

Exotic ideas on mixed proton-neutron symmetry and their manifestation in heavy nuclei

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Abstract. The one-quadrupole phonon excitation of mixed symmetry, the $2^+_{1,ms}$ state, is a fundamental building block of nuclear structure. This article gives a summary of our recent experimental research on this excitation mode in the $A = 90$ and $A = 130$ mass regions.

1. Introduction

The contemporary quest for the structure of exotic nuclei addresses nuclear systems with abnormal ratios of proton and neutron numbers. It, hence, focuses on the isospin dependence of nuclear structure. The isospin degree of freedom of collective nuclear structures has been studied [1] some 35 years ago in the framework of the proton-neutron version [2] of the interacting boson model [3] by Takaharu Otsuka who worked at that time with Arima and Iachello. The formulation of the IBM-2 in its F-spin limit [4, 5] has emphasized the fundamental role of collective isovector valence-shell excitations, so-called mixed-symmetry states (MSSs), for the first time [2]. After the discovery of the scissors mode [6] and the clarification of its quadrupole-collective character [7, 8] it became obvious that the isovector quadrupole excitation of the valence shell represents the building block of mixed-symmetric structures as it is particularly apparent in the framework of the Q -phonon scheme [9] for mixed-symmetry states [10, 11]. The Q -phonon scheme considers ground state correlations by only providing relative wave functions and thereby benefits from a wide applicability to good approximation [12, 13, 14].

Vibrational nuclei exhibit a one-quadrupole phonon excitation as the lowest-lying state of mixed pn symmetry, *i.e.* the $2^+_{1,ms}$ state. Its close relation to the 2^+_1 state is evident in the Q -phonon scheme where the wave functions of the one-quadrupole phonon excitations are in general well approximated by the expressions

$$|2^+_1\rangle \simeq Q_s |0^+_1\rangle = [Q_\pi + Q_\nu] |0^+_1\rangle \quad (1)$$

$$|2^+_{1,ms}\rangle \simeq Q_m |0^+_1\rangle = N \left[\frac{Q_\pi}{N_\pi} - \frac{Q_\nu}{N_\nu} \right] |0^+_1\rangle \quad (2)$$

where $Q_{\pi,\nu}$ ($N_{\pi,\nu}$) denote the proton and neutron quadrupole operators (boson numbers), $N = N_\pi + N_\nu$, and $|0^+_1\rangle$ is the (in general highly correlated) ground state of a collective even-even nucleus. Despite its fundamental role in nuclear structure, the $2^+_{1,ms}$ state has only recently been

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studied systematically, *e.g.*, [15, 16, 17, 18, 19]. The dominant fragments of the one-phonon $2_{1,\text{ms}}^+$ state are observed at about 2 MeV excitation energy. Due to their isovector character, MSSs decay rapidly by dipole transitions and are very short lived, typically a few tens of femtoseconds. Large $M1$ matrix elements of $\approx 1 \mu_N$ are the unique signatures for MSSs and, thus, lifetime information is needed for making safe assignments of mixed symmetry. A review article on the status of experimental information on mixed symmetry states in vibrational nuclei has been published [20]. We use the occasion of Taka Otsuka's 60th birthday to summarize our recent experimental research on one-phonon MSSs. While we have recently been asked to talk on this subject at various occasions the presentation of the present contribution is similar to what we have recently contributed to other conference proceedings.

2. Experimental Method

Projectile-Coulomb excitation has been established as a powerful method for the identification and investigation of one-phonon MSSs [17, 19]. After this approach has first been applied to the investigation of the $2_{1,\text{ms}}^+$ state of ^{96}Ru at the Yale Tandem accelerator [17], we have begun a research programme on the $2_{1,\text{ms}}^+$ state at Argonne National Laboratory with the nucleus ^{138}Ce as a first case study [19]. Crucial influence of sub-shell closures on mixed-symmetry structures was first observed, a phenomenon which sensitively tests the effective proton-neutron interaction in microscopic valence shell models [21, 22]. The one-phonon $2_{1,\text{ms}}^+$ state of ^{136}Ce has recently been identified from similar Coulomb excitation experiments at Gammasphere [23].

A sequence of experiments on Xenon, Barium, and Cerium isotopes has been performed. The superconducting ATLAS accelerator provided the ion beams with energies corresponding to $\sim 85\%$ of the Coulomb barrier for a reaction on ^{12}C nuclei. The beam intensity amounted typically to $\sim 1\text{pA}$. The beam was impinging on a stationary carbon target of thickness 1 mg/cm^2 . Light target ions were chosen in order to favor the one-step Coulomb excitation process over multi-step processes for ease of data evaluation. The γ -rays emitted by Coulomb-excited states of the beam nuclei were detected in the Gammasphere array which consisted of ~ 100 high purity Compton suppressed Germanium detectors arranged in 16 rings. An event was defined by a γ -ray of multiplicity 1 or higher. Two corrections had to be done in order to get the total single spectra, an example of which is displayed in Fig. 1, namely the Doppler correction (recoiling velocity $\sim 6\text{-}8\%$) and the background subtraction (difference between the "in-beam" spectrum and the "off-beam" spectrum scaled to eliminate the $1461\text{ keV }^{40}\text{K}$ line).

The experimental γ -ray spectra are dominated by the decays of low-spin states, such as 2^+ or 3^- states, that are predominantly populated by one-step Coulomb excitation from the ground state. For each state observed we measured the excitation cross section relative to that

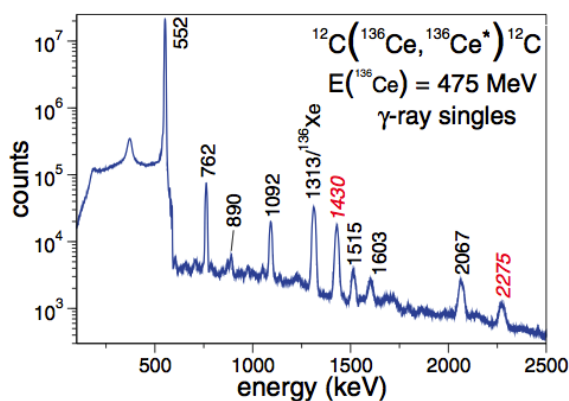


Figure 1. Background-subtracted and Doppler-corrected singles γ -ray spectrum summed over all Ge detectors of the Gammasphere array at ANL after Coulomb excitation of ^{136}Ce on a carbon target [23].

of the 2_1^+ state with an accuracy of 1 - 0.1 %. By calculating the Coulomb excitation cross sections for each excited state with the multiple-Coulomb excitation formalism and fitting them to our experimental data (normalized to the 2_1^+ state), we deduced the electromagnetic matrix elements corresponding to each transition of the excited states. The crucial multipole mixing ratios of the $2^+ \rightarrow 2_1^+$ transitions were obtained from γ -ray angular distributions if sufficient statistics have been obtained. A possible large $B(M1)$ value, signature of the MSS, is then easily derived from the data. For a further description of this method, the reader is referred to Refs. [19, 20]. This experimental technique of projectile-Coulomb excitation on a light target inside the Gammasphere array at ANL has been applied by us to 16 nuclei up to now: $^{136,138}\text{Ce}$, $^{124-134}\text{Xe}$, $^{148,154}\text{Sm}$, $^{194,196}\text{Pt}$, $^{130,132}\text{Ba}$, ^{96}Ru and ^{94}Mo . Figure 1 displays data from the projectile-Coulomb excitation reactions of a ^{136}Ce -ion beam on a carbon target.

3. Evolution of $2_{1,\text{ms}}^+$ states in the $A = 130$ region

The experiments performed so far allow for a nearly complete overview on the properties of the MSS throughout the $A = 130$ region. A recent publication on the first identification of a MSS in an unstable nucleus in ^{132}Te [24] expands the experimental data on the $N = 80$ isotonic chain. A recent publication on the MSS in the nucleus ^{136}Ce [23] completes the experimental data on the stable even-even $N = 78$ isotonic chain. A set of data currently under analysis on the nucleus ^{132}Ba [25] will complete our information on the one-phonon mixed-symmetry state in the stable even-even $N = 76$ isotones. An overview on the $B(M1; 2_i^+ \rightarrow 2_1^+)$ strength distributions in the even-even nuclei in the $A = 130$ region is shown in Figure 2.

In the stable $N = 80$ isotones the excitation energy of the $2_{1,\text{ms}}^+$ state increases with increasing proton number. This trend continues in the unstable nucleus ^{132}Te [24]. In the $N = 78$ isotonic chain, the energy of the MSS again increases with increasing proton number. In the neighboring $N = 76$ isotones, however, the excitation energy of the MSS decreases with increasing proton number. It is also interesting to follow the evolution of the MSS's excitation energies in the different isotopic chains. In the Ce and Ba isotopes, the excitation energy of the MSS increases with increasing neutron number, whereas in the Xe isotopes an increase in N_ν results in a decrease of $E(2_{1,\text{ms}}^+)$. Apparently, the $2_{1,\text{ms}}^+$ state evolves in different ways as a function of valence particle numbers. Whether or not the observed differences are related to a critical point of a nuclear shape phase transition near ^{134}Ba is unclear up to now.

From data on $E(2_1^+)$ and $E(2_{1,\text{ms}}^+)$, an estimate of the proton-neutron quadrupole-quadrupole interaction V_{pn}^{QQ} according to the two-state mixing scheme in [26] has been performed on the

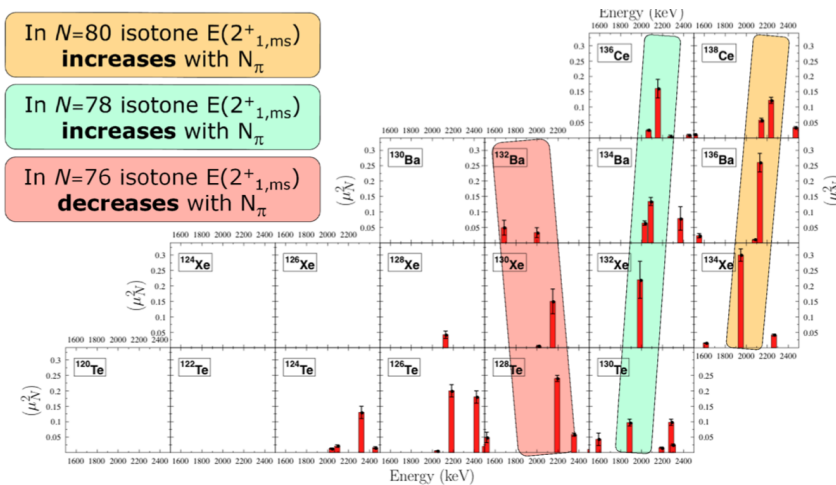


Figure 2. Overview of the $B(M1; 2_i^+ \rightarrow 2_1^+)$ strength distributions for the stable even-even nuclei in the $A=130$ region.

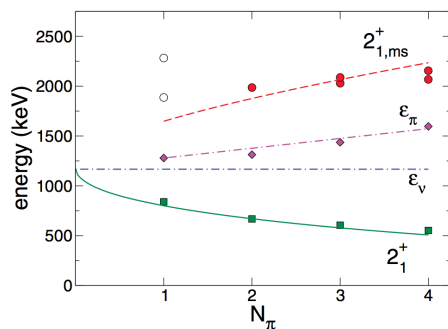


Figure 3. Simultaneous fit of the experimental energies of the 2_1^+ states (solid curve) and of the $B(M1)$ -weighted average energies of the $2_{1,ms}^+$ states (dashed curve) in the $N = 78$ isotones. Taken from [23].

$N = 80$ isotones [27], the Xe isotopes [28], and, just recently, on the $N = 78$ isotones [23]. The results show, that the proton-neutron quadrupole-quadrupole interaction in the $N = 78$ isotonic chain is about 14% smaller than that for the $N = 80$ isotopic chain [27] and about 6% smaller than for the Xenon isotopic chain [28]. An example of the data, taken from Ref. [23], is displayed in Fig. 3.

4. Phase of proton- and neutron-components to MSSs: The case of ^{92}Zr

We studied the formation of quadrupole collectivity in the particularly simple case of a nucleus with a low-energy structure that is dominated by one pair of valence particles each for protons and neutrons. An example is the nucleus ^{92}Zr with 2 neutrons beyond the $N = 50$ shell closure and 2 protons beyond the $Z = 38$ sub-shell closure. The lowest 2-quasiparticle (2qp) states have $\pi(1g_{9/2})^2$ and $\nu(2d_{5/2})^2$ configurations. In ^{92}Zr , the predominantly symmetric and mixed-symmetric one-phonon 2^+ states are experimentally identified as the 2_1^+ and 2_2^+ states [29, 20] with some degree of configurational isospin polarization [30].

To shed light on the microscopic origin of the effective pn-coupling strength in the valence shell we consider the quasiparticle-phonon model (QPM) [31]. The QPM wave functions are dominated by the lowest π and ν 2qp components, that show the expected in-phase and out-of-phase behavior for the 2_{fs}^+ and 2_{ms}^+ states. The electromagnetic properties and excitation energies are in excellent agreement with the data [32]. The magnetic moments of these states and the strong $M1$ transition between them originate almost entirely from the valence-shell configurations. However, the $B(E2)$ strengths are generated to about 80% from many components beyond the valence shell albeit their total contribution to the wave function norm is small. This observation motivates a simple three-state mixing scenario between the proton-valence shell configuration, the neutron-valence shell configuration, and the GQR for a deeper insight in the formation of the one-quadrupole phonon states with symmetric and mixed-symmetry character even on a semi-quantitative level [33]. For the nucleus ^{92}Zr with higher energy for the proton valence-shell component than the neutron valence-shell component at the $Z = 40$ sub-shell closure, this scheme inevitably requires that the neutron valence-shell component flips its phase with respect to the GQR component when going from the proton-neutron symmetric 2_1^+ state to the 2_2^+ state with predominant mixed symmetry.

Apparently, two probes with different sensitivity to protons and neutrons are needed to study this quantum interference experimentally. Electron scattering at low momentum transfer provides a measure of the charge transition radius. An (e, e') experiment was performed at the Darmstadt superconducting electron linear accelerator (S-DALINAC). An enriched (94.6 %) self-supporting ^{92}Zr target of 9.8 mg/cm² areal density was used. Data were taken covering a momentum transfer range between $q \sim 0.3 - 0.6 \text{ fm}^{-1}$ indicating no difference between the charge transition radii of the 2_{fs}^+ and 2_{ms}^+ states within experimental uncertainties (Fig. 4, right). Information about the neutron transition radii can be derived from the proton scattering data

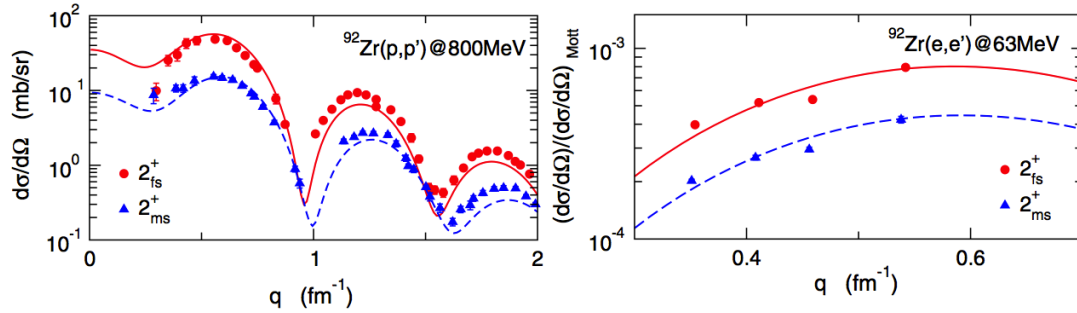


Figure 4. Form factors for the $2_{1,fs}^+$ (red, solid line) and $2_{1,ms}^+$ (blue, dashed line) from $^{92}\text{Zr}(p, p')$ and $^{92}\text{Zr}(e, e')$ experiments (from [33]).

of Ref. [34]. At the incident energy of 800 MeV protons interact predominantly via the isoscalar central piece of the effective projectile-nucleus interaction [35]. Clearly, the refraction pattern of the (p, p') cross section for the 2_{ms}^+ state are shifted to higher q values as compared to those for the 2_{fs}^+ state (Fig. 4, left) corresponding to a smaller transition radius.

Figure 5 displays the proton and neutron transition densities of the 2_{fs}^+ (top) and 2_{ms}^+ (bottom) states calculated in the full QPM approach. The full transition densities (solid curves) are decomposed in a collective part stemming from the GQR (dotted curves) and the predominant $2qp \nu(2d_{5/2})^2$ neutron contributions (dashed curves).

The key point is the different radial behaviour of both parts and their relative signs. An out-of-phase coupling between the neutron valence shell contribution and the contribution from the GQR in the 2_{ms}^+ state leads to a destructive quantum interference that reduces the neutron transition density at large radii (due to the larger radius of the $\nu(2d_{5/2})^2$ orbital) and consequently shifts the maximum of the total neutron transition density to the interior with respect to that one for the 2_{fs}^+ state, as indicated by the arrows in Fig. 5. This effect reduces the neutron transition radius of the 2_{ms}^+ with respect to the 2_{fs}^+ state of ^{92}Zr . In contrast, the proton transition radius remains essentially unchanged since the $\pi(1g_{9/2})^2$ part couples in-phase to the GQR contribution in both states. The combination of both data sets unambiguously demonstrates for the first time that the phase of the neutron valence-shell configurations in ^{92}Zr changes its sign between the 2_{fs}^+ and the 2_{ms}^+ state [33].

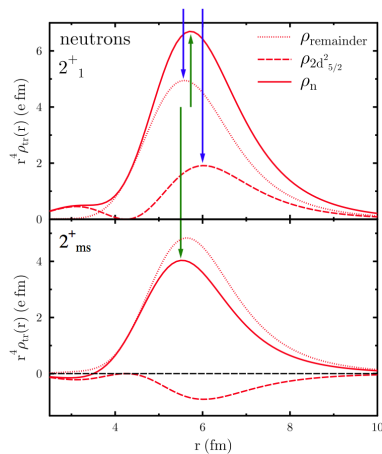


Figure 5. Neutron transition densities of the 2_{fs}^+ (top) and 2_{ms}^+ (bottom) states of ^{92}Zr from QPM calculations. The full transition densities (solid lines) are decomposed in parts stemming from the GQR (dotted lines) and from the main $2qp$ configurations (dashed lines). The arrows indicate the maxima of the corresponding full transition densities.

5. Summary

The isovector one-quadrupole phonon excitation of the valence shell, the $2_{1,\text{ms}}^+$ state with F -spin $F = F_{\text{max}} - 1$, has been systematically investigated in a large number of vibrational nuclei. This state is generally identified from absolute $M1$ transition strengths when the experimental sensitivity is high enough and it occurs at energies around 2 MeV featuring an $M1$ transition matrix element to the 2_1^+ state between 0.5 and 1.5 μ_N with some fragmentation. The details of its evolution as a function of particle number is not entirely understood. It may depend on the local shell structure around the Fermi level and on the evolution of quadrupole deformation.

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