RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 42, NUMBER 5 NOVEMBER 1990

Observation of excited proton and neutron configurations in the superdeformed ^{149}Gd nucleus

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(Received 18 April 1990)

Two excited superdeformed bands in ^{149}Gd have been observed in γ-ray spectroscopy. Based on the behavior of the dynamical moments of inertia we assign one band to a neutron excitation and the other to a proton excitation. The proton excited band γ-ray energies are nearly identical to those already known in ^{150}Tb. In addition, two new members of the ^{149}Gd yrast cascade have been observed extending the band to spin $\frac{135}{2}\hbar$. The results are discussed in terms of high-N intruder orbitals in the cranked shell model.

The discovery of multiple superdeformed bands within one nucleus[1] has opened up the possibility of learning in greater detail the nuclear structure of these very interesting configurations. New impetus in this direction has also been generated by the observation of so-called "twinned" superdeformed bands in $N=86$ nuclei.[2] In the pairs (^{151}Tb, ^{150}Gd*) and (^{152}Dy, ^{151}Tb*), where one asterisk denotes the first excited superdeformed band, the same sequence of γ-ray energies is found to within 1–2 keV over a span of fifteen or more transitions. This is a remarkable and unexpected phenomenon in nuclear structure physics.

In the present work, we have been motivated to search for multiple bands in neighboring nuclei, and have reinvestigated the spectroscopy of ^{149}Gd at a bombarding energy more favorable for populating the known, yrast superdeformed band and with improved statistics over our

TABLE I. Transition energies and relative intensities of superdeformed bands observed in this experiment. Note that these values were derived from coincidence spectra gated by only clean gates.

^{149}Gd		^{149}Gd*		^{149}Gd**		^{150}Tb	
E_γ (kev)	I_γ	E_γ (kev)	I_γ	E_γ (kev)	I_γ	E_γ (kev)	I_γ
						598.0(3)	20(3)
617.4(3)	16(3)					647.8(3)	38(4)
664.4(2)	68(7)					697.6(2)	100(10)
711.7(3)	· · ·					748.2(2)	98(10)
759.9(2)	88(9)					799.3(2)	100
808.0(2)	96(10)	877.0(3)	20(3)			850.6(2)	100(10)
857.0(2)	100	900.6(3)	22(3)	895.9(4)	8(2)	902.1(2)	104(10)
906.5(2)	105(10)	941.0(5)	· · ·	952.0(6)	· · ·	954.8(2)	99(10)
957.3(2)	98(10)	986.7(3)	· · ·	1004.4(4)	8(2)	1006.3(3)	98(10)
1008.8(3)	95(10)	1032.8(3)	43(6)	1056.4(4)	8(2)	1059.2(3)	89(9)
1060.7(3)	90(9)	1081.1(5)	· · ·	1108.6(4)	10(2)	1111.6(3)	88(9)
1113.7(3)	83(8)	1131.1(4)	50(7)	1162.0(4)	12(2)	1165.3(3)	87(9)
1166.8(3)	· · ·	1181.0(4)	51(7)	1215.3(4)	12(2)	1218.1(3)	88(9)
1221.5(3)	80(8)	1232.7(4)	29(5)	1268.5(4)	12(2)	1271.5(3)	68(7)
1276.2(3)	72(7)	1285.7(4)	33(5)	1322.5(4)	15(3)	1325.0(4)	35(5)
1331.9(3)	60(6)	1340.6(4)	28(5)	1376.8(5)	14(3)	1379.3(4)	32(4)
1387.8(4)	51(5)	1395.1(4)	26(5)	1431.2(5)	7(2)	1433.2(4)	20(4)
1444.3(4)	38(5)	1450.7(5)	21(4)	1484.9(5)	7(2)	1486.6(5)	· · ·
1500.5(4)	28(4)	1506.3(5)	13(3)				
1557.8(4)	19(3)						
1613.2(5)	10(2)						
1672.9(5)	6(2)						

earlier work.[3] We have also restudied the nucleus ^{150}Tb and have found some discrepancies with γ-ray energies previously published.[4] Although small, these discrepancies are significant in the context of the twinned band phenomenon. We find two excited superdeformed bands in ^{149}Gd. The first, ^{149}Gd*, has a dynamical moment of inertia very similar to that of ^{150}Gd (Ref. 5) although it is not a twin. We interpret it as a neutron (particle-hole) excitation from the core of ^{149}Gd so that the intruder configuration is identical to that found in ^{150}Gd. The second excited band, ^{149}Gd**, has γ-ray transitions essentially identical to those of ^{150}Tb (using the present energies) and it can be considered a twin. We interpret it as a proton excitation to the intruder ($i13/2$) configuration of ^{150}Tb. Thus, for the first time, both proton and neutron excited superdeformed configurations have been found in the same nucleus. At this time we have found no excited bands in ^{150}Tb.

The experiments were performed at the TASCC facility in Chalk River. The reactions populating superdeformed states were ^{124}Sn(^{30}Si,5*n*)^{149}Gd at 155 MeV incident energy, and ^{124}Sn(^{31}P,5*n*)^{150}Tb at 156 MeV incident energy. The target was a stack of two tin foils ($\sim$400 μg cm^{-2} separated by about 1 mm). γ-ray spectroscopy was performed with the 8π spectrometer, an array of 20 Compton-suppressed HPGe detectors and a bismuth germanate (BGO) ball of 72 detectors. Data were acquired with a trigger made up of a twofold coincidence in the suppressed array and a K equals tenfold or greater coincidence in the BGO array. Approximately 5×10^8 events were recorded in each experiment. The data were replayed into 4096×4096 matrices for the coincident γ-ray pairs $E_\gamma \cdot E_\gamma$ registered in the suppressed array. On replay, we selected events with $K \geq 21$, which resulted in the best peak-to-background ratio for the superdeformed bands. These matrices were symmetrized and could be sliced to generate gated spectra. We also performed the background subtraction procedure described in Ref. 6, which put the matrices in a more convenient form for searching for new superdeformed bands.

With the exception of ^{149}Gd**, the bands observed could be reliably assigned to either ^{149}Gd or ^{150}Tb on the basis of known transitions in these nuclei which appeared in coincidence with gates set on the superdeformed bands. The case of ^{149}Gd** was more difficult because its intensity was so weak, and this assignment depends mainly on the elimination of other possibilities. After ^{149}Gd, the strongest channels observed in the ^{30}Si+^{124}Sn reaction were ^{150}Gd(4*n*) and ^{148}Gd(6*n*). Since yrast superdeformed bands are known in these nuclei,[5,7] we can eliminate them as possible assignments for the band designated ^{149}Gd**. The remaining identified channels were ^{149}Eu(p,4n) and ^{146}Sm(α,4n) with intensities in the range 5%–8% of the ^{149}Gd channel in the $K \geq 21$ $E_\gamma - E_\gamma$ coincidence matrix. A superdeformed band with the intensity of that observed for ^{149}Gd** would represent a population of 4%–6% in these channels, which would be 2–3 times stronger than any such band observed in the mass 150 region and is a very implausible assignment.

Energies and intensities are given in Table I for γ rays associated with the three superdeformed bands assigned to ^{149}Gd and those we obtained for the known band in ^{150}Tb. Examples of spectra are shown in Fig. 1. For each band we present a spectrum obtained by summing spectra selected with the cleanest gating transitions. For the ^{149}Gd** band we chose to sum gates set on γ_{1215}, γ_{1269}, γ_{1323}, and γ_{1377} keV and the background spectrum subtracted was a slice of the matrix selected in the energy range near 1200 keV. In the other cases, Fig. 1 shows results from the background-subtracted matrices. The best energies and intensities as given in Table I were derived from slices of the unsubtracted matrices.

The yrast superdeformed band in ^{149}Gd has a strength of approximately 2.5% of the total ^{149}Gd channel as seen in the $E_\gamma \cdot E_\gamma$ matrix gated with fold $K \geq 21$. The excited bands have 40(5)% and 13(2)% of the superdeformed yrast intensity. The first excited band was also seen, but not previously reported, in our earlier experiment at 150 MeV bombarding energy[3] where its strength was 36(5)% of the yrast superdeformed band. Thus, the relative feeding strength of this band does not appear to be a sharp

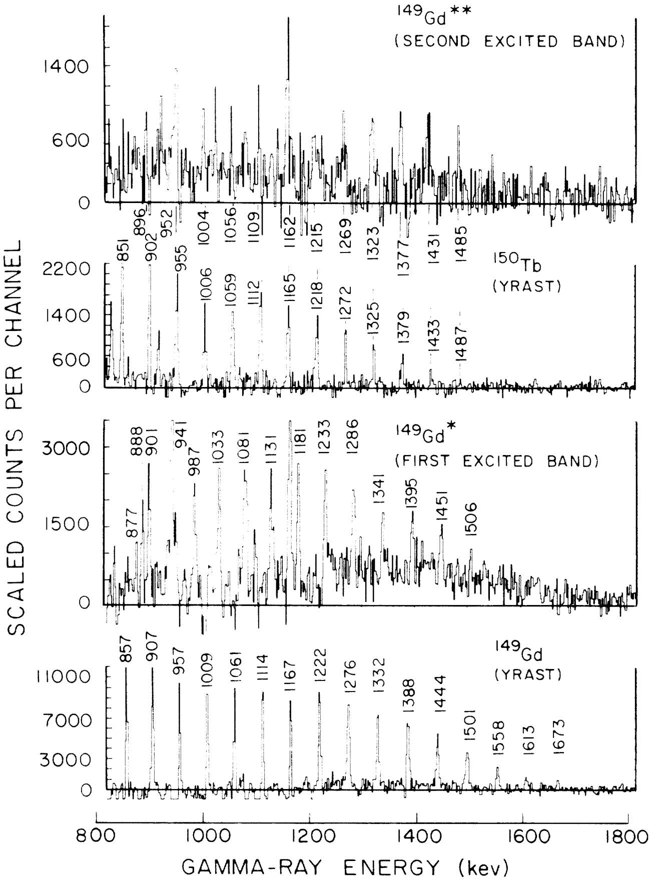

FIG. 1. Sample spectra of superdeformed bands observed in this work. γ-ray transition energies are shown in keV rounded to the nearest integer. The lower three panels are taken from the background-subtracted efficiency-corrected coincidence matrix. The upper panel is also efficiency corrected but was derived from the raw coincidence matrix by summing gates in γ_{1269}, γ_{1323}, γ_{1377}, and γ_{1431} keV with an appropriate background subtracted.

function of bombarding energy.

Bengtsson, Ragnarsson, and Åberg,[8] and more recently, Nazarewicz, Wyss, and Johnson[9] have shown that the behavior of dynamical moments of inertia $J^{(2)}$ in superdeformed bands is a strong indicator of their nuclear structure, particularly with regard to the number of particles in intruder orbitals. The steep fall of $J^{(2)}$ with rotational frequency observed for ^{149}Gd* is characteristic of ^{150}Gd (cf. Fig. 2) where it is understood to be a consequence of the intruder configuration $(\pi i_{13/2})^2(\nu j_{15/2})^2$. There is a general argument, first given by Bengtsson *et al.*,[8] that either 2 or 3 particles in a particular ν or π intruder shell tend to produce down-sloping $J^{(2)}$, whereas 1 or 4 particles tend to produce flat behavior. Thus, ^{149}Gd with the configuration $(\pi i_{13/2})^2(\nu j_{15/2})^1$ has a down-sloping but flatter $J^{(2)}$ behavior than ^{150}Gd. We propose that ^{149}Gd* has the same intruder configuration $(\pi i_{13/2})^2(\nu j_{15/2})^2$ as ^{150}Gd with a neutron hole in some lower orbital. In the case of ^{149}Gd**, the assignment can be made directly since the band is a twin to the superdeformed band in ^{150}Tb, and therefore has the configuration $(\pi i_{13/2})^3(\nu j_{15/2})^1$ with a proton hole in some lower orbital. This case is almost certainly parallel to those observed by Bryski *et al.*[2] so the proton hole is $[301]_{1/2}$. This orbital is predicted[8] to lie just below the intruder orbitals at deformation $\beta = 0.6$ over a wide range of rotational frequency and further has the special property that its decoupling parameter is at or very near unity, a necessary condition for twinned bands.[10] With this assignment, the band has positive parity and signature $\alpha = +\frac{1}{2}$. The occurrence of a proton excitation of sufficiently low energy to be observable suggests that the $Z = 64$ gap calculated with standard parameters in the Nilsson model[11] is too large.

The neutron orbital closest to the intruders in the ^{149}Gd core is the 6_4 orbital[8] or Nilsson $[642]_{5/2}$, and we suppose that ^{149}Gd* has the configuration $(\pi i_{13/2})^2(\nu i_{13/2})^{-1}(\nu j_{15/2})^2$, which is of positive parity and signature $\alpha = +\frac{1}{2}$. A problem with this interpretation is that the signature partners of the 6_4 orbital are nearly degenerate in the calculations, and it is difficult to see how a signature partner to ^{149}Gd* could have escaped detection in this experiment unless it was populated about three times more weakly. This has been a long-standing problem since the same 6_4 orbital should be involved in the yrast superdeformed band of ^{148}Gd where also only one signature has been observed.[7]

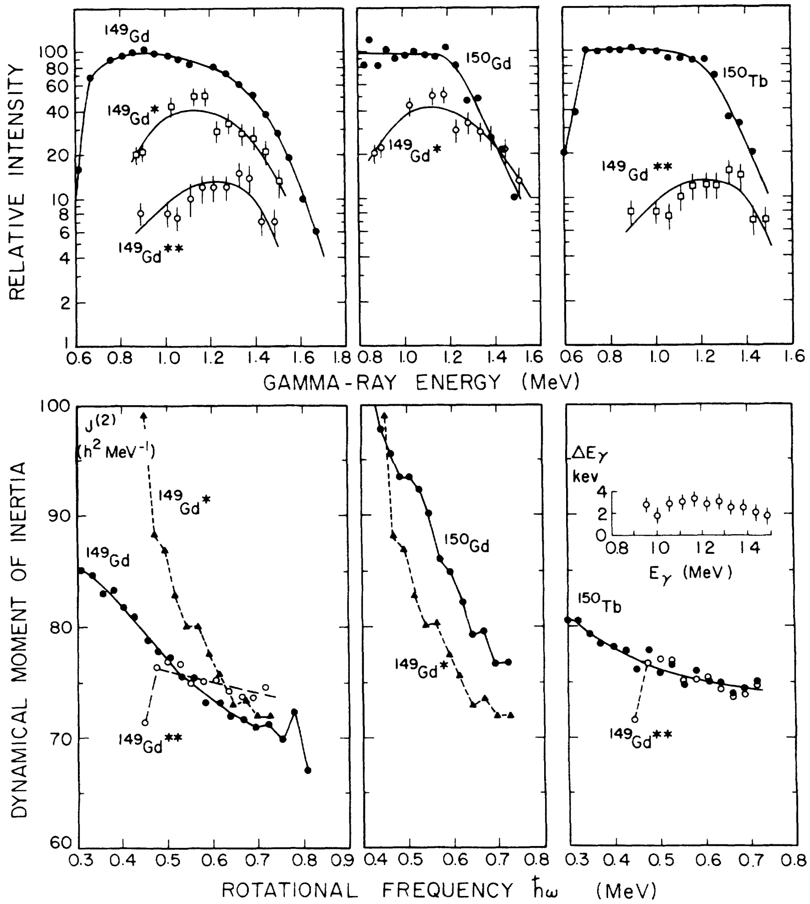

FIG. 2. Relative intensities and dynamical moments of inertia, $J^{(2)}$, observed in this work and in Ref. 5 for the case ^{150}Gd. Solid lines are drawn to link the data points and are not fits. The $J^{(2)}$ plot for ^{150}Gd is irregular beyond the uncertainty quoted in Ref. 5 and the inflections may have significance considering that ^{149}Gd* shows a similar pattern. The $J^{(2)}$ for ^{149}Gd is very regular except for the last two transitions, an effect which can be seen in Fig. 3. The bottom right panel contains an inset detailing the transition energy differences between the twinned bands ^{149}Gd**/^{150}Tb.

The twinning between ^{149}Gd**/^{150}Tb, and the lack of it between ^{149}Gd*/^{150}Gd, can in part be understood as a deformation-driving effect of the hole state. On the one hand, in ^{149}Gd** the $[301]_{1/2}$ orbital is up-sloping in the Nilsson diagram, and a hole in that state increases the deformation, thus cancelling to some extent the effect of the change in nuclear size (which scales as $A^{5/3}$) on the moment of inertia. On the other hand, the neutron hole in ^{149}Gd* is $[642]_{5/2}$, which is strongly down sloping in the Nilsson diagram. A hole in this orbital will cause a decrease in deformation, thus reinforcing the change in nuclear size. We should expect that the corresponding decrease in the moment of inertia would be larger than the average scaling, and indeed this is what we observe. Recent calculations by Ragnarsson[12] substantiate these simple arguments, although many other factors such as pairing and orbital alignment must play a role.

The deexcitation of the excited superdeformed bands to the normal states in ^{149}Gd seems to occur at higher rotational frequency than is the case either for the yrast ^{149}Gd superdeformed band, or for the corresponding configurations in ^{150}Gd and ^{150}Tb. This would be expected considering that they lie higher in the second well and can therefore tunnel to the normal states more easily. However, Byrski *et al.*[2] observed that ^{151}Tb* deexcites at the same frequency as its twin ^{152}Dy (namely $\hbar\omega \sim 0.32$ MeV) rather than at that of the yrast band in ^{151}Tb (~ 0.4 MeV). We suggest that the deexcitation point must be influenced both by the structure of the band, and by the excitation energy in the second well. Clearly more systematic studies are required to elucidate this point.

Although Gd**, being more weakly populated than Gd*, must lie at higher excitation energy in the feeding region around spin $55\hbar$, Gd** does have the smaller $J^{(2)}$ values and, therefore, a crossing of the bands might occur at lower spin. Such a crossing should exhibit an interaction, since these bands would have the same parity and signature with our proposed assignment. We can speculate that the sharp deviation of the energy of the lowest transitions from the systematic trends, namely γ_{877} keV in Gd* (higher than expected), and γ_{896} keV in Gd** (lower than expected) is an indication of the crossing. That is, the level fed by γ_{877} keV is pushed down by the interaction and the level fed by γ_{896} keV is pushed up. The assumption that these levels are essentially degenerate fixes the relative excitation energy of Gd* and Gd**, and we find that, in the feeding region, the bands would be ~ 700 keV apart. This conclusion is very tentative since, on the basis of this experiment, we cannot be sure that the key transitions, γ_{877} and γ_{896} keV, are truly members of their respective bands. Nevertheless, we present the argument since it is the first clue as to the dependence of population intensity on excitation energy in the second well.

In conclusion, we note that excited superdeformed bands involving proton and neutron excitations have been seen in the same nucleus. On the basis of the $J^{(2)}$ moments of inertia, configuration assignments have been suggested which involve particle-hole excitation from a nonintruder orbital to an intruder orbital. Where the hole occupies an up-sloping Nilsson orbital we find a twin band to the yrast superdeformed band with that same intruder configuration. Where the hole occupies a down-sloping Nilsson orbital, no twin is observed. The upsloping character of the hole orbital is then a necessary but not sufficient condition for the occurrence of twinned bands. Since in this experiment we have observed the highest-spin discrete transition known so far (γ_{1673} keV, $I = \frac{135}{2} \rightarrow \frac{131}{2}$, cf. Fig. 3), it is worthwhile to extrapolate the measured feeding intensities for ^{149}Gd, shown in Table I, to estimate how the population of very high spin states might look. The slope corresponds to a decrease in population by a factor of approximately 1.8 per transition. This estimate is of interest in connection with the detection of hyperdeformed nuclei (3:1 axis ratio), which are predicted[13] to lie near the yrast line at spins in excess of $70\hbar$. For example, according to our extrapolation, a discrete transition of, say, spin 74 → 72 would be approximately ten times weaker than the weakest transition assigned in this experiment. The spectroscopy of such weakly populated bands should be possible with the next generation of γ-ray instrumentation.

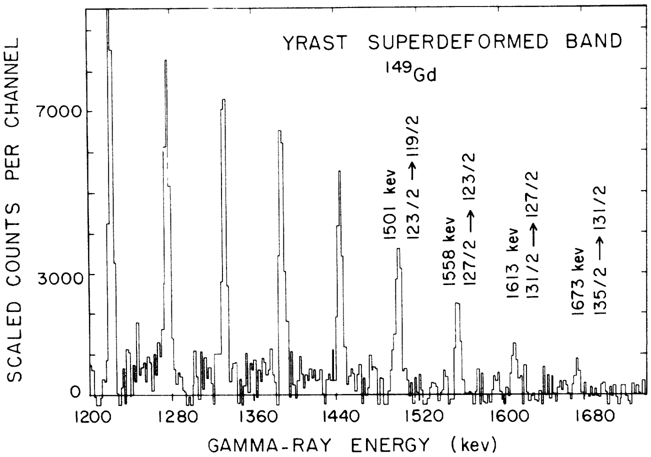

FIG. 3. Spectrum showing the highest spin discrete lines observed in the yrast superdeformed band in ^{149}Gd. This spectrum was obtained by summing appropriate gates in the background-subtracted efficiency-corrected matrix. Accepting the assignments given in Ref. 3 leads to a spin $\frac{135}{2} \rightarrow \frac{131}{2}$ assignment for the 1673 keV γ ray.

This work has been partially funded by the Natural Sciences and Engineering Research Council of Canada and by the Atomic Energy of Canada Limited.

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