Feeding of Discrete-Line Superdeformed Bands at Very High Spin

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The superdeformed band in ^{149}Gd has been populated with various input angular momenta and excitation energies. These, together with all other available data, indicate that the necessary criterion for populating superdeformed bands is to form cold residual nuclei at spins higher than those where the superdeformed states become yrast. In addition, the decrease in the superdeformed band intensity as it is gated by higher-energy γ rays does not support the predictions based on a recently proposed feeding mechanism of these states.

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The recent discovery[1,2] of superdeformed (SD) shapes at very high spin offers exciting possibilities for the study of nuclear structure at the extreme limits of rotational stress and large shape changes, and in the absence of pairing correlations. A major challenge to our understanding of nuclear behavior at very high spin is to comprehend the conditions which would favor the population of SD states. The first known SD band, in ^{152}Dy, was populated much more weakly in (^{40}Ar,4n) than in (^{48}Ca,4n) reactions.[3] Although this result could have been interpreted to indicate a dependence on the input angular momentum and the temperature of the residual nucleus, it could not preclude an explanation based on the use of different projectiles. The fact that the SD band in ^{149}Gd was formed[2] in the reaction (^{30}Si,5n) refuted the possibility that such bands could be populated only by reactions of neutron-rich and moderately heavy projectiles. In the present work, we have tested the spin and temperature dependence directly by measuring the excitation function of the SD states in ^{149}Gd and by comparing reactions with very similar target-projectile combinations.

A related issue is the feeding mechanism of these SD bands. In both ^{152}Dy and ^{149}Gd, the highest discrete spin state ($I \sim 60\hbar$) is populated rather strongly ($\sim$0.2% of the residual nucleus cross section). Such a high intensity exceeds what would be expected from a simple extrapolation in "normally" deformed nuclei by an order of magnitude. Herskind *et al.*[4] have proposed an ingenious mechanism whereby the large splitting of the giant dipole resonance (GDR) built on excited states in the SD minimum, together with the low level density expected in this minimum, will give rise to statistical $E1$ transitions that would cool the SD state an order of magnitude faster than the normal nuclei. A consequence of this mechanism is the prediction[4] that the $E1$ continuum spectra associated with the normal and SD states are very different. Such spectra have been measured for the first time in our work and are reported in this Letter together with the excitation function.

The γ-ray yields of the SD band in ^{149}Gd as well as of the 4n, 5n, and 6n channels were measured with the 8π spectrometer[5] for the reaction ^{124}Sn+^{30}Si at bombarding energies of 140, 145, 150, 155, and 160 MeV. The target consisted of two stacked 0.4-mg-cm^{-2} Sn foils (enriched to 96.4% ^{124}Sn) and the beam was provided by the MP Tandem at Chalk River. With a threshold of ten on the number of BGO detectors firing in the ball of the 8π spectrometer, approximately 70×10^6 Ge-Ge Compton-suppressed coincidence events were recorded at each beam energy.

The intensities of the discrete SD states (obtained as an average of the yields of the 760-, 808-, and 857-keV γ rays gated by the 907-keV γ ray), normalized to those of the normal states in the 5n channel (obtained as the sum of the yields of the 775- and 796-keV γ rays), are displayed as curve (a) in Fig. 1. The normalized intensity rises from (0.3 ± 0.1)% at 140 MeV to (2.0 ± 0.2)% at 155 MeV and appears to decrease to (1.8 ± 0.4)% at 160 MeV, the maximum beam energy available at our tandem. (A measurement of the excitation function of the superdeformed band in ^{152}Dy has also been reported recently.[6]) In all these reactions, the entry state energy centroids can be evaluated from Q values, if we assume an average neutron kinetic energy of 2 MeV. These, as well as the values of l_{max}, the maximum angular momentum[7] brought into the compound nucleus, together with the known[2] SD band in ^{149}Gd, are displayed in Fig. 2. It can be seen that, as the beam energy increases, the input angular momentum also increases but the excitation energy of the nucleus *relative* to the yrast line does not change that much. Thus, the apparent decrease in the intensity of the SD band at 160 MeV probably arises from an intense competition with fission which becomes enhanced by the strong centrifugal forces as the spin increases.

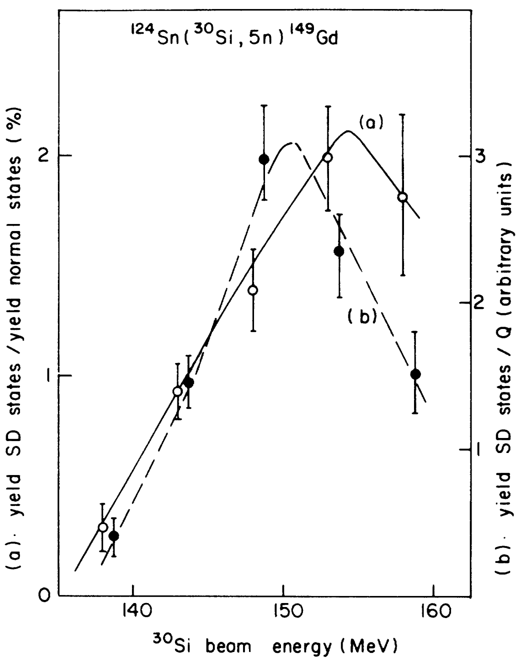

FIG. 1. (a) Intensity of discrete SD states in ^{149}Gd normalized to the intensity of normal states in the same nucleus. (b) Intensity of discrete SD states normalized to the total charge Q impinging on target. The ^{30}Si beam energy has been corrected for the energy loss in the target. The lines have been drawn to guide the eye.

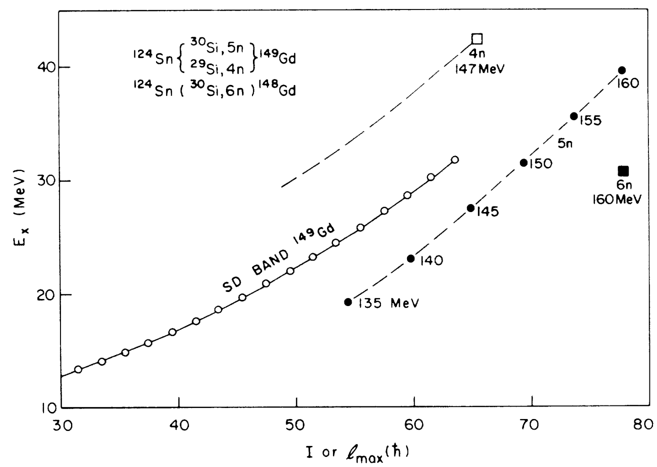

FIG. 2. Open circles: estimated excitation energy vs spin for the known (Ref. 2) SD states in ^{149}Gd. Excitation energy of the residual nucleus vs l_{max} at various bombarding energies for the $5n$ reactions (filled circles), the $4n$ reactions (open square), and the $6n$ reactions (filled square).

To measure more directly the effect of temperature on the formation of the SD states, we have produced ^{149}Gd by a (^{29}Si,$4n$) reaction at 147-MeV beam energy bringing in approximately the same angular momentum as in the $5n$ reaction at 145 MeV but where the excitation energy of the residual nucleus is ~10–15 MeV higher (see Fig. 2). In this case, the SD band was not observed, and with a total of 300×10^6 Ge-Ge coincidence events, an upper limit of 0.5% can be placed on the population of the SD states in that particular reaction. In the same vein, a SD band was observed[8] recently in ^{150}Gd following the reaction ^{130}Te(^{26}Mg,$6n$) at 145 MeV while there is no sign of such a band in any of our ^{124}Sn(^{30}Si,$4n$) reactions even though the input angular momentum is the same. The difference arises from the excitation energy of the residual nucleus which is ~10 MeV higher in the $4n$ reaction.

All these facts can be understood qualitatively if we suppose that a necessary criterion for population of the SD states is that the residual nuclei must be formed at a low excitation energy relative to the yrast line at spins higher than where the SD shape becomes yrast, generally estimated[9] to be around $55\hbar$ in this mass region, but below where fission becomes dominant. It is clear that in the (^{29}Si,$4n$) reaction, this criterion can never be met at any bombarding energy since, for any spin, the estimated centroid of the entry population always lies 5–10 MeV above the SD yrast line (see Fig. 2). On the other hand, the (^{30}Si,$5n$) reaction leads to entry states close[2] to the SD yrast line at spins above $60\hbar$ for bombarding energies in the interval 145–160 MeV. Because of the distribution in l brought into the compound nucleus, a range of states to the left of each curve can be populated at a given excitation energy. All the other known[1,8,10,11] cases of discrete line SD bands, i.e., ^{152}Dy, ^{150}Gd, ^{148}Gd, and ^{151}Dy meet this criterion. In particular, the SD band in ^{148}Gd had been observed previously[10] in the ^{124}Sn(^{29}Si,$5n$) reaction at 147 and 150 MeV, and also in the present work in the ^{124}Sn(^{30}Si,$6n$) reaction at 160 MeV (filled square in Fig. 2).

The above criterion can be understood on the basis of recent calculations which show that the depth of the second minimum in the nuclear potential decreases as the nuclei become warmer. This is due in part[12] to a loss of order in nucleonic motions and in part[13] to the level density becoming dominated by normal states as the temperature rises. Since the probability of our trapping the nucleus in a SD shape depends critically on the well depth, then the trapping probability must depend significantly on temperature.

The γ-ray sum energy (E_s) and multiplicity (M) distributions were also measured with the BGO ball in the ^{124}Sn+^{30}Si reaction at 140, 145, 150, 155, and 160 MeV. The centroids E_s and M, given in Table I, rise smoothly with increasing bombarding energy and those for the SD state lie midway between the $4n$ and $5n$ channels in M and slightly above the $5n$ channel in E_s. This confirms the perception of low-temperature feeding for the SD states. The differences in the spin centroids could be considerably greater than for the M centroids since the SD cascade probably contains a higher propor-

TABLE I. Centroids E_s and M of the γ-ray sum energy and multiplicity distribution measured in the $^{124}Sn + ^{30}Si$ reaction at various beam energies and for different exit channels.[a]

E_{beam}	E_s (MeV)				M			
(MeV)	$6n$	$5n$	SD[b]	$4n$	$6n$	$5n$	SD[b]	$4n$
140	18.7 ± 0.4	22.9 ± 0.4	24.2 ± 0.6	29.8 ± 0.4	18.2 ± 0.2	20.3 ± 0.2	23.4 ± 0.4	26.3 ± 0.2
145	20.0 ± 0.4	25.1 ± 0.4	26.9 ± 0.6	32.4 ± 0.4	19.3 ± 0.2	22.0 ± 0.2	25.3 ± 0.4	28.1 ± 0.2
150	22.9 ± 0.4	28.7 ± 0.4	29.8 ± 0.6	35.8 ± 0.4	21.0 ± 0.2	24.3 ± 0.2	26.8 ± 0.4	30.3 ± 0.2
155	24.4 ± 0.4	30.0 ± 0.4	31.8 ± 0.6	36.9 ± 0.9	22.1 ± 0.2	25.3 ± 0.2	28.3 ± 0.4	31.9 ± 1.0
160	26.9 ± 0.4	32.7 ± 0.4	33.3 ± 0.6	40.2 ± 2.0	23.8 ± 0.2	27.1 ± 0.2	29.7 ± 0.4	33.4 ± 1.0

[a] $6n$: ^{148}Gd; $5n$: ^{149}Gd; $4n$: ^{150}Gd.

[b] SD states observed in the $5n$ channel.

tion of stretched $E2$ transitions than does the cascade through the normal states.

To extract information on the feeding mechanism of the SD bands at very high spin, we have also measured, on an event-by-event basis, the γ-ray spectra of all the BGO elements of the ball of the 8π spectrometer, in coincidence with at least two Ge detectors. The reaction $^{124}Sn + ^{30}Si$ at 150-MeV beam energy was used and a total of 250×10^6 events were recorded. Because of background distortions generated by the neutrons, only the spectra from the elements in the backward hemisphere were processed. These were gated by the appropriate discrete lines in the Ge detectors.

The projected spectra of individual BGO detectors associated with the $4n$, $5n$, and $6n$ channels are displayed in Fig. 3. They show characteristic exponential tails from 3 to 10 MeV, with pronounced bumps arising from decays of GDR states centered around 15 MeV. Although the detailed analysis of these results, if we take into account the ball response, is not yet complete, the systematic weakening of the GDR bump going from the $4n$ to the $6n$ channels is evident in the raw data. This is expected intuitively and is simply the result of conservation of energy: After the emission of the GDR γ rays, less excitation energy is available for the emission of a long sequence of neutrons. There are slight differences in the slopes of the exponential tails in the $4n$, $5n$, and $6n$ channels. In the case of the spectrum projected from the SD full-energy peaks, the slope is somewhat steeper, indicating a lower temperature at the entry point, in agreement with the discussion concerning the excitation function.

Qualitatively, the spectrum associated with the discrete line SD band differs from that of the normal states in the $5n$ channel only by the slope of the exponential tail, although there may be a hint of the low-energy component of the GDR built on SD states and expected[4] at ~8 MeV. The similar shapes of the continuum spectra are in marked contrast with the calculations of Herskind *et al.*[4] who predict very different shapes, in particular, a shallower slope for the SD spectrum compared with the normal spectrum. It may be argued that, since the measured continuum spectrum contains not only the feeding $E1$ statistical transitions but also the $E1$ transitions emitted in the decay of the SD band into the yrast line at lower spins, the shape of this spectrum may be quite different from that expected theoretically.[4] However, it is unlikely that these additional transitions would affect the spectrum shape to such an extent; they should not affect the spectrum above 3 MeV, their estimated maximum energy.[2]

Herskind *et al.* have also proposed that selecting cascades containing a high-energy γ ray ($E_\gamma > 5$ MeV) may be a tool for the enhancement of SD bands relative to the normal states. Although, our statistical spectra do not support this, we have further tested this suggestion be generating Ge-Ge event matrices with gates of 0.2–3, 3–5, and 5–8 MeV on the BGO spectra in the data obtained at a beam energy of 150 MeV. The relative population of the SD band (obtained as a sum of the yields of the 664-, 760-, 857-, 907-, 957-, 1061-, and 1114-keV γ rays from a sum spectrum gated by these same γ rays) normalized to that of the normal states in the $5n$ channel (obtained as the sum of the yields of the 561- and 944-

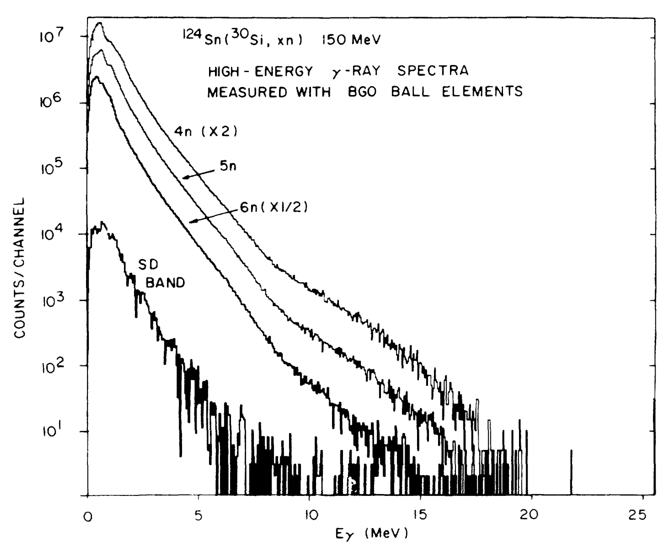

FIG. 3. γ-ray spectra measured with the BGO ball elements of the 8π spectrometer. These were obtained by gating on the appropriate discrete lines in the $4n$, $5n$, and $6n$ channels as well as on γ rays of the SD band in ^{149}Gd.

keV γ rays from a sum spectrum gated by these same γ rays) were found to be 1.0 ± 0.1, 0.65 ± 0.05, and 0.5 ± 0.1 for the three BGO gates used. This decrease is in clear contradiction to the predicted increase in SD population by a factor of 3, for the $E_\gamma > 5$-MeV gate.

It should be pointed out that the detailed prediction[4] of the influence of the GDR based on a SD shape was presented for the ^{48}Ca+ ^{108}Pd reaction at a beam energy corresponding to a higher excitation energy in the ^{152}Dy nucleus. The beam energy of 150 MeV used in our experiment to optimize the population of the SD band in ^{149}Gd leads to states being fed at a low temperature, an excitation energy which may be too low to allow for the mechanism of Ref. 4 to take place. On the other hand, if the average entry temperature assumed[4] for the SD states were to be lowered, relative to the normal states, then the relative slopes of the statistical spectra predicted in Ref. 4 would certainly be affected. It is also possible that the reduced level density for SD states, which gives rise to part of the enhanced SD feeding in Ref. 4, is responsible for increased neutron-emission probabilities into low-energy entry states in a way entirely analogous to the enhancement it is predicted to produce in the $E1$ rates. Such an effect may further increase the SD feeding, and would not be present in the simulation of Herskind *et al.*,[4] since they do not consider neutron emission but rather simply assume an entry state distribution.

In summary, our excitation function in the ^{30}Si+ ^{124}Sn reaction, as well as all the known cases of discrete line SD bands and the nonobservation of SD states in some reactions leading to known SD nuclei, indicate that the necessary criterion for population of SD states is that the residual nuclei be formed at a low excitation energy relative to the yrast line at spins higher than those where the SD shape becomes yrast, but below where fission is dominant. In addition, our results do not confirm the simulations of Herskind *et al.*,[4] possibly because of limited available energy for decay into the superdeformed states. While more refined calculations, including neutron emission, are needed in the context of the proposed feeding mechanism, a different mechanism may be required at the low temperatures where the SD states are populated optimally. It appears that gating on high-energy γ rays will not assist in the search for SD bands, or is at best limited to special cases of projectile-target combinations and/or beam energies.

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