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Shape transition at high spin manifested in the γ-ray decay of the giant dipole resonance in hot Dy nuclei

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The statistical γ-ray decay of the giant dipole resonance built on highly excited states in $^{151-156}$Dy has been used as a probe for studying the evolution of the nuclear shape with increasing angular momentum. The observed shift of the giant dipole resonance strength to lower energy suggests a change of the nuclear deformation from prolate to oblate with increasing spin.

An interesting development in the study of the statistical γ-ray decay of the giant dipole resonance (GDR) superimposed on excited states is the observation of the splitting of the strength in deformed nuclei,[1,2] which indicates that such measurements offer a valuable tool for studying the structure of hot fast rotating nuclei. This is especially interesting in view of the recent theoretical progress in understanding the temperature and angular momentum dependence of the GDR.[3-6] The results of random phase approximation calculations show that the GDR energy is remarkably stable with respect to the intrinsic excitation of the nucleus.[3,4] Furthermore, all models predict only small effects of rotation and temperature on the GDR centroid energy and strength distribution for a stable deformed nucleus. On the other hand, at low temperature dramatic changes in nuclear deformation are predicted with increasing rotational frequency with a general trend first towards an oblate shape and then a transition via a sequence of triaxial shapes towards a prolate superdeformed shape at very large angular momenta. At higher temperatures, where shell effects are predicted to wash out, an evolution to an oblate shape at high angular momenta is expected. These changes will be reflected in the shapes of the GDR strength distribution[3-5] with the restriction that the strength function will become more and more featureless at much higher temperatures due to thermal fluctuations which cause a strong damping of the GDR.[7-9]

In this Rapid Communication we report on the results of an experiment in which the angular momentum dependence of the GDR in $^{151-156}$Dy has been studied up to an average angular momentum $\langle J \rangle \simeq 62\hbar$. We have found a systematic shift of the GDR strength to lower energies with increasing spin. This shift suggests a change of the nuclear deformation from prolate to oblate. The centroid energy of the GDR, which is found to be stable, agrees with the value predicted for the ground state GDR.

The experiment was performed at the Kernfysisch Versneller Instituut (KVI) in Groningen. A 3.2 mg/cm^2 ^{116}Cd target was bombarded with a 205 MeV ^{40}Ar beam. The average excitation energy of the compound ^{156}Dy nuclei was about 90 MeV. The beam and recoiling nuclei were stopped in a Au backing of the target, thus enabling the detection of delayed γ-rays deexciting isomeric states in final nuclei. The beam energy after passing through the target was well below the Coulomb barrier of the Au backing.

High energy γ rays were measured with a 25.4×33 cm NaI detector,[10] surrounded by a plastic scintillator anticoincidence shield and a Pb shield. The NaI detector was placed at 90° with respect to the beam at a distance of 60 cm from the target. Neutron events in the NaI detector were discriminated against by the time of flight. The setup further consisted of a 40 cm long and 40 cm diameter NaI sum spectrometer, a multiplicity filter of ten 12.7×12.7 cm NaI detectors, and a Ge telescope. The two halves of the sum spectrometer, each consisting of three segments, were placed above and below the beam line at a distance of 7 cm from the target. The ten NaI detectors and the Ge telescope were placed in the gap between the two halves of the sum spectrometer at about 20 cm distance from the target.

Gamma-ray spectra corresponding to selected angular momentum domains have been obtained by a proper analysis of the fold distribution and sum spectrum. In the analysis we have accounted for a lowering of the prompt γ-ray multiplicity due to long-living isomers in several daughter nuclei and due to α-particle emission. The angular correlation effect, introduced by the specific geometry of the multiplicity filter, is found to be negligible. Details of the analysis are given in Ref. 11.

The experimental results are shown in Fig. 1. The three spectra indicate a systematic shift of the giant dipole strength to lower energy with increasing angular momentum. A similar effect has been observed in the decay of ^{162}Er* by Hennerici *et al.*[12] This shift is observed more clearly in Fig. 2, where the spectra are multiplied with an exponential $e^{E_\gamma/T}$. The different values of the temperature T account for the angular momentum dependence of the yrast energy.

In order to investigate the origin of the observed shift, γ-ray spectra, calculated with the modified computer code CASCADE,[13] have been fitted to the experimental data. In the calculations, the proper spin distribution and the population matrix for the selected angular momentum domains was used. It was determined from the fold distri-

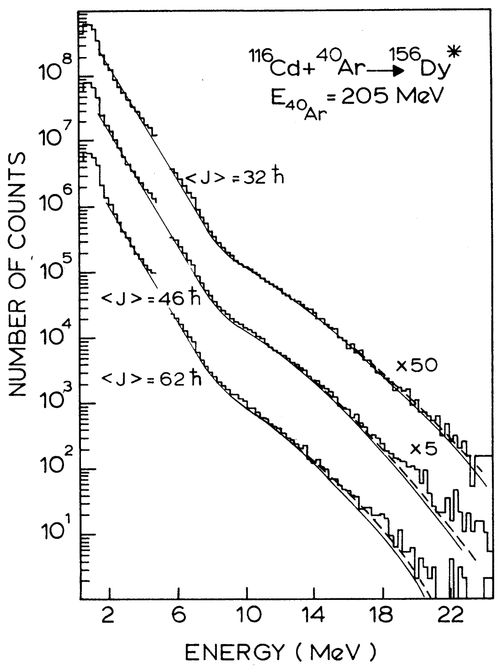

FIG. 1. Prompt high energy γ-ray spectra corresponding to three angular momentum windows. The low energy parts of the spectra ($E_\gamma \lesssim 5$ MeV) have been multiplied with a factor of 200, i.e., the downscale factor during the experiment. The solid lines through the data show the results of fits to the spectra with statistical model calculations performed with the program CASCADE, the dashed lines correspond to fits with a normalization constant R_N increased by 5%.

bution and the detector geometry by a Monte Carlo simulation. The energy loss of the beam in the target was also accounted for. In these calculations a two component Lorentzian shape was assumed for the GDR. The fitting procedure was done in two steps. First, the normalization constants R_N listed in Table I were determined by fitting the calculated spectra folded with the detector response function to the experimental data in the range $E_\gamma=2$–8.5 MeV. This part of the γ-ray spectrum is most appropriate to determine the normalization constant for the cross section since its shape and magnitude are rather independent of the GDR parameters. The level density parameter in the statistical model calculations was $a=A/8$ MeV^{-1}. Then the GDR parameters were deduced from a fit of the calculated spectrum to the experimental data in the energy range $E_\gamma=8.5$–22 MeV. The number of parameters describing the two component GDR strength function was limited to four. The energies of both components E_1 and E_2 were taken as free parameters. Furthermore, the resonance widths were assumed to depend on the energies as $\Gamma_i=cE_i^2$ according to the systematics of the experimental data for the ground state GDR width as evaluated by Carlos *et al.*[14] The proportionality constant c was treated as a free parameter. The fourth parameter was taken to be F_1, the fraction of the TRK sum rule exhausted by the first component. The strength of the second component is then completely determined assuming 100% exhaustion of this sum rule.

The results of the fits are listed for each angular momentum bin in Table I (first row). All three spectra are fitted reasonably well by the statistical model calculations (see solid curves in Figs. 1 and 2). Note that the experimental data are reproduced over the whole energy range from $E_\gamma=2$ to 22 MeV. However, in all three spectra an excess of strength is observed in the energy range $E_\gamma=9$–11 MeV and $E_\gamma=16$–18 MeV. This excess in strength in the experimental data in comparison to the theoretical predictions is a consequence of the fitting procedure followed in this work, in which the normalization is determined from the low energy part ($E_\gamma=2$–8.5 MeV) of the spectrum and the free parameters of the GDR strength distribution are restricted to four as described above.

Although we believe that the normalization procedure we followed resulting in an excess of experimental strength in the above mentioned γ-ray energy regions is the correct one considering the uncertainties in the absolute experimental γ-ray cross sections and assumed theoretical fusion cross sections, we have repeated the calculations to make sure that our results for the deduced GDR

TABLE I. GDR parameters obtained from a fit of spectra calculated with the program CASCADE to the experimental data. The values within parentheses are the results of fits with normalization constants increased by 5%. The deformation parameters have been deduced assuming either a prolate ($F_1<0.5$) or an oblate deformation ($F_1>0.5$). The estimated errors, including the uncertainties in the normalization and level densities for E_{GDR}, Γ_1, and β are ±0.3 MeV, ±0.5 MeV, and ±0.04, respectively. These errors are larger than those obtained from the fits with the program MINUIT.

$\langle J\rangle$ ($\hbar$)	R_N	E_1 (MeV)	E_2 (MeV)	Γ_1 (MeV)	F_1	χ^2/N	E_{GDR} (MeV)	β
32	1.40	13.8	15.8	8.6	0.28	0.7	15.2	0.16
		(14.3)	(16.2)	(9.3)	(0.42)	(0.6)	(15.4)	(0.13)
46	1.00	13.9	15.5	8.5	0.68	1.4	14.4	−0.13
		(13.7)	(15.7)	(8.3)	(0.54)	(1.2)	(14.6)	(−0.13)
62	0.67	13.5	17.1	8.5	0.67	0.9	14.7	−0.28
		(13.6)	(17.0)	(8.8)	(0.65)	(0.8)	(14.8)	(−0.26)

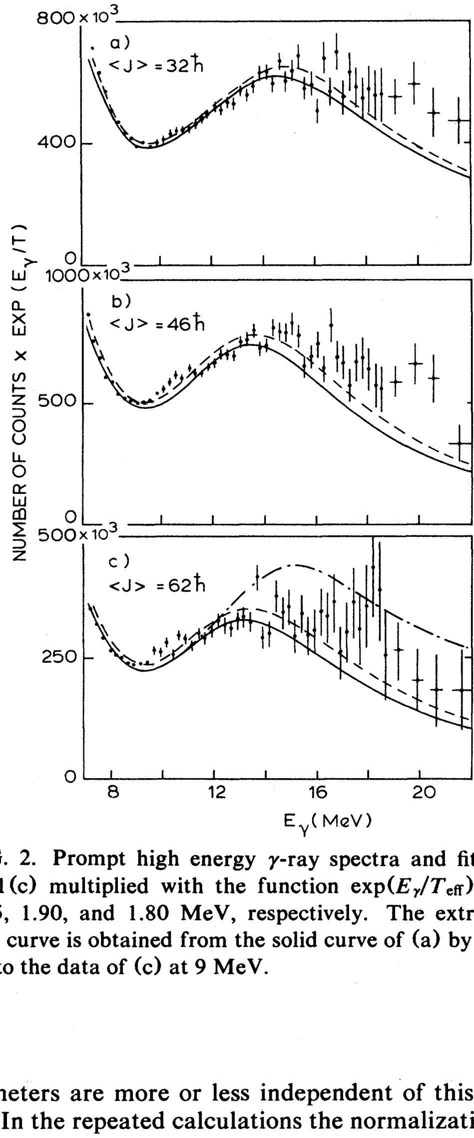

FIG. 2. Prompt high energy γ-ray spectra and fits of Figs. 1(a)–1(c) multiplied with the function $\exp(E_\gamma/T_{\rm eff})$ with $T_{\rm eff}=1.95$, 1.90, and 1.80 MeV, respectively. The extra dashed-dotted curve is obtained from the solid curve of (a) by normalizing it to the data of (c) at 9 MeV.

parameters are more or less independent of this assumption. In the repeated calculations the normalization factor was increased by 5%, yielding a good fit to the data in the region of 8–16 MeV for all three angular momentum domains. The fits to the data are shown in Figs. 1 and 2 as dashed curves. However, the resulting parameters which are listed for each angular momentum bin (second row, within parentheses) in Table I are within the quoted uncertainties in remarkable good agreement with those listed in the first rows. The additional strength still observable in the region $E_\gamma=16$–18 MeV can possibly be attributed to contributions to the GDR built on low angular momentum states with a larger prolate deformation (the ground state deformation of ^{156}Dy is $\beta=0.28$).

Furthermore, to investigate the dependence of the results on the level density parameter we have also performed a statistical model calculation for the highest angular momentum bin taking $a=A/9$ MeV^{-1}. The increase of the level density parameter causes an increase of the normalization constant of about 10% with no sizable effect on the GDR parameters.

The most remarkable results from the fits are the more or less constant centroid energy of the GDR and the systematic change of the shape which is interpreted as a change of the nuclear deformation with increasing angular momentum. The centroid energies $E_{\rm GDR}$ deduced from the energies and strengths of both components are in agreement with the value $E=14.7$ MeV (average for ^{148}Sm and ^{150}Sm) obtained from the systematics of the GDR built on the ground state,[15] indicating that it is neither affected by the rotational motion nor by the high temperature. The deformation parameter β is related to the half-axes a and b of the axially symmetric deformed nucleus by the expression

$$\beta=1.05(d-1)d^{-1/3}\,,$$

where $d=b/a$. The frequencies for oscillations along these axes a and b corresponding to $m=0$ and $m=\pm 1$, respectively, are given by Danos[16]

$$\frac{E_b}{E_a}=0.911\frac{a}{b}+0.089\,.$$

This relation has been used to calculate the deformation parameters given in Table I. The values obtained for the three angular momentum bins indicate that the nucleus changes from a prolate deformation $\beta=+0.16$ at $\langle J\rangle=32\hbar$ to an oblate deformation $\beta=-0.13$ at $\langle J\rangle=46\hbar$ and that a further increase of angular momentum leads to a large oblate deformation $\beta=-0.28$ at $\langle J\rangle=62\hbar$. A fit with a prolate deformation for the spectrum at $\langle J\rangle=62\hbar$ can be excluded as is demonstrated in Fig. 2(c), wherein the dashed-dotted curve is the same as the solid curve from Fig. 2(a) obtained with a prolate deformation but renormalized to the data of Fig. 2(c) at 9 MeV. A larger disagreement would have resulted if the dashed curve from Fig. 2(a) was used instead. A similar result has recently been obtained by Bruce *et al.*[17] in the decay of the same compound nucleus but at a somewhat lower temperature and maximum angular momentum.

The averaged widths $\Gamma_1\sim 8.5$ MeV for the lower component and $\Gamma_2\sim 12$ MeV for the higher component following from the analysis are much larger than the width of the GDR built on the ground state. The increase of the GDR width with increasing temperature is a common feature of the GDR built on highly excited states and can qualitatively be understood in terms of fluctuations of the nuclear shape. Since the angular momentum bins are partly overlapping in this experiment and a strong angular momentum dependence of the nuclear deformation is found, it is likely that an integration over different nuclear shapes also contributes to the relatively large width.

In conclusion, one can say that the centroid energy of the GDR measured in the statistical decay of ^{156}Dy* up to an averaged angular momentum as large as $\langle J\rangle\cong 60\hbar$ is the same as for the ground state. The observed shift in GDR strength suggests a change of the nuclear deformation from prolate to oblate and to a further increase of the deformation with increasing angular momentum.

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