Fragmentation of low-lying dipole strength in the odd-mass nucleus ^{133}Cs

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The fragmentation of low-lying dipole strength in the odd-mass nucleus ^{133}Cs has been investigated in nuclear resonance fluorescence (NRF) experiments performed at the bremsstrahlung beam of the Stuttgart Dynamitron accelerator at an end-point energy of 4.1 MeV. In the excitation energy range 2.3 – 3.7 MeV in total 22 new dipole excitations were observed. From the high-resolution γ-ray spectra measured by three high-efficiency Ge detectors the reduced excitation probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$ were deduced. The fragmentation and absolute total strengths of the detected dipole excitations are compared with results for the neighboring even-even, γ-soft nucleus ^{134}Ba, where both, rather strong *scissors mode-like* $M1$ and two-phonon $E1$ excitations are known from recent NRF experiments. [S0556-2813(97)01609-9]

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I. MOTIVATION

Low-lying dipole excitations in heavy nuclei met with an increased interest in recent years. The orbital $M1$ *scissors mode* in deformed nuclei, after its discovery in 1984 by Richter and co-workers [1], was systematically studied in numerous electron and photon scattering experiments (see, e.g., reviews [2,3]) and stimulated a large number of theoretical work. On the other hand, also enhanced electric dipole excitations ($E1$) were observed in heavy nuclei. In semimagic spherical nuclei such as the $N=82$ isotones (see [4,5], and references therein) or the Sn isotopes ($Z=50$) [6] the corresponding 1^- states were interpreted as the spin 1 member of the $1^-,2^-,\ldots,5^-$ quintuplet due to a two-phonon coupling of the quadrupole and octupole phonons [7–10]. In deformed nuclei low-lying 1^- states were systematically observed in the energy range 1.5–2.5 MeV with enhanced ground-state transition probabilities which can be explained as the bandheads of the $K=0$ octupole bands [11,12]. At somewhat higher energies (≈ 2.5 MeV) candidates for a special two-phonon excitation due to the coupling of the $K=1$ octupole and $K=2$ γ vibrations were found [13,14].

So far all these enhanced dipole excitations were mainly investigated in even-even nuclei [3]. A topic of current interest is the study of the fragmentation of these dipole modes in the neighboring odd-mass nuclei. The coupling of an unpaired nucleon or hole to the even-even core should lead to a splitting of the strength in odd-A nuclei.

The *scissors mode* was detected in odd-mass nuclei first in the Dy isotopes ^{163,161}Dy [15,16] where a concentration of dipole strength was observed fitting into the systematics of the *scissors mode* in the neighboring even-even isotopes ^{164,162,160}Dy [16,17]. However, the first investigations of the odd-mass Gd nuclei ^{157,155}Gd surprisingly revealed an extreme fragmentation of the low-lying dipole strength [16,18]. Further NRF studies including the odd-proton nuclei ^{159}Tb and ^{153}Eu established a certain systematics [18,19] showing an increasing fragmentation and reduction of the *detected* strength with decreasing mass number A. The missing strengths in the experimentally observed strength distributions can be hidden, e.g., in the continuous background, due to an extreme fragmentation, as estimated in a quite recent statistical fluctuation analysis [20] of ^{165}Ho and ^{169}Tm nuclear resonance fluorescence (NRF) spectra [21] or shifted to energies above 4 MeV as suggested from NRF studies on ^{167}Er [22]. These two complications can be addressed by a further increase of the experimental sensitivity (use of high efficiency γ-ray spectrometers and intense photon beams) and by extending the excitation energy range in experiments at accelerators with somewhat higher beam energies.

The coupling of an additional particle or hole to the $(2^-\otimes 3^-)$ multiplet, including the strong $E1$ excitations observed in the $N=82$ isotones [4], was studied in (γ,γ') experiments on ^{143}Nd, ^{141}Pr, and ^{139}La [23–25]. In ^{143}Nd for the first time dipole excitations to a $2^+\otimes 3^-\otimes$ particle multiplet could be observed [23,24]. The summed dipole strength was comparable to the $E1$ strength of the 1^- member of the two-phonon quintuplet in the core nucleus ^{142}Nd. On the other hand, in the odd-proton nuclei ^{141}Pr and ^{139}La, differing by one proton or proton hole from the semimagic $N=82$ core nuclei ^{142}Nd, ^{140}Ce, and ^{138}Ba, respectively, only about 40% of the strength seen in the even-even neighbors could be observed [25].

The aim of the present study of high sensitivity was an investigation of the fragmentation of the dipole strength in the odd-proton nucleus ^{133}Cs, which is the neighbor of the γ-soft O(6) even-even nucleus ^{134}Ba. O(6) nuclei are of special interest in present nuclear structure studies. In the $A\approx 190$ region the almost perfect O(6) nucleus ^{196}Pt was investigated recently in NRF experiments at Darmstadt and evidence for the *scissors mode* was found [26]. Subsequently, *scissors mode* excitations in ^{134}Ba were observed [27]. The nucleus ^{134}Ba belongs to the mass region around $A\approx 130$ where many γ-soft O(6) nuclei are known [28]. In our recent

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NRF experiments on ^{134}Ba, including polarization measurements of the scattered photons, besides the $M1$ *scissors mode* excitations, a strong $E1$ excitation was observed fitting into the energetic systematics of the 1^- member of the two-phonon quintuplet in ^{138,136,134}Ba [29].

II. EXPERIMENTAL METHOD

The NRF method represents by far the most sensitive technique to study low-lying dipole excitations. The formalism describing these photon scattering experiments is outlined in previous publications (e.g., [3,16,30,31]). In experiments using continuous bremsstrahlung as a photon beam the total cross section integrated over one resonance and the full solid angle is measured:

$$I_s = g\left(\pi\frac{\hbar c}{E_\gamma}\right)^2 \frac{\Gamma_0 \Gamma_f}{\Gamma}. \tag{1}$$

Here Γ_0, Γ_f, and Γ are the decay widths of the photoexcited state with spin J to the ground state, to a final lower-lying state and its total width, respectively. The statistical factor $g=(2J+1)/(2J_0+1)$ is called the ''spin factor.'' The product $g\Gamma_0$, which can be directly extracted from the measured scattering intensities is proportional to the reduced excitation probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$:

$$B(\Pi 1)\uparrow = gB(\Pi 1)\downarrow = \frac{9}{16\pi}\left(\frac{\hbar c}{E_\gamma}\right)^3 (g\Gamma_0) \tag{2}$$

and in numerical form

$$B(E1)\uparrow = 0.955\frac{g\Gamma_0}{E_\gamma^3}[10^{-3}e^2 \ \ \mathrm{fm}^2], \tag{3}$$

$$B(M1)\uparrow = 0.0864\frac{g\Gamma_0}{E_\gamma^3}[\mu_N^2]. \tag{4}$$

Here the excitation energies E_x are in MeV and the ground-state transition widths Γ_0 in meV.[1]

Unfortunately, in the case of odd-mass target nuclei the angular distributions of the scattered photons are rather isotropic. Therefore, in general no unambiguous spin assignments to the photoexcited states are possible. The vanishing anisotropy in the angular distributions in addition leads to rather low polarizations of the scattered photons. This implies that no parity assignments are possible by polarization measurements as in the case of even-even nuclei. For the comparison with the strengths in even-even nuclei we introduce the quantity $g\Gamma_0^{\mathrm{red}}$:

$$g\Gamma_0^{\mathrm{red}} = g\frac{\Gamma_0}{E_\gamma^3}, \tag{5}$$

which is proportional to the reduced dipole excitation probabilities [see Eqs. (3) and (4)].

The decay branching ratio R_{expt} defined by

$$R_{\mathrm{expt}} = \frac{B(\Pi L; J\to J_f)}{B(\Pi L; J\to J_0)} = \frac{\Gamma_f}{\Gamma_0}\frac{E^3_{\gamma J_0}}{E^3_{\gamma J_f}} \tag{6}$$

contains valuable information on the spin J and, in the case of deformed nuclei, on the K quantum number of the photoexcited state. Unfortunately, ^{133}Cs is not a well-deformed rotor nucleus.

The present NRF experiments on ^{133}Cs were performed at the bremsstrahlung facility of the Stuttgart Dynamitron accelerator [3,16]. A bremsstrahlung endpoint energy of 4.1 MeV and typical DC electron currents of about 250 μA on the bremsstrahlung production target were used in the present experiments. The scattering target consisted of Cs_2CO_3 with a total mass of 3.441 g sandwiched by ^{27}Al discs (0.761 g; diameter 16 mm), serving as the photon flux calibration [32]. The scattered photons were detected by three high-resolution Ge γ-ray spectrometers installed at angles of 93°, 127°, and 153° with respect to the incoming bremsstrahlung beam. The efficiencies of the detectors amounted to 97, 38, and 22 % [relative to a standard 7.6 cm × 7.6 cm NaI(Tl) detector], respectively. The total time of data collection was 140 h.

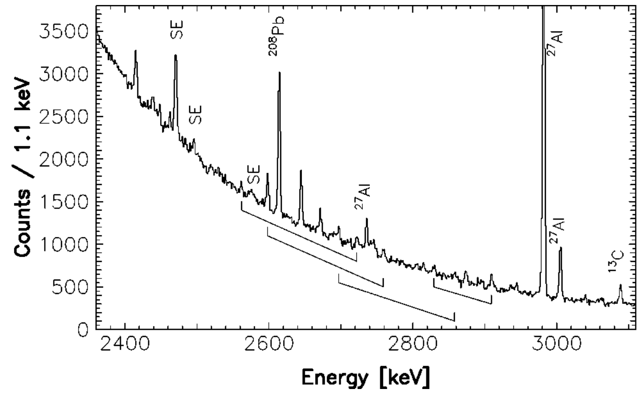

FIG. 1. Spectrum of photons scattered off ^{133}Cs in the energy range 2.4–3.1 MeV. Labeled peaks stem from the photon flux standard ^{27}Al, from background (^{208}Pb), target compounds (^{13}C), or are single escape peaks (SE). Brackets connect ground-state transitions and the corresponding transitions to lower-lying excited states in the case of an observed decay branching of the photoexcited states.

III. RESULTS AND DISCUSSION

Figures 1 and 2 show the spectra of photons scattered off ^{133}Cs, in the energy ranges 2.4–3.1 and 3.1–3.8 MeV, respectively. (The spectra of all three detectors were summed up.) Peaks stemming from the photon flux monitor ^{27}Al, from background (^{208}Pb, ^{13}C), and single escape peaks (SE) are labeled. Brackets connect ground-state transitions with corresponding transitions to the first or second excited states in ^{133}Cs. From the spectra it is already obvious that no strong dipole excitations are present in ^{133}Cs.

In Table I the obtained results are summarized in numerical form. The excitation energies E_x, the measured reso-

[1] In some of our previous articles [3,14,18] in the text, not used in the evaluations, a slightly different scaling factor of 0.0866 was given, due to rounding errors.

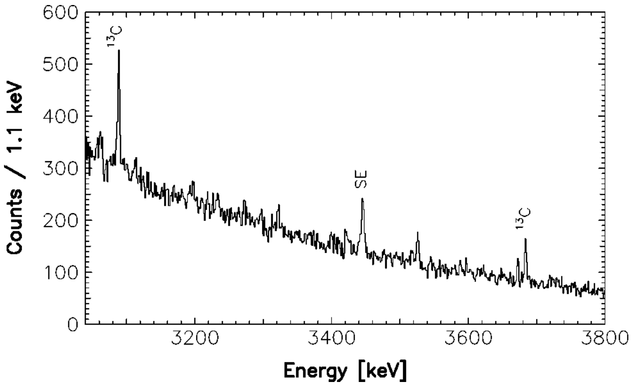

FIG. 2. Spectrum of photons scattered off ^{133}Cs in the energy range 3.1–3.8 MeV. For explanations see caption of Fig. 1.

nance scattering intensities I_s, the deduced products $g\Gamma_0$, and $g\Gamma_0^{\rm red}$ are given, which directly can be converted into the reduced excitation probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$ using the relationships (3) and (4). Besides the transition 2156 keV, which is known from $(n,n'\gamma)$ experiments [33], but could not be placed into the level scheme, all states observed in the present experiments were unknown so far [34].

TABLE I. Results of the present ^{133}Cs(γ,γ') experiment: Excitation energies E_x, integrated elastic resonance scattering intensities I_s, the products $g\Gamma_0$ of the spin factor g and the ground-state decay widths Γ_0, the products $g\Gamma_0^{\rm red}$ of the spin factor g and the reduced ground-state decay widths $\Gamma_0^{\rm red}$, and observed experimental decay branching ratios $R_{\rm expt}$ are given. In cases where no decay branching could be detected the quantity $g\Gamma_0$ has been deduced assuming $\Gamma_0=\Gamma$.

E_x [keV]	I_s [eV b]	$g\Gamma_0$ [meV]	$g\Gamma_0^{\rm red}$ [meV/MeV^3]	$R_{\rm expt}$
2156	1.11±0.18	1.34±0.22	0.134±0.022	
2321	0.60±0.13	0.84±0.19	0.067±0.015	
2415	1.79±0.23	2.72±0.35	0.193±0.025	
2438	0.96±0.17	1.48±0.26	0.102±0.018	
2462	0.70±0.14	1.10±0.22	0.074±0.015	
2645	2.81±0.22	5.12±0.40	0.277±0.022	
2672	1.27±0.16	2.37±0.30	0.124±0.016	
2722	0.82±0.18	2.38±0.45	0.118±0.022	0.60±0.21[a]
2744	1.77±0.26	3.46±0.52	0.167±0.025	
2759	0.65±0.14	3.07±0.38	0.146±0.018	1.63±0.24[a]
2815	0.48±0.13	0.99±0.27	0.044±0.012	
2858	0.57±0.14	2.81±0.48	0.120±0.021	1.55±0.36[a]
2873	1.22±0.16	2.62±0.33	0.110±0.014	
2909	1.39±0.21	4.90±0.63	0.199±0.026	0.66±0.18[b]
2944	0.90±0.13	2.03±0.29	0.080±0.011	
3039	0.40±0.10	0.97±0.24	0.035±0.009	
3296	0.62±0.21	1.76±0.59	0.049±0.016	
3322	0.47±0.12	1.35±0.35	0.037±0.010	
3422	0.56±0.20	1.72±0.60	0.043±0.015	
3517	0.42±0.15	1.37±0.47	0.031±0.011	
3526	1.03±0.17	3.34±0.54	0.076±0.012	
3672	0.91±0.19	3.19±0.65	0.064±0.013	

[a]Branching to the excited $5/2^+$ state at 160.7 keV.
[b]Branching to the excited $5/2^+$ state at 81.0 keV.

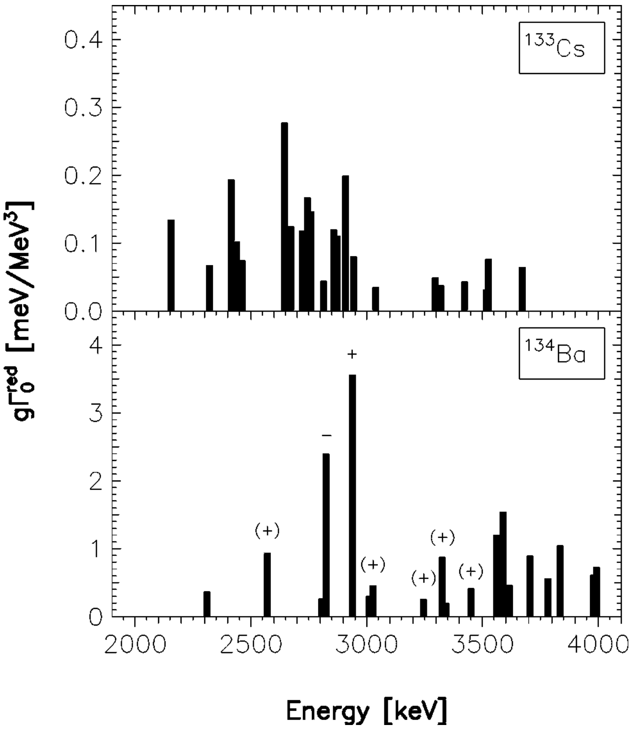

FIG. 3. Comparison of dipole strength distributions in ^{133}Cs [upper panel] and ^{134}Ba [lower panel]. Note that the scale in the upper panel is enlarged by a factor of 10.

In Fig. 3 the dipole strength distribution measured for ^{133}Cs [upper panel (a)] is compared with the one observed for ^{134}Ba [27]. Plotted are $g\Gamma_0^{\rm red}$ values in the energy range 2–4 MeV. For ^{134}Ba parities determined in recent NRF-polarization measurements are given [27]. Tentative parity assignments, given in parentheses, are assumed from the observed population of these levels in the β^--decay of the 1^+ ground state of ^{134}La [35,36]. Please note that the scales already differ by a factor 10. Obviously, the dipole strength detected in ^{133}Cs is more fragmented and reduced as compared to ^{134}Ba. The total observed strength (2–4 MeV, all errors were added linearly) amounts to $\Sigma_{2-4\ {\rm MeV}} g\Gamma_0^{\rm red} = (2.29\pm0.37)$ meV/MeV^3 as compared to a value of (17.0 ± 3.1) meV/MeV^3 in ^{134}Ba. Nevertheless, the strength concentration around 2.0–3.2 MeV in ^{133}Cs seems to correspond to the fragmented strengths of the strong $E1$ and $M1$ excitations at 2824 and 2939 keV in ^{134}Ba, respectively. However, even assuming the whole detected dipole strengths in ^{133}Cs in the energy range 2.0–3.2 MeV corresponds to the fragmented strength of the strong 2824 keV $E1$ transition in ^{134}Ba $[B(E1)\uparrow=(2.30\pm0.3)\times10^{-3}e^2\ {\rm fm}^2]$ alone, only a fraction of about 80% of this strength is observed in ^{133}Cs. On the other hand, the total $M1$ strength in ^{134}Ba, obtained by summing up the strengths of transitions of known $M1$ character in the energy range of the *scissors mode* 2.5–3.5 MeV amounts to $\Sigma_i B(M1)\uparrow=(0.56\pm0.04)\mu_N^2$ [27]. This total $B(M1)$ strength corresponds to a sum value of $\Sigma_i g\Gamma_0^{\rm red}$ of (6.5 ± 0.5) meV/MeV^3, which is much higher than the total strength of (2.0 ± 0.3) meV/MeV^3 observed in ^{133}Cs in the total energy range of the low-lying strength bump from 2–3.2 MeV.

From this one may conclude that both the $M1$ and $E1$ strengths in ^{133}Cs observed with the increased sensitivity of present NRF experiments $[(g\Gamma_0^{\mathrm{red}})_{\mathrm{min}} \approx 0.05$ meV/MeV^3 at 3 MeV] is much lower than the dipole strengths in the neighboring γ-soft even-even nucleus ^{134}Ba. These observations resemble the experimental situation and existing data concerning the fragmentation of the $M1$ *scissors mode* in odd-A deformed nuclei in the rare earth region [18] and of the $E1$ strengths in proton-odd nuclei near the $N=82$ shell closure [25].

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