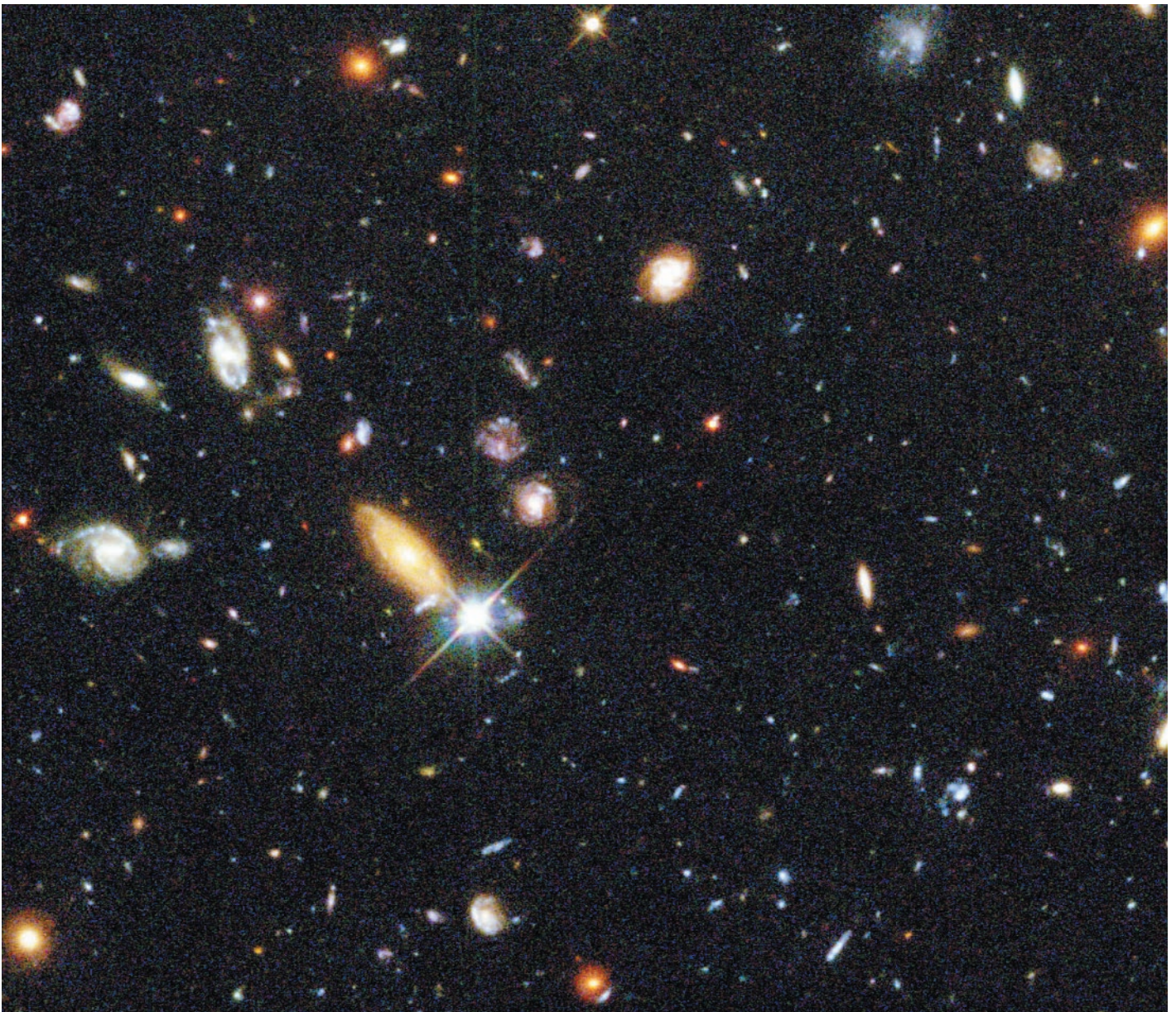

6. The nuclear landscape

The variety and abundance of nuclei

It is obvious, just by looking around, that some elements are much more abundant on Earth than others. There is far more iron than gold, for example – if it were the other way round, both the ship-building and jewellery businesses would be very different. In addition, it is not just on Earth that some elements are rare. Astronomers have found there is far more iron than gold throughout the Universe, although even iron is relatively rare since it, along with all other elements apart from hydrogen and helium, comprise just 2% of all the visible matter in the entire observable Universe. The other 98% is about three-quarters hydrogen and one quarter helium.

Galaxies at the limits of the observable Universe as seen by the Hubble Space Telescope. Their light has taken billions of years to arrive so we see these galaxies as they were billions of years ago. They have had billions of years less nuclear processing than our own Galaxy and therefore contain fewer heavy elements. (NASA/STScI)



The tiny proportion of ‘everything else’ is not uniformly distributed in the Universe. Instead, it is concentrated in particular places, such as on planet Earth. The distribution of elements is also very uneven. Fortunately, Earth has a sufficient quantity of elements such as carbon, oxygen and iron, to make life possible.

It seems that some kinds of atoms have scored much higher in Nature’s popularity stakes than others. What is it about carbon or iron that makes them favoured by Nature in this way, and gold so rare? These questions can now be answered by bringing together knowledge from nuclear physics, astrophysics and cosmology.

Nuclei for life

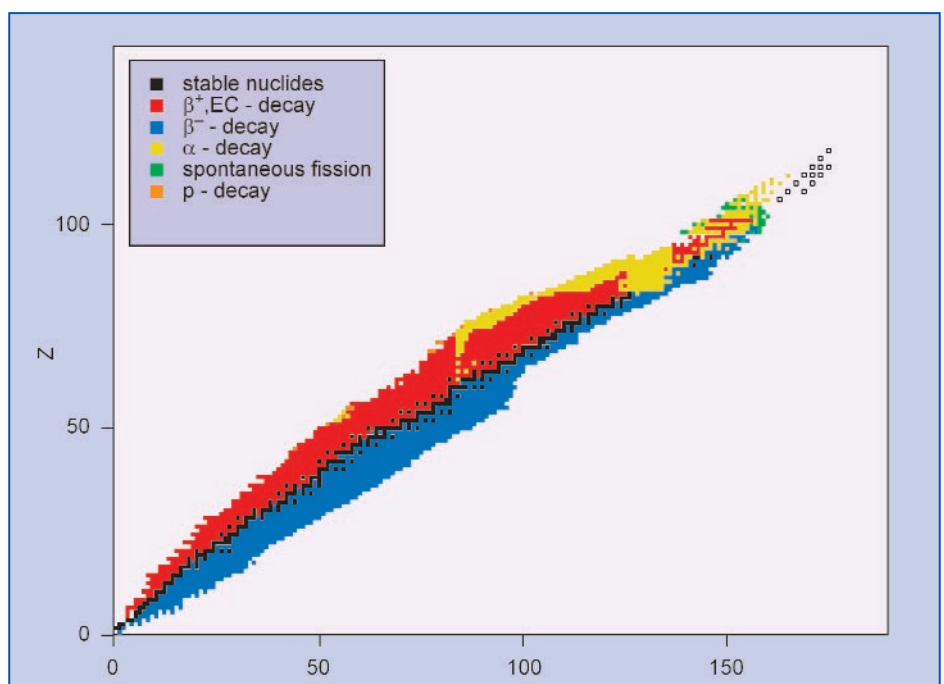
The hydrogen nucleus usually comprises just a single proton, but it occasionally has one or even two additional neutrons, but never more. This limiting factor on the number of neutrons any nucleus can contain has a profound influence on the world of matter. If a nucleus of hydrogen had one proton and 99 neutrons, it would have very strange physical properties – for instance, water made with this isotope would be solid at room temperatures.

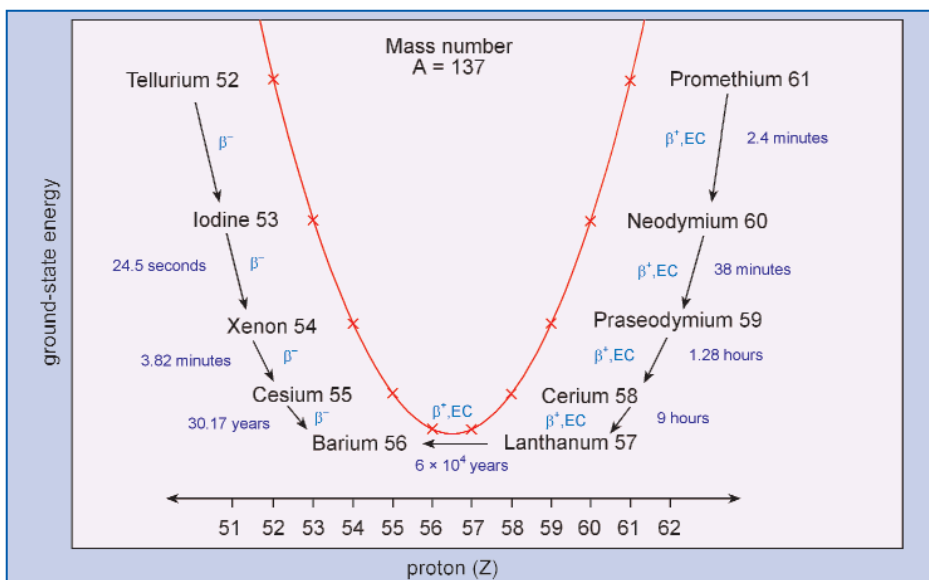
The carbon compounds upon which life depends would be quite different if ^{40}C rather than ^{12}C were the most common isotope of carbon; the fats in our bodies would weigh about three times as much and, even more dramatically, we would have great difficulty breathing out solid carbon dioxide! But ^{40}C does not, and cannot, exist. The key to understanding why lies in the energy stored within nuclei. Not only does this energy provide clues as to why certain nuclei are found in abundance and others are rare, but it also explains how energy is extracted from nuclei, both in the stars and on Earth.

What nuclei are possible?

Nuclei can be classified into two types: stable and radioactive. A stable nucleus lasts forever, but a radioactive one is unstable and decays into a different species. If it decays to another unstable nucleus, then that will also decay. Radioactive decay will continue until a stable nucleus is formed.

The presently known nuclei displayed according to proton number Z on the vertical scale, and neutron number N on the horizontal scale. The black squares denote the stable nuclei, and also the extremely long lived nuclei like ^{238}U that exist on Earth. The blue squares indicate nuclei with an excess of neutrons and so beta decay by emitting electrons. The red squares indicate nuclei which undergo positron decay (or electron capture). The yellow nuclei are those which decay by emitting alpha particles and the green nuclei undergo spontaneous fission. There are a few orange nuclei along the upper edge of the coloured area; these decay by emitting protons. The squares at the top right are recently produced super-heavy nuclei. This sort of diagram is called a Segrè chart.





The unstable nuclei, those indicated with red or blue squares in the previous diagram, have the wrong proportion of protons and neutrons. They correct this by beta decaying to another nucleus with the same atomic mass number. The wrong balance of protons and neutrons gives the nucleus too much energy. This energy is carried off by the electron or positron and the neutrinos. This process of losing excess energy is rather like falling down a hill and this diagram shows how the energy increases rapidly away from the stable nucleus, in this case the barium isotope ^{137}Ba (the 56 indicates that barium is the element with 56 protons). This picture shows how the energies of series of nuclei, all with 137 nucleons, form a shape known as a parabola. The nuclei up the sides of the parabola eventually lose energy, falling down to the bottom in a series of beta decays. The half-lives for the decays are shown.

There are many more radioactive nuclei than stable ones. Some nuclei that have too many neutrons to be stable experience beta decay in which a neutron turns into a proton, emitting an electron and a ghostly neutrino. Nuclei with too few neutrons for stability undergo the other kind of beta decay in which a proton turns into a neutron.

All the possible stable nuclei have been known for many years, but the tally of known radioactive nuclei is continuously expanding. New and interesting radioactive nuclei are regularly produced in laboratories, enriching both our knowledge of nuclei and also helping us understand the workings of stars. Many of these new nuclei are very unstable, having half-lives much less than a second. Some survive for such a brief period, they can hardly be said to exist at all.

It is not yet known exactly how many or how few neutrons can exist in a nucleus with a given number of protons before it becomes so unstable that it effectively does not exist. So it is not yet feasible to predict the total possible number of nuclei.

The nuclei of most elements up to calcium, which has an atomic number, Z , of 20, have a handful of different isotopes, and in each case there is always a stable isotope with either the same number of neutrons as protons, or one additional neutron. The elements with an odd number of protons generally have fewer isotopes than elements with an even number. Fluorine, sodium and aluminium (elements 9, 11 and 13), for example, have just one isotope each, while oxygen, neon and magnesium (elements 8, 10 and 12), each have three isotopes.

For elements up to calcium, stable isotopes have similar numbers of protons and neutrons. Beyond calcium there is a change, and stable isotopes start to exist with more neutrons than protons. The isotope of calcium, ^{40}Ca , having 20 neutrons, is the last stable nucleus with an equal number of protons and neutrons. For heavier elements, stable nuclei contain more neutrons than protons and the excess of neutrons increases with atomic number. For example, stable isotopes of lead, which has 82 protons, contain 122, 124, 125 or 126 neutrons.

Some nuclei are not completely stable, but have long enough half-lives to be found naturally on Earth. Examples are the uranium isotope ^{238}U and the potassium

isotope ^{40}K . The small amounts of ^{40}K that we all have in our bodies makes us slightly radioactive. This radioactivity contributes to the background radiation that we all experience. Half of all the ^{238}U that was present when the Earth was formed, 4.5 billion years ago, still exists in the soil and rocks. In fact, ^{238}U is much more common on Earth than gold, which is a stable element.

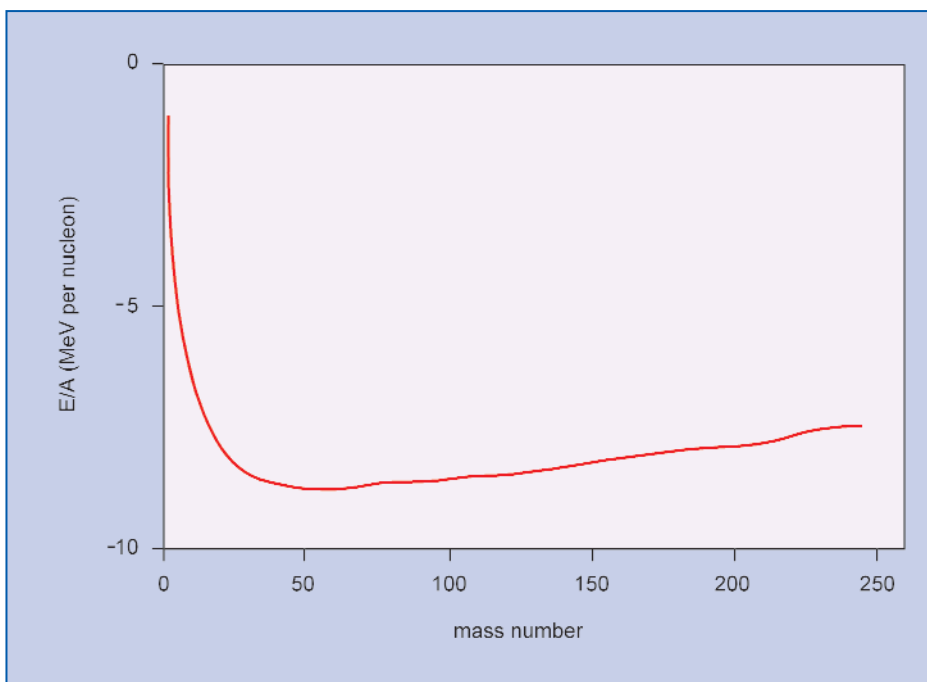
The driplines

There are some nuclei that take even more drastic steps to get their proton–neutron balance right – they emit protons directly. These nuclei, on the very edge of stability, lie along the ‘proton dripline’, marking the limit of the number of protons a nucleus can have, even for a very short time. Similarly, the neutron dripline marks the limiting number of neutrons a nucleus can hold without them being emitted immediately. At the time of writing the neutron dripline has only been reached up to about $Z=12$, since the maximum possible number of neutrons is not yet known for larger nuclei.

For nuclei with more than 60 protons, there are other forms of radioactivity. Some decay by emitting alpha particles, others undergo spontaneous fission: they split, without any prompting, into two, approximately equal, lighter nuclei. This process has had momentous implications for humans and also, together with alpha decay, puts a limit on the total number of protons and neutrons that a nucleus can have.

The energy valley

Generally, the greater the imbalance of protons and neutrons in a nucleus, the shorter its half-life. When a nucleus undergoes beta decay, the emitted electron and neutrino carry off energy. The energy lost in this way is nearly always larger for decays between pairs of nuclei that are highly unstable. The more energy that is lost by the nucleus, the more rapidly the emission takes place and thus the shorter the half-life.



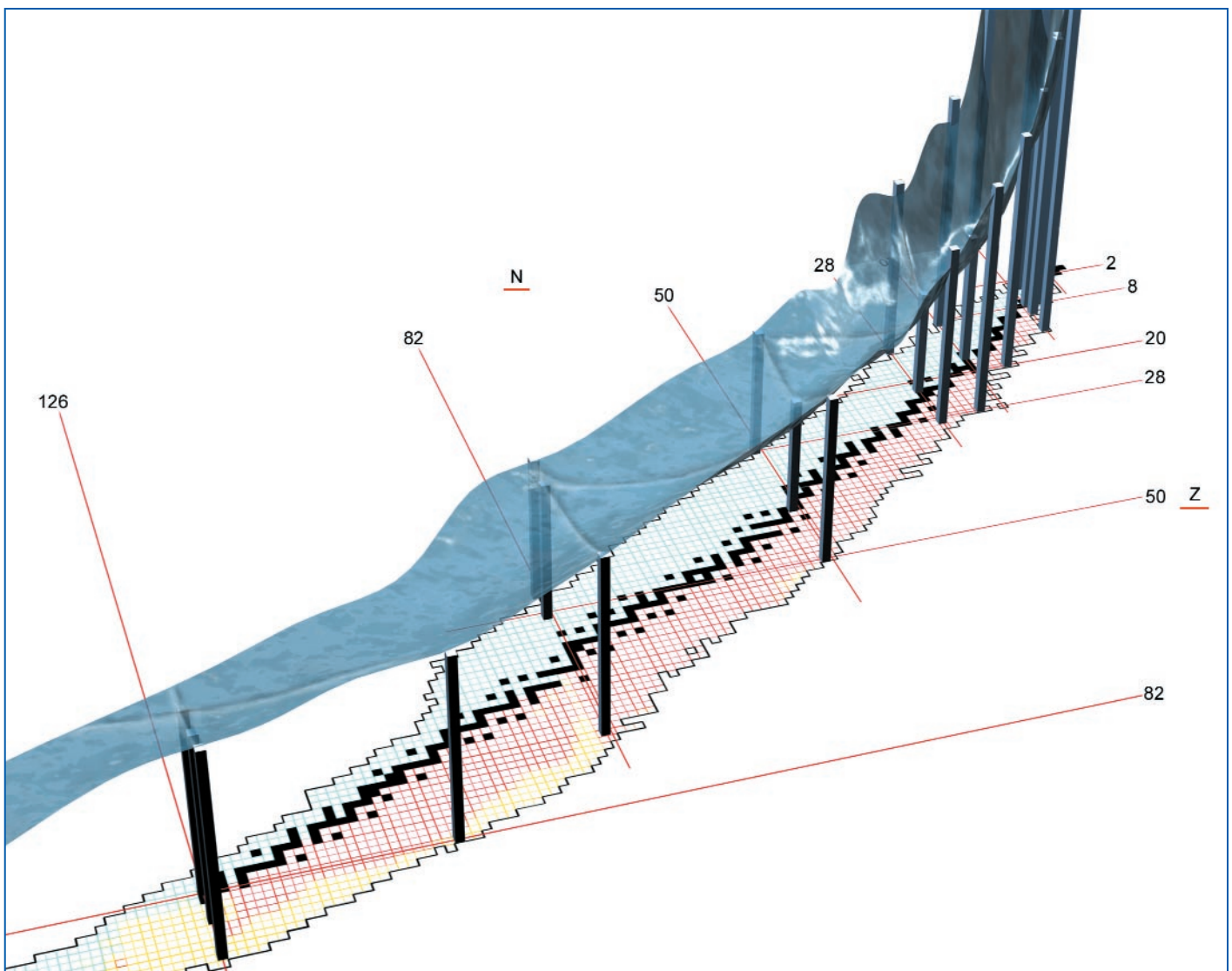
The total energy of a nucleus is not exactly proportional to the mass number, A , the number of nucleons. This graph shows how the energy per nucleon, written E/A , depends on A . The most stable nuclei are those near the lowest point on the curve, around mass number 56 to 60. Both the lightest nuclei and the heaviest nuclei have more energy for each nucleon than the nuclei with about 60 nucleons. That is why energy is released when the lightest nuclei undergo fusion to make heavier nuclei, or the heaviest nuclei undergo fission and split into two lighter nuclei. On this graph, the energy is that of the most stable nuclei with that particular mass number A , in other words the nucleus near the bottom of the parabola in the previous figure.

Among nuclei with a certain number of nucleons, the stable nuclei have the least energy while unstable nuclei have excess energy which they lose by transforming themselves through beta decay. The more unstable the nucleus, the more excess energy it possesses. It is as if the stable nuclei are at the bottom of a valley with the height above the valley floor being a measure of the energy stored in the nucleus. Nuclear physicists refer to this as the valley of stability. Continuing the valley analogy, nuclei with more energy are like boulders perched up the side of the valley; they are less stable than ones at the bottom – a nudge could send them rolling down. Not only does the valley slope upwards, but it also gets steeper further from the bottom. This is why beta decay, in which nuclei lose energy by jumping down the sides of the valley, takes place more rapidly for the distant nuclei – the downward jumps are greater. Boulders lying at the bottom of the valley need to have energy supplied to them to lift them up the side of the valley.

Along the valley floor

The amount of energy stored in a nucleus depends on the total number of protons and neutrons (the atomic weight A) as well as on the proportion of protons to neutrons. The more protons and neutrons in a nucleus, the more energy it has. The important quantity is really the energy per nucleon. This is just the total energy divided by A .

How the energy of a nucleus depends on Z , the number of protons, and N , the number of neutrons. The grey surface is in the form of a valley and the height represents the energy per nucleon, E/A . The valley floor follows the shape of the curve on the previous figure, and the sides of the valley curve upwards as shown for mass number 137 in the figure before that. This figure also shows grooves or 'gullies' crossing the valley – these show the way the energy dips down for the magic numbers. The black pillars are there to guide the eye to the red lines which indicate the magic numbers. One gully crosses the valley for proton number 50, and another for neutron number 82.



When all known nuclei are placed in a figure in which the height represents the energy per nucleon, the stable nuclei all lie along the floor of a valley. This floor is not level, but slopes toward a lowest point that is near particular nuclei with 26 or 28 protons. These nuclei have less energy per nucleon than any other nuclei. The bottom of the valley itself slopes upward slowly in the direction of the heaviest nuclei such as uranium and more steeply toward the lightest nuclei.

Element 26 is iron, and the position of the nuclei of certain isotopes of iron near the bottom of the valley is one reason why iron is very abundant both on Earth (the central core of the Earth is largely iron) and in the rest of the Solar System. Once the nuclei of iron are formed within stars, they are reluctant to transform into anything else without further energy being supplied. Elements with more protons than iron or nickel (element 28) tend to be less abundant on Earth and in the stars than most of the lighter elements. This is due largely to the way elements are made in stars, but the energy valley is a key factor.

In a similar manner to a river flowing along a valley floor towards the lowest point, the lightest atomic nuclei undergoing reactions tend to move towards the region near iron where the energy is lowest, by acquiring more protons and neutrons. Heavy nuclei can do this, somehow transforming themselves into nuclei with fewer protons and neutrons and thereby moving in the other direction. Thus two very different processes are involved, depending on the direction of the flow: nuclear fusion and nuclear fission.

Nuclear fusion and fission

If two very light nuclei can be made to coalesce or 'fuse' into one heavier nucleus, energy will be released because the heavier nucleus has less energy per nucleon than the lighter ones. Energy will therefore be 'left over' after the nuclei have coalesced. This is nuclear fusion, and is the source of the energy from the Sun. Most of this comes from hydrogen fusing to form helium. Fusion reactions that produce energy cannot produce nuclei heavier than iron or nickel, the nuclei at the lowest point of the valley.

In stars hotter and more massive than the Sun, other fusion processes occur. When a magnesium nucleus with 12 protons fuses with a silicon nucleus with 14 protons to make an iron nucleus with 26 protons, a great deal of energy is released. Much of the iron in our Solar System was probably made in processes like this when massive stars exploded more than four billion years ago.

The valley floor sloping upwards from iron in the direction of the heaviest nuclei means the amount of energy per nucleon is getting progressively greater. If a heavy nucleus splits into two, the resultant, lighter nuclei would exist lower down the energy valley and each would have less energy per nucleon. The total amount of energy contained by the resultant nuclei is less than the energy of the original nucleus. Therefore, after the split there would be some surplus energy. Such nuclear splitting is known as nuclear fission. When a heavy nucleus undergoes fission, the surplus energy is released mostly in the energy of motion of the two lighter fragments as they fly apart.

Fission is the source of much of the electrical energy used by many nations and it is the source of the man-made element, technetium, used to treat cancer and other diseases. In addition it forms the basis of weapons of dreadful destruction.

One of Nature's greatest surprises

The discovery of nuclear fission in the late 1930s came as a huge surprise. There was nothing in the behaviour of atoms to suggest that their nuclei should behave in such a way. Ernest Rutherford, and all the other nuclear pioneers, had given up hope that the energy locked within nuclei could be extracted and harnessed. Then, Otto Hahn and Fritz Strassmann were astonished to discover that when uranium was bombarded with slow neutrons, traces appeared of the much lighter element, barium. They worked hard to convince themselves that it really was barium produced, and not radium, an element with similar chemical properties but much closer to uranium in mass.

With hindsight, it might seem obvious that a uranium nucleus had split into two fragments, one of these being a barium nucleus, but this was initially far from obvious. It was only some months later, while on a skiing holiday in Kungälv in Sweden, that Lise Meitner and her nephew Otto Frisch came up with the now accepted picture of nuclei undergoing what they called fission – the word used by biologists for the process by which living cells divide. Frisch soon observed that the barium nuclei flew off at high speed, carrying away a lot of energy. The energy of nuclei could, after all, be extracted and maybe put to use.

When a nucleus undergoes fission, the two lighter nuclei that fly apart are soon slowed down by nearby atoms, to which some of the energy is transferred. In this way, a great deal of heat is generated which can be made to turn water into steam, powering turbines that generate electricity – but there is an unfortunate consequence.

Consider, once more, the bottom of the energy valley. For heavier nuclei, the stable isotopes contain more neutrons than protons, thus the floor of the valley curves away from the diagonal line that represents nuclei with equal numbers of protons and neutrons. If, for example, the uranium isotope ^{235}U absorbs a neutron, the resulting ^{236}U will undergo fission. It can split in a variety of ways, but will often split into nuclei of barium and krypton. These might be ^{146}Ba and ^{90}Kr ; since barium has $Z=56$ and krypton has $Z=36$, the number of protons adds up to 92 – the correct Z for uranium. In addition, the total number of nucleons adds up to 236.

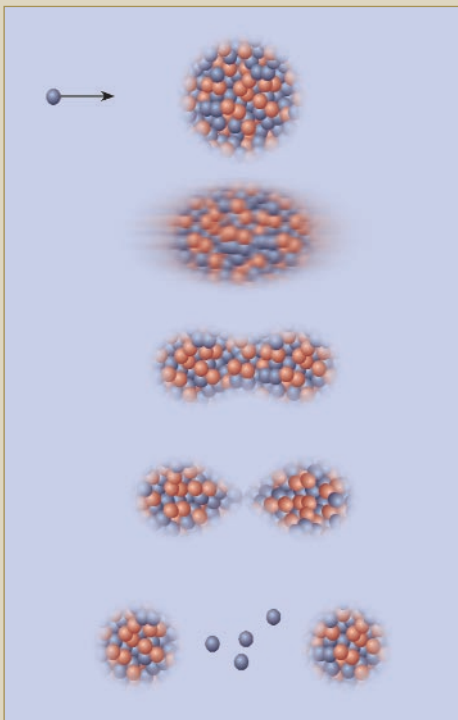
The problem is that the heaviest stable barium nucleus is ^{138}Ba and the heaviest stable krypton nucleus is ^{86}Kr , so both of the nuclei that are produced in fission have a large excess of neutrons. This means they are positioned somewhere up the side of the energy valley, an unstable state from which they will inevitably tumble down in a chain of beta decay steps.

Due to the curve in the energy valley, nuclei produced in fission will always be somewhere high up the neutron-rich side of the valley. The nuclei produced in nuclear fission are therefore highly radioactive, casting a shadow over applications of nuclear fission.

In fact, the fission products of a splitting uranium nucleus will not be quite so far up the valley walls as the example above suggests. When a nucleus divides in two, not all of its neutrons go into the two lighter nuclei. A few, generally two or three, are released. These can then be absorbed by other ^{235}U nuclei, turning them into fissionable ^{236}U . This is of great importance, making nuclear fission a practical source of energy, because these neutrons will then induce more uranium nuclei to



Lise Meitner, 1878–1968. Born in Vienna, she worked for many years in Berlin doing research in radioactivity. Element 109, meitnerium, is named after her. (AIP Emilio Segrè Visual Archives.)



Meitner and her nephew Otto Robert Frisch, 1904–1979, were the first to recognise a certain phenomenon discovered by Hahn and Strassmann as a signature of nuclear fission, the process shown above. Their fission model was based on Niels Bohr's 'liquid drop' model of nuclei, and predicted that fission releases much energy. At that time, in 1939, Meitner was taking refuge in Sweden. She spent her winter holidays with Frisch in the house on the right.

19³⁰⁻³¹/₁₂ 38
LISE MEITNER (1878–1968)
 OCH HENNES SYSTERSON
OTTO ROBERT FRISCH (1904–1979)
 FORMULERADE HÄR
 EN FÖRKLARING TILL
 UPPTÄCKTEN AV URANKARNANS
 KLYVNING

split. These in turn release more neutrons, each of which would cause more uranium nuclei to fission, and so on. This is the famous fission chain reaction.

When the chain reaction takes place in a slow and controlled way, we have nuclear reactors that can produce electricity and isotopes for medical purposes. When it happens in an uncontrolled way, we have a nuclear bomb.

Limitations of mass

In about 1942 it was found that uranium nuclei can, very occasionally, undergo fission without any stimulation by neutrons. This process is called spontaneous fission and helps answer the question of which nuclei can exist. Spontaneous fission becomes more and more important for the very heaviest nuclei, and is one of the factors that determines just how heavy a nucleus can be.

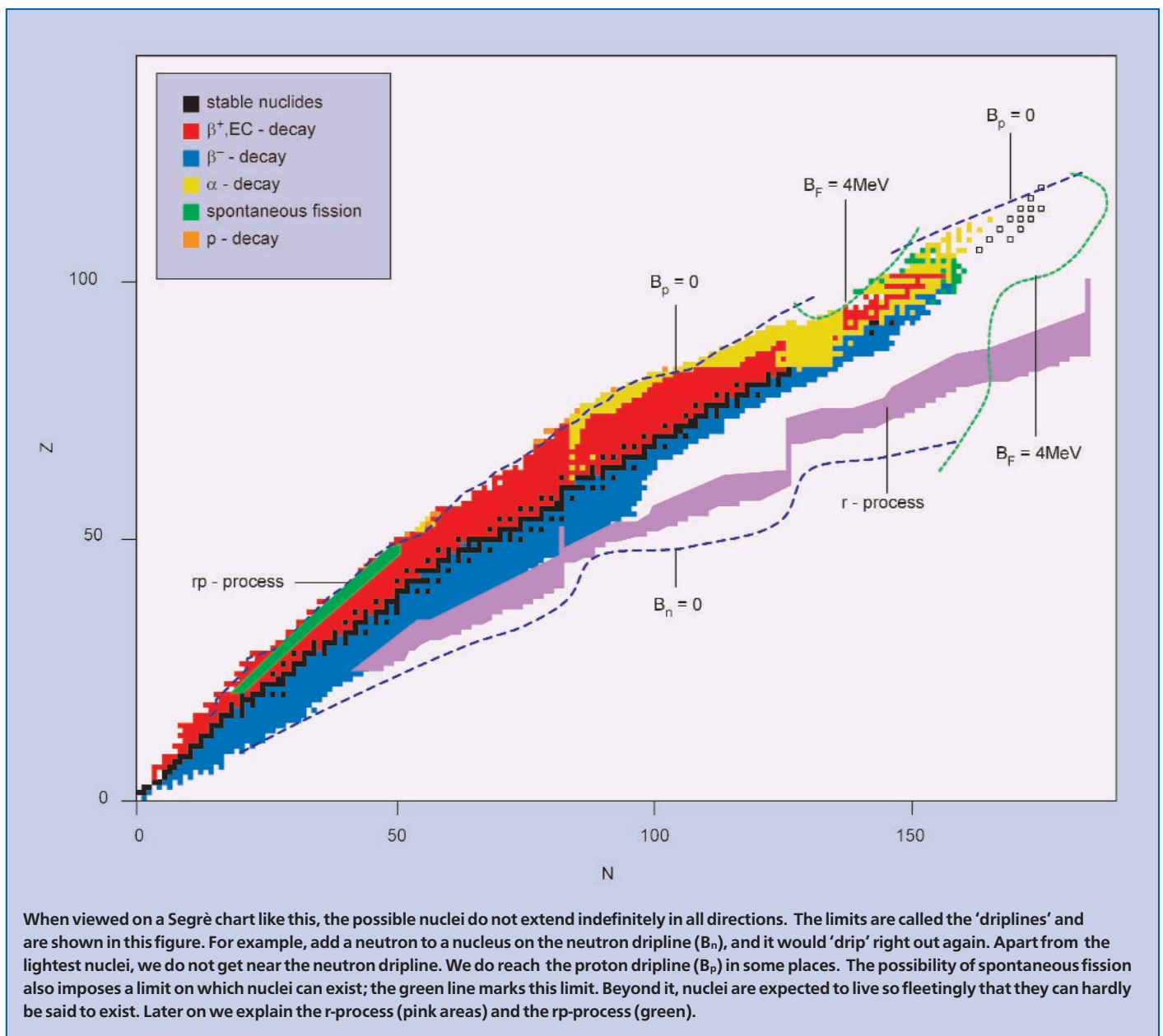
At the top end of the valley of stability, most nuclei decay by emitting alpha particles. Alpha particle decay can also be thought of as a kind of fission in which one of the nuclei produced is very much smaller than the other. Energy is released, and carried off by the alpha particle, in a similar manner to when a nucleus undergoes fission. The resulting nucleus lies further down the energy valley than the original one and, although the alpha particle itself is far down at the other end of the valley floor, it is also a very stable nucleus.

The tendency for nuclei to alpha decay is also a major limiting factor to how heavy nuclei can be. The half-life of a nucleus undergoing alpha decay is exceptionally sensitive to the energy of the alpha particle: the more energy carried off by the

alpha particle, the shorter the half-life. Thus the excess energies of the alphas at the extreme top end of the valley indicate that these nuclei are very short-lived.

Magic numbers

So far, the energy valley has been presented as being smooth, but studied more closely, it is seen to be rather bumpy. This is because the energy per nucleon of stable nuclei does not follow a smooth curve. A select few are slightly lower than their neighbours since they have even less energy per nucleon (more stable). Such nuclei tend to line up together in grooves that criss-cross the valley floor. These grooves occur for particular numbers of protons and neutrons known as magic numbers. A good example occurs with the series of nuclei lying on the line for 50 protons. The isotopes of the element with $Z=50$, tin, have somewhat lower energy per nucleon than their neighbours, and have various other properties that are associated with greater stability. Tin also has more stable isotopes (10 in all) than any other element.



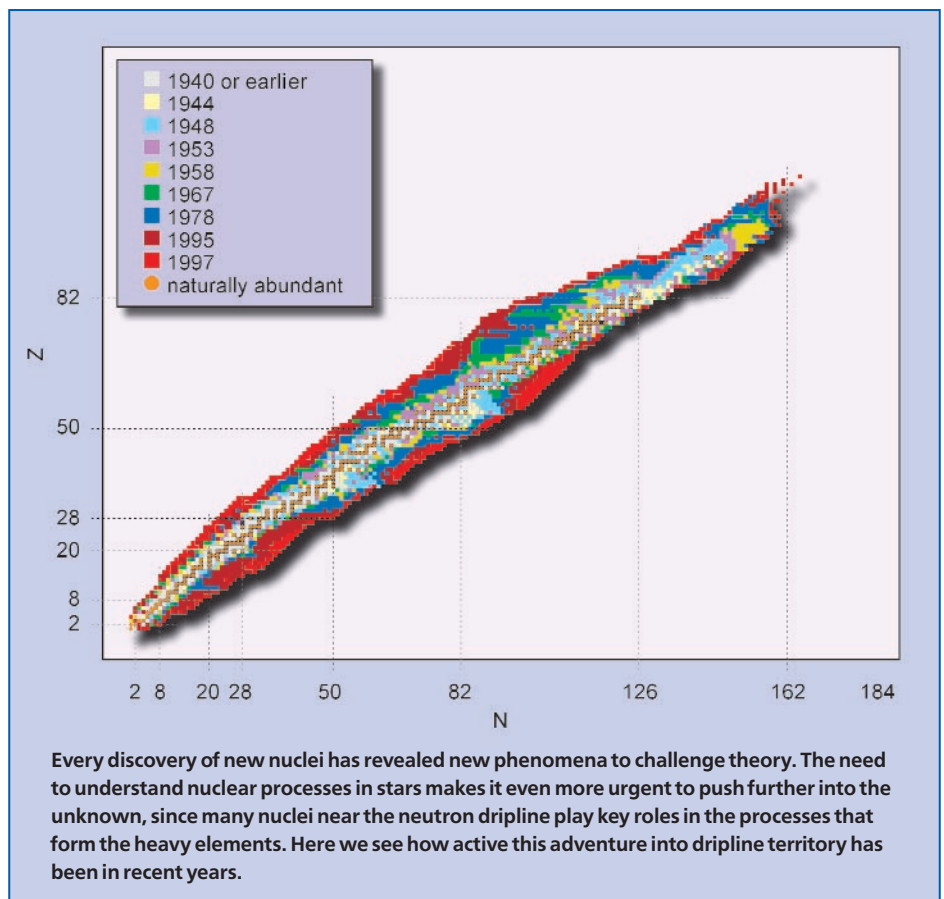
The number 50 is also significant for neutrons. All the nuclei on the line signifying 50 neutrons have a little less energy per nucleon than their neighbours. Thus a nucleus with either 50 protons or 50 neutrons will be significantly more stable than nuclei with slightly fewer, or more, protons or neutrons. Although they are not deep compared to the main energy valley itself, these grooves have a profound effect on what nuclei exist, and also contain vital clues about the structure of nuclei.

There are other magic numbers. The complete set is: 2, 8, 20, 28, 50, 82 and 126.

Nuclei that have magic numbers of both protons and neutrons are especially stable. The simplest example is ${}^4\text{He}$, the alpha particle, with two protons and two neutrons. This is the reason for its exceptional stability. Another example is the isotope of lead, ${}^{208}\text{Pb}$, with 82 protons and 126 neutrons. Lead is common on Earth, and ${}^{208}\text{Pb}$ is its most abundant isotope. However, lead is surrounded by quite rare elements that have relatively unstable nuclei. The next element after lead is bismuth, $Z=83$, which is hundreds of times rarer than lead in the Earth's crust. All elements with more than 83 protons only have radioactive isotopes.

The possible nuclei

The energy valley answers some questions about what nuclei exist; for example, it explains why there are no ${}^{40}\text{C}$ or ${}^{100}\text{H}$ nuclei – they would lie too far from the bottom of the energy valley. The existence of a nucleus containing a particular combination of protons and neutrons depends on the energy of the combination. Some combinations yield nuclei that last forever, others are subject to radioactive decay. In general, the further a nucleus is from the valley floor, the shorter its half-life.



Too far from the valley floor and any protons or neutrons that we might try to add to a nucleus leak right out again. These points mark the boundaries of the region where nuclei either exist or would exist if we could make them. These boundaries are the driplines mentioned earlier. In some places we do know where they are, and in other places we can make informed guesses.

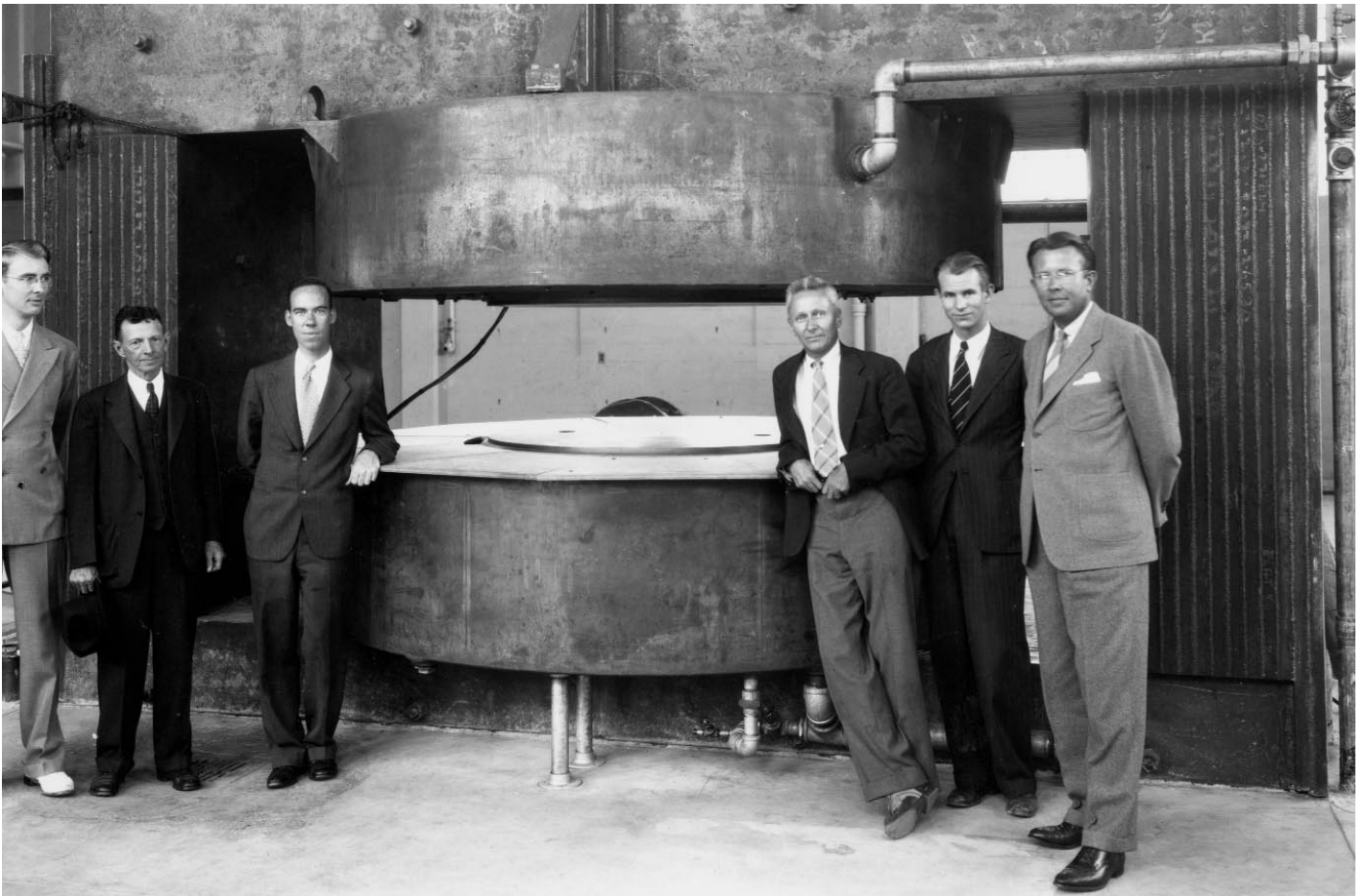
There are many nuclei that must exist but which have not yet been identified in the laboratory. The number of nuclei that have been created and studied increases year by year.

The super-heavies

Although all the isotopes of thorium, $Z=90$, and uranium, $Z=92$, are strictly unstable, both elements have one or two isotopes with extremely long half-lives – as long as the age of the Earth in the case of uranium, and three times longer than that for thorium. All isotopes of elements with more than 92 protons are much too short-lived to have survived since the Solar System was formed. It naturally became an irresistible challenge to make nuclei with more than 92 protons using nuclear reactions! These are known as the transuranic nuclei since they have more protons than uranium.

Element 93, neptunium, was identified by Edwin McMillan and Philip Abelson in Berkeley, California, in 1940. Over the years, elements 94 (plutonium) to 103 (lawrencium) were also produced at Berkeley as a result of heroic efforts by Glenn Seaborg, Albert Ghiorso and their large team using cyclotrons and other accelerators. Elements 104 (rutherfordium) to 107 were for many years the subject of claims by workers at Berkeley and at Dubna in Russia.

One of the first large cyclotrons at the Lawrence Radiation Laboratory, Berkeley, 1944. From left, Luis Alvarez, William Coolidge, William Brobek, Donald Cooksey, Edwin McMillan and Ernest Lawrence. Alvarez and Lawrence were later awarded Nobel prizes in Physics, Lawrence for inventing the cyclotron and Alvarez for discovering many new particles using bubble chambers. McMillan, discoverer of element 93, neptunium, shared a Nobel prize in chemistry with Glenn Seaborg for their work on transuranic elements. McMillan later helped develop the synchrotron, the high energy successor to the cyclotron. (Berkeley National Laboratory, AIP Emilio Segrè Visual Archives.)



Advances in making new elements are currently being made at GSI near Darmstadt in Germany. The challenge the physicists face is formidable. As the number of protons increases, the half-lives of these elements gets shorter. For example, the longest lived isotope of rutherfordium, ^{261}Rf , has a half-life of about one minute. Alpha decay and spontaneous fission compete to make nuclei of the other isotopes vanish even more quickly. Moving up to element 107, half-lives are typically measured in milliseconds, but the ambition to reach higher atomic numbers remains.

For many years, nuclear theory has suggested that 114 is a new magic number for protons. This might lead to an 'island of stability' around elements 112 or 114, where lifetimes are longer than expected and perhaps become long enough for the chemical properties of the elements to be studied. The term 'island' is a little misleading since it implies a higher level than its surroundings – in the picture of the energy valley, these more stable heavy nuclei would actually reside in a lower energy region than their surroundings. It is not yet clear whether this island of super-heavy nuclei exists.

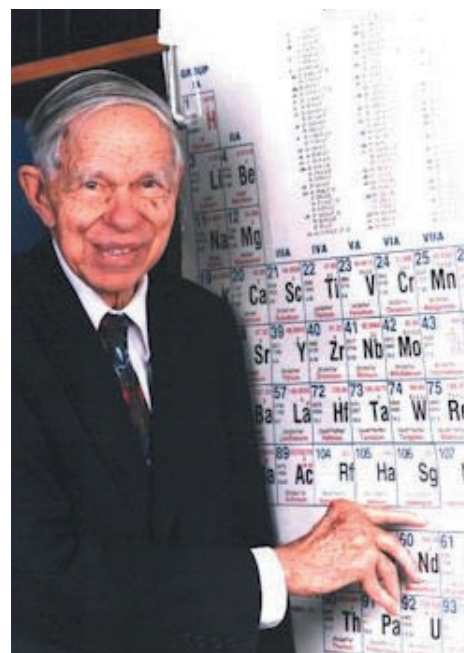
The curvature of the energy valley adds to the difficulty of making super-heavy nuclei. It dictates that the heavier the nucleus, the greater the excess of neutrons over protons, but super-heavy nuclei must necessarily be made using reactions with lighter nuclei, having a smaller ratio of neutrons to protons. It follows that the nuclei made in these reactions will have too few neutrons to be near the bottom of the energy valley. To make the job even harder, these heavy nuclei undergo fission with little prompting, and the very reactions in which they are made are likely to put a lot of energy into the system. Too much energy would nudge any nucleus with a tendency to fission to take the plunge and break up again.

Even if a few super-heavy nuclei are made, identifying them is extremely hard. Finding a needle in a haystack is nothing compared with having to identify the single super-heavy nucleus produced per day when trillions of particles are hitting the detectors every second. The efforts to study these exotic nuclei are very rewarding to both physicists and chemists; chemists can check whether they can predict the chemical properties of hitherto unknown elements, while physicists have an invaluable test of their theories, which predict the probability of alpha decay and spontaneous fission.

Step by step the GSI physicists have worked their way up through new elements with shorter and shorter half-lives. These include element 109, meitnerium (named after Lise Meitner), identified in 1982, and the yet-unnamed elements 110 and 111 discovered in 1994, and 112 discovered in 1996. There have been reports that element 114 might have been discovered in Dubna in 1999, and most recently there is evidence from Dubna for element 116.

Exotic nuclei at the driplines

Great efforts are being made to extend our knowledge of nuclei in the directions of the lowest and highest possible neutron numbers for a given Z – the most neutron-rich and neutron-deficient isotopes of an element. Such unstable nuclei are hard to make on Earth, but they do exist briefly when stars explode. They are created en route to producing many of the elements on Earth, including some of those inside our bodies. We can never fully understand where the elements on Earth come from, or the stars they were made in, without studying the exotic, highly unstable nuclei closely.



Glenn Seaborg, 1912–1999, discoverer of plutonium and other elements. Element 106, seaborgium, is named after him.

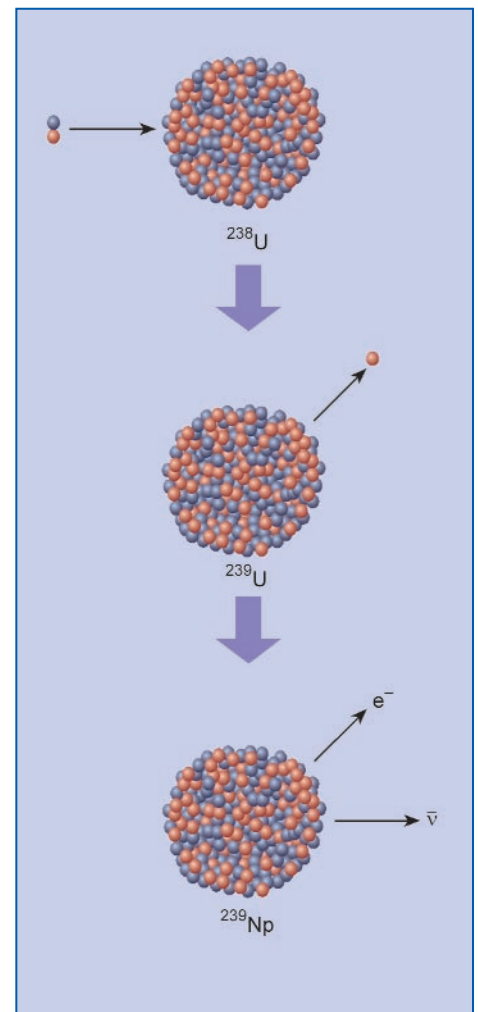
Exotic nuclei are also very interesting because many of them are so unlike the more familiar stable nuclei. Examples are the halo nuclei ${}^6\text{He}$ and ${}^{11}\text{Li}$, which are much larger than the stable isotopes of helium and lithium. Understanding these weird nuclei has proved to be a great challenge to both theorists and experimentalists. Theories can be adjusted to explain all the known stable nuclei quite well, but the real test is whether they can predict the properties of these new exotic nuclei.

The most stable nucleus

Iron makes up most of the Earth's core due to its exceptional stability. It is also one of the most common elements in the Solar System and is near to the lowest point in the energy valley. It is therefore natural to think that there must be a connection, and there is, but, as always when dealing with Nature, there are complications. In fact, the most common isotope of iron, ${}^{56}\text{Fe}$, is not quite at the lowest point in the energy valley. That privilege goes to an isotope of nickel, ${}^{62}\text{Ni}$, the most stable nucleus in nature. However, it is not nearly as abundant in the Solar System as ${}^{56}\text{Fe}$. The reason is simple: a nucleus not only has to be as stable as possible, but there must also be an efficient pathway for its production from other nuclei.

A full account of why some nuclei are abundant and others are rare must take into account both how stable the nucleus is, and the mechanisms by which it can be produced. The iron isotope, ${}^{56}\text{Fe}$, is produced by fusion of lighter nuclei in certain very hot exploding stars. It turns out that there are no nuclei in these stars that could then fuse with ${}^{56}\text{Fe}$ to make ${}^{62}\text{Ni}$.

Thus, the rarity of gold is not only a matter of its position on the energy valley, but also a consequence of the rarity in the Universe of the processes that make it. The reason carbon is more abundant than gold is partly because the stellar processes that make ${}^{12}\text{C}$ occur on a widespread scale in the Universe.



McMillan and Abelson made neptunium by bombarding ${}^{238}\text{U}$ with deuterons. There is a good chance that the neutron in the deuteron will be absorbed while the proton continues on its way. In that case ${}^{239}\text{U}$ will be formed. However ${}^{239}\text{U}$ has too many neutrons for stability and beta decays emitting an electron and anti-neutrino within minutes to form ${}^{239}\text{Np}$.