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NUCLEI
Theory

Phase Transitions and Shape Coexistence in Atomic Nuclei

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Abstract—Examples of phase transitions occurring in atomic nuclei in response to an increase in the excitation energy and angular momenta and in response to a change in the number of nucleons are considered. The possibility of describing such transitions within collective models based on a Hamiltonian that depends on a relatively small number of dynamical variables is demonstrated.

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1. INTRODUCTION

Heavy atomic nuclei are systems that involve an enormous number of degrees of freedom. At relatively low energies, however, their properties may be described in terms of a Hamiltonian that depends on a relatively small number of dynamical variables. For example, a quadrupole mode is among the most important dynamical variables that determine the properties of nuclei. Of course, the equations relating these five quadrupole degrees of freedom to the coordinates that describe the motion of individual nucleons are very complicated, but, within a phenomenological treatment, the Hamiltonian involves only dynamical variables. Such a Hamiltonian describes those excited states of nuclei that are associated with quadrupole shape vibrations with respect to the equilibrium shape and the effect of these states on the motion of nucleons.

Collective variables underlie the concept of an equilibrium shape of atomic nuclei—first of all, the ground-state equilibrium shape of the nucleus. Specifically, the concepts of spherical and deformed nuclei, as well as of nuclei of transitional shape intermediate between the spherical and deformed shapes, arose within collective models. Investigation of the nuclear structure showed that the ground-state shape of a nucleus depends on its proton–neutron content and changes with the numbers of protons and neutrons in nuclei. This brought about the concept of phase transitions [1, 2] from spherical to deformed nuclei in response to a change in the number of nucleons. These are transitions from a higher to a lower symmetry of the nuclear shape but, of course, are not phase transitions well known in thermodynamics and caused by a change in temperature and pressure. Because of a finite number of nucleons in nuclei, these transitions from one nuclear shape to another are smeared, even though sharp changes in the nuclear shape are observed upon an insignificant change in the number of nucleons.

In considering stable nuclei, not only were phase transitions observed upon a change in the number of nucleons, but they were also caused by a change in the angular momentum of a nucleus. In recent years, the interest of nuclear physicists shifted toward studying nuclei lying far from the stability region. These are nuclei in which states corresponding to drastically different nuclear shapes were found to exist at different excitation energies. This led to formulating the concept of shape coexistence.

A self-consistent field formed as the result of consistent motion of a large number of intranuclear nucleons is a basic feature of atomic nuclei that distinguishes them from many other microscopic systems. A shell structure is a characteristic feature of the self-consistent nuclear field. Investigations of the structure of atomic nuclei began from attempts at explaining magic numbers of protons and neutrons—that is, such numbers at which the respective nucleus is the most stable. The answer was found to be determined by the shell structure of nuclei and by the energy gap separating the shells. It also turned out that all magic nuclei are spherical.

The situation began to change when there appeared the possibility of experimentally studying nuclei remote from the region of stable nuclei. It turned

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