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A. Bohr
B. R. Mottelson
J. Rainwater

1975 Nobel Prize in Physics

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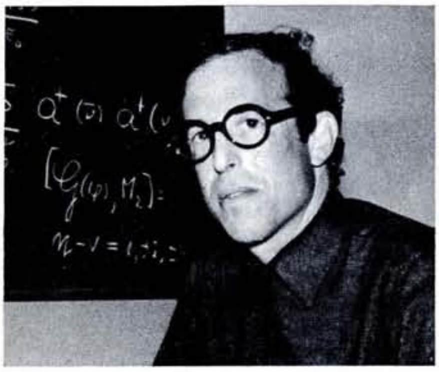

The Royal Swedish Academy of Science has awarded the 1975 physics prize equally to Professors A. Bohr and B.R. Mottelson of the Niels Bohr Institute, Copenhagen, and J. Rainwater of Columbia University, New York, for "the discovery of the coupling of collective nuclear motion to that of valence nucleons and the development of nuclear theory on this basis". This discovery, which was made in the early 1950's led to a complete revolution of nuclear physics.

In order to appreciate fully the large change that the discovery of Bohr, Mottleson and Rainwater caused in the the entire approach to nuclear physics, it is useful to go back to the period just after World War II and to examine in what spirit nuclei were considered. In nuclear reactions, the thinking was strongly dominated by N. Bohr's picture of the nucleus as a liquid drop, held together by surface tension, partially balanced by Coulomb repulsion. In light elements, it was possible to achieve some understanding of the ground state and first excited states by considering valence nucleons moving in a spherical potential. This partial analogy with atomic physics failed completely for heavy elements. It was considered appropriate to think of nuclei as nearly spherical, since nuclear forces were strong and of short range, and many theoreticians felt that this made them inapproriate for deforming the system. Because of the analogy with a liquid drop there had, of course, been thoughts that nuclei could exhibit various vibrational and rotational modes at higher excitations. The notion of rotations had, however, been very harshly dealt with in a brilliant article by E. Teller and J. Wheeler[1]). They showed that if nuclei had rotational spectra with a rigid moment of inertia, it would follow that there would be a large number of nuclear states of very low frequency and with various spins. Consequently, the angular momentum selection rules responsible for nuclear isomerism would break down completely; the lifetimes of isomers would decrease by many magnitudes in gross contradiction with observation. In addition, they demonstrated quite convincingly that for a quantized, spherical system there is no necessity for any rotational spectrum; such a system is somewhat analogous to a superfluid, so that under rotation it transforms into itself. However, they argued, when a large amount of angular momentum is pumped into the nucleus, there is an analogy to the critical velocity in superfluidity; at a certain critical spin there will be a "phase transition", so that for larger spins, rotational motion with rigid moment of

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inertia will set in*). Thus, at the end of the 1940's the situation was that nuclear rotational motion was not strictly ruled out, but there were excellent experimental and theoretical arguments which made the notion unnecessary and even suspect for nuclei.

At the end of the 1940's the nuclear shell model was discovered by M. Goeppert-Mayer and J.-H. Jensen (Nobel prize 1963). There were two crucial ideas in this model. The first was that in spite of the short range of nuclear forces there could be generated an average effective potential which valence nucleons could see as an external potential. The second was that this potential had a strong spin orbit coupling. Suddenly it became possible in this way to understand a large number of nuclear properties in a manner akin to atomic shell structure. In particular, it became possible to undestand not only the regularities of major nuclear shells, but also the spins, magnetic moments and quadrupole moments of many nuclei. This partial understanding of nuclear structure brought some previously known discrepancies more forcefully into focus.

Since the middle of the 1930's it had been known that certain nuclear quadrupole moments were very large and by necessity were associated with many nucleons. In 1949, C. H. Townes, H. M. Foley and W. Low took a careful look at nuclear quadrupole moments from a shell model point of view. They found that the data could be understood rather well with the glaring exception of the rare earths, i. e., halfway between two major closed shells. Here the quadrupole moments were up to 35 times larger than the value for a single valence nucleon. It was clear that the effect was beyond the shell model.

During 1949, A. Bohr arrived at Columbia University as Reserch Fellow. A secretary with foresight assigned him to the same office as J. Rainwater, an experimental physicist working on slow neutron time-of-flight studies and on the completion of the Nevis cyclotron. In the late part of 1949, C.H. Townes presented the analysis of nuclear quadrupole moments at a seminar. Rainwater describes vividly in his Nobel lecture, how during the seminar he was struck by the idea that there could be a simple mechanism which could produce deformed nuclei. Suppose a nucleon is placed in a potential, which is not spherical but deformed. Then it is possible to orient its orbit so that its kinetic energy is lowered, and this lowering of energy is linear in the deformation. If now the bulk of the nucleus resists deformation just as surface tension makes a drop spherical, the dependence on *its* energy of deformation should be quadratic. The competition between the two effects will then produce a net static deformation of the nucleus. During the talk, Rainwater put a few numbers on an envelope and convinced himself that magnitudes were right : nuclei were so easily deformable that here was an excellent chance of getting large quadrupole moments.

During the next months, Rainwater cleaned up the argument and made it more detailed which resulted in an article of a mere 2 ½ pages [2]). In this article he recognizes that for several valence nucleons the deforming effects will add linearly for small deformations, and that the main contribution to the quadrupole moment comes from the distortion of the nuclear core, *not* from the valence nucleons. He further makes the important observation that once one admits that the nucleus is deformed, then it follows that the shell model self-consistent potential well generated by the nucleons is also deformed. « One must then solve the eigenvalue problem for a particle in a speroidal box » [+]). This brief interlude ended Rainwater's contribution to these problems and he returned to the Nevis cyclotron, where his pioneering studies of muonic atoms with his student V. L. Fitch led to the discovery that nuclei were much smaller than believed at the time. The important contribution of Rainwater was thus that he ascribed the mechanism for producing nuclear deformations to the polarizing effect of valence nucleons, which is the correct explanation. Even more importantly, his model fused for the first time the apparently contradictory liquid drop and single particle model.

On the other hand, Rainwater completely failed to appreciate the important dynamical consequences of the coupling between a deformed core and valence nucleons. This crucial further step was taken by A. Bohr.

While Rainwater concentrated his thinking on a specific model for producing a nuclear deformation, Bohr seems immediately to have perceived that the Rainwater picture was only a very special case of more general models. He realized that all reasonable models with a permanently deformed nucleon field implicitly assume that the *rotational* frequencies of the system must be rather small compared to the intrinsic single particle frequencies. He qualitatively understood that the moment of inertia of such rotational motion is associated with a small part of the total number of nucleons only and that rotational levels can appear in spite of their empirical absence at very low excitations. The arguments of Teller and Wheeler against nuclear rotations were therefore invalid in the new situation. Further, he also realized that in spite of the absence of a strictly rigid structure in nuclei, the frequencies associated with bulk nuclear matter are sufficiently low to provide a strong analogy with the rigid structure in molecules, with valence nucleons coupled to a momentarily rigid nuclear core. Because of this, he introduced as a logical quantization scheme the rigid top quantum numbers K and Ω and it is here the rigid top wave functions are first used in this context. An important part of this picture is, of course, that the total angular momentum now is split between the motion of the nuclear core and the valence nucleons. At that time, the strength of coupling of the valence nucleon to the nuclear surface was unknown, and he explored the various possibilities of weak to strong coupling qualitatively, including the case of L. S coupling. He finally compared the predictions of these limits to measured magnetic moments. The comparison was, hovewer, quite inconclusive. These results appeared in an article [3]) published shortly after Rainwater's. Although with the benefit of hindsight it is possible to see a number of important later developments originating in this article, they were as yet at an early stage and the experimental consequences were not dramatic.

Slightly later, M. Goldhaber and A. W. Sunyar at Brookhaven, analyzed experimental electromagnetic transitions in nuclei in terms of the just introduced Weisskopf single particle units. It became strikingly apparent that these rates were generally small with the outstanding exception of the quadrupole E2 transitions which were very much greater than unity by up to two orders of magnitude [4]). Goldhaber and Sunyar clearly realized that this was the transition analogue to the large quadrupole moments.

Apparently unaware of this additional evidence for deformed nuclei, Bohr had now returned to Copenhagen. During the next year he completes the analysis : « The Coupling of Nuclear

*) The idea of a nuclear phase transition came into focus again about 20 years later, and there are presently experiments on nuclei at high spins which indicate such a process.

+) This idea was later taken up in detail in the mid-1950's, particularly by S.G. Nilsson (the Nilsson model), which led to a highly successful description of the behaviour of the level structure and level properties of valence nucleons with deformation.

Surface Oscillations to the Motion of Individual Nucleons » [5]).

Here Bohr took an important additional step beyond previous treatment of the liquid drop by using the relevant angular co-ordinates clearly to identify vibrational and rotational terms in the kinetic energy. Consequently when he introduced the deforming effects of a valence particle by coupling it to the surface of the drop, it became extremely apparent how vibrations are produced around the new equilibrium position, both cylindrically symmetric oscillations (β vibration) and axially asymmetric oscillations (γ vibration). The rotational spectra came out even clearer with the moment of inertia linked to the static deformation. The symmetry of the wave function demands that only terms even in spin occur for even nuclei. The logical quantum numbers for the description of this situation are the ones associated with the rotating top. Bohr's treatment went further ; in the mathematics it is quite apparent that the strength of the coupling and the nuclear deformability can influence spectra importantly, and it is quite clear from the structure that the simple rotational structure of spectra in principle could be strongly disturbed, e.g., because the valence nucleon does not adjust to the rotation of its potential in a fully adiabatic way. The structure of Bohr's equations encompasses such couplings. It was also clear from Bohr's equations that on top of every « intrinsic » state of valence nucleons, there should be bands of rotational and vibrational spectra.

This article by Bohr was a clear-cut penetrating mathematical analysis of the well-defined problem of coupling a valence particle to a liquid drop, and it gave the solution to this problem including its quantization. It contained all the essential mathematical features of the nuclear problem, and there was no essential further progress in the mathematical structure of the theory until Bohr, Mottelson and Pines pointed out seven years later, that pairing interactions made nuclei analogous to superconductors.

In the second half of 1951, Bohr was joined in Copenhagen by a young American postdoc, B. R. Mottelson. This started one of the longest and most fruitful collaborations in physics. At this time the general theoretical foundation was largely in place, but it had now to be translated into hard experimental consequences, since the crucial evidence for the new picture was entirely lacking. For the time being, the new model for nuclei was almost a purely paper construction, unsupported by facts. Experimentalists paid only scant attention, and so did most theorists.

At the end of 1951 and during 1952, Bohr and Mottelson undertook a detailed, systematic analysis of all data on nuclear spectra in heavier nuclei. Much of the material was unpublished and had to be painstakingly collected by personal interviews with experimental groups in many places. The first results of this were presented at the Amsterdam conference in September 1952. Here attention was drawn to the numerous cases of β and γ transitions of various multipolarity which agreed with the nuclear shell model in level assignments, but with transition rates far below prediction. This could qualitatively be explained by a coupling to a nuclear core as proposed, but naturally other explanations could easily be envisaged. More convincing and striking was the clear prediction of spin $(j-1)$ for (j^3) configurations of valence nucleons contrary to the shell model prediction of spin j.

Towards the end of 1952, K. Ford at Princeton analyzed part of the Goldhaber-Sunyar quadrupole transitions according to Bohr's new theory. He established an important link between the transition rates and the position of the first excited 2^+ states. Because of his particular choice of nuclei in a region in which nuclear rotational motion deviates importantly from that of a rigid rotor, he failed to realize that this correlation indicated nuclear rotations and this in spite of the fact that he also considered a few 4^+ states. This is an interesting fact since it indicates how difficult it was to discern nuclear rotational motion at that time.

Towards the end of the year Bohr and Mottelson brought the question of rotations more strongly into focus in a systematic analysis of quadrupole transitions in heavy nuclei. They insisted on the possibility of rotational motion in nuclei and they actually analyzed the lifetimes of the excited states in even nuclei in this way [6]).

During the early spring of 1953, they found the undisputable evidence for nuclear rotational spectra in the existing experimental data for ^{176}Hf and ^{178}Hf which showed clean rotational bands $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$
and $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$
both in terms of level spacings and in transition rates [7]). This was a clinching proof of the correctness of the ideas set forth by Bohr. It is remarkable that this *experimental* confirmation was produced by a correct theoretical interpretation of existing data by Bohr and Mottelson.

At this point most well-informed groups in nuclear physics the world over, quickly realized that a major breakthrough had occurred and a mass of confirming data quickly became available. One early important additional confirmation was the discovery by F. Asaro and I. Perlman that α decay in heavy elements populate rotational bands, which indicated one additional region of deformed elements. Another one was the discovery by T. Huss and Č. Zupančič and by C. L. McClelland and C. Goodman that nuclear Coulomb excitation selectively and preferentially excited collective features of nuclei.

Also during the early spring 1953, Bohr and Mottelson prepared the first coherent presentation and elaboration of the results obtained, which appeared as the influential article « Collective and Individual Particle Aspects of Nuclear Structure » [8]) which has had a profound impact on experimental nuclear physics. While this article gives few new results, it introduces a new perspective by its strong insistence that the breakthrough was not confined to any special subfield of nuclear physics. *All* nuclear properties, spins, moments, transition rates, spectra, nuclear reactions, etc., should be re-examined in the light of the new picture. From this point on, Bohr and Mottelson begin to emphasize that the simultaneous consideration of the collective and shell model features of nuclei gives a more powerful and unified frame within which to consider nuclear properties.

The appearance of this survey ends the first chain of discoveries associated with the realization that nuclei in general are deformed with the deformation produced by the coupling of valence nucleons to nuclear surface motion.

Starting from the ideas set out in the survey article, Bohr and Mottelson in Copenhagen became the centre for a systematic exploration programme of all the many consequences both theoretical and experimental. Since then their ideas have deeply permeated nuclear physics to the extent of being inseparable from it.

Of the later consequences of this programme, I will only briefly mention a few.

1) In the deformed nuclei the individual nucleon orbits have a natural double degeneracy corresponding to motion in opposite direction around the symmetry axis. The perfect spatial overlap in such states provides additional binding which make them the nuclear equivalent of the Cooper pairs in superconductors. From this obser-

vation a nuclear energy gap could be predicted as well as a « phase transition » at a critical angular momentum. This interesting phenomenon is strongly indicated in experiments on nuclei of high spin.

2) The adiabatic nature of the fission process has made it natural to consider the momentary energy as a function of deformations. Since much energy is absorbed by potential energy, the system is effectively at very low excitation in the barrier region. The adiabatic development of intrinsic states therefore governs the details of the fission process. A spectacular confirmation of this picture was found a few years ago with the discovery of fission isomers produced by a secondary barrier minimum. Even the rotational bands in this minimum have been seen. The modern understanding of fission derives directly from the discoveries in the 1950's.

3) The deformation of the self-consistent nuclear field leads in some cases to a radical reordering of the intrinsic states with deformation. In certain nuclear regions, these are so large that new shells occur for large deformations with magic numbers different from those of the shell model. Nuclear shapes can change drastically between nearby intrinsic states. These developments are closely linked to the spectacular success of the Nilsson model.

On closing this historical survey of the background to the 1975 Nobel prizes, I am struck by the following. It is quite possible to maintain the thesis that the initial theoretical discovery was made by an experimental physicist, while on the other hand, the final « experimental proof » was provided by the two theoretical physicists who analyzed existing data correctly. The moral of this is, of course, that one should not just be either an experimentalist or a theoretician. In the final analysis, the important thing is to be a physicist.

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Physics Education in the German Democratic Republic

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Science plays a very important role in a socialist country and consequently, education in science is also a matter of great importance. When the new five-year plan, 1976-1980, was prepared, a long term programme on basic research in mathematics, in the fundamental natural sciences and also in some technical sciences was worked out and adopted by the Central Committee of the Socialist Unity Party of Germany and by the Council of Ministers of the GDR. Many competent physicists took part in the elaboration of this document. It gives a sound basis for the further development of physics in our country. A fundamental idea in the programme is, that basic research should be planned and performed in such a way, that both the internal needs of the sciences to ensure their evolution and, the needs of society are fulfilled at the same time. This may be understood also as a fundamental idea in physics education, underlying the physics education in the schools as well as in the Universities.

Physics Education in the Schools

The main type of school in the GDR is the "allgemeinbildende polytechnische Oberschule" (general polytechnical school). It has 10 forms, beginning in the 1st. form with pupils from six years old. It gives a general education in German and one or two foreign languages, in mathemetics, natural sciences, in some social sciences and arts, as well as some polytechnical training. Attending the school until the age of 16 is a legal obligation and free of charge, as is all education in our country. Pupils intending to go to university, technical highschools (technological institutes) or to the Technical University of Dresden have to complete their general education with two further years in the 11th. and 12th. form of the "erweiterte polytechnische Oberschule" (extended polytechnical secondary school) at the ages of 17 and 18 years, or by some other form of further education. After thorough examinations in the 12th. form, the successful students receive a certificate, the "Abitur", qualifying them to attend university without any further examination.

Physics education together with mathematics and the other natural sciences is essential to the "Integrated Socialist Educational System", as learning physics makes an important contribution to forming the personality of a human being. Exact and systematic knowledge of natural phenomena, of the principles, rules and laws that underlie them, and the theories that are derived from this knowledge, are of great importance in understanding the world, the objective character of nature and science and for getting deeper insight into the philosophy of dialectical materialism. We agree with Casimir[1]) that physics teaching in school "should lead to an understanding of physics underlying everyday life, and more specifically its technological aspect", and we think also with him, that "if it is done well, such teaching should automatically convey an appreciation of the beauty of physics — and help prospective physicists to make up their minds". We agree also with Weisskopf, that physics should be taught in such a way that everybody understands that it is human.

Education in physics begins in the 6th. form (12 years of age) ; it takes 8-10 % of the lessons, that means, as a rule, 3 hours a week. Mathematics takes about 14 %, chemistry 6 % and biology 5 %. For pupils with a special interest in physics, there is additional time for practical scientific work and for voluntary facultative lessons. The total time devoted to physics from the 6th. to the 12th. form of 555 lesson-hours is distributed amongst the different fields of physics as follows : 31 % mechanics, 25 % electricity, 14 % heat, 6 % optics, 6 % quantum physics, 2 % nuclear physics, 1 % relativity, 7 % general questions and revision, 8 % concentrated laboratory work. Besides the 8 % concentrated