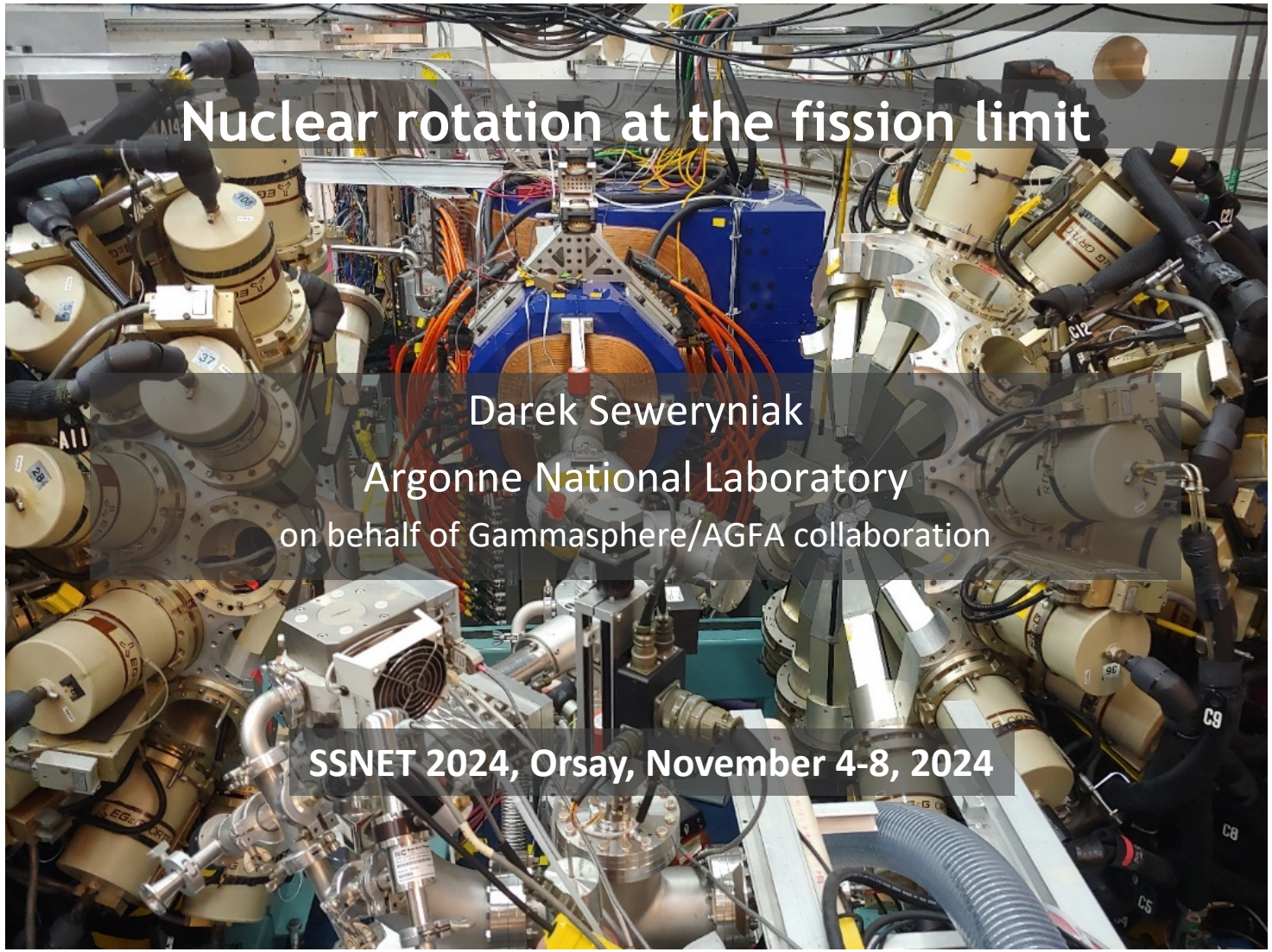
Nuclear rotation at the fission limit



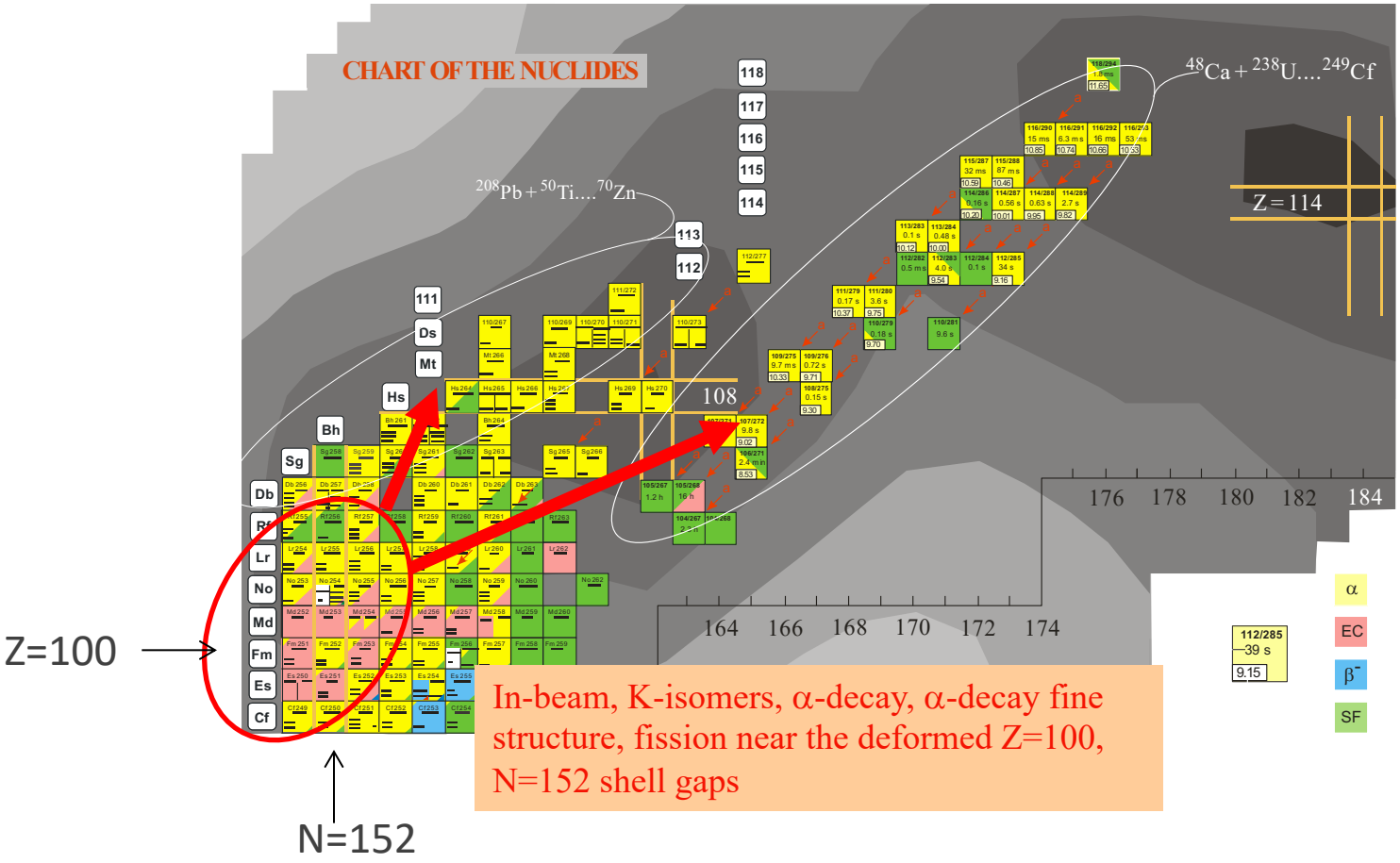
Darek Seweryniak
Argonne National Laboratory
on behalf of Gammasphere/AGFA collaboration

SSNET 2024, Orsay, November 4-8, 2024

Outline

- Landscape of trans-fermium nuclei
- Experimental program with AGFA and AGFA/Gammasphere
- Selected recent results
  - ground-state rotational bands in fissile ^{254}**Rf** and ^{250}**No** nuclei
  - rapidly decaying K-isomers in ^{253}**Lr** and ^{255}**Lr**
  - in-beam spectroscopy of odd-Z ^{255}**Lr** and ^{249,251}**Md** nuclei (briefly)
- Summary and Outlook

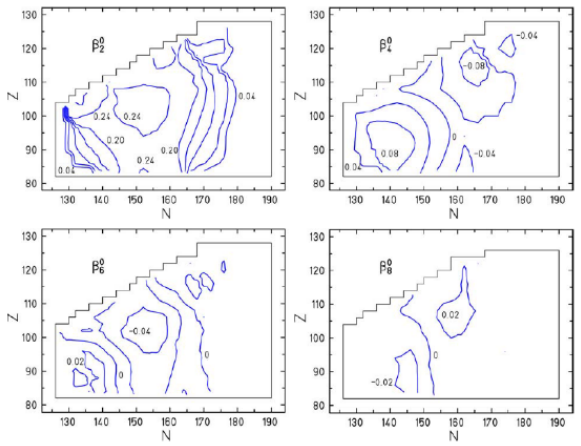
Spectroscopy of trans-fermium nuclei

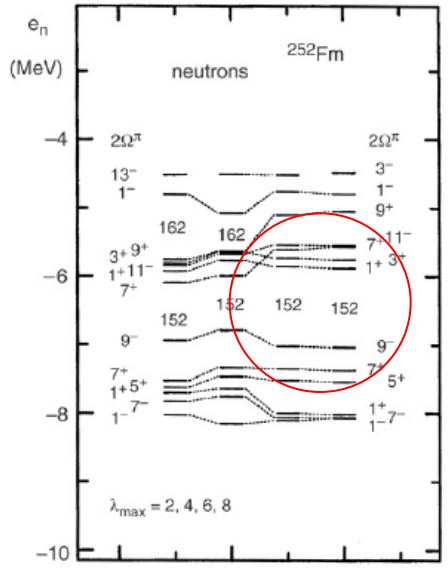


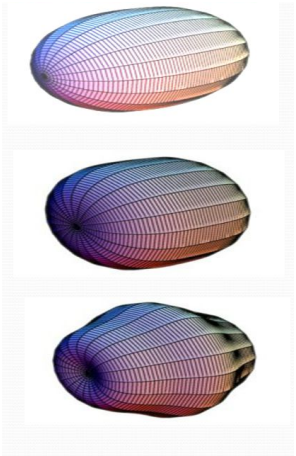
In nuclei with Z>~100, Coulomb repulsion is overcome by shell corrections

Deformation landscape near Z=100, N=152

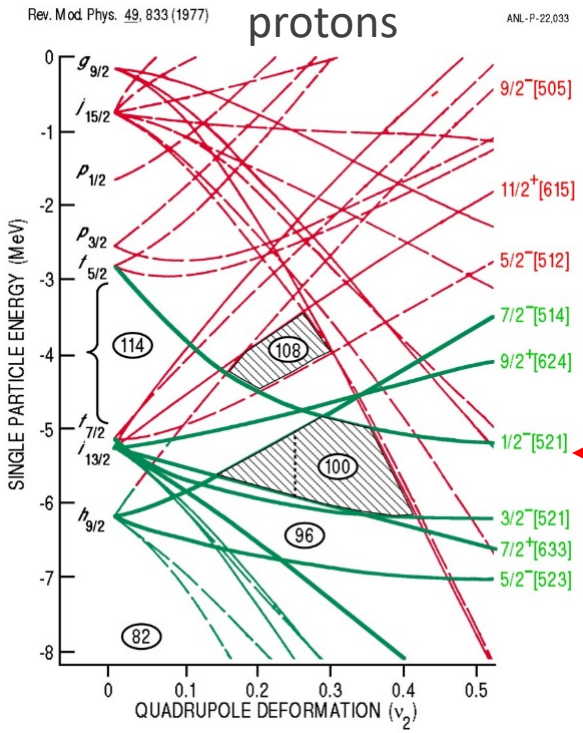
β_2~0.25 plateau



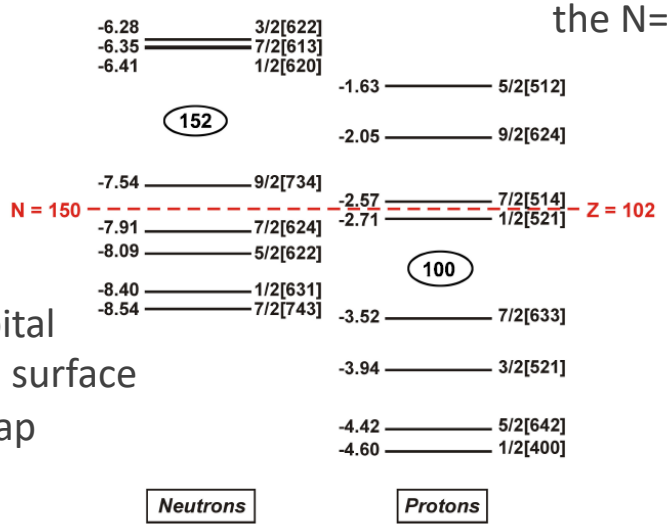




Higher order deformation plays an important role, in particular, β_6 opens the N=152 gap



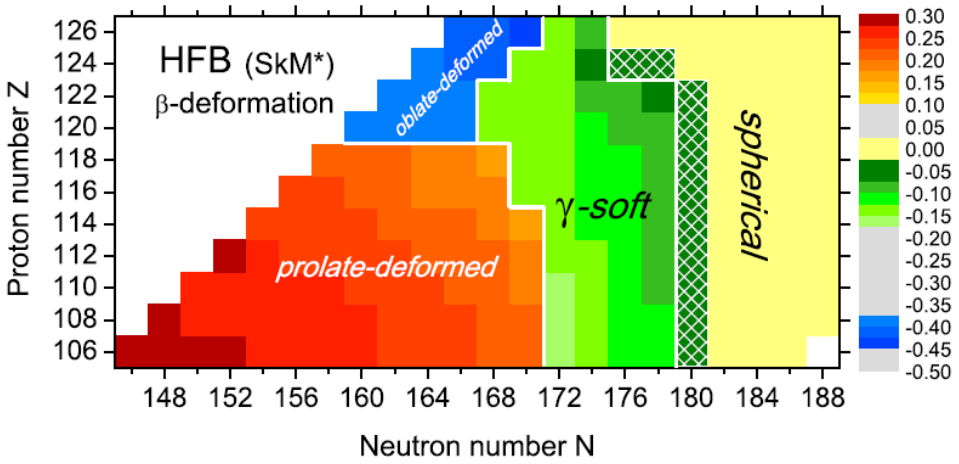
½⁻[521] proton orbital near Fermi surface at Z=114 gap

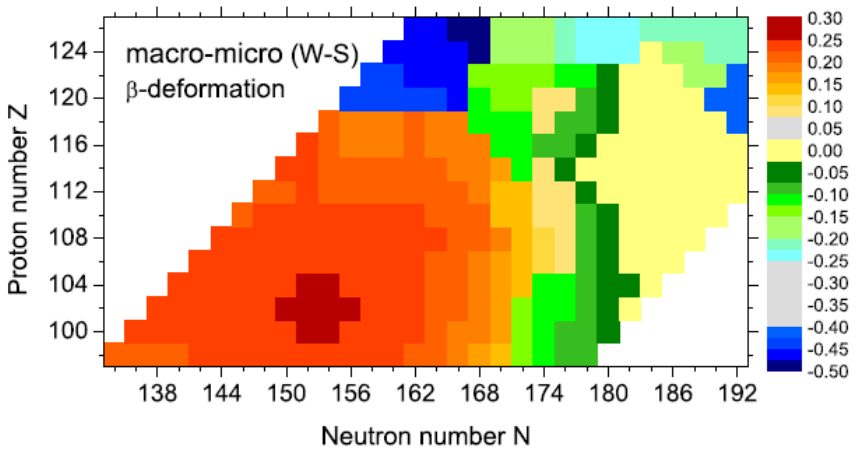


High- and low-K proton and neutron orbitals near Fermi surface leading to K-isomers

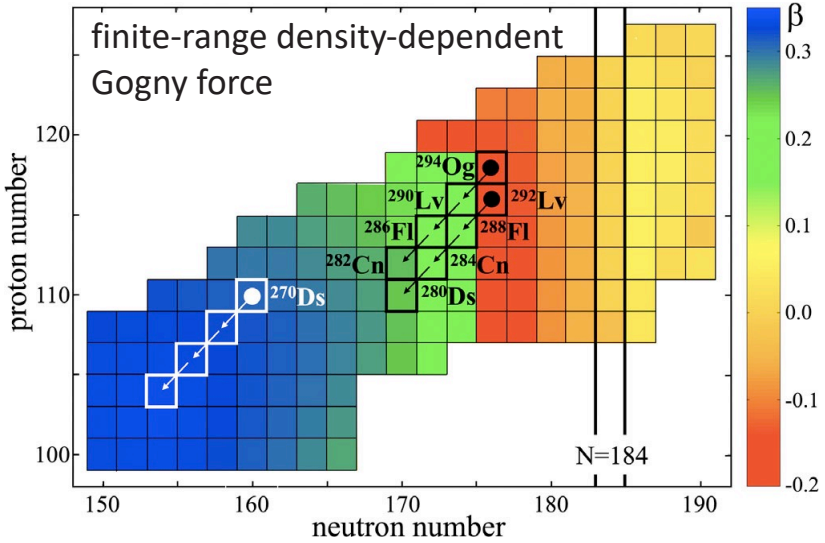
Mic-Mac calculations, A. Sobiczewski and K. Pomorski, Prog. in Part. and Nucl. Phys. 58 (2007) 292–349

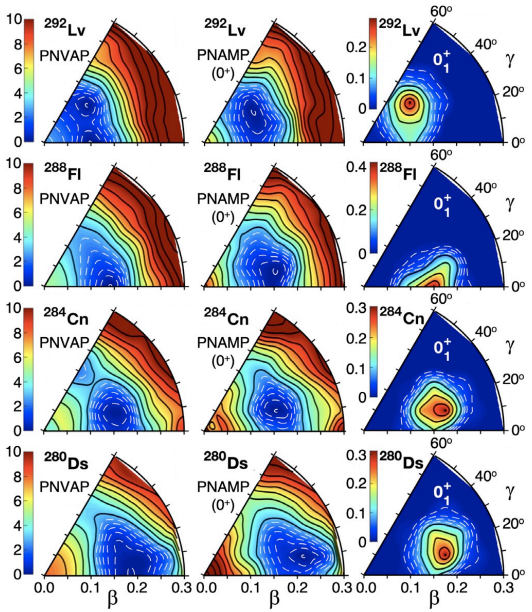
SHN deformation landscape





P.-H. Heenen et al., NP A944, 415 (2015)





γ-unstable
triaxial rotor

axial-symmetric
prolate rotor

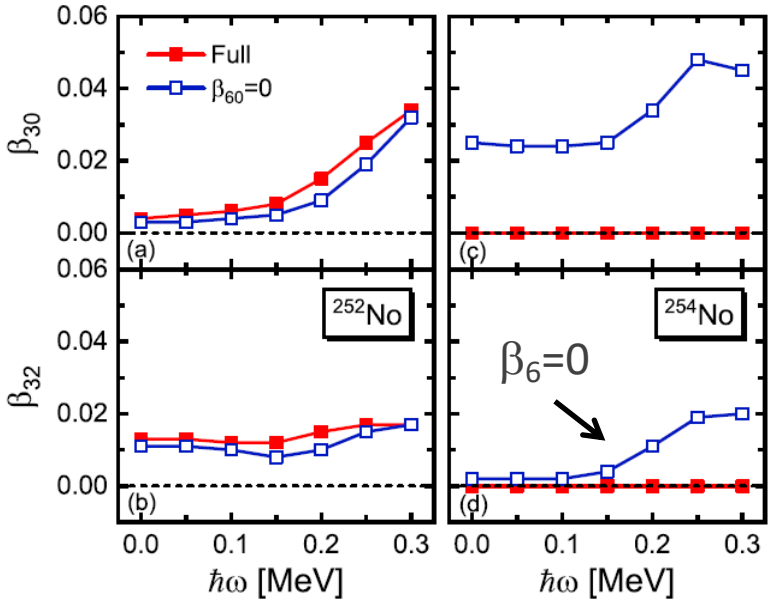
rigid
triaxial rotor

triaxial-symmetry-conserving configuration-mixing approach J. L. Egido, A. Jungclaus, PRL 126, 192501 (2021)

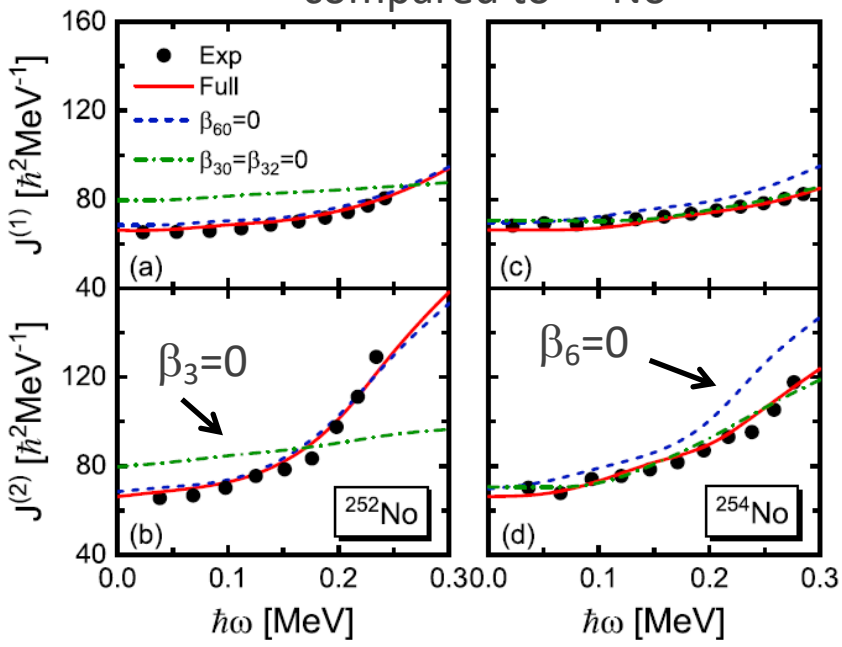
Octupole correlations in ^{252,254}No?

F.F. Xu et al., Phys. Rev. Lett. 133, 022501 (2024)
Talk by Pengwei Zhao at 5 pm on Wednesday

Shell-model-like approach in the **cranking covariant density functional theory** on a 3D lattice, where the pairing correlations, deformations, and moments of inertia are treated in a microscopic and self-consistent way were performed in the full deformation space for **^{252}No, ^{254}No, ^{254}Rf and ^{256}Rf**.

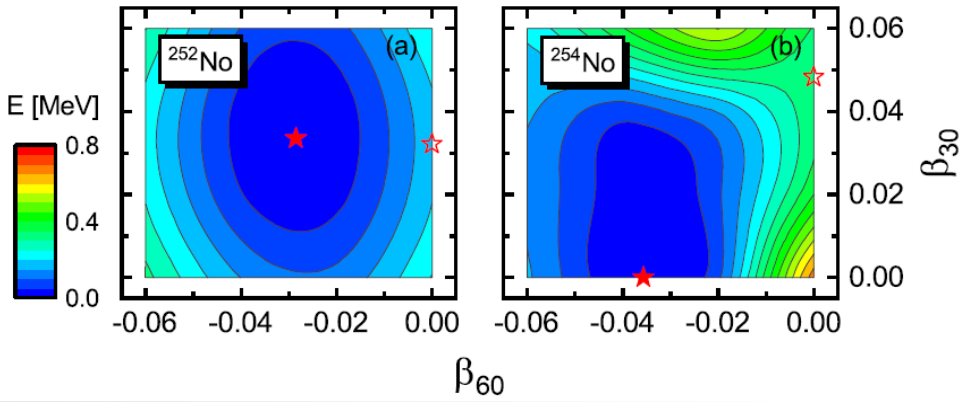


Early upband in ^{252}No compared to ^{254}No



Well defined minimum in β_3/β_6

Spurious β_3 minimum at β_6=0



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

^{257}Db
Search for K-isomers

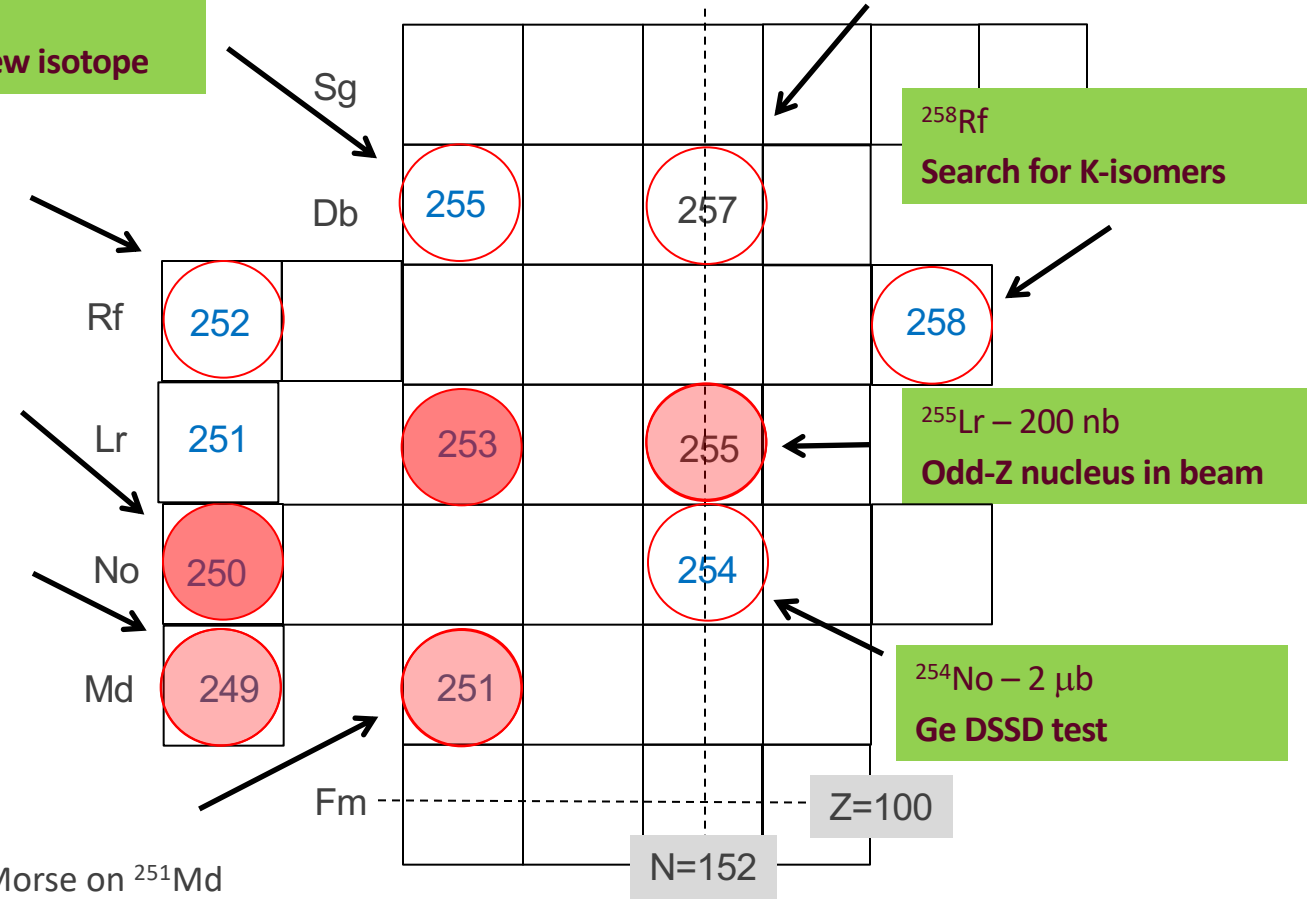
^{255}Db – 200 pb
Search for a new isotope

^{252}Rf – 100 pb
Search for a rapidly fissioning new isotope

^{250}No – 17 nb, SF $T_{1/2}$~4 μs
Ground-state band

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

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



^{258}Rf
Search for K-isomers

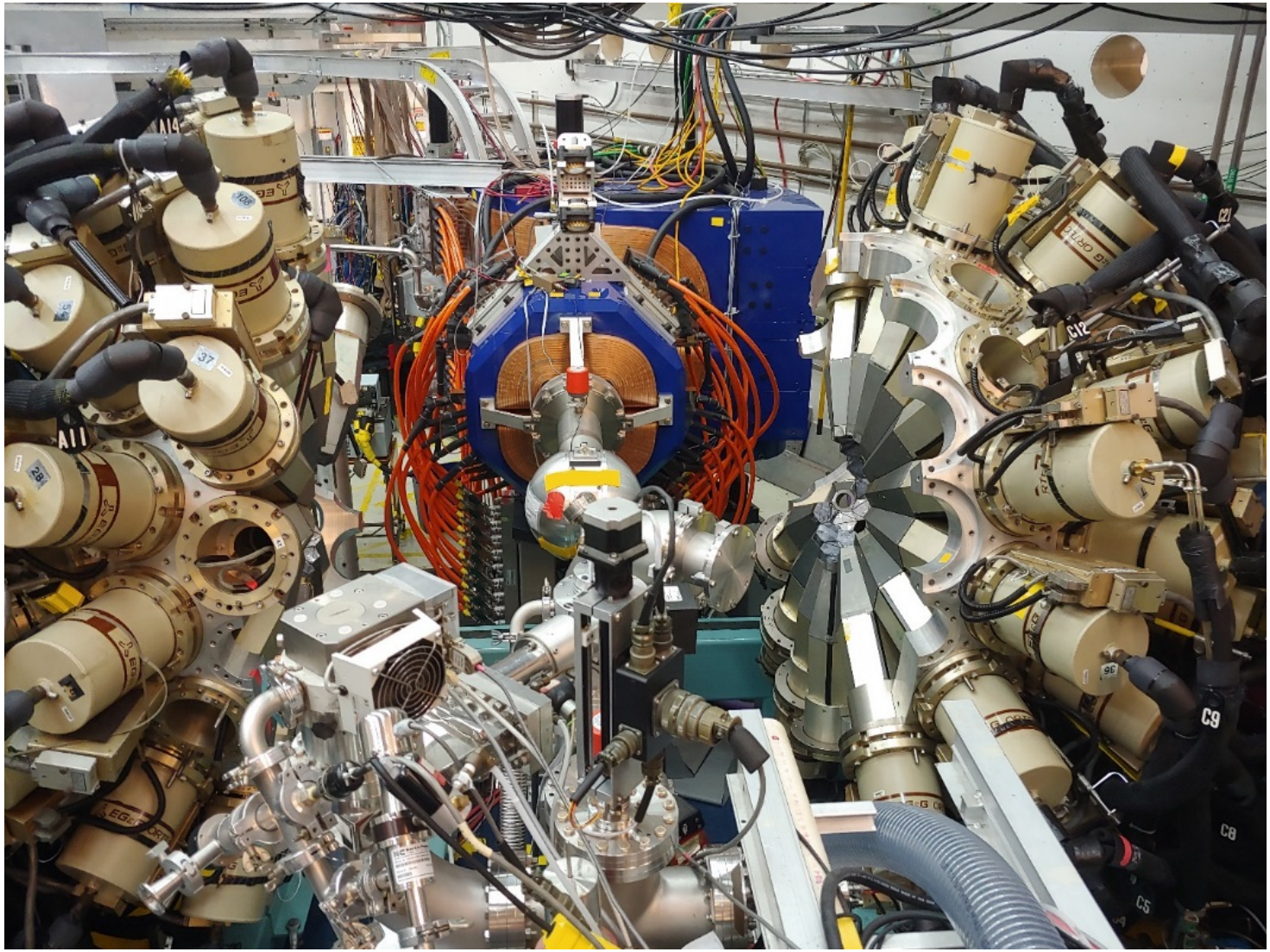
^{255}Lr – 200 nb
Odd-Z nucleus in beam

^{254}No – 2 μb
Ge DSSD test

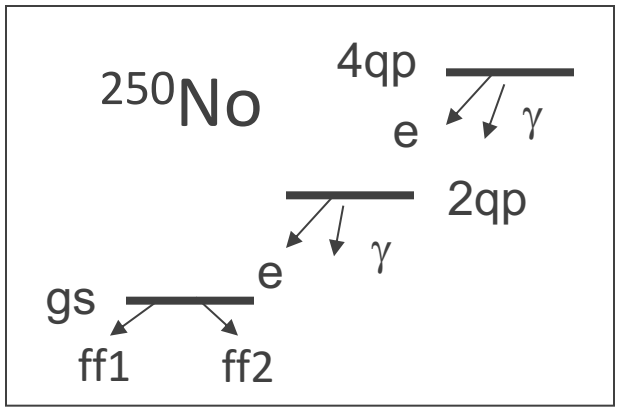
Talk by Chris Morse on ^{251}Md

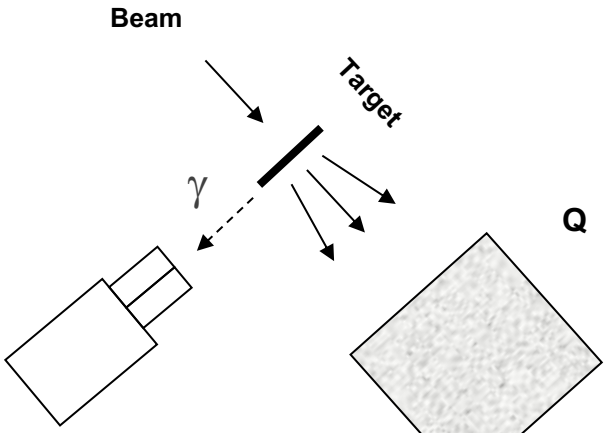
Searches for new isotopes, searches for new K-isomers, in-beam spectroscopy.
We are pushing towards fission limit, heavier elements and N>152.

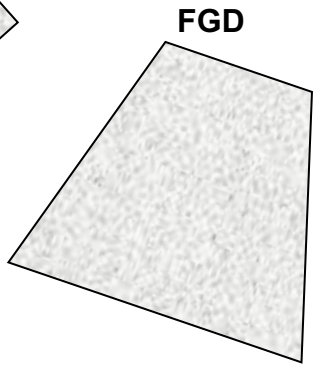
Gammasphere+AGFA

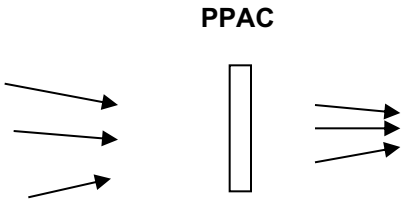


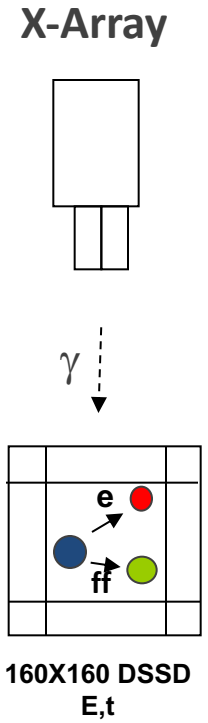
Recoil-Decay Tagging











In-beam γ-rays in coincidence with implants

Implant-decay spatial and time correlations in the DSSD

conversion electrons and gamma rays deexciting isomers followed by α decay

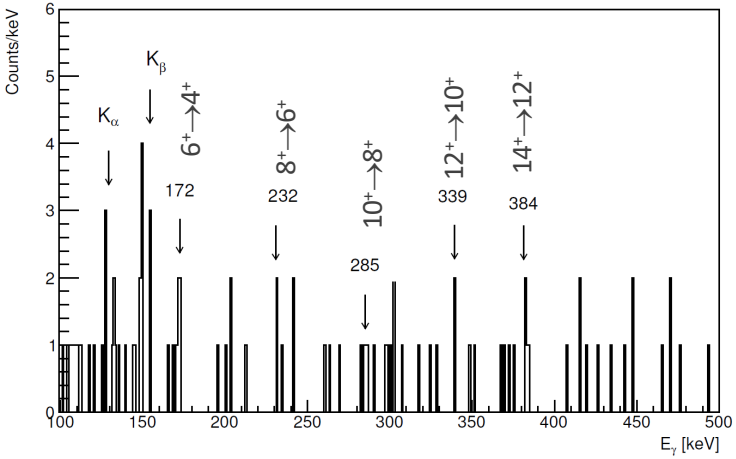
Moment of inertia of fissile ^{254}Rf

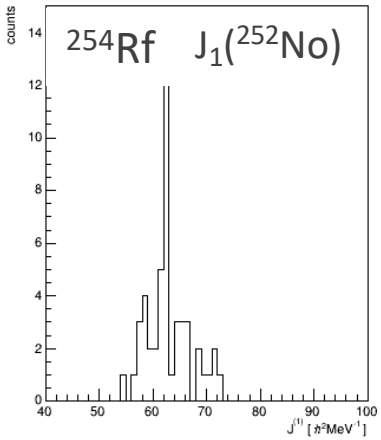
Gammasphere+AGFA

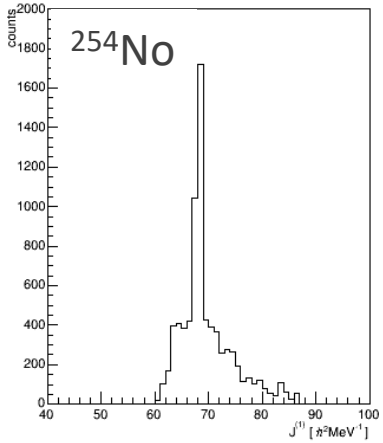
D. Seweryniak, T. Huang et al., Phys. Rev. C **107**, L061302 (2023)

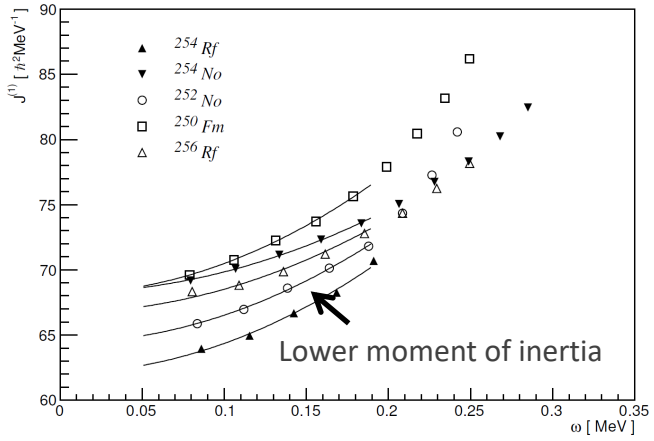
$J_0 \sim (2I-1)/E_\gamma - J_1(E\gamma/2)^2$

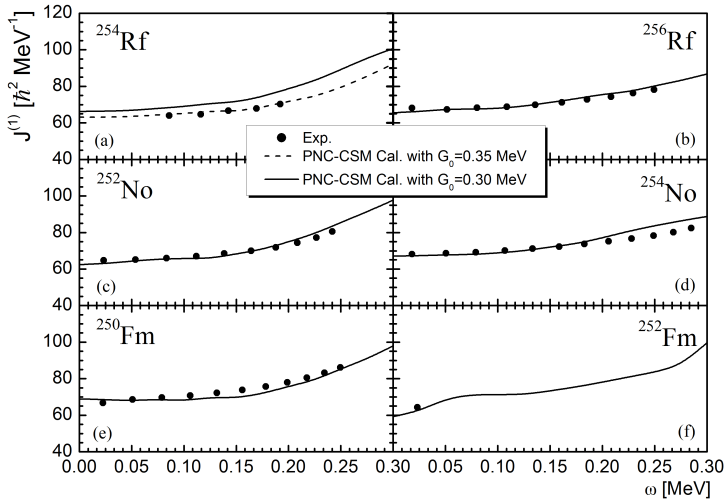
Moment of inertia "spectrum"











Particle-Number-Conserved Cranked Shell Model

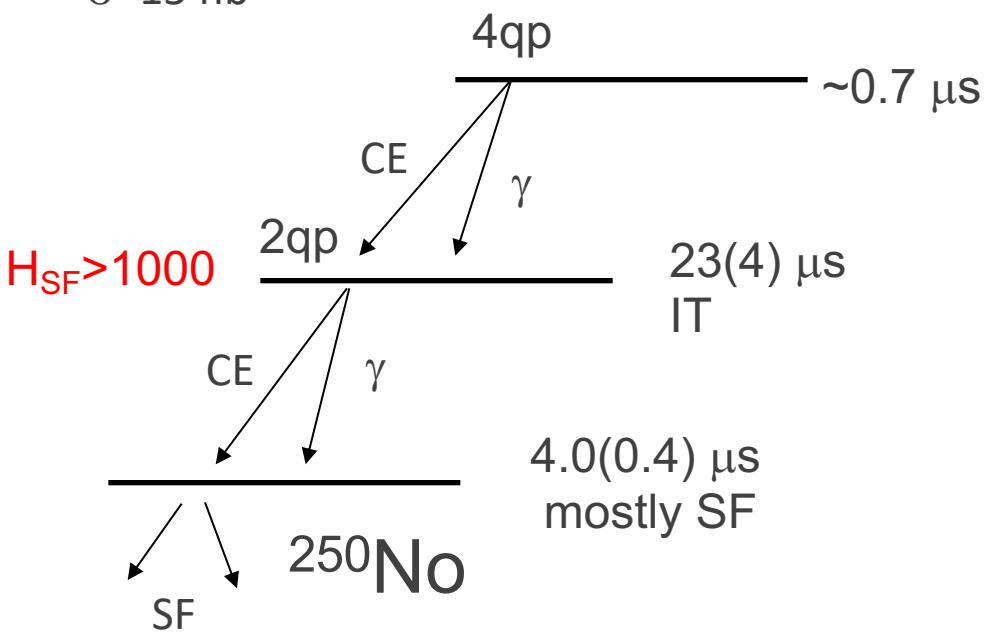
Z.-H. Zhang et al., Phys. Rev. C 87, 054308 (2013)

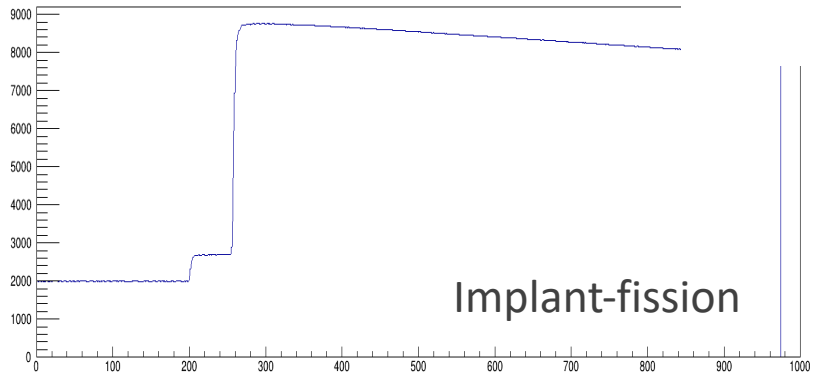
Most fissile nucleus known ^{250}No

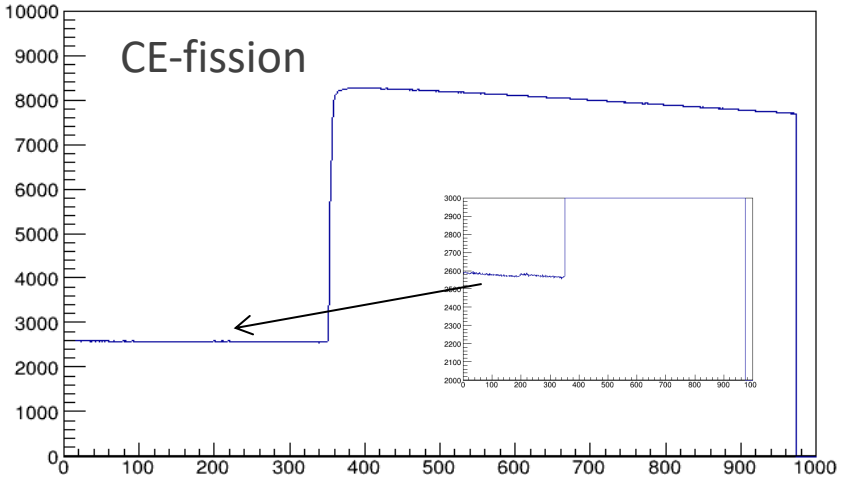
Gammasphere+AGFA
Fall 2023

^{40}Ca+^{204}Pb, ~20-25 pnA, 9 days

σ~15 nb







~2000 fission events detected

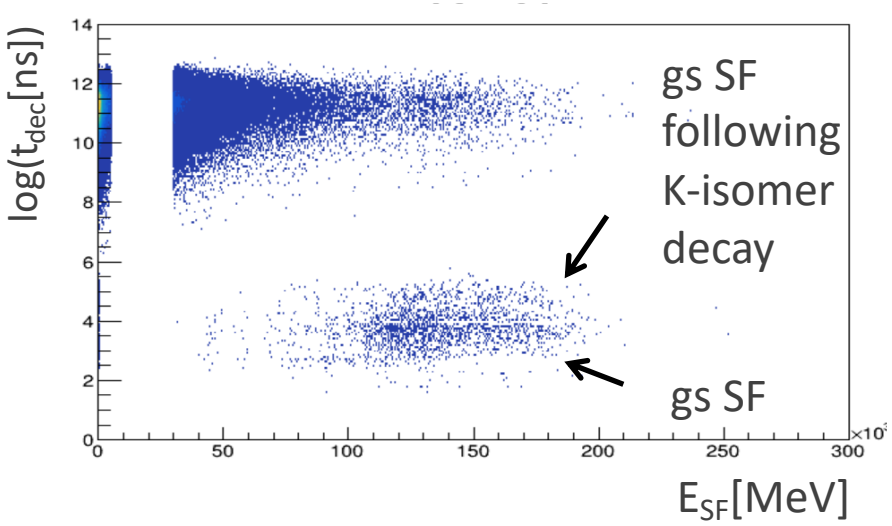
D. Peterson et al. Phys. Rev. C **74**, 014316 (2006) – **ATLAS, FMA, total of 158 SF events, 2 SF lifetimes**

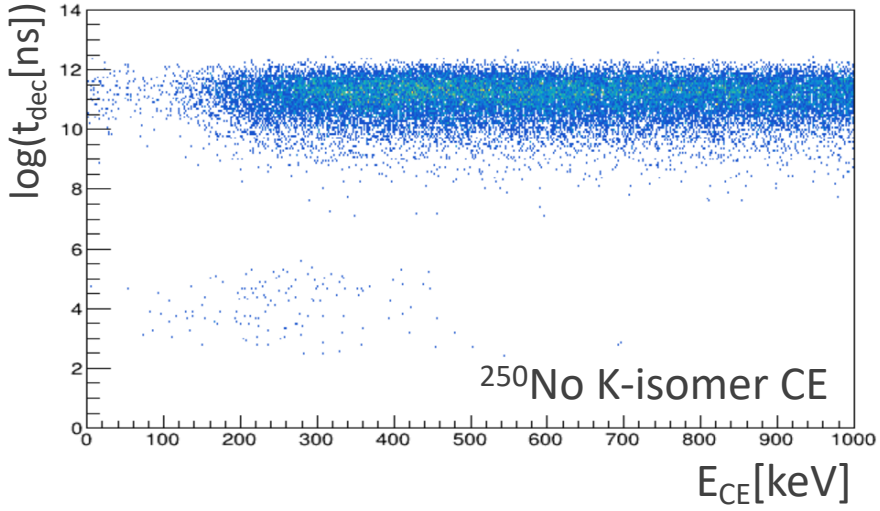
J. Kallunkathariyil et al., Phys. Rev. C **101**, 011301(R) (2020)

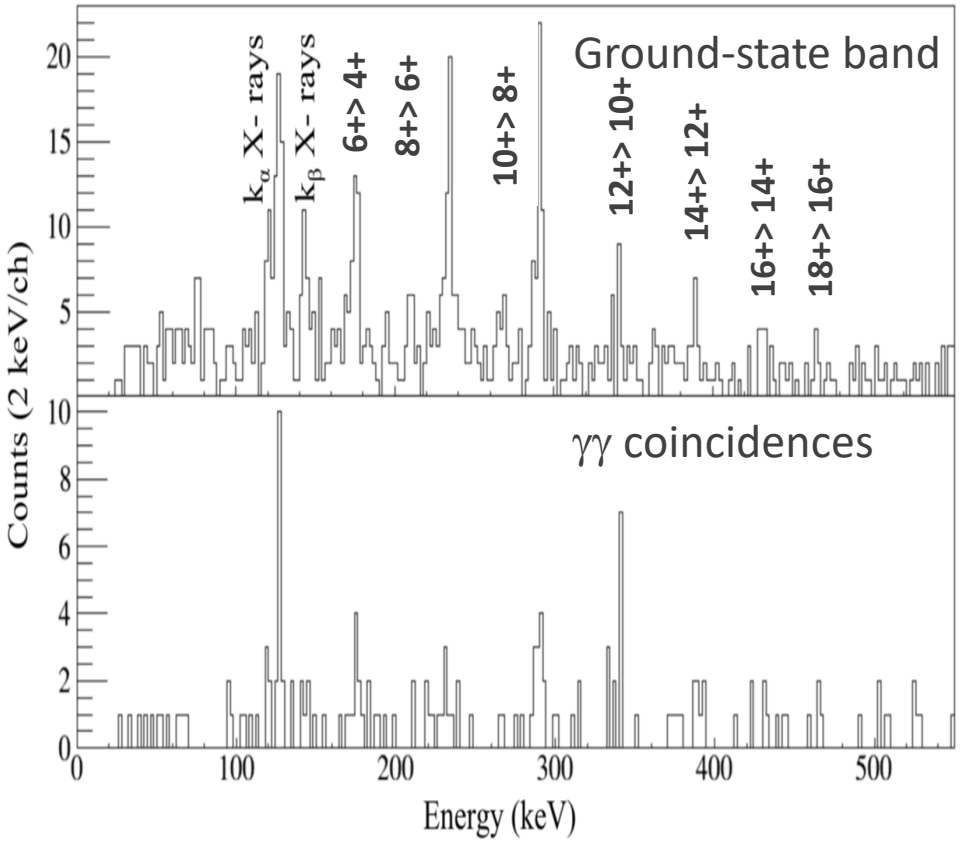
J. Khuyagbaatar et al., Phys. Rev. C **106**, 024309 (2022)

^{250}No ground-state rotational band

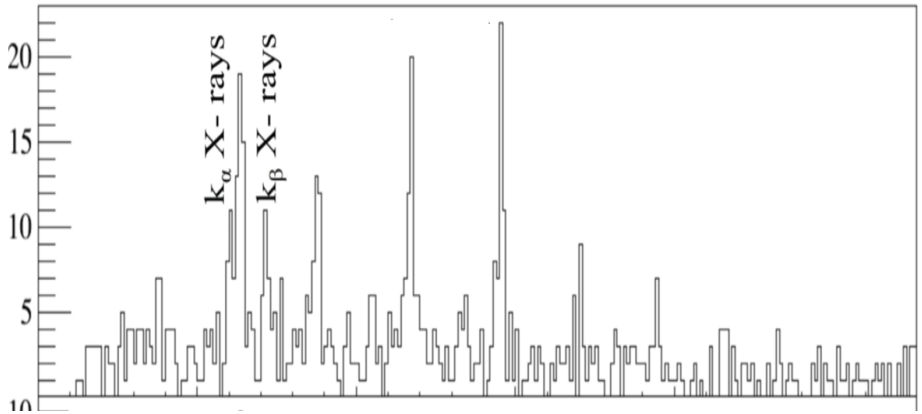
Gammasphere+AGFA







^{254}No and ^{250}No comparison

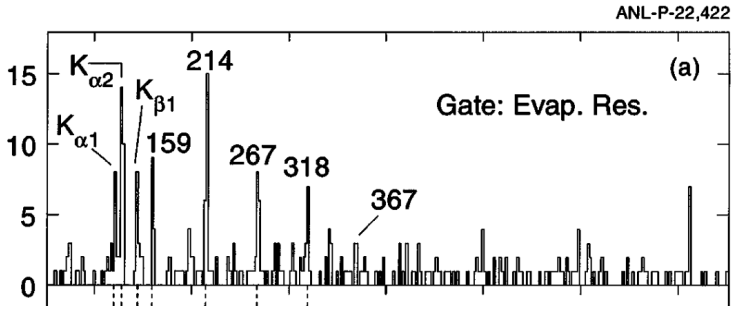


Gammasphere/AGFA
Cross section ~100 times lower

VOLUME 82, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1999

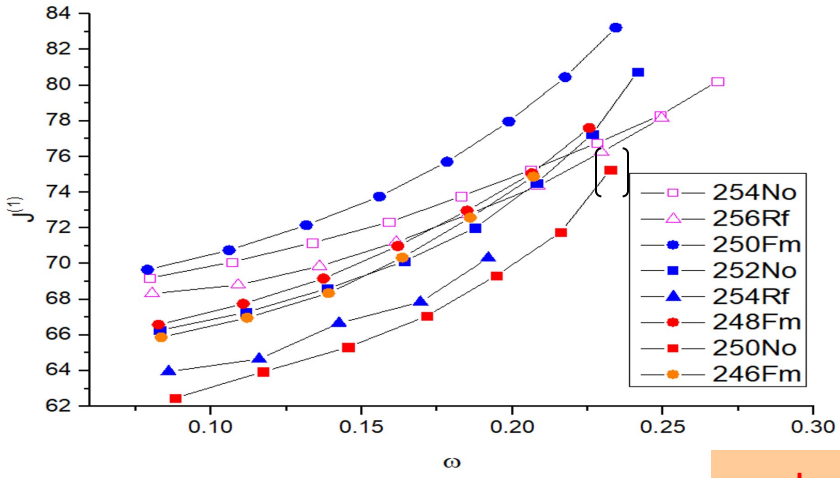
Ground-State Band and Deformation of the $Z = 102$ Isotope ^{254}No

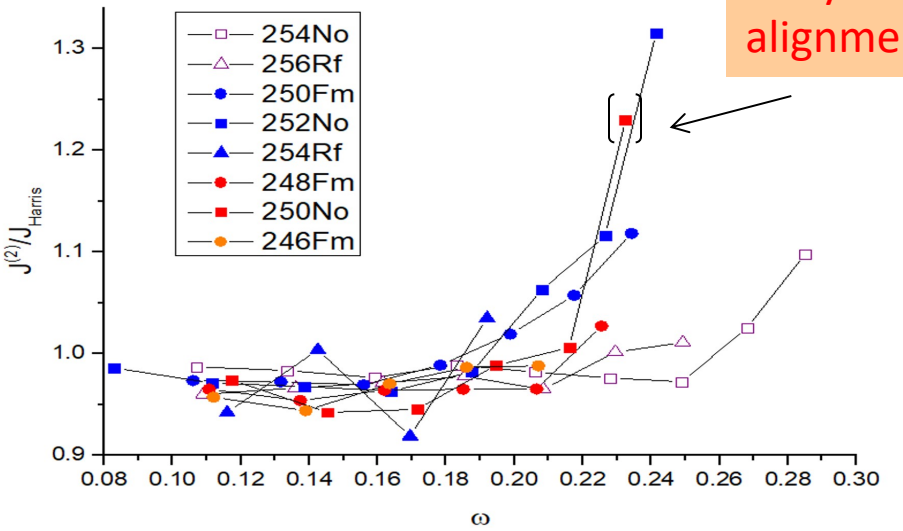
P. Reiter,[1] T. L. Khoo,[1] C. J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M. P. Carpenter,[1] J. A. Cizewski,[1,3] C. N. Davids,[1] G. Gervais,[1] J. P. Greene,[1] W. F. Henning,[1] R. V. F. Janssens,[1] T. Lauritsen,[1] S. Siem,[1,8] A. A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] I. Wiedenhöver,[1] N. Amzal,[2] P. A. Butler,[2] A. J. Chewter,[2] K. Y. Ding,[3] N. Fotiades,[3] J. D. Fox,[4] P. T. Greenlees,[2] R.-D. Herzberg,[2] G. D. Jones,[2] W. Korten,[5] M. Leino,[6] and K. Vetter[7]
[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*University of Liverpool, Liverpool L69 7ZE, England*
[3]*Rutgers University, New Brunswick, New Jersey 08903*
[4]*Florida State University, Tallahassee, Florida 32306*
[5]*DAPNIA/SPhN, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France*
[6]*University of Jyväskylä, Jyväskylä, Finland*
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[8]*University of Oslo, Oslo, Norway*
(Received 21 October 1998)



Gammasphere/FMA
The very first in-beam γ-ray spectrum in a transfermium nucleus

Moments of inertia near Z=100, N=152





early alignment?

Harris formula:

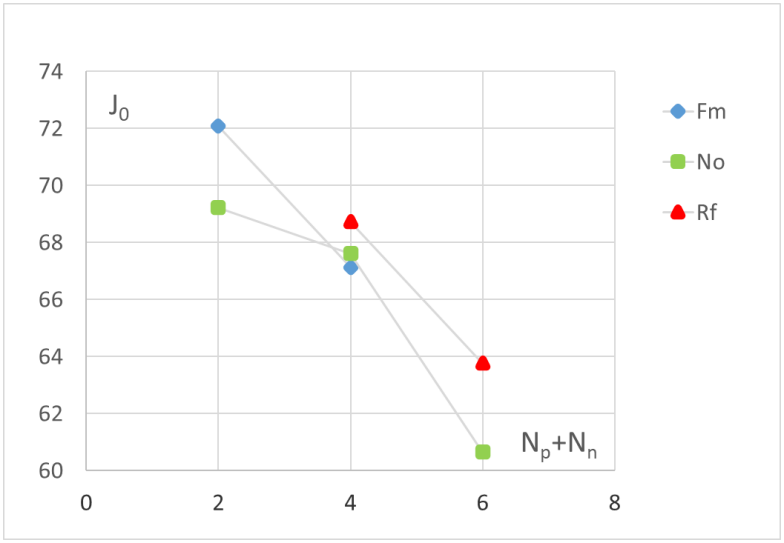
$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2$, kinematic MOI

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

Values fitted for ^{250}No:

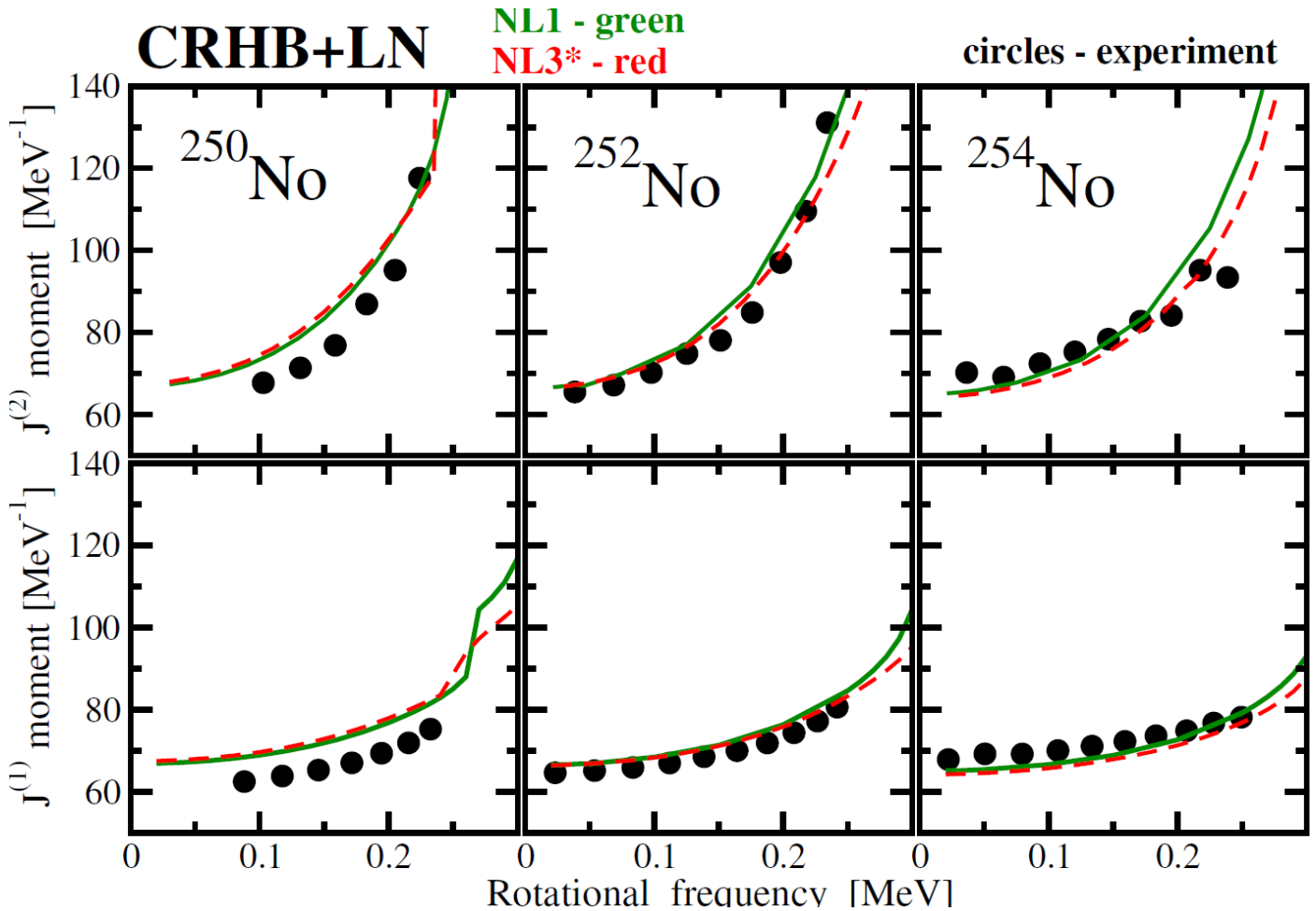
$\Im^{(1)}$=60.7 $\hbar^2$/MeV

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



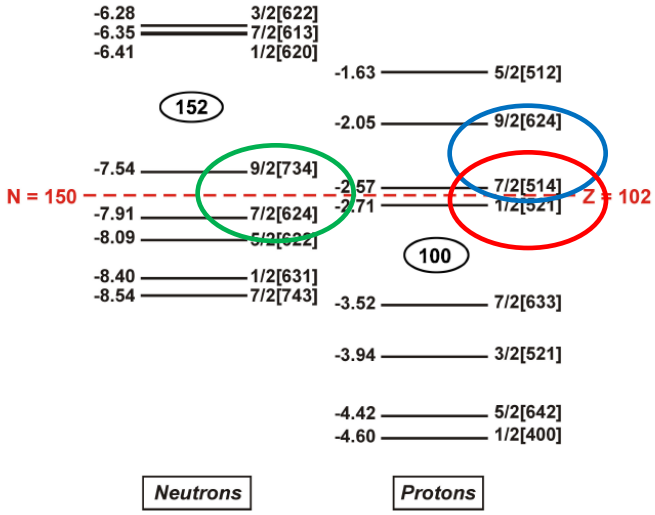
MOI at ω=0 drops down away from Z=100, N=152

Cranked relativistic HFB calculations



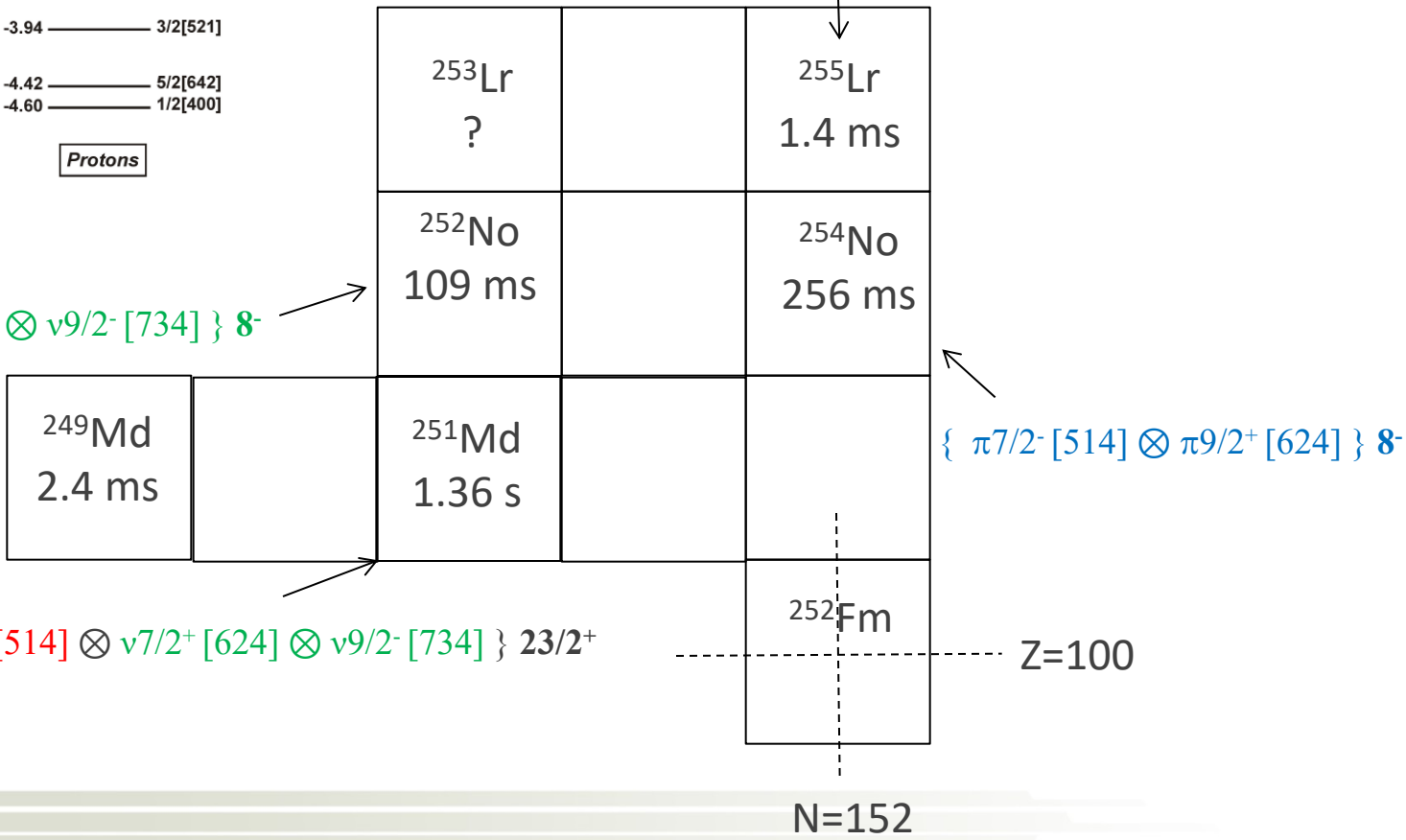
A. V. Afanasjev and O. Abdurazakov, Phys. Rev. C 88, 014320 (2013)

3-qp K-isomers in odd-Z nuclei near Z=100, N=152



{π7/2⁻ [514] ⊗ π11/2⁻ [725] ⊗ π9/2⁺ [624] } **(25/2⁺)**

{π1/2⁻ [521] ⊗ π7/2⁻ [514] ⊗ π9/2⁺ [624] } **15/2⁺**

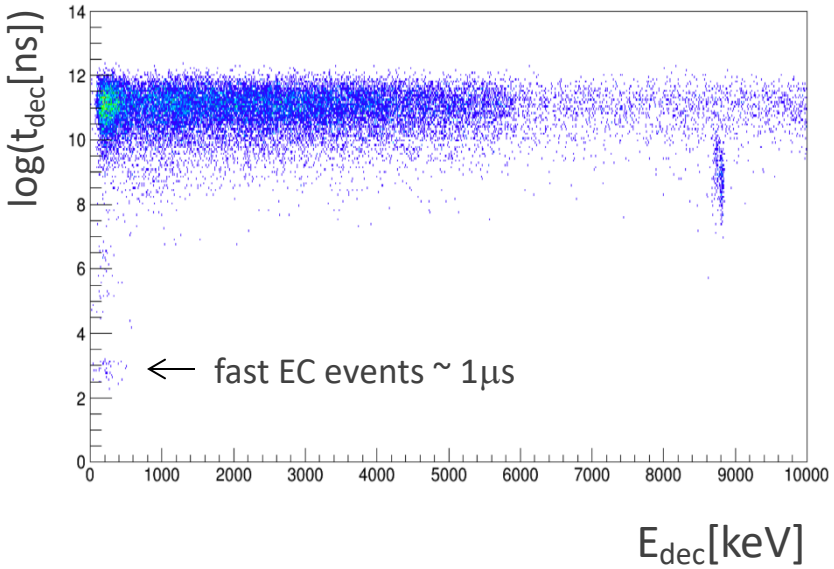


{ ν7/2⁺ [624] ⊗ ν9/2⁻ [734] } **8⁻**

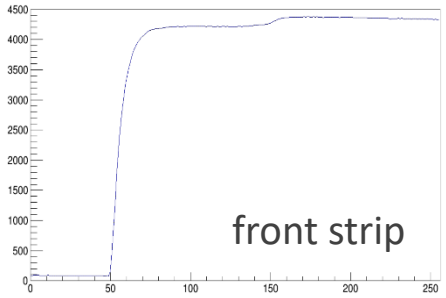
{ π7/2⁻ [514] ⊗ π9/2⁺ [624] } **8⁻**

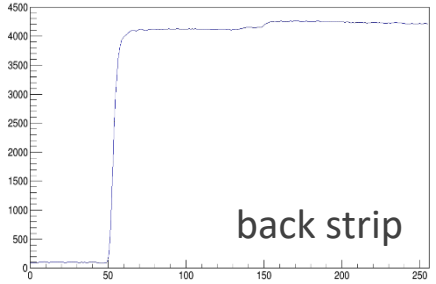
{ π7/2⁻ [514] ⊗ ν7/2⁺ [624] ⊗ ν9/2⁻ [734] } **23/2⁺**

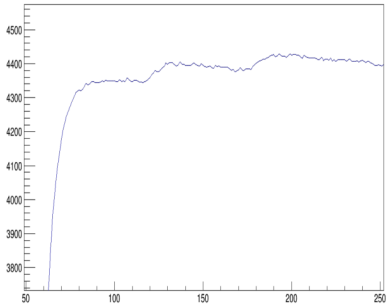
Evidence for two fast (<1 μs) isomers in ^{253}Lr

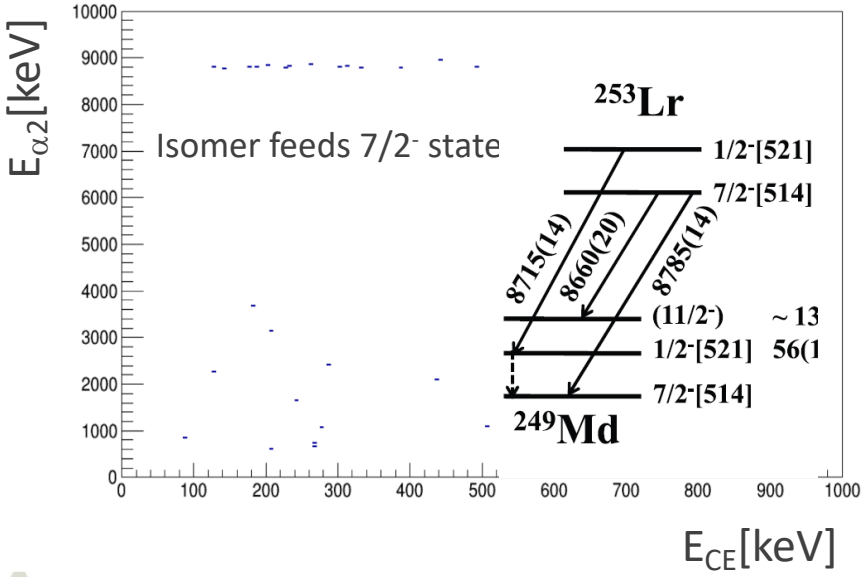


DSSD traces





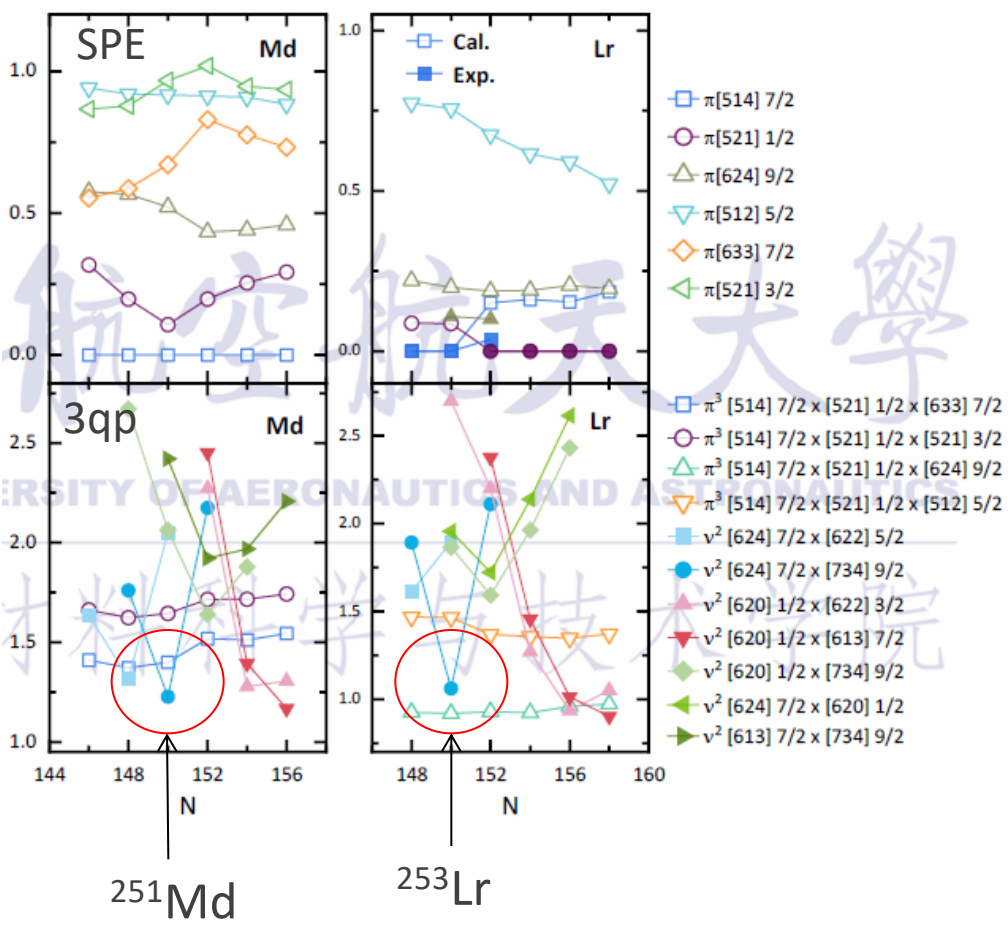




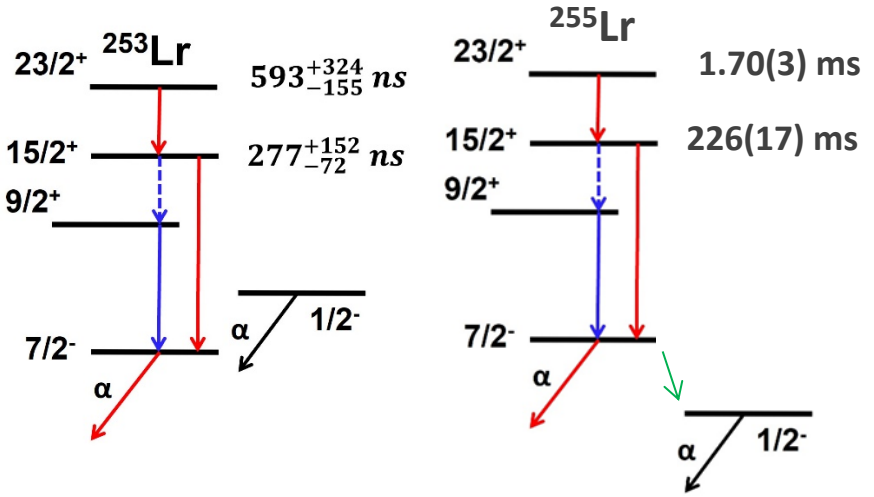
Two fast $T_{1/2}$<1μs isomers followed by ^{253}Lr α decay

Fast isomer also found in ^{255}Lr feeding both ½⁻ and 7/2⁻ levels

Particle-Number Conserving Cranked Shell Model



X.-T. He, of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, private communication



Based on calculations:

{ π7/2⁻ [514] ⊗ ν7/2⁺ [624] ⊗ ν9/2⁻ [734] } **23/2⁺**

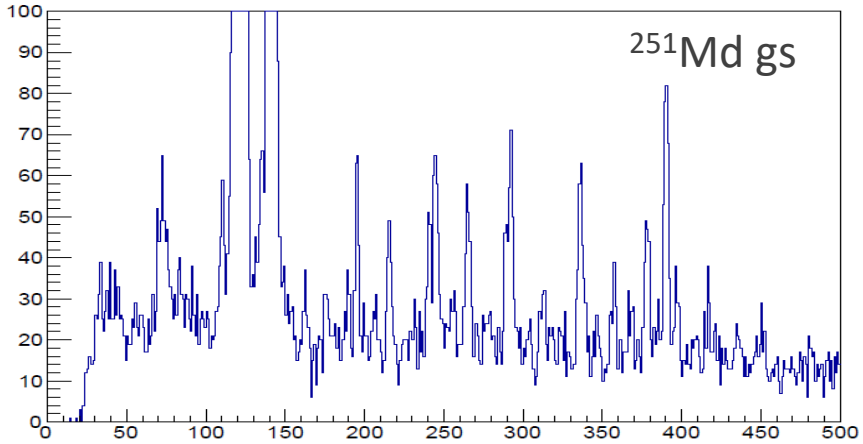
{ π1/2⁻ [521] ⊗ π7/2⁻ [514] ⊗ π9/2⁺ [624] } **15/2⁺**

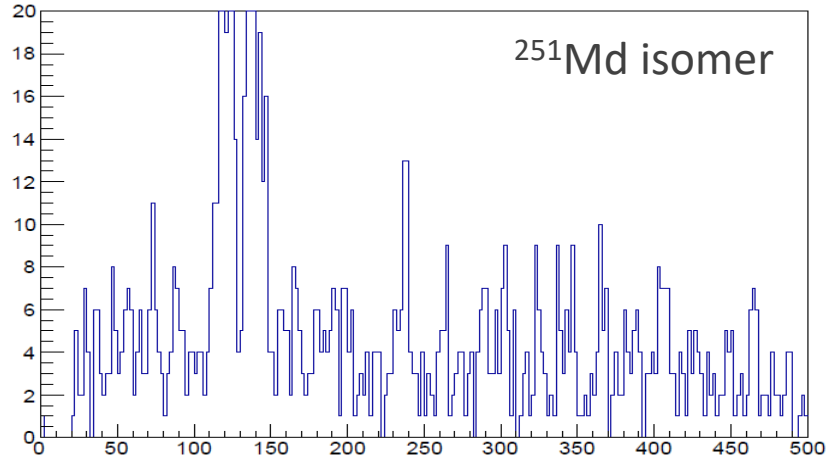
23/2⁺ isomer same as in ^{251}Md but much shorter lifetime due to intermediate π^3 isomer at lower excitation energy

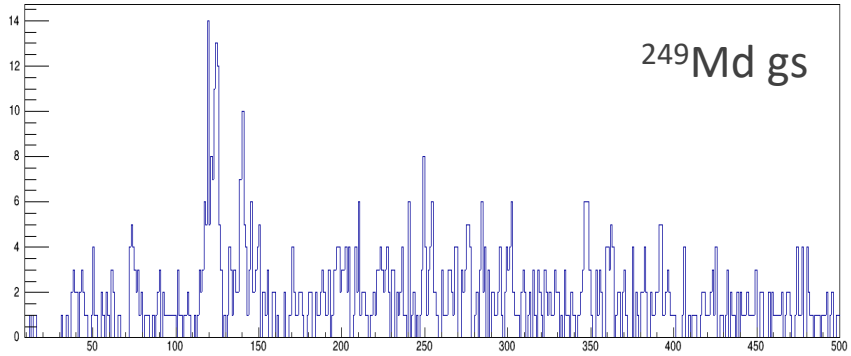
Rotational bands in odd-Z nuclei

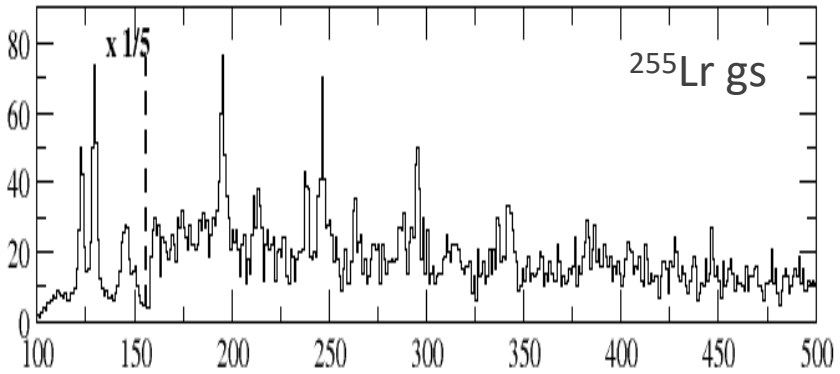
^{249,251}Md, R.M. Clark, C. Morse, C. J. Appleton et al.

^{255}Lr, A. Korichi et al.









Properties of bands feeding isomers can constrain their configurations

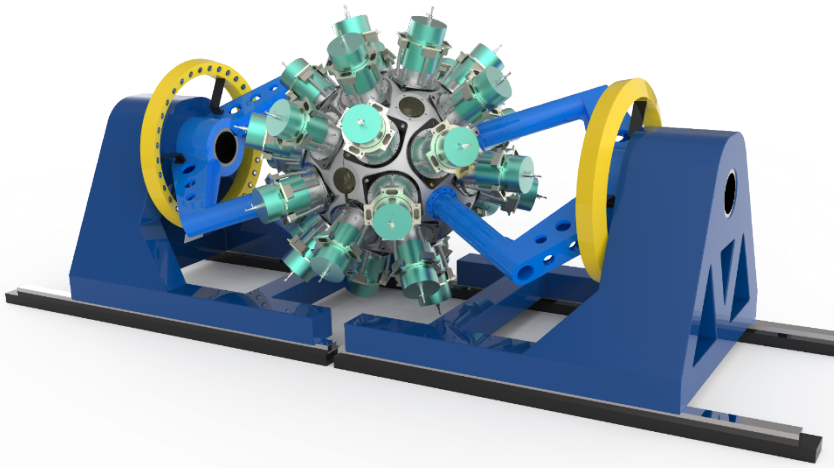
Collaboration

B. Back, T. Budner, M.P. Carpenter, P. Copp, H. Jayatissa, T-L. Khoo, F.G. Kondev, T. Lauritsen, C. Morse, C. Müller-Gatermann, V. Karayonchev, D. Potterveld, W. Reviol, G. Savard, N. Sensharma, M. Siciliano, D. S., **ANL**
K. Hauschild, A. Lopez-Martens, A. Korichi, **IJCLab-Orsay**
R.M. Clark, C.J. Appleton, H. Crawford, C. Porzio, **LBNL**
T. Huang, **Institute of Modern Physics, Lanzhou, China**
P. Chowdhury, C. Burns, G. W. Shaikh, M. Tseng, **UMass Lowell**
C. Morse, **BNL**
R. Herzberg, **University of Liverpool**
D. Rudolph, Y. Hrabar, L. Sarmiento, **Lund University**
G. Morgan, **LSU**
R.S. Sidhu, **University of Edinburgh**
S. Chemey, **Oregon State University**
Xao-Tao He, Yi-Fei Xu, College of Materials Science and Technology, **Nanjing University of Aeronautics and Astronautics, Nanjing, China**

Tianheng Huang

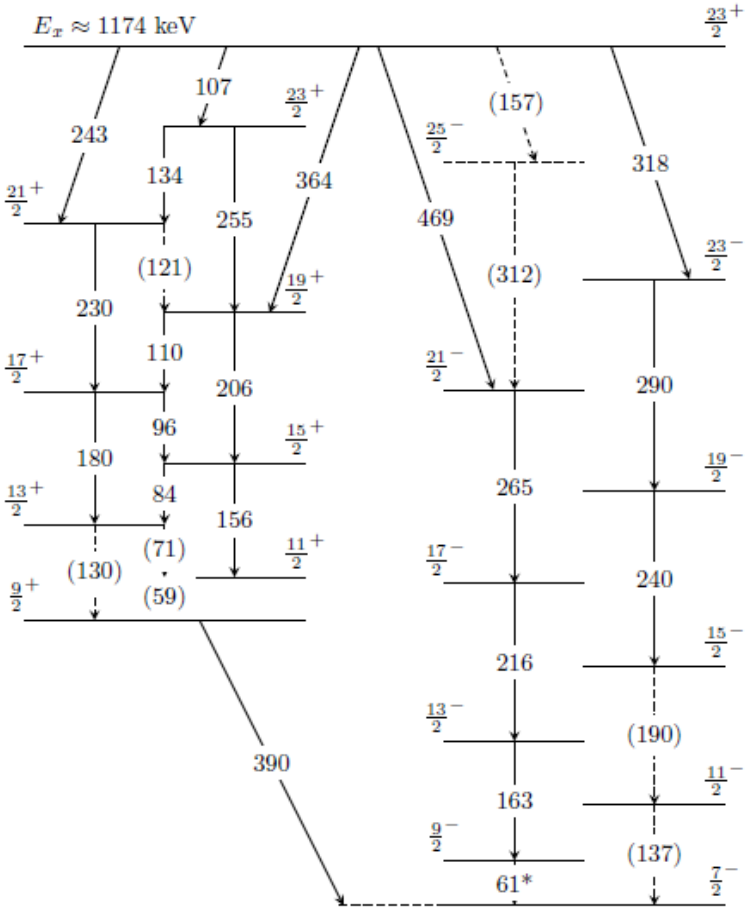
Summary and Outlook

- New in-beam results on trans-fermium nuclei obtained with Gammasphere/ AGFA
  - ground-state rotational bands observed in the most fissile nuclei known **^{254}Rf** and **^{250}No**
  - observation of rapidly-decaying isomers in **^{253}Lr** and **^{255}Lr**
  - rotational bands in **odd-Z** nuclei **^{249,251}Md** and **^{255}Lr** were observed including bands feeding isomers
- Outlook
  - N>152 nucleus **^{256}No**
  - **^{253}No** HK distributions
  - detailed decay spectroscopy of **^{251}Md**
  - new implantation-decay station
- Dream
  - coupling of **GRETA** to AGFA

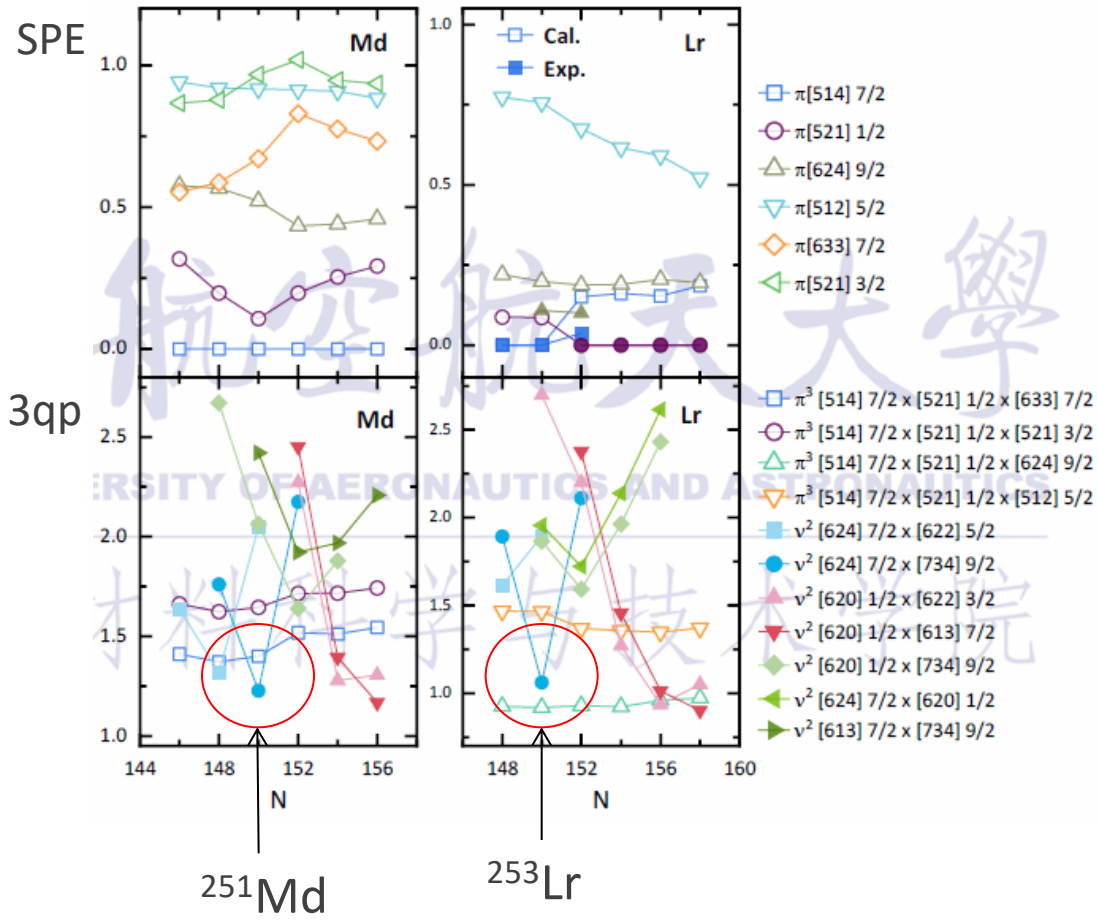


3-qp K-isomer in ^{251}Md

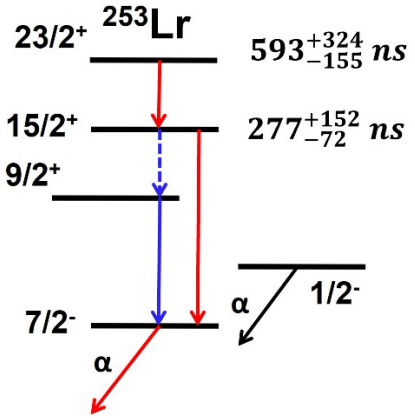
C. Morse, R.M. Clark at al,



Particle-Number Conserving Cranked Shell Model



X.-T. He, of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, private communication



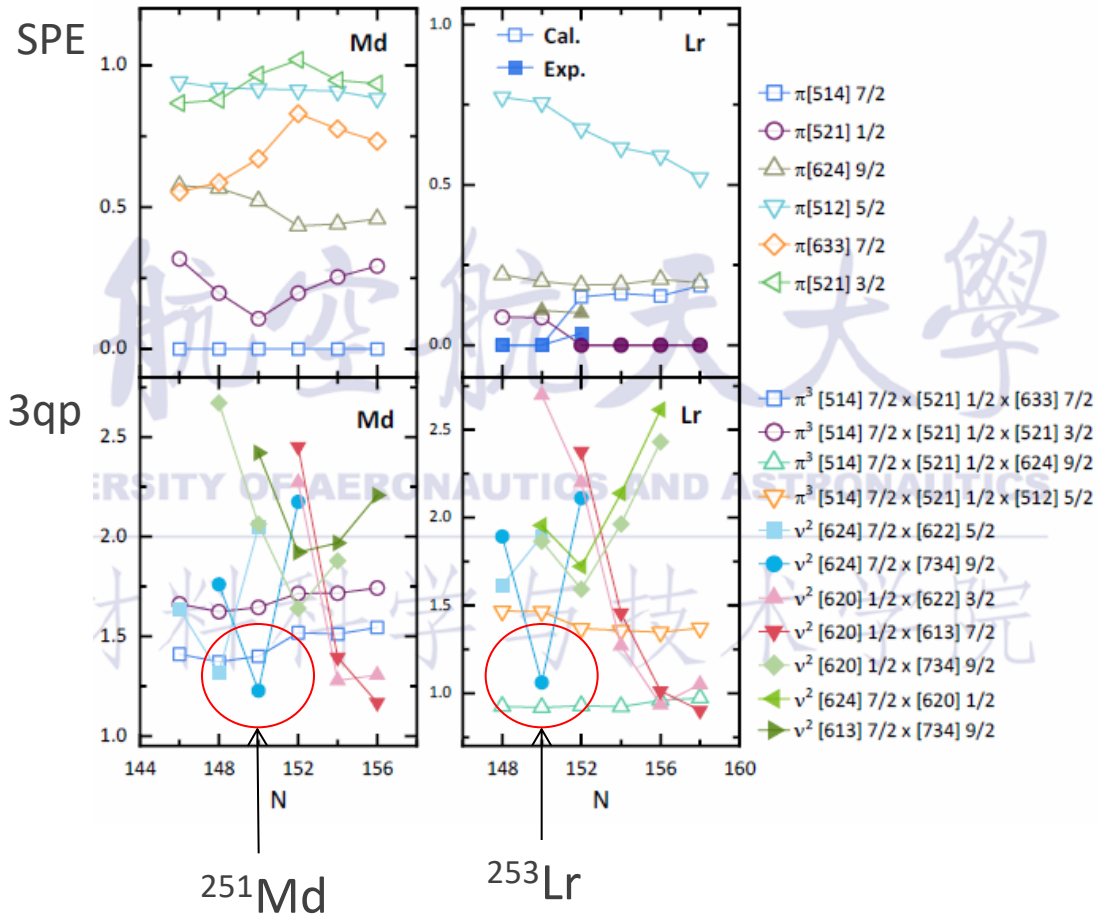
Based on calculations:

{ $\pi 7/2^-[514] \otimes \nu 7/2^+[624] \otimes \nu 9/2^-[734]$ } $\mathbf{23/2^+}$

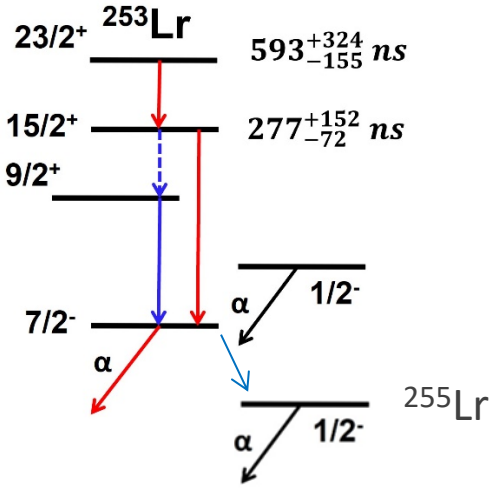
{ $\pi 1/2^-[521] \otimes \pi 7/2^-[514] \otimes \pi 9/2^+[624]$ } $\mathbf{15/2^+}$

$23/2^+$ isomer same as in ^{251}Md but much shorter lifetime due to intermediate π^3 isomer at lower excitation energy

Particle-Number Conserving Cranked Shell Model



X.-T. He, of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, private communication



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{ π7/2⁻ [514] ⊗ ν7/2⁺ [624] ⊗ ν9/2⁻ [734] } **23/2⁺**

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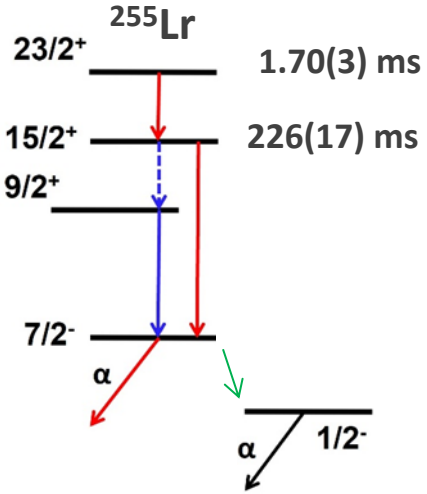
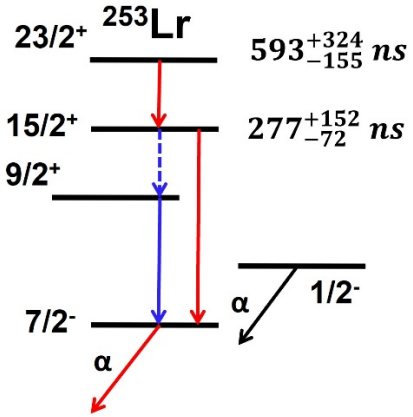
23/2⁺ isomer same as in ^{251}Md but much shorter lifetime due to intermediate π³ isomer at lower excitation energy


^{255}Lr
23/2$^+$
1.70(3) ms
15/2$^+$
226(17) ms
9/2$^+$
7/2$^-$
α
α
1/2$^-$


^{253}Lr
23/2$^+$
593^{+324}_{-155} ns
15/2$^+$
277^{+152}_{-72} ns
9/2$^+$
7/2$^-$
α
α
1/2$^-$

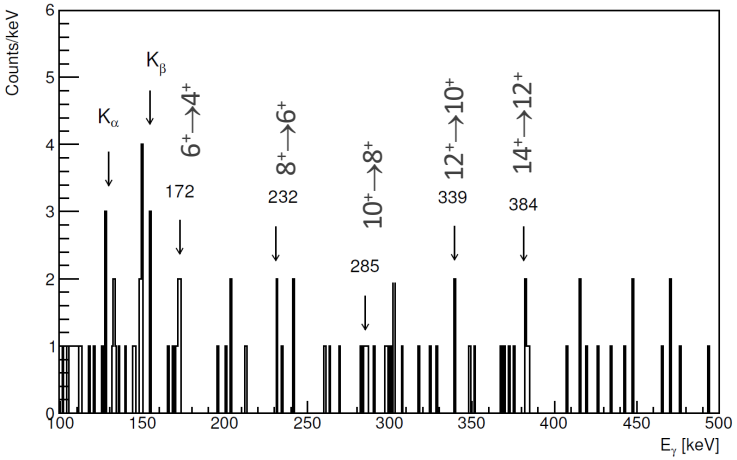
Moment of inertia of fissile ^{254}Rf

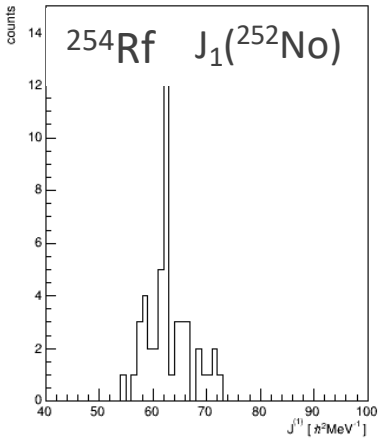
Gammasphere+AGFA

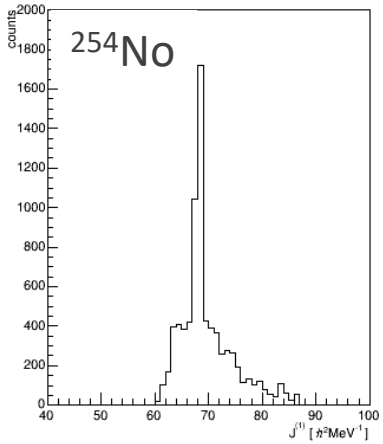
D. Seweryniak, T. Huang et al., Phys. Rev. C **107**, L061302 (2023)

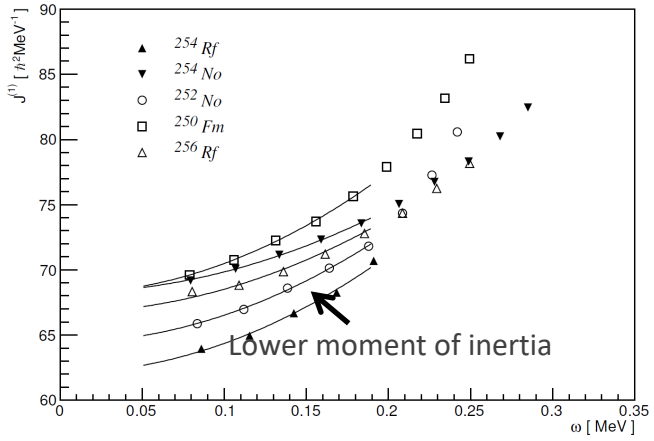
$J_0 \sim (2I-1)/E_\gamma - J_1(E\gamma/2)^2$

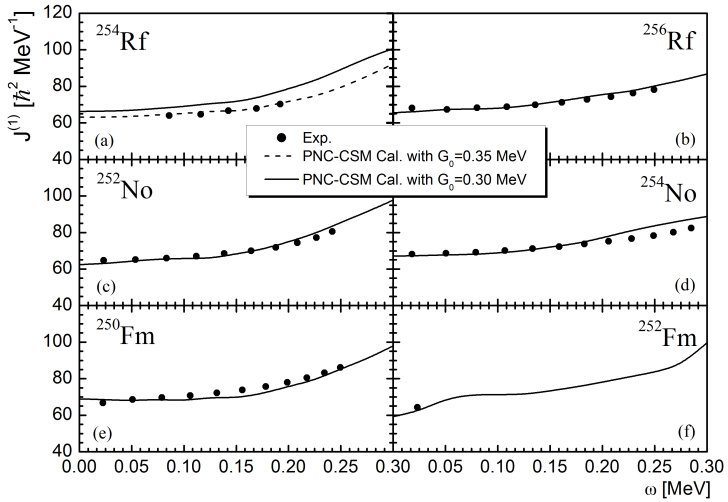
Moment of inertia "spectrum"





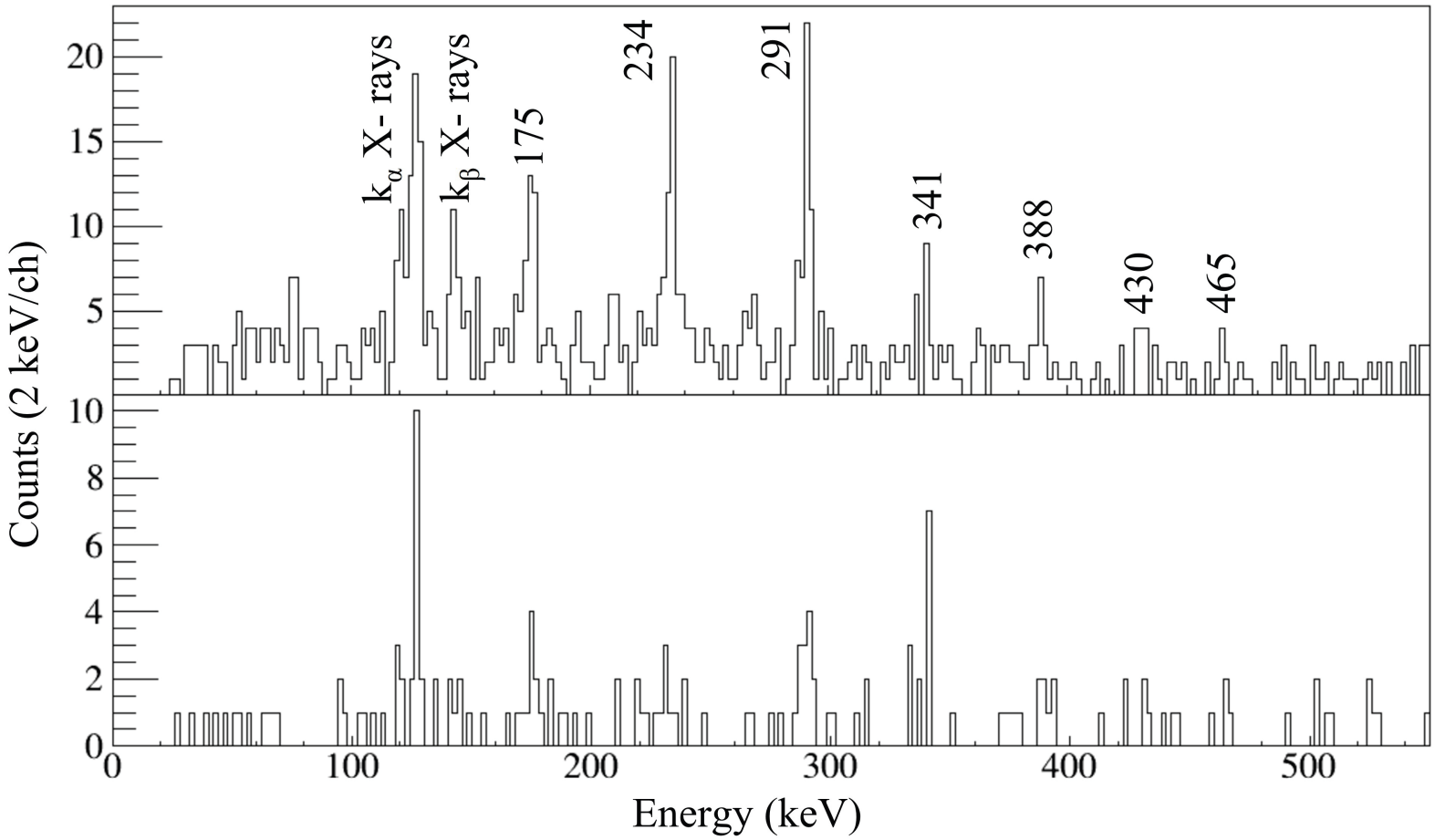






Particle-Number-Conserved Cranked Shell Model

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


Counts (2 keV/ch)
Energy (keV)
k_α X- rays
k_β X- rays
175
234
291
341
388
430
465
0
100
200
300
400
500
0
2
4
6
8
10
5
10
15
20