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HUNTING GROUNDS FOR JACOBI TRANSITIONS AND HYPERDEFORMATIONS*

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In recent attempts to search for exotic shapes, hyperdeformation (HD), and Jacobi transitions in Hf, Ba, Xe, Sn and Nd nuclei, ridge structures presumably originating from nuclei of very elongated shapes have been observed in ^{126}Ba, with Gammasphere (GS) and in ^{126}Xe, with Euroball-IV (EB-IV). After the promising results from GS, a second experiment in ^{126}Ba followed at EB-IV, taking advantage of the use of the BGO Inner Ball (IB) for selecting the highest spins. The decay of the Giant Dipole Resonances (GDR) is also studied, and the analysis in progress. The Quasi-continuum transitions in the Jacobi region, show a significant decrease in energy for both ^{126}Ba and ^{126}Xe, compared to the Thomas–Fermi- and the LSD model predictions. Similar effects were recently found for other nuclei by Ward *et al.*

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1. Introduction

The prediction of hyperdeformation(HD) [1] at high angular momentum has posed important questions about the limits of stability in extremely elongated nuclei, which has not been experimentally answered to satisfaction yet. After the discovery of the superdeformation (SD) in ^{152}Dy by Peter Twin and collaborators in 1986 [2], and the successes of the rich spectroscopy in the second well in several mass regions developed the following years, the confidence in the model predictions also for HD grew. Thus, one of the primary goals of building the $\approx$ 10 % efficient γ-detector arrays, *i.e.* Euroball (EB) and Gammasphere (GS) was to find- and investigate HD configurations. Several unsuccessful attempts were made in the rare earth region, which looked most promising from the early predictions *i.e.* ^{168}Yb [3], and ^{166,168}Hf. Several other interesting results came out from discrete spectroscopy of those nuclei, which formed a good part of 2 thesis projects [4, 5]. It became apparent that more work was needed to understand the population and decay mechanisms of extremely deformed structures in order to be able to choose the best candidates, in addition to further develop the sensitivity of the instruments as well as new analysis techniques.

The enhancement of the population of individual SD states over the equivalent normally deformed (ND) states in the same nucleus for a given spin in the feeding region is observed to be as high as a factor of 10. It was shown by simulation calculations in 1987 [6] that this enhancement was due to two equally important factors, the ratio of level densities $\rho_{\rm SD}/\rho_{\rm ND}$ ≈ 3, and the splitting on the Giant Dipole Resonance (GDR) built on the SD states. The latter results in a low-lying component enhancing the E1 transition probability by a factor of ≈ 3. These numbers refer to ^{152}Dy where the intensity of the SD yrast band is $\approx$ 1 %, the yrast crossing $\mathrm{U_{SD}}=\mathrm{U_{ND}}$ $\approx 54\ \hbar$ and the fission limit for the residual nucleus, $L_{\rm res} \geq 64\ \hbar$.

When the same simulation ideas are applied to the population of states in the predicted HD potential in ^{168}Yb, one finds an intensity of the yrast HD band of $\approx 10^{-5}$, assuming an yrast crossing at $I = 78\ \hbar$ and $L_{\rm res} = 65\ \hbar$. It also shows that the sensitivity to the fission limit is very important. If $L_{\rm res}$ were changed to 75 $\hbar$ then the intensity of the HD-yrast population would increase $\approx$ 50 times. Therefore, a few units higher spin input to the residual nucleus may be essential. Since the reaction channels with a low multiplicity of evaporated particles lead on average to the population of states with higher spin, the use of a $2n$ reaction might be advantageous over *e.g.* a $4n$ reaction, even though the cross section is in general lower.

It is also important to focus on nuclei which show a pronounced HD minimum with an yrast crossing significantly below the $L_{\rm res}$. Such nuclei are only found in the mass 130 region, where the spin range of Jacobi transitions are known to be the largest [10, 11]. We have therefore lately focused our attention on the heaviest Xe, Ba and Nd nuclei which can be produced rather cold by semi-symmetric reactions.

2. Theoretical expectations

2.1. Shell model estimates

We have systematically used the Ultimate Cranker code (UC) originally built by Bengtsson [7], and later modified by Bengtsson [8] to find the most promising cases, looking for stable HD potentials over several neighboring nuclei, and an yrast crossing at reasonably accessible spin values, $I = 68$–$82\ \hbar$.

2.2. Fission limits and Jacobi transitions

The recent Lublin-Strasbourg-Drop(LSD) model by Pomorski and Dudek [9] has been extremely useful in many ways, showing the expected Jacobi transition region very clearly, and the development of the liquid drop potential as a function of spin, until it has no barrier toward fission. Examples are shown in Fig. 1 for ^{126}Ba, ^{126}Xe, ^{144}Nd and ^{168}Hf, for spins where the Jacobi minimum still is stable for the 3 first cases, in contrast to the case of ^{168}Hf where the nucleus jumps directly from normal deformation to fission without any Jacobi stability. This striking difference is also in accordance with the early estimates of Cohen, Plasil and Swiatecki [10]. We believe that the Jacobi stability calculated for ^{126}Ba, ^{144}Nd and ^{126}Xe is very important for the population dynamics, since these potentials are valid also at much higher temperatures, where the population takes place, and the Jacobi transition may work as a gateway to lower lying discrete structures.

2.3. The GDR strength functions at high spin

It is possible to make a simple estimate of the shape of the GDR strength functions as a function of spin. The expected GDR shapes are shown for 6 typical spin values in Fig. 2 covering the Jacobi transition region (3 lowest panels, 50, 60, 68 $\hbar$ and 3 middle panels, 68, 70, 72 $\hbar$). They are weighted by a Boltzmann factor over temperature, and calculated on the basis of the liquid drop potentials as those shown in Fig. 1, for the given spins, using the expression:

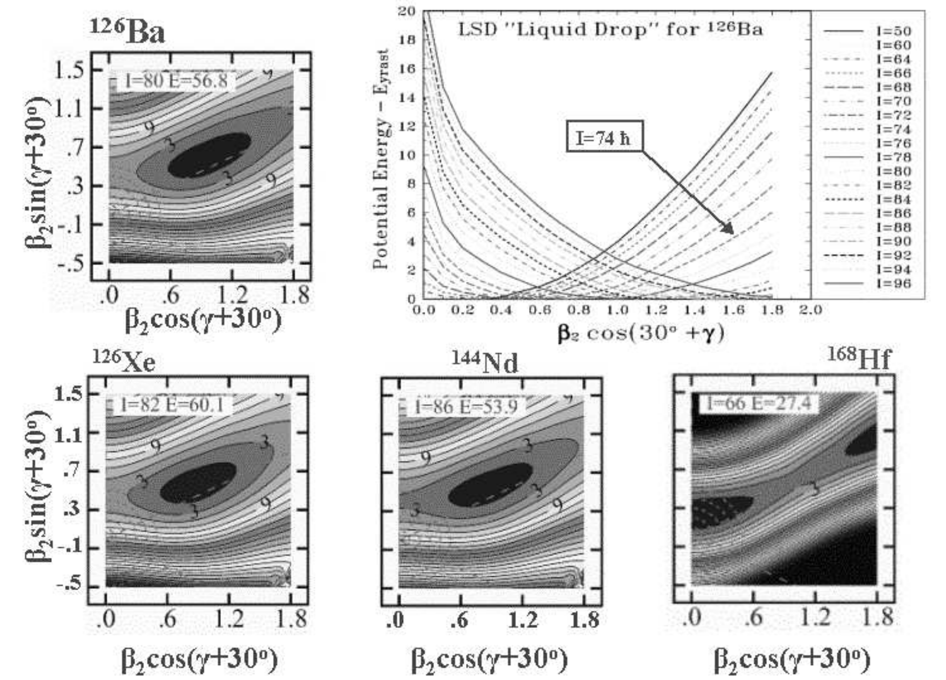

Fig. 1. Liquid drop potentials calculated by the Pomorski–Dudek LSD model [9] for ^{126}Ba, ^{126}Xe, ^{144}Nd and ^{168}Hf in the spin regions just below the fission limit. In the case of ^{126}Ba, the minimum of the barrier is extracted as a function of $\beta_2\cos(\gamma+30°)$ for a wide region of spin values and shown in the upper-right panel.

$$f_{\rm GDR} = \sum_{x,y} f_{\rm GDR}(x,y)\exp\left[(E-E_{\rm yrast})/T\right]\beta^3|\sin(3\gamma)|\,. \qquad (1)$$

Here $f_{\rm GDR}$ is the GDR strength function, T the temperature at (x,y), and where x and y correspond to $\beta_2\cos(\gamma+30°)$ and $\beta_2\sin(\gamma+30°)$, respectively. The summation goes in the prolate to oblate sextant of the β–γ plane only. The sensitivity to the LSD potential surfaces is illustrated in the 4 top panels, for spin $I=68$ (left) and 72 $\hbar$ (right).

The low lying component corresponding to oscillations along the prolate axis, toward fission, is getting well isolated from the other oscillations when approaching the Jacobi region at $I\approx 66$–72 $\hbar$ as seen in Fig. 2. Two of the three Lorentzian strength functions will actually be further split by an energy $2\cdot\hbar\omega$ due to the fast rotation [17].

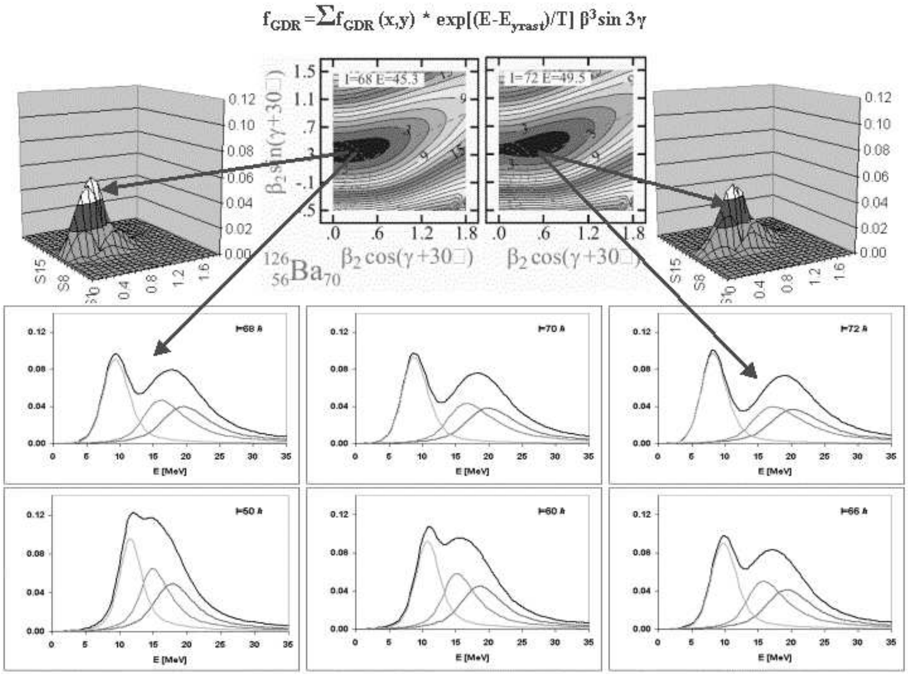

Fig. 2. GDR Lorentzian strength functions calculated for selected spin values in the middle and lower panels. The panels in the upper corners illustrate the shape of the weighting functions as a function of x and y, in the corresponding liquid drop (LSD) surfaces on which they are based, for $I = 68$ and 72 $\hbar$.

3. Experimental searches for HD in ^{126}Ba

The first attempt in the Ba region was made using the GS in Berkeley. The cold fusion reaction, ^{64}Ni + ^{64}Ni $\Rightarrow$ ^{128}Ba with a bombarding energy of 261 MeV was used. At this energy, the $2n$ evaporation channel leading to ^{126}Ba populated the highest spins the nucleus can accommodate, however, with a low cross section corresponding only to 2% of the total fusion cross section. It was possible to suppress the background from the other reaction products by a factor of 10 in the analysis by using the newly developed selective filtering technique [12]. Furthermore, pure rotational correlations selected by applying the equation: $(E_x + E_y - 2E_z) = \delta$, were sorted into a rotational plane, (E_x, E_y) [13,14], with a thickness of $\delta = 8$ keV. This selection of events containing 3 sequential transitions deviating less than $\pm$ 4 keV from a pure rotational sequence with constant moment of inertia, enhanced the rotational structures by an additional factor of 5. The result of this Double-Selection Filter-Technique can be seen in Fig. 3 where ridges from "warm" rotational bands in strongly deformed nuclei are observed (upper curve in the right panel). The distance between the ridges, 4×52.5 keV, corresponds to a moment of inertia of 76 MeV^{-1} $\hbar^2$ compared to 41 MeV^{-1} $\hbar^2$ for the normal states, as showed in the lower curve of Fig. 3. Searches were also made for discrete structures with large moment of inertia, without success.

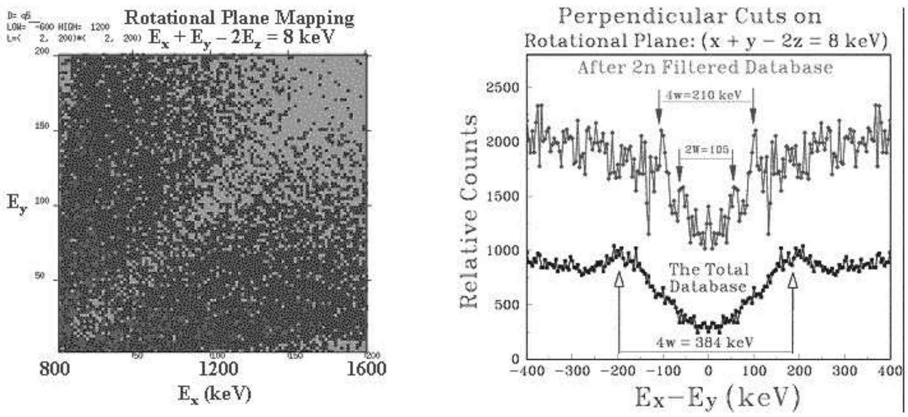

Fig. 3. Left: The 2D Rotational Plane, for the $2n$ filtered data. Right: Spectra of ^{126}Ba for perpendicular cuts across the diagonal $E_x = E_y$ of the rotational plane (left), at 1440 ± 142 keV for the $2n$ filtered data (upper) and for the full database (lower). The $2n$ filtered spectrum shows a ridge structure corresponding to a moment of inertia almost twice that extracted from the full dataset. A very weak glimpse of the ridge structure can also be seen in the $2D$ spectrum to the left.

This led us to make a renewed effort with Euroball-IV, equipped with a BGO inner ball (IB) for detecting the γ-fold distributions, 8 large BaF_2 detectors (HECTOR) for detecting high-energy γ-rays from the decay of Giant Dipole Resonances, and 4 fast BaF_2 trigger detectors to ensure that a possible neutron discrimination could be used when needed. We first studied excitation functions for the two reactions, $^{64}\text{Ni} + {}^{64}\text{Ni} \Rightarrow {}^{126}\text{Ba} + 2n$ and $^{64}\text{Ni} + {}^{65}\text{Cu} \Rightarrow {}^{126}\text{Ba} + p2n$ to ensure that the absolutely highest spin region in ^{126}Ba was populated. The final experiment was carried out with 255 MeV $^{64}\text{Ni} + {}^{64}\text{Ni}$, which in a spin window $I \approx 64$–74 $\hbar$ populates the $2n$ reaction channel rather cleanly when a combination of $2n$-filtering and high fold gating was applied.

When the fold selection is applied differentially to spectra with high resolution, it is possible to determine quite accurately the dependence of the different evaporation channels on fold. This is illustrated in Fig. 4. The highest meaningful differential fold is 28, corresponding to a γ-multiplicity of ≈ 40. Pile-up of two reactions in the target at the same time dominates at

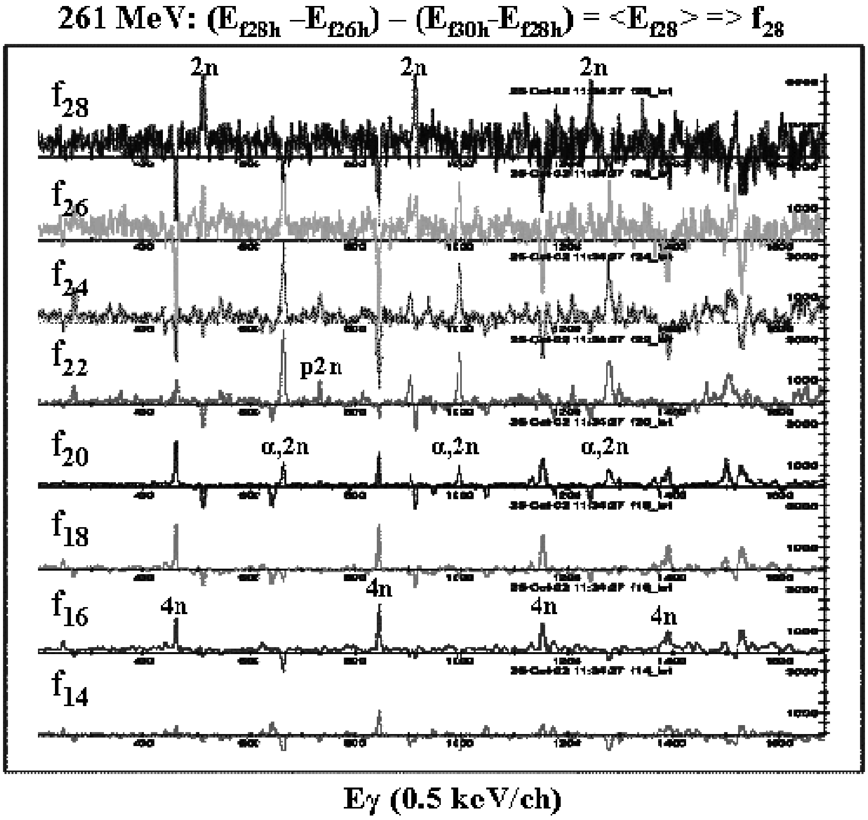

Fig. 4. Differential fold selected spectra shown for increasing fold. Note especially that the lines from the $\alpha 2n$ channel extend over a wide fold range, 20–26 , ending up only 2 fold units below the $2n$ channel.

even higher folds. Fig. 4 shows that the $2n$ evaporation channel populates the highest spin region and that the $\alpha 2n$ channel populates a region a few units of spin below. This is also true when gated by high-energy gamma rays between 7 and 13 MeV, which is surprising, since the threshold for evaporating an extra α-particle in Ba is ≈ 15 MeV and corresponds to 7-8 E2 transitions along the yrast slope at high spin, or $\approx 15\ \hbar$. The explanation may be that there are two different decay modes, one where all particles are emitted before the E2 γ-decay takes place in ^{122}Xe, and another, more interesting one originating from the high spin tail of the $\alpha 2n$ channel, where the α-particle emission comes after a cascade of E2 γ-rays through bands with very large moments of inertia in ^{126}Ba, perhaps of the Jacobi transition type. In this way the energy needed may be partially gained through these

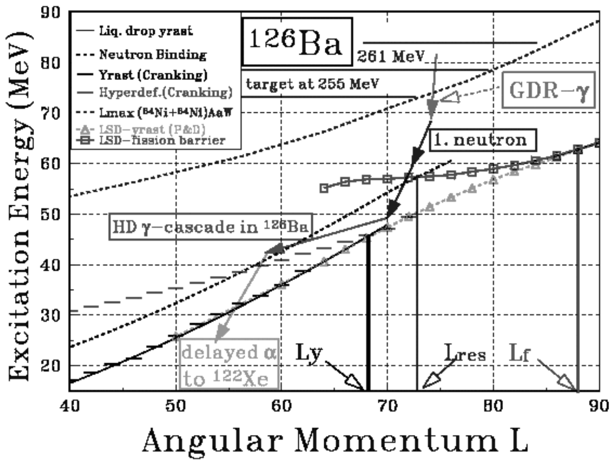

Fig. 5. Population and decay scheme for the compound nucleus ^{128}Ba populated in the ^{64}Ni + ^{64}Ni reaction at 261 or 255 MeV using a thin self-supporting target. It can be seen why the $2n$ channel only can reach the region of the highest spin, especially for the highest bombarding energy of 261 MeV. The possible scenario of a delayed α-decay from an unbound state after a E2 cascade in the continuum with large moment of inertia is illustrated schematically.

particularly low energy E2 cascade transitions with large moment of inertia. Furthermore, the Coulomb barrier may be lowered for α-emission from the tips of the elongated shape. This scenario is shown in Fig. 5.

When the fold selection is applied differentially to Compton unfolded spectra in the high energy region, it becomes possible to extract a bump of transitions from the highest spin region where the Jacobi transition may occur. The extracted energies are shown in Fig. 6, and compared to the theoretical predictions of Jacobi transitions from the LSD calculations and to calculations with the UC code. The E_γ-continuum points extracted from the highest spin region, are found below the giant back-bend from the liquid drop calculations [9]. Similar effects have recently been observed by Ward *et al.* for nuclei where Jacobi transitions also are expected [16]. The Jacobi shape transition and also possible causes of the reduced energy of the γ-transitions are discussed in great detail, and a general modification of the Thomas–Fermi model to account for these effects is actually suggested [16].

It is also appropriate to note that the given spin window just falls within the maximum angular momentum calculated on the basis of the Grazing model of Winther [18] predicting $L_{\rm max}$=$76\hbar$ for the compound nucleus ^{128}Ba at 250 MeV (mid target). Similar results are obtained by Rowley [19] with a 3-barrier parametrization, used to fit the measured cross section of the ^{64}Ni + ^{64}Ni reaction by Beckerman *et al.* [20].

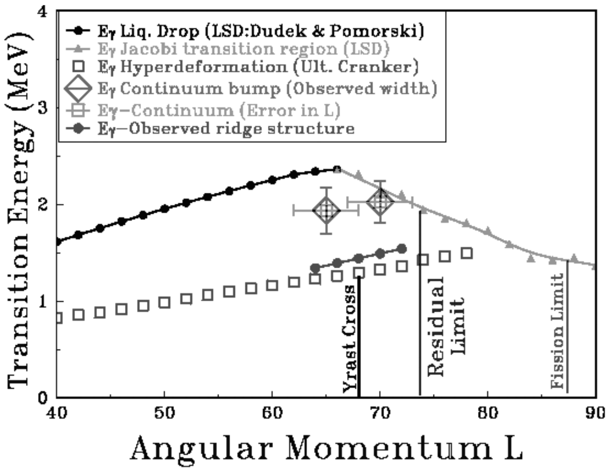

Fig. 6. Transition energies as a function of angular momentum. The ridge structure observed earlier in the Gammasphere experiment around 1440 keV with a slope of 52.5 keV per E2-transition may be compared to the predicted HD transitions from the UC calculation.

4. The experimental search for HD in ^{126}Xe

As can be seen from Fig. 1, the liquid drop LSD potential of ^{126}Xe is not expected to be very different from that of ^{126}Ba. Also the UC calculation shows that the HD potential becomes minimum at $I = 70$–71 $\hbar$ after being triaxial at $I = 58$–68 $\hbar$ with $\epsilon = 0.4$ and $\gamma = 30°$. Potential energy surfaces are shown for the Jacobi transitional region for I = 68,71 and 78 $\hbar$ in Fig. 7. The maximum angular momentum $L_{\max}$ is calculated as a function of excitation energy by the Grazing code [18] and the liquid drop yrast line and fission barrier are again extracted from Ref. [9]. This fission barrier

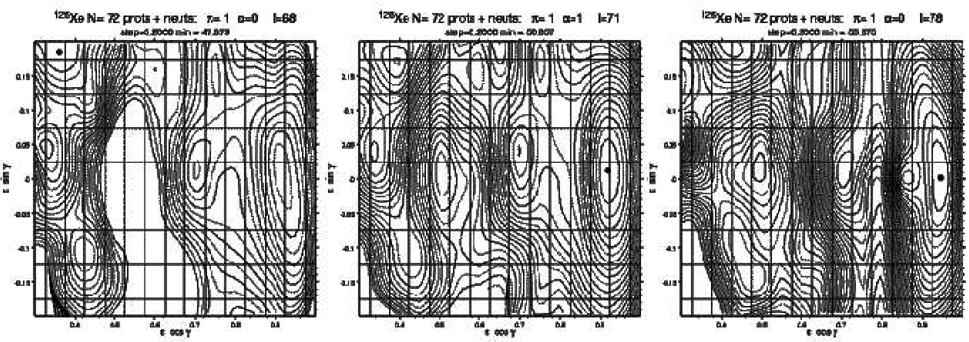

Fig. 7. Potential surfaces for $I = 68, 71{,}78$ $\hbar$ calculated by the UC model [7,8].

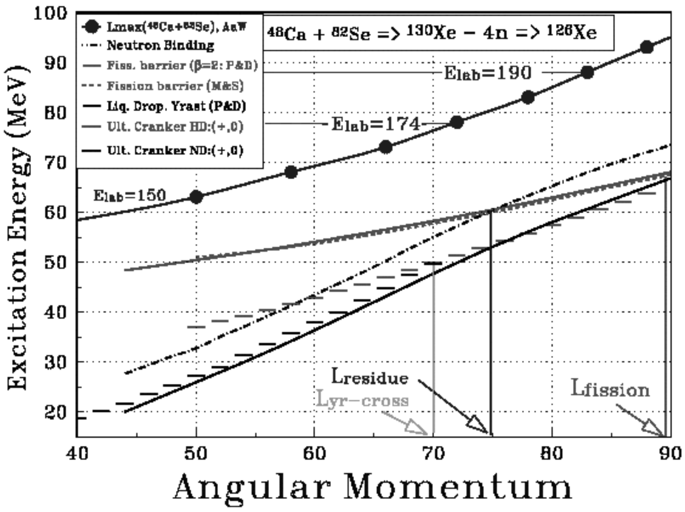

Fig. 8. Yrast diagram constructed for ^{126}Xe, based on models discussed in the text.

in fact agrees very well with calculations using the model of Myers and Swiatecki [11], as illustrated in the yrast diagram shown in Fig. 8. The most favorable L window for population of HD and Jacobi transitions is $L = 70$–75 $\hbar$, namely above the yrast crossing and below the fission limit for the residual nucleus ^{126}Xe.

The experiment was made in Strasbourg in the summer of 2001 using an almost complete EB-IV equipped with the IB for fold selection. The reaction used was $^{48}\mathrm{Ca} + {}^{82}\mathrm{Se} \Rightarrow {}^{130}\mathrm{Xe}^*$, and an excitation function for the $4n$ channel was made to find that the highest fold distribution was observed for a bombarding energy of 195 MeV.

We were only able to obtain at most 1 pnA of ^{48}Ca beam over the 6 days of running, so the statistics obtained was less than anticipated. However we were able to see a promising ridge structure corresponding to a large moment of inertia, 83 MeV^{-1} $\hbar^2$ around 1360 keV. This can be compared to 76 MeV^{-1} $\hbar^2$ around 1440 keV observed in the Ba case.

The same selective analysis technique was used as in Ba. In this case rotational planes were extracted as a function of fold higher than a given fold, simultaneously with a filtering for the $4n$ channel. Examples are shown in Fig. 9. The very weak ridges in the left panel, with a distance of 4×48 keV increase very strongly for all the cuts when selected by fold $=$ 25+higher. In contrast the ridges corresponding to 4×110 keV for normally deformed nuclei decrease significantly. It should be noted that the fold=25+higher selection is the highest possible before pile-up effects become dominant, like for fold=30+higher in the Ba case. However, the efficiency of the fold collec-

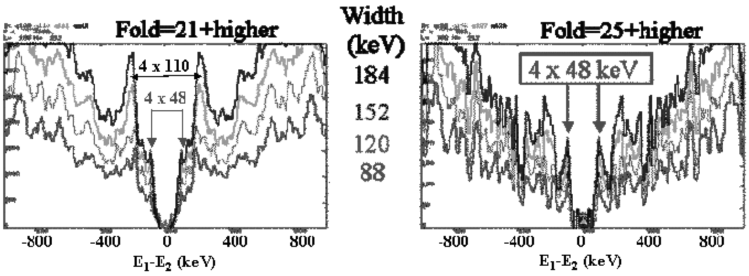

Fig. 9. Perpendicular cuts across the diagonals $E_1 = E_2$ of 2 different rotational planes gated by fold=21+higher (left) and fold=25+higher(right), at $(E_1+E_2)/2 =$ 1360 keV for 4 different width of the cuts, 88, 120, 152, and 184 keV.

tion is very different in the Ba and Xe experiments, which therefore can not be compared directly. In the case of Ba, only 3/4 of Ge+BGO was used due to the mounting of the BaF_2 in the forward hemisphere. In the Xe case the IB was complete and used separately. We estimate that the ridge structures observed in both cases come from similar spin ranges. The grazing calculations show that the ^{48}Ca induced reaction used in the Xe case, brings in $\approx 6\ \hbar$ more to the compound system than the cold ^{64}Ni induced reaction, when bombarding energies of 195- and 255 MeV were used, respectively. This may compensate for the angular momentum lost in the evaporation of 2 additional neutrons before the highest spin region is reached.

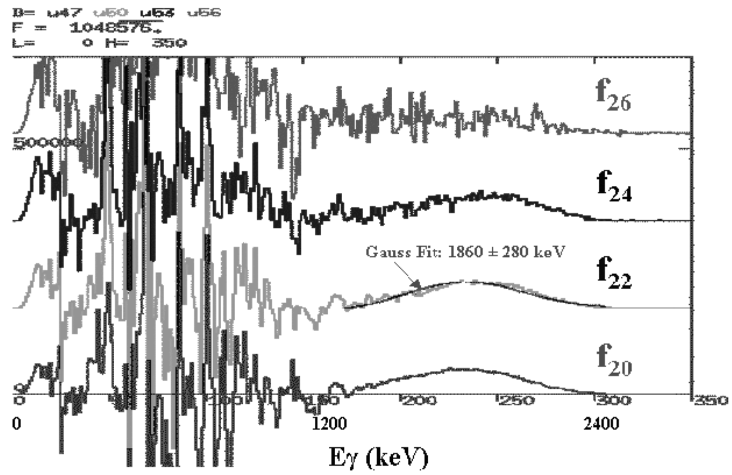

Fig. 10. Unfolded normalized spectra as a function of differential folds, 20,22,24 and 26 showing the transition energies in the continuum at the highest spin obtained in the present experiment on ^{126}Xe. The isolated high energy bump has been Gauss fitted to give the energy and width as the example shown for f_{22}. The results of the fits are included in Fig. 11.

A search for discrete HD bands was also made in ^{126}Xe, by a new sensitive search routine developed by Jonathan Wilson. One very weak rotational band structure was observed in the region 1340-1606 keV with an average spacing between peaks of 33 keV, close to the energies expected from the UC calculations for the HD yrast band. However, the statistical significance was only 2.31σ, and the band has to be regarded as promising only, rather than true, for the time being. In this spirit it is shown together with the overview of both expected and observed transition energies in Fig. 11.

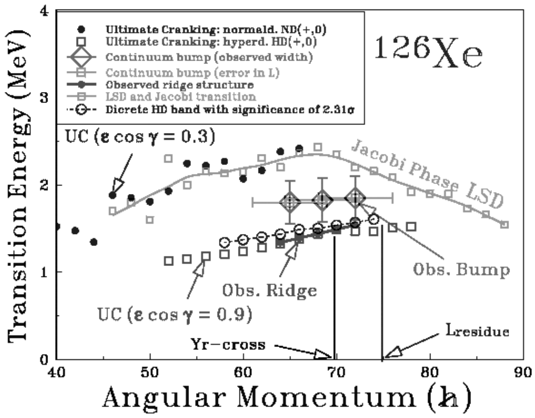

Fig. 11. Transition energies as a function of angular momentum. The ridge structure observed in ^{126}Xe around 1360 keV with a slope of 48 keV per E2-transition may be compared to the predicted HD transitions from the UC calculation, and to the weak indication of a discrete HD band discussed in the text. The spin values used for these points are our best estimates but may as well be several $\hbar$ different.

It also has been possible to isolate the transitions at the highest spin by differential fold gating in a similar way as discussed for the Ba case. This is shown in Fig. 10. The spectra are unfolded for Compton scattering and normalized to fold+(higher folds), for fold 19, 21, 23, 25, 27. The spectra shown correspond to the difference (fold+higher)-(fold+higher-2) $\Rightarrow f_{\text{fold}-1}$. The isolated high energy bumps are almost Gaussian shaped. Individual fits give the energy and width of the continuum states which presumably carry information about the Jacobi transition region. The results are shown in Fig. 11. The E_γ-continuum points extracted from the highest spin region in ^{126}Xe, are seen to fall significantly below the giant back-bend indicated from the liquid drop calculations of [9] in a similar way as shown for ^{126}Ba in Fig. 6, and observed by Ref. [16]. The observed ridge structure in ^{126}Xe, as well as the promising indication of *a discrete HD band* is also shown in Fig. 11. Although the statistical uncertainty is not satisfactory, it may still be used to give an indication of where to look for more well developed structures.

5. Summary and outlook

The analysis of the data obtained in the searches for HD states in both ^{126}Ba and ^{126}Xe, did not give any direct evidence for highly deformed discrete bands as predicted by calculations. Still the results provide good perspectives for extension of the experiments to obtain better statistics and thereby better sensitivity.

The fact that ridge structures with similar large moments of inertia have been observed in both nuclei, most likely originating from the continuum in the Jacobi transition region, looks promising. The gate-way to the low-lying HD structures will most probably go through these states. We can therefore expect that with just slightly higher sensitivity and a few times better statistics, there is a good opportunity for improvements. In the case of ^{126}Ba this already stimulated a new attempt with the Euroball over 4 weeks of beam-time. This experiment was performed in Dec. 2002 and Jan. 2003, and 2×1 Terabyte of data were collected, using ^{64}Ni beam with 2 different energies of 255 and 261 MeV. The DIAMANT ancillary detector was used for detecting charged particles in a $4\,\pi$ geometry, not least to investigate the interesting possibility mentioned earlier of delayed α emission (Fig. 6), after passing through E2 γ-cascades with large angular momentum in the Jacobi transition region. More than 60 scientists made an active contribution to this experiment, which will be analyzed during 2003, in many different ways by several of the 22 groups involved, independently.

The observation of the continuum bump structures at the very highest spin, with energies significantly lower than the predictions for the Jacobi transition [9,11], are well in accordance with similar effects observed recently in ^{91}Nb, ^{108}Cd, ^{140}Nd and ^{168}Yb [16].

The observation of a trace of a discrete rotational band in ^{126}Xe, with a statistical significance of 2.3σ, and well defined ridge structures with a large moment of inertia, 83 MeV^{-1} $\hbar^2$ around 1360 keV in the same nucleus, also led to a renewed proposal for an experiment with GS at Argonne National Laboratory, where a much more intense ^{48}Ca beam can be obtained to improve the statistics and selectivity in the experiment discussed above.

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