EVIDENCE FOR SUPERDEFORMATION IN ^{148}Gd ☆

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γ–γ transition energy correlation measurements were performed in ^{148}Gd using Compton-suppressed Ge detectors. A broad first ridge was observed for $1.00 < E_\gamma < 1.42$ MeV. The deduced moment of inertia $\mathscr{I}^{(2)} = 78\hbar^2$ MeV^{-1} is consistent with superdeformation in ^{148}Gd. The results can be explained by cranked Strutinsky calculations.

The recent discovery [1] of a sequence of discrete transitions in ^{152}Dy corresponding to the rotation of a nucleus with a superdeformed shape (i.e. a prolate shape with an axis ratio of 2:1) has generated great interest, from both the experimental and theoretical point of view. Many questions remain unanswered, such as the exact excitation energy of the superdeformed band, its feeding mechanism in (HI, xn) fusion reactions and the magnitude of the pairing effects in the band. Among these questions, those related to the mapping of the regions of the nuclear chart where superdeformed shapes occur require immediate attention. Work in this direction is currently underway at several laboratories. Discrete states corresponding to very large deformations have now been observed in ^{132}Ce [2] and ^{135}Nd [3]. Recent evidence for superdeformation has also been derived from studies of energy correlations in the quasicontinuum in light Dy and Er nuclei [4]. Furthermore, the most recent theoretical studies of shape evolution at high spin by Dudek and Nazarewicz [5], and Chasman [6] make definite predictions regarding the occurrence of superdeformed minima in several nuclei at the beginning of the rare-earth region. These predictions can be used to guide experimental searches as well as to compare theory with experiment as data become available.

Here we report on evidence for superdeformation in ^{148}Gd based on $E_{\gamma_1} - E_{\gamma_2}$ transition energy correlations. This technique is well suited for the study of nuclear shapes [7]. For a rigid rotor nucleus, no two coincident γ-rays have the same energy and a valley is expected to appear in an E_{γ_1} versus E_{γ_2} coincidence matrix. This valley runs along the $E_{\gamma_1} = E_{\gamma_2}$ diagonal and separates two ridges formed by coincidences between consecutive γ-rays in the band. The ridge separation W is related to the dynamic moment of inertia by the relation $\mathscr{I}^{(2)}/\hbar^2 = 8/W$.

In an earlier publication [8], we have presented a detailed study of the discrete level structure of ^{148}Gd

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up to a spin of $I > 40\hbar$ and an excitation energy $E_x \sim 19$ MeV. Up to $I = 38$ the observed level spectrum consists of spherical and oblate aligned single-particle states. Above this spin a change in structure along the yrast line is indicated by the level energies (even though no clear rotational pattern is visible) and by the presence of a few fast E2 transitions which suggest the onset of collectivity. The present study is an extension of the earlier work into the quasicontinuum.

Details regarding experimental conditions have also been reported earlier [8] and will only be summarized here. ^{148}Gd was produced using a 170 MeV ^{36}S beam from the ATLAS accelerator bombarding a 0.8 mg/cm^2 ^{116}Cd target evaporated on a 10 mg/cm^2 Pb foil. At this energy, the 4n and 5n evaporation channels leading to ^{148}Gd and ^{147}Gd predominate. Together the two Gd nuclei account for 82% of the total intensity seen in the γ-ray spectra. The data were obtained with the Argonne–Notre Dame γ-ray facility which consisted at the time of 7 Compton-suppressed Ge spectrometers (CSG) positioned at 35°, 90° and 145° surrounding a central array of 14 BGO hexagons providing multiplicity and time information. A total of 10^8 coincidence events were recorded.

In the analysis several E_{γ_1} versus E_{γ_2} energy correlation matrices were constructed for all coincidences between any pair of detectors. In the first matrix, prompt events were collected assuming that all of the γ-ray lifetimes are large compared to the slowing down time of the recoiling nucleus in the Pb foil (i.e. no Doppler-shift correction was applied). In a second matrix such corrections were applied assuming full recoil velocity for the emitting nucleus ($v = 0.021c$). This second procedure assumes that the γ-rays cascading down superdeformed bands are emitted before the nucleus is slowed down appreciably. Two matrices similar to those described above were also obtained by requiring the array of BGO hexagons to fire delayed with respect to the beam, thereby tagging the 49/2, $T_{1/2} = 550$ ns isomer in ^{147}Gd [9]. Finally, total γ-ray spectra emitted by the nuclei ^{148}Gd and ^{147}Gd, respectively, were obtained from the coincidence matrices for the 3 angles given above by summing appropriate gates on most of the intense discrete transitions assigned to the two nuclei. In order to derive information on the nature of the quasicontinuum radiation these spectra were unfolded using measured CSG response functions and were then analyzed in terms of their various components in a way similar to that described in refs. [10,11]. Details of this analysis will be given in a forthcoming publication [12]; only aspects relevant to the discussion below are presented here.

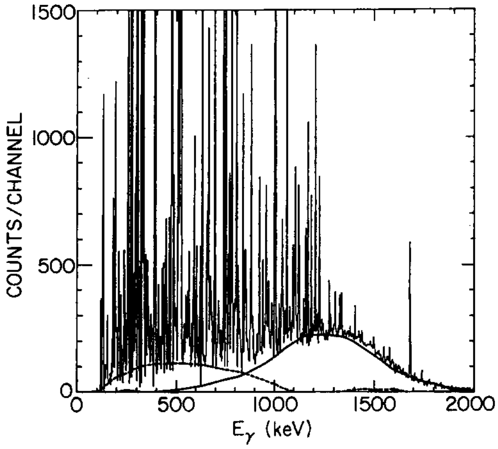

Fig. 1. Total γ-ray spectrum of ^{148}Gd. The data have been unfolded with the measured detector response and corrected for the detector efficiency. The dipole (quadrupole) component of the quasicontinuum is given as a dashed (solid) line. The contribution of statistical γ-rays has been subtracted. The spectra have been corrected for angular distributions and Doppler-shifts.

Fig. 1 shows the unfolded and efficiency corrected total γ-ray spectrum for ^{148}Gd. Aside from a contribution of statistical γ-rays (not shown in fig. 1) two other components of the quasicontinuum spectrum can be recognized: one is dipole in nature while the other is quadrupole. The bump of E2 transitions is of importance here and has the following characteristics: it is centered around 1.24 MeV, has a total γ-ray multiplicity of 7 ± 1 (the corresponding multiplicity for discrete lines is 20 ± 2) and the high energy edge of the bump displays energy shifts as a function of detector angle that are consistent with emission close to full recoil velocity. These results agree very well with those of ref. [10] for ^{153}Ho and ^{152}Dy, two nuclei with yrast structures similar to that of ^{148}Gd, and indicate the presence of collective transitions above the yrast line.

It can be seen (fig. 1) that below 1 MeV a very large number of discrete γ-rays corresponding to yrast and near-yrast transitions exist on top of the quasicontinuum spectrum. The vast majority of these transitions do not show any Doppler shifts, i.e. they were emitted from stopped product nuclei. They are of single-particle character and do not exhibit any valley-ridge structure in the E_{γ_1} versus E_{γ_2} plane. However, they obscure the matrix to the extent that a search for correlated structures below 1 MeV is impossible. Even above this energy the presence of strong discrete transitions hinders the analysis because of the strong vertical and horizontal stripes that these γ-rays add to the matrices. The analysis was done using two different approaches. In the first, data were corrected applying the method proposed in ref. [7] to enhance the correlated events over uncorrelated ones. The method was modified according to ref. [13] to account for the large photoefficiency of the CSGs. Contributions due to discrete lines were also removed by substituting the data in the rows and columns corresponding to discrete lines with values obtained from a smooth interpolation between channels at both sides of the peaks. A second approach used the raw data without any manipulation: it relies only on the excellent suppression of Compton events provided by the CSGs to reveal the correlations of interest. Only those parts of the matrices which are not affected by discrete lines were considered. The results of both types of analyses were found to be in good agreement, and results obtained with the second method are presented below.

Fig. 2 presents sums of a number of selected 20 keV wide energy slices projected perpendicularly to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal. These slices were obtained from the matrix with Doppler shift correction. A ridge-valley structure is clearly visible. The broad first ridge was identified between 1.00 and 1.42 MeV. Similar structures were not found in any of the matrices gated on ^{147}Gd nor in matrices without Doppler shift corrections. This indicates (i) that the transitions building up the ridge structure most likely are γ-rays in ^{148}Gd rather than in ^{147}Gd and (ii) that these transitions are of collective character because of the short decay times implied by the need for Doppler shift corrections. The intensity along the ridge is rather constant and corresponds to 0.9 ± 0.3% of the events producing ^{148}Gd. The ridge separation was derived in every 20 keV wide slice. The average separation is $W = 102 \pm 8$ keV (the errors represent the statistical uncertainties) which corresponds to a value of $\mathscr{J}^{(2)} = 78^{+3}_{-6}\hbar^2\ \mathrm{MeV}^{-1}$ for the dynamic moment of inertia. This value is 1.36 times the rigid-body moment of inertia for a spherical nucleus of mass 148 and is only slightly smaller than the one observed in ^{152}Dy [1,4], i.e. $84\hbar^2\ \mathrm{MeV}^{-1}$. We thus conclude that ^{148}Gd develops a very large deformation.

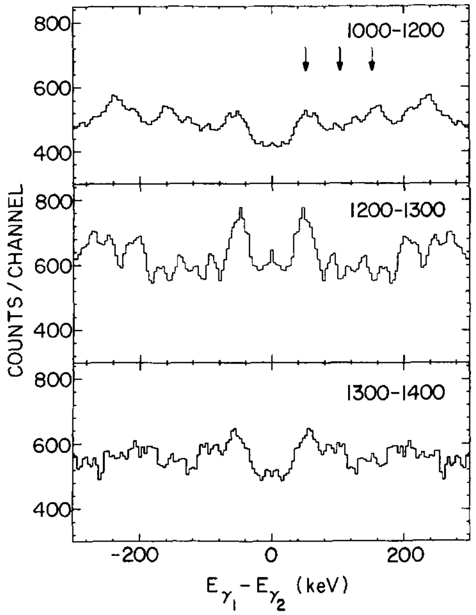

Fig. 2. Cuts perpendicular to the diagonal of the symmetrized, Doppler shift corrected, $E_{\gamma_1} - E_{\gamma_2}$ matrix for the energy intervals indicated. As discussed in the text only 20 keV wide energy slices which are not contaminated with contributions due to discrete lines have been added up. The arrows indicate the observed position of the first ridge and the expected positions of the second and third ridges.

Gaussian fits to the peak defining the ridge were performed for each 20 keV wide slice. The half width was found to be: 9.2 ± 3.2 keV. This value is larger by about a factor of 2 than the width calculated taking into account the instrumental resolution (~4 keV). This suggests that the correlated structure is made up of many γ-ray cascades with different $\mathscr{J}^{(2)}$. This conclusion is consistent with the fact that extensive efforts to identify transitions forming a discrete superdeformed band were unfruitful. The large width could, however, also be attributed to broadening due to effective feeding times (into the superdeformed states) comparable to the stopping time of the recoiling nucleus. This explanation is less likely in view of recent lifetime measurements, on superdeformed states in ^{152}Dy [14]. Finally, while the first ridge is clearly visible, second and higher order ridges are too

Table 1
Calculated moments of inertia in units of ($\hbar^2$ MeV^{-1}) at $I=55$ using the cranked Strutinsky approach. The calculations were performed with shell corrections [6] deduced from the single-particle potentials. As mentioned in the text, the calculations used a value of the rotational radius parameter adjusted to reproduce the measured value of ref. [2] in ^{152}Dy. A value of 0 in the table indicates that there was no minimum calculated at large deformation.

Z	N										
	78	79	80	81	82	83	84	85	86	87	88
68	65.0	67.2	68.8	68.3	65.9	80.4	82.3	81.8	87.7	91.6	93.0
67	65.0	65.4	68.1	0.0	77.6	79.5	81.8	81.7	85.9	89.4	91.4
66	64.6	68.6	70.0	73.2	77.7	78.2	79.3	79.4	$\underline{83.2}$	84.6	85.4
65	68.0	68.5	69.5	73.4	77.6	79.3	80.5	80.3	82.2	83.6	84.0
64	67.7	68.2	68.0	73.2	76.6	77.4	$\underline{78.7}$	78.0	81.3	82.0	82.5
63	62.8	63.6	64.7	69.7	73.2	76.1	77.8	78.0	80.7	81.8	82.3
62	64.6	63.9	64.8	67.5	73.1	76.2	77.2	77.3	80.4	81.5	82.1
61	63.2	63.9	64.6	67.0	72.5	74.1	75.1	74.9	80.6	79.2	79.5
60	61.9	62.6	63.7	66.1	70.6	72.6	75.5	75.4	81.3	81.9	80.1

weak to be observed (their location is indicated by arrows in fig. 2). Thus, superdeformed structures must correspond to cascades with, on the average, only two transitions within a band, i.e. they exhibit strong out-of-band branchings. An alternate possibility is that the second and third ridge are broadened and, hence, more difficult to observe because of a spread in values of $\mathscr{I}^{(2)}$. However, there is no strong suggestion for this in the data (fig. 2). The present ^{148}Gd results are very similar to those reported in ref. [4] for ^{152}Dy and differ from the data of ref. [1] for the same nucleus. In the latter case the ridge is reported to consist of discrete points only (corresponding to the discrete superdeformed band) and, hence, does not exhibit a continuous structure.

The present data are explained rather well by cranked Strutinsky calculations [6]. In these calculations, the single-particle neutron spectrum at $N=84$ does not show a large gap for the superdeformed shapes. In contrast, the results obtained for ^{152}Dy indicate large gaps for both $Z=66$ and $N=86$. This difference might help to explain the observation of discrete lines in ^{152}Dy (where one band is favored due to the lowering of the energy of the single-particle orbitals) and the observation of a continuous rigde instead (reflecting a higher level density) in the quasicontinuum for ^{148}Gd. The relative values of $\mathscr{I}^{(2)}$ for the two nuclei are well reproduced. Using the moment of inertia corresponding to the measured superdeformed band [1] in ^{152}Dy we get a liquid-drop rotational energy radius parameter of $r_0=1.153$ fm. This is slightly smaller than the conventional value (see ref. [15]) of $r_0=1.20$ fm. Using this value, the moments of inertia for all of the superdeformed nuclei considered in ref. [6] were calculated. In table 1 we present the moments of inertia calculated for a spin $I=55$. The agreement with the experimental result for ^{148}Gd is excellent: i.e. the predicted value of $\mathscr{I}^{(2)}=78.7\hbar^2$ MeV^{-1} agrees closely with that deduced from the data. It is worthwhile to note that the calculations predict variations of $\mathscr{I}^{(2)}$ with spin for some of the nuclei of table 1 and not for others. For example, at $I=25$ the following values of $\mathscr{I}^{(2)}$ are calculated (in units of $\hbar^2$ MeV^{-1}): 75.8 (^{146}Gd), 76.2 (^{148}Gd), 86.7 (^{149}Gd) and 86.8 (^{152}Dy).

In conclusion, experimental evidence for superdeformation in ^{148}Gd has been derived from γ-ray energy correlations. The measured properties are reproduced in the calculations of ref. [6]. No evidence for similar structures was found in ^{147}Gd. The possibility of superdeformation in this nucleus is, however, not ruled out since the experimental conditions (angular momentum input and excitation energy) are somewhat different from the ^{148}Gd case. Our result, together with recent findings in ^{149}Gd [16] and ^{146}Gd [17], establishes the Gd isotopes with $N\geqslant 82$ as nuclei with superdeformation at high spin. Isotopes with $N<82$ are also predicted to be superdeformed [5,6], but data are available only for ^{144}Gd where a negative result has been reported [18].

Clearly, more experimental work in this mass region is needed to test the calculations.

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