



2nd COPIGAL WORKSHOP
on Studies of Exotic Nuclei

June 4-6, 2012, Krakow, Poland

Organized by:

The Henryk Niewodniczański Institute of
Nuclear Physics
Polish Academy of Sciences



Perspectives in the studies of collective modes in the Milano - Krakow collaboration

... On going collaboration since 1980's ...

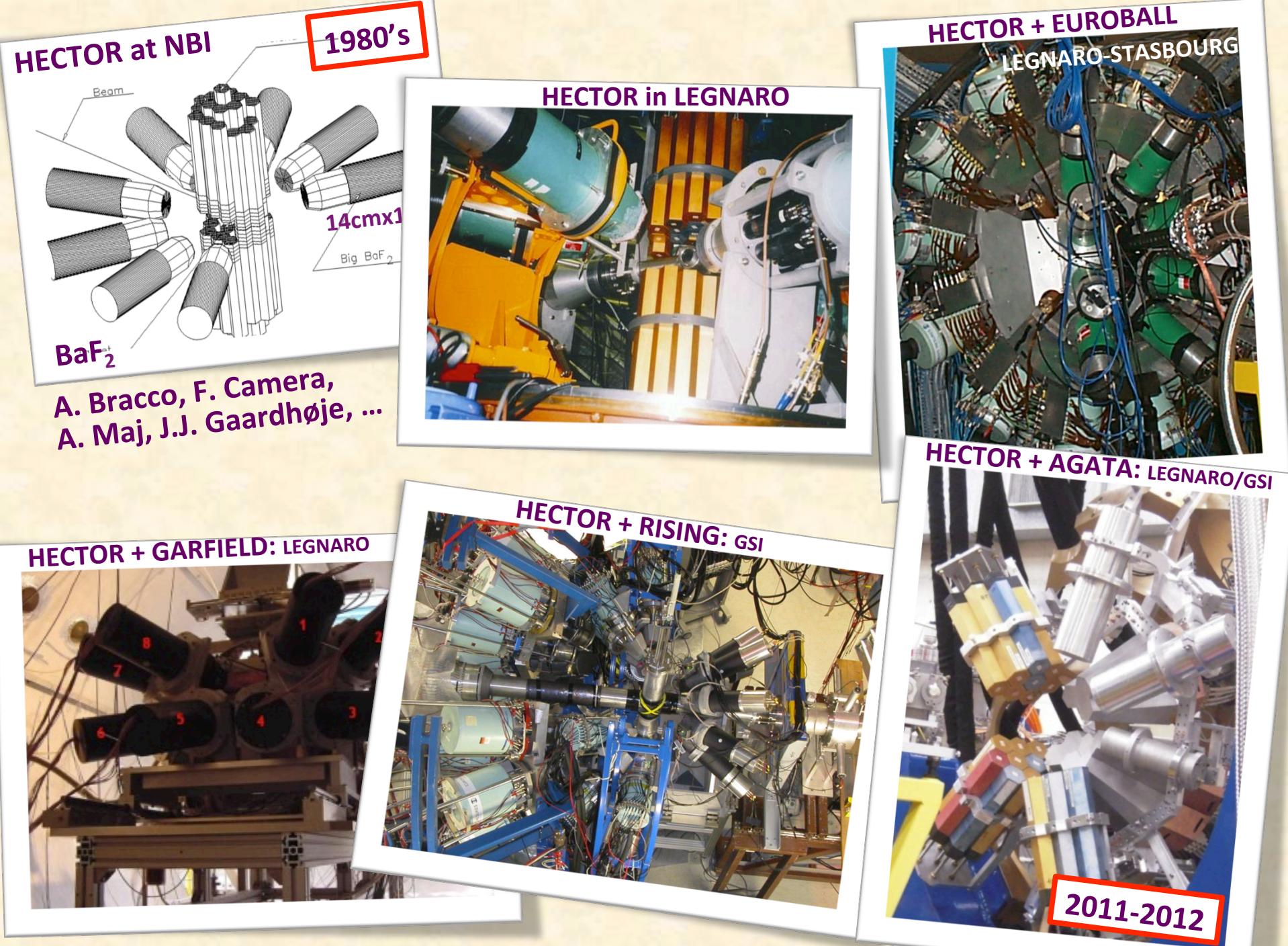
S. Leoni

University of Milano and INFN sez. Milano

on behalf of

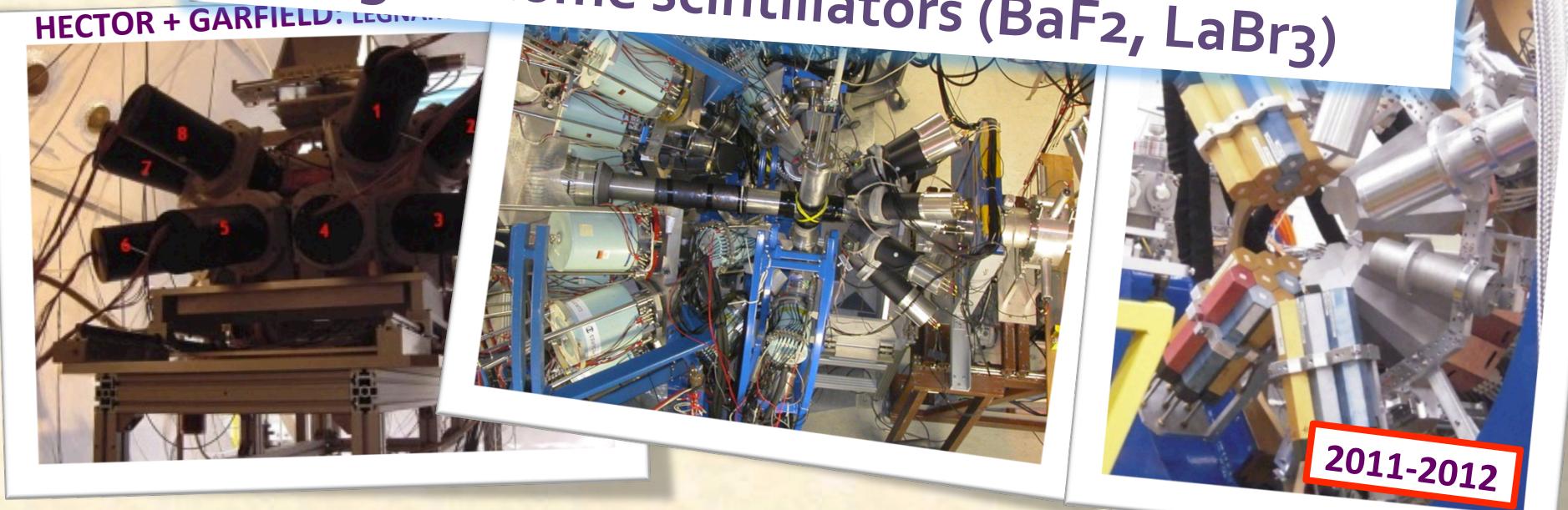
MILANO: A. Bracco, F. Camera, S. Leoni, G. Benzoni, F. Crespi, B. Million, O. Wieland,
S. Brambilla, S. Riboldi, P.F. Bortignon, G. Colò, E. Vigezzi et al., ...

KRAKOW: A. Maj, B. Fornal, M. Kmiecik, P. Bednarczyk, K. Mazurek, W. Męczyński, M. Zieblinski et al., ...





- + Collective Excitations (Giant Resonance ...)
- + Complex detection systems
- + Large Volume scintillators (BaF₂, LaBr₃)



LOOKING to the FUTURE: Towards SPIRAL2, SPES, HIE-ISOLDE, ...

□ Collective Modes in the continuum

(Adam Maj et al., ...)

1. Jacobi-Poincarè shape transitions

Collective Modes in neutron-rich Ba isotopes

(*LOI SPIRAL2, GALILEO+RFD+LaBr3, ...*)

2. Microscopic nature of Pygmy and GR states

High-Lying Bound and Unbound states:

(*Inelastic Scattering and (p,p') at LNL and Krakow*)

3. Asymmetric Fission and GDR studies

Fission properties of PROTON-rich Nuclei

(*GARFIELD + HECTOR at LNL*)

□ Incomplete Fusion of Radioactive Beams on ^7Li target

(Bogdan Fornal, K. Rusek et al., ...)

ISOLDE, SPIRAL2 and SPES Physics program

1- Search for Jacobi-Poincarè shape transitions in Ba nuclei

Study of collective modes of excitations in the neutron-rich Ba region via fusion-evaporation reactions

LOI SPIRAL2

Spiral2 Day1-Phase2 LoI

Adam Maj (Kraków), Silvia Leoni (Milano) - spokespersons
Christell Schmitt - GANIL Liaison

A. Maj^a, K. Mazurek^{ac}, M. Kmiecik^a, P. Bednarczyk^a, M. Ciemala^a, B. Fornal^a, W. Meczynski^a, J. Grebosz^a, J. Styczeń^a, M. Ziebinski^a et al.,
S. Leoni^b, A. Bracco^b, G. Benzon^b, F. Camera^b, F.C.L. Crespi^b, N. Blasi^b, B. Million^b,
O. Wieland^b, P.F. Bortignon^b, G. Colo^b, E. Vigezzi^b et al.,
Ch. Schmitt^c, J.P. Wieleczko^c, M. Lewitowicz^c, G. de France^c, M. Rejmund^c,
N. Alahari^c, E. Clement^c al.,
F. Azaiez^d, I. Matea^d, I. Stefan^d, M. Niikura^d, D. Beaumel^d, A. Korichi^d, A. Lopez-Martens^d et al.,
O. Stezowski^e, N. Redon^e, D. Guinet^e, G. Lehauf^e et al.,
J. Dudek^f, O. Dorvaux^f, S. Courtin^f, M. Rousseau^f, G. Duchene^f, D. Curien^f, Ch. Beck^f et al.,
D.R. Chakrabarty^g, V. Nanal^g, I. Mazumdar^g et al.,
T. Dossing^h, B. Herskind^h et al.,
G. De Angelisⁱ, D.R. Napoliⁱ, J.J. Valiente-Dobonⁱ et al.,
D. Bazzaccoⁱ, E. Farneaⁱ, S.M. Lenziⁱ, S. Lunardiⁱ, D. Mengoniⁱ, C. Urⁱ, F. Recchiaⁱ et al.
A. Gadea^m, T. Hüyük^m et al.,
J. Simpsonⁿ et al.,
W. Korten^o et al., A. Goergen^p et al.,
D. Jenkins^q, R. Wadsworth^q et al.,
M. Palacz^r, G. Jaworski^r, K. Hadynska-Klek^r, P. Napiorkowski^r, K. Wrzosek-Lipska^r et al.,
A. Atac^s et al.,

and the PARIS-EXOGAM-AGATA collaborations

Fusion reactions with radioactive beams (SPIRAL2)

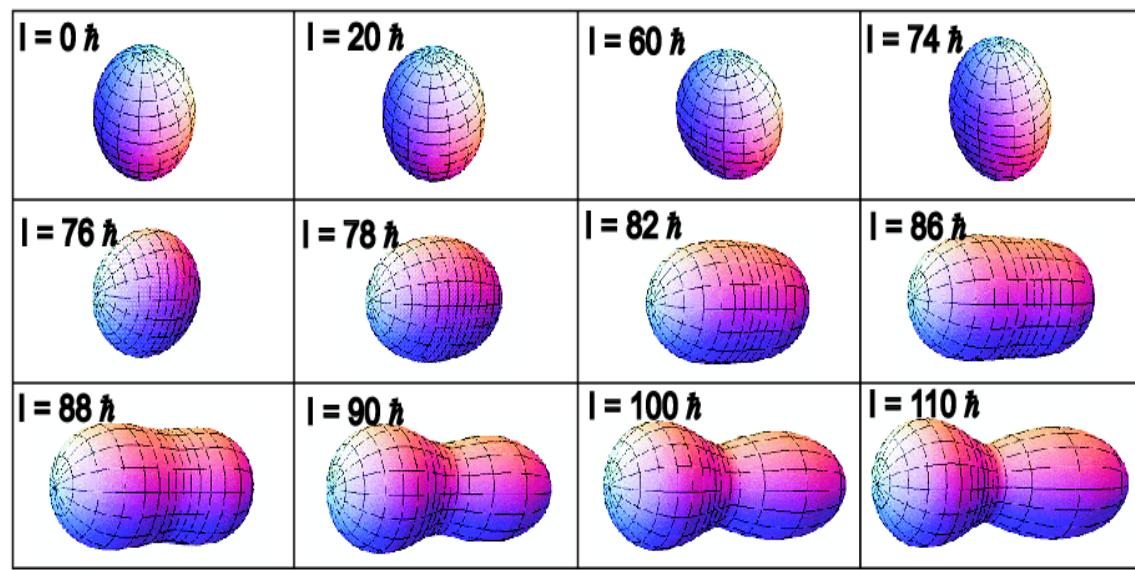
Experimental Strategy:

→ A Step Approach from Legnaro to GANIL

Evolution of Nuclear Shapes of HOT nucleus at the Highest angular momenta

Lublin-Strasbourg liquid Drop (LSD) model
by K. Pomorski and J. Dudek, PRC67 (2003) 044316

Analogous effect in fast rotating gravitating bodies



A.Maj *et al.* Int. J. Mod. Phys. E19, 532 (2010);
K.Mazurek *et al.*, Acta Phys. Pol. B42, 471 (2011)

Oblate (**MacLaurin**)
↓
Elongated triaxial (**Jacobi**)
-> gateway to
Hyperdeformed shapes at $T \sim 0$
↓
Octupole, left-right
asymmetric (**Poincarè**)

Search for Jacobi-Poincarè Transitions

→ Important for FISSION dynamics, search for HyperDeformed shapes at $T \approx 0$

Search for Jacobi-Poincarè Transitions

Experimental Signatures



Fission:

- Symmetric (Jacobi)
- Asymmetric (Poincarè)



Line Shape of Giant Dipole Resonance



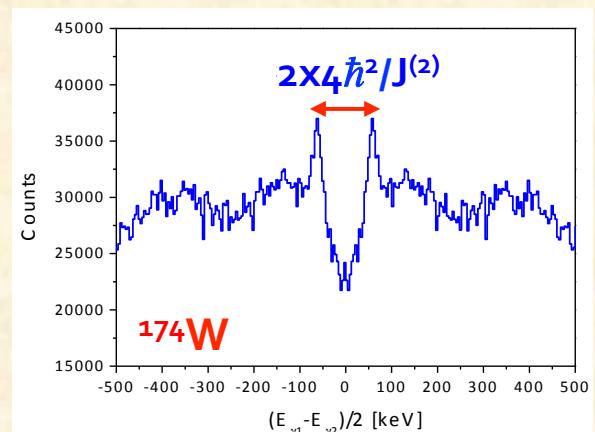
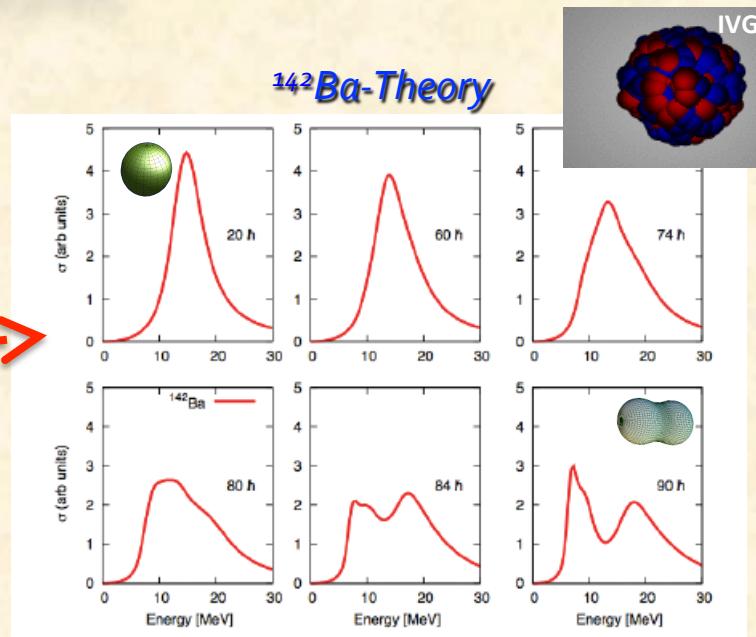
Warm Rotation:

(Variation in moment of Inertia)

- Giant Backbending
- Ridge-Valley Structures in $\gamma-\gamma$ spectra

Complex Experimental setup:

AGATA/EXOGAM2 array +
 2π PARIS scintillator array +
Recoil Detector (RFD/VAMOS)
(selection residues from fission)



... Superdeformed ^{152}Dy
was FIRST observed as ridge structures ...

Search for Jacobi-Poincarè Transitions

Experimental Signatures

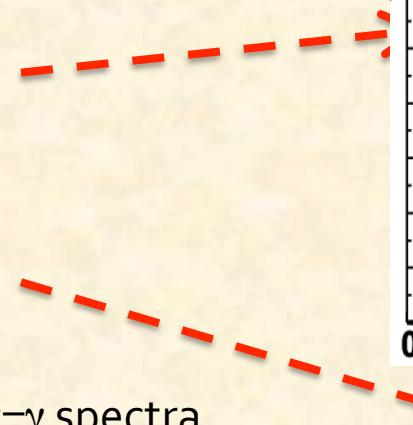


Fission:

- Symmetric (Jacobi)
- Asymmetric (Poincarè)



Line Shape of Giant Dipole Resonance



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(Variation in moment of Inertia)

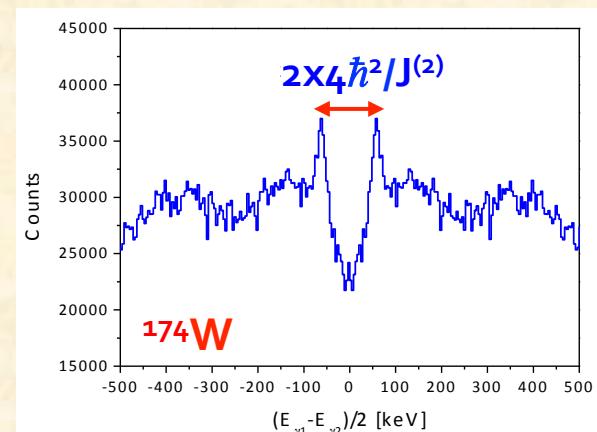
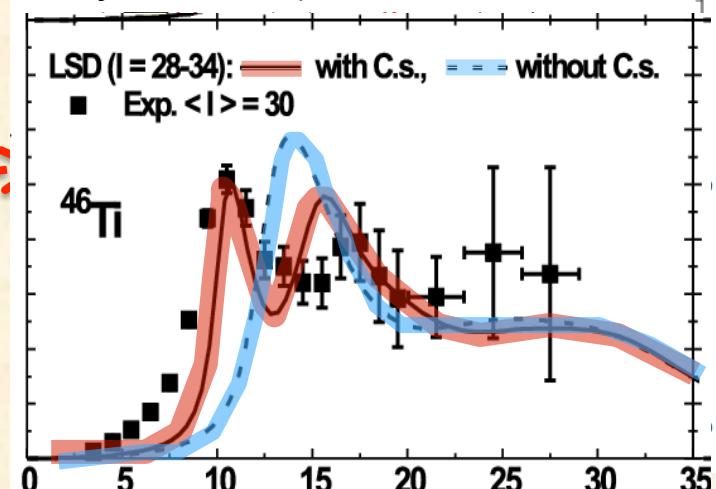
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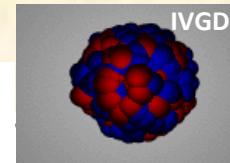
AGATA/EXOGAM2 array +
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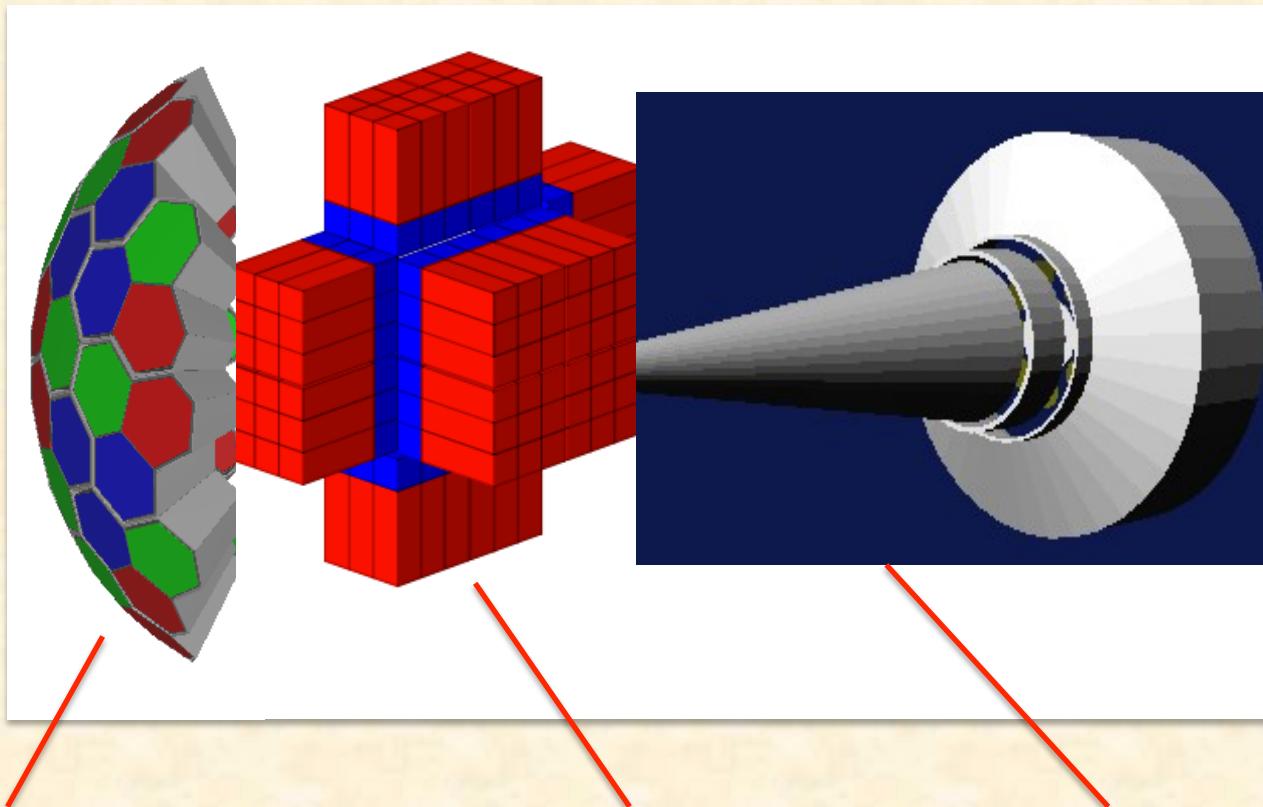
Euroball + HECTOR

A.Maj et al, Nucl. Phys. A731 (2004)319



... Superdeformed ^{152}Dy
was FIRST observed as ridge structures ...





AGATA/EXOGAM/GALILEO + PARIS/LaBr₃ + Recoil Filter/VAMOS

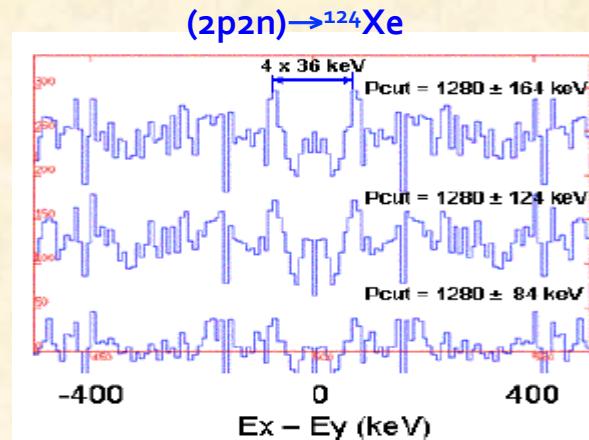
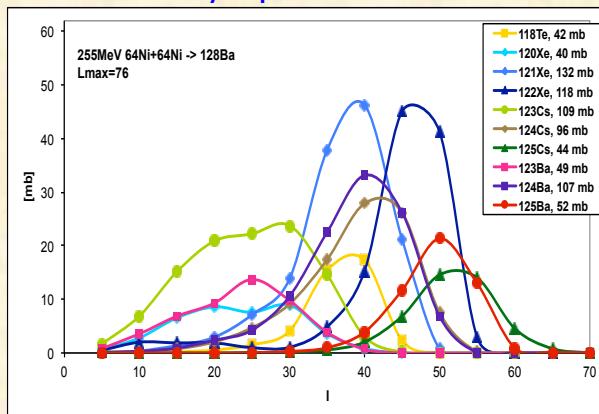
Experimental/Technical challenge ...

Expected Best Candidates: neutron-rich Ba nuclei

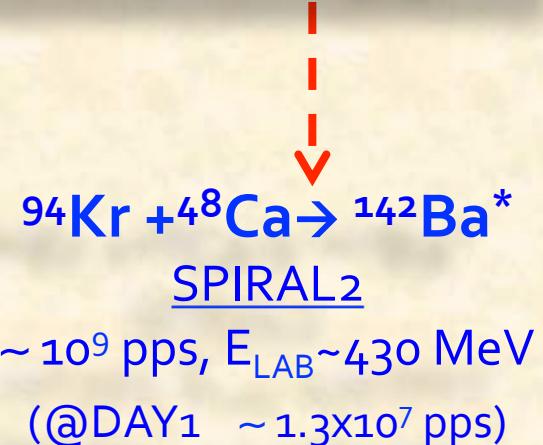
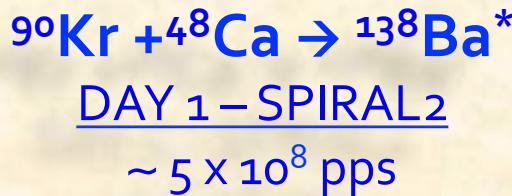
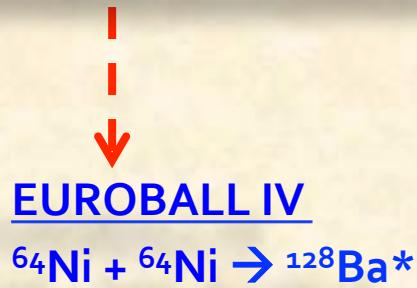


- NO discrete HyperDef bands
- Particle gated Ridge with very large $J^{(2)}$

Many open channels



Expected Best Candidates: neutron-rich Ba nuclei



DAY 0 @ Legnaro (2013-2015)

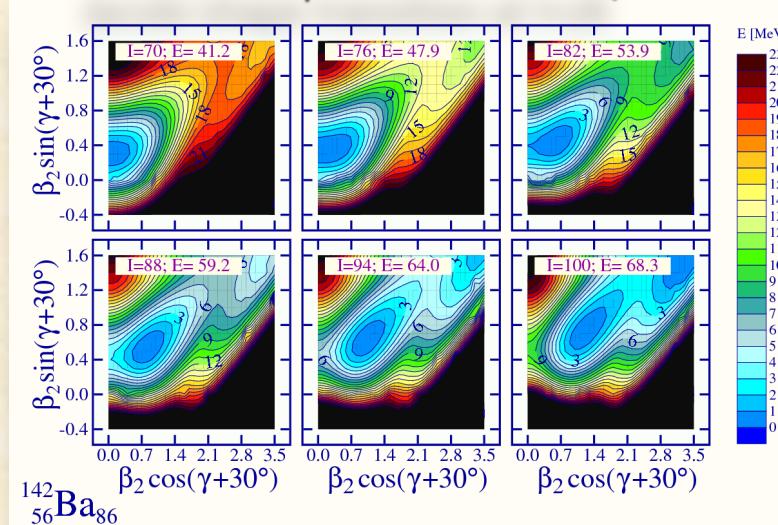
Stable beam

TEST of

- inverse kinematic reaction:
- Competition with fission at extreme spins
- Detectors: PARIS prototype, $^{10}\text{LaBr}_3$, GALILEO and RFD

Bilateral Mobility Application “CANALETTO”
to Ministry of Foreign Affairs
(M. Kmiecik and S. Leoni)

Jacobi shape transition at $I=76$



... More Perspectives at LNL for GALILEO + RFD

Physics Case 1:

(P. Bednarczyk et al.)

Evolution of quadrupole and octupole collectivity around the γ -soft $N=Z$ ^{64}Ge nucleus,
up to and beyond a rotational band termination.

Physics Case 2:

(S. Leoni et al.)

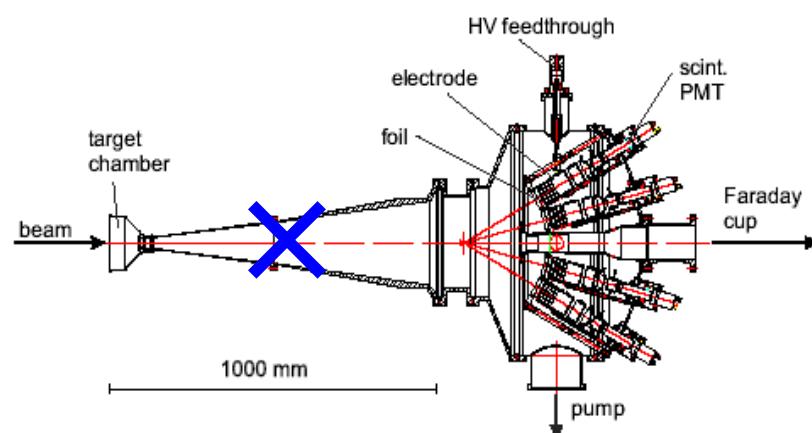
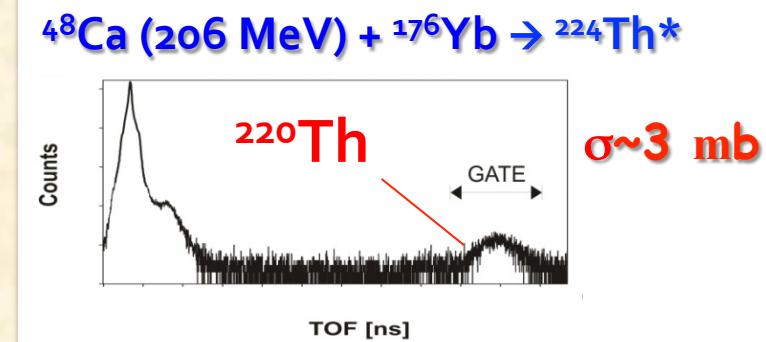
Robustness of Shell Structure with temperature
in very heavy systems Th, Ra, Rn

Fusion Evaporation with
 $\sigma \sim 100 \mu\text{b} - 50 \text{ mb}$ (due to fission)

LETTER OF INTENT for AGATA+RFD
LNL PAC June 2009

Coupling the AGATA Demonstrator
with the Recoil Filter Detector

Very positive PAC response

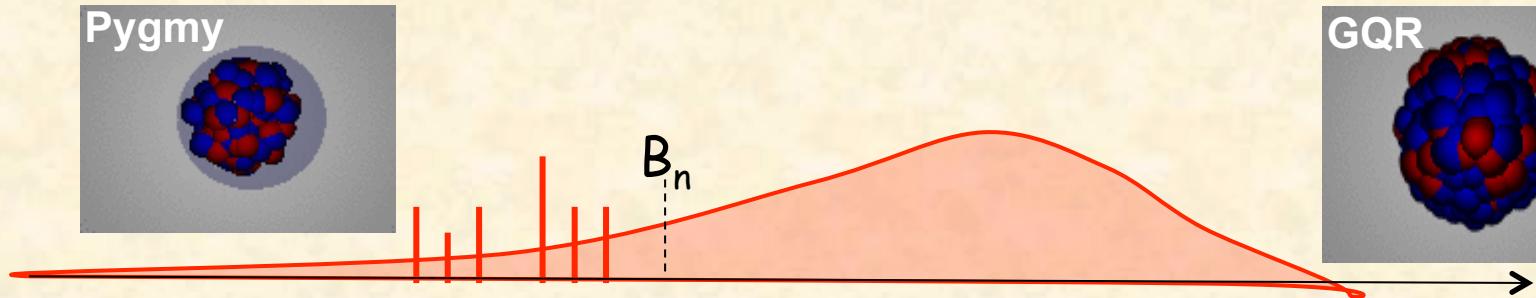


Mechanical work to couple RFD to GALILEO

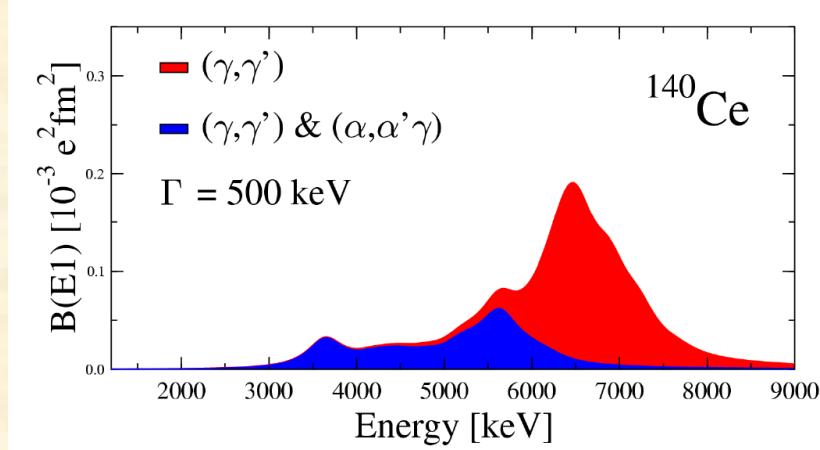
2- Microscopic nature of Pygmy and GR states: High-Lying Bound and Unbound states

- ^{17}O Inelastic Scattering @ LNL
- ... Perspectives at SPIRAL₂/SPES
- (p, p') : opportunities in Krakow

Microscopic structure of highly excited states in STABLE nuclei: inelastic scattering ^{17}O at 20 MeV/A



**Pygmy
substructure**

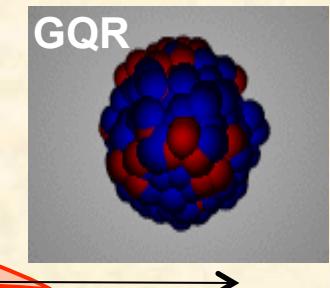
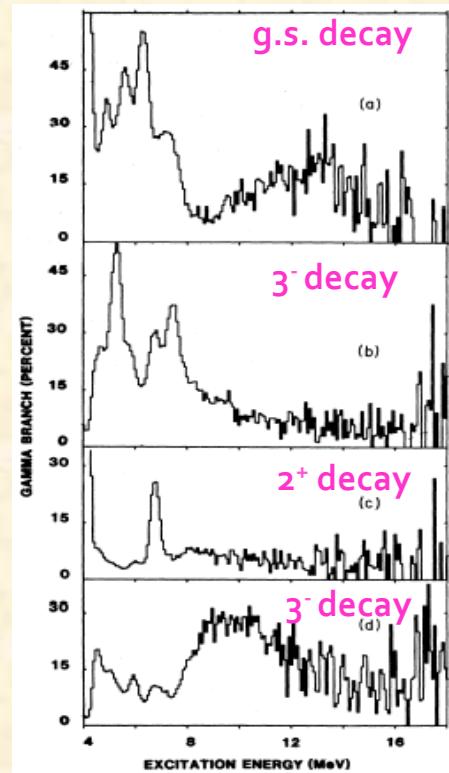


(γ, γ') experiments

$(\alpha, \alpha' \gamma)$ experiments @ 30 MeV/A

Selective Population

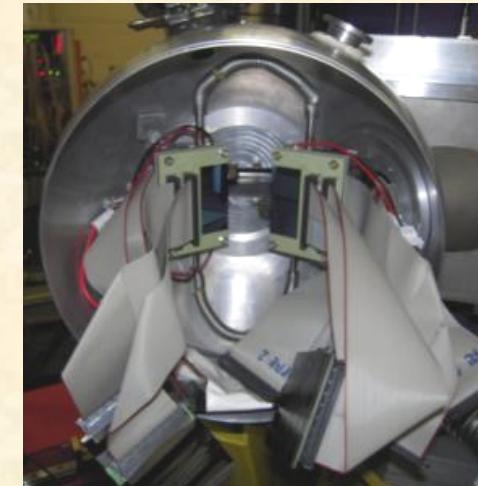
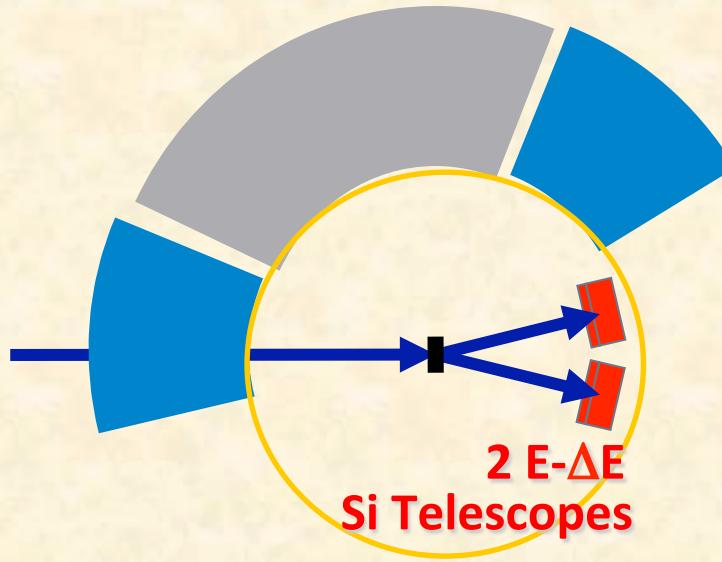
gamma-ray gated spectra



Branching to Excited states

AGATA experiment at LNL: inelastic scattering of light ion beams + γ -decay

^{17}O @ 20 MeV/A on ^{208}Pb , ^{90}Zr , ^{140}Ce , ^{124}Sn



- 3 – 5 AGATA triple clusters
- 3 – 8 LaBr₃:Ce detectors
Large volume (up to 9x20 cm)
- 20 Helena BaF₂ clusters

Si pixel detectors : 60 (5x12)

Pixel area of 4x4 mm²

- E detector: 1 mm thick
- ΔE detector: 200 μm thick
- $E_{\text{res}} \approx 0.5\%$

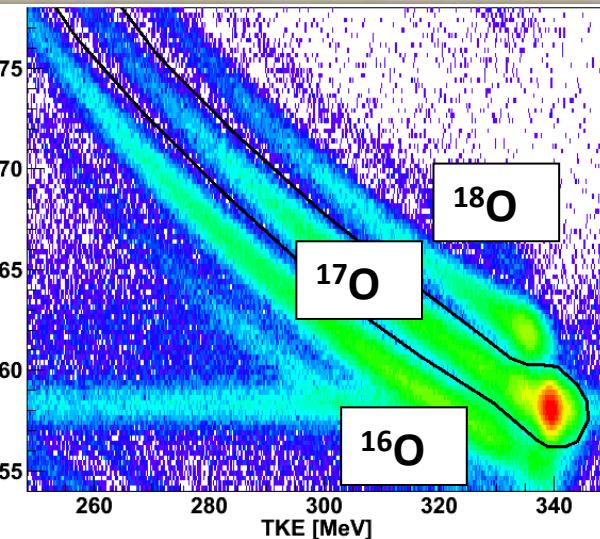
June 2010:

R. Nicolini, A. Bracco (Milano), D. Mengoni (LNL): ^{208}Pb , ^{90}Zr targets

December 2011:

M. Kmiecik (Krakow), F. Crespi (Milano): ^{140}Ce , ^{124}Sn targets

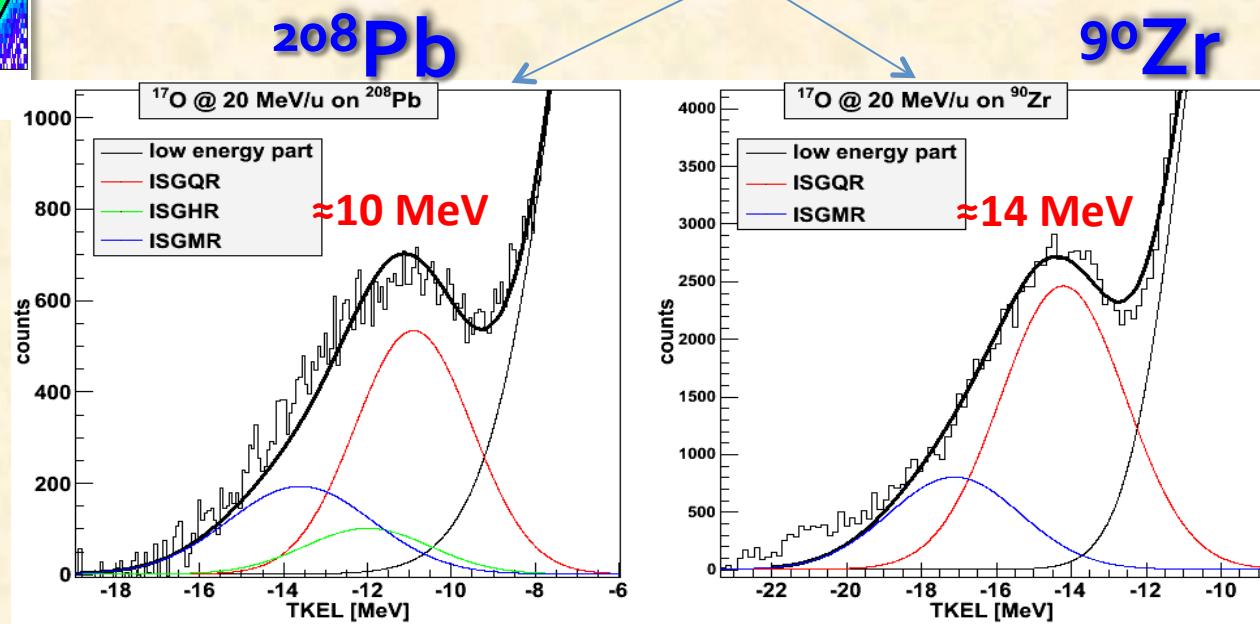
Excitation of high lying modes: Isoscalar Giant Quadrupole and Monopole Resonance



Silicon telescope-
ion identification

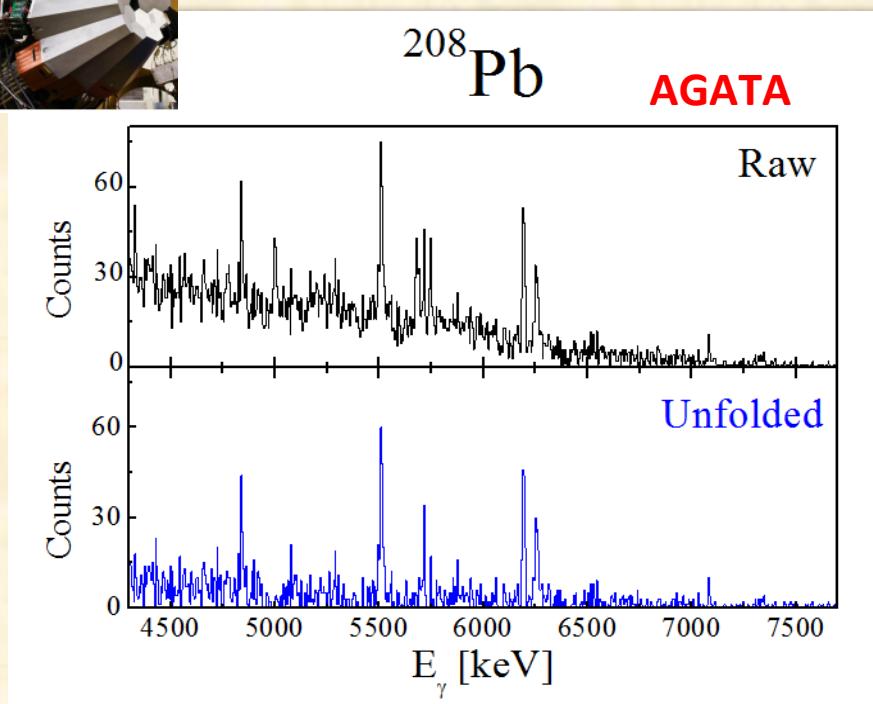
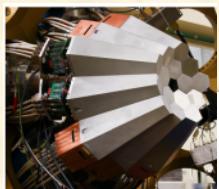
Energy spectra of ^{17}O
in GQR e GMR regions

^{17}O is loosely bound:
above 4.5 MeV mainly
target excitation only



γ -decay to be done

$^{208}\text{Pb}(\text{O}, \text{O}'\gamma)$ - decays to the ground state ($E_\gamma \approx E_x$)



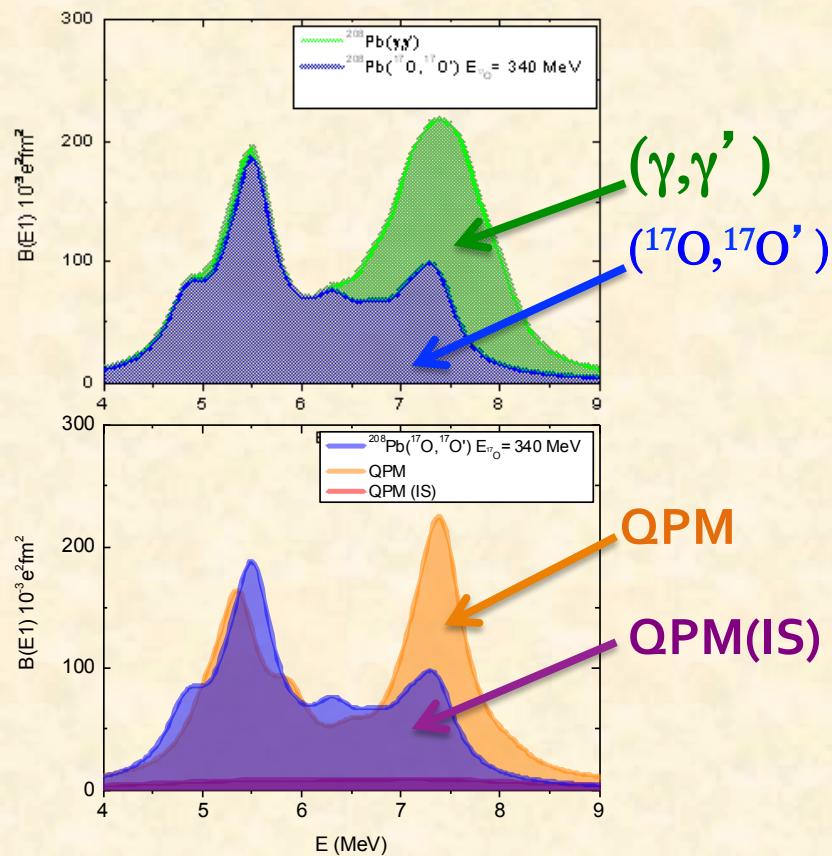
pygmy states in ^{208}Pb

gate on energy of ^{17}O corresponding to direct decay to ground state:

$$E_x = E_\gamma$$

Work in progress in ^{90}Zr , ^{124}Sn , ^{140}Ce , ...

A number of lines known by gamma scattering are seen in the region 4.5 - 7.5 MeV



(γ, γ') : probing entire volume
 $(^{17}\text{O}, ^{17}\text{O}')$: isoscalar character similar to (α, α')

□ ... Perspectives at LNL

Systematic Studies of Microscopic structure of highly excited

Inelastic Scattering ^{17}O (20 MeV/A) on STABLE nuclei

Pygmy states and GQR decay ...

GALILEO + LaBr₃ + Si Telescopes

□ ... Perspectives at SPIRAL2/SPES

Microscopic structure of highly excited states in EXOTIC nuclei:

Inverse Kinematics

Inelastic Scattering (10-20 MeV/A) on ^{13}C target ($S_n = 4.9$ MeV)

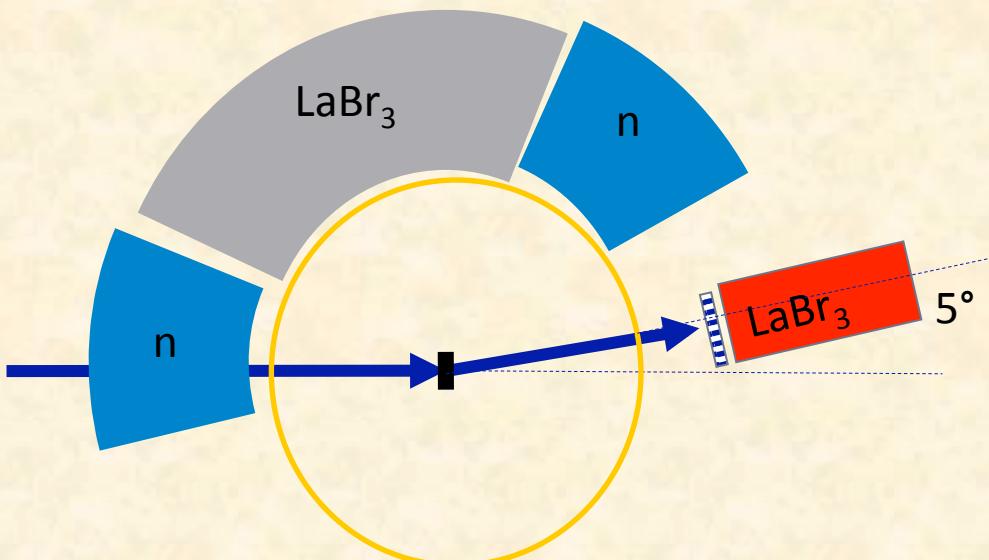
Evolution of Pygmy states in n-rich systems, ...

AGATA/EXOGAM/GALILEO + PARIS/LaBr₃ + Si Telescopes

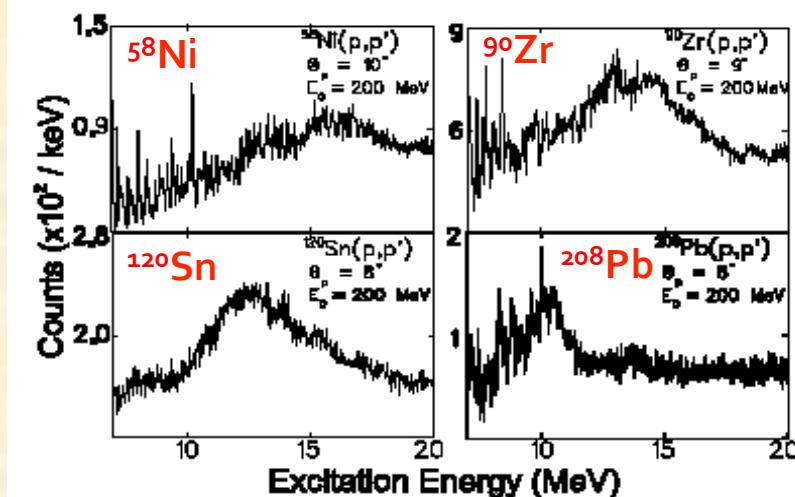
□ ... (p, p') : opportunities in Krakow

230 MeV proton: isovector probe

- Population of GR modes
- Study of decay branching (γ, n, \dots)



Population of GQR



Shevchenko PRL93(2004)122501-1

p identification:

- ΔE detector: Si strip
- E detector: 3" x 8" LaBr₃
- $E_{\text{res}} \approx 0.7 \% @ 200 \text{ MeV}$

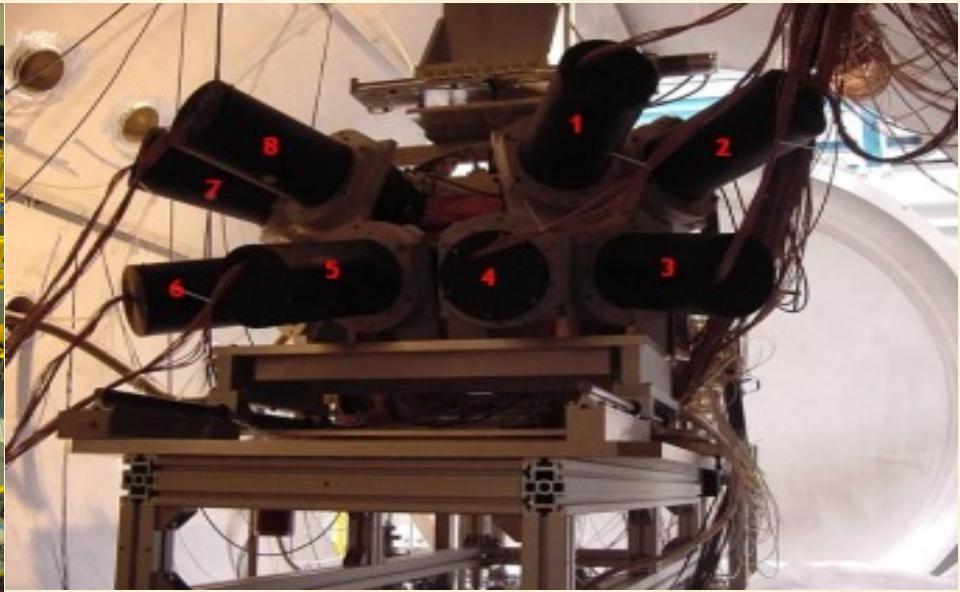
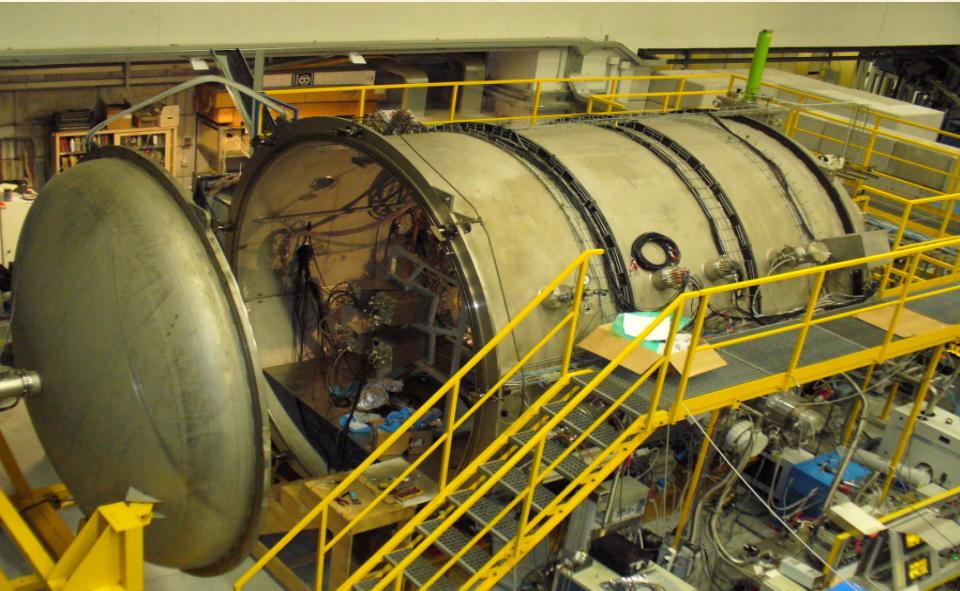
F. Quarati et al., private communication

3- Asymmetric Fission and GDR studies

- Fission properties of PROTON-rich Nuclei
(A. Bracco et al., ...)
- Jacobi-Poincarè transitions
(A. Maj et al., ...)

GARFIELD + LaBr₃/BaF₂

Charged particles and Fission Fragments



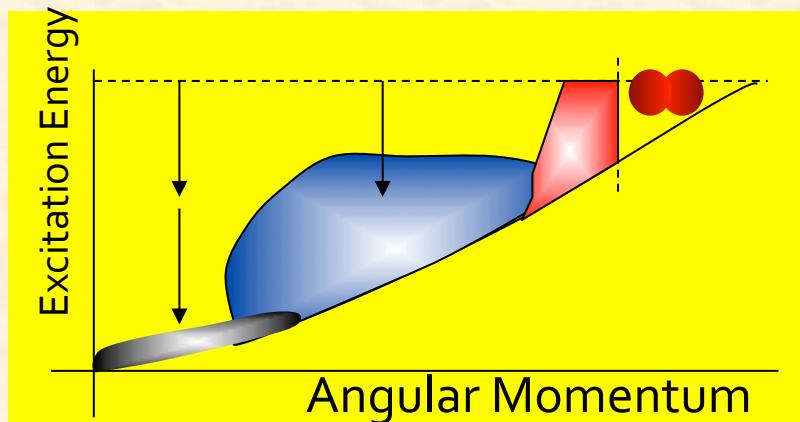
Fission properties of PROTON-rich Nuclei at $E^* \approx B_f$

Challenging Task: proton-rich nuclei never fission from g.s.

Cold Reaction $^{90}\text{Zr} + ^{90}\text{Zr} (^{89}\text{Y}) \rightarrow ^{179}\text{Au}$:

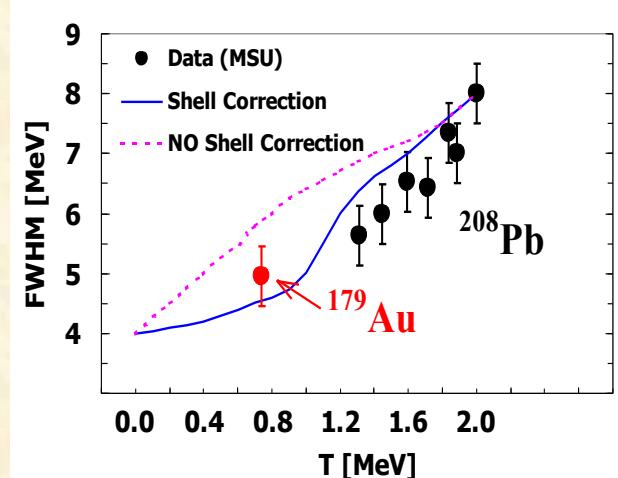
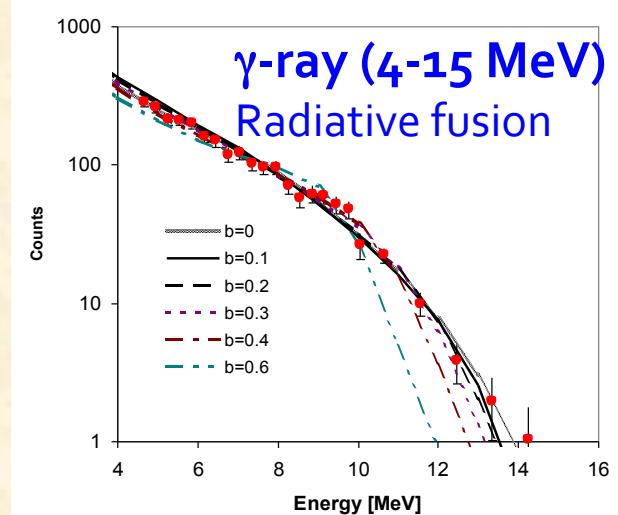
$T = 0.7 \text{ MeV}, E^* = 26 \text{ MeV}$

Radiative Fusion: Only γ emission



- High spin
- Competition with fission
- Phase space for warm GDR γ -decay
- Strong sensitivity to deformation
- **Strong SHELL EFFECTS**

→ FISSION Probed by GDR



Observation of Asymmetric Fission in ^{180}Hg (β -delayed)

PRL 105, 252502 (2010)

PHYSICAL REVIEW LETTERS

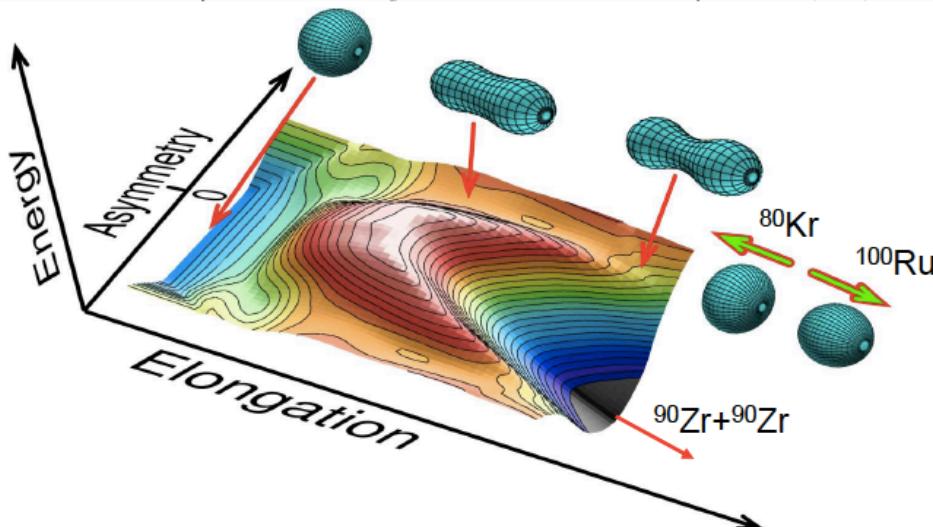
week ending
17 DECEMBER 2010

New Type of Asymmetric Fission in Proton-Rich Nuclei

A. N. Andreyev,^{1,2} J. Elseviers,¹ M. Huyse,¹ P. Van Duppen,¹ S. Antalic,³ A. Barzakh,⁴ N. Bree,¹ T. E. Cocolios,¹ V. F. Comas,⁵ J. Diriken,¹ D. Fedorov,⁴ V. Fedosseev,⁶ S. Franschoo,⁷ J. A. Heredia,⁵ O. Ivanov,¹ U. Köster,⁸ B. A. Marsh,⁶ K. Nishio,⁹ R. D. Page,¹⁰ N. Patronis,^{1,11} M. Seliverstov,^{1,4} I. Tsekhanovich,^{12,17} P. Van den Bergh,¹ J. Van De Walle,⁶ M. Venhart,^{1,3} S. Vermote,¹³ M. Veselsky,¹⁴ C. Wagemans,¹³ T. Ichikawa,¹⁵ A. Iwamoto,⁹ P. Möller,¹⁶ and A. J. Sierk¹⁶

¹Instituut voor Kern- en Stralingsfysica, K.U. Leuven, University of Leuven, B-3001 Leuven, Belgium

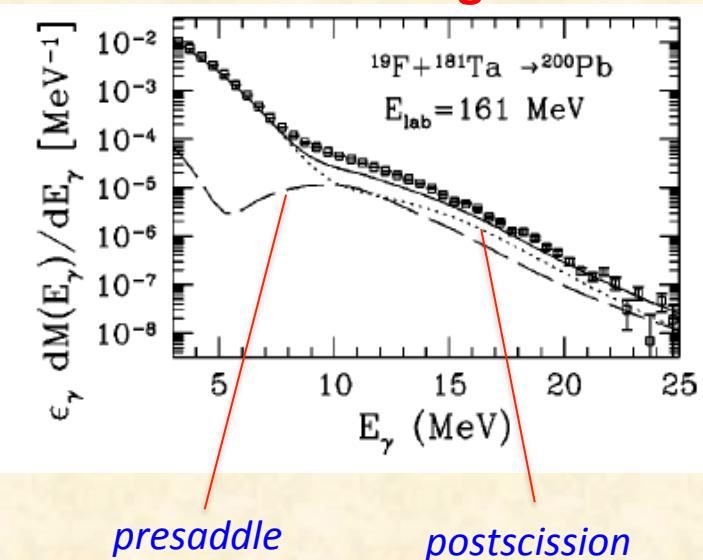
²School of Engineering, University of the West of Scotland,
Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)



Absence of proton/neutron shell effects
In FISSION of proton-rich Nuclei

In contrast to the fission of neutron rich nuclei for which shell effects play an important role (see ^{132}Sn for the fission of U)

γ -spectra of Fission Fragments

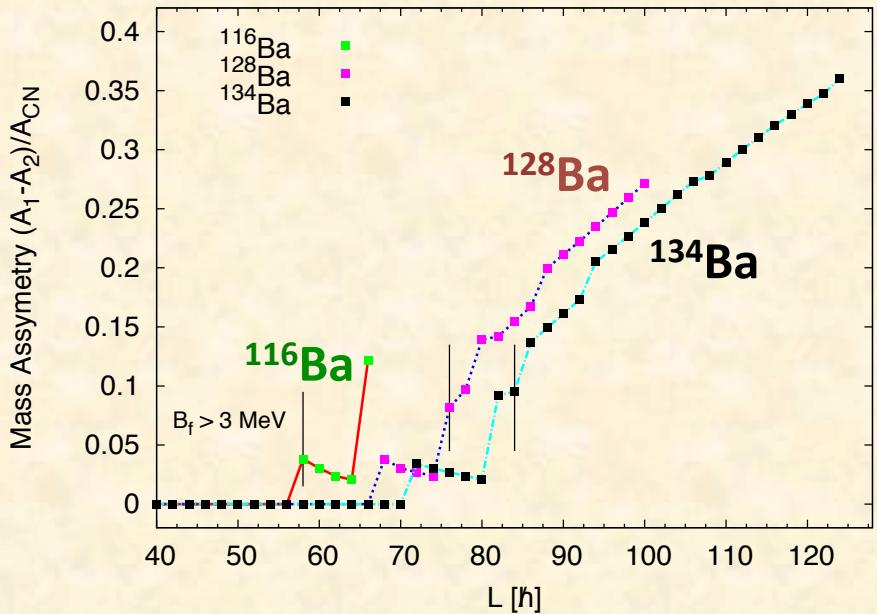


- Strong sensitivity to deformation
- Nuclear Viscosity

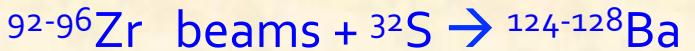
Dioszegi, A Bracco, F. Camera et al.,
PRC63(2000) 014611

Jacobi and Poincarè transitions probed by fission: Mass asymmetry of fission fragments in $^{124-134}$ Ba chain

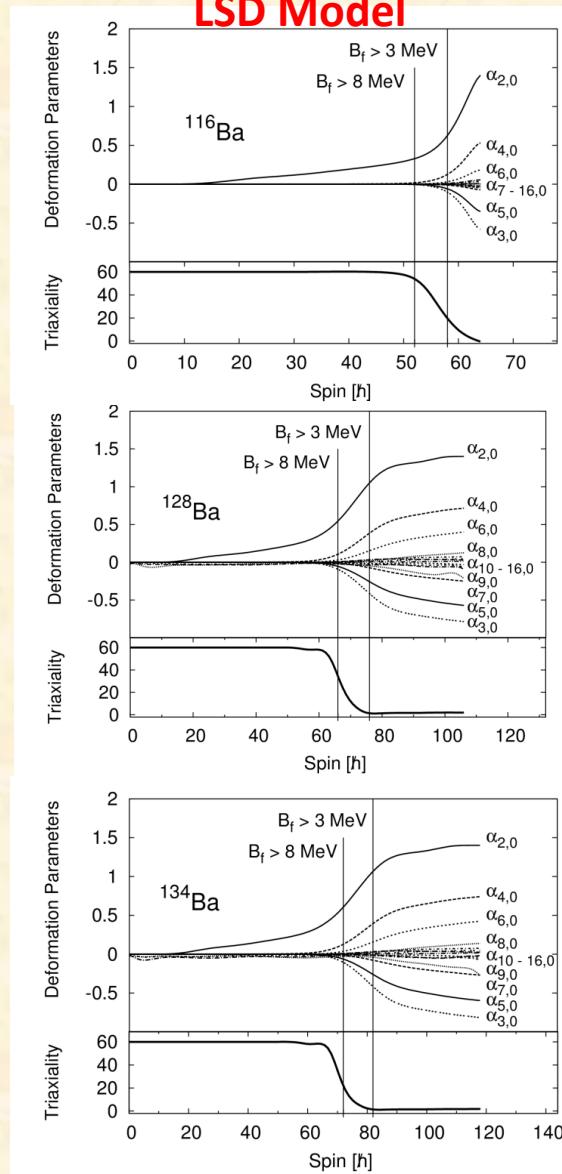
Fission fragments mass asymmetry



^{116}Ba : fission is almost mass **symmetric**
 ^{128}Ba and ^{134}Ba : Strong **asymmetry**



Equilibrium shape evolution LSD Model



→ Complementary to SPIRAL2 physics program

Incomplete Fusion of Radioactive Beams on ^7Li target

(Bogdan Fornal, K. Rusek et al., ...)

HIE-ISOLDE, SPIRAL2 and SPES Physics program

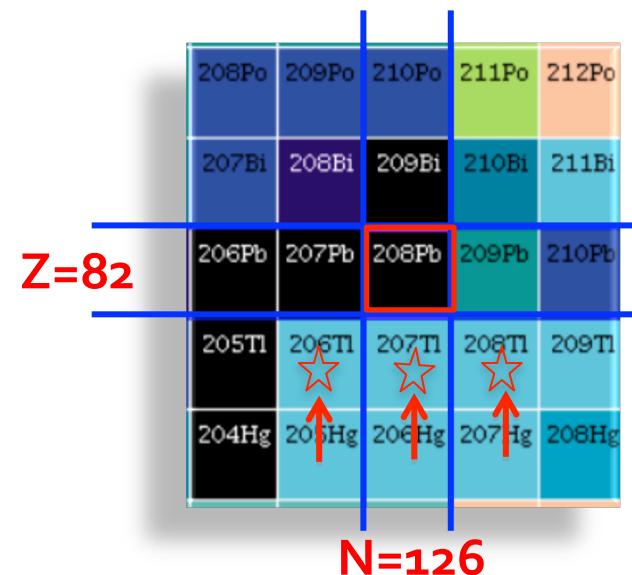
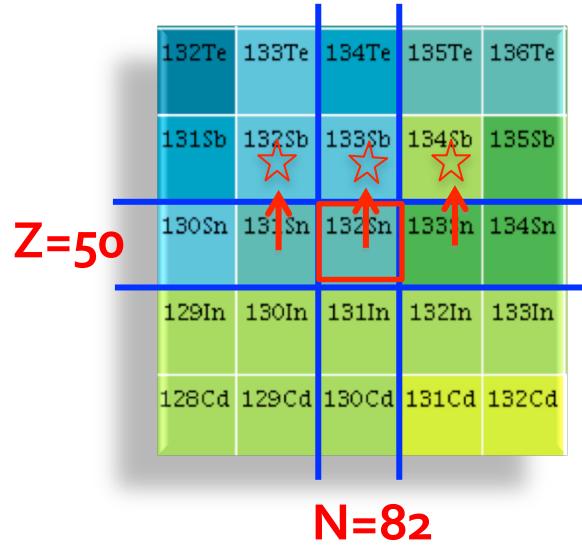
Further strength to the
MILANO-KRAKOW collaboration ...!

LOI's for HEI-ISOLDE, SPIRAL2 and SPES

$^7\text{Li}({}^A\text{Sn}, \alpha 2n)$, $^7\text{Li}({}^A\text{Hg}, \alpha 2n)$

High Spins, Excited States

^{132}Sb , ^{134}Sb , ^{206}Tl , ^{208}Tl : 1 and 2 nucleons away from doubly magic cores
TEST Bench for SHELL model and Particle-Phonon model ...



Complementary to YRAST Spectroscopy from
Fission, Fragmentation, transfer, deep-inelastic,...

APPROVED TEST Case at REX-ISOLDE:

Spectroscopy of n-rich
 $^{95,96}\text{Rb}$ nuclei with $^7\text{Li}(^{94}\text{Kr}, \alpha xn)$ at $\sim 3\text{ MeV/u}$

maximum available energy

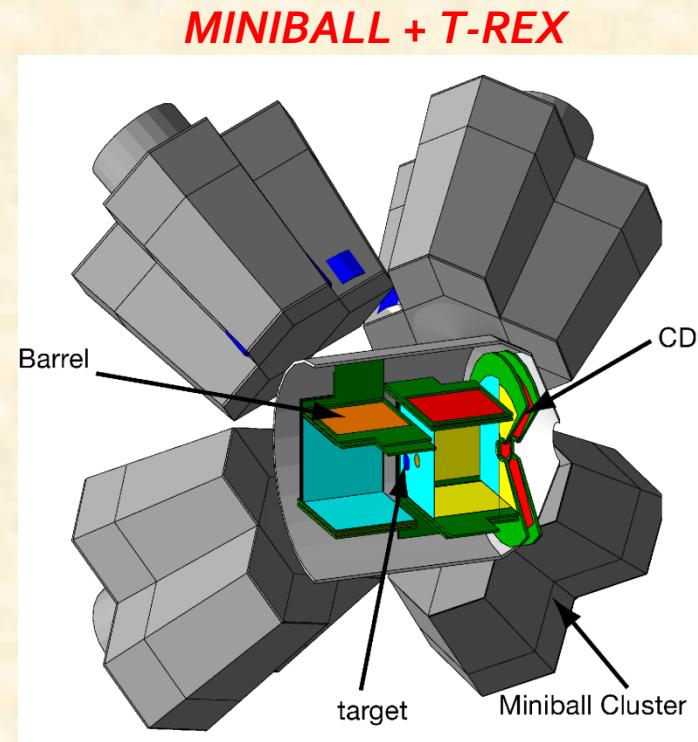
- Acquire Experience with Incomplete Fusion Reactions with a RIB

Reaction Mechanism, Inverse kinematics, particle detection, Backgrounds, ...

- Spectroscopy of $^{95,96}\text{Rb}$

*Moderate High Spins, Highly Excited States, ...
Region of Shape Changes
from $N=56$ (spherical) to $N=60$ (deformed)
importance for r-process path*

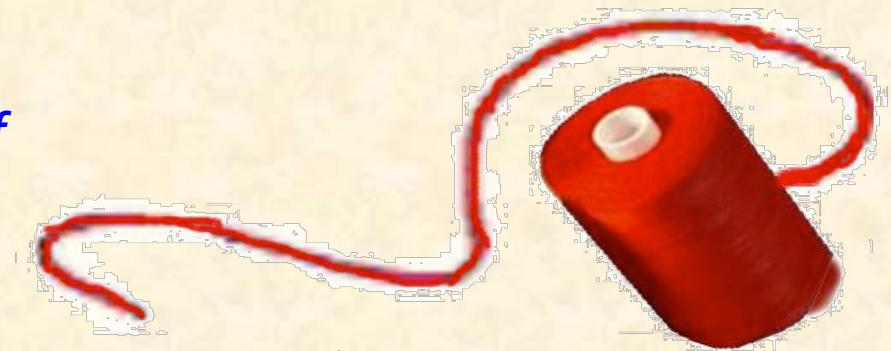
Gamma spectroscopy tagging on α particles



Strong on-going Milano-Krakow collaboration (since 1980's)

+ *Collective excitations at the extremes of
SPIN, TEMPERATURE, ISOSPIN*

+ *Complex Detector System
Large Volume Scintillators ($BaF_2/LaBr_3$) + Ge Arrays + Ancillaries*



Perspectives ...

*Step approach physics program towards SPIRAL2, HIE-HISOLDE, SPES, ...
Based on states of the art detection systems
(GALILEO, AGATA, EXOGAM, PARIS, HECTOR+, GARFIELD, ...)*

Theoretical Support (P.F. Bortignon, G. Colò, E. Vigezzi, ...)

Thank You for the Attention