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Superdeformed Band in ^{148}Gd: a Test of Shell Effects in the Mass 150 Region

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Abstract: A discrete superdeformed band was found in ^{148}Gd, and was produced both in Ca- and Si-induced compound-nucleus reactions. It is the third band found in the mass 150 region and its properties provide the clearest indication that ^{152}Dy is a "magic" superdeformed nucleus.

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The observation of superdeformed (SD) nuclei offers the possibility to address new and challenging questions. The approximate symmetries of the nuclear potential[1] lead to the prediction of shell gaps at large deformations. These symmetries can be explored by testing the location and strength of shell effects rather far removed from those known for spherical and weakly deformed shapes. Calculations suggest that high-j orbitals from two shells above the valence shell are sometimes responsible for the occurence of SD shapes. The correct prediction of the location of these special orbitals is another test of present shell-model calculations. On the other hand, the observed bands are extremely regular, with no evidence for such band crossings. If these crossings turn out to be systematically absent, it may indicate the presence of strong octupole or hexadecapole shapes that mix the bands and destroy their special quantum numbers. Thus, in these SD nuclei, there is a competition between the elements of "chaos" brought in by these more complicated shapes, and elements of "order" contributed by the existence of simple periodic trajectories of nucleons when the shell effects correspond to integer ratios of axes (e.g. a 2:1 axes ratio). This may be of interest to the growing field of order-to-chaos studies.

Also, in SD nuclei, deformation-dependent effects (like pairing) should be more easily studied. The SD bands are the most strongly populated bands in the very high-spin region where the pairing correlations are unstable, not only offering a better opportunity to study the approach towards the limiting behavior of these short-range correlations, but also providing information about the effect of deformation. In addition, the decay of SD states towards normal deformations will involve dramatic structure rearrangements, and therefore unusual electromagnetic transitions which are not often observed. These shapes provide a unique opportunity to study nuclei that are significantly different from any others known.

The search for discrete SD bands has recently become very active. There are two main regions where these bands have been found. In the lower mass region (A=100-140) seven bands have been found, six of them[2-4] in the mass 130 region, and recently, one[5] has been discovered in ^{105}Pd. All these bands vary in intensity, but they seem to have similar deformation, around

ε=0.4. In contrast, for a long time, only one SD band was known[6] in one nucleus (^{152}Dy) in the heavier mass region around 150. In this band, the deformation was greater, around ε=0.6, corresponding to a "2:1" ratio of axes. This suggested that a strong shell effect favors this band in that particular nucleus. Contrary to this hypothesis, a second SD band has recently been found[7] in ^{149}Gd. This paper reports a new SD band found in an even-even nucleus of this region, ^{148}Gd. The intensity and moments of inertia of these SD bands will be discussed and compared, suggesting that the band in ^{152}Dy is indeed unique.

The nucleus ^{148}Gd was produced at the 88-inch cyclotron of the Lawrence Berkeley Laboratory. Two sets of reactions were used. The first was ^{48}Ca+^{104}Ru$\rightarrow$^{152}Gd* at 215 and 202 MeV, and the second was ^{29}Si+^{124}Sn$\rightarrow$^{153}Gd* at 157 and 150 MeV. These reactions were calculated to produce ^{148}Gd at about the same excitation energy and spin. The Ru target was composed of two 0.5 mg/cm^2 foils, each on a 0.3 mg/cm^2 Au backing. The gold was facing the beam, so that the reaction products recoiled into vacuum with full (or nearly full) velocity. The Sn target consisted of two self-supporting foils, 0.5 mg/cm^2 thick. The γ-rays emitted by the reaction products were observed in 20 Ge detectors of the HERA array. Two of the reaction products have isomeric states, namely a 550ns isomer at 8.5 MeV in ^{147}Gd, and a 16ns isomer at 2.5 MeV in ^{148}Gd. The γ decay of these isomeric states was used to produce reasonably clean γ-ray spectra of these nuclei: the 0° (downstream) Ge detector was removed and a lead catcher, to stop the recoils, was positioned inside the 0° BGO suppressor, around 20 cm from the target. A lead collimator whose front was located ~8 cm downstream shielded the recoils from the Ge detectors. Thus, most of the γ rays emitted from the isomeric states are not seen by the Ge detectors (which detect only the prompt γ rays), but are detected in the 0° BGO suppressor (which has a solid angle of 70% as seen by the lead catcher). The time spectrum between this suppressor and the Ge detectors was recorded and used as a gate to select the ^{147}Gd or ^{148}Gd nuclei, depending on the time range chosen. The total γ-ray energy deposited in this BGO was also recorded, and could also be used to enhance a particular product since the total energies of the two isomers mentioned above are very different.

The prompt γ rays seen by the Ge detectors are Doppler-shifted, and the gains of the Ge detectors have been adjusted accordingly so that all the spectra have the same energy calibration and can be added.

Only the three- and higher-fold (in the Ge detectors) events were recorded on magnetic tape, together with the 0° BGO energy and time information as discussed above. The two-fold events were recorded directly into a two-dimensional matrix (of dimension 2048x2048) of a histogramming external memory. In order both to reduce the event rate being digitized, and to clean the spectra, the two-fold events were gated by the 0° BGO-Ge coincidence requirement. In the first experiment, 50 million three- and higher-fold events were recorded at 215 MeV, and 25 million such events at 202 MeV. In the second experiment, 36 million of these events were recorded at 157 MeV, and 170 million at 150 MeV. In this last case, 240 million events were recorded in the external memory, but were not as clean as the higher-fold events.

The first analysis (of the Ca-induced reaction) was a double-coincidence analysis where each three- and higher- fold event was broken into pairs, with, in some cases, an additional gate on the 0° BGO-Ge time spectrum to select a product by its isomer. Ridges about 50 keV apart were observed in the full (no isomer gate) background-subtracted[8] matrix and in the (gated) matrix of ^{148}Gd, but not in the matrix of ^{147}Gd. A systematic search for a discrete SD band was then undertaken by adding spectra in coincidence with gates 50 keV apart. An SD band of ~10 lines was found in this way and shown to belong to ^{148}Gd both by appropriate "time" gating and by analysis at different bombarding energies where the proportion of ^{148}Gd varies. However, about half those lines are also strong lines in ^{148}Gd. We performed the Si-induced reaction to get better statistics in order to be able to do a triple-coincidence analysis. Fig.1 shows a comparison of two spectra obtained in this experiment. Fig.1a is a sum of double-coincidence spectra gated on the 748,797,952 keV lines in the SD band. The lines in this spectrum mostly belong to ^{148}Gd, which further confirms the location of the SD band in this nucleus. However, this spectrum does not show the SD band very clearly, as several other lines in this nucleus appear in the energy range of the SD lines. Fig. 1b shows the sum of all double-gate combinations of ten SD lines. This is a very clean spectrum where the only lines (above 700 keV) are the SD lines. Moreover, each composite double-gated spectrum (which is a sum of spectra gated by one given line and each of the others), brings back the whole band, establishing that all the lines form a single band.

The properties of the SD band in ^{148}Gd seem to be generally similar to the other known SD bands in that mass region, namely those in ^{149}Gd and ^{152}Dy, but a more detailed study reveals a tendency towards lower deformation, less regular behavior, and lower population as one moves away from ^{152}Dy.

The intensity (from three- and higher-fold data) of the SD band in ^{148}Gd is of order 0.5% of the cross section for producing this nucleus. This is an average over all the data in the different reactions mentioned earlier. With the precision obtained, the intensities do not differ significantly from one reaction to the other, confirming earlier findings[9] that entrance channel effects (that would depend on the nature of the target-projectile pair) are unlikely. The values are not very precise since most of the known lines seen lie below one or more isomers, and for a lifetime $\tau > 1$ns, this will affect the intensity of these lines observed in an unbacked target. This loss was estimated by gating on a known high-lying (prompt) line and comparing the measured coincidence intensities above and below the isomers to these obtained from a backed target in ref. 10 (assumed to be the same here).

The excitation energy of this band could not be found. The triple coincidences gated on the SD lines only show (see Fig. 1b) the strong bottom lines of ^{148}Gd , but this could be due to poor statistics. The double coincidences gated on the SD lines show (Fig. 1a) high-lying lines (around spin 35) in the ^{148}Gd nucleus but it is not clear how clean the gates are. This latter measurement would imply spins in the SD band which are similar to those in ^{149}Gd and ^{152}Dy. The 701 keV line appears with an intensity lower than that of the SD lines in Fig. 1b. This could indicate either that it is an in-band transition above which there was some decay out of the band, or that it is one of the linking transitions to the lower deformed states. No conclusion about this could be drawn from the single-gated spectra since lower-lying strong lines at 697 and 699 keV were also populated (see Fig. 1a). This very interesting question of the decay of the SD band is (except for one case[3]) unsolved at present and an answer may well have to wait for the next generation of more powerful detector systems.

Only twelve lines could be found to belong with certainty to the SD band, with possibly the 701 keV line as an additional one. This may reflect a less stable second minimum for ^{148}Gd than for the other two. This would explain the earlier loss of population on the low-spin side where the barrier between SD states and normally deformed states , which governs the deexcitation of the SD band,[11,12] would be lower. Cranking-model calculations[13] of potential-energy surfaces seem to indicate a higher barrier between SD and prolate deformation in ^{152}Dy than in ^{148}Gd. On the high-spin side, the moment of inertia drops more than in ^{149}Gd and ^{152}Dy (see Fig. 2), thereby increasing the energy of the highest spin states relative to others. This may be the reason they are less favorably populated. It may also be that we do not have enough statistics to see the highest (weakest) transitions.

The dynamic moments of inertia $2\mathcal{J}^{(2)}_{band}/\hbar^2$ also provide interesting new information on the behavior of these nuclei. At these high spins, the static pairing correlations are probably quenched, and the regularity and large collectivity of these SD bands suggest that no large sudden alignment is taking place in the regions observed. Therefore the moments of inertia may be more directly related to deformation or shape than for other (lower deformation) bands. These moments of inertia are plotted in Fig. 2 for the three nuclei mentioned, after normalization to the mass A=152 by an $A^{5/3}$ factor. This gives the first clear indication that ^{152}Dy is a special nucleus, since (in contrast with ^{149}Gd) no odd-even effect can be invoked to explain the difference in moment of inertia between

^{152}Dy and ^{148}Gd. The lifetime measurements indicate[7,14] a slightly lower deformation for ^{149}Gd than for ^{152}Dy. The calculations[13,15] agree with this and also predict[13] (from a Woods-Saxon potential calculation) a lower deformation for ^{148}Gd (β_2~0.59 compared to β_2~0.62 in ^{152}Dy). Whereas at present, the low statistics obtained in lifetime measurements only permit one to deduce an average deformation over the SD band, the variation of the moment of inertia within the band may add some interesting information. In general, the decrease of the moment of inertia within a band is related to the so-called band-termination effect; i.e. as a nucleus of fixed configuration rotates and therefore tends to align its nucleons, it becomes progressively more difficult to do so as the angular momentum increases and fewer unaligned nucleons remain. Thus, as the aligned angular momentum increases, the collectivity decreases and the shape becomes more triaxial until the nucleus reaches an oblate shape at the band termination (when no more angular momentum can be obtained from the configuration). The moments of inertia in Fig. 2 suggest that both ^{149}Gd and ^{148}Gd are in that regime, whereas ^{152}Dy is not. One possible explanation is that the superdeformed ^{152}Dy nucleus lies in a deeper pocket where it maintains its deformation and shape and thereby remains more efficient in producing angular momentum. An alternative explanation would be simply that, as the number of valence particles increases with mass, the generation of angular momentum becomes less restricted and therefore easier, resulting in a more constant moment of inertia. In this case, ^{152}Dy would not be a special nucleus. A combination of these effects is also possible. The observation of a SD band in heavier nuclei of this region would help clarify this situation.

The total population of superdeformed states has been estimated from the intensity of the ridges of the two-dimensional full matrix (from the Si-induced reaction at 150 MeV) in the 900 to 1200 keV region. This intensity was found to be around 2% of the ^{148}Gd cross section. Although some of the previously known lines in ^{148}Gd do (accidentally) contribute to the ridge intensity, it seems likely that some additional (unresolved) SD bands contribute to the ridge.

In summary, a very weak discrete SD band has been found in the ^{148}Gd nucleus. Of the three SD bands known in this mass region, it is the weakest, has the fewest transitions, and is the least regular. This suggests that the SD bands become less "perfect" as one moves away from the nucleus ^{152}Dy which is thought[16,17] to be a superdeformed "magic" nucleus. The properties of the SD bands observed in ^{148}Gd and ^{149}Gd are consistent with that idea, but a study of SD bands in the slightly heavier nuclei would be needed to confirm the magicity of ^{152}Dy.

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Figure Captions.

Fig. 1. (a) Sum of double-coincidence spectra in ^{148}Gd gated on the three cleanest SD lines at 748, 797 and 952 keV. (b) Triple-coincidence spectrum summed over all double-gate combinations of ten lines in the SD band.

Fig.2. Dynamic moment of inertia $2\mathcal{J}^{(2)}_{\mathrm{band}}/\hbar^2$, normalized to mass 152 (see text) for the nuclei ^{152}Dy (●), ^{149}Gd (□) and ^{148}Gd (■). A representative error bar is given for ^{148}Gd.

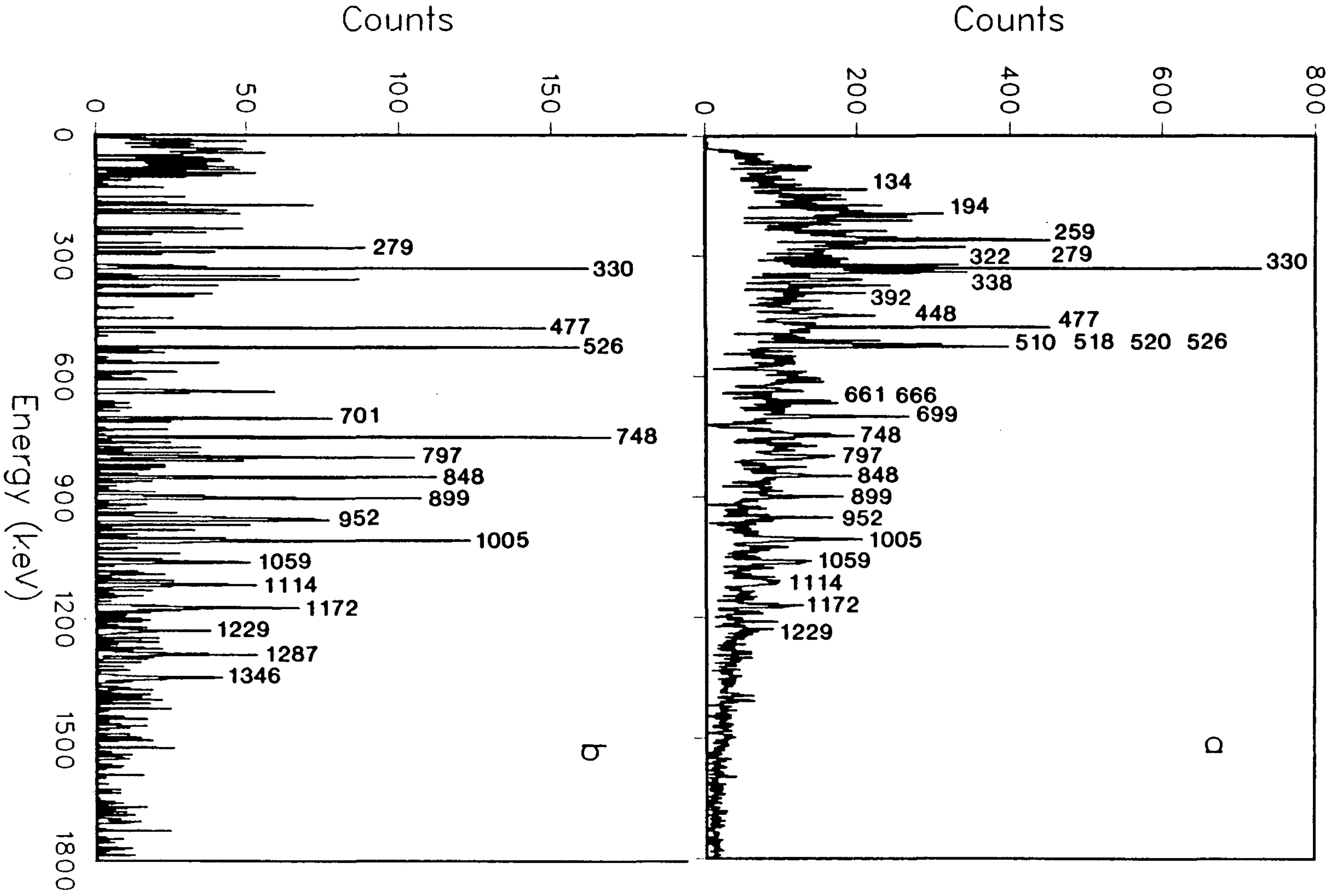
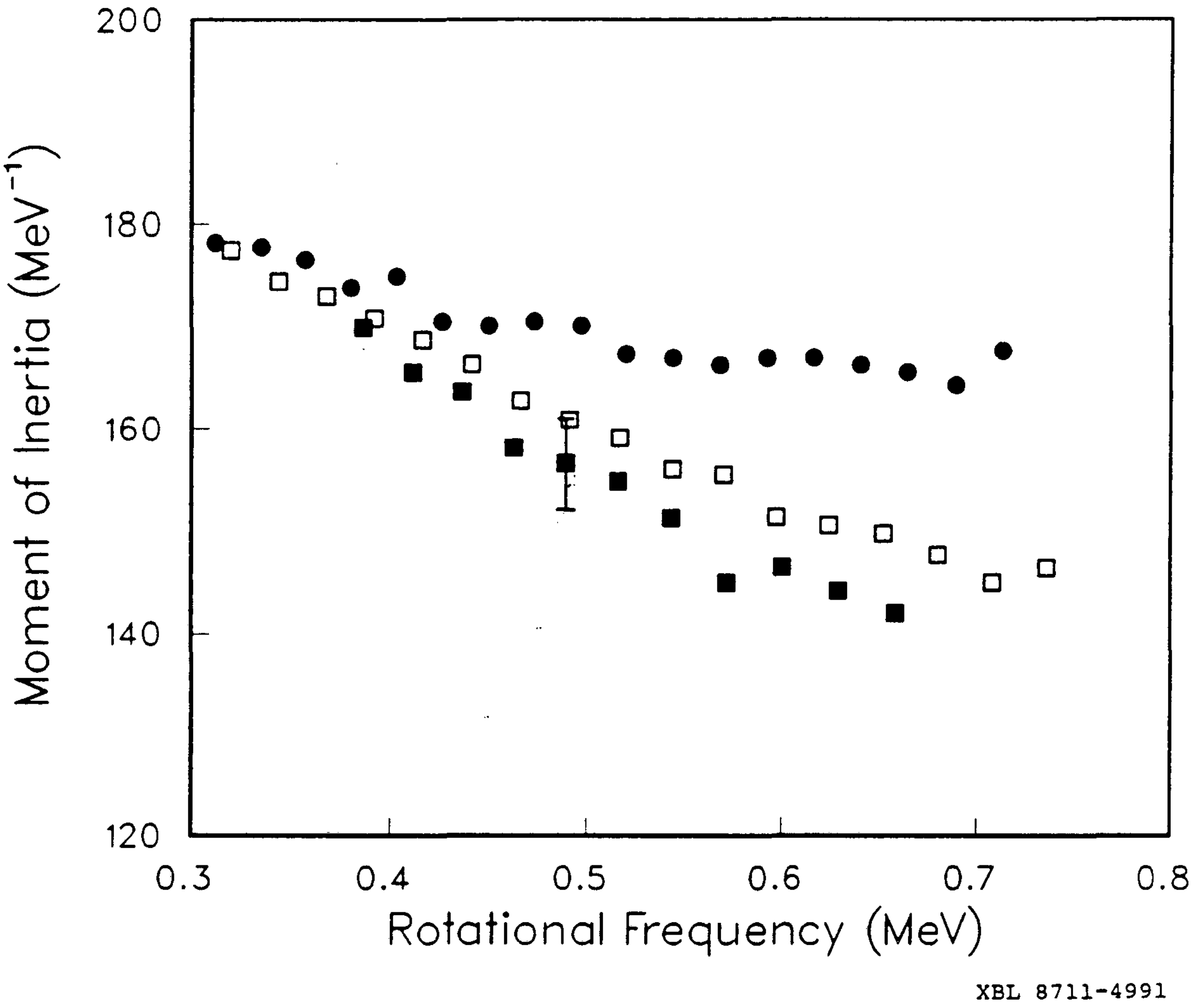


Fig. 1

XBL 8711-4990



Moment of Inertia (MeV^{-1})
200
180
160
140
120
0.3
0.4
0.5
0.6
0.7
0.8
Rotational Frequency (MeV)
XBL 8711-4991

Fig. 2

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