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Isovector Quadrupole Excitations in the Valence Shell studied in Projectile Coulomb Excitation

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One-phonon states of heavy vibrational nuclei with mixed proton-neutron symmetry have recently been made accessible by the technique of projectile Coulomb excitation. Gamma-rays following Coulomb excitation of the nuclides ^{136,138}Ce and ^{134}Xe have been measured with the Gammasphere-array run in singles-mode. $M1$, $E2$, and $E3$ transition matrix elements from low-spin states were measured relative to the known $B(E2; 0^+_1 \rightarrow 2^+_1)$ values. The $2^+ \rightarrow 2^+_1$ $M1$ strength distributions up to about 2.7 MeV serve for identifying the main fragment of the $2^+_{1,\mathrm{ms}}$ one-quadrupole phonon mixed-symmetry state. The data are presented and their significance is discussed.

1. INTRODUCTION

Atomic nuclei are naturally occuring examples of strongly-correlated many-body quantum systems formed by two kinds of equivalent particles, protons and neutrons. Therefore, besides the study of the complicated nuclear forces, nuclear structure physics addresses three aspects that are of general interest for such systems. (*i*) The quantum nature of the system induces a shell structure. (*ii*) The many-body character induces collective phenomena due to the strong correlations between the particles. (*iii*) The equivalence of the two components (with respect to their interactions) induces isospin symmetry. In many ways these three aspects form the motivations for much of contemporary nuclear structure research (see, *e.g.*, [1]).

Particularly appealing objects of study are those nuclear structures that combine these three key-aspects, shell structure-dependence, collectivity, and the isospin degree of freedom, such as the isovector quadrupole excitations of the valence shell of heavy nuclei. These nuclear structures have been modeled [2] in simple terms of proton-neutron Mixed-Symmetry States (MSSs) in the framework [3] of the interacting boson model (IBM-2). The IBM-2 represents an effective phenomenological model for collective excitations of the nuclear valence shell and describes the proton-neutron degree of freedom through the inclusion of N_π proton bosons and N_ν neutron bosons where N_ρ is taken as half the number of valence particles (or holes) of isospin ρ. The IBM-2 represents a simple framework for a semi-quantitative understanding for quadrupole-collective isovector excitations of the nuclear valence shell.

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The strong forces between valence protons and neutrons lead to a coupling of collective proton and neutron excitations. This coupling can be quantified in the IBM-2 by the concept of F-spin [4]. Proton bosons and neutron bosons are considered as an F-spin doublet with projections $F_z = +1/2$ (proton boson) and $-1/2$ (neutron boson). F-spin for "elementary" bosons is analogous to isospin for "elementary" nucleons. In the F-spin limit [5], *i.e.*, if F-spin is a good quantum number, the boson wave functions with maximum F-spin $F_{\max} = (N_\pi + N_\nu)/2$ are totally symmetric with respect to the mutual exchange of any two boson isospin labels and hence they are called Full-Symmetry States (FSSs). They correspond to wave functions of the IBM-1 where no distinction at all is made between proton bosons and neutron bosons. The strong coupling between proton and neutron bosons energetically favors the FSSs. This fact is considered one of the reasons why isoscalar collective models such as the IBM-1 are successful in describing many features of collective nuclear structures at low excitation energy [6]. MSSs are those boson states that do not have maximum F-spin, $F \leq F_{\max} - 1$. They contain at least one pair of bosons consisting of one proton boson and one neutron boson that are coupled anti-symmetrically. Due to their isovector character MSSs are particularly sensitive to the isovector parts of the residual interactions in the nuclear valence shell and their outstanding signature is the occurence of strong $M1$ transitions to FSSs with matrix elements of the order of 1 μ_N [7].

Four key questions arise. At what energy do the MSSs occur in heavy nuclei and what are their properties ? How do their properties vary as a function of valence particle numbers and underlying shell model orbitals ? To what extent is F-spin a good quantum number ? How could knowledge on MSSs be extended to exotic nuclei ?

Many authors have approached these questions previously in many ways, see, *e.g.*, [8–18] and references therein. The $J^\pi = 1^+$ scissors mode is the most prominent and best studied example of a MSS. The scissors mode occurs in deformed nuclei. It has been discovered by Richter and his group at the DALINAC electron facility at the Univ. of Technology Darmstadt [8,9]. Considerable progress was recently made on the investigation of MSSs of vibrational nuclei, *e.g.* [19–28]. New species of MSSs with spin, parity, and d-parity quantum numbers $J^{\pi,\pi_d} = 3^{+,+}$ and $2^{+,+}$ have been experimentally identified [21,22,25,27] from pronounced absolute $M1$ transition rates. Gamma-ray transitions *between* MSSs have recently been identified for the first time [20,21,25,27,29] yielding direct evidence for the concept that MSSs represent an entire class of collective states with similar wave functions.

Progress over the last couple of years has been made possible by use of one or more of the following scattering techniques: photon scattering [19,20] electron scattering [28,30], or neutron scattering [15,25,27,31]. Since these scattering techniques require stable isotopically enriched targets, knowledge on MSSs is limited to stable nuclei so far. New techniques with potential applicability to radioactive nuclei are highly desirable. Projectile-Coulomb excitation might offer a new approach to mixed-symmetry nuclear structures in radioactive nuclei that can be made available as energetic ion beams. It has previously been demonstrated [23] that the fundamental $2^+_{1,\mathrm{ms}}$ one-quadrupole phonon MSS can be studied in projectile-Coulomb excitation. We have recently initiated a program for exploiting this method. We report here on the first results [32].

The low-abundant nuclei ^{136,138}Ce and the $N = 80$ isotone ^{134}Xe have been studied at the Gammasphere detector array at Argonne National Laboratory. The data on the $N = 80$ nucleus ^{138}Ce yield the first measurement of an F-spin mixing matrix element which has been determined directly from the dominant fragment of the lowest-lying state with mixed-symmetry character, the one-phonon $2^+_{1,\mathrm{ms}}$ state. MSSs of ^{138}Ce were previously unknown.

2. EXPERIMENTS

In order to identify the one-phonon $2^+_{1,\mathrm{ms}}$ state of the vibrational nucleus ^{138}Ce we have performed a Coulomb excitation experiment at Argonne National Laboratory. A beam of ^{138}Ce ions was delivered by the ATLAS accelerator with an intensity of about 1 pnA. It has been extracted from the ATLAS-ECR ion source loaded with cerium material moderately enriched in the isotope ^{138}Ce which only has a natural abundance of 0.25%. The ion beams with energies of 480 MeV and 400 MeV bombarded a 1 mg/cm^2 thick carbon target for 15 h and 5 h, respectively. The γ-rays issued by the predominantly one-step Coulomb-excited projectiles were detected with the Gammasphere array which

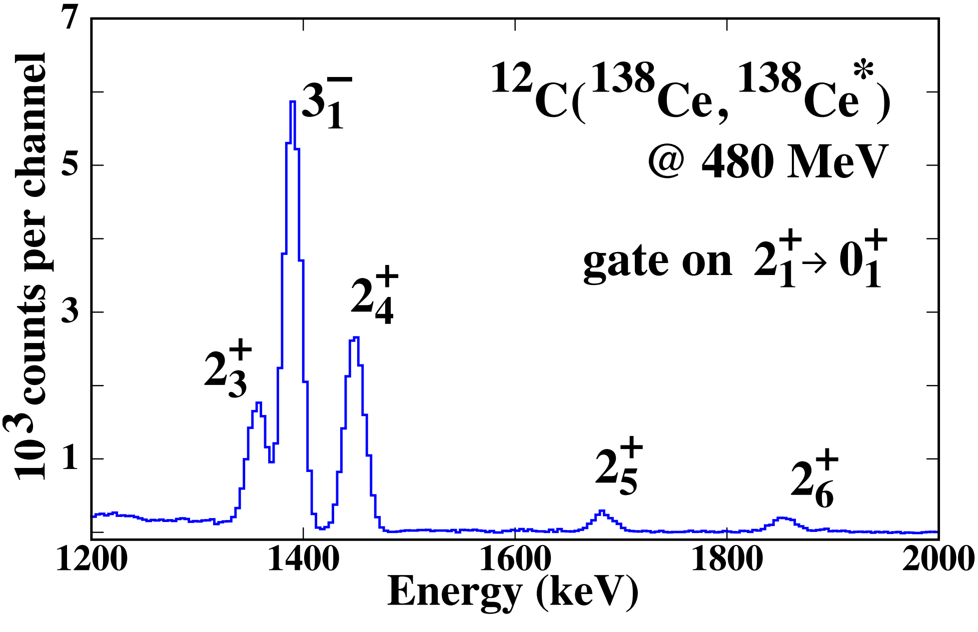

Figure 1. Doppler-corrected background-subtracted γ-ray spectrum observed with Gammasphere in the Coulomb excitation reaction of a ^{138}Ce ion beam at 480 MeV on a 1 mg/cm^2 thick natural carbon target in coincidence with the 789-keV $2^+_1 \to 0^+_1$ transition of ^{138}Ce. The five transitions shown feed directly the 2^+_1 state and originate from the states indicated by the labels.

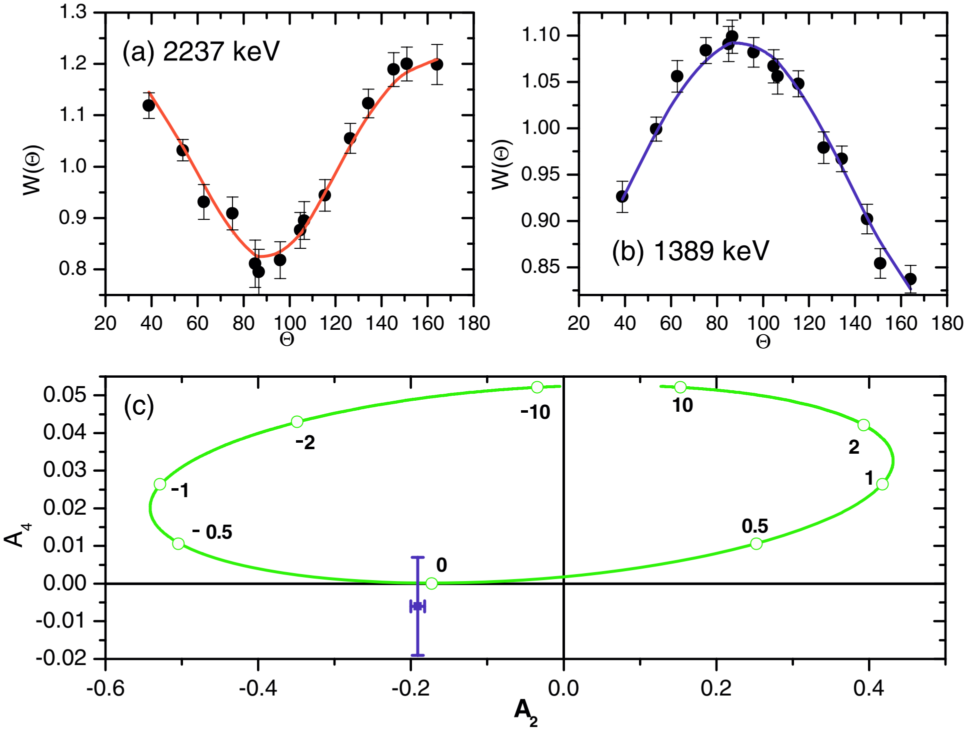

Figure 2. Assignment of γ-ray multipolarities from angular γ-ray intensity distributions with respect to the beam direction. The top shows the Lorentz boost-corrected angular distributions for the $2^+_4 \rightarrow 0^+_1$ (a) and the $3^-_1 \rightarrow 2^+_1$ (b) stretched $E2$ and stretched $E1$ transitions at 2237 keV and at 1389 keV, respectively. The bottom shows the experimental distribution parameters for the latter transition in comparison to the expected values as a parametric function of a possible quadrupole/dipole mixing ratio δ. The transition at 2237 keV has quadrupole character, the 1389-keV transition is consistent with pure $3 \rightarrow 2^+_1$ dipole radiation ($\delta = 0$) and the $2^+_4 \rightarrow 2^+_1$ transition with $\delta = +0.18(5)$ consists of dipole radiation to 97(2)%.

consisted of 98 HPGe detectors arranged in 17 rings around the beam axis. Gammasphere was used in singles mode at an average counting rate of about 4000 events per second. A total of 2.4×10^8 events of γ-ray fold 1 or higher were collected at a beam energy of 480 MeV in 15 h beam time.

Figure 1 shows a part of the γ-ray energy spectrum in coincidence with the $2^+_1 \rightarrow 0^+_1$ transition in ^{138}Ce. The velocity of the ^{138}Ce ejectiles amounted to $v/c \approx 6.9\%$. This induced a Doppler-broadening of the γ-ray lines leading to an effective energy resolution of about 1.4%. Two new γ-rays at 1354 keV and at 2143 keV were observed, the first

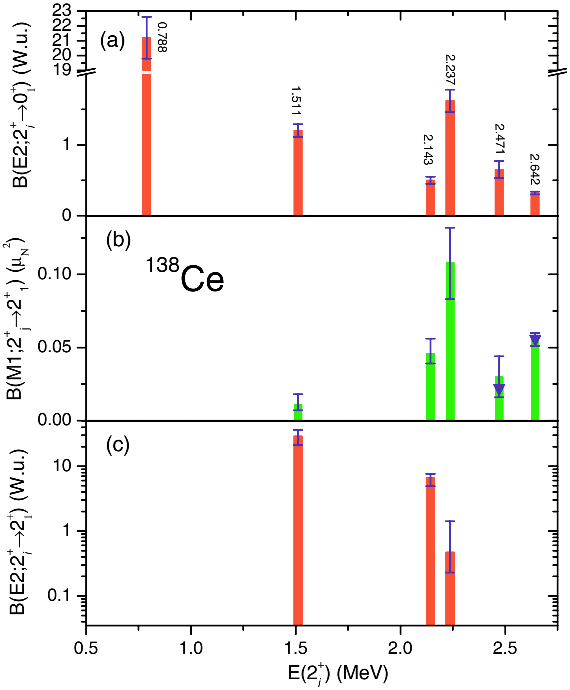

Figure 3. $E2$ and $M1$ transition strength distributions for all observed 2^+ states of ^{138}Ce below 2.7 MeV excitation energy. Data are taken from Ref. [32].

one of them being in coincidence with the 789-keV transition from the 2_1^+ state to the ground state of ^{138}Ce. This γ-ray coincidence, the 2143-keV ground state transition, and the predominantly one-step population mechanism prove the existence of the previously unknown 2_3^+ state of ^{138}Ce at 2143 keV. Beside the 0_2^+, 3_1^-, and 4_1^+ states, the first six $2_{1,2,3,4,5,6}^+$ states up to an excitation energy of 2.7 MeV were observed.

Assignments of γ-ray multipolarities and spin quantum numbers are based on angular γ-ray intensity distributions as it is exemplified in Fig. 2. The 722-keV $2_2^+ \to 2_1^+$ transition is assigned 80(5)% $E2$ while the $2_{3,4}^+ \to 2_1^+$ transitions at 1354 and 1448 keV contain 59(4)% and 97(2)% $M1$ contribution, respectively. Measurement of the COULEX cross sections relative to the 2_1^+ state with a ground state transition strength of $B(E2; 2_1^+ \to 0_1^+) = 21.2(14)$ W.u. [33] yields information on the $B(E2; 2_i^+ \to 0_1^+)$ transition strength distribution. Observed decay branching ratios $I_\gamma(2_i^+ \to 2_1^+)/I_\gamma(2_i^+ \to 0_1^+)$ and deduced $E2/M1$ multipole mixing ratios for the $2_i^+ \to 2_1^+$ transitions also enable us to determine the $B(E2; 2_i^+ \to 2_1^+)$ and $B(M1; 2_i^+ \to 2_1^+)$ transition strength distributions as shown in Fig. 3.

Similar data have been taken for the $Z = 58$ isotope ^{136}Ce and for the $N = 80$ isotone ^{134}Xe. The data are presently under analysis.

3. DISCUSSION

The $B(M1; 2^+_i \rightarrow 2^+_1)$ strength distribution up to 2.7 MeV is found to be dominated by the 2^+_4 state at 2.237 MeV with an absolute $M1$ matrix element of $|\langle 2^+_1 \parallel M1 \parallel 2^+_4\rangle| = 0.78\,\mu_N$. This state can be considered as the dominant fragment of the one-phonon $2^+_{1,\mathrm{ms}}$ state of ^{138}Ce with $F = F_{\mathrm{max}} - 1$. Its excitation energy corresponds within 5% to the excitation energy of the $2^+_{1,\mathrm{ms}}$ state of the neighboring even-even $N = 80$ isotone ^{136}Ba which has been previously identified at 2.129 MeV from the transition strength $B(M1; 2^+_4 \rightarrow 2^+_1) = 0.26(3)\,\mu_N^2$ deduced from photon scattering data [19]. This corresponds to a larger $M1$ matrix element of $|\langle 2^+_1 \parallel M1 \parallel 2^+_4\rangle|(^{136}\mathrm{Ba}) = 1.14\,\mu_N$.

In contrast to the situation in ^{136}Ba, the nearby 2^+_3 state of ^{138}Ce at 2.143 MeV also acquires a considerable $M1$ strength with an $M1$ matrix element of $|\langle 2^+_1 \parallel M1 \parallel 2^+_4\rangle| = 0.54\,\mu_N$. We interpret this situation as a fragmentation of the $2^+_{1,\mathrm{ms}}$ one-phonon mode [13,15,31]. The $2^+_{3,4}$ states share the total $M1$ strength $\sum B(M1; 2^+_{3,4} \rightarrow 2^+_1) = 0.18\,\mu_N^2$ which is about 30% less than in ^{136}Ba. These two states are separated from the next 2^+ states by more than 230 keV. We, thus, consider a two-state mixing scenario

$$\begin{aligned} |2^+_3\rangle &= \alpha|2^+_{\mathrm{FSS}}\rangle - \beta|2^+_{1,\mathrm{ms}}\rangle \\ |2^+_4\rangle &= \beta|2^+_{\mathrm{FSS}}\rangle + \alpha|2^+_{1,\mathrm{ms}}\rangle \end{aligned}$$

between the $2^+_{1,\mathrm{ms}}$ one-phonon MSS and a close-lying FSS[1]. Figure 4 schematically shows the rationale of this two-state mixing scenario. Since the 2^+_1 state can be considered as a FSS and since $M1$ transitions between any two FSSs are forbidden, the ratio of the wave function probabilities can be obtained from the ratio of the $M1$ transition strengths to

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[1] The one-phonon $2^+_{1,\mathrm{ms}}$ state is the lowest MSS in a vibrational IBM-2 spectrum and might thus be surrounded only by FSSs or non-collective states outside of the IBM

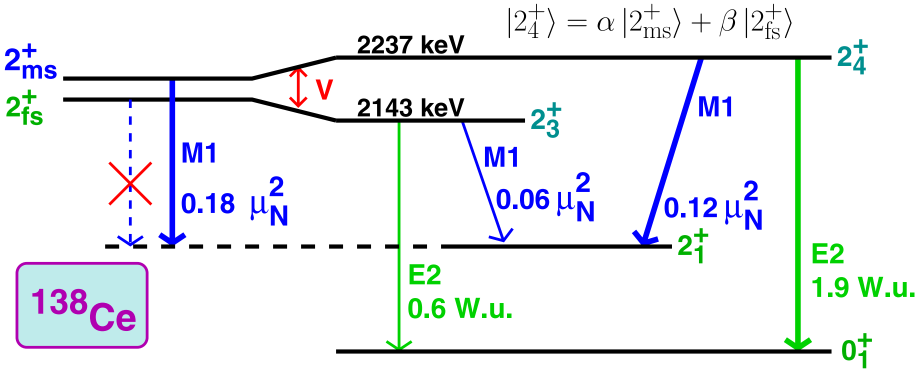

Figure 4. Schematic of the mixed-symmetry–full-symmetry two-state mixing scenario discussed in the text.

the 2_1^+ state

$$\frac{\beta^2}{\alpha^2} = \frac{B(M1; 2_3^+ \to 2_1^+)}{B(M1; 2_4^+ \to 2_1^+)} = \frac{0.058(6)}{0.122(10)} = 0.48(6) \tag{1}$$

which results in $\alpha^2 = 68(3)\%$ and $\beta^2 = 32(3)\%$. From the energy separation of 94 keV between the $2_{3,4}^+$ states a mixing matrix element of $V_{F-\mathrm{mix}} = 44(3)$ keV can be concluded. A similar analysis for the data on the isotone ^{136}Ba results in a much smaller mixing matrix element of $V_{F-\mathrm{mix}}(^{136}\mathrm{Ba}) < 10$ keV. Since the neutron configuration is not expected to differ much for the isotones $^{136}\mathrm{Ba}_{80}$ and $^{138}\mathrm{Ce}_{80}$, 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 $\pi(1g_{7/2})$ 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 $\pi(2d_{5/2})$ sub-shell in $^{138}_{58}$Ce the corresponding configuration for $^{136}_{56}$Ba can still be formed within the $\pi(1g_{7/2})$ sub-shell [34]. 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 might be considered as a *shell-stabilization of mixed-symmetry structures* near sub-shell closures [32]. This mechanism is consistent with the observed reduction of the $M1$ strength in ^{138}Ce with respect to ^{136}Ba.

Very recent data on $E2/M1$ multipole mixing ratios in the isotope ^{136}Ce obtained from observed $\gamma\gamma$-angular correlations following ^{136}Pr β-decay reactions indicate a mixing matrix element $V_{F-\mathrm{mix}}(^{136}\mathrm{Ce}) = 43(5)$ keV [35] which is close to the value for ^{138}Ce discussed above. The factor of 4 difference in the F-spin mixing matrix element between these Ce isotopes at the $Z = 58$ sub-shell closure on one side and the $Z = 56$ nucleus ^{136}Ba on the other demonstrates the specific sensitivity of MSSs to the underlying shell structure. This fact makes the MS structures a particularly appealing object of study.

4. OUTLOOK

The technique of projectile-Coulomb excitation has been demonstrated to give access to one-quadrupole phonon excitations with proton-neutron symmetry in heavy vibrational nuclei. Experiments have been performed so far for 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 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 Oak Ridge, REX-Isolde or at future facilities such as FAIR, MAFF, and RIA 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.

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