Recent studies of heavy nuclei with Argonne Gas-Filled Analyzer

Amel Korichi

IJCLab CNRS and Argonne National Laboratory

on behalf of Gammasphere/AGFA collaboration

21st TASCA workshop

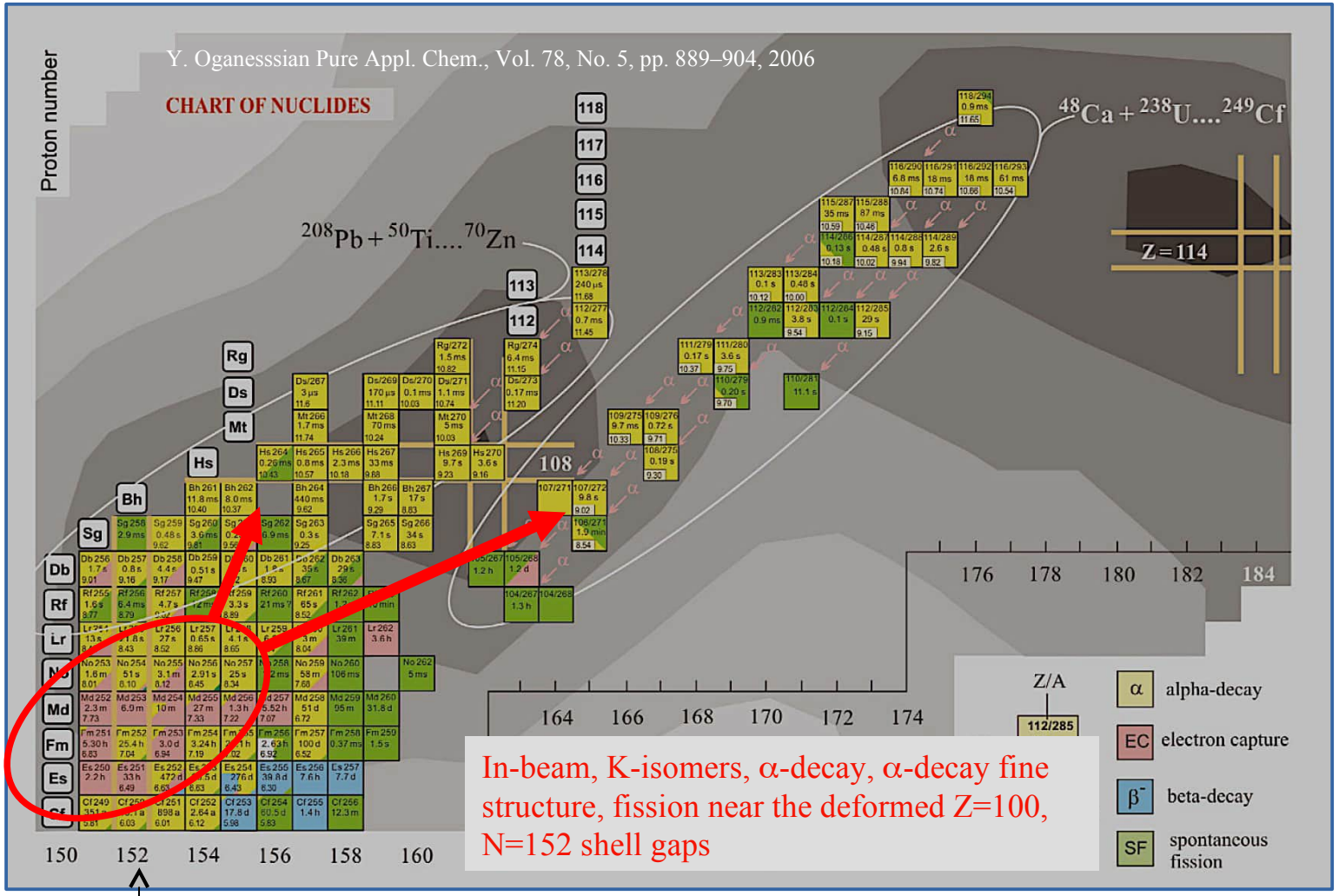
“Recoil Separator for Superheavy Element Chemistry & Physics”

GSI, April 23rd-24th, 2025

Outline

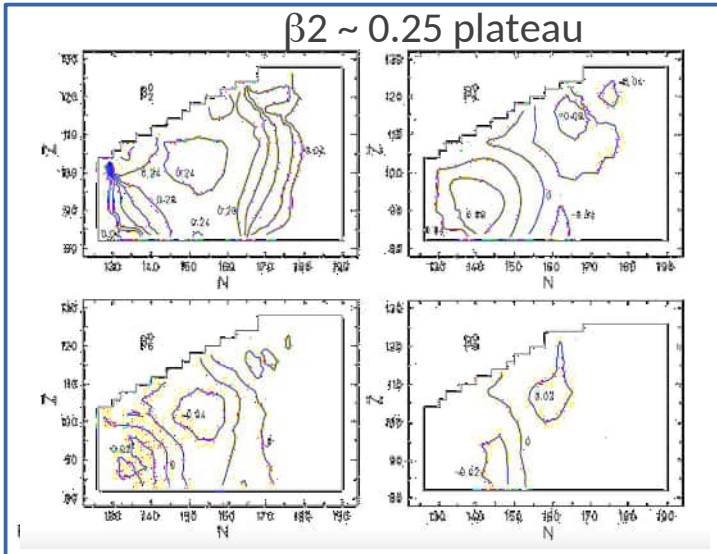
- Landscape of trans-fermium nuclei and their interest
- Experimental program with AGFA and AGFA/Gammasphere
- Selected recent results
  - ground-state rotational bands in fissile ^{254}**Rf** and ^{250}**No** nuclei
  - complete decay spectroscopy in ^{255}**No**
  - in-beam spectroscopy of odd-Z ^{255}**Lr** and ^{251}**Md** nuclei
- Summary and Outlook

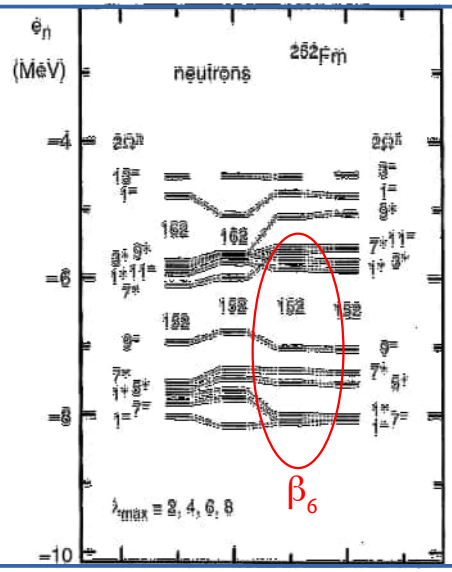
Spectroscopy of trans-fermium nuclei

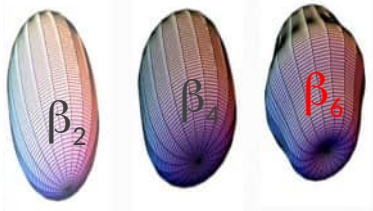


In nuclei with Z>~100, Coulomb repulsion is overcome by shell corrections

Deformation landscape near Z=100, N=152



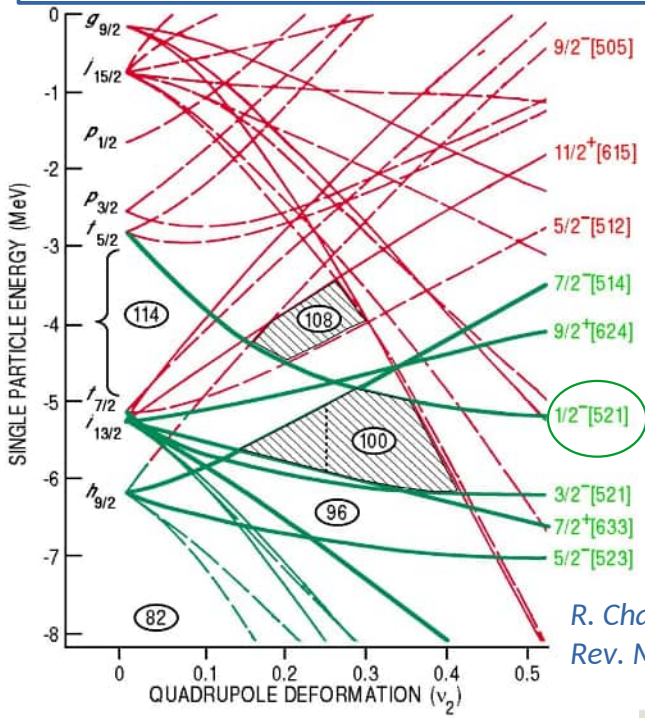




Higher order deformation plays an importtant role, in particular, β_6 opens the N=152 gap

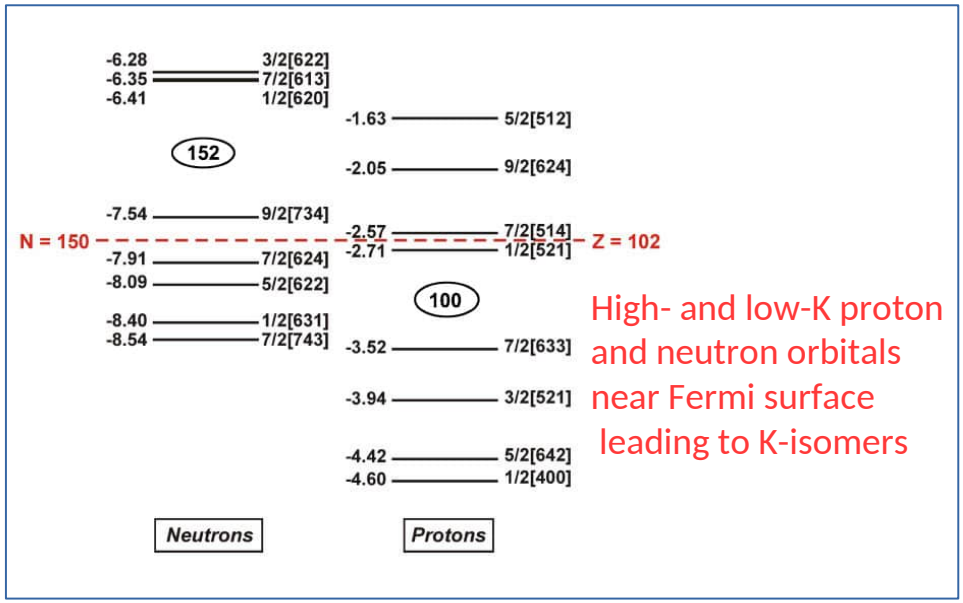
Mic-Mac calculations

A. Sobiczewski and K. Pomorski, Prog. in Part. and Nucl. Phys. 58 (2007) 292–349



proton orbital near Fermi surface at Z=114 gap

R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)



High- and low-K proton and neutron orbitals near Fermi surface leading to K-isomers

Octupole correlations in ^{252,254}No?

Y.S Chen et al, Phys. Rev. C 77, 061305R (2008)

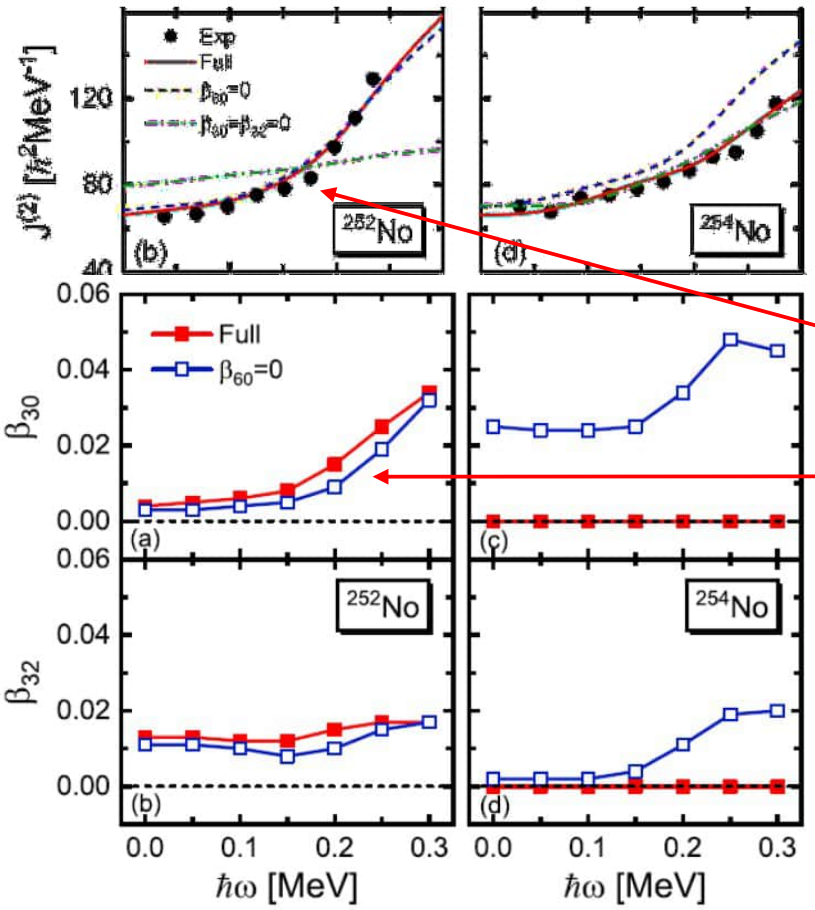
Reflection asymmetric shell model

Non axial-Octupole effect in superheay nuclei

N. Minkov and P.M Walker EPJ Web of Conf 107, 03008 (2016)

Deformed Shell Model +BCS

Octupole Deformations in High-K isomeric states of heavy and super heavy nuclei



F.F. Xu et al., Phys. Rev. Lett. 133, 022501 (2024)

Shell-model-like approach in the **cranking covariant density functional theory** on a 3D lattice

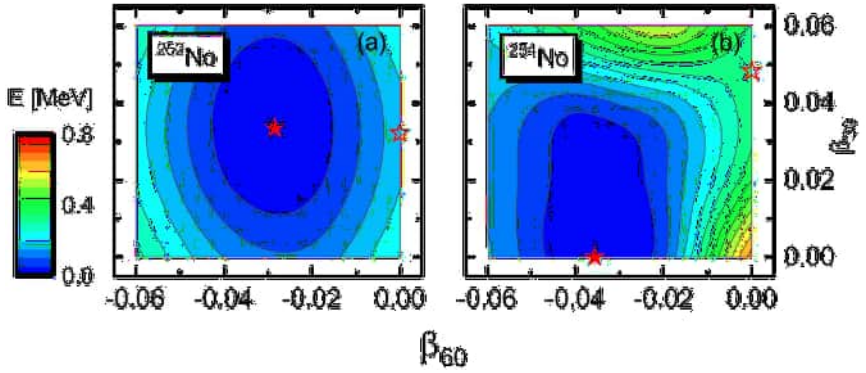
Emergence of High-Order Deformation in Rotating Transfermium Nuclei: A Microscopic understanding

Early unpending in ^{252}No at $\hbar\omega \approx 0.15$ MeV compared to ^{254}No

A sharp increase in ^{252}No at $\hbar\omega \approx 0.15$ MeV

Coupling of the octupole and β_{60}

A well defined minimum in ^{252}No



Recent AGFA and Gammasphere/AGFA campaigns
Fall 2022 - Spring 2024

^{255}Db 200 pb
Search for a new isotope

^{257}Db
Search for K-isomers

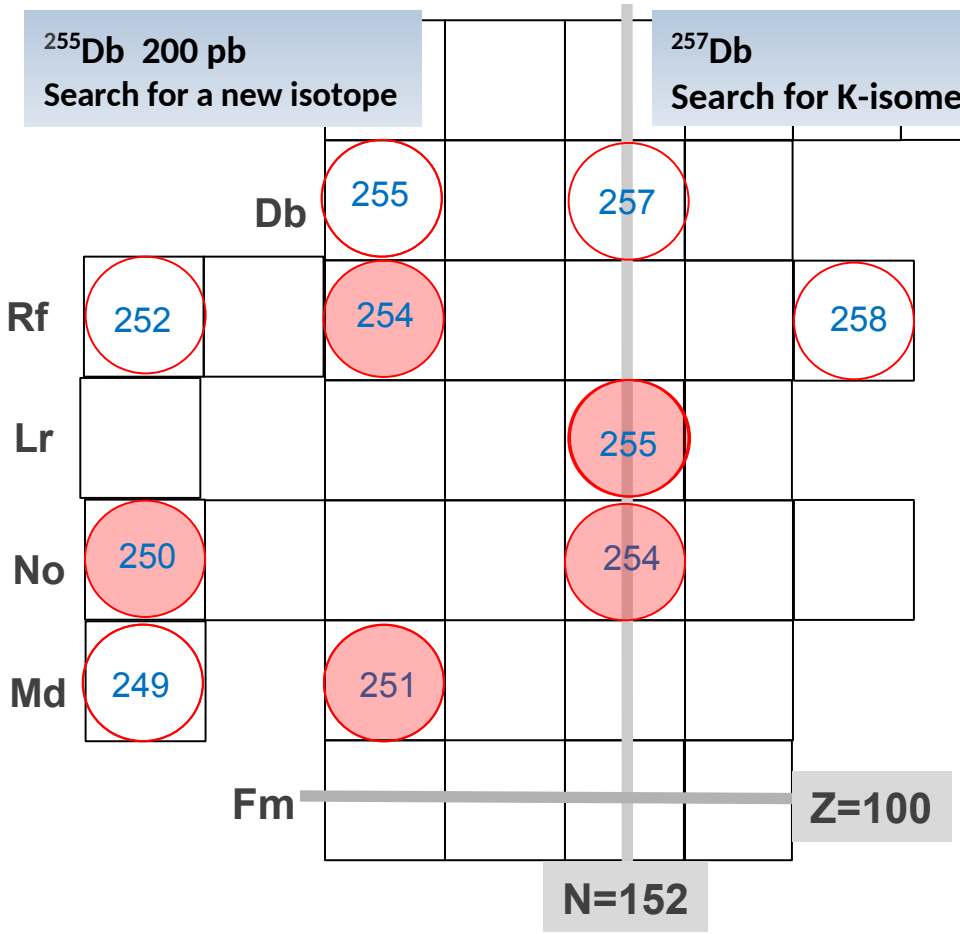
^{252}Rf 100 pb
Search for rapidly fissioning New isotope

^{254}Rf 2.6 nb
Ground state band

^{250}No 17 nb
Ground-state band

^{249}Md 300 nb
Odd-Z nucleus in-beam

^{251}Md 700 nb
Odd-Z nucleus in-beam



^{258}Rf
Search for K-isomers

^{255}Lr 200 nb
Odd-Z nucleus in-beam

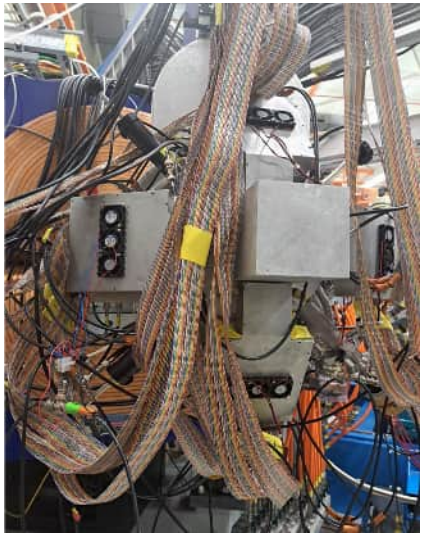
^{254}No 2 μb
Ge DSSD test

OTHER experiments:
^{136}Xe+^{238}U MNT
^{196,197}Fr – proton drip line

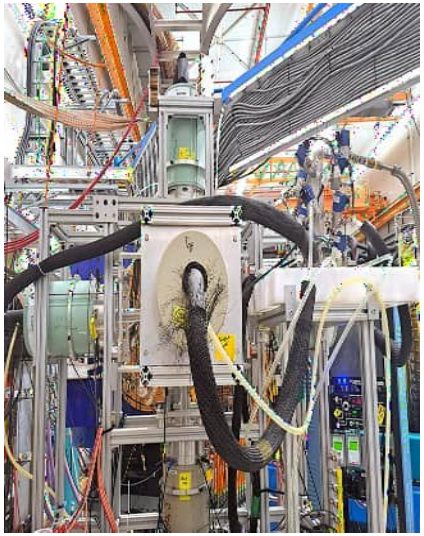
Searches for new isotopes, searches for new K-isomers, Decay and in-beam spectroscopy.
We are pushing towards fission limit, heavier elements and N>152.

Gammasphere+AGFA at ATLAS

up to 100 Ge+ BGO shields

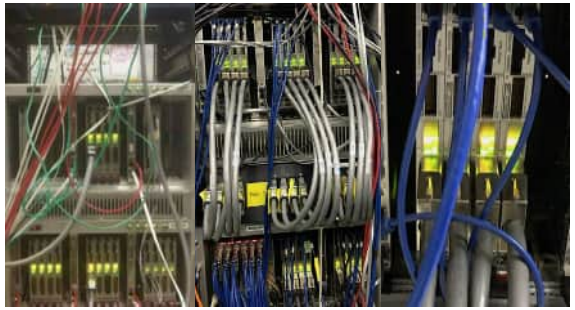


DSSD,Si tunnel, Si veto + PPAC



5 Clovers in box geometry

Target wheels



Digital DAQs (DGS, DGMA, DXA)

High-Granularity Fast Decay Spectroscopy
High Granularity & efficiency Fast in-beam Spectroscopy
Argonne Gas Filled Analyser & Fragment Mass Analyser

Moment of inertia of fissile ^{254}Rf Gammasphere+AGFA

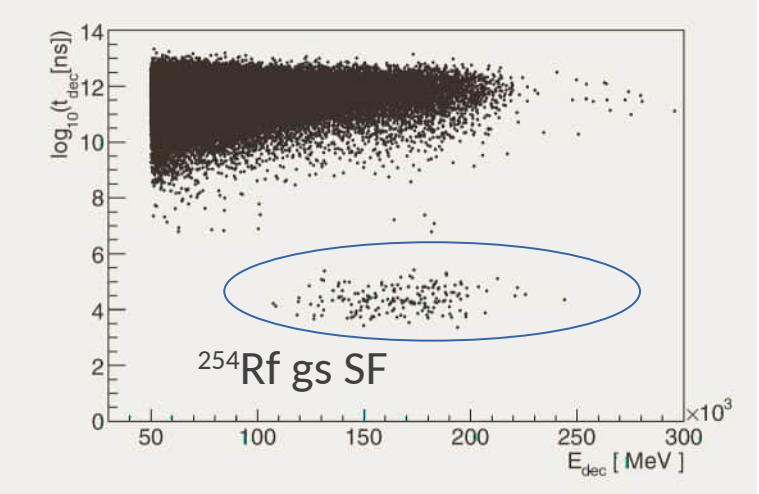
PHYSICAL REVIEW C 107, L061302 (2023)

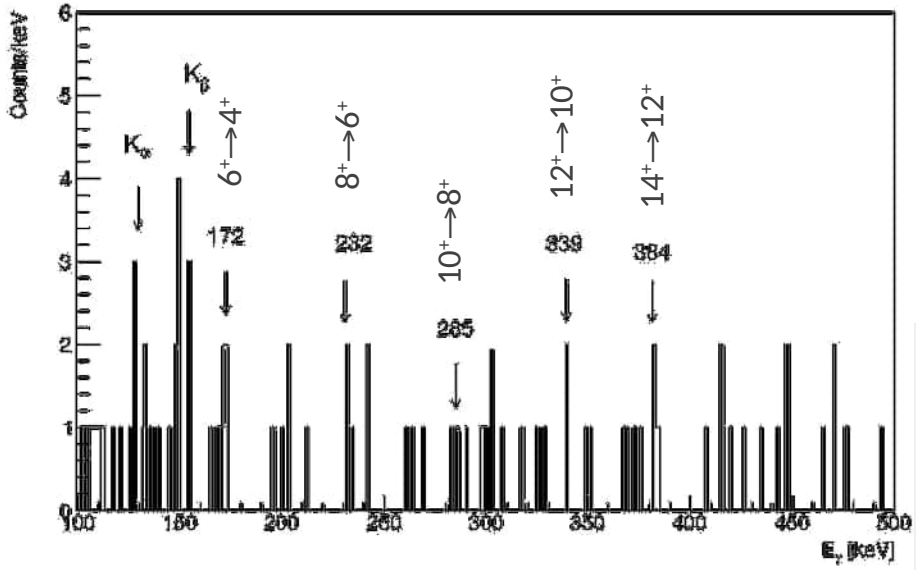
Letter

Nuclear rotation at the fission limit in ^{254}Rf

D. Seweryniak,[1,*] T. Huang,[1,2] K. Auranen,[1] A. D. Ayangeakaa,[3,4] B. B. Back,[1] M. P. Carpenter,[1] P. Chowdhury,[5] R. M. Clark,[6] P. A. Copp,[1] Z. Favier,[7] K. Hauschild,[8] X.-T. He,[9] T. L. Khoo,[1] F. G. Kondev,[1] A. Korichi,[8] T. Lauritsen,[1] J. Li,[1] C. Morse,[6] D. H. Potterveld,[7] G. Savard,[1] S. Stolze,[1] J. Wu,[1] J. Zhang,[10] and Y.-F. Xu[9]

^{50}Ti+^{206}Pb, ~20-25 pnA, σ~2.6 nb





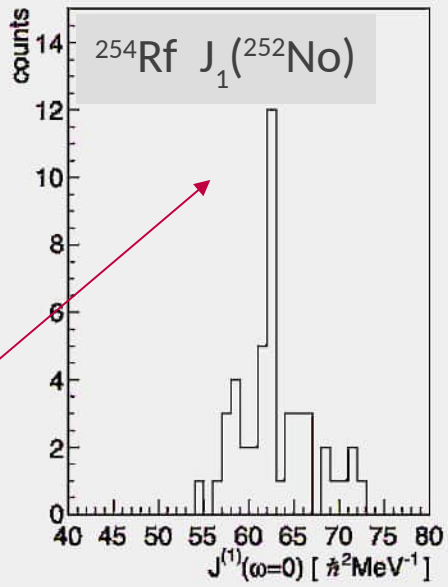
$$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2, \qquad \omega = E_\gamma(I)/2,$$

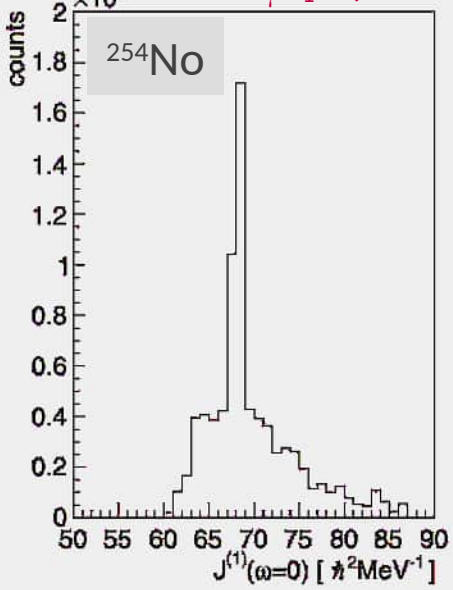
$$\mathcal{J}^{(1)} = (2I-1)/E_\gamma(I)$$

$$\mathcal{J}_0^{\exp}(i) = (2I(j)+1)/E_\gamma(i) - \mathcal{J}_1(E_\gamma(i)/2)^2,$$

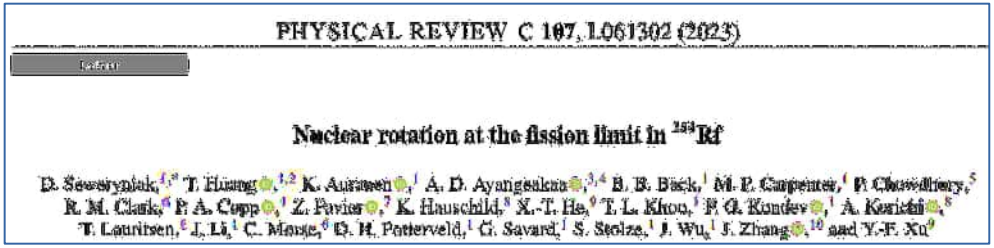
Experimental moment of inertia :
Calculated with J1 = 211.2 $\hbar^2$MeV^{-3} from the fit to the ^{252}No

Moment of inertia "spectrum" $\mathcal{J}^{(1)}=(2I-1)/E_\gamma-J_1(E\gamma/2)^2$



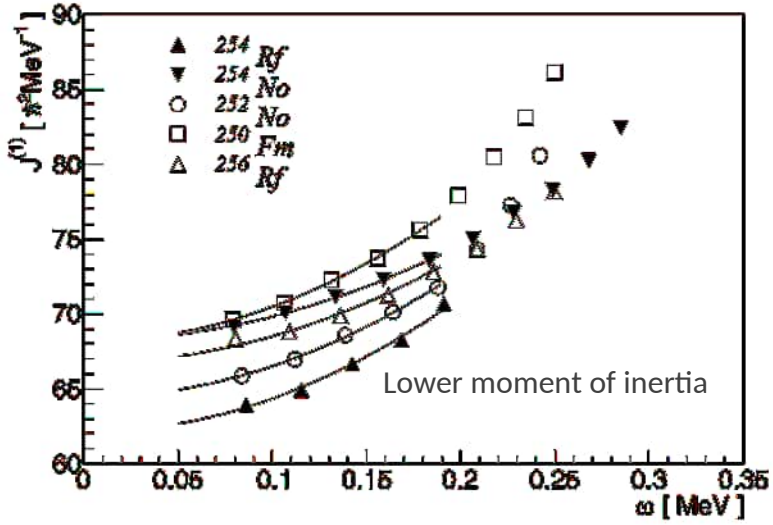


Moment of inertia of fissile ^{254}Rf


PHYSICAL REVIEW C 107, L061302 (2023)

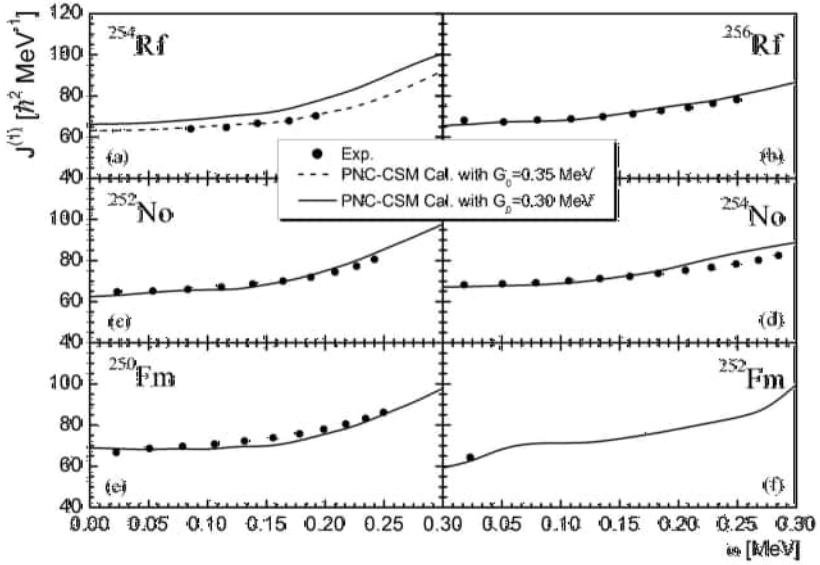
Nuclear rotation at the fission limit in ^{254}Rf

D. Seweryniak, T. Huang, K. Auranen, A. D. Ayangeakaa, B. B. Back, M. P. Carpenter, P. Chowdhury, R. M. Clark, P. A. Copp, Z. Favier, K. Hauschild, X.-T. He, T. L. Khoo, F. G. Kondev, A. Korichi, T. Lauritsen, J. Li, C. Müller, D. H. Potterveld, G. Savard, S. Stolze, J. Wu, F. Zhang, and Y.-F. Xu



Particle-Number-Conserved Cranked Shell Model

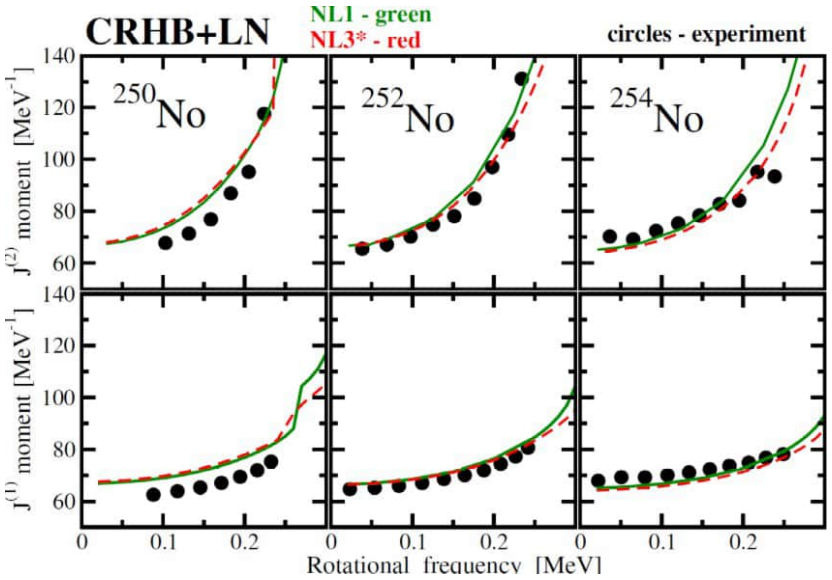
Z.-H. Zhang et al., Phys. Rev. C 87, 054308 (2013)



Good agreement between the calculations and the ^{254}Rf data obtained with higher pairing strength

Cranked relativistic HFB calculations

A. V. Afanasjev and O. Abdurazakov,
Phys. Rev. C 88, 014320 (2013) and Private com.



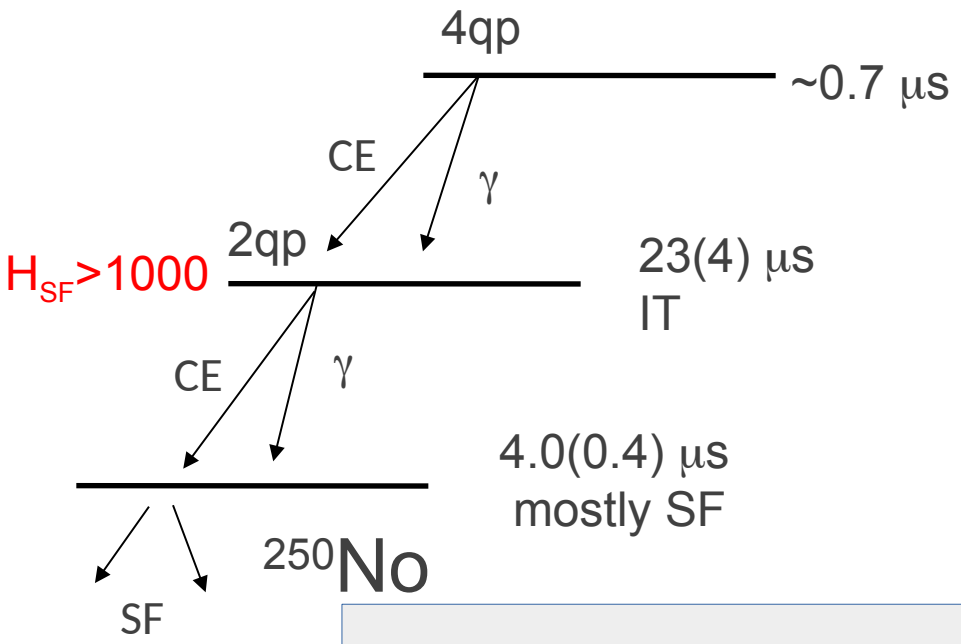
A search for a rotational band in ^{250}No should shed light on the rotational alignment in ^{254}Rf

Most fissile nucleus known ^{250}No

D. Peterson et al. Phys. Rev. C **74**, 014316 (2006)
- **ATLAS, FMA, total of 158 SF events, 2 SF lifetimes**
  3.5 days, 40-90 pnA

J. Kallunkathariyil et al., Phys. Rev. C **101**, 011301(R) (2020)
- **JYFL, RITU, total of 370 SF events**
  5 days, 50-100 pnA

J. Khuyagbaatar et al., Phys. Rev. C **106**, 024309 (2022)
- **GSI, TASCA, total of 780 Fission events**

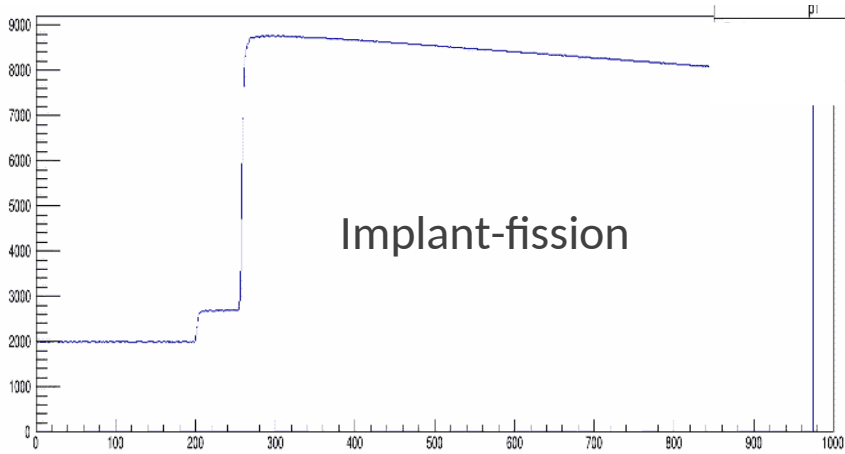


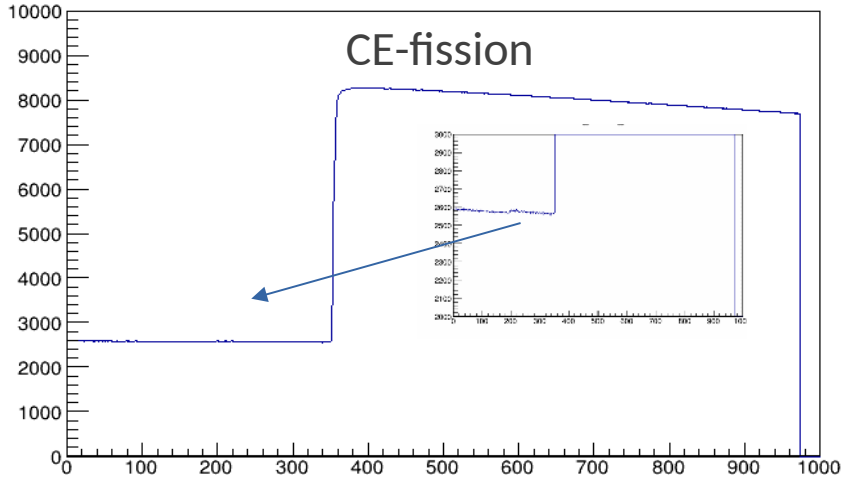
~2000 fission events detected

Gammasphere+AGFA

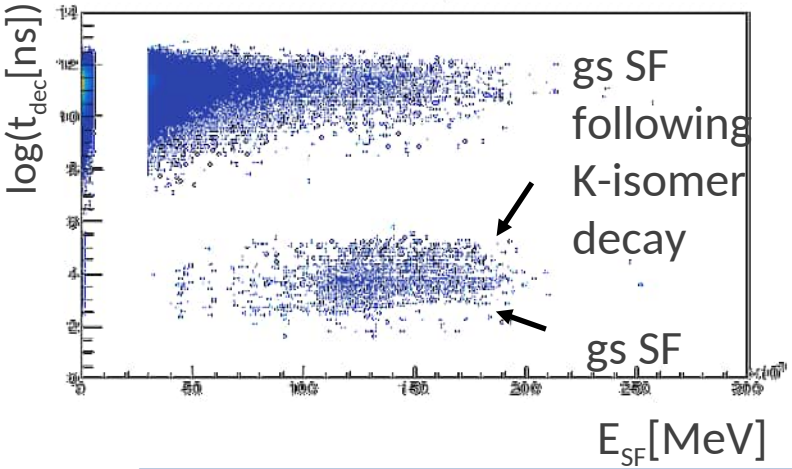
D. Seweryniak and T. Huang

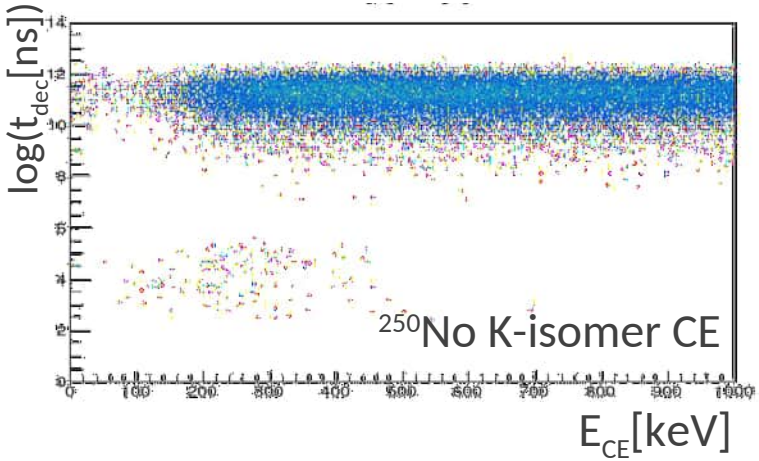
^{48}Ca+^{204}Pb, ~20-25 pnA, 8 days
σ~15 nb

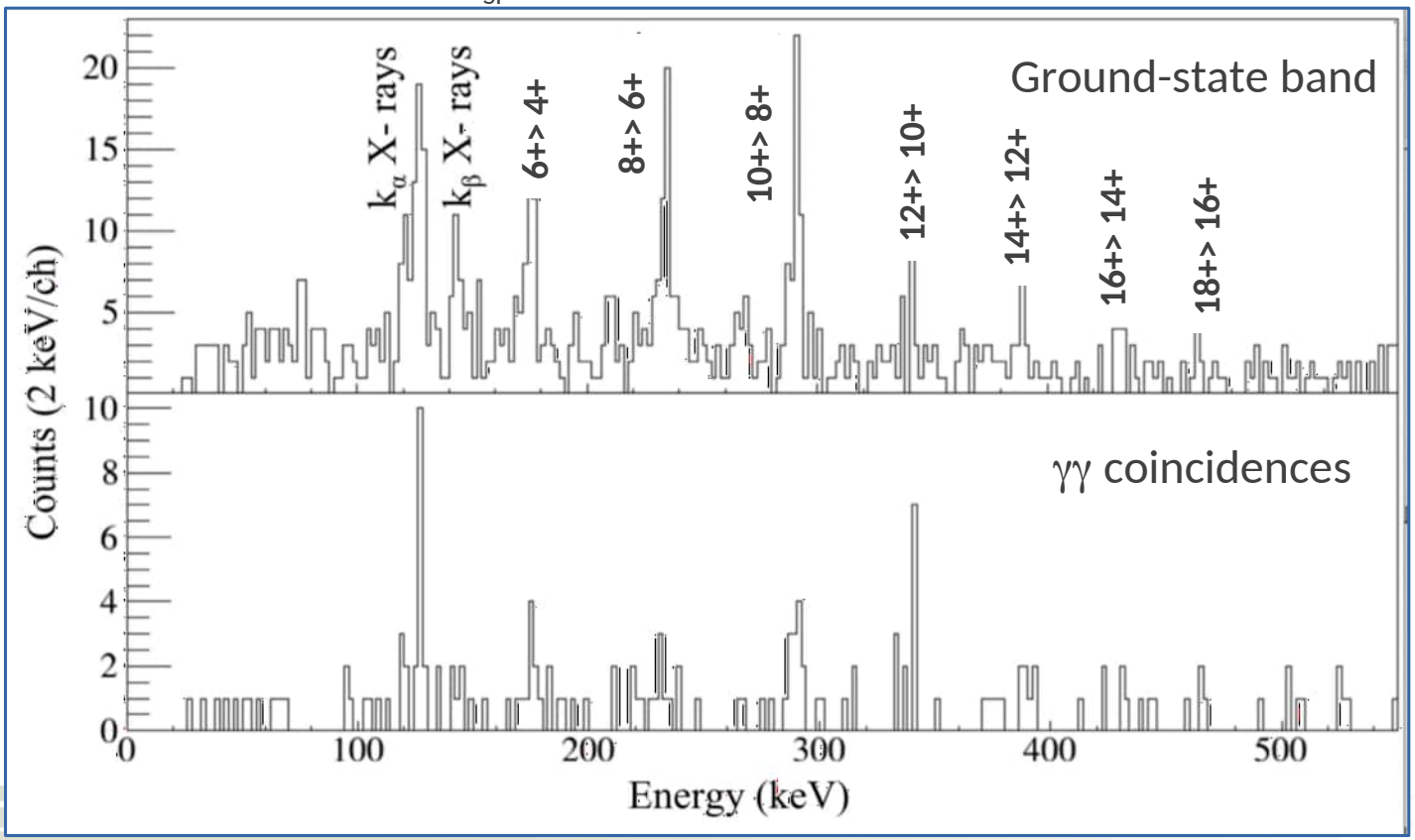




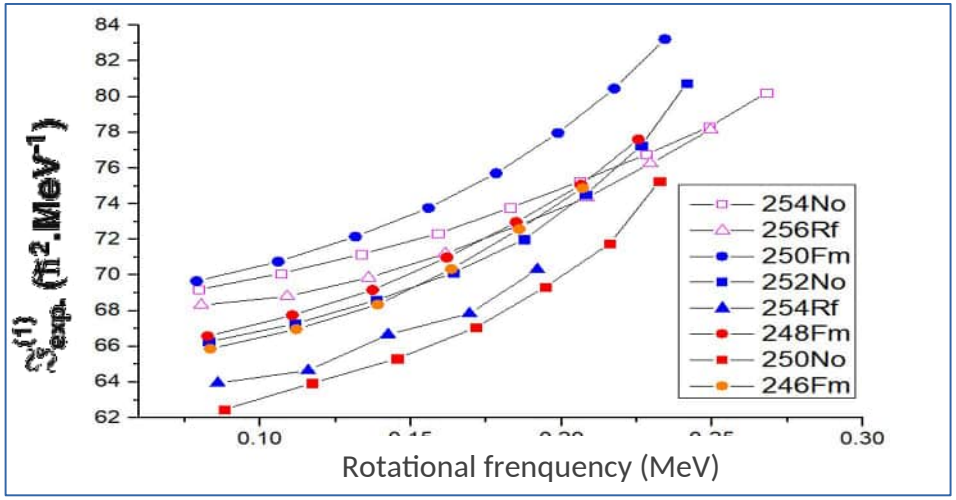
^{250}No ground-state rotational band







Moments of inertia near Z=100, N=152



Harris formula:

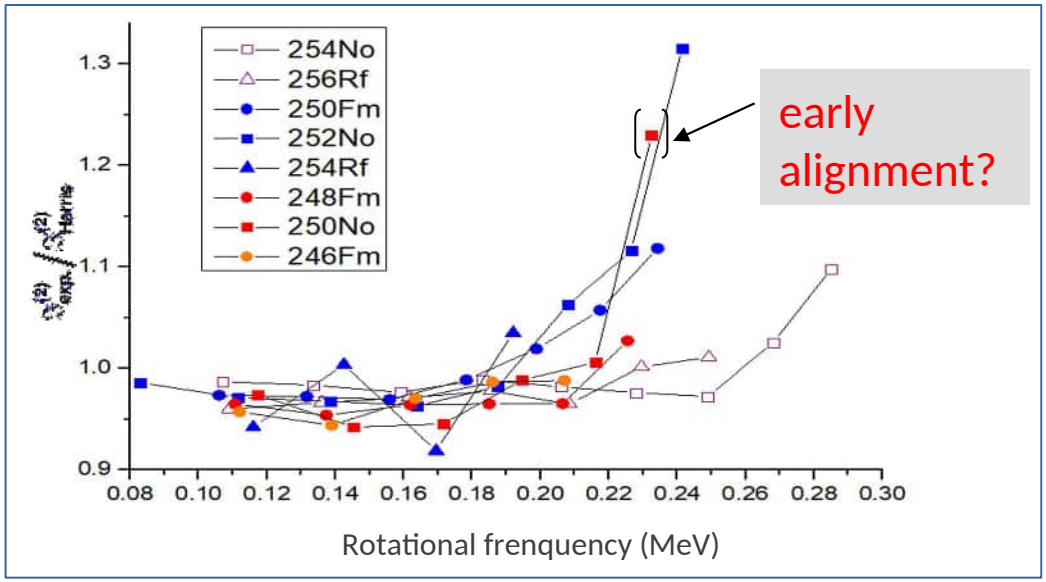
$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2$, kinematic MOI

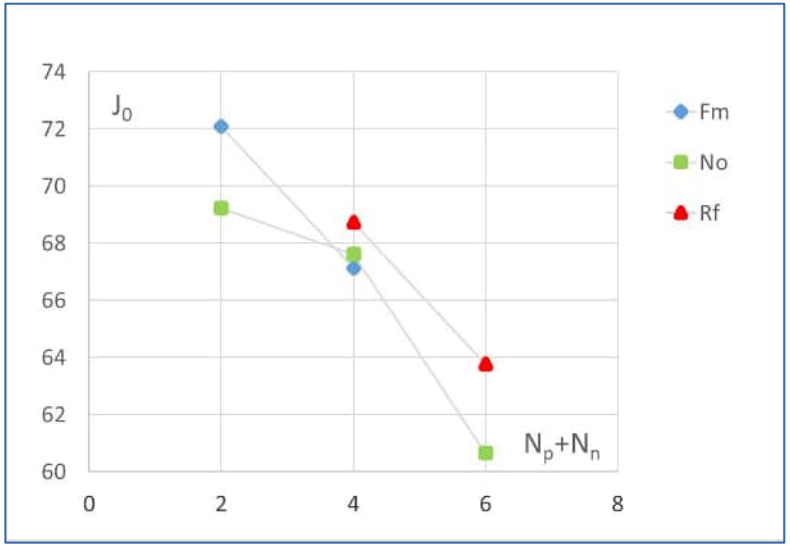
$\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2$, dynamic MOI

Values fitted for ^{250}No:

$\Im^{(1)}$=60.7 $\hbar^2$/MeV

$\Im^{(2)}$=225 $\hbar^2$/MeV^3





MOI at ω=0 drops down away from Z=100, N=152

D. Seweryniak, T. Huang et al, paper in preparation

Complete decay spectroscopy of ^{254}No

AGFA+ XArray
P. Chowdhury et al,

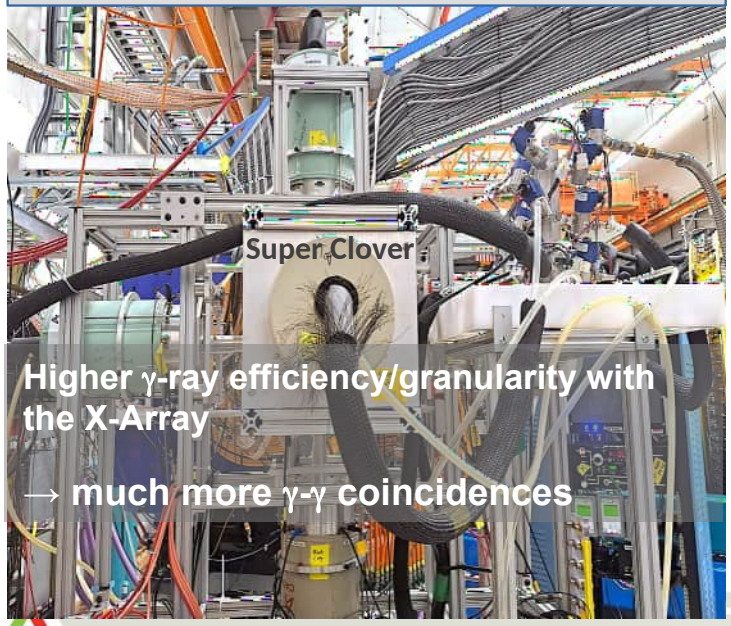
PHYSICAL REVIEW C 111, 034320 (2025)

Isomers and hindrances in ^{254}No: A touchstone for theories of superheavy nuclei

S. G. Wahid,[1,*] P. Chowdhury,[1,†] D. Seweryniak,[2] T. L. Khoo,[2] F. G. Kondev,[2] R. M. Clark,[3] B. B. Back,[2,‡] P. C. Bender,[1] M. P. Carpenter,[2] P. A. Copp,[2] K. Hauschild,[4] G. Henning,[5] R.-D. Herzberg,[6] D. E. M. Hoff,[1,§] T. Huang,[7,2] H. Jayatissa,[2] A. Korichi,[8] T. Lauritsen,[2] A. Lopez-Martens,[4] G. Morgan,[9] C. Morse,[3,∥] C. Müller-Gatermann,[2] D. H. Potterveld,[2] W. Reviol,[2] A. M. Rogers,[1] S. Saha,[1] G. Savard,[2] K. Sharma,[1] S. Wanigaratthi,[1] G. L. Wilson,[2] J. Wu,[2,¶] and S. Zhu[10,2]

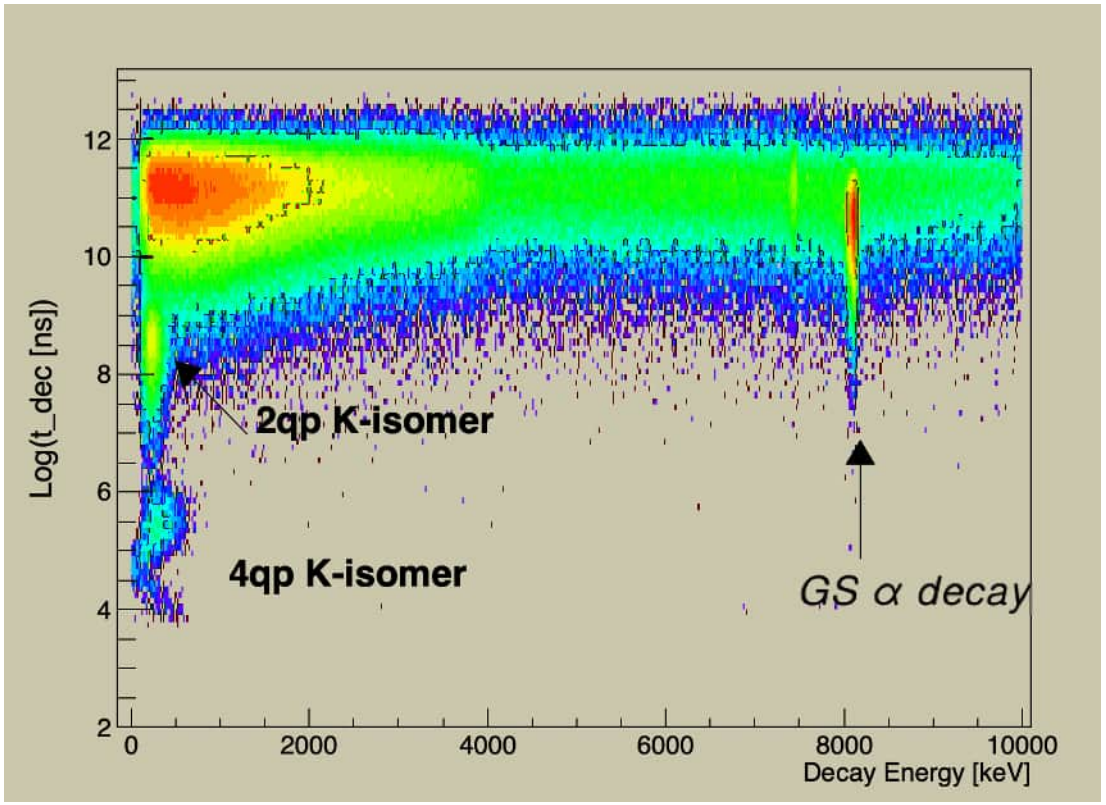
^{48}Ca(^{208}Pb,2n)^{254}No,
~2 μb, ~week , ~300 pnA

800000 ^{254}No implanted in the DSSD



Higher γ-ray efficiency/granularity with the X-Array

→ much more γ-γ coincidences



PHYSICAL REVIEW C 111, 034320 (2025)

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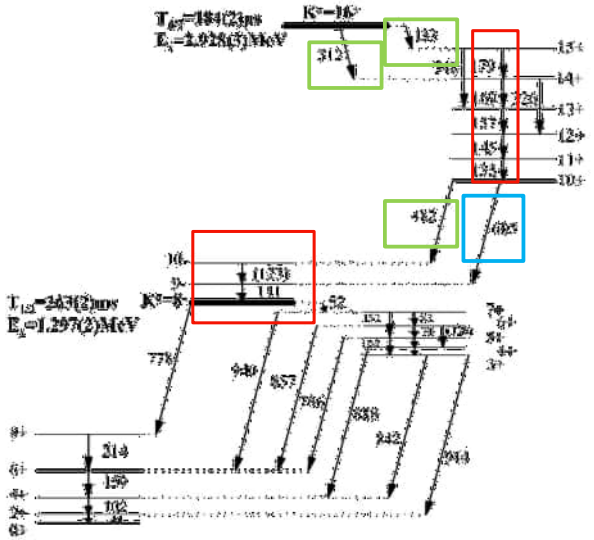
Level scheme ambiguities % to other meas.

605 keV observed as prompt in other meas.

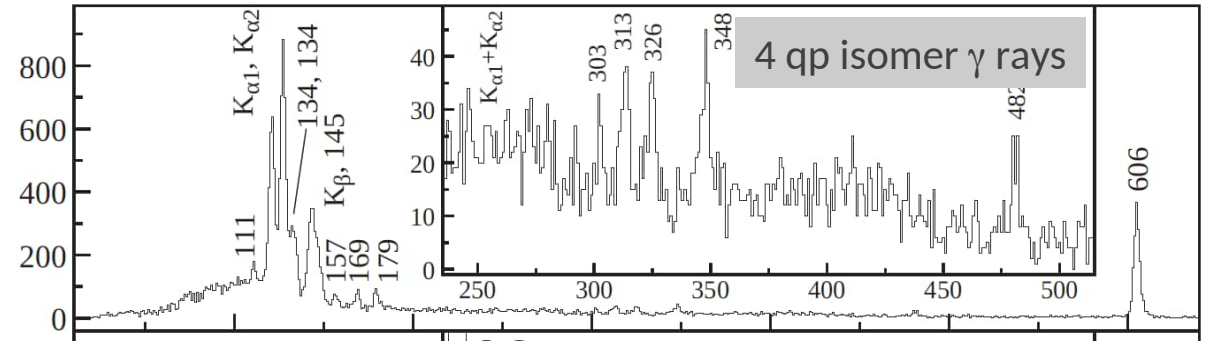
Weak transitions

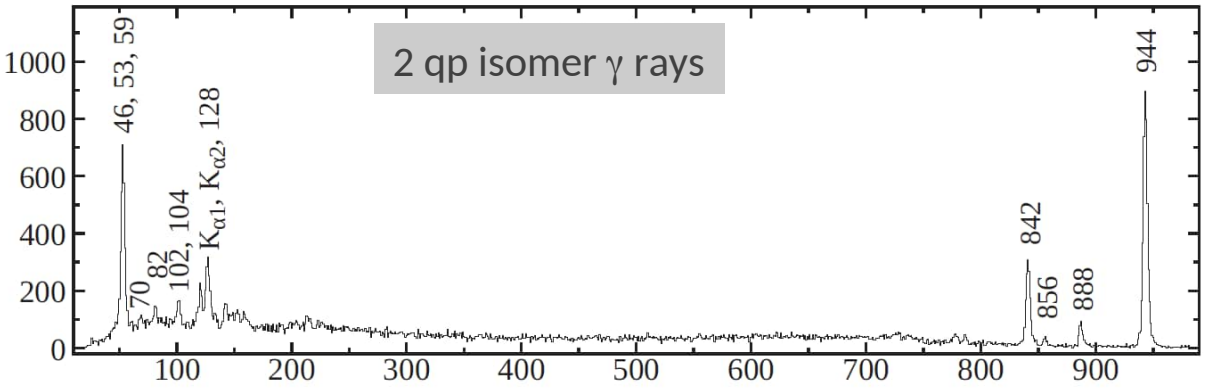


Previous experiment with high statistics

9.0×10^5 recoil implants @BGS at LBNL

R.M. Clark et al., Phys. Lett. B (2010)





all γ rays present, **10x more γγ coincidences**

PHYSICAL REVIEW C 111, 034320 (2025)

Isomers and hindrances in ^{254}No: A touchstone for theories of superheavy nuclei

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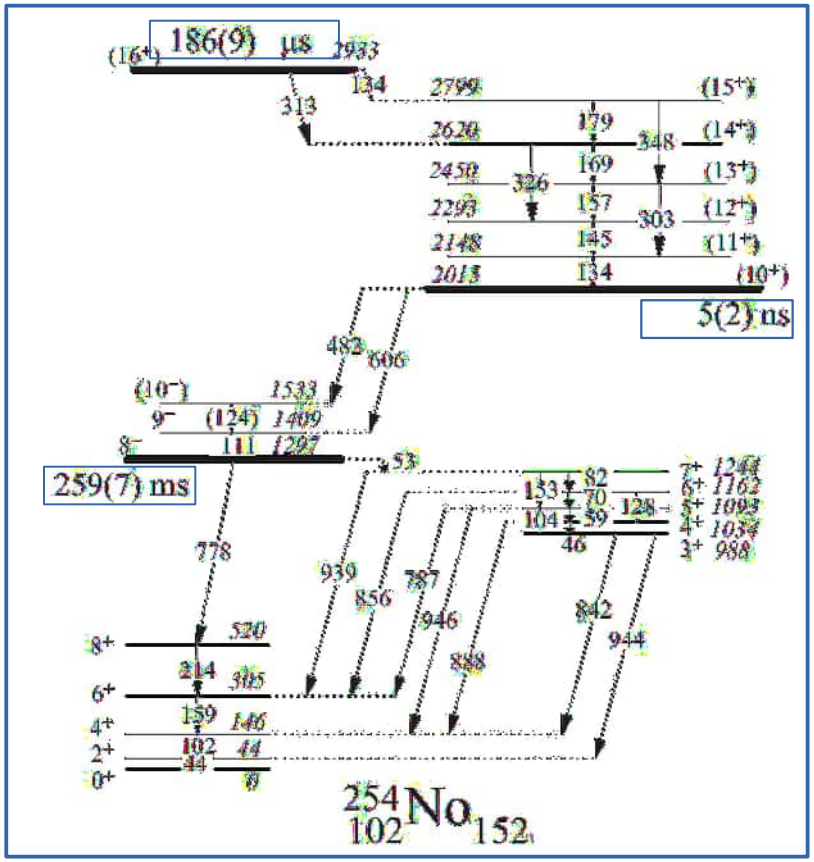
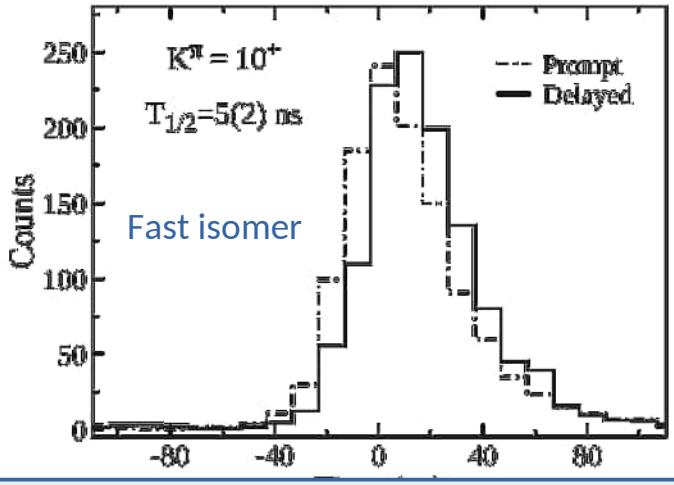


A careful analysis was performed including:

Energy-dependent walk in the time response correction for DSSD and Clovers



A firm level scheme and spin-parity assignments with the highest $\gamma - \gamma$ statistics is obtained for the first time

This new high-K isomers decay-spectroscopy with AGFA resolves the long-standing level scheme ambiguities

3-qp K-isomer in ^{251}Md

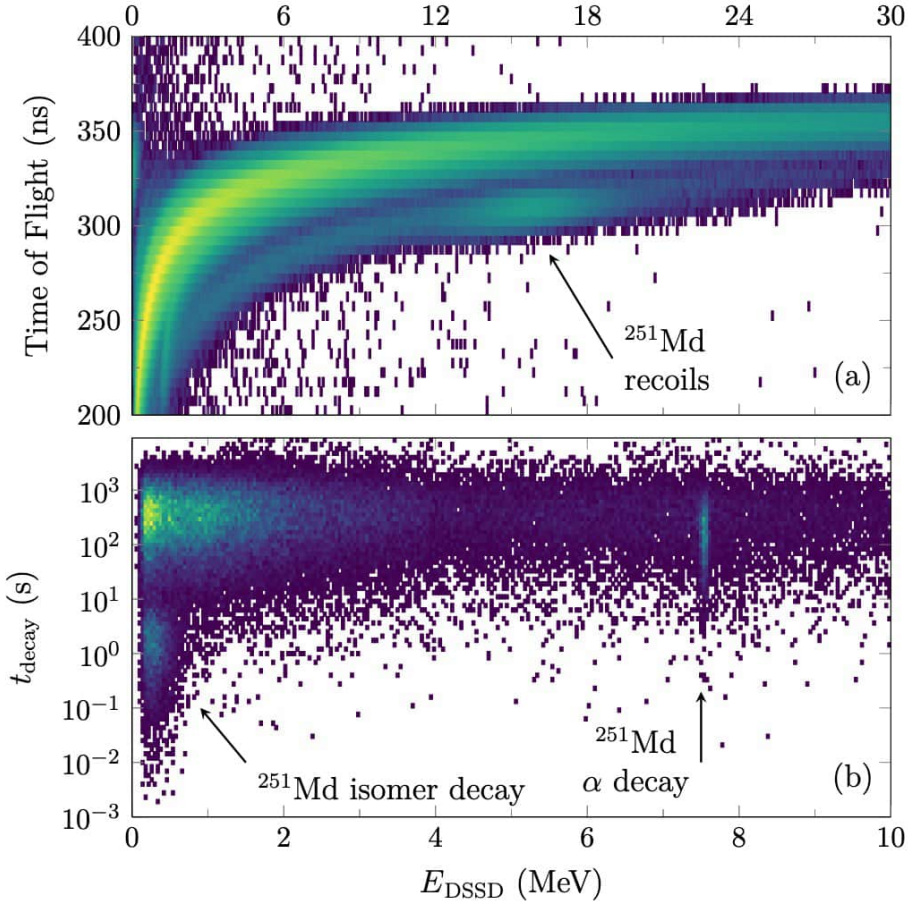
PHYSICAL REVIEW C 111, 044320 (2025)

Decay spectroscopy of an isomeric state in ^{251}Md

C. Morse,[1,2] R. M. Clark,[2] D. Seweryniak,[3] C. J. Appleton,[2] C. M. Campbell,[2] M. P. Carpenter,[3] P. Chowdhury,[4] H. L. Crawford,[2] M. Cromaz,[2] P. Fallon,[2] Z. Favier,[3] T. Huang,[5,6] F. G. Kondev,[3] A. Korichi,[7] T. Lauritsen,[3] D. H. Potterveld,[3] W. Reviol,[3] D. Rudolph,[8] C. Santamaria,[2] G. Savard,[3] G. L. Wilson,[9] and S. Zhu[1,3,*]

AGFA+ XArray

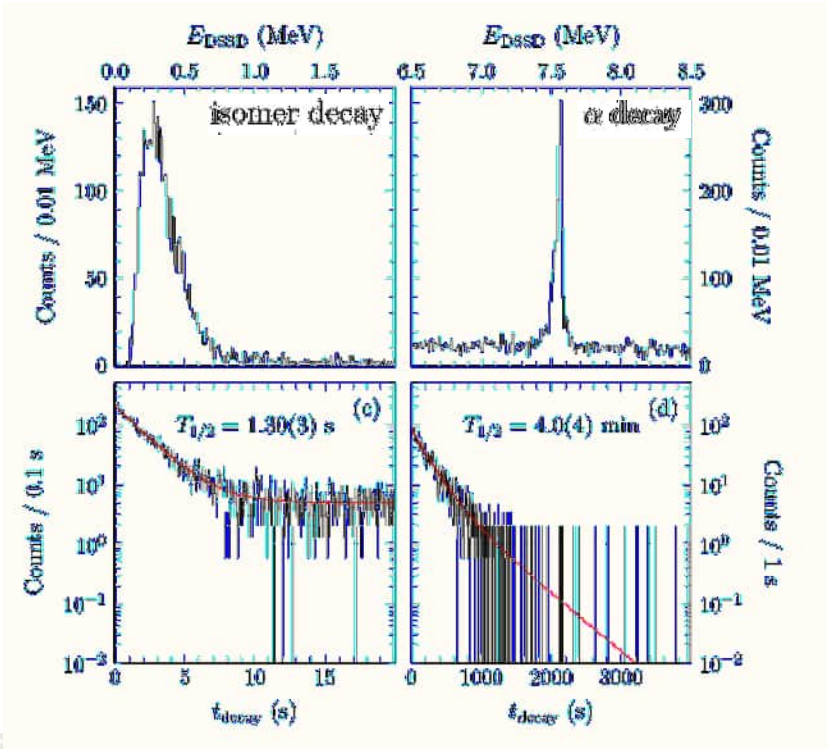
C. Morse, R. M. Clark et al,



^{48}Ca(^{205}Tl,2n)^{251}Md, ~700 nb

~week , ~20 pnA, 216 MeV

52000 ^{251}Md implanted in the DSSD

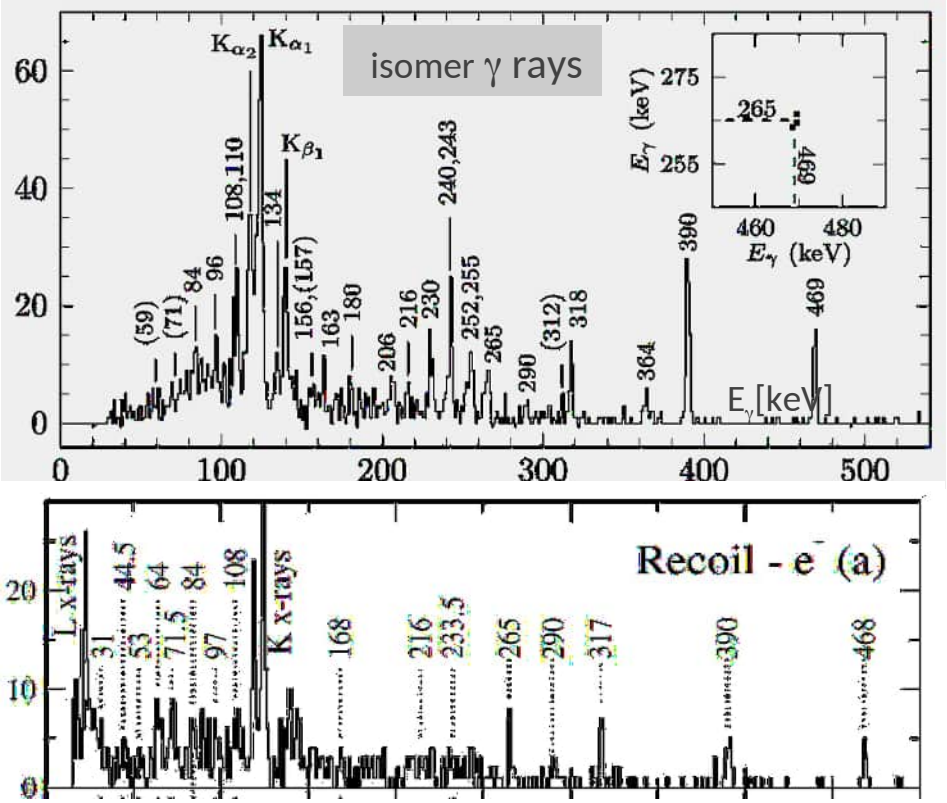


ACCEPTED PAPER

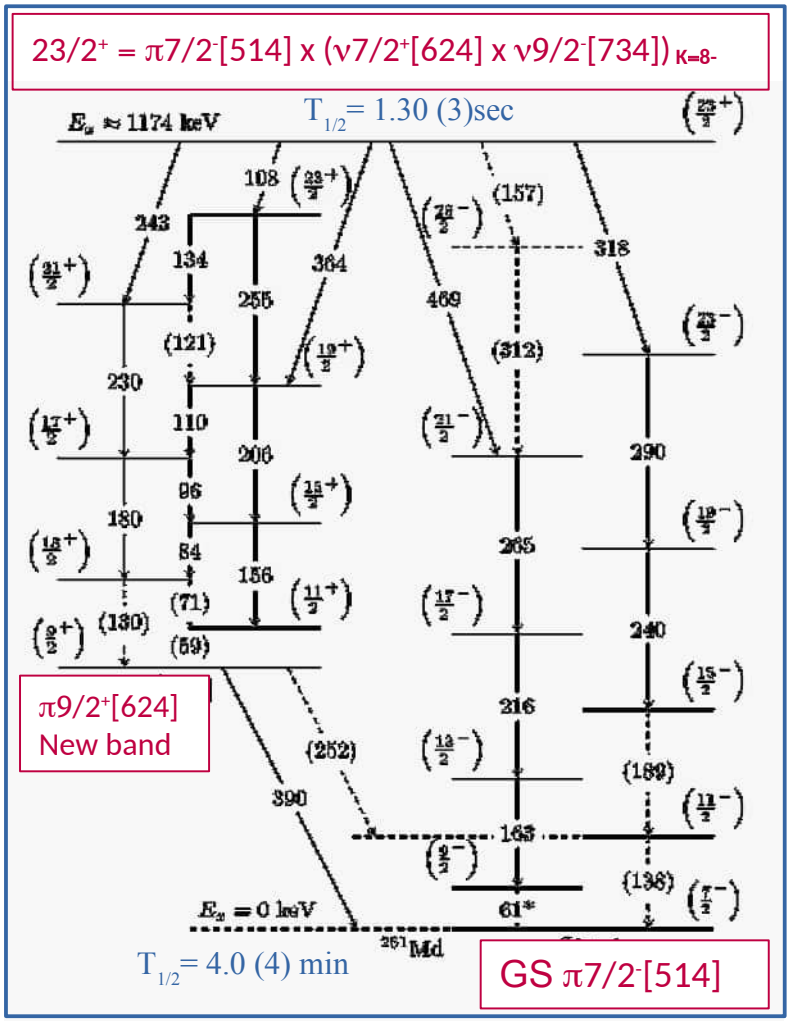
Decay spectroscopy of an isomer state in ^{251}Md

Physical Review C

C. Morse, R. M. Clark, D. Seweryniak, C. J. Appleton, C. M. Campbell, M. P. Carpenter, P. Chowdhury, H. L. Crawford, M. Cromaz, P. Fallon, Z. Favier, T. Huang, F. G. Kondev, A. Korichi, T. Lauritsen, D. H. Potterveld, W. Reviol, D. Rudolph, C. Santamaria, G. Savard, G. L. Wilson, and S. Zhu



T. Goigoux et al, Eur. Phys. J. A (2021) 57:321
Same reaction @JYFL with RITU (216 MeV, 11 pnA) ~ 9 days



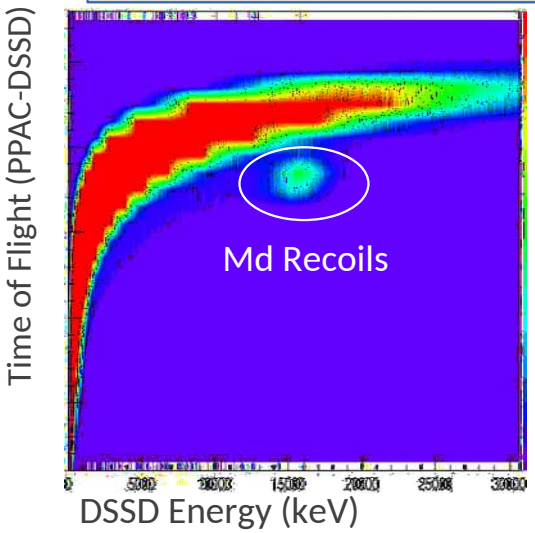
Decay scenario based on γ ray intensities &energies

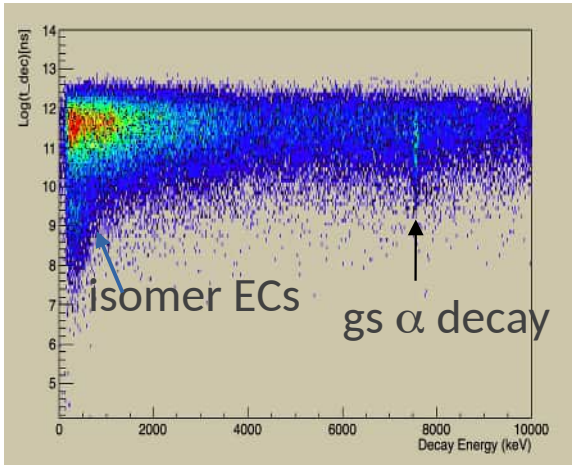
In-beam Spectroscopy of the odd-Z ^{251}Md

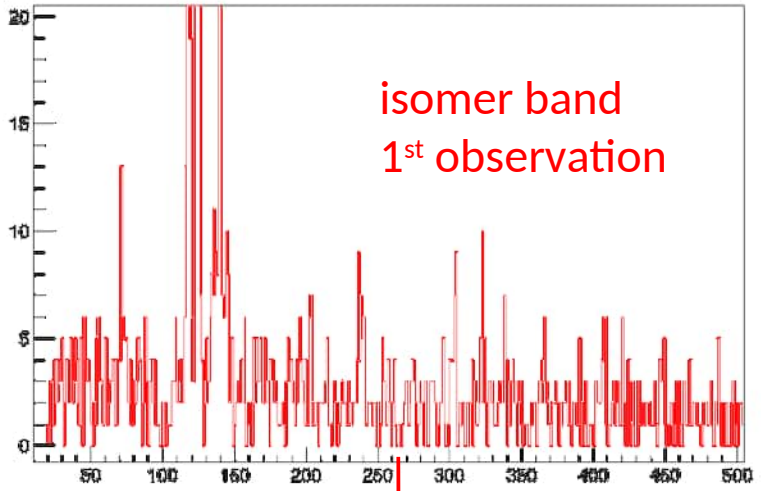
^{48}Ca(^{205}Tl,2n)^{251}Md ~700 nb

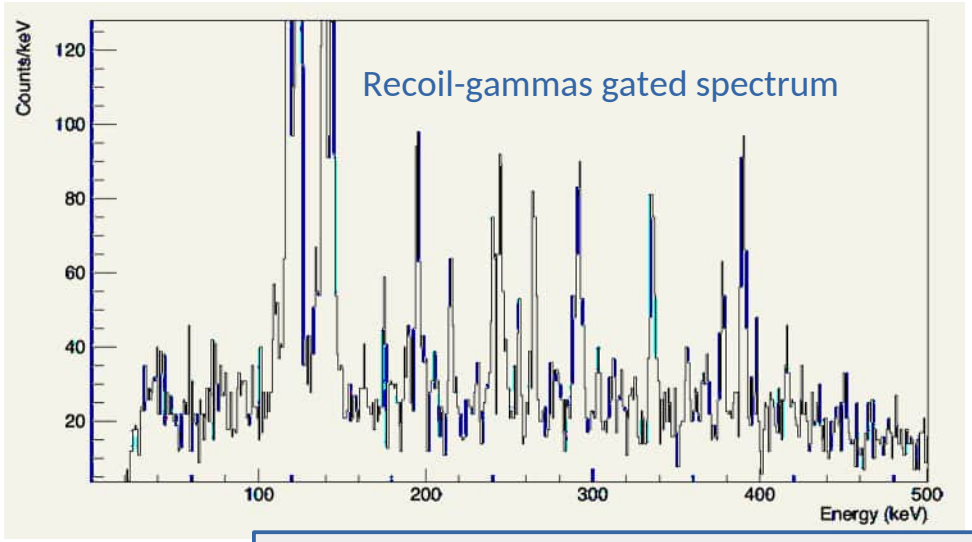
AGFA+Gammasphere +XArray

C. Morse, R.M Clark et al,

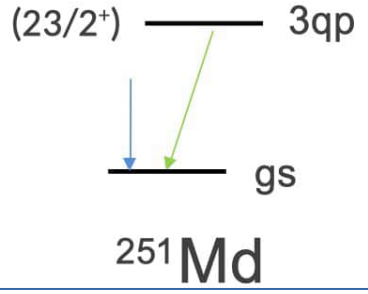








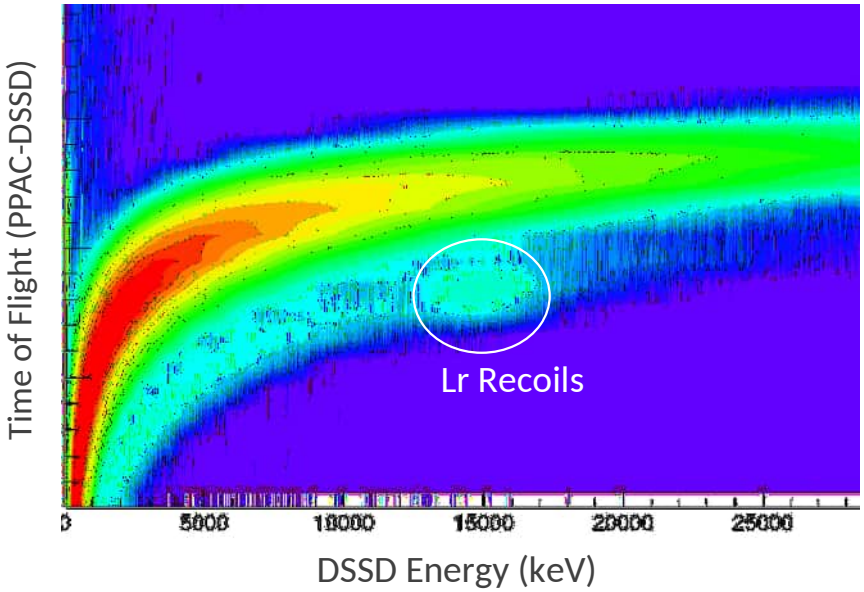
$23/2^+ = \pi 7/2^-[514] \times (\nu 7/2^+[624] \times \nu 9/2^-[734])_{K=8^-}$



The analysis is still under way and more in the next coming meeting

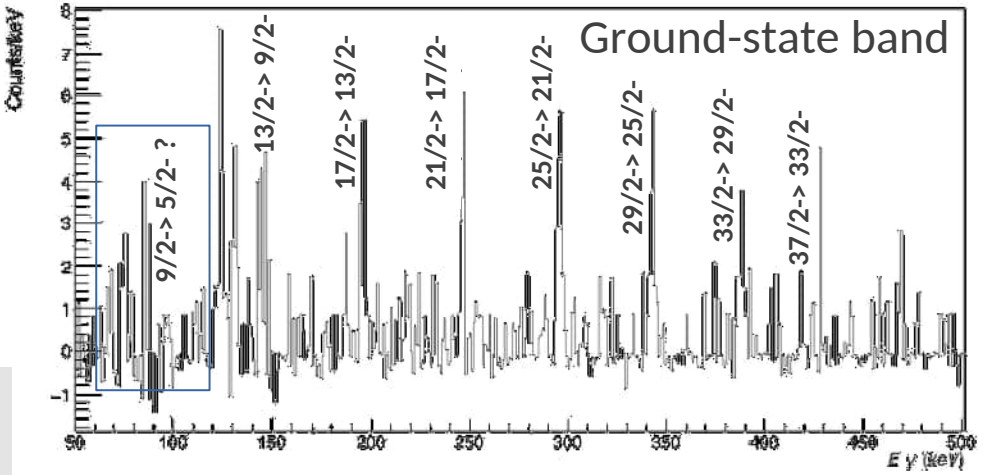
In-beam Spectroscopy of the odd-Z ^{255}Lr

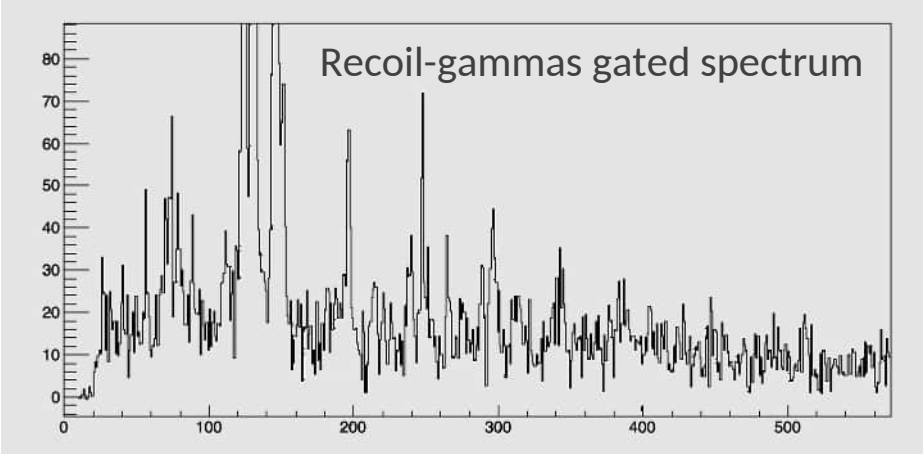
AGFA+Gammasphere +XArray

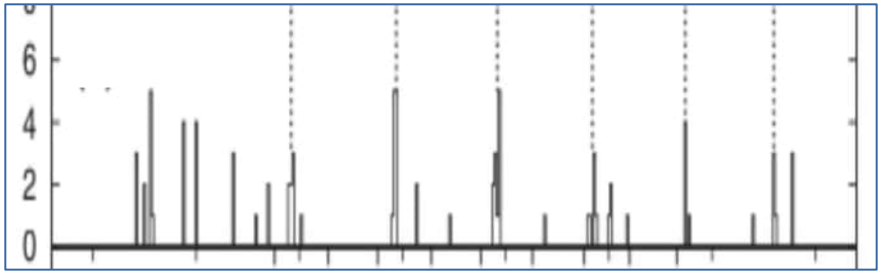


^{48}Ca(^{208}Pb,2n)^{255}Lr, ~200 nb
~week , ~20-25 pnA, 220 MeV

γγ coincidences- sum gates (197+247+296+343+388)





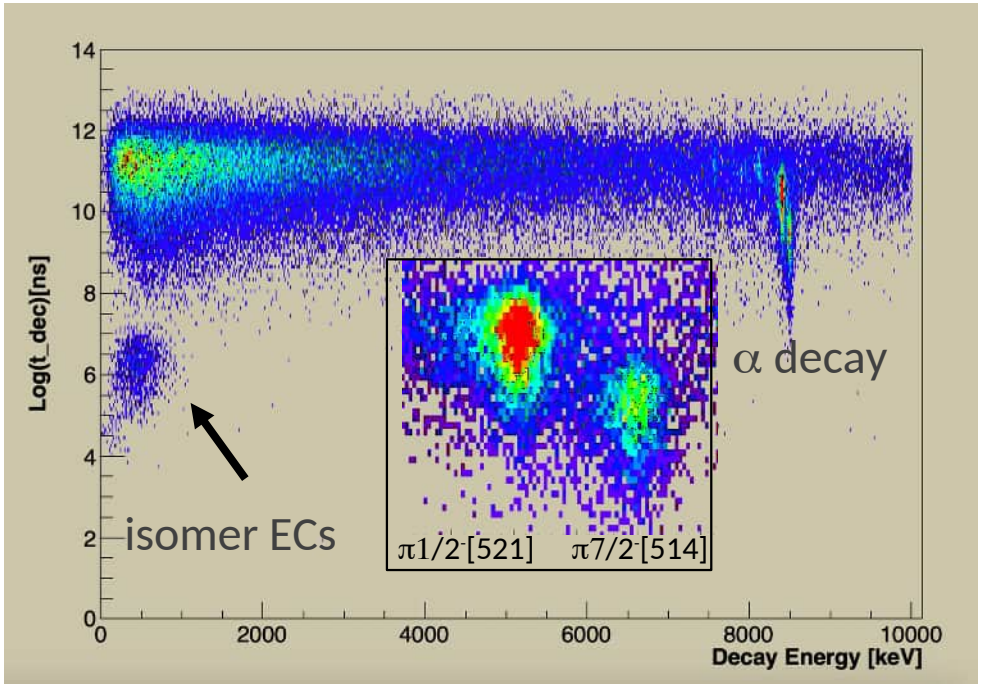


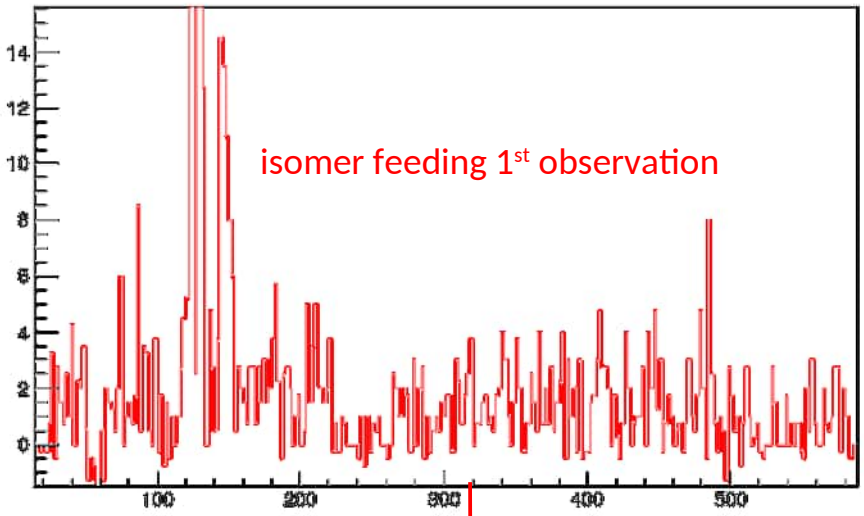
S. Ketelhut et al., Phys. Rev Lett 102 (2009)212501

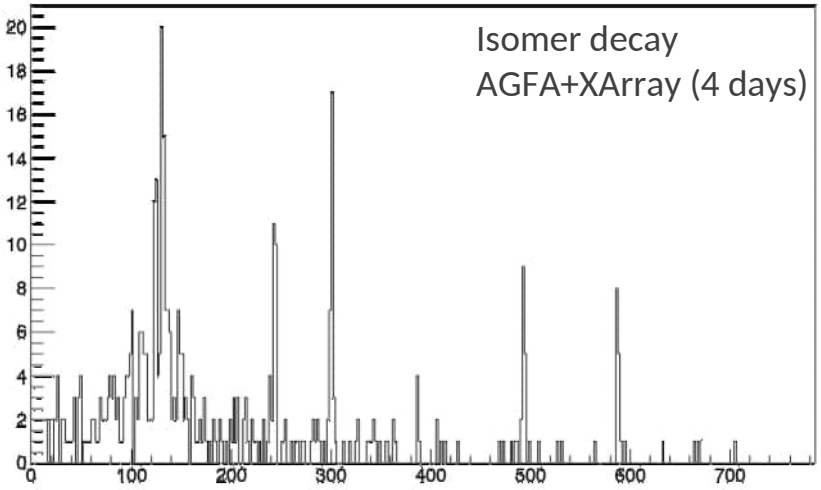
The complex analysis is still under way and more in the next coming meeting

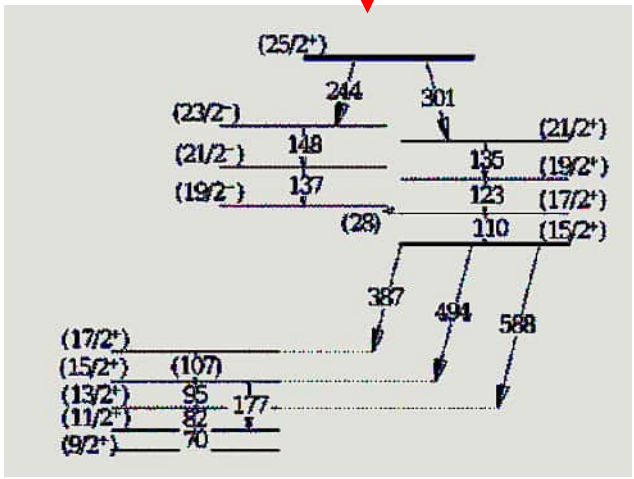
In-beam Spectroscopy of the odd-Z ^{255}Lr

AGFA+Gammasphere +XArray









H.B Jeppesen et al., Phys. Rev C (2009)
BGS decay spectroscopy meas. @200 pnA

Summary and Outlook

New results on trans-fermium nuclei obtained with AGFA, Gammasphere and XArray

-Ground state rotational band observed in the most fissile nuclei known ^{254}**Rf** and ^{250}**No**

-Key experimental insight into ^{254}**No**

-Rotational bands in **odd-Z** nuclei ^{251}**Md** and ^{255}**Lr** were observed including bands feeding isomers

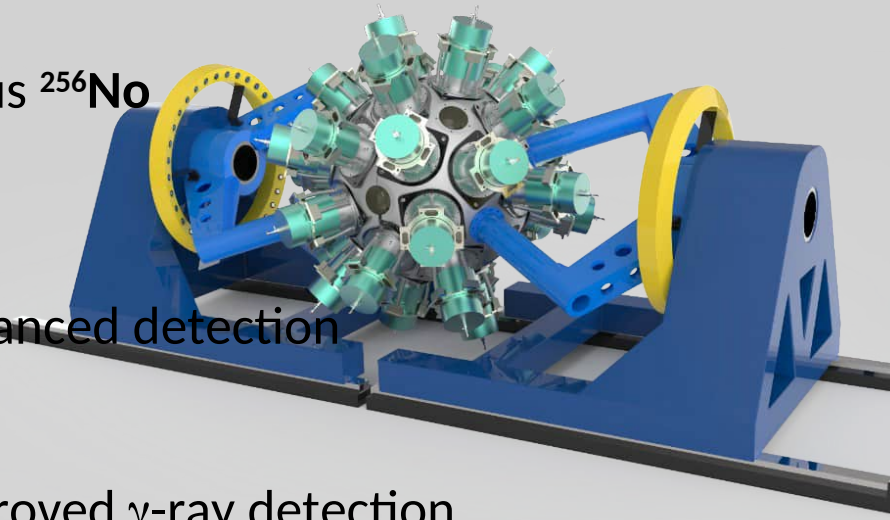
Outlook

-Further investigation into N>152 nucleus ^{256}**No**

-^{253}**No** HK distributions to be explored

-detailed decay spectroscopy of ^{251}**Md**

-new implantation-decay station for enhanced detection



Dream, yet realistic goal

-coupling of **GRETA** to AGFA for improved γ-ray detection.

Collaboration

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AGFA
Gammasphere
X-Array
Staff
collaborators




Working hard,


Thinking harder

With amazing
Collaborators,
post-docs,
and students


Always
having fun!

Thank for your attention

Special thanks to Darek for his contribution of materials
and support throughout