Observation of Superdeformation in ^{152}Dy

B. M. Nyakó,[a] J. R. Cresswell, P. D. Forsyth, D. Howe, P. J. Nolan, M. A. Riley, J. F. Sharpey-Schafer, J. Simpson, and N. J. Ward
Oliver Lodge Laboratory, The University of Liverpool, Liverpool L69 3BX, United Kingdom

and

P. J. Twin
Science and Engineering Research Council, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom

(Received 15 November 1983)

High-resolution, low-background, two-dimensional γ-ray energy correlations $E(\gamma_1)$ vs $E(\gamma_2)$ have been measured at high spin in ^{152}Dy with the spectrometer TESSA2. Ridges characteristic of rotational behavior are observed for γ-ray energies $0.8 \leq E(\gamma) \leq 1.35$ MeV. The separation of the ridges gives a dynamical moment of inertai $\mathscr{g}_{\rm band}^{(2)} = (85 \pm 2)\hbar^2$ MeV^{-1} indicating a quadrupole deformation of $\epsilon \approx 0.51$ for a rigid body assuming $\gamma = 0$.

PACS numbers: 21.10.Ft, 21.10.Re, 23.20.En, 27.70.+q

The nucleus ^{152}Dy is a classic example of a spherical/oblate nucleus containing isomeric states at high spin.[1,2] Along the yrast line it increases its angular momentum by alignment of many high-j single-particle orbitals.[3,4] Recent experiments[5] have shown that a rotational structure, in which two $i_{13/2}$ particles are aligned with the axis of rotation of a weakly deformed core, coexists with the spherical states up to spin $J = 20^+$. Studies[6,7] of the unresolved γ radiation feeding the isomeric states and the spherical/oblate yrast levels below $J = 40$ have shown that between γ-ray energies of 1.0 and 1.5 MeV the average multipolarity of the unresolved radiation is predominantly $E2$ in character. It has been suggested[6] that at spins above $J = 40$ the nucleus could have a strongly deformed prolate shape and produce its high spin by rotation about an axis perpendicular to the symmetry axis.

Calculations of the high-spin structure of nuclei in the region of ^{152}Dy have consistently predicted[8-11] that the nucleus will become prolate with a large deformation before it becomes unstable to fission decay. With use of different cranking approaches[10,11] it is predicted that this superdeformation should occur when the nucleus is a prolate ellipsoid with a major-to-minor axis ratio approaching 2:1. This shape corresponds to deformation parameters of $\epsilon \approx 0.6$ and $\gamma = 0$. Åberg[12] has pointed out that, although the superdeformation is only yrast at the highest spins, most of the decay intensity will remain in this superdeformed structure until it becomes sufficiently nonyrast for the decays out of band to compete with the strongly enhanced in-band $E2$ decays.

To establish such a deformed rotational behavior γ-γ coincidence experiments are required in which the particular nucleus can be preferentially selected from other open channels. The γ-ray energy correlation matrix $E(\gamma_1)$ vs $E(\gamma_2)$ may then be constructed in which the rotational behavior is characterized[13] by ridges parallel to the $E(\gamma_1) = E(\gamma_2)$ diagonal. The dynamical moment of inertia $\mathscr{g}_{\rm band}^{(2)}$ is obtained[13] from the separation of the ridges. High resolution is required in such experiments if a value of $\mathscr{g}_{\rm band}^{(2)}$ is to be obtained that will give accurate information about the nuclear deformation. Also a high instrumental photopeak efficiency is required as the signal in the energy correlation is proportional to p^2 [where p = (photopeak efficiency)/(total efficiency)]. Indeed, in a previous attempt[11] to look for deformed structures in ^{152}Dy, Ge(Li) detectors without Compton suppression ($p^2 < 0.04$) were used and continuous ridge structures could not be discerned in the correlation spectrum.

We have carried out a high-resolution experiment with channel selection and a high value of p using the γ-ray coincidence spectrometer TESSA2.[14] This spectrometer consists of six escape-suppressed germanium (Ge) detectors surrounding a fifty-detector bismuth germanate (BGO) "crystal ball" which indicates the total energy and number of γ rays (multiplicity) in the γ-ray cascade. The suppressed Ge detectors had $p = 0.57$ for 1.2-MeV photons giving $p^2 = 0.32$. The reaction studied was ^{108}Pd(^{48}Ca, $4n$)^{152}Dy at a bombarding energy of 205 MeV and it was estimated that the ^{152}Dy nuclei were produced with angular momenta up to $63\hbar$. The ^{48}Ca beams were supplied by the tandem Van de Graaff Nuclear Structure Facility at the Daresbury Laboratory operating at 18.64 MV with single-stripper operation to provide 7 nA (particle) on the target. The target positioned at the center of the spectrometer consisted of two slightly separated 500-μg-cm^{-2} self-supporting foils. The emitted γ rays were fully Doppler shifted so that the resolution of the γ rays in a Ge detector was governed by the Doppler effect over the solid angle of both detector and recoil cone. The amplifer gain of each Ge detector was adjusted to correct for the relevant Doppler shift. The overall spectrometer resolution was 4.5 keV for a 1-MeV γ ray.

At the bombarding energy chosen the main reaction channels open were $4n$ and $5n$ leading to the final nuclei ^{152,151}Dy. These residual nuclei were allowed to recoil along the beam line so that the BGO crystal ball detected mainly γ-ray decays from levels above the $\tau > 5$ ns isomers in these nuclei. The collimation of the Ge detectors was such that decays occurring more than 20 mm downstream of the target could not be detected. Hence in ^{152}Dy none of the γ rays from levels below the 17^+ 60-ns isomer were seen and the three γ rays below the 21^- 10-ns isomer were observed only very weakly. Events from the $4n$ and $5n$ channels were not completely resolved in plots of BGO total energy versus multiplicity but gates set on such two-dimensional arrays eliminated most of the $5n$ events. We measured the contribution of the other channels to the ^{152}Dy correlation data to be less than 10%.

Figure 1 shows part of the $E(\gamma_1)$-vs-$E(\gamma_2)$ correlation spectrum for γ rays between 0.6 and 1.5 MeV detected in the Ge escape-suppressed spectrometers. In the untreated data the structures of interest exist on a surface of varying intensity. To bring out these features in a conventional intensity plot we have corrected for the response function and the efficiency of the Ge detectors and then flattened the contribution from the average behavior of the unresolved radiation using an iterative technique.[13] The horizontal and vertical stripes in Fig. 1 are due to strong discrete γ rays from yrast levels below $I = 40$. Well defined ridges parallel to the $E(\gamma_1) = E(\gamma_2)$ diagonal extend from 0.80 up to about 1.35 MeV. The ridges could possibly extend to lower γ-ray energies but any ridge structure below 0.8 MeV is masked by intense peaks from discrete lines.

In order to make accurate measurements on these narrow-ridge structures, high resolution must be maintained perpendicular to the $E(\gamma_1)$

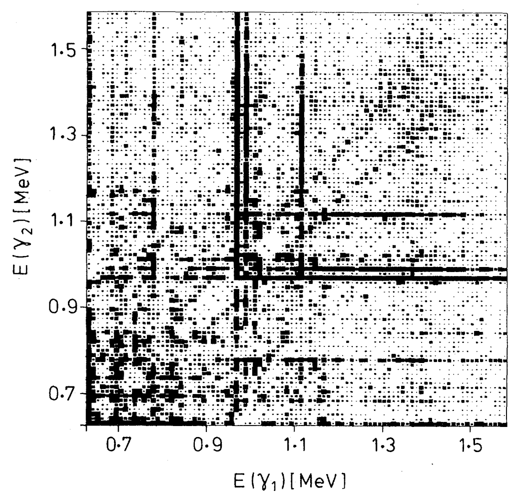

FIG. 1. Correlation spectrum of $E(\gamma_1)$ vs $E(\gamma_2)$ for ^{152}Dy, measured in the Ge escape-suppressed spectrometers. The channel has been selected by use of the BGO crystal ball. Vertical and horizontal stripes are due to discrete lines from yrast γ rays below spin 40. The superdeformed prolate structure is identified by the ridges parallel and close to the $E(\gamma_1) = E(\gamma_2)$ diagonal for energies between 0.80 and 1.35 MeV.

$= E(\gamma_2)$ diagonal. Hence a matrix of $\Delta E(\gamma) = |E(\gamma_1) - E(\gamma_2)|$ vs $\langle E(\gamma)\rangle = \{E(\gamma_1) + E(\gamma_2)\}/2$ was created with dispersions of 1.3 and 5.2 keV/channel, respectively. Figure 2 shows the $\Delta E(\gamma)$ spectrum which results from summation of $\langle E(\gamma)\rangle$ from 785 to 1330 keV for the untreated correlation data after subtraction of contributions from the strongest discrete line at 967 keV. A peak, due to the projection of the ridges in Fig. 1 onto the $\Delta E(\gamma)$ axis, can be seen at $\Delta E(\gamma) = 47 \pm 1$ keV, this being the centroid of a Gaussian fitted to the peak. The fitted Gaussian has a half-width of 6.8 keV which is close to the 6.4-keV instrumental resolution expected from a spectrometer resolution of 4.5 keV. However, the peak must have a finite intrinsic width in order to explain the fact that equally strong peaks are not observed at $\Delta E(\gamma)$ values which are multiples of 47 keV.

With use of the relation $\mathcal{S} = 4\hbar^2/\mathcal{I}_{\rm band}^{(2)}$, where $\mathcal{S} = (47 \pm 1)$ keV is the separation of the ridges from the $E(\gamma_1) = E(\gamma_2)$ diagonal, a value for $\mathcal{I}_{\rm band}^{(2)}$ of $(85 \pm 2)\hbar^2$ MeV^{-1} is obtained. This is 1.4 times the rigid-body moment of inertia for a spherical nucleus of mass number 152, where the latter is given by $0.0139A^{5/3}\hbar^2$ MeV^{-1} (see, e.g., Stevens[15]). Such a large moment of inertia implies that the nucleus must be strongly deformed with a deformation $\epsilon \gtrsim 0.5$, if one assumes only quadrupole deformation.[16] The actu-

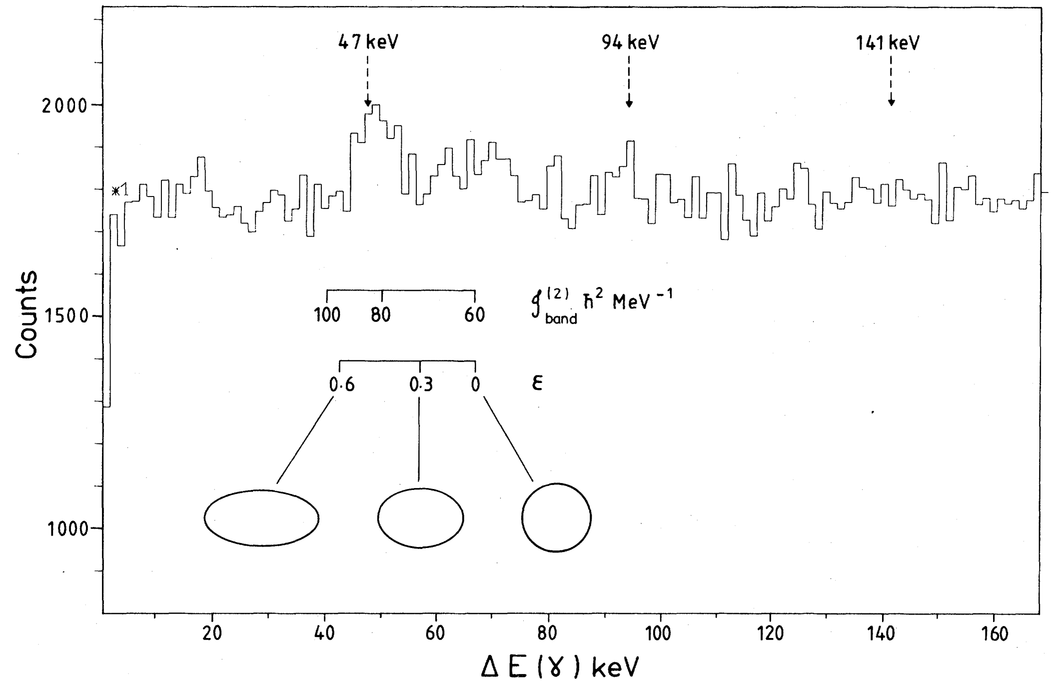

FIG. 2. The spectrum of $\Delta E(\gamma)=|E(\gamma_1)-E(\gamma_2)|$ obtained from the untreated correlation data for ^{152}Dy by summation over values of $\langle E(\gamma)\rangle=\{E(\gamma_1)+E(\gamma_2)\}/2$ from 785 to 1330 keV. The contribution from the discrete line at 967 keV has been subtracted. The arrows show the position of the peak at 47 keV arising from the ridge structure shown in Fig. 1 and the positions where subsidiary peaks might be expected to be seen. Also shown in the figure are scales for $\mathcal{J}_{band}^{(2)}$ and for the deformation ϵ calculated with the assumption of an axially symmetric prolate nucleus and a rigid-body spherical-nucleus moment of inertia of $0.0139A^{5/3}\hbar^2$ MeV^{-1}. Appropriate nuclear shapes for different deformations conserving volume are also shown.

al value depends on the triaxiality of the nucleus, a rigid prolate nucleus having $\epsilon \approx 0.51$. The constancy of $\mathcal{J}_{band}^{(2)}$ along the ridges, which is reflected in the small intrinsic width of the peak in Fig. 2, suggests that the highly deformed shape is particularly stable and hence is associated with a deep minimum in the total energy at the deformation concerned. Thus we conclude that the observed ridge structure corresponds to transitions down one or more rotational bands based on a superdeformed shape.

Theoretical calculations assuming either a Nilsson potential[10] or a Woods-Saxon potential[11] predict such a stable shape over a wide range of nuclear spin at slightly larger prolate deformations (ϵ or β, respectively) around 0.6. Although the calculations predict that the superdeformed shape only becomes yrast at very high spin, the ridge structure is observed over a spin range from about 34 to 58 calculated from the γ-ray energy range 0.80 to 1.35 MeV on the assumption that $I=\mathcal{J}\omega$. The upper value is near the maximum value of the angular momentum carried into the nucleus and this suggests that the superdeformed bands are populated directly by statistical transitions following the formation of the ^{152}Dy nuclei. As mentioned earlier because of the large deformation of these bands the γ-ray strength feeding them will remain in the bands until they become sufficiently nonyrast for the out-of-band transitions to compete with the fast $E2$ in-band transitions. This occurs at around spin 34 or possibly slightly lower if the ridge structure actually continues to lower energy than 800 keV. Such a picture would explain various features regarding the feeding of the yrast levels which have been observed in a study of the reaction ^{122}Sn(^{34}S, 4n)^{152}Dy between 144- and 184-MeV bombarding energy.[17] Firstly, the yrast feeding pattern is insensitive to bombarding energy provided this is large enough. Secondly, the yrast feeding at high bombarding energies is restricted to states in a spin range between 30 and 40. Presumably at higher spins the superdeformed bands are too close in energy to the yrast levels for the out-of-band transitions to compete with the in-band ones.

In conclusion, a ridge structure has been observed in the γ-ray energy correlations in ^{152}Dy which is characteristic of transitions down rotational bands. The separation of the ridges yields a mean value of $\mathscr{G}_{\rm band}^{(2)}$ of $(85\pm 2)\hbar^2$ MeV^{-1}, the small intrinsic width of the ridges reflecting the constancy of $\mathscr{G}_{\rm band}^{(2)}$ along the length of the ridges. This value is considerably larger than that associated with rigid-body rotation of a spherical nucleus and indicates that the nuclear shape is strongly deformed. The data correspond to the nucleus having a prolate deformation with $\epsilon \approx 0.51$ and it is proposed that the observed ridges are composed of transitions in rotational bands based on such a superdeformed shape. The data thus provide the first direct experimental observation of the theoretically predicted superdeformed shapes at high angular momentum.

We would like to thank Mr. J. Reynolds for making the targets, Dr. C. D. Wooff for programming assistance, all those responsible for the design, construction, and setting of TESSA2, and the crew of the Nuclear Structure Facility for their enthusiastic cooperation. This work was supported by grants from the Science and Engineering Research Council, United Kingdom, from whom two of us (D.H. and M.A.R.) received postgraduate studentships during the period of this work.

[a]Permanent address: Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001 Debrecen Pf51, Hungary.

[1]T. L. Khoo, R. K. Smither, B. Haas, O. Häusser, H. R. Andrews, D. Horn, and D. Ward, Phys. Rev. Lett. 41, 1027 (1978).

[2]B. Haas, D. Ward, H. R. Andrews, O. Häusser, A. J. Ferguson, J. F. Sharpey-Schafer, T. K. Alexander, W. Trautmann, D. Horn, P. Taras, P. Skensved, T. L. Khoo, R. K. Smither, I. Ahmad, C. N. Davids, W. Kutschera, S. Levenson, and C. L. Dors, Nucl. Phys. A362, 254 (1981).

[3]B. Haas, H. R. Andrews, O. Häusser, D. Horn, J. F. Sharpey-Schafer, P. Taras, W. Trautmann, D. Ward, T. L. Khoo, and R. K. Smither, Phys. Lett. 84B, 178 (1979).

[4]D. Horn, O. Häusser, I. S. Towner, H. R. Andrews, M. A. Love, and P. Taras, Phys. Rev. Lett. 50, 1447 (1983).

[5]J. Styczen, Y. Nagai, M. Piiparinen, A. Ercan, and P. Kleinheinz, Phys. Rev. Lett. 50, 1752 (1983).

[6]W. Trautmann, J. F. Sharpey-Schafer, H. R. Andrews, B. Haas, O. Häusser, P. Taras, and D. Ward, Phys. Rev. Lett. 43, 991 (1979), and Nucl. Phys. A378, 141 (1982).

[7]D. Ward, H. R. Andrews, B. Haas, P. Taras, and N. Rud, Nucl. Phys. A397, 161 (1983).

[8]R. Bengtsson *et al.*, Phys. Lett. 57B, 301 (1975); G. Andersson *et al.*, Nucl. Phys. A268, 205 (1976).

[9]K. Neergard and V. V. Pashkevich, Phys. Lett. 59B, 218 (1975); K. Neergard, V. V. Pashkevich, and S. Frauendorf, Nucl. Phys. A262, 61 (1976).

[10]I. Ragnarsson, T. Bengtsson, G. Leander, and S. Åberg, Nucl. Phys. A347, 287 (1980); S. Åberg, Phys. Scr. 25, 23 (1982).

[11]Y. Schutz, J. P. Vivien, F. A. Beck, T. Byrski, C. Gehringer, J. C. Merdinger, J. Dudek, W. Nazarewicz, and Z. Symanski, Phys. Rev. Lett. 48, 1534 (1982).

[12]S. Åberg, private communication.

[13]B. Herskind, J. Phys. (Paris), Colloq. 41, C10–106 (1980).

[14]P. J. Twin, P. J. Nolan, R. Aryaeinajad, D. J. G. Love, A. H. Nelson, and A. Kirwan, Nucl. Phys. A409, 343c (1983).

[15]F. S. Stevens, J. Phys. (Paris), Colloq. 41, C10–1 (1980).

[16]D. J. G. Love, private communication.

[17]P. Chowdhury, J. Borggreen, T. L. Khoo, I. Ahmad, R. K. Smither, S. R. Faber, P. J. Daly, C. L. Dors, and J. Wilson, Phys. Rev. Lett. 47, 778 (1981).