Aage Bohr: following in father's footsteps.

Why they were worth it

Peter Hodgson assesses the achievement of the physics Nobel prizewinners Bohr, Mottelson and Rainwater; and overleaf, Michael Stoker writes about the winners of the prize for medicine, Dulbecco, Temin and Baltimore.

THE physics prize this year was awarded to Aage Bohr, Ben Mottelson and James Rainwater for their fundamental work on collective motion in nuclei. Bohr is already a famous name in physics, and Aage has now received the same distinction as his father Niels, who won the Nobel Prize in 1922 for his application of quantum theory to the hydrogen atom. This is not the first time a father and son have both received the physics prize: the Braggs received it jointly in 1915 for their work on X-ray crystallography, and the Thomsons for their work on the electron, 'J.J.' for discovering it in 1906 and 'G.P.' for showing its wave nature in 1937.

Bohr and Mottelson have worked togather for many years at the Niels Bohr Institute in Copenhagen, and have maintained its reputation as one of the world's leading centres for theoretical physics, while Rainwater works at Columbia University in the USA.

The work that earned them the Nobel Prize forms one of the most recent chapters in four decades of effort to understand the atomic nucleus. The early work of Rutherford and his collaborators established that there is a tiny nucleus consisting of neutrons and protons. The problem is to understand how they are bound together, and hence to explain the observed features of nuclear reactions and nuclear structure.

We can learn something about the forces between the nucleons (a term denoting either protons or neutrons) by studying the collisions of individual nucleons with each other. The forces are certainly very complicated, and it is far too difficult to calculate the properties of the nucleus directly from them. But we do know that their net effect is to hold the nucleus together so we can represent this by an overall attractive potential parametrised by a depth and a radius. Unfortunately, calculations of nuclear properties from this model showed that some of them did not agree with experiment.

This extreme single-particle model, as it was called, was superseded in 1936 by the compound nucleus model of Niels Bohr, which took full account of the way the nucleons strongly interact. According to this model, a nuclear reaction takes place firstly by the capture of the incoming particles by the nucleus, followed by a relatively long period when its energy is shared and re-shared among all the nucleons. Finally by a statistical fluctuation enough energy is concentrated on a nucleon or group of nucleons near the nuclear surface to enable it to escape.

This model worked very well and was able to account for many nuclear reactions, until in the 1940s it was found that many properties of the nucleons show marked changes whenever the number of neutrons (or protons) was one of the so-called 'magic' numbers 2, 8, 20, 28, 50, 82, 126, . . . This pointed to some sort of shell structure, as with atomic electrons, and these numbers were shown to follow readily from a model with a term effectively depending on the orbital angular momentum and the spin of the nucleons added to the central potential already considered. This potential has energy levels, which when filled with nucleons, one in each possible state to satisfy the Pauli exclusion principle, give automatically the magic numbers. For their independent discoveries of this Maria Mayer and Johannes Jensen were awarded the Nobel prize in 1963.

It was puzzling that the compound nucleus model requires the nucleons to interact strongly, while the shell model requires that they interact so weakly that they can follow relatively undisturbed orbits in the nucleus. This paradox is understood when we realise that the Pauli exclusion principle forbids most of the collisions that would otherwise take place within the nucleus because they would lead to states that are already occupied. A particle entering the nucleus from outside, however, has much higher energy so that the final states are seldom occupied and the interaction takes place strongly. This absorption was included in the simple models by allowing the potential to become complex at higher energies.

In all this work it was assumed that the nucleus is spherical, but data began to accumulate showing that some nuclei are quite markedly deformed. This evidence came mainly from their large quadrupole moments. Closed shell nuclei, in which the neutron and proton numbers are both magic, such as ^{16}O, ^{40}Ca and ^{208}Pb, are spherical, as is to be expected from the high symmetry of the closed shells. For other nuclei, the deformation increases with the number of nucleons outside the closed shells. It is notable that the quadrupole moment is always positive immediately before a shell is filled and negative immediately after. The quadrupole moments calculated from the orbitals only of the nucleons outside the closed shells were inadequate to explain to date.

In 1950 Rainwater suggested that the extra nucleons can polarise the core so that it becomes spheroidal. Thus the shape of the nucleus results from its own stabilising forces, tending to make it spherical, and the forces from the extra-core nucleons, which tend to deform it.

If the nucleus is considered to be a liquid drop, the surface and Coulomb energies are proportional to the square of the eccentricity, for a spheroidal deformation. The effect of the distortion on the individual shell model orbits can be found by calculating the eigenvalues for a particle in a spheroidal potential, and together they give an energy that decreases linearly with the eccentricity e. Thus the total change in energy due to the distortion is

$$\Delta E \approx c_1 e^2 - c_2 e$$

and the stable shape for minimum energy is given by $e = c_2/c_1$. The constants c_1 and c_2 are known quite well, and Rainwater showed that this gives quadrupole moments that are similar to those found experimentally, and accounts for their variation with shell structure.

This vital suggestion removed the main difficulties about nuclear quadrupole moments, and provided the essential basis for a detailed theory of nuclear deformations. This was developed by Bohr and Mottelson and collaborators during the following decade. In their earlier calculations they treated the nuclear core as a charged, deformed drop of nuclear liquid interacting with the few nucleons outside the core. The motion of the core is described by a few dynamical variables, while the extra-core nucleons are treated individually. In later work they considered all the nucleons, and allowed them to move in a non-spherical potential, which represents the long range correlations between the nucleons.

Rainwater (left) and Mottelson: prize for work on collective motion in nuclei.

Bohr and Mottelson recognised that nuclear deformations can be of two types, static and dynamic, or more simply that nuclei are either hard or soft. Hard nuclei keep their shape, but if they are deformed they can be set into rotation, like a rotating rugby football. The energy levels of such a system can be calculated quantum mechanically, and are given by the formula

$$E = h^2 J(J+1)/2I$$

where I is the moment of inertia. In many nuclei, particularly the rare earths, whole series of rotational bands, each with many states, have now been identified. The theory, with its more detailed development, predicts these levels very accurately.

Soft nuclei, on the other hand, are easily given oscillations or vibrations, like the wobbling of a jelly. Calculated energy levels agree with those observed in some nuclei. The vibrational spectra are not as well marked as are the rotational spectra in hard nuclei because the vibrations are easily coupled to other types of motion, thus complicating the spectra.

One of the best known examples of nuclear collective motion is fission, when the nucleus breaks into two nearly equal parts. Niels Bohr did much of the early work on fission during the war years using the liquid drop model of the nucleus. In the 1950s Aage Bohr approached the problem from the microscopic point of view, in terms of the energy states of the fissioning nucleus. He showed that low energy fission takes place through very few reaction channels even though the level density is very high. This happens because most of the energy of the incoming neutron is spent on deforming the nucleus instead of exciting it internally. He has also made important contributions to the theory of the mass distribution of the fission fragments and of their angular distribution.

These rotational and vibrational models of the nucleus are known as collective models because unlike the independent particle or shell model for spherical nuclei they both require the nucleons to show collective or bulk motion. The nucleons are still moving rapidly along the independent shell model orbits but on a longer time scale the orbits change so that there is a resultant bulk motion of the nucleons, first in one direction and then in another, that forms the rotation or vibration of the nucleus as a whole.

The great achievement of Bohr and Mottelson was to put all this work on nuclear collective motion on a sound and detailed quantum mechanical basis, and to apply the theories to account in detail for the properties of deformed nuclei throughout the Periodic Table. The hard nuclei are represented by a potential whose surface is expressed as a series of spherical harmonics, each with a coefficient giving a measure of the quadrupole, octupole, hexadecupole . . . deformations. The vibrations are similarly represented by dynamical deformation parameters that vary with time. All this work is described in detail in a monumental work on nuclear structure that Bohr and Mottelson have been writing for many years and which is being published in three volumes, the first of which appeared in 1969. These grew out of a series of lectures that is a continuing feature of the life of their institute. They are still full of activity, and will continue to contribute to our knowledge of nuclei, and to provide a source of stimulus and encouragement to younger workers in the years to come. □

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