Search For Hyperdeformation In Xe Nuclei

C. Rønn Hansen*, G.B. Hagemann*, B. Herskind*, D.R. Jensen*, G. Sletten*, J.N. Wilson†, S. Ødegård*, P. Bringel**, C. Engelhardt**, H. Hübel**, A. Neusser**, A.K. Singh**, G. Benzoni‡, A. Bracco‡, F. Camera‡, S. Leoni‡, A. Maj§, Th. Byrski¶, D. Curien¶, P. Bednarczyk‖, A. Korichi†, J. Roccaz†, J.C. Lisle,††, T. Steinhardt‡‡, O. Thelen‡‡, M.P. Carpenter§§, R.V.F. Janssens§§, T.L. Khoo§§, T. Lauritsen§§, R.M. Clark¶¶ and P. Fallon¶¶

*The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark.
†CSNSM, F-91406 Orsay, France.
**ISKP, University of Bonn, Nussallee 14-16, D53115 Bonn, Germany.
‡Dipartemento di Fisica, Universita di Milano and INFN, Italy.
§IFJ, PAN, Krakow, Poland.
¶IReS, IN2P3/CNRS, F-67037 Strasbourg, France.
‖GSI, 64291 Darmstadt, Germany.
††Schuster Laboratory, University of Manchester, UK.
‡‡Institut für Kernphysik, Universität zu Köln, Germany.
§§Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA.
¶¶Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA.

Abstract. Two experiments to identify hyperdeformation in Xe-nuclei have been made using the reaction ^{82}Se(^{48}Ca,xn)$^{130-x}$Xe, the first one with the EUROBALL-IV array equipped with a BGO calorimeter and the second one with the Gammasphere array. A bombarding energy of 195 MeV was used with the VIVITRON and 206 MeV with the ATLAS accelerator. No discrete hyperdeformed bands have been identified, but a ridge structure with $4\hbar^2/\Im \sim 0.048$ MeV corresponding to a very large deformation was observed. A fluctuation analysis revealed that these ridges are composed of more than 10 rotational bands with ≥ 5 transitions each. Seven and four discrete bands extending from I $\sim$ 20 to I $\sim$ 60 have been identified in ^{125}Xe and in ^{126}Xe respectively, with a ΔE_γ of 100 - 120 keV. These bands are most probably related to a potential energy minimum at $\varepsilon \sim 0.35$ and a small γ-deformation predicted by Ultimate Crancker calculations. The transition quadrupole moments, crossing frequencies and alignments observed in the bands compare very well with those expected for this minimum.

INTRODUCTION

Hyperdeformed nuclei are nuclei with a sizeable prolate deformation corresponding to an axis ratio of 3 : 1. The liquid drop model (LDM) predicts small fission barriers for such nuclei and the barriers are particularly low at high angular momentum. For Xe nuclei, however, LDM calculations by Pomorski and Dudek (LSD model) [1] predict fission barriers of several MeV in the spin range 68 - 90$\hbar$. For the same nuclei there are calculations with the cranked shell model (CSM), taking microscopic features into account, which show pronounced minima in the potential energy surface at deformations corresponding to hyperdeformed nuclei. These predictions which are illustrated in Fig. 1 and Fig. 2 have motivated a search for hyperdeformed band-structures in the Xe nuclei with use of the most sensitive experimental equipment world wide.

CP764, *Nuclei at the Limits,* edited by D. Seweryniak and T. L. Khoo

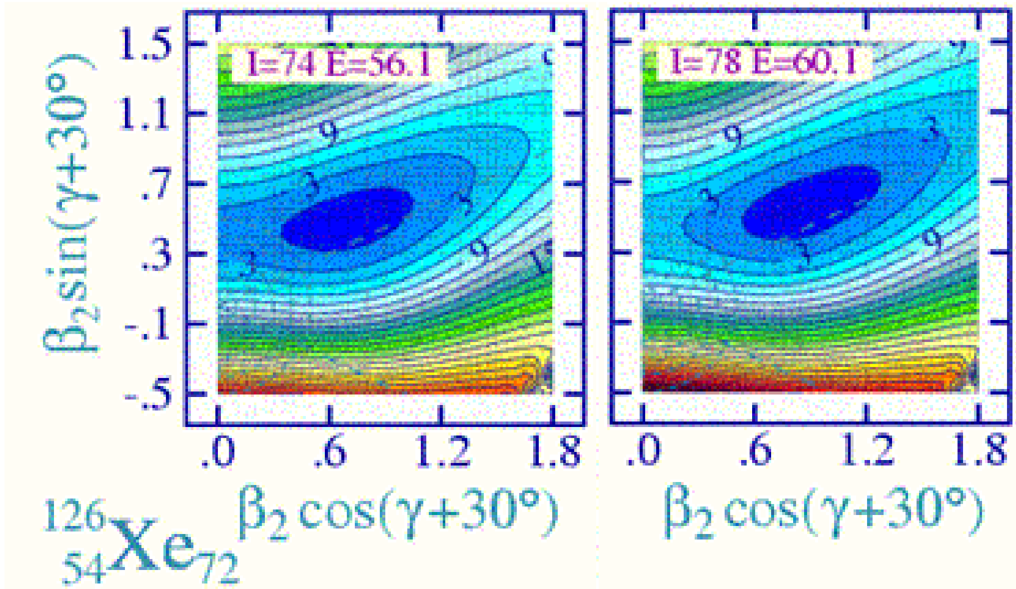

FIGURE 1. Liquid drop potentials displayed in 2D calculated for ^{126}Xe [1] at I = 74 and 78$\hbar$, close to the fission limit where hyperdeformed nuclei are expected to be populated.

EXPERIMENTAL DETAILS

The Xe nuclei were produced in two different experiments both utilising the reaction ^{82}Se(^{48}Ca,xn)$^{130-x}$Xe. In the first experiment with the VIVITRON tandem accelerator at IReS in Strasbourg, data were taken at 185, 195 and 205 MeV and the target was a 0.50 mg/cm^2 layer of ^{82}Se on a 0.50 mg/cm^2 backing of Au and the Selenium was protected by a less than 50 μg/cm^2 window of Au which reduced the velocity of the recoiling Xe nuclei only slightly. The EUROBALL array was equipped with 239 Germanium detectors and a BGO innerball for multiplicity and sum energy measurements. The trigger condition was set to 3 or more suppressed Ge detectors firing and a condition of fold $\geq$ 5 on the inner ball. The multiplicity distribution resulting from the 3 different bombarding energies were compared. Since the population at high folds increased from 185 to 195 MeV beam energy and only a very slight increase was observed going to 205 MeV, the 195 MeV was chosen for the experiment. The beam intensity was $\leq$ 1 particle nA. A total of 1.69$\cdot$10^9 events were recorded, and this experiment is referred to as Xe1 in the following.

The second experiment referred to as Xe2 was done with the Gammasphere array at ANL with the beam provided by the ATLAS accelerator. Since a strong dependence on the bombarding energy was observed for the highest spin states in an experiment on ^{126}Ba with EUROBALL [3] an incident beam energy of 206 MeV was chosen. This resulted in a mid-target energy of about 200 MeV. A major motivation for Xe2 was also the 4 times higher beam intensity which resulted in the maximum data rate the acquisition system could handle at a suppressed Ge fold selection $\geq$ 5. A total of 2.77$\cdot$10^9 such events were accumulated. The use of as much as 4 pnA beam intensity on the volatile Se target was made possible by a defocussing of the beam while wobbling it and at the same time rotating the target foil, mounted on a wheel, through the beam [4].

ANALYSIS OF DISCRETE LINE SPECTRA

The γ-ray coincidences were sorted into 3 and 4-dimensional arrays and the analysis was carried out using the RADWARE software package [5]. The 4n and 5n reaction products leading to ^{126}Xe and ^{125}Xe, respectively, are dominating the spectra. The former has been studied in great detail by Seiffert *et al.* [6] and the latter by Lieberz *et al.* [7] up to a spin of about 20$\hbar$. The most conspicous feature of the present spectra is a very pronounced E2-bump on which there is a superposition of long rotational cascades with quite regular ΔE_γ. These cascades extend to a spin of about 60$\hbar$ with transition energies of more than 2.5 MeV at the top. Four such bands are identified in ^{126}Xe and 7

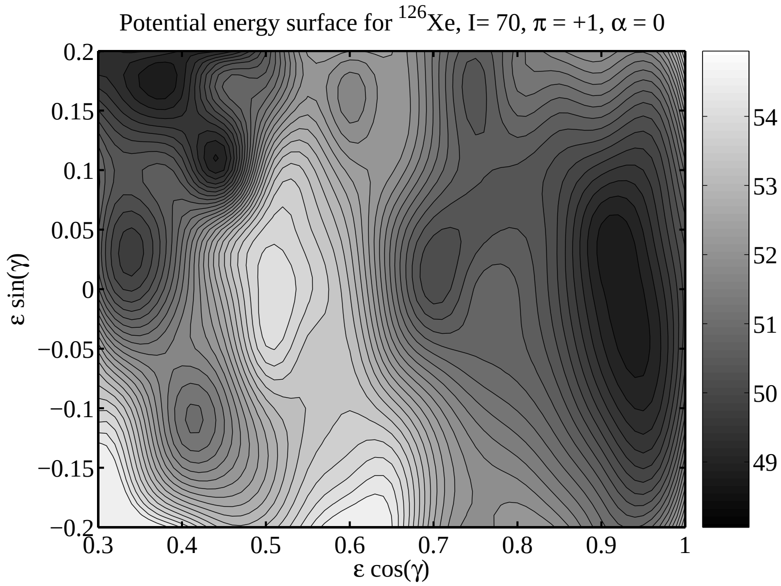

FIGURE 2. Potential energy surface calculated with the UC programme [2] at I = 70$\hbar$ for a positive parity configuration with α = 0. Hyperdeformation is related to the deep minimum at $\varepsilon\cos(\gamma) \sim 0.95$.

in ^{125}Xe. Figure 3 shows a partial level spectrum for ^{126}Xe. In the following the discussion will be restricted to ^{126}Xe, but the main features of the ^{125}Xe band structures beyond I $\sim 25\hbar$ are very similar.

The transition rate at the top of these bands is very high and decays from the entry state to about I = 30$\hbar$ take place within the 500 μg/cm^2 thick target. This opens the possibility for estimates of the rates by the observation of peak-shapes from the highest spins and down. Following the ideas suggested by Cederwall *et al*. [9], we have measured the peak widths of the transitions using different v/c values for the Doppler shift corrections. For each value of v/c a cube was produced and double gated spectra were projected out. For transitions in band **a**, the strongest populated band, the minimum peak width in the energy range 1200 to 2300 keV could be determined. The corresponding v/c, provides information on the effective fractional Doppler shift, F(τ) which is ranging from 92 - 100 % of the full shift. By use of stopping power data from [8], lifetimes of the states in the cascades can be deduced and for band **a** a transition quadrupole moment of 5.2 b was estimated. Transitions in the minimum at $\varepsilon\cos(\gamma) \sim 0.35$ and a small γ-deformation shown in Fig. 2 have a Q_t of about 5.5 b which is in good agreement with the experiment. Very tentatively we therefore assign the long cascades to this minimum. The transition rate in hyperdeformed bands, however, will be much faster than this and for the minimum which appears at $\varepsilon\cos(\gamma) \sim 0.95$ in Fig. 2 a Q_t of about 24 b is expected. Extensive searches for other discrete band-structures feeding the newly identified cascades and using the most advanced filtering techniques [10], have so far not been successfull from neither the Xe1 nor the Xe2 dataset. The expected transition energy in the hyperdeformed minimum would be $\sim$ 1400 keV.

By a detailed analysis of the band structures shown in Fig. 3 we can investigate to which extent the energy minimum at $\varepsilon\cos(\gamma) \sim 0.35$ from the UC calculations provides a microscopic structure corresponding to the data. If we restrict ourselves to bands **a,b,c** and **d** and analyze their alignment curves, we find crossings which we can relate to the single particle Routhians. Seifert *et al*. [6] and Lieberz *et al*. [7], who worked at lower spin where the nuclear shape is fluctuating strongly, find that the structures are dominated by the $h_{11/2}$ and $i_{13/2}$ neutrons together with $h_{11/2}$ and $g_{7/2}$ protons. We find that the structure at $\hbar\omega \sim 450$ keV is dominated by the same particles, but now in the potential energy minimum at $\varepsilon\cos(\gamma) \sim 0.35$ and a small γ-deformation which seems to be stable over a long spin range. At the present state of the analysis only band **b** is firmly connected to the low lying structures and has well identified excitation energy and quantum numbers. Band **a** which is the most strongly populated band has transition energy degeneracies which introduce an uncertainty of two spin units to the high side. Bands **c** and **d** are given the most likely excitation energies and quantum numbers but are still uncertain. An analysis of the dynamic moment of inertia group the bands pairwise at $\Im^{(2)} \sim 35\hbar^2$/MeV for bands **a** and **d** and $\Im^{(2)} \sim 42\hbar^2$/MeV for bands **b** and **c**.

The tentative assignments given in Fig. 3 are in agreement with this observation and the prediction for the 4 lowest

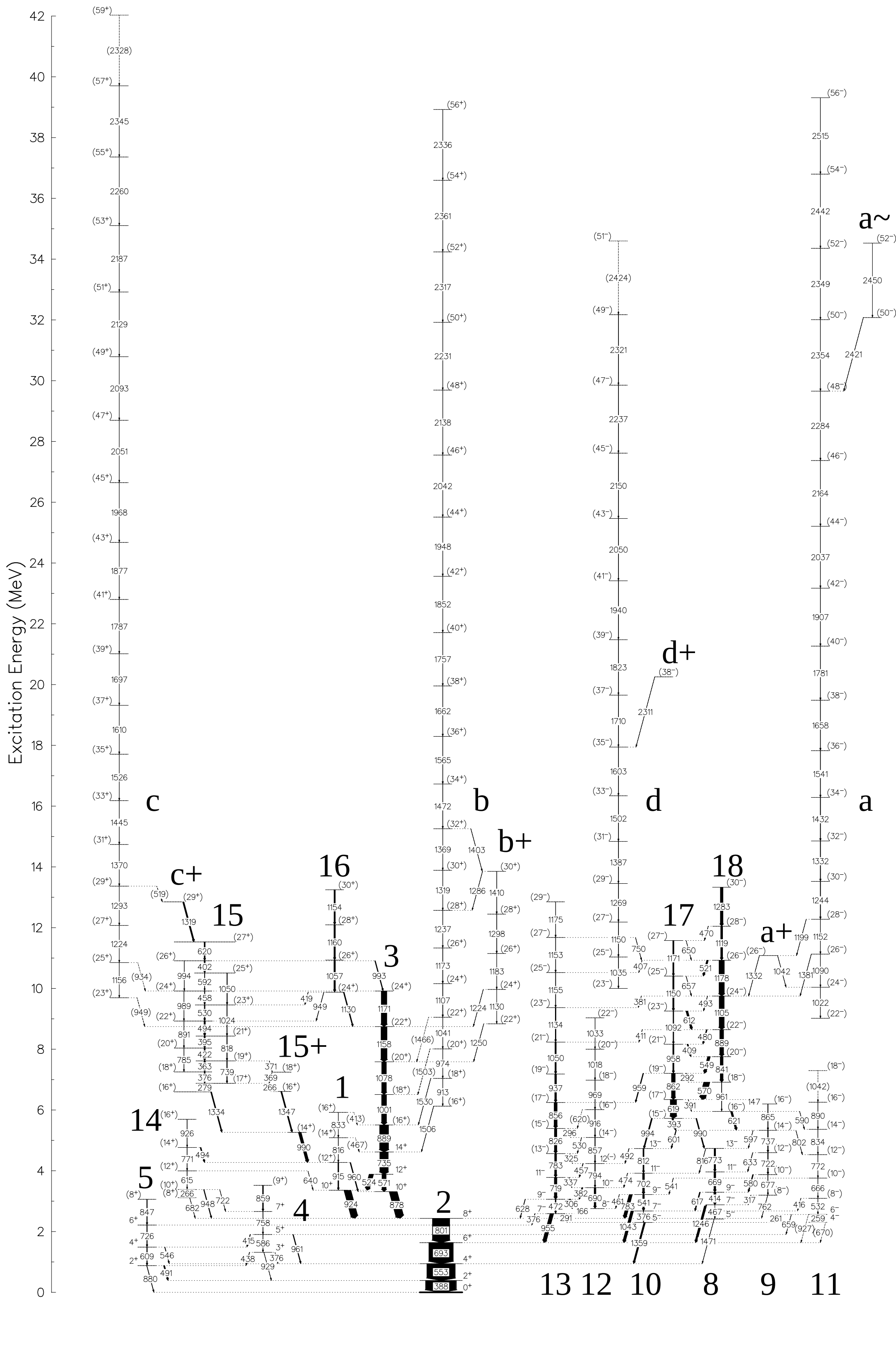

FIGURE 3. Partial level scheme of ^{126}Xe. Levels extending beyond I = 20$\hbar$ has been identified in the present work. Band **b** is firmly connected to the low-spin levels, while band **a,c** and **d** are placed at their most probable excitation energy with connecting transitions which still are tentative.

lying bands by the UC calculations. Bands **a** and **d** are proposed to be signature partners π,α = -1,0 for band **a** and π,α = -1,1 for band **d**, respectively, wheras bands **b** and **c** are partners with positive parity. The calulations suggest the initial structure $\nu(h_{11/2},i_{13/2})$ x $\pi(h_{11/2})^2$ for bands **a** and **d** and for **b** and **c** one of the $h_{11/2}$ protons is replaced by a $g_{7/2}$ proton. A detailed discussion of crossing frequencies and alignments in the bands requires firm assignments and one can only conclude that the stuctures as shown in Fig. 3 correspond in general terms to the predicted crossings in the theoretical Routhians. However, a sharp crossing and strong alignment in the **a** and **b** bands at 1150 keV observed experimentally is reproduced by the theoretical Routhian for the $j_{15/2}$ neutron. The agreement between the experimental level spectra and the UC predictions give confidence in the general features of the theoretical calculations and the potential energy surface shown in Fig. 2.

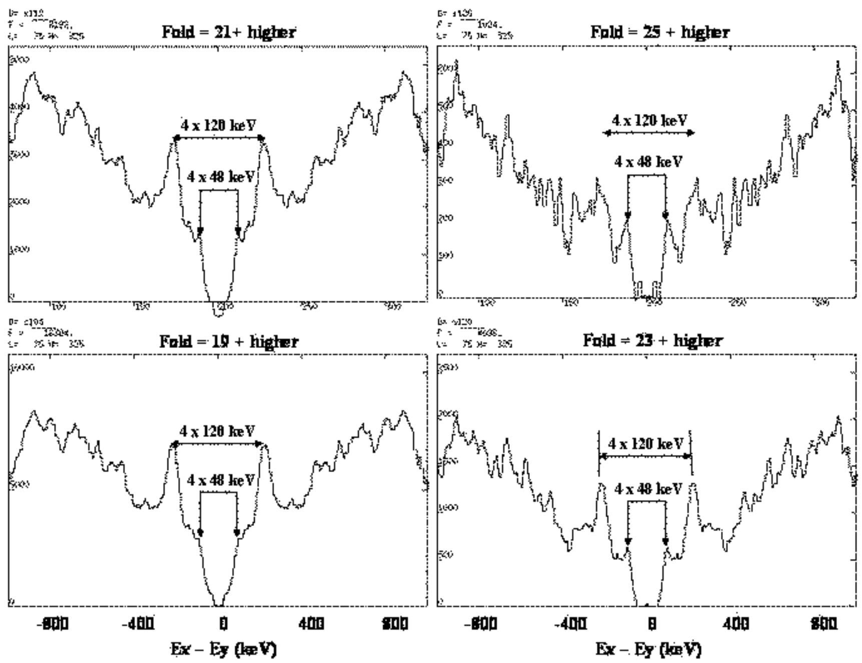

FIGURE 4. Perpendicular cuts at $(E_x + E_2)/2$ = 1360 $\pm$ 92 keV in slices of cubes built from the Xe1 data which satisfy the condition $E_x + E_y - 2E_z = \delta$ (δ = 24 keV). The fold selection is from the BGO-ball multiplicity spectra. Note that in the x + y = 2z (N = 1) plane of the cube, the first ridge interspacing is 4 x ΔE_γ.

ANALYSIS OF THE CONTINUUM

Both datasets have been analysed by rotational plane mapping RPM as well [11]. In Fig. 4 perpendicular cuts at $(E_1 + E_2)/2$ = 1360 keV with a width of 184 keV are shown for coincidence-fold selection by the inner BGO ball of EUROBALL. A pronounced ridge with a spacing of approximately 4 x 120 keV appears at all folds and cut widths in the range from 88 to 184 keV. This ridge we assign to the dominant cascades observed in the discrete line analysis, see Fig. 3. At fold 23 and higher, however, a ridge emerges at 4 x 48 keV, and this ridge becomes more pronounced at fold $\geq$ 25. This value corresponds to the moment of inertia expected for a hyperdeformed nucleus. At the same time as the 4 x 48 keV ridge increases in intensity, we observe that the 4 x 120 keV ridge is becoming weaker in correspondance with the decreasing intensity at the top of bands **a - d** shown in Fig. 3. The RPM analysis of the much larger Xe2 data-set allowed more narrow perpendicular cuts at 1360 keV. In this case a cut width of $\pm$ 22 keV was used and is shown for fold selection 20 - 28 in Fig. 5. Ridges with a spacing of 4 x 120 keV appear at the lowest folds as expected and at the highest folds a ridge at 4 x 48 keV appears as well, in correspondance with the results from the Xe1 data from EUROBALL. Finally a fluctuation analysis has been performed for the 4 x 48 keV ridge of the Xe2 data-set. The analysis with a slice width of Δ = 8 or 24 keV respectively both indicate a number of bands, $N_{path} \geq 10$ in the fold range from 18 to 26.

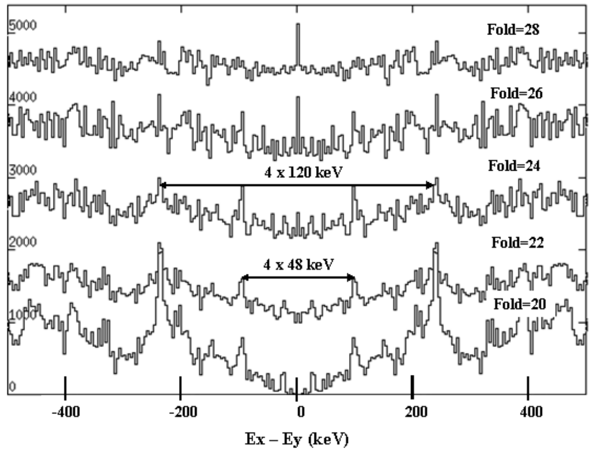

FIGURE 5. Perpendicular cuts at $(E_x + E_2)/2 = 1360 \pm 22$ keV in slices of cubes built from the Xe2 data which satisfy the condition $E_x + E_y - 2E_z = \delta$ ($\delta = 12$ keV). The fold selection is by the total Ge-fold spectra. The first ridge interspacing is 4 x ΔE_γ.

SUMMARY

Two experiments have been performed with the aim of identifying discrete line transitions between hyperdeformed states in Xe nuclei. In both experiments discrete line spectra were measured up to I $\sim 60\hbar$ and their spectroscopic features compare well with theoretically calculated single particle Routhians. The moment of inertia of these bands, deduced from their regular ΔE_γ of $\sim$ 110 keV and an estimate of the transition quadrupole moment in the bands are both compatible with a minimum at $\varepsilon\cos(\gamma) \sim 0.35$ and a small γ deformation from the UC calculations. No discrete band structures compatible with the minimum at $\varepsilon\cos(\gamma) \sim 0.95$ could be identified. However, analysis of the continuum by use of the rotational plane mapping technique reveals a strong indication of hyperdeformed structures and the presence of more than 10 bands of this type at the highest spins. From the analysis of the present data it has not yet been possible to bridge from the observed discrete line spectra near I = $60\hbar$ to predicted Jacobi shape transitions or discrete hyperdeformed transitions. This next step will presumably have to await the next generation of γ-ray spectrometers.

REFERENCES

1. K. Pomorski and J. Dudek, Phys. Rev. C **67**, 044316 (2003).
2. T. Bengtsson, Nucl. Phys. **A496**, 56 (1989); T. Bengtsson, Nucl. Phys. **A512**, 124 (1990).
3. B. Herskind *et al.*, AIP Conf. Proc. **701**, 303-315 (2004).
4. J. P. Green, Target expert at ATLAS, ANL.
5. D. C. Radford, Nucl. Instrum. Methods **A361**, 297 (1995).
6. F. Seifert, W. Lieberz, A. Dewald, S. Freund, A. Gelberg, A. Granderath, D. Lieberz, R. Wirowski, and P. von Brentano, Nucl. Phys. **A554**, 287-321 (1993).
7. W. Lieberz, S. Freund, A. Granderath, A. Gelberg, A. Dewald, R. Reinhardt, R. Wirowski, K.O. Zell, and P. von Brentano, Z. Phys. A - Atomic Nuclei **330**, 221-222 (1988).
8. J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Ranges of Ions in Matter* (Pergamon, London, 1985).
9. B. Cederwall, I. Y. Lee, S. Asztalos, M. J. Brinkman, J. A. Becker, R. M. Clark, M. A. Delaplanque, R. M. Diamond, P. Fallon, L. P. Farris, E. A. Henry, J. R. Hughes, A. O. Macchiavelli, F. S. Stephens, Nucl. Instrum. Methods **A354**, 591 (1995).
10. J. Wilson *et al.*, Phys. Rev. C **56**, 2502 (1997).
11. B. Herskind, J. J. Gaardhøje, and K. Schiffer, ANL-PHY-88-2, 179 (1988).