Superdeformed Bands at High Spin in $Z=66$ and 68 Isotopes

M. J. A. de Voigt,[a] J. C. Bacelar, E. M. Beck, M. A. Deleplanque, R. M. Diamond, J. E. Draper,[b] H. J. Riezebos,[a] and F. S. Stephens

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 17 November 1986)

The nucleus ^{152}Dy, with sharp ridges in the γ-γ energy correlation matrix, stands out from three neighboring nuclei which exhibit less pronounced structures. The ridges include the observed discrete superdeformed band, but must be composed mainly of unresolved superdeformed bands, which decay predominantly to less deformed states. A simple decay model is proposed.

PACS numbers: 21.10.Re, 23.20.Lv, 27.70.+q

The previously reported[1] observation of a discrete superdeformed (SD) rotational band in the nucleus ^{152}Dy established the existence of a strongly deformed prolate shape down to spin $\simeq 26$. This finding followed the reports[2,3] on the coexistence of "normal" prolate and oblate structures up to spin 40. The moment of inertia associated with the observed[4] ridges in the γ-γ correlation matrix is $J^{(2)}=85\pm 2$ MeV$^{-1}\hbar^2$, which corresponds to a deformation of $\epsilon=0.51$ (if one assumes rigid flow). This deformation is not far from the value $\epsilon=0.6$, corresponding to a ratio of 2:1 for the nuclear principal axes, found earlier for some fission isomers. Further evidence of large deformations associated with the ridges in the ^{152}Dy matrix has been derived[5] from the measured fast lifetime limits. Calculations indicate[6,7] favorable conditions for SD states at high spin ($\simeq 50$–60) in rare-earth nuclei near the $Z=64$ and $N=82$ closed shells.

In this paper we investigate further the SD states in ^{152}Dy and neighboring nuclei. In contrast with the sharp ridges in ^{152}Dy we find the ridges broadened in ^{154}Er and smeared out in ^{150}Dy. In ^{150}Dy the valley is pronounced, but hardly visible in ^{154}Er. In the case of ^{156}Er no special structures can be identified with statistical significance. Details of the special deexcitation of the discrete SD band in ^{152}Dy and of the other SD structures are derived from the correlation matrices and from double-gated discrete-line spectra.

We have employed the High-Energy-Resolution Array (HERA), with 21 bismuth germanrate (BGO) Compton-suppressed Ge detectors, at the Berkeley 88-in. cylcotron and measured $E_\gamma(1)$-$E_\gamma(2)$ correlations. Thin targets of $\simeq 500$ μg/cm^2 of enriched ^{114,116}Cd and ^{118,120}Sn were bombarded with 180-MeV ^{40}Ar beams. The recoils were stopped in a lead catcher, positioned at a distance of 20 cm behind the target in the case of ^{151,152}Dy, which corresponds to a flight time of $\simeq 20$ ns, and at a distance of 13 cm in the other cases. For this particular application, the Ge detector at 0° was removed and its BGO anti-Compton shield, which surrounded the beam pipe at the position of the catcher foil, provided a signal to indicate delayed γ-ray emission of recoils. The prompt γ rays were measured with the twenty Compton-suppressed Ge detectors. A total of about 2×10^8 threefold and higher-fold events were recorded. The time difference between the delayed radiation, observed in the 0° BGO, and the first prompt Ge detector was also recorded whenever a delayed event occurred.

These events were sorted into a matrix of double coincidences, $E_\gamma(1)$ vs $E_\gamma(2)$, which was symmetrized and corrected for uncorrelated events.[8] Matrices were also updated in the case that delayed γ rays were detected in the time ranges of 5–33 and 60–260 ns as well as for prompt γ rays only. Matrices for the four cases studied are labeled by their principal (i.e., $4n$) product and are compared in Fig. 1. The ridge structure is most clearly observed in the ^{152}Dy matrix in the γ-ray energy region 800–1350 keV. Spectra were produced by our making diagonal cuts, 50 keV wide, projecting perpendicular to the $E_\gamma(1)=E_\gamma(2)$ diagonal. This was done for the matrices containing the raw data and the corrected data as well as for unfolded matrices, covering the full energy region of interest, 500–1500 keV. From these spectra the average ridge separation in ^{152}Dy was determined to be 94 ± 4 keV, yielding an average moment of inertia of $J^{(2)}=85\pm 4$ meV$^{-1}\hbar^2$, which is the same as the previously reported value.[4] The average width at FWHM of the ridge is 10 ± 4 keV. From the data we obtain a rather constant intensity along the first ridge in the energy region 800–1350 keV, with an average value of $(5\pm 2)\%$ of the reaction events producing ^{152}Dy. However, the second ridge, corresponding to two nonadjacent transitions (with only one intermediate) appears to be very weak or absent with an upper limit of 20% of the first ridge, that is, less than 1% of the ^{152}Dy reaction events. A sizable fraction, $(35\pm 15)\%$, of the γ-ray flow from the SD states bypasses the 17^+ (60 ns) isomer, as deduced from matrices gated on discrete lines above and below the isomer and from those with and without the delayed γ-ray requirements.

In a comparison of the four matrices in Fig. 1 it is important to distinguish "ridge" width and intensity from those of the "valley." The ridge refers to an excess of events parallel to the matrix diagonal caused by a simple rotational-band decay pattern. The valley intensity is measured by the area missing with respect to the com-

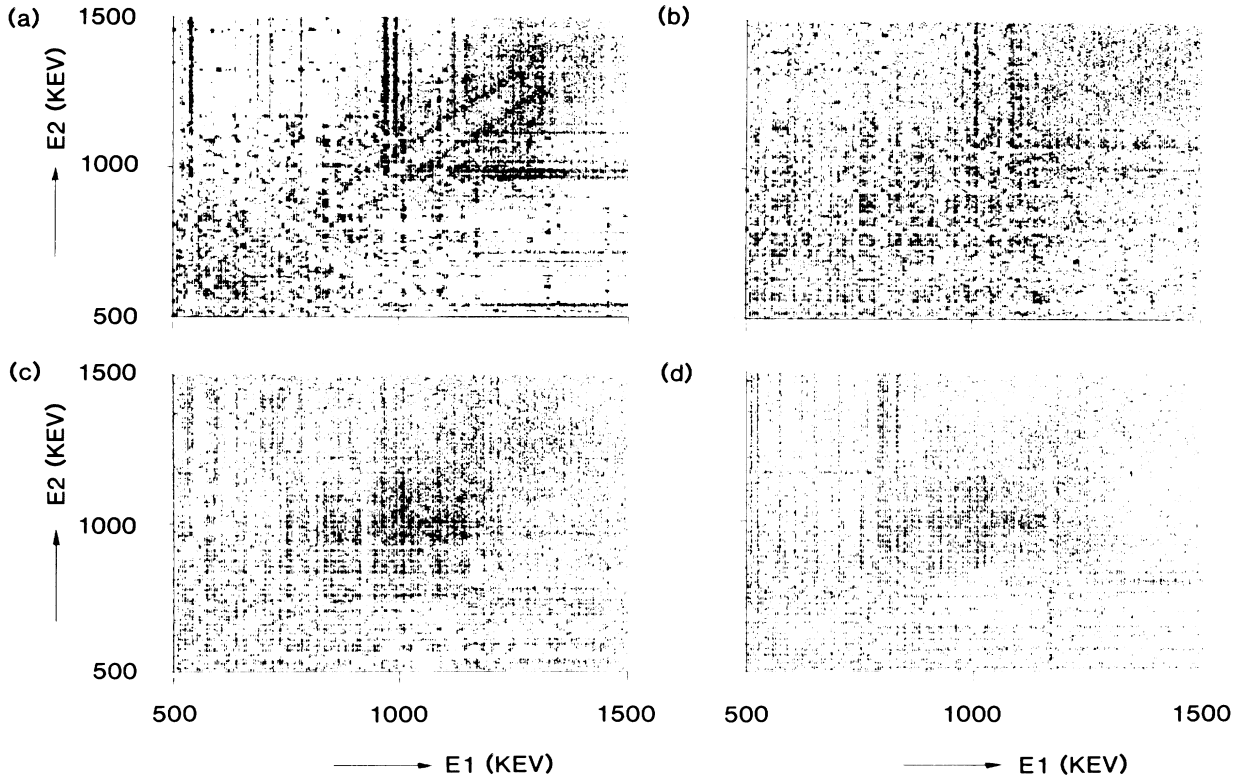

FIG. 1. Symmetrized $E_\gamma(1)$-$E_\gamma(2)$ correlation matrices for the energy region of E_γ=500–1500 keV (2 keV/channel), obtained from (^{40}Ar,xn) reactions at 180 MeV. The matrices are corrected for uncorrelated events. (a) ^{152}Dy, 1.92×10^8 counts in the displayed energy region. The two strong lines in the center are due to the known 968- and 991-keV discrete transitions in ^{152}Dy. (b) ^{150}Dy, 7.3×10^7 counts. (c) ^{154}Er, 6.4×10^7 counts. (d) ^{156}Er, 7.6×10^7 counts.

pletely uncorrelated case. A valley is probably related to the presence of cool rotational bands.[9] The underlying nuclear motion is yet to be fully understood, but the four correlation spectra shown in Fig. 1 show distinctly different behavior. For ^{152}Dy, strong and sharp SD ridges are observed in the high γ-ray energy region above 800 keV, but the valley is rather shallow. In ^{154}Er the ridges may be as strong but are much more spread out (see Fig. 2). This indicates that the spread in the moments of inertia of the SD bands in ^{154}Er is larger than in ^{152}Dy. The valley in ^{154}Er is also quite shallow. For ^{150}Dy only weak ridges are observed but a valley is clearly present (Fig. 2). For ^{156}Er there is little evidence of a ridge or a valley in the correlation plot. It is indeed interesting, but also quite puzzling, that nuclei which have comparable Fermi levels behave so differently at higher spins and temperatures. Gating on discrete lines in ^{151}Dy did reveal a valley as well as weak ridges 94 keV apart. Although this is consistent with the existence of SD bands in ^{151}Dy, the poor statistics does not allow a definite assignment.

Spectra showing the discrete lines of the SD band in ^{152}Dy were produced by our putting double gates at the energies of the known[1] lines. Almost all double-gate

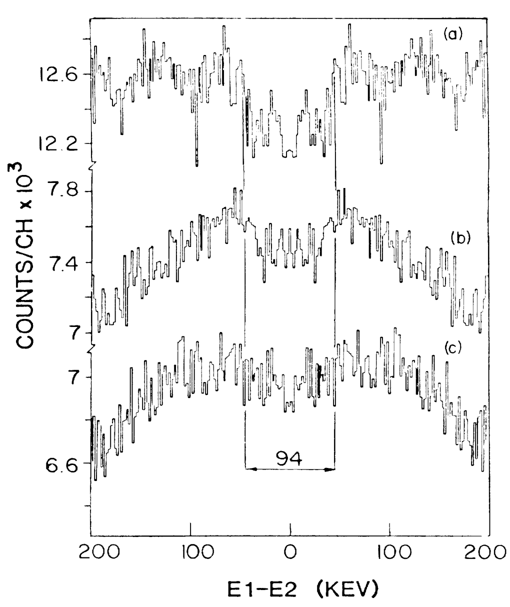

FIG. 2. Projections perpendicular to the $E1=E2$ diagonal in the energy region 800–1350 keV of the raw matrices of ^{150}Dy (curve a), ^{154}Er (curve b), and ^{156}Er (curve c). The spacing between the first ridges of ^{152}Dy is indicated.

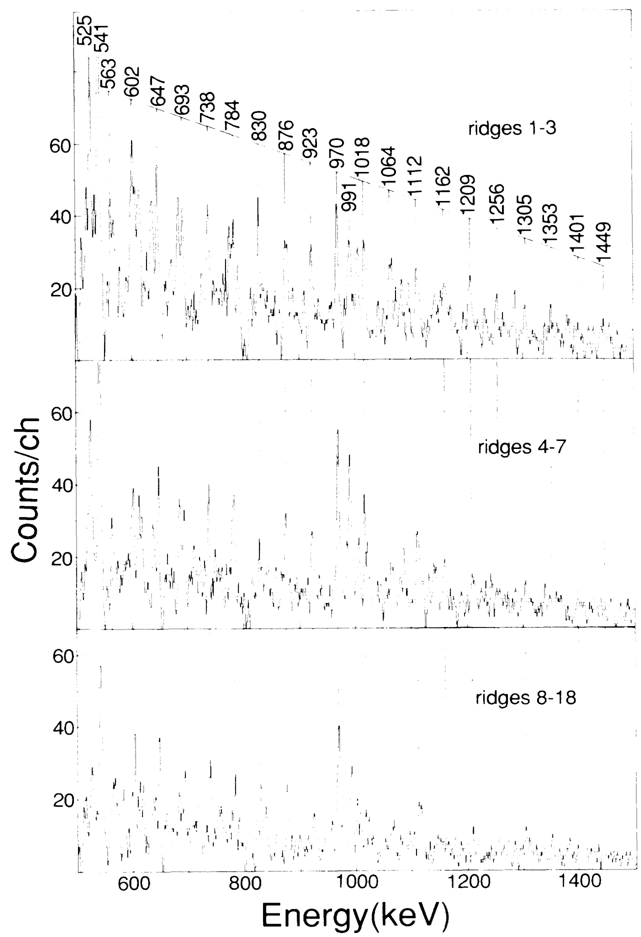

FIG. 3. Comparison of spectra of the third γ ray in coincidence with all possible combinations of two SD discrete-line transitions. The upper spectrum is a sum of combinations within the first three ridges, i.e., gates on any two consecutive transitions, or on those separated by one or two other transitions. The middle spectrum represents the sum of the fourth to the seventh ridges and the lower one the sum of the eighth to the eighteenth ridges. The three spectra are normalized in intensity with respect to the number of possible double-gate combinations. A background has been substracted by use of the full projection of the total (ungated) matrix.

combinations of the nineteen lines were used to update the third coincident γ ray in one of three spectra. These spectra were generated by the summing of contributions from any double-gate combination in the three lowest ridges, the next four ridges, and the highest eleven ridges, and are shown in Fig. 3. They are not very clean, but the existence of the SD lines in comparable intensity in all three spectra is unmistakable. This is the first unambiguous evidence that there is little or no decay out of this SD band over a spin region of $\simeq 35\hbar$, down to the state fed by the 602-keV transition. The discrete SD band was found to comprise $\simeq 0.5\%$ of the reaction events leading to ^{152}Dy.

If the strong first ridge [$(5\pm2)\%$] in the correlation matrix were solely due to the discrete SD band,[1] then it would consist of points 47 keV apart, which is certainly not the case in Fig. 1(a), and would have an intensity about 10 times lower. Also, the second and higher ridges should show up with comparable strength, but they are too weak to be observed in the (ungated) matrix of Fig. 1(a). We conclude that the first ridge represents mainly other SD structures, which do not produce appreciable second and higher ridges. These other SD structures must therefore exhibit a strong out-of-band branching, and consequently they must also be fed over a broad spin region to maintain their intensity. The out-of-band branching has to proceed eventually to other less deformed structures since there is very little sidefeeding into the discrete SD band. The small intensity of the discrete SD bands as compared with that of the first ridge, as well as the different decay pattern of the discrete SD band with respect to the other SD structures, differs from the earlier findings[1] and may be due to higher excitation energy (at a given spin) in the present work.

The different behavior of the discrete band relative to the other SD structures may be explained by a lowering in energy of the discrete band with respect to the others, together with a mixing of SD states with other types of states which are at a high density. Recent calculations[10] indicate that such a lowering of one SD band is possible because of strong shell (or possibly pairing) effects. The large moment of inertia of the discrete SD band brings its lower-spin members continually higher above the yrast line of the less deformed states. These members must then be located in an increasing density of less deformed (background) states, which will eventually lead to a sufficiently close coincidence in energy to mix the SD and background states.[11] This implies that the connection between the discrete SD band and the oblate yrast sequence is made via only one (or a few) mixed states(s), i.e., the lowest-spin member(s) observed. The other SD structures, however, are in a region of much higher (background) level density where this accidental coincidence is much more probable, and thus decay out of the band is rather rapid. We suppose that the feeding into these SD structures is roughly proportional to their level density relative to other types of states.

We would like to thank Dr. S. Patel and Dr. C. Schuck for their assistance in one of the experiments and Dr. W. J. Swiatecki for his interest and suggestions. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

[a]Permanent address: Kernfysisch Versneller Instituut, Rijksuniversiteit, 9747-AA Groningen, The Netherlands.

[b]Permanent address: University of California, Davis, Davis, California 95616.

[1]P. J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
[2]J. Styczen *et al.*, Phys. Rev. Lett. **50**, 1752 (1983).
[3]B. M. Nyakó *et al.*, Phys. Rev. Lett. **56**, 2680 (1986).
[4]B. M. Nyakó *et al.*, Phys. Rev. Lett. **52**, 507 (1984).
[5]P. J. Twin *et al.*, Phys. Rev. Lett. **55**, 1380 (1985).
[6]T. Bengtsson *et al.*, Phys. Scr. **24**, 200 (1981).
[7]J. Dudek and W. Nazarewicz, Phys. Rev. C **31**, 298 (1985).
[8]O. Andersen *et al.*, Phys. Rev. Lett. **43**, 687 (1979).
[9]F. S. Stephens *et al.*, Phys. Rev. Lett. **57**, 2912 (1986).
[10]I. Ragnarsson and S. Aberg, Lund University Report No. MPH-86/11 (to be published).
[11]G. T. Garvey, private communication.