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SCIENCE

Concepts of Nuclear Structure

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The three or four decades since Charles Lauritsen (*1*) together with other pioneers opened the field of nuclear structure and nuclear reactions to systematic study have witnessed an astounding development and precision of the experimental tools for these studies. I shall not attempt to describe the tremendous richness of phenomena that have become accessible through this development, and the far-reaching ramifications in many fields of science; but I should like to comment on some of the concepts that have played a role in the interpretation of the nuclear phenomena and some of the issues that have been involved (*2*).

Quantal Theory and the Many-Body Problem

The nucleus is an example of a quantal many-body system. At all the steps of the quantum ladder, from the macromolecules and matter in bulk to the elementary particles, one deals with composite systems or more generally with the problem of how the quanta themselves are built out of other quanta. The many-body problem in its different manifestations is a common theme in the current broad development of quantal physics.

The early phases of quantal theory gave emphasis to phenomena which could be described in terms of one-particle motion or a few simple degrees of freedom or, as in electrodynamics, in terms of a perturbation in the motion of free quanta, and which could therefore be directly mastered by a solution of the basic equations of motion. In the study of the many-body systems, however, the situation has been a different one. The structural possibilities and the variety of correlation effects that may occur in a system such as the nucleus are so vast that a crucial problem has been the identification of the appropriate concepts and degrees of freedom to describe the phenomena that one encounters. Progress in this direction has been achieved by a combination of many different approaches, including the clues provided by experimental discoveries, theoretical studies of model systems, and the establishment of general relations following from considerations of symmetry.

In the developing understanding of nuclear structure, the attempts to achieve a proper balance between independent-particle and collective degrees of freedom has been a recurring and central theme. This may be true of all many-body systems, but, in the nucleus, because of the possibility of detailed studies of individual quantum states, this issue was encountered in an especially concrete form.

The earliest discussions of nuclei, as built out of neutrons and protons, were based on an independent-particle picture, similar to that which had been successfully employed in the analysis of atomic structure. However, the pioneering studies of nuclear reactions soon revealed features that could not be comprehended on this basis. Especially striking was the frequent occurrence of resonance capture of incident nucleons. The earliest evidence for such processes was obtained by Lauritsen and his coworkers in the Kellogg Laboratory.

The startling new situation had a strong appeal to my father's imagination, and he was able to bring the available experience together into a picture of the nuclear dynamics that gave emphasis to the strong coupling in the motion of the nucleons. On this basis, the course of the nuclear reactions could be understood in terms of the formation of a compound nucleus involving the excitation of a large number of degrees of freedom, and many features of its decay could be described by statistical concepts. The basic modes of excitation of the nucleus envisaged in this picture are of collective vibrational character, similar to the oscillations of a liquid drop. A few years later, a striking example of collective nuclear motion was provided by the discovery of the fission process.

On this background, the definite establishment of nuclear shell structure and its interpretation in terms of a long mean free path for motion of a nucleon in the nucleus came as another big surprise. One was then faced with the problem of reconciling the occurrence of single-particle and collective degrees of freedom and of exploring their mutual relationship.

Many phenomena could be immediately understood in terms of the interplay of the two components in the nuclear dynamics. An especially striking effect, first noted by Rainwater, is the tendency of the nucleons in unfilled shells to produce large spheroidal deformations in the nuclear shape.

While the need to include both single-particle and collective degrees of freedom in the description of the nucleus was apparent, one faced problems arising from the fact that such a description employs an overcomplete set of variables. Thus, it was recognized that the particle degrees of freedom

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must be significantly modified by the presence of the collective modes, and that in turn the shell structure could have a profound effect on the collective motion.

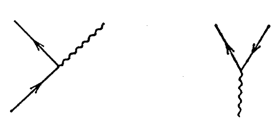
Nuclear Field Theory

In the development that has led to a gradual clarification of these issues, the concept of the single-particle field (or potential) generated by a collective deformation has played a central role. The field is, to a first approximation, proportional to the deformation amplitude α, and gives a contribution to the nucleonic energy of the form

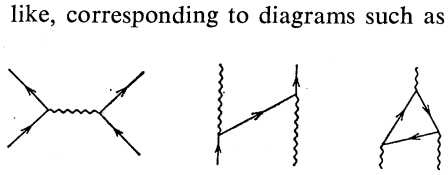
$$H' = \kappa\alpha\, F(x)$$

where κ is a coupling constant while $F(x)$ gives the dependence of the potential on the nucleonic variables. The energy H' constitutes a coupling between particle and vibrational motion and is analogous to the electron-phonon and electron-plasmon interactions in a metal and to the particle-phonon coupling in liquid helium.

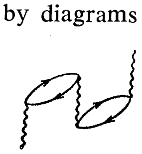
In terms of the particle-vibration coupling, one can develop a systematic treatment of the elementary modes of excitation in the nucleus. The first-order effects of the coupling can be illustrated by Feynman diagrams, such as



representing inelastic scattering of a particle with the excitation of a phonon and the decay of a collective phonon into a particle-hole pair. In higher orders, one obtains effective interactions between two particles, between a particle and a phonon, anharmonicity effects in the vibrational motion, and the like, corresponding to diagrams such as



At the same time, the coupling emerges as the mechanism that organizes the collective motion of the particles, as illustrated by diagrams such as



and the properties of the quanta are determined by a self-consistency condition.

Such a nuclear field theory appears to handle the delicate relationship between collective and single-particle aspects in the nuclear dynamics in a consistent manner, and the scope of the description is being intensively explored. The modification in the motion of the individual particles implied by the presence of the collective modes is expressed in terms of the renormalization of the various moments of the particles. The antisymmetry between the particles including those involved in the collective motion and, more generally, the requirements of orthogonality between the different types of quanta, are expressed in terms of interactions of exchange type. Thus, the collective modes appear just as elementary as the particle degrees of freedom out of which they are built. The various interactions between the quanta, including the width for their decay, provide the natural limitation to the description in terms of elementary modes of excitation.

The dynamic fields involved in the coupling (Eq. 1) are, of course, manifestations of the forces between the nucleons. The relationship is similar to that involved in the analysis of the average static field in the nucleus on the basis of the nucleonic interactions. These connections have proved more elusive than anticipated because of the many subtle correlation effects involved in the collective properties of the nuclear many-body system. However, the challenge that these problems present has led to extensive progress in many-body theory, which has focused attention on the deep similarities in the structure of matter in the very different forms in which it occurs in condensed atomic systems, nuclei, and elementary particles.

The nuclear vibrational fields are directly encountered in the study of the collective modes and provide a unifying quantity in terms of which one may attempt to establish the relation between the different properties of the nuclear excitations. In the efforts to determine these fields, many lines of attack are pursued including direct probing of the collective modes by nucleonic scattering, the analysis of the various observed coupling effects, and the comparison with the known static fields, as well as the deductions based on the two-nucleon forces.

Elementary Modes of Excitation

The study of the elementary modes of excitation in the nucleus and their analysis in terms of the particle-vibration coupling is an extensive domain of research, and investigations are proceeding in a variety of different directions. Thus, with the further refinement of the analysis of nuclear spectra, one expects to find many new types of collective modes, the study of which may elucidate aspects of nuclear dynamics that are at present little explored.

In another direction, the analysis of nuclei with large deformations is making contact with the study of the fission process and the related exploration of nuclear matter under the extreme conditions that are becoming accessible with the advent of high-quality heavy-ion beams. The discovery of the fission isomers and their interpretation in terms of a second minimum in the potential energy surface at very large deformations is a striking reminder of the rich structural effects that may arise from the interplay of single-particle and collective motion in the many-dimensional space of the nuclear deformations.

In yet another direction, one faces the challenge of exploring the properties of the compound nucleus in terms of the couplings between the elementary modes observed in the low energy excitation spectrum. One can envisage the development of a new branch of statistical physics concerned with the study of correlations in the structure of individual quantum states under conditions where many coupled degrees of freedom are involved and with the analysis of the concept of randomness under such conditions.

Collective Modes Involving Nucleon Transfer

While some of the collective modes, such as shape oscillations, can be described in terms of a classical picture, there are other modes associated with the more specifically quantal features of the nucleon, such as spin, isospin, and nucleon number. In recent years, there has been considerable progress in the study of collective motion with quanta carrying nucleon number. The phenomenon is related to the nuclear pairing effect, which was recognized as a systematic feature in nuclear properties at a very early stage of nuclear physics.

The striking difference in the binding energies of nuclei with even and odd numbers of nucleons finds a dramatic expression in the different fissionability properties of the even and odd isotopes of uranium. But only gradually the collective significance of the pair correlation effect and its far-reaching consequences for many nuclear properties were recognized. The correlation effect is intimately related to that of the electrons in a superconductor.

A powerful tool for the study of the nuclear pair correlations has become available in the two-nucleon transfer reactions, such as the (t,p) process, involving an incident triton (^3H) and an outgoing proton. In these reactions, one observes transitions of a strength much greater than would correspond to the transfer of two nucleons, each into a definite orbit in the nucleus. The enhancement implies that the pair of nucleons is transferred into a highly correlated state, and these pairs can be regarded as elementary entities, as quanta.

In some situations, one can superpose such quanta to form a vibrational spectrum, consisting of a family of states in nuclei with different numbers of neutrons or protons. In this vibrational motion, the quantity that oscillates is the amplitude of a field, the pair field, that creates two nucleons. These oscillations occur not in the usual space but in other dimensions, referred to as gauge space. This space was invented as a mathematical abstraction to express the conservation and quantization of nucleon number, or more generally of baryon number, which is identified with the angular momentum operator in gauge space. Usually, however, the nucleon number operator is assigned a rather passive role, as an overall constant of the motion, a superselection rule, that divides the phenomena into sharply separated sets, each with a definite value of nucleon number.

In the nuclear pair correlation effects, however, we have examples of phenomena that relate states with different nucleon number and that therefore involve operators, such as the orientation of the pair field in gauge space, that are complementary to the nucleon number. In the study of these nuclear phenomena, one experiences the physical significance of such operators and the reality of the new dimensions in a forceful manner.

In the development of quantal physics, the scope of symmetry concepts has greatly expanded, but also the significance of symmetry breaking has come more and more into focus. In the study of the nuclear collective modes, these themes have played a prominent role and have continued to reveal interesting new aspects, some of which may be illustrated by considering the role of isospin symmetry in the nuclear excitation spectrum.

Charge Symmetry

Crucial evidence for charge symmetry of the nuclear forces came from the original studies of mirror nuclei by Fowler, Delsasso, and Lauritsen as far back as 1936, and striking support for the more comprehensive charge independence of the forces has been provided by the impressive evidence on the occurrence of isobaric multiplets in the spectra of light nuclei, in the digestion of which the review articles emanating from the Kellogg Laboratory have played an important role.

It was generally assumed that, in heavy nuclei, the strong Coulomb forces would completely destroy the isobaric symmetry. The discovery of quite sharply defined isobaric analog states in all nuclei revealed, however, that the symmetry-breaking power of the Coulomb forces had been vastly overrated. The Coulomb interaction gives rise to major energy separations between members of a multiplet, but the relatively small variation of the Coulomb potential inside the nucleus is rather ineffective in mixing the symmetry of the wave function. Moreover, the strong tendency of the nuclear forces to favor states of low isospin acts to preserve the symmetry. One can view the isospin impurity in the nuclear wave function as a polarization effect produced by the Coulomb potential, and the relevant polarizability of the nucleus can be expressed in terms of the virtual excitation of collective monopole modes of isovector symmetry. Estimates indicate that, in the nuclear ground states, the isospin impurity does not exceed a small fraction of a percent, even in heavy nuclei.

If we consider an excitation of the nucleus, we not only can assign a total isospin quantum number, T, to the excited state, but can also talk about the isospin τ carried by the excitation. For example, if T equals the isospin T_0 of the ground state, the excitation may be isoscalar ($\tau = 0$), or isovector ($\tau = 1$), or even of higher multipolarity in isospace. However, because of the neutron excess, the generalized vacuum state for the elementary excitations (the nuclear ground state) may be highly anisotropic in isospace. The quantum number τ is therefore not in general conserved, even in the absence of Coulomb forces, corresponding to the fact that the neutrons and protons that participate in the excitation occupy different orbits. Thus, for large neutron excess, the low flying particle excitations completely violate τ symmetry. Collective modes of excitation involving neutrons and protons in different orbits also completely violate τ symmetry at the microscopic level, but the symmetry may reappear at the macroscopic level, where we consider the collective properties of the modes such as the average long wavelength density variations and the associated deformations of the average potential. In fact, it is found that the collective modes tend to preserve such a macroscopic τ symmetry, even in heavy nuclei with large neutron excess. For example, in the shape vibrations, the oscillating potential is predominantly isoscalar, while the dipole mode excited by photoabsorption is isovector to the accuracy of the available experimental data. Considerable interest attaches to the study of the small components of opposite symmetry, which can be determined, for example, by comparing the excitation of the modes by projectiles that interact differently with isoscalar and isovector fields [inelastic scattering of α particles, deuterons or individual nucleons, charge-exchange processes, such as (p,n), and other reactions].

For the isovector modes, one can go a step further and consider the relationship between the modes with T equal to $T_0 - 1$, T_0, and $T_0 + 1$ formed by the excitation of a $\tau = 1$ quantum. In the case of weak coupling between T_0 and τ, there is a simple relation between the modes, and the relative amplitudes follow from considerations of symmetry. The triplet of modes corresponds to different orientations of the isospin τ with respect to the orientation of the nuclear vacuum state in isospace and, in a nucleus with large neutron excess, the modes may have quite different properties. The weak coupling relations can then be completely violated, and it may even happen that the mode with $T_0 + 1$ is missing and reappears as a second, lower mode with $T_0 - 1$.

Occurrence of Rotational Motion

New aspects of symmetry and symmetry-breaking appear in the study of rotational motion in nuclei. The problem of whether nuclei possess rotational spectra became an issue already in the very early days of nuclear spectroscopy. Some quantal systems, such as molecules, were known to have rotational spectra, while other systems, such as atoms, do not rotate collectively.

The earliest available data on nuclear spectra, as obtained for example from the fine structure of α-decay, appeared to provide evidence against the occurrence of low-lying rotational excitations. But the discussion was hampered by the expectation that rotational motion would either be a property of all nuclei or be generally excluded, and by the assumption that the moment of inertia would have the classical value as for rigid rotation.

The establishment of the nuclear shell structure and the recognition, which came almost simultaneously, that many nuclei have equilibrium shapes deviating from spherical symmetry, created a new basis for the discussion of rotational motion in the nucleus. It was evident that the existence of a nonspherical shape implied collective rotational degrees of freedom, but one was faced with the need for a generalized treatment of rotations applicable to quantal systems that do not have a rigid or semirigid structure, such as molecules.

The existence of a deformation, taken in the general sense of an element of anisotropy in the structure of the system, may be recognized as the hallmark of quantal systems that exhibit rotational spectra. Indeed, such an element of anisotropy is required to make it possible to specify the orientation of the system. This definition of a deformation includes the lattice-like structure in molecules and rotating pieces of solid matter; a classical physical object that may seem perfectly spherical is in fact highly anisotropic, on account of the atomic constitution of matter.

The occurrence of rotational degrees of freedom may thus be said to originate in a breaking of rotational invariance. In a similar manner, the translational degrees of freedom are based upon the existence of a localized structure. However, while the different states of translational motion of a given object are related by Lorentz invariance, there is no similar invariance applying to coordinate frames rotating with respect to the matter distribution of the universe. The Coriolis and centrifugal forces that act in such coordinate frames perturb the structure of a rotating object.

In a quantal system, already the frequency of the lowest rotational excitations may be so large that the Coriolis and centrifugal forces affect the structure in a major way. The adiabatic condition, which requires these perturbations to be small, thus provides an alternative way of expressing the criterion for the occurrence of rotational spectra. It is intimately connected with the existence of an equilibrium deformation that is large compared with the zero-point fluctuations in the shape parameters.

Rotational Degrees of Freedom

The extent to which the deformation is symmetry-breaking determines the rotational degrees of freedom. A complete breaking of the rotational invariance, in the sense that the collective deformation permits a unique specification of the orientation of the system, leads to the full degrees of freedom of rotational motion in three-dimensional space, as for the asymmetric rotor, with rotational bands containing $(2I + 1)$ levels for each set of values of the total angular momentum quantum number I and its component M. A reduction in the rotational degrees of freedom occurs if the deformation preserves invariance with respect to a subgroup of rotations, including axial symmetry or a group of finite rotations or both. These operations are then part of the intrinsic degrees of freedom, and the rotational degrees of freedom are correspondingly constrained. Thus, for systems with axial symmetry, which include the well-established nuclear deformations, the bands form trajectories of states with only a single level for each IM.

The concept of rotation has gained new perspective from the recognition that the transfer of a pair of nucleons to superfluid nuclei can be viewed as rotational transitions in gauge space. The superfluid state of matter, as encountered in liquid helium, superconductors, and the majority of nuclei, is characterized by a stable deformation in gauge space; and the associated rotational motion involves a family of states with different numbers of particles, such as, for example, the ground states of nuclei with even numbers of neutrons and protons. In superconductors, the Josephson junction can be viewed in terms of rotational motion of this type involving two coupled rotors, forced to rotate with respect to each other with a frequency determined by the difference in binding energy associated with the transfer of electrons, that is, by the electrostatic potential across the junction.

One can envisage a rich variety of generalized rotational spectra associated with deformations in larger dimensions obtained by combining different spaces including isospace, gauge spaces, and orbital space. The resulting rotational band structure may involve comprehensive families of states labeled by the different quantum numbers of the internally broken symmetries, and there may be relations between quantum numbers referring to different spaces, if the deformation connects these spaces by retaining invariance with respect to combinations of different symmetry operations.

The Regge trajectories that play such a prominent role in the current study of the structure of hadrons have features reminiscent of rotational spectra, but as yet there appears to be no definite evidence concerning the degrees of freedom involved or the nature of the deformation that would define an orientation in the intrinsic structure of a hadron.

In the analysis of rotational spectra, one can develop a general phenomenological description of how the various matrix elements depend on the rotational quantum numbers, on the basis of the symmetry of the deformation and an expansion in powers of the angular momentum. A very extensive body of data on nuclear rotational spectra, to which the Norman Bridge Laboratory at the California Institute of Technology has yielded important contributions, has provided detailed tests of such a description and has thus established a firm basis for a deeper-going analysis of the dynamics of the rotational motion. Many of the observed relations can be interpreted in terms of the Coriolis coupling acting on the individual nucleons in the rotating nucleus, in a manner similar to the particle-vibration coupling described above. However, there are also indications that we have yet much to learn about the basic coupling between rotational and intrinsic motion.

The spectra of the light nuclei—and here the Kellogg Laboratory continues to be a main source of evidence—offer the opportunity to study the emergence of collective rotational motion in a system with few degrees of freedom. In such a situation, the problem of identifying the spurious particle-degrees of freedom—those out of which the rotational motion is formed—becomes especially acute.

The behavior of the rotational bands for large values of the angular momentum constitutes a frontier of vigorous activity. The current developments involve the problem of the limit of convergence of the power series expansions in the rotational frequency or angular momentum and of the many types of discontinuities that may occur in the bands for large values of the angular momentum when the rotational forces distort the nuclear structure in a major way. Some of these discontinuities may resemble phase transitions in macroscopic systems, and, in the nucleus, it may become possible to follow such transitions in terms of the properties of the individual quantum states. For the very large values of the angular momentum that can be transferred to a nucleus in an impact with a heavy ion, we encounter nuclear matter in a hitherto unknown form.

Epilogue

The development of nuclear physics in the past decades has been characterized by the great richness of the phenomena that have been encountered, and I have tried to describe a few of the concepts that have been involved in the attempt to understand these phenomena. Looking ahead, one can already see great new areas that may be explored by means of the new tools that are becoming available, and one can look forward to the inspiration which this expansion of our horizon will provide for the refinement and further development of concepts for the description of quantal phenomena (*3*).

Notes

1. For an account of C. C. Lauritsen's scientific work, see the biographical memoirs by W. A. Fowler in the *American Philosophical Society Yearbook* (1969), p. 131. The early development of nuclear research at California Institute of Technology is also vividly described by T. Lauritsen in the special issue of *Eng. Sci.* **32**, No. 9 (June 1969) published by the California Institute of Technology.
2. The development has been the result of a lively interplay of evidence and ideas coming from so many different sources that it would fall outside the scope of this presentation to attempt to mention the individual contributions. A more detailed account, with inclusion of references to the main steps in the development, has been prepared in another context, in collaboration with Ben R. Mottelson.
3. The lecture concluded by a comment on the proposed establishment of an International Science Foundation. The idea of channeling part of the resources available for scientific research through such an organization arises naturally in view of the international character of science. An International Science Foundation will be able to base its functioning on the existence of an international community of scientists who by and large share the same standards and goals for scientific research and will be in a position to evaluate research projects in an international perspective. It will be a primary task for the Foundation to help ensure that scientific talent and initiative, wherever in the world they appear, can contribute to the progress of science and, in this spirit, the Foundation might be of considerable value in promoting science in the developing countries. Plans for the establishment of an International Science Foundation were discussed at a meeting in Stockholm in July 1970, sponsored by the Royal Swedish Academy of Engineering Sciences, the Royal Swedish Academy of Sciences, Unesco, and the American Academy of Arts and Sciences, and are at present being studied by an interim committee set up at this meeting.

Marihuana in Man: Three Years Later

Mental and physical effects have been confirmed, but their causes and implications remain uncertain.

Leo E. Hollister

Few drugs have been used so long and by so many people as that derived from *Cannabis sativa*. Until the spectacular resurgence of use of marihuana by Western society during the past decade, scientific interest had been largely dormant. During the past 3 years, in particular, this interest has been rekindled, in part because of the social importance of the drug, in part because of the possibility of doing more precise studies, and in relatively small part because research funds became available. After a slow start while legal hobbles were being ameliorated, the rate of increase in scientific inquiry into the effects of marihuana has risen in almost an exponential manner. It may soon be impossible to keep current with the rapidly growing literature. It seems propitious, therefore, to assess accomplishments in regard to marihuana's effects in man during the past 3 years, comparing these with those of the past, as well as taking inventory of what still needs to be done.

Marihuana in Man: Past

Customarily, those of us engaged in research with marihuana deplore the ignorance that existed about the drug before we came along. Much of the work of the past, to be sure, was based on descriptions of effects by individuals exposed to uncertain doses of the drug. Still, much of the newer work with marihuana involves the rediscovery of phenomena known for a long time, sometimes camouflaged by coining new names for old phenomena or by elegantly proving the obvious. Looked at in its historical context, the present flurry of experimentation may have contributed less that is really new than we like to believe.

Baudelaire, an avid member of the hashish cult fashionable in Paris during the middle of the 19th century, provided an elegant description of its clinical effects. He may either have used more than a little poetic license or have taken enormous doses of the drug (*1*). If we brush aside much of his rhetoric, we find that he clearly described such phenomena as euphoria, uncontrollable

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