Stabilization of Nuclear Isovector Valence-Shell Excitations


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Excited states in $^{138}$Ce have been studied via the $^{12}$C($^{138}$Ce, $^{138}$Ce') Coulomb excitation reaction at 480 MeV. Relative cross sections have been determined from the γ-ray yields observed with Gammasphere. The $E2$ and $M1$ strength distributions between the lowest six $2^+$ states up to 2.7 MeV enables us to identify the $2^+_1$ state in $^{138}$Ce as the dominant fragment of the one-phonon $2^+_1$ms mixed-symmetry state. Mixing between this level and a nearby isoscalar state is observed and is more than 4 times larger than in the neighboring isotope $^{136}$Ba. This is direct evidence that the stability of mixed-symmetry states strongly depends on the underlying subshell structure.

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Atomic nuclei are examples of mesoscopic two-fluid quantum systems. The physics of these systems is determined by three main properties: the many-body aspect, the quantum nature, and the two-fluid character. Nuclear phenomena that reflect these three properties are collectivity, shell structure, and the isospin degree of freedom. Of particular importance for studying the mutual balance of these aspects 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 MSS, the $J^\pi = 1^+$ scissors mode, was first discovered in nuclei [2] and was reported or suggested to exist in Bose-Einstein condensates [3] and metallic clusters [4].

The fundamental MSS in collective two-fluid quantum systems with quadrupole residual interactions, such as heavy nuclei, is the one-quadrupole phonon $2^+_1$ms state [1]. Because of its role as a building block of isovector excitations in nuclei, and in quadrupole-collective two-fluid quantum systems in general, it is important to study its properties and the mechanisms that determine those. However, information on MSSs is scarce. Due to experimental challenges, MSSs have been observed so far for stable nuclei only. The best examples are found in the mass region $A = 90$ region [5–7], while there are only a few reported cases in the $A = 130$ region below the $N = 82$ shell closure, e.g., [8–10]. Apparently, to investigate MSSs, new experimental methods, in particular, those that could potentially be applied to radioactive isotopes, are needed.

It is the purpose of this Letter to demonstrate that the observation of γ rays from inverse kinematics Coulomb excitation with a $4\pi$ spectrometer can identify and probe the $2^+_1$ms state of any vibrational nucleus that can be made available as an ion beam. Here, we study the nucleus $^{138}$Ce which has a natural abundance of 0.25%. The technique is generic and equally applicable to radioactive beams [11] that can be produced with sufficient intensity ($\sim 10^6$ ions/s for detailed spectroscopy, $\sim 10^7$ ions/s for identification). The high selectivity for $J = 2$ states avoids much traditional searching and reveals the entire $E2$ strength distribution in a few hours. The data, when compared to the neighboring $N = 80$ isotope $^{136}$Ba [10], provide first evidence for a direct influence of subshell structure on the properties of the MSSs. This can be viewed as shell stabilization of the quadrupole isovector excitations. Microscopic wave functions for the $2^+_1$ms state in $^{136}$Ba have previously been calculated [12] in the quasiparticle-phonon model [13] and support this interpretation.

The experiment was carried out at Argonne National Laboratory. The $^{138}$Ce beam with intensity of $\approx 1$ pnA 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 $2.4 \times 10^8$ events of γ-ray fold 1 or higher was collected in about 14 hours.

The contribution of the room background was eliminated in the offline 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 from $^{40}$K, is shown in Fig. 1. All γ rays in the spectrum originate from $^{138}$Ce nuclei recoiling with $v/c = 6.9\%$. Most of these γ rays have already been identified in $^{138}$Ce [15–19]. We have observed two new transitions with respective energies of 1354 and 2143 keV. Because of the Doppler...
broadening, the energy resolution is 1.4% and translates into γ-ray energy uncertainties of about 1 keV. This excludes the possibility that the new γ rays originated from the decay of the 4_2^+ state at 2137 keV. About 3% of the data have γ-ray fold higher than 1. The coincidence relationships suggest that the two new γ rays depopulate a level at 2143 keV in ^138Ce, which is observed here for the first time.

The coincidences further show that any contribution of the 1348-keV, 4_2^+ → 2_1^+ transition [19] to the peak area of the 1354 keV line is statistically insignificant. The spectroscopic information is summarized in Table I.

The spins of the levels were assigned on the basis of an angular distribution analysis [21]. The intensities of the γ rays were measured over the 15 rings of Gammasphere, corrected for the Lorentz boost [22] and fitted with the angular distribution function [21]. The experimental A_2/A_0 and A_4/A_0 coefficients for the stretched transitions unambiguously determined the γ-ray multipolarity and, hence, the spins of the excited states and their orientations. The latter were used to determine the multipole mixing ratios for the transitions between the excited states, as illustrated in Fig. 2. In the cases where the stretched transitions to the ground state are weak and do not allow for an angular distribution analysis, the orientation parameters from the closest level were used. The results for the mixing ratios are summarized in Table I. The mixing ratio for the 1448 keV transition is small which shows that the 2_1^+ → 2_1^+ transition is 97(2)% of magnetic dipole character.

In the present experiment, we have observed the decay of the 0_2^+, 3_1^−, and 4_1^+ states, and the first six 2_1^+, 3_1^−, 4_1^+, 5_1^−, 6_1^+ states up to an excitation energy of 2.7 MeV. The relative γ-ray

![Graph](image)

**FIG. 1** (color online). Background-subtracted, Doppler-corrected γ-ray spectrum in ^138Ce observed with Gammasphere after Coulomb excitation on a carbon target.

| E_{level} (keV) | J^π | τ (fs) | E_γ (keV) | I_γ | J^π_{final} | A_2/A_0 | A_4/A_0 | δ | Transition strength
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<tbody>
<tr>
<td>788 2_1^+</td>
<td></td>
<td></td>
<td>2970(200)</td>
<td>788</td>
<td>10^6(97)</td>
<td>0_1^+</td>
<td>0.112(5)</td>
<td>−0.003(7)</td>
<td>B(E2) = 21.2(14)</td>
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<tr>
<td>1476 0_2^+</td>
<td></td>
<td></td>
<td>688</td>
<td></td>
<td>69(6)</td>
<td>2_1^+</td>
<td></td>
<td></td>
<td>B(E2) = 1.16(8)</td>
</tr>
<tr>
<td>1511 2_2^+</td>
<td></td>
<td></td>
<td>1510</td>
<td></td>
<td>9682(59)</td>
<td>0_1^+</td>
<td>0.201(7)</td>
<td>−0.056(10)</td>
<td>B(M1) = 0.011(2)</td>
</tr>
<tr>
<td>1826 4_1^+</td>
<td></td>
<td></td>
<td>1038</td>
<td></td>
<td>2565(15)</td>
<td>2_1^+</td>
<td>0.347(10)</td>
<td>−0.033(13)</td>
<td>B(E2) = 28(2)</td>
</tr>
<tr>
<td>2143 2_1^−</td>
<td></td>
<td></td>
<td>2143</td>
<td></td>
<td>378(8)</td>
<td>0_2^+</td>
<td>−0.203(15)</td>
<td>−0.005(15)</td>
<td>B(M1) = 0.058(6)</td>
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<tr>
<td>2177 3_1^−</td>
<td></td>
<td></td>
<td>1354</td>
<td></td>
<td>1173(13)</td>
<td>2_1^+</td>
<td>−0.191(9)</td>
<td>−0.006(12)</td>
<td>B(E2) = 7.5(9)</td>
</tr>
<tr>
<td>2237 2_1^−</td>
<td></td>
<td></td>
<td>2237</td>
<td></td>
<td>1811(25)</td>
<td>0_2^+</td>
<td>0.298(21)</td>
<td>−0.084(27)</td>
<td>B(E2) = 1.86(16)</td>
</tr>
<tr>
<td>2471 2_1^−</td>
<td></td>
<td></td>
<td>2471</td>
<td></td>
<td>508(13)</td>
<td>0_2^+</td>
<td>0.308(14)</td>
<td>0.012(18)</td>
<td>B(M1) = 0.122(10)</td>
</tr>
<tr>
<td>2642 2_0^+</td>
<td></td>
<td></td>
<td>2642</td>
<td></td>
<td>87(35)</td>
<td>0_2^+</td>
<td>0.347(10)</td>
<td>−0.033(13)</td>
<td>B(E2) = 0.74(20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1854</td>
<td></td>
<td>250(10)</td>
<td>2_1^+</td>
<td></td>
<td></td>
<td>B(M1) ≤ 0.034(3)</td>
</tr>
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</table>

^aB(E2) values are given in W.u.(1 W.u. = 42.4 e^2 fm^4), B(M1) values are given in μ^2_N, and the B(E3) value is given in e^2 b^3.
^bFrom Ref. [20].
^cThis transition can only be observed in coincidence with the 2_1^+ → 0_1^+ transition.
^dThe orientation of the state is assumed to be the same as for the 2_1^- state.
^eSince the multipole mixing ratio is not measured we assume here δ = 0 for an upper limit of the M1 transition strength.
^fDetermined by the branching ratio from Ref. [17].
yields (Table I) with respect to the $2^+_1$ state measure the relative Coulomb excitation (CE) cross sections. These data were fitted to the Winther–de Boer theory [23] using a multiple CE code [24] 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 $B(E2; 0_1^+ \rightarrow 2_1^+) = 0.450(30)e^2b^2$ [20,25]. Unknown quadrupole moments of excited states were varied between the extreme rotational limits which introduces additional uncertainties for the matrix elements of about 2%. An unambiguous set of matrix elements $\langle I_T^f || EA || 0_1^+ \rangle$ for one-step excitations of interest was obtained. The matrix elements for the excited $2^+_1$ states together with observed decay branching ratios $I_\gamma(2^+_2 \rightarrow 2^+_1)/I_\gamma(2^+_2 \rightarrow 0^+_1)$ and deduced $E2/M1$ mixing ratios for the $2^+_2 \rightarrow 2^+_1$ transitions provide the $B(E2)$ and $B(M1)$ transition strengths (cf. Table I and Fig. 3).

The $2^+_2$ state at 2.237 MeV dominates the $2^+_2 \rightarrow 2^+_1 M1$ strength distribution. This identifies this level as the major fragment of the one-phonon $2^+_1$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 $2^+_1$ms strength are spread over nearby $2^+$ levels. In particular, the $2^+_2$ state at 2.143 MeV acquires a considerable $B(M1; 2^+_2 \rightarrow 2^+_1)$ value. The $2^+_2$ states are separated from the next $2^+$ state by more than 230 keV. For further analysis of the mixing of the $2^+_1$ms state with symmetric configurations we can, thus, consider a two-state mixing scenario between the $2^+_1$ms MSS and a close-lying fully symmetric state (FSS). Treating the $2^+_1$ state as a FSS is justified because the one-phonon $2^+_1$ms state is the lowest MSS in vibrational nuclei and can, thus, be surrounded only by FSSs. Since $M1$ transitions between FSSs ($2^+_1$ is a FSS) are forbidden by $F$-spin selection rules, the mixing amplitudes can be obtained from the $M1$ strengths. This scenario leads to a mixing matrix element of $44(3)$ keV. The measured finite $M1$ strength between the $2^+_2$ and the $2^+_1$ FSSs might indicate the presence of some $M1$ strength from sources outside of the IBM-2 framework that one may want to take into account for arriving at even more model-independent information on the $F$-spin mixing matrix element. Therefore, we have extended the mixing calculations assuming that $M1$ strength between FSSs had the size of the measured $B(M1; 2^+_2 \rightarrow 2^+_1)$ value. In this case the mixing problem has two solutions leading to mixing matrix elements of 47 and 30 keV. As our central result we have adopted $V_{F\rightarrow 0} = 44(3)_{-14}^{+3}$ keV where the first parenthesis gives the statistical uncertainty and the second estimates systematical errors of the mixing analysis. The $F$-spin mixing matrix element is determined here for the first time in a procedure involving a state with predominantly mixed-symmetry character.

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 $2^+_1$ state at 2.129 MeV in $^{136}$Ba has previously been identified as a one-phonon $2^+_1$ms state [10] and its excitation energy agrees to within 5% with the excitation energy of the $2^+_1$ms state in $^{138}$Ce. However, in $^{136}$Ba the transition strength $B(M1; 2^+_1 \rightarrow 2^+_2) = 0.26(3)\mu^2_N$ [10] is larger than the total $M1$ strength $\sum B(M1; 2^+_1 \rightarrow 2^+_3) = 0.180(13)\mu^2_N$ shared between the $2^+_1$ 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 collec-
tive states points precisely to their sensitivity to the under-
ing subshell structure and enables us to study quantita-
tively the mutual balance between collective and single-
particle contributions in the valence-shell isovector excita-
tions.

In the framework of the quasiparticle-phonon model
(QPM) [13], Lo Iudice and Stoyanov [12] have shown
that the microscopic structure of the one-phonon FSSs
and MSSs in $^{136}$Ba is dominated by seniority-two ex-
citations in the $\nu(h_{11/2})$ and in the $\pi(g_{7/2})$ orbitals.
Analogously, the leading components of two-phonon states
of $^{136}$Ba are seniority-four excitations involving the same
orbitals [12], while the three-phonon states are predomi-
nantly seniority-six excitations that require an additional
proton excitation to the $d_{5/2}$ orbital. Therefore, the one-
phonon $2^+_{1,ms}$ state of $^{136}$Ba has a simpler configuration than
the more highly excited, predominately symmetric states
that surround it around 2 MeV excitation energy. This
difference in wave function complexity suppresses mixing
induced by the proton-neutron residual interaction, in
agreement with the experimentally determined small mix-
ing matrix element $V_{F-\text{mix}}(^{136}$Ba) $< 10$ keV.

This situation changes when going to the $N = 80$ iso-
tone $^{138}$Ce. Ground state spins for proton-odd $N = 80$
isotope indicate the presence of a $\pi(g_{7/2})$ subshell closure
at $Z = 58$ (cerium). Therefore, the leading one-phonon $2^+$
proton configuration of $^{138}$Ce requires promotion of pro-
tons to the $d_{5/2}$ orbital. The higher-seniority $2^+$ states are
then also formed within the same proton space as the one-
phonon states. Consequently, the proton configuration of the
$2^+_{1,ms}$ state does not differ substantially from that of the
nearby $2^+$ states at 2 MeV. Residual proton-neutron in-
teractions, such as the quadrupole-quadrupole interaction,
easily lead to an enhanced mixing which concurs with our
measurement of $V_{F-\text{mix}}(^{138}$Ce) $= 44(3)(+^3_{14^-})$ keV.

This scenario also implies an increased neutron charac-
ter for the symmetric $2^+_1$ state at $Z = 58$ with respect to
the pure $F$-spin limit since the excitations within the $\nu(h_{11/2})$
orbital are energetically favorable over promotion of pro-
tons to higher orbitals. Such an asymmetry causes a reduc-
tion of the total $M1$ transition strength between the one-
phonon $2^+$ states of $^{138}$Ce relative to $^{136}$Ba.

The proposed picture suggests that exceptionally pure
one-phonon MSSs can be observed in nuclei where one-
phonon states have simple configurations while, due to
nearby subshell closures, multiphonon excitations must
contain more involved configurations. Such situations oc-
cur when both proton and neutron numbers differ by one
pair from a (sub-)shell closure, such as for the nucleus
$^{98}$Mo [5]. This mechanism might also explain the fragmen-
tation and strength reduction of $2^+_{1,ms}$ states in stable $^{100}$Cd
and Te neutron midshell nuclei, see, e.g., Ref. [26], and is
expected to apply in the same way to other two-fluid
quantum systems.

In summary, we have studied $^{138}$Ce using projectile
Coulomb excitation, an experimental technique which
can straightforwardly be applied to RIBs. The data yields
the $E2$ and $M1$ strength distributions between low spin
states which reveals the $2^+_{1,ms}$ state of $^{138}$Ce. In contrast
to the isotope $^{136}$Ba, the $2^+_{1,ms}$ state is strongly mixed with
a nearby $2^+$ FSS with a mixing matrix element of $V_{F-\text{mix}} =
44(3)(+^3_{14^-})$ keV first measured directly for a MSS. The
observed mixing in $^{138}$Ce can be attributed to the lack of
shell stabilization at the proton $g_{7/2}$ subshell closure. The
evolution of the MSSs from $^{136}$Ba to $^{138}$Ce shows for the
first time that the strength concentration of isovector ex-
citations in the valence shell reflects the mutual balance
between the isospin degree of freedom and the shell
structure.

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