

5. Strange nuclear material

The contents of a nucleus

So far, an atomic nucleus has been described as a collection of Z protons and N neutrons. The protons each carry one unit of positive charge, whereas the neutrons are uncharged and are very slightly heavier than protons. A nucleus has been assumed to contain only protons and neutrons. However, enough quantum mechanical surprises have been introduced to suggest that, when it comes to nuclei, nothing is as simple as it seems.

When nuclei fall apart

One way of finding the constituents of nuclei is to observe what is emitted from them. In radioactivity, some nuclei spontaneously eject particles and change into different kinds of nuclei without any prompting. Stable nuclei, however, need inducement before they will eject particles. In fact, any nucleus can be broken apart by hitting it hard enough with another nucleus. This can be done in the laboratory by using high energy particles from accelerators, but it also happens naturally in stars.

Nuclear reactions were important even before stars existed; most of the nuclei in the Universe were created a few minutes after the Big Bang. At that time, the Universe was an extremely hot and crowded place, with nuclei being formed and, almost as fast, broken apart. Almost immediately, the Universe expanded and cooled sufficiently for nuclei not to be broken apart as soon as they were created. These surviving nuclei formed the primordial material which eventually condensed into stars.

Radioactivity and the constitution of nuclei

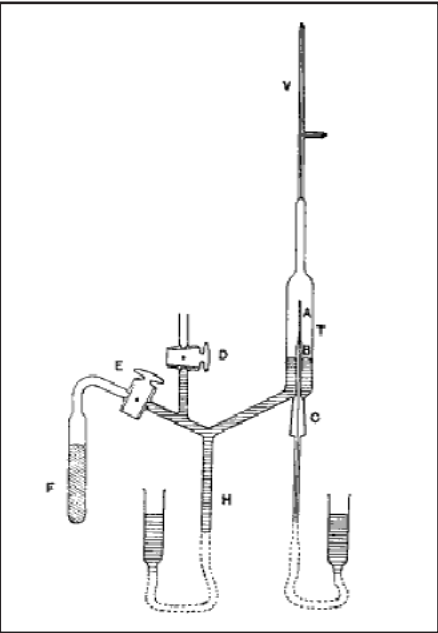
The idea that most of the mass of atoms resides in compact nuclei was still years in the future when Rutherford first noticed that radioactivity involved two kinds of particles. It soon became clear that beta rays were J.J. Thomson's recently discovered electrons, since their paths were bent by magnetic fields in exactly the same way. They also penetrated matter much more readily than alpha particles. It took a little longer to identify alpha particles as helium nuclei.

One possible conclusion to be drawn from radioactivity is that atomic nuclei are made of alpha particles and electrons, but this would not work for hydrogen since the hydrogen nucleus has much less mass than an alpha particle. To solve this problem, a very old idea was revived: that all atoms are composed of multiples of hydrogen. This idea originated with William Prout in 1815, and is known as Prout's hypothesis. It was applied a hundred years later to nuclei rather than atoms; all nuclei were predicted to be composed of various numbers of hydrogen nuclei (protons).

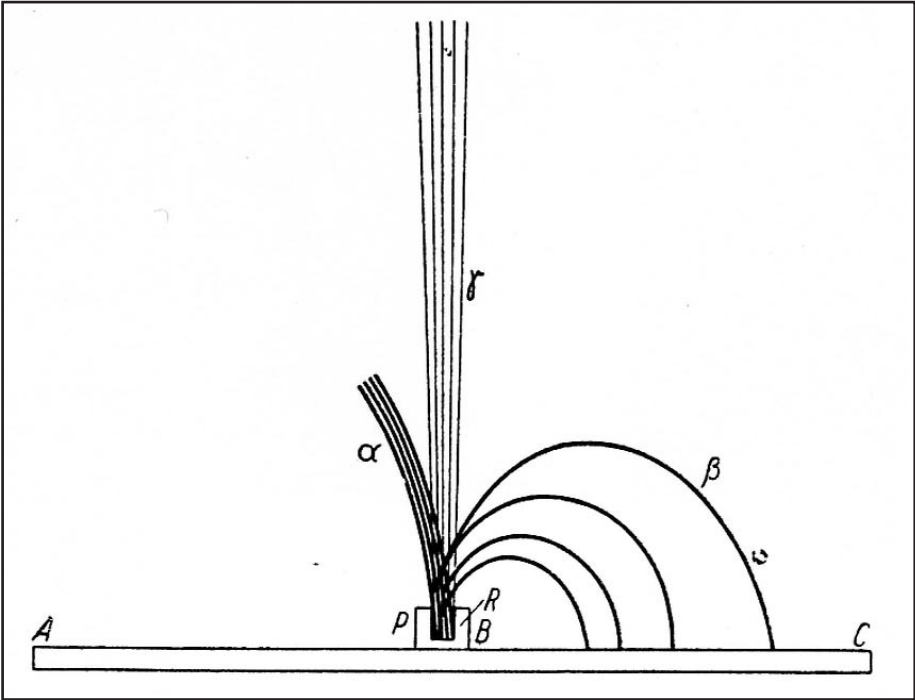
This theory cannot be quite right as, for example, the nucleus of a nitrogen atom has the mass of fourteen protons, but the charge of just seven protons. The textbooks of the 1920s had a simple answer to this: the nitrogen nucleus has fourteen

Do nuclei have alpha particles within them?
By far the most common isotope of all the even Z elements from carbon to sulphur have the same number of protons and neutrons as three, four, five etc. alpha particles. It is not true for argon for which ^{36}Ar has an abundance of less than 1%. These facts are best explained in terms of the the energy valley (discussed in Chapter 6) and the tendency of protons and neutrons to pair up. Before the discovery of the neutron, it was natural to suppose that nuclei are composed of protons, electrons and alpha particles.

A figure from Marie Curie's thesis illustrating the way that alpha rays are bent very little by a magnetic field whereas beta rays are bent much more. Gamma rays are not bent at all. (ACJC-Archives Curie and Joliot-Curie.)



The apparatus used by Rutherford and Royds in 1908 to prove that alpha particles were helium ions (in modern terms: helium nuclei). Alpha particles penetrated through a thin window into a vacuum chamber. When an electric discharge was passed through this chamber the light given out was analysed by a spectroscope, which confirmed the presence of helium.



protons and also seven electrons to balance out the charge of half the protons. After all, there must be electrons inside atomic nuclei since they come out of them in beta decay.

In this proton–electron model, alpha particles would consist of four protons and two electrons. Many nuclei decay by ejecting this particular structure from the nucleus as a complete particle, so there must be something special about this configuration. Another feature also suggests the helium nucleus is somehow special: the most common isotopes of many light elements are apparently multiples of the alpha particle. By far the most common isotope of carbon, for example, is ¹²C which has the same charge and mass as three alpha particles. ¹³C is very uncommon and ¹⁴C is unstable. From this, the alpha particle appears to be special in some way, and indeed some nuclei do contain alpha particles but not in a straightforward way, as we see at the end of this chapter.

Do nuclei contain electrons?

Like alpha particles, electrons appear to be ejected from nuclei. Unlike alpha particles, there is a very straightforward answer to the question of whether they exist in nuclei. They do not, and they cannot.

¹² C	¹⁶ O	²⁰ Ne	²⁴ Mg	²⁸ Si	³² S	³⁶ Ar	⁴⁰ Ca
							
3α	4α	5α	6α	7α	8α	9α	10α
98.9%	99.8%	90.5%	79.0%	92.2%	95.0%	<1%	96.9%

Firstly, the absence of electrons within nuclei can be understood from Heisenberg's Uncertainty Principle. This principle is commonly, and wrongly, taken to mean that everything on the microscopic level is uncertain. In fact, it implies that the more we try to localize a quantum particle such as an electron – that is to confine it to a smaller and smaller region of space – the larger the fluctuations in its motion due to the uncertainty in its momentum. The result is that for an electron to be confined to the tiny nucleus, its motion would be too violent for it to stay there for long. Protons on the other hand, which are nearly two thousand times heavier than electrons, can easily be confined to the volume of a nucleus since they move about more slowly and the uncertainty in their motion is much less.

Another argument against atomic nuclei having any electrons in them comes from the light emitted when an electric discharge is passed through nitrogen gas. The fine details in the pattern of spectral lines indicate clearly, according to certain quantum rules, that the nitrogen nucleus has an even number of particles, but if this nucleus is made of protons and electrons it would have to be an odd number: fourteen protons plus seven electrons.

In 1932, Chadwick's discovery of the neutron, which is a neutral particle with about the same mass as a proton, solved this problem. Werner Heisenberg then suggested, correctly, that atomic nuclei consist purely of protons and neutrons. Chadwick's discovery was to mark the beginning of modern nuclear physics. Now the nitrogen nucleus would have seven protons and seven neutrons: an even number of particles in total.

The question now arose that if nuclei consist of just protons and neutrons, where do the beta decay electrons come from? These electrons also posed another problem, one of the greatest problems of physics in the twentieth century, and a problem which drove physicists to desperate remedies.

Missing particles

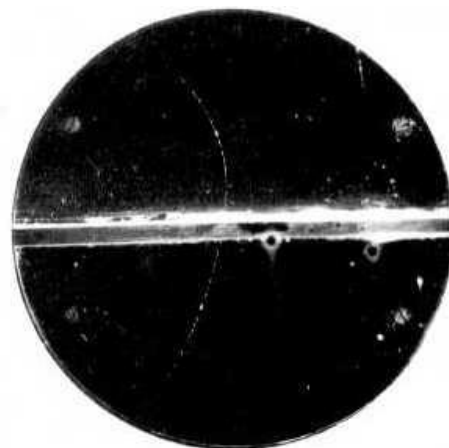
Beta decay electrons appeared to break the law of conservation of energy. The nucleus emitting the electron has a definite energy, and the nucleus produced in the decay has a definite energy, but the electrons emerge with a range of energies always less than the difference in energy between the initial and final nuclei. The missing amount of energy suggested energy is not always conserved in beta decay, but as the law of conservation of energy is so sacred in physics, few physicists dared to speculate that there was an exception to the rule. Despite this, Niels Bohr did just that – and turned out to be wrong.

Another proposal, made by Wolfgang Pauli in 1930, was that a second, virtually undetectable particle was emitted at the same time as the electron. This new particle, later called a neutrino (meaning 'little neutral one'), shared energy with the electron in a random way such that the total energy of the two particles was equal to the difference in energy between the parent and daughter nuclei. In this manner, energy is conserved after all.

Pauli's idea was radical, but it became a key part of a theory of beta decay proposed by the brilliant Italian physicist, Enrico Fermi, in 1934. Over the years, Fermi's theory has been greatly extended and incorporated into more modern models, but still successfully accounts for a wide range of phenomena connected with beta decay. According to this theory, in a nucleus that has more than the ideal number of neutrons, a neutron turns into a proton, creating both an electron and a neutrino.



James Chadwick, 1891–1974. His discovery of the neutron in 1932 was a turning point in nuclear physics. Chadwick was well aware that the neutron had been predicted by Rutherford in 1920. (Copyright the Nobel Foundation.)



The first evidence for the positron, the anti-particle of the electron. The cloud chamber track bends the wrong way in a magnetic field for it to be caused by an electron, and it is not a proton track. Anderson's unprecedented discovery was highly controversial until it was confirmed a year later. (Courtesy C.D. Anderson.)



Wolfgang Pauli, 1900–1958, and Niels Bohr, 1885–1962. One of Pauli's many contributions to quantum physics concerned the spin of elementary particles such as electrons. The spin of much larger objects like this top was clearly also of great interest. (AIP Emilio Segrè Visual Archives.)

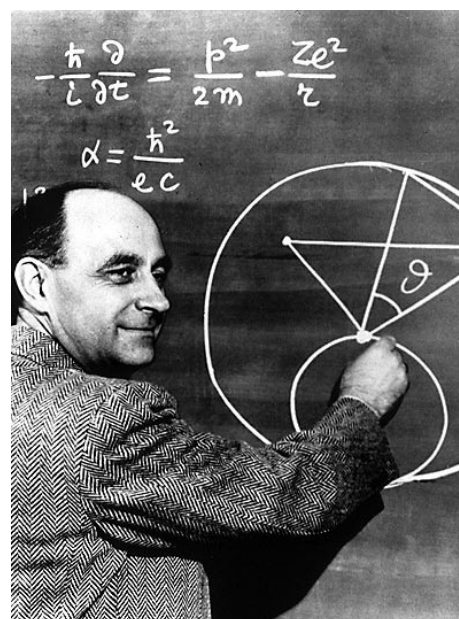
Neutrinos are exceptionally hard to detect. More than 150 million neutrinos pass through every square centimetre of your body every second, and even a body the size of the Earth will very rarely stop a neutrino. It is therefore not surprising that it was 1956 before Reines and Cowan could announce neutrinos had been positively detected. This was long after Pauli's speculation (1930) and Fermi's theory (1934), but proved that they had been correct. Today, neutrinos play a vital role in astronomy and cosmology as well as in nuclear physics.

Antimatter

Fermi's theory embodies one of the most revolutionary ideas of twentieth century physics: the number of fundamental particles in the world is not fixed. Electrons are not emitted from nuclei in beta decay, but are created, along with neutrinos. The idea that particles can be created was one consequence of combining quantum mechanics with Einstein's special theory of relativity, a feat achieved by Paul Dirac.

Combining relativity and quantum mechanics had another consequence: the existence of anti-particles. Dirac's theory predicted that for every kind of particle there is a corresponding anti-particle having the same mass. If the particle has an electric charge, the anti-particle has the opposite charge, but even neutral particles like neutrons have anti-particles. The anti-particle for the electron, called the positron, was discovered in 1932 by Carl Anderson.

When a particle meets its anti-particle, they annihilate each other releasing pure energy that is carried off as radiation. The energy released is that predicted by Einstein's famous equation, $E = mc^2$. When an electron and a positron annihilate each other, for example, the energy released, E , is equal to their combined mass, m , multiplied by the square of the speed of light. The process of annihilation is reversible and when a high energy photon, maybe from cosmic rays, interacts with a nucleus it quite often disappears, with its energy reappearing as two particles, an electron–positron pair.



Enrico Fermi, 1901–1954, was unique in the 20th century for his eminence in both theoretical and experimental physics. (AIP Emilio Segrè Visual Archives.)

Beta decay as it was originally discovered takes place when nuclei with too many neutrons correct the imbalance by transmuting a neutron into a proton, an electron and an anti-neutrino. Nuclei with the opposite imbalance, too many protons, decay in the opposite fashion: a proton is converted into a neutron, a positron and a neutrino. This kind of beta radioactivity was first discovered by Irène Joliot-Curie (Marie Curie's daughter) and Frederic Joliot in 1934 and is now of immense importance in modern medicine, particularly in positron emission tomography (known as PET for short). PET is a much used diagnostic tool, especially important for diagnosing brain disease.

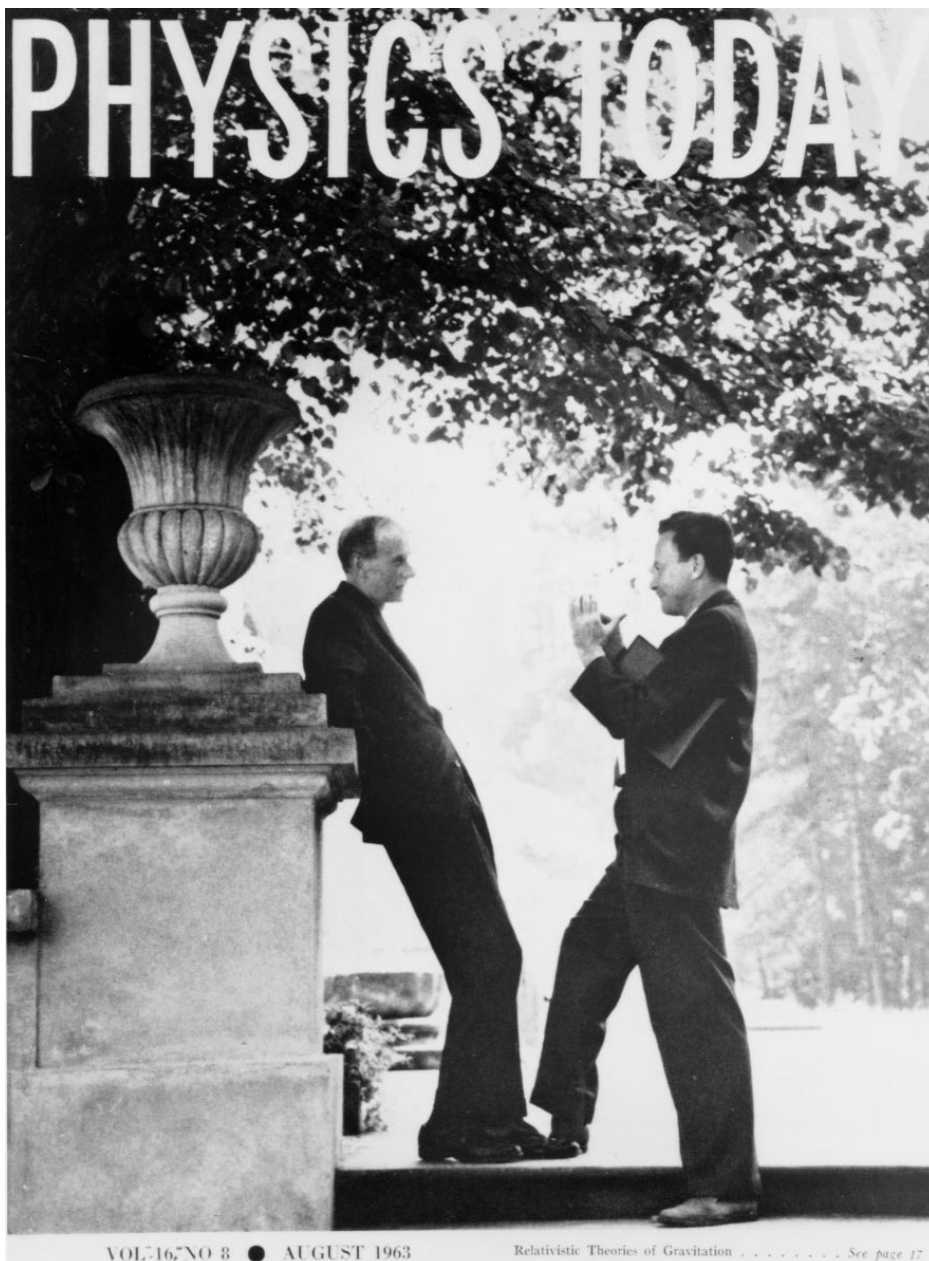
Chadwick's discovery of the neutron provided the foundations for a very successful picture of nuclear structure which has been the cornerstone of nuclear physics for many years. In this model, nuclei consist of protons and neutrons, and the emission of electrons and positrons does not mean that these particles are contained within them.



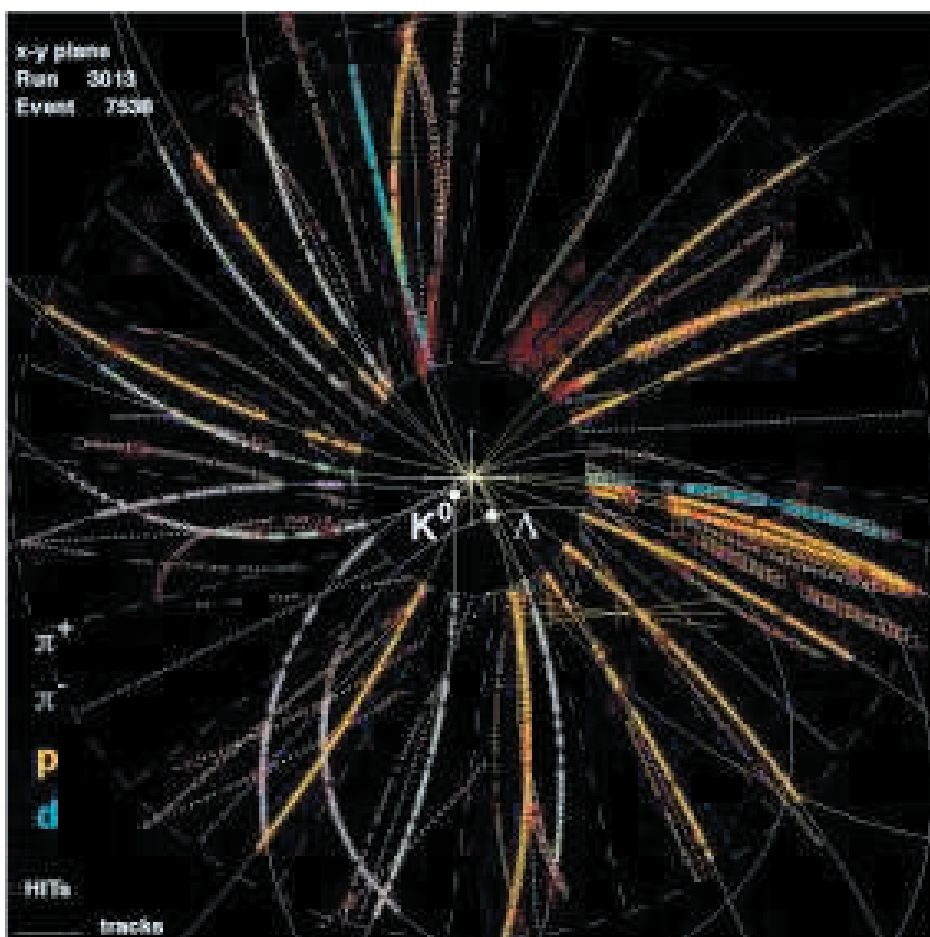
Carl D. Anderson, 1905–1991,
discoverer of the positron.
(AIP Emilio Segrè Visual Archives.)



Owen Chamberlain, 1920–, together with Emilio Segrè, discovered the antiproton, the negatively charged anti-particle of the proton, in 1955.
(Copyright the Nobel Foundation.)



Paul Adrien Maurice Dirac, 1902–1984, left, and **Richard P. Feynman, 1918–1988.** Dirac was the first to successfully combine quantum theory and relativity; in doing so, he predicted the existence of positrons. Feynman developed a formalism for doing the very complex calculations involving electrons, positrons and light.
(AIP Emilio Segrè Visual Archives.)



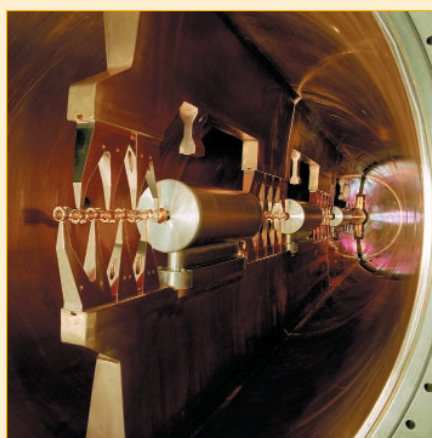
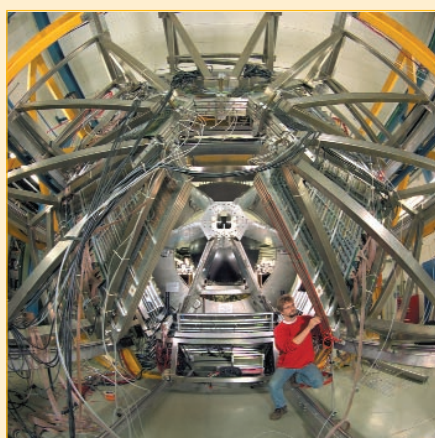
When two nickel nuclei collide at 89% of the speed of light, many particles are released. This picture, taken using a 'drift chamber' at GSI in Darmstadt, Germany, allows them to be identified. Two of these particles are exotic: a K-zero (K^0) and a lambda (Λ). They did not exist in the incoming nuclei, and very quickly decay into more familiar particles. Such experiments yield vital clues concerning neutron stars and supernova explosions. (Courtesy GSI.)

When nuclei collide

In 1919, Rutherford discovered that when alpha particles from a radioactive source travel through air, a proton is sometimes produced. The alpha particles had knocked protons out of the nuclei of nitrogen atoms in the air – the first time a nuclear reaction had been observed.

Nuclear reaction experiments are no longer performed with alpha particles from radioactive sources. Large accelerators produce beams of a wide variety of particles, ranging from electrons and protons to uranium nuclei. The energy of these projectiles is very much higher than alpha particles emitted in radioactive decay and can be precisely controlled. In addition, the number of particles per second is vastly greater than a radioactive source could possibly produce. Beams of high energy particles can be directed onto targets containing any chosen nuclei, where they collide and nuclear reactions take place.

When two nuclei collide at high energies, many different processes occur, leading to the production of a variety of final products. Sometimes the resulting nuclei have a great deal of internal energy as a result of the collision. By choosing suitable beams and targets, it is possible to select what new types of nuclei will be produced in order for these to be studied. Some of these products have found a vital role in modern medicine, and many have quite different properties to the nuclei of atoms found naturally on Earth. However, as long as the energy of the incident particle is not too high, all the transmutations are consistent with the proton–neutron model: the total numbers of protons and neutrons in the products of the collision are the same as those in the original. If the energy of the collision is higher, other particles can be produced.



Taking nuclei apart

One particular kind of reaction is known as photo-disintegration which, as the name suggests, involves the breaking up of nuclei by light. Just as the ultraviolet radiation in sunlight breaks up dye molecules and, in so doing, fades clothes and fine tapestries, so high energy photons can break up nuclei. These are not photons of visible light, but high energy gamma rays, the same radiation that nuclei emit when they lose energy by jumping down from one quantum energy level to another.

Just as there are machines for making high energy particles of matter, so there are machines that produce high energy gamma ray photons. However, when Chadwick and Goldhaber carried out photo-disintegration for the first time, breaking up a deuteron into a proton and a neutron, they used gamma rays from

Top: Aerial view of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the United States. Heavy nuclei collide head on at close to the speed of light to produce a quark-gluon plasma. (Brookhaven National Laboratory)

Below: The outer pictures show part of the HADES spectrometer being built at GSI near Darmstadt in Germany to study the electron-positron pairs produced when heavy nuclei collide at high energies. This will help us to understand nuclear matter at high density. The central picture is a view inside the linear accelerator which gives the nuclei at GSI their first boost towards high energy. (Courtesy A. Zschau, GSI.)



radioactivity. Today, with a machine like the one at Mainz, in Germany, it is possible to knock a proton or a neutron out of any nucleus with photons or electrons. It is easy to imagine doing this repeatedly to a nucleus, one nucleon at a time, until ending up with a deuteron, and then finally just a proton or neutron. If it is possible to take a nucleus apart one nucleon at a time in this way it suggests that nuclei must contain only protons and neutrons.

Quantum mechanics, being quantum mechanics, implies matters are not so simple.

Top: The Mainz Microtron (MAMI), an accelerator at Mainz, in Germany, produces high energy electrons for probing fine details of nuclear structure. (Johannes Gutenberg-Universität Mainz)

Below: Three images from GANIL, a complex of accelerators at Caen in France devoted to experiments with beams of heavy nuclei. The central picture shows the main cyclotron (CSS), on the left is a resonator, and on the right is the CIME cyclotron which accelerates exotic nuclei produced using the CSS. (Copyright M. Desauay, J.M. Enguerrand/GANIL.)



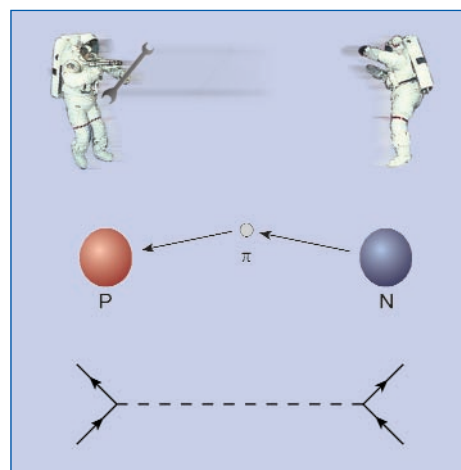
Hideki Yukawa, 1907–1981, put forward a theory for the force that holds protons and neutrons together based on the exchange of a new kind of particle, the meson. The first meson to be discovered is now known as a pion. (AIP Emilio Segrè Visual Archives, W.F. Meggers Collection.)

Something else inside nuclei

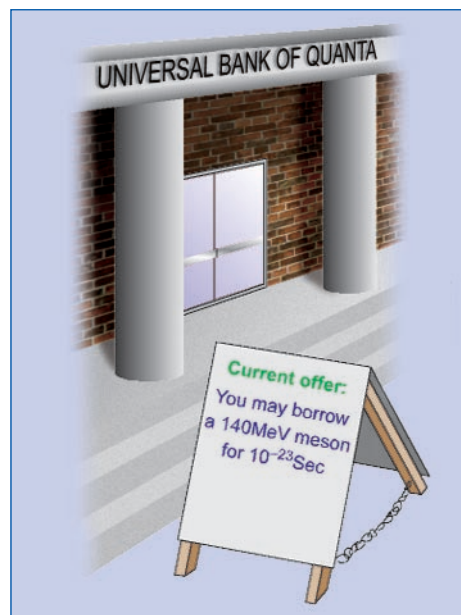
Particles can be created and destroyed, like the electrons of beta decay which are created in the decay process, or the electron–positron pairs created from high energy photons. In 1935 the Japanese physicist Hideki Yukawa proposed a radical, and Nobel prize winning, theory for the attractive force between nucleons. This is the force that binds a proton and a neutron into a deuteron and holds together all nuclei. Yukawa proposed that the origin of this force is an entirely new kind of particle. It is created at one of a pair of neighbouring nucleons and jumps across at near the speed of light to be absorbed by the other nucleon. It may seem surprising that this gives rise to an attractive force, but such an attraction was a clear prediction of Yukawa's calculations. There are also other examples. The electric force between charged particles (repulsive for like charges, attractive for unlike charges) is also due to exchange of particles, but in this case the particles are photons.

Yukawa's particle was eventually discovered more than a decade later, and is now known as the pion; it is the lightest of a class of particles known collectively as mesons. Originally, mesons were so-called because they were intermediate in mass between electrons and protons, the pion being about 273 times as heavy as an electron, whereas a proton has about 1835 times the mass of an electron. Over the years many other mesons have been found, including some so heavy they have the mass of a large nucleus.

According to the modern versions of Yukawa's theory, the nucleons in the nucleus are held together by mesons coming into a very brief existence during which they jump from one particle to another before vanishing again. The energy to create the meson is a loan from a quantum bank and has to be very quickly repaid. So, at any given time nuclei must contain some mesons as well as protons and neutrons.



If two astronauts in space were to throw spanners to each other, it would tend to force them apart. Nucleons are not like this. The reason why particle exchange causes attraction lies in the depths of the mathematics. The bottom section, with the dashed line indicating the exchanged meson, shows the diagram invented by Feynman that symbolizes the exchange process.



Nature allows energy to be borrowed briefly to allow an exchange meson to be created out of nothing. The law of energy conservation can be challenged only for a VERY brief period; the bigger the energy loan, the more quickly it must be paid back.

Mesons cannot explain everything about the force between a pair of nucleons, especially when they are very close together. A fuller understanding involves the fact that protons and neutrons, like all the mesons, are themselves composite objects. They consist of even more fundamental building blocks, called 'quarks', which are held together within the nucleons and mesons by the exchange of particles known as gluons. Modern nuclear research has opened up the whole question of how nuclei can provide a new window into Nature at the quark–gluon level.

No simple answer

When very high energy projectiles collide with other nuclei, they sometimes apparently knock pions out. However, this is not strictly evidence that there are pions inside nuclei since pions can also be created out of the energy of the incident projectile. As has been seen previously, the fact that particle 'X' comes out of nuclei is not proof that nuclei have particle 'X' inside them. There are, however, some rather difficult experiments involving beams of electrons and photons which can only be understood if it is assumed that there are pions within nuclei.

It is quite typical of the quantum world that the answer you get to any question depends on how you ask it. If you ask what is in the nucleus, and ask the question with low energy particles, then the answer is: just protons and neutrons; in such a low energy experiment if a nucleus is taken apart nucleon by nucleon, it can never end up with just a pion. Asking the question with high energy particles, the answer will be different and will include a whole variety of other particles.

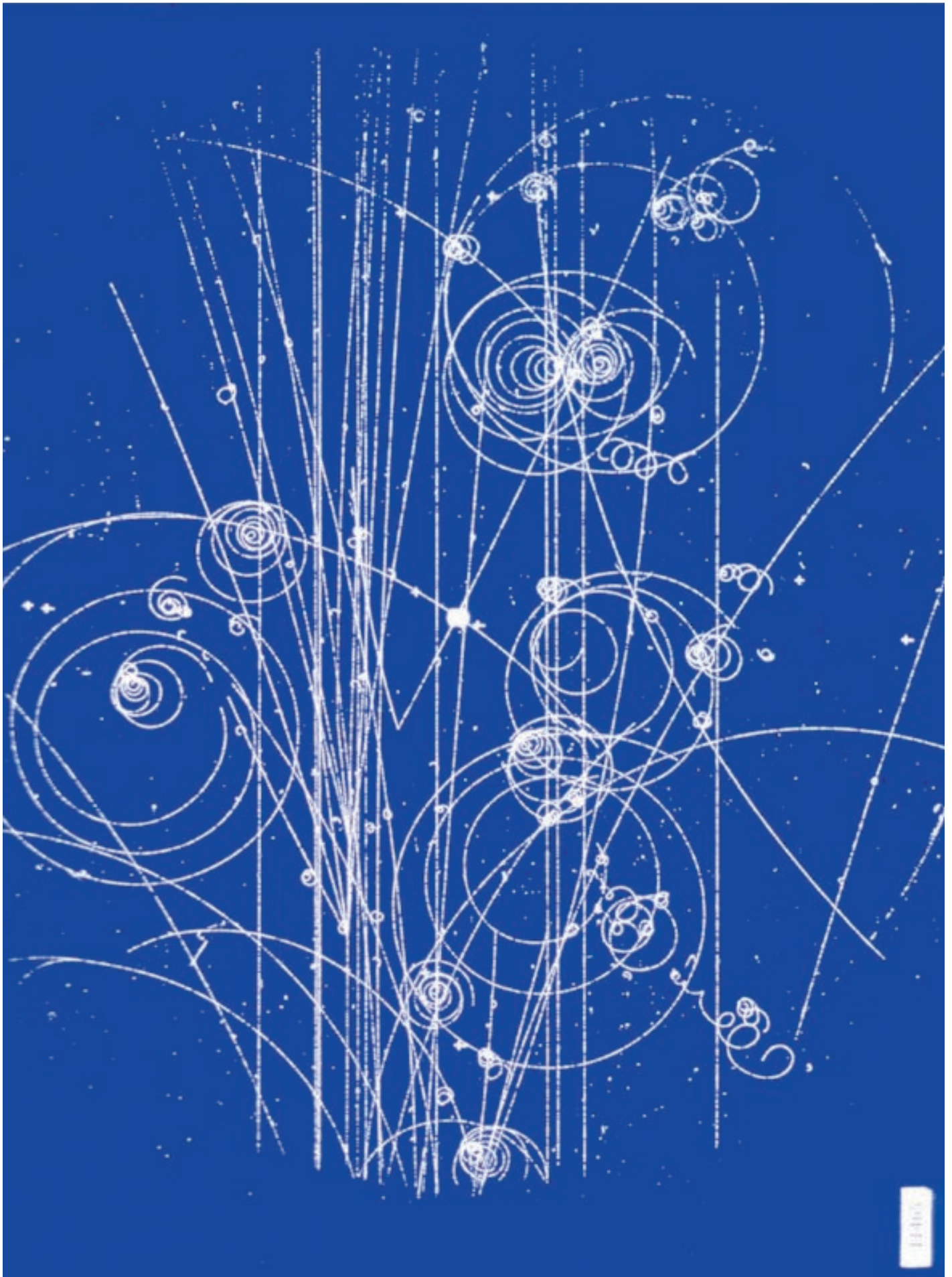
Mesons do not end the list of what might be in nuclei. Atomic nuclei, like atoms, have excited states and if a nucleus is in one of its excited states, it will quickly lose its excess energy by emitting gamma rays and jumping down to the state with the least energy, the ground state. In the 1950s it was found that protons and neutrons can also be excited to higher energy states whereby their properties are changed and they become new particles.

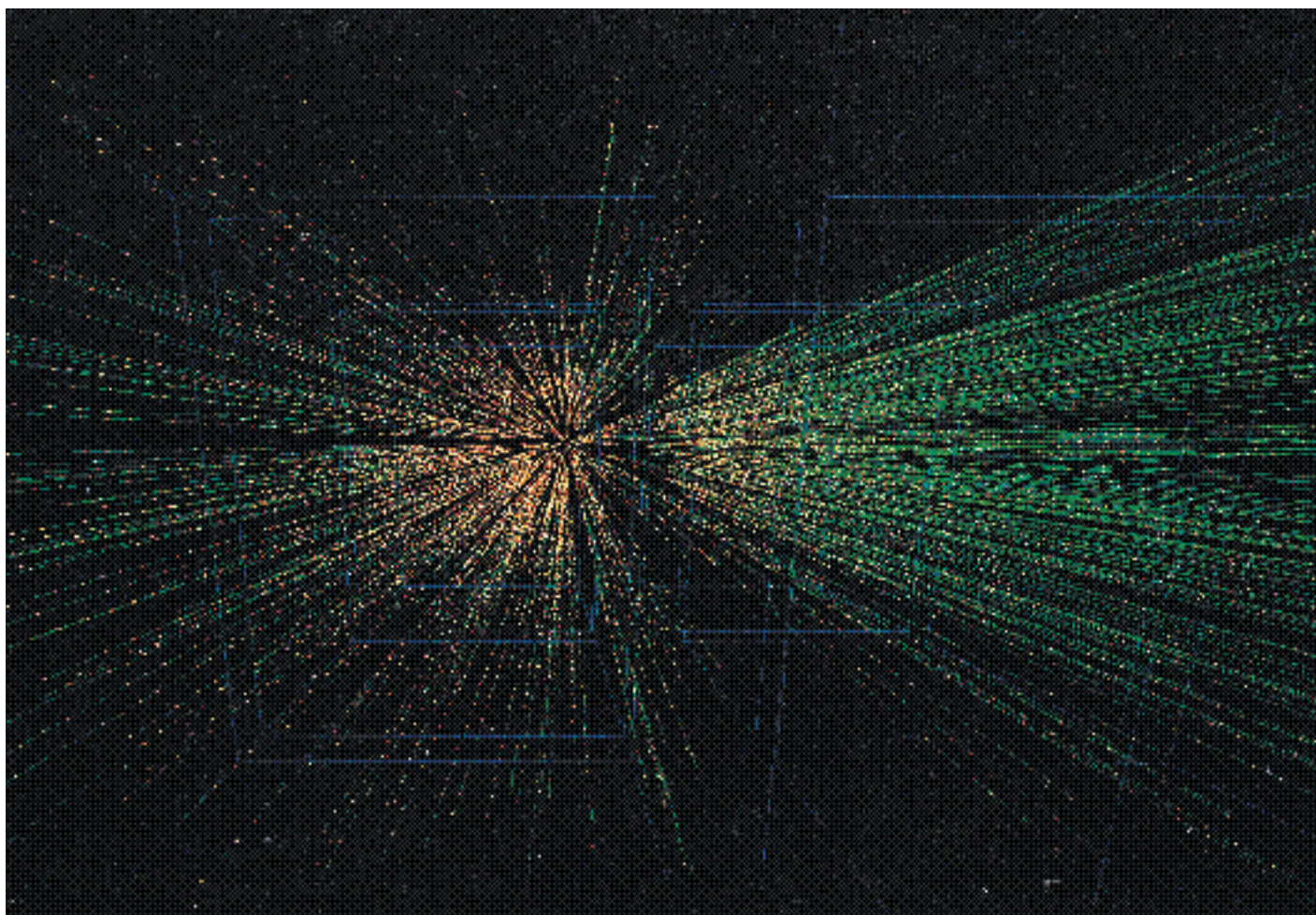
The most common state that an excited nucleon can be in is known as a 'delta resonance', or a delta. Outside nuclei, deltas live for a very short time (about the time it takes for light to cross from one side of a proton to the other), but inside a nucleus, a proton can take a very short-term loan of energy from the same mysterious quantum bank that provides energy for mesons. Protons and neutrons use this energy to fund a brief transformation into delta particles. The result is that the proton within a deuteron is actually a delta for around one percent of the time.

It is possible to knock deltas out of a deuteron, but only by hitting the deuteron with enough energy to turn the nucleon into a delta. But only pions come out to be seen in detectors. This is not evidence that there are deltas ready-formed inside deuterons. The evidence for deltas is either indirect or due to the fact that certain nuclear theories depend for their success on deltas, and other types of particles, being formed from excited states of the nucleon, and existing fleetingly in nuclei.

Nuclear matter at high energies

We have seen that ordinary nuclei contain not only protons and neutrons but also mesons and other particles which exist very briefly before disappearing altogether when the nuclei are dismantled with low energy reactions. Examining reactions at high energies is also important because there are locations in the Universe where nuclei, or the matter of which nuclei are composed, exist in extraordinary states. Neutron stars, for example, are composed of nuclear matter, but not quite the





When two lead nuclei collide at the highest possible energy, a quark–gluon plasma is fleetingly produced. It then disappears in this spectacular shower of particles as registered in a track chamber. The beam direction is towards the observer. The Universe consisted of a quark–gluon plasma a few microseconds after the Big Bang. (CERN)

same type of nuclear matter as the ingredients of ordinary nuclei in their ground states. The stuff of neutron stars cannot be made on Earth, but clues about it can be gained from the study of what happens when very high energy nuclei collide. Not surprisingly, many new particles are created.

When two complex nuclei collide at high energy, many different kinds of mesons besides pions emerge, and these give clues as to the behaviour of nuclear matter at high energy and pressure. This information is needed by physicists who are trying to understand neutron stars and the processes which take place in supernovae, the explosions of stars which are the source of many of the elements found on Earth.

There does not appear to be a limit to the variety of particles that can be made to come out of nuclei if enough energy is pumped in. The vast array of particles which emerge in the highest energy collisions has recently provided evidence that in very hot nuclei the individual protons and neutrons melt away leaving a soup of quarks and gluons, the so-called ‘quark–gluon plasma’. It is important to understand this state of matter since conditions in the very early Universe were once fleetingly extreme enough for it to exist.

Tracks left by high energy particles in a bubble chamber. Some particles are bent much more easily by a magnetic field than others, just as in the diagram from Marie Curie’s thesis on page 57. A little to the left of the centre, a ‘V’ shows a particle–antiparticle pair created from a neutral particle that has left no track. (CERN)

Quantum tunnelling

The suggestion that whatever comes out of nuclei must be inside them has already been shown not to be true for electrons. The question of whether this is true for alpha particles reveals, yet again, that the quantum world makes the answer (both

yes and no) extremely intriguing. Alpha particles are tightly bound nuclei with their two protons and two neutrons fitting together very snugly. It is for this reason that they often have an independent existence, of a sort, within many nuclei.

The nucleus of ^{20}Ne , the isotope of neon composed of ten protons and ten neutrons, has a structure similar to five alpha particles. This is predicted even by models which assume the twenty nucleons move freely throughout the nucleus. Although the nucleons within certain nuclei do tend to group themselves into alpha-like clusters, the clusters do not consist of four particular nucleons, or always the same four nucleons. In quantum mechanics, every proton in the nucleus is partly in every alpha-like cluster and the same is true for every neutron. The fact that all protons are identical in the special quantum mechanical sense means that every proton is equally part of every cluster. Thus the simple intuitive picture of alpha particles bouncing around in nuclei, each with its own unique set of nucleons, is not quite accurate.

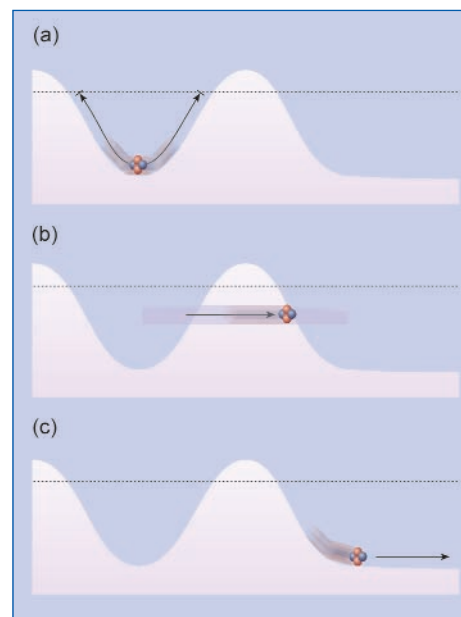
A heavy nucleus like the uranium isotope ^{238}U , which decays by emitting alpha particles, has many more neutrons (146) than protons (92). It therefore cannot be thought of as a collection of alpha particles. Nevertheless, alpha particle-like structures do occur in the nucleus and sooner or later these appear outside the nucleus as alpha particles, and can be picked up in detectors.

The greater the probability that the alpha particles are emitted, the shorter the half-life of the nucleus. The half-life of a nucleus such as ^{238}U is determined by two factors. The first is the likelihood that the protons and neutrons arrange themselves into structures that look like a nucleus of the thorium isotope ^{234}Th , plus a single alpha particle. The second factor is how rapidly the alpha particle can tunnel out of the nucleus.

In 1928 George Gamow calculated the tunnelling probability of an alpha particle. It is the different rates of alpha tunnelling that determines the huge difference in half-lives: 4.5 billion years for ^{238}U and a third of a microsecond for the polonium isotope ^{212}Po . The essential point of quantum mechanical tunnelling is that quantum theory makes it possible for particles to tunnel through a barrier which it does not have enough energy to jump over. Such a barrier would be absolutely impenetrable according to pre-quantum physics.

The ease with which a particle gets through this barrier depends extremely sensitively on the amount of energy possessed by the particle. Just how sensitively can be seen from the huge difference in the half-lives of the uranium and polonium isotopes. The vast ratio of half-lives corresponds to a factor of just two in energy: the alpha particle emitted by ^{212}Po has about twice the energy of the alpha particle emitted by ^{238}U .

The importance of tunnelling in nuclear physics extends far beyond understanding alpha decay. The fusion reactions by which stars get their energy and by which elements are built up from hydrogen, depend on tunnelling inwards through otherwise impenetrable barriers. The sensitivity of the rate of tunnelling to the energy of the particles is a crucial ingredient in governing the rate at which stars burn and evolve. Tunnelling makes this possible and governs not only the energy from the Sun, but is a key to producing the very elements from which we are made.



(a) shows a particle (imagine a marble) rolling back and forth simply does not have enough energy to get out of the well. However, quantum mechanics allows something amazing to happen: a particle with too little energy to get over the top can occasionally tunnel through the well (b) in a way that has no parallel in the world of human-sized objects. After tunnelling through, the particle accelerates 'down the hill' just as everyday experience would suggest (c).



The Thomas Jefferson National Accelerator Facility in Virginia, United States, represents a new step in electron accelerators. It is already producing new information about nuclear structure at the quark level. (Courtesy the Thomas Jefferson National Accelerator Facility.)