Experimental evidences for low-lying octupole isovector states

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Abstract. An evaluation of data obtained with the \((n, n')\) technique revealed in near spherical nuclei strong M1 components in transitions connecting higher-lying \(3^{-}\) states with the \(3^{-}\) state. The \(\langle 3^{-}|M1|3^{-}\rangle\) matrix elements of these transitions are in the order of 1 \(\mu_N\). In the quadrupole sector strong \(\langle 2^{+}_{ms}|M1|2^{+}_{ms}\rangle\) matrix elements serve as fingerprints for the identification of low-lying \(2^{+}_{ms}\) isovector states, which are commonly referred to as mixed-symmetry states. The ratio of the two matrix elements scales for most candidates to unity indicating similar physics. Additional evidence for the assignment of the \(3^{-}\) states as low-lying octupole isovector states is provided by particle-scattering experiments, e.g. \((e, e')\) or \((p, p')\). The octupole states under investigation exhibit enhanced scattering cross sections. This observation is in accordance with the assignment of a one-phonon nature to these octupole excitations.

1. Introduction

Low-lying isovector states, such as the \(1^+\) Scissors mode in deformed nuclei \([1, 2]\) or the \(2^{+}_{ms}\) state \([3, 4]\) in near spherical nuclei, continue to have impact on the understanding of low-energy nuclear structure physics. The importance of these kind of nuclear excitations is based on the fact, that their observation yields direct experimental information about the strength of the isovector (proton-neutron) part of the nuclear interaction. The existence of isovector states is a feature of the nucleus as a two-component quantum system. From a more general perspective, these class of excitations can be seen as the anti-symmetric coupling of proton and neutron subsystems. Similar excitations have been observed in other two-component quantum systems, as for example quantum dots \([2]\).

Low-lying quadrupole isovector, in the language of the IBA \([5]\) so-called mixed-symmetry, states are well established. Currently, their fine details are subject to experimental and theoretical work. Therefore, nowadays, the theoretical description often uses microscopic models, such as the shell model \([6]\) (e.g. see ref. \([7]\)) or the Quasiparticle-Phonon Model (QPM) \([8]\) (see ref. \([9]\) and references therein). However, the sdf-IBA-2 predicts low-lying isovector excitations for the octupole degree of freedom \([10]\) as well. Within the \(U(1) \otimes U(5) \otimes U(7)\) limit of the spf-IBA-2 the experimental signature of these octupole mixed-symmetry states is a strong M1 transition to the first excited \(3^{-}\) state:

\[
B(M1, 3^{-}_{ms} \rightarrow 3^{-}) = \frac{9}{\pi}(g'_\pi - g'_\nu)^2 \frac{N_\pi N_\nu}{N}. \tag{1}
\]

Thus, the strength of the M1 transition connecting the two \(3^{-}\) states only depends of the proton \((\pi)\) or neutron \((\nu)\) g-factors, \(g'_\rho(\rho = \pi \text{ or } \nu)\), the number of neutron and proton bosons, \(N_\rho\), and
Figure 1. Partial level scheme of $^{94}$Mo: E2 transitions are marked with blue arrows, E1 transitions with green arrows and M1 transitions with dashed, red arrows. The thickness of the arrows is for each multipolarity proportional to the strength of the transition. The numbers give the $B(\pi L, J^x \rightarrow (J^y)')$ strength in units of W.u. (E2) and $\mu^2_N$ (M1). Data are taken from [11].

the total number of bosons, $N = N_\nu + N_\pi$. However, the prediction of the excitation energy, where the isovector-octupole states are expected is vaguely given as above 3.5 MeV.

As long as particle-hole excitations over a shell closure can be excluded, the microscopic structure of octupole excitations is dominated by particle-hole excitations including the unique parity intruder subshell. The latter is a necessary condition for a negative parity excitation. Therefore, in the low-energy regime octupole excitations have, compared to quadrupole states, the advantage that less microscopic configurations are available. This lower density of two-quasiparticle excitations near the Fermi surface results in much simpler wavefunctions. Nuclei, for which the Fermi levels of protons as well as neutrons are situated between the intruding unique-parity subshell and the subshell three units lower in total ($j$) and orbital ($l$) angular momentum, exhibit enhanced effects associated with the octupole degree of freedom [12]. The main signatures for enhanced octupole collectivity are a low-lying first excited $3^{-}_1$ state and a high $B(E3, 0^+_gs \rightarrow 3^{-}_1)$ value. Near spherical nuclei in such mass regions ($Z$ or $N \approx 34, 56, 88, 134$) are favorable cases to search for octupole-isovector excitations.

2. Evaluated data and discussion

An evaluation of data sets obtained in inelastic neutron scattering (INS) experiments [13] revealed for several nuclei near the $N=50$, $Z=50$, and $N=82$ shell closures higher-lying $3^{-}$ states, which decay via strong M1 transitions to the first excited $3^{-}_1$ state.

The INS technique represents one of the most powerful experimental tools for the investigation of the low-energy level scheme of stable nuclei [14]. This spectroscopic complete tool allows for the determination of transition energies, branching ratios, and $\gamma$-ray angular distributions. Consequently, it is possible to deduce level energies, level spins and multipole-mixing ratios. The use of mono-energetic neutrons, as it is successfully done for decades at the University of Kentucky, additionally allows the application of the Doppler-shift attenuation method (DSAM) [15] to determine level lifetimes and, therefore, in combination with the other observables also absolute transition probabilities.

The limitations of INS are given by the maximum angular momentum transfer of six units and by the excitation energy range, from which on the level density becomes too high. The latter results in a lower excitation cross section for the individual states, which results in low $\gamma$-ray yields and in crowded spectra with a large number of overlapping peaks. This drawback led to considerable uncertainties in the data sets discussed in this contribution.

States that were identified by having a strong M1 component in their $3^{-}_i \rightarrow 3^{-}_1$ transition to be a candidate for an isovector octupole excitation are listed in table I of ref. [13]. Uncertainties
in the evaluated data sets, due to the above mentioned reasons, are discussed extensively in the given reference. Two examples of partial level schemes are shown in figures 1 and 2. While for $^{94}$Mo an additional E2 component exhausting 50% of the $B(E2, 2^+_1 \rightarrow 0^+_gs)$ strength indicates a mixing of the octupole isovector excitation with the quadrupole-octupole coupled $3^-$ two-phonon state, the octupole isovector candidate ($3^+_3$ level) in $^{144}$Nd exhibits only a small mixing with the quadrupole-octupole coupled $3^+_1$ state at 2605 keV. However, as later will be discussed, the candidate in $^{92}$Zr given in ref. [13] is not the state at 3039.8 keV.

For the two Cd isotopes, where candidates for isovector octupole excitations were assigned, it should be mentioned, that an assignment of octupole isovector states based on strong M1 transitions is not as trivial as it seems. Recent measurements of the $B(E2, 2^+_1 \rightarrow 0^+_gs)$ strength in light Sn isotopes (e.g. see ref. [17]) provided evidence for proton contributions in the wavefunctions of their $2^+_1$ states. This observed weakening of the Z$\times$50 shell closure allows for the contribution of two-quasiparticle components containing the $g_{7/2}$ subshell in the wavefunction of excited $3^-$ states. The decay of such a $3^-$ state to the first excited $3^-_1$ state with components containing the $g_{9/2}$ subshell in the wavefunctions results in strong spin-flip M1 transitions.

The ratio of the M1 matrix element connecting the $3^-_{1V}$ octupole isovector candidate and the first excited $3^-_1$ state and the M1 matrix element connecting the $2^-_{ms}$ quadrupole mixed symmetry state and the first excited $2^+_1$ state scale for almost all candidates to unity. The comparable strengths of the matrix elements indicate similar physics.

Besides the first evidence provided by the strong M1 components in the $3^-_{1V} \rightarrow 3^-_1$ transitions, an evaluation of data sets obtained in light-particle scattering experiments, such as $(p,p')$ and $(e,e')$, provides additional evidence. These data sets exhibit enhanced cross sections for the direct excitation of the candidates. As the isovector octupole excitations are one-phonon states a relatively high excitation probability can be expected. Two exemplary spectra obtained with the $(p,p')$ reaction measured using 200 MeV protons at iThemba Labs (RSA) are shown in figure 3. Indeed, the excitation probability for the candidate in $^{94}$Mo is, next to the $3^-_1$ symmetric octupole phonon, the only excited $3^-$ state with a noteworthy cross section. The ratio of the maximum scattering cross sections measured in this experiment for the excitation of the first $3^-_1$ state and the candidate for the isovector excitation are presented in table 1. Additionally, the ratio of the $2^-_{ms}$ quadrupole mixed-symmetry state and the first excited $2^+_1$ state is given. Furthermore, the ratios of the excitation probabilities for $^{144}$Nd, as obtained in $(p,p')$, $(d,d')$ [18] and $(e,e')$ experiments [19], are presented. Indeed, the enhanced excitation strength from the ground state indicates an one-phonon nature for the proposed candidates. For $^{92}$Zr the results of the $(p,p')$
Figure 3. Spectra of $^{92}$Zr and $^{94}$Mo as measured in the $(p, p')$ reaction using 200 MeV protons at iThemba labs (RSA). Figure is taken from [20].

measurement qualify a state at 3450 keV as isovector octupole excitation, not as stated in [13] the state at 3039.8 keV. In the $(n, n'\gamma)$ reaction [21] at 3452 keV a level with a transition to the $3_1^-$ state was observed. However, for two of the four transition depopulating this level to states with a firmly assigned positive parity a multipole-mixing ratio with values deviating from zero was measured. The latter indicates a positive parity of the state observed in the $(n, n'\gamma)$ experiment. Nevertheless, a scenario with two degenerated levels, one with positive and one with negative parity, is possible. Certainly, further experimental investigations are necessary to clarify the situation.

Table 1. Ratios of selected quantities from light-particle scattering experiments. The same ratios as presented for the first excited $3^-_1$ state and the $3^-_{IV}$ octupole isovector candidate are given for the first $2^+_1$ state and the firmly identified $2^+$ mixed-symmetry state(s). For $^{144}$Nd the summed B(E2) strength for the two fragments of the mixed-symmetry state were considered.

| Nucleus | Method | Octupole | Quadrupole | Reference |
|---------|--------|----------|------------|-----------|
| $^{92}$Zr | $(p, p')$ | $\frac{\sigma(3^-_{1})_{max}}{\sigma(3^-_{IV})_{max}} = 8.7$ | $\frac{\sigma(2^+_1)_{max}}{\sigma(2^+_1)_{max}} = 4.0$ | [20] |
| $^{94}$Mo | $(p, p')$ | $\frac{\sigma(3^-_{1})_{max}}{\sigma(3^-_{IV})_{max}} = 20.5$ | $\frac{\sigma(2^+_1)_{max}}{\sigma(2^+_1)_{max}} = 13.2$ | [20] |
| $^{144}$Nd | $(p, p'), (d, d')$ | $\frac{B(E2; 0^+ \rightarrow 3^-_{1})}{B(E3; 0^+ \rightarrow 3^-_{IV})} = 4.7(7)$ | $\frac{B(E2; 0^+ \rightarrow 2^+_1)}{B(E3; 0^+ \rightarrow 3^-_{IV})} = 9.4(15)$ | [19] |
| | $(e, e')$ | $\frac{B(E3; 0^+ \rightarrow 3^-_{1})}{B(E3; 0^+ \rightarrow 3^-_{IV})} = 5.8(12)$ | $\frac{B(E2; 0^+ \rightarrow 2^+_1)}{B(E3; 0^+ \rightarrow 3^-_{IV})} = 8.1(10)$ | [18] |
3. Summary
Data sets of near spherical nuclei, obtained with the \((n, n'\gamma)\) technique, reveal strong M1 components in \(3^-_i \rightarrow 3^+_i\) transitions. For several of the \(3^-_i\) states light-particle scattering experiments exhibit enhanced excitation cross sections from the ground state. The two experimental features are with respect to the first excited \(3^-\) state in the order of magnitude as observed for the combination of \(2^+_m\) quadrupole mixed-symmetry state and the \(2^+_1\) quadrupole phonon. The possibility of assigning the \(3^-_i\) states as candidates for isovector octupole excitations was discussed.

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