

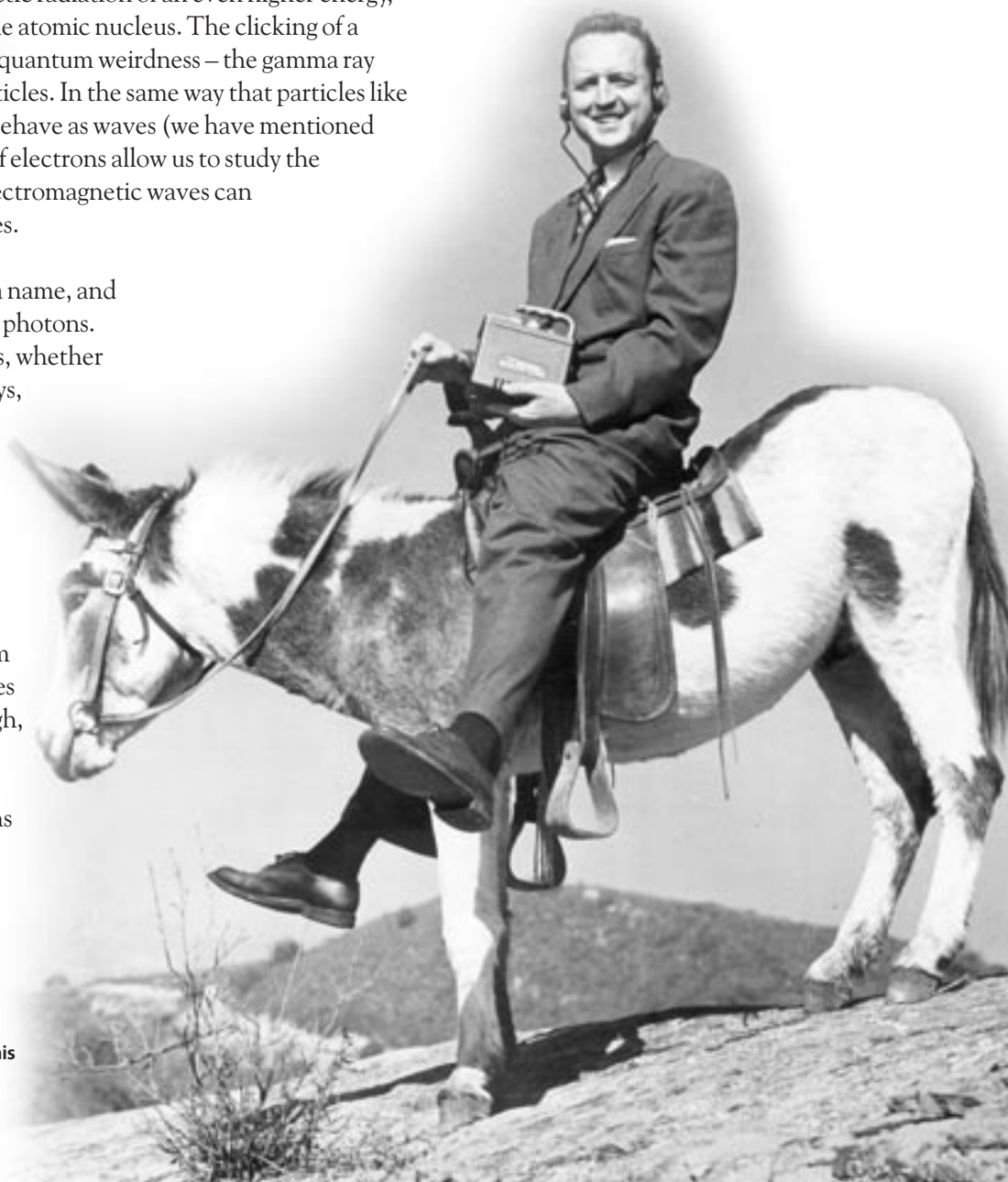
3. Particles or waves?

Strange laws at the heart of matter

Television news items or films sometimes show someone using a Geiger counter... maybe a prospector is searching for uranium, or perhaps a hospital worker is accounting for vital radioactive materials used to treat cancer. Geiger counters are particle detectors that make a characteristic clicking sound every time a high energy particle enters. Click – one particle; click – another particle.

It is known that X-rays are emitted by electrons in the atom, whereas gamma rays, electromagnetic radiation of an even higher energy, are emitted from within the atomic nucleus. The clicking of a Geiger counter is a sign of quantum weirdness – the gamma ray waves are behaving as particles. In the same way that particles like electrons can sometimes behave as waves (we have mentioned how the wave properties of electrons allow us to study the structure of matter), all electromagnetic waves can occasionally act as particles.

Every type of particle has a name, and particles of light are called photons. All electromagnetic waves, whether they are gamma rays, X-rays, visible, ultraviolet light, or radio waves, consist of photons. Another important property of electromagnetic waves is that, unlike other forms of waves such as sound, they do not need a medium to carry them. Sound waves require air to travel through, but all forms of light can propagate through empty space. It is because photons happily travel in the near vacuum of space that the radiation emitted by the Sun can heat the Earth.



J. L. Cassingham with one of his company's Geiger counters, featured in an advertisement from 1955. (Courtesy J. L. and Curtis Cassingham.)



James Watson (top), 1928–, and Francis Crick, 1916–, analysed the diffraction of X-rays by DNA. In 1953 they discovered the remarkable double-helix structure of the molecule on which our genome is encoded. (AIP Emilio Segrè Visual Archives.)



The strange world of photons

Every day we use photons of visible light to find our way about and to enjoy our environment. We can extend our visual sense with microscopes to study objects that would otherwise be too small to see with the naked eye. But ordinary microscopes are no help when it comes to discerning structures smaller than the wavelength of visible light. To see the details of such structures we need to use photons with shorter wavelengths. Investigating the diffraction patterns caused by shining X-rays through salt crystals, for example, allows the spacing between the atoms to be measured. The process by which the diffraction pattern is created is a consequence of quantum effects.

Imagine turning down the intensity of the X-ray beam until just one photon passes through the crystal at a time. A single photon like this can act like a particle, blackening a single minute grain of sensitive material on a photographic film, but if we fire a huge number of photons one at a time at the crystal, aiming exactly the same way each time, then the spots eventually build up into a diffraction pattern.

While each photon arrives at the film as a tiny particle, the only way the diffraction pattern could build up is for each photon to ‘see’ the whole array of ions. Somehow, like a wave, it must pass through the whole crystal and yet, like a particle, it will blacken a single grain on a photographic film. A single minute spot on a film is not a diffraction pattern; only after many individual photons have passed through the crystal does the pattern build up.

Weird quantum effects

In our X-ray shoot-out, the photons do not pile up at the same spot on the film even though they were aimed and fired in exactly the same way. The pattern that builds up reveals the wave nature of the particles as more and more photons hit the film. It is impossible to predict where any particular photon will turn up on the film, yet the overall pattern that eventually builds up consists of groups of spots clustered together in bands with gaps in between where there are no spots. This interference pattern is a feature that always shows up whenever quantum effects are important.

Many people find this ‘uncertainty’ one of the most disconcerting characteristics of quantum behaviour. For centuries, science has been based on the idea that a particular situation always leads to the same outcome. In the X-ray diffraction experiment, this rule is broken: it is simply impossible to predict where a photon will leave its mark on the film.

All is not lost, however. A new, but limited, kind of predictability emerges from the ruins of the old predictability, in which people believed they could say where a particle would go. The pattern that builds up from a large number of unpredictable spots is itself predictable, and can be reproduced whenever the entire experiment is repeated. We just have to abandon the idea that we can ever say where an individual photon will blacken the film. This strange new interplay of predictability and unpredictability turns up repeatedly in the realm of atomic nuclei.

Further quantum weirdness

In diffraction experiments, the regular array of atoms in the crystal determines the final pattern. Somehow each photon has to ‘see’ the crystal as a whole – even if it turns up at a single point on the screen. Try to determine exactly where the photon went through the crystal, however, and the diffraction pattern is destroyed. It is as



Werner Heisenberg, 1901–1976, left, one of the creators of quantum theory, with his mentor Niels Bohr, 1885–1962, the first person to apply quantum ideas to atoms. Heisenberg was the first to incorporate neutrons into a model of nuclei. (AIP Emilio Segrè Visual Archives.)

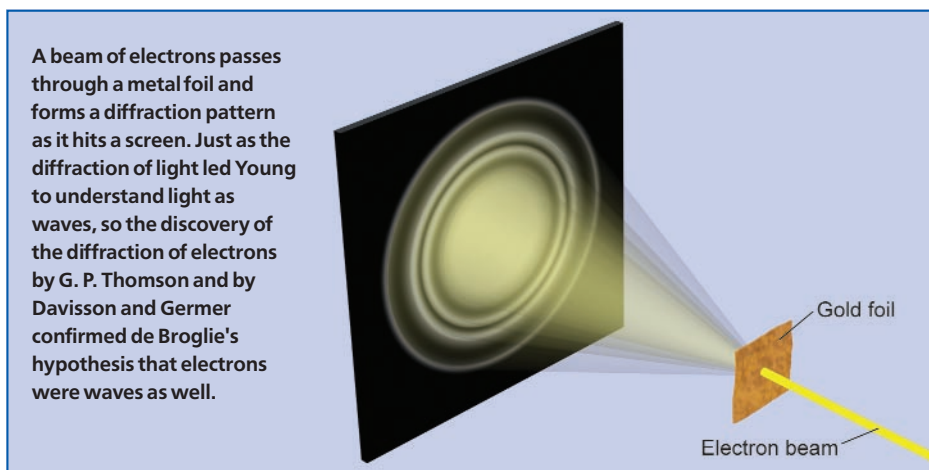
if the photon fills a large volume; yet when it is detected, it is found at particular point. This is one consequence of Heisenberg's Uncertainty Principle – a law that affects absolutely everything in the sub-microscopic world.

Quantum effects are not just confined to photons – electrons, protons and neutrons behave strangely too, which is one reason why it is so hard to visualize what an atom really looks like.

Electrons orbit the nucleus, but not in a manner that resembles a miniature Solar System of planets orbiting a sun. If electrons behaved like planets, they would pass through a sequence of precise and measurable positions. The position of an electron can only be given as a probability; an electron does not have a precise position until we try to measure where it is. Moreover, just as trying to measure where the X-ray passed through the crystal destroys the diffraction pattern, so measuring the position of an electron will almost certainly knock it right out of the atom.

There is scarcely a more natural idea than that an object is located at a certain place; an idea that has risen from our experience of everyday objects. The new quantum view of the world forces us to rethink what is meant by 'position'. In the case of the electron, all we can do is predict the likelihood of the electron being found at a given place in an atom. This is not due to any shortcomings in our theories or measuring instruments, but rather because it is a property of nature itself at this minuscule scale.

The wave-like behaviour of electrons can also be used to measure the size of nuclei and the structure of crystals. In a similar manner to X-rays, predictable



and repeatable diffraction patterns can be built up spot by spot on a photographic film by using electron beams, although there is just no way of predicting where a particular electron will leave its mark.

Electrons and photons do not have a monopoly on quantum weirdness. All atomic and nuclear particles, including protons and neutrons, exhibit the same schizophrenic behaviour we call wave–particle duality. Sometimes they behave like a wave and show diffraction effects, and at other times they behave like particles.

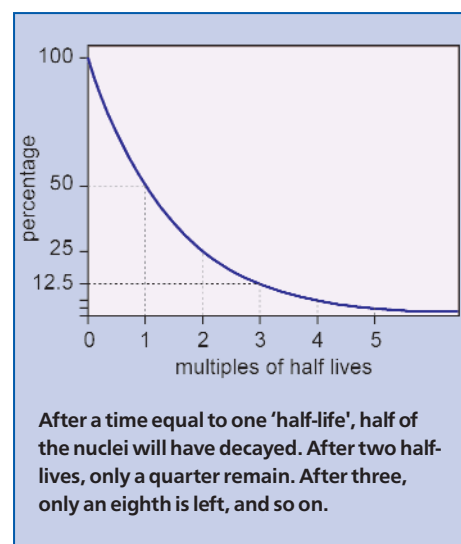
Since 1925, physicists have come to accept that the world of atoms and nuclei is utterly different from the familiar world of objects measured in metres and centimetres. One of the pioneers of quantum theory, Niels Bohr, once said: “If you’re not shocked by quantum mechanics, you don’t understand it.” Another legendary physicist, Richard Feynman, went further, claiming that no one understands quantum mechanics. Certainly, physicists who use quantum physics every day still find it deeply puzzling.

Living the half-life

Radioactivity provides a clear example of the concept of indeterminacy; that is, identical initial situations lead to different outcomes. Consider a million identical uranium nuclei, identical in a way which goes beyond the everyday meaning. They are not just identical in the sense that toothbrushes coming off a production line are the same, the nuclei are indistinguishable by any conceivable measurement. These nuclei are also unstable, and undergo radioactive decay, but they do not decay in an identical time. All that can be said is that they have an equal likelihood of decaying in a given interval of time.

After a certain time (the half-life), half of the nuclei will have decayed, but there is no way of predicting when a particular uranium nucleus will decay. However, one very interesting aspect of determinism does hold true: if we take another large sample of uranium nuclei then it will take the same length of time for half of it to decay as it took for the first sample.

We can imagine a way to avoid the indeterminism in the decay of a nucleus if the unpredictable nature of decay is only a matter of our ignorance. Perhaps all the seemingly identical uranium nuclei are not identical after all. Rather, they have some kinds of unobservable characteristics that distinguish them from each other. These ‘hidden variables’ would be locked away inside each individual uranium nucleus, telling it when to decay.



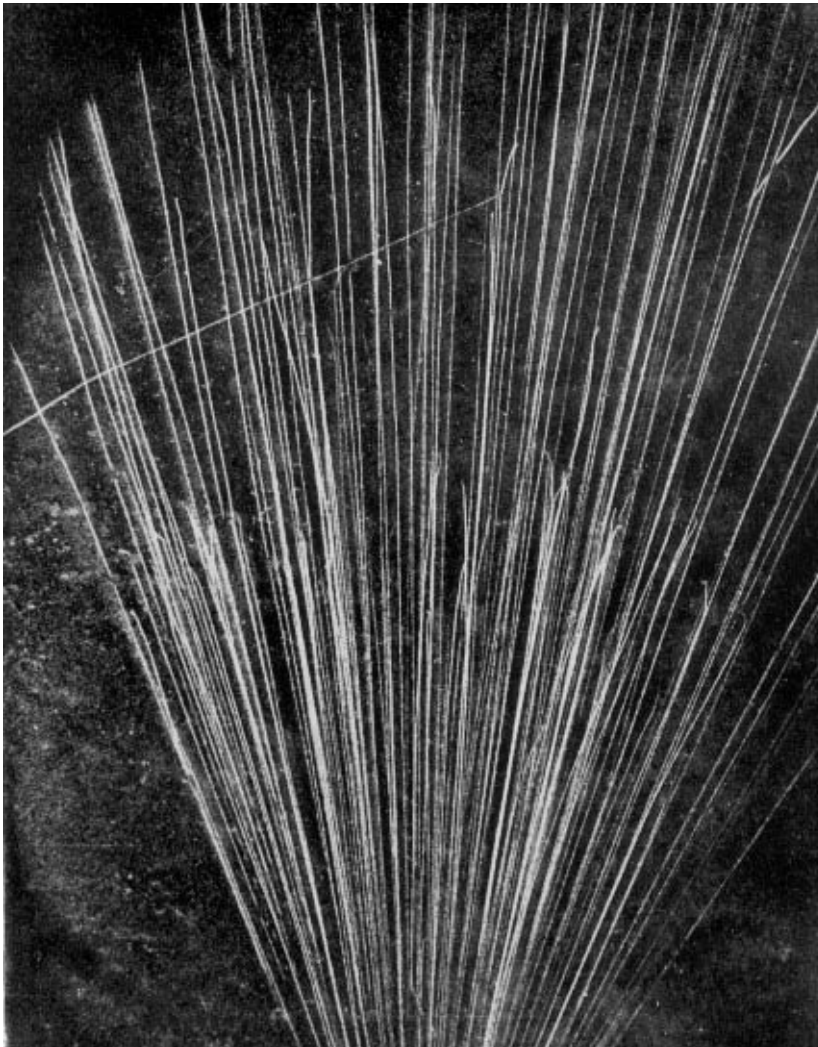
However, most physicists are these days convinced that Nature does not resort to hidden variables to explain the unpredictable behaviour of radioactive decay. We just have to live with the idea that Nature is unpredictable.

Making tracks

‘Taking a quantum leap’ is an expression that has filtered into everyday language – but what does it mean? Quantum leaps are another way the quantum world differs from our familiar world of human-sized objects.

Once again the radioactive decay of nuclei provides a window into the subatomic domain. Visible trails left by particles emerging from nuclei can be imaged in cloud chambers. A great deal of information can be determined from the tracks, including the energy of the particle. The particles with the highest energy leave the longest trails: they travel the furthest before slowing down and coming to a halt. Close measurement of tracks in cloud chambers reveal some alpha particles possess a little bit less energy than others.

Measuring the energy of the alpha particles is very important, and cloud chambers have long since been replaced by silicon detectors. These are rather special



Each of these tracks is a trail of tiny water droplets left by a single alpha particle passing through a cloud chamber. These tracks are evidence of particles, but to understand how alpha particles are emitted from nuclei, they must be treated as waves.

silicon chips that give an electrical signal when a nuclear particle hits them. This signal allows the energy of the particle to be measured very accurately. Results from silicon detectors confirm that some alpha particles have a little less energy. The energies differ by distinct amounts that get progressively lower than the maximum energy.

An important physical concept that is employed here is the law of conservation of energy. Richard Feynman called it the cornerstone of physics. It means that the total energy of a system is always the same. If some alpha particles, emitted by exactly the same kind of nuclei, have a little less energy than the others, then the missing energy must stay in the so-called daughter nucleus: the nucleus left behind when the alpha particle is emitted.

The energy the alpha particle has as it flies out of a nucleus comes from nuclear energy that is normally locked away inside the nucleus. Since the alpha particles only ever come out with one of a set of distinct energies, then the daughter nucleus left behind can only have one of a set of certain values of energy. These values are known as energy levels and are often represented symbolically in diagrams by a series of horizontal lines. The fact that a nucleus can exist only in a series of distinct energies is an example of a new universal property. What is true of the daughter nucleus created in alpha decay is true of all nuclei, as well as of atoms and molecules. All these tiny objects can possess any one of a series of fixed amounts of energy, known as energy states. It is only when we compare this with everyday life that we realize just how strange it is.

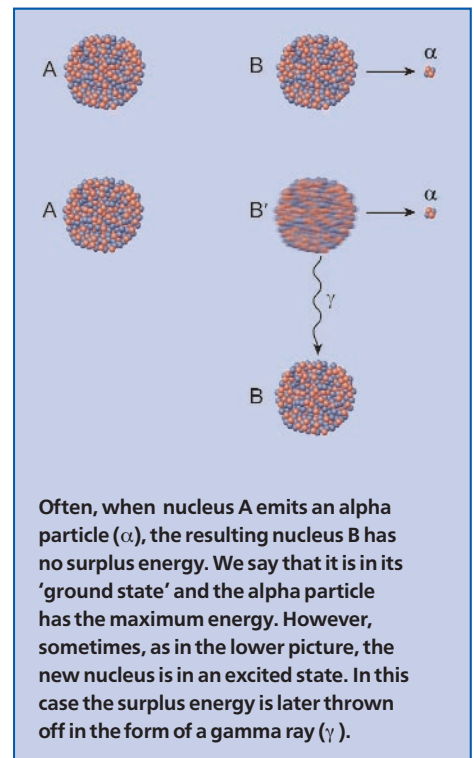
Think of a car. The faster it moves, the more energy it has. In principle it can have any energy up to the energy corresponding to its top speed. Now imagine that the fuel runs out when the car reaches top speed. It slows down, passing continuously through all possible energies until it comes to a halt. It does not slow down in discrete steps and there are no missing energies that are avoided as the speed decreases.

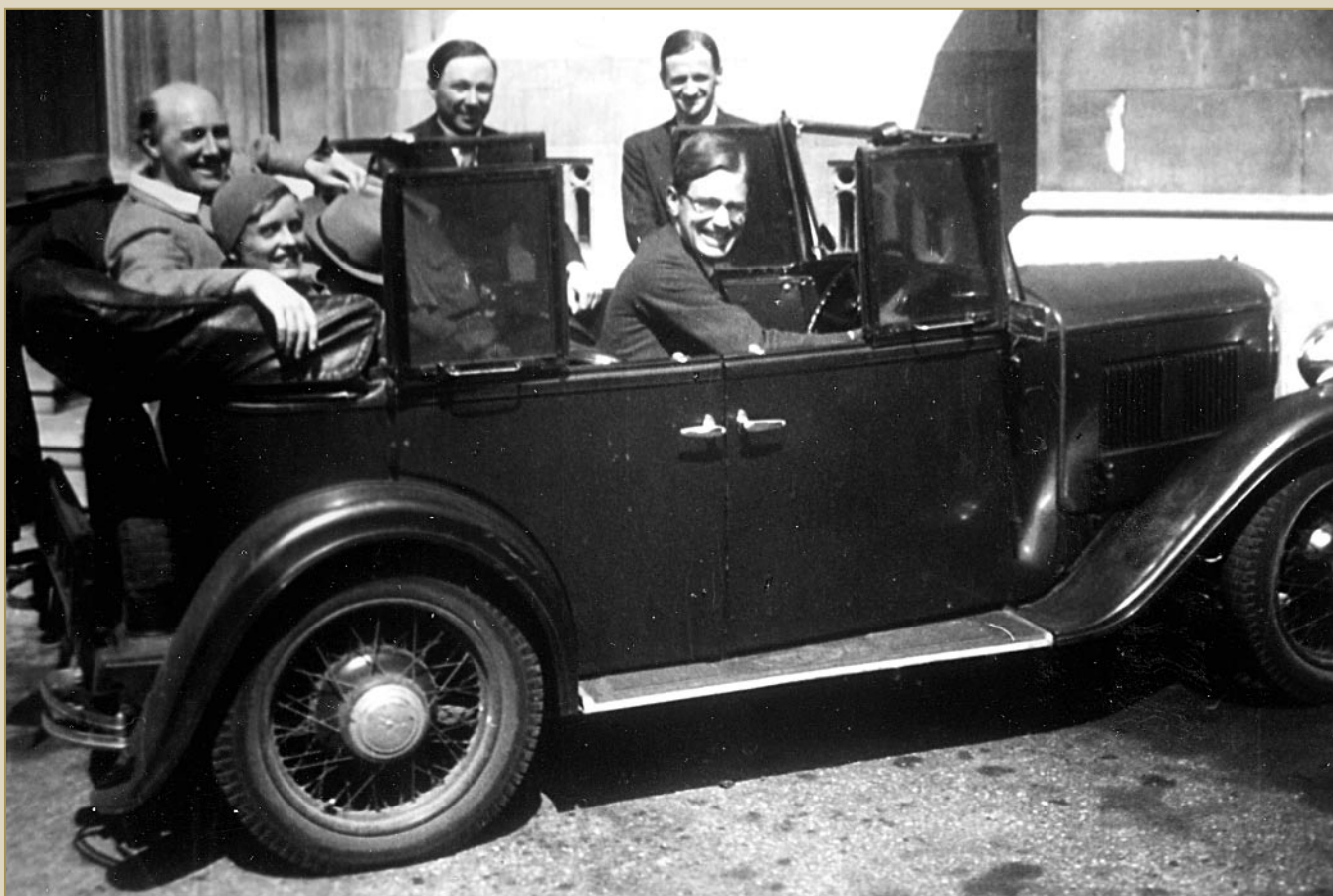
Alternatively, imagine a red-hot poker cooling down. Since heat is a form of energy, the poker loses energy as it cools, but it does not cool down by stopping at a particular temperature and then jumping to a lower one. It cools continuously, passing through all possible temperatures on the way. This is so familiar that we never feel the need to call it a 'no-jump' process.

In the atomic world, nuclei do jump in energy. If a nucleus emits an alpha particle with less than the maximum possible energy, the daughter nucleus is left with a certain amount of extra energy above its 'ground state' (when it has the lowest energy possible). The daughter is said to be in an 'excited state'. So, unlike the car or the red-hot poker, it loses energy by jumping to a state with lower energy. It might do this several times until it eventually reaches the ground state.

With each jump, it gets rid of a packet of its energy. This energy packet is none other than a gamma ray photon. Most of the clicks a uranium prospector hears coming from a Geiger counter are caused by gamma ray emission, a secondary effect of the alpha decay process. Most alpha particles themselves do not penetrate through the walls of the Geiger counter.

The term 'quantum leap' refers to the way the nucleus loses energy by discrete amounts rather than smoothly, but the energy lost by a single nucleus is absolutely





Nevill Francis Mott, 1905–1996, driving, was one of the first to show how alpha particles, described by waves in alpha decay, appear as particle-like tracks in a cloud chamber (AIP Emilio Segrè Visual Archives, courtesy Sir Nevill Mott.)

minute compared to the energy required to make a cup of coffee. A quantum leap does not actually mean a big jump by everyday standards – the colloquial meaning of the phrase. However, it captures the idea that the nucleus undergoes a discontinuous change in energy – and also a discontinuous change in its structure. The atomic kind of quantum leap occurs on a very short timescale: sometimes a million millionth (10^{-12}) of a second after the one before, and sometimes a thousand times less (10^{-15} of a second).

Excited nuclei

Almost all nuclei have a series of excited states. The only exceptions are the few that are so fragile that they break up if they have too much energy. An example is the nucleus of deuterium, or heavy hydrogen, consisting of just a proton and a neutron bound together very weakly.

Each nucleus has its own unique pattern of possible excited energies. These ‘fingerprints’ are important in applications ranging from medicine to archaeology. Alpha decay is not the only process that leaves nuclei in excited states. Energy can be given directly to nuclei, for example, by bombarding them with fast particles from accelerators. The key point is that if a nucleus does find itself in a highly excited state then it will decay via a cascade of energy jumps, called transitions, until it reaches its lowest energy state.

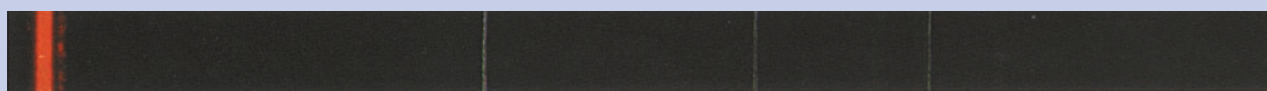
When a nucleus makes a quantum leap between states, a gamma ray is emitted which carries off the energy difference between the states. These gamma ray

656.210 nm

486.074 nm

434.010 nm

410.12 nm



Each of these four lines in the visible spectrum of hydrogen corresponds to a specific amount of energy emitted by hydrogen atoms. These energies are the 'quantum leaps' which occur when the hydrogen atom drops from one of its possible energies to a lower energy.

energies can be measured very accurately with special detectors, allowing each nucleus to be identified from the pattern of gamma ray energies that it leaves behind, called its spectrum.

The same idea also applies to atoms and molecules where the energy of the emitted light corresponds to frequencies spanning the visible part of the electromagnetic spectrum. Green fireworks, for example, are that colour because they contain copper which has prominent green frequencies in its atomic spectrum, and when a pan of boiling, salted water spills onto a gas flame, the flame appears yellow due to the sodium in the salt.

This property is extraordinarily useful to astronomers who can use the spectra of atoms to determine what elements exist in distant stars and galaxies. They can also determine how common different elements are in the Universe.

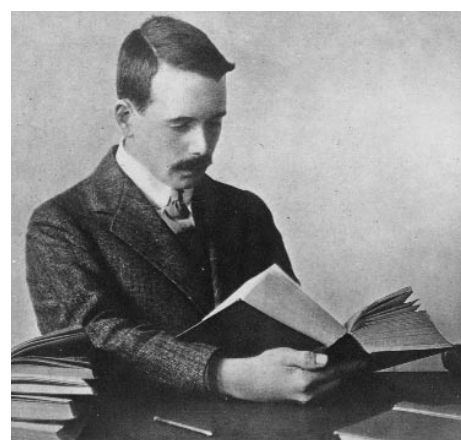
Closer to home, some archaeologists study data from the spectra emitted from nuclei. These nuclear archaeologists can determine the precise location an artefact was made.

Wave–particle duality

Alpha particle radioactivity is a window into the strange behaviour of subatomic matter. What we have glimpsed through that window is so strange that there is still great debate about what it all really means today, a century after quantum physics was born. A natural reaction to hearing about the mysterious behaviour of the quantum world is to ask if it can really be like that. Yes, it can – there is now indisputable evidence that particles can sometimes behave like waves, and vice versa.

In alpha decay, both alpha particles and photons exhibit dual wave–particle behaviour. When a nucleus emits an alpha particle, the new nucleus which is formed may well be in an excited state in which case it will lose the excess energy by emitting packets of electromagnetic energy: gamma ray photons. Being electromagnetic radiation, gamma rays exhibit all the usual properties of waves; in particular they can create diffraction patterns. They also sometimes behave like particles: each photon is a package of energy and gives a single click in a Geiger counter, a pulse in a germanium crystal, or blackens a single grain on a photographic plate.

Alpha particles are helium ions, the very dense, electrically charged nuclei left after helium atoms have been stripped of their electrons. So far, we have concentrated on the particle nature of alpha particles. Each tiny flash of light on a zinc sulphide screen that eventually led Rutherford to his model of the nucleus marked the impact of an individual alpha particle. Similarly the tracks left in a cloud chamber are the result of particle behaviour. Yet alpha particles are as much waves as photons. Over the years there have been many experiments



Henry Gwyn Jeffreys Moseley, 1887–1915.
(AIP Emilio Segrè Visual Archives,
W.F. Meggers collection.)

in which high energy alpha particles have been seen to give rise to diffraction patterns when they collide with other nuclei.

If you find the fact that waves can leave tracks in a cloud chamber deeply puzzling, you are not alone. Einstein wrestled on and off through the first two decades of the twentieth century with a similar problem related to light. He was very well aware of how electromagnetic waves are emitted from a source. Think for a moment about a radio signal: radio waves are emitted in all directions from an antenna. This must be the same for atoms radiating visible light and for nuclei emitting gamma rays, and yet when photons are detected, they seem to have travelled in some specific direction to arrive at a point.

Many great names of physics have struggled with this problem. Today the process is explained by the wave ‘collapsing’, and we can do no better than quote the perplexed letter of the great physicist Moseley, who was killed very young at Gallipoli in 1915, ten years before the advent of quantum theory in its modern form:

“The X-ray problem is becoming intensely interesting. We have now got what seems to be definite proof that an X-ray, which spreads out in spherical form from a source as a wave can, when it meets an atom, collect up all its energy from all round and concentrate it on the atom. It is as if when a circular wave on water met an obstacle the wave were all suddenly to travel around the circle and disappear and concentrate its energy on attacking the obstacle. Mechanically, of course, this is absurd, but mechanics have in this direction been for some time a broken reed.”

Moseley was right. As far as atoms and nuclei are concerned, the mechanics of Newton is useless. In 1929 Mott showed how an alpha particle emitted as a spherical wave from a nucleus can do much as Moseley surmised, and form a track in a cloud chamber. Although we now have a mathematical picture that can predict what happens when an alpha particle is emitted from a nucleus, a full understanding of what those equations really mean is still elusive. Most physicists would agree that this interplay of particle and wave properties is still as deeply mysterious as ever.

The work that originally convinced physicists that alpha particles can behave as waves was a crucial calculation carried out by George Gamow, and also by Gurney and Condon in 1928, which brilliantly solved a long standing puzzle concerning the properties of alpha decay. The wave properties of alpha particles were a crucial ingredient in the explanation. The same theory has other wide-ranging implications and plays a key part in explaining where the Sun gets its energy (see chapter 9).



George Gamow, 1904–1968, whose work in 1928 showed that alpha particles can behave as waves. In so doing, he solved the long-standing puzzle about the half-life of alpha decay. This demonstrated for the first time that quantum mechanics applies to nuclei. (AIP Emilio Segrè Visual Archives.)