Spectroscopy of isotopically identified neutron-rich Pm isotopes

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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 $\gamma$ 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 $\gamma$-ray spectrum

• Channels of interest typically
  ~ a few to tens of mb $\times$-section

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Onset of deformation at $N \sim 88-90$ region

- $N=88-90$ 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

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

Systematics of $A \sim 150$ region

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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** $\rightarrow$ **large intrinsic dipole moments**
Intruder orbitals of opposite parity and $\Delta J, \Delta L = 3$ close to the Fermi level

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

Probable regions to show octupole effects
Spectroscopic fingerprints of Octupole deformation

Actinide region: \( N \approx 132, Z \approx 88 \)

Rare earth region: \( N \approx 88, Z \approx 56 \)

\( ^{150}\text{Ce} \)
\( N=92 \)

\( ^{142}\text{Ba} \)
\( N=86 \)

\( ^{144}\text{Ba} \)
\( N=88 \)

\( ^{146}\text{Ba} \)
\( N=90 \)

\( ^{222}\text{Th} \)
\( N=132 \)

\( ^{220}\text{Ra} \)
\( N=132 \)

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

J. F. Smith et al.,
PRL 75, 1050 (1995)

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

S. Bhattacharyya
Colloque GANIL, 9-13 September 2019.
Odd-A Pm (Z=61) isotopes beyond N=82

$^{143}\text{Pm}$  
N=82

$^{147}\text{Pm}$  
N=86

$^{145}\text{Pm}$  
N=84

$^{149}\text{Pm}$  
N=88

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

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

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

M.A. Jones et al., NPA 609, 201 (1996)
Odd-\(A\) Pm (\(Z=61\)) isotopes beyond \(N=90\)

\[ ^{150}\text{Nd}(\alpha,p2n)^{151}\text{Pm} \]

\(N=90\)

Urban et al, PLB 247 (1990)

\[ ^{151}\text{Pm} \]

\(N=92\)

\[ ^{153}\text{Nd} \beta\text{-decay} \]


\[ ^{153}\text{Pm} \]

\[ ^{157}\text{Pm} \]

\(N=96\)


\[ ^{155}\text{Pm} \]

\(N=94\)

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

\[ ^{161}\text{Pm} \]

\(N=100\)

S. Bhattacharyya Colloque GANIL, 9-13 September 2019.
Deformation for nuclei around $Z \sim 62, N \sim 90$

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

S. Bhattacharyya  Colloque GANIL, 9-13 September 2019.
Even-$A$ Pm (Z=61) isotopes beyond N=90

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

\[
\begin{align*}
13.8 \text{ min} & \quad 150 + X \\
7.52 \text{ min} & \quad 150.0 \\
1.73 \text{ min} & \quad X \\
<5 \text{ sec} & \quad 150.3 \\
>16 \mu\text{s} & \quad 121+X \\
4.12 \text{ min} & \quad 0.0 \\
2.68 \text{ min} & \quad 0.0 \\
5.368 \text{ d} & \quad 0.0 \\
4.8 \text{ sec} & \quad 0.0 \\
152\text{Pm} & \quad N=91 \\
154\text{Pm} & \quad N=93 \\
156\text{Pm} & \quad N=95 \\
158\text{Pm} & \quad N=97
\end{align*}
\]
Prompt spectroscopy fission fragments
Data from two complimentary techniques

- **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

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

GANIL France

LBNL USA

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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)

Beam: $^{238}\text{U}$
6.2 MeV/u

Target: $^9\text{Be}$

Doppler correction for the emitted $\gamma$-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++


Prompt spectroscopy of fission fragments using high fold $\gamma$ coincidence at Gammashpere, USA

Spontaneous fission of $^{252}$Cf

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


S. Bhattacharyya Colloque GANIL, 9-13 September 2019.
Fragment - $\gamma$ coincidences obtained from VAMOS++ & EXOGAM from $^{238}\text{U} + ^9\text{Be}$-induced fission

(A,Z) gated Doppler corrected singles $\gamma$ spectra of odd-\(A\) Pm

- 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 $\gamma$ spectra of even-$A$ Pm

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

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

- $^{152}$Pm
  - N/Z=1.49
  - N=91

- $^{154}$Pm
  - N/Z=1.52
  - N=93

- $^{156}$Pm
  - N/Z=1.56
  - N=95

- $^{158}$Pm
  - N/Z=1.59
  - N=97
$^{153}\text{Pm (N=92)}$

Fragment-$\gamma$-$\gamma$ coincidence from EXOGAM+VAMOS

$[532]5/2^-$

$[413]5/2^+$

$\gamma$-$\gamma$-$\gamma$ coincidence from Gammasphere
Identified for the first time

Fragment-$\gamma$-$\gamma$ coincidence from EXOGAM+VAMOS

$^{155}$Pm ($N=93$)

$^{157}$Pm ($N=95$)

$\gamma$-$\gamma$ coincidence from Gammasphere
All transitions are identified from the present work for the first time.
$^{156}\text{Pm (N}=95\text{)}$

No coincidence possible from $(A,Z)$ gated data

$\gamma-\gamma-\gamma$ coincidence information from $^{252}\text{Cf}$ fission with Gammasphere
Possibility of octupole deformation in Pm isotopes

Pm isotopes \(\rightarrow\) located at the boundary of octupole deformed lanthanide region

Possible occurrence of reflection asymmetric shapes \(\rightarrow\)

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

For Z=60, boundary for octupole correlations \(\rightarrow\) N=88 / 90

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

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

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

A. V. Afanasjev, 

S. Bhattacharyya  
Colloque GANIL, 9-13 September 2019.
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 $^{155-157}$Pm are similar to the ground band in $^{153}$Pm.
  - $[532]5/2^-$ configuration assignment to -ve parity band of $^{153-157}$Pm.

- The higher alignment at higher frequency for $^{153-157}$Pm compared to $^{151}$Pm.
  - Involvement of high-j $h_{11/2}$ orbital.

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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 \(N = 90\).

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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

$\rightarrow$ $5/2^+[532]$ 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!!

$^{238}\text{U}$ ($^9\text{Be}, f$) at 6.2 MeV/u at GANIL

High resolution data: AGATA - VAMOS++ - EXOGAM

(b) $^{153}\text{Pm}$

(c) $^{155}\text{Pm}$

(d) $^{157}\text{Pm}$

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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

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


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Thank you.