Superdeformation in ^{146}Gd

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Superdeformation in ^{146}Gd has been studied using the EUROGAM I spectrometer at the NSF Daresbury. The two known superdeformed (SD) bands in ^{146}Gd have been extended to 15 transitions. All transitions within each band were clearly observed in coincidence among each other and accurate γ-ray energies were determined. The association of both bands to ^{146}Gd has been unambiguously confirmed. In addition a band with energies corresponding to the first known SD band in ^{147}Gd was also observed. Several methods to search for new SD bands were applied.

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I. INTRODUCTION

The development of large germanium detector arrays like EUROGAM, GAMMASPHERE, or GASP has made it possible to study even the weakly populated states of superdeformed bands with accurate statistics. New phenomena like a $\Delta I=4$ structure [1], a proton backbending [2], an excited superdeformed (SD) band which decays to the yrast SD band [3], and linking transitions between signature partner bands [4] have been observed. Furthermore, first results could be obtained in the search for linking transitions to the normal deformed states [5,6].

In ^{146}Gd, two superdeformed bands are known [7,8], which are among the weakest SD bands found in this mass region. The earlier investigations had been performed using mainly sum spectra with poor statistics. The aim of the experiment we report here was to study these bands with sufficient statistics in order to prove by means of individual gates the mutual coincidence of the SD band transitions and to determine the transition energies more accurately. In addition a search for linking transitions between the normal and the superdeformed states and for further excited SD bands in ^{146}Gd was planned.

II. EXPERIMENT

Excited states in ^{146}Gd were populated by the ^{102}Ru(^{48}Ca,$4n$)^{146}Gd reaction at a beam energy of 203 MeV. The beam was supplied by the tandem Van de Graaff accelerator at the Nuclear Structure Facility, Daresbury. The target consisted of two self-supporting Ru foils of about 0.5 mg/cm^2 thickness mounted with a separation of approximately 1 mm. γ rays were detected with the EUROGAM I spectrometer, comprising 45 large volume Compton suppressed germanium detectors. In total 7×10^8 events with an unsuppressed fold $\geqslant$ 6 were recorded.

III. INVESTIGATION OF THE KNOWN BANDS

To check the coincidence relations of the SD transitions and to determine the transition energies precisely, all events with a Ge fold $\geqslant$3 (fold $\geqslant$4) were sorted into $2k\times2k$ matrices for both bands with the additional condition that at least one (two) of the coincident transitions belong to the SD band. These matrices will be called in the following discussion single gated and double gated matrices respectively. Preliminary gated spectra from these matrices, obtained by using all clean SD transitions, were used to optimize the gate positions, and the gated matrices were then resorted with the improved gates. This procedure was repeated several times until no further improvement could be obtained.

A. Coincidence relations of the SD band transitions

Figure 1 shows examples of gated spectra where in each case the gate was set on an individual SD transition in the single gated matrices. The background was removed by subtracting the product of the matrix projections normalized to the total number of counts from the raw matrix. These spectra show for both SD bands that the transitions are mutually coincident and that one is really observing single cascades. This was not clearly demonstrated up to now for both SD bands because of the poor statistics of the single gated spectra obtained previously [8].

B. γ-ray energies of SD transitions

The γ-ray energies of transitions for both SD bands were obtained from the sum spectra in the double gated and single gated matrices (see Fig. 2). The sum spectra in the double gated matrices are very clean. As this is important for a precise energy determination mainly these spectra were used. For the higher energy transitions we had to refer to the single gated matrices because of the poor statistics in the double gated matrices. In the sum spectra from twofold events (ungated matrices) superimposed transitions from the normal deformed level scheme prohibited a precise energy determination. The results for both bands are given in Table I. For the stronger transitions the transition energies agree with those from earlier experiments [9,7,8] within the errors which are smaller than before. For the weak transitions some

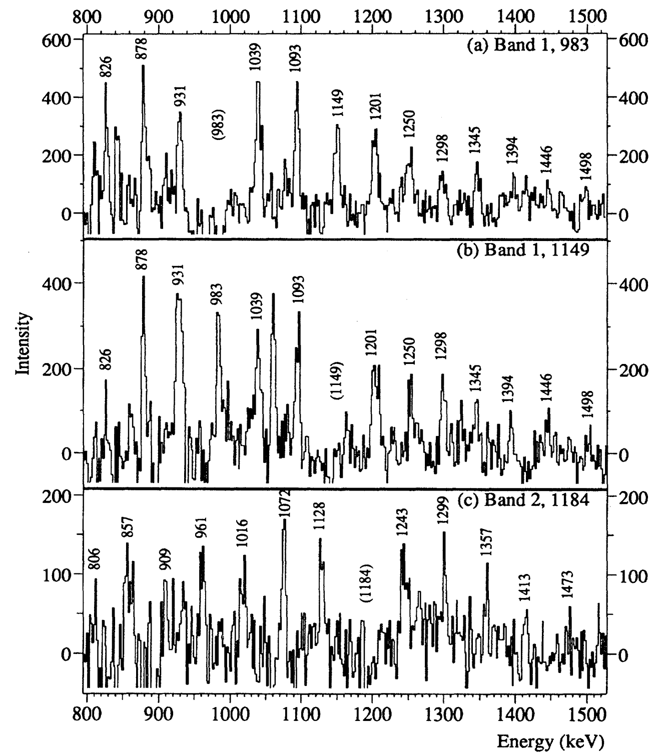

FIG. 1. Spectra from single gates on the transitions at 983 keV of band 1 (a), 1149 keV of band 1 (b), and 1184 keV of band 2 (c), respectively.

deviations from these experiments are larger but not systematic and most probably due to the poor statistics in the earlier experiments.

Band 1 could be extended by the 1498.5 keV and the 1553.6 keV transitions. The 1553.6 keV peak is close to the strong 1552.8 transition of ^{145}Gd, but as the sum spectra in the double gated matrix do not contain any peaks from ^{145}Gd we are confident that this transition belongs to the superdeformed band. Band 2 was extended by the 1582.0 keV transition.

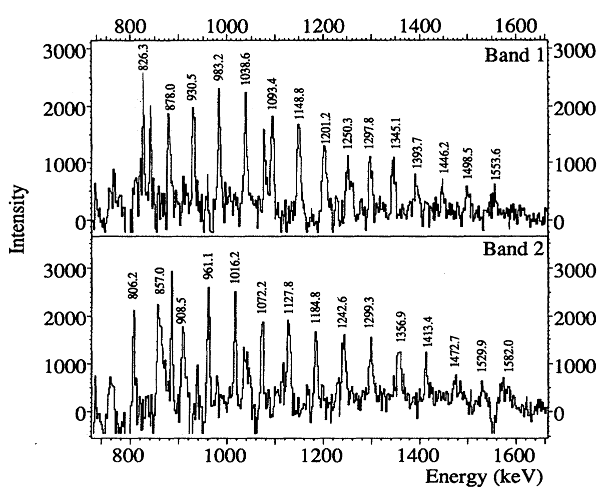

FIG. 2. Sum spectra of the two superdeformed bands in ^{146}Gd. In both cases the eight cleanest gates have been added.

Figure 3 shows the moments of inertia $\Theta^{(2)}$ versus the rotational frequency for both bands. The band crossing in band 1 reported in [7] at $\hbar\omega = 0.65$ MeV can be clearly confirmed.

IV. ASSIGNMENT OF THE SD BANDS TO ^{146}Gd AND LINKING TRANSITIONS TO NORMAL DEFORMED STATES

A. Assignment of the SD bands to ^{146}Gd

Before searching for linking transitions, it was necessary to check that the two bands really belong to ^{146}Gd. This is not trivial because of the small peak-to-background ratio (about 2%) of superdeformed transitions: if the backgound in the slice of a γ-γ matrix from a gate on a superdeformed transition exceeds the assumed background shape at certain positions by a few percent, one will find peaks at these positions in the resulting background subtracted spectrum. So the applied method of global background subtraction has a strong influence on the peaks appearing in coincidence with the superdeformed bands (see [9]).

Figure 4 shows that in the single gated spectrum from a sum gate on band 1 (twofold data, upper part) not only peaks from ^{146}Gd, but also the stronger transitions of ^{145}Gd (labeled by arrows) appear in coincidence with the band. ^{145}Gd is the second strongest reaction channel in our data. Peaks from other nuclides produced with smaller cross sections (^{147}Gd, ^{146}Eu, ^{145}Eu, ^{144}Eu, ^{144}Sm, ^{143}Sm, ^{142}Sm) are not observed in the spectrum. In the sum spectrum of double gated spectra with gates on band 1 (threefold data, lower part) only transitions from ^{146}Gd remain in coincidence with the band. The gates were chosen in such a way that they did not contain any transitions from the known discrete level schemes of ^{145}Gd and ^{146}Gd. The elimination of ^{145}Gd by the double gating procedure indicates that the remaining peaks in the resulting double gated spectrum do correspond to real coincidences and not to the background structure which contains transitions from ^{145}Gd. The situation for band 2 is similar and confirms that this band also belongs to ^{146}Gd.

There are even more arguments against an assignment of the bands to a europium isotope. First the transitions in the bands discussed in the present paper have an energy separation of about 53 keV instead of 60 keV as observed in ^{143}Eu and ^{144}Eu. Secondly the weak population of Eu nuclei would imply a SD intensity of 20% of the reaction channel which is very unlikely.

B. Search for linking transitions between superdeformed and normal deformed states

In order to search for linking transitions between superdeformed and normal deformed states, the normal deformed states which are directly populated by the decaying bands have to be identified.

From the coincidence analysis it was found that the 29^+, 27^+, and 26^+ levels (see Fig. 5) are most strongly populated from band 1. Whether the 29^+ level is also popu-

TABLE I. Transition energies and intensities of the superdeformed bands observed in this experiment. The intensities are given in % of the strongest transition in the corresponding band.

^{146}Gd, band 1		^{146}Gd, band 2		band 3	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ
826.3±0.3	61±5	806.2±0.3	51±5		
878.0±0.3	71±8	857.0±0.3	68±6		
930.5±0.2	84±7	908.5±0.3	89±9	958.5±0.5	100±16
983.2±0.2	91±5	961.1±0.2	100±7	1006.1±0.6	84±14
1038.6±0.3	100±6	1016.2±0.2	91±7	1064.9±0.6	94±16
1093.4±0.3	92±5	1072.2±0.2	78±8	1123.5±0.8	73±16
1148.8±0.2	81±5	1127.8±0.3	77±7	1175.7±0.8	69±16
1201.2±0.3	60±4	1184.8±0.3	73±8	1225.6±1.0	64±18
1250.3±0.4	52±4	1242.6±0.3	73±7	1278.0±1.4	49±17
1297.8±0.3	51±5	1299.3±0.4	60±7	1322.4±1.1	59±17
1345.1±0.3	47±5	1356.9±0.4	55±6	1368.9±1.9	30±17
1393.7±0.4	37±6	1413.4±0.4	37±5		
1446.2±0.5	23±4	1472.7±0.6	20±4		
1498.5±0.7	24±5	1529.9±0.8	13±3		
1553.6±0.9	16±5	1582.0±1.1	12±4		

lated by band 2 cannot be decided since the 958 keV transition depopulating this level is close to the 961 keV transition of band 2. The details of the population by band 1 are given in Table II. Because of the strong fragmentation of the level scheme into many different decay paths below the 26^+ state, only the states with the strongest depopulating transitions could be analyzed. The intensities of coincidences between the SD band and the weaker transitions of the normal deformed level scheme were estimated using branching ratios observed in spectra with gates on the 295 and 958 keV transitions. No candidates for discrete linking transitions populating these levels could be established.

If the bands decay in two steps and many branches via intermediate levels one can set a gate on one γ-ray transition of the SD bands in triple coincidence events and add the two other γ-ray energies. In the resulting sum spectra peaks should be observable at the sum energies of the decay paths. This method described in [6] was applied to the three- and higher-fold data of our experiment. No indication of linking transitions was found. This is not surprising as Table II shows that the strongest feeding of a normal deformed level directly by band 1 is about 20% of the total intensity of band 1 and therefore close to the observational limit even if the whole feeding intensity is contained within only one linking transition.

A decay of three or more steps would require an analogous examination of four- and higher-fold events. In our experiment, the statistics were not sufficient for such investigations.

V. SEARCH FOR NEW BANDS

To search for new superdeformed bands a grid search method in two ([9]) and three dimensions was used. For the three dimensional search events were sorted with Ge fold

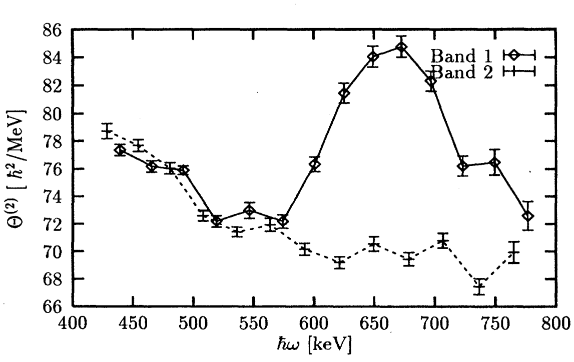

FIG. 3. Moment of inertia of the two superdeformed bands in ^{146}Gd.

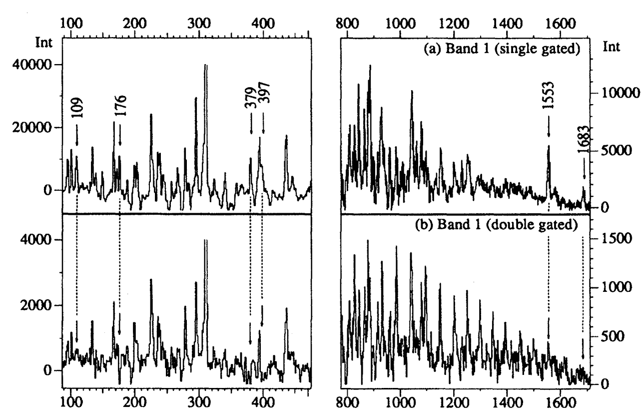

FIG. 4. Two energy regions of single gated (a) and double gated (b) sum spectra of band 1. In the single gated spectrum also the strongest transitions in ^{145}Gd are seen, which are indicated by energy labels and arrows. In the double gated spectrum only transitions of ^{146}Gd are present. The transitions of ^{145}Gd have disappeared (the small peak at 1554 keV corresponds to a transition of the SD band).

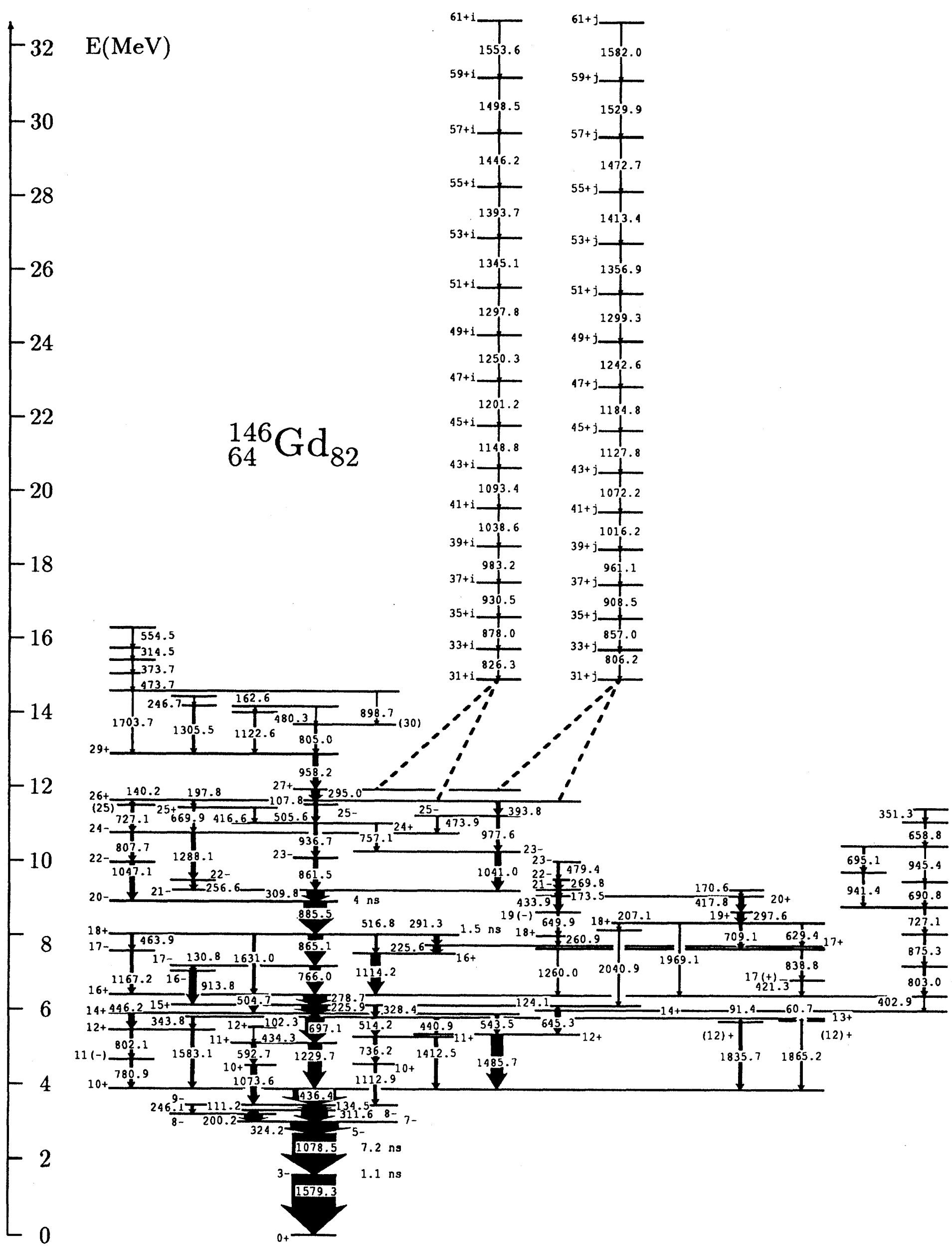

FIG. 5. The level scheme of ^{146}Gd from [12] and [13] with the two bands. The dashed lines represent unobserved linking transitions. The detailed patterns of the linking transitions, the excitation energies, and the spins of the SD bands are unknown.

$\geqslant$ 3 into a $1k\times1k\times1k$ cube. To remove the background, the generalization of the Palameta-Waddington formula ([10]) to three dimensions ([11]) and various approximations of it were used.

The grid search code generates a spectrum by summing up the counts at the grid points defined by hypothetical coincidences of a trial cascade with equally spaced transitions. The trial grid is moved along the $E_{\gamma_1}=E_{\gamma_2}=E_{\gamma_3}$ diagonal. If a rotational band is present, the resulting spectrum shows a large signal wherever the grid happens to overlap the peaks from the band. Grid points at which the intensity exceeds a certain threshold are ignored to reduce the influence of strong transitions from the normal deformed levels. For the two dimensional grid search, the best results were obtained using a background subtraction based on a two dimensional automatic fit [11] to the background and the strongest peaks. In all cases the quality of the three dimensional spectra was much better as could be easily checked by the two known bands.

All grid point distances between 30 and 70 keV were examined in 2 keV steps. The strongest structure which was discovered is a group of nine equidistant peaks between 959

TABLE II. Population of the normal deformed states by band 1. The additional intensity is the intensity coming directly from the SD band (not via the decay of states above). The errors of the intensities are about 10–15 % of the total intensity.

Level	Observed depop. transition (keV)	Total intensity (in % of I_{1039})	Add. intensity (in % of I_{1039})
29^+	958.2	20	20
27^+	295.0	44	24
26^+	393.8	54	10
25^-	977.6	28	7
23^-	1041.0	50	0
21^-	309.8	100	

and 1369 keV with about 1/8 of the intensity of band 1 (see Table I and Fig. 6). Within the errors all energies are identical to the energies of the first band of ^{147}Gd ([9]), but the strongest peaks of the ^{147}Gd band, namely, the 697, 745, 795, 848, and 900 keV transitions, could not be observed. Although even the sum gated spectrum of the band has poor statistics, the transitions at 1006, 1065, 1124, and 1176 keV can be observed in single gates and are shown in this way to be coincident to each other. It was not possible to relate this band unambiguously to ^{146}Gd or ^{147}Gd because the contaminants from various reaction channels are very strong.

No further superdeformed bands were found. From the intensity of the third band it can be estimated that in our experiment the lower limit for detecting new bands is at about 1/10 of the intensity of the first band, and the intensity of any additional band in ^{146}Gd should be below that limit.

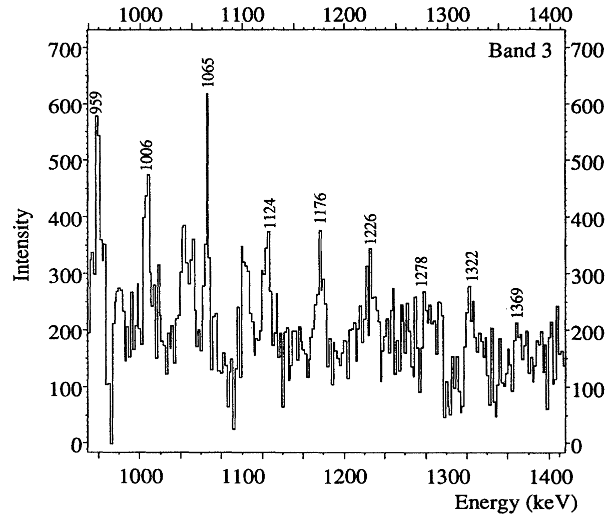

FIG. 6. Sum spectrum of band 3.

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