ISOVECTOR MULTIPHONON EXCITATIONS IN NEAR SPHERICAL NUCLEI

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The lowest isoscalar and isovector quadrupole and octupole excitations in near spherical nuclei are studied within the the proton–neutron version of the interacting boson model including quadrupole and octupole bosons (sd–IBM-2). The main decay modes of these states in near spherical nuclei are discussed.

1 Introduction

The low-lying collective $J^\pi = 2^+$ and $3^-$ excitations in near spherical nuclei can be considered as quadrupole and octupole vibrations, which represent the most important vibrational degrees of freedom at low energies. The bosonic phonon concept suggests the occurrence of multiphonon states at excitation energies of $n$ times the one-phonon energy. A two-quadrupole-phonon $(2^+ \otimes 2^+)$ triplet of states $(J^\pi = 0^+, 2^+, 4^+)$ is usually known in near spherical nuclei. Multi-quadrupole-phonon states, $(3^- \otimes 3^-)$ double-octupole states, and double giant dipole resonances are actively debated in the literature.

Another interesting example of two-phonon excitations is the $(2^+ \otimes 3^-)$ quadrupole-octupole coupled quintuplet $(J^\pi = 1^- - 5^-)$. The two-phonon $1^-$ state has been well investigated in magic and near spherical nuclei, while there are only few examples, where besides the $1^-$ state other multiplet members have been identified experimentally (see e.g. [1] for references). The $(2^+ \otimes 3^-)$-states decay besides collective $E2$ and $E3$ transitions to the $3^-_1$ octupole phonon
state and to the $2^+_1$ quadrupole phonon state, respectively, by relatively strong $E1$ transitions (see the schematic decay pattern in Fig. 1a). This fact was considered as the evidence of quadrupole-octupole collectivity.

All the low-energy one- and two-phonon states mentioned above involve isoscalar phonons. Another class of low-lying collective states, namely the isovector quadrupole excitations in the valence shell, or mixed-symmetry states, has been identified in some nuclei. The fundamental $2^+_n$ state decays by a weakly collective $E2$ transition to the ground state and by a strong $M1$ transition to the isoscalar $2^+_1$ state ($B(M1) \sim 1 \mu^2_N$). In an harmonic phonon coupling scheme one can expect also the existence of mixed-symmetry two-phonon multiplets, that involve at least one excitation of the mixed-symmetry quadrupole phonon (Fig. 1b). Two members of the $(2^+_1 \otimes 2^+_n)$ quintuplet, $J^{\pi} = 1^+$ and $3^+$ states, are already identified in the near spherical nucleus $^{94}$Mo. In this contribution we discuss the variety of possible proton-neutron non-symmetric excitations in the presence of quadrupole and octupole degrees of freedom and their decay properties as predicted by the $sdf$–IBM-2.

2 IBM description of isovector excitations

The $sd$–IBM-2 is the version of the IBM which considers $s$ ($l^\pi = 0^+$), $d$ ($l^\pi = 2^+$) and $f$ ($l^\pi = 3^-$) proton and neutron bosons. A realistic Hamiltonian relevant for the description of near spherical nuclei can have the form

$$\hat{H} = \epsilon_d \hat{n}_d + \epsilon_f \hat{n}_f + \alpha \hat{P}^+ \hat{P} + \beta \hat{L}^2 + \lambda \hat{M}_{13} + \lambda' \hat{M}_6 + \lambda'' \hat{M}_7, \quad (1)$$
where the first four terms provide the spectrum of isoscalar quadrupole and octupole excitations, while the last three terms called Majorana operators determine the excitation energies of proton-neutron non-symmetric states.

In case of no octupole bosons, the model reduces to the standard IBM-2.

The states of Eq. (1) can be classified by the following group reduction chain quantum numbers (see for details).

\[
U_\pi(13) \otimes U_\nu(13) \supset U_{\pi \nu}(13) \supset U_{\pi \nu}(6) \otimes U_{\pi \nu}(7).
\]

\[
[N_\pi] \quad [N_\nu] \quad [N_1, N_2] \quad [n_1, n_2] \quad [m_1, m_2]
\]

The isoscalar excitations (proton–neutron symmetric ones) are described by the totally symmetric irreducible representations of the groups from Eq. (2). For these states the $sdf$-IBM-2 reduces to the $sd$-IBM-1.

The two-rowed representations of the $U_{\pi \nu}(13)$ group $[N-1,1]$ correspond to the simplest proton-neutron mixed-symmetry states. From the reduction $U_{\pi \nu}(13) \supset U_{\pi \nu}(6) \otimes U_{\pi \nu}(7)$, we can distinguish three main types of these states:

1. The $[N-1,1] \supset [N-m-1,1] \otimes [m]$ decomposition corresponds to the usual mixed-symmetry states in the $sd$-space, coupled to $m$ octupole-bosons with a wave function, which is symmetric in the $f$-sector. Examples are all the states provided by the IBM-2, such as the fundamental $2^+_ms$ state and the $1^+_ms$ scissors mode ($m = 0$). The coupling to the octupole bosons give rise to new mixed-symmetry states with negative parity. We denote the lowest-lying mixed-symmetry two-phonon quintuplet with negative parity as $(2^+_ms \otimes 3^+_1)$. These states are generated by the coupling of the lowest $2^+_ms$ state in the $sd$-sector and one symmetric $f$-boson ($m = 1$), and they should show a very characteristic decay pattern. For instance, the $J^m = 1^+_ms$ state (see Fig. 1c) should decay by relatively strong $E1$, strong $M1$, weakly-collective $E2$, and collective $E3$ transitions to the ground and to the $1^+_sc$ states, to the isoscalar $1^-$ two-phonon state, and to the one-phonon $3^-_{ms}$ and $2^+_ms$ states, respectively.

2. The $[N-1,1] \supset [N-m] \otimes [m-1,1]$ reduction describes the mixed-symmetry states in the $f$-sector and are not considered here.

3. Finally, $[N-1,1] \supset [n] \otimes [m]$ states are symmetric separately in the $sd$- and in the $f$-sectors, but coupled in a non-symmetric way within the full $sdf$-space. The simplest example is the $3^-_{ms}$ state ($N-1$ $s$-bosons and $m = 1$ $f$-boson), which is the mixed-symmetry analogue of the symmetric $3^-_{1s}$ state. It should decay by a weakly collective $E3$ transition to the ground state and by a strong $M1$ transition to the $3^-_{sc}$ state. Higher excited mixed-symmetry states of this type can be obtained by replacing some of the $s$-bosons by $d$-bosons along with appropriate angular momentum coupling. We can schematically denote the lowest quintuplet of one $d$-boson states as $(2^+_1 \otimes 3^-_{ms})$. The characteristic
Electromagnetic decay rates of the newly predicted mixed-symmetry states with negative parity can be derived analytically in the dynamical symmetry limits of the $sdf$-IBM-2. For instance the ratio of the quadrupole-octupole collective $E1$ excitation strengths to the $1^{-}_{ms}$ state and to the well known symmetric two-phonon $1^{-}_{1}$ state is predicted in the U(5) limit to be

$$\frac{B(E1; 0^+_1 \rightarrow 1^{-}_{ms})}{B(E1; 0^+_1 \rightarrow 1^{-}_1)} = \frac{N(N-2)(1-\eta^2)N_\pi N_\nu}{(N-1)^2 (N_\pi + \eta N_\nu)^2},$$

where $\eta \equiv e_\nu/e_\pi$ is the ratio of the $E2$ effective boson charges.

### 3 Application to experiment

The non-symmetric one- and two-phonon quadrupole excitations have been observed and studied in a number of near spherical nuclei. Their coupling to the octupole degree of freedom is an unavoidable prediction of the $sdf$-IBM-2. The perhaps most easily observable mixed-symmetry states with negative parity should be the $(2^+_{ms} \otimes 3^-)$ states. Both constituting phonons (isovector quadrupole and isoscalar octupole) are known in some nuclei, i.e. $^{142}$Ce, $^{144}$Nd, $^{94}$Mo, $^{134,136}$Ba. The excitation energy of the new states is expected to be close to the sum energy of the constituting phonons, namely around 3.5–4 MeV.

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