Evidence for superdeformation in ^{149,150}Dy: Onset of the collapse of the $Z=66$ deformed shell closure?

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An experiment has been performed to search for superdeformed (SD) states in ^{149,150}Dy. While no evidence for discrete superdeformed states has been observed, a superdeformed ridge with a separation of $\Delta E_{\gamma}=52$ keV with a total intensity of $1.8\pm0.5\,\%$ that of ^{150}Dy has been observed. An upper limit of 0.8% (0.9%), of the intensity of ^{150}Dy (^{149}Dy), is placed for observation of the most intense discrete line states. The relative weakness in the SD population is suggested to be due to a rapid decrease in the depth of the superdeformed minimum, as one moves away from doubly magic ^{152}Dy.

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Over the past decade an exhaustive amount of theoretical and experimental effort has been devoted to the search for, and understanding of, superdeformed (SD) states in atomic nuclei. While many SD nuclei are known [1], concentrated in several mass islands which are scattered over a broad range of Z and N, there still remain many unanswered questions and puzzles. For example, the spins and excitation energies for the majority of SD bands remain ambiguous as only in a few cases are the decay paths to the normal-deformed (ND) states known [2]. Another important question regards the limits of the SD islands. How are these influenced by macroscopic and microscopic nuclear quantities, for example, the intruder orbital positions and character? How does the SD well depth vary as one moves further away from the center of the ''islands of superdeformation''?

Of the five known regions of high-spin SD nuclei, the one of relevance to this paper is that centered on the doubly magic SD nucleus ^{152}Dy. The $A\approx150$ island ranges from $^{142}_{63}$Eu$_{79}$ to $^{155}_{66}$Dy$_{89}$ with the gadolinium ($Z=64$) isotopes forming the longest chain of SD nuclei, with nine SD Gd nuclei observed to date ($79\leqslant N\leqslant87$).

The limits of this island of superdeformation have been calculated by a variety of theoretical methods, e.g., Refs. [3–6]. However, surprises have been observed. For example, in the dysprosium isotopes SD states have been observed in ^{154}Dy [7] and ^{155}Dy [8] which are well beyond the predicted shores of the island. Thus the exact limits of the $A\approx150$ island remain to be determined experimentally.

For the lighter dysprosium nuclei the limit has long been predicted to lie around neutron number 84. Thus, ^{150}Dy is predicted to be SD, while the neighboring odd-N nucleus ^{149}Dy is not predicted to have a stable superdeformed minimum [5]. To date there is no experimental evidence for discrete SD states in either nucleus. In the 1980s, de Voigt *et al.* [9] performed a series of experiments to search for SD states in ^{154,156}Er and ^{150,152}Dy by attempting to identify ''SD ridges'' in E_{γ}-E_{γ} coincidence matrices. While a strong superdeformed ridge was identified in ^{152}Dy, in agreement with the earlier observation of Twin *et al.* [10] only weak evidence for ridges was observed in ^{150}Dy and ^{154}Er, while no SD ridges were observed in ^{156}Er. These results indicate that any SD bands in these nuclei are populated with a significantly lower cross section than that of the yrast SD band in ^{152}Dy. Further, the ridge structures observed in ^{154}Er were found to have a greater width than those observed for ^{152}Dy or ^{150}Dy, indicating a larger spread in the moments of inertia for any SD states. Recently, Bernstein *et al.*, observed a rotational cascade in ^{154}Er, which they assigned as a SD band [11]. This band has been measured to have an intensity of only 0.4% of the total strength of ^{154}Er, a population intensity significantly lower than that of the yrast SD band in ^{152}Dy, in agreement with the work of de Voigt. This result has prompted the current investigation to determine the population of SD states in the nuclei ^{149}Dy and ^{150}Dy.

High-spin states in ^{150}Dy were populated by the reaction ^{120}Sn(^{34}S,4n)^{150}Dy. The ^{34}S beam, at an energy of 175 MeV, was provided by the Yale ESTU Tandem Van De Graaff accelerator. The target consisted of 1 mg/cm^2 ^{120}Sn on a thick, 15 mg/cm^2, lead backing. The γ rays were detected with the YRAST Ball array [12]. At the time of this experiment YRAST Ball contained 20 Compton-suppressed Ge detectors: three 25% efficient (relative to a $3''\times3''$ crystal of NaI) detectors were located at 160° (with respect to the beam line), seven 25% detectors at 126°, four segmented clover Ge detectors [13] situated at 90°, and five 25% and one 70% efficient detectors were situated at 50°. In addition a 32-element BGO array was used to provide multiplicity information on the reaction.

A total of 4.7×10^{8} events were recorded with a requirement of a suppressed Ge multiplicity $\geqslant2$ in coincidence with at least one element of the BGO array. The most strongly populated nucleus in this experiment was the 4n channel leading to ^{150}Dy. The 5n channel leading to ^{149}Dy and the 6n channel (^{148}Dy) were populated with 90% and 20% of the cross-section observed for the dominant channel respectively.

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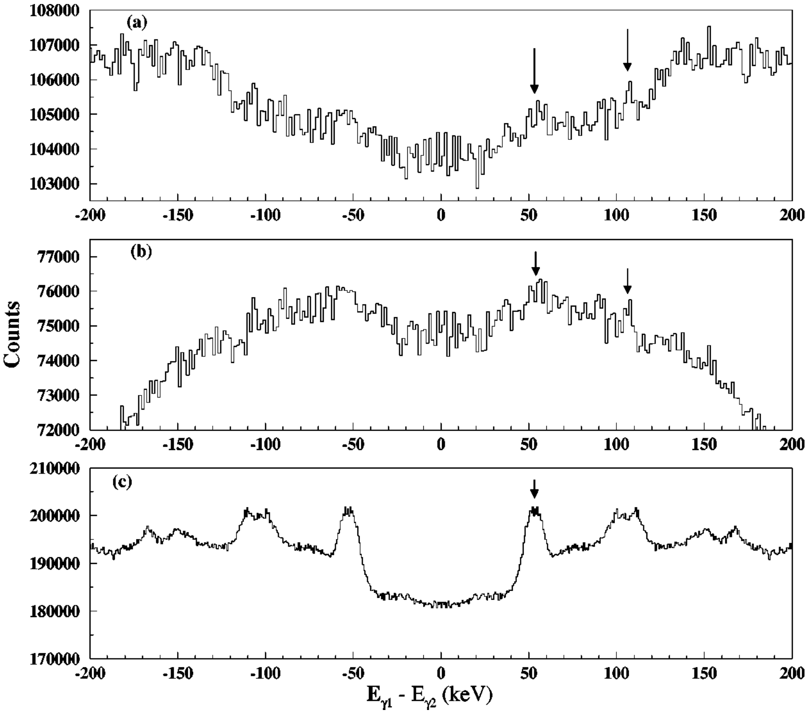

FIG. 1. Projections of matrices taken perpendicular to the line $x=y$ (a) over the energy range 900–1400 keV in a Doppler corrected matrix. (b) As in (a) but over the energy range 1000–1500 keV. For panels (a) and (b) the arrows are used to mark the presence of tentative ridges at 52 and 104 keV. (c) A slice from a matrix in which the predominant nucleus was ^{150}Gd, the arrow clearly marks the first SD ridge in ^{150}Gd.

The data were sorted into two E_γ-E_γ coincidence matrices. In one matrix no Doppler correction was made while in the second a correction was made so as to compensate for the maximum Doppler effect on the recoiling nuclei. The former matrix was used to perform spectroscopy of the normal-deformed (long-lived) states, while the latter was used to search for cascades of γ rays displaying the characteristic signatures of a SD band (such transitions are expected to have short half-lives compared to the nuclear stopping time). Several different automatic search algorithms, based on both the traditional grid search [14] and the biological propagation mechanism [15], were used to search for SD states. The parameters used in these searches were based on the known properties and characteristics of SD bands in adjacent nuclei, namely, $600 \leqslant E_\gamma(\text{initial})(\text{keV}) \leqslant 900$ and $45 \leqslant \Delta E_\gamma(\text{keV}) \leqslant 55$. In addition to the automatic search algorithms, an exhaustive search of the data was performed by hand. No evidence for discrete rotational SD structures was observed as a result of these searches.

To place limits on the experimental sensitivity of this experiment a series of simulations were performed to determine the minimum population intensity at which discrete SD bands could be observed in these data. For the simulation a typical in-band intensity distribution (similar to that of the yrast band in ^{150}Gd) was employed. The start energy and number of band transitions were varied to determine the ability of the search algorithms and manual methods for observing the bands. In addition, two different band moments of inertia were employed. In the first case a constant moment of inertia, equal to that of ^{152}Dy, was assumed. However, it is predicted [5] that the yrast SD band in ^{150}Dy undergoes a band crossing at lower rotational frequencies with a corresponding variation in the $\mathcal{J}^{(2)}$ moment of inertia. Therefore, a second band was simulated using a moment of inertia similar to that of the yrast band in ^{150}Gd. The resultant bands were added to the Doppler-corrected matrix which was then searched using the same methods as before.

As a result of these simulations it was determined that the weakest discrete line SD band that could be observed in our data set would have an intensity of $\approx 0.8\%$ ($\approx 0.9\%$) relative to the population of ^{150}Dy (^{149}Dy) (assuming that a minimum of 13 states were populated; clearly a decrease in this number results in an increase in the observation limit).

An analysis similar to that described in Ref. [9] was performed to search for evidence of a SD continuum ridge population in ^{149,150}Dy. An example of a projection from the Doppler-corrected matrix, taken perpendicular to the matrix diagonal ($x=y$), is presented in Fig. 1(a). This spectrum has been obtained by taking a sum of channels with $E_{\gamma1}+E_{\gamma2}=\text{const.}$ in the energy range $900 \leqslant E_\gamma(\text{keV}) \leqslant 1400$ (similar to that shown in Fig 2(a) of Ref. [9]). Weak ridges at spacings of at 52 and 104 keV (highlighted by arrows) can be seen in Fig. 1(a). These correspond to a dynamical moment of inertia of $(76\pm3)\hbar^2\text{MeV}^{-1}$ (for comparison the average dynamical moments of inertia for ^{151}Dy and ^{152}Dy are $79\hbar^2$ and $83\hbar^2\text{MeV}^{-1}$).

To test if these ridges are caused by accidental coincidences a second slice of the matrix was taken over the energy range $1000 \leqslant E_\gamma(\text{keV}) \leqslant 1500$, Fig. 1(b). Weak evidence for SD ridges persists over this higher-energy cut. For comparison Fig. 1(c) shows the result of taking a slice over the same energy range as in Fig. 1(a), but from a matrix in which the predominant nucleus was ^{150}Gd.

On the assumption that these ridges are solely composed of SD states, then the total population of SD states from this reaction would be $1.8\pm0.5\%$ relative to the population of ^{150}Dy.

In order to populate SD bands a suitable minimum has to be present in the potential energy surface [5]. In addition, to

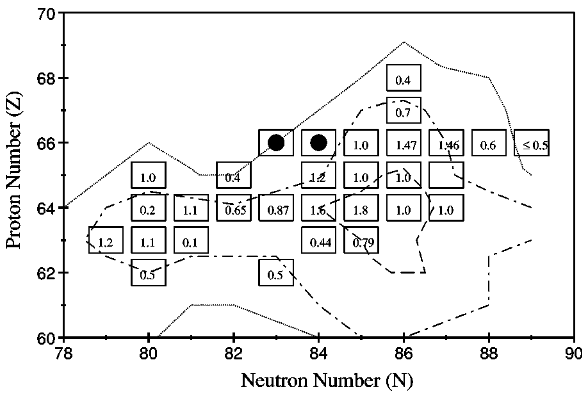

FIG. 2. The experimentally determined population intensity of the yrast superdeformed band in each nucleus as a function of *Z* and *N*. The lines are contours representing the depth of the SD minimum at $I=50\hbar$ (dashed line,3 MeV; dot-dashed line, 2 MeV; dotted line, 1 MeV). The population intensity data are taken from [1] while the well depth is taken from [4]. Two SD bands have been reported in ^{152}Tb [17]; however, no intensity data are currently available. The solid circles denote the nuclei ^{149,150}Dy.

generate long cascades, the barrier separating this minimum from the non-SD well has to be sufficiently high in order to minimize the tunneling probability between the two wells. Finally, the minimum must become yrast at a reasonable spin to allow for preferential population. Theoretical calculations based upon the deformed Woods-Saxon potential [3,16] predict that ^{150}Dy should support a well-developed SD minimum, which becomes yrast at a lower spin than in the neighboring doubly magic SD nucleus ^{152}Dy.

In our data we have found no clear evidence for the presence of discrete SD states in either ^{149}Dy or ^{150}Dy. Since the reaction used in this experiment was similar (maximum angular momentum and excitation energy input) to reactions used to populate SD states in nearby nuclei, there are several possible explanations for our nonobservation of discrete line SD states. A likely possibility is that the population intensity of any SD bands in ^{149,150}Dy is below the limit of observation for this experiment. Based on our simulations an upper limit of 0.8% has been determined for the observation of a discrete line SD band in these data.

The intensity of the yrast SD bands in all the known SD nuclei in this mass region has been plotted in Fig. 2. In addition, the calculated depths of the SD minimum at $I=50\hbar$ has been overlayed on this figure. Thus Fig. 2 serves as a crude road map which may be used to estimate the expected intensity of SD states in ^{149,150}Dy. The deepest SD minima are predicted to lie around ^{149}Gd [4]. This is in good agreement with the large population intensity of the yrast SD band and with the number and intensity of excited SD bands observed for ^{149}Gd. The 1 MeV contour can be used to determine the ''high-tide'' mark for this island of superdeformation; it passes very close to the weakest known SD nuclei in this region, and no SD nucleus has been observed beyond this contour. Crudely extrapolating from the known experimental data and the theoretical contours, one might expect the intensity of the yrast SD band in ^{150}Dy to be $0.7\leqslant I_{pop}(\%)\leqslant 1.0$, while the intensity expected for ^{149}Dy would be $0.4\leqslant I_{pop}(\%)\leqslant 0.8$. Thus, with our experimental sensitivity it would be expected that a discrete SD band could be observed for ^{150}Dy, but not in ^{149}Dy.

Another possibility is that the available SD intensity is spread over a large number of discrete bands, with no one band dominating the population. This possibility arises when there exists a large level density of states close to the nuclear Fermi surface. In this case the majority of the SD intensity should be evident in ridge structures, as appears to be the case here. Such behavior is indicative of the predictions of Nazarewicz *et al.*. [5], who suggested that the $N=84$ shell closure would polarize the nuclear shape to lower deformations than the higher-mass isotopes of dysprosium, in turn leading to an increased proton level density at the Fermi surface (cf Sec. 4.5 of Ref. [5]). The most strongly populated SD band in ^{150}Dy is predicted [5] to have the configuration $\pi 6^4 \nu 7^1$ (i.e., the lowest two orbitals from the proton $i_{13/2}$ shell occupied and the $\alpha=1/2$ signature of the [770]1/2 orbital) with a corresponding quadrupole deformation of $\beta_2\approx 0.58$. At this deformation Woods-Saxon calculations for the proton single-particle Routhians (see, for example, Figs. 1 and 4 in Ref. [5]) indicate that the proton [651]3/2, [530]1/2, [404]9/2, [411]3/2, and [523]7/2 orbitals are nearly degenerate, thus increasing the density of states available for occupation by the protons at the Fermi surface. An analogy to this behavior is found in $^{147}_{63}$Eu$_{84}$. Haslip *et al.* [18] observed five SD bands in ^{147}Eu, the yrast band being populated with $\approx 0.44\%$ of the reaction channel to ^{147}Eu, while the four excited bands were populated with similar intensities relative to the yrast band ($91\pm 9\%$, $63\pm 6\%$, $69\pm 7\%$, and $50\pm 5\%$, respectively). This high population intensity of the excited bands, three of which are based on proton excitations from the ''core,'' suggests a high level density at the proton Fermi surface, leading to a large number of orbitals available for population. If the resolving power of the spectrometer used to study ^{147}Eu had been insufficient to observe the discrete line bands, then a structure similar to that resolved from these data would have been evident in an E_γ-E_γ correlation matrix.

Finally it is possible that any SD band in ^{150}Dy has an irregular moment of inertia or a small number of transitions. Either of these possibilities would make the experimental observation of SD states very difficult.

In summary, no evidence for discrete line SD bands has been observed in either ^{149}Dy or ^{150}Dy, following the reaction ^{120}Sn(^{34}S,xn)$^{154-x}$Dy. Evidence for a weak continuum of SD states is presented. Using simulated data, an upper limit of 0.8% (0.9%) for the population of the strongest SD band in ^{150}Dy (^{149}Dy) has been determined. Evidence of SD states is presented via the observation of a ridge in an E_γ-E_γ correlation matrix, leading to a total SD population intensity of $1.8\pm 0.5\%$. These results are compared with the available data for the adjacent SD nuclei. It is suggested that this low SD intensity and lack of observation of a discrete line SD band can be attributed to the breakdown of the shell closure at $Z=66$.

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[1] Table of Superdeformed Bands and Fission Isomers, B. Singh, R.B. Firestone, and S.Y.F. Chu, Nucl. Data Sheets **78**, 1 (1996).
[2] E.g., C.E. Svensson *et al.*, Phys. Rev. Lett. **82**, 3400 (1999), and references therein.
[3] J. Dudek and W. Nazarewicz, Phys. Rev. C **31**, 298 (1985).
[4] R.R. Chasman, Phys. Rev. Lett. **187**, 219 (1987).
[5] W. Nazarewicz, R. Wyss, and A. Johnsson, Nucl. Phys. **A503**, 285 (1989).
[6] T. Werner and J. Dudek, Phys. Rev. C **44**, R948 (1991).
[7] D. Nisius *et al.*, Phys. Rev. C **51**, R1061 (1995).
[8] S.M. Fischer *et al.*, Phys. Rev. C **54**, R2806 (1996).
[9] M.J.A. de Voigt, J.C. Bacelar, E.M. Beck, M.A. Deleplanque, R.M. Diamond, J.E. Draper, H.J. Riezebos, and F.S. Stephens, Phys. Rev. Lett. **59**, 270 (1987).
[10] P.J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
[11] L. Bernstein *et al.*, Phys. Rev. C **52**, R1171 (1995).
[12] C. W. Beausang *et al.* (unpublished).
[13] P.M. Jones *et al.*, Nucl. Instrum. Methods Phys. Res. A **362**, 556 (1995).
[14] J.K. Johansson *et al.*, Phys. Rev. Lett. **63**, 2200 (1989); D.S. Haslip, G. Hackman, and J.C. Waddington, Nucl. Instrum. Methods Phys. Res. A **345**, 534 (1994).
[15] J.N. Wilson and D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **385**, 108 (1997).
[16] J. Dudek, T. Werner, and L.L. Riedinger, Phys. Lett. B **213**, 120 (1988).
[17] G. de. France *et al.*, Phys. Lett. B **331**, 290 (1994).
[18] D.S. Haslip *et al.*, Phys. Rev. C **57**, 2196 (1998).