Superdeformation and Double Blocking in ^{142}Eu

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A superdeformed band of twenty transitions has been found in ^{142}Eu following the reaction ^{110}Pd(^{37}Cl,5n)^{142}Eu at 160 MeV. This is the first case to be found intermediate to the $A\sim135$ and $A\sim150$ regions. The $\mathcal{J}^{(2)}$ dynamic moment of inertia remains remarkably constant, suggesting that the configuration is $\pi6^1\nu6^3$, blocking both proton and neutron band crossings. The band has been estimated to have $\sim3.6\%$ of the channel intensity. This is remarkably intense, and is possibly due to a lowering of the odd-odd configuration by a strong residual n-p correlation.

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Collective rotational motion in atomic nuclei implies the presence of a significant deformation of the nuclear shape. The most spectacular collective rotors are "superdeformed" (SD) nuclei, where long cascades of rotational γ-ray transitions are observed, extending to very high angular momenta. The study of SD bands began with the discovery of a cascade in ^{132}Ce,[1] followed soon after by a band in ^{152}Dy.[2] These two initial cases were later joined by many other examples, and two regions became recognizable—the $A\sim135$ region corresponding to prolate shapes with a major:minor axis ratio of $\sim3{:}2$ (or quadrupole deformation of $\beta_2\sim0.4$) and the heavier more deformed $\sim2{:}1$ ($\beta_2\sim0.6$) $A\sim150$ region. A third region of superdeformation ($\beta_2\sim0.5$) around $A\sim190$ has also been established following the discovery of a band in ^{191}Hg ($Z=80$).[3] Many more bands have been found in other Hg isotopes, and also in neighboring Pb and Tl nuclei.

Existing nuclear mean-field models were able to correctly predict shell gaps, which stabilize the deformed shape, for particle numbers corresponding to these regions (see, for example, Ref. 4). The occupancy of a number of high-N intruder orbitals provides the drive to enhanced deformation (N is the major oscillator quantum number), with each high-N orbital contributing uniquely to the nuclear dynamic moment of inertia $\mathcal{J}^{(2)}$.[5] This provides a convenient labeling scheme for the SD bands. The $A\sim135$ bands are driven by one or two neutrons in the lowest $N=6$ orbitals (conventionally written as $\nu6^m$), while in the more deformed $A\sim150$ and 190 bands, both protons and neutrons occupy high-N intruder orbitals, and are labeled as $\pi6^n\nu7^m$.

The calculations also predict that nuclei with neutron number $N=80$ will be good candidates for possessing similar bands with deformations between 3:2 and 2:1 ($\beta_2\sim0.5$). Extensive searches have been made, notably in ^{144}Gd,[6,7] but without success. The occurrence of so many bands in the proximity of $Z=80$ as mentioned above made the lack of discovering a band near $N=80$ even more puzzling. Recent calculations[8] seem to offer an explanation in terms of the strength with which one might expect to populate these bands, as suggested by the depth and relative excitation energy of the SD well. These calculations indicated the favorability of the SD well for Eu isotopes near $N=80$, and therefore an experiment was undertaken to study these nuclei.

In this Letter we report on the discovery of a superdeformed band in ^{142}Eu. The band is the first example intermediate to the $A\sim135$ and $A\sim150$ regions. It has two striking features. The first of these is the remark-

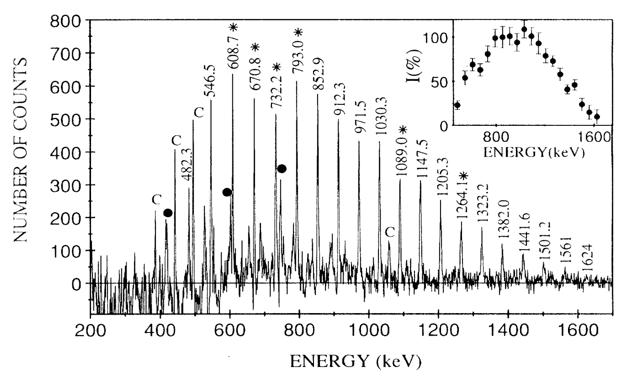

FIG. 1. Sum of coincidence spectra showing the superdeformed band in ^{142}Eu. The band members have been labeled according to energy in keV, the errors ranging from 0.2 for the strongest transitions up to 1 keV for the weakest peaks. Those contributing to the spectrum have been marked with a ∗. Peaks belonging to ^{142}Eu have been marked with a ●, while some of the larger contaminant peaks (introduced mainly by the 671- and 793-keV gates) have been marked with a C. Inset: The relative intensities of the SD transitions, normalized to the 853-keV γ ray.

ably constant energy spacing ($\sim$60 keV) between adjacent transitions. This corresponds to a nuclear dynamic moment of inertia ($\mathcal{J}^{(2)}$) of $\sim 68\hbar^2$ MeV^{-1}, and this remains very constant with rotational frequency, more so than for any other SD band. The second is the strength with which the band is populated ($\sim$3.6% of the total going into ^{142}Eu).

The experiment was carried out using the TESSA3 spectrometer[9] at the Daresbury Nuclear Structure Facility (NSF). States in ^{142}Eu were populated via the reaction ^{110}Pd(^{37}Cl,$5n$)^{142}Eu at a beam energy of 160 MeV. A band of twenty γ rays with a very constant energy spacing of $\sim$60 keV was observed. This is shown in Fig. 1. Coincidence relationships with known transitions in ^{142}Eu,[10] and the fold/sum-energy information from the TESSA3 BGO ball, have allowed us to assign the band to ^{142}Eu. No linking transitions have been established. Many of the SD γ rays lie under large peaks in ^{143}Eu,[11] since this was the major channel.

The $\mathcal{J}^{(2)}$ dynamic moment of inertia has been extracted from the differences in adjacent γ-ray energies, and is shown in Fig. 2. An outstanding feature is how remarkably constant the $\mathcal{J}^{(2)}$ remains with rotational frequency. Shown for comparison are theoretical $\mathcal{J}^{(2)}$ moments of inertia for ^{143}Eu and ^{144}Gd taken from Ref. 12, and also for ^{142}Eu calculated in the same manner using a Woods-Saxon potential. The renormalization of the potential radius r_0, which reduces the calculated $\mathcal{J}^{(2)}$ in order to reproduce the magnitude of the experimental $\mathcal{J}^{(2)}$ for ^{152}Dy (Ref. 12) (and also the other $A\sim150$ cases), has been employed. The deformation has been kept constant, since our calculations indicate that β_2 shows a negligible variation with rotational frequency. Pairing has been treated self-consistently using particle-number-projected wave functions. Clearly, the rapid increase predicted to occur at $\omega\sim0.4$ MeV/$\hbar$ for ^{144}Gd is absent. In this case the high-N configuration is $\pi6^2\nu6^4$, and the rapid change is caused by a paired band crossing involving the two $N=6$ protons. The removal of one these protons blocks this crossing. The calculated $\mathcal{J}^{(2)}$ for ^{143}Eu shows a much smoother variation, and in this case the high-N configuration is $\pi6^1\nu6^4$. The variation is caused by a paired crossing involving the $N=6$ neutrons, and again the removal of one particle will block the crossing. The constancy of the experimental $\mathcal{J}^{(2)}$ indicated that both of these band crossings are blocked, and that the configuration for ^{142}Eu is $\pi6^1\nu6^3$. [Cf. $\pi6^3\nu7^1$ for the SD band in ^{150}Tb (Ref. 13) which is also an odd-odd nucleus.] The corresponding calculation for ^{142}Eu shows some variation due to a decrease in pairing caused by the Coriolis antipairing (CAP) effect.[14] The reduction in pairing due to CAP leads to an increase in $\mathcal{J}^{(2)}$, as observed in the $A\sim190$ SD bands,[15] and probably explains the slight increase in the experimental $\mathcal{J}^{(2)}$ over the frequency range $\omega\sim0.26$–0.38 MeV/$\hbar$. The calculations also underestimate the magnitude of the $\mathcal{J}^{(2)}$ by up to approximately ten units.

If the renormalization is removed, the magnitude of the experimental $\mathcal{J}^{(2)}$ is reproduced rather better as shown in Fig. 3. Hence, unlike the $A\sim150$ region, no reduction in the calculated $\mathcal{J}^{(2)}$ is required. A much improved agreement with experiment is obtained when the static self-consistent pair gaps for both protons and neutrons are reduced by $\sim$25% and kept constant with rotational frequency. The proton pairing has been reduced to 0.697 MeV and the neutron pairing to 0.633 MeV.

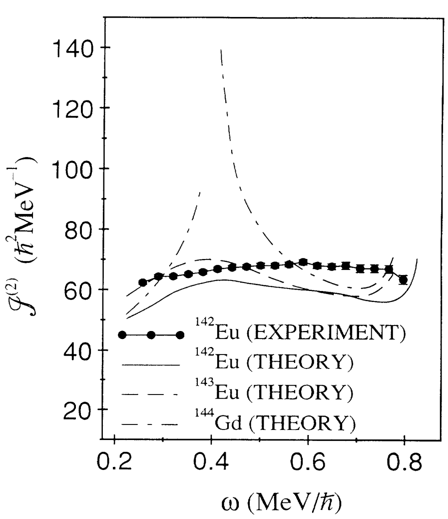

FIG. 2. Experimental $\mathcal{J}^{(2)}$ for ^{142}Eu extracted from the differences in transition energies, compared with theoretical predictions for ^{142}Eu, ^{143}Eu, and ^{144}Gd calculated as described in the text.

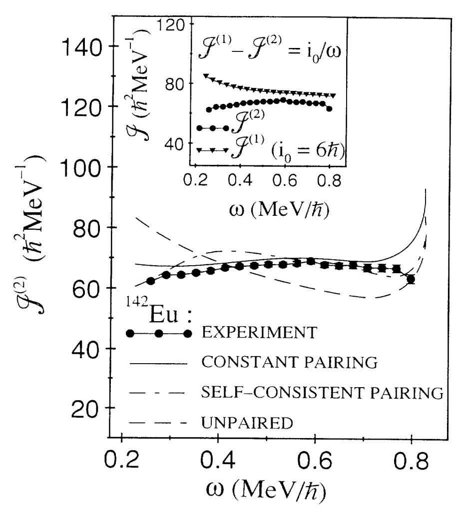

FIG. 3. Comparison of the experimental $\mathcal{J}^{(2)}$ for ^{142}Eu with calculations performed using constant pairing, self-consistent pairing, and zero pairing (unpaired). Inset: The experimental $\mathcal{J}^{(2)}$ is compared with a calculated $\mathcal{J}^{(1)}$ moment of inertia corresponding to spin assignments of $19\hbar \rightarrow 59\hbar$.

This removes the variation due to the decrease in pairing, and reproduces the behavior of the experimental $\mathcal{J}^{(2)}$ quite well as shown in Fig. 3. An unpaired calculation is also shown in Fig. 3, but this shows very poor agreement with the data. Any further reduction in the pairing gives results similar to the unpaired calculation. It is perhaps important to make the comment that if similar constant pairing is used for ^{143}Eu and ^{144}Gd, the crossings responsible for the variations in $\mathcal{J}^{(2)}$ still occur.

The intensity pattern versus γ-ray energy is shown in the inset of Fig. 1. The maximum intensity of the band is estimated to be $(3.6\pm0.4)\%$ relative to the total population of ^{142}Eu. This is remarkably strong when compared with the typical $\sim 1\%-2\%$ intensity of the $A\sim150$ SD bands. A possible explanation for this comes from estimating the spins I of the band members. The "normal" states into which the SD band decays have $I\leq(10-11)\hbar$, suggesting that a reasonable estimate for the spin of the lowest observed SD level is $I=13\hbar$. If the method discussed in Refs. 16 and 17 is used, then $I-i_0\sim13\hbar$ results, where i_0 is the "apparent alignment." This suggests that $i_0\sim0$, but the two unpaired $N=6$ particles are calculated to give a "true" alignment i of $\sim6\hbar$ for the pairing strengths which give the best reproduction of the $\mathcal{J}^{(2)}$. Now i_0 and i are related by

$$i_0=i+\omega[\mathcal{J}^{(2)}(\text{ground})-\mathcal{J}^{(2)}(\text{aligned})]$$

which shows that they are equal if $\omega=0$, or if the ground and aligned configurations have identical $\mathcal{J}^{(2)}$'s. Assuming that we are observing the ground SD configuration at low spins, then the constancy of the $\mathcal{J}^{(2)}$ indicates that there are no rotationally induced alignments, that is, no change in configuration from a band crossing. Hence it has been assumed that $i_0=i$ for all frequencies. Spin values of $19\hbar\rightarrow59\hbar$ result, which can probably be taken as an upper limit. A lower limit $(i_0\sim0)$ can be taken as $13\hbar\rightarrow53\hbar$. The $\mathcal{J}^{(1)}$ kinematic moment of inertia corresponding to the upper limiting spins is shown in the inset of Fig. 3. It follows that the band is fed to $\sim50\%$ of the maximum intensity at no more than $\sim45\hbar$. This point is conventionally taken as an indication of where the SD yrast line crosses the normal yrast line,[2] and is $\sim(5-7)\hbar$ lower than in the $A\sim150$ SD region. The relatively low crossing point may result in a longer feeding region, and hence lead to greater maximum intensity. This is thought to be the case in the $A\sim135$ region where relative intensities of $\sim5\%-20\%$ are found.

A second experiment has been performed to search for an SD band in ^{143}Eu using the reaction ^{27}Al+^{122}Sn at 138 MeV. This reaction was chosen to populate ^{143}Eu at an excitation energy similar to that of ^{142}Eu from the ^{37}Cl-induced reaction. A band has not been found in this data set, implying that if it exists, the relative intensity is probably below $\sim0.4\%$ of the ^{143}Eu channel. Alternatively, the crossing point in ^{143}Eu may be rather higher and hence was "missed" in this reaction.

The favorability of the band observed in ^{142}Eu is possibly due to the doubly odd $\pi6^1\nu6^3$ configuration being depressed in energy by a strong residual correlation between the odd proton and the odd neutron. This type of residual interaction is discussed in Refs. 18–20, and is particularly strong when the occupied orbitals have similar N (or j) and K quantum numbers. It has been shown that for light nuclei residual n-p correlations tend to increase the moment of inertia.[21] This may explain why the $\mathcal{J}^{(2)}$ is rather larger than expected. Clearly, it would be of interest to attempt a calculation in which the residual n-p interaction is included in a proper way.

The decay out of the band occurs over five transitions, unlike the rapid depopulation over one or two states seen in the $A\sim190$, $A\sim135$, and $A\sim150$ regions. In the latter two cases, the decay out of the SD bands into the normal states has been explained by a transition to a regime of increased pairing, conventionally due to a band crossing. The blocking of both proton and neutron crossings in ^{142}Eu seems a likely explanation for the protracted decay out of the band, despite being presumably far above the yrast line over the range of rotational frequencies where the feeding out occurs. The band persists down to $\omega\sim0.24$ MeV/$\hbar$. Only ^{133}Nd (Ref. 22) continues lower (~0.21 MeV/$\hbar$) in either the $A\sim135$ or 150 region.

In summary, an intense superdeformed band of twenty transitions has been discovered in ^{142}Eu. This is the first example intermediate to the $A\sim135$ and $A\sim150$ regions. The energy spacing and hence the $\mathcal{J}^{(2)}$ moment of inertia remain remarkably constant. Comparison with theory suggests that the high-N configuration is $\pi6^1\nu6^3$, and that the flatness of the $\mathcal{J}^{(2)}$ is due to the blocking of band crossings in the presence of constant pairing. The configuration gives the band positive parity and odd spins. The large intensity of the band may result from a lowering of the SD states due to a strong residual correlation between the unpaired $N=6$ nucleons.

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