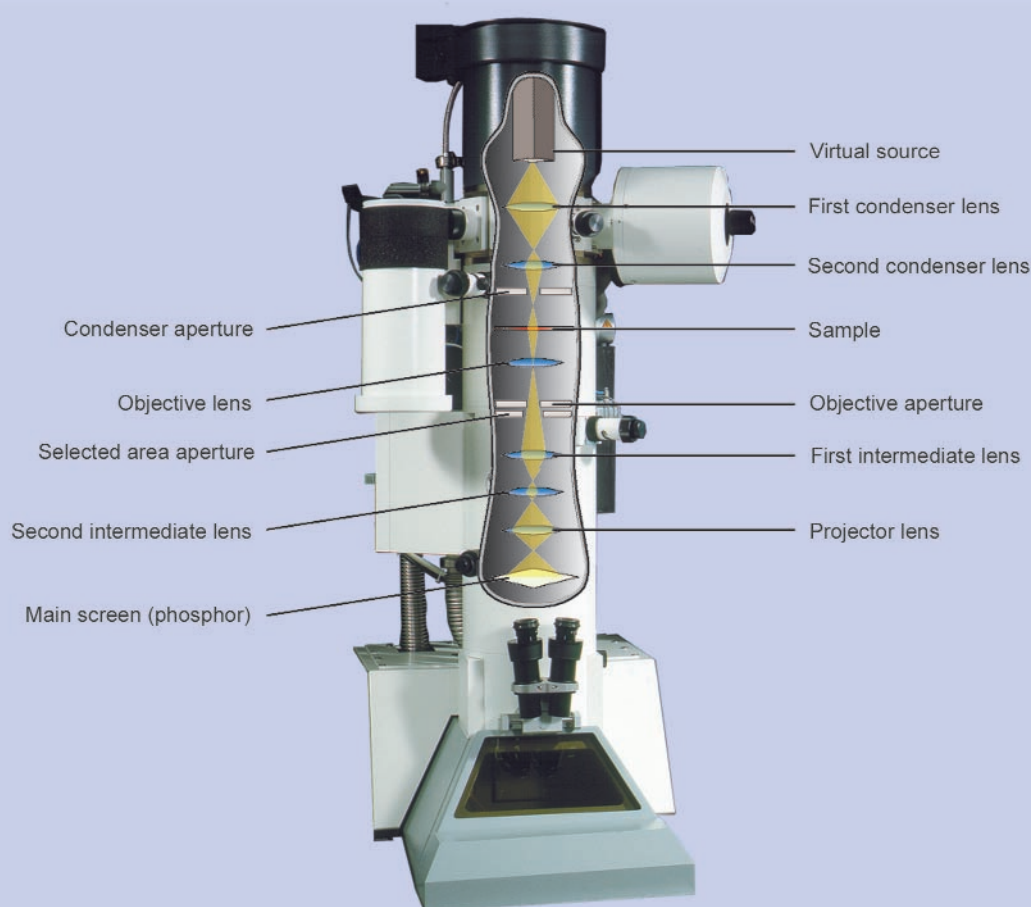


4. Measuring nuclei

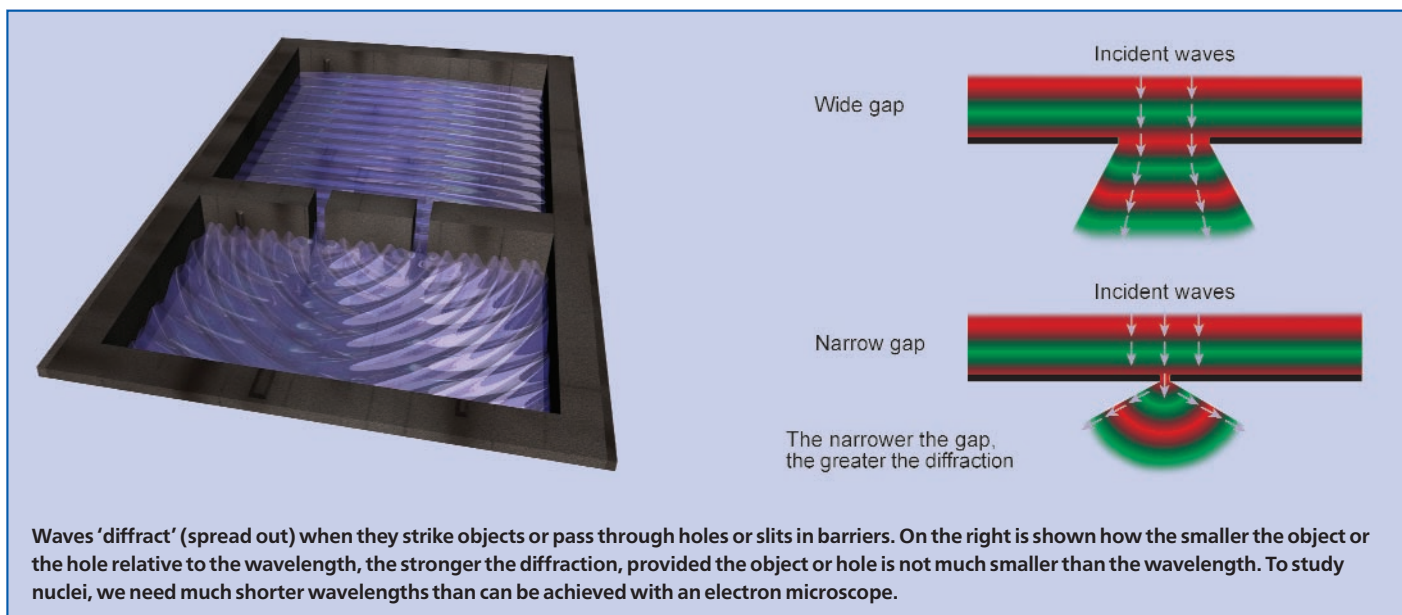
Determining the shape and size of minute objects

One of the most basic properties of nuclei is their size, and measuring something thousands of times smaller than the atoms of the measuring instruments poses problems. Yet by 1911 Rutherford knew something about the size of atomic nuclei. His discovery that they were some 10,000 times smaller than the atoms that contained them was due to the remarkable way that alpha particles scatter from metal foils. Nature had given us a wonderful and unexpected gift – a completely new way to learn about the deep secrets of matter.

Today we can go a long way towards determining the exact sizes and shapes of nuclei. What has been learned about nuclear sizes has become a cornerstone in our understanding of atoms. How this knowledge has been achieved is a story in which the oddness of the quantum realm plays an important part.



The components in this simplified schematic of an electron microscope have much the same function as the corresponding parts of a light microscope. The power of the electron microscope lies in the short wavelength of the electrons, allowing extremely fine details of the object to be resolved.



Mega-microscopes

Previously we have described how it is not feasible to use ordinary microscopes in order to see objects smaller than a certain size. Instead, we depend on electron microscopes – which rely on the wave nature of electrons – to resolve objects as tiny as a virus, and even individual atoms.



Robert Hofstadter, 1915–1990, pioneered the use of electrons for studying the size and density of nuclei and of the nucleons they are made of.
(Copyright the Nobel Foundation.)

The wavelength of electron waves can be made shorter if their energy is increased. So electrons need to be given enough energy to make their wavelength shorter than the details of the object under study. It is a big step from viewing viruses or individual atoms to seeing atomic nuclei, but it is one that has been taken. For achieving this step, a pioneer of the art, Robert Hofstadter, was awarded the Nobel prize in physics.

Hofstadter thought big. He had to, because the laws of physics demanded that large machines – what we might call 'mega-microscopes' – are needed to produce electrons with high enough energies to penetrate the secrets of the nucleus.

To understand how it is possible to gain an idea of the size of nuclei by observing matter waves, consider what happens when sea waves wash up against a hole in a breakwater. The smaller the hole, the more the waves are scattered, or spread out, on the other side. If you did not know the size of the hole, you could, in principle, work it out from seeing how the waves behave. If the distance between successive wave crests (the wavelength) is too large, then you do not get a pattern at all.

In a similar manner, light waves can produce a diffraction pattern when shone through various tiny holes. Again we can work out the size of the hole from the different patterns of light and dark rings.

The idea that particles like electrons really do act like waves was put to the test by Hofstadter and his colleagues in the 1950s when they asked for the large sums of money needed to build the first machines that accelerated electrons to high energies. To build such a machine was an act of faith, but their faith was rewarded. Today, thanks to experiments with particle accelerators, a great deal is known about a huge number of nuclei.

Another quantum concept

You are probably becoming familiar with the idea that many common words do not mean quite the same when applied to atoms and nuclei as they do for everyday objects. 'Size' is one of these words. This is because, in the quantum world, objects such as nuclei simply cannot ever have sharp edges. Size is generally defined as the distance from one edge of an object to the other. If it does not have a definite edge, then its size is not clear-cut.

Nuclei are composed of protons and neutrons (nucleons) which obey the laws of quantum mechanics. According to these laws, we simply cannot say where a nucleon is in a nucleus; we can only say how likely it is to be found at a given point.

The laws of quantum mechanics are not just about uncertainty: they have a lot to say about how likely it is to find a nucleon in a given place. If you select some point in a nucleus, quantum mechanics determines the probability of a nucleon being at that point. This probability does not suddenly become zero at some particular distance from the nuclear centre. If it did, then that distance would be a sharp surface of the nucleus. Instead, nuclei have a diffuse (fuzzy) surface in which the probability of finding a nucleon drops off gradually.

Measuring fuzzy nuclei

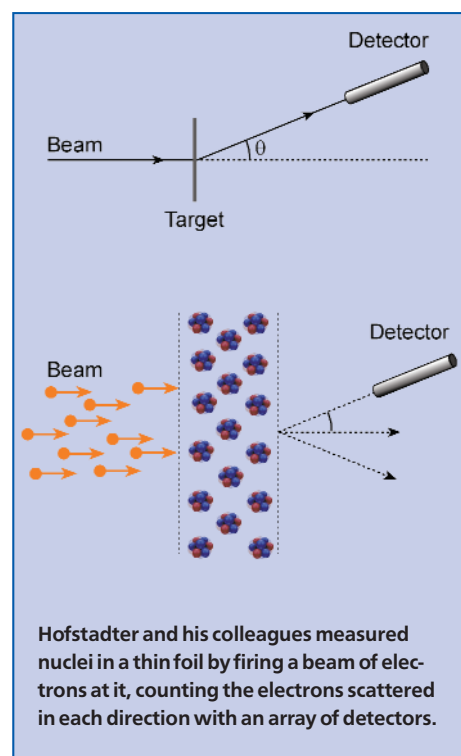
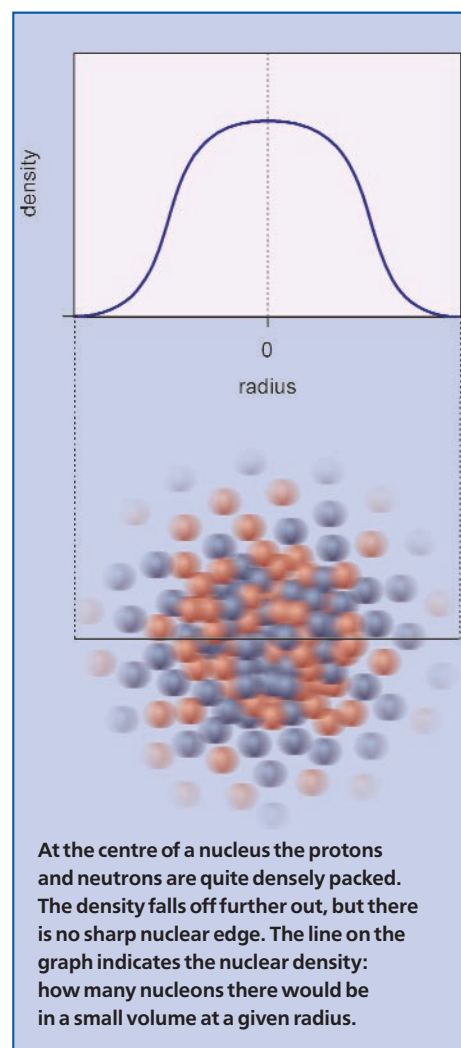
How can this diffuse nuclear surface be measured? A proton carries positive electric charge, so the more likely that protons will be at a particular point in the nucleus, the more charge there will be at that point. The positive electric charge on the nucleus must therefore also be spread out in a way that has a fuzzy edge. Since electrons are electrically charged, a high speed electron moving through a nucleus is deflected by the positive charge in a way that depends on how that charge is distributed. This allows us to use a beam of electrons to measure a nucleus. It does not matter that the electron is unaware of the neutrons in the nucleus; it is sufficient that protons are evenly distributed throughout its volume.

Since electrons behave like waves, a beam of them striking a nucleus will produce a diffraction pattern. Although the electrons are detected as particles, the pattern is produced because greater numbers are found at certain angles and fewer at other angles. For water waves, both a barrier and a hole produce quite sharp diffraction patterns, but the patterns left by electrons scattering from nuclei are less distinct. The difference is that the hole and the barrier in the water have sharp edges and the water waves either pass through completely or not at all, but the fuzzy edge of the nucleus causes a gradual change in the quantity of deflected electrons. The details of the electron diffraction pattern reveal how the nuclear charge is spread out and we can determine just how fuzzy the nucleus is.

The size of atomic nuclei

To compare nuclear sizes we have to define what is meant by the word 'size' when applied to these diffuse objects. From electron scattering, we know nuclei have a rather constant density which falls off to zero at the surface in a way that is much the same for a wide range of nuclei. This allows a nuclear radius to be defined in spite of the fuzzy edge. The nuclear radius is the distance from the centre of the nucleus to a point where the density is half that at the centre.

Apart from the diffuse surface, all nuclei have about the same density. This can be deduced from the way that the volume of the nucleus depends on the number of nucleons it contains. Thus if nucleus A has twice the radius of nucleus B, then



nucleus A will have eight times ($2 \times 2 \times 2$) as many protons and neutrons as nucleus B. This is what is expected of everyday material that cannot be compressed. If a solid ball has twice the radius of another made of the same material, it would have eight times the mass. The volume, and hence mass, of a spherical object is proportional to the cube of its radius.

As nuclei obey this rule, it suggests all nuclei are made out of incompressible material of the same density. Atoms, however, are quite different.

It is remarkable that atoms and their nuclei behave in opposite ways: to a first approximation, atoms of different mass all have the same size and therefore different densities, whereas nuclei of different mass have the same density and therefore different sizes. There are exceptions in both cases: for instance alkali atoms like sodium are larger, and halogens like chlorine are smaller, but the difference is not dramatic. The fact that all atoms do not have the same density is crucial; if atoms of magnesium and of lead had identical density, then equal amounts of magnesium and lead material would also have the same density. We know this is not true – magnesium sinkers are not used for fishing, and lead wheels are inappropriate for fast cars!

For nuclei, however, the converse is true. A plutonium nucleus with about 240 protons and neutrons does have about twice the radius of a nickel nucleus containing an eighth as many protons and neutrons. This is because both nuclei have similar density, a density they share with almost all nuclei. The exception to this rule of uniform density is found in some remarkable cases that have caused a stir in recent years – the so-called ‘halo nuclei’, discussed later in this chapter.

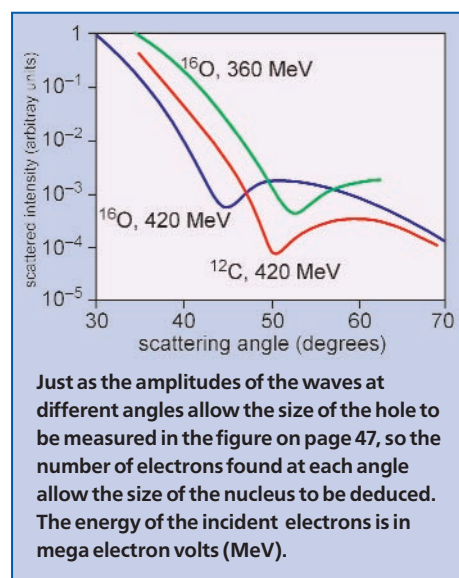
The density of a nucleus is large compared with everyday objects. If a solid football were made of pure nuclear matter, it would weigh as much as Mt Everest.

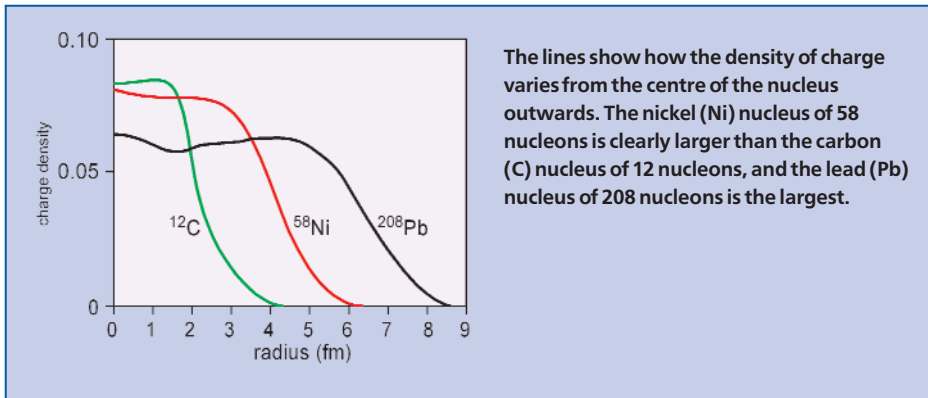
Measuring nuclei with lasers

To measure nuclei using electrons, a target containing the atoms whose nuclei are to be measured has to be made, but not all nuclei are stable enough to sit in a target long enough for such experiments to be performed. There is a need to study such short-lived nuclei; they may well be different from stable nuclei, in which case a completely biased view of nuclear sizes would be obtained if only stable nuclei were studied. Other ways are therefore needed to measure nuclei.

There is a method that allows the measurement of nuclei that exist only fleetingly. It is based on the fact that, although the electrons in an atom are spread out through a vastly greater volume of space than the nucleus itself, there is nevertheless some probability that they can exist at the centre of the atom in the space occupied by the nucleus. This modifies the wavelengths of the light given out by the atom in a way which depends on the size of the nucleus. The effect is tiny, but lasers allow us to measure the wavelengths with incredible precision – enough precision, in fact, to turn the tiny effects of different nuclear sizes into a practical way of measuring them.

This method of measuring nuclei is known as the ‘isotope shift method’ because it is based on the way the wavelengths of light emitted by an atom varies from one isotope of the element to the next. Since different isotopes of the same element have the same number of electrons (and protons), their electrons will be distributed in almost exactly the same way. Where they do differ is in the number





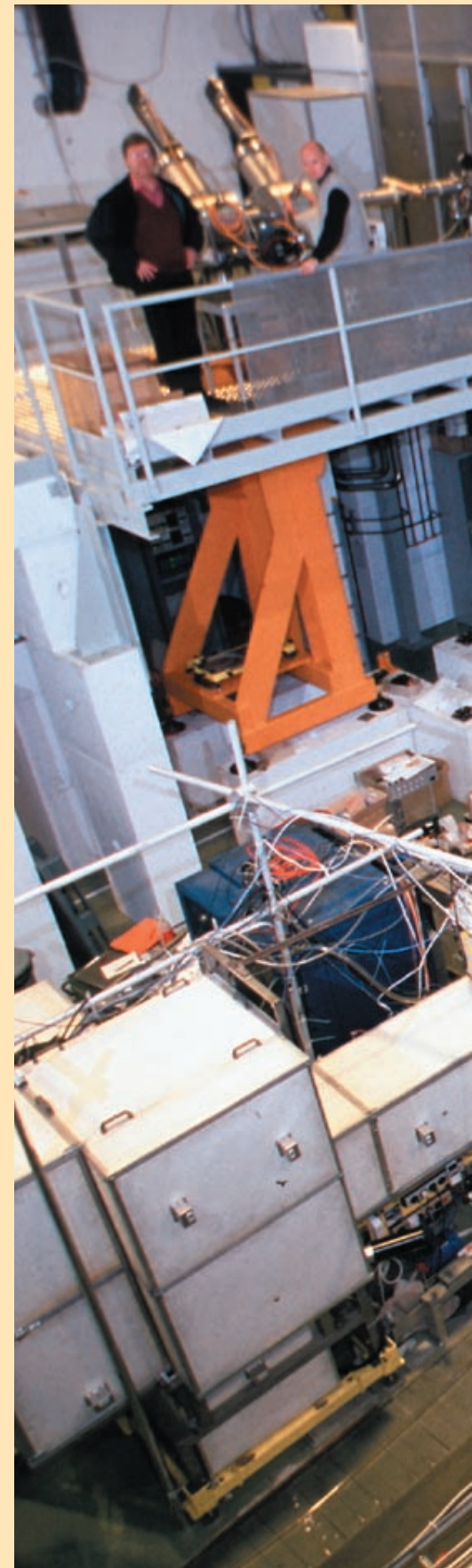
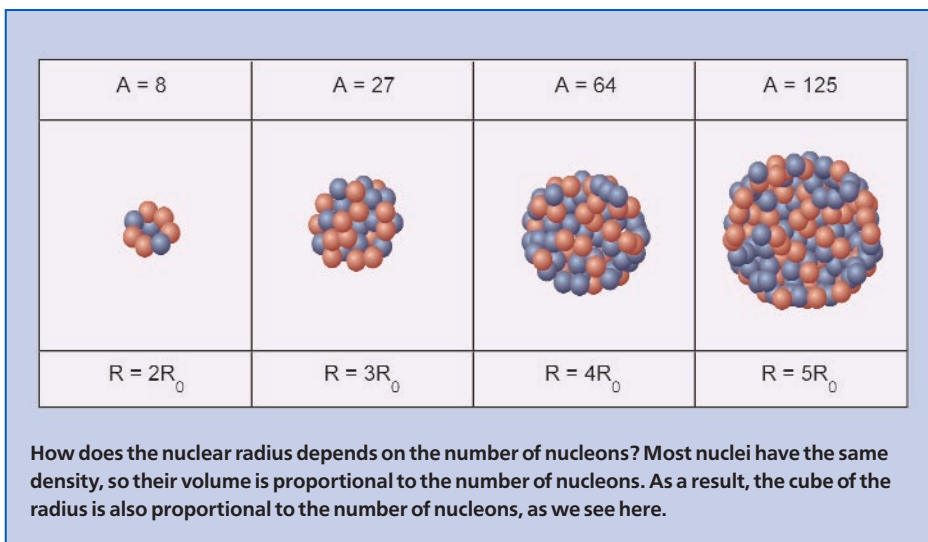
of neutrons their nuclei contain, and this affects the size of the nuclei. Thus the light emitted by their electrons will differ very slightly due to the manner in which the electrons' probability distributions overlap the different-sized nuclei.

The difference in the wavelengths of light for different isotopes can be used to determine the variation in size of the nuclei. As long as the size of the nucleus of a stable isotope can be determined, for example by using the Hofstadter method of electron scattering, then the sizes of all the other isotopes of that element can be deduced.

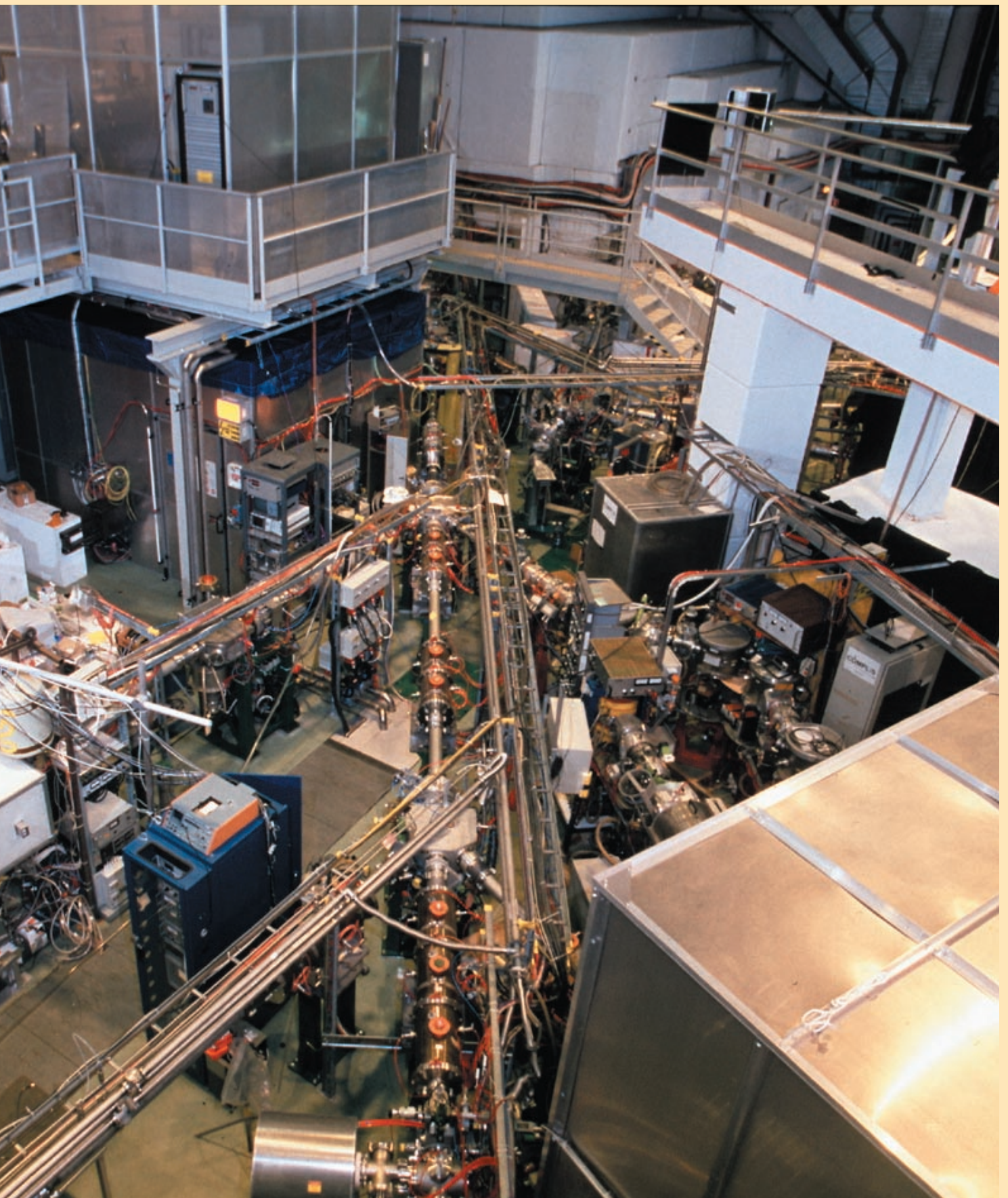
Nuclear shapes

It is a natural assumption to imagine nuclei as tiny spheres. In the 1930s, even before lasers were invented, crude isotope shift measurements were used on different isotopes of the fairly rare element, samarium. They showed that nuclei of the heavier samarium isotopes appeared larger than expected. We now know this is because they are not spherical. Today it is known that quite a large proportion of nuclei have non-spherical shapes. Such nuclei are said to be deformed.

Most of our evidence about nuclear shapes arises from the fact that non-spherical nuclei can be made to spin. Another rather odd quantum concept is that if a quantum object, such as a nucleus, is perfectly spherical, then there is nothing to distinguish its orientation in space. It is meaningless to state whether or not a spherical nucleus is spinning, since we could never tell.



To study the properties of a nucleus that lives for a thousandth of a second (the LHC) at CERN in which such experiments were pioneered



length of a second, it is necessary to do 'on line' experiments in which nuclei are created and studied in the same apparatus. This is ISOLDE (Isotope Separator On-Line). In this picture you can see the beam lines down which the radioactive ions are steered in a vacuum towards the experimental stations. (CERN)

The more deformed a nucleus is, the more easily it can be made to rotate. This rotation is another way in which the nucleus can store energy – energy it can lose by emitting gamma rays and hence slowing down. The more deformed it is, the more quickly a spinning nucleus slows down by radiating gamma rays. By measuring how easily nuclei are set spinning when other nuclei are fired at them, or by seeing just how quickly spinning nuclei slow down by emitting gamma rays, the amount they deviate from the spherical can be determined.

Most nuclei have one of two basic shapes. They are either spherical or prolate (shaped like an American football). An important exception is the nuclei of carbon, which are oblate (like a squashed sphere). Both prolate and oblate nuclei are nearly always axially symmetric.

Quantum mechanics has another trick up its sleeve concerning deformed nuclei. A deformed nucleus can no more lie with its long axis fixed pointing in a given direction than a proton or neutron can sit still at some fixed point within the nucleus. Both are a result of the Heisenberg Uncertainty Principle. Thus, the long axis of a prolate nucleus has equal probability of pointing in every direction. In other words it is pointing in all directions at once!

If an isotope shift experiment is performed on an atom containing a prolate nucleus, the electrons in the atom see a fuzzier nucleus than usual. The tip of the long axis of the nucleus traces out a larger volume of space than any point on the surface of a spherical nucleus with the same mass because it lies farther out. As a result, the surface is even more uncertain than for spherical nuclei, causing a shift in the spectra.

Modern experiments reveal more about the shape of deformed nuclei than just whether they are prolate or oblate. Amongst the many nuclei which are strongly deformed are the isotopes of uranium and plutonium, a fact important for the process of nuclear fission.

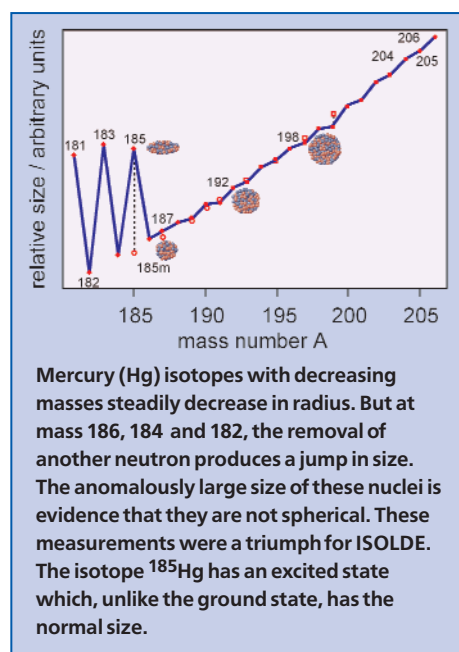
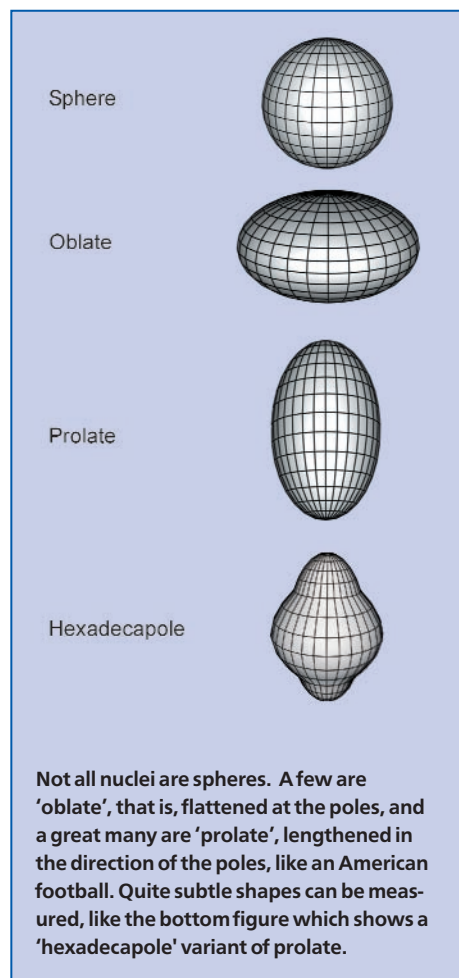
Super-deformed nuclei

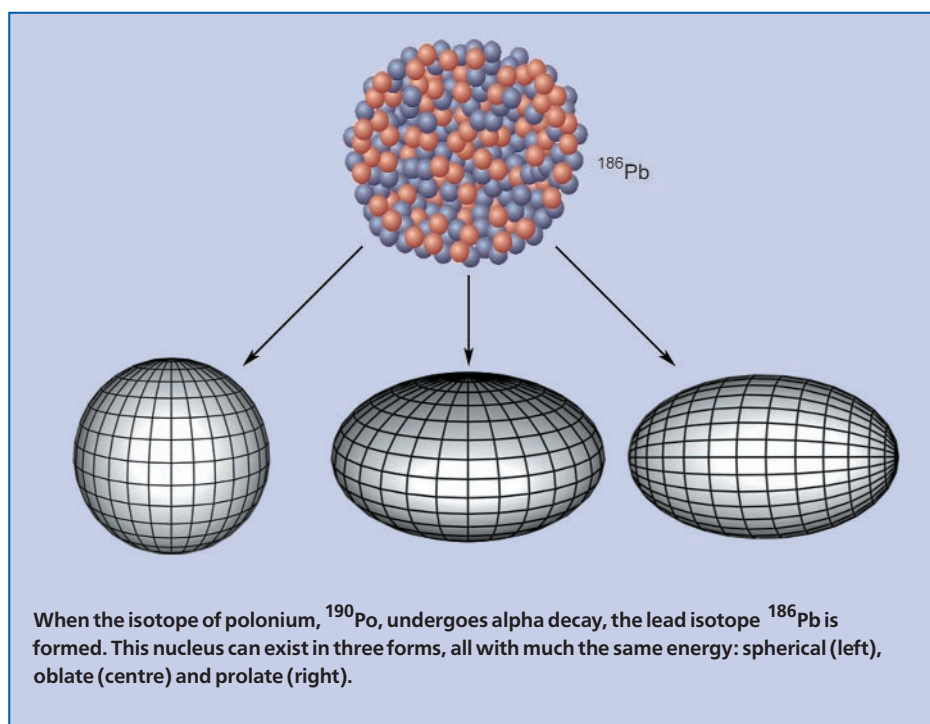
Most prolate-shaped nuclei are only slightly deformed. However, in the mid 1980s, physicists at the Daresbury Laboratory in the UK discovered a remarkable phenomenon: super-deformation. Sometimes nuclei are twice as long as they are wide.

When nuclei rotate they have a tendency to stretch. This is due to the same force you feel when sitting in a fast car as it turns a tight corner. Nuclei are generally too tough to stretch very much, but at Daresbury it was found that if certain nuclei are made to rotate really fast, it is as if something suddenly gives and the stretching force takes the nucleus into an entirely new shape. The nucleus becomes super-deformed. As they slow down, by emitting lots of gamma rays the nuclei revert back to the normal deformed or even spherical shapes.

Halo nuclei break the rules

Although most nuclei have the same density, there are exceptions. One such nucleus, the deuteron, has been studied for a long time. The deuteron is the nucleus of heavy hydrogen, consisting of just one proton and one neutron that are very weakly bound together. As a result of this weak binding, the proton and neutron have a significant probability of lying very far apart. The probability distribution of the deuteron extends out in space to such an extent it has the same size as that of a





very much heavier nucleus. This is where we catch another glimpse of how strange the quantum world is: the proton and neutron spend part of the time outside the range of the force that holds them together, yet they still remain bound together unless the deuteron is hit by something like a powerful gamma ray.



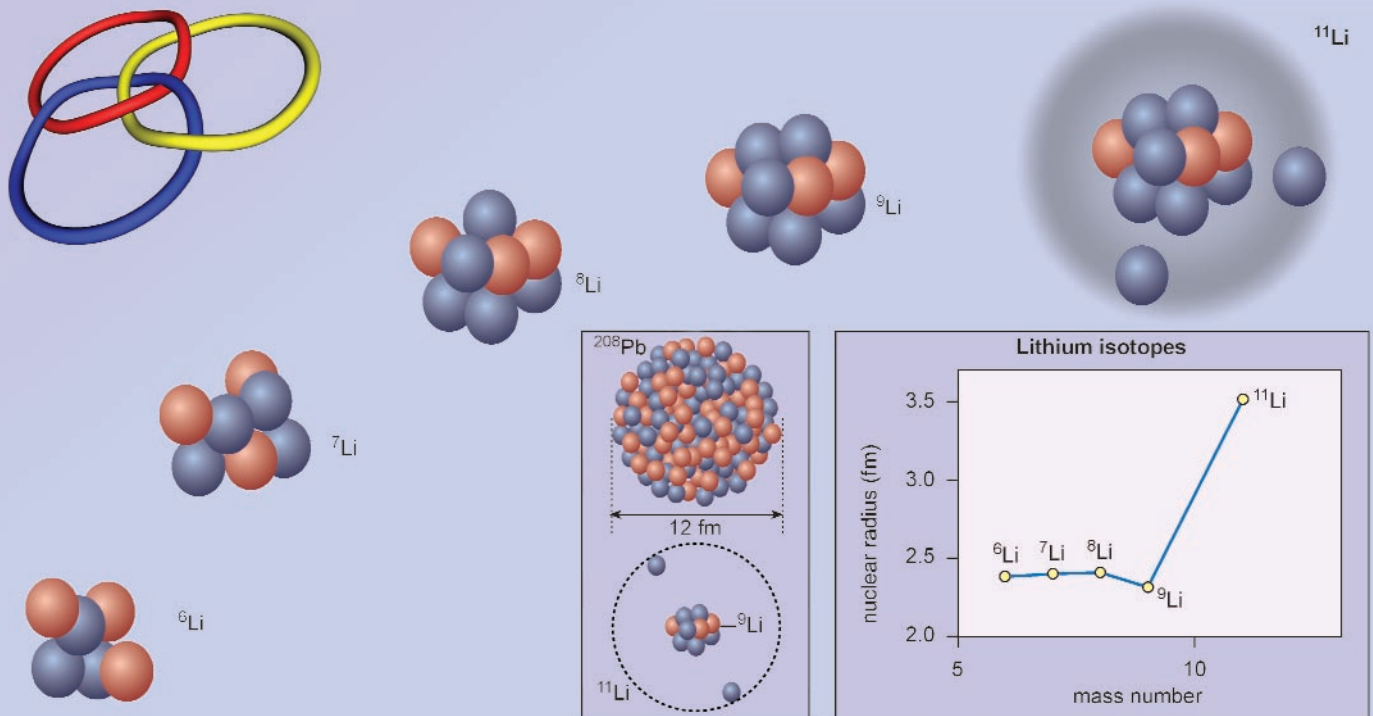
Ben Mottelson, 1926–, American-born physicist living in Denmark. He was awarded the Nobel Prize in 1975 with James Rainwater, 1917–1986, and Aage Bohr, 1922–, the son of Niels Bohr, for work on vibrations and rotations of nuclei. (Copyright the Nobel Foundation.)

Adding a second neutron to a deuteron makes a nucleus of tritium, an even heavier isotope of hydrogen. This extra neutron draws the original proton and neutron closer together so the tritium nucleus (a triton) is actually smaller than the deuteron. Adding a second proton to a triton continues this process, making a tightly bound helium nucleus – an alpha particle. The two protons and two neutrons in the alpha particle are so close together that this nucleus has much the same density as most heavier nuclei. Subsequently, adding protons or neutrons does not affect the nuclear density.

In recent years a remarkable new class of nuclei has been discovered, the halo nuclei. The most famous is a lithium isotope with no less than eight neutrons accompanying its three protons. This is ^{11}Li . The last two neutrons in this nucleus are very weakly bound, and are spread out in a volume which extends far outside the range of the other nine nucleons. As a result, this nucleus is as large as a nucleus of lead with over 200 protons and neutrons.

The discovery of halo nuclei in the mid-1980s electrified the community of nuclear physicists. These nuclei present a rich variety of phenomena to study, and stretch our understanding of nuclei theory to the limits. As halo nuclei have only a fleeting existence, they need special facilities to study them. Halo nuclei are now studied in many laboratories around the world.

Halo nuclei



The isotope of lithium with three protons and six neutrons has just the size that would be expected for a nucleus with nine nucleons. There is no stable lithium nucleus with seven neutrons, but there is a lithium nucleus with eight neutrons ... and it stretches out as far as a lead nucleus. Its surface is very tenuous, containing just two neutrons in a large volume. Several of these 'halo nuclei' have now been found, and they present a huge challenge to experimenters and theorists struggling to understand their many strange properties. The Borromean rings at top left are such that if one is cut, all three fall apart. This is also true of the ${}^9\text{Li}$ core and two outer neutrons that make up the halo nucleus ${}^{11}\text{Li}$. ${}^{10}\text{Li}$ does not exist, nor does a nucleus containing just two neutrons.