Giant dipole resonances in excited Er isotopes

D. R. Chakrabarty,* M. Thoennessen, S. Sen, P. Paul, R. Butsch, and M. G. Herman
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 8 October 1987)

The shape evolution of ^{160}Er at high excitation energies was studied by measuring the giant dipole resonance following the heavy ion fusion reaction ^{19}F+^{141}Pr at excitation energies of 59.2, 61.2, 74.3, and 90.3 MeV. The data analysis yields prolate, oblate, and triaxial solutions and without theoretical systematics none of them can be ruled out. Detailed comparison with theoretical predictions favor the prolate solution with a deformation decreasing from $\beta=0.28$ at 59.2 MeV to 0.24 at 90.3 MeV. No phase transition from a prolate to an oblate deformation was found in the temperature range ($T\sim1.1-1.5$ MeV) covered by this experiment.

I. INTRODUCTION

The evolution of nuclear shapes as a function of angular momentum and temperature is a topic of great current interest. It is predicted[1] that a rise in nuclear temperature and rotational angular momentum, by increasingly breaking down particle correlations, will drive a prolate nucleus to a triaxial and eventually to an oblate shape. Experimentally, the nuclear deformation at high spin (J) and temperature (T) may be obtained from the energy parameters of the excited-state giant dipole resonance (GDR) observed in heavy ion fusion reactions. Specifically, in deformed spheroidal nuclei the GDR is split into two components which correspond to the two eigenfrequencies of vibration along the symmetry axis (a) and the other two perpendicular axes (b). The ratio of the two energy centroids are related to the axis ratio of the nucleus by the Danos[2] relation, $E_b/E_a=0.911a/b+0.089$. The nuclear deformation parameter β is then defined by

$$\beta=\sqrt{4\pi/5}(E_b/E_a-1)/(E_b/2E_a+0.8665)$$

for a quadrupole shaped nucleus.

Erbium nuclei, which have prolate deformed ground states, have been the focus of several theoretical and experimental studies along these lines. The phase transition from prolate to oblate shape, as a function of J and T, has been calculated in ^{166}Er by Alhassid *et al.*[1] and by Goodman[3] who predict the transition to occur at $E_x\sim60-70$ MeV or, equivalently, at $T\sim1.6-1.7$ MeV. Experimentally, from GDR studies, Gossett *et al.*[4] found that ^{160}Er and ^{166}Er retain prolate shapes at $E_x\sim49$ MeV, while Gaardhøje *et al.*[5] report an oblate shape for ^{166}Er at $E_x\sim61$ MeV. These two observations have been interpreted[1,3] as an indication of the predicted phase transition.

The present work is a study of the excited state GDR in ^{160}Er from $E_x=60$ to 90 MeV. The extended excitation energy range substantially covers the region of the predicted phase change and thus might provide clearer evidence of a shape transition from the systematic evolution of the observed GDR parameters.

II. EXPERIMENTAL DATA AND ANALYSIS

A monoisotopic ^{141}Pr target of 2 mg/cm^2 thickness was bombarded with ^{19}F beams from the Stony Brook superconducting LINAC at bombarding energies of 94.1, 96.5, 111.1, and 129.0 MeV. The experimental geometry corresponded to that used in our earlier experiments[6] on Sn nuclei. Gamma rays were detected in a 25.4 cm$\times$38.1 cm NaI crystal with plastic anticoincidence shield, at a distance of 60 cm from the target. A γ-multiplicity array consisting of ten 7.6 cm$\times$10.2 cm NaI detectors in coincidence with the beam burst and the large NaI detector served to enhance the fusion events. Prompt γ rays produced in the reaction were separated from fast neutrons by time of flight. Further details about energy calibration and pileup rejection are given in Ref. 6.

Gamma-ray spectra from the decay of ^{160}Er nuclei at initial excitation energies of 59.2, 61.2, 74.3, and 90.3 MeV are shown in Fig. 1. They show the typical broad bump from the GDR, here at ~14 MeV, superimposed on the exponentially decaying cross section. The spectra were fitted with statistical model calculations using the code CASCADE.[7] The GDR strength function was assumed to consist of a lower (E_1) and a higher (E_2) energy component according to

$$F(E_\gamma)=S_1F(E_\gamma,E_1)+S_2F(E_\gamma,E_2)\ ,$$

where

$$F(E_\gamma,E_D)=2.09\times10^{-5}\frac{NZ}{A}\frac{\Gamma_DE_\gamma^4}{(E_\gamma^2-E_D^2)^2+\Gamma_D^2E_\gamma^2}\ ,\qquad (D=1,2)$$

with all energies in MeV. S_1 and S_2 add to the sum rule S. The hydrodynamical model predicts $S_2/S_1\sim2$ for a prolate nucleus and ~0.5 for an oblate nucleus.

The fit parameters entering into the present calculations were the GDR energies E_1 and E_2, their widths Γ_1 and Γ_2, and the nuclear level density parameter a. The strength ratio S_2/S_1 was kept at 2.0 for prolate and at 0.5 for oblate searches. The total strength was fixed at one sum rule. Since the GDR strength function determines the region of statistical γ rays, below 8 MeV, as

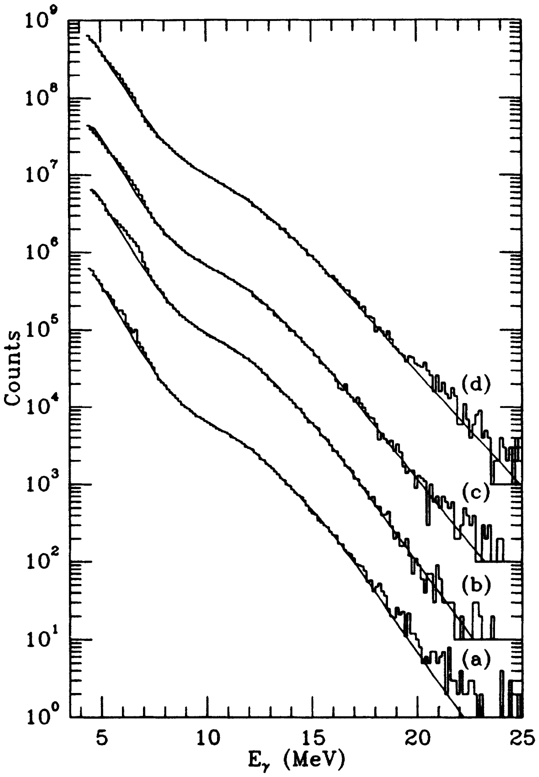

FIG. 1. Experimental γ spectra from the reaction $^{19}F + ^{141}Pr$ at E_{beam} of (a) 94, (b) 96, (c) 111, and (d) 129 MeV, and CASCADE fits assuming prolate shapes for the compound system.

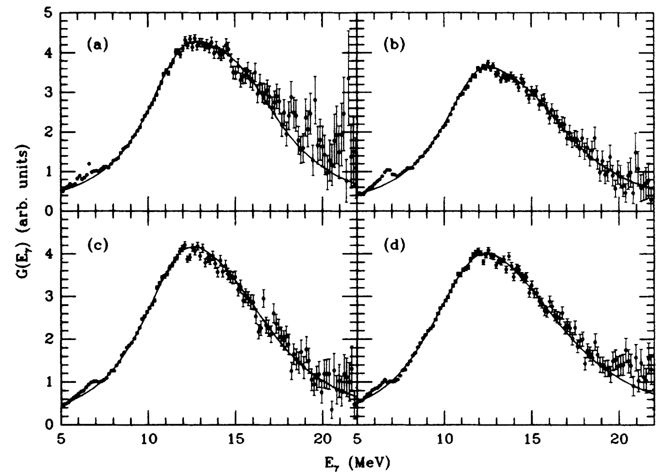

FIG. 2. Divided plots of the experimental data and of the CASCADE fits for prolate deformation at the different energies. The ordinate is proportional to the strength function $G(E_\gamma)=F(E_\gamma)/E_\gamma^3$ with $F(E_\gamma)$ as defined in the text.

well as the GDR region itself, it is important to obtain a good, consistent fit to the entire γ spectrum above $\sim$5 MeV. In the present case a least squares fit was done to the region between 8 and 20 MeV yielding typically $\chi^2 \leq 3$. Because of the exponential nature of the spectrum, the χ^2 of this fit is dominated by the low energy part and relatively insensitive to the GDR region. Thus, the parameter set was varied further to obtain the best fit to the GDR region as judged from visual inspection, consistent with the best χ^2 fit to the spectrum from 8 to 20 MeV. A sensitive comparison between the data and the fits can be made by representing each spectrum on a linear scale. This was achieved by dividing the experimental and calculated spectrum by a third spectrum generated by CASCADE calculations assuming a constant $E1$ strength of 0.2 W.u. The energy and width parameters were searched in steps of 0.1 MeV. The best choice of the level density parameter was found to be $a = A/9$ MeV^{-1}. The angular momentum distribution in the compound nucleus was calculated from the extra-push[8] fusion cross sections with a diffuseness of $2\hbar$.

TABLE I. GDR parameters obtained from fits assuming either prolate or oblate shapes. In the prolate case a vibration along the symmetry axis corresponds to E_1 and a vibration perpendicular to the symmetry axis to E_2. For the oblate deformation the roles are reversed.

E_x (MeV)	Shape	E_1 (MeV)	Γ_1 (MeV)	E_2 (MeV)	Γ_2 (MeV)	β
59.2	Prolate	12.4±0.2	4.9±0.2	15.7±0.3	6.9±0.3	0.28±0.03
	Oblate	13.1±0.2	6.0±0.2	16.6±0.3	5.0±0.3	−0.27±0.03
61.2	Prolate	12.4±0.2	4.8±0.2	15.5±0.3	7.5±0.3	0.27±0.03
	Oblate	12.9±0.2	5.8±0.2	16.3±0.3	5.3±0.3	−0.26±0.03
74.3	Prolate	12.4±0.2	5.3±0.3	15.3±0.3	7.9±0.4	0.25±0.03
	Oblate	12.8±0.2	6.0±0.3	16.1±0.3	5.8±0.4	−0.26±0.03
90.3	Prolate	12.4±0.2	6.1±0.3	15.2±0.3	9.3±0.4	0.24±0.03
	Oblate	12.8±0.2	6.9±0.3	16.3±0.3	7.3±0.4	−0.27±0.03
g.s.[a]	Prolate	12.0	2.9	15.45	5.0	0.29
43.2[b]	Prolate	12.2±0.1	3.1±0.2	15.2±0.2	4.8±0.5	0.25±0.04
49.2[c]	Prolate	12.2±0.1	3.7±0.2	15.8±0.2	5.8±0.7	0.30±0.04
61.5[d]	Oblate	12.6	5.2	16.4	5.2	−0.27±0.07

[a] ^{nat}Er, Ref. 9.
[b] ^{160}Er, Ref. 4.
[c] ^{166}Er, Ref. 4.
[d] ^{166}Er, Ref. 5.

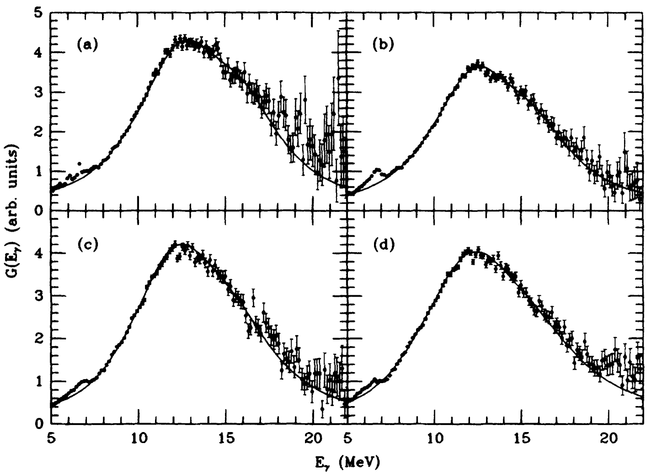

FIG. 3. Same as Fig. 2, only with the CASCADE fits for oblate deformation.

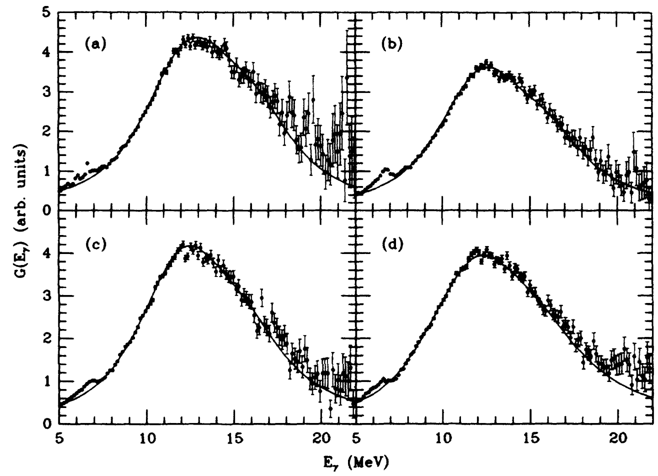

FIG. 4. Same as Fig. 2, but with triaxial CASCADE fits.

Figure 2 shows the divided plots of the data and of the best fits obtained with the assumption of a prolate shape. Figure 3 shows, similarly, the best oblate fits. Both deformed fits are of equal quality. However, no good fits could be obtained at any energy with a single-component GDR, i.e., assuming a spherical shape. The extracted GDR parameters for prolate and oblate solutions are listed in Table I, along with the results of earlier works. The deformation parameters β were calculated using the Danos relation, as mentioned above, for both prolate and oblate shapes.

III. DISCUSSION

The results on GDR parameters and deformation parameters β obtained in this experiment agree in a systematic way with the earlier results which had reported both prolate and oblate deformations. The values for β for the prolate solution are similar to the ground state value (see Table I) and decrease, as expected, with excitation energy. On the other hand, the oblate solutions yield an essentially constant deformation, much larger than that predicted[1,3] for the noncollective oblate shapes beyond the phase transition. The prolate and oblate solutions differ in the widths of the two components: the prolate fits have $\Gamma_2/\Gamma_1 \sim 1.5$ in agreement with 1.7 for the ground state GDR (Ref. 9), whereas the oblate fits have $\Gamma_2/\Gamma_1 \sim 1$. These arguments would seem to favor the prolate solution. However, the reasons for $\Gamma_2/\Gamma_1 > 1$ of the ground state GDR are not entirely obvious (and there are no oblate cases to compare to) and are even less apparent for the GDR formed on excited states in a fusion evaporation reaction. For instance, the width ratio for either the prolate or the oblate solution might be simulated by a triaxial nuclear shape.

We have explored this possibility by attempting fits to the data with a three-component GDR strength function. To make such fits practical the number of free parameters was reduced by assuming equal width and strength for all components (which is reasonable within the hydrodynamical model). Initial values of energy and width parameters were obtained by fitting the prolate or oblate strength functions from the two-component fits with a three-component strength function. These values were finally used in new CASCADE calculations and produced the good fits shown in Fig. 4. Table II lists the triaxial fit parameters. Deformation parameters β and γ were calculated assuming the simple relation $E_k \propto R_k^{-1}$ ($k=1,2,3$), from the equations

$$\tan\gamma = \sqrt{3}\frac{E_1(E_3-E_2)}{E_3(E_2-E_1)+E_2(E_3-E_1)} ,$$

$$\beta = \left[\frac{4\pi}{5}\right]^{1/2} \frac{E_2-E_1}{E_1\cos\gamma - E_2\cos\left[\gamma-\frac{2\pi}{3}\right]} .$$

The convention chosen here is such that $\gamma=0°$ defines a prolate and $\gamma=60°$ an oblate shape.

Since we obtain good fits with prolate, oblate, and triaxial shapes, it is clear that no conclusions about the

TABLE II. GDR parameters obtained from triaxial fits.

E_x (MeV)	E_1 (MeV)	E_2 (MeV)	E_3 (MeV)	Γ (MeV)	β	γ
59.2	12.3±0.2	14.1±0.2	16.9±0.3	5.3±0.3	0.29±0.04	(32±4)°
61.2	12.2±0.2	13.6±0.2	16.6±0.3	5.3±0.3	0.28±0.04	(37±4)°
74.3	12.3±0.2	13.3±0.3	16.2±0.3	5.8±0.4	0.25±0.04	(42±6)°
90.3	12.6±0.3	12.9±0.3	16.2±0.4	7.0±0.4	0.24±0.04	(55±8)°

TABLE III. Average temperatures T and angular momenta J at different excitation energies. E_x, $E_{\rm eff}$, $E_{\rm rot}$ are the initial excitation energy in the compound nucleus, the effective excitation energy of the decaying compound system (see text), and the average rotational energy, respectively. The temperature T is calculated from $E^*=aT^2$ with (A) $E^*=E_x$, (B) $E^*=E_x-E_{\rm rot}-E_{\rm GD}$, and (C) $E^*=E_{\rm eff}-E_{\rm rot}-E_{\rm GD}$. $E_{\rm GD}\sim 14.5$ MeV.

E_x (MeV)	$E_{\rm eff}$ (MeV)	$E_{\rm rot}$ (MeV)	J ($\hbar$)	T (MeV) (A)	T (MeV) (B)	T (MeV) (C)
60.2	47.2	4.0	25	1.8	1.5	1.3
74.3	56.8	7.1	34	2.0	1.7	1.4
90.3	68.0	10.8	42	2.2	1.9	1.5

shape of the nucleus can be drawn from the singles spectra alone, without either independent knowledge of the width ratio or theoretical guidance as to which solution is reasonable. Such a discussion is aided in the present case by two detailed theoretical predictions on the shape parameters β and γ as a function of J and T in ^{166}Er. No calculations exist for ^{160}Er. It is well known that ^{160}Er is a transitional nucleus and not as rotational as ^{166}Er. However, since earlier measurements[4] for ^{160}Er and ^{166}Er show similar GDR parameters at nonzero temperatures, such a comparison may be meaningful. Goodman[3] predicts an almost pure prolate shape ($\gamma < 10^0$) with β decreasing from 0.28 at $T=0$ MeV to 0.04 at a phase transition temperature at which the nucleus rapidly changes to $\gamma=-60°$, i.e., a noncollective oblate shape with β decreasing further. The transition temperature varies from 1.7 MeV at $J=0$ to 1.3 MeV at $J=60\hbar$. The other theoretical prediction is that of Alhassid *et al.*[1] who also compute the evolution of β and γ as a function of angular momentum and temperature, obtaining similar results. In each case the predicted phase transition is abrupt.

For a comparison with our data the average temperatures of the excited states bearing the dipole vibrations were calculated from the relation $E^*=aT^2$ with $a=A/9$ MeV^{-1}. The energy E^* was obtained by subtracting an average rotational energy ($\sim$4 to 11 MeV) and a GDR energy ($\sim$14.5 MeV) from an effective excitation energy $E_{\rm eff}$ of the decaying system. The latter was calculated by averaging over the cross sections and the relative probabilities of emitting a GDR γ ray at the various decay steps, as given by the CASCADE outputs. This gave $T=1.3$, 1.4, and 1.5 MeV at the three excitation energies. We note that these average temperatures are significantly lower than those of the initial compound nucleus. Table III shows how the system cools from an initial temperature (column B) to the average temperature (column C). With increasing temperature only the β values for the prolate solutions agree even qualitatively with the predictions from Goodman[3] and Alhassid *et al.*,[1] decreasing from 0.28 to 0.24. From the large magnitude and the small change of β with T it appears very unlikely that a sharp phase transition occurs near $T=1.6$ MeV for this nucleus. It should be mentioned at this point that these comparisons depend on how the temperatures are calculated for the decaying system. The temperature of 1.6 MeV quoted in Ref. 5 for a phase transition in ^{166}Er at 61.5 MeV is in disagreement with the value of 1.3 MeV which we obtain at nearly the same excitation energy, and corresponds probably to the T of column A in Table III. More precisely, we have no evidence for a rapid change in deformation up to 90.3 MeV excitation energy.

Our triaxial solutions show the expected trend of decreasing β as a function of J and T, and a transition of the γ parameter from triaxial to oblate shape. However, over the angular momentum and temperature range of the present work, the extracted γ values are much larger than predicted. We note that the triaxial solutions assumed equal widths for all three components of the GDR and may not be unique.

IV. CONCLUSIONS

The present work establishes the excited state GDR in the deformed ^{160}Er nuclei up to an excitation energy of 90 MeV and an average angular momentum of $42\hbar$ for the compound nucleus. The deformed nature of the excited nuclei over the entire range of spin and temperature is demonstrated by the data. However, a model-independent conclusion about the shape of the nucleus directly from the measured γ spectra is not possible. Sets of prolate, oblate, and triaxial shapes are all compatible with the data. This ambiguity is a general one and can only be resolved after knowing the dependence of the width of the GDR components on spin and temperature. Comparisons with detailed theoretical predictions favor the prolate solutions with $\beta=0.28-0.24$. This indicates that the ground state shape of ^{160}Er persists up to $E_x=90$ MeV and $T\sim 1.5$ MeV. Although the experimental β values show a systematic decrease with temperature and spin, no indication of any imminent phase transition is apparent in the present data.

*Present address: Nuclear Physics Division, Bhabha Atomic Research Center, Bombay, India.

[1]Y. Alhassid, S. Levit, and J. Zingman, Phys. Rev. Lett. **57**, 539 (1986).
[2]M. Danos, Nucl. Phys. **5**, 23 (1958).
[3]A. L. Goodman, Phys. Rev. C **33**, 2212 (1986).
[4]C. A. Gossett, K. A. Snover, J. A. Behr, G. Feldman, and J. L. Osborne, Phys. Rev. Lett. **54**, 1486 (1985).

[5]J. J. Gaardhøje, C. Ellegaard, B. Herskind, and S. G. Steadman, Phys. Rev. Lett. **53**, 148 (1984).
[6]D. R. Chakrabarty, S. Sen, M. Thoennessen, N. Alamanos, P. Paul, R. Schicker, J. Stachel, and J. J. Gaardhøje, Phys. Rev. C **36**, 1886 (1987).
[7]F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).
[8]W. Swiatecki, Nucl. Phys. **A376**, 275 (1982).
[9]B. L. Berman, At. Data Nucl. Data Tables **15**, 319 (1975).