The 1975 Nobel Prize for Physics

The Nobel award to A. Bohr, B. Mottelson, and J. Rainwater recognizes the singular importance for the study of nuclear structure of both the discovery that the shape of the atomic nucleus is generally nonspherical (deformed) and the development of an understanding, both qualitative and quantitative, of the underlying mechanism.

One can imagine the sense of excitement that prevailed among nuclear physicists at the time their investigations were begun. The nuclear shell model had just been proposed and discussions of its validity and the exact form it should take raged throughout the world of nuclear physics. It appeared to be in conflict with the older liquid drop model. And, in fact, in the same year (1949) in which Maria Goeppert-Mayer made her suggestion regarding the shell model, experimental results on the size of the electric quadrupole moments of atomic nuclei which violently disagreed with the predictions of the shell model theory were published. It was the resolution of these apparently irreconcilable results by Bohr, Mottelson, and Rainwater that led to the generation of a unified picture of the nucleus which provides a basis for the understanding of the low lying states of all nuclei, one of the great achievements of modern physics. Characteristically, there was extraordinarily strong and intimate interaction between theory and experiment. It was no accident that the initial insights were obtained at the institution where experiments on the nuclear electric quadrupole moments were performed. In the succeeding decades Bohr and Mottelson acted as an intellectual center orchestrating in a very direct way the experimental programs pursued at many of the nuclear laboratories throughout the world, both with regard to their direction and to the interpretation of the results obtained.

In the shell model of the atomic nucleus the constituent nucleons (the neutrons and protons) move independently in orbits about the center of mass of the nucleus, each orbit being determined by the "shell model potential." This description is strikingly similar to that of the atom, in which the electrons move about the atomic nucleus in orbits. But there are very important differences between the two systems. In the case of the atom there is a long-range central force acting on the electrons, provided by the electrostatic field of the nucleus. Moreover, the electrostatic force between the electrons is relatively weak and repulsive. These circumstances, together with the effects of the Pauli principle, serve to guarantee that the total potential in which each electron moves is to a very good approximation spherically symmetric. In the nuclear case, there is no central source which determines the nature of the force in which a nucleon moves. The force acting on a particular nucleon is actually a sum of all the forces exerted by all the other nucleons in the nucleus. The shell model asserts that to some approximation that sum can be replaced by a suitable average taken over the nucleon motions. The resultant potential is then the shell model potential. It was assumed independently by both Goeppert-Mayer and J. H. D. Jensen and his co-workers that the shell model potential is spherically symmetric. A second significant difference from the atomic case is that the residual force between the nucleons—that is, the force which remains after the average is taken into account—is attractive and of short range. The Pauli principle applies to both the atomic and nuclear system, an important similarity.

Shell and Liquid Drop Models

The nuclear shell model and the earlier liquid drop nuclear model seemed to be inconsistent. The latter pictures the nucleus to be a charged liquid drop. This model is thought to follow from the short range of nuclear forces and appears to be verified by the empirical result that the binding energy of a nucleus is, to a first approximation, proportional to the number of nucleons. One correction to this result was found empirically to be proportional to the surface area of the nucleus, which could be interpreted as arising from surface tension, while a second originated in the electrostatic energy of the drop, assuming that the nuclear charge is distributed throughout its volume. Many of the features of the fission reaction could be understood on the basis of these considerations. The liquid drop picture in this form differs sharply from the shell model, which assumes that each of the nucleons moves independently in the shell model potential.

Although the nuclear shell model successfully predicts the "magic numbers" at which unusually large changes in binding energy occurs, ground state nuclear spins, the degree of the forbiddenness of beta decay, and the correct order of magnitude for nuclear magnetic moments, it fails in the case of nuclear electric quadrupole moments. In, for example, the rare earth nuclei, the quadrupole moment is as much as 20 times the shell model estimates. Clearly many of the nucleons are cooperating to produce these large values. It was Rainwater's contribution (1950)* to point out that a nucleus could become more strongly bound if the shell model potential were not spherical but deformed into the shape of a spheroid. The deformed potential implied that the nucleus which produces it must also be deformed, which in turn implies a finite quadrupole moment. Adding a nucleon to a spherical nucleus thus deforms the latter and provides a spheroidal potential for the former. Rainwater's rough estimates gave, in fact, too large a value for the quadrupole moment. But this difficulty was immediately removed by A. Bohr, who pointed out that the deformed nucleus must rotate since there can be no preferred direction in space. The observed quadrupole moment was thus, roughly speaking, a projection of the intrinsic quadrupole moment on the axis of rotation.

A number of problems immediately presented themselves. At the simplest level, do these deformed nuclei exhibit rotational spectra? Bohr and Mottelson drew on the experience developed in the understanding of molecular spectra. As in the case of molecules, the spectra of deformed nuclei exhibit rotational band structures, the bands being based on different intrinsic states of the nucleus. For molecules these intrinsic states commonly are different vibrational states of the nuclei of the atoms making up the molecule. Vibrational states occur for nuclei as well, but there are other possibilities, such as differing types and magnitudes of deformation, which need to be specified in order to describe the shape of the deformed nuclei completely. The spheroidal nucleus was found to rotate only about an axis perpendicular to the axis of symmetry, as in the case of diatomic molecules, the reasons being more obscure in the nuclear case. If the band picture is correct, the intrinsic structure of the nucleus will be the same for each member of a rotational band, and this leads to predictions, for example, regarding the ratios of intraband electromagnetic transition probabilities.

In their definitive 1953 article Bohr and Mottelson examined the empirical situation for the impact of a possible nuclear deformation on not only the energy level spectra but also the spins, magnetic moments, and quadrupole moments of ground

*A moral for the present lies in the fact that Rainwater's main research interest at the time of his paper lay in the nuclear reactions induced by low energy neutrons. But that did not preclude his appreciating the dilemma which was presented by the discovery of large nuclear quadrupole moments and contributing significantly to its resolution.

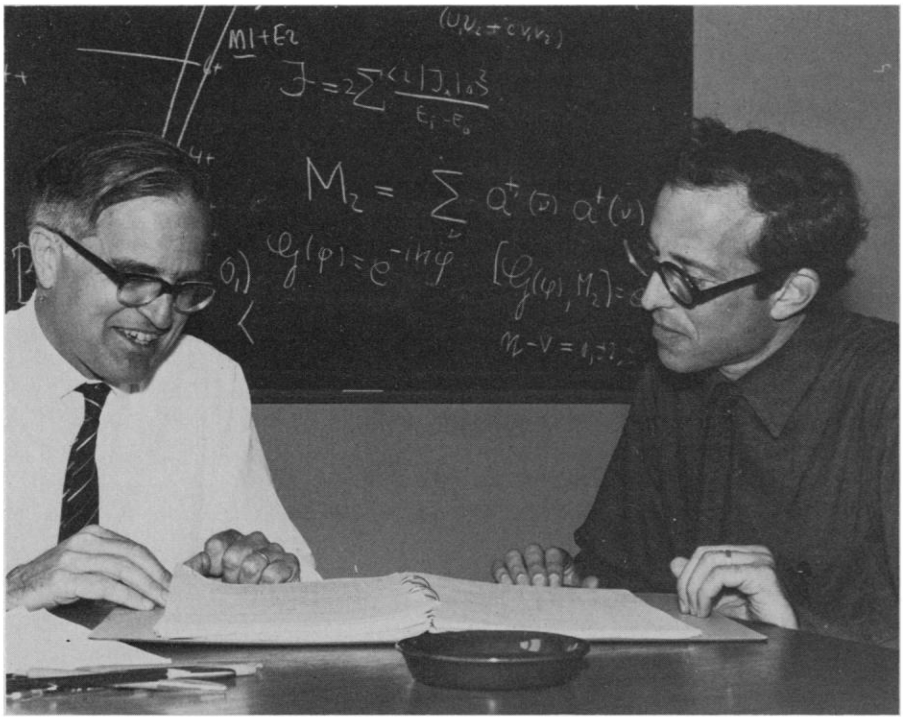

Photo courtesy of Nordita

Aage Bohr and Ben Mottelson

Photo courtesy of Columbia University

James Rainwater

states, and the electromagnetic and beta decay transition probabilities.† That article contains a survey of the experimental data which is remarkable because of its encyclopedic nature and because each group of data is thoroughly analyzed to determine any information it might provide on the nuclear shape. Of course, many new phenomena were uncovered, but that is too long a story to tell here. Suffice it to say it was found that many nuclei in their ground states are indeed deformed. Islands of substantial deformation were found for nuclei with mass numbers between 9 and 14, 19 and 25, 155 and 185, and greater than 225. It was discovered that nuclei with spherical ground states could have deformed excited states upon which bands could be built. The phenomenon of nuclear deformation thus appears in various guises throughout the periodic table.

Presuming the rotational motion of the nucleus, is it possible to reconcile that motion, in which a substantial number of nucleons participate, with the shell model, which assumes their independent motion? The resolution of this dilemma is obtained if one appropriately generalizes the shell model to a deformed shell model in which the nucleons move in a deformed potential. The motions of the nucleons within this potential are independent, but it follows from general principles that the potential rotates slowly, imposing its motion on all the nucleons. The intrinsic state of the nucleus is thus determined by the deformed shell model, the rotational motion being superimposed. An analogy has often been made to a swarm of bees. The motion of each bee seems rapid and erratic, but the swarm will move slowly as a unit. It would take us too far afield to discuss the deformed shell model and calculations of nuclear properties based on it in detail. The definitive work was carried out by S. G. Nilsson, a collaborator of Bohr and Mottelson, and the results were compared with experiment by Nilsson and Mottelson, who quantitatively determined the nuclear shape for a wide range of nuclei.

The separation of the motion of the nucleons in the nucleus into rapid independent particle motion plus an overall coordinated and relatively slow motion is not restricted to the circumstance in which the nucleus is deformed and the coordinated motion is a rotation. The liquid drop, for example, suggests surface and volume vibrations of various sorts as other possibilities. The "slow" nuclear degrees of freedom are referred to by Bohr and Mottelson as "collective" modes of motion and are described in terms of appropriate "collective" variables. One of the principal aims of the study of nuclei is the discovery and description of the various collective modes. It was Bohr who very early pointed to the origin of these slowly varying potentials and consequently slow collective motions. They are present because the average force acting on a nucleon exerted by the other nucleons in the nucleus is a dynamical quality and thus can vary with time. This situation is very different from the atomic system, where the principal component of the force acting on the electrons is provided by the nucleus and is not affected by the motion of the electrons. To return to the nucleus, Bohr's first example of the dynamic properties of the average potential focused on the radius of the shell model potential for a particular nucleon. Assuming that the rest of the nucleus (the core) is vibrating, the radius of the potential will also vibrate, or equivalently the nucleon exchanges phonons with the core. This description is correct if the coupling between the particle and the core is weak. If it is strong, multiphonon exchanges occur and the classical limit in which the core and the shell model potential are deformed and rotating results. Of course, vibrations of the deformed core can occur in addition to the rotation.

The motion associated with a given collective variable depends on the inertial parameters and the effective force constants needed to specify the energy of the system in terms of that variable and its conjugate momentum. In the first papers on this subject Bohr and Mottelson relied on the liquid drop model to evaluate these parameters. However, these estimates soon proved to be in contradiction with experiment. The inertial parameter for rotation is the moment of inertia. Assuming that the nucleus rotated rigidly gave too large a moment of inertia. Assuming that the rotation could be described by irrotational flow in a

†Applications were made in other papers to alpha decay and fission.

liquid drop model turned out to give too small a value. The deformed shell model, in which each of the nucleons moves independently, was found to give the rigid body value. This remarkable result was first discovered in another context by Niels Bohr, Aage Bohr's father and Nobel Laureate, in 1911. Neither the liquid drop model nor the independent particle model is correct. In fact, in order to obtain the experimental values it is necessary to take account of the residual forces between the nucleons, the precise values thus providing information on their nature.

These results are important for understanding not only nuclear structure but also the many body problem, the fundamental problem underlying all of modern physics. The nucleus provides a rich variety of phenomena. Their elucidation for these relatively small systems and for the moderately strong interactions that exist between the constituent nucleons will undoubtedly provide new insights into the characteristic quantal forms of motion which a many body system can undergo.

It is intended by this brief account to give some insight into the catalytic nature of Rainwater's contribution and the mighty edifice Bohr and Mottelson have built. I have concentrated on their early work. There have, of course, been many subsequent developments, both experimental and theoretical. Many fundamental problems remain unsolved. The reader is referred to the forthcoming second volume of Bohr and Mottelson's book, *Nuclear Structure*, for a complete discussion. And, of course, I must apologize to the many physicists whose significant contributions have not been mentioned. But with regard to the developments discussed above, Bohr, Mottelson, and Rainwater played a central and decisive role.

H. FESHBACH

Laboratory for Nuclear Science and *Department of Physics, Massachusetts Institute of Technology, Cambridge 02139*

References

1. J. Rainwater, *Phys. Rev.* **79**, 432 (1950).
2. A. Bohr, *ibid.* **81**, 134 (1951).
3. ———, *ibid.*, p. 331.
4. ———, *Dan. Mat. Fys. Medd.* **26**, No. 4 (1952).
5. ——— and B. R. Mottelson, *ibid.* **27**, No. 16 (1953).
6. A. Bohr, *Rotational States in Atomic Nuclei* (Munksgaard, Copenhagen, 1954).
7. ——— and B. R. Mottelson, *Dan. Mat. Fys. Medd.* **30**, No. 1 (1955).
8. S. G. Nilsson, *ibid.* **29**, No. 16 (1955).
9. B. R. Mottelson and S. G. Nilsson, *Phys. Rev.* **99**, 1616 (1955).
10. A. Bohr and B. R. Mottelson, *Nuclear Structure*, (Addison-Wesley, Reading, Mass., in press), vol. 2.

Malodor Counteractants: The Nose No Longer Knows

The complex mechanism by which we perceive odors is still largely a mystery. It is generally accepted that the shape of a molecule is one of the most important factors in determining its aroma and that the molecule must interact with specific receptors in the nose to produce an effect, but the receptors have never been isolated and their nature can only be guessed. A little bit more may be learned about these receptors as the result of the serendipitous discovery of a new class of chemicals that inhibit the interaction of malodorous compounds with the receptors.

The chemicals, called malodor counteractants, were discovered about 7 years ago by Alfred A. Schleppnik of Monsanto Flavor/Essence Inc. of St. Louis. Little was done with them for the first few years after their discovery, however, since the effect they produced was so contrary to established theories of olfaction. Only about 2 years ago did officials at Monsanto begin to accept the fact that the phenomenon was real and initiate a vigorous research program to document the effect and to find commercial applications for the chemicals.

The majority of commonly encountered malodorous chemicals, Schleppnik says, are small molecules that can either accept or donate a proton. These include low-molecular-weight carboxylic acids (the primary offenders in perspiration and rancid foods), thiols, phenols, and amines (many of which produce fishy odors). How these molecules interact with receptors in the nose is still a matter of speculation, but there is much evidence to suggest that they all interact with just one type of receptor.

Conventional deodorizers and air fresheners act by flooding these receptors with a large number of molecules, creating a strong odor that masks the malodor. In the process, a much higher total odor level is produced. In contrast, very small quantities of the malodor counteractants appear to react with an allosteric site (a second site distant from the receptor) on the receptor molecule (which is presumed to be a protein) to produce a conformational change that blocks the receptor site. The net effect is that the olfactory nerves do not perceive the malodor, and there is an apparent lessening of the total odor level. The counteractants do, however, also interact slightly with trigeminus nerve receptors in the nose (which are thought to produce a warning in the form of stinging, burning, or tingling sensations) to produce what Schleppnik describes as a "fresh air" smell indicating that "something indefinable is there."

Others Are Similar

In one sense, the counteractants are not unlike other aroma chemicals. Many commonly used aroma chemicals can enhance or inhibit the awareness of an accompanying odor even though they have no aroma of their own. Perfumes often contain many such ingredients. The model of allosteric interaction proposed by Schleppnik provides one possible explanation for how these seemingly odorless ingredients can modify the aromas of the primary ingredients. The malodor counteractants, he adds, differ from these other modifiers only in the completeness of the inhibition and in the larger number of odors affected.

The identity of the counteractants has not yet been disclosed because Monsanto has not completed its patent applications. All of the many counteractants, however, are relatively simple compounds with masses from 150 to 250 daltons. All have, or can assume, the same three-dimensional shape, and all have similar distributions of electron density and polarity, even though they do not all contain the same functional groups. They are not ionic, they contain no aromatic rings, and they are not soluble in water. Their activity is highly stereospecific, but unresolved mixtures of stereoisomers can be used commercially to reduce costs. Some of the chemicals produce their own aromas (by interacting with a second receptor), while others do not. The counteractants are so simple, Schleppnik says, that the revelation of their identities will probably be "anticlimactic."

The counteractant effects persist for as long as concentration of at least 1 part per million is maintained in the air. When exposure to the chemicals is stopped, sensitivity to malodors returns within seconds; a concentration of a few parts per million will remain in a room for hours, though. A large number of tests—including his own extensive exposure, Schleppnik says—indicate that there are no residual effects associated with either prolonged exposure to the counteractants or exposure to abnormally large quantities of them. There are no government requirements for testing of

(Continued on page 919)