First Evidence for the Hyperdeformed Nuclear Shape at High Angular Momentum

A. Galindo-Uribarri,[1] H. R. Andrews,[1] G. C. Ball,[1] T. E. Drake,[2] V. P. Janzen,[1,3]
J. A. Kuehner,[3] S. M. Mullins,[3] L. Persson,[3] D. Prévost,[3] D. C. Radford,[1]
J. C. Waddington,[3] D. Ward,[1] and R. Wyss[4]
[1] *AECL Research, Chalk River Laboratories, Ontario, Canada K0J 1J0*
[2] *Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7*
[3] *Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
[4] *Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831*
(Received 1 February 1993)

A ridge structure consisting of stretched $E2$ transitions and extending from $\hbar\omega \simeq 0.6$ to 0.75 MeV has been found in a proton-selected γ-γ matrix in the reaction ^{120}Sn(^{37}Cl,$p\,xn$)^{152,153}Dy at 187 MeV. The ridge spacing corresponds to a dynamic moment of inertia, $\mathcal{J}^{(2)}$, of about $130\hbar^2$ MeV^{-1} and suggests the existence of a hyperdeformed prolate shape with a quadrupole deformation $\beta_2 \geq 0.9$. Furthermore, a cascade of 10 discrete transitions with an average energy spacing of 30 ± 3 keV has been found. This result is consistent with calculations indicating conditions favorable to hyperdeformed structures.

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

One of the most important developments in nuclear structure physics was the prediction and observation of superdeformed (SD) shapes at high angular momentum. These highly deformed shapes are stabilized by collective rotation unlike the fission isomers in heavy nuclei, for which a minimum in the potential exists even at spin zero. The first experimental observation of superdeformation at high spin was a ridge-valley structure in a γ-γ coincidence matrix for the ^{152}Dy nucleus [1]. Such ridges are generated by rotational transitions which decay down bands of similar moments of inertia; in this case the separation between the ridges corresponded to a moment of inertia, $\mathcal{J}^{(2)}$, of $85\hbar^2$ MeV^{-1} which for rigid rotation implies a deformation parameter $\beta_2 = 0.65$ [2]. Subsequently, SD bands consisting of discrete transitions were discovered in this nucleus [3] and in ^{132}Ce [4] and lifetimes were measured [5, 6]. Intense research activity in this area of nuclear physics has led to the discovery of (i) SD bands in several nuclei in the neighborhood of ^{132}Ce and ^{152}Dy, (ii) multiple SD bands in a single isotope, and (iii) new SD regions at masses $A \sim 190$ and $A \sim 140$ [7, 8]. The theories that have been successful in explaining superdeformation also predict other exotic shapes [9]. In particular, rotational bands built upon hyperdeformed (HD) shapes with axis ratios around 3:1 are expected. In the most favorable cases, these states are predicted to become yrast at spins as low as $70\hbar$, and could therefore be populated in heavy-ion fusion reactions. However, very strong competition is expected from fission, and we may anticipate that only very few fusion residues will survive fission at the angular momentum required to enter the HD shape. Nevertheless, despite the low cross sections expected, the behavior of nuclei at the most extreme deformations and the highest angular momenta is of great interest, and raises many questions. What shape parametrizations will accurately describe the fission barrier? What is the maximum angular momentum that a nucleus is able to sustain?

We report here an experiment which has produced first evidence for hyperdeformation at high angular momentum. It was performed at the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at Chalk River. Gamma rays were detected with the 8π spectrometer, which consists of a ball of 70 bismuth germanate (BGO) crystals and an array of twenty high-resolution Compton-suppressed Ge detectors. Charged particles were detected with a 24-element CsI(Tl)-photodiode detector array [10]. In searching for a manifestation of HD we have used a reaction channel in which a charged particle was evaporated, namely $^{37}\mathrm{Cl} + {}^{120}\mathrm{Sn} \to {}^{156-x}\mathrm{Dy}+p+xn$. The rationale was twofold: first, at the high input angular momenta needed to populate HD bands there is considerable fractionation of the fusion cross section into (xn, yp, $z\alpha$) channels, even if the compound nucleus is not very neutron deficient. Thus a tag on a particular charged particle enhances the contribution of a particular nuclide to the γ-γ coincidence data, and results in a cleaner data set. Second, there is some possibility that charged-particle evaporation could be a trigger for the formation of highly deformed nuclear shapes. This follows from the argument that the lowering of the Coulomb barrier at the tips of a very deformed nucleus might lead to an enhanced evaporation of charged particles relative to that from a more spherical shape.

A beam of 187 MeV ^{37}Cl ions bombarded two self-supporting ^{120}Sn foils with a thickness of 0.6 mg/cm^2 each. This reaction with a grazing angular momentum L_{gr} of $85\hbar$ [11] leads to a ^{157}Ho* compound nucleus with an excitation energy E^* of 87 MeV. Approximately 4×10^8 events characterized by twofold and higher Ge coincidences above a multiplicity-10 trigger on the BGO ball were recorded, of which 2.7×10^8 corresponded to γ-γ events having no charged particles in coincidence (leading mainly to ^{153}Ho and ^{152}Ho) and 1.3×10^8 to γ-γ-particle coincidences (Dy, Tb isotopes). Triples and higherfold events correspond to about 10% of the total. The data, corrected on line for Doppler shifts, were sorted with a requirement of a single identified proton and a γ-ray sum energy of $H \geq 19$ MeV registered in the BGO ball. After these conditions were applied, 3×10^7 events remained in the γ-γ coincidence matrix of which 60% were in the $p4n$ reaction channel (^{152}Dy) and 35% in the $p3n$ channel (^{153}Dy) as deduced from known transitions in these nuclei. A three-dimensional matrix (cube) was also generated from proton-gated γ-γ-γ Ge coincidences with the on line trigger condition of a tenfold hit on the BGO ball but no additional conditions on the sum energy.

We subtracted uncorrelated events from the efficiency-corrected, proton-gated γ-γ matrix using the procedure of Palameta and Waddington [12]. The known SD band in ^{152}Dy and SD ridges in ^{152}Dy and ^{153}Dy separated from the diagonal by 48 keV were seen, but more strikingly we also observed ridges at 30 ± 3 keV in the range of γ-ray energies from about 1.2 to 1.5 MeV. The dynamic moment of inertia of the rotational bands is related to the separation of the ridges by $\mathcal{J}^{(2)} = 4\hbar^2/\Delta E_\gamma$; therefore this ridge corresponds to $\mathcal{J}^{(2)}$ of about $130\hbar^2$ MeV^{-1}. This implies a large quadrupole deformation of $\beta_2 \geq 0.9$, consistent with a hyperdeformed prolate shape with major-to-minor axis ratio of 3:1.

The characteristics of the ridges are best studied by making cuts in the γ-γ matrix perpendicular to the main diagonal $E_{\gamma 1} = E_{\gamma 2}$. Figure 1(a) shows the spectrum of $\Delta E_\gamma = E_{\gamma 1} - E_{\gamma 2}$ obtained with a cut in the energy range of $1375 \leq (E_{\gamma 1} + E_{\gamma 2})/2 \leq 1500$ keV. The ridges appear as peaks at energies of $\Delta E_\gamma = \pm 30 \pm 3$ keV. Figure 1(b) shows the spectrum of ΔE_γ obtained with a cut in the $1200 \leq (E_{\gamma 1} + E_{\gamma 2})/2 \leq 1325$ keV energy range. In the higher-energy spectrum, the SD ridge is much weaker, and the 30 keV ridge structure predominates. An estimate of the relative intensity of the continuous plus discrete radiation lying on the HD to that on the SD ridges was obtained from cuts 100 keV wide centered at 1450 keV and 1250 keV, respectively. The determination of this relative intensity is far from ambiguous because both ridges contain discrete peaks. The relative intensity HD:SD is in the range 0.1–0.3. Figures 1(c) and 1(d) show spectra obtained from cuts in the same energy range as 1(a) and 1(b) in the γ-γ coincidence matrix generated from a replay of the same data with the condition of no particles in coincidence (i.e., for population of Ho isotopes). No evidence of the 30 keV ridge was found. We have looked for similar structures in matrices taken from previous data. In particular, we analyzed data from the reaction ^{124}Sn(^{34}S,5n) at 165 MeV ($L_{\rm gr} = 74\hbar$) used to populate SD states in ^{153}Dy [13]. As seen in Figs. 1(e) and 1(f) there is no evidence of a 30 keV ridge. Notwithstanding, the HD ridge might be in ^{153}Dy if the angular-momentum input of this reaction were too low or if a charged-particle evaporation were a necessary condition to provide a detectable signal-to-noise ratio. In fact, energy balance for this reaction favors the $p3n$ exit channel (to ^{153}Dy) over the $p4n$ to populate the very highest spins.

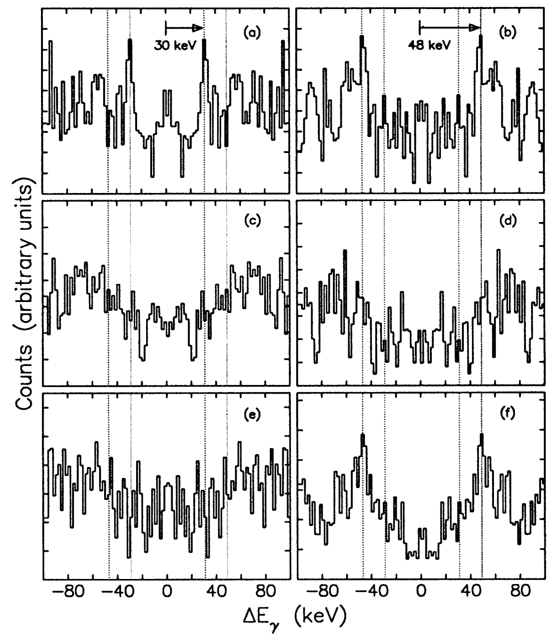

FIG. 1. Spectra of $\Delta E_\gamma = E_{\gamma 1} - E_{\gamma 2}$ obtained with cuts 125 keV wide. Spectra on the left [(a),(c),(e)] correspond to $1375 \leq (E_{\gamma 1} + E_{\gamma 2})/2 \leq 1500$ keV and those on the right [(b),(d),(f)] to $1200 \leq (E_{\gamma 1} + E_{\gamma 2})/2 \leq 1325$ keV. The top row spectra (a),(b) were obtained in coincidence with protons. The HD ridges appear as peaks at energies of $\Delta E_\gamma = \pm 30 \pm 3$ keV in (a); the peaks at $\Delta E_\gamma = \pm 48$ keV in (b) correspond to known superdeformed ridges. The second row [(c),(d)] shows no evidence of the 30 keV ridge in the γ-γ coincidence matrix generated from a replay of the same data with the condition of no particles in coincidence. The last row was obtained for data from the reaction ^{124}Sn(^{34}S,5n) at 165 MeV ($L_{\rm gr} = 74\hbar$) used to populate SD states in ^{153}Dy [13]. The spectrum (f) shows the known superdeformed ridge in ^{153}Dy.

To investigate the multipolarity of the radiation comprising the ridge structure, a third replay of the data was performed. Two γ-γ coincidence matrices were generated: one in which both γ rays were detected in the rings closest to the beam axis ($\pm 37°$) and one in which both γ rays were detected in the rings closest to 90°, namely $\pm 79°$. The γ-γ directional correlation ratios (DCO) showed that the radiation was consistent with a stretched quadrupole character. The intensity ratio $I_{\gamma\gamma}(37°,37°)/I_{\gamma\gamma}(79°,79°) = 1.93 \pm 0.76$ was obtained. A value of 2.2 ± 0.2 (depending upon the degree of spin alignment) was calculated for stretched $E2$ transitions in the geometry of the spectrometer. This was confirmed by a measurement of intense discrete transitions of known character which gave an intensity ratio ranging from 1.9–2.5 for stretched quadrupoles and 0.5–0.7 for stretched dipoles.

Two- and three-dimensional correlation techniques embodied in the codes BANDAID and CUBEAID [14] were used to search the γ-γ matrix and γ-γ-γ cube for coincidence patterns indicative of a rotational cascade of discrete transitions with constant $\mathcal{J}^{(2)}$. The positions of the band members were located by the correlation method in both γ-γ and γ-γ-γ data sets. Figure 2 shows a γ spectrum obtained by summing gates in the background-subtracted efficiency-corrected γ-γ matrix. The band is very weak and no definite assignment to either ^{152}Dy or ^{153}Dy was possible. Insufficient statistics preclude an accurate measurement of the energies of the band members.

The nucleus ^{152}Dy is considered to have a doubly magic SD core because of the very large energy gaps present in the single-particle spectrum [15]. A HD structure in this mass region raises the question as to what extent a similar shell structure might be responsible.

Total Routhian surface (TRS) calculations were performed for nuclei in the vicinity of ^{152}Dy (see Fig. 3). The shape parameters β_2, β_4, and γ of the nucleus were minimized in the rotating frame (for details see Ref. [15]). In the calculations, there is a deep minimum at $\beta_2 \approx 0.6$ which corresponds to the SD shape. At a frequency of $\hbar\omega = 0.66$ MeV, a new minimum occurs in the surface, corresponding to a hyperdeformed shape with $\beta_2 \approx 0.9$ which becomes yrast at about $80\hbar$. The calculations suggest that the underlying physics of the HD minimum is very different from that of the SD minimum. In contrast to the SD shape, there are no pronounced shell gaps at the calculated equilibrium deformation. In consequence, static pairing correlations are strong whereas they are reduced even at spin 0 for the SD shape.

It was predicted in Ref. [15] that the SD band is crossed at $\hbar\omega = 0.8$ MeV by aligned $j_{15/2}$ protons. This high-j intruder configuration originating from *two* shells above those active at $\beta_2 \approx 0$ will tend to polarize the nuclear shape to large quadrupole deformation as suggested by the TRS calculations. The next calculated crossing involves $k_{17/2}$ neutrons. Theory also suggests that the occupation of the $\nu\ N = 8$ orbitals polarizes the shape to an even larger deformation. In addition, both these ν and π "super"-intruder orbitals contribute a large aligned angular momentum to the total spin of the nucleus. The occupation of the highly alignable "super" intruders, which can be associated with a "superbackbend" [9], is thus the origin of the minimum in the TRS calculation at HD shapes. With increasing spin, minima at larger deformation will occur in the potential energy landscape, created by succesive alignment of even higher-lying "super"-intruder configurations.

It is difficult to estimate the spins of the observed structure. If we assume that $\mathcal{J}^{(2)}$ equals the static moment of inertia $\mathcal{J}^{(1)}$, then the observed structure extends from about spin $78\hbar$ to spin $98\hbar$. However, since the TRS calculations predict that band crossings should occur, this

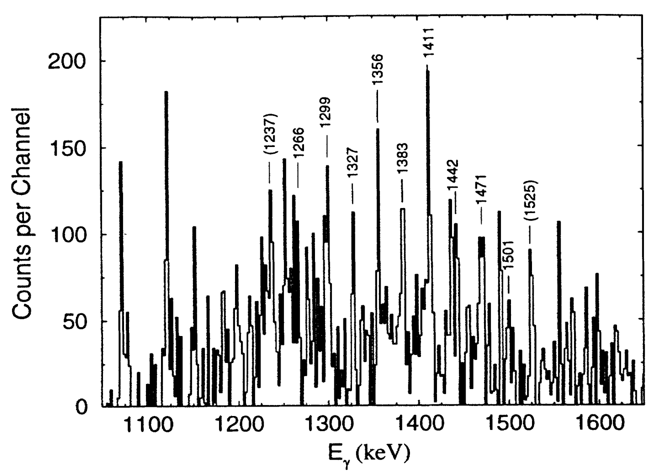

FIG. 2. Summed γ-ray spectrum obtained for the band located by the correlation method. The energies of the band are shown and correspond with approximately 30 keV spacing. The uncertainties on the energies are estimated to be 1–2 keV.

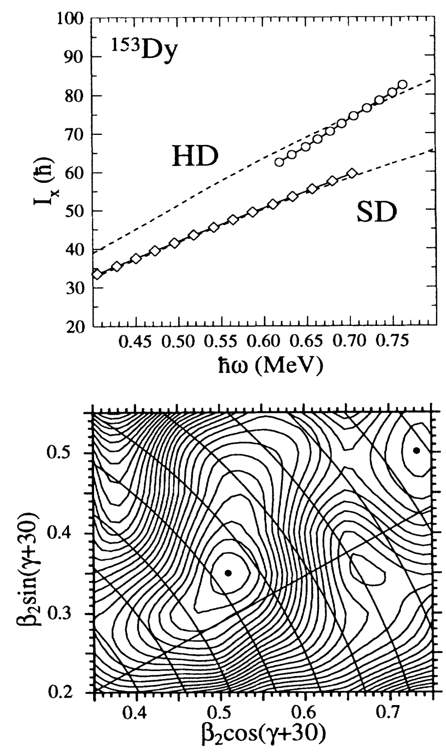

FIG. 3. Example of total Routhian surface plots for ^{153}Dy showing the development of a HD minimum corresponding to a value of $\beta_2 \approx 0.9$ at $\hbar\omega = 0.84$ MeV. The energy difference between contour lines is 200 keV. The top panel shows the total spin projections $I_x(\hbar)$ calculated (dashed lines) for the SD and HD bands in ^{153}Dy. The points plotted for the SD band assume the spins estimated and published [13]. The points plotted for the HD band assume $\Delta I = 2$ transitions, thus defining the slope. The experimental points are normalized to the predicted spin at $\hbar\omega \simeq 0.7$ MeV.

estimate is unreliable. In the TRS calculation the frequency region over which the band is observed, namely, 0.55 to 0.75 MeV corresponds with spins of $62\hbar$ to $82\hbar$ for the HD shape (see Fig. 3). The moment of inertia in this spin range is calculated to be $\mathcal{J}^{(2)}$ =(90–110)$\hbar^2$ MeV^{-1} which is appreciably smaller than the observed value $\mathcal{J}^{(2)} = (130 \pm 13)\hbar^2$ MeV^{-1}. This could be accounted for if the predicted $\pi\ j_{15/2}$ crossing occurred within the frequency range observed rather than at $\hbar\omega = 0.5$ MeV as in the calculation. In that case, the predicted $\mathcal{J}^{(2)}$ value would be approximately $130\hbar^2$ MeV^{-1}. A discrepancy of this magnitude between predicted and observed crossing frequencies is plausible considering the extreme deformation. Also we note that a similar shift involving the $\nu\ j_{15/2}$ orbital is required to explain $\mathcal{J}^{(2)}$ values in the SD region centered at ^{192}Hg [16].

These high spins are surprising since one would expect very strong competition with fission above spin $70\hbar$. However, the disappearance of the fission barrier does not set an upper limit on the angular momentum that a compound nucleus can sustain, since the entrance channel is in a very different part of the potential-energy surface from the fission channel. Theoretically, the maximum angular momentum a nucleus in this mass region is able to sustain is around $90\hbar$ [17]. These calculations are based on the liquid-drop model and the shell structure is not taken into account. It is interesting to note that recent calculations [18], derived from the liquid-drop model and including nuclear proximity effects, show that very high angular momenta can be sustained by nuclei in elongated shapes without fissioning. The same authors predict for nuclei like ^{152}Dy the existence of a quasistable state with a ratio $s = 0.3$ between the neck diameter and the elongation of the system [19], corresponding to $\beta_2 = 0.9$ for spins between $70\hbar$ and $115\hbar$ with a moment of inertia of about $110\hbar^2$ MeV^{-1}. In their model the nuclear proximity interaction in the crevice around the neck strongly modifies the macroscopic potential barriers encountered.

In conclusion, ridges have been found in a protongated γ-γ coincidence matrix from the reaction ^{120}Sn(^{37}Cl,pxn) at 187 MeV. They correspond to a moment of inertia $\mathcal{J}^{(2)}$ of about $130\hbar^2$ MeV^{-1}, are comprised of stretched $E2$ transitions, and arise from ^{152}Dy or ^{153}Dy. Such a large moment of inertia suggests a hyperdeformed shape with a $\beta_2 \geq 0.9$. Two- and three-dimensional correlation techniques revealed a regular coincidence pattern which led to a cascade of about 10 discrete transitions with an average energy spacing of 30 keV. Still more powerful instrumentation will be needed to probe the nucleus at the highest angular momentum it can sustain.

This work has been partially funded by the Natural Sciences and Engineering Research Council of Canada and by AECL Research. This work has benefited from discussions with G. Smith, J. Sharpey-Schafer, J. P. Vivien, W. Nazarewicz, G. Royer, and J. Leigh.

[1] B. M. Nyakó *et al.*, Phys. Rev. Lett. **52**, 507 (1984).
[2] M. A. Bentley *et al.*, J. Phys. G **17**, 481 (1991).
[3] P. J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
[4] P. J. Nolan *et al.*, J. Phys. G **11**, L17 (1985).
[5] M. A. Bentley *et al.*, Phys. Rev. Lett. **59**, 2141 (1987).
[6] A. J. Kirwan *et al.*, Phys. Rev. Lett. **58**, 467 (1987).
[7] P. J. Nolan and P. J. Twin, Annu. Rev. Nucl. Part. Sci. **38**, 533 (1988).
[8] R. V. F. Janssens and T. L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321 (1991).
[9] T. Bengtsson *et al.*, Phys. Scr. **24**, 200 (1981).
[10] A. Galindo-Uribarri, Prog. Part. Nucl. Phys. **28**, 463 (1992).
[11] H.V. Klapdor, H. Reiss, and G. Rosner, Nucl. Phys. **A262**, 157 (1976).
[12] G. Palameta and J. C. Waddington, Nucl. Instrum. Methods Phys. Res., Sect. A **234**, 476 (1985).
[13] J. K. Johansson *et al.*, Phys. Rev. Lett. **63**, 2200 (1989).
[14] J. A. Kuehner, J. C. Waddington, and D. Prévost, BANDAID and CUBEAID programs, in *Proceedings of the International Conference on Nuclear Structure at High Angular Momentum, Ottawa, Ontario, 1992*, edited by D. Ward and J. C. Waddington (AECL Research Report No. AECL-10613, Vol. II), p. 413.
[15] W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A503**, 285 (1989).
[16] M. W. Drigert *et al.*, Nucl. Phys. **A530**, 452 (1991).
[17] S. Cohen *et al.*, Ann. Phys. (N.Y.) **82**, 557 (1974); R. A. Broglia *et al.*, Nucl. Phys. **A349**, 496 (1980).
[18] G. Royer and J. Mignen, J. Phys. G **18**, 1781 (1992); G. Royer and B. Remaud, *ibid.* **10**, 1057 (1984).
[19] G. Royer and F. Haddad, Phys. Rev. C **47**, 1302 (1993).