Spectroscopy of isotopically identified neutron-rich Pm isotopes

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Points for discussion ……

- Spin-isospin domain of neutron-rich nuclei
- Deformation in rare earth region
  - Octupole deformation
  - Experimental signatures
- Possibility of parity doublet bands in neutron rich odd-A Pm isotopes
  - Deformed band structures
- High spin states of Pm isotopes as a function of N/Z
  - Experiment at GANIL: EXOGAM and VAMOS++
  - In-beam prompt spectroscopy : Direct identification
  - Experiment at Gammsphere
  - ^{252}Cf fission, high fold γ coincidence
- Band structures in odd-A and odd-odd Pm isotopes Beyond N=90

Neutron Rich – Accessing higher spin and iospin

- High Spin in neutron-rich region is a comparatively unexplored area

- Physics to be addressed
  - Shape change as a function of spin
  - Large deformation

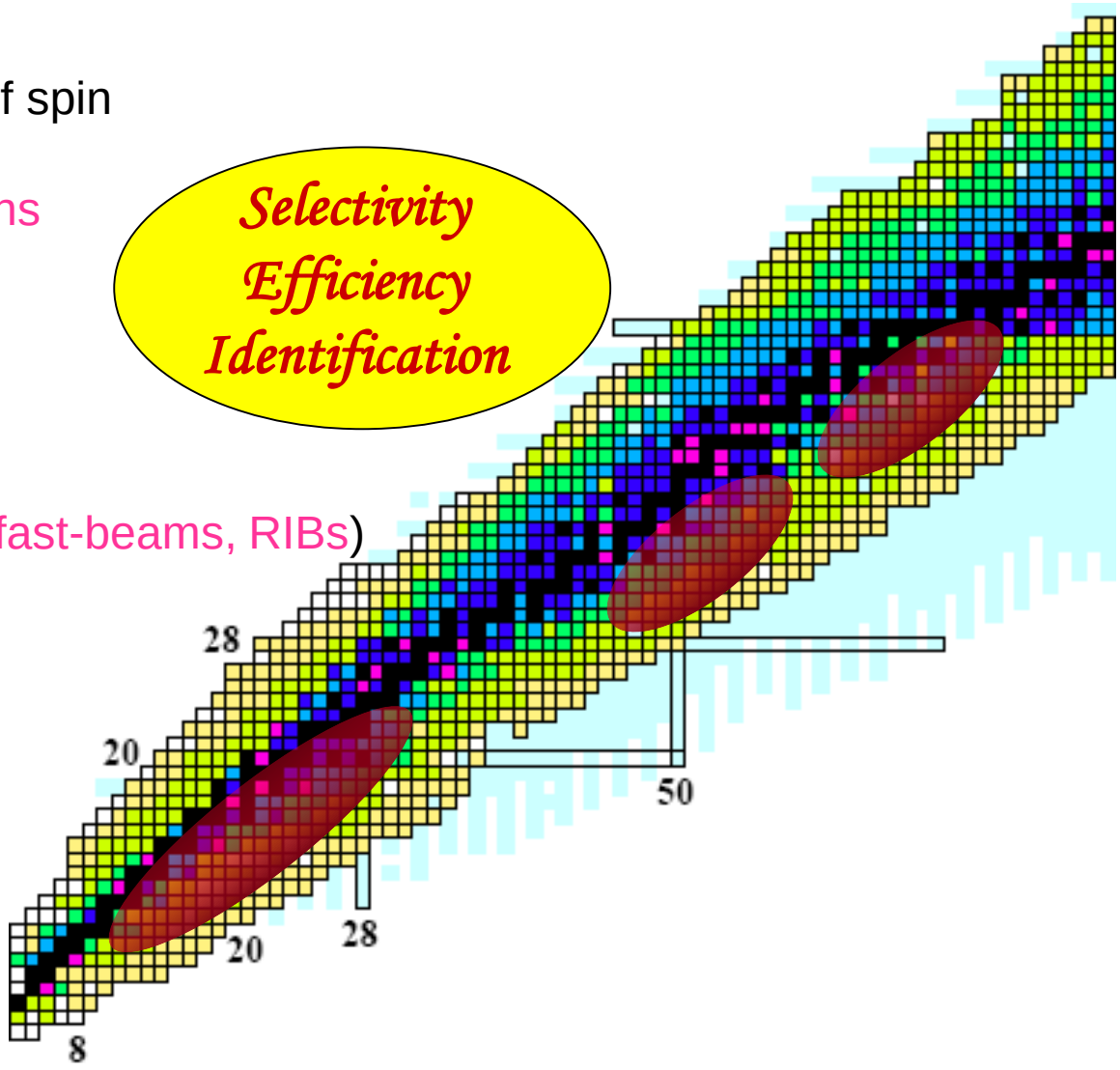
    Rotations, pairing, correlations

Experimental challenges:

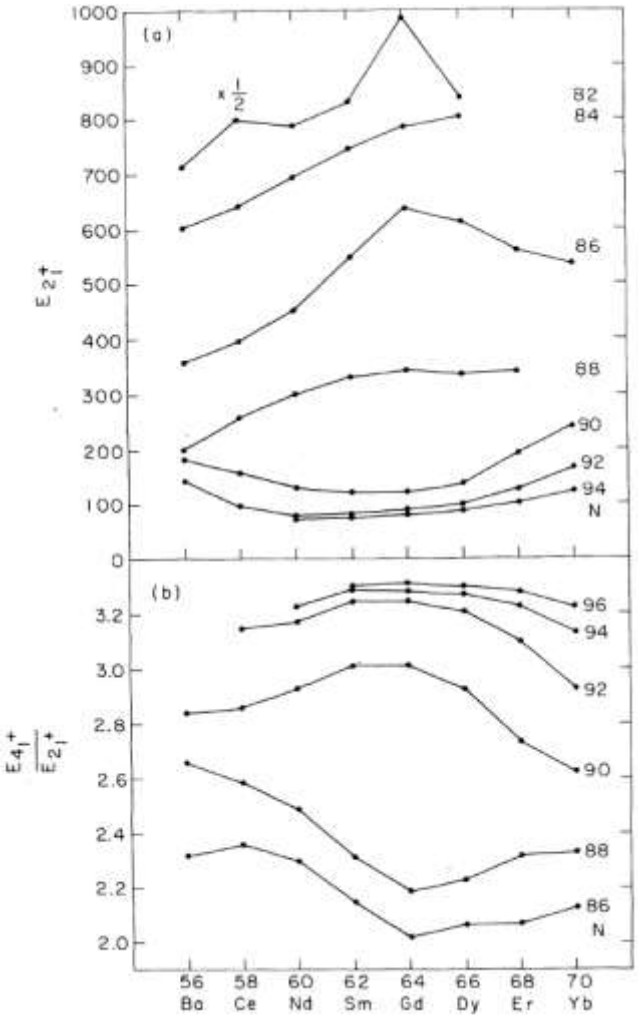
- Limited available reactions

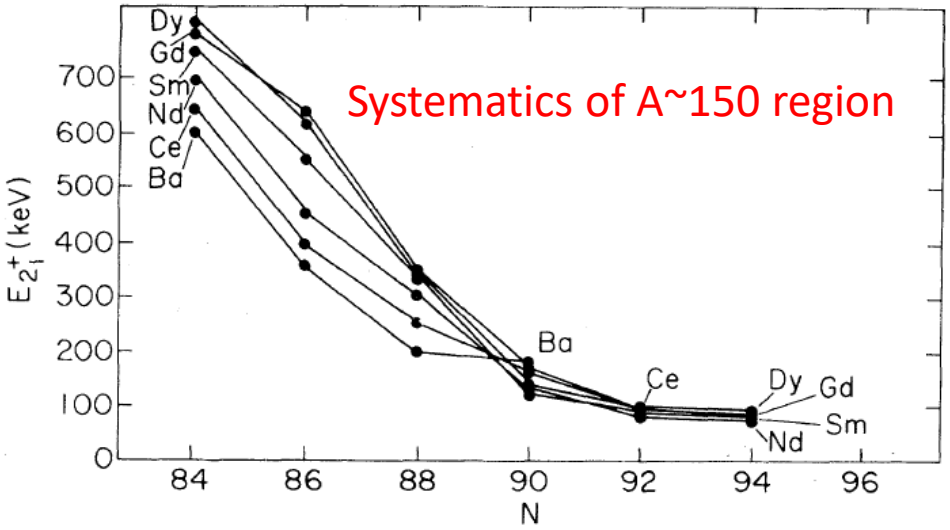
  (Deep-inelastic transfer, fission, fast-beams, RIBs)
- Low cross sections
- Complex γ-ray spectrum
- Channels of interest typically

  ~ a few to tens of mb x-section



Onset of deformation at N ~ 88-90 region

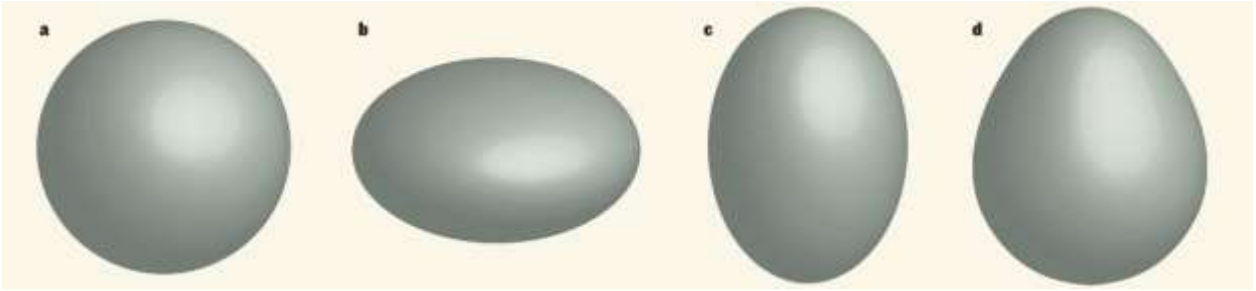




R. F. Casten et al., PRL 47, 1433 (1981)

- N=88-90 transition region
  - Spherical to quadrupole prolate deformation
- Onset of deformation between N=88 and N=90
- Role of n-p correlation
  - Availability of spin-orbit partner orbits

Octupole Deformations: Reflection Asymmetric Shape



Sphere Oblate Spheroid Prolate Spheroid Pear Shape

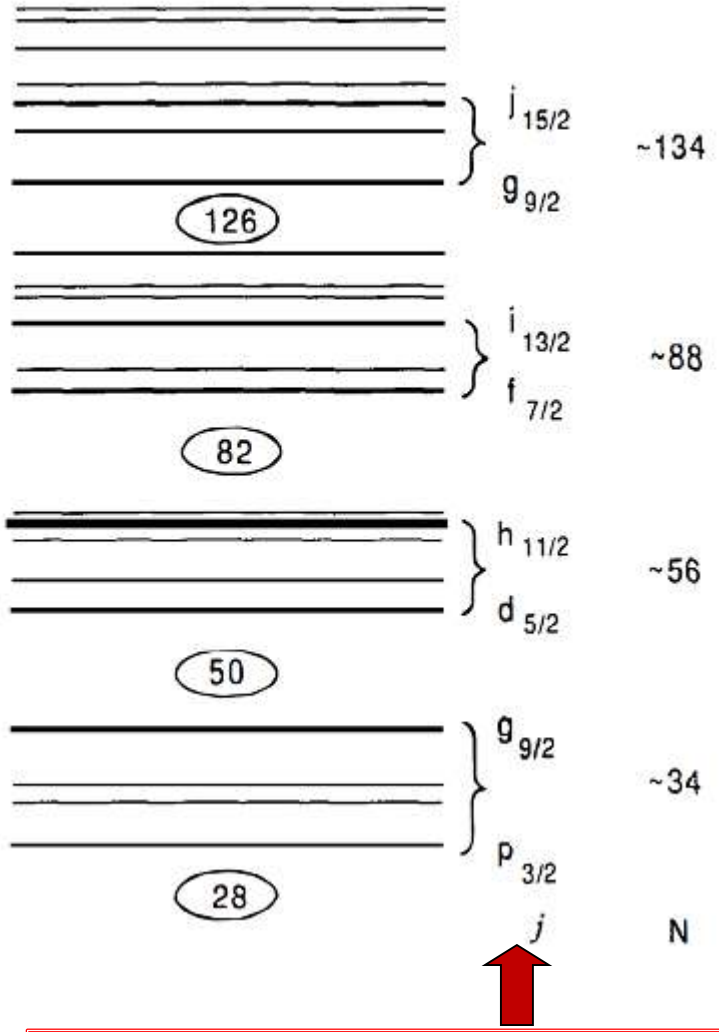
L.P. Gaffney et al., Nature 497, 199 (2013)

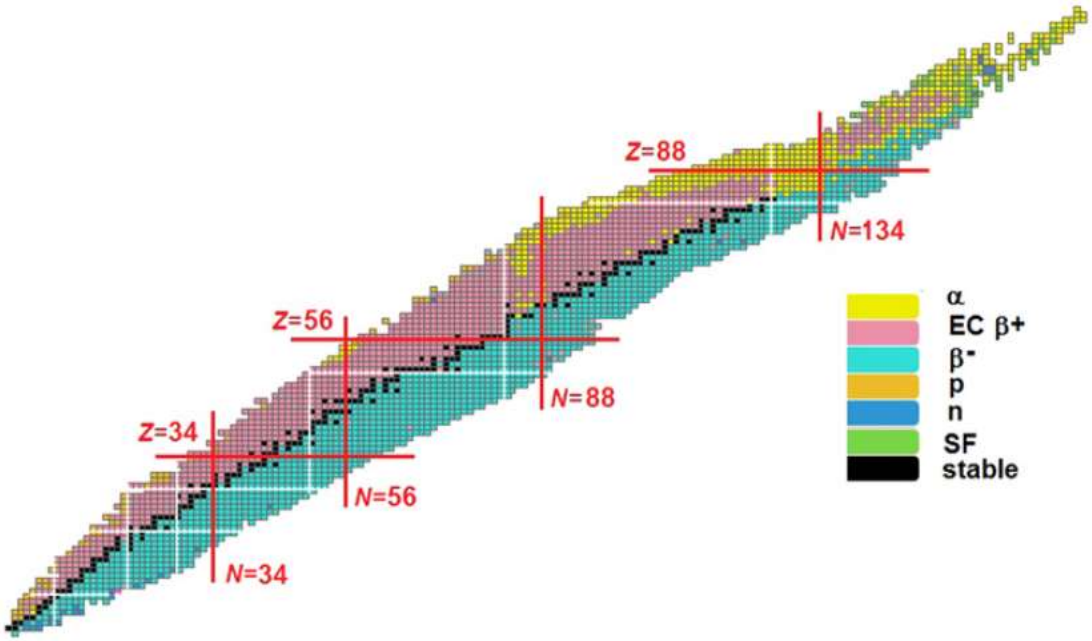
- Existence of octupole static/dynamic deformations
- Dynamic and static correlations

Experimental signatures:

- Alternating parity bands of negative- and positive-parity states with sequence I^{+},$(I+1)^{-}$,$(I+2)^{+}$… appear in even-even nuclei
- Parity doublet bands in odd-A and odd-odd nuclei (pair of alternating parity bands)
- Large B(E1) transition probabilities → large intrinsic dipole moments

Probable regions to show octupole effects





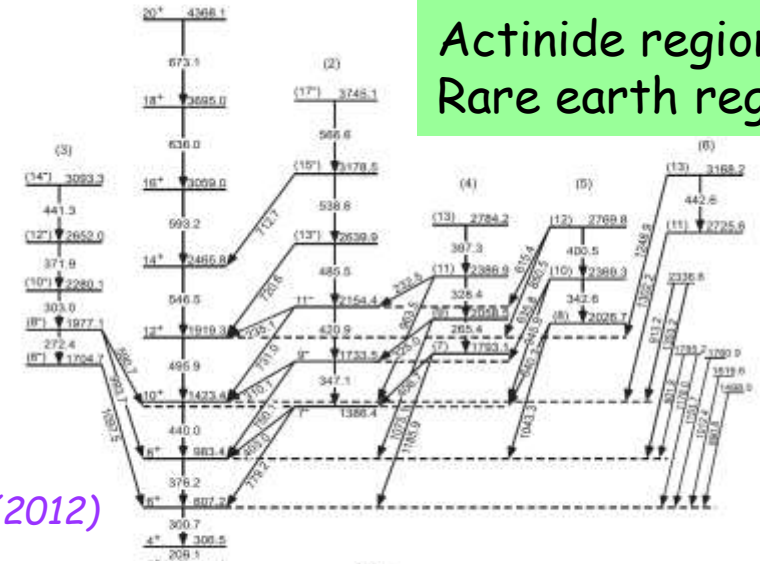
- Correlation between orbitals which differ in ℓ and j by 3 units
- Best candidates to show octupole effects N =34,56,88,134
- Reflection-asymmetric shapes

Intruder orbitals of opposite parity and $\Delta J, \Delta L = 3$ close to the Fermi level

Spectroscopic fingerprints of Octupole deformation

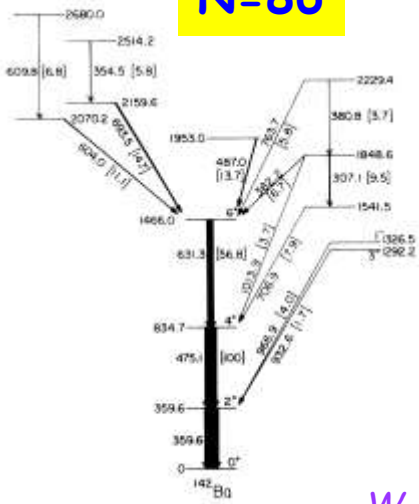
Actinide region: N~132, Z~88
Rare earth region: N~88, Z~56

^{150}Ce N=92

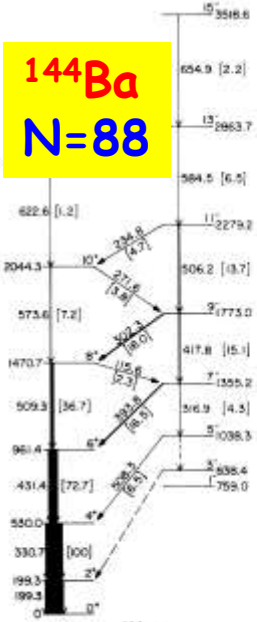


S. J. Zhu et al., PRC 85 014330 (2012)

^{142}Ba N=86



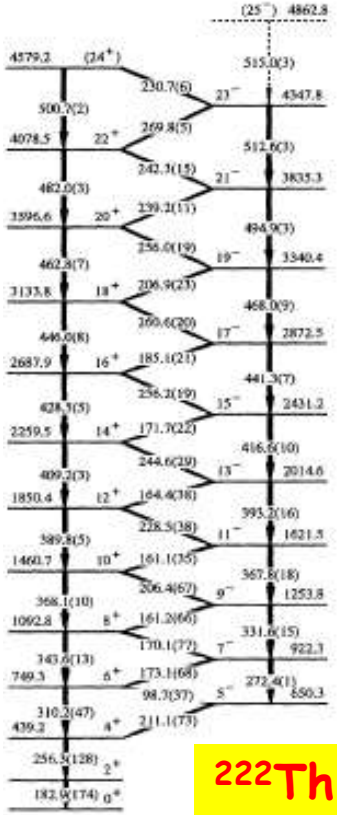
^{144}Ba N=88



W. R. Phillips et al., PRL 57, 3257 (1986)

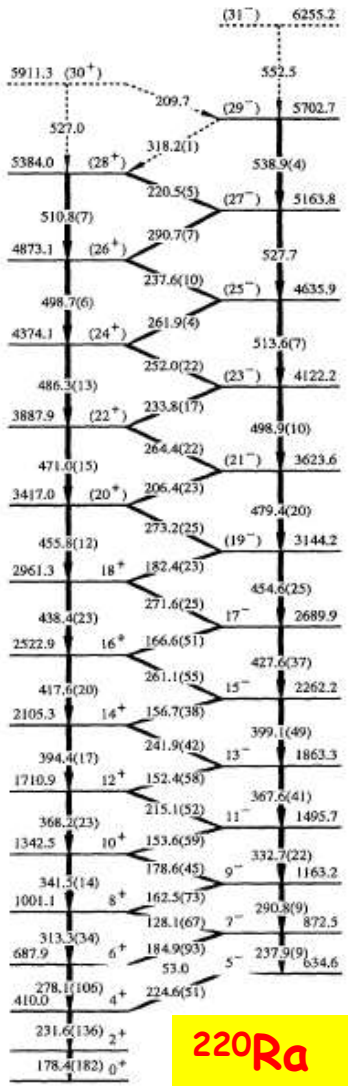
^{146}Ba N=90

^{222}Th N=132



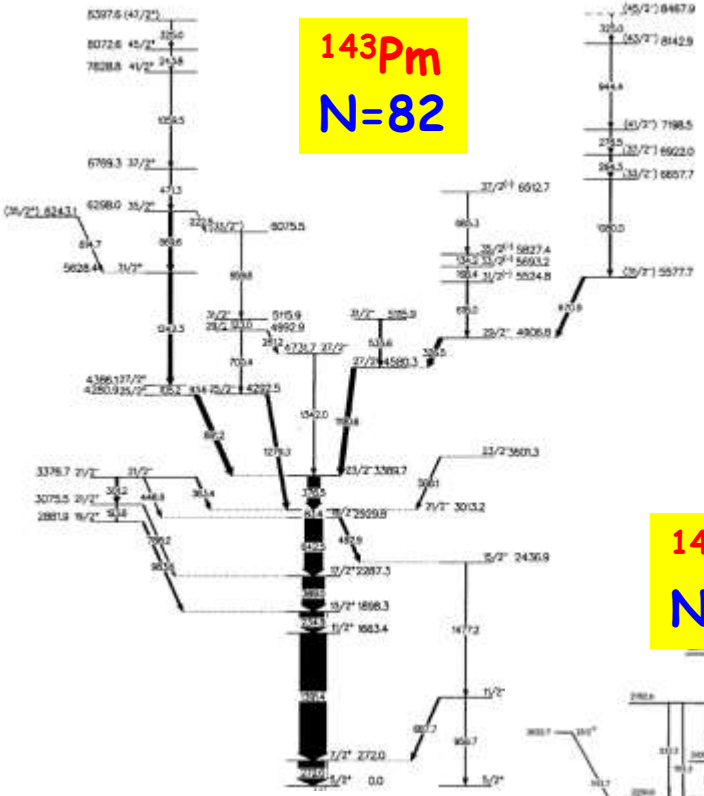
J.F. Smith et al., PRL75, 1050 (1995)

^{220}Ra N=132



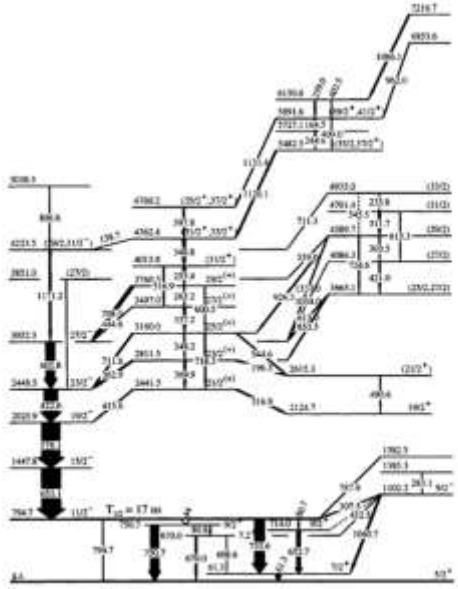
Odd-A Pm (Z=61) isotopes beyond N=82

^{143}Pm
N=82



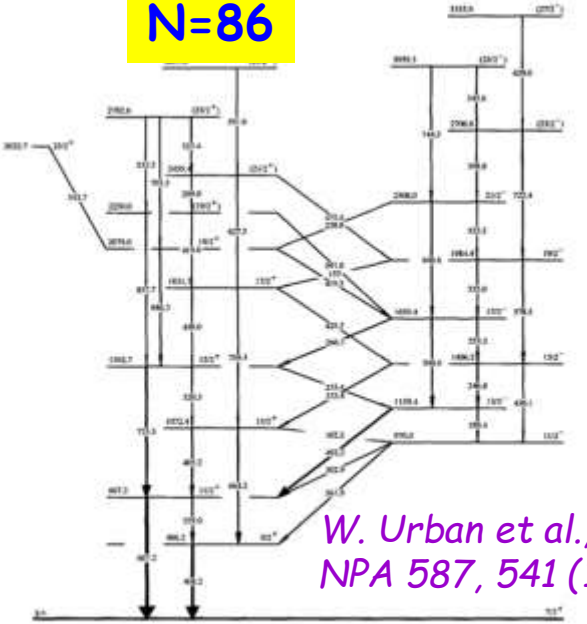
S. Bhattacharyya et al.,
PRC, 62, 024317 (2000)

^{145}Pm
N=84



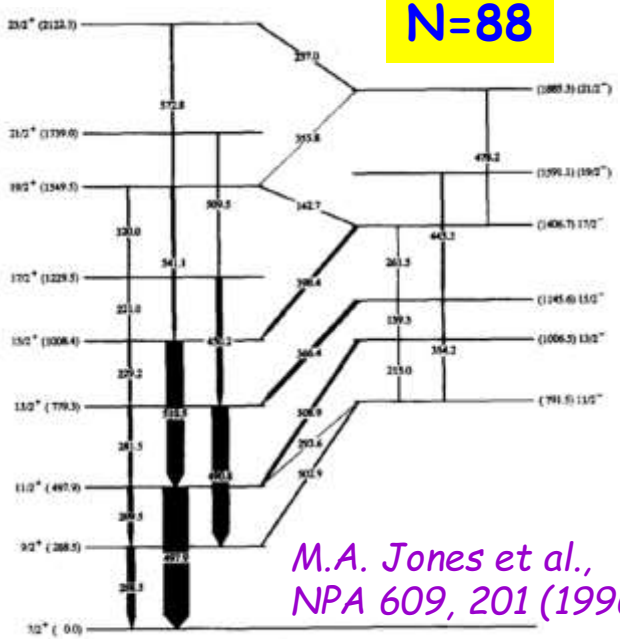
W. Urban et al.,
PRC 54, 2264 (1996)

^{147}Pm
N=86



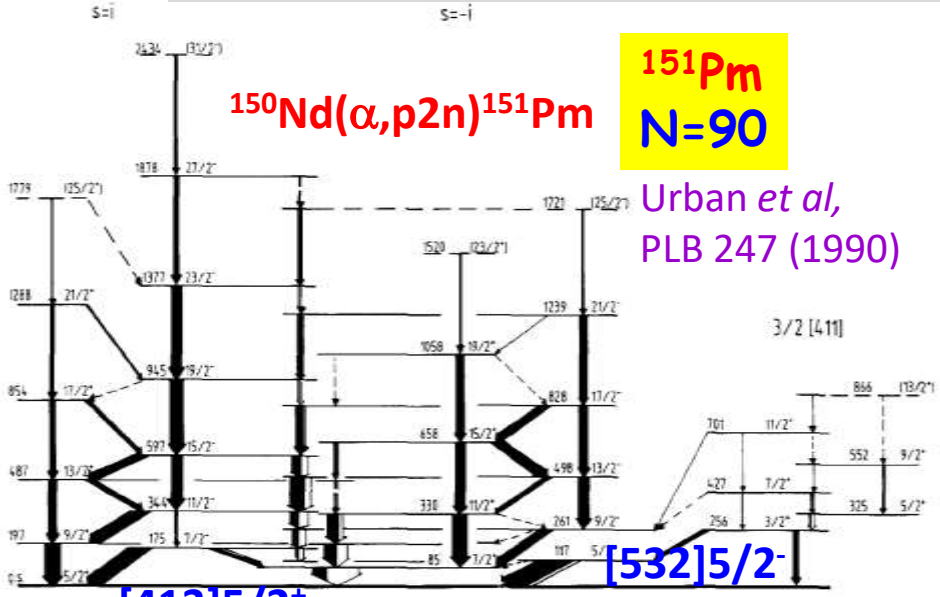
W. Urban et al.,
NPA 587, 541 (1995)

^{149}Pm
N=88



M.A. Jones et al.,
NPA 609, 201 (1996)

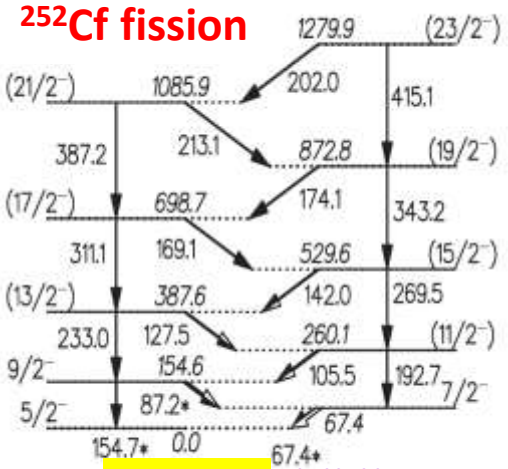
Odd-A Pm (Z=61) isotopes beyond N=90



^{151}Pm N=90

^{150}Nd(α,p2n)^{151}Pm

Urban *et al*, PLB 247 (1990)

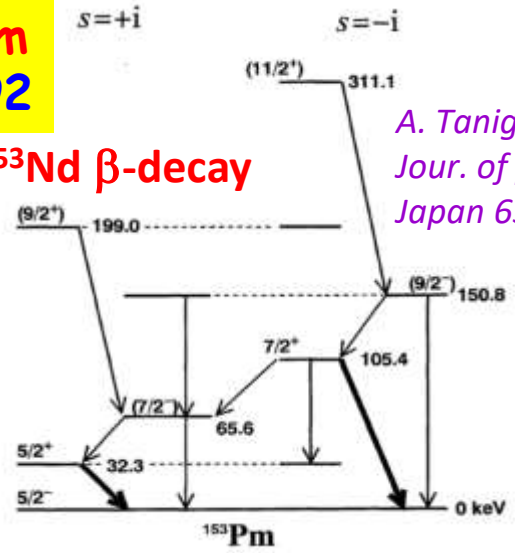


^{155}Pm N=94

J. K. Hwang et al., PRC 80, 037304 (2009)

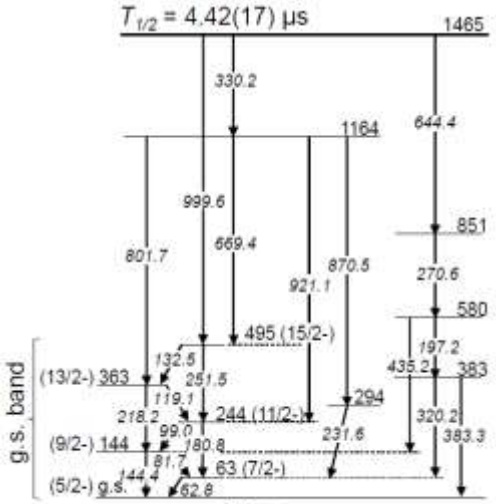
^{157}Pm N=96

^{153}Pm N=92



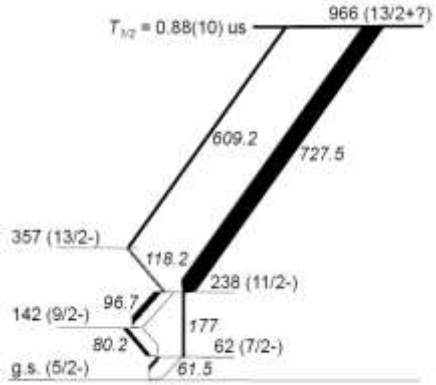
^{153}Nd β-decay

A. Taniguchi et al, Jour. of ph. Soc. Japan 65, 3824 (1996)



^{159}Pm N=98

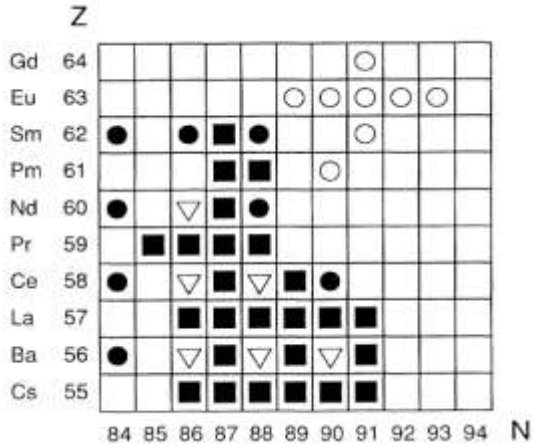
R. Yokoyama et al., JPS Conf. Proc. , 030021 (2015)



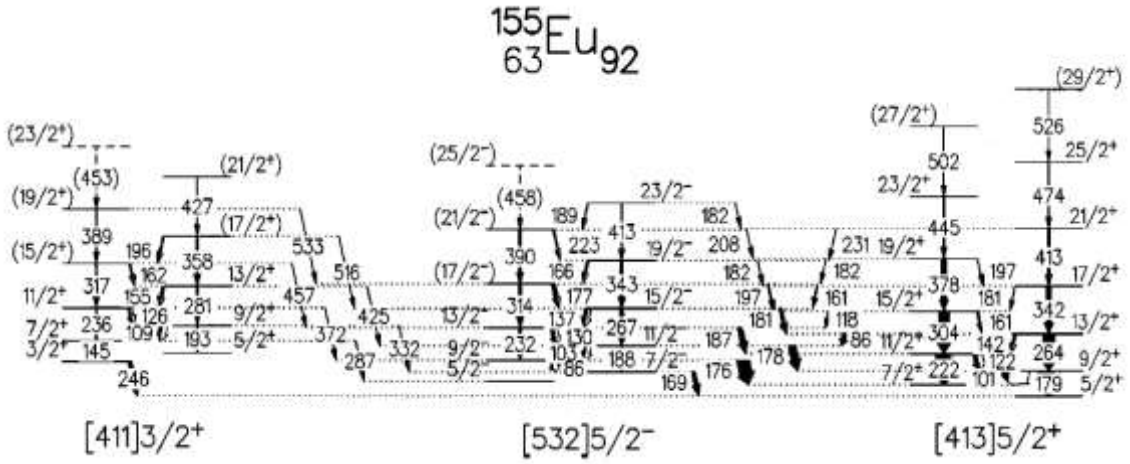
^{161}Pm N=100

Deformation for nuclei around Z ~ 62, N ~90

Reflection symmetric / asymmetric ?



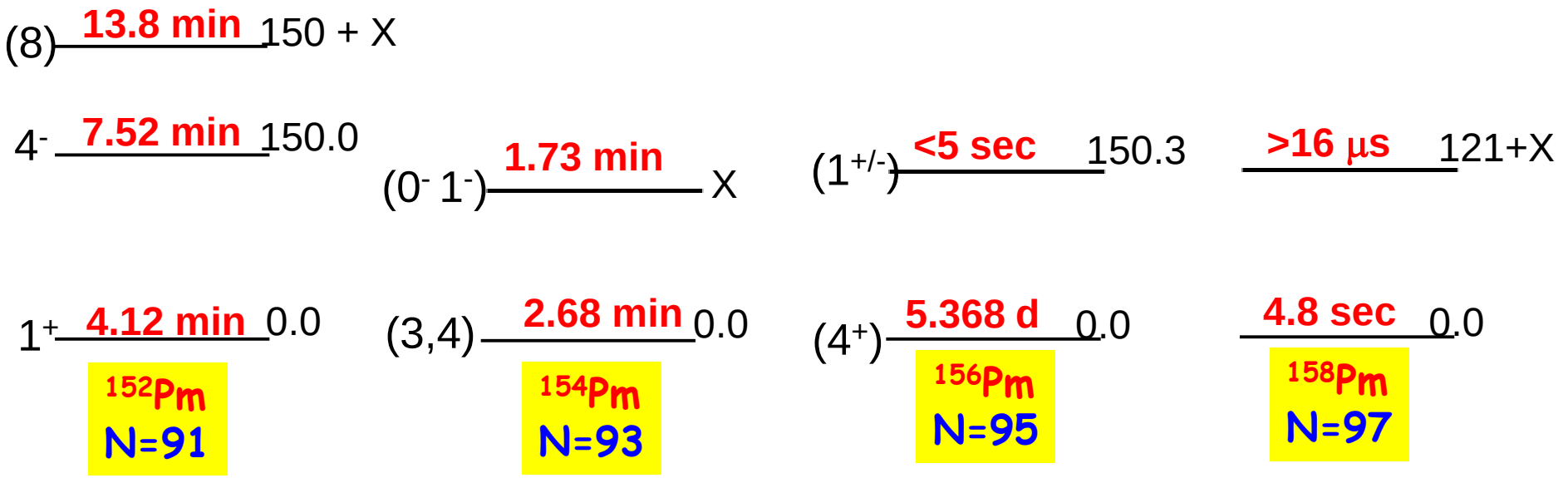
A. V. Afanasjev and I. Ragnarsson
PRC 51, 1259 (1995)



Large B(E1) strength in N=92 isotones could also be explained without considering static octupole deformation

Even-A Pm (Z=61) isotopes beyond N=90

- Long lived isomers reported from β-decay of Nd isotopes
- No excited / high spin states known so far above the isomers
- Identification / assignment of γ is the main issue
- γ–γ coincidence across the long lived isomer is not possible

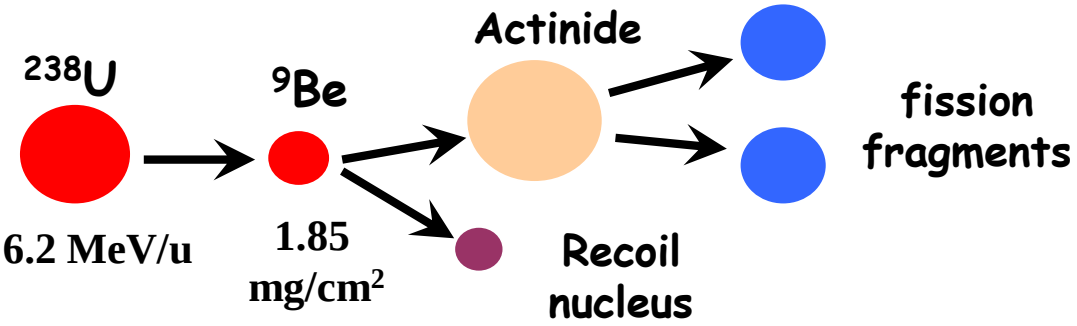


Prompt spectroscopy fission fragments
Data from two complimentary techniques

GANIL France

Direct identification (Z,A) of fission products
- at the focal plane of magnetic spectrometer : **VAMOS++**

Prompt gamma transitions in coincidence
- segmented Clover HPGe array : **EXOGAM**



Selectivity

High fold
High statistics

LBNL USA

High-fold γ coincidence of fission products
- spontaneous fission of ^{252}Cf : **GAMMASPHERE**

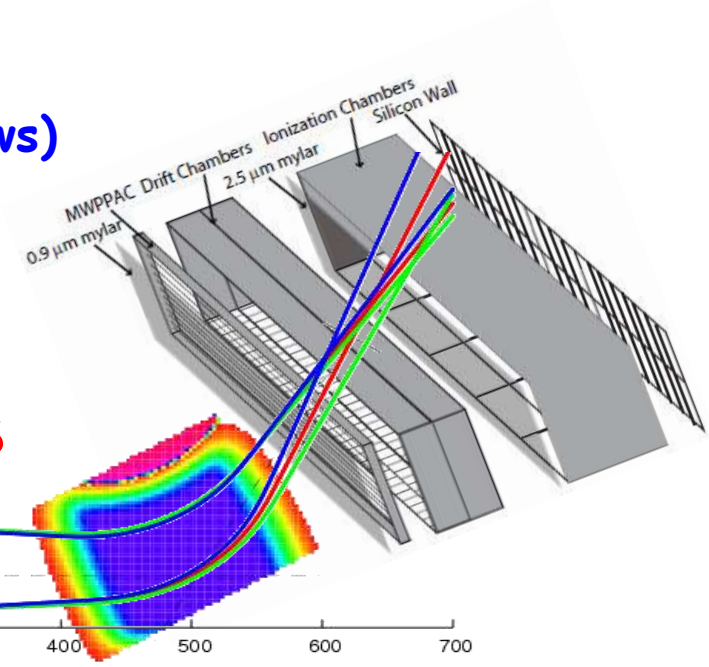
Prompt spectroscopy of (A,Z) identified fragments at GANIL

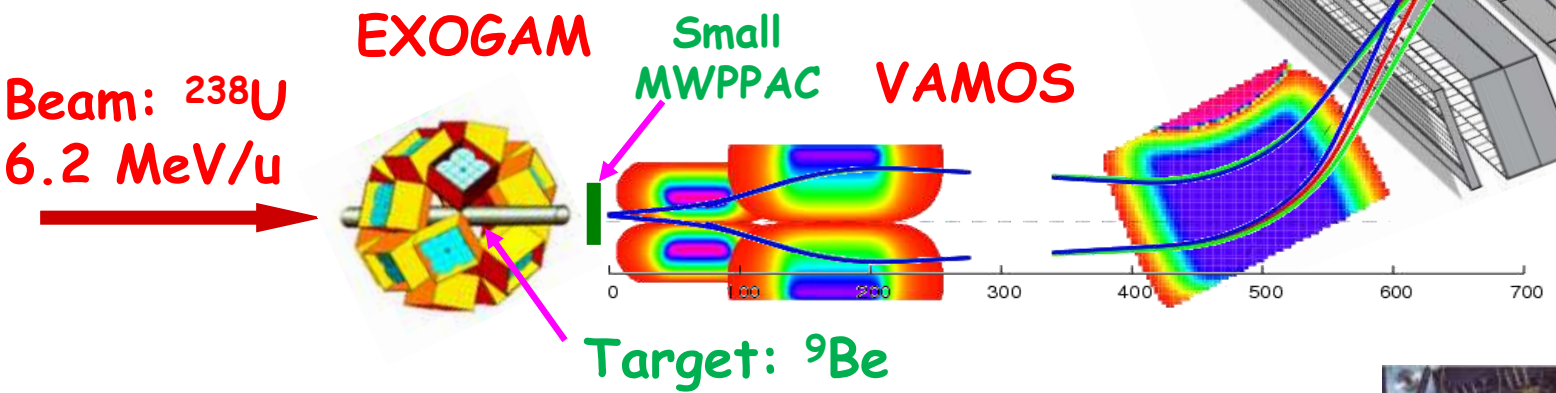
Large Acceptance Magnetic Spectrometer VAMOS++ @ 20°

Segmented Ge Clover Array EXOGAM @ around target

Focal Plane detector active area : 1000mm x 150mm

- MWPPAC (20 seg cathode)
- Drift Chamber (160 pads of cathode x 2 rows)
- Ionization Chamber (5 segments x 3 rows)
- Si Wall (20 x 2 rows)





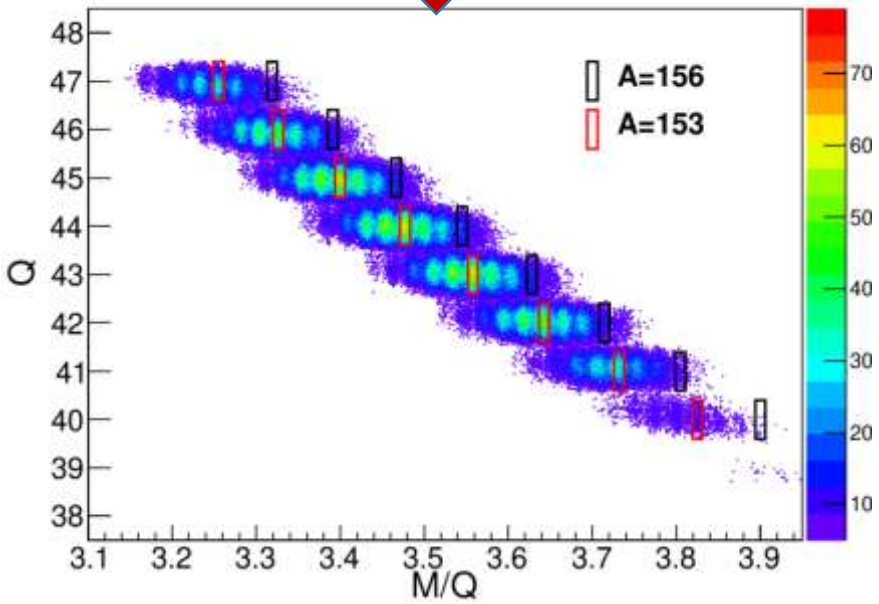
Doppler correction for the emitted γ -rays

→ Angle of the fragment and segment of the clover detector

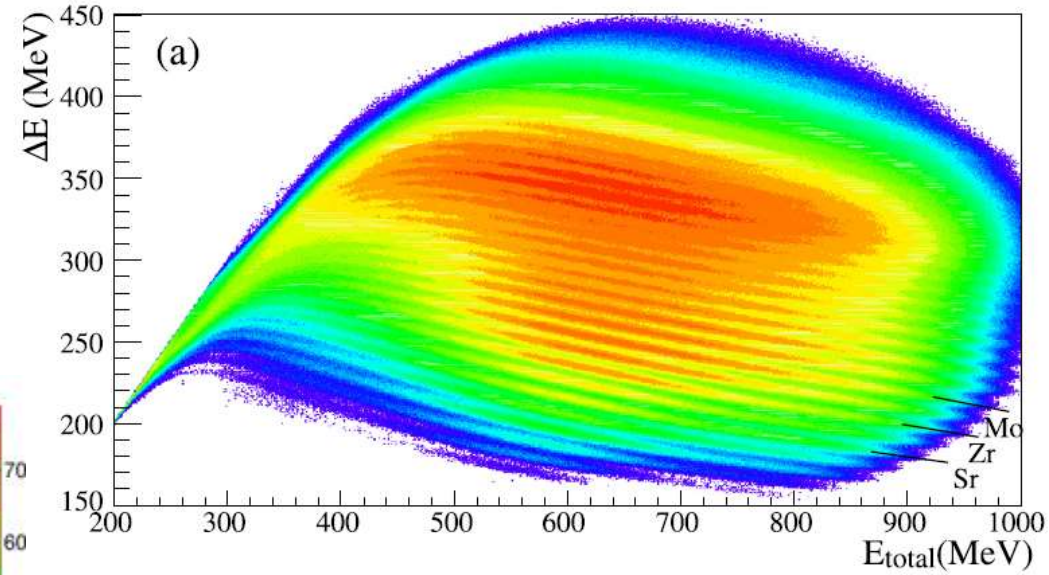
(A,Z) Identification of Fission Fragments

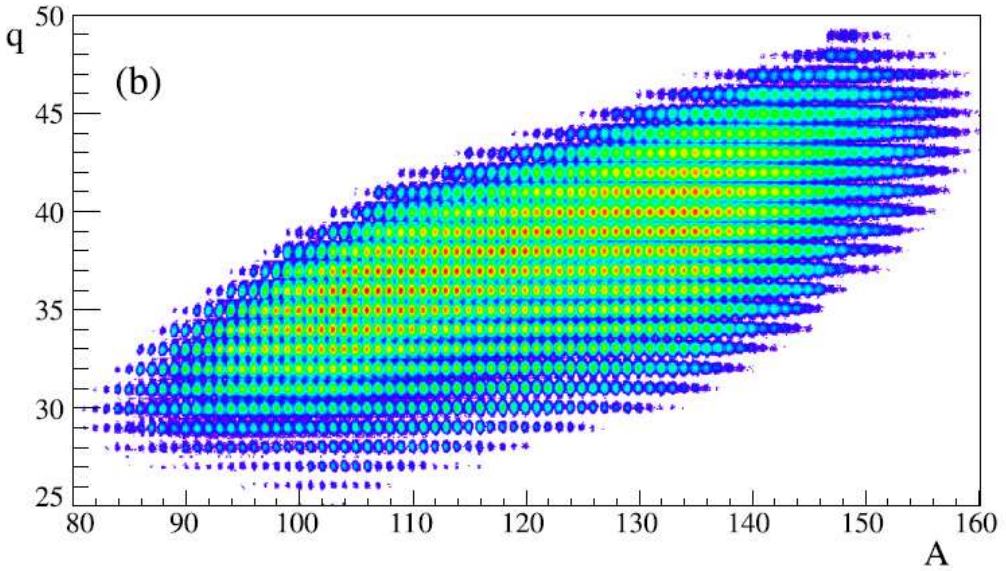
Uniquely identified M and Z

Selection of Pm (Z=61) isotopes at the focal plane of VAMOS++



S. Bhattacharyya, E. H. Wang, A. Navin et al., PRC 98, 044316 (2018)

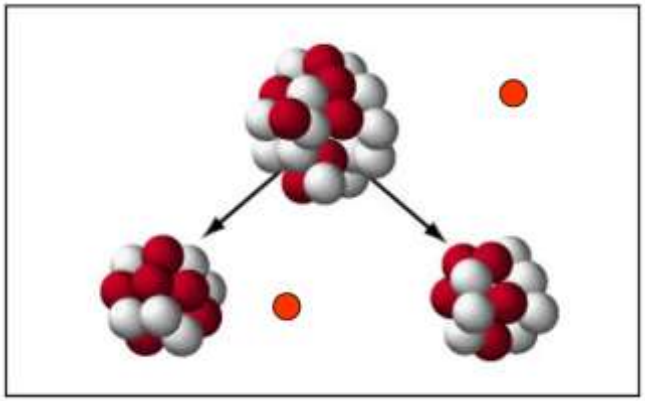




A.Navin and M.Rejmund, McGrow-Hill yearbook of science and Technology, p137 (2014)

Prompt spectroscopy of fission fragments using high fold γ coincidence at Gammashphere, uSA

Spontaneous fission of ^{252}Cf

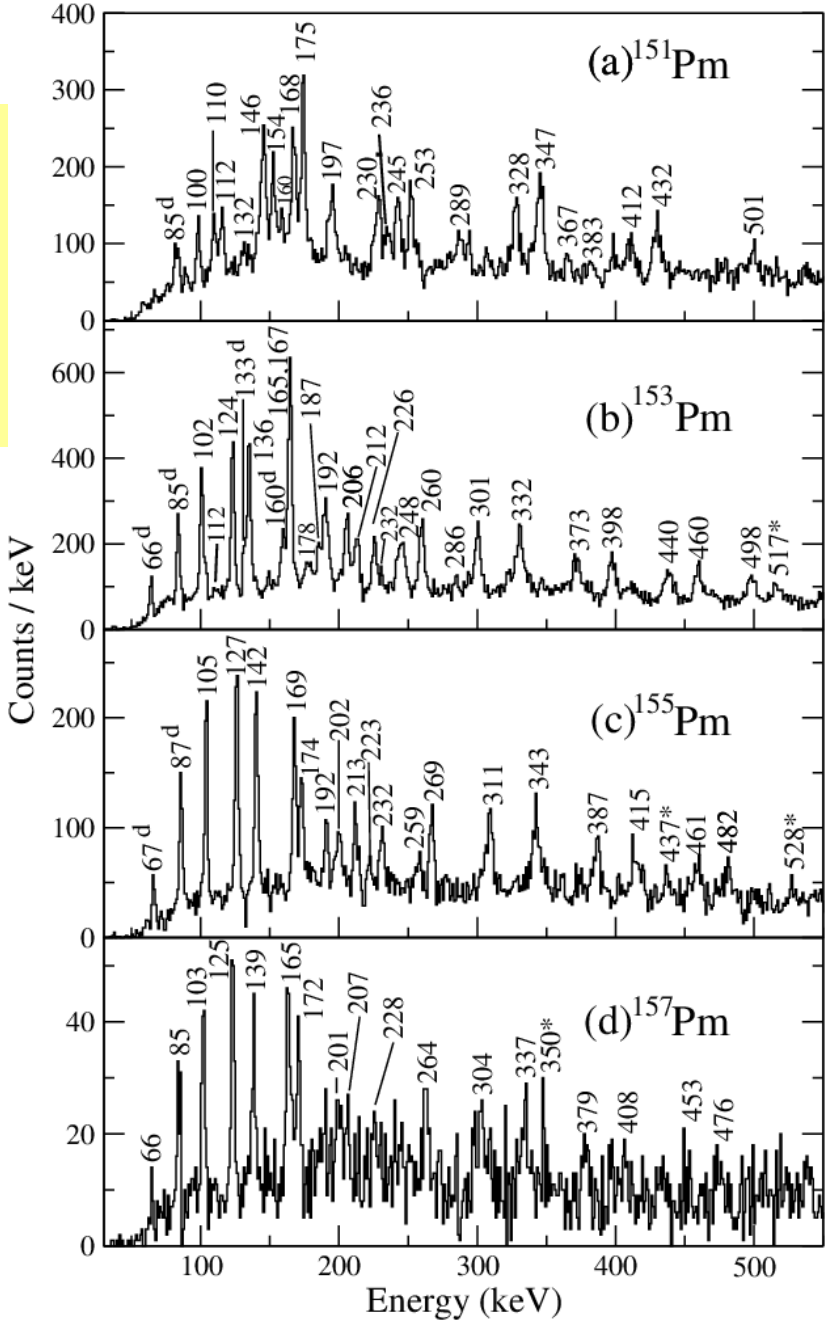


- ✓ High fold-γ coincidence
- ✓ No Doppler correction
- ✓ At least one known g-ray is needed for gating
- ✓ Cross coincidence with other partner
- ✓ Identification is difficult for extreme neutron-rich

J. H. Hamilton, A. V. Ramayya, E. H. Wang, J. K. Hwang, J. Ranger et al, Vanderbilt University, USA.

(A,Z) gated Doppler corrected singles γ spectra of odd-A Pm

Fragment - γ coincidences obtained from VAMOS++ & EXOGAM from ^{238}U + ^{9}Be-induced fission



N/Z=1.47
N=90

N/Z=1.51
N=92

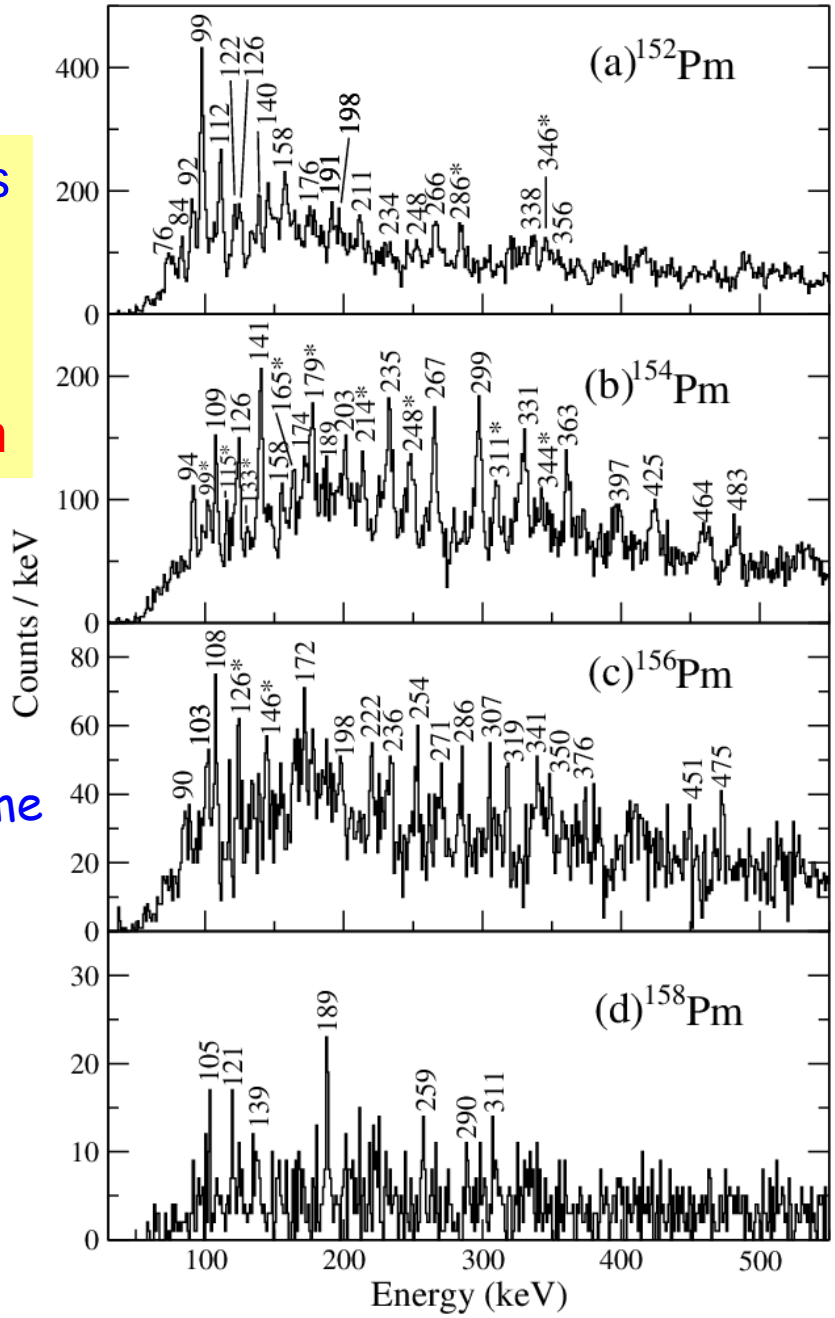
N/Z=1.54
N=94

N/Z=1.57
N=96

(A,Z) gated Doppler corrected singles γ spectra of even-A Pm

Fragment - γ coincidences obtained from VAMOS++ & EXOGAM from $^{238}U + ^{9}Be$-induced fission

All new transitions
Observed for the first time from the present work



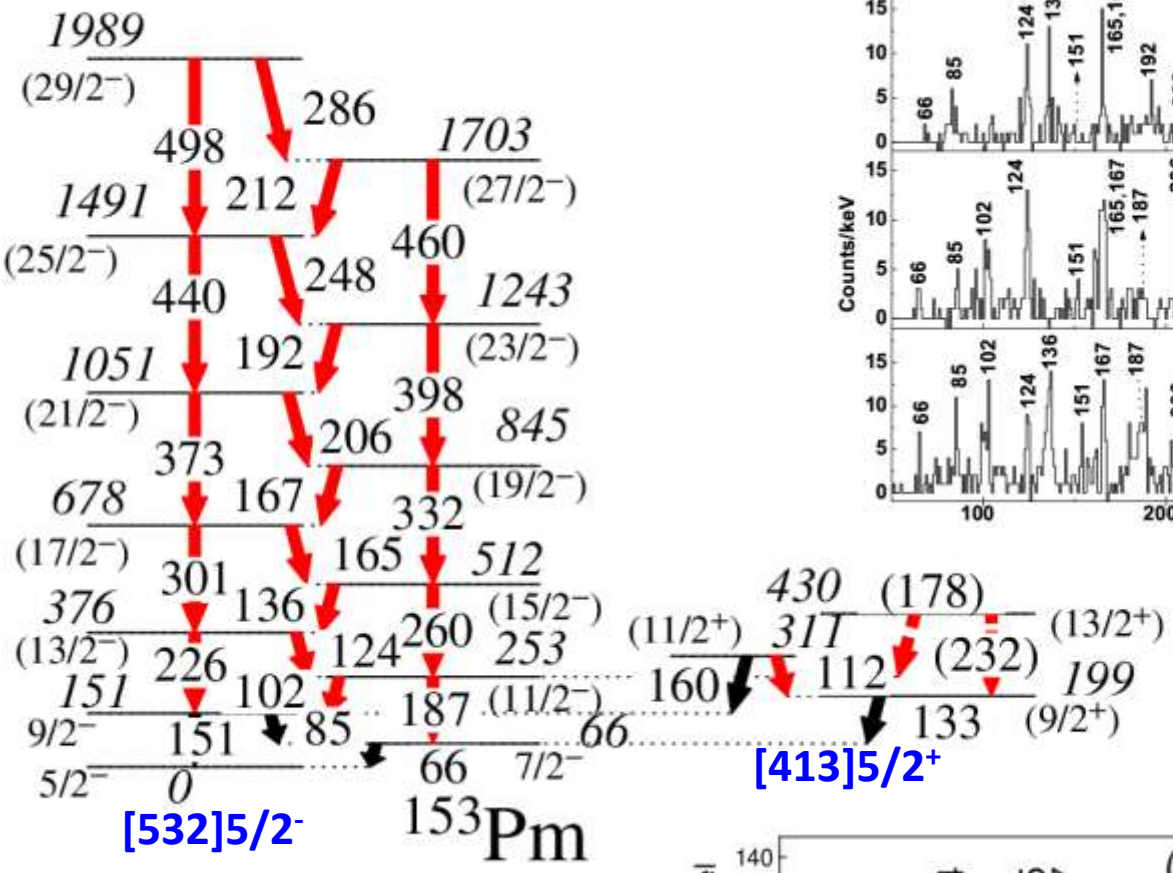
N/Z=1.49
N=91

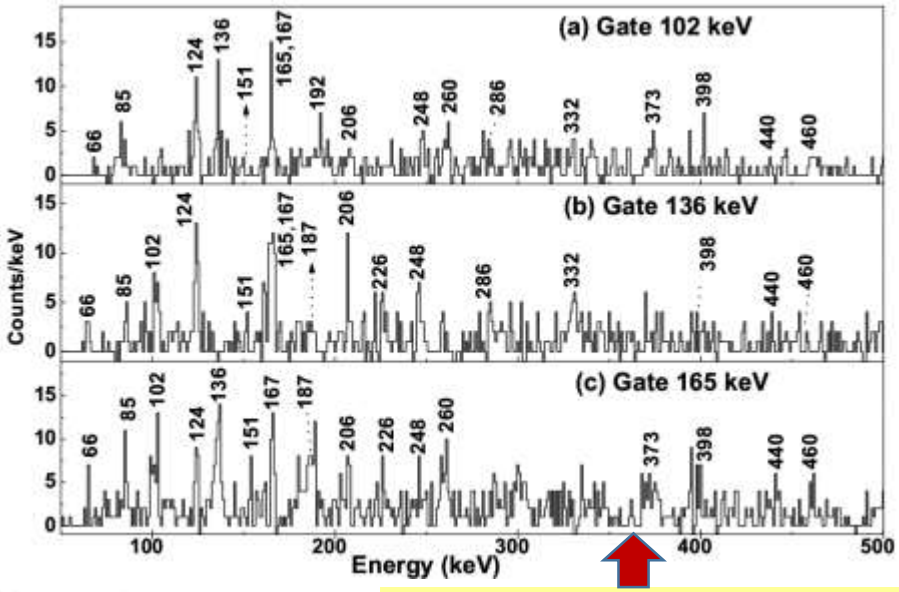
N/Z=1.52
N=93

N/Z=1.56
N=95

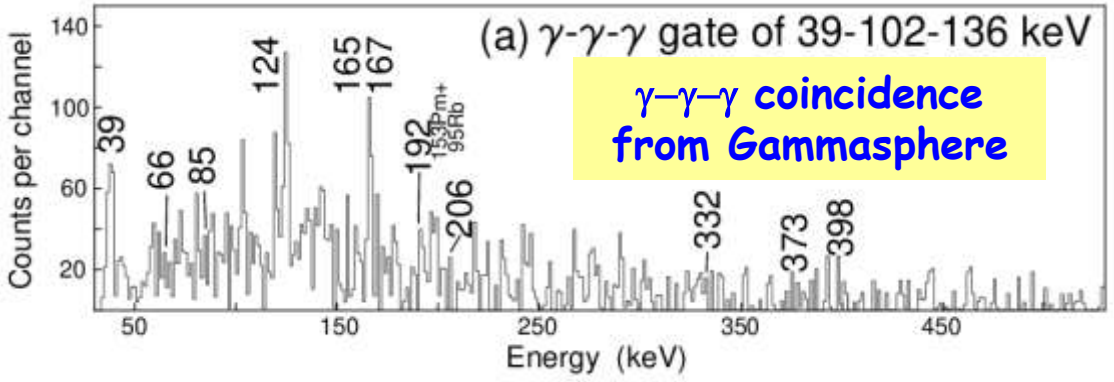
N/Z=1.59
N=97

^{153}Pm (N=92)



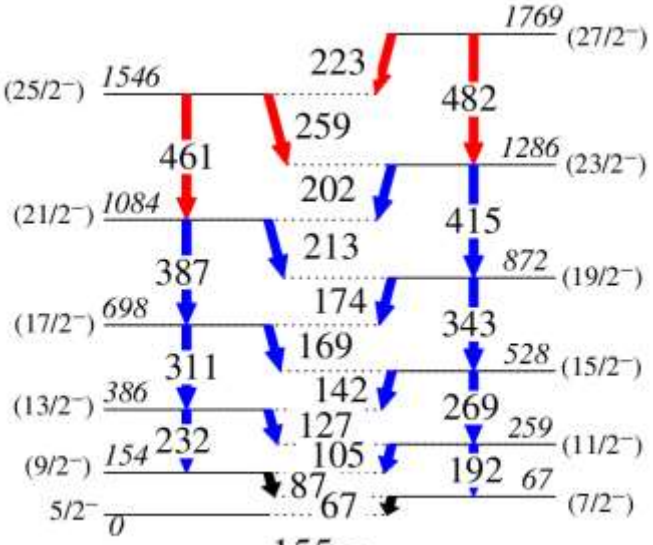


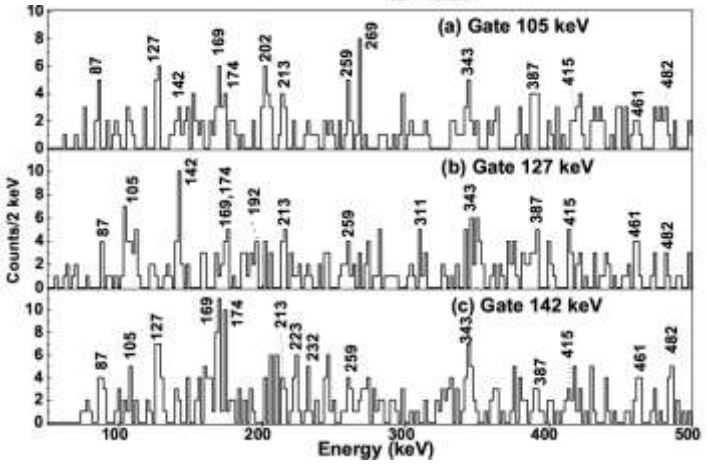
Fragment-γ–γ coincidence from EXOGAM+VAMOS



γ–γ–γ coincidence from Gammasphere

^{155}Pm (N=93)

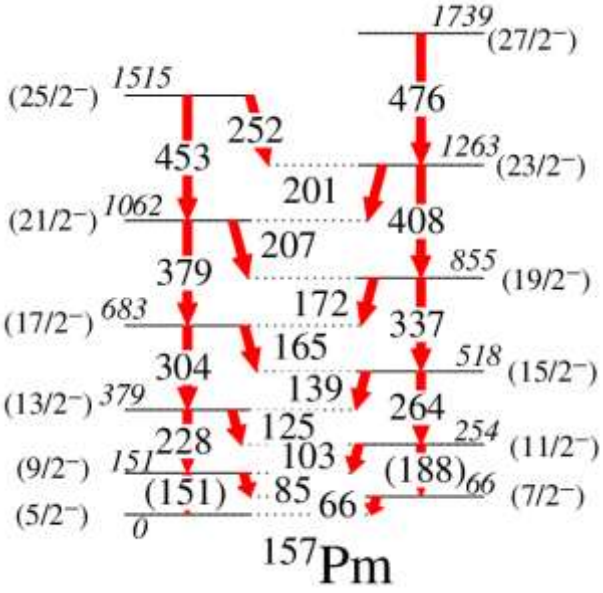


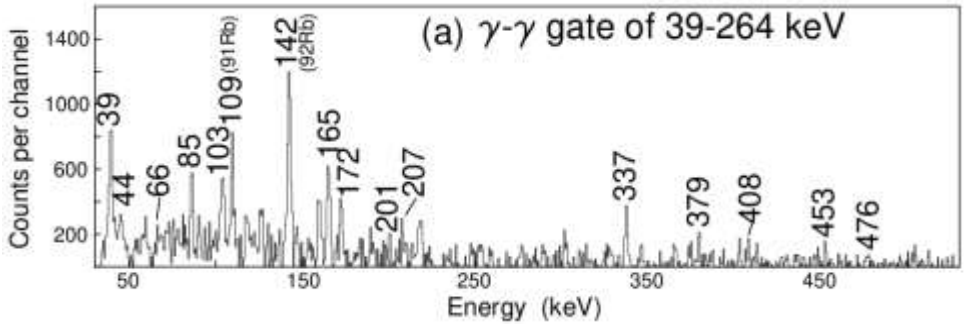


Fragment-γ–γ coincidence from EXOGAM+VAMOS

^{157}Pm (N=95)

Identified for the first time



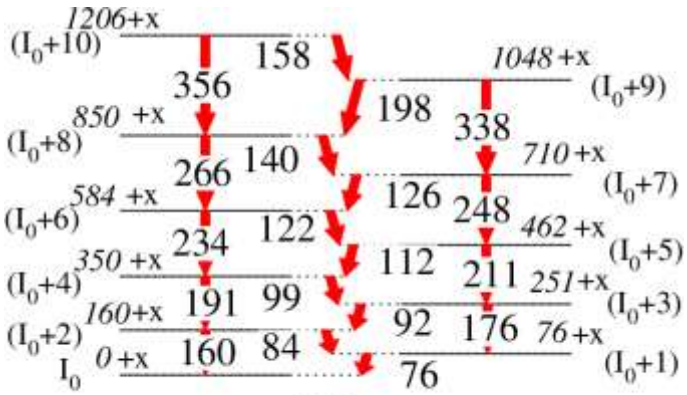


γ–γ coincidence from Gammasphere

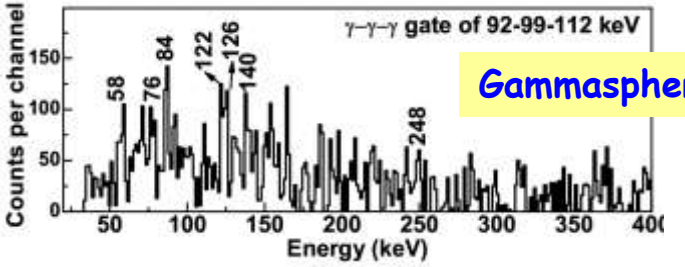
^{152}Pm (N=91)

^{154}Pm (N=93)

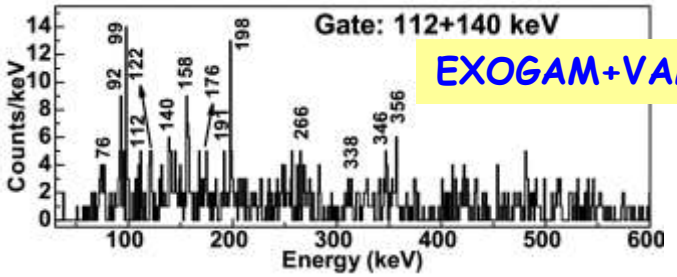
All transitions are identified from the present work for the first time



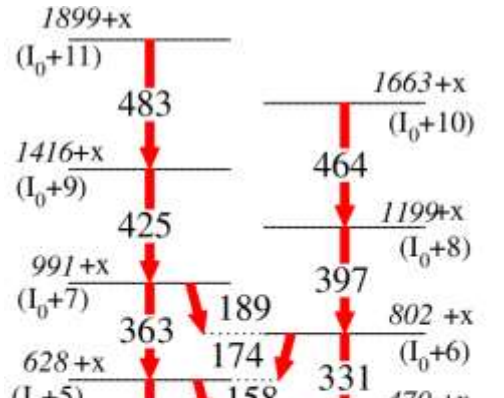
^{152}Pm



Gammasphere

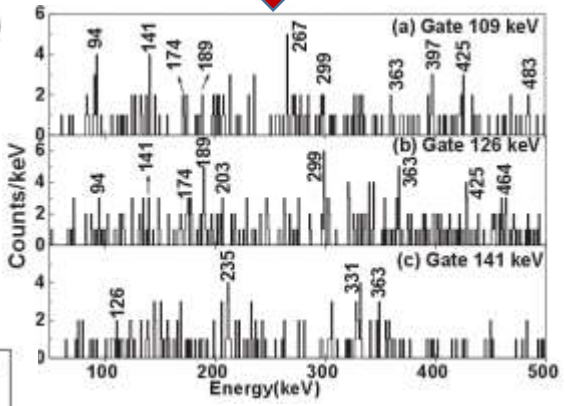


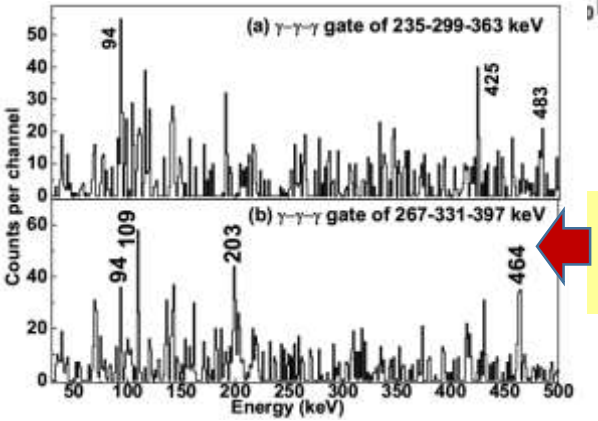
EXOGAM+VAMOS



^{154}Pm

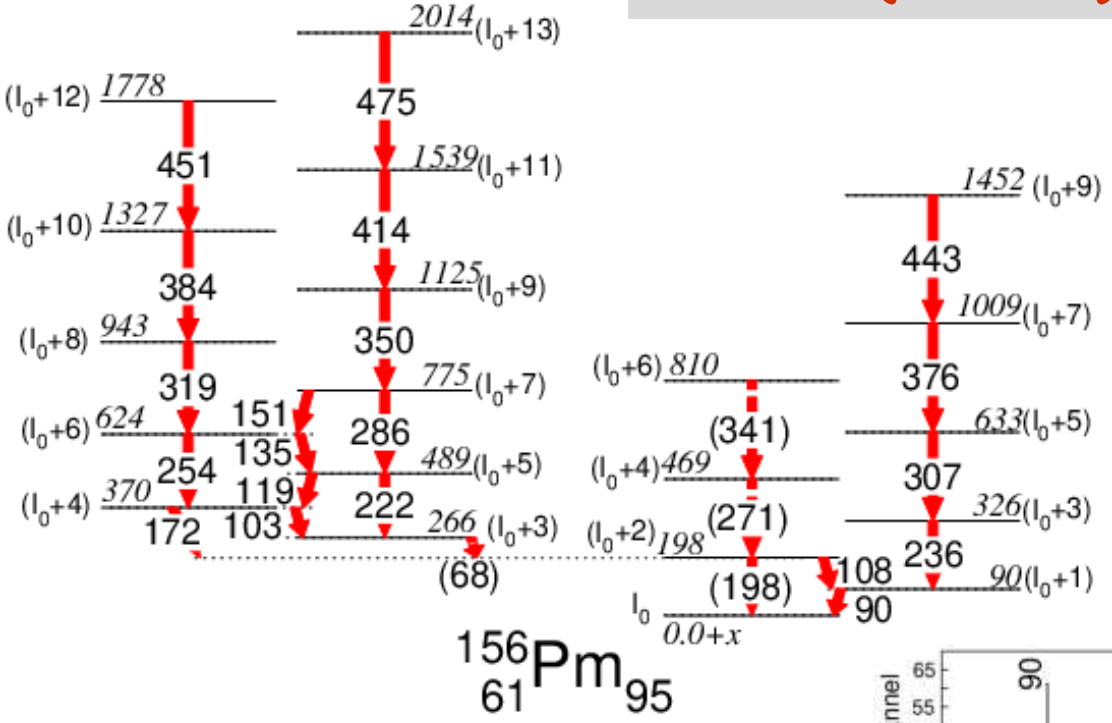
Fragment-γ–γ coincidence from EXOGAM+VAMOS





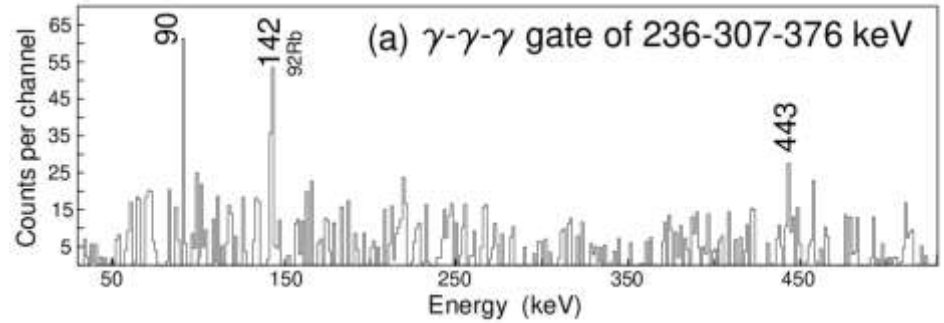
γ–γ–γ coincidence from Gammasphere

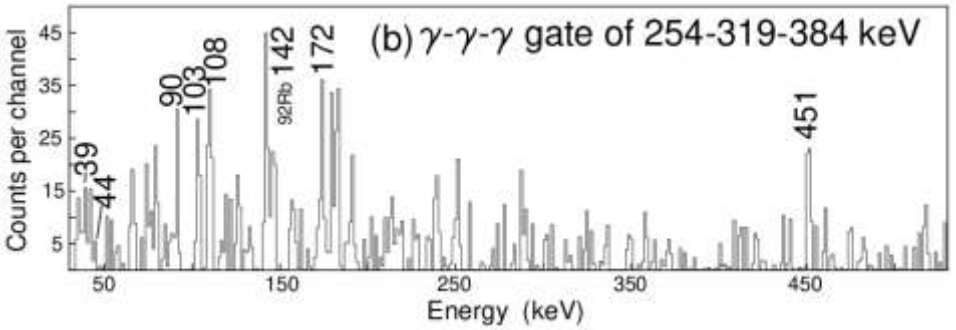
^{156}Pm (N=95)



No coincidence possible from (A,Z) gated data

γ–γ–γ coincidence information from ^{252}Cf fission with Gammasphere



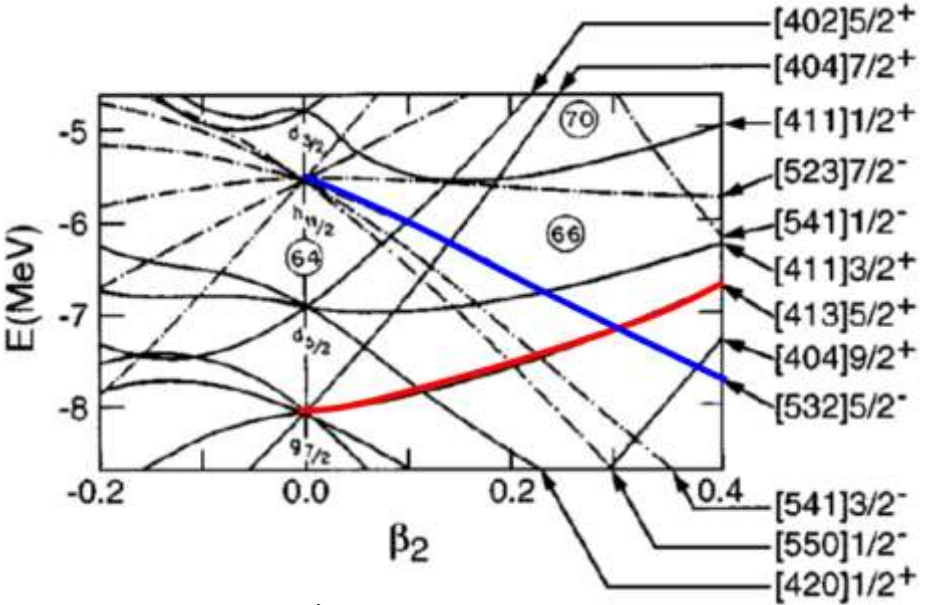


Possibility of octupole deformation in Pm isotopes

Pm isotopes →
located at the boundary of octupole deformed lanthanide region

Possible occurrence of reflection asymmetric shapes →

Proton: $d_{5/2}$ and $h_{11/2}$
Neutron: $f_{7/2}$ and $i_{13/2}$



For Z=60, boundary for octupole correlations → N=88 / 90

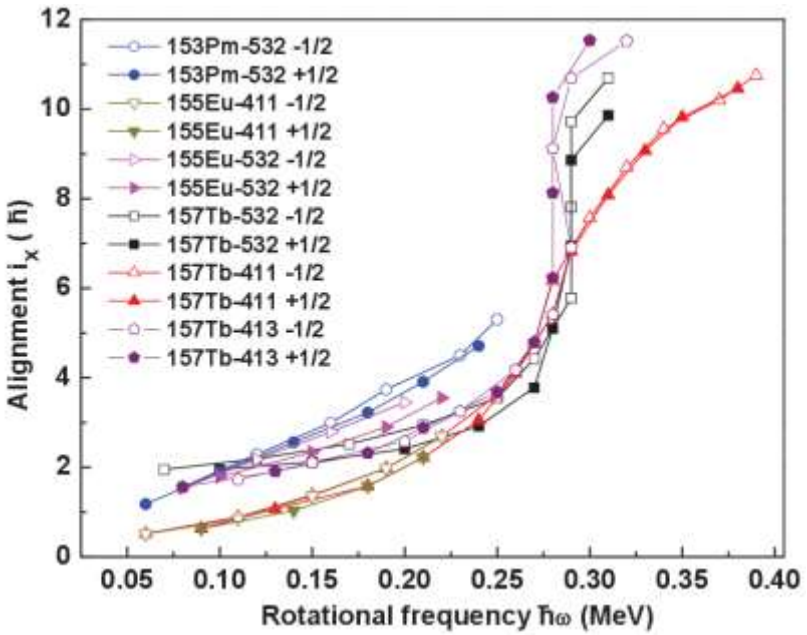
A. V. Afanasjev, J. Phys. G: Nucl. Part. Phys 19, L143 (1993).

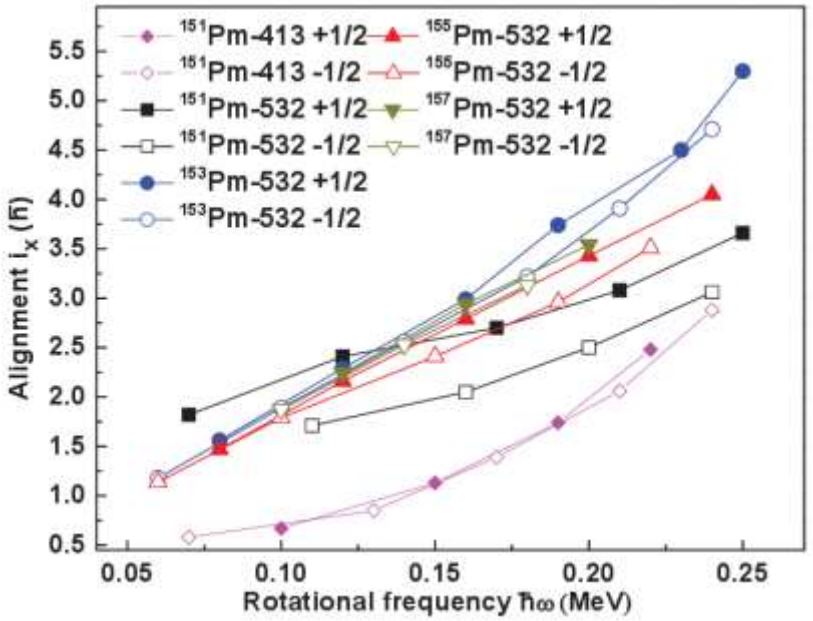
For odd-A and odd-odd nuclei :
Two factors which can stabilize octupole deformation
→ polarization effects of unpaired particles in specific Nilsson orbitals and rotation

^{153}Pm: yrast ground-state band: K = 5/2− (5/2−[532])
→ deformation driving $\pi h_{11/2}$ orbital.

^{151}Pm: yrast ground band is 5/2+ based on 5/2+[413]
K = 5/2− (5/2−[532]) is the non-yrast structure

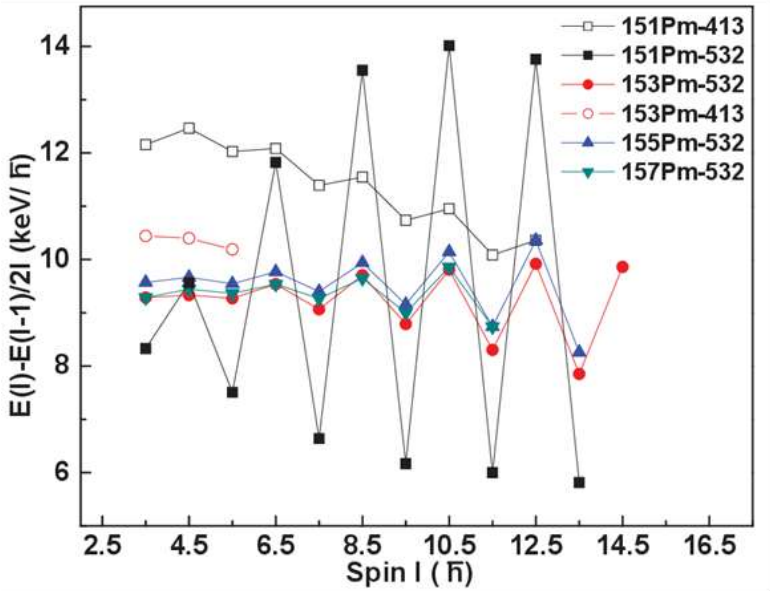
Rotational properties of odd-A Pm isotopes

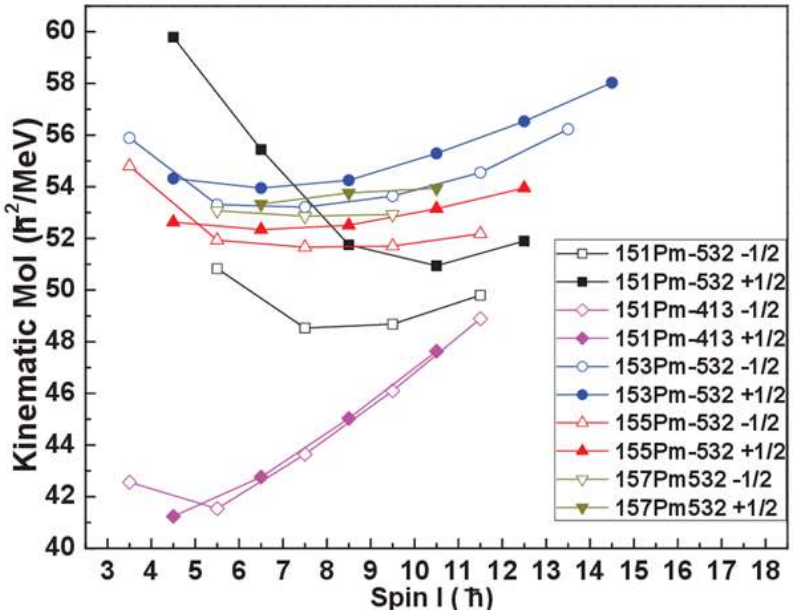




- Slopes of the alignments for the bands in ^{151}Pm (N = 90) are different compared to all other odd-A Pm isotopes with higher N/Z.
  - Nature of the bands in ^{151}Pm is different compared to higher N odd-A Pm
- Alignments of the bands in $^{155\text{-}157}$Pm are similar to the ground band in ^{153}Pm.
  - [532]5/2$^-$ configuration assignment to –ve parity band of $^{153\text{-}157}$Pm
- The higher alignment at higher frequency for $^{153\text{-}157}$Pm compared to ^{151}Pm
  - involvement of high-j $h_{11/2}$ orbital.

Rotational properties of odd-A Pm isotopes

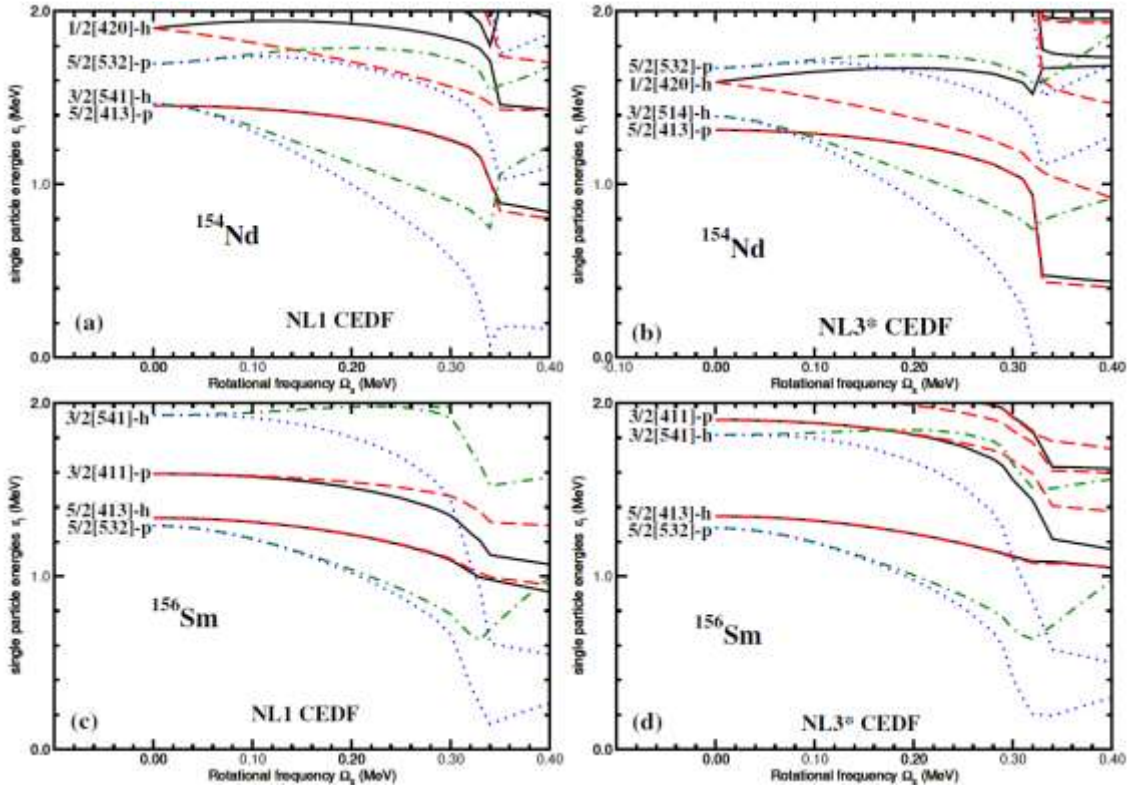




- Negative parity band in ^{151}Pm, corresponding to the [532]5/2$^-$orbital shows pronounced splitting compared to the positive parity band
- The odd-A Pm isotopes with higher N/Z show increasing signature splitting at higher spins.

The observed band structures of odd-A Pm isotopes do not show any indication of presence of octupole deformation beyond N = 90.

proton quasiparticle Routhian



Proton quasiparticle Routhian for even-even nuclei neighboring ^{155}Pm

Cranked Relativistic Hartree-Bogoliubov calculations employing two covariant energy density functionals : NL1 and NL3*

- by A. V. Afanasjev

The interaction of hole-type 3/2[514] and particle-type 5/2[532] orbitals leads to substantial signature splitting in Nd (Z=60).

With increasing Fermi surface (going to Sm, Z=62) coupling between the 3/2[541] and 5/2[532] negative parity orbitals is significantly reduced

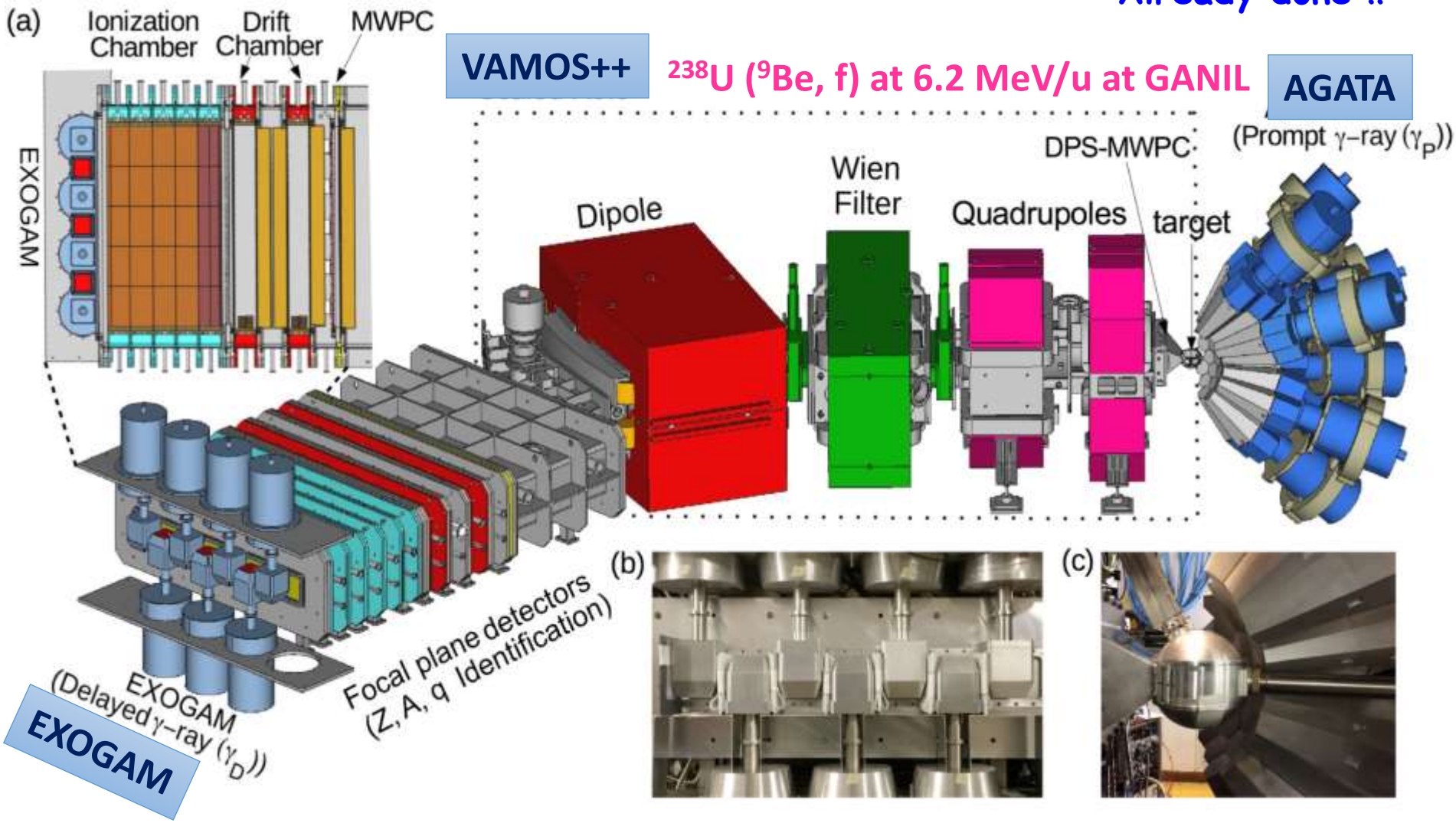
→ 5/2[532] orbital is signature degenerated at low frequencies but small signature degeneracy develops with increasing frequency.

Similar feature in experimental 5/2[532] bands of ^{153,155,157}Pm

Next step: AGATA - VAMOS++ - EXOGAM

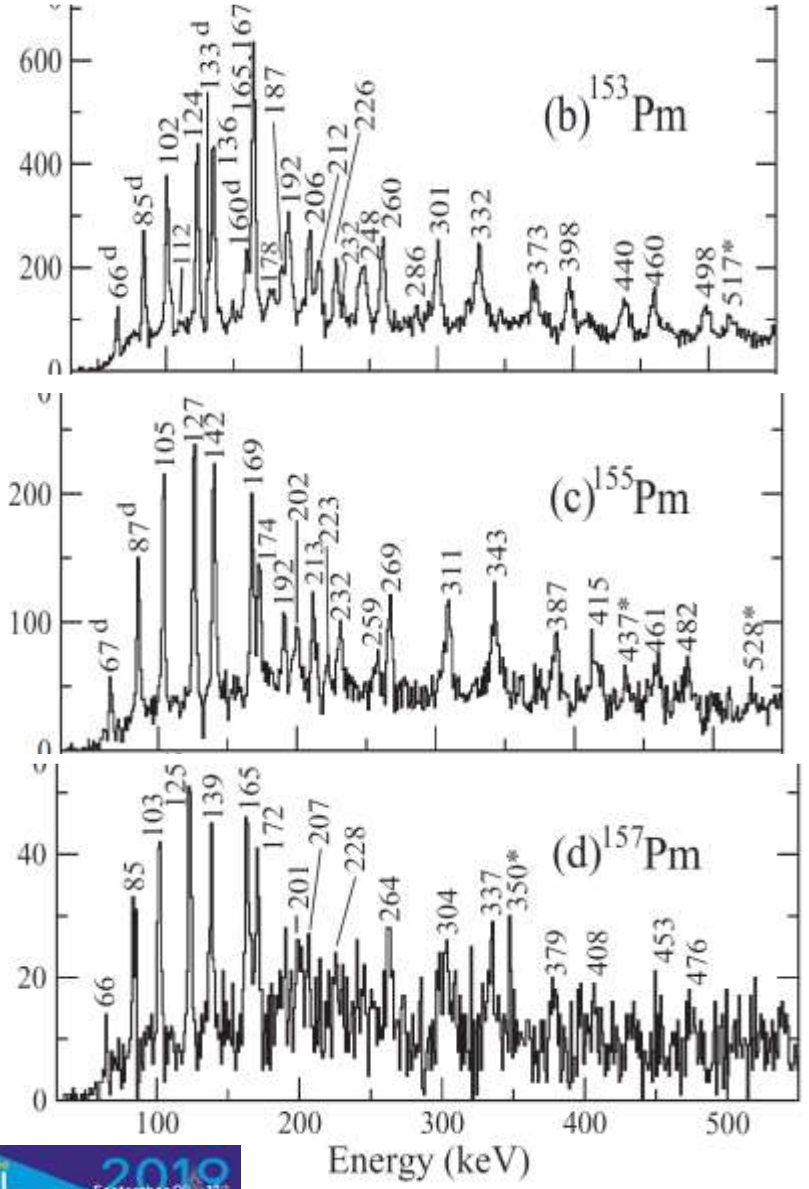
Prompt and delayed spectroscopy of fission fragments with (A,Z) identification

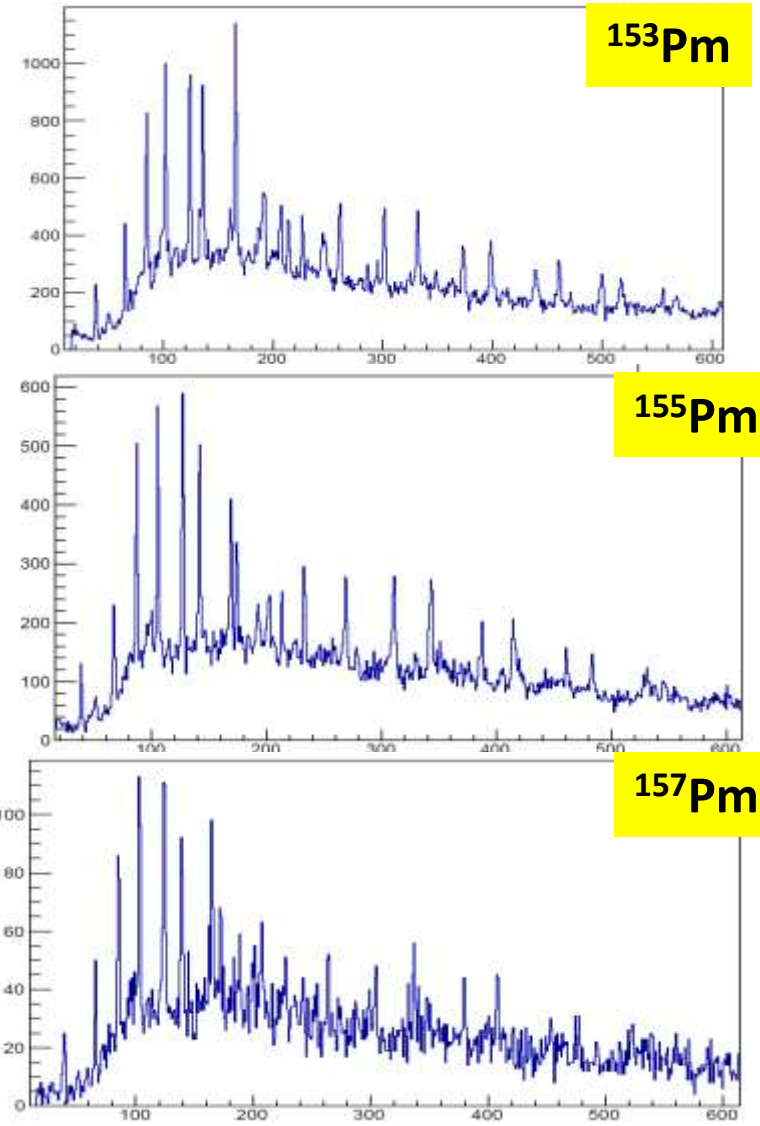
Already done !!



Y. H. Kim et.al, Eur. Phys. J. A, 53, 162 (2017)

High resolution data:
AGATA - VAMOS++ - EXOGAM





Summary

- ✓ Deformation in rare earth region beyond N=90
  - ✓ Possibility of octupole deformation
  - ✓ Alternating parity and parity doublet bands
- ✓ Neutron-rich Pm isotopes till N=97 (N/Z=1.59)
- ✓ Power of combining data from two complimentary techniques
  - ✓ In-beam prompt spectroscopy from fussion-fission ($^{238}U+^{9}Be$)
    - ✓ Direct (A,Z) identification → **Selectivity at high N/Z**
  - ✓ Spontaneous fission of ^{252}Cf
    - ✓ High-fold γ high statistics data → **Accessing high spins**
- ✓ Odd-A Pm → **Parity doublet band is not observed for N > 92**
- ✓ Odd—odd Pm → **First observation of band structures above isomers**
- ✓ New data from AGATA – EXOGAM - VAMOS++ campaign
  - ✓ prompt-prompt, prompt-delayed spectroscopy with (A,Z) identification

Collaboration

PHYSICAL REVIEW C **98**, 044316 (2018)

Deformed band structures in neutron-rich $^{152-158}$Pm isotopes

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Thank you