New Class of Low-Lying Collective Modes in Nuclei

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A new class of low-lying collective modes in nuclei is discussed and experiments to detect these modes are suggested.

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Recently, LoIudice and Palumbo,[1] expanding on some previous ideas of Suzuki and Rowe,[2] and Dieperink and myself,[3] elaborating earlier concepts based on the interacting boson model,[4] have suggested that a low-lying collective magnetic, 1^+, mode should exist in deformed nuclei. This mode can be viewed classically as an oscillation of the proton versus the neutron deformation. In one interpretation,[1] the entire nucleus is assumed to participate in the collective motion, leading to larger estimates of excitation energies (5–10 MeV) and transition probabilities $[B(M1)\uparrow \approx 10\mu_N^2]$, while in the other,[2] only valence particles are considered, leading to smaller estimates of excitation energies (≈ 3 MeV) and transition probabilities $[B(M1)\uparrow \approx 2\mu_N^2]$. The mode has now been discovered[5] in several deformed nuclei, with properties somewhat closer to those predicted in Ref. 3, and has become the subject of several experimental[6] and theoretical investigations.[7] The purpose of this Letter is to point out that this collective 1^+ mode is not the only one to be expected in the energy range 2–3 MeV, but that in fact *it is the prototype of an entire class of states which occur at that energy and have collective properties.* In particular, here I shall discuss a collective 2^+ mode expected in *spherical* nuclei at 2–3 MeV excitation energy and with $B(E2)\uparrow \approx 3$ single particle units (s.p.u.). It should be remarked that, although in Ref. 1 a 2^+ state with $B(E2)\uparrow \approx 3$ s.p.u. is discussed, this is not the same state as described here, since Ref. 1 deals with *deformed* nuclei while the state described below occurs in *spherical* nuclei. Indeed, as mentioned above, it is the purpose of the present note to stress the larger validity of this class of collective states which extends far beyond the case of deformed nuclei.

I shall base my discussion on the interacting boson model, which, being built on the microscopic shell model, contains explicitly proton and neutron degrees of freedom.[4] Collective low-lying states in this model are obtained by coupling proton (π) and neutron (ν) pairs, treated as bosons. It is clear then that there are several ways in which these degrees of freedom can be coupled, leading to several classes of collective states. In order to keep the discussion transparent, it is convenient to assign to proton and neutron bosons a two-valued variable, called F spin.[4] This variable is not precisely isospin but it is related to it, as discussed by Elliott.[8] By coupling proton and neutron degrees of freedom in a nucleus with N_π proton pairs and N_ν neutron pairs, one obtains then collective states characterized by F spin values ranging from $F_{\max} = \frac{1}{2}|N_\pi + N_\nu|$ to $F_{\min} = \frac{1}{2}|N_\pi - N_\nu|$. The properties of the proton-neutron interaction are such that states with maximum F spin (totally symmetric states) are lowest in energy. In order of increasing excitation energy, they are followed by states with $F = F_{\max} - 1$, $F = F_{\max} - 2, \ldots$. Up to one year ago, experimental information on low-lying collective states was confined to states of maximum F spin, but the recent discovery of the 1^+ mode indicates that these states may be experimentally accessible. The excitation of states with $F = F_{\max} - 1$ starting from the ground state requires $\Delta F = 1$. Thus, these states could also be called F-vector excitations. In the remaining part of this Letter, I shall discuss the structure of F-vector excitations in nuclei.

(a) *Vibrational nuclei.*–The states of the F-spin multiplets $F = N/2$ and $F = N/2 - 1$ which lie lowest in energy are shown in Fig. 1(a). Here $N = N_\pi + N_\nu$. An ideal tool to investigate F-vector excitations is provided by inelastic electron scattering. I will therefore be mostly concerned here with states that can be reached from the ground state in (e,e') experiments. Using the interacting boson model, one can show that, in the limit of an exact F-spin symmetry and of purely vibrational motion [U(5) limit], one has

$$B(M1;0_s^+ \to 1_a^+) = 0,$$
$$B(E2;0_s^+ \to 2_a^+) = \left(\frac{N_\pi N_\nu}{N_\pi + N_\nu}\right)(e_\pi - e_\nu)^2, \qquad (1)$$

where e_π, e_ν are the boson effective charges, 0_s^+

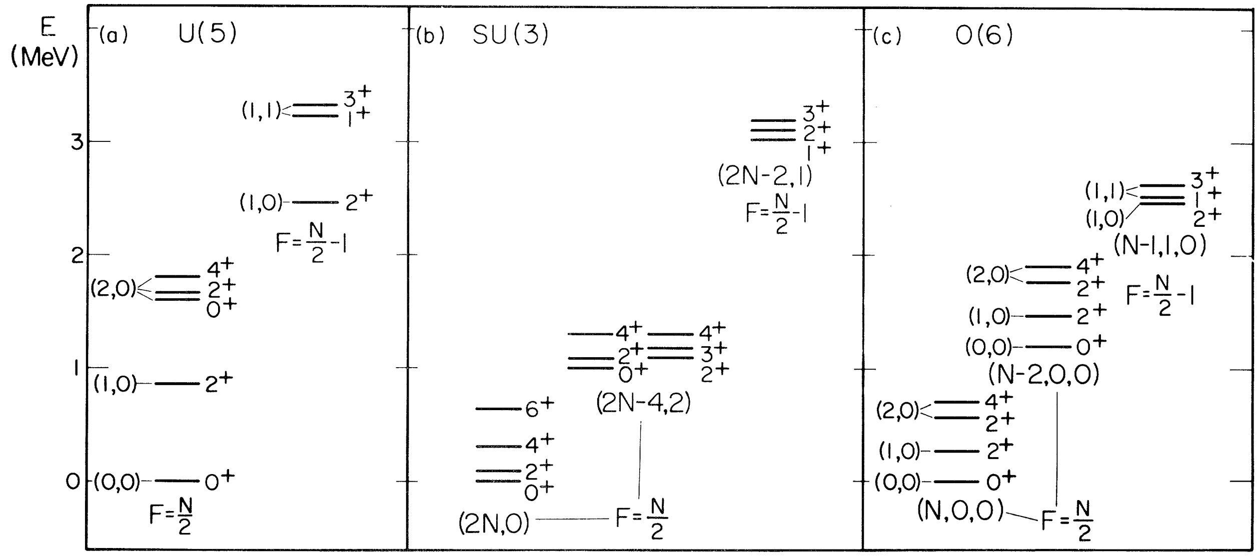

FIG. 1. Structure of F-vector excitations in (a) vibrational nuclei, (b) rotational nuclei with axial symmetry, and (c) rotational nuclei with γ instability. The numbers in parentheses label the representations of the appropriate groups and are discussed in Refs. 9, 12, and 13.

denotes the ground state, and $1_a^+, 2_a^+$ the states of the multiplet $F=N/2-1$ shown in Fig. 1(a). Thus, in vibrational nuclei, the $M1$ mode cannot be excited, while the $E2$ mode can be excited. In order to understand the magnitude of the excitation, it is convenient to compare it with the $B(E2)$ value for excitation of the first 2^+ state (denoted by 2_s^+) given by

$$B(E2;0_s^+ \to 2_s^+) = \left(\frac{1}{N_\pi + N_\nu}\right)(e_\pi N_\pi + e_\nu N_\nu)^2. \quad (2)$$

For example, when $N_\pi = N_\nu$, Eqs. (1) and (2) give

$$\frac{B(E2;0_s^+ \to 2_a^+)}{B(E2;0_s^+ \to 2_s^+)} = \left(\frac{e_\pi - e_\nu}{e_\pi + e_\nu}\right)^2. \quad (3)$$

For $e_\pi \simeq 2e_\nu$, the ratio in Eq. (3) is $\simeq \frac{1}{9}$. Typically, $B(E2;0_s^+ \to 2_s^+) \simeq 30$ s.p.u., and thus one expects $B(E2;0_s^+ \to 2_a^+) \simeq 3$ s.p.u. This value is large enough that the peak corresponding to the inelastic excitation of the state should stand out of the background due to other (noncollective) $E2$ excitations, expected to be of the order of $\simeq 0.3$ s.p.u. It is clear from Eq. (1) that experimental detection of the 2_a^+ state would be of utmost importance for our understanding of collective properties of nuclei, since it would measure directly the difference between proton and neutron boson effective charges. Furthermore, if, in addition, one would measure transition densities, a direct comparison of the transition densities leading to the states 2_a^+ and 2_s^+ would provide information on the proton and neutron densities, a problem whose solution has remained elusive up to now.

In order to look for the state 2_a^+, one would also need an estimate of its excitation energy. A straightforward application of the interacting boson model gives

$$E(2_a^+) = 2aN + \epsilon + 5\alpha + 4\beta + 6\gamma \simeq 2aN + \epsilon, \quad (4)$$

where $\epsilon, \alpha, \beta, \gamma$ are parameters[9] that can be extracted from the experimental spectrum of states with $F=N/2$, and $2a$, the strength of the Majorana interaction, can be estimated from the measurements of Ref. 5. Using $2a \simeq 200$ keV, one has $E(2_a^+) \simeq 2.5$ MeV. This value should be regarded as a rough estimate. A more careful evaluation, based on microscopic theories,[10,11] gives values ranging from $\simeq 1.7$ to $\simeq 2.7$ MeV. Inspection of the available data suggests the state at 1.934 MeV in ^{110}Pd as a possible candidate. Other candidates could be looked for in the remaining Pd isotopes or in the neighboring Cd, Te, and Xe isotopes, all of which have a vibrational-like structure.

(b) *Deformed nuclei with axially symmetric deformation.*—This case, the SU(3) limit,[12] has been discussed previously.[3,5] I only mention here the structure of the spectrum, Fig. 1(b), and the fact that, contrary to case (a), there are now large $M1$ matrix elements connecting the states 0_s^+ and

1_a^+. The corresponding $B(M1)$ has been estimated by Dieperink to be[3,5]

$$B(M1;0_s^+ \to 1_a^+) = \left(\frac{3}{4\pi}\right)\left(\frac{4N_\pi N_\nu}{N_\pi + N_\nu}\right)(g_\pi - g_\nu)^2, \quad (5)$$

where g_π, g_ν are the boson g factors ($g_\pi \simeq 1$, $g_\nu \simeq 0$).

(c) *Deformed nuclei with γ-unstable deformation.* —This case is the O(6) limit.[13] The structure of the spectrum of states is shown in Fig. 1(c). This case is intermediate between (a) and (b) in that both $M1$ and $E2$ excitations are expected to occur with sizable strengths. For lack of space, it is not possible to give here details of the corresponding excitation probabilities, but these can be calculated in a straightforward way with the interacting boson model. A good candidate for experimental study here could be ^{196}Pt. The excitation energy of the state 2_a^+ in this nucleus is again estimated to be $\simeq 2$ MeV.

In conclusion, I have pointed out in this Letter that an entirely new class of low-lying collective modes is expected to occur in nuclei in the range of excitation energy $\simeq 2$–3 MeV. In addition, I have shown by way of a few, selected, examples that these modes (F-vector excitations) have properties that vary from nucleus to nucleus, depending on the nature of the underlying collective motion (vibrational, rotational,...) Further experimental exploration of these new modes is of utmost importance in understanding the role played by protons and neutrons in generating collective states in nuclei. A detailed account of the properties of this class of states, within the framework of the interacting boson model, is being prepared by van Isacker *et al.*[14]

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