

SEARCH FOR HYPERDEFORMATION IN ^{146,147}Gd

D.R. LAFOSSE, D.G. SARANTITES, M. DEVLIN, F. LERMA

Department of Chemistry Washington University, St. Louis, MO, 63130

C. BAKTASH, M.J. BRINKMAN, C.J. GROSS, H.-Q. JIN, D. RUDOLPH, D.W.
STRACENER, C.-H. YU

Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831

S. ASZTALOS, R.M. CLARK, P. FALLON, I.Y. LEE, A.O. MACCHIAVELLI,
R.W. MACLEOD

*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA,
94720*

B. CEDERWALL

Royal Institute of Technology, Stockholm, Sweden

A search was undertaken to look for evidence of hyperdeformation in ^{146,147}Gd. Three experiments employing Gammasphere for gamma-ray detection coupled with the Microball for channel selection via charged particle detection were carried out with increasing detection sensitivity and statistics. No definitive evidence for band structures that could be assigned to hyperdeformation could be found. Candidates previously reported are shown not to have properties consistent with a band structure.

1 Introduction

One of the interesting advances of high spin nuclear structure physics in recent years has been the observation of superdeformed (SD) nuclei. In addition to fission isomers¹, 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^{2,3,4,5,6}. 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, corresponding to prolate spheroids with a 3:1 axis ratio. Such elongated structures, termed "hyperdeformed" (HD), were predicted to become yrast (lowest in energy for a given spin) in ¹⁵²Dy at spins in excess of $80\hbar$ ⁷. The question is then raised as to whether such structures can be populated in heavy-ion induced fusion reactions, since the conventional fission barriers⁸ 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 parameterization at very high angular momenta.

Recently, Galindo-Uribarri *et al.*⁹ reported the observation of a ridge in an E_γ - E_γ correlation matrix in the rotational frequency range from 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 $^{152,153}\text{Dy}$. The ridge of Ref.⁹ was confirmed by Lunardon *et al.*¹⁰.

In the work of Galindo-Uribarri *et al.* the $^{152,153}\text{Dy}$ were populated by the $^{120}\text{Sn}(^{37}\text{Cl}, pxn)$ reaction. Attempts to populate such structures by fusion reactions emitting only neutrons gave negative results^{9,11}. Proton detection was used to clean up the spectra. Thus far there is no evidence indicating that proton emission plays an important role in the population of the HD structures.

Simple arguments⁹ based on the assumption that the dynamic moment of inertia $\mathfrak{I}^{(2)}$ equals the kinematic moment of inertia $\mathfrak{I}^{(1)}$ indicated spins extending from about 78 to $98\hbar$. Recent calculations by Åberg¹² 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 .

Recently we have undertaken a series of three experiments to search for the existence of HD band structures in the $^{146,147}\text{Gd}$ isotopes. From the first of these experiments we reported¹³ preliminary evidence for the population of two HD bands consisting of 9 and 11 γ -ray transitions with a regular spacing of about 29 keV which corresponds to a very large dynamic moment of inertia consistent with a spheroid having a 3:1 axis ratio. The weakness of the population of these bands dictated additional experiments with improved statistics in order to investigate these band structures. These experiments are described here and suggest that there is no evidence for the population of the HD structures in $^{146,147}\text{Gd}$ and that the candidate γ rays proposed in Ref.¹³ do not form a band.

2 Experimental Part

All three sets of experiments were performed at the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. Self supporting $306 \mu\text{g}/\text{cm}^2$ foils of highly enriched ^{100}Mo were bombarded with a 230 MeV beam of ^{51}V with intensities $(1.9\text{-}4.0)\times 10^{10}\text{s}^{-1}$. Gamma rays were detected by the Gammasphere array¹⁴. In the first experiment 36 Ge detectors of the early implementation were used. In the second and third experiments the partially filled Gammasphere array with 57 Ge detectors was used in its final configuration.

In order to select the pxn channels from the remaining fusion products and remove the fission background, light charged particles (p, d, t and α particles) were detected with the Microball¹⁵, a 4π charged particle array. The Microball was actually used only in the first and third experiments. The pertinent in-

formation about the experiments is summarized in Table 1. The first column in Table 1 gives the experiment number, the second column indicates whether the Microball was present in the experiment or not, the third column gives the γ -fold employed in the trigger, and the last column summarizes the number and type of events accumulated in each run. For the experiments involving the Microball the associated charged particle information was recorded when one or more of the Microball detectors fired. Of the latter events about 20% and 17% were coincident with one proton and one α particle, respectively. In all the Microball experiments the peak-to-background ratio for the $p\alpha n$ and $\alpha\alpha n$ particle gate improved by approximately the reciprocal of the particle channel fraction relative to that from the total fusion. The inclusion of the Microball causes significant absorption of γ rays only below 200 keV. Also the presence of the Microball reduced the peak-to-total ratio of the Gammasphere detectors from 0.54 to 0.49 and 0.57 to 0.51 for the ^{60}Co γ rays for experiments EI-32 and GS-26/30, respectively. It is important to emphasize the similarities and

Table 1: Summary of the experimental conditions employed in this work.

Experiment	Microball	γ - Fold	No. Events
1. EI-32	Yes	≥ 3	1.6×10^8 p-gated
2. GS-17/21	No	≥ 4	1.8×10^9
3A. GS-26	Yes	≥ 3	4.5×10^8 p-gated
3B. GS-30	Yes	≥ 4	4.0×10^8 p-gated

differences between the experiments. For experiments one and three, the particle identification was done by utilizing the pulse shape information from the CsI(Tl) scintillators in the Microball. In the first experiment the ratio of the early part of the CsI(Tl) pulses was used to separate the particles, and only a broad gate of ~ 300 ns was placed on the CsI(Tl) time signals. In addition, for the third experiment the times relative to the RF were also recorded. This permitted an additional particle identification scheme to be employed by taking advantage of differences in the crossover time of the constant fraction discriminator, which differs considerably for protons and α particles. By combining the ratio and the cross over time methods in two dimensions it was possible to reduce the random events by approximately a factor of three relative to the first experiment. Furthermore, the shaping times for the CsI(Tl) signals were reduced to give a peaking time of $3 \mu\text{s}$ for the third experiment instead of $5 \mu\text{s}$ in the first. This allowed us to increase the counting rates by about a factor of ~ 1.5 with the same fraction of about 4% pileup in the CsI(Tl) signals. The detailed properties and performance of the Microball are described in Ref. ¹⁵.

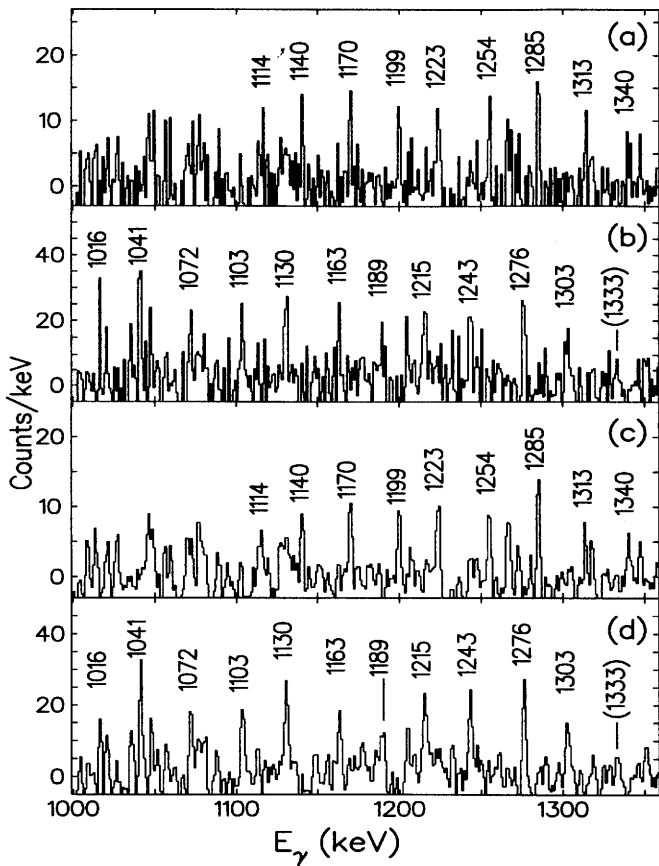


Figure 1: Results shown in Figure 1 of Ref. 6. Panel (a) shows the sequence termed band 1 in that reference; (b) same as in (a) but smoothed; (c) the sequence termed band 2; (d) same as (c) but smoothed. The spectra were generated by double gating a cube from a list of γ -ray energies. The two lists contained all the transitions labeled in the figure with the exception of 1254-keV in band 1, and 1189-keV in band 2.

The number and type of events from the three experiments are summarized in Table 1. The events from the third experiment were accumulated and processed both separately and combined. In order to identify the band structures, E_γ - E_γ - E_γ cubes were created from the p - $\gamma^{(3+higher)}$ and p - $\gamma^{(4+higher)}$ events from the runs EI-32 and (GS-26)+(GS-30), with latter having about 15 times the number of counts in the cube.

3 Results

3.1 The first experiment

The results of the analysis of the first experiment (Run EI-32 in Table 1) were summarized in Ref. ¹³. Briefly, two band locating procedures ^{16,17} were used on a proton gated cube with 1 keV/channel resolution and both produced candidate sequences of γ transitions. Two of these led to the sequences of γ rays that were interpreted as evidence of HD bands in ¹⁴⁷Gd in Ref. ¹³ (see Fig. 1). The statistical quality of those band structures was poor and did not allow unambiguous proof that they are indeed mutually coincident sequences. The evidence for their assignment as bands came from the fact that they appear in summed doubly gated γ -ray spectra, and hence appear in triple coincidence; supporting evidence was given based on removing one transition at a time from the gating list and evaluating the decrease in intensity of the remaining transitions in the spectrum. These are necessary but not sufficient conditions for establishing complete band structures. The statistical quality of the data and the small fraction of fourfold events did not allow triple gating to produce these structures.

The transitions in bands A and B exhibit rather regular energy spacings, ranging from 26.3-33.8 and 25.0-32.8 (averages 28.3 and 28.8) keV, respectively. These correspond to a very large value of $\mathfrak{I}^{(2)}$ of $140 \hbar^2 \text{MeV}^{-1}$, which is consistent with a hyperdeformed spheroidal shape with major-to-minor axis ratio of 3:1. If this interpretation is given to these data then the assumption of $\mathfrak{I}^{(1)} = \mathfrak{I}^{(2)}$ (see discussion in Ref. ¹³) leads one to conclude that spins of about 70 to 90 \hbar are involved. This result is at odds with the expected fission barriers in this region, which vanish near 75 \hbar . Furthermore, if the spins are as high as indicated by these structures, then only very small population from the tails of extended spin distributions should be expected. The observed yields for the sequences reported in Ref. ¹³ are high for such large spins in light of these arguments.

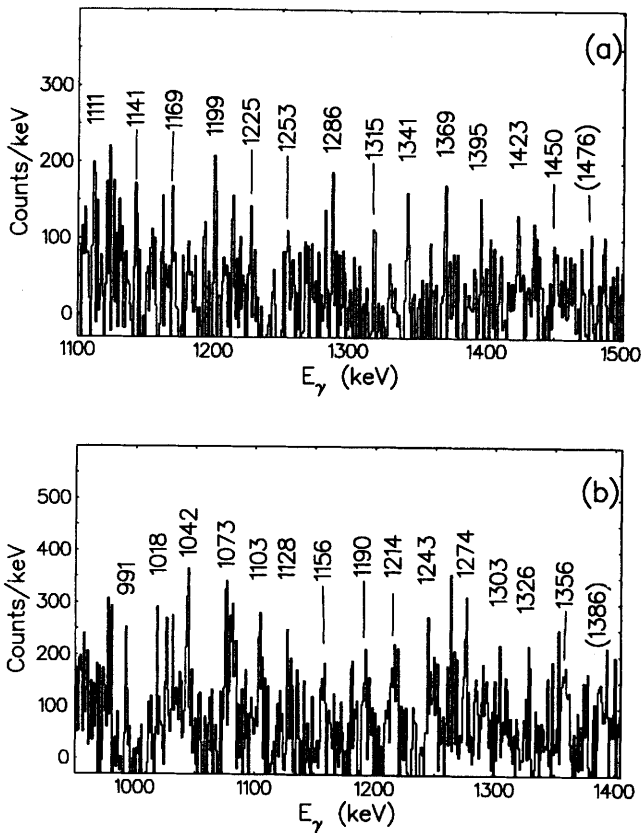


Figure 2: (a) Spectrum of γ rays for sequence A observed by doubly gating a cube from experiment two with all the possible combinations on the indicated transitions; (b) Same as in (a) but for sequence B.

3.2 The second experiment

An attempt was made to confirm the band structures discussed in the previous section. As discussed in Sect.2 an experiment was performed with the same reaction, including projectile energy and target (see run GS-17/21 in Table 1). Here the particle selection with the Microball was not employed. Only four fold and higher data were acquired in this experiment. The increase in the number of Ge detectors in Gammasphere from 36 to 57 provided an increase in statistics by a factor of ~ 6 for the same amount of running time.

The data were analyzed using E_γ - E_γ - E_γ cubes created by properly unpacking the higher fold events. The same band searching procedures^{16,17} were applied to this cube but did not produce any new transition sequences. By placing all the possible double gates corresponding to the sequences A and B the spectra shown in Fig. 2 were obtained. Counts at all peak positions for sequences A and B are seen in the spectra. Furthermore, a few extra transitions with about the same spacing appear in these triple coincidence spectra. The number of counts in the peaks is consistent with those from the first experiment, after the number of double gates have been taken into account. The quality of the spectra is poor, presumably because channel selection with the Microball (factor of 5:1) was not employed.

With the increased statistics it should have been marginally possible to produce the bands by triple gating. Attempts to produce the band structures by direct triple gating of the four and higher fold events failed. Subsequently for sequences A and B, singly gated cubes were produced and examined for these band structures. No evidence for either band was found in the singly gated cubes. It should be noted here that the extremely large background in these data and the loss of efficiency by the additional gating could account for the absence of evidence in the four fold coincidence spectra. However, estimates indicate that statistics in the 4-fold spectra comparable to those for 3-fold data of run 1 might be expected.

We conclude that from the second experiment unambiguous confirmation of the band structures could not be obtained. More specifically, we could not confirm that the observed γ -line sequences constitute a consecutively coincident band structure.

3.3 The third experiment

The purpose of the third experiment (see runs GS-26 and GS-30 in Table 1) was to obtain a confirmation that the sequences seen in the first two experiments constitute true band structures and/or to search for new possible bands in the ^{146,147}Gd nuclei. For this purpose, the conditions of the first experiment

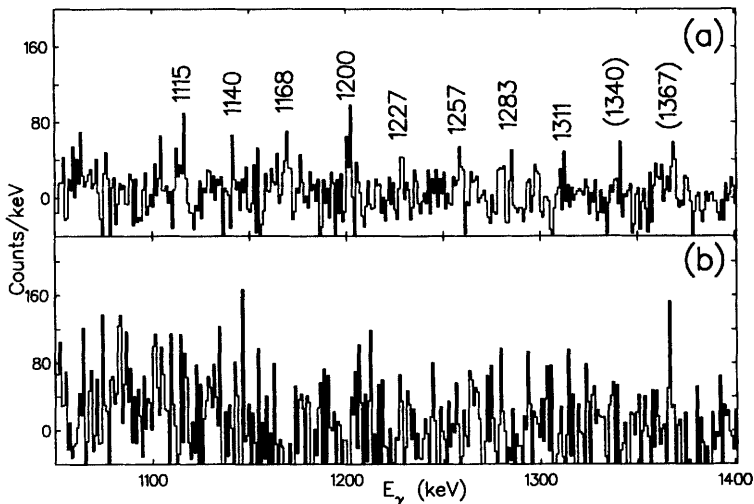


Figure 3: (a) Spectrum of γ - rays for sequence A observed from experiment three by gating on all the possible combinations of double gates on the indicated transitions placed on a proton gated cube. (b) Same as in (a) but from a cube that was not gated by protons.

were duplicated, but 57 instead of 36 Ge detectors were used. The Microball was used to separate the charged particle channels as discussed in Sect. 2. In addition, the bombardment was extended to 11 days instead of 4 employed in the first experiment. This produced increased statistics as shown in Table 1.

Cubes were produced by combining the events from GS-26 and GS-30. Examination of doubly gated projections with the transition energies corresponding to band B did not produce any evidence for a band-like structure. The sequence A produced a weak band-like structure which is shown in Fig. 3(a). Precisely the same gates were placed on a cube that was not gated by protons. The resulting background-subtracted spectrum is shown in Fig. 3(b) and shows no evidence for the sequence A of the γ transitions.

Spectra of the superdeformed bands from ^{147}Gd and ^{146}Gd were constructed and are shown Fig. 4. The counts in these spectra are ~ 13 times higher than those from the first run, while the number of unpacked triple

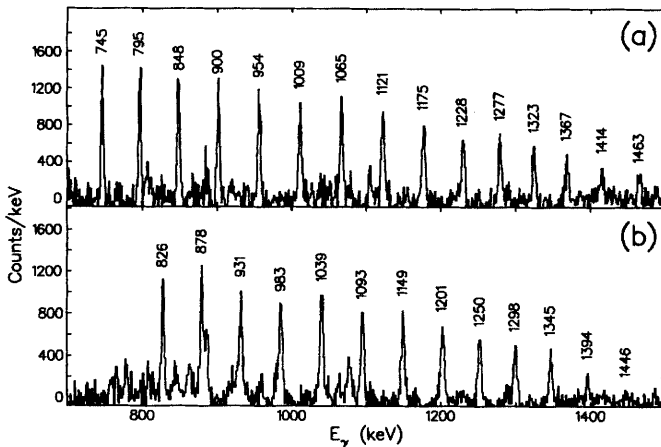


Figure 4: Spectra of the yrast superdeformed bands (a) in ^{147}Gd and (b) in ^{146}Gd obtained by adding all the double gates on the indicated transitions in a proton-gated cube from experiment three.

events in the cube scaled by a factor of 16. Similarly, the SD band from ^{143}Eu , the $\alpha 4n$ exit channel, shown in Fig. 5 also scaled with statistics in the three runs. In contrast, the statistics in the HD candidate sequence A [Fig. 3(a)] scales only by a factor of three between experiments one and three. The missing factor of four or five in the statistics of the third experiment indicates that this sequence of γ rays is not likely to be a coincident sequence of γ -transitions. Surprisingly, the sequences A and B from experiments one and two scaled with statistics. We point out that the γ rays in sequence A were not seen in any of the detailed decay schemes for the $^{145,146,147}\text{Gd}$ isotopes that were constructed based on the high statistics experiment three. Thus it is unlikely that the spectra shown in Ref. ¹³ are the result of coincidences between low-lying transitions in the decay schemes of $^{145,146,147}\text{Gd}$.

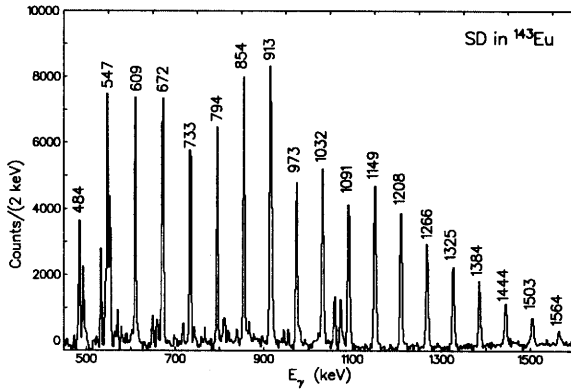


Figure 5: Spectrum of the yrast SD band in ^{143}Eu obtained by adding double gates on many of the indicated transitions in an α particle gated cube the third experiment.

4 Discussion and Summary

The channel yields from the three experiments were carefully examined and found to be consistent within the experimental uncertainties (the relative channel cross sections were found to be in the ratios of $33\pm 3\%$, $54\pm 4\%$ and $13\pm 1\%$ for $^{145,146,147}\text{Gd}$, respectively). This indicates that indeed the experimental conditions for all three experiments were the same.

Numerous attempts were made to definitively identify the origin of sequences A and B that were observed to be enhanced in experiment one compared to experiment three. For this purpose, the data from experiment one were re-examined as follows: (a) we carefully presorted all the event data to eliminate any spurious events; (b) the gain matching and efficiency calibrations were repeated; (c) we examined a cube from the $(^{51}\text{V}, xn)$ for evidence of sequences A and B and found none; (d) we looked for the transitions of sequences A and B in the fully constructed decay schemes for $^{145,146,147}\text{Gd}$ and could not observe any number of them that could explain sequences A and B in the doubly gated spectra; (e) a cube consisting only of 3-fold events

produced both sequences A and B with intensities consistent with the decrease in statistics (this was done to avoid any random spikes in the spectra due to unpacking the events and combing spectra from different sets of gates,¹⁸); and (f) a cube was produced by randomly rejecting 1 γ -ray from 4-fold events, 2 γ -rays from 5 - fold events, etc.; this cube showed sequences A and B again with intensities consistent with the decrease in statistics.

A possible source of contamination was identified with the reactions $^{12}\text{C}(^{51}\text{V}, pxn)^{59,60}\text{Ni}$ which are present in the proton gated spectra from carbon build-up on the targets. The transitions from these reactions are broad due to the large Doppler shifts. We were able to eliminate these partially from the constructed cubes by first performing a Doppler shift correction according to the reaction $^{12}\text{C}(^{51}\text{V}, pxn)^{59,60}\text{Ni}$ and then rejecting the events that had transitions in gates corresponding to the strongest γ -rays from $^{59,60}\text{Ni}$. Then, Doppler shift corrections were applied to the remaining events for the reaction $^{100}\text{Mo} + ^{51}\text{V}$ and these events were added to the cube. Although this procedure removed most of the contamination from the carbon impurities, it did not remove sequences A and B from the resulting spectra from experiment one. In conclusion no spurious origin of bands A and B in experiment 1 could be identified.

The data from the third experiment were carefully analyzed in order to: (a) reject spurious events; (b) reject more random events from the particle identification procedure from the Microball data; (c) gain match the events to better than 0.1 keV over the entire run by gain matching for every ~ 4 hours of running; (d) simulate experiment two by producing a cube without proton gating; and (e) look for differences in intensities for sequences A or B in separate cubes from runs GS-26 and GS-30 (see Table 1). In all the cases above sequence B could not be observed and sequence A was not produced with more counts than those shown in Fig. 3(a).

The origin of sequences A and B is not understood at the present time. One could speculate that under limited counting statistics weak sequences that look like band structures can be created from the elaborate background subtraction procedures. In such a case one may not expect reproducibility in different data sets.

In conclusion, we presented experimental evidence based on improved counting statistics showing that the sequence A and B of γ - rays reported in Ref. ¹³ are not sequences of mutually coincident γ - rays and thus do not constitute evidence for hyperdeformation.

Acknowledgments

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