In-Beam γ-Spectroscopy of Low-Spin Mixed-Symmetry States of ^{138}Ce with Gammasphere in Singles-Mode

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Abstract. Gamma-rays from the nuclide ^{138}Ce have been measured with the Gammasphere-array following Coulomb excitation. Beams of ^{138}Ce ions were focussed on a carbon target at beam energies of 480 and 400 MeV. Gamma-ray yields and relative Coulomb excitation cross sections were measured in singles-mode. $M1$, $E2$, and $E3$ transition matrix elements from low-spin states were measured relative to the known $B(E2;0^+_1 \to 2^+_1)$. The $2^+ \to 2^+_1$ $M1$ strength distribution from the lowest six 2^+ states up to 2.7 MeV enables us to identify the 2^+_4 state of ^{138}Ce as the dominant fragment of the one-phonon $2^+_{1,\mathrm{ms}}$ mixed-symmetry state with F-spin quantum number $F_{\max} - 1$. From its mixing with the nearby 2^+_3 state an F-spin mixing matrix element of 44 keV can be estimated.

Keywords: *radioactivity:* Coulomb excitation of ^{138}Ce on carbon target, $E_{\mathrm{beam}} = 400$, 480 MeV; *measured:* γ-singles, $\gamma\gamma$-coinc., $I_\gamma(\theta)$, Gammasphere-array; *deduced:* E_x, J^π, multipole mixing ratio δ, COULEX cross section, EM matrix elements, mixed-symmetry state, F-spin mixing
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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 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

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is taken as half the number of valence particles (or holes) of isospin ρ.

The strong forces between valence protons and neutrons leads 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 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 nuclear collective 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 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, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18] and references therein. Considerable progress was recently made on the investigation of MSSs of vibrational nuclei, *e.g.* [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. We report here on a measurement of an F-spin mixing matrix element for the $N = 80$ nucleus ^{138}Ce which has been determined directly from the lowest-lying state with predominantly mixed-symmetry character, the one-phonon $2^+_{1,\mathrm{ms}}$ state. No MSS of ^{138}Ce was previously known.

EXPERIMENT

In order to identfy 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 natural cerium in which ^{138}Ce has a 0.25% abundance. 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 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 $2^+_1 \rightarrow 0^+_1$

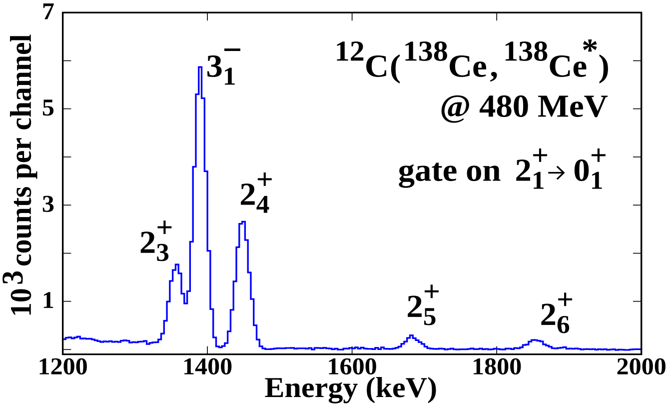

FIGURE 1. Doppler-corrected background-subtracted γ-ray spectrum observed with GAMMASPHERE in the Coulomb excitation reaction of a ^{138}Ce ion beam at 480 MeV on a 1 mg/cm^2 thick natural carbon target in coincidence with the 789-keV $2_1^+ \rightarrow 0_1^+$ transition of ^{138}Ce. The five transitions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

transition in ^{138}Ce. The velocity of the γ-ray emitting ^{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 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. The 722-keV $2_2^+ \rightarrow 2_1^+$ transition is assigned 80(5)% $E2$ while the $2_{3,4}^+ \rightarrow 2_1^+$ 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 $B(E2;2_1^+ \rightarrow 0_1^+) = 21.2(14)$ W.u. [30] yields information on the $B(E2;2_i^+ \rightarrow 0_1^+)$ transition strength distribution. Observed decay branching ratios $I_\gamma(2_i^+ \rightarrow 2_1^+)/I_\gamma(2_i^+ \rightarrow 0_1^+)$ and deduced $E2/M1$ multipole mixing ratios for the $2_i^+ \rightarrow 2_1^+$ transitions also enable us to determine the $B(E2;2_i^+ \rightarrow 2_1^+)$ and $B(M1;2_i^+ \rightarrow 2_1^+)$ transition strength distributions.

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 $|\langle 2_1^+ \| M1 \| 2_4^+ \rangle| = 0.78\,\mu_N$. This state can be considered as the dominant fragment of the one-phonon $2_{1,\mathrm{ms}}^+$ state of ^{138}Ce with $F = F_{\max} - 1$. 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]. 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 the 2^+_1 state

$$\frac{\beta^2}{\alpha^2} = \frac{B(M1;2^+_3 \rightarrow 2^+_1)}{B(M1;2^+_4 \rightarrow 2^+_1)} \tag{1}$$

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 $V_{F-\mathrm{mix}} = 44(4)$ 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 already the leading one-phonon 2^+ proton configuration 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 [32]. Thus, the one-phonon $2^+_{1,\mathrm{ms}}$ state of ^{136}Ba is expected to consist of considerably simpler configurations than the more highly excited predominantly symmetric states that surround it at about 2 MeV excitation energy. 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*. This scenario is consistent with the observed reduction of $M1$ strength in ^{138}Ce with respect to ^{136}Ba.

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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

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