

Possible existence in transition nuclei of long-lived high-lying states with a nonzero spin: Dynamic nonaxial isomers

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A new branch of vibrational-rotational states has been discovered at energies of several MeV. This branch begins at a certain angular momentum I determined by the adiabaticity of the vibrations and the rotations.

In an effort to describe the quadrupole-octupole excitations of a nuclear surface, with allowance for the interaction of these excitations through rotations around the symmetry axis, we have proposed a method²⁻⁴ which is based on a self-consistent analysis of the interacting oscillations and which pursues the classical approach of Bohr.¹ This approach rests on the fact that the interaction potential of the oscillations is determined by moments of inertia, which are determined in turn by a set of vibration amplitudes. It is thus reasonable to suggest that the potential is a rather smooth function of each of the vibrational variables. The method of self-consistent vibrations (phonons) which has been proposed yields a very good description of the vibrational-rotational spectra of deformed nuclei.

Initially, only so-called hard nuclei were considered, and the following conditions were used:

$$|(a_{\lambda\mu} - \bar{a}_{\lambda\mu}) / \beta_0| \ll 1 \quad (1)$$

($a_{\lambda\mu}$ are vibrational variables, $\bar{a}_{\lambda\mu}$ are their expectation values, and β_0 is the parameter of the static deformation). It was subsequently found possible to generalize the method of self-consistent phonons in such a way that it can be applied to not only hard nuclei but also soft nuclei, in which the dynamic deformation is comparable to the static deformation, and conditions (1) do not hold. The equilibrium deformation $\bar{\beta}_{\lambda\mu}$ is determined from the condition for a minimum of the total vibrational-rotational energy. This approach dates back to the well-known paper by Davydov and Chaban.⁵

Since all the moments of inertia depend strongly on the vibration amplitudes, the interaction between vibrations occurs through rotations around all the axes. The structure of the interaction accordingly becomes more complicated, and it includes all vibration modes whose stiffnesses are determined by equations of the type

$$c_{\lambda\mu}^{(p)} = c_{\lambda\mu} + F_{\lambda\mu}(\{c_{\lambda'\mu'}^{(p)}, \tilde{\beta}_{\lambda'\mu'}\}), \quad (2)$$

where the functions $F_{\lambda\mu}$ describe the interaction of the vibrations and depend on the set of quantum numbers, $I, K, \{n_{\lambda\mu}\}$ (I is the angular momentum, K is its projection onto the symmetry axis of the nucleus, and $n_{\lambda\mu}$ is the number of quanta of excitations of the type $\lambda\mu$) of the given collective state. Along with the equations

$$\tilde{\beta}_{\lambda\mu} = \beta_{\lambda\mu} + G_{\lambda\mu}(\{c_{\lambda'\mu'}^{(p)}, \tilde{\beta}_{\lambda'\mu'}\}), \quad (3)$$

which follow from the requirement that the total energy be minimized, Eqs. (2) form a closed system of nonlinear algebraic equations for a self-consistent determination of the parameters of the vibrational wave functions in the given collective state of the nucleus. These parameters directly determine the moments of inertia, the excitation energy, and the probabilities for transitions between collective states. In this approach, the moments of inertia may change significantly in a transition from one level to another in a given rotational band, so that there would be a substantial change in the structure of the rotational spectra. Comparison of the calculated results with the experimental data leads to the conclusion that the approach of this paper is legitimate for describing both soft and hard nuclei up to rather large angular momenta. For example, the quality of the description of the ground band of the nucleus $^{238}\text{U}(|E_{\text{expt}} - E_{\text{theo}}|/E_{\text{expt}} \lesssim 1\%$ up to an angular momentum $I = 24$ inclusively) is significantly better than that of the phenomenological model of a variable moment of inertia,⁶ and it is at least no worse than that of a three-parameter phenomenological approximation proposed recently⁷ (a refinement of the model of a variable moment of inertia). The advantage of our model is that we use only a single parameter, determined from the position of the 2^+ level, to describe the same ground band, while the other parameters of the Bohr Hamiltonian are fixed by the positions of the leading levels of the other bands.

The important nonlinearity of Eqs. (2) and (3) for the new equilibrium positions $\tilde{\beta}_{\lambda\mu}$ and the stiffnesses $c_{\lambda\mu}^{(p)}$ makes it important to examine the uniqueness of the solution discussed above (uniqueness for a given set of quantum numbers $I, K, \{n_{\lambda\mu}\}$). That solution is the "free" solution slightly modified by the interaction between vibrations:

$$c_{\lambda\mu}^{(p)} = c_{\lambda\mu}, \quad \tilde{\beta}_{\lambda\mu} = \beta_{\lambda\mu}. \quad (4)$$

It turns out that for angular momenta $I \gtrsim \omega J_0$ (ω is the minimum energy of the vibration quantum, and J_0 is the static moment of inertia) the interaction of the vibrations is strong enough to cause a qualitative change in the structure of the system and to give rise to additional solutions characterized by a substantially nonaxial deformation, $\tilde{\beta}_{22} > \tilde{\beta}_{20}$.

Since the parameters of the dynamic deformation, $\tilde{\beta}_{20}$ and $\tilde{\beta}_{22}$, are different from those for "normal" and "anomalous" states, the transitions between these states are also weakened.

The parameter $\omega J_0 \sim 3\omega/E_{2^+g}$, a measure of the stiffness of the nucleus, takes on its lowest values in the transition nuclei, and among these nuclei we can probably expect some additional states. As an example we consider one of these nuclei, ^{194}Pt , for which we have $\omega J_0 \approx 6$. The anomalous state arises at a minimum angular momentum $I = 6$ and has an energy $E = 4895$ keV and the parameter values

$$\tilde{\beta}_{20}/\beta_0 = 0.56, \quad \tilde{\beta}_{22}/\beta_0 = 1.55, \quad \omega_{20}^{(p)} J_0 = 25.4, \quad \omega_{22}^{(p)} J_0 = 13.04, \quad (5)$$

while the normal 6^+ state corresponds to an energy $E = 1482$ keV ($E_{\text{expt}} = 1412$ keV) and the parameter values

$$\tilde{\beta}_{20}/\beta_0 = 1.20, \quad \tilde{\beta}_{22}/\beta_0 = -0.07, \quad \omega_{20}^{(p)} J_0 = 18.1, \quad \omega_{22}^{(p)} J_0 = 5.3 \quad (6)$$

(the corresponding parameters of the Hamiltonian are $\beta_{20}/\beta_0 = 1$, $\beta_{22}/\beta_0 = 0$, $\omega_{20} J_0 = 15.6$, $\omega_{22} J_0 = 5.8$). The ratio of the reduced probabilities for $E2$ transitions from these 6^+ states to the 4^+ level ($E = 823$ keV, $E_{\text{expt}} = 811$ keV) is 0.8×10^{-3} , so that the total probabilities for these transitions are comparable:

$$T(E2, 6^+ (4892) \rightarrow 4^+) = 7.2 T(E2, 6^+ (1482) \rightarrow 4^+) \simeq 1.1 \times 10^{15} \text{ s}^{-1} \quad (7)$$

The states that have been found are thus long-lived and may be interpreted as nonaxial isomers. Since the possible existence of additional solutions stems from the interaction of vibrations through rotations, the isomerism is dynamic in nature.

The experimental detection and study of such states would be interesting in itself and would also serve as a test of the predictions of the model. We do not rule out the possibility that the anomalies in the spectra of light isotopes of mercury which have recently been discussed widely (see Refs. 8 and 9 and the bibliographies there) are closely related to the additional branch of solutions with the quantum numbers of the ground band discussed above.

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