Nuclear physics is the study of the properties and behaviour of the 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!

At the heart of the atom
The atomic nucleus is made up of 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=10.

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 nuclei with the right ‘magic’ number of protons or neutrons to fill a shell are more stable. Nucleon with full proton and neutron shells are called ‘double 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.

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 mediates the exchange of particles called gluons. Quarks and gluons are now considered to be elementary particles.

The first nucleons
A few radiations 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 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 nuclear mass come from? For protons and neutrons, only about 1% of their mass arises from the quarks themselves, the rest is somehow responsible for the rest.

Superheavy elements
Nuclear physicists across the world work together to push the boundaries of fundamental discoveries. They are probing 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 20th century. Currently the heaviest element has atomic number, Z = 118 and its temporary name Ununpentium.
INSIDE THE ATOM: nuclear activity in the UK

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: decontamination and clean-up of radioactive waste, in screening cargo and baggage in transit.

Radioactive 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. As a result, 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 5770 years, so it can be used to date material, up to 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 medicine
Everybody will know someone who has benefited 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-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 radionuclides 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 breast 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 shrinks 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 cigars. 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.

Nuclear power
Nuclear power stations generate energy through nuclear fission, the splitting apart of heavy atomic nuclei, such as 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 ISS 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 being 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
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 Acceleration 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 also home to the Central

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