Observation of the 1^+ scissors mode in the γ-soft nucleus ^{134}Ba

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A photon scattering experiment was performed on the γ-soft nucleus ^{134}Ba with photon energies of $E_\gamma < 4.1$. Around 3 MeV excitation energy a fragmented 1^+ scissors mode as well as the $(2^+ \otimes 3^-)_{1^-}$ two-phonon dipole state were identified. The dipole excitation strengths were measured. The excitation strength of the scissors mode in this γ-soft nucleus is well reproduced by an empirical $M1$ sum rule that generalizes the ''δ^2 law'' to nuclei without axial symmetry. The IBM-2 describes the mixed-symmetry states in ^{134}Ba and their decay pattern. A large $E2/M1$ mixing ratio for the $1^+ \rightarrow 2_1^+$ decay of the scissors mode to the 2_1^+ state is predicted by the IBM-2. The new result from ^{134}Ba together with a similar previous observation in ^{196}Pt corroborates the scissors mode as a typical excitation mode of γ-soft nuclei. [S0556-2813(96)51011-3]

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The scissors mode is a fundamental excitation mode of heavy deformed nuclei. Recently it was observed [1,2] in ^{196}Pt. This was the first observation of the scissors mode in a deformed nucleus with a soft triaxiallity. Besides the Pt,Os region another wide region of γ-soft triaxiallity is the Xe,Ba one with mass numbers around $A=130$. Here we report on the observation of the scissors mode in the γ-soft nucleus ^{134}Ba. This observation corroborates the scissors mode as a typical excitation mode of γ-softly deformed nuclei.

In a simple geometrical model the scissors mode can be visualized as a scissorslike counter rotating oscillation of the deformed proton body against the neutron body. In 1984 this excitation mode was discovered experimentally [3] in the well-deformed nucleus ^{156}Gd in a high-resolution electron scattering experiment. Subsequently the scissors mode has been investigated intensively in electron and in high resolution photon scattering experiments in many deformed nuclei [4]. In addition to the even-A rare earth nuclei (see references in [5]) it was found in the actinides [6,7], fp-shell nuclei [8], and in odd-A rare earth nuclei [9–11]. The excitation strength of the mode is fragmented around excitation energies of 3 MeV. The total $M1$ strength in this energy region correlates to other collective observables [5,12,13], such as the low-lying $E2$ strength, and depends quadratically on the nuclear quadrupole deformation in axially symmetric nuclei. This fact is known as the so-called ''δ^2 law'' [14–17].

A scissors mode in deformed nuclei has been predicted theoretically in various nuclear models [18–22]. A splitting of the scissors mode is predicted for nuclei with rigid triaxiallity [23,24]. For γ-soft nuclei predictions for the scissors mode have been made in the O(6) dynamical symmetry of the IBM-2 [25–27]. The recently reported [1] properties of the scissors mode in ^{196}Pt correspond to the predictions of the O(6) dynamical symmetry of the IBM-2 [28]. It is thus a crucial test of models of the scissors mode to investigate also the low-lying dipole excitations in another region of γ-soft nuclei namely in the nuclei around $A=130$ [29]. We mention that the mixed-symmetry 2_m^+ state in ^{134}Ba has already been studied [30,31]. The low-lying positive parity states of ^{134}Ba are well described by the O(6) dynamical symmetry of the IBM [32]. Hence, we performed a photon scattering experiment on ^{134}Ba in order to observe the scissors mode in the $A=130$ region and to confirm the scissor as a general excitation mode of γ-soft nuclei.

This experiment was carried out at the photon scattering site [4,33] at the 4.3 MeV Dynamitron accelerator in Stuttgart. A photon scattering spectrum is displayed in Fig. 1. This spectrum was observed at a scattering angle of $\theta=127°$ with a Ge detector of 20% efficiency relative to a 3 in.×3 in. standard NaI detector. Sharp resonance scattering lines appear above the nonresonant background. These lines stem from the decays of the resonantly excited states. Some states were observed that decay both to the ground state and to other excited states. Decays to the first or second 2^+ states were identified from their transition energies. With respect to the elastic ground-state decay their γ energies are lowered by

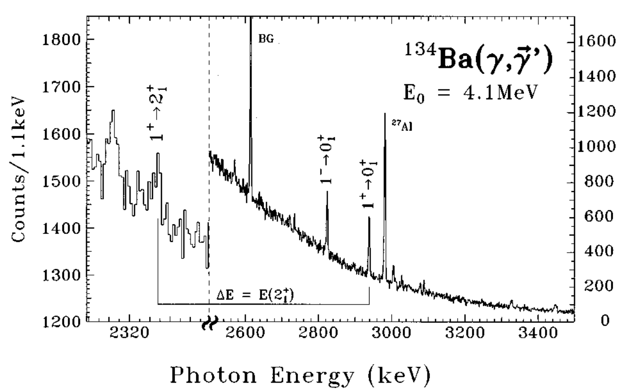

FIG. 1. Photon scattering spectrum off ^{134}Ba at a scattering angle of θ=127°. Above the smooth background, sharp γ lines are visible. The strongest lines are ground-state transitions of the dipole excitations. Some of these states also decay to other excited states as, e.g., the 2_1^+ state. The inelastic transition from the 1^+ state at 2939 keV to the 2_1^+ state is emphasized in the left box. Note the change of scale in the left part.

TABLE I. Results of the ^{134}Ba(γ,γ') experiment. Tabulated are the excitation energies E_x, the spins J and the parities π, the energy integrated elastic photon scattering cross sections $I_{s,0}$, the ground-state decay widths $\Gamma_{0_1^+}$, the relative ground-state decay width ratios $\Gamma_{0_1^+}/\Gamma$ used for the data analysis, and the dipole excitation strengths $B(\pi1;0_1^+\rightarrow1^\pi)$ in units of $\mu_N^2=11.06\times10^{-3}\ e^2\ \mathrm{fm}^2$.

E_x [keV]	J^π [$\hbar$]	$I_{s,0}$ [eV·b]	$\Gamma_{0_1^+}$ [meV]	$\Gamma_{0_1^+}/\Gamma$	$B(\pi1)\uparrow$ [μ_N^2]
2311	(1)	3.2±0.9	1.5±0.4		0.031±0.009
2571	$1^{(+)}$	5.2±1.1	5.3±0.8	0.56±0.05[a]	0.081±0.012
2806	(1)	2.8±0.9	1.9±0.6		0.023±0.007
2824	1^-	22.2±2.5	18.0±2.3	0.85±0.07	0.208±0.027[b]
2939	1^+	25.2±2.7	30.1±3.6	0.63±0.04	0.307±0.037
3011	(1)	3.5±0.9	2.7±0.7		0.026±0.007
3027	(1^+)	5.3±1.1	4.2±0.8		0.039±0.008
3246	(1^+)	3.2±0.9	2.9±0.8		0.022±0.006
3327	(1^+)	5.2±1.1	10.7±2.1	0.46±0.07	0.075±0.015
3343	(1)	2.5±0.9	2.4±0.8		0.017±0.006
3450	(1^+)	5.5±1.2	5.6±1.2		0.036±0.008
3560	1	16.3±2.4	18.0±2.6		0.103±0.015
3589	1	21.2±2.9	23.7±3.3		0.133±0.018
3617	(1)	6.3±1.5	7.2±1.7		0.039±0.009
3705	1	12.7±2.3	15.1±2.7		0.077±0.014
3783	(1)	8.1±2.0	10.1±2.4		0.048±0.012
3836	1	15.3±3.0	19.6±3.8		0.090±0.018
3980	(1)	9.3±3.4	12.8±4.6		0.053±0.019
3992	(1)	11.1±3.8	15.3±5.2		0.062±0.021

[a]The branching ratios to the $2^+_{1,2}$ states are taken from Ref. [38].
[b]$B(E1;0_1^+\rightarrow2824\ \mathrm{keV})=2.3(3)\times10^{-3}\ e^2\ \mathrm{fm}^2$.

605 keV and 1168 keV corresponding to the excitation energies of the $2^+_{1,2}$ states.

The observed decay intensities yield the ratios $\Gamma_{2^+_{1,2}}/\Gamma_{0^+_1}$ of the partial widths for the decays to the $2^+_{1,2}$ states and the ground state, respectively. The angular correlations of the ground-state decay intensities observed at 90° and 127° prove all strongly excited states to be dipole excitations leading to spin assignments $J=1$. Absolute values for the inelastic photon scattering cross sections of the ^{134}Ba states are obtained relative to the well-known [34] cross sections of several states in ^{27}Al. From the cross sections and the relative widths, total level widths and thus the lifetimes of the observed dipole states are deduced in a model-independent way. The parities of the dipole excitations were measured with a Compton polarimeter [4,35]. In our experiment we used a sectored single-crystal Ge polarimeter [36] with a high coincidence efficiency [37]. For the most intense decay transitions at 2824 keV and 2939 keV statistically significant coincidence asymmetries in the Compton polarimeter lead to parity assignments of $\pi=-$ and $\pi=+$, respectively.

The results are summarized in Table I. Due to the low cross sections, firm assignments of spins and parities were not possible for many levels. For some states additional information comes from other reactions [38]. Some states were known from a previous experiment [39] where the β^+ decay of the 1^+ ground state of ^{134}La was studied. Due to the population of these states in both reactions, namely in the parity selective β decay and in the spin selective photon scattering reaction, they are most probably 1^+ states. For cases where we lack other information we quote these assignments in parentheses. Within the experimental accuracy the branching ratios that we obtain from our data agree with the literature [38] with one exception. A strong 1859 keV decay branch of the state at 3028 keV to the 2^+_2 state does not appear in our data. We believe that the observed intensity at 1859 keV in the β-decay experiment [39] comes from the 1859 keV decay of the level at 2464 keV level to the 2^+_1 state. This interpretation has been suggested by Fazekas *et al.* [31] due to their inelastic neutron scattering data. Therefore, we use $\Gamma_{2^+_2}/\Gamma_{0^+_1}=0$ for the determination of the 3028 keV level width. The relative partial decay widths $\Gamma_{0^+_1}/\Gamma$ that were used for the extraction of the dipole excitation strengths $B(\pi1;0^+_1\rightarrow1^\pi)=(27/16\pi)(\hbar c/E_{\gamma_0})^3\Gamma_{0^+_1}$ from the measured photon scattering cross sections are included in Table I. The spectral distribution of the dipole excitation strengths is plotted in Fig. 2 in units of $\mu_N^2=11.06\times10^{-3}e^2\ \mathrm{fm}^2$.

The energy of the 1^- dipole state at 2824 keV is close to the sum energy of the 2^+_1 and the 3^-_1 states, $E(2^+_1)+E(3^-_1)=2860$ keV. This state is thus a good candidate for the 1^- member of the $2^+\otimes3^-$ two-phonon multiplet in ^{134}Ba. In the neighboring isotopes ^{136,138}Ba such states have been identified previously [40–42]. The excitation energies of the two-phonon dipole states in the even-A isotopes ^{134,136,138}Ba closely correlate to the sum energies of the constituent phonons. The occurrence of the strongly dipole excited 1^- two-phonon state in ^{134}Ba in the energy region of the scissors mode shows the necessity of parity measurements for the correct determination of the scissors mode strength.

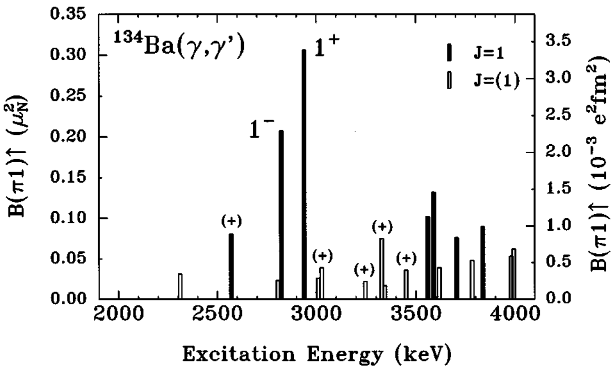

FIG. 2. Dipole excitation strength distribution below 4 MeV ($1\ \mu_N^2 = 11.06\times 10^{-3}\ e^2\ \mathrm{fm}^2$). Open bars are plotted if $J=1$ is uncertain. A tentative parity assignment (+) is made if this state is also populated in the β^+ decay of the 1^+ ground state of ^{134}La.

In the following we focus on the magnetic dipole excitations. The 1^+ state at 2939 keV has a relatively large $M1$ excitation strength of $B(M1;0_1^+ \to 1^+) = 0.31(4)\mu_N^2$ It can be considered as the main fragment of the scissors mode in ^{134}Ba. The total $M1$ strength summed over all states, where $J^\pi = 1^+$ is at least tentatively assigned in Table I, amounts to

$$\sum_i B(M1;0_1^+ \to 1_i^+) = 0.56(4)\mu_N^2. \quad (1)$$

The error was obtained by adding quadratically the errors of the individual fragments.

The inclusion of the excitation strengths of those states for which spin and parity are assigned to $J^\pi = (1)$ would increase the summed strength between 2.5 MeV and 3.5 MeV from Eq. (1) by $0.07(1)\mu_N^2$ Above an excitation energy of 3.5 MeV we observed eight states, four of them with spin assignment $J=1$. In total they have a large dipole excitation strength of $B(\pi 1)\uparrow = 0.61(5)\mu_N^2$ From a RPA calculation [43] it can be expected that magnetic dipole excitations above 3.5 MeV have a low orbit-to-spin ratio of $R_{\mathrm{os}} \approx 1$ or less and thus do not belong to the scissors mode. But from the systematics of the dipole excitations in the nuclei around $N=82$ these states most probably have negative parities. We consider other transitional nuclei, namely ^{146}Nd and ^{148}Sm, that have four valence neutron particles as compared to the four valence neutron holes in ^{134}Ba. In these nuclei the strongest dipole excitations above 3.48 MeV are $E1$ excitations [15,44]. Thus the total strength of the scissors mode in ^{134}Ba presumably does not deviate too much from the value given in Eq. (1), where we only included states for which we have experimental evidence for positive parities. Therefore, we use this number for a comparison to the predictions of empirical and theoretical $M1$ sum rules and to other nuclei where the data have also been obtained below a certain cutoff energy [1,5].

The scissors mode strength (1) in ^{134}Ba amounts to about 1/5 of the strength in a typical rotor nucleus in the rare earth region [5]. This could be expected from the close correlation of the total low-lying $M1$ strength to the excitation strength of the 2_1^+ state. An empirical sum rule for the excitation strength of the scissors mode

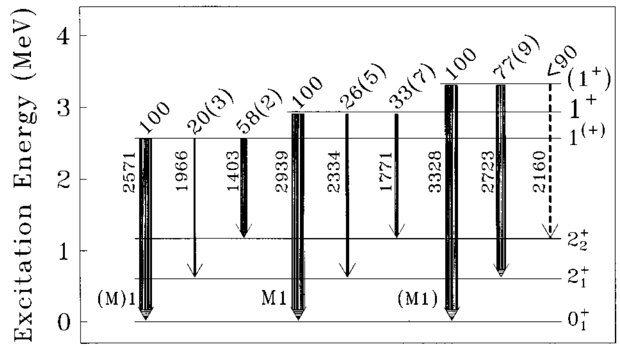

FIG. 3. Relative decay widths $\Gamma_{L_f}/\Gamma_{0_1^+}$ of the main fragments of the scissors mode in ^{134}Ba. For the levels at 2571 keV and 3328 keV the relative widths (branching ratios), plotted here, are taken from the adopted values for the decay intensities reported in the Nuclear Data Sheets [38]. The strongest dipole excitations below 3.5 MeV decay to the ground state and to the $2_{1,2}^+$ states.

$$B(M1)_{\mathrm{sc}} = \frac{10.6}{Z^2} B(E2;0_1^+ \to 2_1^+) \quad (2)$$

has been formulated in Ref. [5] where the transition strengths are given in single-particle units. This formula generalizes the "δ^2 law" to nuclei without axial symmetry, since a model dependent extraction of a nuclear deformation parameter δ from the $B(E2)$ value is not necessary. For ^{134}Ba this formula predicts the $M1$ strength of the scissors mode from the value $B(E2;0_1^+ \to 2_1^+) = 0.680(16)\ e^2\ \mathrm{b}^2$ [45] to be

$$B(M1)\uparrow_{\mathrm{sc}} = 0.61(2)\mu_N^2,$$

in agreement with the experimental value from Eq. (1).

In the O(6) dynamical symmetry of the IBM-2 the scissors mode is described by the lowest 1^+ state. For the boson numbers $N_\pi = 3$, $N_\nu = 2$ with $N = N_\pi + N_\nu$ and bare g factors $g_\pi(g_\nu) = 1(0)\mu_N$, the IBM-2 predicts [28] the excitation strength of the scissors mode in the O(6) dynamical symmetry to be

$$B(M1)\uparrow_{\mathrm{O(6)}} = 0.72\mu_N^2 \quad (3)$$

in rough agreement with the experiment.

Besides the ground-state transitions decay branches to lower-lying excited states could be observed for the largest fragments of the scissors mode. Figure 3 shows the intensity ratios $\Gamma_{L_f}/\Gamma_{0_1^+}$ of the strongest magnetic dipole excitations to the lowest states $L_f = 0_1^+, 2_1^+, 2_2^+$. We stress that the accurate width ratios from the Nuclear Data Sheets are converted into absolute widths from the (γ,γ') ground-state excitation width data. The decay intensities to the 2^+ states are of the same order of magnitude as the ground-state decays although the larger transition energy favors the latter. If converted to reduced transition strengths $B(M1)\downarrow$, the strengths of the decays to the quasi-γ bandhead exceed the corresponding ground-state decay strengths. In rotational nuclei where the scissors mode is well studied such a decay behavior of the scissors mode fragments has never been observed. But a similar decay pattern of the scissors mode was found for the γ-soft nucleus ^{196}Pt [1]. Systematically the $1^+ \to 2_2^+$ decay branching strongly increases in the transition from axially deformed rotors to γ-soft nuclei [46].

Actually a strong $M1$ decay of the 1^+ state to the 2_2^+ state is anticipated in the O(6) dynamical symmetry of the IBM-2. For ^{134}Ba with a boson number of $N=5$ a branching ratio of $R_{\mathrm{O(6)},2}=B(M1;1_1^+\rightarrow 2_2^+)/B(M1;1_1^+\rightarrow 0_1^+)=2.25$ is predicted [47] in the O(6) limit. This number must be compared to the measured values $R_{\mathrm{exp},2}=\Gamma_{2_2^+}E_{\gamma_0}^3/\Gamma_{0_1^+}E_{\gamma_2}^3=3.57(12)$ for the state at 2571 keV and $R_{\mathrm{exp},2}=1.51(32)$ for the state at 2939 keV. In both cases we assume pure dipole radiation for the inelastic decays. On average these values agree with the IBM-2 prediction.

In addition to the $1^+\rightarrow 2_2^+$ transitions we observe $1^+\rightarrow 2_1^+$ transitions for the strongest fragments of the scissors mode at 2571 keV, 2939 keV, and 3328 keV. In rotor nuclei $1^+\rightarrow 2_1^+$ transitions are frequently observed and interpreted as $M1$ decay transitions to the ground state band. This interpretation changes for γ-soft nuclei. In the pure O(6) dynamical symmetry of the IBM-2 an $M1$ decay of the 1_1^+ state, which has mixed-symmetry $F=F_{\max}-1$, to the symmetric 2_1^+ state with $F=F_{\max}$ is forbidden. Due to their τ quantum numbers these two states contain different numbers of d bosons (1_1^+: even number of d bosons, 2_1^+: odd number of d bosons) [48]. Thus, the d-boson number conserving $M1$ operator cannot induce a transition between them. However, in the IBM-2 a $1_1^+\rightarrow 2_1^+$ decay can be explained by an F-vector $E2$ transition as suggested in [1,2] for the corresponding data in ^{196}Pt. In the O(6) dynamical symmetry the analytical formula

$$B(E2;1_1^+\rightarrow 2_1^+)=(e_\pi-e_\nu)^2\frac{N+4}{2N(N+1)}N_\pi N_\nu \tag{4}$$

has been derived by Van Isacker *et al.* [28]. A finite F-vector $1_1^+\rightarrow 2_1^+$ transition is obtained if different values for the effective quadrupole boson charges e_ρ for proton and neutron bosons are used. $E2$ transition strengths between symmetric states with $F=F_{\max}$ are proportional to the square of $N_\pi e_\pi+N_\nu e_\nu$ and are not sensitive to the *difference* of the effective charges $e_\pi-e_\nu$. The boson charges can be chosen to reproduce the mainly F-scalar $B(E2;0_1^+\rightarrow 2_1^+)$ value as well as the F-vector $B(E2;1_1^+\rightarrow 2_1^+)$ strength from Eq. (4). If the observed $1^+\rightarrow 2_1^+$ decay transitions are assumed to consist of pure $E2$ radiation then the summed strength from the decays of the states at 2571 keV, 2939 keV, and 3328 keV amounts to $\Sigma B(E2;1^+\rightarrow 2_1^+)=0.025(4)\ \mathrm{e}^2\,\mathrm{b}^2$. Combining this with the low-lying $E2$ excitation strength $B(E2;0_1^+\rightarrow 2_1^+)=0.680(16)\ e^2\,\mathrm{b}^2$ from Ref. [45] the effective boson quadrupole charges

$$e_\pi=0.22\ e\ \mathrm{b},\quad e_\nu=0.06\ e\ \mathrm{b} \tag{5}$$

can be obtained for ^{134}Ba if the condition $e_\pi-e_\nu>0$ is required.

These values can be tested independently by the excitation strength of the mixed-symmetry 2_m^+ state that depends on the difference $e_\pi-e_\nu$ of the effective charges as well. In the O(6) dynamical symmetry this excitation strength is given by [47]

$$B(E2;0_1^+\rightarrow 2_m^+)_{\mathrm{O(6)}}=(e_\pi-e_\nu)^2\frac{2(N+2)}{N(N+1)}N_\pi N_\nu. \tag{6}$$

In ^{134}Ba the mixed-symmetry 2_m^+ state has been identified by Molnár *et al.* [30]. Due to their decay behavior the 2^+ states at 2029 keV and at 2088 keV are interpreted as the fragments of the mixed-symmetry 2_m^+ state. Their summed $E2$ excitation strength [38] $\Sigma B(E2)\uparrow=0.041(4)\ \mathrm{e}^2\,\mathrm{b}^2$ is actually reproduced within a factor of two by the expression (6) if one uses the effective charges (5) derived above in the O(6) limit of the IBM-2. A slight theoretical overestimate of the $B(E2;0_1^+\rightarrow 2_m^+)$ value may be explained by an overestimate of the difference $e_\pi-e_\nu$ due to the assumption of a *pure* $E2$ decay of the scissors mode to the 2_1^+ state. An accurate measurement of the $E2/M1$ mixing ratio of the $1_{\mathrm{sc}}^+\rightarrow 2_1^+$ transitions in ^{134}Ba would thus be a crucial test of the predictive power of the O(6) dynamical symmetry of the IBM for γ-softly deformed nuclei.

The surprising interpretation of the $1^+\rightarrow 2_1^+$ decay as an F-vector $E2$ transition is based on the $M1$ selection rules in the O(6) dynamical symmetry of the IBM-2. Better descriptions of real nuclei can usually be achieved by a breaking of the dynamical symmetries. Then the strict $M1$ selection rule is no longer valid. It is thus of crucial importance to study whether a breaking of the O(6) dynamical symmetry may lead to a $1^+\rightarrow 2_1^+$ $M1$ transition that is strong enough to account for the experimentally observed intensities. Outside of the dynamical symmetries of the IBM there exist no simple analytical expressions for the excitation energies and transition strengths as a function of the Hamiltonian parameters. The Hamiltonian must be diagonalised numerically and its parameters must be fitted to the observables. Puddu, Scholten, and Otsuka [49] performed such a fit for the Xe,Ba,Ce isotopic chains. Using their fit parameters for ^{134}Ba the $M1$ strength of the $1_1^+\rightarrow 2_1^+$ transition amounts to $B(M1;1_1^+\rightarrow 2_1^+)=0.0035\mu_N^2$ This value is about 30 times too small to explain the totally observed $1^+\rightarrow 2_1^+$ decay intensity as pure $M1$ transitions.

To summarize, we have performed an $E_\gamma<4.1$ MeV inelastic photon scattering experiment on the γ-soft nucleus ^{134}Ba. Around 3 MeV excitation energy we observed the $M1$ scissors mode and the $2^+\otimes 3^-$ two-phonon $E1$ excitation. This demonstrates the fact that γ-soft nuclei exhibit both the properties of deformed rotors as, e.g., the existence of the scissors mode and the properties of vibrators as, e.g., the two-phonon states. We have measured the dipole excitation strength distribution in ^{134}Ba below 4 MeV excitation energy. The low-lying $M1$ excitation strength is well predicted by an empirical proportionality to the low-lying $B(E2)$ value that generalizes the ''δ^2 law'' to deformed nuclei without axial symmetry. A description of the mixed-symmetry states in ^{134}Ba can be obtained in the IBM-2 that predicts a large $E2/M1$ mixing ratio for the $1_1^+\rightarrow 2_1^+$ decay transition. Together with the recent observation of strongly magnetic dipole excited 1^+ states in the γ-soft nucleus ^{196}Pt the existence of strong low-lying magnetic dipole excitations in ^{134}Ba confirms the scissors mode as a fundamental excitation mode also of γ-soft nuclei.

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[1] P. von Brentano *et al.*, Phys. Rev. Lett. **76**, 2029 (1996).
[2] N. Pietralla, Ph.D. thesis, Universität zu Köln, 1996.
[3] D. Bohle *et al.*, Phys. Lett. **137B**, 27 (1984).
[4] U. Kneissl *et al.*, Prog. Part. Nucl. Phys. **37**, 349 (1996).
[5] N. Pietralla *et al.*, Phys. Rev. C **52**, R2317 (1995).
[6] R.D. Heil *et al.*, Nucl. Phys. **A476**, 39 (1988).
[7] J. Margraf *et al.*, Phys. Rev. C **42**, 771 (1990).
[8] C. Djalali *et al.*, Phys. Lett. **164B**, 269 (1985).
[9] I. Bauske *et al.*, Phys. Rev. Lett. **71**, 975 (1993).
[10] J. Margraf *et al.*, Phys. Rev. C **52**, 2429 (1995).
[11] C. Schlegel *et al.*, Phys. Lett. B **375**, 21 (1996).
[12] C. Rangacharyulu *et al.*, Phys. Rev. C **43**, R949 (1991).
[13] J. Margraf *et al.*, Phys. Rev. C **45**, R521 (1992).
[14] W. Ziegler *et al.*, Phys. Rev. Lett. **65**, 2515 (1990).
[15] J. Margraf *et al.*, Phys. Rev. C **47**, 1474 (1993).
[16] P. von Neumann-Cosel *et al.*, Phys. Rev. Lett. **75**, 4178 (1995).
[17] A. Zilges *et al.*, Nucl. Phys. **A599**, 147c (1996).
[18] A. Faessler, Nucl. Phys. **85**, 653 (1966).
[19] S.I. Gabrakov *et al.*, Nucl. Phys. **A182**, 625 (1972).
[20] N. Lo Iudice and F. Palumbo, Phys. Rev. Lett. **41**, 1532 (1978).
[21] F. Iachello, Nucl. Phys. **A381**, 89c (1981).
[22] R.R. Hilton, Z. Phys. A **316**, 121 (1984).
[23] N. Lo Iudice *et al.*, Phys. Lett. **161B**, 18 (1985).
[24] A. Faessler *et al.*, Z. Phys. A **324**, 235 (1986).
[25] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).
[26] P. Van Isacker *et al.*, Phys. Lett. **144B**, 1 (1984).
[27] O. Scholten *et al.*, Nucl. Phys. **A438**, 41 (1985).
[28] P. Van Isacker *et al.*, Ann. Phys. (N.Y.) **171**, 253 (1986).
[29] R.F. Casten and P. v. Brentano, Phys. Lett. **152B**, 22 (1985).
[30] G. Molnár *et al.*, Phys. Rev. C **37**, 898 (1988).
[31] B. Fazekas *et al.*, Nucl. Phys. **A548**, 249 (1992).
[32] A. Arima and F. Iachello, Ann. Phys. (N.Y.) **123**, 468 (1979).
[33] U. Kneissl *et al.*, Prog. Part. Nucl. Phys. **34**, 285 (1995).
[34] N. Pietralla *et al.*, Phys. Rev. C **51**, 1021 (1995).
[35] B. Kasten *et al.*, Phys. Rev. Lett. **63**, 609 (1989).
[36] H. Maser *et al.*, Phys. Rev. C **53**, 2749 (1996).
[37] B. Schlitt *et al.*, Nucl. Instrum. Methods Phys. Res. A **337**, 416 (1994).
[38] Yu. V. Sergeenkov, Nucl. Data Sheets **71**, 557 (1994).
[39] R.C. Greenwood *et al.*, Phys. Rev. C **14**, 1906 (1976).
[40] F.R. Metzger, Phys. Rev. C **18**, 2138 (1978).
[41] R.-D. Herzberg *et al.*, Nucl. Phys. **A592**, 211 (1995).
[42] H. Maser, Ph.D. thesis, Universität Stuttgart, in preparation.
[43] H. Harter *et al.*, Phys. Lett. B **205**, 174 (1988).
[44] W. Ziegler *et al.*, Nucl. Phys. **A564**, 366 (1993).
[45] S. Raman *et al.*, At. Data Nucl. Data Tables **36**, 1 (1987).
[46] N. Pietralla *et al.*, in the 9th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Budapest, 1996 (in press).
[47] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, 1987).
[48] T. Otsuka, private communication.
[49] G. Puddu *et al.*, Nucl. Phys. **A348**, 109 (1980).