PHYSICAL REVIEW C VOLUME 54, NUMBER 6 DECEMBER 1996

Superdeformed band in ^{155}Dy: Where does the ''island'' of superdeformation end?

S. M. Fischer,[1] R. V. F. Janssens,[1] M. A. Riley,[2] R. R. Chasman,[1] I. Ahmad,[1] D. J. Blumenthal,[1] T. B. Brown,[2]
M. P. Carpenter,[1] G. Hackman,[1] D. J. Hartley,[2] T. L. Khoo,[1] T. Lauritsen,[1] W. C. Ma,[3] D. Nisius,[1]
J. Simpson,[4] and P. G. Varmette[3]
[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Florida State University, Tallahassee, Florida 32306*
[3]*Mississippi State University, Mississippi State, Mississippi 39762*
[4]*CCLRC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
(Received 9 September 1996)

A superdeformed band of 15 transitions has been found in the ^{155}Dy nucleus. The measurement was performed with a backed target and the large deformation was inferred from the measured Doppler shifts. The new band displays an intensity pattern much different from typical superdeformed bands in this mass region. The dynamic moment of inertia is essentially identical to that of band 1 in ^{153}Dy and is somewhat larger than those of the yrast superdeformed bands in ^{152,154}Dy, suggesting that the associated configuration has an additional $N=7$, $j_{15/2}$ intruder orbital occupied with respect to the ^{154}Dy core. [S0556-2813(96)50512-1]

PACS number(s): 21.10.Re, 21.10.Tg, 23.20.Lv, 27.70.+q

The recent discovery of a superdeformed (SD) band in ^{154}Dy [1] has been viewed as somewhat of a surprise as none of the cranked mean-field calculations, which have been so successful in predicting the existence of the island of SD nuclei near ^{152}Dy [2–5], had suggested that a SD band would be observed in ^{154}Dy. In these calculations the SD minimum is less pronounced than in, e.g., ^{152}Dy and, more importantly, the minimum is not predicted to be yrast or near yrast at spins $I<65\hbar$ where the known SD bands of this region are thought to be populated. Thus, the observation of the ^{154}Dy SD band raises issues about the limits of the region of superdeformation centered around the doubly magic SD nucleus ^{152}Dy and/or about the feeding mechanism of the SD bands. In order to investigate these questions further, an experiment was performed to study the nucleus ^{155}Dy. This measurement was also motivated by recent calculations [6] suggesting the presence at the highest spins of collective excitations having moments of inertia $\sim$10–15% larger than that of SD nuclei around ^{152}Dy and corresponding to shapes with a somewhat larger elongation.

Here we report on the discovery of a weak SD band in ^{155}Dy. The experiment was performed with a backed target, and the measured Doppler shifts confirm that the associated deformation is indeed very large. This result can be viewed as an indication that the shell effects remain strong as one moves three neutrons away from the $N=86$ SD shell gap. Furthermore, from a comparison of the dynamic moment of inertia $\mathfrak{I}^{(2)}$ with those of the neighboring nuclei, a configuration can be proposed. Finally, the intensity profile in the SD band and the absolute intensity with which the band is fed suggest that it is located at higher excitation energy than in lighter Dy isotopes.

States in ^{155}Dy were populated via the ^{124}Sn(^{36}S,5n) reaction with a 175 MeV beam from the Lawrence Berkeley Laboratory 88 in. Cyclotron. The target consisted of a 1 mg/cm^2 ^{124}Sn layer evaporated on 15 mg/cm^2 of Au, with a thin 50 μg/cm^2 buffer layer of Al between the Sn and Au to prevent the migration of the Sn material into the Au stopper. The decay γ rays were detected with the Gammasphere spectrometer [7], which consisted at that time of 67 Compton-suppressed Ge detectors. A total of 1.6×10^9 events was collected where five or more suppressed Ge detectors were required to fire in prompt coincidence. The data were analyzed by sorting all events into a three-dimensional histogram. The initial sort was performed assuming that all γ rays are emitted with the full Doppler shift corresponding to the velocity of the compound nucleus at the center of the target (β_0 = 0.0227), as is appropriate for transitions associated with the deexcitation of a SD band. Double-gated one-dimensional histograms were created using full background subtraction and proper propagation of errors [8].

A systematic search through the coincidence cube uncovered two weak bands (see Fig. 1): one corresponds to the ^{154}Dy SD band reported by Nisius *et al.* [1] while the other is new to this work. Its assignment to a particular nucleus is complicated by the fact that transitions in a SD band are emitted with approximately the full Doppler shift, while the majority of transitions between normal deformed states are emitted from a nucleus at rest. Thus, the yrast transitions that would normally identify the nucleus to which a band belongs do not appear as sharp peaks in a spectrum where all energies have been corrected for the full Doppler shift. For this reason, another three-dimensional histogram was created such that the full Doppler shift correction was applied only to γ rays with energies larger than 900 keV (i.e., the spectral region including the new band), while no Doppler shift correction was used for γ rays below this energy. The coincidence relationships from this new cube revealed that the band can be firmly assigned to ^{155}Dy. For example, spectra resulting from the sum of double coincidence gates including one transition from the yrast band in ^{155}Dy [9] and one transition from the new band produce a spectrum analogous to that of Fig. 1. In contrast, similar sum spectra with one of the gates placed on yrast transitions in either ^{154}Dy or ^{156}Dy (from the two competing reaction channels present in the data) did not show evidence for this new sequence of γ rays. The new band is therefore assigned to the ^{155}Dy nucleus,

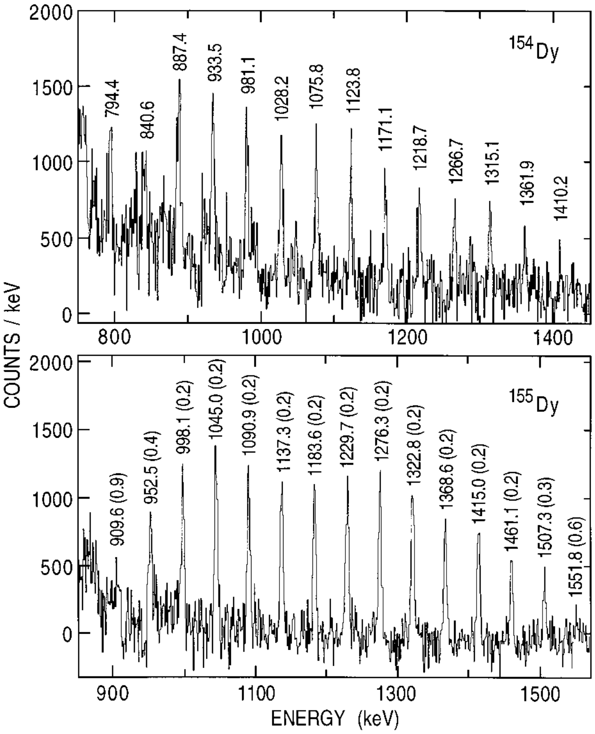

FIG. 1. Sum of double-gated coincidence spectra showing the two SD bands observed in this work. A full Doppler shift correction has been applied to the data (see text for details). The upper panel shows the SD band of ^{154}Dy, with transitions labeled by the energies of Ref. [1]. The lower panel shows the new SD band of ^{155}Dy. The transitions and the associated errors are given in keV.

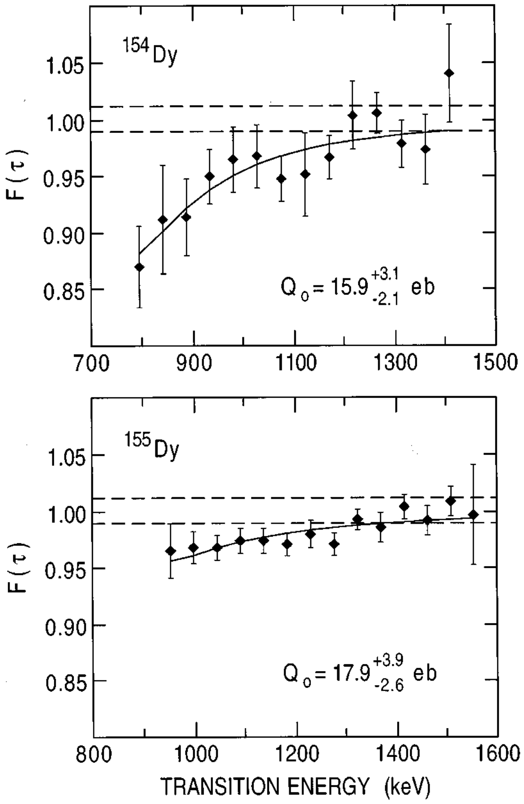

FIG. 2. Values of the fraction of full Doppler shift $F(\tau)$, obtained for the SD bands in ^{154}Dy (upper panel) and ^{155}Dy (lower panel). The dashed curves represent the spread in full shift due to the slowing down of the beam across the target. The solid curves represent the best fit to the data, with the resulting Q_0 moments indicated in each panel.

with an intensity that was measured to be $\leq$ 0.5% of the total γ-ray flux feeding the ^{155}Dy ground state. Unfortunately, unlike in ^{154}Dy [1], the small intensity of the new band combined with the fragmented nature of the yrast and near-yrast band structure of ^{155}Dy made it impossible to delineate the decay profile of the band into the yrast states.

This new band displays many of the characteristics of known SD bands in the $A\sim150$ region: i.e., (1) A long, regular sequence of 15 transitions in coincidence with one another (see Fig. 1); (2) energy spacings between transitions in the band ($\sim$48 keV) very similar to those of known SD bands in the $A\sim150$ region [10]; and (3) an in-band γ-ray intensity that increases with decreasing transition energy until a constant value is reached before a sudden decay out occurs over 1–2 transitions at the lowest energies. Beyond these familiar characteristics in the intensity pattern, there are also marked differences (i.e., the "plateau" in the intensity pattern and the decay out both occur at higher frequencies than in the other SD bands); these will be discussed below.

Confirmation of the large deformation associated with the new band was derived from a lifetime analysis (DSAM). As pointed out above, Fig. 1 was obtained after a correction for full Doppler shift and all the γ rays in the figure are clearly emitted before substantial slowing down in the Au stopper took place, indicating lifetimes much shorter than the stopping time ($\sim$ 3 ps). In another analysis, the data were sorted according to the detector angles and the customary fractions of full Doppler shift $F(\tau)$ were measured. These are presented in Fig. 2 for both bands together with calculated curves corresponding to the best values obtained for the quadrupole moment Q_0. The calculations were performed with the code FITFTAU which is described fully in Refs. [11,12]. The average recoil velocity at which the decay from a particular SD state occurs is calculated under the following assumptions: (1) The Q_0 values are postulated to be the same for all SD levels within a band, (2) the sidefeeding into each SD state is approximated by a single rotational cascade of five transitions, having the same dynamic moment of inertia $\mathfrak{I}^{(2)}$ as the main band, controlled by a sidefeeding quadrupole moment $Q_{\rm sf}$ which is assumed to remain the same throughout an entire SD band (this description of the sidefeeding is one of the most commonly used in this type of analysis [11–13]). The detailed slowing down histories in the target, in the Al buffer and in the Au backing were calculated with the 1995 version of the code TRIM by Ziegler [14], which uses the most recent and complete evaluation of existing stopping-power data. From Fig. 2, it is clear that the ^{154}Dy band is associated with a large quadrupole moment ($Q_0 = 15.9\pm^{3.1}_{2.1}$ eb, $10 \leq Q_{\rm sf} \leq 30$ eb), even though the errors on the $F(\tau)$ values are large. Thus, the present data confirm the occurrence of superdeformation in ^{154}Dy as proposed in Ref. [1]. In the case of the band in ^{155}Dy, a fit to the measured $F(\tau)$ values yields a value $Q_0 = 17.9\pm^{3.9}_{2.6}$ eb, with the same large uncertainties on $Q_{\rm sf}$ as in the ^{154}Dy case. This Q_0 value is consistent with a β_2 deformation close to 0.6. In

TABLE I. Comparison of the Q_0 values extracted from this experiment with those from Refs. [11,13]. As stated in the text, the values quoted here have all been obtained under similar experimental conditions and, hence, can be compared without suffering from the usual ~15% systematic uncertainty associated with the stopping powers.

Nucleus	Q_0^{exp}	Intruder conf.	Reference
^{151}Dy	$16.9(\pm^{0.2}_{0.3})$	$\pi 6^4 \nu 7^1$	[11]
^{152}Dy	17.5(0.2)	$\pi 6^4 \nu 7^2$	[13]
	$17.5(\pm^{0.4}_{0.2})$		[11]
^{154}Dy	$15.9(\pm^{3.1}_{2.1})$	$\pi 6^4 \nu 7^2$	This work
^{155}Dy	$17.9(\pm^{3.9}_{2.6})$	$\pi 6^4 \nu 7^3$	This work

this case, the accuracy is limited not only by the statistical accuracy of the $F(\tau)$ values, but also by the fact that the decay out of the SD band occurs at a rather high frequency. This has the unfortunate consequence that the $F(\tau)$ values remain close to unity throughout the entire cascade, i.e., unlike in other SD nuclei of this mass region, they never reach values between 0.5 and 0.8 where the sensitivity to the Q_0 value is the largest. While a Q_0 determination comparable in accuracy to those made recently in other SD nuclei [11,13] of the region is impossible, the SD character of the new band is, nevertheless, established beyond any doubt. Furthermore, as the experimental conditions (recoil velocity of the residues and stopping material) are essentially the same as those in Refs. [11,13], the Q_0 values presented here can be compared directly with those reported for the isotopes ^{151,152}Dy without invoking a ~15% uncertainty associated with the knowledge of the stopping powers. Such a comparison is given in Table I.

The dynamic moment of inertia $\mathfrak{J}^{(2)}$ for the new SD band is presented as a function of the average rotational frequency $\hbar\omega$ in Fig. 3. The same figure also provides a comparison with the $\mathfrak{J}^{(2)}$ values of the yrast SD bands in ^{152,153}Dy [16–19] and of the ^{154}Dy SD band. From the figure, a striking ''identicality'' can be noted between the $\mathfrak{J}^{(2)}$ moments in the odd nuclei on the one hand, and in the even nuclei on the other. Furthermore, the $\mathfrak{J}^{(2)}$ moments in the odd nuclei are larger over the entire $\hbar\omega$ range than those of the even isotopes by ~4%. These features can be used to propose a configuration for the new SD band. As was first shown by Bengtsson *et al.* [15], the behavior of $\mathfrak{J}^{(2)}$ with respect to $\hbar\omega$ is mainly influenced by the number of high-N intruder orbitals occupied, and differences in the $\mathfrak{J}^{(2)}$ moments between SD bands have been used to determine the occupation of specific high-N orbitals [10]. Thus, it appears that the configuration associated with the ^{155}Dy SD band includes the same high-N intruder orbitals as ^{153}Dy–band 1, i.e., in the language of Ref. [15], a $\pi 6^4 \nu 7^3$ configuration is proposed, where four $i_{13/2}$ proton and three $j_{15/2}$ neutron intruder orbitals are occupied. It is worth noting that this assignment implies that the yrast SD configurations in the two odd-neutron nuclei involve one more $j_{15/2}$ intruder orbital than in the respective cores. As pointed out in Ref. [1], this observation is best understood (at least for the ^{154,155}Dy pair) if a small change in β_2 deformation is postulated to occur, i.e., [$\beta_2(^{154}\mathrm{Dy}) \sim 0.57$] < [$\beta_2(^{155}\mathrm{Dy}) \sim 0.6$], where the difference reflects the shape driving effects of the additional intruder orbital. Unfortunately, the accuracy in the Q_0 determinations reported here is not sufficient to verify this point.

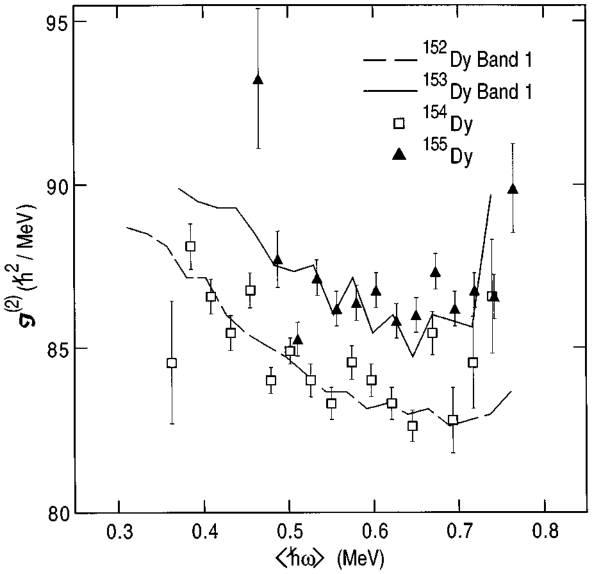

FIG. 3. Dynamic moments of inertia $\mathfrak{J}^{(2)}$, as a function of average rotational frequency $\hbar\omega$ for the yrast SD bands in ^{152}Dy [16,17] , ^{153}Dy [18,19], ^{154}Dy [1], and ^{155}Dy. The striking similarity of the $\mathfrak{J}^{(2)}$ moments in both the odd-A pair and the even-A pair of nuclei is obvious. The associated configurations are discussed in the text.

As mentioned above, mean-field calculations of Refs. [2–5] do not predict the SD minimum in ^{155}Dy to come near the yrast line in the spin range reached in the present reaction. However, it is worthwhile to revisit this issue using the latest cranked Strutinsky calculations of Chasman [6]. The latter indicate that in ^{155}Dy a SD band (with a $\mathfrak{J}^{(2)}$ moment ~4% larger than that of the ^{152}Dy band, in excellent agreement with the average experimental value) becomes yrast at $I \sim 70\hbar$ relative to a noncollective oblate minimum. This SD band also crosses the normally deformed prolate minimum at somewhat lower spin ($I \sim 66\hbar$). For comparison, the same crossing between SD and normally deformed prolate minima is calculated to occur at $I = 62\hbar$ in ^{154}Dy. Several features of the present data can be viewed as indications that, if the ^{155}Dy SD band ever becomes yrast or near yrast, it does so at higher spin than the corresponding bands in the lighter isotopes. First, the trend of a reduction of the population intensity (with respect to that seen in ^{152}Dy [16]), which was first noted in ^{154}Dy [1], is accentuated in ^{155}Dy: the population is of the order of ~2% in the light Dy isotopes [16,18], drops to 0.6% in ^{154}Dy and below 0.5% in ^{155}Dy. Furthermore, the comparison of the intensity profiles in the ^{155,154,152}Dy SD bands (see Fig. 4) indicates that the sidefeeding into the new SD band ceases at a transition energy of ~ 1400 keV, i.e., much higher than in the two lighter nuclei where the 100% intensity level is reached for transitions energies ⩽ 1200 keV. These two observations can be related to the excitation energy of the SD band in the following way. Calculations describing the feeding of SD states [20,21] have shown that

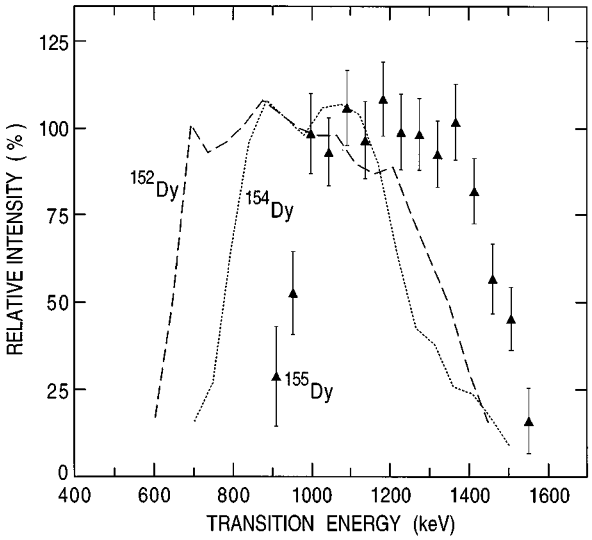

FIG. 4. Intensity profiles of the yrast SD bands of ^{152,154,155}Dy. Note that the sidefeeding into the ^{155}Dy SD band ceases at a transition energy approximately 200 keV higher than for the ^{152,154}Dy SD bands. A clear mass dependence is also present for the decay out of the SD bands.

these levels are fed only from a subset of entry states in the residual nucleus located at the highest spins and excitation energies. This reflects the fact that statistical feeding (of the SD levels) will occur only in the region where the SD level density is higher than that of the normal deformed states, i.e., in the high-spin region where the SD band is near yrast. Conversely, the statistical decay from the entry states tends to bypass the SD levels once the latter are located high above the yrast line as the level density for normal states becomes larger than that for SD levels. In other words, cooling from the entry states proceeds more effectively by deexcitation towards the states of smaller deformation in this case. The impact of these considerations on the intensity profile in the SD bands is clear: the in-band intensity will grow with decreasing γ-ray energy (reflecting the entry states intensity distribution) only until the SD band is no longer in the yrast region, at which point the intensity becomes constant and a ''plateau'' in the intensity profile develops. Thus, under the assumptions that this picture of the feeding of the SD bands is valid and that transition energies can be related directly to spin, the ^{155}Dy intensity pattern implies that the SD band is fed from an entry region narrower in spin and located at higher angular momentum than in the lighter Dy isotopes. Whether a higher-energy SD band alone can account for the observations needs to be studied in more detail with a model describing the feeding of SD bands. Indeed, other parameters such as the height and width of the barrier separating SD and normal states also affect the intensity [20,21]. Furthermore, while the qualitative arguments given above explain the variation of the absolute intensity with mass number, they do not account for the similarity of the intensity patterns seen at high transition energies in ^{154}Dy and ^{152}Dy as ^{154}Dy is also calculated to become yrast at higher spin than ^{152}Dy, yet displays the same profile (Fig. 4).

From Fig. 4 it is also clear that the trend noted in Ref. [1] for the point at which the decay out of the SD bands occurs is amplified in ^{155}Dy: the lowest transition to carry more than 50% of the in-band intensity has an energy of 693 keV in ^{152}Dy, 795 keV in ^{154}Dy, and 952 keV in ^{155}Dy. Such a trend would be expected if the excitation energy of the SD band continued to increase with mass and/or if the height of the potential barrier separating the SD minimum from the yrast minimum decreases with increasing mass. The calculations of Ref. [6] for the Dy isotopes indicate that at $I=40\hbar$ the height of the inner barrier is 2.5, 2.0, 1.5, and 0.7 MeV respectively when going from $A=152$ to $A=155$, while the corresponding values for the excitation energy relative to the yrast state are 4.0, 4.9, 5.4, and 6.3 MeV. Considering the small value of the inner barrier and the high excitation energy, it remains surprising that the minimum in ^{155}Dy sustains a SD band at $I=40\hbar$. Clearly, measurements of (i) energy and spin distributions leading to the SD states in ^{154,155}Dy and of (ii) the complete spectrum of γ rays connecting SD and ''normal'' states in both nuclei would allow some of the issues about feeding and decay raised here to be addressed in more detail.

Finally, returning to the calculations of Ref. [6], it is worth noting that the SD band in ^{155}Dy was calculated to be crossed around $65\hbar$ by a rotational band associated with a larger elongation and a $\mathfrak{J}^{(2)}$ moment of $\sim 100\hbar^2$ MeV^{-1}. Searches for a sequence of γ-ray transitions with the energy spacings ΔE_γ between 30 and 50 keV performed with the code ANDband [22] offer no firm evidence for a band of this character.

To summarize, the data above establish the presence of superdeformation in the ^{155}Dy nucleus and some aspects of data also suggest that the SD band is located at higher excitation energy than in lighter Dy isotopes. It is clearly of interest to extend SD studies to ^{156}Dy. Such studies are necessary not only to establish whether the shores of the island of superdeformation have finally been reached at neutron number $N=89$, but also to explore further the possibility that bands associated with more elongated shapes might be present at the highest angular momenta in this heavier Dy isotope.

This work is supported in part by the Department of Energy, Nuclear Physics Division, under Contracts Nos. W-31-109-ENG-38 (ANL) and DE-FG05-95ER40939 (MSU), and by the National Science Foundation and the State of Florida (FSU). M.A.R. and J.S. acknowledge the receipt of a NATO Collaborative Research Grant.

---

[1] D. Nisius *et al.*, Phys. Rev. C **51**, R1061 (1995).
[2] J. Dudek and W. Nazarewicz, Phys. Rev. C **31**, 298 (1985).
[3] W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A503**, 285 (1989).
[4] T. Werner and J. Dudek, Phys. Rev. C **44**, R498 (1991).
[5] R.R. Chasman, Phys. Lett. B **187**, 219 (1987).
[6] R.R. Chasman, Phys. Lett. B **364**, 137 (1995).
[7] I.Y. Lee, Nucl. Phys. **A520**, 614c (1990).
[8] B. Crowell *et al.*, Nucl. Instrum. Methods Phys. Res. A **355**, 575 (1995).

[9] R. Vlastou *et al.*, Nucl. Phys. **A580**, 133 (1994).

[10] R.V.F. Janssens and T.L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 301 (1991).

[11] D. Nisius *et al.* (to be published).

[12] E.F. Moore *et al.*, in *Proceedings of the Workshop on Gammasphere Physics*, Berkeley, 1995, edited by M.A. Deleplanque, I.-Y. Lee, and A.O. Machiavelli (World Scientific, Singapore, 1996), p. 137.

[13] H. Savajols *et al.*, Phys. Rev. Lett. **76**, 4480 (1996).

[14] J.F. Ziegler, J.P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon, New York, 1985); J.F. Ziegler (private communication).

[15] T. Bengtsson, I. Ragnarsson, and S. Aberg, Phys. Lett. B **208**, 39 (1988).

[16] P.J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986); M.A. Bentley *et al.*, J. Phys. G **17**, 481 (1991).

[17] P.J. Dagnall *et al.*, Phys. Lett. B **355**, 313 (1994).

[18] J.K. Johansson *et al.*, Phys. Rev. Lett. **63**, 2200 (1989).

[19] B. Cederwall *et al.*, Phys. Lett. B **346**, 244 (1995).

[20] K. Schiffer, B. Herskind, and J. Gascon, Z. Phys. A **332**, 17 (1989).

[21] T. Lauritsen *et al.*, Phys. Rev. Lett. **69**, 2479 (1992).

[22] D.S. Haslip, G. Hackman, and J.C. Waddington, Nucl. Instrum. Methods Phys. Res. A **345**, 534 (1994).