

7. Applications of nuclear physics

Interactions with everyday life

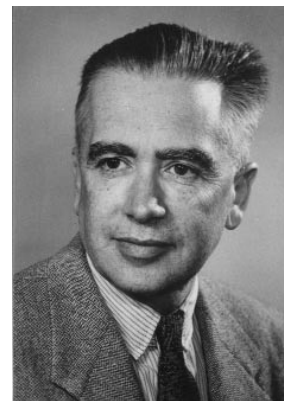
By the 1930s, nuclear physics was entering a golden age. Almost all the elements were known and their chemical properties established: from hydrogen with its nucleus consisting of just one proton, to uranium with 92 protons and well over a hundred neutrons. There remained just a few conspicuous gaps in the periodic table – apparently, elements with certain atomic numbers simply did not exist on Earth. Nuclear physicists have since artificially created and identified the nuclei of these elements; one, in particular, has turned out to play a vital role in modern medicine and has also become of great significance to astronomers.

The element in question has atomic number 43 and was discovered in 1937. In that year Ernest Lawrence used his new particle accelerator, the cyclotron, to send a beam of deuterons onto a target containing element 42, molybdenum. When the deuterons, the nuclei of an isotope of hydrogen containing just a proton and a neutron bound together, interacted with the molybdenum nuclei, reactions took place making the target radioactive. Some deuterons deposited their neutron in the molybdenum target nuclei, while their proton continued on its way; the extra neutron in these molybdenum nuclei caused them to become unstable and suffer beta decay, with a neutron becoming a proton accompanied by the emission of an electron and an anti-neutrino. In this manner, element 42 becomes element 43.

Lawrence did not study the molybdenum targets himself – he sent them off to a promising young student of Fermi, Emilio Segrè, who had just taken up a post in Palermo, Sicily. Segrè and his colleague, Carlo Perrier, analysed the targets and found traces of a hitherto unknown element which they succeeded in identifying as the missing element 43. Later, they called this element technetium, since it was the first element produced by artificial, or ‘technological’ means. It was given the symbol Tc and a gap in the table of the elements was filled.

No one had found technetium on Earth because it has no stable isotopes. Even the longest-lived isotope has a half-life of just over four million years – short enough for any amount of technetium originally present on Earth when the Solar System was formed to have decayed away.

Subsequently a number of other missing elements – 61 (promethium), 85 (astatine) and 87 (francium) – were also produced using nuclear reactions, but it is technetium which has become deeply significant to the lives of many thousands of people. As an example of its importance, when the world supply of technetium was threatened by a strike at a nuclear laboratory in Canada in 1998, the President of the American College of Nuclear Physicians wrote a strongly worded letter to the Canadian Prime Minister pointing out that 47,000 medical procedures per day, in the USA alone, were under threat. In addition, medical procedures throughout the world were being cancelled.



Emilio Segrè, 1905–1989,
shared the 1959 Nobel prize in
physics with Owen Chamberlain for
the discovery of the anti-proton.
He had many other discoveries to his
credit, including new elements.
(AIP Emilio Segrè Visual Archives)

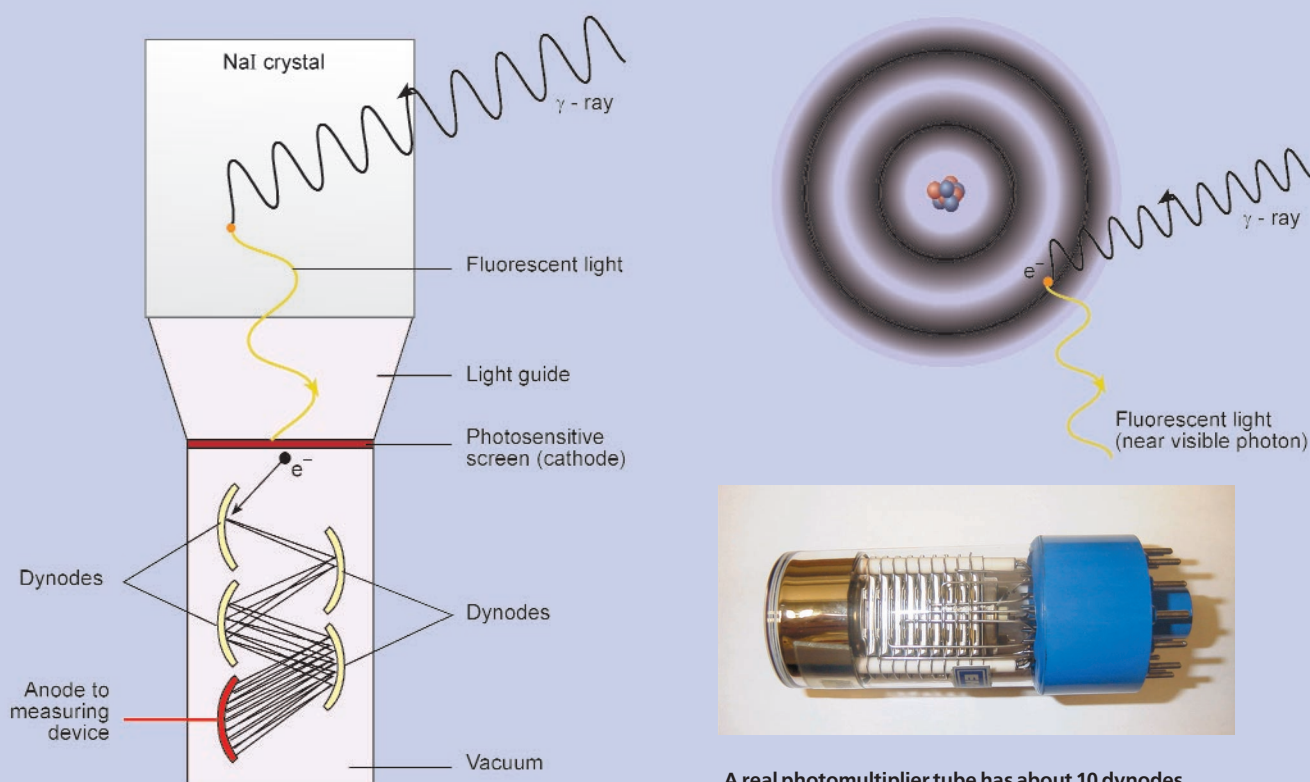
The technetium story is one example of how human exploration of the heart of matter has led to discoveries which have become part of everyday life. Modern medicine and industry would be untenable without them.

Detecting and measuring radiation

Before exploring how radioactive elements are used in medicine and industry, we must examine what happens when radiation passes through matter and how it is detected and measured.

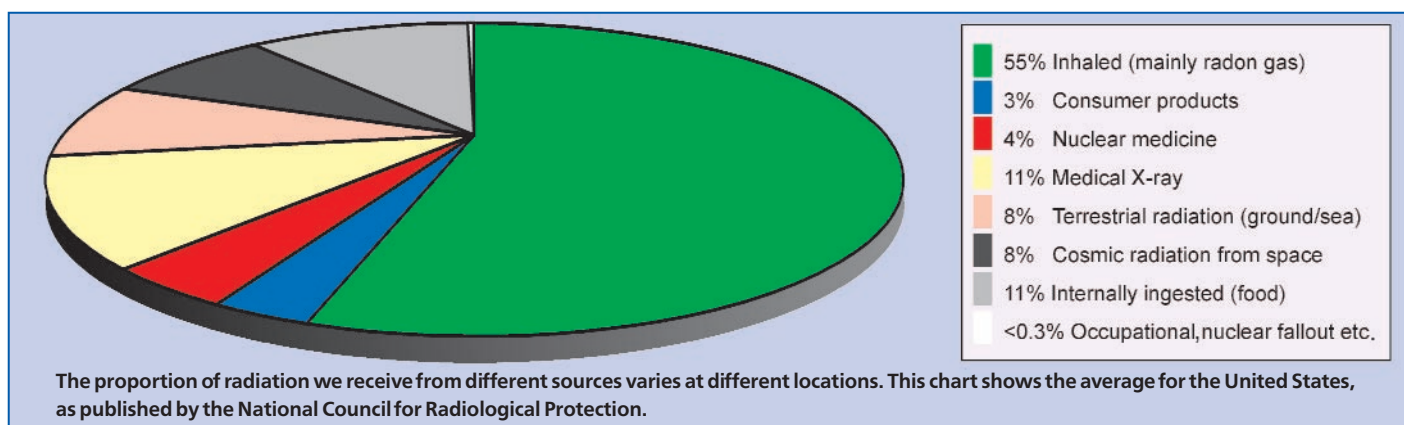
The key to all the effects of radiation – useful and life saving, as well as damaging and life threatening – is its power to ionize the material through which it passes. Alpha, beta and gamma rays are all examples of ionizing radiation. As an alpha particle, for instance, passes through matter, it knocks electrons out of atoms and molecules, ionizing them. This can destroy the molecules and, if they are in living tissue, temporarily or permanently damage the cells containing them. As it ionizes matter, the alpha particle will lose energy and slow down until it eventually comes to rest.

Detecting gamma rays



A real photomultiplier tube has about 10 dynodes, and about a million electrons reach the anode for each electron ejected from the photocathode.

A modern means of detecting gamma rays and measuring their energy relies on scintillations, the flashes of light given off as gamma ray photons interact with suitable substances. A common choice is a crystal of sodium iodide, NaI, doped with about 1% of thallium. A gamma ray disturbs the electrons of many atoms (one is shown here) and each atom emits photons of visible light as it settles down. The higher the energy of the gamma ray, the more photons are emitted. By measuring the intensity of the flash, the energy of the gamma ray can be measured. Photons comprising the flash are guided to a photomultiplier where they release electrons from a photocathode into a vacuum tube containing a series of dynodes. The electrons are accelerated from dynode to dynode by an electric field, and each time they strike a dynode more electrons join the stream, ending up at the anode where they enter an electronic measuring circuit. The whole system is called a gamma ray spectrometer.



Gamma rays and X-rays also ionize the material they pass through. They eventually disappear by being absorbed by the atoms, rather than losing energy by slowing down. As they are forms of electromagnetic radiation, there is only one possible speed for X-ray and gamma ray photons: the speed of light.

All kinds of ionizing radiation have a range beyond which they are effectively fully absorbed. This range depends on the energy and the nature of the material; lead, for example, is more effective than most materials at stopping radiation and is therefore used for shielding.

Natural and artificial radiation

Natural radiation is all around us. Over the history of life on Earth, living creatures have evolved senses which warn of dangers such as excessive temperature and approaching predators, but humans, at least, have no sense that responds rapidly to ionizing radiation. We are quite unaware of any variation in the radiation to which we are subjected. Natural sources of radiation include the ground we walk on, the air we breathe and the food we eat. Some naturally occurring radioactive isotopes, such as uranium and thorium, are left over from the time when the Earth was formed – others, such as the carbon isotope ^{14}C , and tritium, ^3H , are made by interactions within the atmosphere when high energy particles (cosmic rays) bombard the Earth from space.

One of the most abundant radioactive isotopes found on Earth is that of potassium, ^{40}K , which makes its way into the food chain. It exists as small traces alongside the stable isotope, ^{39}K , which is vital for life. Once ingested, the traces of ^{40}K decay inside our bodies. Another radioactive element absorbed by humans is ^{14}C . All living organisms take in carbon, which contains a constant fraction of radioactive ^{14}C . Once an organism dies and stops taking in carbon, the amount of ^{14}C can be used to determine the time elapsed since death. This is the basis of carbon dating.

The largest amount of natural radiation to which humans are exposed is by breathing in the noble gas, radon. Radon is a decay product of uranium found in rocks. It is chemically inactive allowing it to migrate through porous materials such as house foundations. Once in the air inside the house it can be breathed in, where it has a chance of decaying inside the lungs.

The amount of radiation we receive depends on the kind of rocks in the ground beneath us, how high we live above sea level and, in recent times, what sort of job we do. Dentists giving X-rays to their patients, or miners working underground in certain kinds of rock, will receive extra radiation. Airline crews who spend more time than most at high altitudes also receive extra radiation from the effects of

cosmic rays. The natural background radiation varies a great deal, and is usually much greater than man-made radiation.

We all experience some man-made ionizing radiation – from minute amounts emitted by smoke detectors to sometimes quite substantial doses encountered in medical treatments. Many people have jobs involving low levels of radiation and we also receive radiation from the nuclear power industry. While these sources are usually very much smaller than the background, the Chernobyl incident serves as a warning that this powerful force must be treated with respect.

Nuclear physics in medicine

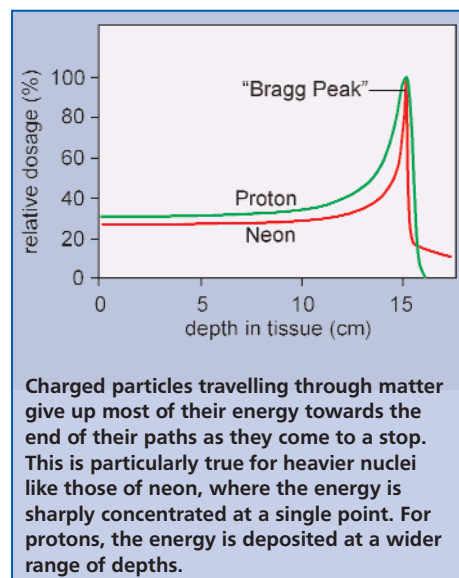
Everybody will know of someone who has benefited directly from applications of nuclear physics in medicine. Some measure of its importance can be judged from the cold monetary figures: worldwide, nuclear medicine is a \$10 billion per year business. In Europe and the US, radioisotopes are used in some way in the treatment of almost half of all patients admitted to hospital.

Nuclear medicine is important for both diagnosis and therapy. Diagnosis ranges from routine use of X-rays to injection of radioactive material for gamma imaging, while the best-known use of radiation for treating disease is radiotherapy used against cancer. The power of radiation to cure is often less publicized than its power to do harm – radiation as invisible scalpel rather than invisible dagger. Just as a scalpel must be wielded with extreme care, so radiation must be carefully controlled. Doctors who prescribe such radiotherapy must weigh the risks of radiation against the benefit of the treatment.

The effect of radiation on living tissue does not just depend on how much energy is deposited, but also on the type of particles involved. When a gamma ray strikes the nucleus of a cell, one half of the double strand of the genetic material DNA might be broken, but there is a good chance that the cell will repair itself. When an alpha particle passes through a cell, the much more intense trail of ionization is more likely to destroy both strands, something the cell cannot repair. Fortunately, alpha particles have a short range, and will not pass through human skin; unfortunately, there are some sources of alpha particles, such as radon gas, which can enter the body just from the air we breathe. However, extensive surveys in the US and UK have found virtually no correlation between environmental radon levels and disease, which illustrates the adaptive power of living organisms.

There are two reasons why radiation from radioactive nuclei and high energy particles from accelerators are powerful weapons against disease. Firstly, radiation preferentially destroys fast growing tissues such as cancers. Secondly, radiation can be concentrated in the specific tissues which need to be destroyed. This is particularly true for beams of protons and heavier nuclei. Such particles give up most of their energy at the end of their path so that it is possible to arrange for the dose to be delivered to a well-defined volume within the patient's body.

Before a medical condition can be treated, it must be detected and a diagnosis made. Many gamma-emitting radioisotopes, such as technetium, can be used as 'tracers'. Wherever a tracer goes in the body it can be followed by suitable detectors which measure its characteristic radiation. It can be made into a chemical form that concentrates in particular organs, allowing the precise location, shape and biochemical function of those organs to be mapped out. This is something X-rays cannot do with soft tissue.





Using beams of carbon nuclei to destroy cancer; the first patient on the treatment couch at GSI, Darmstadt, Germany. (Gaby Otto, GSI.)



A patient prepared for therapy for a brain tumour using a beam of high energy carbon nuclei at GSI. (Achim Zschau, GSI.)



The neutron beam treatment room at Harper Hospital in Detroit. (Courtesy Harper Hospital, Detroit, Michigan, United States.)

Unlike X-rays, heavy ions deliver their energy towards the end of their path through tissue. At GSI in Darmstadt, Germany, accelerated beams of carbon nuclei concentrate their destructive power precisely throughout the volume of a cancer, with relatively little damage to the rest of the body. Neutron beams, used at Harper Hospital in Detroit are effective against particular cancers such as prostate cancer. Since they are uncharged, they cause no ionization along their path through the tissue, until they strike their target.



The magnetic pole-piece, an essential part of the neutron therapy cyclotron at Harper Hospital. (Courtesy Harper Hospital, Detroit, Michigan, United States.)

The particular form of technetium used as a tracer is called $^{99\text{m}}\text{Tc}$. This is an excited state of the isotope of technetium with 56 neutrons as well as the 43 protons. The 'm' (for metastable) indicates a very unusual property – it is an 'isomer', a long-lived excited state. Nuclei, like all quantum systems, have excited states which decay to states of lower energy, usually giving off the energy difference as gamma rays (photons). Normally, the photons are emitted within billionths of a second of the nuclear state being produced, but there are a few cases where they are delayed. Such a case is $^{99\text{m}}\text{Tc}$ in which the delay is quite long, with a half-life of six hours. This is helpful in that the $^{99\text{m}}\text{Tc}$ does not emit gamma rays for long in the patient. Moreover, the gamma ray is readily detectable outside the patient.

In addition to technetium, the radioisotopes of a number of other elements such as cobalt, copper, cesium and iodine, are crucial in medicine. Others, such as phosphorus, calcium, chromium, selenium, strontium and xenon, have uses in biomedical research to study anything from metabolism to bone formation and cell function.

An important method in which radioactive tracers are used in medicine, is positron emission tomography (more commonly known as PET). When compounds containing short-lived isotopes such as ^{11}C , or ^{13}N are injected into a patient, they can be followed as they concentrate in particular organs. This is



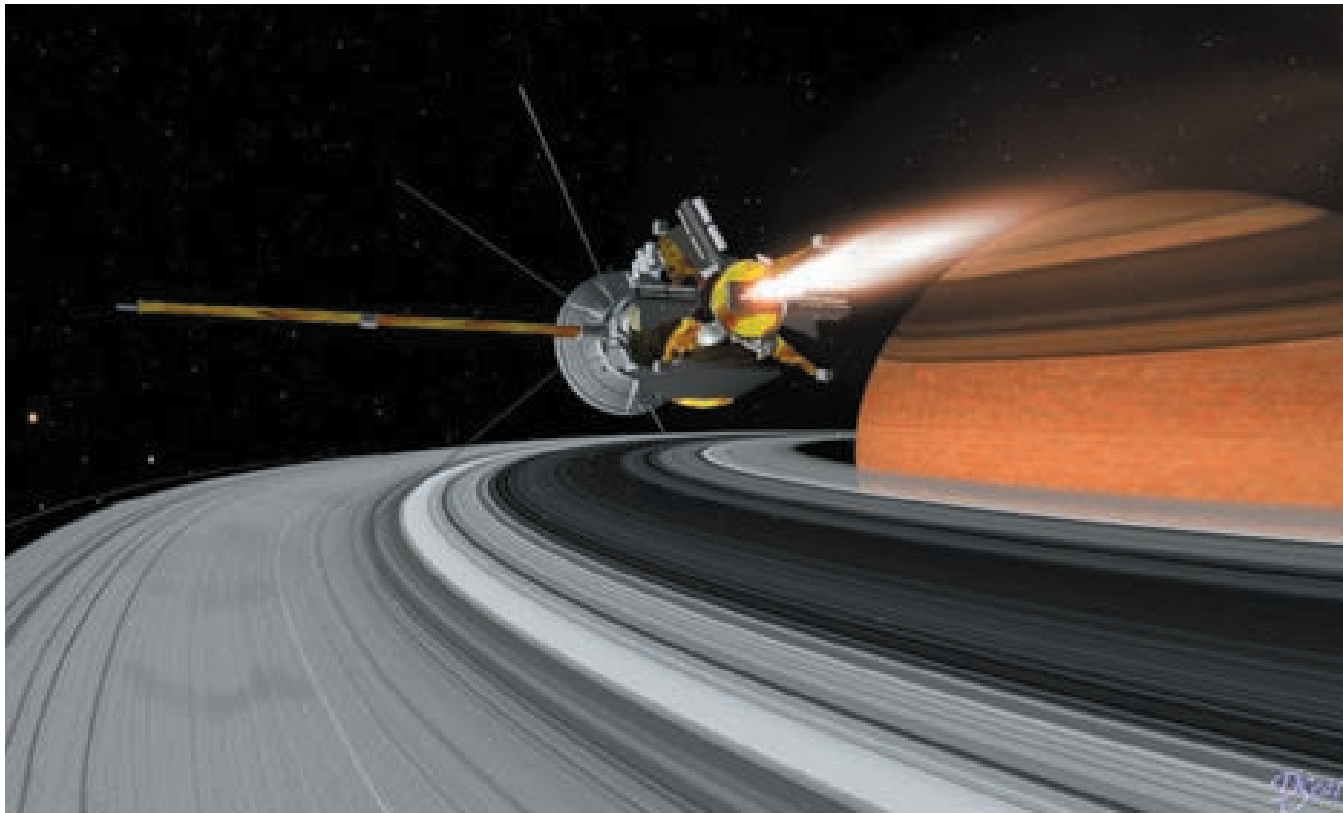
A 'swimming pool' research reactor at the Institute for Nuclear Technology in Portugal. The blue glow (Čerenkov radiation) arises when radiation passes through water, which is used to slow down (moderate) the neutrons formed in fission so they are able to cause other uranium nuclei to undergo fission. Reactors like this have many industrial and scientific uses. (Courtesy the Institute for Nuclear Technology, Lisbon, Portugal.)

possible because they emit positrons as they decay and these particles very quickly encounter their anti-particles, electrons. When this happens, the two particles rapidly annihilate each other and two energetic photons are emitted in precisely opposite directions. By detecting such pairs of photons, with sub-microsecond timing, the place in the body where an ^{11}C or ^{13}N nucleus has decayed can be determined quite accurately. By detecting many such pairs over a period of time, the detailed changes in concentrations of key biological chemicals can be mapped out. The functioning of living hearts, brains and other organs can be studied and their diseases diagnosed. Brain damage suffered in a stroke, for example, can be mapped out precisely. PET has also become an important method for understanding the normal function of the brain and other organs.

Some medical isotopes, such as technetium, are now produced in specialized variants of nuclear power reactors, whereas others are produced by nuclear reactions using small cyclotrons. Many hospitals have their own cyclotrons for making certain radioactive isotopes which live much too briefly to be transported to the hospital.

Nuclear power

The process of nuclear fission releases a tremendous amount of energy and during the second half of the 20th century many countries developed the technology to harness this energy to produce electricity. Nuclear reactors currently supply 16% of the world's electric power. In these reactors, the energy is provided by the fission of uranium into two or more pieces, releasing a tremendous amount of heat in the process. The same kind of reaction also generates the explosive energy of an atomic bomb; but whereas in an atomic bomb the energy is released all at once,



The Cassini spacecraft on a seven-year journey to explore Saturn and its moons. The electrical power for the on-board equipment comes from energy released by the decay of radioactive nuclei. The plutonium isotope ^{238}Pu in the form of plutonium oxide releases enough heat for the 'Radioisotope Thermoelectric Generators' (RTGs) to produce 870 watts of electrical power. (Courtesy ESA.)

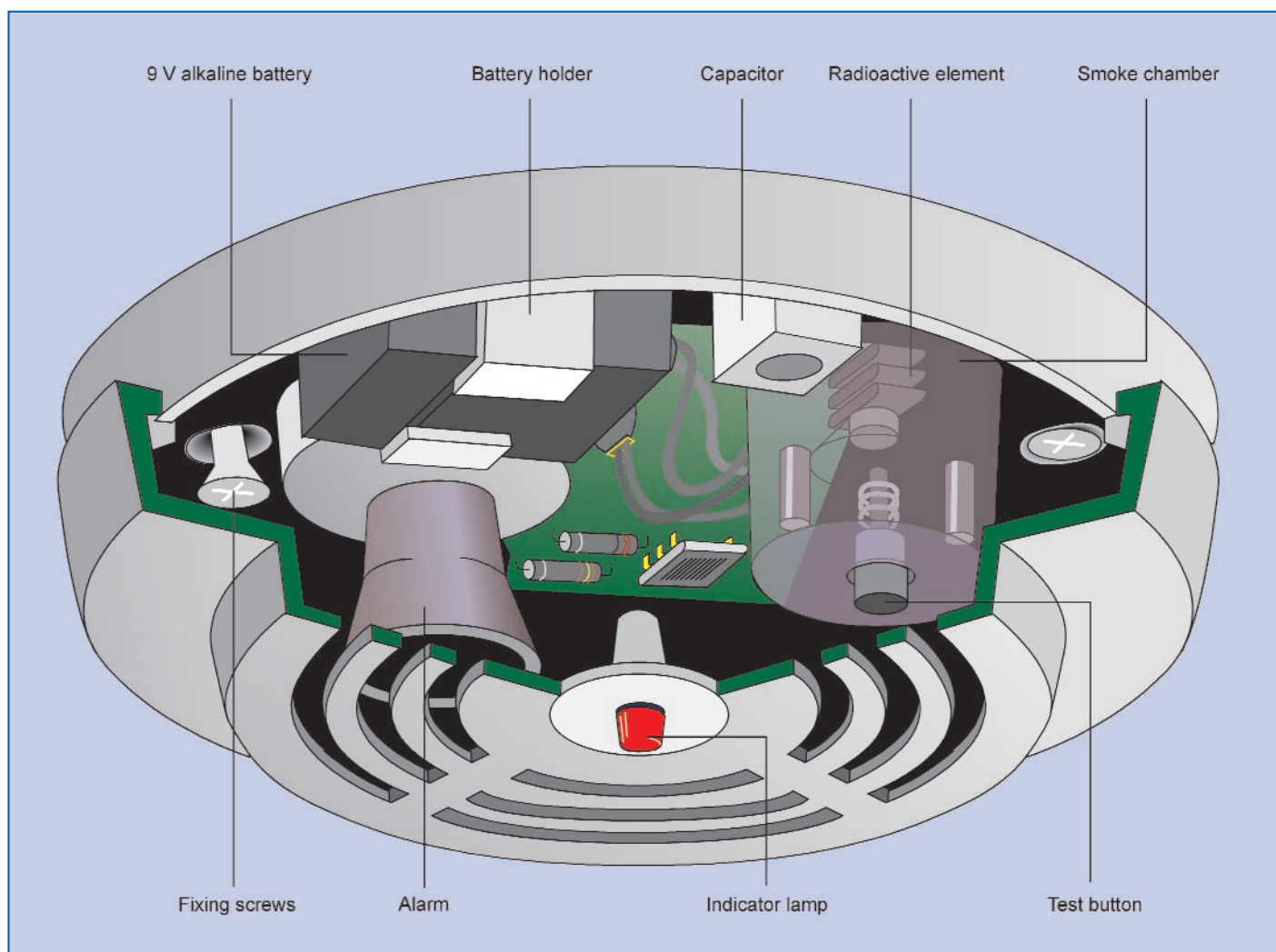
in a reactor the energy is released at a controlled rate. As an illustration of how effective nuclear energy can be, the total fission of one kilogram of uranium releases as much heat as a million kilograms of coal. However, commercial reactors 'burn' only a few percent of the fresh uranium fuel placed in them; the rest must be reprocessed chemically before it can be used again.

Naturally occurring uranium consists almost entirely of the isotope ^{238}U with just under one percent of ^{235}U . Unfortunately, it is only this rare isotope that will burn in an ordinary nuclear reactor, and there is only so much economically recoverable uranium ore in the Earth's crust. The most common type of reactor operates with 'enriched' uranium, which consists of a few percent of ^{235}U , but this mix is not capable of sustaining a chain reaction on its own. Reactors therefore use a moderator such as water or graphite to slow down the neutrons that are released during fission to make them much more likely to initiate further fission reactions. The heat produced in the reactor is then used to produce steam that drives turbines, which in turn produce electricity.

In a breeder reactor, the abundant ^{238}U can be converted into an isotope of plutonium, ^{239}Pu , which provides an alternative fissionable material to ^{235}U . This is accomplished when neutrons released in the fission process convert a little of the uranium into plutonium. Such reactors therefore produce new fuel as well as energy.

Nuclear fission contributes a considerable fraction of the developed world's current energy requirements. In so doing, it replaces the burning of fossil fuels (coal and oil) that appear to be the cause of damaging global climate changes resulting from CO_2 emissions. Already, nuclear fission contributes over half the electrical power requirements of some countries, for example France. However, of understandable concern to the public is the fact that it yields highly radioactive waste that has to be confined and stored safely for many years. There is hope, however; a number of practicable solutions which involve transforming this waste into a far less harmful state are under development.

There are several alternative approaches which might tackle the waste problem. A number of countries are considering ways of developing a revolutionary type of reactor that would either incinerate or transmute the radioactive waste products. The idea of a hybrid reactor has been around since the early 1990s when initial studies were carried out at Los Alamos in the US and CERN in Switzerland. It involves connecting up a high energy proton accelerator to a sub-critical nuclear reactor (one in which there are not enough neutrons to sustain a chain reaction). The protons collide with a nuclear target producing neutrons which are then used to incinerate the long-lived waste products by transforming them into nuclei that are far less radioactive and have shorter half-lives. The intention is that the final products of this process would be no more harmful than the natural uranium that was originally mined from the ground. Finding a satisfactory solution to this problem may yet make nuclear energy an ecologically sound alternative to fossil fuels before the environment is irretrievably damaged.



Industrial, environmental and domestic applications

Radioactive isotopes, or simply ‘radioisotopes’, are used throughout industry. Often they are a source of penetrating gamma rays that can be used, rather like super X-rays, for examining such things as ball bearings and jet turbine blades for flaws. Just as radioactive tracers allow particular chemicals to be followed through the human body, so there are a vast number of applications of tracer techniques in industry, biological sciences, and in monitoring pollution in the environment.

The inventor of tracer techniques, George de Hevesy, even applied the method to restaurant evaluation. He had heard rumours that steak left by customers in his favourite restaurant was reused at a later date in ground, or minced, form. He injected some mildly radioactive isotope in a steak and left it on his plate. The next day, the ground beef that he ordered set the Geiger counter clicking; a classic application of tracers back in the 1930s!

Many radioisotopes that are routinely used today in a wide range of industrial applications belong to elements that are not well known. The elements americium, cesium and curium, for example, are vital to the mining industry to help decide where to drill oil wells. Americium is probably best known for its use in domestic smoke detectors, but it is also used to measure levels of toxic lead in paints. Other radioisotopes used in industry include cadmium, which is used for sorting scrap metals and analysing alloys; californium, which is used to inspect

The key to the operation of a smoke detector is a tiny amount of americium isotope, ^{241}Am , a by-product of nuclear reactors. The alpha particles from the americium ionize the air which then conducts a tiny electric current between two electrodes. When smoke penetrates the space between the electrodes, the particles remove the ions which conduct the current, the current is reduced, and the alarm is triggered.

airline luggage for hidden explosives; and krypton, which is used in the indicator lights of many household appliances from washing machines to coffee makers. In addition, tritium, the isotope of hydrogen with two neutrons (as compared with deuterium which has one), is used to make self-luminous signs and paint, and is found in wrist watches for the same purpose.

Even uranium isotopes have many uses, such as in dental fixtures and wall tiles, while plutonium, the element most closely associated with nuclear weapons, has safely powered many spacecraft since 1972.

Nuclear physics in astronomy

Almost everything we see when we look up into the night sky is the result of nuclear reactions. Stars shine because nuclear reactions are taking place at their centres, but their nuclear fuel does not last forever. The detection of the short-lived element technetium in stars which are billions of years old proved such elements are created within them.

As nuclear fusion processes turn hydrogen into heavier elements, generating heat, stars undergo a series of changes at a rate which depends on their mass. The heaviest burn their nuclear fuel very quickly before exploding as supernovae. Lower mass stars like the Sun will, after shining for a few billion years, expand and cool. During this stage they are known as 'red giants', and when the Sun becomes one, its outer atmosphere will swallow the Earth.

Red giants also played a vital part in our history. The Solar System condensed out of gases and dust that was enriched by cinders from exploding stars and by material thrown off by an earlier generation of red giants. Many of the heavy elements existing on Earth, like the lead on our roofs, were produced by these red giants in the 's-process' which allows heavy elements to be formed by the slow addition of neutrons.



The constellation of Orion. The star at top left appears to have a distinctly reddish colour when seen with the naked eye. It is the red giant star Betelgeuse. Betelgeuse is large enough to contain the path of the Earth around the Sun. Our understanding of the processes taking place in such stars rests critically on what happens when nuclei collide.
(Courtesy Christopher Doherty.)

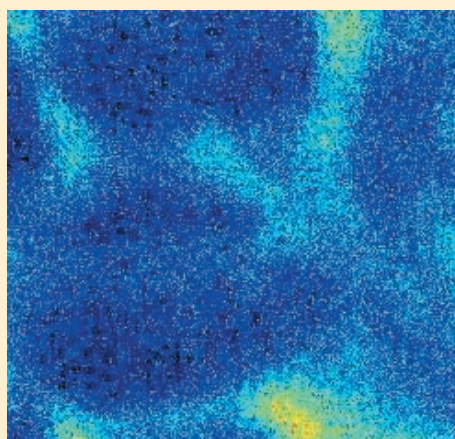
What elements are present on the surface of Mars? How much carbon, or any other element, is there in a biopsy sample and how is it distributed in the sample? Questions like these arise time and again in medicine, in industry and in all kinds of research including planetary exploration.

A very old idea, reborn with modern techniques, comes to the rescue. It harks back to the alpha particle scattering experiments which revealed to Rutherford that all atoms had central nuclei. In those experiments, alpha particles were fired at a sample and a few came straight back. Geiger and Marsden's targets were pure metals such as gold. But a sample might have many different elements in it. If so, the energy the alpha particles have when they fly back to be detected depends on the mass of the nucleus which they strike, just as a tennis ball bounces back with more energy if it hits a soccer ball rather than a ping-pong ball. So if we can measure the exact energy of each alpha particle which bounces straight back, and count how many have particular energies, we can say exactly how much of each element there is in the part of the sample we are studying. This way of studying samples is called Rutherford Backscattering Spectrometry (RBS). It was used to make the first measurements of what elements were on the Moon long before people went there. Alpha particles from an Americium, ^{241}Am , source, which was landed on the Moon, were bounced off the lunar surface. The alpha particles were then counted and sorted by energy and the numbers beamed back to Earth.

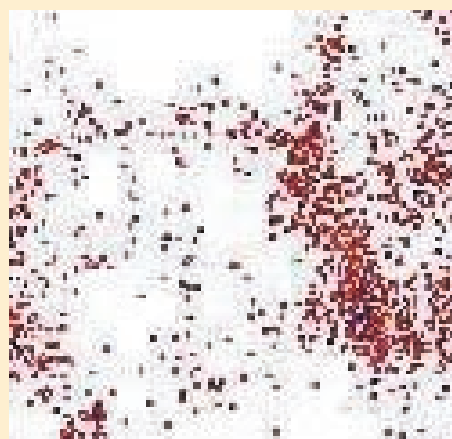
More recently, in 1997, RBS was employed by the Mars Pathfinder rover, named Sojourner, to send back to Earth information about the elements on the surface of Mars. In this case, it was part of a package of three methods which all made use of alpha particles emitted by the transuranic element Curium 244 (^{244}Cm). The lighter elements in the rocks, like carbon and oxygen, were measured by RBS. Somewhat heavier elements, like fluorine and sulphur, were analysed by nuclear reactions in which an alpha particle is absorbed by a nucleus and knocks out a proton. By measuring the energy of the proton, the target nucleus can be identified. The third technique is called PIXE (Particle Induced X-ray Emission). When the alpha particles strike somewhat heavier atoms, such as iron, they knock electrons out of their atomic orbits. As a result, the atom emits X-rays as they settle down after the disturbance. These X-rays allow the element to be identified just as Moseley discovered early in the 20th century. In this way, using the combined package of RBS, nuclear reactions and PIXE, Sojourner was able to send back a detailed account of what elements there were in the rocks it encountered on Mars. Earlier Viking missions to Mars had no means for measuring the lightest elements. Sojourner is shown on the next page.

We also find RBS and PIXE working together in medicine. For example, there are diseases caused by too much iron in cells. Can we see where iron might be concentrated within the cells? Ordinary chemical techniques could tell you how much iron was in a sample of tissue, but only by destroying the tissue — then you could never know how it was distributed within the cells. When working together, PIXE finds heavier elements, such as iron, in samples of tissues and RBS measures the lighter elements in the same samples, thus revealing the cell structure. By putting this information together, RBS and PIXE allow us to map out the excess iron within the cells. Very finely focussed beams of nuclear particles are needed to do this. In the case shown below, proton beams were used. In the left-hand picture we see the carbon intensity as revealed by RBS using a proton beam that can be narrowed down to a few millionths of a metre. This is a skin sample obtained by biopsy from a patient. The colour is coded with yellow indicating a greater concentration of carbon; the walls of a single cell can be seen. The picture on the right shows the location of iron as revealed by PIXE with the same proton beam. Too much iron in some cells has caused their membrane to burst, killing the cells. Liver cells are particularly susceptible. RBS and PIXE together allow doctors to study exactly what goes on when this fatal disease, called haemochromatosis, strikes, a necessary first step to finding a cure.

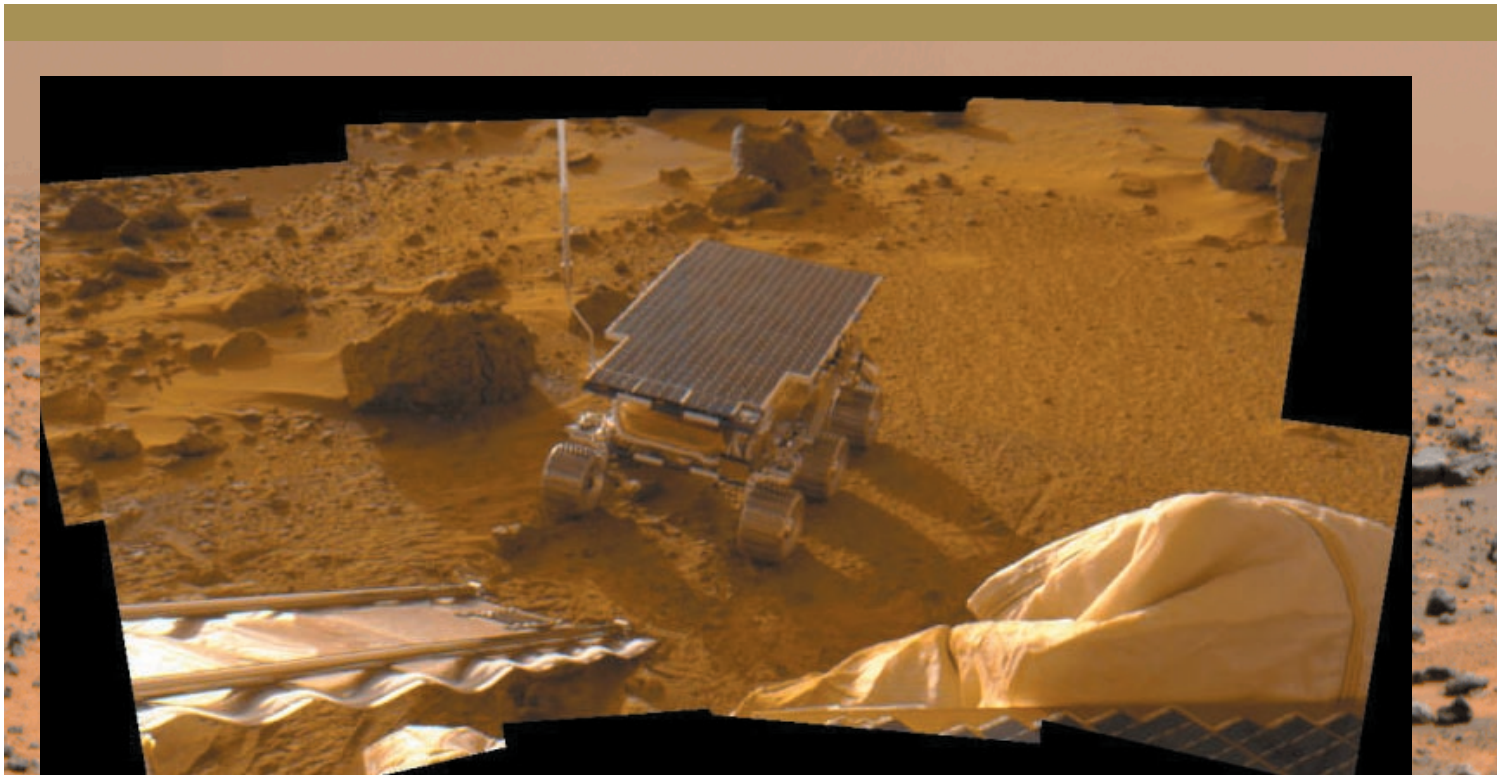
Today, RBS has a wide range of industrial applications. It is an ideal way of looking for defects in the very thin multi-layered structures found in modern micro-electronics. RBS can call upon the full range of modern nuclear physics techniques for detecting particles, measuring their energies and counting them. Particle accelerators can provide beams of whatever particle is most suitable, not just alpha particles, and direct them with great precision onto the part of the specimen to be studied.



The yellow areas are the cell walls, where the carbon concentration is higher, as revealed by Rutherford backscattering using a fine beam of protons.



The red dots represent iron as revealed by PIXE using the same beam. Together, the figures show us where the carbon is within the cell. These two elemental maps were obtained at the Institute for Nuclear Technology, Lisbon, Portugal.



Inset into the wide field view of the Martian surface seen from the Mars Pathfinder lander is the rover, named Sojourner, which was equipped with an alpha-proton-X-ray spectrometer to analyse the elements in the Martian rocks. (Courtesy NASA/JPL/Peter Smith.)

