Large deformation in \( A \sim 170 \) nuclei at high excitation energies

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The \( \gamma \)-ray decay of the giant dipole resonance (GDR) built on highly excited states has not only become a very important tool for the study of nuclear shape effects as a function of temperature and angular momentum \([1]\), but is also sensitive to reaction dynamical effects \([2]\). For example, a reduction of the fission probability at the early stages of the decay of a highly excited compound nucleus was observed as an enhancement of GDR \( \gamma \) rays preceeding fission \([3,2]\). This enhancement of pre-fission \( \gamma \) rays by dynamical effects provides a means to study such nuclear structure effects as the evolution of the nuclear shape at high temperatures which is otherwise not accessible. Especially interesting are mass regions and excitation energies where only a part of the total fusion cross section leads to fission, so that by measuring \( \gamma \)-ray–fission coincidences one probes the small range of angular momenta where fission is dominant \([4]\). In this letter we present \( \gamma \)-ray–fission coincidence measurements in the mass region \( A \sim 170 \). Our motivation is to provide information on the shape of highly excited nuclei with very large angular momenta. The analysis reported here suggests very highly deformed shapes.

The \( \gamma \)-ray decay of the giant dipole resonance (GDR) built on highly excited states was measured in coincidence with fission fragments following the fusion reaction \( ^{160}\text{O} + ^{159}\text{Tb} \) forming \( ^{175}\text{Ta} \) at 123.4 MeV excitation energy. A large splitting of the giant dipole resonance (GDR) energies in the compound system was observed corresponding to a large deformation of \( \beta = 0.55 \).

The experiment was performed using 160 MeV \( ^{160}\text{O} \) ions from the Holifield Heavy Ion Research Facility tandem at Oak Ridge National Laboratory. A self-supporting, 632 \( \mu \text{g/cm}^2 \) thick \( ^{159}\text{Tb} \) target was bombarded to form \( ^{175}\text{Ta} \) at an excitation energy of 123.4 MeV. The target was placed inside the Spin Spectrometer \([5]\) in which the most forward NaI detectors (\(<25^\circ\) ) were removed and two large (6 cm \( \times \) 9 cm) position sensitive parallel plate avalanche counters were placed 37 cm from the target, covering laboratory angles from 3° to 17°. High-energy \( \gamma \) rays (6–25 MeV) were detected with the Oak Ridge BaF\(_2\) array of four close-packed clusters of 19 hexagonal detectors each; the individual detectors are 6.5 cm face to face and 20 cm long. Two clusters were positioned at 21° at a distance of 77 cm from the target, while the other two clusters were placed at 63° and 57 cm. More experimental details are described elsewhere \([6,7]\).

A modified version of the statistical model code CASCADE \([8]\), which includes the decay of the fission fragments \([4]\), was used to predict the \( \gamma \)-ray spectra. The compound nucleus angular momentum population was taken to be triangular with a diffuse-ness of \( \Delta L = 2 \). We used fission barriers calculated by Sierk \([9]\) which reproduced the measured fission cross section \([10]\) of \( \sim 280 \text{ mb} \). For 160 MeV \( ^{16}\text{O} \), the contribution of incomplete fusion to the fission cross section is negligible because of the small angu-
lar-momentum transfer involved in these reactions [11]. The total calculated γ-ray spectrum is a sum of γ rays from the fused system (compound γ rays) and γ rays from the fission fragments (post-fission γ rays). The calculation methods employed in the CASCADE code do not allow us to explicitly generate simulated γ-ray spectra in coincidence with fission. The γ rays which precede fission (pre-fission γ rays) have to be calculated separately from the γ rays which lead to evaporation residues (residue γ rays). This can be achieved by calculating the angular momentum distribution of the cross sections leading to fission and to evaporation residues. The γ-ray spectrum for decays leading only to evaporation residues can be calculated using the residue angular-momentum distribution as the entrance channel population in CASCADE. The pre-fission γ-ray spectrum was extracted by subtracting this residue contribution from the compound γ-ray spectrum. This method has been shown to agree with Monte Carlo simulations [4].

Level density parameters were chosen to be $a=A/10$ for both the compound and the fragment calculations. GDR energies for the compound system ($E_1=12.4$ MeV, $E_2=15.3$ MeV) and widths ($\Gamma_1=8.0$ MeV, $\Gamma_2=10.5$ MeV) were taken from previous experiments at somewhat lower energies and were extrapolated to what would be expected at 123.4 MeV excitation energy [12]. The decay of the fission fragments was treated exactly following the description in ref. [4] which contains a detailed description of the CASCADE modifications which were necessary in order to calculate the γ-ray spectra from the fission fragments. The width of the fission fragment mass distribution was 34 and the average resonance energy of the fission fragment was 16 MeV ($\Gamma_f=10$ MeV). Both values were extracted from experimental data in the corresponding mass regions [13,14]. The calculations were folded with the response functions of the BaF2 array, and the compound- and post-fission γ-ray spectra were corrected for Doppler shift with the corresponding source velocity. The fact that the post-fission γ rays could be emitted from either one of the two fragments going in opposite directions in the center-of-mass system was taken into account.

Fig. 1a shows the measured γ-ray spectrum in coincidence with evaporation residues with close to ~100% momentum transfer. The CASCADE calculation for the residue γ-ray spectrum using the parameters given above results in a very good fit to the data. The measured γ-ray spectrum in coincidence with the fission fragments is shown in figs. 1b and 1c. Calculations using standard statistical model parameters could not reproduce the overall strength of the data in the region of the compound nucleus GDR. Thus, a different version of CASCADE was used which included the effect of nuclear dissipation as described in ref. [2]. A nuclear dissipation coefficient of $\gamma=10$ was taken from γ-ray–fission coincidence measurements in neutron-deficient thorium isotopes [2] and could reproduce the overall γ-ray strength as shown in fig. 1b. The total calculated spectrum (solid) is a sum of the pre-fission (dot-dashed) and post-fission (dashed) γ-ray spectra.

Although the strength can now be well described, the spectral shape, particularly in the 8–11 MeV energy range, can still not be fitted. Therefore, the GDR parameters for the decay from the highest partial waves were adjusted in order to provide a best fit to the γ-ray–fission coincidence data. This fit is shown in fig. 1c. The fit requires a large splitting of the GDR energies ($E_1=9.5 \pm 0.5$ MeV, $\Gamma_1=5 \pm 1.0$ MeV and
$E_2 = 15.0 \pm 1.0 \text{ MeV}, \Gamma_2 = 7.0 \pm 2.0 \text{ MeV}$) that corresponds to a nuclear deformation of $\beta = 0.55 \pm 0.11$. The strength ratio of the two components were fixed to $E_2/E_1 = 2$, corresponding to a prolate deformation. It should be mentioned that the mean resonance energy of this fit is about one MeV lower than the value for the normal deformation. Fig. 2a shows a linear presentation of the same fits. These spectra were created in the following way. A calculated post-fission contribution was subtracted from the data as well as from the total calculations. These subtracted spectra were then divided by a pre-fission calculation which did not include the GDR strength function but only a constant strength function. Thus, fig. 2 shows approximately the shape of the pre-fission GDR strength function. When compared with the calculation using GDR parameters corresponding to a normal deformed system (dashed), the data clearly show excess strength around 9 MeV. However, the calculation with the large GDR splitting (solid) provides a good description of the data.

It should be mentioned that it might be possible to fit the data without the large deformation of the compound system by changing the slope of the $\gamma$-ray spectrum from the fission fragments. However, variations of all known parameters involved in the population and decay of the fission fragments within reasonable limits did not result in an acceptable fit to the data. Thus, we think that this possibility is highly unlikely.

The value of $\beta = 0.55 \pm 0.11$ extracted in our analysis is the largest deformation thus far obtained from the decay of the GDR built on highly excited compound nucleus states. The pre-fission $\gamma$ decay samples a hot (temperature, $T = 1.8 \text{ MeV}$) system in a relatively narrow range of very high angular momenta ($J \sim 60h - 80h$). The large deformation certainly implies that the excited system sampled by the GDR decay in this angular-momentum range has a very extended shape, but beyond this qualitative conclusion the interpretation of our result must be based to some extent on conjecture. It is important to keep in mind, as we explore some speculative possibilities, that thermal fluctuations have a significant influence on the quantitative relationship of the observed splitting of the GDR to the underlying landscape of the free energy surface as a function of deformation to which we might hope to compare our data. This has recently been discussed in some detail [1,15]. It is pointed out that the average over the free energy surface in the fluctuation theory results in a GDR splitting somewhat larger than that which nominally corresponds to the deformation at the free energy minimum. Clearly such calculations need to be made to provide a more quantitative investigation of some of our conjectures. Unfortunately calculated free energy surfaces are not available for the nuclei populated in the present reaction.

However, a detailed discussion of the evolution of the shape of another nucleus, $^{152}$Dy, at elevated temperature and spin has recently been provided by Dudek et al. [16]. Their discussion supports the conventional view that shell effects should be insignificant at $T = 1.8 \text{ MeV}$; however, they point out that in the vicinity of the so-called Jacobi instability critical spin, $J_c$, a stable minimum at large deformation develops in the free energy surface. This minimum is entirely due to macroscopic effects and is largely unaffected by increasing temperature, at least to $T \sim 2.3 \text{ MeV}$ [17]. These macroscopic results are obtained from the rotating liquid drop (RLD) model [18].

![Fig. 2. Linearized presentation of the data, generated by subtracting the calculated post-fission contribution from the total $\gamma$-ray spectrum, and then dividing by a pre-fission calculation with a constant strength function. All the calculations, as well as the data, were divided by the same constant strength function calculation. The calculations shown in figs. 1b and 1c are plotted in part (a) as dashed and solid curves, respectively. Part (b) shows the sum (solid) of the calculation with GDR parameters corresponding to a normal (dashed) and large deformation (dot-dashed).](image)
The two basic parameters of this model are the fissility, $x$, and the angular momentum. Within the RLD, $^{175}\text{Ta}$ ($x=0.63$) should behave very much like $^{152}\text{Dy}$ ($x=0.58$). The critical spin above which $^{175}\text{Ta}$ is predicted by the RLD to rapidly evolve from the normal, moderately deformed, oblate shape to a superdeformed triaxial, but nearly prolate shape, is $J_c=79\hbar$ ($J_c=80\hbar$ for $^{152}\text{Dy}$). This minimum survives only over a narrow range of spins ($\Delta J=5\hbar$), over which we can expect \cite{16}, as in $^{152}\text{Dy}$, a broad, rather flat free energy surface with a minimum at a deformation $\beta\sim 0.6$, or larger. Explicitly, for $^{175}\text{Ta}$ the RLD predicts a minimum with a major to minor axis ratio of $\sim 2.2/1$ at $\sim 80\hbar$, coexisting with a moderately deformed (axis ratio 1.2/1) oblate minimum.

In light of the previous discussion, and because the qualitative appearance of the data suggests it, we tried to describe the data as a mixture of normal deformation and a very large deformation. The GDR parameters for the normal deformation were chosen as before with reduced widths ($\Gamma_1=6.0$ MeV, $\Gamma_2=8.5$ MeV) to account for the smaller effective excitation energy at these high spins and the smaller angular-momentum range. The GDR energies for the large deformation were taken to be $E_1=8.5$ MeV and $E_2=17.5$ MeV, which yield the same mean resonance energy and corresponds to an axis ratio of $\sim 2.1/1$. The widths were $\Gamma_1=5$ MeV and $\Gamma_2=7$ MeV. Fig. 2b shows the sum (solid) of the normal (dashed) and very large (dot-dashed) deformed contributions compared to the data in a linearized plot.

It seems natural to speculate that the observed large deformation results from macroscopic effects, i.e. the Jacobi instability. A potential difficulty with this interpretation is the spin range of $79\hbar-84\hbar$ predicted by the RLD for the effect in $^{175}\text{Ta}$. Based on systematics and statistical model calculations, we estimate that the bulk of the fission events in our data result from spins in the $60\hbar-80\hbar$ range. We note however that a refinement \cite{9} of the RLD model, including finite range effects, reduces the value of $J_c$ by about 5 units in vicinity of $^{175}\text{Ta}$.

Another possibility is that the large deformation inferred from the fission gated GDR data reflects the average shape of the compound system as it traverses the dynamical path toward fission. We can explore this possibility by comparing the present data with previous measurements of $\gamma$ rays from the GDR decay in coincidence with fission fragments. In the decay of excited $^{200}\text{Pb}$ compound systems \cite{4}, much smaller deformations ($\beta=0.38$) were extracted. This system has a fissility $x=0.7$ not very different from $^{175}\text{Ta}$. Taking the much wider range ($\sim 25\hbar-70\hbar$) of angular momenta leading to fission in the Pb case \cite{4} into account, we find that the RLD model predicts very similar and very extended saddle point shapes (axis ratios $\sim 4/1$) for both $^{200}\text{Pb}$ and $^{175}\text{Ta}$. It is interesting, however, that $^{200}\text{Pb}$ is close to the critical fissility at which the macroscopic superdeformed minimum resulting from the Jacobi instability vanishes: in $^{200}\text{Pb}$ it is predicted \cite{18} to exist only for a single spin value, $80\hbar$, and should therefore have an unobservable effect in the data of ref. \cite{4}.

It should be noted that independent of the present study, $\gamma$-ray spectra from the decay of the GDR built on highly excited states in $^{48}\text{Sc}$ show effects which can also be explained with the existence of prolate deformed shapes due to the Jacobi instability \cite{19}.

In conclusion, we observe large nuclear deformations at moderate temperatures and large angular momenta ($>50\hbar$) in the mass region $A\sim 170$ by measuring $\gamma$-ray–fission coincidences, which we relate to the so-called Jacobi instability. In this mass region, the effect is predicted to exist only for a narrow window ($\Delta J=5\hbar$) of very high angular momenta. Thus the fission-gated data reported here, which experimentally picks out a narrow range of the largest angular momenta available in the reaction, is particularly well suited to an exploration of this effect.

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References

\begin{itemize}
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