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Experimental studies of proton-neutron mixed symmetry states in the mass A $\approx$ 130 region

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Abstract. Considerable progress has been achieved recently in the experimental investigation of quadrupole-collective isovector excitations in the valence shell, the so called mixed-symmetry states (MSSs), in the mass $A \approx 130$ region. This is due to a new experimental technique for study MSSs which is based on the observation of low-multiplicity γ-ray events from inverse kinematics Coulomb excitation with the large 4π spectrometer, such as Gammasphere. The obtained experimental information for the MSSs of stable $N = 80$ isotones indicates that for low-collective vibrational nuclei the underlying single-particle structure can be the most important factor for preserving or fragmenting the MSSs through the mechanism of **shell stabilization**. The evolution of the MSSs from ^{134}Xe to ^{138}Ce is also used to determine the local strength of the proton-neutron interaction derived for first time from states with symmetric and antisymmetric nature.

1. Introduction

Atomic nuclei are quantum, many body systems which consist of two equivalent entities (protons and neutrons). In this respect the atomic nuclei are examples of mesoscopic two-fluid quantum systems which nature is defined by the collectivity, the isospin symmetry and the shell structure. The question how these three aspects coexist, interplay and compete comprises one of the main questions of the quantum theory and the atomic nuclei present a unique laboratory where this question can be studied experimentally. Nuclear phenomena that reflect these three general aspects are nuclear collectivity, shell structure, and the isospin degree of freedom. Of particular importance for studying the mutual balance of these properties are those excitations that are related to the collective two-fluid character of nuclei and to their shell structure. Quadrupole-collective isovector valence shell excitations, so-called Mixed-Symmetry States (MSSs) [1], are the best studied examples of this class of phenomena. A special type of MSSs, the $J^\pi = 1^+$ scissors mode has first been discovered in nuclei [2] and has then been reported or suggested to exist in Bose-Einstein condensates [3] and metallic clusters [4].

States with proton-neutron mixed symmetry have first been defined in the framework of the interacting boson model with proton-neutron degree of freedom (IBM-2) [1]. The concept of proton-neutron mixed symmetry is formalized by the F-spin quantum number [5], which is the isospin analogue for bosons. Within this concept the fully symmetric states have $F = F_{max} = (N_\pi + N_\nu)/2$ ($N_{\pi,\nu}$ denote the proton/neutron boson numbers), while MSSs are those states with $F \leq F_{max} - 1$ [5]. In other words, the F-spin quantum number counts the number of protons and neutrons pairs which are in phase in the quantum state. The IBM-2 states with maximum F-spin quantum number are called Full Symmetry States (FSSs). The F-spin is an approximate quantum number for low-lying collective states of heavy nuclei. The lowest states in a given nucleus are those formed by the FSSs. The $M1$ transitions between these states are forbidden and indeed they are observed to be small on an absolute, single-particle scale. With little modifications due to symmetry restrictions, the MSSs in the IBM-2 repeat the multiplet structure observed for the FSSs albeit at higher energy and with different decay properties.

The most distinct feature of MSSs is the existence of allowed F-vector ($\Delta F = 1$) $M1$ transitions to FSSs. This comprises most prominent experimental signature of MSSs - due to their isovector character they decay to FSSs by strong $M1$ transitions with matrix elements of the order of 1 μ_N [1]. However, finding this signature is a major experimental challenge because it requires full spectroscopic information, *i.e.* the spin-parities of these highly excited non-yrast states, their lifetimes, branching and multipole mixing ratios of their γ-decay have to be determined. Until recently obtaining all this information was possible for a hand-full of stable nuclei only and it required a series of experiments to be measured. Available information on MSSs of vibrational nuclei has recently been summarized in a review article [6]. The best examples of MSSs in stable nuclei are found in the mass $A \approx 90$ region [7, 8, 9], while there are only a few reported cases in the $A \approx 130$, region below the $N = 82$ shell closure, *e.g.* [10, 11, 12]. Apparently, to investigate MSSs, new experimental methods, in particular those that could potentially be applied to radioactive isotopes, are needed. We have shown recently that the observation of low-multiplicity γ-ray events from inverse kinematics Coulomb excitation with the large 4π spectrometers, such as Gammasphere, is a powerful tool to study MSSs. It is worth noting that this experimental technique can straightforwardly be applied to Radioactive Ion Beams (RIBs).

2. Experimental method

The technique which combines the observation of low-multiplicity γ-ray events from inverse kinematics Coulomb excitation with the large 4π spectrometers was first used to study the one-phonon MSS of ^{96}Ru [8] and then exploited to its full capacity in the case of ^{138}Ce [13] which is a low-abundant nucleus. We will use this experiment here to illustrate the method. The experiment was carried out at Argonne National Laboratory. The ^{138}Ce beam with intensity of ≈ 1 pnA ($\sim 6 \times 10^9$ ions/s) was delivered by the ATLAS accelerator. The 480 MeV beam was incident on a 1 mg/cm^2 ^{12}C target. The deexcitation γ rays, following the Coulomb excitation of the projectile, were detected with the Gammasphere array [14] which consisted of 98 HPGe detectors arranged in 15 rings. Gammasphere was used in singles mode resulting in an average counting rate of 4000 counts-per-second (cps), while the room background was producing about 600 cps. A total of 2.4×10^8 events of γ-ray fold 1 or higher was collected in about 14 hours. The contribution of the room background was eliminated in the off-line sort by correlating the γ rays with the accelerator radio-frequency (RF) signal. The final spectrum, which is a difference between the "beam-on" (with respect to the RF) spectrum and the "beam-off" spectrum, scaled to eliminate the 1461-keV room background transition in ^{40}K, is shown in Fig. 1. All γ rays in the spectrum originate from ^{138}Ce nuclei recoiling with $v/c \approx 6.9\%$. The spins of the levels were assigned on the basis of an angular distribution analysis [15].

In this experiment, we have observed the decay of the first six $2^+_{1,2,3,4,5,6}$ states up to an excitation energy of 2.7 MeV. The relative γ-ray yields with respect to the 2^+_1 state measure the relative Coulomb excitation (CE) cross-sections. These data were fitted to the Winther-De

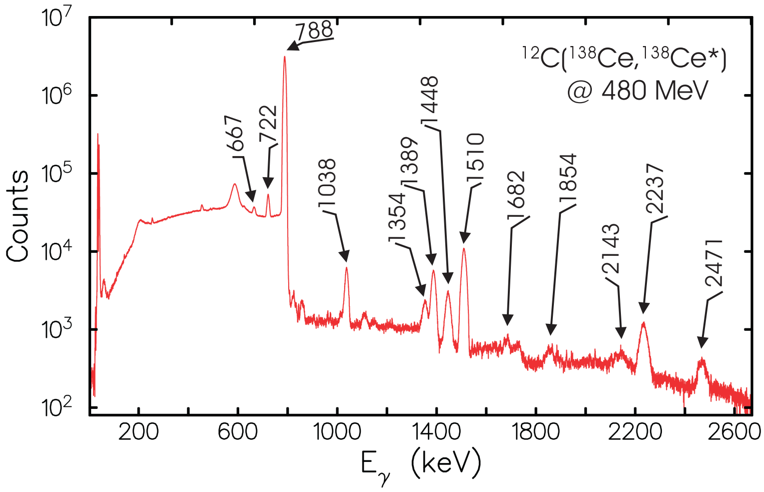

Figure 1. Background-subtracted, Doppler-corrected γ-ray spectrum in ^{138}Ce observed with Gammasphere after Coulomb excitation on a carbon target. Taken form Ref. [13].

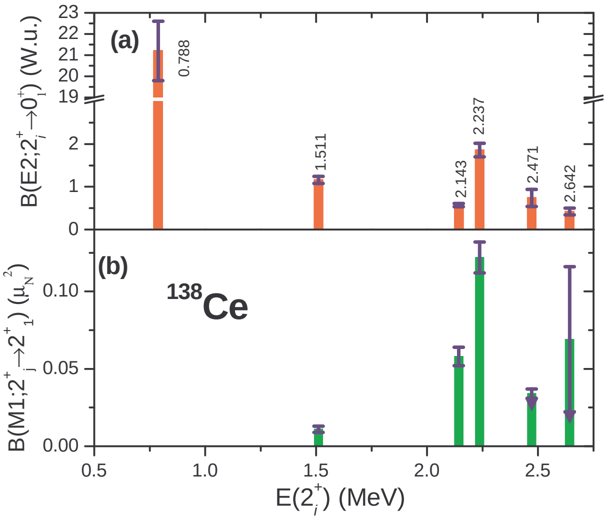

Figure 2. (a) E2 and (b) M1 transition strength distributions for all observed 2^+ states below 2.7 MeV in ^{138}Ce. The arrows indicate upper limits. Taken from Ref. [13].

Boer theory [16] using a multiple CE code [17] and taking into account the energy loss of the beam in the target. Absolute cross-sections were derived using the previously measured value for the B(E2;$0^+_1 \to 2^+_1$) = 0.450(30) e^{2}b^2 [18, 19]. An unambiguous set of matrix elements $|\langle I^\pi_\mathrm{f} \parallel E\lambda \parallel 0^+_1\rangle|$ for one-step excitations of interest was obtained. The matrix elements for the excited 2^+_i states together with observed decay branching ratios $I_\gamma(2^+_i \to 2^+_1)/I_\gamma(2^+_i \to 0^+_1)$ and deduced $E2/M1$ mixing ratios for the $2^+_i \to 2^+_1$ transitions provide the $B(E2)$ and $B(M1)$ transition strengths (see Fig. 2).

3. One-phonon MSSs in N=80 isotones

In ^{138}Ce the 2^+_4 state at 2.237 MeV dominates the $2^+_i \rightarrow 2^+_1$ $M1$ strength distribution (see Fig. 2). This identifies this level as the major fragment of the one-phonon $2^+_{1,\mathrm{ms}}$ state in ^{138}Ce. Its one-phonon character is further corroborated by the fact that the 2^+_4 state exhibits the largest $E2$ strength to the ground state after the 2^+_1 state. However, some parts of the $2^+_{1,\mathrm{ms}}$ strength are spread over nearby 2^+ levels. In particular, the 2^+_3 state at 2.143 MeV acquires a considerable $B(M1; 2^+ \rightarrow 2^+_1)$ value. For analysis of the mixing of the $2^+_{1,\mathrm{ms}}$ state with symmetric configurations we have considered a two-state mixing scenario between the $2^+_{1,\mathrm{ms}}$ MSS and a close-lying fully symmetric state (FSS). This scenario leads to a mixing matrix element of 44(3) keV.

One might expect that excited states in the ^{136}Ba and ^{138}Ce $N = 80$ isotones are quite similar. The energies of the first three 2^+ states indeed correspond to each other within 4%. The 2^+_4 state at 2.129 MeV in ^{136}Ba has previously been identified as a $2^+_{1,\mathrm{ms}}$ state [12] and its excitation energy agrees to within 5% with the excitation energy of the $2^+_{1,\mathrm{ms}}$ state in ^{138}Ce. However, in ^{136}Ba the transition strength $B(M1; 2^+_4 \rightarrow 2^+_1) = 0.26(3)\,\mu_N^2$ [12] is larger than the total $M1$ strength $\sum B(M1; 2^+_{3,4} \rightarrow 2^+_1) = 0.180(13)\,\mu_N^2$ shared between the 2^+_4 and 2^+_3 states in ^{138}Ce. Moreover, if the above mixing scenario is applied to ^{136}Ba, the resulting mixing matrix element is < 10 keV. This drastic change in the properties of predominantly collective states points precisely to their sensitivity to the underling sub-shell structure. Since the neutron configuration is not expected to differ much for the isotones ^{136}Ba$_{80}$ and ^{138}Ce$_{80}$, it is suggested that this difference in size of the F-spin mixing matrix elements is related to the proton configurations. Ground state spins for proton-odd N = 80 isotones and the shell model indicate the $\pi g_{7/2}$ sub-shell closure for cerium isotopes at proton number Z = 58. While the leading one-phonon 2^+ proton configuration already requires promotion of protons to the $\pi d_{5/2}$ sub-shell in $^{138}_{58}$Ce, the corresponding configuration for $^{136}_{56}$Ba can still be formed within the $\pi g_{7/2}$ sub-shell [20]. Thus, the one-phonon $2^+_{1,\mathrm{ms}}$ state of ^{136}Ba is expected to consist of considerably simpler configurations than the closely lying predominantly symmetric states that surround it at an excitation energy of about 2 MeV. This prevents strong mixing between the $2^+_{1,\mathrm{ms}}$ state and nearby 2^+ states in ^{136}Ba in contrast to the situation in ^{138}Ce. This mechanism is considered as a *shell-stabilization of mixed-symmetry structures* near sub-shell closures [13].

According to the mechanism of shell stabilization one might expect that the one-phonon state of ^{134}Xe will be a single isolated state, while the one-phonon MSS of ^{136}Ce will be fragmented. In order to check this hypothesis we have performed two experiments with Gammasphere at Argonne National Laboratory using the technique described above. Spectra form these experiments are presented in Fig. 3. The $B(E2)$ and $B(M1)$ transition strengths distribution from the observed 2^+ states in ^{134}Xe [21] are presented in Fig. 4. From the $M1$ distribution the 2^+_3 state of ^{134}Xe at 1947 keV can unambiguously be identified as the one-phonon MSS. This result is in agreement with the mechanism of shell stabilization. However, the preliminary results for ^{136}Ce [22] show that the observed spectrum is quite similar to the one of ^{138}Ce but the $M1$ strength is almost completely concentrated in the 2^+_4 state at 2155 keV as the neighboring 2^+_3 state takes almost no $M1$ strength. This fact is in contradiction with the mechanism of shell stabilization. At this point we have to conclude that even though we have found some strong indication that the properties of MSSs reflect the underling sub-shell structure through the effect of shell stabilization, the available experimental data are still not sufficient to allow for any conclusion on the generic nature of this effect.

The experimental efforts, presented above have revealed the evolution of the one-phonon MSSs in the stable $N = 80$ isotones. This has inspired extended microscopic calculations of the structures of the MSSs of the $N = 80$ isotones [23]. It has been demonstrated that a simultaneous description of the properties of the MSSs in the $N = 80$ isotonic chain, including

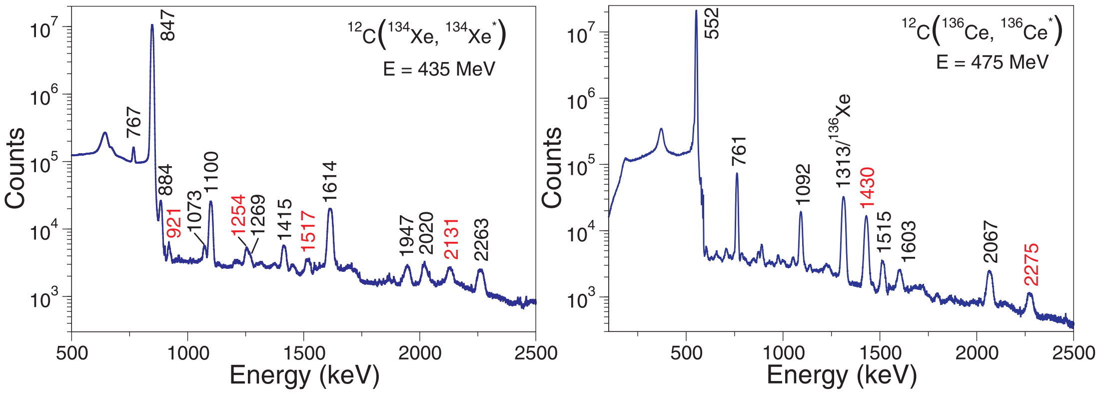

Figure 3. Background-subtracted, Doppler-corrected γ-ray spectra in ^{134}Xe and ^{136}Ce observed with Gammasphere after Coulomb excitation on a carbon target. Taken from Ref. [21, 22].

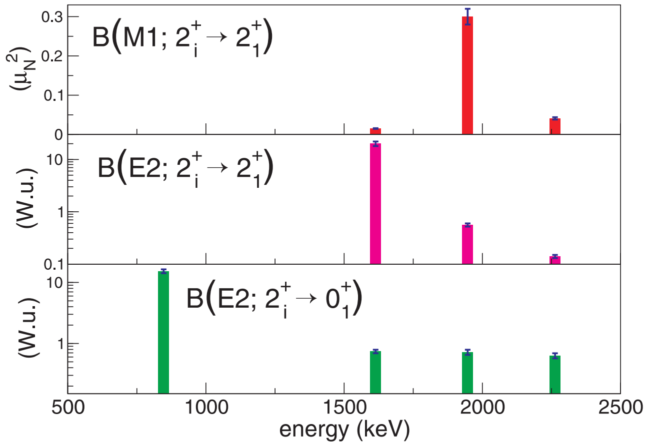

Figure 4. $E2$ and $M1$ transition strength distributions for all observed 2^+ states below 2.5 MeV in ^{134}Xe. Taken from Ref. [21].

the fragmentation of the one-phonon MSS in ^{138}Ce, can be achieved [23] within the frame work of the qasiparticle-phonon model [24]. The QPM calculations show that the splinting of the $M1$ strength in ^{138}Ce is a genuine shell effect due to the specific shell structure of this nucleus and the pairing correlations [23].

Looking at the $N = 80$ isotones, an increase in the energy splitting between the 2^+_1 and $2^+_{1,\mathrm{ms}}$ states can be seen [21]. This separation in energy was empirically fitted using a simple two-state mixing scheme where the interaction between the two states increases in strength as $V(N_\pi) = \beta\sqrt{N_\pi N_\nu}$. As a result of the fit, the relative strength of the proton-neutron quadrupole interaction was derived for the first time from the properties of both, symmetric and mixed-symmetric one-phonon states [21]. These calculations also suggest that a 2^+ state in ^{132}Te at an excitation energy of ~1.6 MeV should be the dominant fragment of the $2^+_{1,\mathrm{ms}}$ state.

4. Summary and outlook

We have proven that the technique of projectile-Coulomb excitation is an efficient tool to study the MSSs of low abundant nuclei because it allows complete spectroscopy to be performed within one experiment. Using this technique we have identified the MSSs of several nuclei from the

$A = 130$ region. The new experimental data reveals some exciting new effects but to prove and understand them more completely it is obvious that MSSs of unstable nuclei have to be identified. For example, the experimental identification of the one-phonon MSS of ^{132}Te will show how precise is the prediction for the energy of this state [21]. To study further the shell stabilization effect, the MSSs of ^{140}Nd and ^{140}Ba have to be identified. All these task face the question: can MSSs of radioactive nuclei be identified on the basis of large absolute $M1$ transition rates? In other words, can we measure the lifetimes of these highly excited, off-yrast states in radioactive nuclei? The technique of projectile-Coulomb excitation may provide the answer to this question. Experiments we have performed so far using this technique were aimed at stable isotopes that are either rare, with natural abundances <1%, or that are noble gases which both complicate the production of massive isotopically enriched targets for traditional scattering experiments. Simple scaling of the available data on stable beams with intensities of the order of 10^9 ions/sec to beam intensities of 10^6 ions/sec, achievable for a large number of radioactive isotopes at present facilities such as REX-Isolde, suggests that this technique offers the potential for identifying and studying MSSs in radioactive isotopes. Given the sensitivity of MSSs to details of the local shell structure, they can become an important tool for testing and refining modern quantitative nuclear structure theories.

Acknowledgments

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