future needs of the UK.





National laboratories

Science & Technology Facilities Council

See the science

STFC's national laboratories house world leading science and technology facilities. They offer a wide range of unique opportunities for visits and events to enhance and enrich science learning.

The STFC **Daresbury Laboratory**, south west of Warrington in Cheshire, is home to the STFC Nuclear Physics Group. Additionally Daresbury houses the Accelerator Science and Technology Centre and the Cockcroft Institute of accelerator science.

The STFC **Rutherford Appleton Laboratory** in Harwell, Oxfordshire is home to ISIS, one of the world's leading neutron scattering accelerators. It is also home to the Central Laser Facility and the Diamond Synchrotron Light Source.

At Daresbury and RAL you can meet world class scientists and engineers through visits, masterclasses and public talks, as well as participate in work experience, apprenticeships and continued professional development for educators.

To find out more go to **www.stfc.ac.uk/seethescience**

Nuclear medicine

Everybody will know someone who has benefitted from a medical procedure based on applications from nuclear physics. Whether they have had a routine X-ray or undergone radiotherapy to treat cancer – nuclear medicine is important for both diagnosis and treatment of disease.

Many radioactive isotopes are used for imaging in medicine. Single Photon Emission Computed Tomography (SPECT) uses γ-ray emitting isotopes to image the patient, while Positron Emission Tomography (PET) use those that beta-plus decay and emit positrons. SPECT is cheaper than PET, mainly because the radioisotopes used are longer lived and more easily obtained, but SPECT has a lower image resolution. Nuclear physicists in the UK are working on a novel SPECT imager that could be a factor 30-100 more efficient than existing scanners. This would allow more detail to be seen in images faster or enable shorter imaging times to lower the dose of radiation to patients. This could potentially mean SPECT could be used to screen for breast cancer in patients with dense tissue where X-ray screening often fails to spot tumours. These advances are a direct result of the technical developments in detectors and electronics made in the Advanced Gamma Tracking Array (AGATA) project for gamma-ray imaging, in which UK nuclear physicists have taken a leading role.

Nuclear physics in the home

The most common domestic smoke alarms use a radioactive isotope of the element americium, Z=95, to detect smoke. In a smoke detector a very small americium-241 source emits alpha particles into an ionisation chamber that is open to the air. The air in this chamber becomes ionised, allowing a very small electrical current to flow. If smoke is present this current drops and the alarm sounds.

A wide variety of household items are sterilised using ionising radiation; from plastic materials, cables, wires and car parts; to food packaging and even gemstones. The radiation, usually γ-rays, destroys bacteria and viruses using much less energy than sterilisation through heating. Medical equipment and some food are also sterilised using ionising radiation, as sterilisation can occur after packaging, further reducing the risk of contamination.