Deformation of Heated Nuclei Observed in the Statistical Decay of the Giant Dipole Resonance

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Splitting of the giant dipole resonance built on excited states of Er nuclei, observed in continuum γ-ray spectra from $^{12}C+^{148}Sm$ and $^{12}C+^{154}Sm$ reactions, reveals the persistence of prolate, ground-state-like deformation at elevated temperature $T \sim 1$ MeV and spins $I=0$ to $25\hbar$.

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Recent experiments[1,2] have shown that high-energy γ rays are emitted from highly excited compound nuclei formed in complex particle collisions, and that this emission process is governed by the average properties of the giant dipole resonance (GDR) built on excited nuclear states. In analogy with the well-known splitting of the GDR built on the ground state of statically deformed nuclei, the GDR strength function for compound-nuclear γ decay should provide information on the deformation of the ensemble of excited nuclear states populated by the γ decay. Such information would be particularly interesting since, in contrast to the properties of rapidly rotating "cold" nuclei near the yrast line, very little is known about the deformation of highly excited "hot" nuclei, in which most of the excitation energy resides in internal degrees of freedom. Recently it has been shown[2] that effects of nuclear deformation at high excitation can be observed in continuum γ-ray spectra from heavy-ion–induced fusion reactions.

In this Letter we show, for the first time, that nuclei which are deformed at low energy and spin have the *same* (prolate) deformation at moderate spin and temperature. This conclusion follows from our observation of split GDR shapes in γ-ray spectra from the decay of the compound nuclei $^{166}Er^*$ at an initial energy $E_i=49.2$ MeV and $^{160}Er^*$ at $E_i=43.2$ MeV formed in $^{12}C+^{154}Sm$ and $^{12}C+^{148}Sm$ reactions, respectively, at mean initial angular momenta $\bar{I} \sim 15\hbar$. Our observed GDR shapes are remarkably similar to the shapes observed in ground-state (γ,n) studies of rare-earth nuclei. Our results indicating unchanged deformation are consistent with theoretical expectations, and are in contrast with recent results[2] which suggest oblate deformation for the $^{166}Er^*$ compound nucleus at a somewhat higher energy and spin.

Samarium targets of 2.8-mg/cm^2 thickness isotopically enriched to 91% for ^{148}Sm and to 99% for ^{154}Sm were bombarded with ~ 250 nA of 63-MeV ^{12}C (6^+) ions from the University of Washington FN tandem accelerator. Singles γ rays were detected in a large γ-ray spectrometer consisting of a 25.4-cm$\times$25.4-cm NaI crystal surrounded by a plastic anticoincidence shield and encased in passive ^6LiH and Pb shielding, with ≈ 40 cm of paraffin between the detector and the target. The use of pulsed-beam time of flight with 3-ns time resolution over a 1-m flight path allowed a clean separation of prompt γ rays produced in the target from all other sources of background. The NaI gain was stabilized to better than 1% by use of light-emitting diode pulser, with a calibration based on discrete lines measured in $^{11}B+p$ reactions. Contributions from small (0.2% to 0.6% by weight) C and O impurities in the target were visible in the region $4.4 \leq E_\gamma \leq 7.1$ MeV, and were subtracted by use of spectra measured with C and O targets.

Gamma-ray spectra from the decay of $^{166}Er^*$ and $^{160}Er^*$ are shown in the left-hand part of Fig. 1. These spectral shapes are qualitatively characteristic of compound-nulcear statistical γ decay, with a steeply falling low-energy component ($E_\gamma < 8$ MeV) arising from γ emission following particle evaporation, and a broad bump extending above the GDR energy ($E_\gamma \sim 14$ MeV), characteristic of γ emission at an early stage in the cooling-off process in direct competition with particle evaporation. The shape of the γ-ray spectrum in the high-energy region is sensitive to the shape of the GDR. Accordingly, we have performed a least-squares fit of a statistical-model calculation to our data, from $E_\gamma=9$ to 21 MeV, using a modified CASCADE[3] computer code. The average $E1$ radiative width at energy E_i and spin J was assumed to have the form

$$\Gamma_\gamma^J \rho_J(E_i) = (\pi\hbar c)^{-2} \sigma_{\rm abs}(E_\gamma) E_\gamma^2/3,$$

where $\rho_J(E_i)$ is the density of initial states. We assumed a Lorentzian form for $\sigma_{\rm abs}(E_\gamma)$, the cross section for the *inverse* process of γ absorption by the ensemble of excited nuclear levels populated by the γ decay:

$$\sigma_{\rm abs}(E_\gamma) = (60\ \text{MeV mb})(2/\pi)(NZ/A) \sum_{j=1}^{2} S_j \Gamma_j E_\gamma^2 [(E_\gamma^2 - E_j^2)^2 + E_\gamma^2 \Gamma_j^2]^{-1},$$

where S_j, E_j, and Γ_j and the resonance strengths (in units of the classical sum rule), energies, and widths of

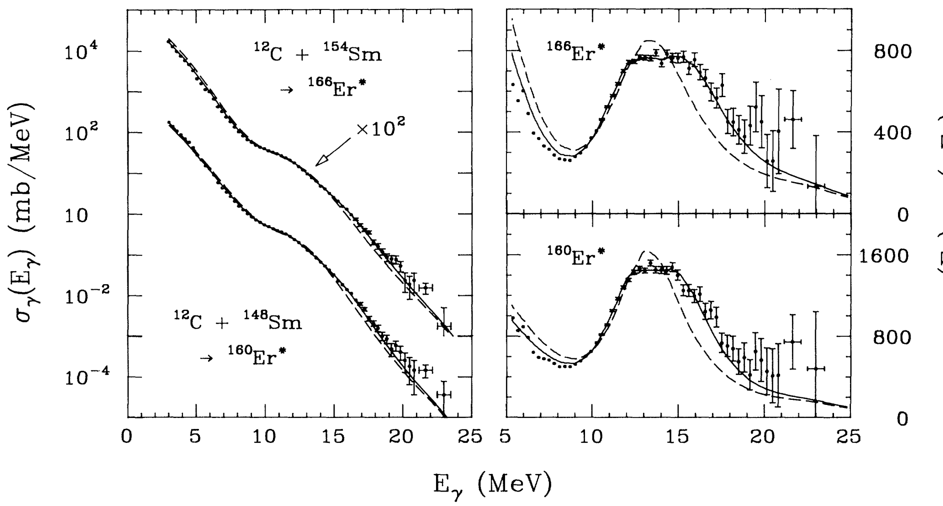

FIG. 1. Left: Gamma-ray spectra from the decay of ^{166}Er* (49.2 MeV) and ^{160}Er* (43.2 MeV) produced in ^{12}C + ^{154}Sm and ^{12}C + ^{148}Sm, respectively, at $\bar{E}(^{12}\mathrm{C}) = 61.2$ MeV. Dashed and solid curves: CASCADE statistical-model least-squares fits for $E_\gamma = 9$–21 MeV assuming a one- and two-component GDR, respectively. The measured detector response function has been folded into the calculations. The ordinate approximately represents the γ-ray production cross section $\sigma_\gamma(E_\gamma)$ averaged over $\theta_\gamma = 65°$–$140°$. Right: The product $\sigma_\gamma(E_\gamma)\exp(\alpha E_\gamma)$, where $\alpha^{-1} = 1.45$ MeV for ^{166}Er* and 1.40 MeV for ^{160}Er*.

a one- or two-component resonance.

The dashed and solid curves in Fig. 1 show the best fits to the measured spectra for a one- and a two-component Lorentzian shape, respectively, for both ^{166}Er* and ^{160}Er*. The right half of Fig. 1 shows a plot of the spectra and the fitted curves multiplied by $\exp(\alpha E_\gamma)$. This smoothly varying exponential factor roughly cancels the effect of varying level density with energy and allows theory and experiment to be compared on a linear plot over a wide range of E_γ. The factor α is chosen so that the resulting shape at high energies is similar to the input shape of $\sigma_{\mathrm{abs}}(E_\gamma)$ in the calculation.

The one-component GDR fits are clearly inadequate for both ^{166}Er* and ^{160}Er*, while the two-component GDR fits agree well with the data. These fits represent independent three- and six-parameter variations, respectively, and include small contributions from isoscalar and isovector giant quadrupole resonances calculated with fixed parameters. The results for the two-component fits[4] are shown in Table I, along with results[5] from Saclay obtained from measured ground-state photoneutron cross sections for ^{154}Sm and $^{\mathrm{nat}}$Er. Plots of $\sigma_{\mathrm{abs}}(E_\gamma)$ derived from our ^{166}Er* and ^{160}Er* data and from ground-state ^{154}Sm(γ, n) are shown in Fig. 2.

The shape of the GDR in deformed nuclei may be quantitatively related[6] to the nuclear deformation by use of the hydrodynamic model,[7] which specifies a strength ratio S_2:S_1 of 2:1 for a prolate deformation, 1:2 for an oblate deformation, and an energy splitting $E_2/E_1 = 0.911d + 0.089$, where d is the major-to-minor axis ratio. The strength ratios obtained in our best fits are $S_2/S_1 = 1.7 \pm 0.5$ for decays of ^{166}Er* and 1.6 ± 0.5 for decays of ^{160}Er* indicating prolate shapes. The energy ratios from our fits imply $d = 1.33 \pm 0.01$ and 1.27 ± 0.01, corresponding to nuclear deformations $\delta \simeq (d-1)d^{-1/3} = 0.30$ and 0.25, respectively. These values of δ are the *same* as those deduced[8] from measured quadrupole moments of these nuclei at low en-

TABLE I. GDR parameters.

Reaction	χ^2	E_1 (MeV)	Γ_1 (MeV)	S_1	E_2 (MeV)	Γ_2 (MeV)	S_2
^{12}C + ^{154}Sm → ^{166}Er* [a]	1.03	12.15 ± 0.09	3.69 ± 0.23	0.43 ± 0.07	15.77 ± 0.17	5.75 ± 0.71	0.74 ± 0.11
^{12}C + ^{148}Sm → ^{160}Er* [a]	1.12	12.21 ± 0.09	3.13 ± 0.21	0.39 ± 0.07	15.17 ± 0.18	4.81 ± 0.51	0.64 ± 0.09
^{154}Sm(γ,n) [b]		12.35 ± 0.10	3.35 ± 0.15	0.45 ± 0.03	16.10 ± 0.10	5.25 ± 0.20	0.76 ± 0.05
$^{\mathrm{nat}}$Er(γ,n) [b]		12.0	2.9	0.42	15.45	5.0	0.84

[a]These error bars as well as those in the text include correlations and are statistical only. Strengths have an additional ±20% systematic uncertainty.

[b]Ground-state (γ,n) results of Ref. 5.

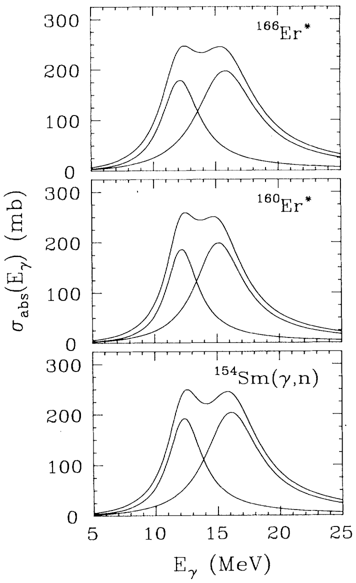

FIG. 2. Photoabsorption cross sections $\sigma_{abs}(E_\gamma)$ inferred from fitted data. Top and middle: Best two-component fits to the decay of $^{166}Er^*$ and $^{160}Er^*$ from Fig. 1 and Table I. Bottom: Fits to ground-state $^{154}Sm(\gamma,n)$ data (Ref. 5 and Table I).

ergy! Thus our results for these excited nuclei strongly favor prolate deformations which are unchanged from the values known at low energy. In addition, both the total strengths and the mean resonance energies obtained here are in good agreement with ground-state photoabsorption[6] in this mass region.

How certain are we of our conclusion that these excited nuclei have prolate shapes? Fits with S_2/S_1 constrained to the value $\frac{2}{3}$, as was estimated in Ref. 2 for $^{166}Er^*$ at a somewhat higher energy and spin, and all others parameters free to vary, yield poorer χ^2 in both cases,[9] 1.14 for $^{166}Er^*$ and 1.23 for $^{160}Er^*$. This corresponds in each case to a two-standard-deviation change in the strength ratio from the best-fit value given above. In addition, the energy ratios E_2/E_1, which are insensitive to the other fit parameters, unambiguously determine the deformation magnitude. It would be a remarkable coincidence if the nuclear shape had changed from prolate to oblate and yet the deformation magnitude would agree so well with the known ground-state values in two different cases. Furthermore, the detailed shapes of the GDR deduced from decays of $^{166}Er^*$ and $^{160}Er^*$ are very similar to the shapes found in ground-state (γ,n) studies of rare-earth nuclei: For example, compare the four cases in Table I, for which the width ratio Γ_2/Γ_1 and, separately, the strength ratio S_2/S_1, all agree within experimental error (see also Fig. 2). All of this information constitutes a compelling case for the conclusion that the deformations of these excited Er nuclei are prolate and unchanged in magnitude from the deformations known at low energy.

The deformations which we have determined represent in each case an average over the ensemble of excited states populated by high-energy γ decay. This ensemble consists[10] mainly of $^{166-164}Er^*$ nuclei for $^{166}Er^*$ decays and $^{160-158}Er^*$ nuclei for $^{160}Er^*$ decays with spins of 0–25$\hbar$ and a mean energy $\bar{E} \sim 30$ MeV corresponding to a nuclear temperature $T = (\bar{E}/a)^{1/2} \sim 1$ MeV for $a = A/8$ MeV^{-1}. Our results are consistent with the idea that yrastlike deformation should persist for temperatures less than a limiting value[11] $T_{lim} \sim 40\delta A^{-1/3}$ which is ~ 2 MeV for these nuclei, as well as with detailed calculations.[12] However, neither the distribution of deformations nor the increase in the spreading width of the GDR at finite temperature has yet been calculated. Our results indicate a narrow distribution of deformation in the excited ensemble, an upper limit of (10–20)% on the increase in the width of the individual GDR components relative to the ground-state GDR.

The suggestion[2] that $^{166}Er^*$ becomes oblate at a somewhat higher energy and spin would, if true, be very exciting and surprising. However, we feel this is unlikely for two reasons. (1) The energy and spin differences between the two experiments are not very large: in Ref. 2, $E_i = 61.5$ MeV and the mean initial spin[10] $\bar{I} \sim 22\hbar$ as compared with 49.2 MeV and $\sim 15\hbar$ in the present study. Even though the initial spin distribution of Ref. 2 extends to higher values, half of the formation cross section in that experiment corresponds to spins sampled in the present study. (2) As discussed above, the χ^2 minimum as a function of S_2/S_1 is rather shallow and thus the method of visual estimation of GDR parameters employed in Ref. 2 can lead to error. We note that the magnitude of the splitting is similar in the two experiments.

In summary, we have found GDR shapes in hot deformed nuclei which are remarkably similar to ground-state GDR shapes and which indicate prolate, ground-state-like deformation at moderate temperature $T \sim 1$ MeV and spin $I \sim 0$–25$\hbar$. The fact that the GDR is still relatively sharp at high energies, and has a shape which can be analyzed in quantitative detail in heavy-ion reactions, offers exciting prospects for future studies. Our next goal is to achieve a comparably quantitative understanding of the GDR shape in heavy spherical hot nuclei, and in the transition region between spherical and deformed nuclei.

[(a)] Deceased.

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[4]The recommended (Ref. 3) level-density option (KOPTEB = 1) was used. Other commonly used level-density parameters leave the two-component GDR energy and width ratios unchanged and increase the strength S_2/S_1 ratios. A complete discussion of these and other details will be published separately.

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[8]$\delta \simeq 0.95\beta$ with β taken from K.E.G. Löbner *et al.*, Nucl. Data Tables **7**, 495 (1970). Averaging over ^{166,164}Er and ^{160,158}Er (see text) yields $\delta \simeq 0.30$ and 0.24, respectively.

[9]This relatively small change in χ^2 reflects a strong correlation between S_2/S_1 and Γ_2/Γ_1.

[10]Estimated from the CASCADE calculation.

[11]S. Bjornholm *et al.*, in *Proceedings of the Third IAEA Symposium on the Physics and Chemistry of Fission, Rochester, 1973* (IAEA, Vienna, 1974), Vol. 1, p. 367.

[12]See, for example, P. Ring *et al.*, Nucl. Phys. **A419**, 261 (1984).