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GDR γ-ray decay in ^{156}Dy* from regions selected on temperature and angular momentum

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Abstract

The strength distribution of the GDR built on highly excited states in a restricted temperature domain in ^{156}Dy and ^{155}Dy nuclei has been deduced by subtraction of γ-ray spectra obtained for the decay of ^{154}Dy* and ^{156}Dy* from regions selected on angular momentum. The resulting difference spectra have been analyzed within the statistical model. The results show a large deformation ($|\beta| \sim 0.51 \pm 0.29$ and 0.35 ± 0.14) for the angular-momentum regions with $\langle J \rangle \sim 32\hbar$ at $T \approx 1.8 \pm 0.2$ MeV and $\langle J \rangle \sim 46\hbar$ at $T \approx 1.7 \pm 0.2$ MeV, respectively, in satisfactory agreement with calculations performed in the framework of Landau theory of shape transitions and statistical fluctuations. The deduced centroid energies are in agreement with the systematics of the GDR built on the ground state. The width of the GDR shows a systematic increase with increasing temperature.

Studies of the γ-ray decay of the GDR built on highly excited states have proved to be a valuable tool to investigate the shapes of hot fast-rotating nuclei [1]. Such studies give most detailed information on the nuclear structure if specific domains of angular momentum and temperature are selected. Several groups have studied the GDR systematics as a function of temperature or angular momentum [1], but only a few measurements of the GDR decay have been made for selected domains of angular momentum of the compound nucleus. Angular momentum selection using the γ-ray multiplicity and the total sum energy of the γ-ray cascade [2,3] or by gating on isomer decay [4] have been made.

The γ-ray yield in these angular-momentum-selected spectra still originates from states at different excitation energies or temperatures ($T \sim 1$–2 MeV). A priori there is no reason to assume that the strength distribution of the GDR is the same throughout the complete cascade. On the contrary, recent calculations [5–8] performed for nuclei in the rare-earth region within the framework of the Landau theory of shape

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transitions predict a phase change from a prolate to a triaxial shape and finally a phase transition to an oblate shape with increasing temperature. These calculations nicely reproduce the measured changes in deformation in ^{160}Er and ^{166}Er [9,10]. Furthermore, it is shown that thermal fluctuations are very important for the understanding of the properties of the GDR at intermediate and high temperatures, $T \geqslant 1$ MeV. In the adiabatic limit, these fluctuations can cause a smearing of the strength of the resonance due to the averaging over different nuclear shapes [6,8]. In spherical nuclei this leads to thermal broadening of the resonance when compared with the GDR built on the ground state.

It is evident that exclusive data, including a selection on angular momentum as well as temperature, are needed to study the predicted shape evolution in more detail. A selection of states with a restricted range in temperature can be achieved by performing two experiments in which initial compound nuclei differing by one or two neutrons are formed. If in both reactions the same final nuclei are populated, spectra corresponding to a restricted temperature interval can be obtained by subtracting the data taken in both experiments [11].

Here, we report on a study wherein the techniques to select a restricted domain in angular momentum and temperature have been combined. Two experiments have been performed in which the statistical γ-decay of the GDR in ^{154}Dy and ^{156}Dy has been investigated by bombarding ^{114}Cd and ^{116}Cd targets with ^{40}Ar beams of 173 and 200 MeV, respectively. A detailed description of the experimental set-up and the data analysis can be found in Ref. [12].

The ^{154}Dy* compound nucleus was formed at an initial excitation energy $E^* = 69$ MeV and angular momentum up to $\sim 70\hbar$ with an average value of $55\hbar$. After emission of a high-energy γ-ray and two or three neutrons, the decay cascade will end in the nuclei ^{152}Dy and ^{151}Dy. In the other reaction, the ^{156}Dy* compound nucleus was formed at an initial excitation energy of 92.5 MeV and an angular momentum up to $\sim 90\hbar$ with an average value of $75\hbar$. The initial excitation energy of the ^{156}Dy* nucleus differs from that of the ^{154}Dy* nucleus by approximately twice the energy removed by an evaporated neutron, such that in both reactions the same final nuclei are populated. The angular-momentum-selected spectra resulting from both reactions have already been published elsewhere [3,12]. They correspond to three angular-momentum bins with a full width at half maximum of $\sim 20\hbar$. The difference spectra presented in this letter were obtained by subtracting the spectra for two of these bins, i.e. those for $\langle J \rangle \sim 32\hbar$ and $\langle J \rangle \sim 46\hbar$. The overlap in the population matrices for these angular-momentum bins in the two reactions was larger than 90%. This overlap was much smaller for the highest angular-momentum windows which were therefore not included in our present analysis.

The low-energy parts ($E_\gamma < 6$ MeV) of the γ-ray spectra, corresponding to the same angular-momentum domain, are dominated by statistical E1 transitions below the particle decay threshold and are expected to be approximately the same. They differ only by a normalization factor which accounts for the difference in population cross sections of the initial compound nuclei and the difference in the experimental conditions, such as the total number of recorded events. This normalization is estimated from results of statistical-model calculations also presented in Refs. [3,12]. For each of the measured spectra $N_\gamma(E_\gamma)$, the normalization constants $R_{\rm N}^{154,156}$ were obtained by fitting the spectra calculated with CASCADE [13] to the angular-momentum-selected data for ^{154}Dy and ^{156}Dy, respectively, in the energy range from 2.9 MeV to 6 MeV. Hence:

$$\int_{2.9}^{6} N_\gamma^{154,156}(E_\gamma)\,{\rm d}E_\gamma = R_{\rm N}^{154,156} \int_{2.9}^{6} \sigma_{\rm CASC}^{154,156}(E_\gamma)\,{\rm d}E_\gamma . \qquad (1)$$

These normalization constants $R_{\rm N}^{154,156}$ and the ratio between the calculated spectra $R_{\rm CASC}$, which is defined as

$$R_{\rm CASC} = \frac{\int_{2.9}^{6} \sigma_{\rm CASC}^{156{\rm Dy}}(E_\gamma)\,{\rm d}E_\gamma}{\int_{2.9}^{6} \sigma_{\rm CASC}^{154{\rm Dy}}(E_\gamma)\,{\rm d}E_\gamma}, \qquad (2)$$

then give the following normalization $R_{\rm N}$ to be used in obtaining the experimental difference spectrum:

$$R_{\rm N} = \frac{\int_{2.9}^{6} N_\gamma^{156}(E_\gamma)\,{\rm d}E_\gamma}{\int_{2.9}^{6} N_\gamma^{154}(E_\gamma)\,{\rm d}E_\gamma} = \frac{R_{\rm N}^{156}}{R_{\rm N}^{154}} R_{\rm CASC} . \qquad (3)$$

This normalization procedure ensures consistency in the comparison of the experimental and calculated difference spectra as well as the experimental and calcu-

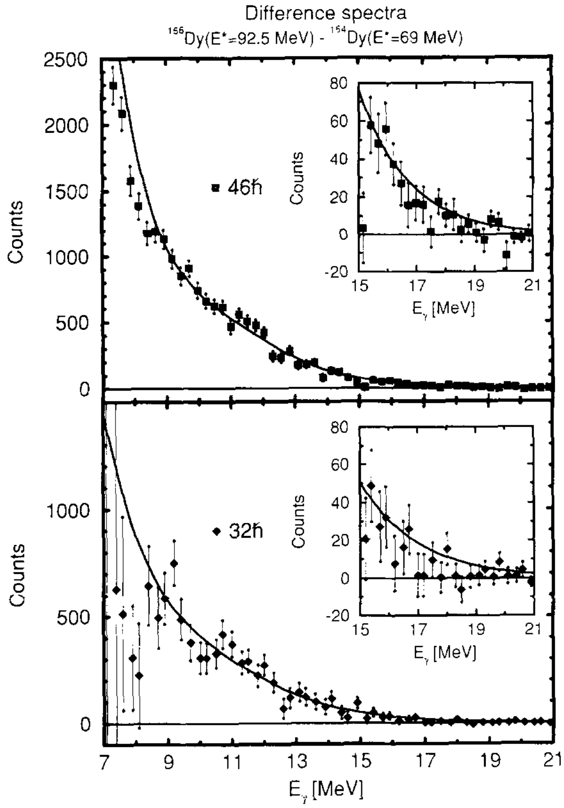

Fig. 1. Data and theoretical calculations for difference spectra with average angular momenta of 32ħ (T = 1.8 MeV) and 46ħ (T = 1.7 MeV). The difference spectra were obtained by subtracting the data for ^{154}Dy at $E^* = 69$ MeV from data for ^{156}Dy at $E^* = 92.5$ MeV (see text for details). The insets show the regions above 15 MeV in an expanded scale.

lated angular-momentum-selected spectra from which they have been obtained.

The experimental and calculated difference spectra are presented in Fig. 1. The temperatures corresponding to the selected regions are $T = 1.8$ MeV for $\langle J\rangle \sim 32\hbar$ and $T = 1.7$ MeV for $\langle J\rangle \sim 46\hbar$, with a width $\Delta T \sim 0.2$ MeV. These temperatures are obtained by weighting the mean temperature of the states populated in ^{156}Dy* and ^{155}Dy* with the population cross sections for these nuclei.

The difference spectra have been calculated with the program CASCADE assuming that the average excitation energy of the levels populated in ^{154}Dy after emission of two neutrons by the ^{156}Dy* compound nucleus is the same as the energy at which the compound nucleus ^{154}Dy* is produced in the other reaction. In this case, the decay of the ^{156}Dy* compound nucleus can be separated in two parts: the first two steps in the decay cascade, i.e. the decay in the nuclei ^{156}Dy* and ^{155}Dy*, and the subsequent decay of ^{154}Dy*. The latter is approximately the same as the decay cascade of the ^{154}Dy* compound nucleus formed at $E^* = 69$ MeV.

The validity of this assumption has been verified by comparing the population cross sections, per angular-momentum bin, for ^{154}Dy* populated in the decay of ^{156}Dy* with those of ^{154}Dy* formed as the initial compound nucleus. The cross sections were calculated in the same way as described in Ref. [3]. The CASCADE calculations further show that the cross sections for the decay channels which do not proceed via ^{154}Dy are small. The sum of the population cross sections for ^{154,155}Tb and for ^{153,154}Gd are 8% and 0.2% of the ^{156}Dy formation cross section, respectively.

The fits to the difference spectra were then calculated as follows. The GDR strength distributions were described [3] by a double lorentzian with four free parameters: the energies of both components E_1 and E_2, the strength in the first component S_1 and the width parameter C, where $\Gamma_i = C\,E_i^2$. The sum rule was assumed to be exhausted i.e. $S_1 + S_2 = 1$. The level-density parameter was $a = A/8\ \mathrm{MeV}^{-1}$.

The ^{156}Dy* spectra were calculated with a modified version of CASCADE, such that the GDR parameters in the first two decay steps could be varied, whereas the parameters describing the GDR strength distribution in the subsequent steps were fixed to the values used in calculating the ^{154}Dy* spectra. The ^{154}Dy* spectra were calculated with the standard version of CASCADE using the parameters of Ref. [12]. Both spectra were then folded with the detector response function and the ^{154}Dy spectrum, multiplied by the normalization constant R_{CASC} (see Eq. (2)), was subtracted from the ^{156}Dy spectrum. The best fit of the calculated spectrum to the experimental data was obtained in an iterative process performed with MINUIT [14] where only the GDR parameters in the first two steps of the ^{156}Dy decay were varied. The results of these fits are listed in Table 1 and shown in Fig. 1 by the solid lines.

The errors for the extracted parameters, the centroid energy $\langle E\rangle$, deformation parameter β and constant of proportionality for the width C, are relatively large, in particular for $\langle J\rangle \sim 32\hbar$. This is partly due to the relatively large statistical errors and partly to a discrepancy

Table 1
The GDR parameters resulting from the best fits to the difference spectra using $a = A/8\ \text{MeV}^{-1}$

$\langle J\rangle$ [$\hbar$]	E_1/E_2	S_1/S_2	$\langle E\rangle$ (MeV)	β	C ($10^{-2}\ \text{MeV}^{-1}$)	χ^2/N
32	0.66 ± 0.08	0.52 ± 0.11	15.2 ± 1.3	$\pm 0.51 \pm 0.29$	5.5 ± 0.8	1.285
46	0.73 ± 0.10	1.00 ± 0.37	14.5 ± 0.7	$\mp 0.35 \pm 0.14$	4.7 ± 0.8	2.116

The quoted errors have been obtained by adding the systematic and statistical errors.

between the data and the results of the CASCADE calculations in the range $E_\gamma = 7$–8 MeV. Due to the low statistical accuracy in this angular-momentum window (see inset Fig. 1), the fit procedure increases the energy and the strength in the second component of the double lorentzian slightly leading to large errors in the extracted parameters and a large deformation β, in particular.

The following observations can be made. The deduced centroid energies are both in good agreement with the value obtained from the systematics of the GDR built on the ground state, and with the values found for the angular-momentum-selected spectra for ^{156}Dy* [3] and for ^{154}Dy* [12]. The values of the deformation $|\beta|$ are consistent with the values reported in Ref. [3]. The deduced width parameters C are significantly larger than those reported for the angular-momentum-selected spectra for ^{154}Dy [12], obtained at lower average temperature, and for ^{156}Dy [3]. As can be seen in Fig. 2, the width increases systematically with temperature.

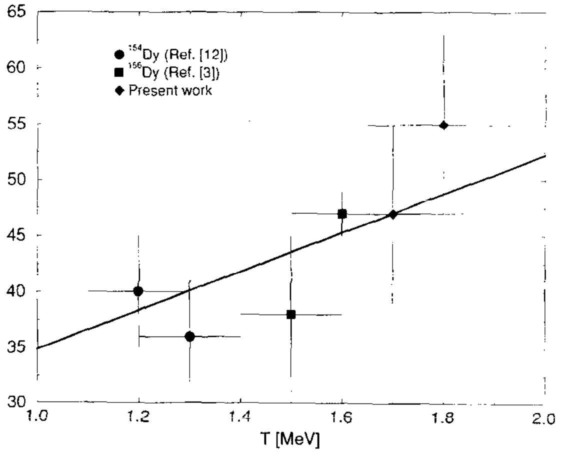

Fig. 2. Width parameter C as function of temperature. Values are taken from Refs. [3,12] and the present work. The line is a linear interpolation from the width of the ground-state GDR (not shown in the figure).

The experimental difference spectra have been converted to "absorption" cross sections using a procedure similar to that of Gundlach et al. [15]. The resulting "absorption" spectra are shown in Fig. 3a together with the GDR absorption strength distribution calculated with the parameters obtained from the fit.

In Fig. 3b, converted data are compared with the results of calculations performed within the framework of the Landau theory (see Alhassid et al. [5,8,10]) in which shape transitions and thermal shape fluctuations are taken into account. These calculations have been performed in the adiabatic limit as described in Ref. [8] using $E_0 = 14.61$ MeV and $\Gamma_0 = 3.96$ MeV (determined from the ground-state GDR systematics in this region) and assuming full exhaustion of the TRK sum rule. For $\langle J\rangle \sim 32\hbar$ ($46\hbar$) the free-energy surface $F(T, \omega, \beta, \gamma)$ has been calculated for $T = 1.8$ MeV ($T = 1.7$ MeV) and $\hbar\omega = 0.45$ MeV ($\hbar\omega = 0.63$ MeV), respectively, corresponding to the average values in the selected bins. In both cases the nucleus has an oblate equilibrium shape. As in Ref. [3], the theoretical curves in Fig. 3b have been multiplied by 0.8. The overall agreement between the experimental data and the results of the calculation is satisfactory. The shape of the strength distribution is well reproduced. The excess in experimental cross section (compared to the calculated strength) at $E_\gamma < 10$ MeV could be due to a slight shift in the centroid energy but is more likely due to small inaccuracies in the normalization. The weighted average deformations resulting from the calculations are -0.33 and -0.34 for $\langle J\rangle = 32\hbar$ and $46\hbar$, respectively. These are in reasonable agreement with those determined from the CASCADE fits.

In conclusion, we have measured γ-rays emitted in the first steps of the decay cascade from a restricted region in angular momentum *as well as* in temperature. The resulting photoabsorption spectra are found to be

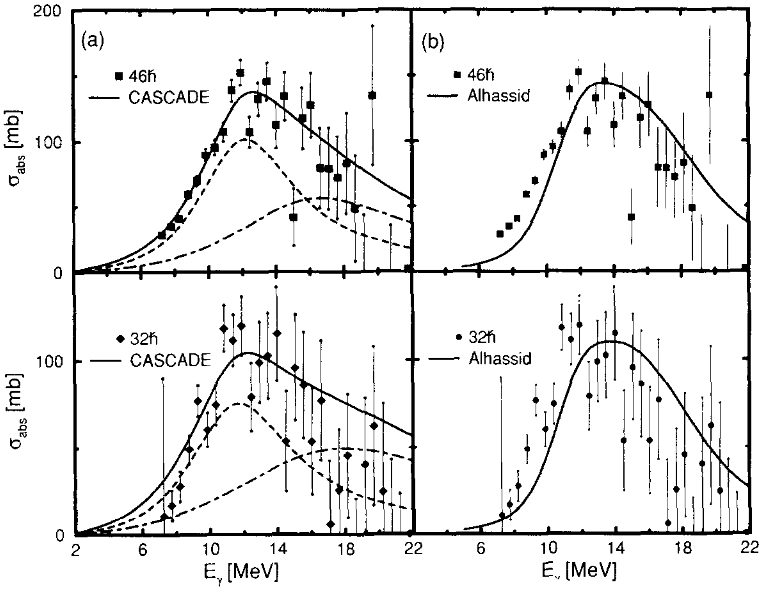

Fig. 3. (a) Converted "absorption" spectra deduced from the difference spectra for $\langle J\rangle \sim 32\hbar$ ($T = 1.8$ MeV) and $\langle J\rangle \sim 46\hbar$ ($T = 1.7$ MeV). Note that after the conversion the data have been rebinned over two data points with respect to Fig. 1. "Absorption" spectra calculated by CASCADE are shown as solid curves. The dashed and dash-dotted curves indicate the two components of the GDR. (b) Comparison between the converted "absorption" spectra and calculations performed in the framework of the Landau theory with thermal shape fluctuations (see text).

in agreement with calculations performed in the framework of Landau theory of shape transitions and statistical fluctuations. Furthermore, the centroid energies extracted from comparison to CASCADE calculations are found consistent with values obtained from systematics of the GDR built on the ground state. As in the case of the angular-momentum-selected spectra, we observe large deformations. A systematic increase of the width of the strength distribution as a function of temperature is also observed.

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