Linking Transitions from the Superdeformed Band in ^{143}Eu

A. Ataç,[(1)] M. Piiparinen,[(1),(a)] B. Herskind,[(1)] J. Nyberg,[(1),(b)] G. Sletten,[(1)] G. de Angelis,[(2)] S. Forbes,[(3)] N. Gjørup,[(1)] G. Hagemann,[(1)] F. Ingebretsen,[(4)] H. Jensen,[(1)] D. Jerrestam,[(5)] H. Kusakari,[(1)] R. M. Lieder,[(1)] G. V. Marti,[(6)] S. Mullins,[(3)] D. Santonocito,[(1)] H. Schnare,[(6)] K. Strähle,[(6)] M. Sugawara,[(1)] P. O. Tjøm,[(4)] A. Virtanen,[(1)] and R. Wadsworth[(7)]

[(1)]*The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[(2)]*Laboratori Nazionali di Legnaro, Legnaro, Italy*
[(3)]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[(4)]*Department of Physics, University of Oslo, Oslo, Norway*
[(5)]*The Studsvik Neutron Research Laboratory, Uppsala University, Nyköping, Sweden*
[(6)]*Institut für Kernphysik, Kernforschungsanlage, Jülich, Germany*
[(7)]*Department of Physics, University of York, York, United Kingdom*
(Received 9 July 1992)

Connections between the superdeformed and normal-deformed states in ^{143}Eu have been established by measuring energy sums of two consecutive γ-ray transitions in the linking cascade. Six decay paths have been observed connecting discrete states in the two potential wells. The absolute excitation energy and the most likely spin of a superdeformed band have been determined directly for the first time.

PACS numbers: 23.20.Lv, 21.10.Re, 25.70.Gh, 27.60.+j

Discrete γ-ray transitions between superdeformed (SD) states were first observed [1] in the nucleus ^{152}Dy as a rotational band at very high spin. This band corresponds to a nucleus with a very elongated prolate shape ($\beta_2 \approx 0.6$) rotating about an axis perpendicular to its symmetry axis. Later, many SD bands have been observed in various mass regions (see, e.g., review articles Refs. [2] and [3]). In all cases studied so far the connection between the SD and the normal-deformed (ND) states has been unknown, most probably due to a highly fragmented decay path out of the SD bands. This has left the spin, the parity, and the excitation energy of the SD bands undetermined. In this paper we present results of a new experimental approach where we take advantage of triple and higher fold coincidences to study the decay out of a SD band. The method provides us with an excitation energy and a most likely spin assignment for a SD band for the first time.

It is known from previous work [2,3] that the decay out of a SD band starts from a few of the lowest lying observed states of the band and ends in a few near yrast ND states. We assume that a significant fraction of the decay proceeds through cascades of only two transitions. Because of the high level density there are a large number of intermediate levels in the cascade, but the sum of the two consecutive γ-ray energies has a well-defined value. In the triple coincidence events we set a gate on one γ-ray transition of the SD band and sum up the two other γ-ray energies to produce a sum spectrum. In this spectrum we can identify discrete peaks related to the deexcitation of the SD band.

The experiment was carried out at the Niels Bohr Institute Tandem Accelerator Laboratory using the NORDBALL detector array which consisted of 20 Compton-suppressed Ge detectors, one of which was a LEP detector, and a BaF_2 inner ball for multiplicity and sum energy selection. The states in ^{143}Eu were populated by the reaction ^{110}Pd(^{37}Cl,4n)^{143}Eu at a beam energy of 160 MeV. The target consisted of 2–3 self-supporting foils isotopically enriched to 98.6% in ^{110}Pd with a total thickness of 1.2 mg/cm^2. A total of 10^9 triple (Ge-Ge-Ge) and higher fold coincidence events were collected. In the analysis a narrow energy-dependent time gate was set on the Ge energies and a carefully selected gate was put on BaF_2 fold (≥ 12) and high sum energy. After these cuts a total number of 500×10^6 3 or higher fold and 50×10^6 4 or higher fold events remained and were used in the final analysis.

Figure 1 shows a double gated γ-ray spectrum with both gates on transitions of the SD band. The spectrum is a sum of 42 relatively clean gate combinations and shows the SD band with twenty-two members. Twenty of them were previously reported [4] and assigned to ^{142}Eu. However, our results, which were obtained with the same reaction and beam energy, unambiguously show that the SD band belongs to ^{143}Eu. By double gating and selection of gates which do not overlap with known transitions between ND states, we have obtained a spectrum which shows strongly the known transitions in ^{143}Eu but only weakly ^{142}Eu and other contaminants. In the same NORDBALL experiment, using a Au-backed target, the Q_0 of the SD band was measured [5] to be 13 ± 1 eb which corresponds to a quadrupole deformation of $\beta_2 = 0.52\pm0.05$, assuming a $\beta_4 = 0.05$ from Ref. [6].

The relative intensities of the SD transitions are shown in Fig. 2. The general behavior of this intensity distribution is similar to the results of the other SD nuclei in the $A = 150$ mass region. The intensity gradually increases as the γ-ray energy decreases, flattens out at the maximum, and then drops rapidly as the band decays to the ND states. The flat region corresponds to 1.1% of the total yield of ^{143}Eu. The decay out of the band occurs from

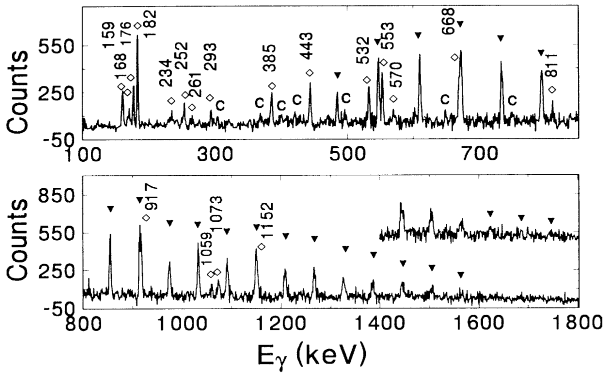

FIG. 1. Gamma-ray spectrum coincident with two SD band members. It is a sum of 42 clean gate combinations. The band members with energies of 483.7, 546.5, 609.3, 671.7, 732.9, 793.9, 854.1, 913.3, 972.9, 1031.8, 1090.7, 1148.6, 1207.6, 1266.0, 1325.0, 1384.3, 1443.8, 1503.1, 1563.5, 1623, 1684, and 1743 keV (errors ranging from 0.2 keV for the strongest transitions up to 2 keV for the weakest peaks) are marked by ▼ and known ND states in ^{143}Eu are denoted by ◇. Contaminations from ^{140}Pm, ^{142}Eu, and ^{144}Eu are indicated by "C." The spectrum is shown background subtracted and corrected for the detector efficiencies. The inset is a sum of all double gated spectra with both gates on the SD band members. The highest energy transitions are also shown enhanced.

the three lowest lying levels with 29%, 34%, and 36% of the full intensity emitted from the first, second, and third lowest members of the band, respectively.

To establish the connection between the SD band and the ND structure we have to know the ^{143}Eu yrast level scheme in the region where the SD band feeds in. The level scheme, previously known [7] up to spin $\frac{35}{2}$ has been extended [8] up to $I=\frac{75}{2}$ at 15.6 MeV excitation energy, using the same NORDBALL data. A partial level scheme is shown in Fig. 3. In the γ-ray spectrum of Fig. 1 all strong ^{143}Eu transitions up to the $I=\frac{35}{2}$ level at 4949 keV are seen in coincidence with the band. The 168 and 261 keV transitions higher up in the level scheme are also observed weakly, indicating that at least part of the decay from the SD band feeds into the higher-lying levels. The level scheme is particularly complex in this region and it is obvious that the decay out of the SD band is strongly fragmented and that no single level receives a major fraction of the decay intensity.

The sum spectrum of two γ-ray energies which are in coincidence with one of the SD transitions is shown in Fig. 4. In the energy region between 1.8 MeV to about 3.0 MeV, all the prominent peaks are identified as being the sum of two transitions in the SD band. The intensities of these peaks are strongly enhanced since many sums fall at the same energy due to a very constant moment of inertia $\mathcal{J}^{(2)}$ in the band (see the inset). Above 3.0 MeV, six peaks may be considered as being the sum of two linking transitions between the SD band and the ND states. The analysis is made by comparing the energy differences between pairs of such peaks to the level energy differences in the region where the SD band feeds the yrast structure. The final identification is made on the basis of the three well-defined peaks (3187, 3211, and 3634 keV) which are above the 2σ intensity limit, and have the expected width of 9–12 keV. The three weaker peaks at 3274, 3476, and 3925 keV complement the decay routes and give further support to the identification.

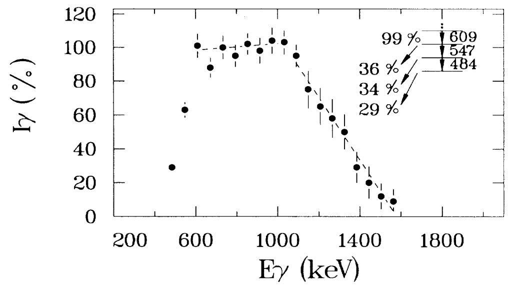

FIG. 2. Relative intensities of the SD transitions, normalized to an average of the highest points. The inset shows the intensity flow out of the SD band obtained from the intensities of the lowest three transitions.

In the partial level scheme displayed in Fig. 3 the SD band is shown together with the ND states. Cascades of two transitions with energies adding up to the sum peaks of Fig. 4 are marked in the figure. The energy difference between the 3925 and 3634 keV sum peaks is 291 ± 6 keV and is within the experimental uncertainty the same as 293.3 ± 0.2 keV which is the energy difference between the $I=\frac{33}{2}$ level at 4656 keV and the $I=\frac{35}{2}$ level at 4949 keV in the ND regime. This provides us with the energy of the initial SD state which is determined to be 8582 ± 4 keV. Similarly, the energy differences between the 3187, 3211, and 3476 keV sum peaks agree with a decay into the ND levels at $I=\frac{35}{2}$ ($E_x=5872$ keV), $I=\frac{39}{2}$ ($E_x=5851$ keV), and $I=\frac{37}{2}$ ($E_x=5590$ keV), respectively. The energy of the initial SD state determined from these three decay routes is 9062 ± 4 keV. Within the experimental uncertainty this agrees with the energy of the second lowest SD state at 9066 ± 4 keV which is the energy sum of the first SD state (8582 keV) and the first observed transition in the SD band (484 keV). The sum peak at 3274 keV can be a link between the 9066 keV SD state to the $I=\frac{35}{2}$, $E_x=5795$ keV ND state or from the 9613 keV SD state to the $I=\frac{39}{2}$, $E_x=6336$ keV ND state. Both cases are indicated as dashed lines in Fig. 3. Generally, there seems to be a tendency for the decay routes from the SD band to select the ND levels closest to the yrast line in agreement with statistical considerations [9]. The encircled numbers in Fig. 3 show the intensity flow into the ND states relative to the full intensity in the SD band. They are obtained from the double dated spectrum (Fig. 1).

Two consecutive γ rays which link the SD band to the ND states are most likely [10] stretched or nonstretched

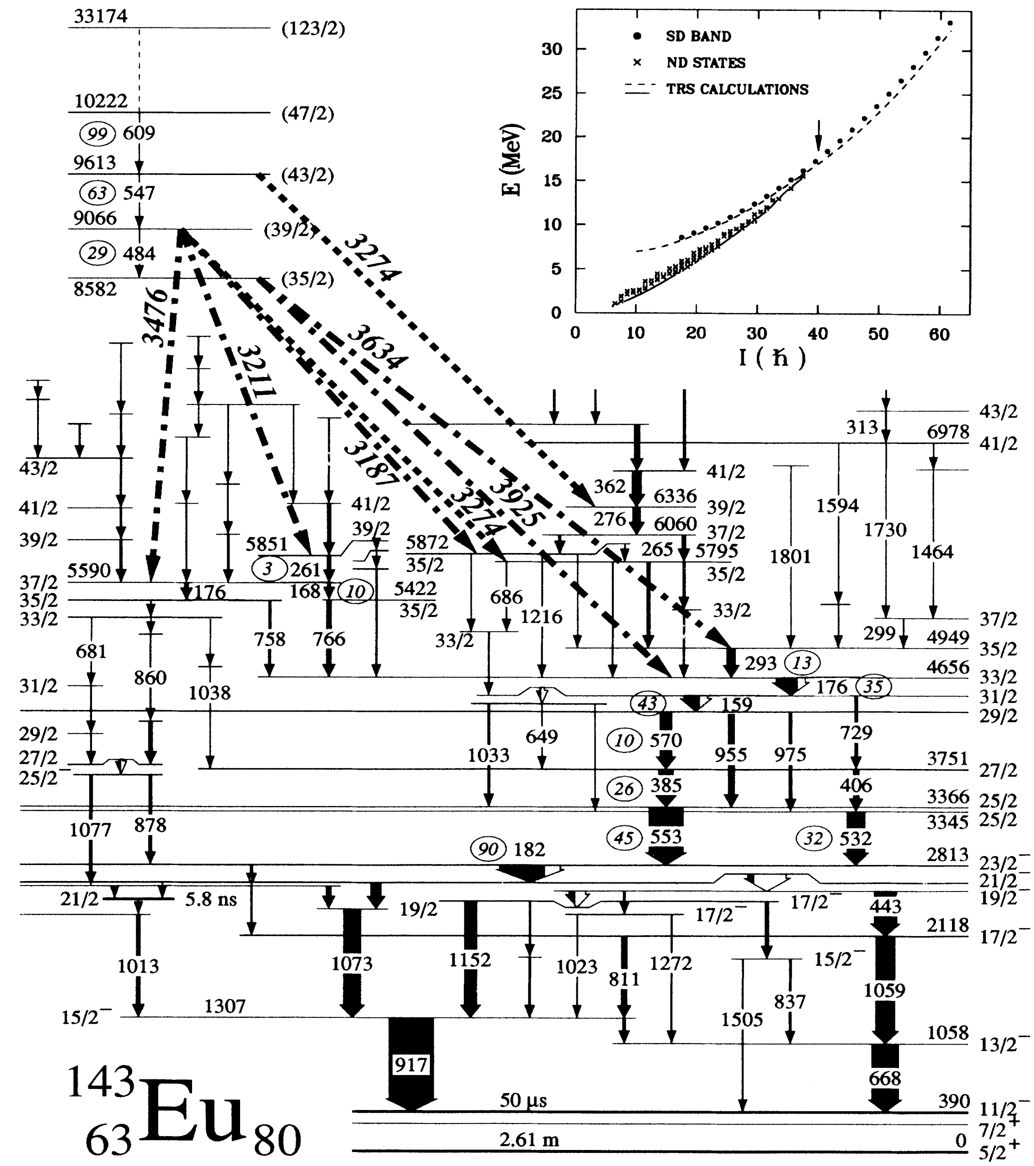

FIG. 3. Partial level scheme of ^{143}Eu. The sum peaks of Fig. 4 which connect the SD band with the ND states are indicated by thick dash-dotted and dashed lines in the figure. The encircled numbers show the intensities of the transitions relative to the full intensity of the SD band. The uncertainties in the intensities range from 20% for the stronger to 50% for the weaker transitions. An excitation energy vs spin diagram is shown in the inset, displaying the known yrast and near-yrast ND levels together with the SD band. The result of a TRS calculation is also indicated.

$E1$ transitions taking away 0 or 1 unit of angular momentum each. With this in mind, the spins of the two lowest states in the SD band are assigned as $\frac{35}{2}$ and $\frac{39}{2}$ so that the decay routes with two γ rays take away 0, 1, or 2 units of spin. Thus, the observed decay routes will not change the parity between the SD and the ND states.

A possibility of assigning the spins of the two lowest states as $\frac{37}{2}$ and $\frac{41}{2}$ cannot be excluded since the decay out of the SD band could proceed by an $E1$ transition followed by an $E2$ transition. Indeed, the level scheme shows examples of high-energy (1.5 to 1.8 MeV) $E2$ transitions in the region of interest. Such a decay route may take away up to 3 units of angular momentum and it allows the SD band to decay into a ND state with opposite parity.

The total intensity in the marked peaks of the sum spectrum in Fig. 4 is estimated to be more than 30% relative to the full intensity in the SD band. Considering also

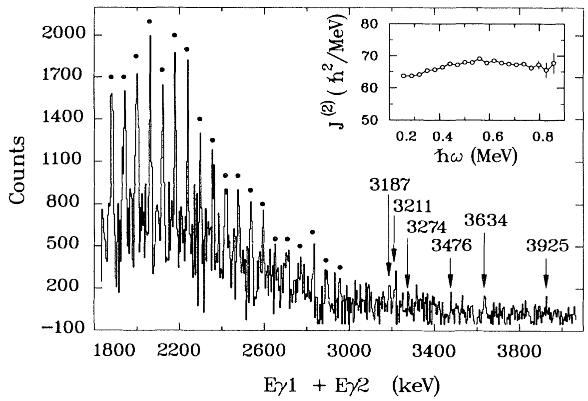

FIG. 4. The energy sum of two γ-ray transitions which are in coincidence with one of the SD band members, shown with a resolution of 4 keV/channel. It is obtained by adding 15 clean gates and is background subtracted. The sums of two transitions which are in the SD band are shown by ●'s. The peaks which are identified as sums of two linking transitions are marked by arrows. The energy uncertainty is 4 to 5 keV. The inset shows the dynamical moment of inertia, $\mathcal{J}^{(2)}$, as a function of rotational frequency.

the fact that the weak sum peak at 3274 keV in Fig. 4 does not explain the intensity (36%) which is lost from the 9613 keV state, we conclude that there must be other decay routes which are not identified in this analysis. The missing routes are most likely the ones which have three consecutive γ rays before they reach the known ND yrast states. They cannot be seen in our sum spectrum.

The energy and spin assignment allows us to plot the SD band in an energy versus spin diagram together with the known ND states, as shown in the inset of Fig. 3. The SD band is 3634 keV higher than the yrast line at $I=\frac{35}{2}\hbar$ and it extends to $I=\frac{123}{2}\hbar$ at an excitation energy of 33 174 keV. The SD band crosses the yrast line at about a spin of $40\hbar$. These properties are compared to the results of a total Routhian surface (TRS) calculation [6] performed using a Woods-Saxon potential and including pairing. The theory predicts a SD ($\beta_2=0.5$) yrast band with a configuration $\pi 6^1 \nu 6^4$ and $(\pi,\alpha)=(+,+\frac{1}{2})$. The calculated energies are shown as a dashed line in the inset of Fig. 3. Similarly other configurations with smaller deformations have been calculated and a convolution of the ND states is shown as a solid line. The intersection of the two calculated curves is near spin $40\hbar$ which corresponds to the experimentally observed value. The crossing between the SD yrast and the ND yrast lines may be reflected in the sidefeeding to the SD band, usually taken as the spin where the band has reached 50% of its intensity [1]. The value extracted from Fig. 2 gives a spin of $46\hbar$ which is 6 units higher than the experimental and calculated values of $40\hbar$. It should be mentioned here that the signature $\alpha=+\frac{1}{2}$ predicted by the TRS calculation for the SD band favors the spin assignment of $\frac{37}{2}$ for the lowest SD state.

In conclusion, we have observed a superdeformed band of 22 transitions in ^{143}Eu and identified cascades of two consecutive transitions from the lowest SD states to the ND states. From the measured cascade energies and a detailed knowledge of the ND level spectrum, the excitation energy of the initial SD state has been determined to be 8582 ± 4 keV and the most likely spin $\frac{35}{2}\hbar$ with $\frac{37}{2}\hbar$ as an alternative possibility. The yrast line convoluting the ND states crosses the SD yrast line at $I=40\hbar$ in full agreement with theoretical predictions.

Stimulating discussions with T. Døssing, W. Nazarewicz, I. Ragnarsson, R. Wyss, and S. Åberg are acknowledged. This work was partially supported by the Swedish Natural Science Research Council, the Academy of Finland, and the Danish Natural Science Foundation.

(a)Permanent address: Department of Physics, University of Jyväskylä, Jyväskylä, Finland.

(b)Permanent address: The Svedberg Laboratory, Uppsala University, Uppsala, Sweden.

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