Isovector quadrupole excitations in the valence shell of the vibrator nucleus ^{136}Ba: Evidence from photon scattering experiments

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Photon scattering experiments have been performed on the nucleus ^{136}Ba with photon energies of $E_\gamma \leq 4.1$ MeV and $E_\gamma \leq 2.8$ MeV. At 2.1 MeV clear evidence for the 2^+_{ms} state has been found. From the measured lifetime we extract signatures for the isovector quadrupole excitation in the valence shell: a weakly collective $E2$ decay to the ground state and a strong $M1$ decay to the 2^+_1 state. As the resonant photon scattering with bremsstrahlung is a complete reaction, we can conclude that the 2^+ state at 2129 keV is a rather pure 2^+_{ms} state with little fragmentation. This is in contrast to the 1^+ scissors state. A comparison with an IBM-2 calculation is given. [S0556-2813(98)02908-2]

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I. INTRODUCTION

Isospin is a useful concept in nuclear structure physics due to its conservation by nuclear forces. Conservation of isospin suggests that it is reasonable to decompose the quadrupole excitations of the protons and the neutrons into isoscalar and isovector excitations. In this paper we will focus on the isovector quadrupole excitation in the valence shell of a heavy nonmagic nucleus ^{136}Ba.

The description of isovector excitations in the valence shell is possible using a nuclear structure model, which treats the valence space of a heavy nucleus separately with regards to protons and neutrons. Such a model is, e.g., the proton-neutron version [1–3] of the interacting boson model (IBM-2), which we will employ below. Apart from low-lying symmetric states which are multiple isoscalar quadrupole excitations, there exist also eigenstates of the IBM-2 Hamiltonian with wave functions, which are not symmetric with respect to the exchange of proton and neutron bosons [4,5]. These states are called mixed-symmetry states and they correspond to multiple combinations of isoscalar and isovector quadrupole excitations.

Formally, the mixed-symmetry states are distinguished from the symmetric ones by the F spin quantum number [4], which is for bosons the analog of isospin for nucleons. In most practical applications F spin is a rather good quantum number for the low-lying states. For the following discussion we assume that F spin is good. While the symmetric states with $F=F_{max}=(N_\pi+N_\nu)/2$ decay by collective electric quadrupole transitions, the lowest mixed-symmetry states with $F=F_{max}-1$ predominantly decay to the symmetric states by magnetic dipole transitions. The best studied mixed-symmetry state is the 1^+ state which in deformed nuclei appears as a scissors mode [6]. The scissors mode was discovered [7] in Darmstadt in the early 1980's and is nowadays well established in the different regions of deformed nuclei (for a recent review on this topic see Ref. [8]). The $M1$ excitation strength is usually distributed among several 1^+ states forming the fragments of the scissors mode. The total $M1$ strength is proportional to the $E2$ excitation strength of the 2^+_1 state, see, e.g., Refs. [9,10]. In the nuclei of the rare earth region the scissors mode lies at an excitation energy of about 3 MeV [11]. Besides the cases of strongly deformed nuclei the scissors mode has been observed recently both in weakly deformed [12] and in γ-soft nuclei [13,14], as well.

The other known example of a mixed-symmetry state is the 2^+_{ms} state. There are observations of 2^+_{ms} states in spherical vibrators and γ-soft nuclei in the $100<A<150$ mass region [15–17]. Only in a few cases could the short lifetime of the collective 2^+_{ms} state be measured. This was done by Coulomb excitation [18], and by a DSAM analysis of γ rays observed after inelastic neutron scattering [19,20], or after an (α,n) reaction [21]. However, due to reaction mechanisms, the experimental sensitivities for the detection of all the large fragments of the 2^+_{ms} state depend on their excitation energies and/or the total level density in this energy region around 2 MeV. It might have happened that even large fragments of the 2^+_{ms} state remained undetected which could change the interpretation of the observations. It is, thus, desirable to apply a highly sensitive, selective reaction mechanism in order to obtain complete information about the large fragments of the 2^+_{ms} state. First, we discuss the signatures of the isovector quadrupole excitation in the valence shell, which are expected theoretically. Second, we give the results of our photon scattering investigation and compare them, third, to a calculation in the framework of the interacting boson model.

II. SIGNATURES OF THE ISOVECTOR QUADRUPOLE EXCITATION IN THE VALENCE SHELL

In order to find a selective reaction for the population of the isovector quadrupole excitation in the valence shell we

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consider the Q-phonon scheme [22–25] in the IBM-2 [26]. By definition, the isoscalar quadrupole excitation in the valence shell takes the form

$$|2^+_{S,\mathrm{val}}\rangle=\mathcal{N}_S(Q_\pi+Q_\nu)|0^+_1\rangle\equiv\mathcal{N}_S Q_S|0^+_1\rangle, \quad (1)$$

where

$$Q_\rho=s^+_\rho\tilde{d}_\rho+d^+_\rho s_\rho+\chi(d^+_\rho\tilde{d}_\rho)^{(2)} \quad (2)$$

is the IBM-2 quadrupole operator for proton bosons ($\rho=\pi$) and for neutron bosons ($\rho=\nu$), respectively, where we have put the condition $\chi_\pi=\chi_\nu=\chi$. $\mathcal{N}$ denotes a normalization factor. The isovector quadrupole excitation in the valence shell can be generated by a linear combination of Q_π and Q_ν, which yields, in the limit of good F spin, an orthogonal configuration to Eq. (1), i.e., [26],

$$|2^+_{IV,\mathrm{val}}\rangle=\mathcal{N}_{\mathrm{ms}}\left(\frac{N}{2N_\pi}Q_\pi-\frac{N}{2N_\nu}Q_\nu\right)|0^+_1\rangle\equiv\mathcal{N}_{\mathrm{ms}}Q_{\mathrm{ms}}|0^+_1\rangle. \quad (3)$$

If the ground state is totally symmetric, so that $F(0^+_1)=F_{\max}=(N_\pi+N_\nu)/2$, then the wave vector Eq. (3) has no overlap with the space spanned by the symmetric states, because it has $F=F_{\max}-1$.

In the F-spin dynamical symmetries of the IBM-2 Eq. (1) gives the wave function of the 2^+_1 state with F-spin quantum number $F_{\max}$ exactly and Eq. (3) gives the one of the lowest mixed-symmetry 2^+_{ms} state with F-spin quantum number $F_{\max}-1$. Consequently, the lowest members of the F-spin multiplet $F=F_{\max}-1$ can be obtained by the application of Q_S onto the 2^+_{ms} state and along with appropriate angular momentum coupling. For example, in the Q-phonon scheme of the IBM-2, the 1^+_1 state has the form

$$|1^+_1\rangle=\mathcal{N}_{\mathrm{sc}}(Q_S Q_{\mathrm{ms}})^{(1)}|0^+_1\rangle. \quad (4)$$

The 1^+_1 state in vibrators has been interpreted in a similar way in an RPA framework [27].

The properties of the 2^+_{ms} state in the dynamical symmetry limits of the IBM-2 have been discussed in the literature [3,5,28,29]. It is known that the 2^+_{ms} state decays by a strong magnetic dipole transition to the symmetric 2^+_1 state. Mixed-symmetry states and some F-spin changing $M1$ and $E2$ transitions outside of the dynamical symmetries are discussed, e.g., in Refs. [30,31]. Let us, however, mention two additional points also known from the literature, which are evident in the Q-phonon picture: (1) the $E2$ decay from the 2^+_{ms} state to the ground state can be weakly collective, because it represents the difference of the proton and neutron parts of the collective $E2$ transition from the 2^+_1 state to the ground state and (2) the $E2$ decay from the 1^+_{sc} state to the 2^+_{ms} should have a strength comparable to the $2^+_1\rightarrow0^+_1$ transition.

In order to observe the signatures for the isovector quadrupole excitation in the valence shell, we must measure the following quantities: spin and parity $J^\pi=2^+$, the ground state excitation strength $B(E2,0^+_1\rightarrow2^+)$, the $M1$ decay strength to the 2^+_1 state, which means the branching ratio $\Gamma(2^+\rightarrow2^+_1)/\Gamma(2^+\rightarrow0^+_1)$, the $E2/M1$ mixing ratio δ of the $2^+\rightarrow2^+_1$ γ transition, and the lifetime τ. The fragmentation of the isovector quadrupole excitation in the valence shell can be studied by the observation of all fragments in a complete reaction.

III. PHOTON SCATTERING INVESTIGATION

Due to the weakly collective $E2$ and the strong $M1$ decay transitions from the 2^+_{ms} state to the ground state and to the 2^+_1 state, respectively, the 2^+_{ms} state decays rapidly and is, thus, short lived. A very effective method for the measurement of short-lived levels which can be populated from the ground state by strong dipole and quadrupole transitions is the photon scattering reaction [32], frequently called nuclear resonance fluorescence (NRF). Due to the low momentum transfer induced by the real photon, the NRF technique is highly sensitive to dipole and electric quadrupole excitations. This sensitivity and the excellent energy resolution of γ spectroscopy allows for the investigation of strong dipole and quadrupole excitations far above the yrast line, where the level density is high. The reaction mechanism is purely electromagnetic and, thus, well understood. In principle, from the direct observables, the energy and scattering-angle-dependent photon scattering intensity and its polarization, one can determine in a model-independent way excitation energies, decay branching ratios, spins, parities, level widths, absolute transition strengths, and lifetimes of the resonance states. By the use of bremsstrahlung as a continuous energy photon source, all dipole and quadrupole excitations of appropriate strength can be detected simultaneously. In the sensitive energy range a complete survey of dipole and quadrupole excitations with excitations strengths above a certain experimental sensitivity limit can be obtained. This allows for the investigation of the excitation strength distribution.

It was our aim to study the fragmentation of the isovector quadrupole excitation in the valence shell and, therefore, to obtain for ^{136}Ba a rather complete set of data for the strong $E2$ excitations in the energy range of the 2^+_{ms} state. The choice of the nucleus ^{136}Ba was due to several reasons. Evidence for 2^+_{ms} states has been found for some $N=84$ isotones [15,18], the neutron number of which differ from the shell closure $N=82$ by two units. The neutron number of ^{136}Ba ($N=80$) differs from the shell closure also by two units and, therefore, we expect the existence of the 2^+_{ms} state close to 2 MeV excitation energy, as is the case for the $N=84$ isotones. In addition, in the neighboring nucleus ^{134}Ba the 2^+_{ms} state is well known from the Budapest-Lexington Collaboration [17] and its total excitation strength has been measured [19]. In ^{134}Ba the 2^+_{ms} state is fragmented into two 2^+ states between 2.0 and 2.1 MeV excitation energy. It is of considerable interest to see whether the 2^+_{ms} state is a pure state or whether it is fragmented as the mixed-symmetry 1^+ scissors mode in deformed nuclei. Photon scattering experiments on ^{136}Ba have already been carried out earlier by Metzger [33]. While he used a scattering target of 92.8 g isotopically enriched (65.1%) $^{136}Ba(NO_3)_2$, we only had 1076 mg $^{136}BaCO_3$ with higher isotopical enrichment (98.6%). However, due to the low efficiency of the Ge detectors Metzger used in his pioneering work twenty years ago, the old measurements were sensitive only in narrow energy regions below the end points of the bremsstrahlung photon spectrum [33,34].

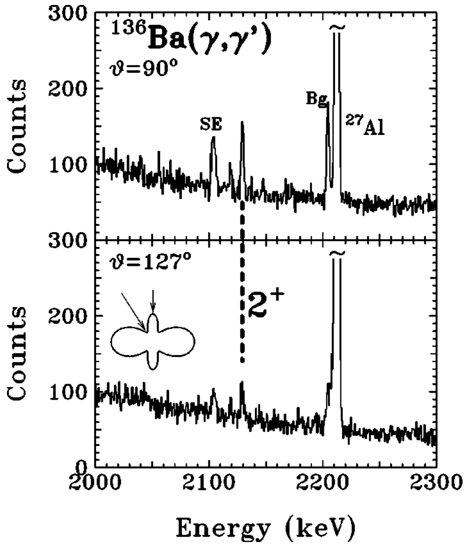

FIG. 1. Part of the photon scattering spectrum of ^{136}Ba using an incident bremsstrahlung beam with energies $E_\gamma \leqslant 2.8$ MeV. The angular distribution of the resonant photon scattering intensity observed at 2129 keV clearly indicates the excitation of a 2^+ state.

Our experiments were carried out at the photon scattering site [32] of the Dynamitron accelerator in Stuttgart. Results on dipole excitations around 3 MeV in ^{136}Ba have been discussed elsewhere [35]. A part of the photon scattering spectrum around 2 MeV is displayed in Fig. 1. This spectrum was measured at two scattering angles $\theta = 90°$ and $\theta = 127°$ with Ge detectors of 100% relative efficiency. Sharp γ lines appear above the nonresonant background. These lines stem from decays of the resonantly excited states. Some states were observed which decay both to the ground state and to other lower-lying excited states.

From the ground state decay intensities observed at scattering angles of 90° and 127°, we could unambiguously distinguish dipole and quadrupole excitations. Absolute values for the photon scattering cross sections of the ^{136}Ba states are obtained relative to the well-known [36] cross sections of several states in ^{27}Al. Total level widths and, thus, the lifetimes of the observed dipole and quadrupole excitations are deduced from the cross sections and the relative decay widths in a model-independent way. Parities of the observed states were already known from the literature [37,38].

TABLE I. Measured effective widths for elastic resonance scattering Γ_0^2/Γ in comparison to the data obtained earlier by Metzger. The parity assignments are taken from the literature [37,38].

E [keV]	J^π [$\hbar$]	Γ_0^2/Γ [a] [meV]	Γ_0^2/Γ [b] [meV]
2080	2^+	<0.1	$-0.04(14)$
2129	2^+	1.00(6)	0.7(2)
2694	1^+	2.58(35)	
3044	1^-	13.6(6)	17(2)
3116	2^+	3.6(4)	4.1(6)
3370	1^+	24.8(13)	30(5)
3436	1^-	76.3(46)	71(10)
3981	$1^{(-)}$	22.2(44)	21(6)

[a]This work.
[b]Reference [33].

In Table I we compare our data to those obtained previously by Metzger. He missed a strong magnetic dipole excitation at 2694 keV. All other values coincide within two standard deviations. In most cases the experimental error of the effective elastic resonant scattering width Γ_0^2/Γ could be reduced by a factor 2–4. Most importantly, in addition to the 2_4^+ state at 2129 keV we can exclude the existence of another 2^+ state between 2 and 4 MeV which decays comparably strong to the 2_4^+ state by $E2$ and $M1$ transitions to the ground state and the 2_1^+ state, respectively.

Thus, the 2^+ state at 2129 keV is the main fragment of the 2_{ms}^+ state in ^{136}Ba. It has a short lifetime of $\tau = 67(7)$ fs. Its excitation strength of $B(E2;0_1^+ \rightarrow 2_4^+) = 0.045(5) e^2$ b^2 is weakly collective. It corresponds to 2.1 single particle units and amounts to 11% of the excitation strength of the 2_1^+ state. This is a factor of 3 larger than the excitation strength of the 2_2^+ state, which in the vibrator nucleus ^{136}Ba is interpreted as the 2^+ member of the isoscalar two-quadrupole phonon triplet. The short lifetime and the weakly collective $E2$ excitation strength are signatures for the 2_{ms}^+ state.

Another signature of the 2_{ms}^+ state is the strong $M1$ transition to the 2_1^+ state. From angular correlations of γ decays after neutron capture it is known [38] that the $2_4^+ \rightarrow 2_1^+$ transition has a pure $M1$ character with a very small $E2/M1$ mixing ratio $\delta = +0.005(9)$. From the branching ratio and the lifetime observed in the present (γ,γ') experiment we deduce a decay strength $B(M1;2_4^+ \rightarrow 2_1^+) = 0.26(3)\ \mu_N^2$. This value is close to the $B(M1;1^+ \rightarrow 0_1^+) \leqslant 0.5\ \mu_N^2$ values of the largest fragments of the 1^+ scissors mode in deformed rare earth nuclei [8]. Given the errors of about 10%, this value coincides with the total $M1$ decay strength of the fragmented 2_{ms}^+ state in the neighboring nucleus ^{134}Ba which amounts to $\Sigma B(M1;2_{3,4}^+ \rightarrow 2_1^+) = 0.20(2)\ \mu_N^2$ [19]. With the spin and parity $J^\pi = 2^+$, together with the small mixing ratio $\delta_{2^+ \rightarrow 2_1^+}$ and with the absolute $E2$ and $M1$ decay strengths to the ground and 2_1^+ states, we obtain a complete set of signatures for the isovector quadrupole excitation in the valence shell of ^{136}Ba.

IV. IBM-2 CALCULATION

In order to prove the mixed-symmetry character of the 2_4^+ state at 2129 keV, we performed an IBM-2 calculation, wherein this state can be understood as the 2_{ms}^+ state. We used the code NPBOS [39] for the numerical calculation. Experimental data for the $E2$ excitation strengths require small F-spin mixing between the 2_3^+ state at 2080 keV and the 2_4^+ state at 2129 keV. In order to reproduce this feature and to explain the structure of the 2_4^+ state in simplest way, we generalize the IBM-1 Hamiltonian, by choosing the following F-spin scalar IBM-2 Hamiltonian:

$$H = \epsilon(n_{d_\pi} + n_{d_\nu}) + a(n_{d_\pi} + n_{d_\nu})^2 + \kappa(Q_\pi + Q_\nu)\cdot(Q_\pi + Q_\nu) + \lambda L\cdot L + M(\xi_1,\xi_2,\xi_3), \quad (5)$$

where for $\rho = (\pi,\nu)$ n_{d_ρ} is the d-boson number operator, Q_ρ is the quadrupole operator defined in Eq. (2), $L = L_\pi + L_\nu$ is

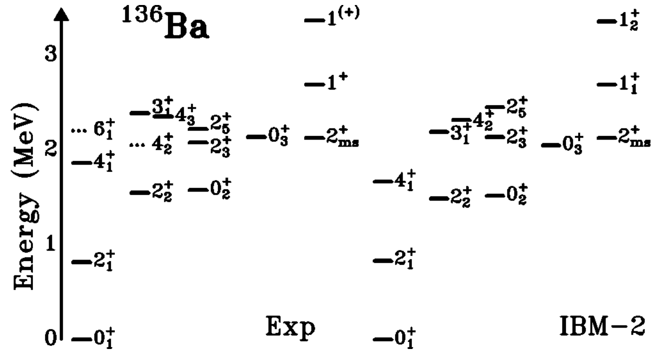

FIG. 2. Low-lying positive parity states of ^{136}Ba (left) for which unambiguous spin assignments are known from the Nuclear Data Sheets and from our experiments. The 6^+ state at 2.2 MeV is a noncollective 3 ns isomer. The 4_2^+ state at 2.05 MeV is presumably the hexadecupole vibration. On the right we give the result of an IBM-2 fit using the simple F-scalar Hamiltonian from Eq. (5). The mean relative energy deviation $\langle |E_{\mathrm{exp}}-E_{\mathrm{IBM}}|/E_{\mathrm{exp}}\rangle$ amounts to 4%.

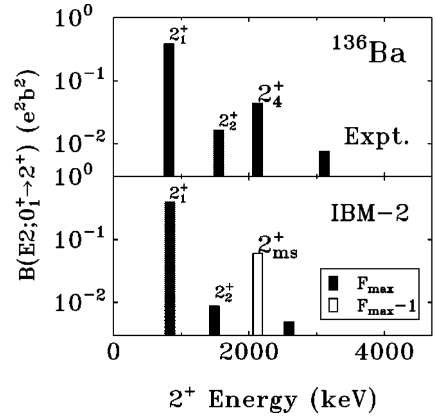

FIG. 3. Experimental (top) and calculated (bottom) $E2$ excitation strength distribution in ^{136}Ba. In the IBM-2 transition operator, effective charges $e_\pi = 0.1562\ e$ b and $e_\nu = 0$ were used.

the total angular momentum operator, and M is the Majorana operator [3]. The term $(n_{d_\pi}+n_{d_\nu})^2$ corresponds to the n_d^2 term used previously in IBM-1 for τ compression [40], which improves the moment of inertia. With the parameter values $\epsilon = 0.85$ MeV, $a = -0.52$ MeV, $\kappa = -0.08$ MeV, $\chi = -0.25$, $\lambda = 0.018$ MeV, $\xi_1 = \xi_3 = 0.7$ MeV, and $\xi_2 = 0.228$ MeV we obtain a good fit of the excitation energies of the positive parity states, for which firm spin assignments are known from the literature [37] and from our experiment. Figure 2 shows the quality of the IBM-2 fit. The 6_1^+ state is a 3.1 ns isomer [37], which is outside of the IBM-2 model space. Furthermore, the 4_2^+ state, to which the 6_1^+ state decays [37], cannot be satisfactorily described in the sd-IBM-2. This 4^+ state presumably contains the hexadecupole 4^+ vibration, which occurs in the semimagic neighboring nucleus ^{138}Ba at a comparable excitation energy of 1.9 MeV. The other states—in particular the mixed-symmetry 2^+ and 1^+ states—are nicely described with a mean relative energy deviation of about 4%.

As we have information on the lifetimes of 1^+ and 2^+ states, it is valuable to compare the experimentally found $B(M1)$ and $B(E2)$ values to the calculated results. We used the standard IBM-2 transition operators [3]

$$T(M1) = g_\pi L_\pi + g_\nu L_\nu \tag{6}$$

and

$$T(E2) = e_\pi Q_\pi + e_\nu Q_\nu . \tag{7}$$

In order to reduce the number of free parameters we used the orbital values $g_\pi = 1\ \mu_N$ and $g_\nu = 0$ for the boson g factors and a vanishing effective neutron boson quadrupole charge $e_\nu = 0$.[1] We also used the same χ parameters as in the Hamiltonian (5), leaving $e_\pi = 0.1562\ e$ b as the only adjustable parameter of the transition operators.

While the $M1$ properties are satisfactorily described (with the exception of the $0_1^+ \to 1^+$ fragmentation; this shortcoming of the sd-IBM-2 is known), we are particularly interested in the distribution of the $E2$ excitation strength from the ground state. The calculated $E2$ excitation strength distribution is compared to the experimental distribution in Fig. 3 and Table II. The $E2$ strengths of the lowest 2^+ states, including the 2_{ms}^+ state at 2129 keV, are well reproduced. In both theory and experiment, the 2_{ms}^+ state is essentially unfragmented.

TABLE II. Comparison of the relevant experimentally known data on magnetic dipole and electric quadrupole transitions with the results of the IBM-2 calculation. For the transition operators only one scaling parameter ($e_\pi = 0.1562\ e$ b) has been adjusted in order to reproduce the $B(E2;0_1^+ \to 2_1^+)$ value on an absolute scale. The experimental data are taken from this work (footnotes) and from the literature [37] (else).

Observable	Unit	Experiment	IBM-2
$g(2_1^+)$	$[\mu_N]$	0.7(1)	0.750
$2_{2129}^+ \to 2_1^+$	$[\mu_N^2]$	0.26(3)[a]	0.290
$0_1^+ \to 1_{2694}^+$	$[\mu_N^2]$	0.13(2)[b]	0.214
$0_1^+ \to 1_{3370}^+$	$[\mu_N^2]$	0.17(2)[b]	0.002
$1_{2694}^+ \to 2_2^+$	$[\mu_N^2]$	0.6(1)[c]	0.397
$Q(2_1^+)$	$[e\mathrm{b}]$	−0.19(6)	−0.278
$0_1^+ \to 2_1^+$	$[e^2\mathrm{b}^2]$	0.400(5)	0.400
$0_1^+ \to 2_2^+$	$[e^2\mathrm{b}^2]$	0.016(4)	0.009
$0_1^+ \to 2_3^+$	$[e^2\mathrm{b}^2]$	< 0.004[b]	0.002
$0_1^+ \to 2_{\mathrm{ms}}^+$	$[e^2\mathrm{b}^2]$	0.045(5)[b]	0.060
$2_2^+ \to 2_1^+$	$[e^2\mathrm{b}^2]$	0.09(4)	0.074

[a]This work using the $E2/M1$ mixing ratio $\delta = 0.005(9)$ from Ref. [38].
[b]This work.
[c]This work, assuming pure $M1$ decay, which is in agreement with the IBM-2 calculation.

[1]Alternatively, one could treat the neutron effective charge e_ν as a free parameter. If e_π and e_ν are fitted to reproduce the $E2$ excitation strengths of the 2_1^+ state and the 2_{ms}^+ state, one obtains $e_\pi = 0.151\ e$ b and the small value $e_\nu = 0.0156\ e$ b, which weakly affects calculated $B(E2)$ values.

V. SUMMARY

We have performed photon scattering experiments on the vibrator nucleus ^{136}Ba. Apart from dipole excitations we measured the lifetime of three electric quadrupole excitations above yrast. The 2^+ state at 2129 keV could be identified as the main fragment of the isovector quadrupole excitation in the valence shell. Within the framework of the IBM-2 it can be understood as the first 2^+_{ms} state. We have shown that the 2^+_{ms} state is essentially unfragmented in the $N=80$ vibrator nucleus ^{136}Ba. We have demonstrated the ability of the photon scattering technique investigating the isovector quadrupole excitation in the valence shell of heavy nuclei. Scattering of continuous energy bremsstrahlung photons can yield a complete survey of weakly collective electric quadrupole excitations, which enables the study of the fragmentation of the isovector quadrupole excitation in the valence shell.

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