Search for superdeformed shapes in ^{144}Gd

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Two-dimensional γ-γ transition energy correlation measurements were made in ^{144}Gd using Compton-suppressed Ge detectors in the spin spectrometer. A ridge-valley structure was observed and shown to originate from discrete, fast transitions. The deduced moment of inertia is less than that of the superdeformed collective bands that have been predicted by Strutinsky cranking calculations.

Evolution of nuclear shapes with angular momentum has become a focus of nuclear structure studies in recent years. Nuclei are expected to become oblate under the stress of the centrifugal force according to the rotating liquid drop model,[1] and change over to a triaxial shape before fissioning at very high angular momentum. This general behavior, however, will be modified by shell effects. Applying the Strutinsky method[2] to calculate the potential energy surfaces of rapidly rotating nuclei, Neergård and Pashkevich[3] and Neergård, Pashkevich, and Frauendorf[4] concluded that shell corrections can stabilize superdeformed shapes at high spins in some nuclei. In a more detailed study, Andersson *et al.*[5] have pointed out that these shell corrections are particularly important in the light rare-earth nuclei ($Z\simeq64$, $N\simeq82$) and may result in a transition from oblate shapes at low spins to superprolate ($\beta\simeq0.6$) shapes at high spins. Such large deformations correspond to a major-to-minor axis ratio of 2:1 and have been observed in the fission isomers.[6]

In the most recent theoretical study of shape evolution in the rare-earth region, Dudek and Nazarewicz[7] have performed cranked shell model calculations with a deformed Woods-Saxon potential. For ^{144}Gd, three different excitation modes are predicted: (1) a single-particle mode (oblate, $\gamma=60°$) which remains yrast up to $I\simeq35$; (2) a triaxial collective mode ($\beta_2\simeq0.22$, $\gamma\simeq33°$) which forms the yrast line between $I\simeq35$ and $I\simeq48$; and (3) the superdeformed collective mode ($\beta_2\simeq0.51$, $\gamma\simeq5°$) which becomes yrast about $I\simeq48$. It has been suggested that if the nucleus is formed at high enough spins and excitation energy, it may decay along such superdeformed rotational bands down to quite low spins.[5,8] The above calculations suggest that ^{144}Gd is potentially the most favorable case for observing superdeformation.

Generally, γ-ray spectra for the rare-earth nuclei near the $N=82$ closed shell exhibit two distinct bumps.[9–11] The lower energy bump is centered around 0.7 MeV and consists of both dipole and quadrupole γ rays which are mostly associated with the discrete yrast transitions of a noncollective character.[9,10,12] The higher energy structure is centered around 1.3 MeV and develops only at high spins.[9–11,13,14] Angular distribution[9–13] and linear polarization measurements[10,12] show that stretched $E2$ transitions dominate this structure. The average lifetime of these $E2$ transitions has been shown to be very short by Doppler shift attenuation measurements,[13,14] and is comparable to the lifetimes of similar transitions in collective nuclei. These observations have been cited as evidence for the existence in these nuclei of collective rotational bands at high spins.[9,10,14,15] However, the high energy edge of this structure does not increase with increasing multiplicity[11] as expected for a collective rotor. Therefore, additional tests are needed to firmly establish the presence of a collective rotational mode.

It has been suggested[5] that the γ-γ energy correlation technique[16] is particularly suited for the study of superdeformed shapes. Since, for an ideal rigid rotor no two coincident γ rays have the same energy, in E_{γ_1} vs E_{γ_2} space one observes a valley that runs parallel to the $E_{\gamma_1}=E_{\gamma_2}$ diagonal and separates the two ridges formed by coincidences between neighboring γ rays. The moment of inertia of the rotating body is then related to the width of this valley, W, through $2\mathcal{J}^{(2)}/\hbar^2=16/W$. The method can be improved considerably if Compton-suppressed Ge detectors, which have both good energy resolution and high peak-to-total ratios, are used. Employing multielement Ge-detection systems, two groups[17,18] have reported observation of correlated γ rays in ^{152}Dy. The deduced moments of inertia are very close to the values predicted for superdeformation. However, an attempt to observe correlated γ rays in ^{154}Er by a similar technique proved inconclusive,[19] probably because of poor reaction channel selection.

In the present experiment, the residual ^{144}Gd nucleus was formed in the fusion-evaporation reaction induced by a 145-MeV ^{28}Si beam from the HHIRF tandem accelerator at the Oak Ridge National Laboratory. The target consisted of a 1.5 mg/cm^2 thick isotopically enriched ^{120}Sn target evaporated on a 20 mg/cm^2 thick ^{208}Pb backing. The γ-γ coincidences were recorded with nine Ge detectors, each of which replaced a single element of the Spin Spectrometer. Six detectors were inserted in annular, truncated conical Compton suppression shields of NaI with pentagonal cross sections, and placed at $\pm 64.4°$ with respect to the beam direction. The average of the peak-to-total ratios for the suppressed detectors was approximately 0.4 for 1 MeV γ rays. During data acquisition, the 4n exit channel was selected with nearly 100% efficiency by requiring in the Spin Spectrometer at least three delayed γ rays which tagged the 10^+, $T_{1/2}=131$ ns isomer assigned[20] to ^{144}Gd. In this experiment a total of over 30 million pairs of γ rays were recorded with the six suppressed detectors. From a Monte Carlo simulation (JULIAN-PACE) (Ref. 21) of the deexcitation of the compound nucleus formed in this reaction, we deduced that the entry state spin distribution for ^{144}Gd spans I values between 26 and 56, with the mean value at $I=41$.

In the off-line analysis all the detector gains were matched and two γ-ray energy correlation matrices (E_{γ_1} vs E_{γ_2}) were constructed for all possible coincidences between any pair of these detectors. One matrix was not Doppler-shift corrected, assuming that all of the γ-ray lifetimes are large compared to the slowing-down time of the recoiling nucleus in the lead backing. The second matrix was Doppler-shift corrected to take into account that γ rays cascading along possible superdeformed rotational bands would be emitted before the nucleus comes to rest in the backing. A recoil velocity of $0.02c$ was calculated. The matrices were then unfolded to remove the remaining contribution from Compton-scattered events and the resulting data were corrected for the photopeak efficiency of the Ge detectors. For this purpose, the response function of the detectors was carefully studied by using γ-ray sources which cover an energy range between 260 and 1800 keV. The measured response function was fitted by an analytical function. The obtained parameters, which vary logarithmically with the energy of the incoming γ rays, were used to generate response functions at all other energies.

Figure 1(a) shows unfolded and efficiency corrected (Ge) energy spectra of ^{144}Gd for two coincidence fold intervals of $6<k<16$ and $k>16$, measured in the spin spectrometer. The mean k values are, respectively, 13 and 19. Figure 1(b) shows the difference of these two spectra and clearly indicates the presence of a broad, unresolved structure centered at 1.3 MeV which grows in intensity with increasing k. Figure 2 shows a number of energy slices projected perpendicularly to the $E_{\gamma_1}=E_{\gamma_2}$ diagonal. They correspond to the energy intervals of 200 keV between 1.1 and 1.5 MeV. The two projections in Fig. 2(a) are taken from the unfolded matrix without Doppler correction. A very weak ridge structure is observed in the lower panel. This structure is enhanced and becomes quite apparent following Doppler-shift correction, as shown in Fig. 2(b). It could thus be concluded that the transitions building up this ridge structure are faster than

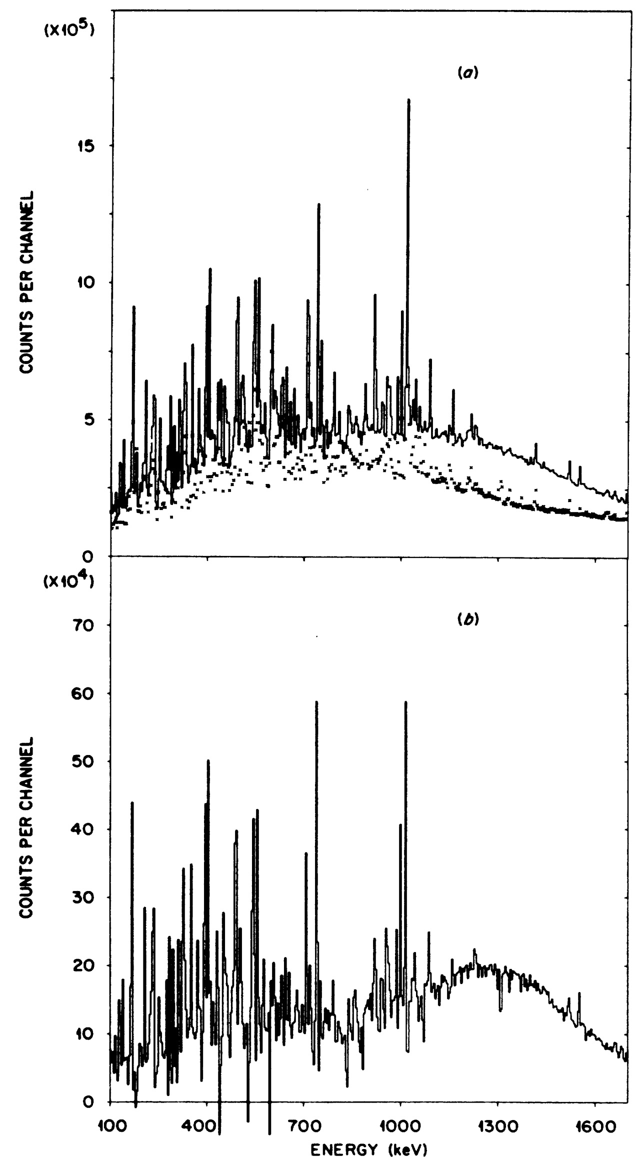

FIG. 1. (a) ^{144}Gd spectra which have been unfolded, efficiency corrected, and normalized to the fold for two fold intervals centered at $k=13$ (crosses) and $k=19$ (heavy line). (b) The difference of the two spectra.

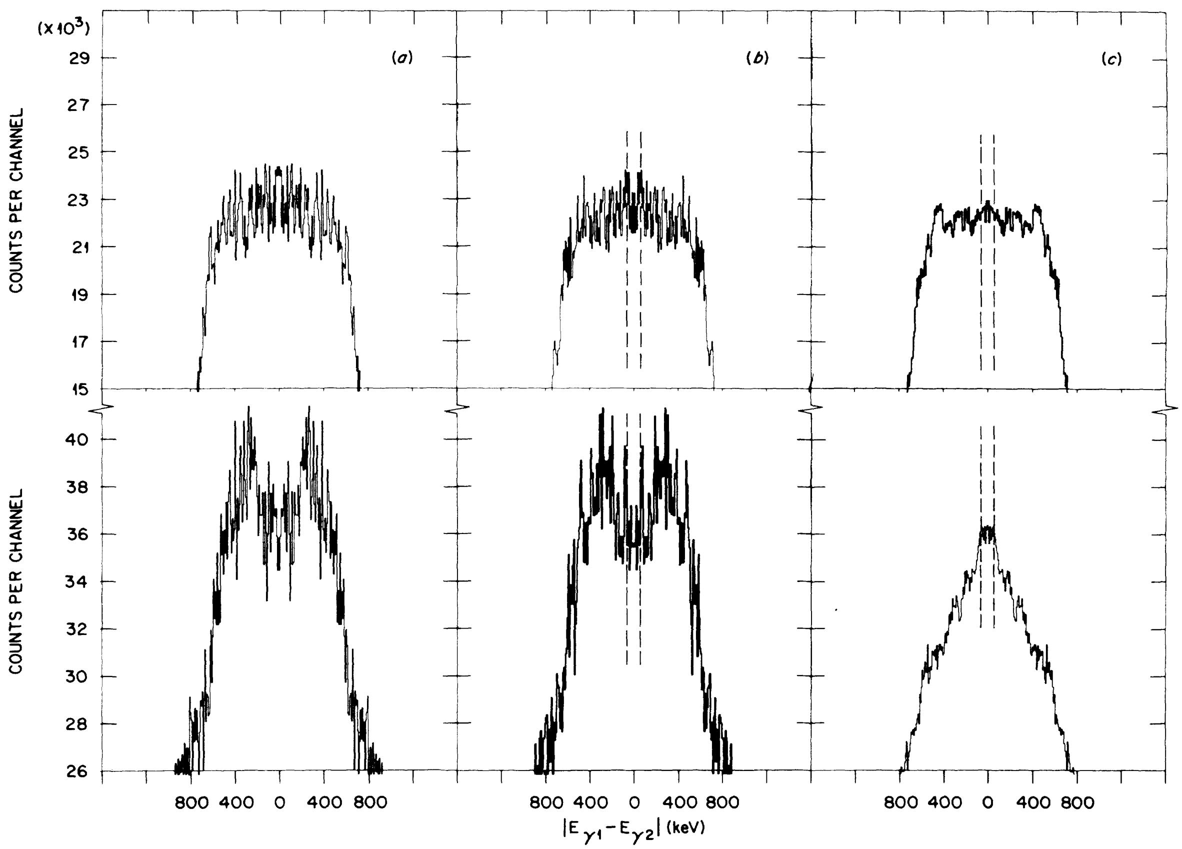

FIG. 2. For ^{144}Gd: Projections perpendicular to the diagonal valley in the E_{γ_1}-E_{γ_2} energy correlation map for two average energy intervals $1.1 \leq (E_{\gamma_1}+E_{\gamma_2})/2 \leq 1.3$ MeV (lower spectrum in each case) and $1.3 \leq (E_{\gamma_1}+E_{\gamma_2})/2 \leq 1.5$ MeV (a) from the unfolded and efficiency corrected matrix; (b) from the Doppler-shift corrected matrix; (c) from the matrix obtained after discrete lines removal. The dashed vertical lines point to the position of the ridges in panels (b) and (c) and correspond to $(2\mathscr{I}^{(2)}/\hbar^2) \simeq 120$ MeV^{-1}.

the slowing-down time of the recoiling nucleus in the lead backing (a fraction of a ps). Assuming that the implied collectivity is attributable to collective rotational bands, one infers a moment of inertia of $2\mathscr{I}^{(2)} \simeq 120\hbar^2$ MeV^{-1} for such bands. This moment of inertia, however, is significantly smaller than the 150 MeV^{-1} value predicted for the superdeformed structures ($\beta \simeq 0.5$) in ^{144}Gd.[7] Thus, our data do not reveal any evidence for the predicted superdeformed bands. The observed ridge structure, however, may be indicative of the presence of collective rotational bands with smaller deformation.

To further investigate the origin of these fast transitions, we have closely examined the E_γ-E_γ correlation matrix and found the two-dimensional matrix did not show a continuous ridge structure. This is true even after applying the method proposed in Ref. 16 which would enhance the correlated events over uncorrelated ones. The implication is that the ridge structure observed in the projections [Fig. 2(b)] are mostly due to discrete transitions, rather than the continuum γ rays that build up the quadrupole bump at 1.3 MeV. To verify this, we have removed from the matrix the contributions due to the discrete peaks in the following manner: For each channel of a given peak in the total-projection spectrum, we generated two one-dimensional spectra from the E_γ-E_γ matrix by gating on the "peak channel" and its associated "background." By subtracting the "background" gate from the "peak" spectrum, we produced a "peak-minus-background" spectrum for that channel. Treating them as rows, all such one-dimensional spectra were then subtracted, channel by channel, from the parent two-dimensional matrix. We estimate that this procedure removes from the two-dimensional matrix, contributions due to the discrete transitions that are discernible in the total-projection spectrum. Figure 2(c) shows the projections from the matrix following this subtraction. The ridge structure completely disappears in both projections, suggesting that little or no correlated structures are present in the continuum quadrupole bump.

In a similar experiment, Twin *et al.* recently utilized a lead-backed target to examine the decay properties of the superdeformed states in ^{152}Dy.[22] They have concluded that although the ridge-valley structure is not apparent in the uncorrected data, it could be recovered by applying the full Doppler-shift correction to the matrix. This is similar to our conclusion regarding the ridge structure apparent in Fig. 2(b). The deduced deformations are, however, quite different in the two nuclei. To explain this difference between ^{144}Gd and ^{152}Dy nuclei, one could invoke at least two scenarios: First, despite the predicted similarity, the two nuclei could be structurally different. For example, structural differences at high excitation energies could hinder feeding into and/or population of the superdeformed states in ^{144}Gd relative to ^{152}Dy. A less likely, but yet plausible alternative would be that the effective feeding times into the superdeformed states in ^{144}Gd have accidentally become degenerate with the stopping time of the recoiling nucleus in the lead backing. In this case, the smearing of the ridge-valley structure (due to variations in the recoil velocity) can not be corrected for in the off-line analysis of the data. Such an experimental aberration, however, could be avoided by using a thin, unbacked target.

In summary, we have measured the E_{γ_1}-E_{γ_2} correlations from the decay of the highly excited ^{144}Gd nucleus. Although a high-energy quadrupole bump centered at 1.3 MeV was observed in the one-dimensional γ-ray spectrum, the two-dimensional map did not reveal any correlated structure originating from these γ rays. The ridges observed in the projections perpendicular to the diagonal were shown to be due to discrete photopeaks. On the basis of the present data, it is too early to interpret this result as proving the nonexistence of superdeformation in ^{144}Gd. It is suggested that structural effects at high temperatures may effectively hinder feeding into and/or population of the superdeformed states in this nucleus.

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