Nuclear hyperdeformation: observations and predictions ?

Nuclear structure investigations at ultra high spin

GT2 working group meeting of the GDR RESANET

October 9th , 2018 – Caen

Amel Korichi

Nuclei are 'mesoscopic' systems : Z protons, N neutrons

Single-particle effects:

Excitation and alignment of nucleons

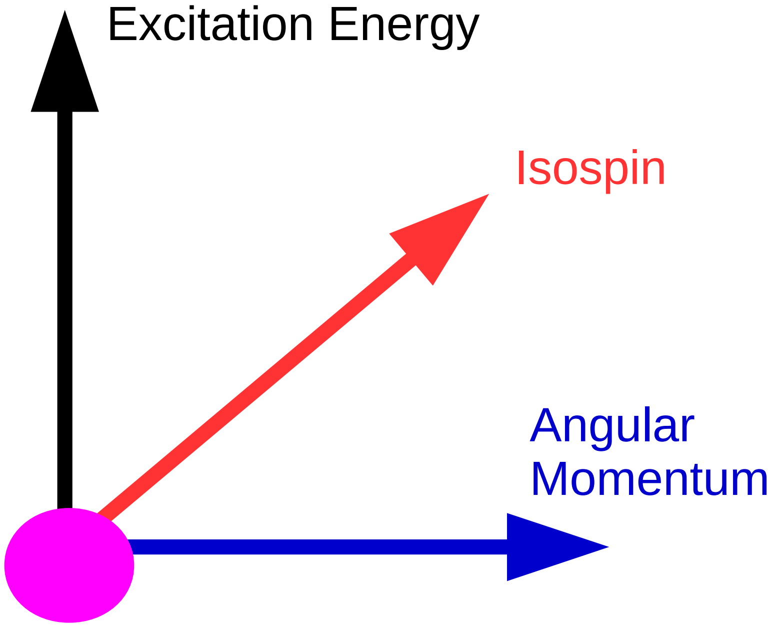
Collective effects:

Rotation and vibration

Interplay:

Polarization

Coriolis and centrifugal forces



What is the maximum angular momentum a nucleus can sustain?

What exotic shapes can be stabilized? Hyperdeformation?

How do collective states evolve?

What are the excitation modes at the limits of angular momentum?

How is the rotational behavior affected by the quenching of pairing?

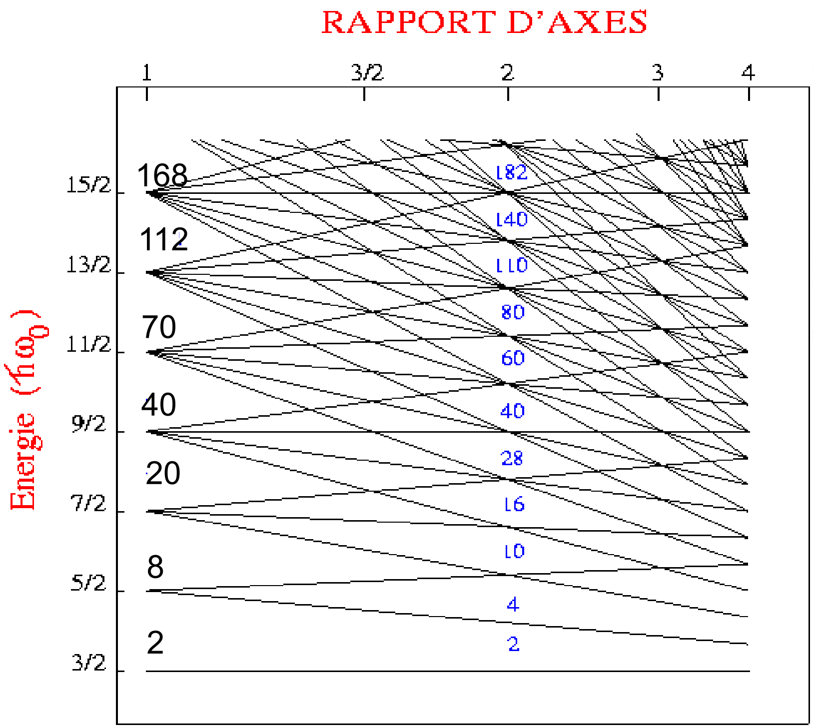
How is the shell structure changed?

Existence of the 2nd and 3rd minimum is related to the concept of gaps in the energy of single particle levels

Structure of the nucleus : intruder orbitals

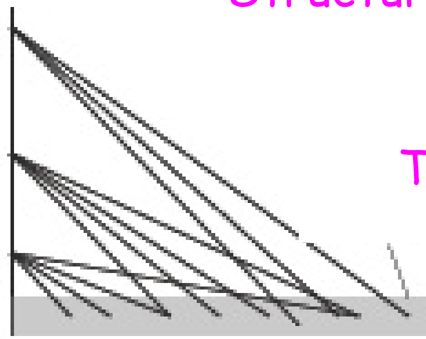
N+1 N+2 N+3

The reality is more complex



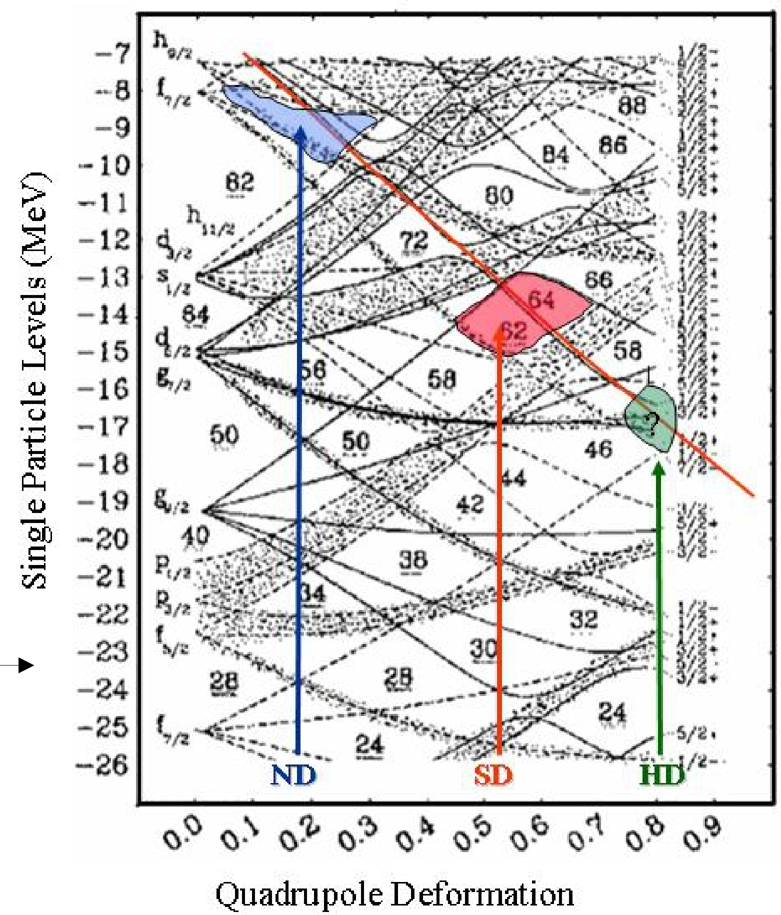
Simple idea

Axially symmetric harmonic oscillator potential



Fermi level

Shell Model for Deformed Nuclei : Nilson Model



Physics Letters B
Volume 211, Issue 3, 1 September 1988, Pages 252-258
open access

Prediction of hyperdeformed nuclear states at very high spins

J. Dudek [a, b], T. Werner [b, c], L.L. Riedinger [d]

From this paper :

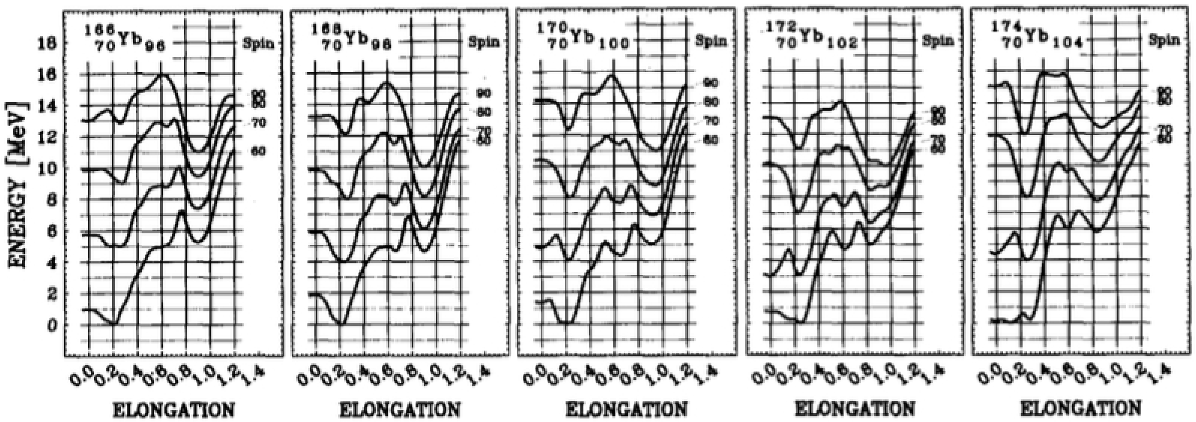
Calculations based on the generalized cranking-Strutinsky method with the deformed Woods-Saxon potential predict the exitence of extremely elongated hyperdeformed nuclear shapes with the axis ratios ***significantly exceeding 2:*** 1.

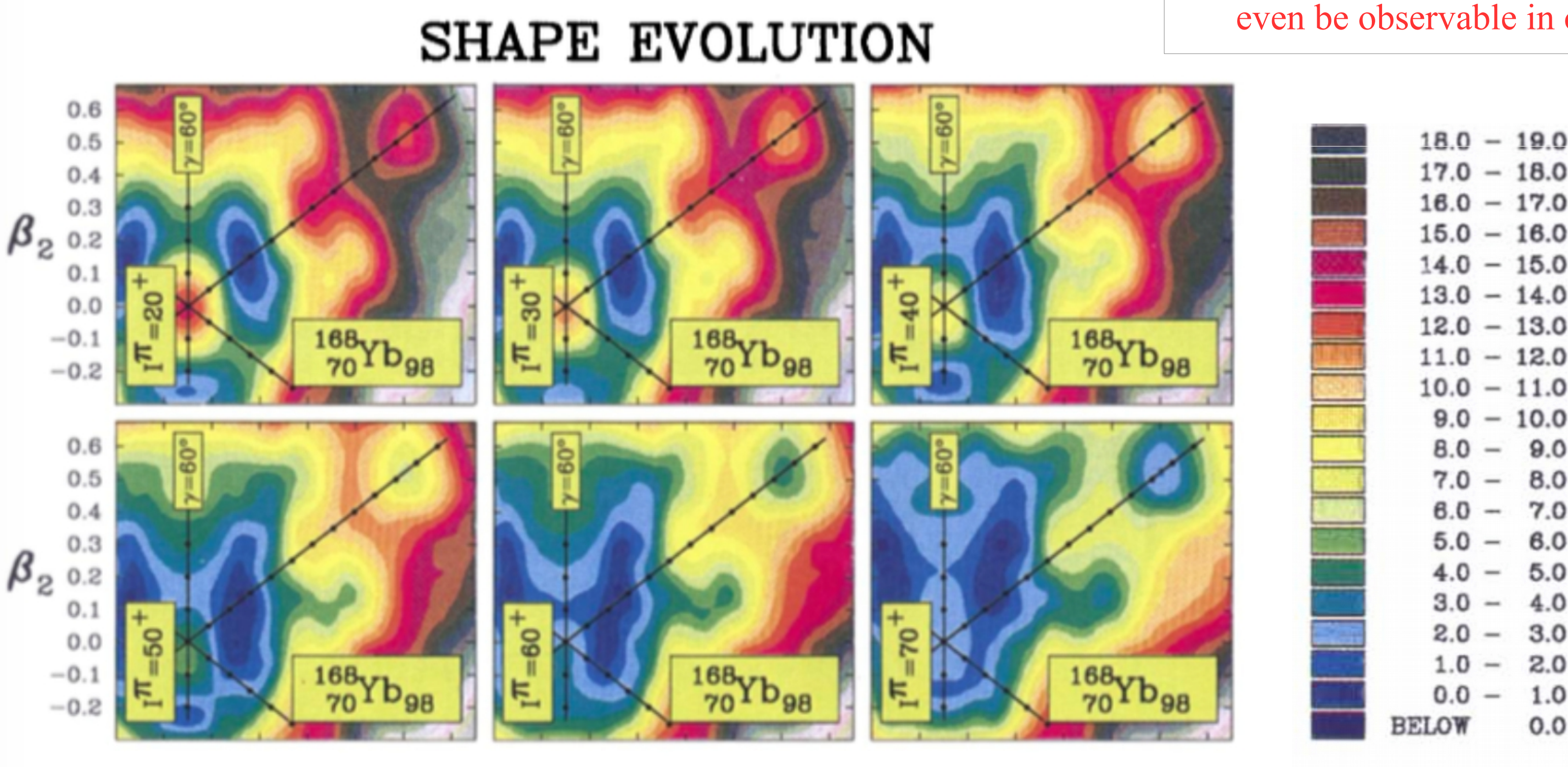
The strongest effect is expected to take place for nuclei around 166Er, 168Yb, and 170Hf (Z=68, 70, 72; N=98) for spins as high as the fission limit down to ***I***- 10-20.

The chances for observing those states in nature are discussed in detail.

Systematic occurrences of the superdeformed and hyperdeformed states also in lighter (***A*** - 70, and ***A***- 100) nuclei are suggested as a consequence of the approximate pseudo-oscillator (or pseudo-SU (3)) symmetries of the realistic nuclear mean field.

Hyperdeformed states should exist in nuclei and even be observable in carefully selected cases.





Later on :

Physics Letters B 302 (1993) 134–139
North-Holland

PHYSICS LETTERS B

Very extended minima in the $A = 180$ mass region

R.R. Chasman
Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843, USA

Received 23 November 1992; revised manuscript received 11 January 1993

A search for very extended nuclear shapes in the $A = 180$ mass region has been carried out in a three dimensional deformation space, using the cranked Strutinsky procedure. Many such minima have been found and their properties are described in detail.

In this calculations reported here, we consider the effects of a necking degree of freedom on very extended minima (VEMs) in the A= 180 mass region, using the cranked Strutinsky method

More than 30 nuclei have been tracked

In table 1, we present results of our calculation. We show the properties of each VEM at the point that it becomes yrast; giving the angular momentum at which it becomes yrast (I_y) is units of $\hbar$; the static moment of inertia ($\mathscr{I}_1$) in units of $\hbar^2$ (MeV)$^{-1}$; the inner barrier height (B_{in}) in MeV; the barrier at an elongation of 1.0 ($B_{1.0}$) in MeV; the axis ratio and the values of ν_2, ν_4 and ν_{nk}. We have not included cases where the outer barriers are less then 3 MeV. In cases where there are two VEMs that become yrast at similar angular momenta, we show the properties of both of them. In such cases, the inner barrier height listed for the more extended VEM is the barrier between the two VEMs.

These calculations suggested that there are many VEMs in the mass region 166 <A < 196

N=106 W-Re-Os best candidates .

However, most of them will be hard to populate, because of fission competition.

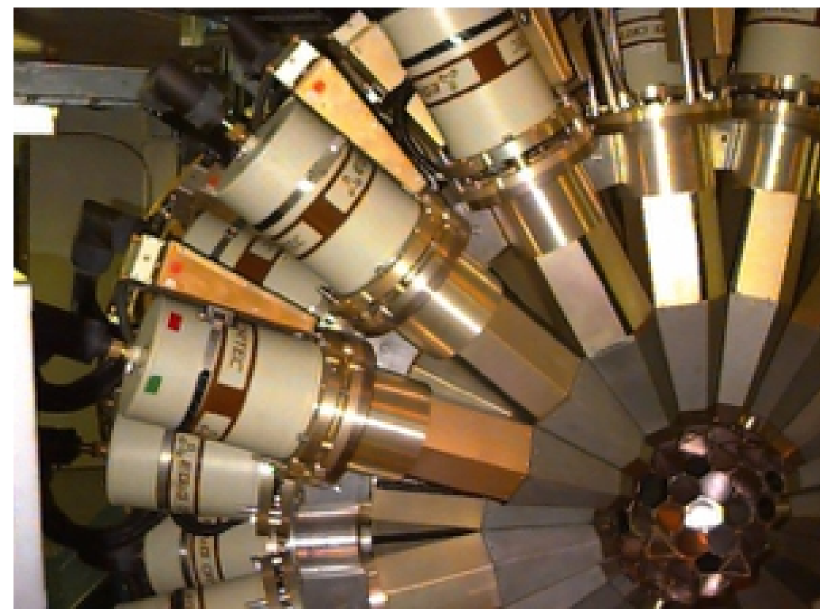
The 168Yb isotopes also predicted as good candiate

PHYSICAL REVIEW C VOLUME 56, NUMBER 5 NOVEMBER 1997

Search for hyperdeformation in ^{168}Yb

J. N. Wilson,[1] S. J. Asztalos,[2] R. A. Austin,[1] B. Busse,[2] R. M. Clark,[2] M. A. Deleplanque,[2] R. M. Diamond,[2] P. Fallon,[2] S. Flibotte,[1] G. Gervais,[1] D. S. Haslip,[1] I. Y. Lee,[2] R. Kruecken,[2] A. O. Macchiavelli,[2] R. W. MacLeod,[2] J. M. Nieminen,[1] G. J. Schmid,[2] F. S. Stephens,[2] O. Stezowski,[3] C. E. Svensson,[1] K. Vetter,[2] and J. C. Waddington[1]
[1]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
[2]*1 Cyclotron Road, Lawrence Berkeley Laboratory, Berkeley, California*
[3]*Institut de Recherche Subatomique, Strasbourg Cedex 2, France*
(Received 5 May 1997)

The choice of this nucleus was based on the calculations of Dudek and Chasman



Very high-spin states in ^{168}Yb and its neighbors were populated via :

^{124}Sn(^{48}Ca,*x n*) $^{172\text{-}x}$ Yb reaction at 215 MeV.

Lmax= 87 hbar E*= 82 MeV

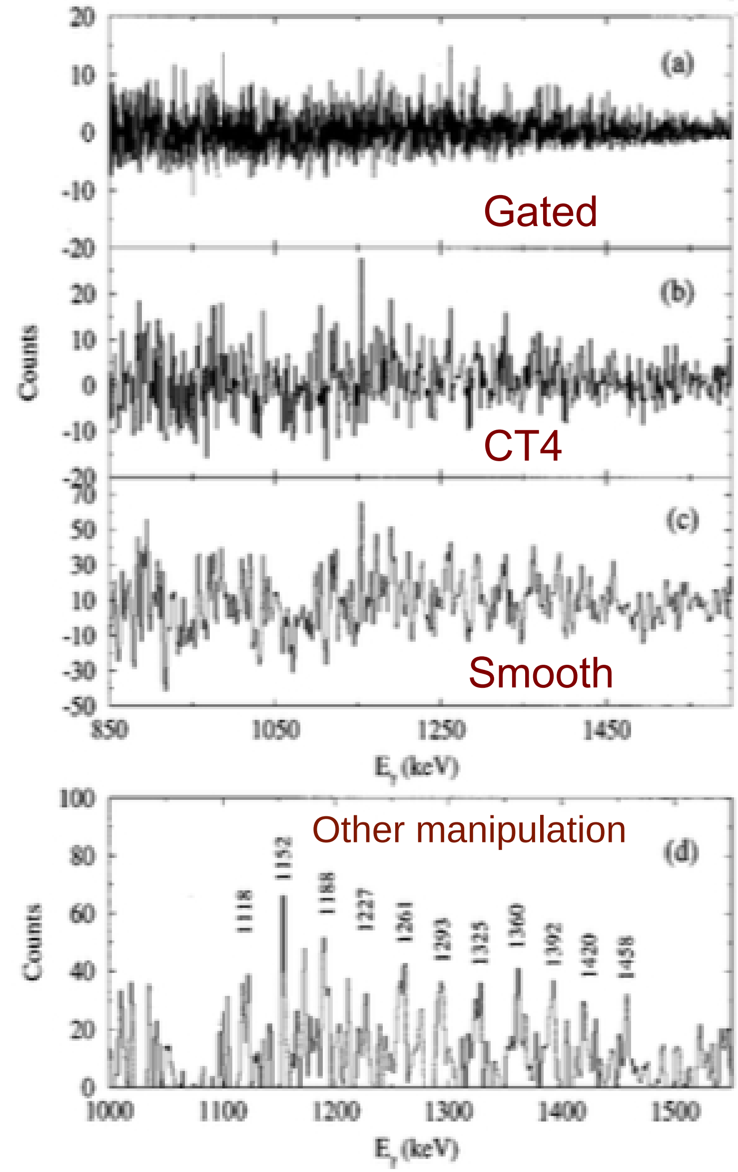
2.06 10^9 events, with a Compton suppressed Germanium fold 5 (5 days)

1.85 10^9, with a suppressed fold 3 (after pre-sorting/calibration/selction)

The Analysis of the data was performed with many different methods : **did not rely on one method alone.**

J.N. Wilson et al NIM A 399 (1997)147
Determination of optimum gating fold, shape and width for analysis of high-fold gamma-ray coincidence data

J.N. Wilson et al,NIM A455 (2000)612
The use of gamma-ray fiters to increase the selection power of detector arrays



In the search for potential hyperdeformed bands where the average transition number might be very low   6 transitions, a ridge analysis was performed, involving the use of special matrices

For short bands 6–12 transitions cubes were created using full unpacking of higher-fold events

For longer bands 10–25 transitions , 4*n*-channel-gated and ungated multifold databases were created

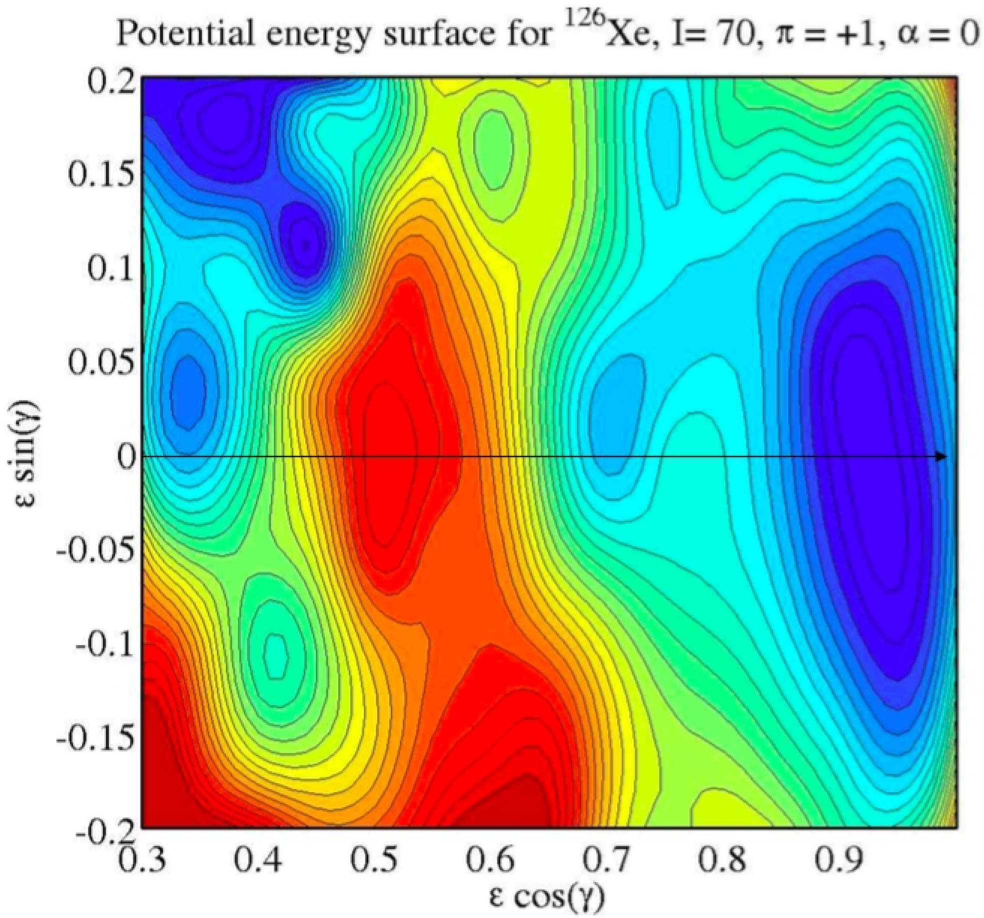
Also gated matrices ….

Very careful and long analysis
No evidence for hyperdeformation

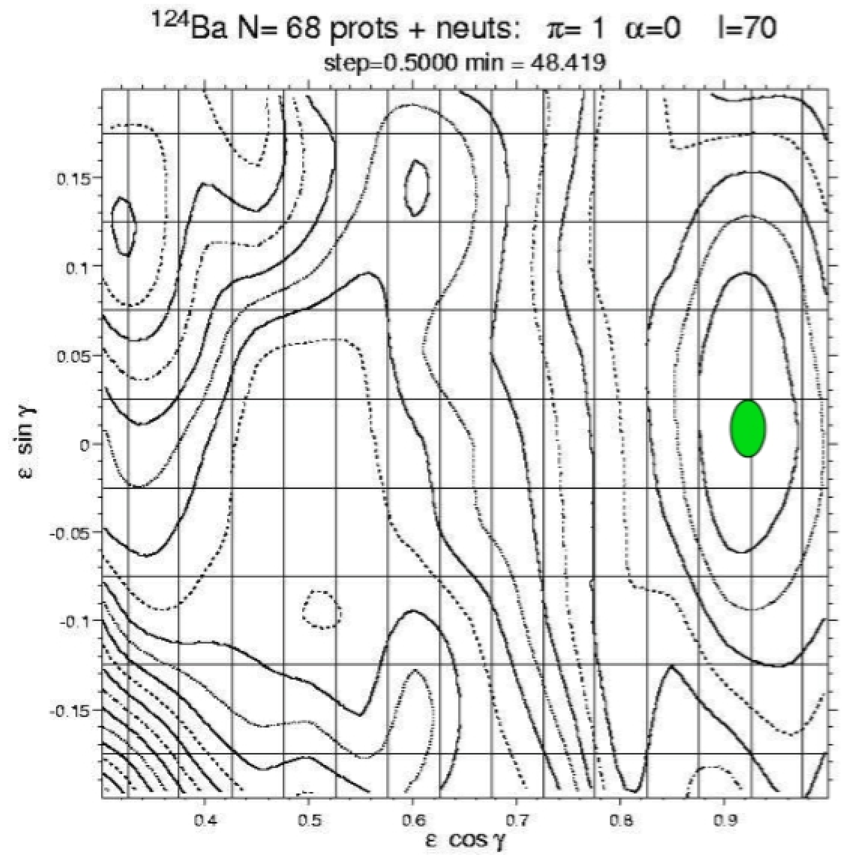
1- Hyperdeformed bands were populated at a level lower than the limit of sensitivity?
2- The amount of angular momentum brought into the compound system was sufficient?
3- Fission of the compound nucleus prevented population of hyperdeformed states?
4- Hyperdeformed states do not exist in these nuclei?

Other nuclei predicted to be a good candidates have been investigated

Just an example :



Ultimate cranker



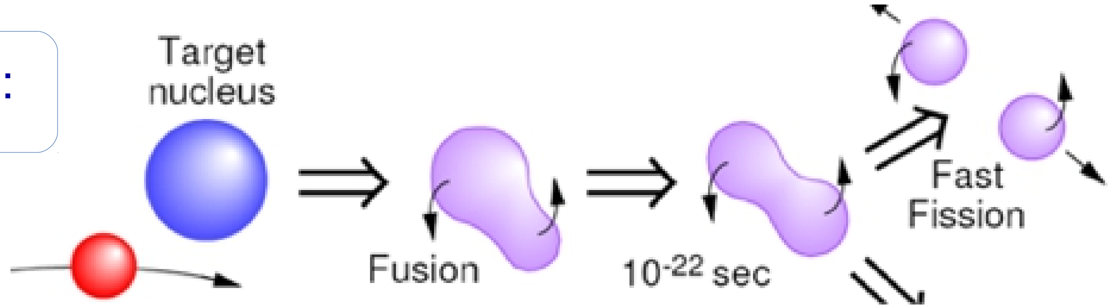
Many other calculations also performed for different nuclei A=80, 120, 170, 180

^{80}Sr : P. Bonche,H. Flocard and P.H. Heenen, NPA 523 (1991)300
^{180}Hg : Lars-Ove Jonsson and Sven Aberg , NPA 627 (1997)53

Just another example

From the experimental point of view :

Conditions for the Population of the highest spin states were Investigated : 8π at LBNL



Measured multiplicity with inner ball and intensity for each xn-channel
Analyzed angular momentum transfer in different channels

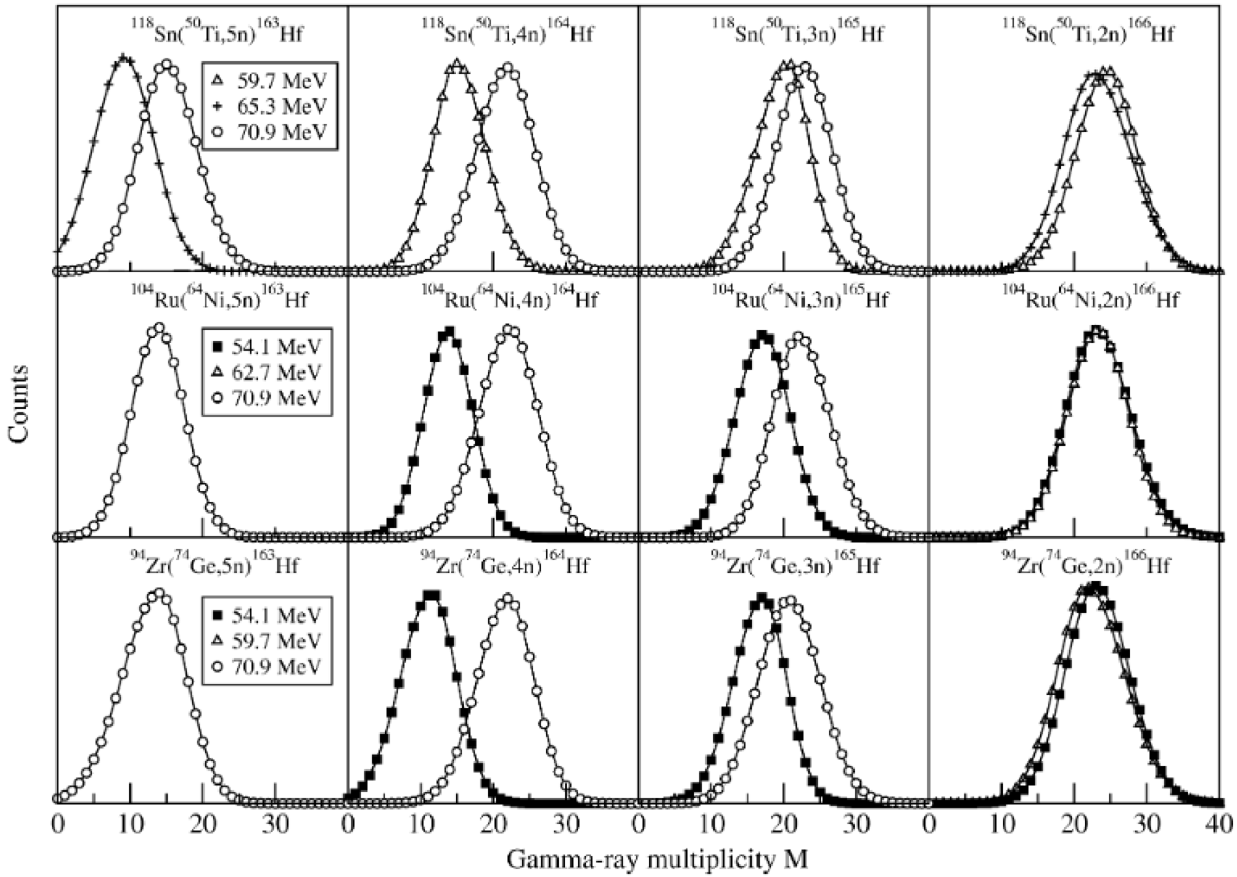
J. Domscheit et al, NPA 689 (2001)655
No difference observed for the 3 reactions

118Sn(50Ti,4n)164Hf 118Sn(50Ti,4n)165Hf 118Sn(50Ti,2n)166Hf

118Sn(50Ti,5n)163Hf

104Ru(64Ni,5n)163Hf

94Zr(74Ge,5n)163Hf



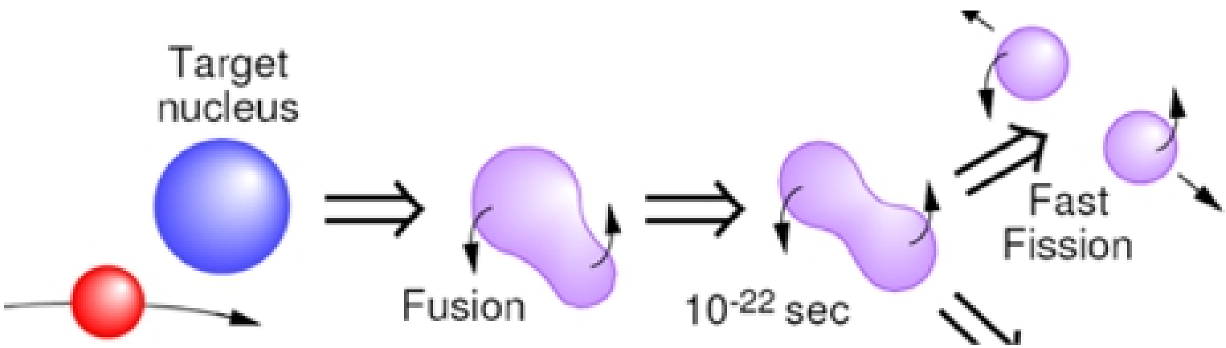
Various reactions were invetigated too :

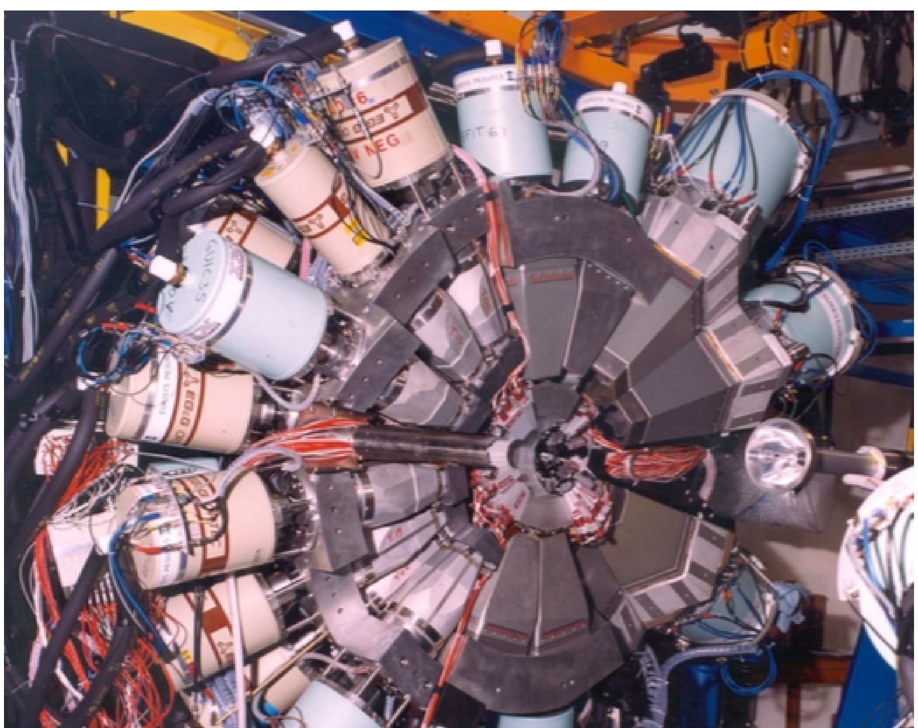
^{76}Ge(^{74}Ge,xn)$^{150-x}$Gd

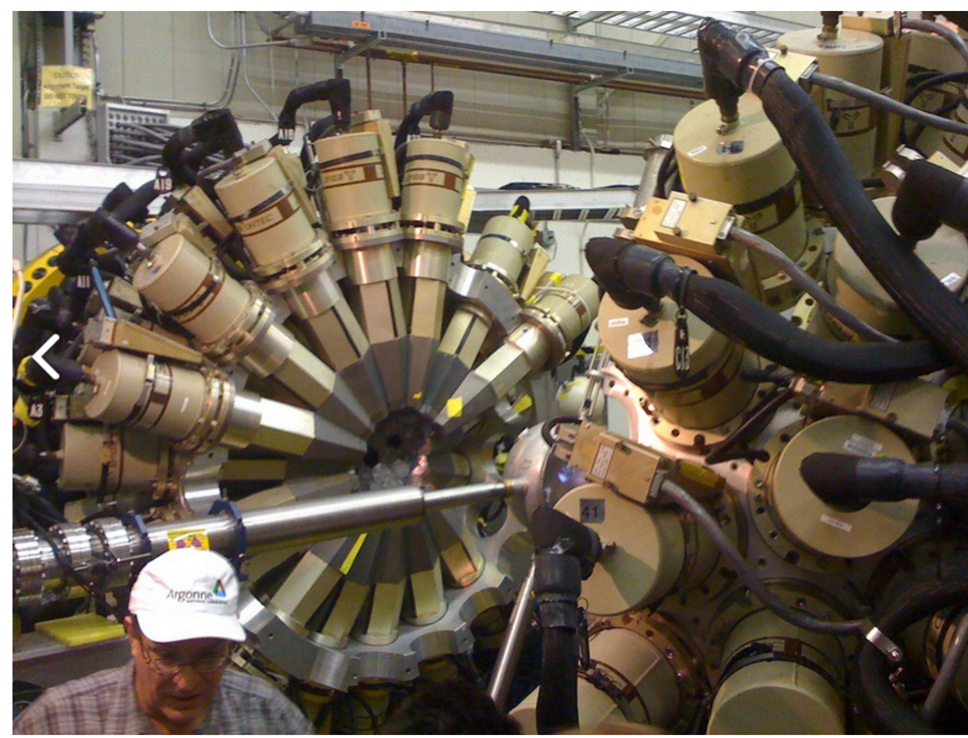
^{64}Ni(^{64}Ni,xn)$^{128-x}$Ba

Performed experiments with Gammasphere and Euroball using different reactions
Tracking different candidates in different conditions (beam energy) in the (E*,I) plane

Compound Nuclei Produced: $^{174}Hf^{*}$ $^{144}Nd^{*}$ $^{130}Xe^{*}$ $^{128}Ba^{*}$ $^{128}Xe^{*}$







$^{82}Se(^{48}Ca,xn)^{130-x}Xe$ case :

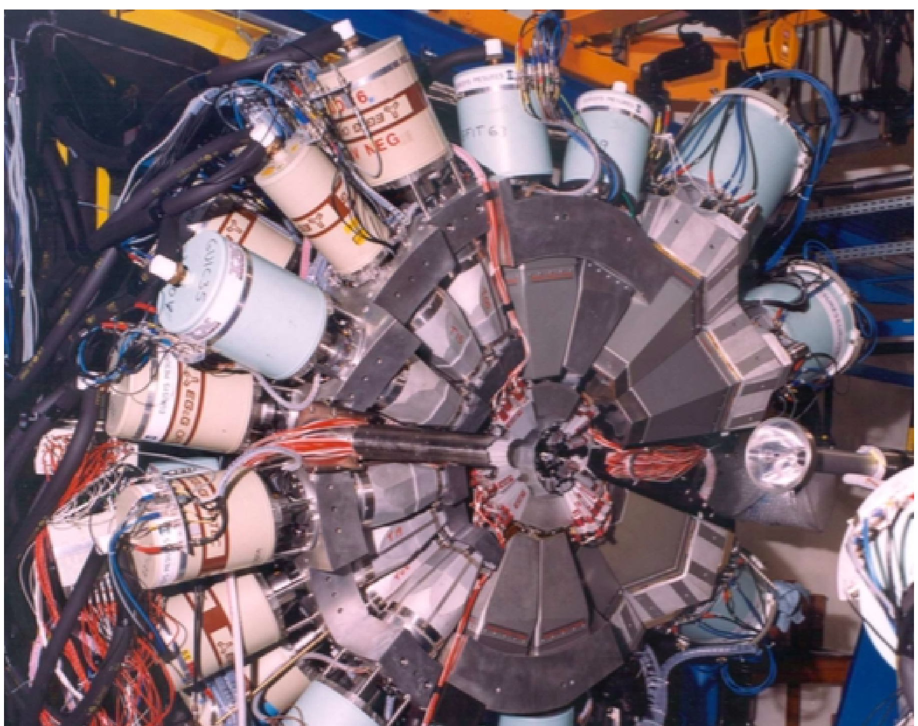
EUROBALL at Strasbourg

- Excitation function: 185, 195, 205 MeV;
  Exp.: 195 MeV

Target: 625 μg/cm^2, Au protected

- Accelerator: Vivitron Strasbourg
- Beam time: ~5 days, ~0.8 pnA
- Trigger: 4 Ge's (unsuppr.) and 11BGO's

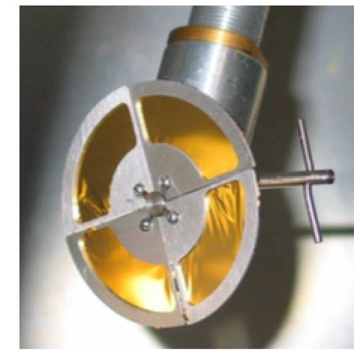
Events: 5×10^8 with fold >=4



Gammasphere at Argonne

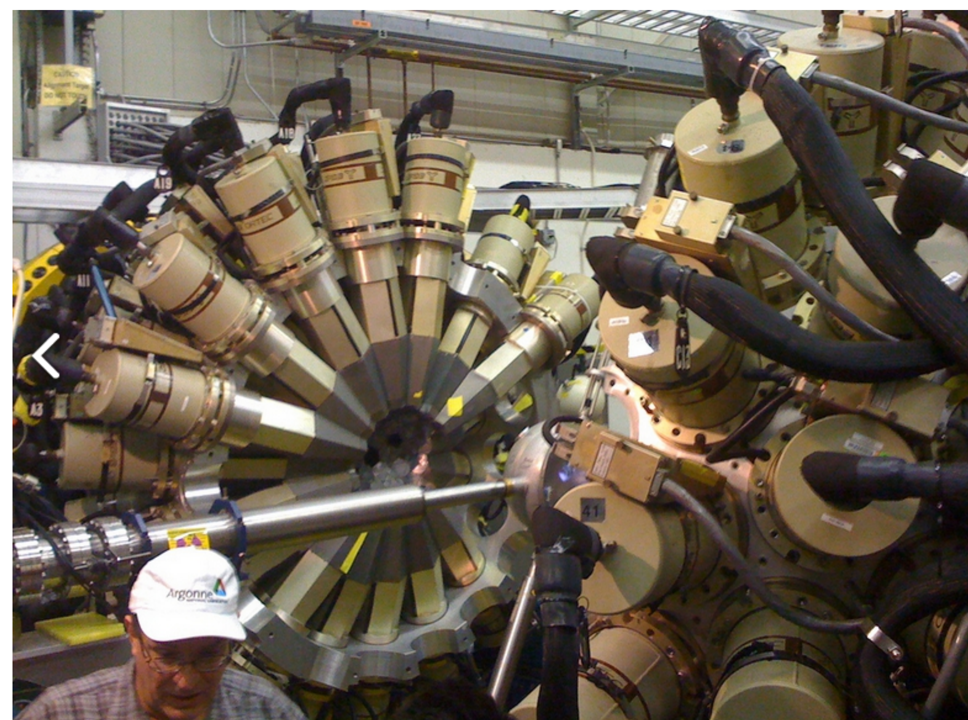
- Beam energy: 205 MeV

Target: ~500 μg/cm^2 Au protected, rotating wheel



- Accelerator: ATLAS Argonne
- Beam time: 7 days, ~4 pnA
- Trigger: 6 Ge's and 10 'module

Events: 6×10^9



$^{128-x}$Ba case :

EUROBALL at Strasbourg

Reaction: ^{64}Ni(^{64}Ni,xn)$^{128-x}$Ba

Beam energy : 245, 255 and 261 MeV,

Target: 476 μg/cm^2

Reaction: ^{65}Cu(^{64}Ni,p2n)^{126}Ba

Beam energy 275 and 285 MeV,

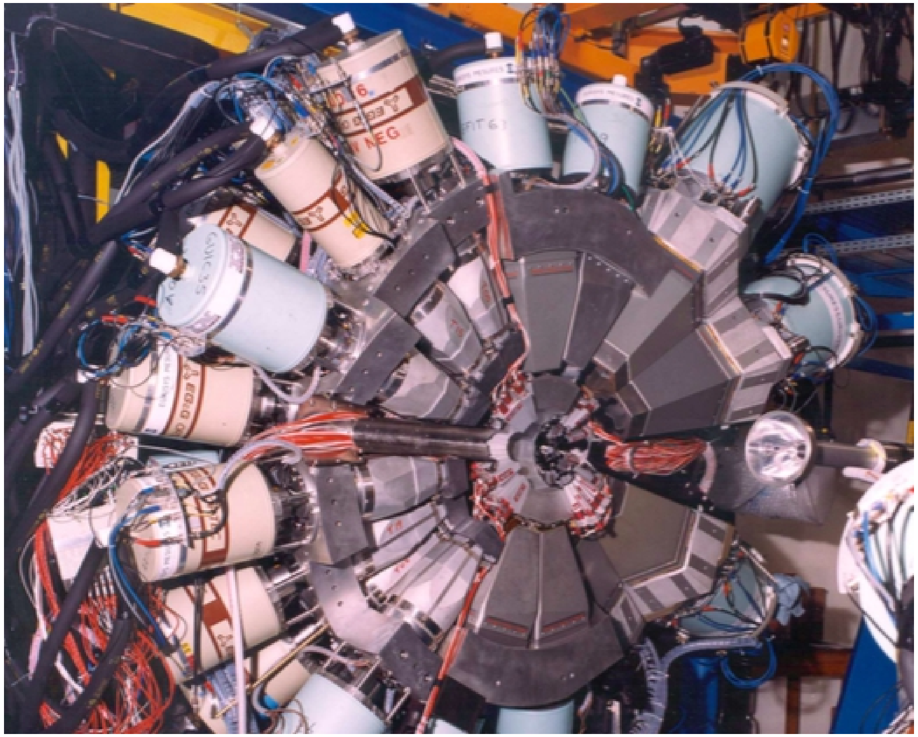
Target: 500 μg/cm^2

Beam time: 10 days, ~1.5 pnA

Trigger: 3 Ge's and 12 BGO's;

Events with fold>=4 : 1.3×10^9

Additional detectors: **HECTOR** under forward angles



Gammasphere at LBNL

Reaction : ^{64}Ni(^{64}Ni,xn)$^{128-x}$Ba

Beam energy: 268 MeV

Target: ~476 μg/cm^2

Accelerator: 88 inch cyclotron

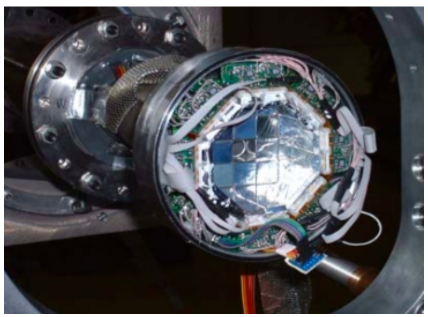
Beam time: 5 days, ~1.6pnA

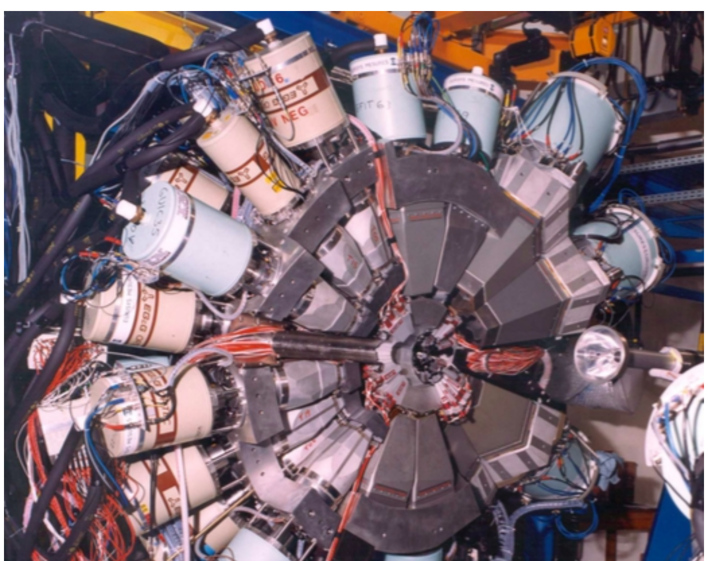
Trigger: 6 Ge's and 15 'modules'

Events with fold >=4 : 1.2×10^9

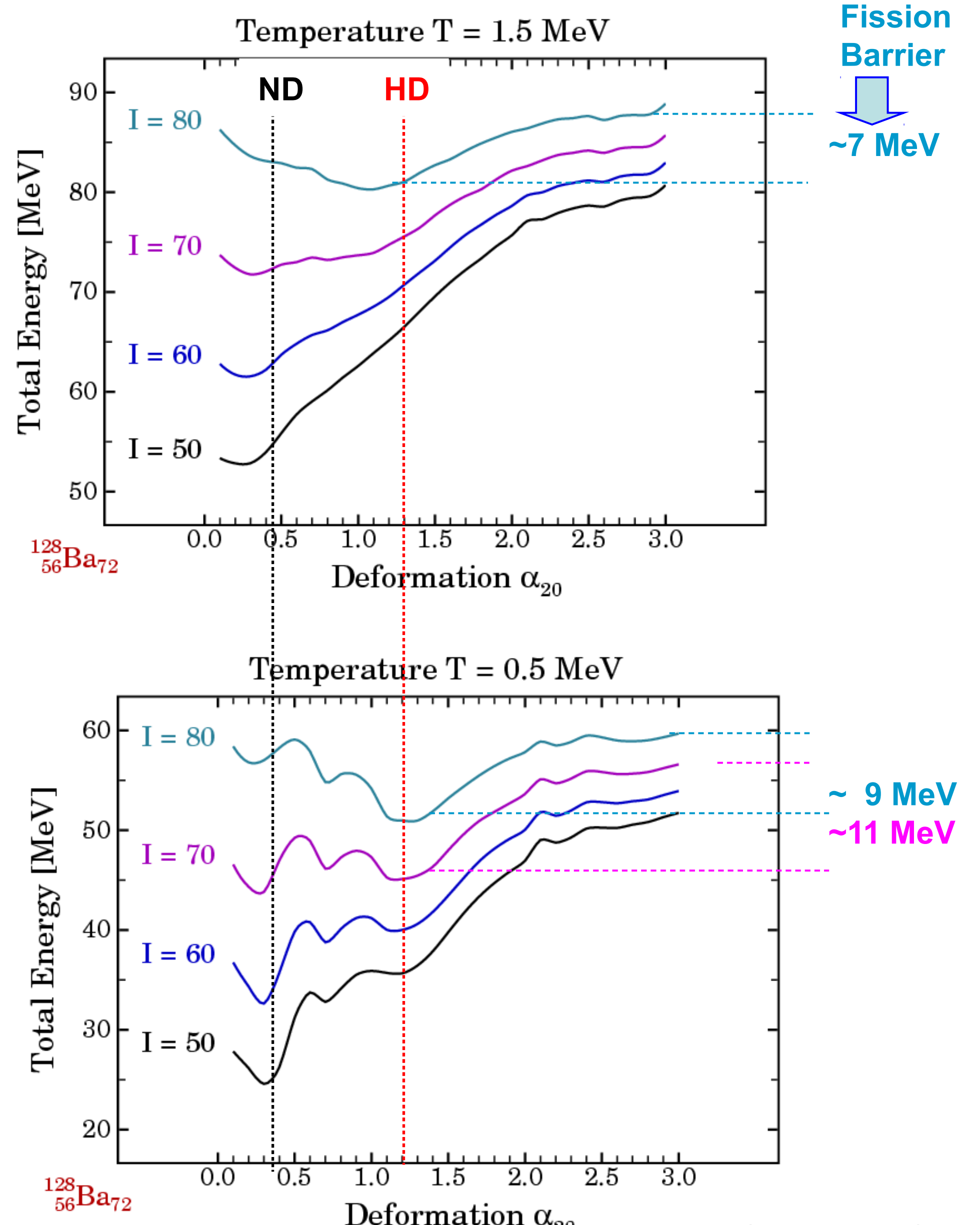
$^{128-x}$Ba case : The HLHD experiment- Euroball @Strasbourg

Reaction: ^{64}Ni(^{64}Ni,xn)$^{128-x}$Ba
Beam energy : 255 and 261 MeV,
Target: 500 μg/cm^2
Beam time: 30 days, ~1.5 pnA
Trigger: 3 Ge's and 12 BGO's
Total Events : 12 x 10^9
additional etectors: DIAMANT
A factor of 10 more statistics !





Calculations including shells and temperature effects N. Schunck et al, PRC 74 (2007)

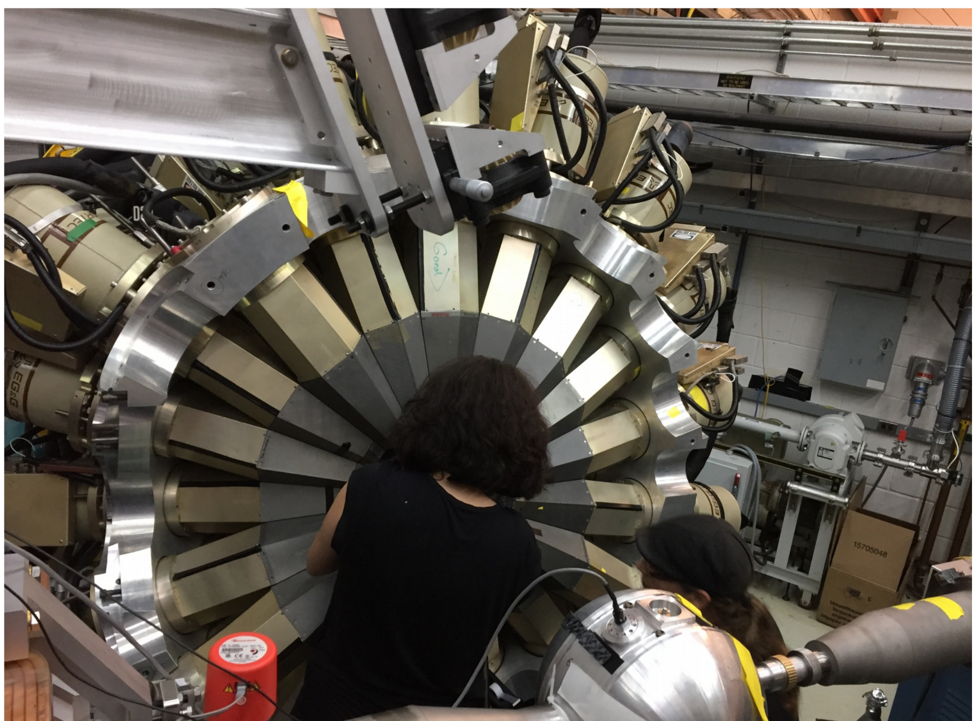


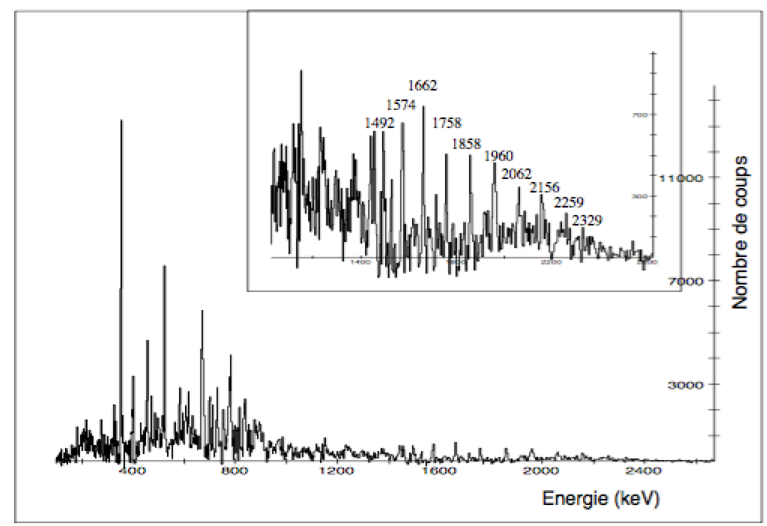
Courtesey of B. Herskind

$^{128-x}$Xe case

GAMMASPHERE at Argonne
Reaction: ^{80}Se(^{48}Ca,xn)$^{128-x}$Xe
Beam energy: 207 MeV
Target: ~600 µg/cm2, Au protected, rotating wheel
Accelerator: ATLAS Argonne
Beam time: 10 days, ~4 pnA
Trigger: 6 Ge's and 10 'modules';
Events: 3 x 10^9 with fold >= 4

In all cases, for all this large number of experiments/nuclei we search for :
Discrete line HD search using different
analysis packages:
Radware, Rebel, J. Wilson auto-search ...

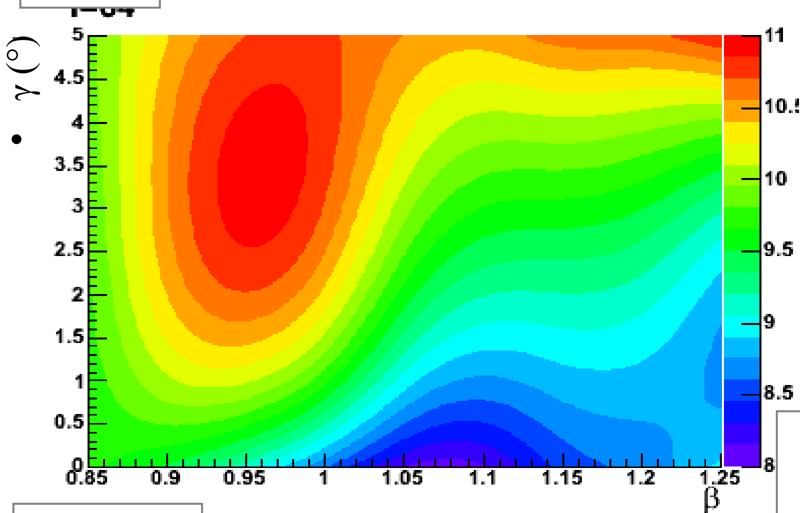




From Hoa Ha thesis (2009) CSNSM
No convincing signals seen ...

• Understanding what's going on : CHFB calculations using Gogny D1 : ^{124}Xe

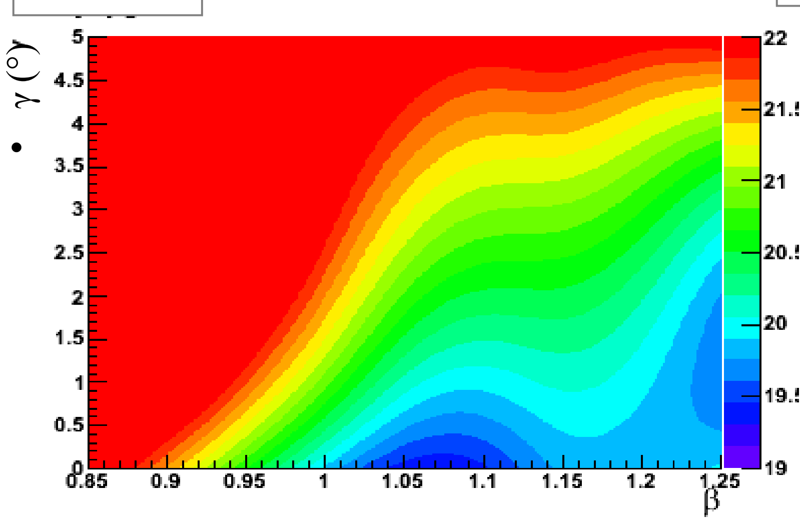
- I=64ħ
- Surfaces d'énergie potentielle



- $0.85 < \beta < 1.25$
- $0 < \gamma < 5°$

- Énergies normalisées
- à $\beta = 0.6$

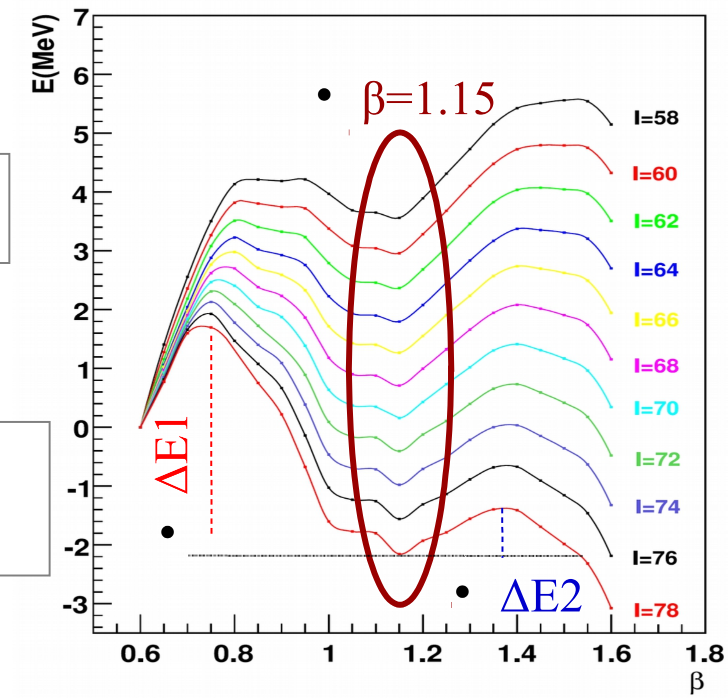
- I=76ħ



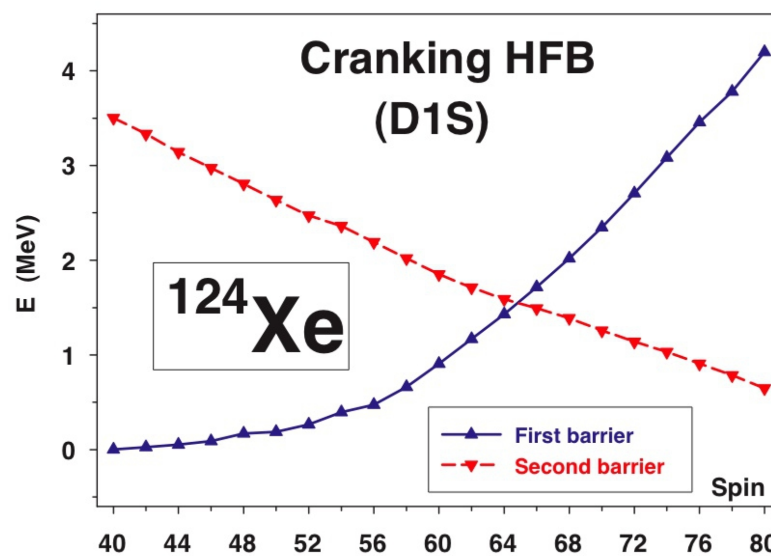
- Intervalle d'intérêt en spin: 58ħ → 78ħ

Xe124

- $E \sim f(\beta, I)$



« γ-back»
fission



Calculations performed in collab. J. Libert

A systematic theoretical tracking has been performed for the even 122-126Xe nuclei

Understanding the experimental results of Hoa Ha PhD work

The crossing between the 2 barriers occurs around the same spin (62-64 hbar) for the 3 nuclei :

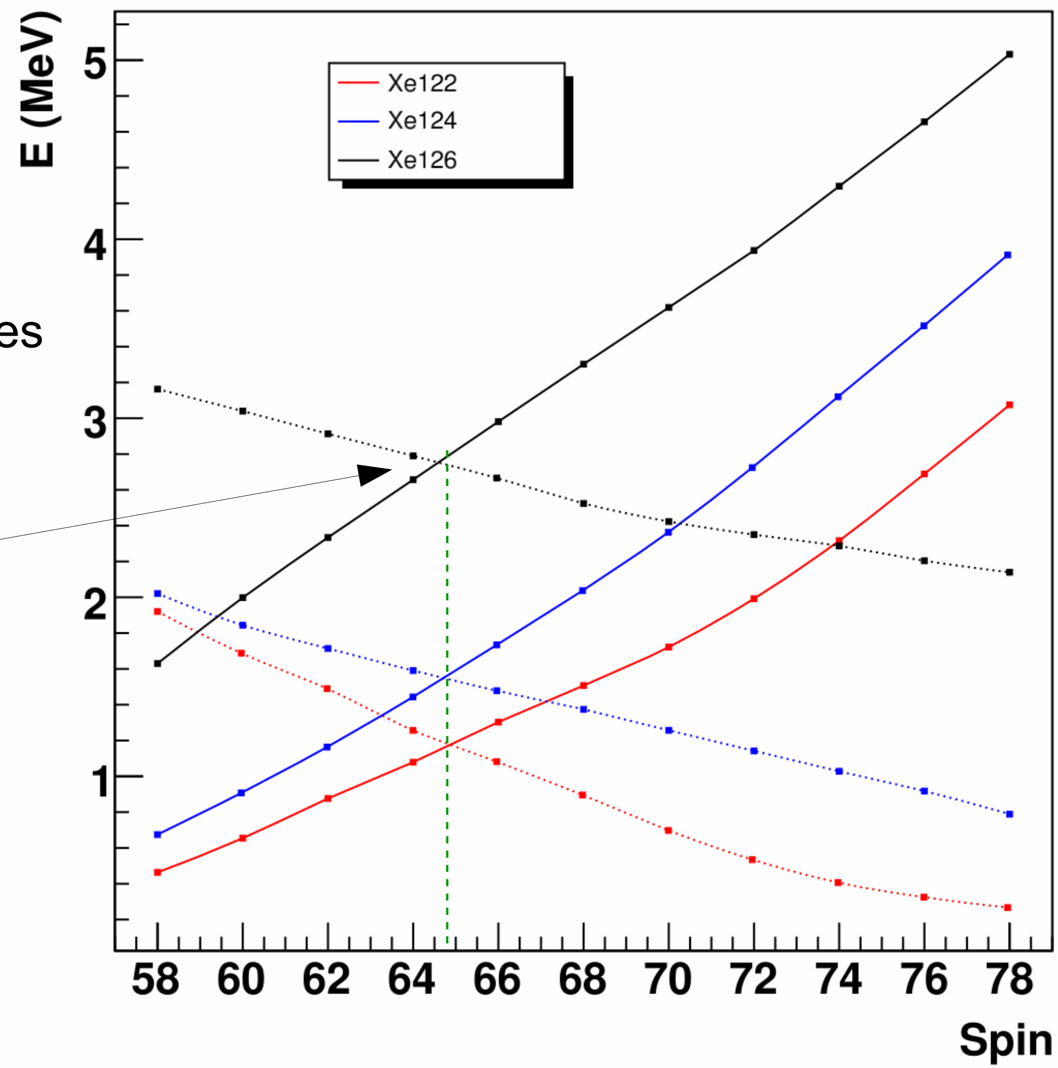
Trapping probability of the HD structure is optimum for the 3 cases

But!

2.8 MeV (126Xe)

1.6 MeV (124Xe)

1.1 MeV (122Xe)



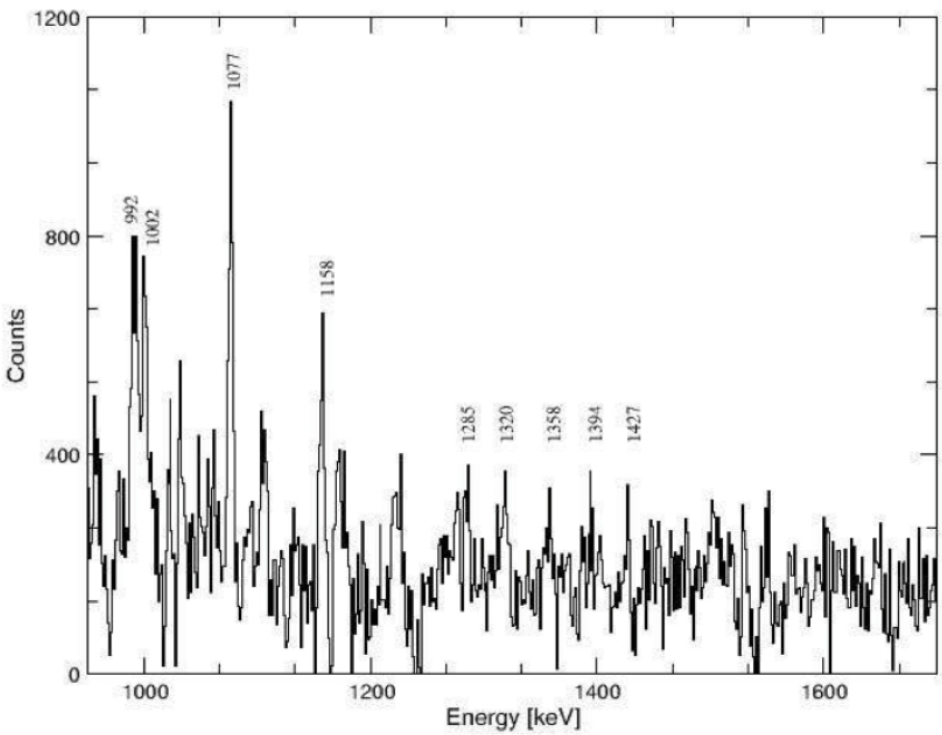
126Xe is found to be the best case for HD hunting ?

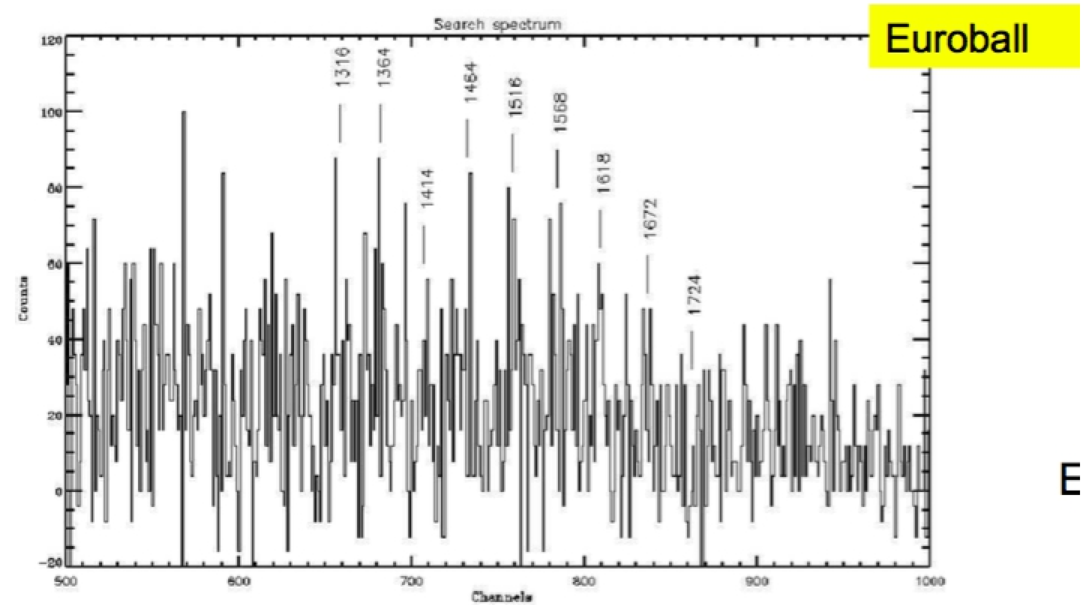
126Xe analysed with data from a dedicated experiments

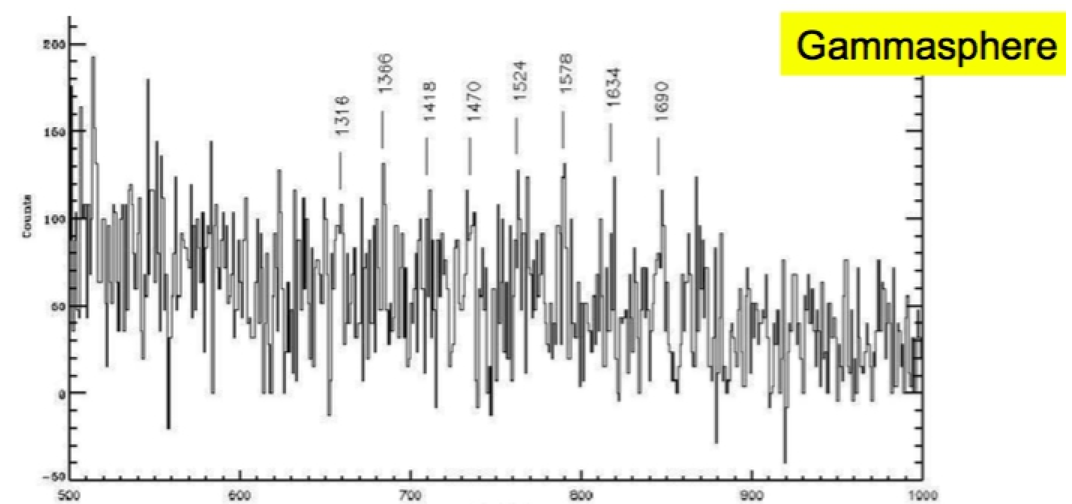
Courtesy of H. Hubel

Radware search routine
J. Wilson's program

Energy spacing ΔEγ= 36 keV





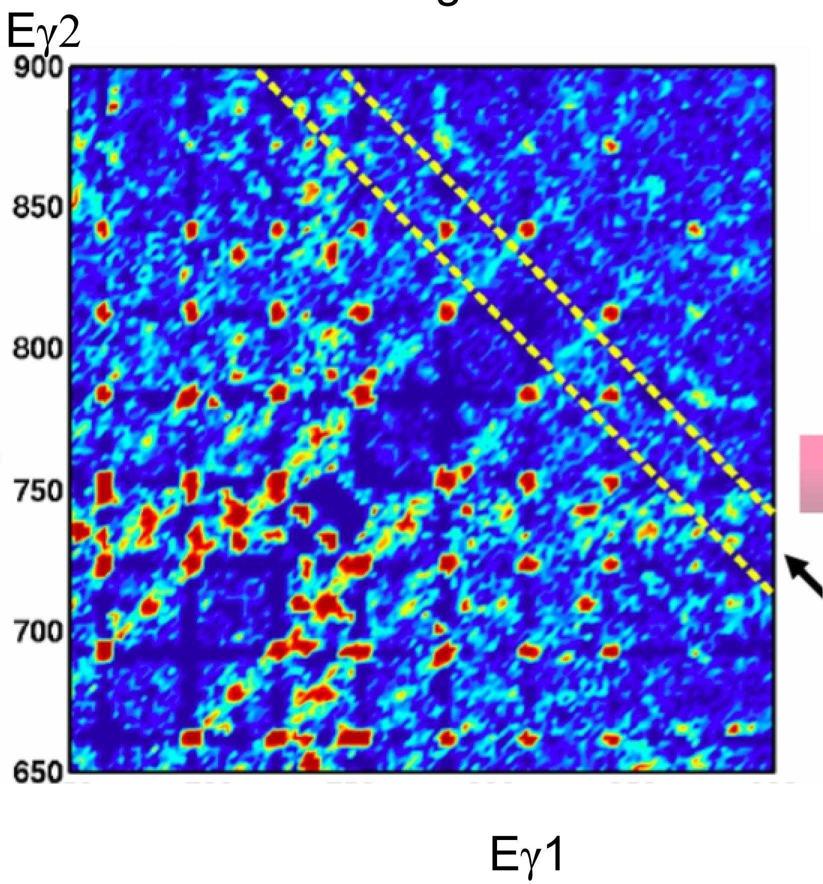


Search with different E spacing ΔEγ= 50, 52, 53 keV … No signal

Beside the discrete band search

Unresolved part of the spectrum has been investigated as done for superdeformation

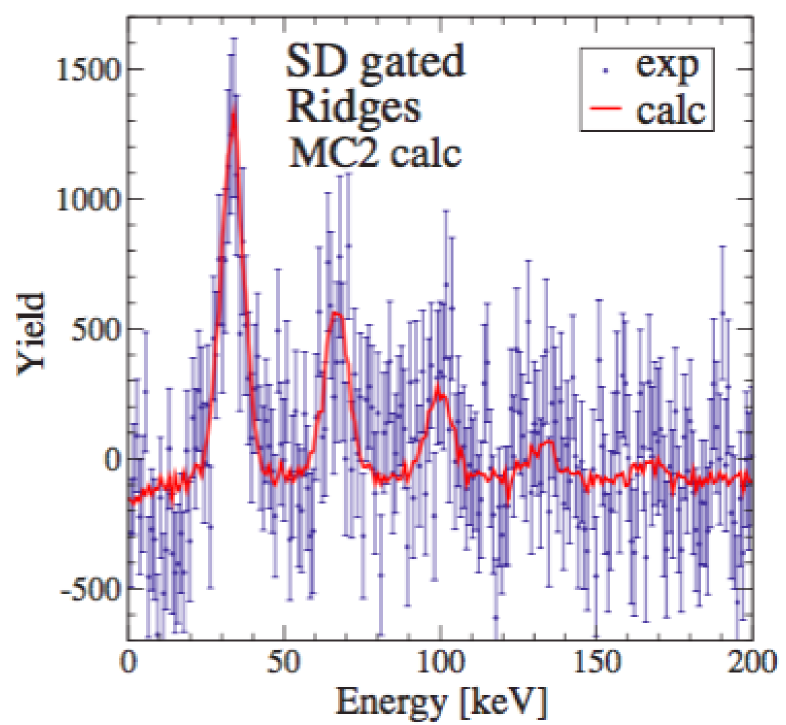
A. Lopez-Martens et al,
194Hg



Cut perpendicular to the diagonal

$E_\gamma E_\gamma$ correlations

T. Lauritsen et al, 152Dy



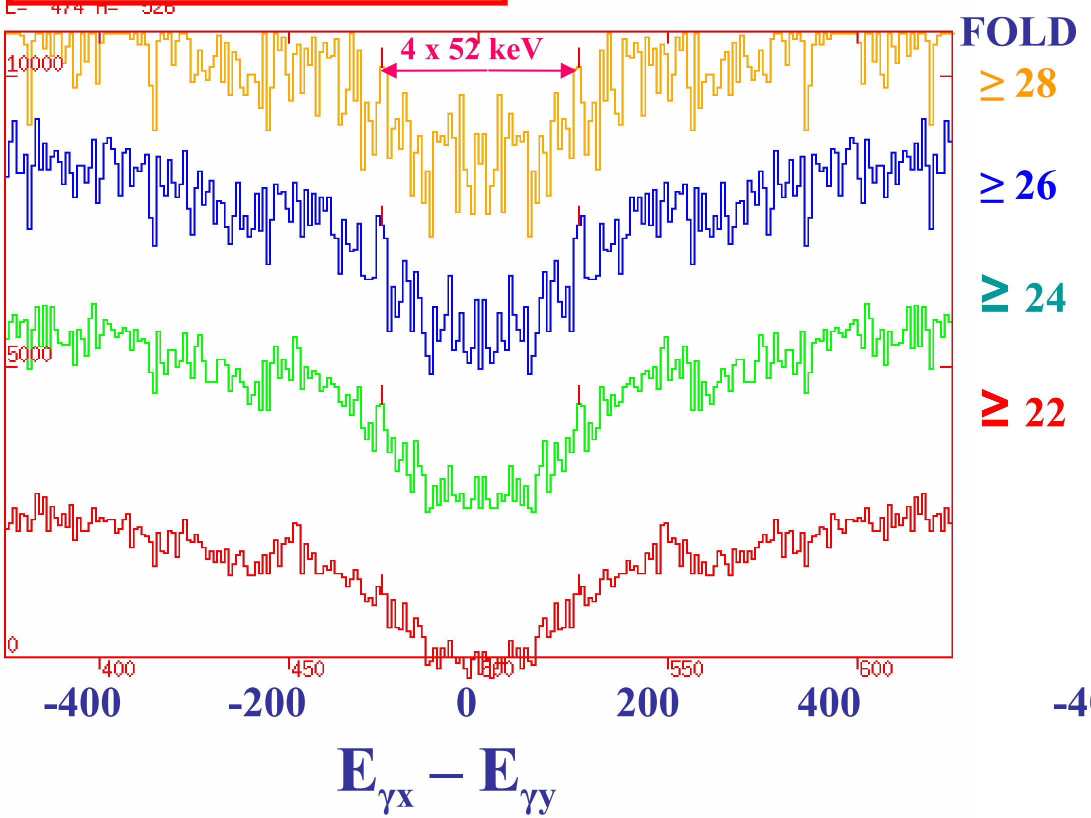
Courtsey of B. Herskind

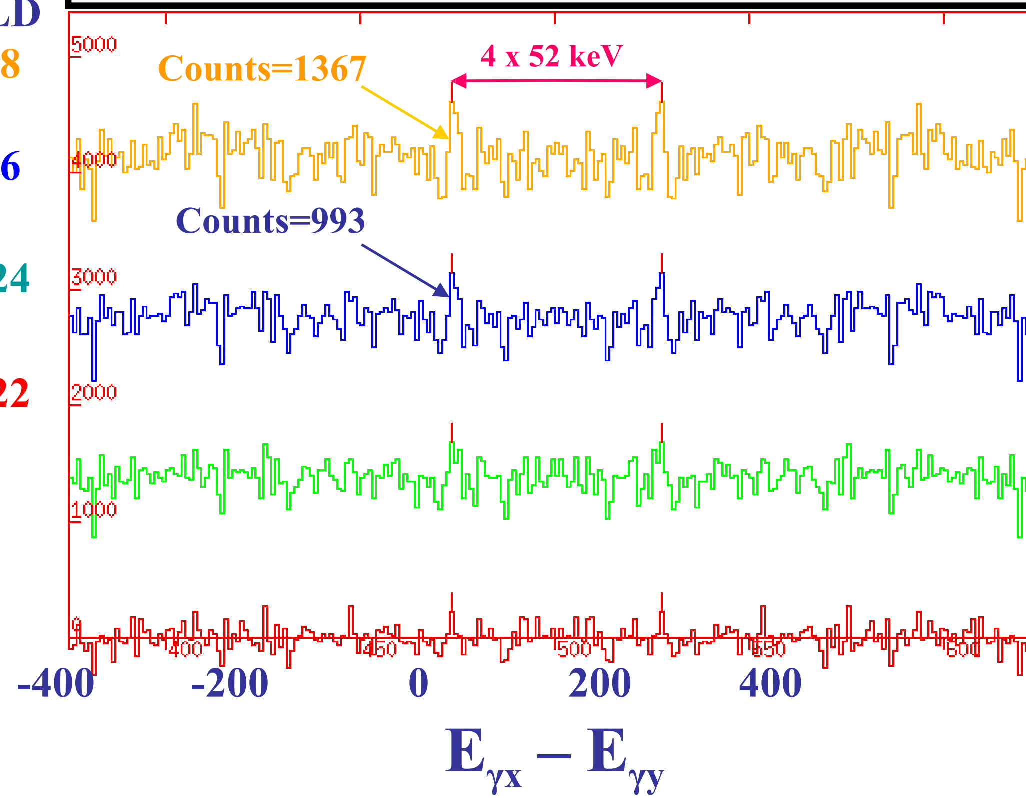
3D Rotational Plane (width = 3 x 2 keV)
261 MeV $^{64}Ni + ^{64}Ni - 2n \Rightarrow ^{126}Ba$

Rotational Plane (width = 3x2 keV)
Data: 261 MeV – 255 MeV

From xn Data-Base
veto for charged particles

Perpendicular Cuts (PCut) = 1440 ± 102 keV





Confirm the Berkeley results => $J^{(2)} \sim 77\ \hbar^2$/ MeV => SD,
and show a Strong Beam Dependent Effect for ΔE_{CM} = 3 MeV

Several cases were investigated with mass numbers of the compound nuclei between A = 174 and 128

Sufficiently high angular momentum is only transferred in ‘cold’ reactions with residues with small Z^2/A: best region A = 100 -130 ?

Several high-statistics experiments in A = 120 region

HD searches: No convincing discrete-line spectra.

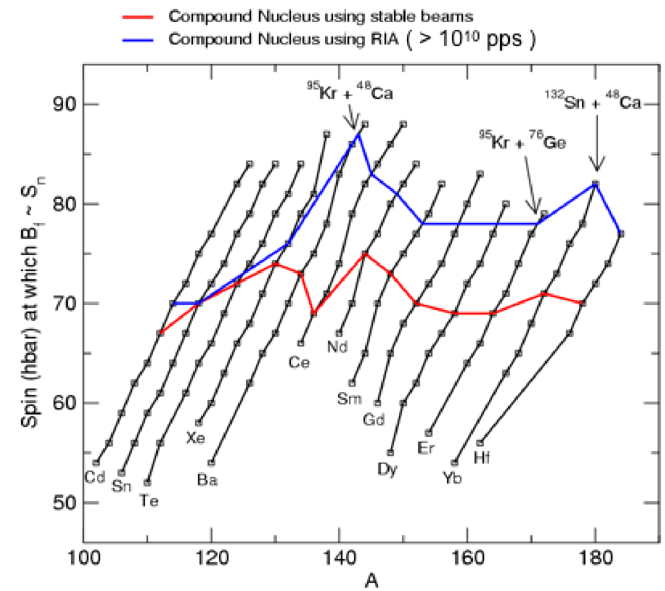
Continuum ridges with energy spacing between 40 and 52 keV corresponding to very large moments of inertia

Search for Hyperdeformation at ultra-high spin : requires intense radioactive beams?

112Cd-110Pd: Predicted to be the best !
LoI for Spiral2 : dream experiment!

Table1 : Rates comparison between

Reaction	Target thickness mg/cm^2	Beam intensity	xn/fission cross sections	Nuclei of interest/sec
^{26}Mg(^{92}Kr,6n)^{112}Cd at Spiral2	2 x0.5	>2.6E+08	300 mb/ 0.1 mb	1806
^{64}Ni(^{64}Ni,4n)^{124}Ba with Euroball	0.6	9.3E+09	100mb/ 200 mb	5248

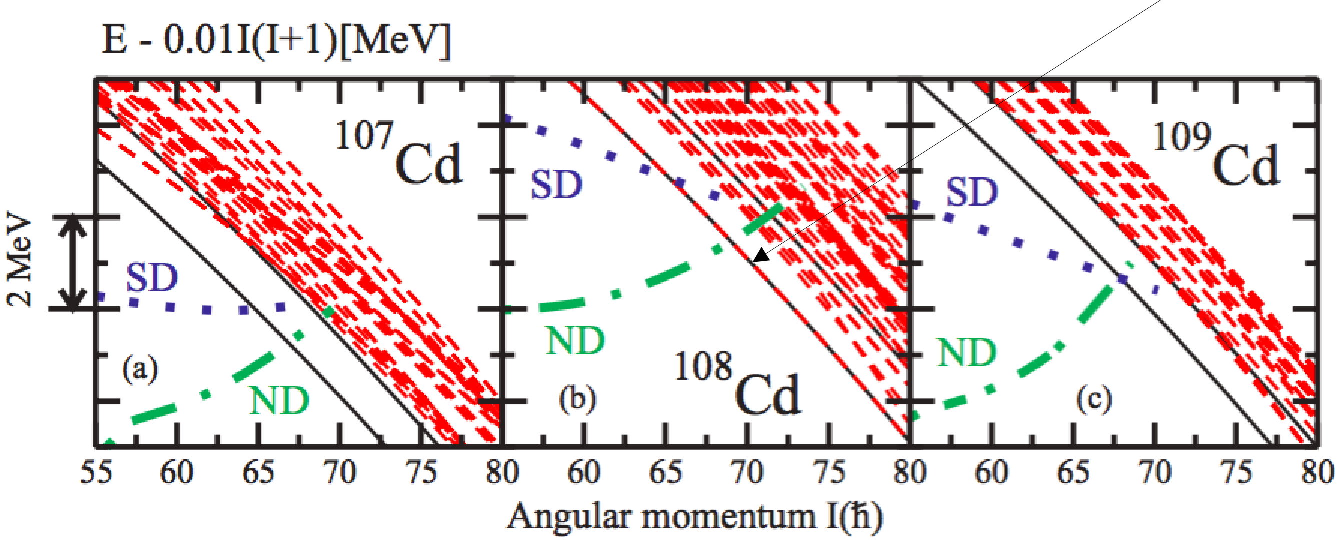


PHYSICAL REVIEW C **79**, 024317 (2009)

Hyperdeformation in the Cd isotopes: A microscopic analysis

H. Abusara and A. V. Afanasjev
Department of Physics and Astronomy, Mississippi State University, Mississippi 39762, USA
(Received 8 December 2008; revised manuscript received 24 January 2009; published 25 February 2009)

But later on 107Cd came out ...
Yrast HD line



Feasible with stable beams

To move forward : More accurate predictions/discussions theory-exp

PHYSICAL REVIEW C **72**, 031301(R) (2005)

Superdeformation and hyperdeformation in the ^{108}Cd nucleus

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(Received 1 July 2005; published 28 September 2005)

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PHYSICAL REVIEW C **94**, 014310 (2016)

From superdeformation to extreme deformation and clusterization in the $N \approx Z$ nuclei of the $A \approx 40$ mass region

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(Received 20 April 2016; revised manuscript received 4 June 2016; published 14 July 2016)

PHYSICAL REVIEW C **78**, 014315 (2008)

Hyperdeformation in the cranked relativistic mean field theory: The $Z = 40$–58 region of the nuclear chart

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Nuclear Physics A 975 (2018) 77–96
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Sensitivity of the nuclear deformability and fission barriers to the equation of state

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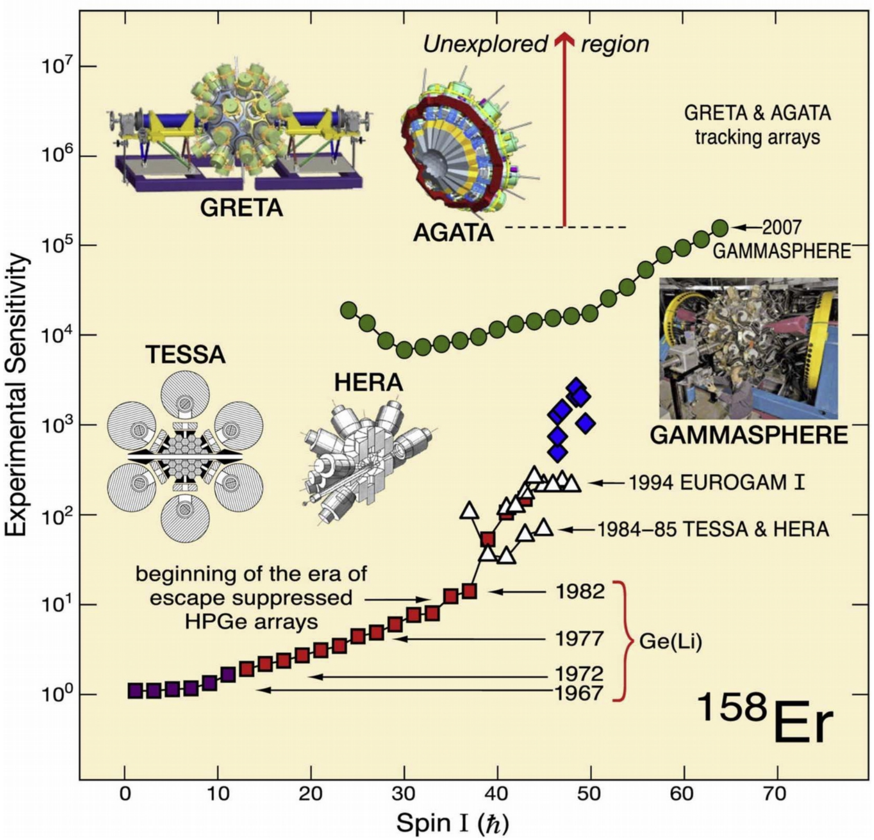
Received 12 February 2018; received in revised form 28 March 2018; accepted 13 April 2018
Available online 17 April 2018

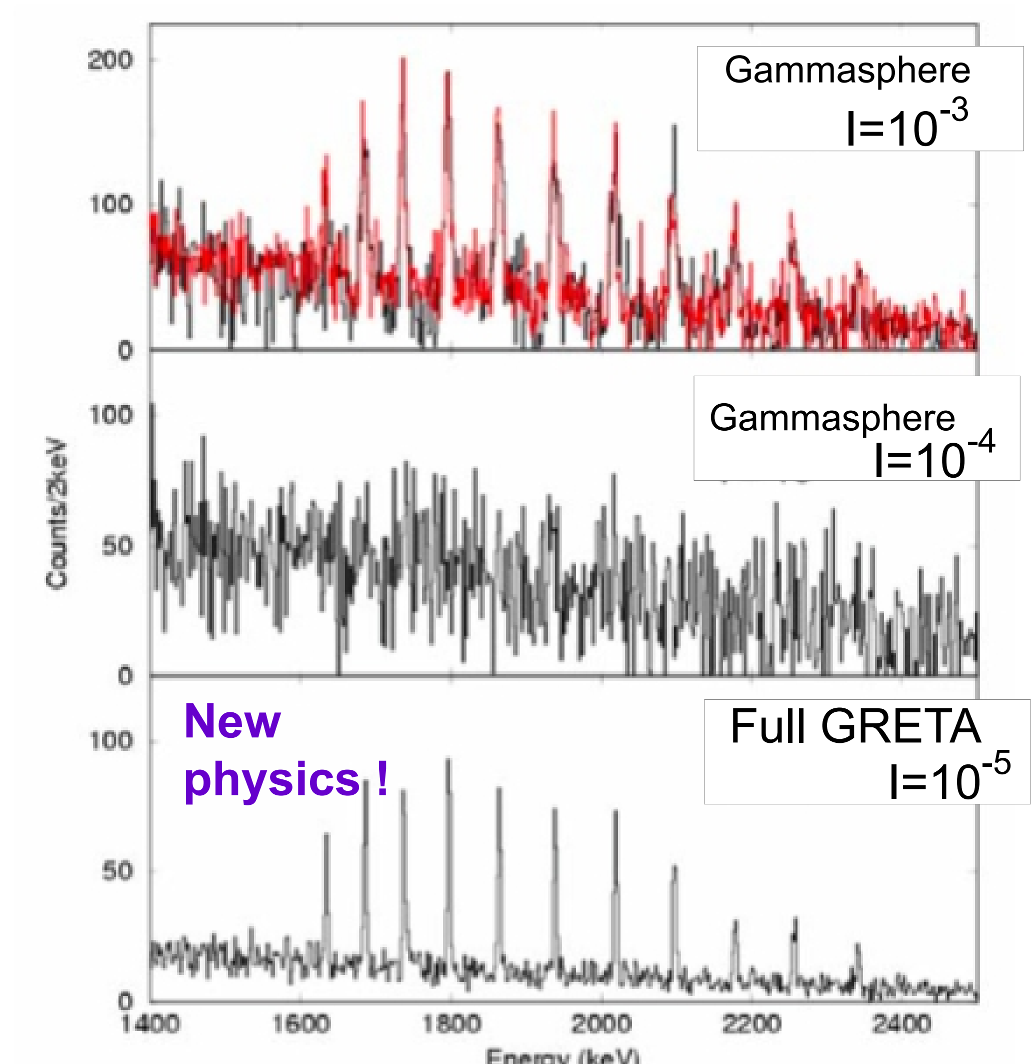
HD versus neutron stars ?

RESANET is an opportunity for that!

AGATA and GRETA full 4pi are needed



From the LRP GRETA



With AGATA/GRETA : calorimetric mode and high resolution mode at the same time !

Can measure (H,K) and select the best reactions conditions for the HD population

Conclusion

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News & Views | Published: 04 November 1993

Hopes for hyperdeformation

W. R. Phillips

Nature **366**, 13–14 (04 November 1993) | Download Citation