Emerging simplicity: Evidence for the formation of collectivity from hadronic and EM probes

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Abstract
The one-quadrupole phonon excitation of mixed symmetry, the $2^+_{1,\mathrm{ms}}$ 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 nuclear proton-neutron degree of freedom and its fundamental impact on nuclear structure represents one of the central aspects of nuclear structure physics. The evolution of nuclear shells as a function of proton and neutron numbers sets the conditions for the emergence of excited nuclear quantum states with wave functions that include many proton excitations and neutron excitations within the valence shell that collectively couple in phase. This in-phase coupling of proton and neutron valence-shell excitations simultaneously leads to the occurrence of orthogonal nuclear valence-shell excitations with partial out-of-phase coupling of proton and neutron components. These states represent a closely related aspect of the nuclear proton-neutron degree of freedom. Indeed, nuclear excitations may be classified according to the proton-neutron symmetry of their wave functions, either in terms of isospin in the framework of models that use nucleons as the fundamental degree of freedom or in terms of F-spin in approximate bosonic nuclear models for collective valence-shell excitations at low energies.

The formulation of the interacting boson model (IBM-2) in its F-spin limit [1–3] has emphasized the fundamental role of collective proton-neutron non-symmetric valence-shell excitations. Nuclear excitations with F-spin quantum number $F < F_{\mathrm{max}} = (N_\pi + N_\nu)/2$, where $N_{\pi(\nu)}$ is half the number of valence protons (neutrons), contain parts in their wave functions where proton bosons and neutron bosons are coupled antisymmetrically. These states have been called mixed-symmetry states (MSSs). Prominent examples of MSSs are the $J^\pi = 1^+$ scissors mode of deformed nuclei or the mixed-symmetry $2^+_{1,\mathrm{ms}}$ one-phonon vibration in heavy spherical nuclei. Information on the proton-neutron symmetry of the low-energy nuclear states, including the ground state, its collective excitations, and MSSs, is needed for a correct interpretation of the role of the nuclear proton-neutron degree of freedom in the formation of nuclear structure. After the discovery of the scissors mode [4] and the clarification of its quadrupole-collective character [5, 6] it became obvious that the isovector quadrupole excitation of the valence shell represents the building block of mixed-symmetric structures.

Vibrational nuclei exhibit a one-quadrupole phonon excitation as the lowest-lying state of mixed-pn symmetry, *i.e* the $2^+_{1,\mathrm{ms}}$ state. Its close relation to the 2^+_1 state is evident in the Q-phonon scheme [7], where the wave functions of the one-phonon excitations are well approximated by the expressions

$$|2^+_1\rangle \simeq Q_s\,|0^+_1\rangle = [Q_\pi + Q_\nu]\;|0^+_1\rangle \tag{1}$$

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

Here, $Q_{\pi,\nu}$ $(N_{\pi,\nu})$ 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 collectively vibrating even-even nucleus. Despite its fundamental role in nuclear structure, the $2^+_{1,\mathrm{ms}}$ state has only recently been studied systematically, [8–12]. The dominant fragments of the one-phonon $2^+_{1,\mathrm{ms}}$ 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 in fact the unique signatures for MSSs. Consequently, lifetime information is needed for making safe assignments of mixed symmetry to a nuclear energy level. A review article on the status of experimental information on mixed-symmetry states in vibrational nuclei has been published [13]. We report on our recent progress in this field. Due to the strong interest of the community in this topic we have been asked to do so on several occasions during this summer. Therefore, this contribution follows closely the presentations [14, 15] that we have recently tried to formulate as best as we can.

2 Experimental Method

Projectile-Coulomb excitation has been established as a powerful method for the identification and investigation of one-phonon MSSs [10]. After this approach has first been applied to the investigation of the $2^+_{1,\mathrm{ms}}$ state of ^{96}Ru [10], we have initiated a research programme on the $2^+_{1,\mathrm{ms}}$ state at Argonne National Laboratory with the nucleus ^{138}Ce as a case study [12]. Crucial influence of sub-shell closures on mixed-symmetry structures was observed [12], *i.e.*, MSSs sensitively test the effective proton-neutron interaction in microscopic valence shell models [16–18].

A sequence of experiments has been performed at ANL. The superconducting ATLAS accelerator provided beams of stable even-even isotopes of the Xenon, Barium and Cerium isotopic chains. Beam energies corresponded to ~ 85 % of the Coulomb barrier for a reaction on ^{12}C nuclei. The beam intensities amounted typically to $\sim$ 1pnA. The ions were 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. The γ-rays emitted by Coulomb-excited states of the beam nuclei were detected in the Gammasphere array [19, 20]. An event was defined by a γ-ray of multiplicity 1 or higher. Doppler correction (recoiling velocity $\sim$ 6-8%) and background subtraction (difference between the "in-beam" spectrum and the "off-beam" spectrum scaled to eliminate the 1461 keV ^{40}K line) were applied. Figure 1 displays data from the projectile-Coulomb excitation reactions of a ^{136}Ce-ion beam on a carbon target.

The 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 excitations. For each state observed we measured

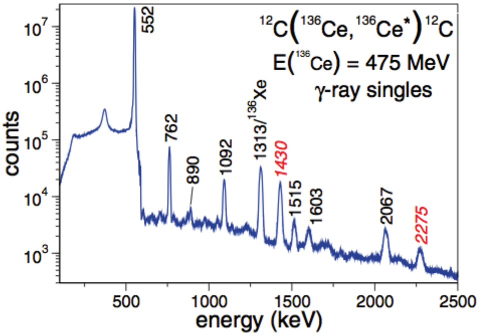

Fig. 1: Background-subtracted and Doppler-corrected singles γ-ray spectrum summed over all Ge detectors of the Gammasphere array at ANL after Coulomb excitation of ^{136}Ce on a carbon target [21].

the excitation cross section relative to that of the 2_1^+ state with an accuracy of 1 - 0.1 %. We deduced electromagnetic matrix elements corresponding to each transition of the excited states by calculating the Coulomb excitation cross sections with the multiple-Coulomb excitation code CLX and fitting them to our experimental data (normalized to the 2_1^+ state). The crucial multipole-mixing ratios of the $2^+_{(i>1)} \to 2_1^+$ transitions were obtained from γ-ray angular distributions if sufficient statistics had been obtained. A possible large $B(M1)$ value, signature of the MSS, can then be derived from the data. For a further description of this method, the reader is referred to Refs. [12, 13].

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

The experiments [12, 21–23] allow for a nearly complete overview on the properties of the one-phonon MSS throughout the stable isotopes of the $A = 130$ region. A recent publication on the first identification of a MSS in the unstable nucleus ^{132}Te [24] expands the data on the $N = 80$ isotonic chain to the neutron-rich radioactive isotopes. Data currently under analysis on the nucleus ^{132}Ba [25] will complete our information on the one-phonon MSS in the stable even-even $N = 76$ isotones. An overview on the $B(M1; 2_i^+ \to 2_1^+)$ strength distributions in the $A = 130$ region is shown in Fig. 2.

In the stable $N = 80$ isotones the excitation energy of the $2^+_{1,\mathrm{ms}}$ state increases with proton number. This trend continues in the unstable nucleus ^{132}Te [24]. The evolution of one-quadrupole phonon MSSs along the $N = 80$ isotonic chain has been studied microscopically in the nuclear shell model either using large-scale diagonalization [17] or very recently using a new importance-sampling iterative algorithm for matrix diagonalization [18]. 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 opposite trend can be observed. It is also interesting to follow the evolution of the MSS 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 $E(2^+_{1,ms})$. Apparently, the $2^+_{1,\mathrm{ms}}$ state evolves in different ways as a function of valence particle numbers. The evolution of $M1$ transitions between mixed-symmetry states and fully symmetric states in the γ-soft nuclei of the xenon isotopic chain have recently been described in a schematic microscopic approach [26] and in the nuclear shell model using the importance-sampling algorithm [27]. Whether or not the observed evolutions are related to a nuclear shape transition near ^{134}Ba is unclear up to now.

From data on $E(2_1^+)$ and $E(2^+_{1,ms})$, an estimate of the proton-neutron quadrupole-quadrupole interaction V_{pn}^{QQ} according to the two-state mixing scheme in [28] has been performed on the $N = 80$ isotones [22], the Xe isotopes [23], and, just recently, on the $N = 78$ isotones [21]. The results show,

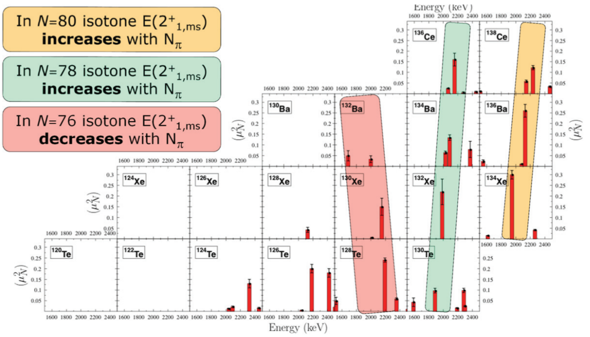

Fig. 2: Distributions of $B(M1; 2_i^+ \to 2_1^+)$ strengths for the stable even-even nuclei in the A=130 region.

that the value derived for the proton-neutron quadrupole-quadrupole interaction in the $N = 78$ isotonic chain is about 14% smaller than that for the $N = 80$ isotopic chain [22] and about 6% smaller than the value for the xenon isotopic chain [23].

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 dominated by one pair of valence particles each for protons and neutrons. An example is ^{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 will therefore have $\pi(1g_{9/2})^2$ and $\nu(2d_{5/2})^2$ configurations. Due to the residual proton-neutron interaction two different classes of collective excitations appear at low energy in which the amplitudes of the two most important 2qp configurations are coupled in a symmetric or antisymmetric way, respectively. In ^{92}Zr, these are experimentally identified as the 2^+_1 and 2^+_2 states [13, 30] with some degree of configurational isospin polarization [31, 32]. To shed light on the microscopic origin of the effective coupling strength in the valence shell we consider the quasiparticle-phonon model (QPM) [33]. 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 $2^+_{1,\mathrm{fs}}$ fully symmetric and $2^+_{1,\mathrm{ms}}$ mixed-symmetry states. The electromagnetic properties and excitation energies are in good agreement with the data [34]. The magnetic moments of these states and the $M1$ transition between them originate almost entirely from the valence-shell configurations. However, up to 80% of the $B(E2)$ strengths are generated from many components beyond the valence shell although 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 Giant Quadrupole Resonance (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 [35]. For the nucleus ^{92}Zr which has a higher energy for the proton valence-shell component than the neutron valence-shell component at the $Z = 40$ sub-shell closure, the three-state mixing scheme 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 predominantly mixed-symmetric 2^+_2 state.

Two probes with different sensitivity to protons and neutrons are necessary 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 high-energy-resolution spectrometer [36] of the Darmstadt superconducting electron linear accelerator (S-DALINAC). A self-supporting zirconium metal target of 9.8 mg/cm^2 areal density and with enrichment to 94.6 % in the isotope ^{92}Zr was used. Data were taken covering a momentum transfer range between $q \sim 0.3 - 0.6$ fm^{-1} indicating

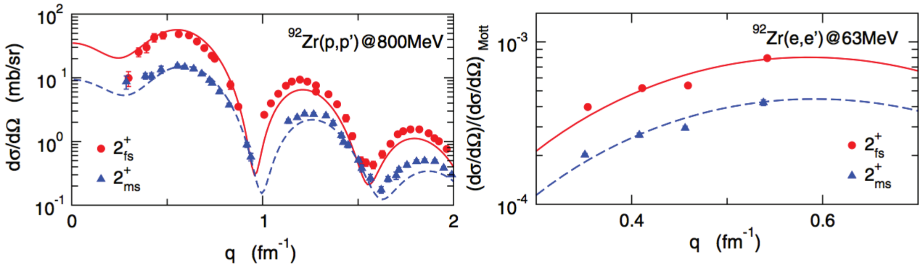

Fig. 3: Form factors for the $2^+_{1,\mathrm{fs}}$ (red, solid line) and $2^+_{1,\mathrm{ms}}$ (blue, dashed line) from $^{92}Zr(p, p')$ and $^{92}Zr(e, e')$ experiments (from [35]).

no difference between the charge transition radii of the 2_1^+ and 2_2^+ states within experimental uncertainties (Figure 3, bottom). Information about the neutron transition radii can be derived from the proton scattering data of Ref. [37]. At the incident energy of 800 MeV protons interact predominantly via the isoscalar central piece of the effective projectile-nucleus interaction [38]. Clearly, the refraction pattern of the (p, p') cross section for the $2^+_{1,\mathrm{ms}}$ state are shifted to higher q values as compared to those for the $2^+_{1,\mathrm{fs}}$ state (Figure 3, left) corresponding to a smaller transition radius.

We have studied [35] proton and neutron transition densities of the $2^+_{1,\mathrm{fs}}$ and $2^+_{1,\mathrm{ms}}$ states calculated in the full QPM approach. The full transition densities are decomposed into a collective part stemming from the GQR and the predominant $\nu(2d_{5/2})^2$ 2qp neutron contributions. 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 $2^+_{1,\mathrm{ms}}$ 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_1^+ state. This effect reduces the neutron transition radius of the $2^+_{1,\mathrm{ms}}$ state with respect to the 2_1^+ 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_1^+ and the $2^+_{1,\mathrm{ms}}$ state [35].

5 Summary

The isovector one-quadrupole phonon excitation of the valence shell has been systematically investigated in a large number of vibrational nuclei in the mass regions $A = 90$ and $A = 130$. It carries the signatures of the $2^+_{1,\mathrm{ms}}$ state with F-spin quantum number $F = F_{\max} - 1$. This state is generally observed from absolute $M1$ transition strengths when the experimental sensitivity is high enough. This state is typically concentrated in a single 2^+ state or distributed over two or three fragments. It is found at energies around 2 MeV and features an $M1$ transition matrix element to the 2_1^+ state between 0.5 and 1.5 μ_N. 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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