Evidence for Hyperdeformation in ^{147}Gd

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A pair of rotational bands with 9 and 11 discrete γ rays with a regular spacing of about 29 keV extending from 1016 to 1340 keV have been identified as belonging to ^{147}Gd. Evidence from their population, decay characteristics, very large dynamic moments of inertia of $\Im^{(2)} = 140\hbar^2$ MeV^{-1}, and agreement with theoretical predictions support the hyperdeformed character of these bands. These band structures correspond to a spheroid with major-to-minor axis ratio of about 3:1.

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One of the most exciting aspects of high spin nuclear structure physics in recent years has been the observation of superdeformed (SD) nuclei. In addition to fission isomers [1], SD band structures at high spin have been observed in other lighter regions of the nuclear chart with A near 190, 150, 130, and 80 [2–6]. The same theoretical models that explain the existence of the SD structures predict yet a third minimum in the potential energy surface at much larger deformations that correspond to prolate spheroids with a 3:1 axis ratio. Such elongated structures termed "hyperdeformed" (HD) were predicted to become yrast (lowest in energy for given spin) in ^{152}Dy at spins in excess of $80\hbar$ [7]. The question is then raised as to whether such structures could be populated in heavy-ion induced fusion reactions, since the conventional fission barriers [8] vanish at spins near $75\hbar$ for rare earth nuclei. Despite the low expected cross sections for the population of HD states, their observation would raise serious questions about our understanding of fission barriers and their shape parametrization at very high angular momenta. Recently, Galindo-Uribarri *et al.* [9] reported the observation of a ridge in a E_γ-E_γ correlation matrix in the $\hbar\omega$ region of 0.6 to 0.74 MeV and a very weak band with transition energies possibly up to 1525 keV with approximately a 30-keV spacing. These were attributed to a HD shape in ^{152,153}Dy. The ridge of Ref. [9] was confirmed by Lunardon *et al.* [10]. Simple arguments [9] based on the assumption that the dynamic moment of inertia $\Im^{(2)}$ equals the kinematic moment of inertia $\Im^{(1)}$ indicated spins extending from about $78\hbar$ to $98\hbar$. In the work of Galindo-Uribarri *et al.* ^{152,153}Dy were populated by the ^{120}Sn(^{37}Cl, pxn) reaction. There is no experimental evidence indicating that proton emission plays an important role in the population of the HD structure. However, attempts to populate such structures by fusion reactions emitting only neutrons gave negative results [9,11]. Recent calculations by Åberg [12] suggest that perhaps a better candidate for the population of a HD band may be ^{146}Gd for which it becomes yrast at spin $80\hbar$ compared to $90\hbar$ for ^{152}Dy.

In this Letter we report the first clear evidence of hyperdeformation in ^{147}Gd. It is based on a pair of HD bands consisting of 9 and 11 γ-ray transitions with a regular energy spacing of about 29 keV, giving rise to a very large dynamic moment of inertia that corresponds to a spheroid with a 3:1 axis ratio.

The experiment was performed at the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. A self supporting 357 μg/cm^2 foil of highly enriched ^{100}Mo was bombarded with a 230 MeV beam of ^{51}V with an intensity of 1.9×10^{10} s^{-1}. Gamma rays were detected by the Gammasphere array having then 36 Ge detectors [13]. In order to select the pxn channels from the fusion products and suppress the fission background, light charged particles (p, d, t, and α particles) were detected with the Microball [14], a 4π charged-particle detector array. The event trigger was determined by any three or more Ge detectors firing. The information from the associated coincident charged particles (energy, pulse shape, and time) was also recorded if one or more of the Microball detectors fired. A total of 1.2×10^9 events were recorded in 4 days of beam time. Of these about 25% and 20% were in coincidence with protons and α particles, respectively. A total of 2.5×10^8 one-proton gated events were selected in the off-line analysis. The peak-to-background ratio for the pxn and αxn particle gate improved by a factor of 4.0 and 5.0, respectively, consistent with the estimated fractions of the pxn and αxn channels relative to total fusion. The presence of the Microball caused significant absorption of γ rays only below 200 keV and a reduction of

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the peak-to-total ratio of the Gammasphere detectors from 0.54 to 0.49 for the ^{60}Co γ rays.

In order to identify and study the properties of the HD structures, the proton-gated events from the present reaction were subjected to a number of analyses. First, E_γ-E_γ matrices and E_γ-E_γ-E_γ cubes were created from p-$\gamma^{(3+\text{higher})}$ events. Background was subtracted from the efficiency corrected spectra projected from E_γ-E_γ matrices and E_γ-E_γ-E_γ cubes using the procedures of Refs. [15,16]. A weak ridge structure with $\Delta E_\gamma = 29$ keV was found for a few cuts perpendicular to the diagonal of the E_γ-E_γ matrices. Gates parallel to the diagonal at a distance of ΔE_γ were examined for a band structure, but none was found in this manner due to limited statistics and a number of contaminating structures. Further efforts based on cuts parallel to the cube diagonal, or to the diagonal of a four-dimensional hypercube, failed to produce a clear band structure.

Two band locating procedures [17,18] were applied to a proton gated cube with a 1 keV/channel resolution. Both procedures produced a number of candidate decay sequences with two of them common in both searches. Two bands with the following transition energies (A): 1113.8 (1.7), 1140.1 (2.1), 1169.7 (1.7), 1199.2 (1.7), 1223.2 (2.2), 1254.2 (1.8), 1284.6 (1.7), 1313.2 (2.3), 1340.0 (2.6) keV, and (B): 1016.1 (1.8), 1041.1 (1.5), 1071.7 (1.6), 1103.3 (1.9), 1130.2 (1.8), 1162.7 (2.6), 1189.1 (2.2), 1215.1 (2.2), 1243.0 (1.8), 1275.8 (1.9), 1302.6 (2.3), 1333.0 (2.2) keV were produced by setting 3.0-keV-wide gates on all possible double combinations of the energies in each case, except the 1254- and 1189-keV transitions. These bands are shown in Figs. 1(a) and 1(b). To aid visually the appearance of these bands, Figs. 1(c) and 1(d) show the same spectra smoothed by a procedure in which five consecutive points of the spectrum at a time were fitted by a cubic equation and the middle point was replaced with the fit. This preserves the energy resolution, the peak position, and the count normalization. Small variations in the position of the energy gates produced spectra similar to those of Figs. 1(a)–1(d). However, when the gates were displaced by several keV the produced spectra showed no regular pattern of any spacing. The transitions in bands A and B exhibit rather regular energy spacings, ranging from 26.3 to 33.8 and 25.0 to 32.8 (averages 28.3 and 28.8) keV, respectively. These correspond to a very large value of $\Im^{(2)}$ of 140$\hbar^2$ MeV^{-1}, which is consistent with a hyperdeformed spheroidal shape with major-to-minor axis ratio of 3:1. The $\Im^{(2)}$ is generally independent of $\hbar\omega$, but local variations are present that do not exhibit a regular pattern within the experimental uncertainties. Because of the limited statistics, quantitative patterns for the feeding in and out of the bands cannot be extracted. However, the intensity patterns of the HD bands A and B show that they terminate rather suddenly below the 1114- and 1016-keV transitions, respectively. The observed intensity remains constant for about seven and nine transitions and then falls off at higher energies. Such intensity patterns are typical in SD bands.

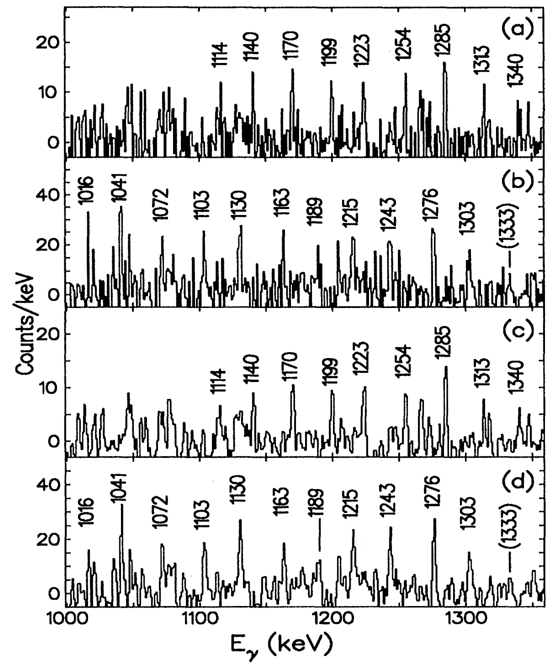

FIG. 1. (a), (b) Spectra of the HD bands A and B from all the possible combinations of double gates on the indicated transitions except those at 1254 and 1189 keV. The peaks are marked in keV. (c), (d) Smoothed spectra (see text) from (a) and (b), respectively, shown to aid visually the appearance of the two HD bands. The counts in the two bands A and B are proportional to the number of double gates 21 and 45, respectively, used to make the spectra.

The weak population of these bands (see below) does not permit us to bring back the other members of each band by either one single gate or one double gate (the latter gives only one or two counts per peak). In order to gain further confidence about the rotational band character of each decay sequence, it was possible to remove any single transition from the above combination of all double gates and produce spectra showing a clear decrease in the intensity of the remaining transitions in the gates. For band B an average reduction factor of 1.23 $\pm$ 0.07 was measured for ten transitions compared to the expected 1.25, with similar results for band A. In addition, the fact that all the transitions in bands A and B are produced in triple coincidences establishes the band character of these structures.

Interestingly, the alternate transitions at 1016, 1072, 1130, 1189, 1243, and 1303 keV in the HD band B are similar but distinguishable from those in the known excited SD band in ^{146}Gd [19] at 1017, 1071, 1127, 1185, 1245, and 1303 keV. From the number of gates employed it was estimated that less than 20% of the counts in the 1016-, 1072-, and 1303-keV transitions in the HD band B could be due to the excited SD band in ^{146}Gd. This similarity of the transition energies might suggest that the observed structure in band B is either (a) a pair of noninteracting independently decaying SD bands with accidentally interleaved energies or (b) a pair of strongly coupled SD signature partners with reasonably small signature splitting that decay strongly into each other by connecting dipole transitions. Definitive arguments against both of these scenarios can be given. First, a spectrum was created by requiring only all the possible pairwise *consecutive* double gates from the sequence of the HD transitions. In this case, scenario (a) or (b) should produce no band structure for either alternate sequence of transitions. Instead, this gating brings back the complete HD band as shown in Fig. 2 with an intensity consistent with the reduced number of gates. Secondly, placing alternate double gates on the odd numbered members of the band B brought back all the HD band members with the even ones about twice as intense, and vice versa.

The assignment of both the HD bands to ^{147}Gd can be made on the basis of the following evidence. Gating on the protons produces a clean selection of exit channels including mainly the $^{145-147}$Gd isotopes. The ^{145}Gd + $p5n$ channel involves six evaporated particles and can be excluded as a candidate for the HD bands, because it is a low spin channel. Figure 3(a) shows the low energy part of the spectrum that brings the HD band B with the ^{147}Gd lines marked by their energies. They are significantly enhanced relative to those from ^{146}Gd, which are indicated by asterisks. This is to be contrasted with the channel cross section ratio 4.2:1.0 (see below) for the ^{146}Gd relative to ^{147}Gd. For comparison, a spectrum with the same gates displaced by a few keV is shown in Fig. 3(b). It is seen that the ^{146}Gd lines now dominate. An enhancement of the ^{147}Gd lines relative to those of ^{146}Gd was also found in coincidence with band A. This argues for assigning the two HD bands to ^{147}Gd, which is the high spin channel in the present reaction.

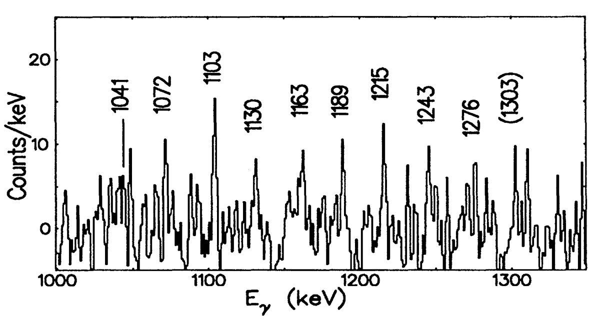

FIG. 2. A smoothed spectrum produced by doubly gating the cube with all the possible combinations of consecutive transitions of the HD band B. All the strong members of this HD band are visible. This argues against the scenarios where two interacting signature partners of a SD band, or two independent but interleaved SD bands with approximately twice the energy spacing produce the observed cascade (see text).

A good estimate of the spins in the HD bands is difficult to make at the present time. However, a number of arguments can be given for very high spins in the HD bands, based on their mode of formation and decay. First, the reaction ^{51}V + ^{100}Mo at 230 MeV (85.5 MeV initial excitation) has a Bass-model fusion cross section of 921 mb, corresponding to $\ell_{\rm crit} = 84\hbar$. Finite-range fission barriers [8] in a statistical model lead to a fission cross section of 260 mb, which gives a sharp cutoff value $\ell_{\rm ER}$ of $71\hbar$ for evaporation residues. The same calculations indicate that ^{147}Gd is populated at the highest spins possible in this reaction. The diffuseness of the residue distribution is determined by the fission versus particle competition and could extend the distribution to considerably higher spins with low yield. The finite-range fission barrier [8] in the present compound nucleus vanishes at spin $82\hbar$. This means that states with spins of the order of $75\hbar$ or higher may be populated with low cross sections in the evaporation residues. The experimental relative cross sections for the main pxn channels $^{145-147}$Gd were found to be 23 ± 3, 62 ± 3, and 15 ± 1, respectively. From the present data the known yrast SD bands in ^{146}Gd and ^{147}Gd [19] were populated at the (1.21 ± 0.11)% and (1.64 ± 0.21)% levels, respectively. The intensities of the HD bands A and B were found to be only (0.27 ± 0.07)% and (0.23 ± 0.07)% of the ^{147}Gd channel. The

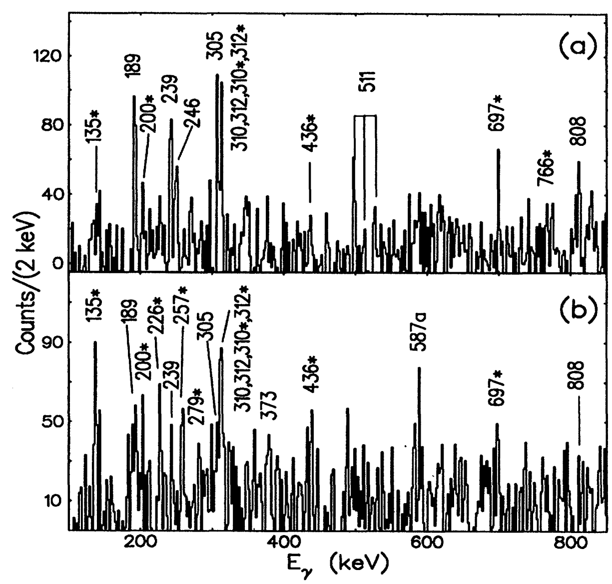

FIG. 3. (a) Low energy part of the spectrum in Fig. 1(b) that brings the HD band B, produced by double gating on all combinations of the transitions in the band except those at 1041, 1072, and 1333 keV. The ^{147}Gd lines are marked in keV, while those from ^{146}Gd are marked by an asterisk. Despite the preponderance of the ^{146}Gd nucleus in the data set, the strongest lines are from ^{147}Gd. (b) Spectrum created with the above set of gates displaced by about 5 keV. The ^{146}Gd lines now dominate. Peaks from ^{145}Gd are marked by a. An enhancement by a factor of ≈4 of the ^{147}Gd lines relative to those from ^{146}Gd is seen in panel (a) compared to (b).

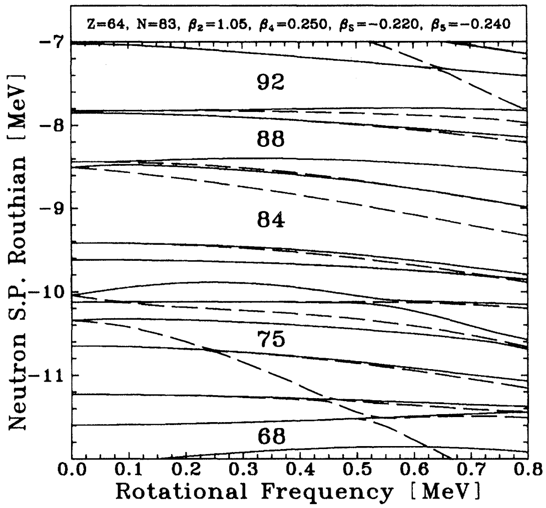

FIG. 4. Neutron single-particle Routhians calculated in the Woods-Saxon plus cranking model [20] using the deformation parameters shown. Solid lines indicate simplex $s = -i$ and dashed lines $s = i$. Note the large gap at $N = 84$ and the pair of simplex partners at $N = 83, 84$ with a small simplex splitting near the experimental rotational frequencies.

above population patterns and the very low yields of the HD bands suggest that they are populated at the highest spins that the present reaction can provide. Theoretical calculations described below suggest that $\Im^{(1)} = \Im^{(2)}$ for the HD structures in ^{147}Gd and that the lowest and highest experimental rotational frequencies correspond to spins of about $70\hbar$ and $90\hbar$, respectively. These values are lower by about $9\hbar$ than those in Ref. [9].

Using Åberg's [12] values for the deformation parameters, we have carried out calculations of the relevant single-particle energies and Routhians for ^{147}Gd. Instead of the Nilsson model used in Ref. [12], we used the Woods-Saxon plus cranking model [20]. The deformation parameters used were $\beta_2 = 1.05$, $\beta_3 = -0.22$, $\beta_4 = 0.25$, and $\beta_5 = -0.24$. In this model, a smaller value of β_4 than that used by Åberg ($\beta_4 = 0.42$) gave stronger shell effects at the neutron number 84 as shown in Fig. 4. The present calculations yielded $\Im^{(2)} = 138\hbar^2\,\text{MeV}^{-1}$ with $\Im^{(1)}$ essentially equal to $\Im^{(2)}$. Both moments of inertia were found to be constant with rotational frequency. This is in good agreement with experiment. Furthermore, the present calculation predicts a pair of simplex-partner bands with a small simplex splitting as seen in Fig. 4. Each of these can produce a pair of parity partners. This suggests an assignment of the two HD bands either as signature or simplex partners.

In summary, we presented evidence for hyperdeformation in ^{147}Gd. Two rotational bands of hyperdeformed character were identified with a regular spacings of ≈ 29 keV that lead to a very large value for $\Im^{(2)}$ of $140\hbar^2$ MeV^{-1}. It corresponds to a rigid spheroid with a major-to-minor axis ratio of about 3:1. This is in good agreement with theoretical predictions. The mode of formation and decay of these two bands is consistent with their having the highest spins that the present fusion reaction can provide.

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