SEARCH FOR HYPERDEFORMATION*

H. Hübel

Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn
Nussallee 14-16, D-53115 Bonn, Germany

(Received November 30, 2004)

Experiments performed in recent years using the Euroball and Gammasphere spectrometer arrays to search for hyperdeformed shapes in Hf, Nd, Xe and Ba nuclei are discussed. In ^{126}Xe and ^{126}B ridge structures in quasi-continuum γ-ray correlation spectra with a small energy separation are observed, probably resulting from rotational bands with large moments of inertia. These ridges are only found when the highest-multiplicity cascades are selected in the data from experiments with the highest bombarding energies. A statistical analysis shows that the ridges are formed by ten or more bands and that the intensity of the individual bands is below 10^{-6} of the reaction-channel intensity. Selected examples of results for normal-deformed and superdeformed states are also presented.

PACS numbers: 21.10.Re, 21.60.–n, 27.60.+j, 27.70.+q

1. Introduction

The investigation of extremely elongated shapes is an interesting topic of nuclear structure research, both theoretically and experimentally. Spectacular examples of very large deformations are the superdeformed (SD) states in nuclei where, in the extreme limit, the major-to-minor axis ratio approaches 2:1. This is the limit expected for an harmonic-oscillator potential which leads to large shell gaps that produce potential-energy minima for integer axis ratios. However, more realistic potentials modify this simple picture and SD nuclei have axis ratios in the range of $c/a \approx 1.5$ to 2.0. Similarly, hyperdeformed (HD) shapes, associated with a third potential-energy minimum, may have axis ratios between 2.0 and 3.0 [1].

Extremely elongated shapes have been predicted in various mass regions and in different ranges of excitation energy and angular momentum, see *e.g.* [1, 2]. Experimental evidence for hyperdeformation already exists in light

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

and very heavy nuclei. A classic example in light nuclei is the HD state in ^{12}C, a linear cluster of three α particles built on the first excited 0^+ level at 7.65 MeV [3]. For heavy nuclei, in the actinide region, experimental evidence for HD states was obtained in fission transmission-resonance experiments [4, 5]. Calculations using the Nilsson–Strutinsky shell-correction approach have shown that the density distribution at the HD minimum in the actinides resembles a di-nucleus with a pronounced octupole shape [2]. Similar calculations also predict HD shapes at very high spins in nuclei in various mass regions, see *e.g.* [1,6–8]. This contribution is a report on recent experiments to search for high-spin HD states in Hf, Nd, Xe and Ba nuclei using the Euroball (EB) and Gammasphere (GS) spectrometer arrays.

Several previous attempts to search for HD structures in ^{147}Gd [9, 10], ^{152}Dy [11,12] and ^{168}Yb [13] did not lead to convincing evidence for discrete-line rotational bands in the third potential wells at high spin. The results showed that the population of HD states was below the achievable observational limit [13]. Thus, for any new experiments to search for HD structures it is important to choose cases for which theory predicts the most pronounced shell effects. Furthermore, it is essential that the studied systems can accommodate the highest angular momenta.

Candidates for discrete HD bands have been discovered in ^{108}Cd [14, 15] where moments of inertia and limits on average transition quadrupole moments are consistent with extremely large deformations. A report on these results is presented in a different contribution to this conference [16].

2. Theoretical predictions

The Nilsson–Strutinsky calculations have been successful in predicting SD potential-energy minima and such calculations may also be used to help choose the best cases for searches for HD states. However, one has to keep in mind that at the extremes of deformation and angular momentum the shapes may deviate from a pure ellipsoid and the microscopic structure may be modified in an unknown way. Furthermore, the potential energy surfaces usually are more flat and small changes in the choice of the parameters may have drastic effects.

The experiments reported here have been guided by calculations with the Ultimate Cranker (UC) code which was originally developed by T. Bengtsson [17] and was later modified by R. Bengtsson [18]. It uses the Nilsson potential for the shell corrections to the liquid-drop energies. It appears that favourable cases, among others, are ^{170}Hf, ^{140}Nd, ^{126}Xe and ^{126}Ba. Examples of the calculations are presented in Figs. 1 and 2. While in ^{170}Hf the HD minimum is already well pronounced at a rather moderate spin of 50 $\hbar$, in the lighter cases the third minimum appears only at higher spins.

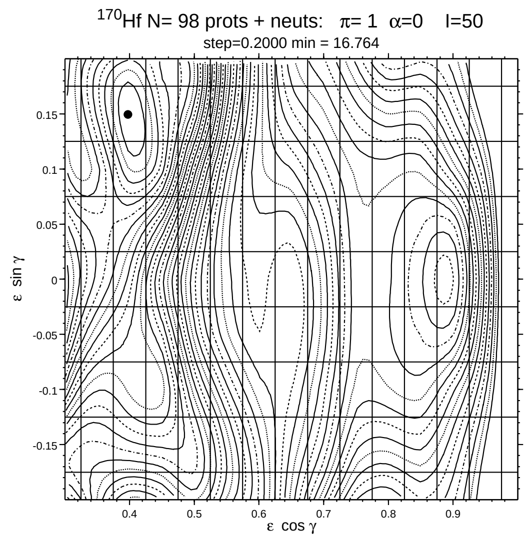

Fig. 1. Potential-energy surface for ^{170}Hf at spin 50 $\hbar$ for parity and signature (+,0) calculated using the UC code. The energy separation of the contour lines is 200 keV.

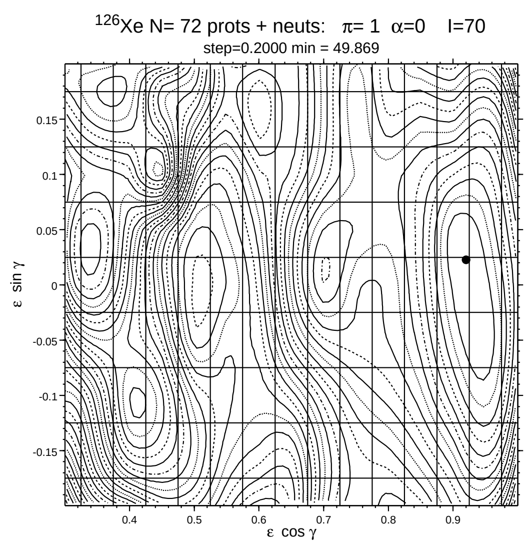

Fig. 2. Potential-energy surface for ^{126}Xe at spin 70 $\hbar$ for parity and signature (+,0) calculated using the UC code. The energy separation of the contour lines is 200 keV.

3. Population of the highest-spin states

Even in the most promising cases with well pronounced HD potential wells it is important to reach the highest angular momentum states which the nuclei can accommodate. It is desirable to choose 'cold' reactions, *i.e.* reactions with large negative Q values, since in these cases the excitation energy above the yrast line is small. The highest-spin states are then populated in the reaction channels with a small number of evaporated particles because at each evaporation step there is a fission competition.

Large angular momentum is best transferred in fusion–evaporation reactions with heavy beam particles, and symmetric or near-symmetric reactions may be preferable. These ideas have been tested in an experiment using the 8π-Spectrometer at Berkeley [19]. Various reactions were used to produce Hf, Gd and Ba isotopes. For several different beam energies the intensity and γ-ray multiplicity for the different xn-evaporation channels were determined, using the γ-ray spectra measured with the Ge detectors and the coincidence fold distributions obtained from the inner ball of BGO detectors. As expected, it was found that the angular momentum transfer is highest in the reaction channels with a low multiplicity of evaporated neutrons and that the $A \approx 130$ nuclei can accommodate higher angular momenta than the $A \approx 170$ nuclei [19]. The angular momentum transfer depended not much on the choice of the investigated reactions since all of them were cold reactions with a similar dependence of the excitation energy on angular momentum. These results were used as guidelines to choose reactions and beam energies to produce the compound nuclei ^{174}Hf, ^{144}Nd, ^{130}Xe and ^{128}Ba for the searches for HD structures.

4. Experiments to search for hyperdeformation

Extensive searches for HD structures were made in discrete-line as well as in quasi-continuum γ-ray spectra. In addition, normal-deformed (ND) and SD structures were investigated. The analysis of the large data sets, from several experiments in some cases, is still in progress and only a small fraction of the results can be presented here, in particular of the ND spectroscopy. From the HD searches, the most promising results are obtained from an analysis of the quasi-continuum correlation spectra of ^{126}Xe and ^{126}Ba. Preliminary results of these investigations have been presented elsewhere [20–22].

4.1. The $^{50}Ti + ^{124}Sn \rightarrow ^{174}Hf$ reaction

In the reaction ^{50}Ti + ^{124}Sn high-spin states in ^{170}Hf were populated in the $4n$-evaporation channel. The beam of 215 MeV was provided by the Vivitron accelerator at the Institut de Recherches Subatomiques (IReS), Strasbourg. Gamma-ray coincidences were measured with the EB spectrometer array. A stack of two thin ^{124}Sn foils with thicknesses of 460 and 600 μg/cm^2 was used as a target. In an effective beam time of $\sim$5 days with a beam intensity of ~ 1 pnA a total of 2.3×10^9 events were collected. The trigger condition was that $\geq$4 Ge detectors before Compton suppression and $\geq$8 BGO detectors of the inner ball were in prompt coincidence.

In the off-line analysis γ-ray coincidence matrices in two, three (cubes) and four (hypercubes) dimensions were sorted using the Radware program package [23]. Searches in the cubes and hypercubes for discrete-line rotational bands with the energy spacings expected for HD shapes did not result in any convincing spectra. Therefore, it had to be concluded that the angular momentum input was not sufficient to populate HD states with detectable intensity in this reaction, despite the theoretical prediction of a well developed potential-energy minimum already around spin 50 $\hbar$ in ^{170}Hf. Apparently the fission barrier is too low in this rather heavy system.

The high statistics of the data allows to extend the ND level scheme of ^{170}Hf considerably [24]. Several new bands were discovered and previously known bands could be extended to higher spins. In addition, a band with a moment of inertia similar to those of triaxial strongly deformed bands in neighbouring Hf and Lu isotopes was found [25] in ^{170}Hf. It has an intensity of $\sim 1\%$ of the low-spin transitions. Coincidence spectra of this band typically contain about 10^3 counts in the peaks. Therefore, it was estimated that the achievable observation limit lies below 10^{-4} of the reaction channel.

4.2. The $^{48}Ca + ^{96}Zr \rightarrow ^{144}Nd$ reaction

High-spin states in ^{140}Nd were populated in the reaction ^{96}Zr(^{48}Ca,$4n$) at a beam energy of 194 MeV at the Vivitron accelerator at IReS. The target was an enriched ^{96}Zr foil of 735 μg/cm^2 thickness. Gamma-ray coincidences were measured with the EB spectrometer array. With a trigger demanding $\geq$4 Ge detectors before Compton suppression in coincidence with $\geq$11 BGO detectors, a total of 1.5×10^9 events were recorded in an effective beam time of $\sim$6 days with an average beam intensity of $\sim$0.8 pnA.

The off-line analysis of the data did not reveal any HD bands in both the discrete and quasi-continuum spectra. Also in this case the HD bands are not populated with sufficient intensity to be detected with EB, probably due to a fission cutoff of the highest angular momentum states.

A very high-spin SD band as well as several new ND bands were found in ^{140}Nd. The SD band has a moment of inertia and a quadrupole moment lying between those of the $A \approx 130$ and the $A \approx 150$ regions [26]. It represents an important link between the two mass regions and gives insight into the development of deformation-driving effects of the intruder orbitals. The band is not connected to lower-lying known states, but its decay pattern and an analysis using spin-fitting methods suggest that it extends from $I \approx 36$ to 66 $\hbar$.

4.3. The ^{48}Ca + ^{82}Se → ^{130}Xe reaction

Two experiments were performed to search for HD states in ^{126}Xe, the first one using EB and the second one with the GS spectrometer. In both cases the reaction ^{82}Se(^{48}Ca,4n) was used to populate high-spin states. The first experiment was carried out at the Vivitron accelerator at IReS. A target of enriched ^{82}Se with 625 μg/cm^2 thickness, protected by thin Au layers, was used. The excitation functions measured at beam energies of 185, 195 and 205 MeV showed a saturation of the inner ball fold distributions in the 4n-evaporation channel at 195 MeV and the experiment was run with this beam energy. In an effective beam time of ~ 5 days with an average beam intensity of ~ 0.8 pnA, a total of 5×10^8 events with Ge-detector coincidence fold ≥ 4 and BGO fold ≥ 11 were obtained.

A search for discrete HD bands was made using the Radware techniques [23] and a new software package to automatically scan the data set for discrete bands with various moments of inertia [27]. A very weak band-like structure with an average energy spacing of 33 keV between the peaks was observed in the region between 1340 and 1610 keV. The moment of inertia derived from the energy spacings is close to the expectation from the HD minimum seen in the calculated potential-energy surfaces, see Fig. 2. However, the statistical significance was not sufficient and a second experiment with higher statistical accuracy was planned.

The second experiment was carried out at the ATLAS accelerator at Argonne National Lab. using the GS spectrometer. The off-line analysis of inner-ball fold distributions and fold-gated discrete and continuum γ-ray spectra from the first experiment suggested that the population of the highest-spin states could be enhanced if the beam energy would be raised. The new run was therefore carried out at 205 MeV. The target was a 500 μg/cm^2 ^{82}Se foil protected be thin Au layers. It was mounted on the four sections of a rotating wheel. The beam spot on the target was slightly defocused and wobbled up and down by a few millimetres for further heat dissipation. With these precautions the maximum sustained beam was ~ 4 pnA. In a beam time of seven days, 3×10^9 events were collected with clean Ge fold ≥ 4.

The suspected discrete HD band from the first experiment could not be confirmed, despite the higher statistics of the data. The search routines produced several new candidates, however none of them with sufficient statistical significance. Therefore, the further analysis was concentrated on the quasi-continuum spectra [20, 22].

Rotational correlations, selected under the condition $(E_x+E_y-2E_z) \leq \delta$, were sorted into a rotational plane (E_x,E_y). This selection of events containing three sequential transitions deviating by less than δ from a pure rotational sequence with constant moment of inertia enhances the rotational structures [28, 29]. The allowed variation δ of the energy diff keV. Rotational planes were produced with different thresholds on the γ-ray fold. For a suppression of the background from other reaction channels a new filtering technique [30] was used. In the data sets from both experiments ridge structures with an energy separation of 48 keV appear in perpendicular cuts in the rotational planes gated by high folds. Fig. 3 shows an example of the results. The width of the cut at 1360 keV was varied between 88 and 184 keV. In the GS experiment the statistical accuracy was sufficient to work with even higher thresholds on the γ-ray fold and in the highest-fold data an additional ridge with an energy separation of 40 keV becomes visible above 1440 keV.

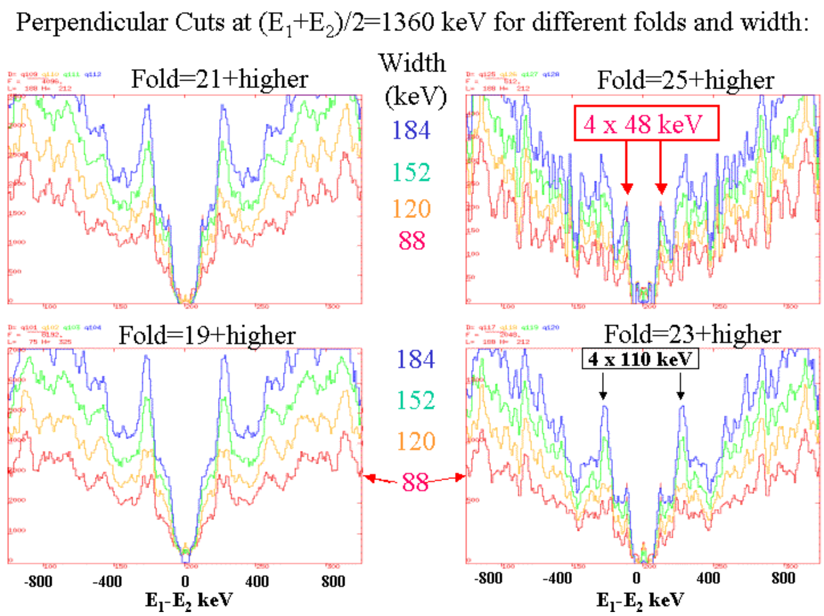

Fig. 3. Perpendicular cuts across rotational planes for ^{126}Xe with four different thresholds on the coincidence fold and for four widths of the cuts between 88 and 184 keV [20].

The energy separation of 48 keV between the ridges in cuts at 1360 keV and of 40 keV at 1440 keV correspond to moments of inertia of 83 $\hbar^2$/MeV and 100 $\hbar^2$/MeV, respectively. This has to be compared to the moments of inertia of about 40 $\hbar^2$/MeV for the ND bands in this mass region.

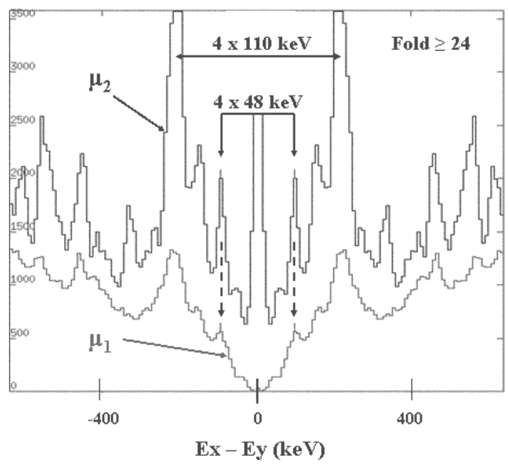

Fig. 4. Result of a fluctuation analysis on a perpendicular cut at 1360 keV across a rotational plane for ^{126}Xe [31].

A fluctuation analysis [29] was performed on the perpendicular cuts shown in Fig. 3 [31]. Fig. 4 shows, as an example of these results, the μ_1 and μ_2 spectra for a fold threshold of 24 where the ridges with 48 keV energy separation are clearly visible. The ridges contain 10 or more bands with an average intensity of $\sim 10^{-6}$ or less for each of the bands. As this lies below the observational limit of the spectrometer arrays it may not be surprising that no discrete-line bands were observed.

The excellent statistical accuracy of the data allows also to extend the level schemes of ^{126}Xe and neighbouring nuclei. *E.g.*, more than 10 new bands, one of them extending in spin up to 59 $\hbar$, were discovered in ^{125}Xe and ^{126}Xe [22]. Fig. 5 shows the spectra of three of these bands in ^{126}Xe.

The population of the highest-spin states of the discrete ND bands, like the ones shown in Fig. 5, can be compared in the two experiments with the two beam energies of 195 and 205 MeV, respectively. The population of states above 50 $\hbar$ is significantly higher at 205 MeV compared to 195 MeV bombarding energy. This demonstrates the necessity to overshoot in beam energy compared to the one deduced from the average fold distribution for the reaction channel.

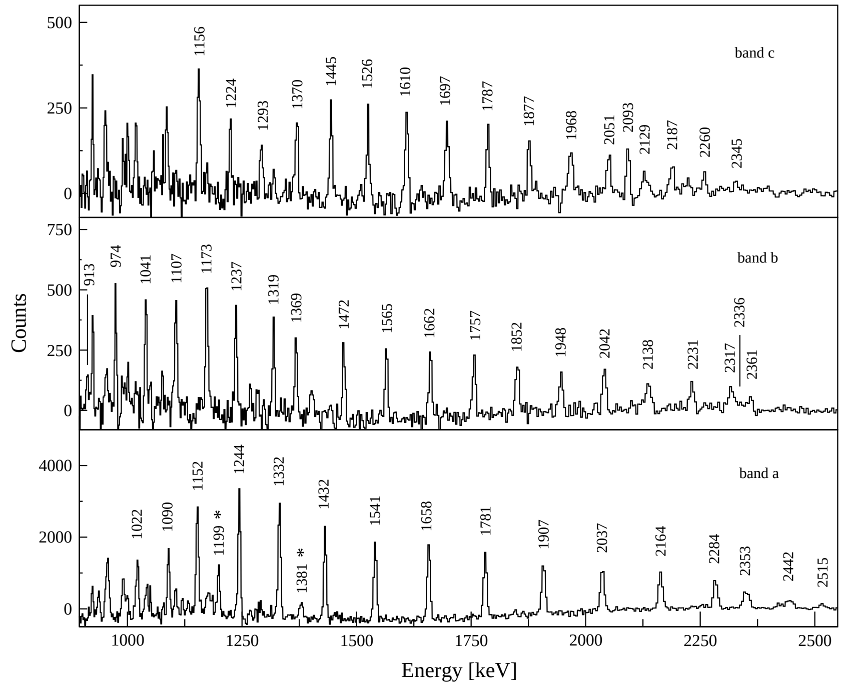

Fig. 5. Gamma-ray coincidence spectra of three new ND bands in ^{126}Xe. For band a, lower-lying transitions are marked by an asterisk.

4.4. The $^{64}Ni + ^{64}Ni \rightarrow ^{128}Ba$ reaction

Three experiments have been performed to investigate ^{126}Ba and neighbouring nuclei, the first one with GS in Berkeley and the following two with EB at Strasbourg. The cold symmetric reaction ^{64}Ni + ^{64}Ni was used with different beam energies. In the $2n$-evaporation channel, leading to ^{126}Ba, the highest-spin states were populated, however with a low cross section. Using the Wilson–Herskind filtering technique [30] it was possible to suppress the background from competing reaction channels by a factor of 10 and a further enhancement was obtained by selecting events with the highest γ-ray fold.

In the first experiment the ^{64}Ni beam of 265 MeV with an intensity of $\sim$1.5 pnA was delivered by the 88-Inch Cyclotron. The target consisted of a selfsupporting ^{64}Ni foil of 480 μg/cm^2 thickness. In a beam time of five days, 1.2×10^9 events with Ge-detector coincidence fold ≥ 4 were recorded.

The searches for discrete-line HD rotational bands did not result in any convincing candidates. However, the rotational-plane mapping, as described above in the case of ^{126}Xe, revealed a ridge structure with an energy separation of 52 keV in ^{126}Ba [20, 21]. Examples of perpendicular cuts in the rotational plane are shown in Fig. 6. Rotational correlations were selected with a thickness of $\delta = 8$ keV when sorting into the rotational plane. The upper spectrum was obtained from the data filtered for the $2n$-evaporation channel while the lower spectrum is from the total data base. The 52 keV distance between the ridges corresponds to a moment of inertia of 77 $\hbar^2$/MeV, compared to 41 $\hbar^2$/MeV for the average of the ND bands, as seen from the larger distance between the broad ridges in the lower spectrum.

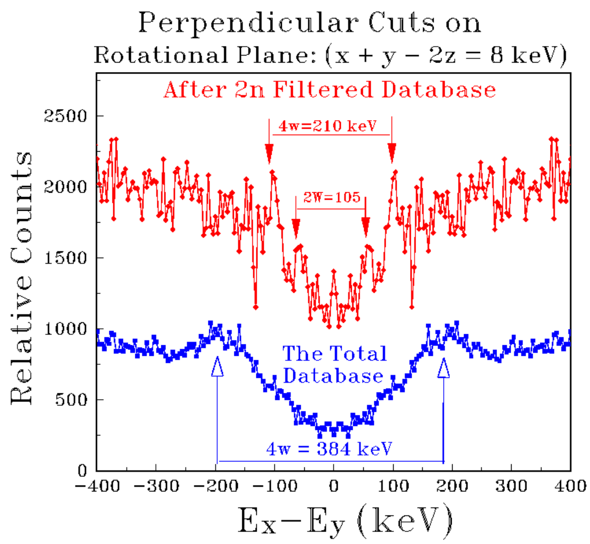

Fig. 6. Perpendicular cuts, 142 keV wide, across the rotational planes at 1440 keV for the ^{126}Ba filtered data, upper spectrum, and for the total data set, lower spectrum [20, 21].

These encouraging results stimulated further investigations using EB with different ancillary detectors. In a first experiment excitation functions for the ^{64}Ni + ^{64}Ni and ^{64}Ni + ^{65}Cu reactions were measured to find the optimal conditions to populate the highest-spin region in ^{126}Ba. The tapered Ge detectors in the forward hemisphere of EB were replaced by eight large BaF_2 scintillation spectrometers from the HECTOR array and four small BaF_2 trigger detectors for a possible neutron discrimination. In the large BaF_2 counters high-energy γ rays from the decay of giant dipole resonances (GDR) were detected. This will allow to test the prediction that the population of HD states may be enhanced through the GDR decay [20].

During the first days of the run the fold distributions, measured with the inner ball BGO detectors and gated by γ rays from the different reaction channels, were determined at beam energies of 245, 255 and 261 MeV for the ^{64}Ni + ^{64}Ni reaction and at 275 and 285 MeV for the ^{64}Ni + ^{65}Cu reaction. The results showed that the highest-spin states are populated in the 2n channel. As the fold distributions saturated at 255 MeV for the ^{64}Ni + ^{64}Ni reaction [20], this energy was chosen for the major part of the available beam time. This energy is lower than the one used in the previous run with GS, but had the advantage of a higher cross section for the $2n$-evaporation channel. However, the off-line analysis of these data which comprise 1.3×10^9 events showed neither discrete HD bands nor ridges corresponding to bands with large moments of inertia.

The intention of the final experiment with EB was to collect as much statistics as possible with a presently available spectrometer array. Four weeks of beam time were divided into two runs with ^{64}Ni beam energies of 255 and 261 MeV, respectively. With a target of $\sim$500 μg/cm^2 thickness and an average beam intensity of $\sim$1.5 pnA, a total of 12×10^9 coincidence events of $\geq$3 Ge and $\geq$11 BGO detectors was collected. The charged-particle detector array DIAMANT [32] was mounted inside the EB target chamber. It was run as a 'slave' in the event trigger. A report on the progress of the analysis of the data in which charged particles were detected is given in a separate contribution to this conference [33].

Searches for discrete rotational bands with the small energy spacings expected for HD states in the data without a charged particle detected did not give a positive result. Furthermore, also the analysis of the quasi-continuum spectra of the data measured at 255 MeV did not show the ridge structure with the 52 keV energy spacing observed with GS at 265 MeV, despite the improved statistical accuracy. However, that structure did appear in the data measured at 261 MeV. Fig. 7 shows differences of perpendicular cuts across the rotational planes for 261 and 255 MeV for different thresholds on the BGO-detector fold. The cuts were made under identical conditions for the two beam energies and were properly normalised before subtraction. The ridges with 52 keV energy separation become more pronounced with increasing fold. Using the result of the statistical analysis suggesting ten or more bands contributing to the ridges, a limit on the intensity of less than 10^{-6} may be estimated for the individual bands.

It is interesting to note that a beam-energy difference of only 6 MeV makes such a big difference in the population of states which feed into the ridge structure. The channel-gated fold distributions measured in the inner ball was investigated for the two beam energies to check if this could be an angular momentum effect. Indeed, the ratio of the yields measured at 261 and 255 MeV, $Y(261)/Y(255)$, shows a significant increase above fold 28 and peaks at $f = 36$ [21]. Although it is not straight forward to translate the additional high-fold events observed at 261 MeV directly into a population of very high-spin states, it seems plausible that the extra events originate

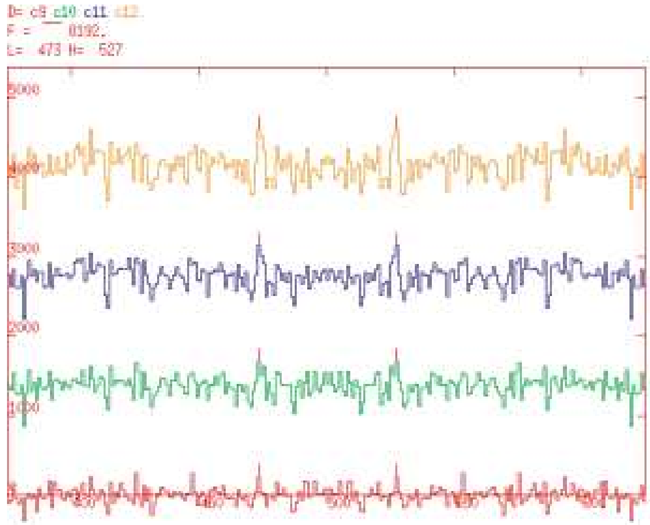

Fig. 7. Differences of perpendicular cuts, 204 keV wide, at 1440 keV across rotational planes with $\delta = 12$ keV from data measured at 261 and 255 MeV beam energy for ^{126}Ba. The four spectra, from bottom to top, are for thresholds of 22, 24, 26 and 28 on the coincidence fold [21].

from nuclei which survive fission and decay through very elongated shapes responsible for the ridge structure with the small separation of 52 keV. This also shows that it is necessary to overshoot in beam energy by several MeV above the energy at which the overall fold distribution for the desired reaction channel saturates.

The high-statistics data set also contains a wealth of new information on ND states. The analysis of these data is in progress. An extended level scheme for ^{124}Ba is presented in a separate contribution to this conference [34].

5. Summary

Several experiments performed in recent years to search for HD structures with the spectrometer arrays EB and GS have been described. No convincing evidence for discrete-line HD rotational bands was found so far. However, rotational-plane mapping in quasi-continuum correlation spectra revealed ridge structures with small energy separations in ^{126}Xe and ^{126}Ba. The separation of the ridges, if resulting from rotational bands, corresponds to moments of inertia of 77 and 83 $\hbar^2$/MeV, and possibly 100 $\hbar^2$/MeV. These ridges are only observed when the highest-multiplicity cascades are selected in the data from experiments with the highest bombarding energies. The sensitivity to the beam energy suggests a small entrance window for the population of very elongated shapes through the highest-spin states.

The data sets have high statistics and contain a wealth of information also on ND and SD structures. Only a small fraction of these data is analysed up to date. Selected examples of ND and SD bands have been mentioned.

I wish to thank all the members of the large collaboration formed for the search for hyperdeformation for their hard work during the experiments and the analysis of the data. Special thanks goes to Bent Herskind for his continued encouragement and optimism. He performed the analysis of the quasi-continuum spectra and supplied the figures showing the ridge structures.

REFERENCES

[1] J. Dudek *et al.*, *Eur. Phys. J.* **A20**, 15 (2004).
[2] S. Cwiok *et al.*, *Phys. Lett.* **322B**, 304 (1994).
[3] D.M. Brink *et al.*, *Phys. Lett.* **33B**, 143 (1970).
[4] J. Blons *et al.*, *Nucl. Phys.* **A502**, 121c (1989).
[5] A. Krasznahorkay *et al.*, *Phys. Lett.* **461B**, 15 (1999).
[6] T.R. Werner, J. Dudek, *At. Data Nucl. Data Tables* **50**, 179 (1992).
[7] R.R. Chasman, *Phys. Lett.* **302B**, 134 (1993).
[8] W. Nazarewicz, *Phys. Lett.* **305B**, 195 (1993).
[9] D.R. LaFosse *et al.*, *Phys. Rev. Lett.* **74**, 5186 (1995).
[10] D.R. LaFosse *et al.*, *Phys. Rev.* **C54**, 1585 (1996).
[11] A. Galindo-Uribarri *et al.*, *Phys. Rev. Lett.* **71**, 231 (1993).
[12] G. Viesti *et al.*, *Phys. Rev.* **C51**, 2385 (1995).
[13] J.N. Wilson *et al.*, *Phys. Rev.* **C56**, 2505 (1997).
[14] R.M. Clark *et al.*, *Phys. Rev. Lett.* **87**, 202502 (2001).
[15] A. Görgen *et al.*, *Phys. Rev.* **C65**, 027202 (2002).
[16] P. Fallon, *Acta Phys. Pol. B* **36**, 1003 (2005), contribution to this conference.
[17] T. Bengtsson, *Nucl. Phys.* **A512**, 124 (1990).
[18] R. Bengtsson, `http://www.matfys.lth.se/~ragnar/ultimate.html`
[19] J. Domscheit *et al.*, *Nucl. Phys.* **A689**, 655 (2001).
[20] B. Herskind *et al.*, *Acta Phys. Pol. B* **34**, 2467 (2003).
[21] B. Herskind *et al.*, *AIP Conf. Proc.* **701**, 303 (2004).
[22] C. Ronn Hansen *et al.*, AIP Conf. Proc. (Argonne 2004), in press.
[23] D.C. Radford, *Nucl. Instrum. Methods Phys. Res.* **A361**, 297 (1995).

[24] A. Neusser *et al.*, to be published.

[25] A. Neusser *et al.*, *Eur. Phys. J.* **A15**, 439 (2002).

[26] A. Neusser *et al.*, *Phys. Rev.* **C70**, 0664315 (2004).

[27] J.N. Wilson, private communication.

[28] B. Herskind *et al.*, ANL-PHY-88-2 179 (1988).

[29] T. Dossing *et al.*, *Phys. Rep.* **286**, 1 (1996).

[30] J.N. Wilson, B. Herskind, *Nucl. Instrum. Methods Phys. Res.* **A455**, 612 (2000).

[31] B. Herskind, private communication.

[32] J.N. Scheurer *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A385**, 501 (1997).

[33] B.M. Nyako *et al.*, *Acta Phys. Pol. B* **36**, 1033 (2005), contribution to this conference.

[34] A. Al-Khatib *et al.*, *Acta Phys. Pol. B* **36**, 1029 (2005), contribution to this conference.