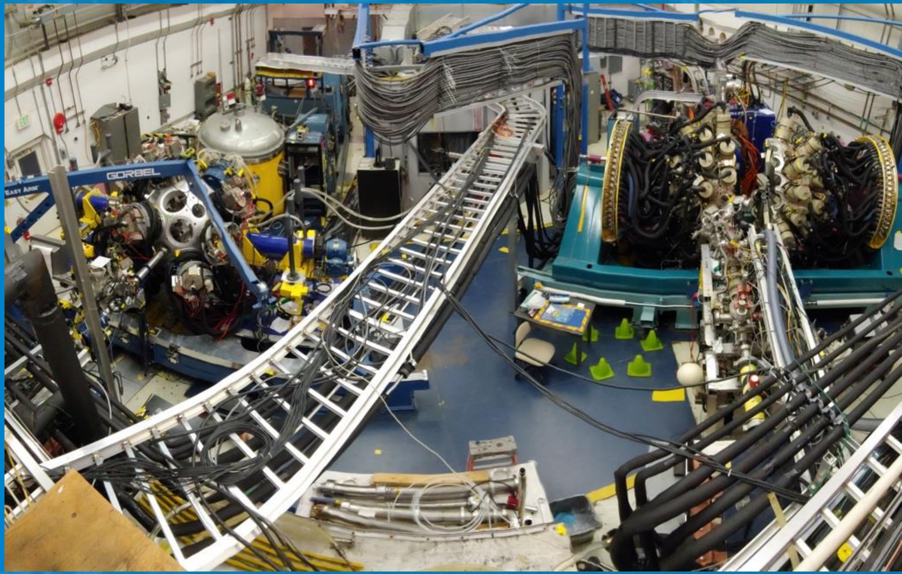
Nuclear Physics Over The Years: From the high spin era to rare isotopes

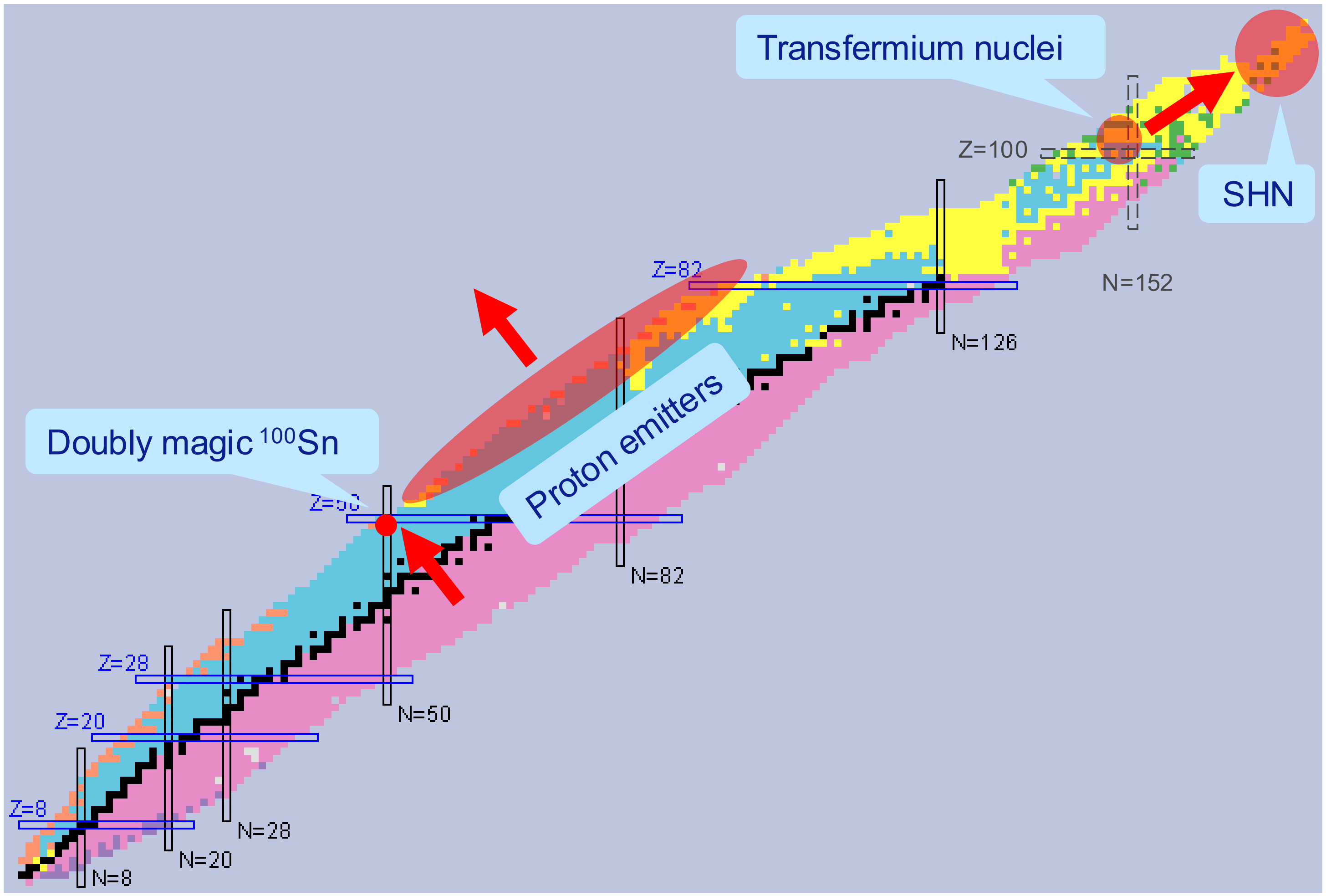
UNC Chapel Hill, September 19-20, 2025

Marrying In-Beam and Decay Spectroscopy to Reveal the Structure of Exotic Nuclei

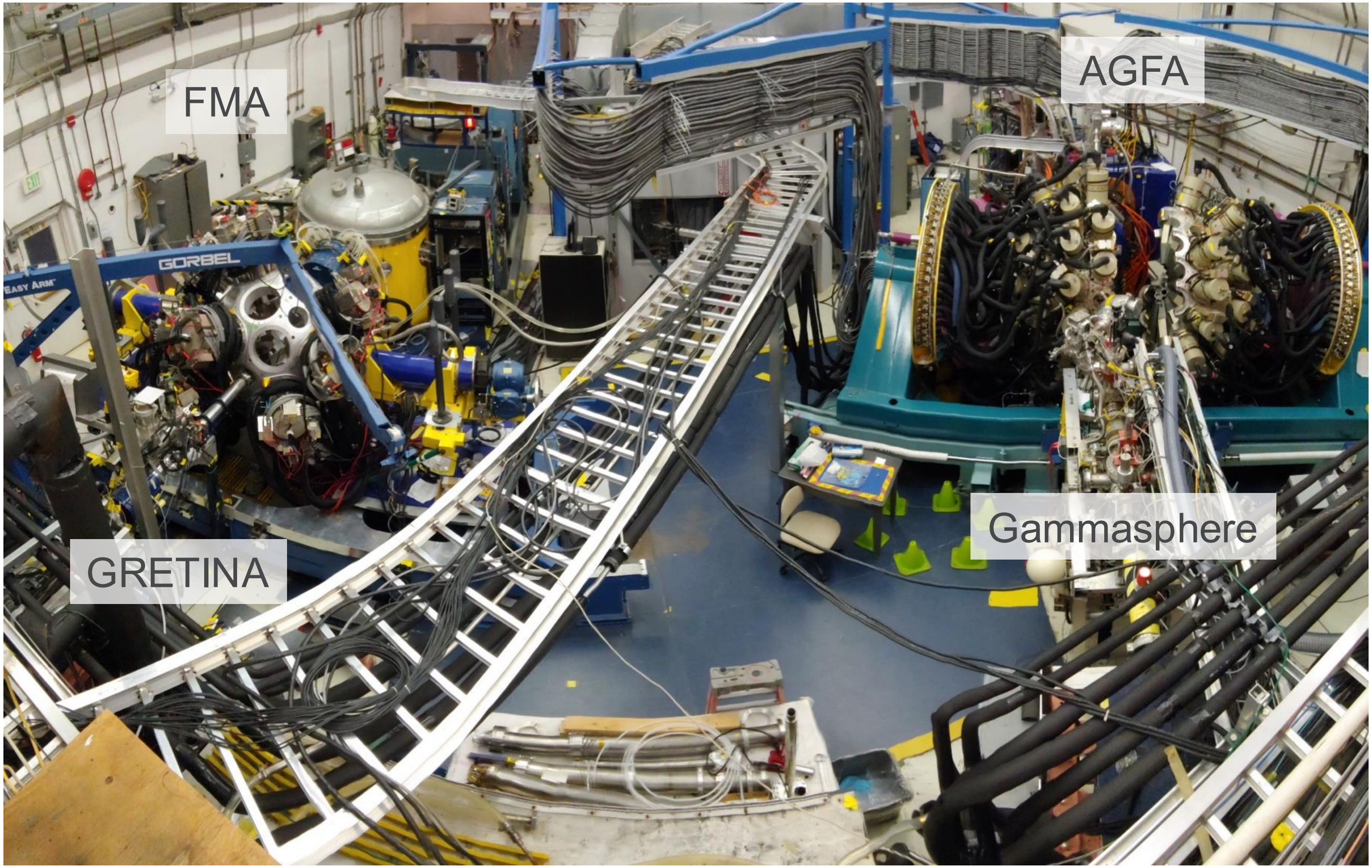


Darek Seweryniak
Argonne National Laboratory

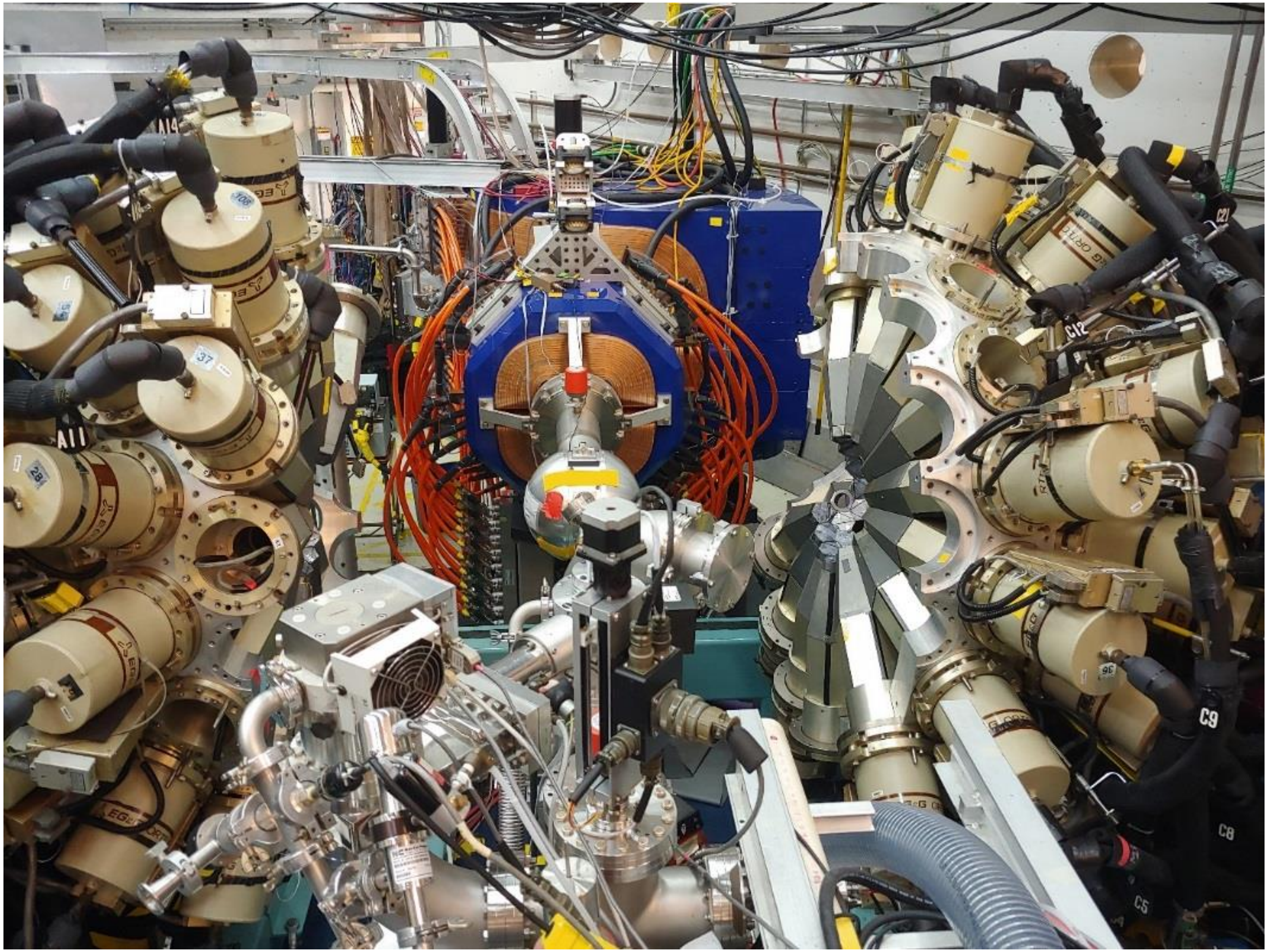
Spectroscopy of exotic nuclei at ATLAS



ATLAS experimental Area IV



Gammasphere and Argonne Gas-Filled Analyzer

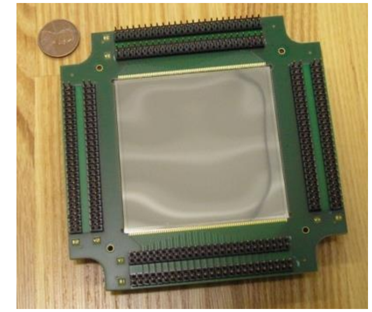


GRETINA and Fragment Mass Analyzer

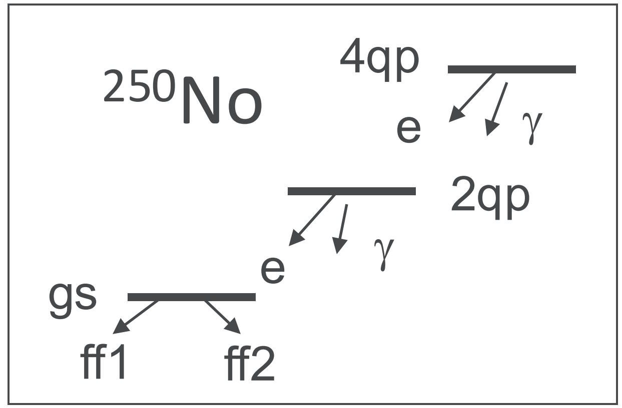
Custom FMA entrance quadrupole doublet fits inside the GRETINA frame resulting in ~6 times larger solid angle compared to experiments with Gammasphere

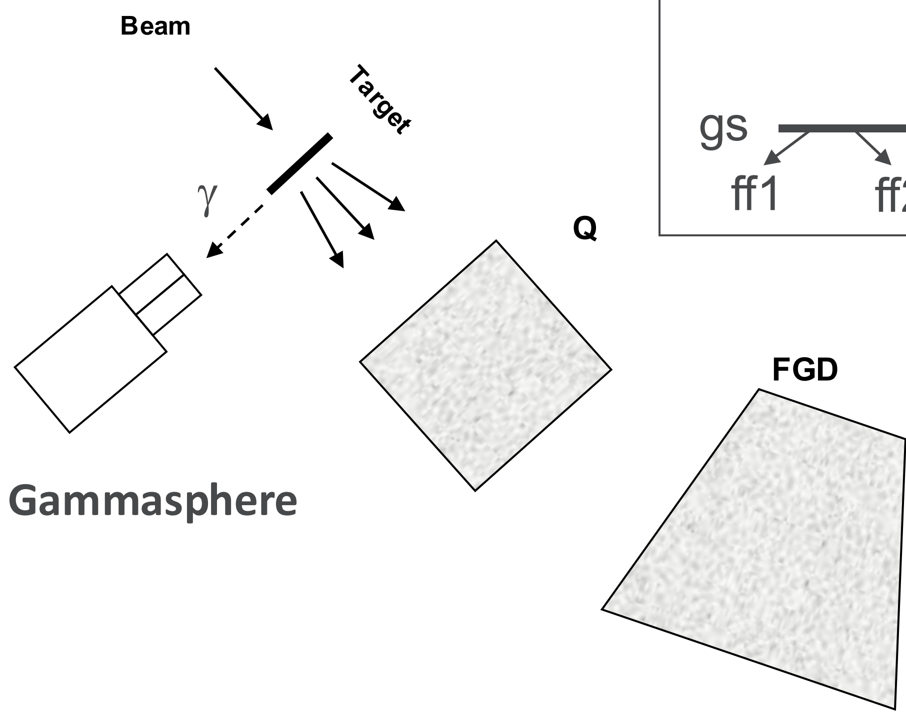
21 GRETINA-FMA experiments so far

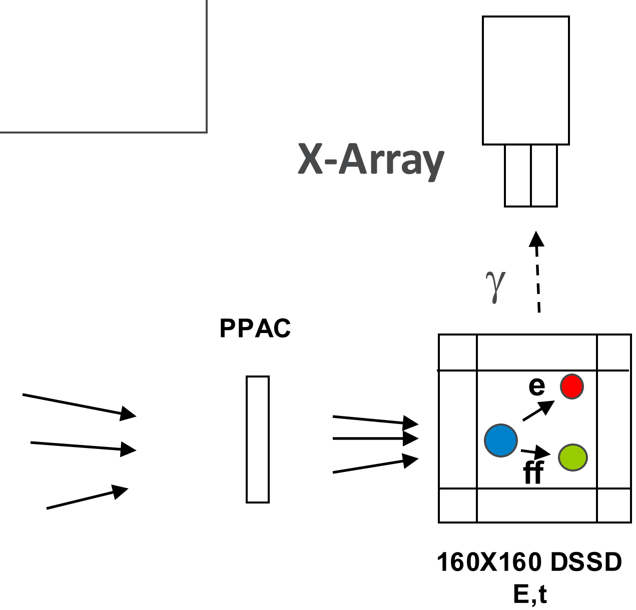
RECOIL-DECAY TAGGING



160X160, 64mmX64mm DSSD



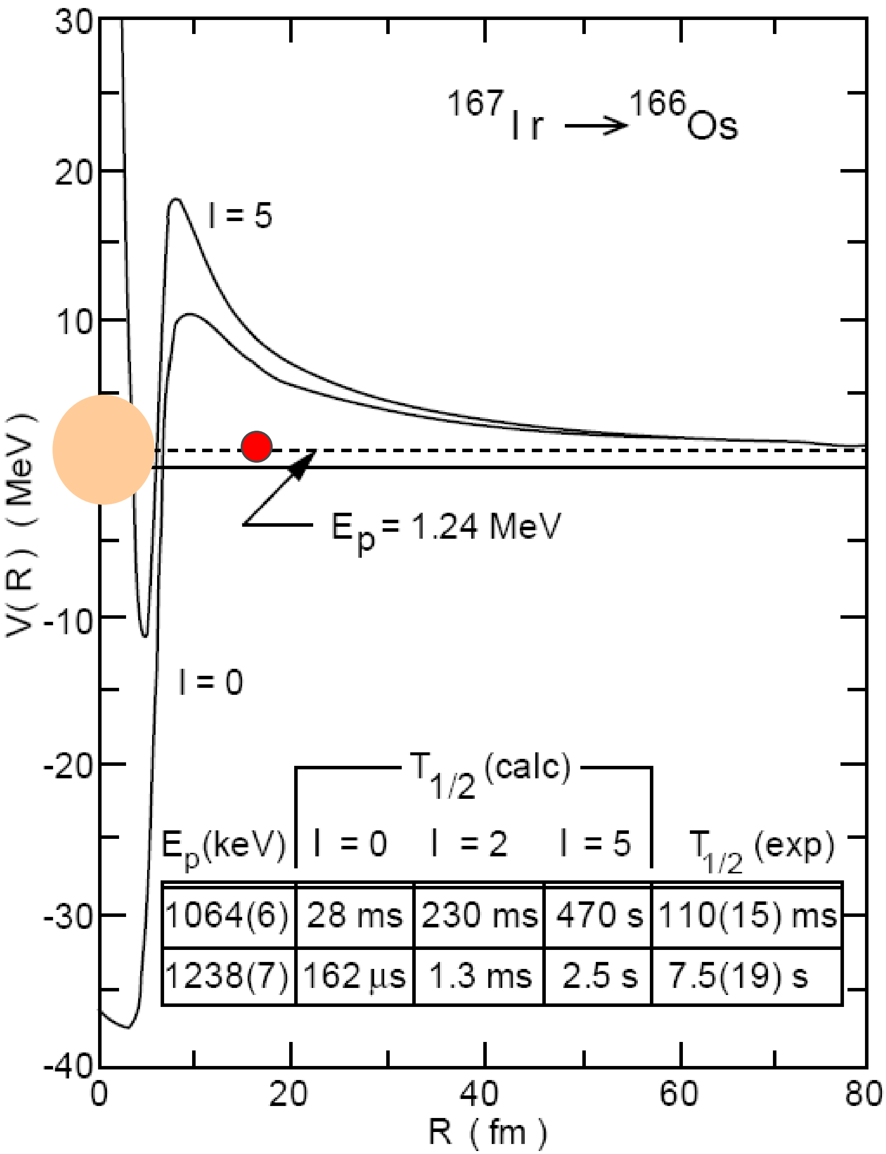




In-beam γ-rays in coincidence with implants ← **Implant-decay spatial and time correlations in the DSSD** → **conversion electrons and gamma rays deexciting isomers followed by α decay**

Proton drip line

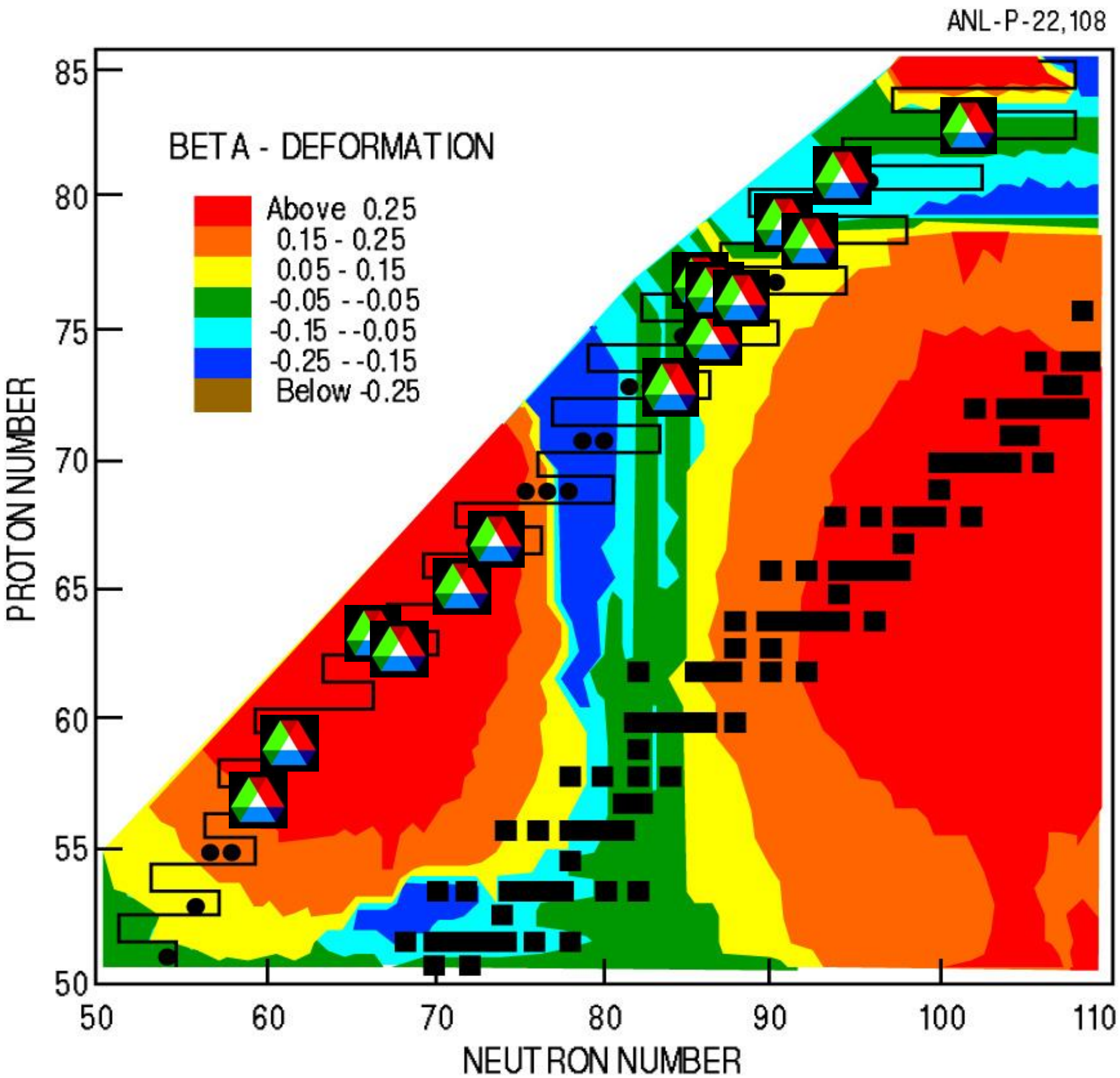
Spontaneous proton emission



E_p(keV)	$T_{1/2}$ (calc) l = 0	l = 2	l = 5	$T_{1/2}$ (exp)
1064(6)	28 ms	230 ms	470 s	110(15) ms
1238(7)	162 μs	1.3 ms	2.5 s	7.5(19) s

- ✓ Analogous to α decay
- ✓ No pre-formation factor
- ✓ Decay rates sensitive to E_p and l_p
- ✓ Unique laboratory to study tunneling through a 3D barrier
- ✓ Source of information on nuclear structure and masses far from stability
- ✓ Γ_p important for (p,γ) cross sections in light p-rich nuclei in the path of the rp-process

Proton emitter landscape

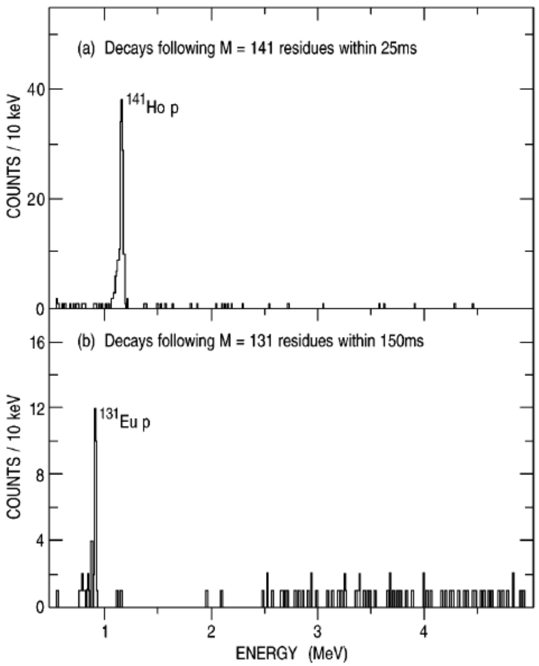


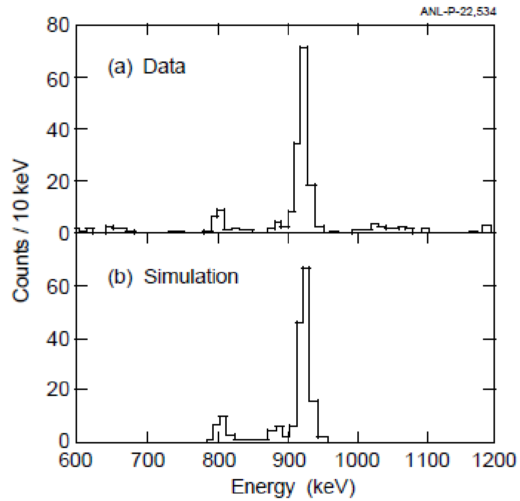
- ✓ 15 new isotopes!
- ✓ ~20-30 mass units away from the line of stability
- ✓ Often less exotic neighbors not known

Program with FMA initiated by C.N. Davids in mid 1990s in collaboration with P.J. Woods from University of Edinburgh

Recently with FMA:
^{116}La (T=0 np pairing)
^{125}Pm ("missing" proton emitter)
and AGFA:
^{185}Bi (PRL, isomer)
heavy At, Fr proton emitters

First deformed proton emitter ^{131}Eu





- ✓ Spherical
- ✓ Axially deformed
- ✓ Odd-odd axially deformed
- ✓ Coupling to vibrations
- ✓ Non-axial deformation

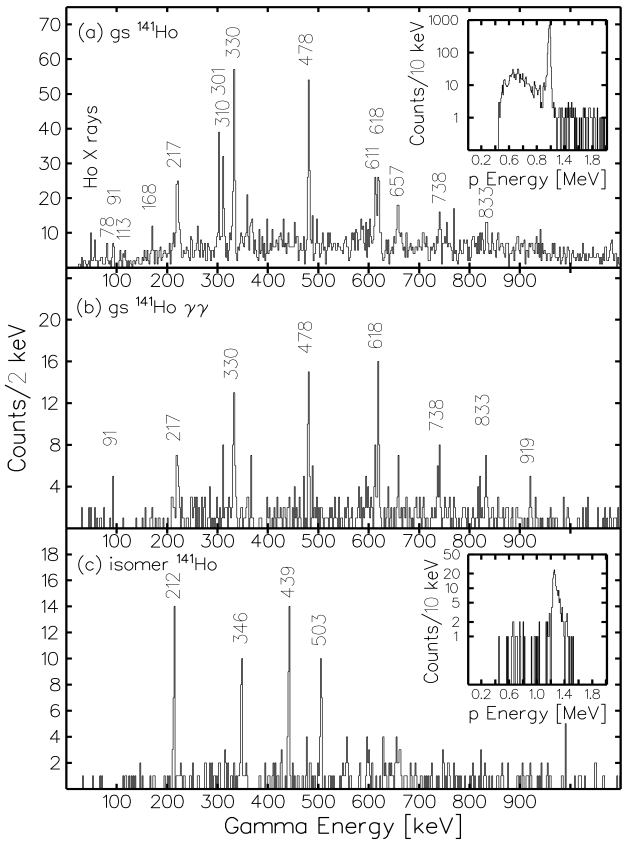
First deformed proton emitters
Anomalous decay rates explained by introducing deformation

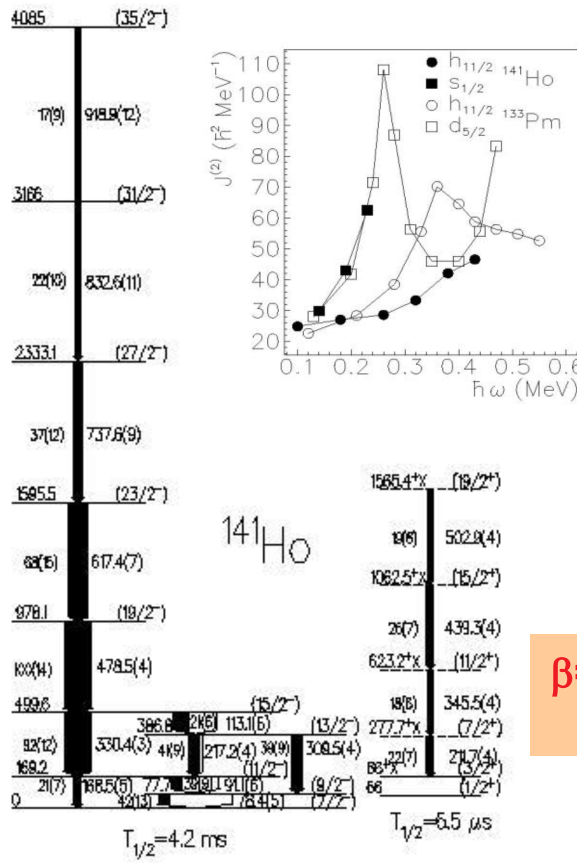
First fine structure

C.N. Davids, P.J. Woods, D. Seweryniak, A.A. Sonzogni et al., PRL C55, 2255 (1997)

A.A. Sonzogni, C.N. Davids, P.J. Woods, D. Seweryniak et al., PRL 83, 1116(1999)

Rotational bands in deformed proton emitter ^{141}Ho





7/2$^-$[523] ½$^+$[411]

Unexpectedly large signature splitting indicates triaxial shape!

β=0.25(4) from Harris formula

D. Seweryniak et al., PRL **86**, 1458 (2001)

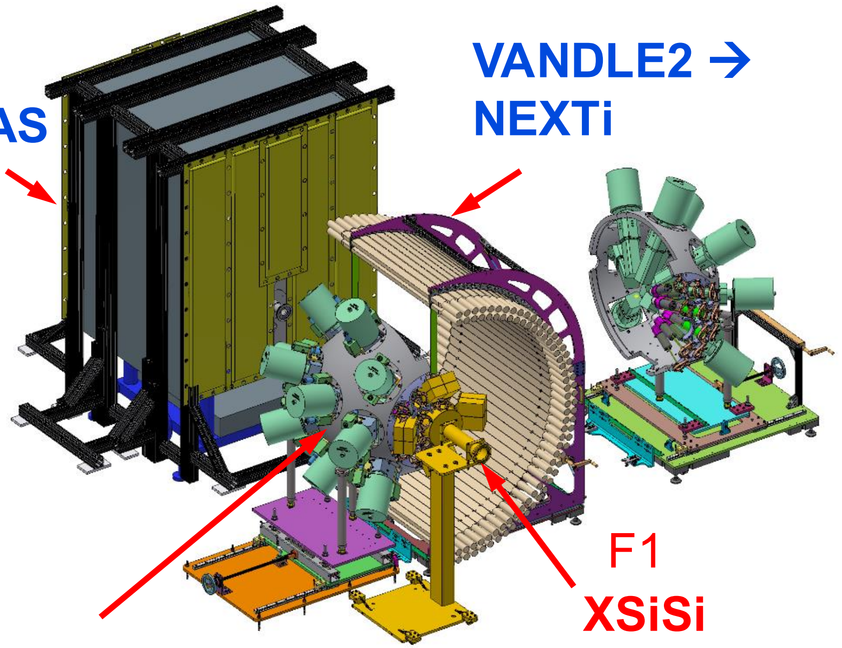
^{145}Tm - D. Seweryniak et al., PRL **99**, 082502 (2007)

FRIB Decay Station initiator (FDSi)

Total absorption

F2
MTAS

VANDLE2 → NEXTi

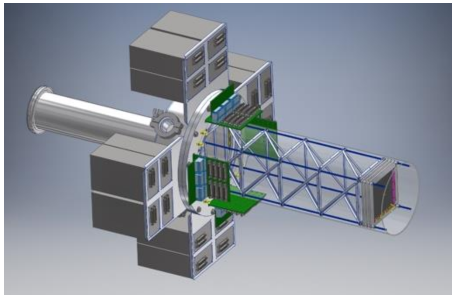


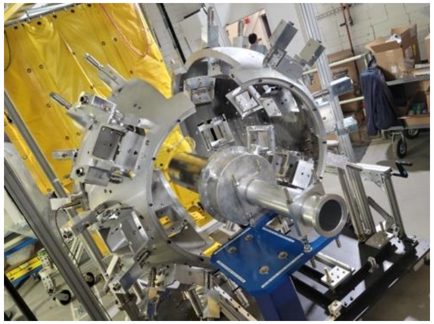
F1
XSiSi

CLARION → DEGAi

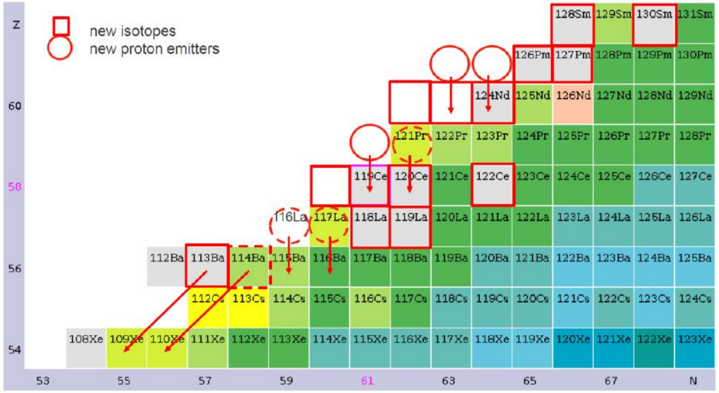
Discrete Spectroscopy

XSiS





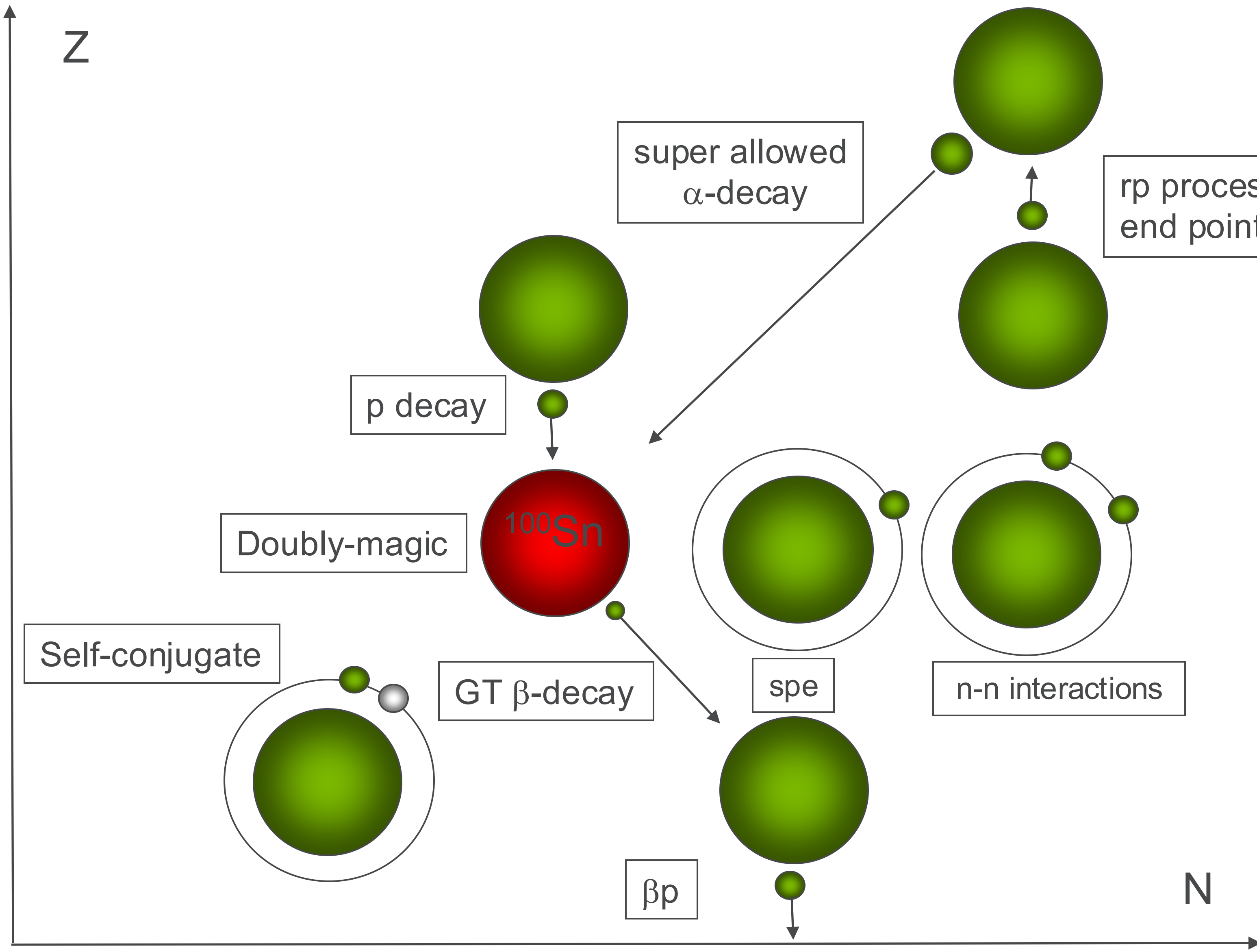
High-Granularity Implantation-Decay Si DSSD
Detection of **fragments, β, protons and α with very good energy resolution**



FRIB experiment 23071
“The Study of Proton-Rich Isotopes Along the Proton Drip-Line above ^{100}Sn”

Doubly magic ^{100}Sn

^{100}Sn physics



Single-neutron states in ^{101}Sn

PRL 99, 022504 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Single-Neutron States in ^{101}Sn

D. Seweryniak,[1] M. P. Carpenter,[1] S. Gros,[1] A. A. Hecht,[2] N. Hoteling,[2] R. V. F. Janssens,[1] T. L. Khoo,[1] T. Lauritsen,[1] C. J. Lister,[1] G. Lotay,[3] D. Peterson,[1] A. P. Robinson,[1] W. B. Walters,[2] X. Wang,[4] P. J. Woods,[3] and S. Zhu[1]

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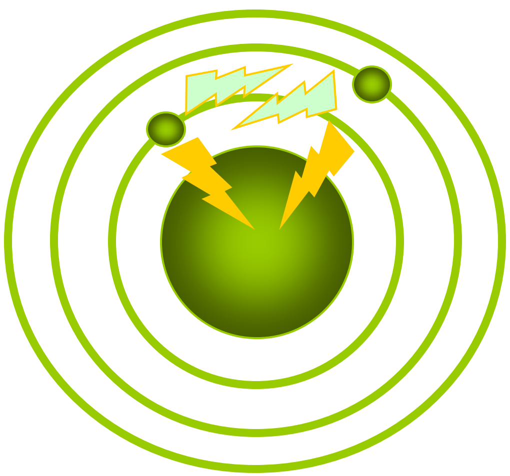
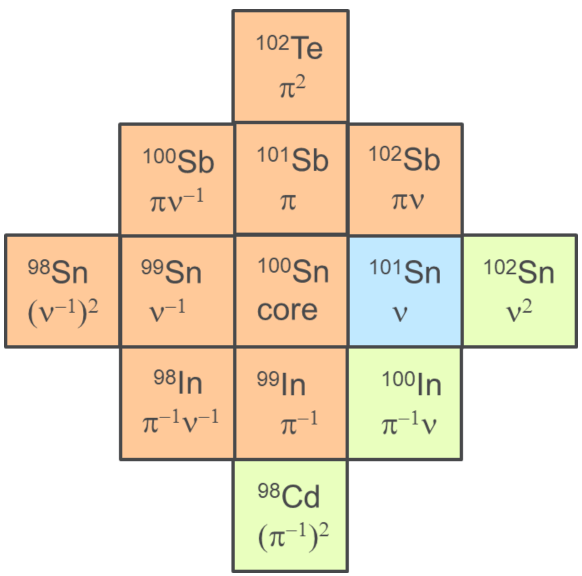
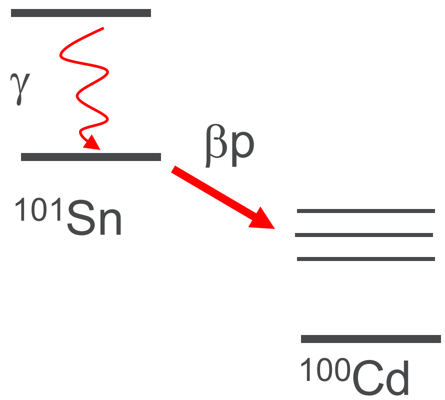
(Received 15 April 2007; published 12 July 2007)

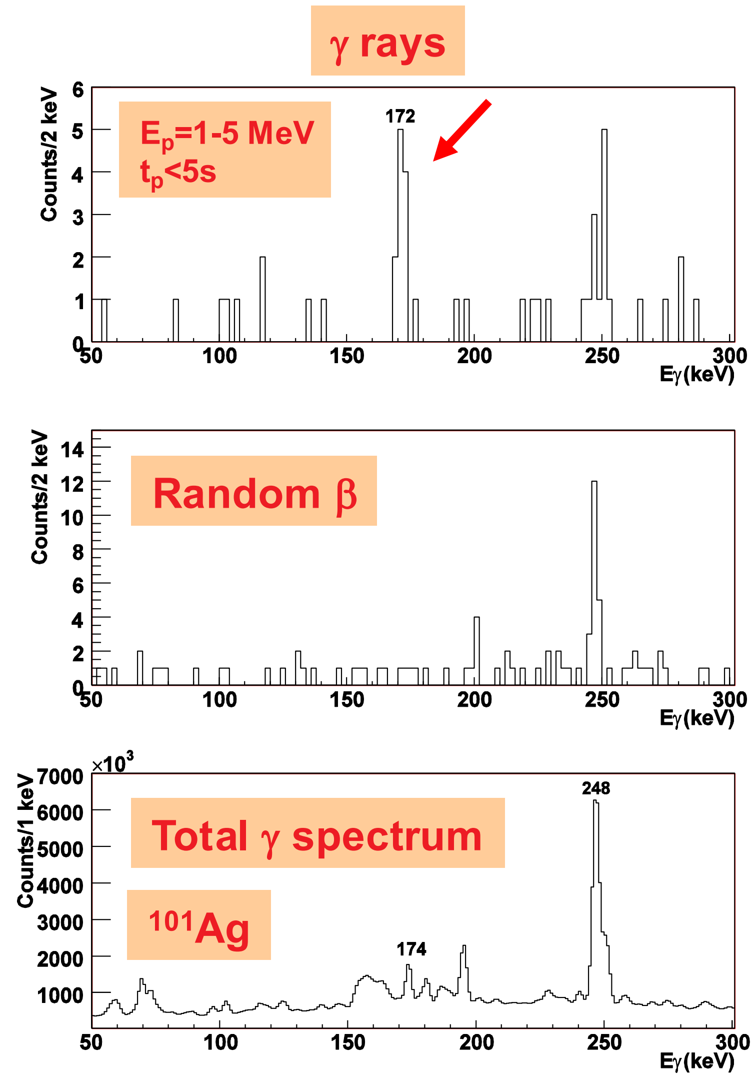




Gamma-ray transition(s) in ^{101}Sn

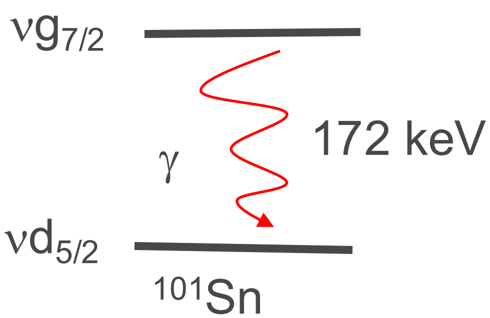


Ep=1.5-5 MeV
$T_{1/2}$=1.9(3)s
σ~50 nb
$b_{\beta p}$~15%

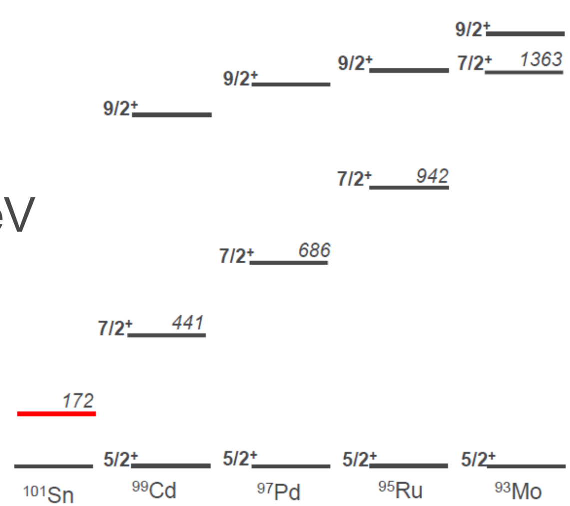


1 out of ~10^8 γ rays emitted!

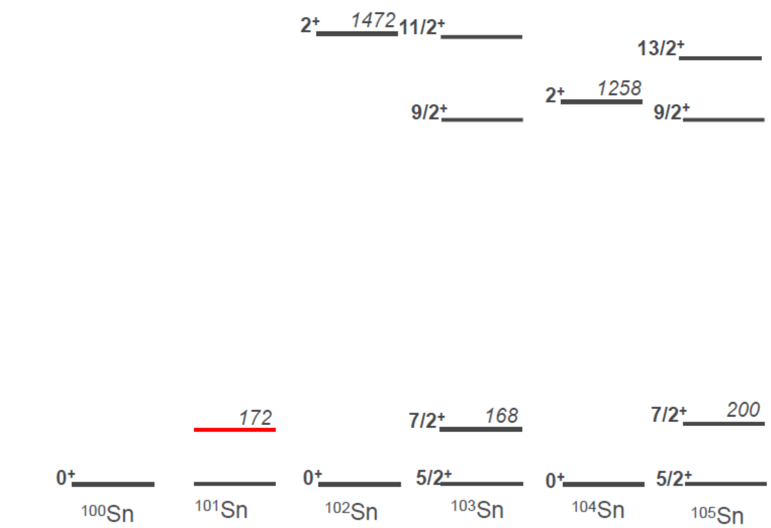
^{101}Sn single-neutron level ordering

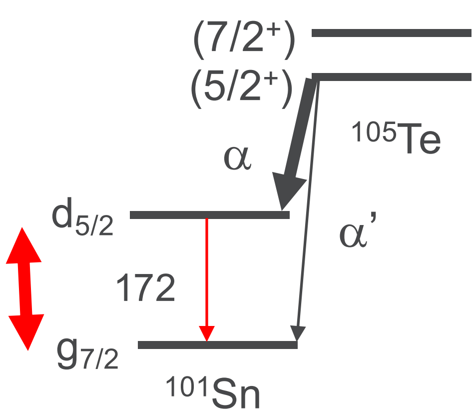


N=51 ISOTONES



LIGHT Sn ISOTOPES





ORNL

I. Darby et al., PRL 105, 162502 (2010)

Reversed order was proposed based on ^{105}Te α decay to ^{101}Sn. Additional experimental evidence needed.

Core excited states could be observed with GRETA

Coupled-cluster calculations

PHYSICAL REVIEW LETTERS **120,** 152503 (2018)

Editors' Suggestion

Structure of the Lightest Tin Isotopes

T. D. Morris,[1,2] J. Simonis,[3,4] S. R. Stroberg,[5,6] C. Stumpf,[3] G. Hagen,[2,1] J. D. Holt,[5] G. R. Jansen,[7,2] T. Papenbrock,[1,2] R. Roth,[3] and A. Schwenk[3,4,8]

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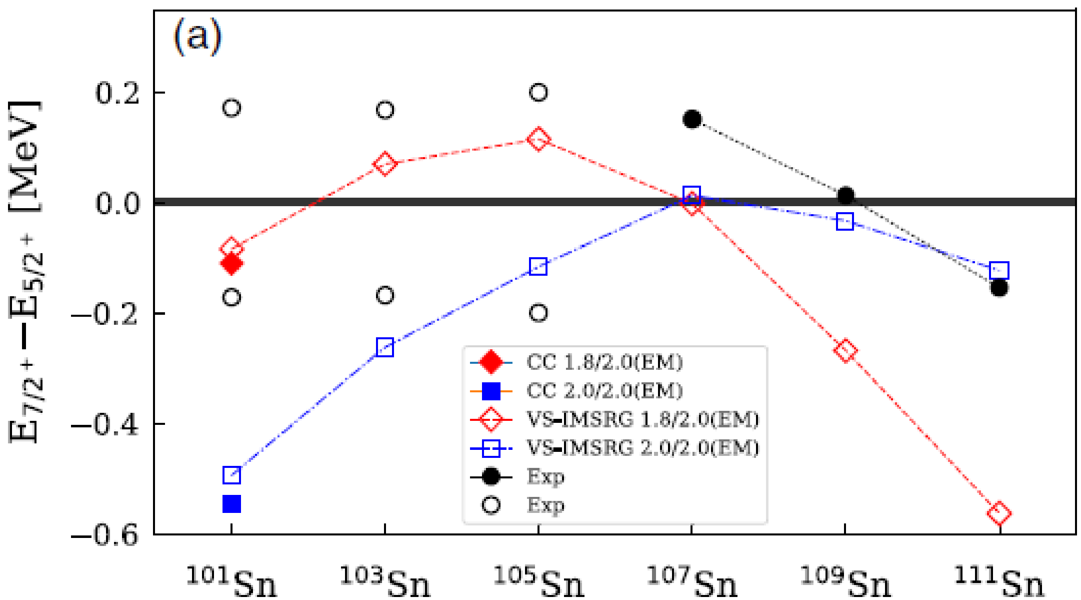

"Clearly, theory is not sufficiently precise to make a definite prediction for the ground-state spin of ^{101}Sn, as the predicted range for the energy splitting can support either $5/2^+$ or $7/2^+$ as the ground state."

Super-allowed α decay to doubly magic ^{100}Sn

PHYSICAL REVIEW LETTERS **121**, 182501 (2018)

Editors' Suggestion   Featured in Physics

Superallowed α Decay to Doubly Magic ^{100}Sn

K. Auranen,[1,*] D. Seweryniak,[1] M. Albers,[1] A. D. Ayangeakaa,[1,†] S. Bottoni,[1,‡] M. P. Carpenter,[1] C. J. Chiara,[1,2,§] P. Copp,[1,3] H. M. David,[1,∥] D. T. Doherty,[4,¶] J. Harker,[1,2] C. R. Hoffman,[1] R. V. F. Janssens,[5,6] T. L. Khoo,[1] S. A. Kuvin,[1,7] T. Lauritsen,[1] G. Lotay,[8] A. M. Rogers,[1,**] J. Sethi,[1,2] C. Scholey,[9] R. Talwar,[1] W. B. Walters,[2] P. J. Woods,[4] and S. Zhu[1]

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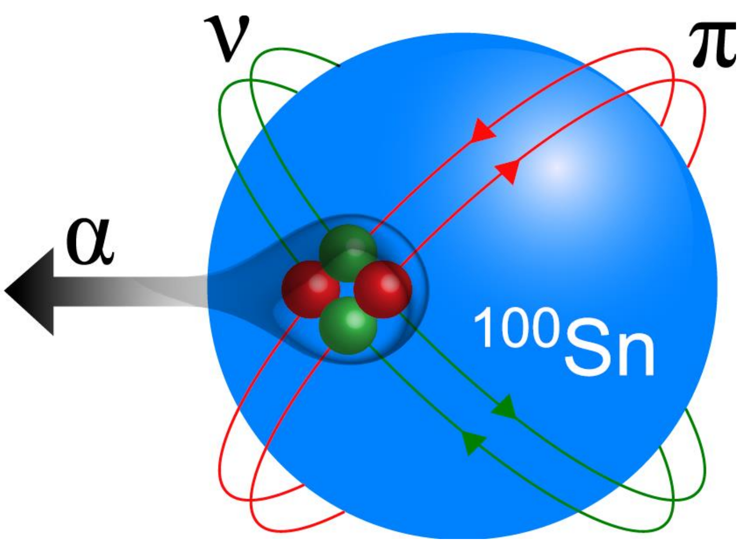
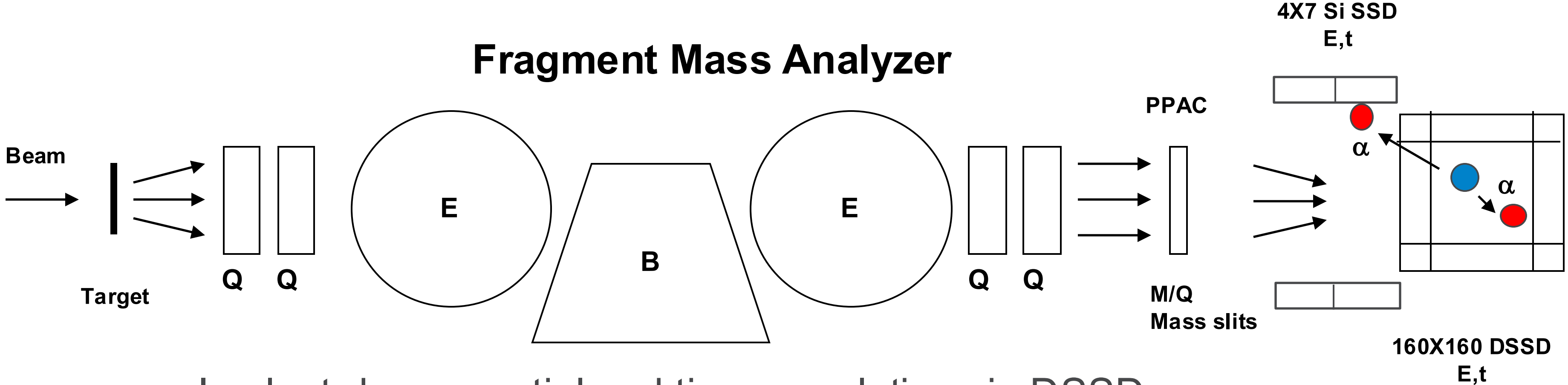
[9]*Department of Physics, University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*

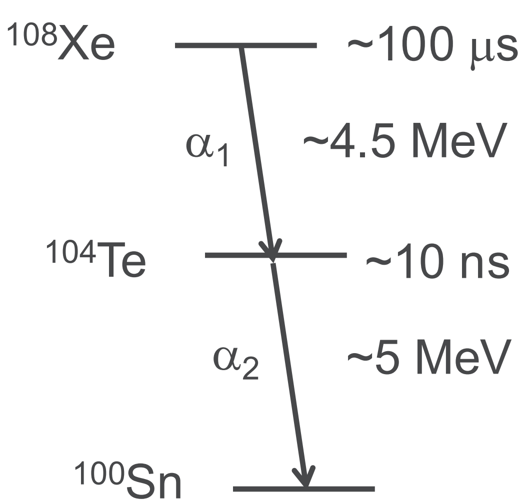


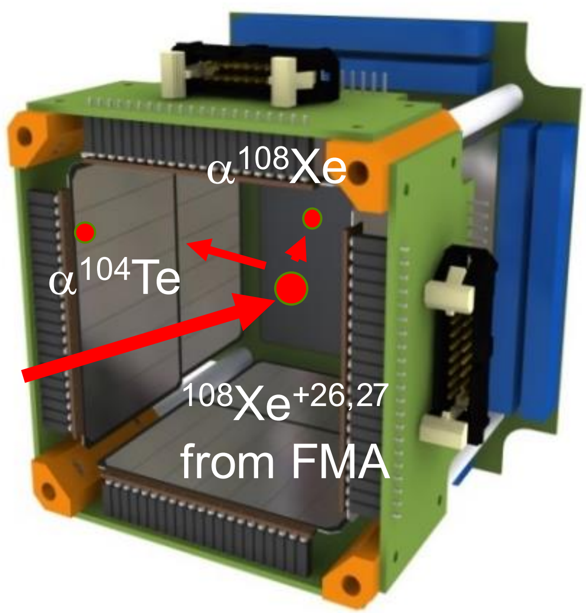
Super-allowed α decay ^{108}Xe-^{104}Te-^{100}Sn



Implant-decay spatial and time correlations in DSSD

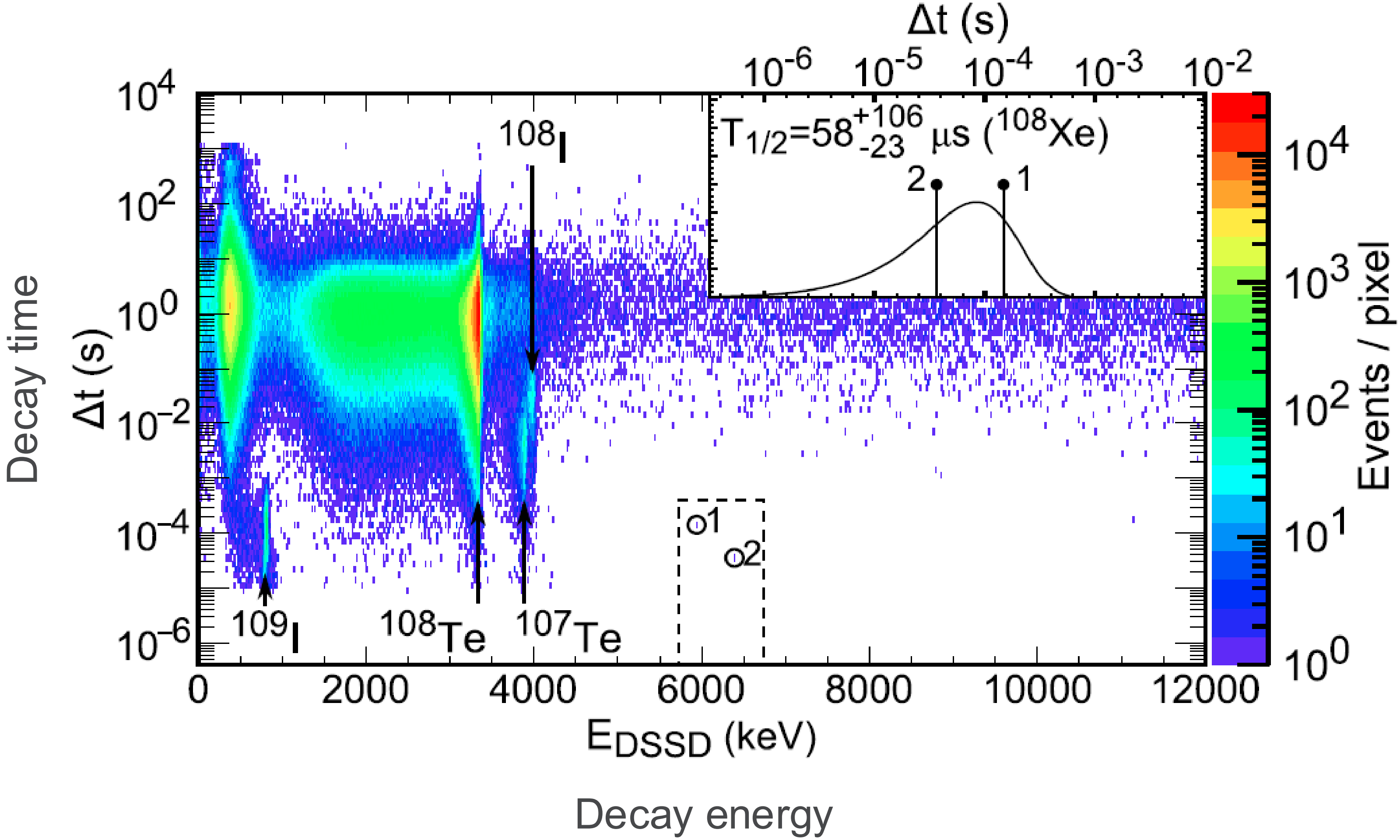
^{58}Ni(^{54}Fe,4n)^{108}Xe reaction, **cross section ~100 pb out of 1b!**





Digital DAQ to detect α^{108}Xe-α^{104}Te pileup
Si box to catch escaping alphas

Recoil-decay correlations

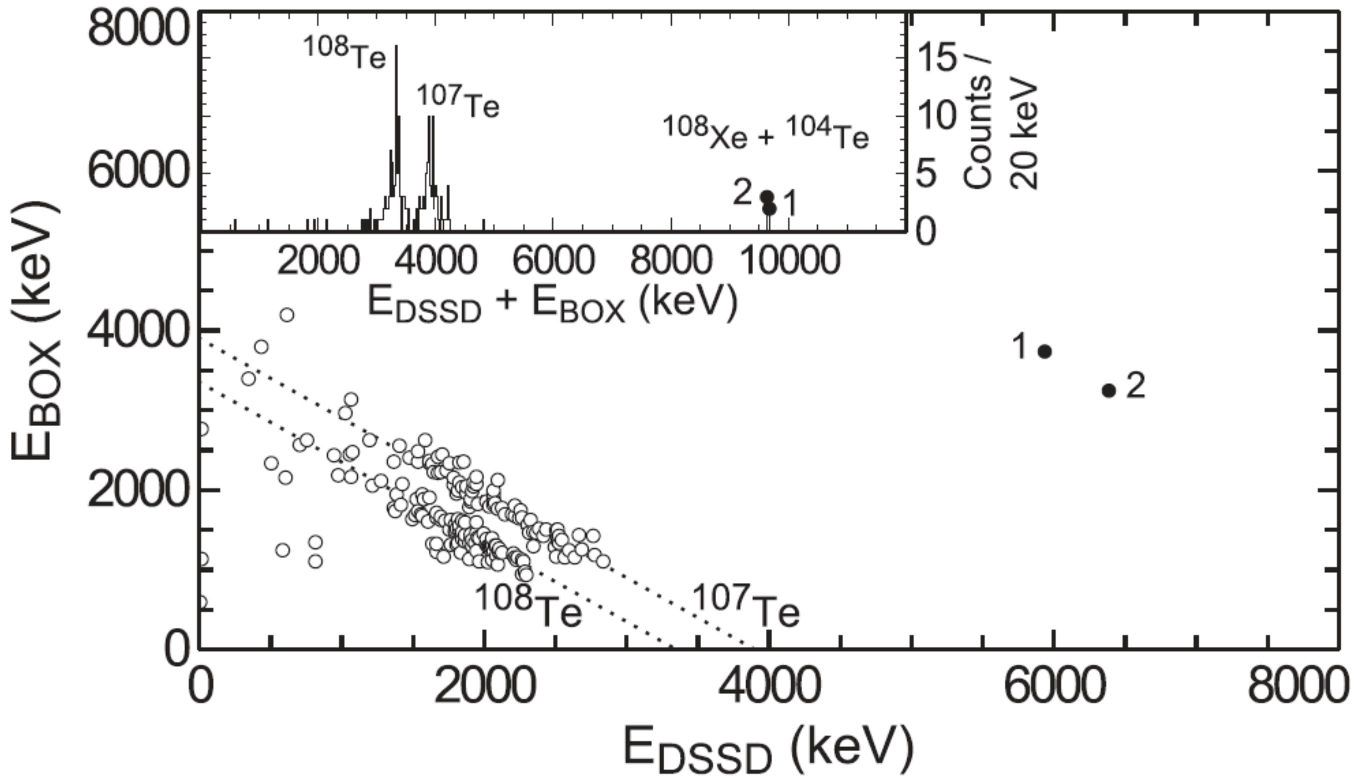


TWO fast high energy decay events

Expected **0.09** random events

BOTH events where in coincidence with the Si box (1 out of 400)

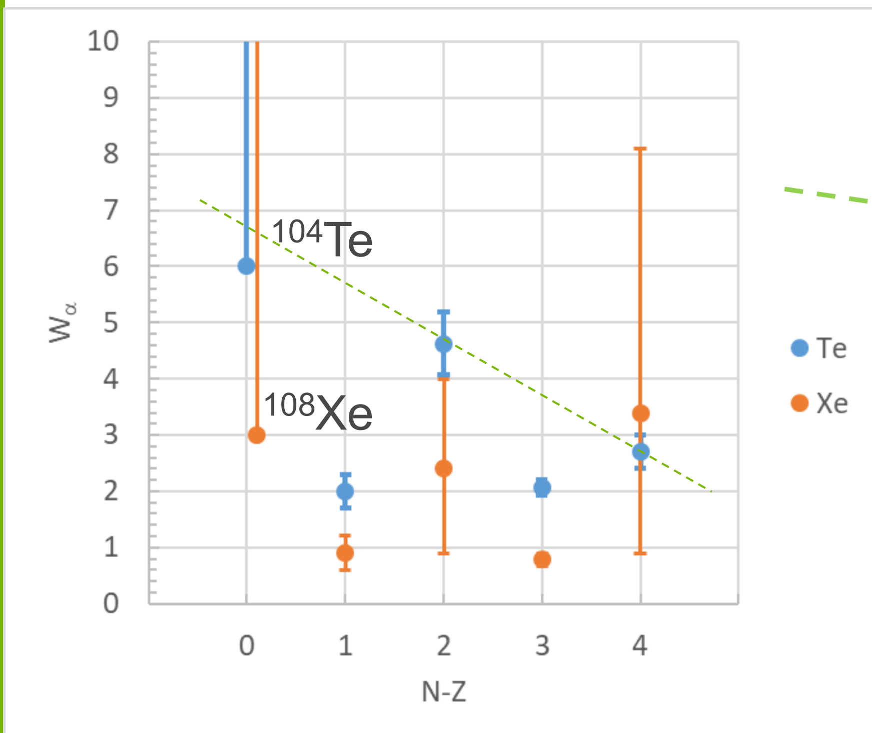
DSSD-Si box coincidences

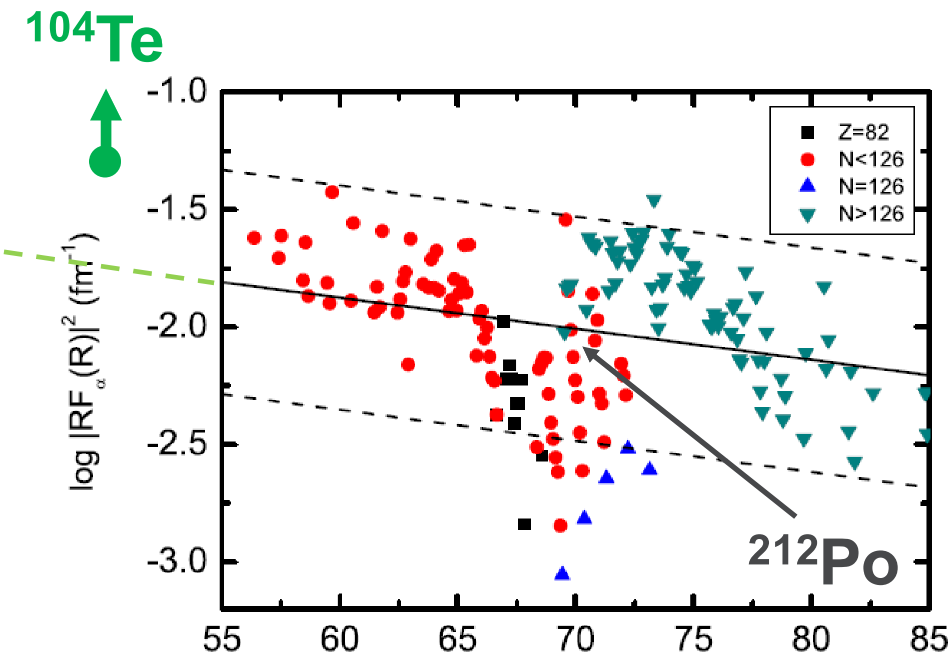


- The same total energy for both events - ΣE_α**=9.3(1) MeV**
- Compared to α emitters different energy split

$E_\alpha(^{104}Te)$=4.9(2) MeV, $E_\alpha(^{108}Xe)$=4.4(2) MeV
$T_{1/2}(^{104}Te)$<18 ns, $T_{1/2}(^{108}Xe)$=60(-20,+100) μs

Reduced α-decay widths near ^{100}Sn





$$\rho' = \sqrt{A_{\alpha d} Z_\alpha Z_d (A_d^{\frac{1}{3}} + A_\alpha^{\frac{1}{3}})}$$

If **W_α(Te)/W_α(Xe)~2** as for ^{106}Te/^{110}Xe pair: **W_α(^{104}Te)>6, W_α(^{108}Xe)>3**

Recent calculations for ^{104}Te/^{108}Xe

Density-dependent cluster model plus two-potential approach

Dong Bai and Zhongzhou Ren, Eur. Phys. J. A 54, 220 (2018)

$T_{1/2}(^{108}Xe)$=4-213 μs, $T_{1/2}(^{104}Te)$=7-166 ns

The super-fluid tunneling model

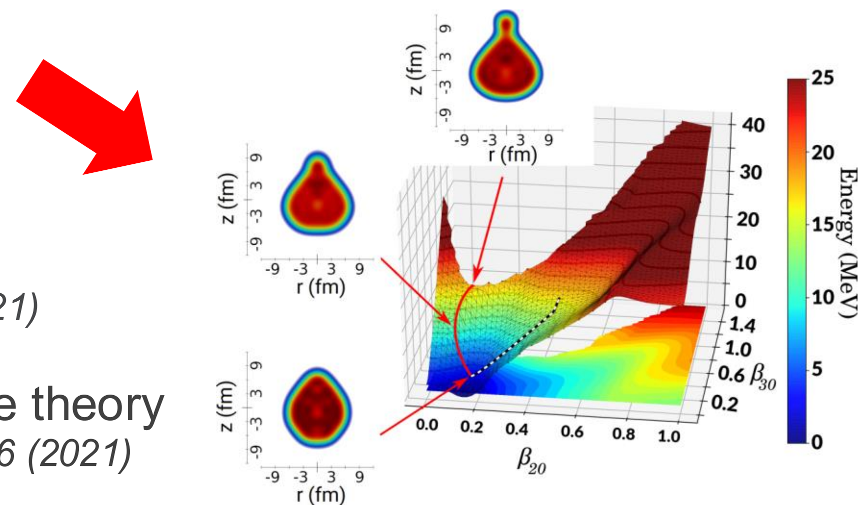
R.M. Clark et al., Phys. Rev. C 101, 034313 (2020)

Relativistic Density Functional DD-PC1+separable pairing of finite range

Dynamical least-action paths from equilibrium deformation to scission

*F. Mercier et al., Phys. Rev. C **102**, 011301(R) (2020)*

$T_{1/2}(^{108}Xe)$=50 μs, $T_{1/2}(^{104}Te)$=197 ns



Quartetting wave function approach

Shuo Yang et al., Phys. Rev. C 101, 024316 (2020)

$T_{1/2}(^{104}Te)$=18 ns

Cluster-Formation Model+DDCM

*Niu Wan and Jingya Fan, Phys. Rev. C **104**, 064320 (2021)*

$T_{1/2}(^{108}Xe)$=43 μs, $T_{1/2}(^{104}Te)$=54 ns

Double-folding potentials from chiral effective theory

Dong Bai and Zhongzhou Ren, Phys. Rev. C 103, 044316 (2021)

$T_{1/2}(^{104}Te)$>30ns

Improved density-dependent cluster model

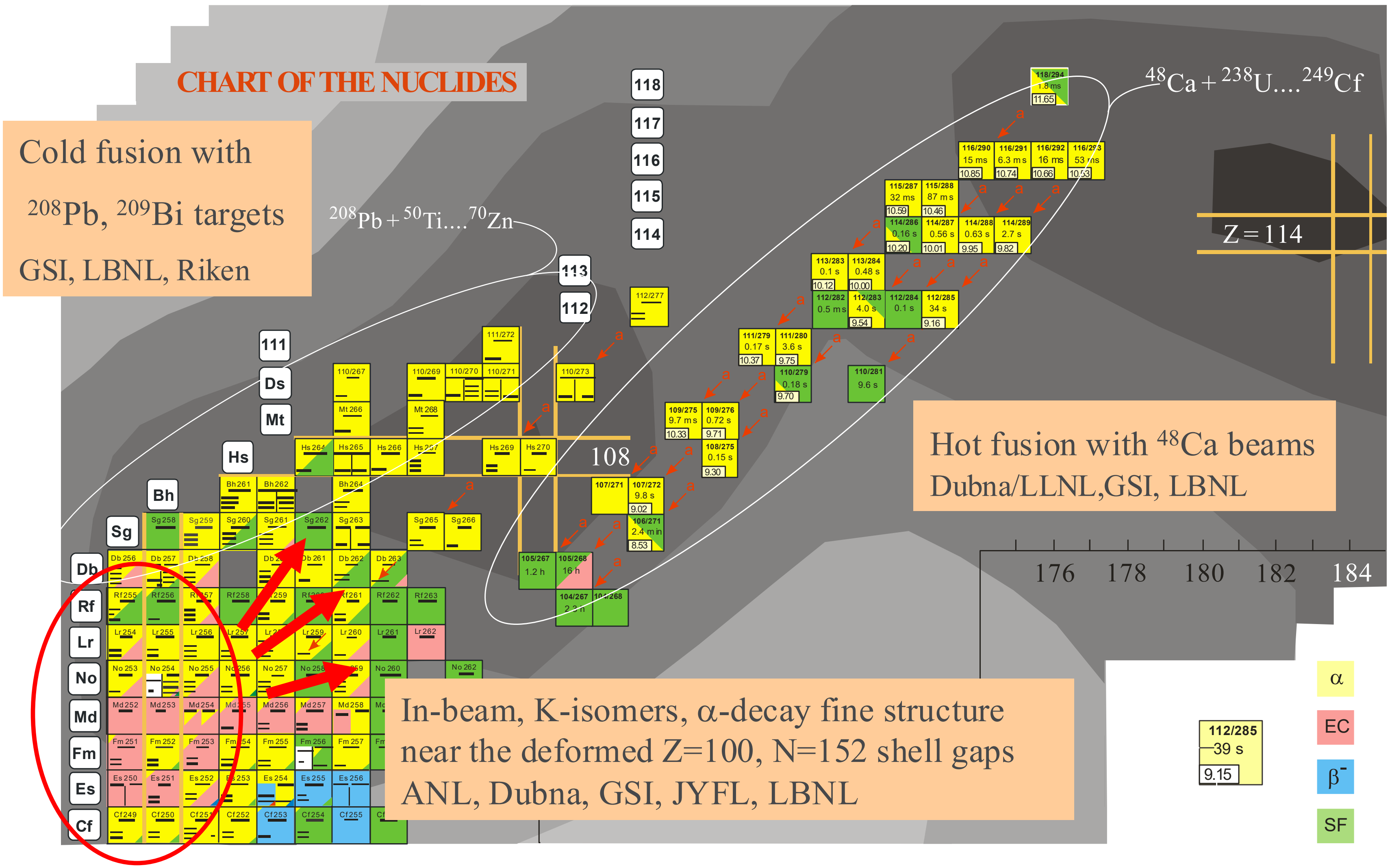
Zhen Wang, Dong Bai and Zhongzhou Ren, Phys. Rev. C 105, 024327 (2022)

$T_{1/2}(^{108}Xe)$=62 μs, $T_{1/2}(^{104}Te)$=92 ns

^{108}Xe reproduced well, ^{104}Te lifetimes longer (enhanced preformation, higher Qα)

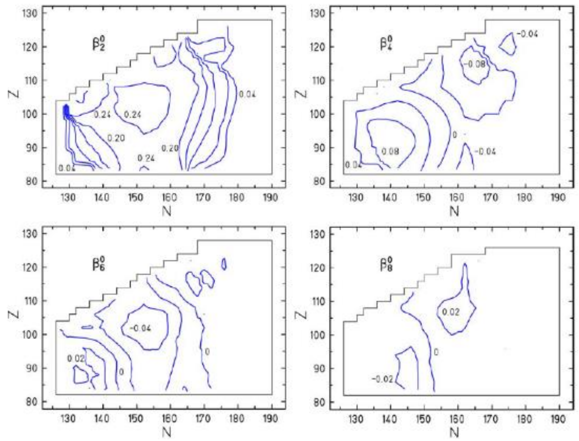

The island of super-heavy nuclei

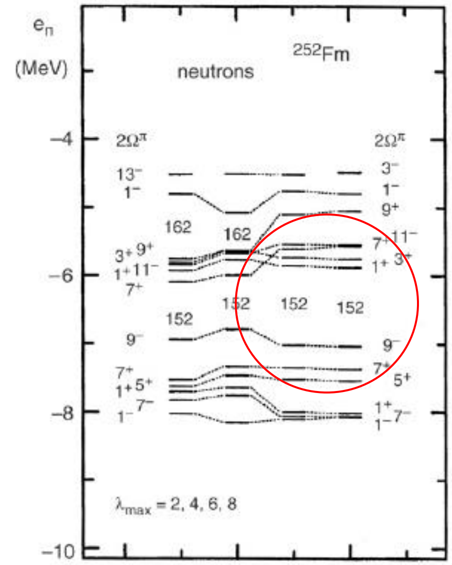
Spectroscopy of Super-Heavy Nuclei



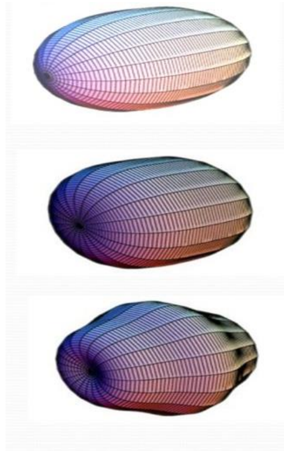
Deformation landscape near Z=100, N=152

β_2~0.25 plateau

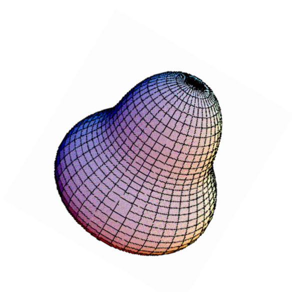




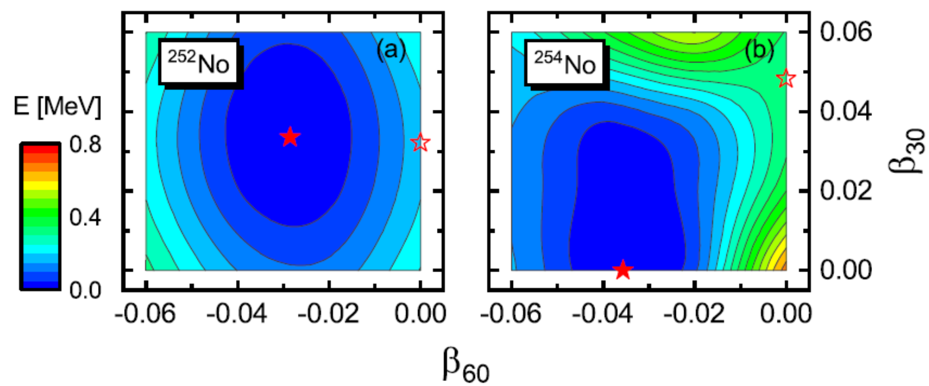
Microscopic-Macroscopic calculations
A. Sobiczewski and K. Pomorski, Prog. in Part. and Nucl. Phys. 58 (2007) 292–349



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



β_3

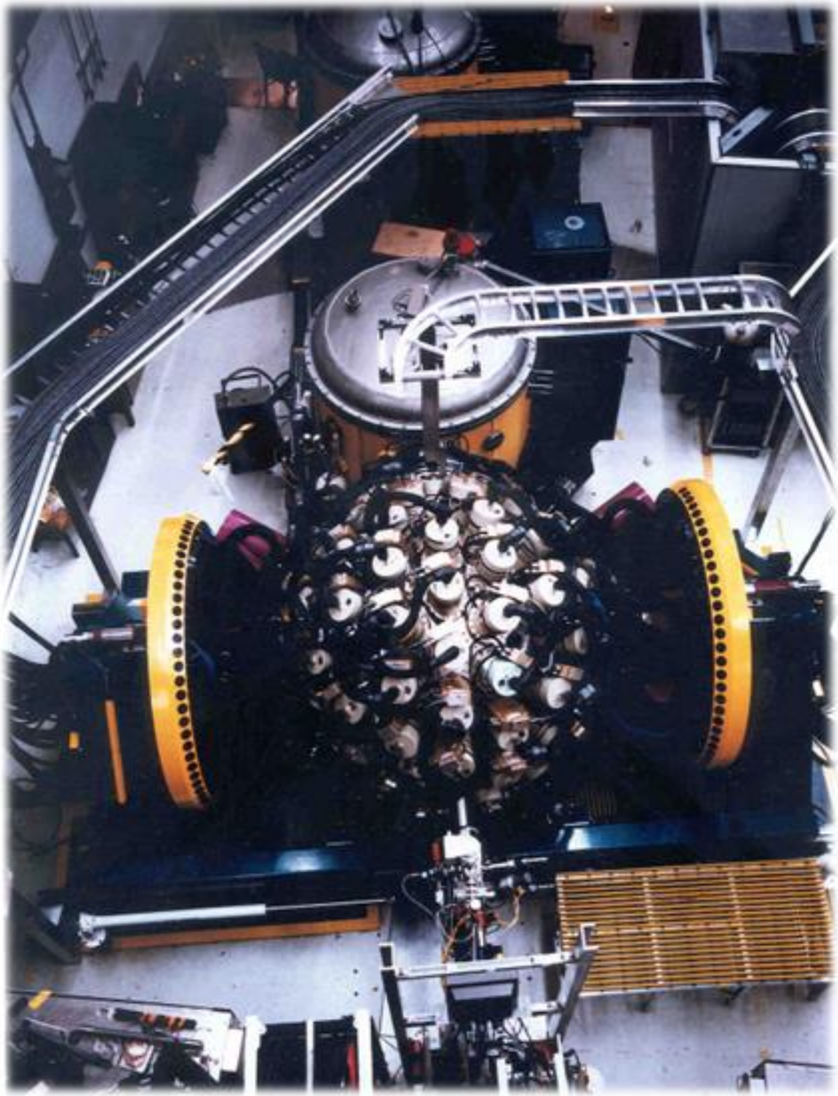


Earlier upbend in moment of inertia in ^{252}No explained by onset of octupole correlations

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

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

Pioneering experiments with Gammasphere and FMA



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]
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[2]*University of Liverpool, Liverpool L69 7ZE, England*
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(Received 21 October 1998)

VOLUME 84, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 2000

Entry Distribution, Fission Barrier, and Formation Mechanism of $^{254}_{102}$No

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P. Bhattacharyya,[4] P. A. Butler,[3] M. P. Carpenter,[1] A. J. Chewter,[3] J. A. Cizewski,[1,5] C. N. Davids,[1] K. Y. Ding,[5]
N. Fotiades,[5] J. P. Greene,[1] P. T. Greenlees,[3] A. Heinz,[1] W. F. Henning,[1] R.-D. Herzberg,[3] R. V. F. Janssens,[1]
G. D. Jones,[3] H. Kankaanpää,[7] F. G. Kondev,[1] W. Korten,[6] M. Leino,[7] S. Siem,[1,8] J. Uusitalo,[1]
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(Received 3 January 2000)

PRL 97, 082502 (2006) PHYSICAL REVIEW LETTERS week ending 25 AUGUST 2006

K **Isomers in ^{254}No: Probing Single-Particle Energies and Pairing Strengths in the Heaviest Nuclei**

S. K. Tandel,[1] T. L. Khoo,[2] D. Seweryniak,[2] G. Mukherjee,[1,2,*] I. Ahmad,[2] B. Back,[2] R. Blinstrup,[2] M. P. Carpenter,[2]
J. Chapman,[2] P. Chowdhury,[1] C. N. Davids,[2] A. A. Hecht,[2,4] A. Heinz,[5] P. Ikin,[3] R. V. F. Janssens,[2] F. G. Kondev,[2]
T. Lauritsen,[2] C. J. Lister,[2] E. F. Moore,[2] D. Peterson,[2] P. Reiter,[6] U. S. Tandel,[1] X. Wang,[2,7] and S. Zhu[2]
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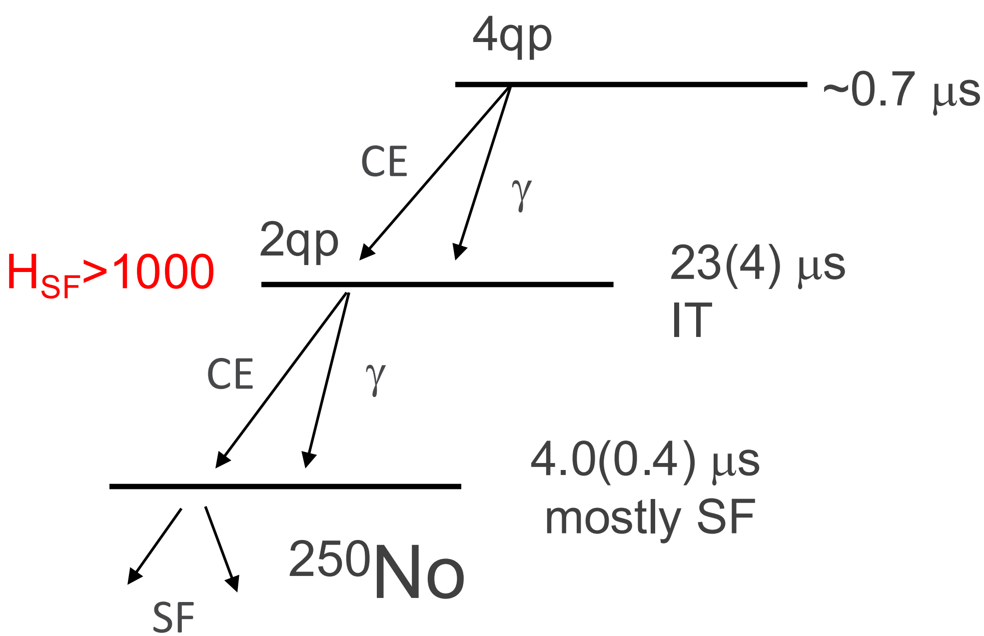
(Received 13 April 2006; published 22 August 2006)

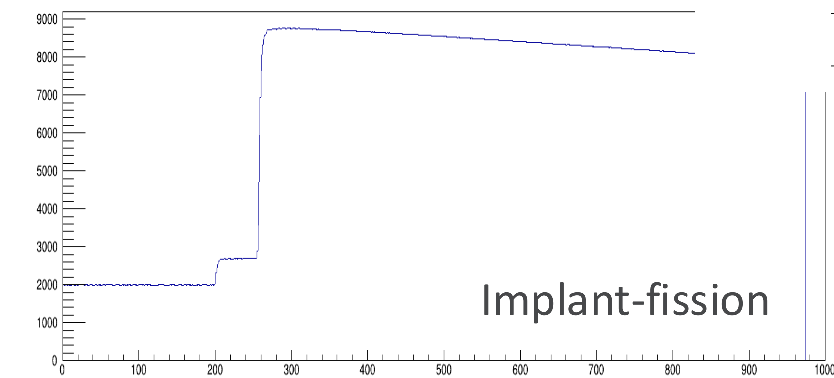
Most fissile nucleus known ^{250}No

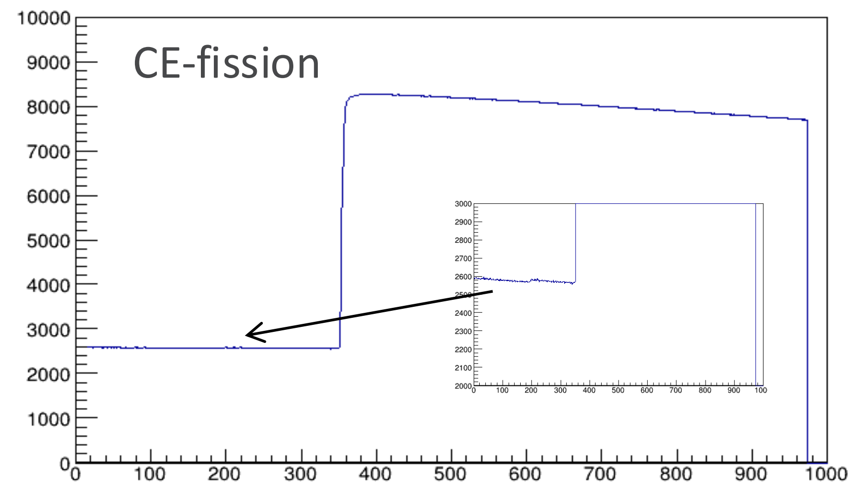
^{40}Ca+^{204}Pb, ~20-25 pnA, 9 days

σ~15 nb



~2000 fission events detected





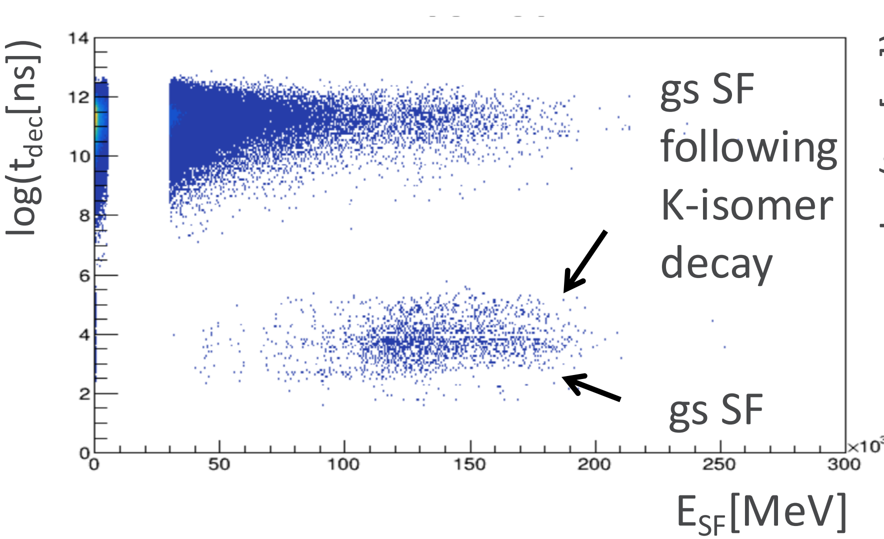
D. Peterson et al. Phys. Rev. C **74**, 014316 (2006) – **ATLAS, FMA, total of 158 SF events, 2 SF lifetimes**

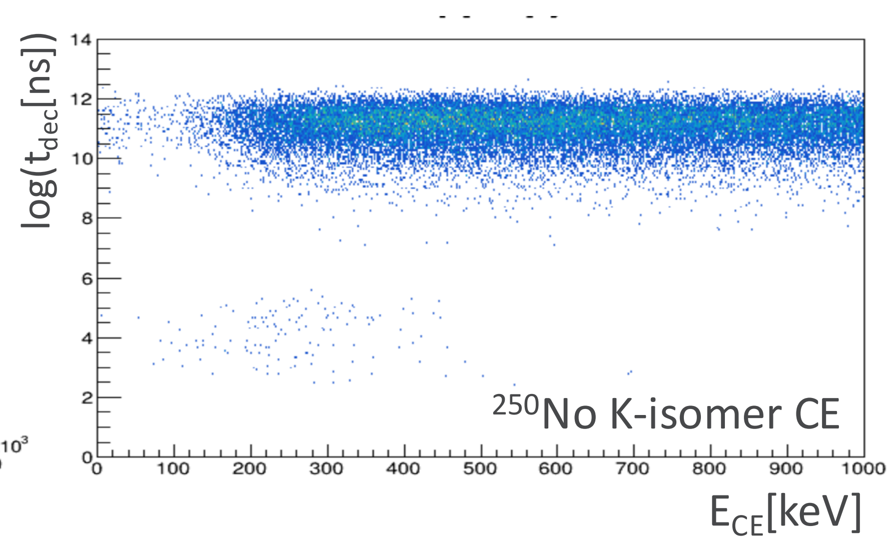
J. Kallunkathariyil et al., Phys. Rev. C **101**, 011301(R) (2020)

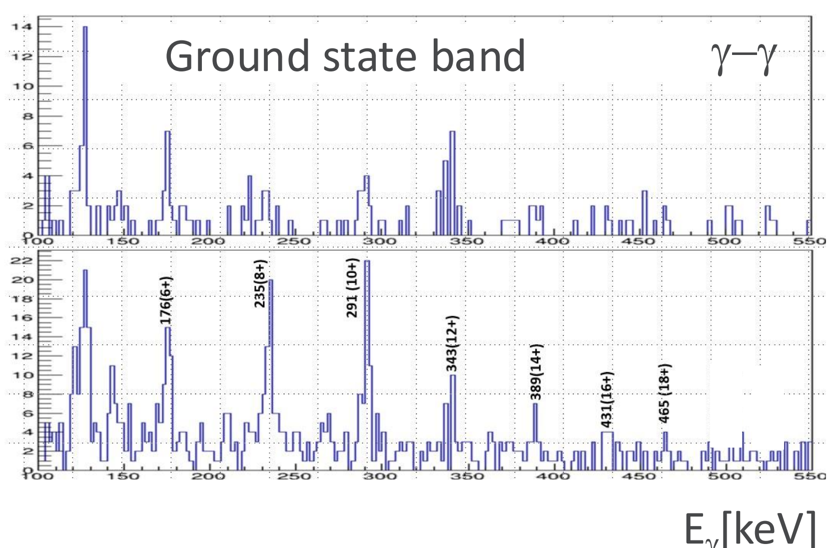
J. Khuyagbaatar et al., Phys. Rev. C **106**, 024309 (2022)

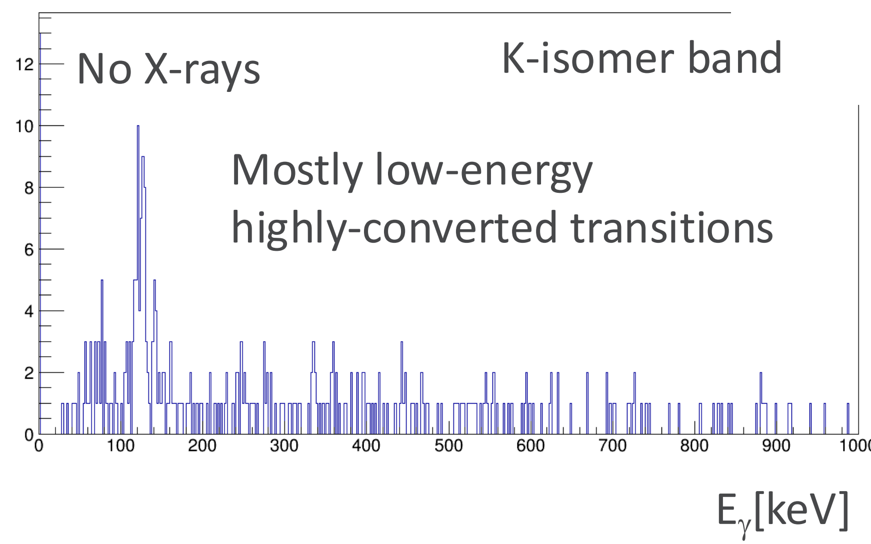
^{250}No ground-state rotational band

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



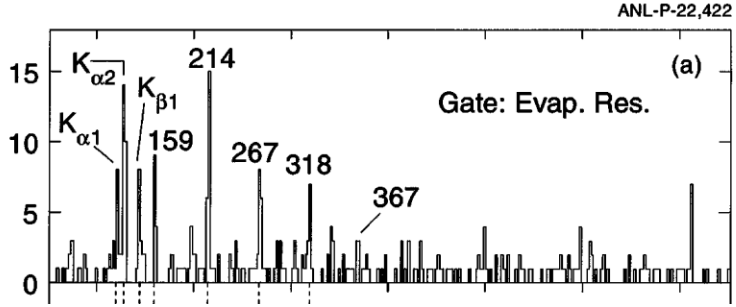






FMA 2001 and AGFA 2024 comparison

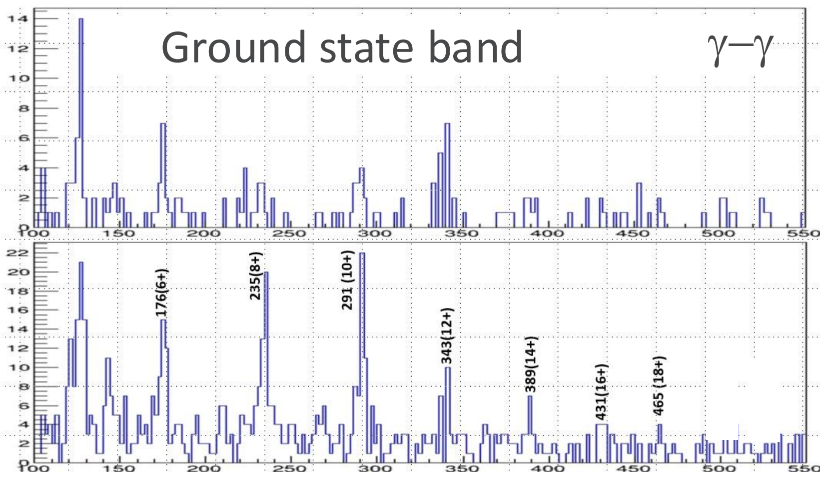
^{254}No



Gammasphere/FMA 2001

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

^{250}No

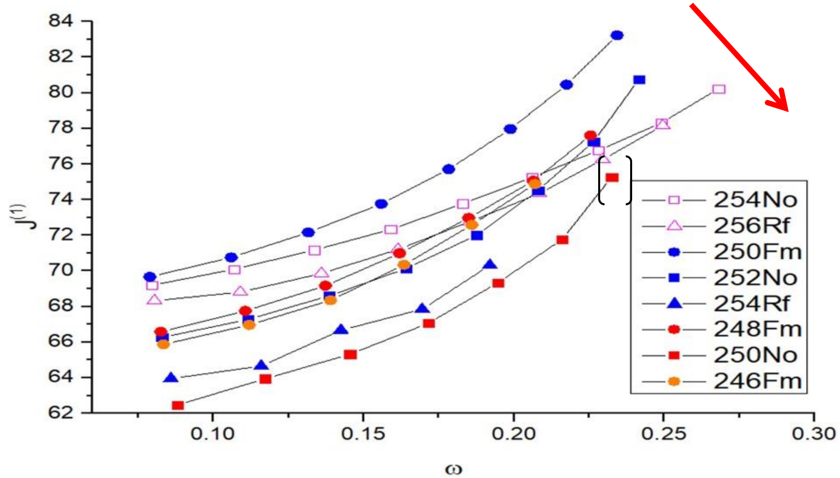


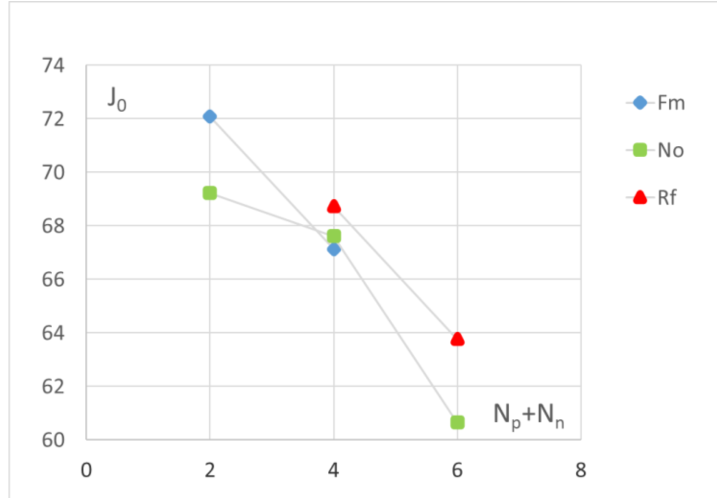
Gammasphere/AGFA 2024

Cross section ~100 times lower

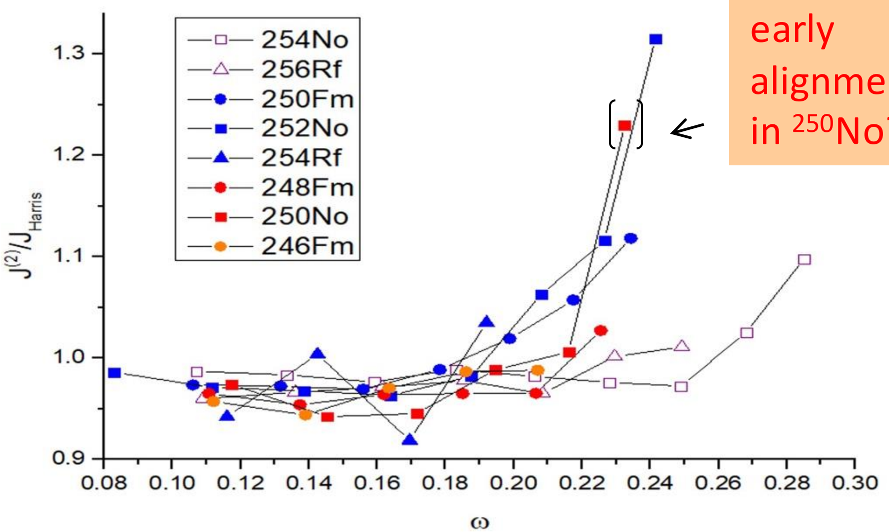
Moments of inertia in transfermium nuclei

Increasing pairing

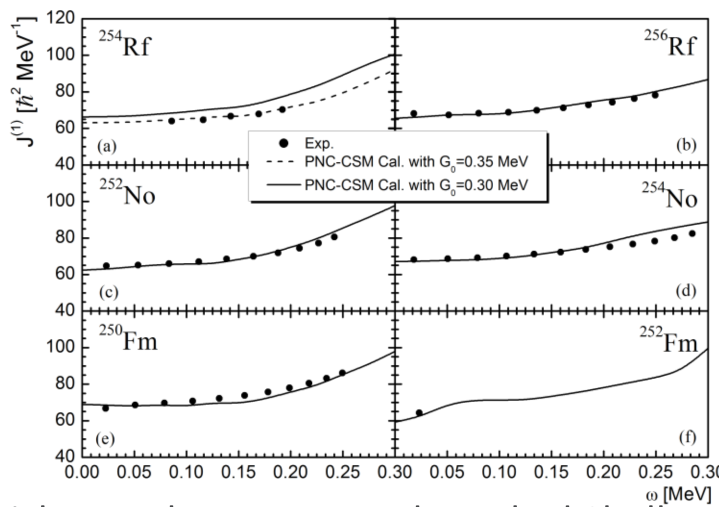




early alignment in ^{250}No?



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

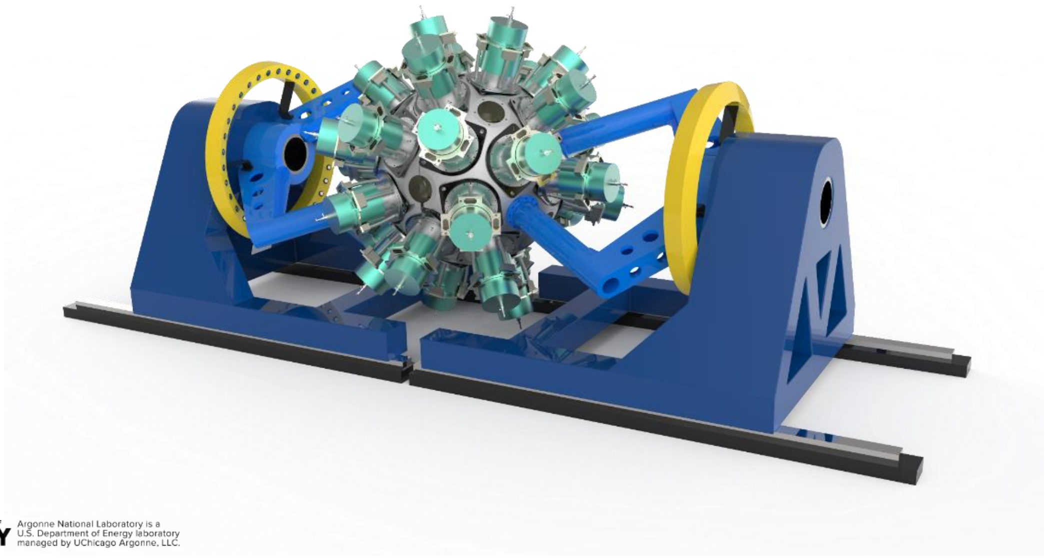


Particle-Number-Conserved Cranked Shell Model

Pairing correlations stronger away

Opportunities with GRETA at ATLAS

- ^{100}Sn region (GRETA/FMA)
  - ^{101}Sn core excited states
  - Excited states in ^{100}Sn
- Transfermium nuclei (GRETA/AGFA)
  - Super-heavy nuclei ^{260}Sg
- Hyperdeformation (GRETA stand-alone or with FMA)

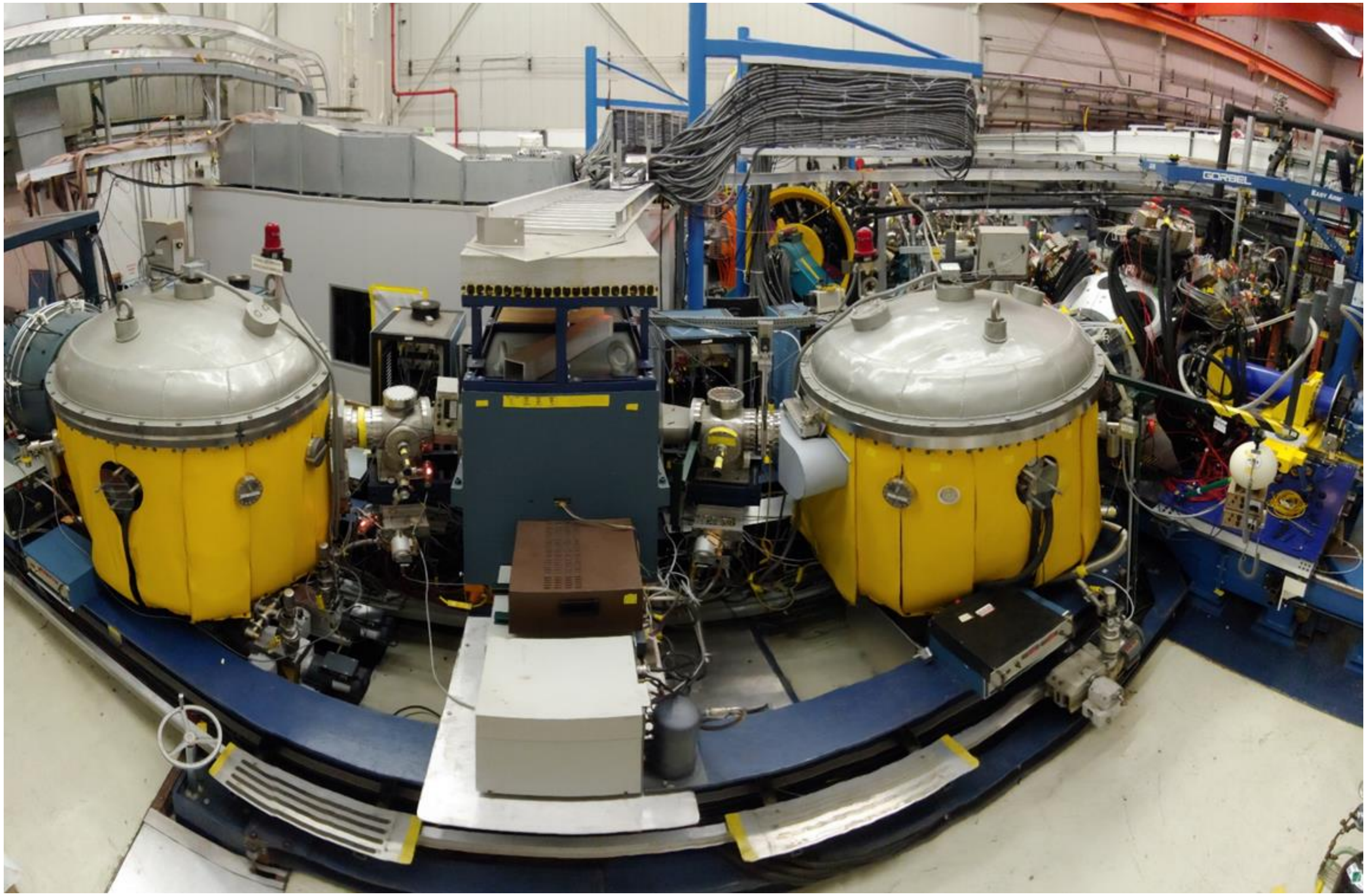


4TH OF JULY PARTIES AT CLAIR AND ROBERT'S

In-beam and decay spectroscopy of exotic nuclei at ATLAS

- Spontaneous proton emission
  - Decay studies
  - In-beam studies
- Nuclei near ^{100}Sn
  - Single-neutron states in ^{101}Sn
  - Super-allowed alpha decay
- Trans-fermium nuclei
  - pioneering experiments with Gammasphere/FMA
  - experimental program with AGFA
- Outlook
  - GRETA

Argonne Fragment Mass Analyzer



Argonne Gas-Filled Analyzer (AGFA)

D. Potterveld, ANL

Use Combined Function bending magnet

– Overlapping bending, focusing fields

– Fewer magnets, ultra-compact design

$Q_v D_m$ design

2.5 Tm max Bρ

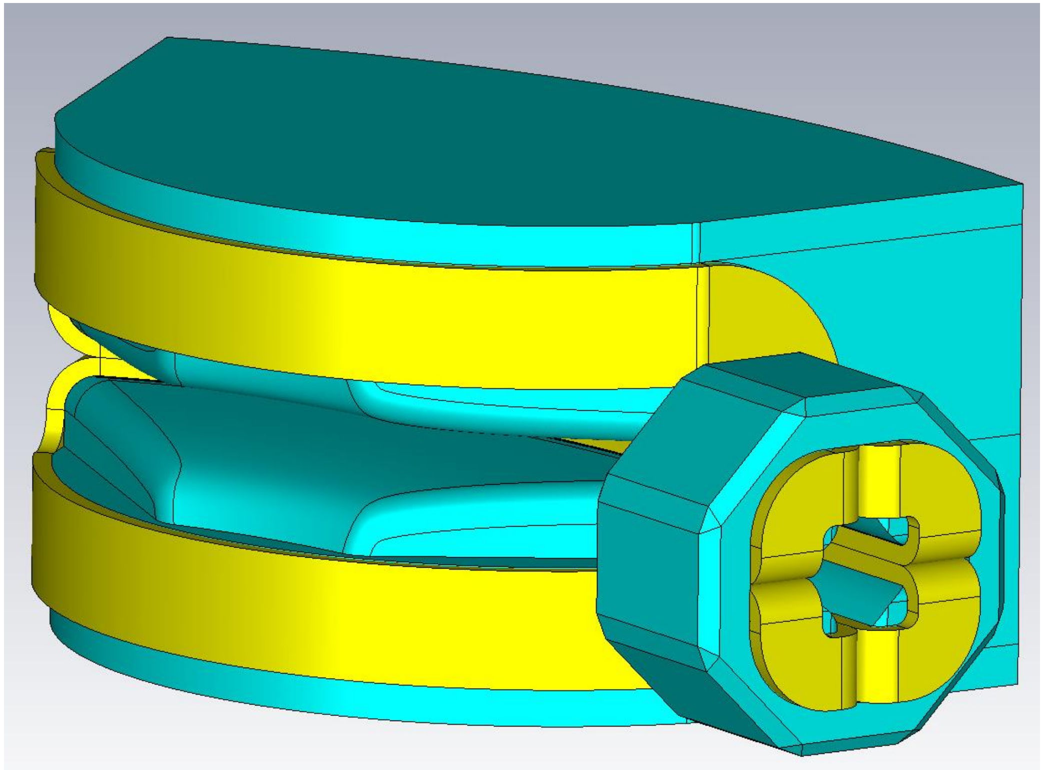
38º bend

22.5 msr @ 80 cm

(44 msr @ 40 cm)

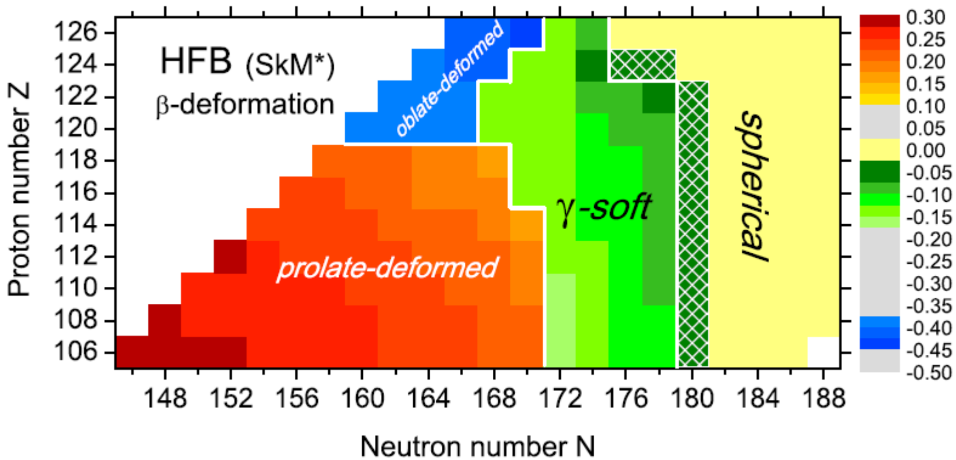
4.2 total length @ 80 cm

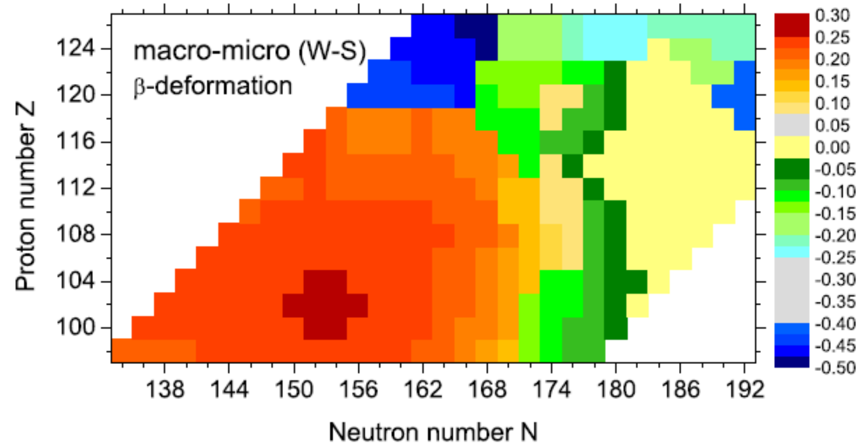
(3.9 m @ 40 cm)



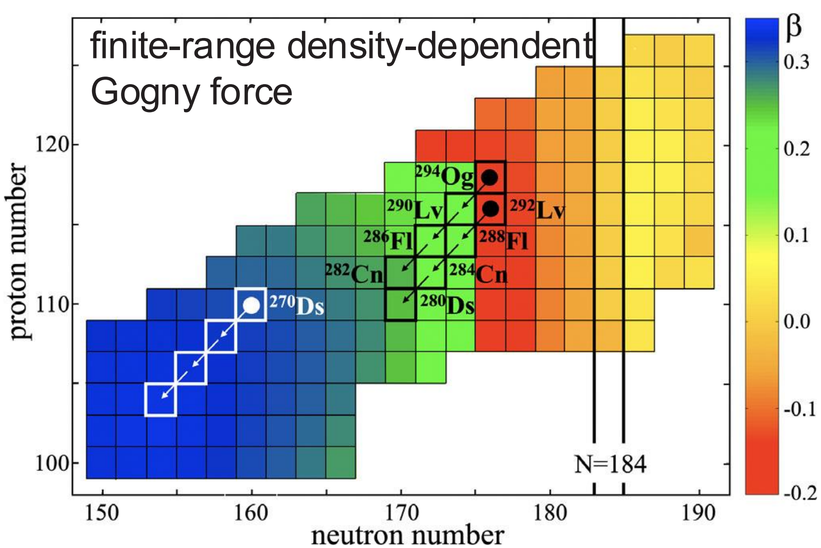
Optimized for spectroscopy, commissioned in late 2018

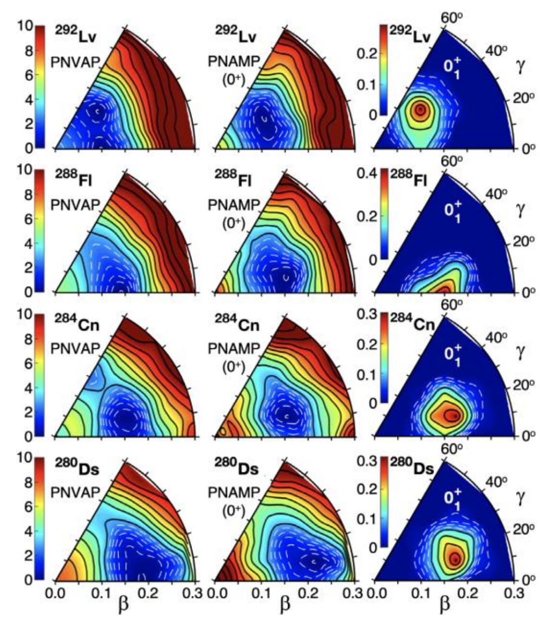
SHN deformation landscape





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





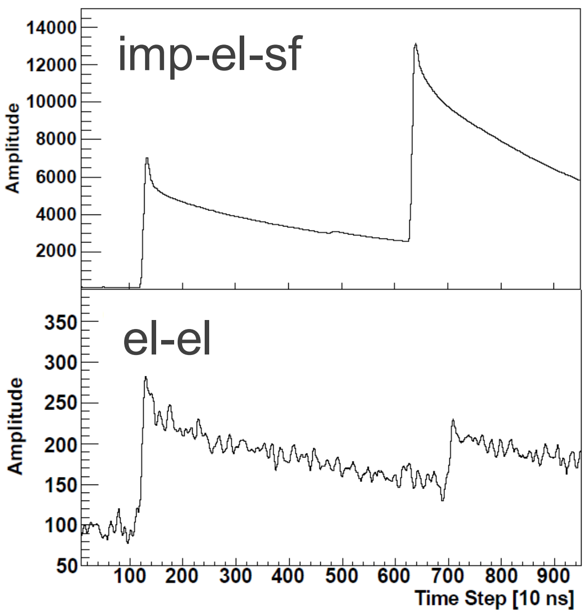
γ-unstable
triaxial rotor

axial-symmetric
prolate rotor

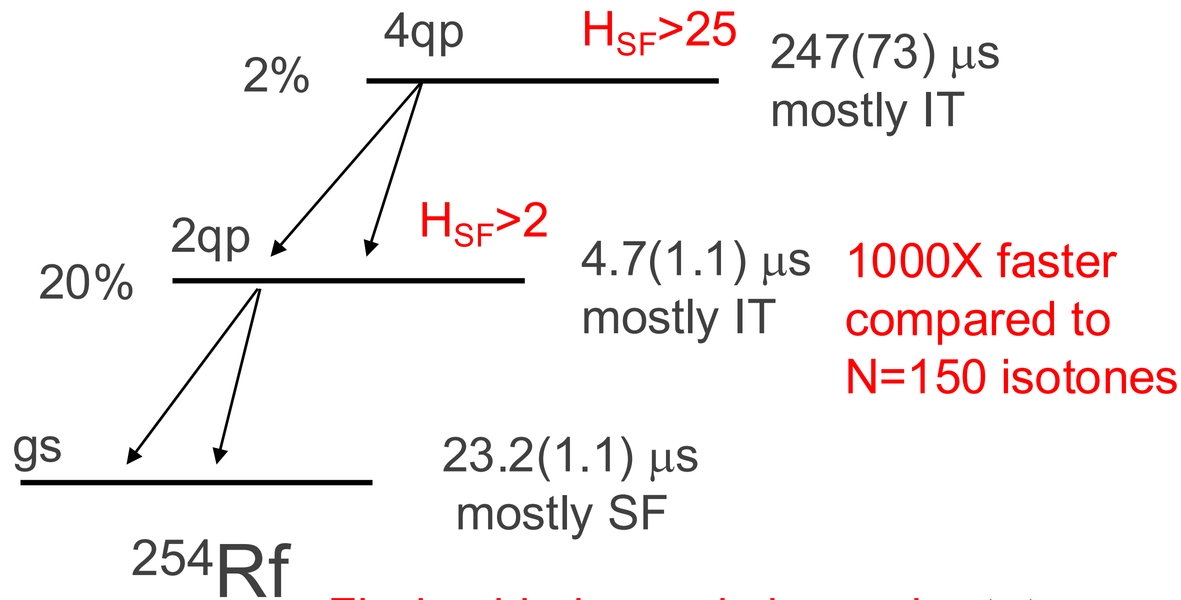
rigid
triaxial rotor

J. L. Egido, A. Jungclaus, PRL 126, 192501 (2021)

The fissile ^{254}Rf nucleus
FMA, BGS



Traces from the FMA digital DAQ



Fission hindrance in isomeric states. This can be a mechanism to extend the number of accessible super-heavy elements

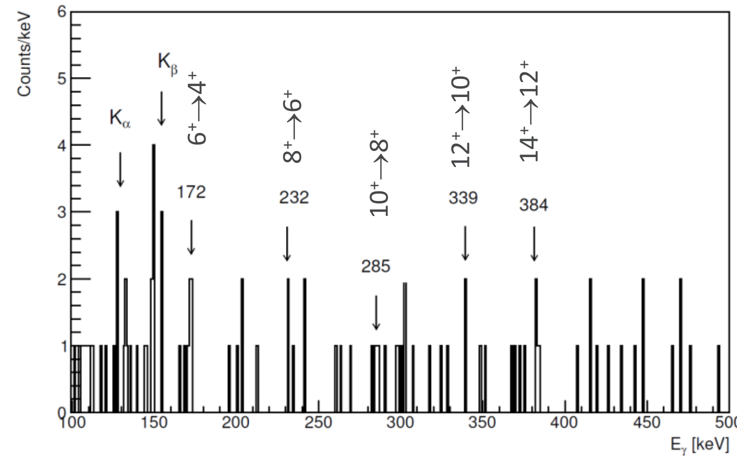
H.M. David, J. Chen, D. Seweryniak, F.G. Kondev et al., Phys. Rev. Lett. **115**, 132502 (2015)

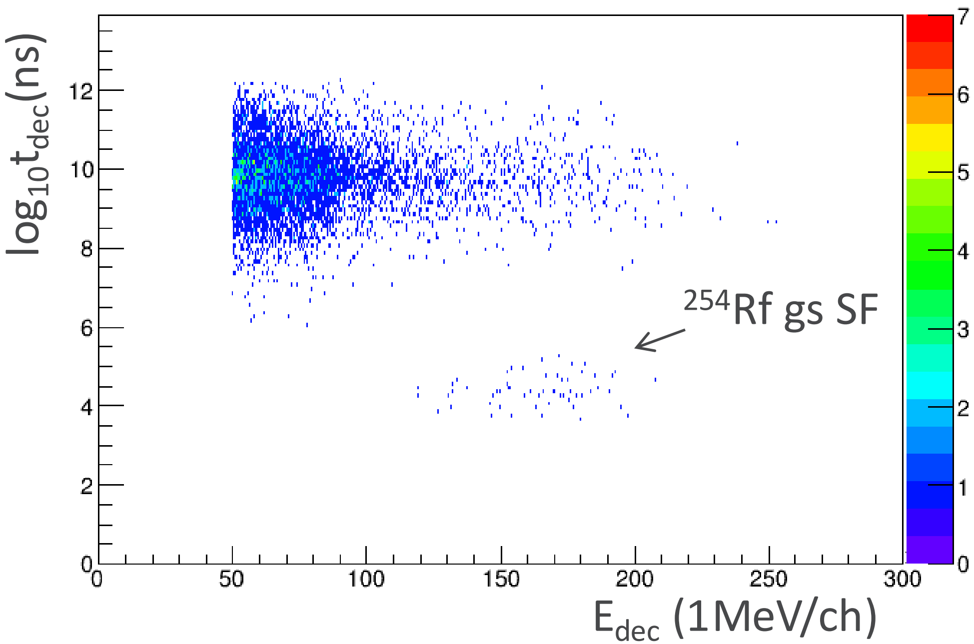
^{254}Rf ground-state rotational band
Gammasphere+AGFA

^{50}Ti+^{206}Pb, ~20-25 pnA, 7 days

σ~2.6 nb

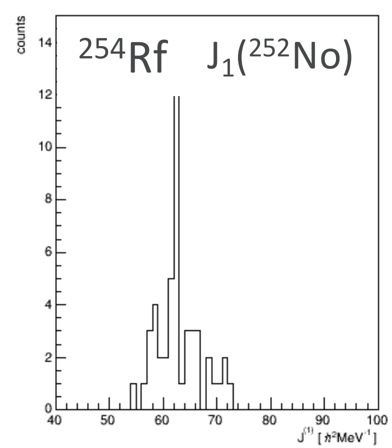
Smallest xsection so far: ^{256}Rf, σ~17 nb

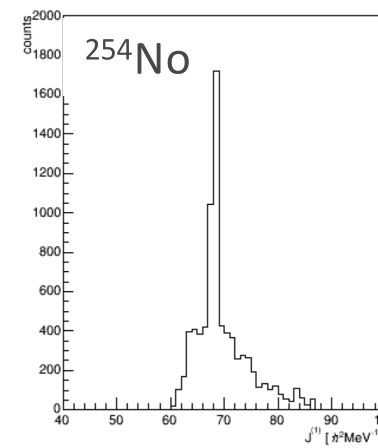




$J_0 \sim (2I-1)/E_\gamma - J_1(E\gamma/2)^2$

Moment of inertia "spectrum"

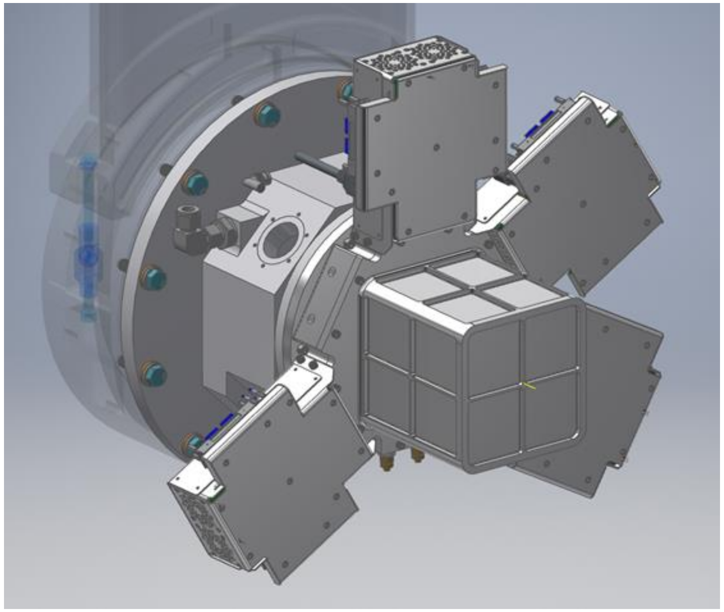




D. Seweryniak, T. Huang et al., Phys. Rev. C 107, L061302 (2023)

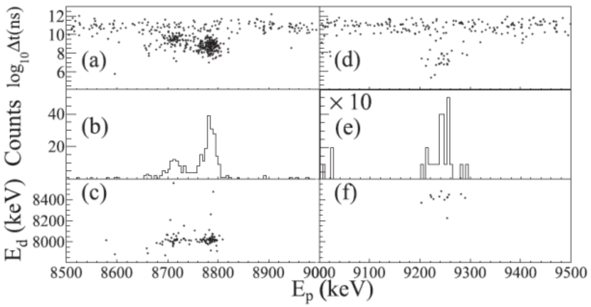
SHN outlook

- Scheduled experiments
  - ^{253}**No** HK distributions
  - N>152 nucleus ^{256}**No** (with radioactive ^{210}Pb targets)
  - Detailed decay spectroscopy of ^{251}**Md**
  - Decay of ^{249}**Fm**
- Developments
  - AGFA implantation-decay station
  - ECR source upgrade
- Future
  - GRETA
  - New ECR source
  - Search for new elements

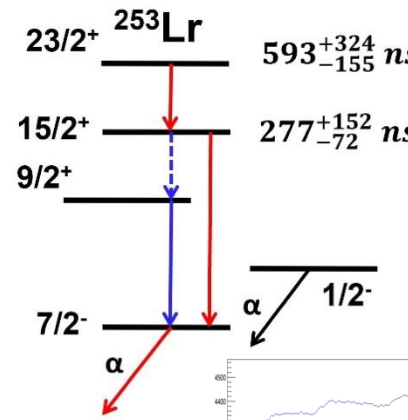


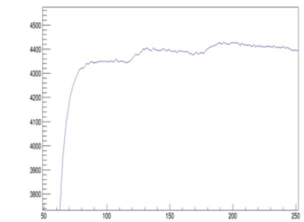
Selected AGFA highlights

PRL, 2 PRC letters, 5 PRCs



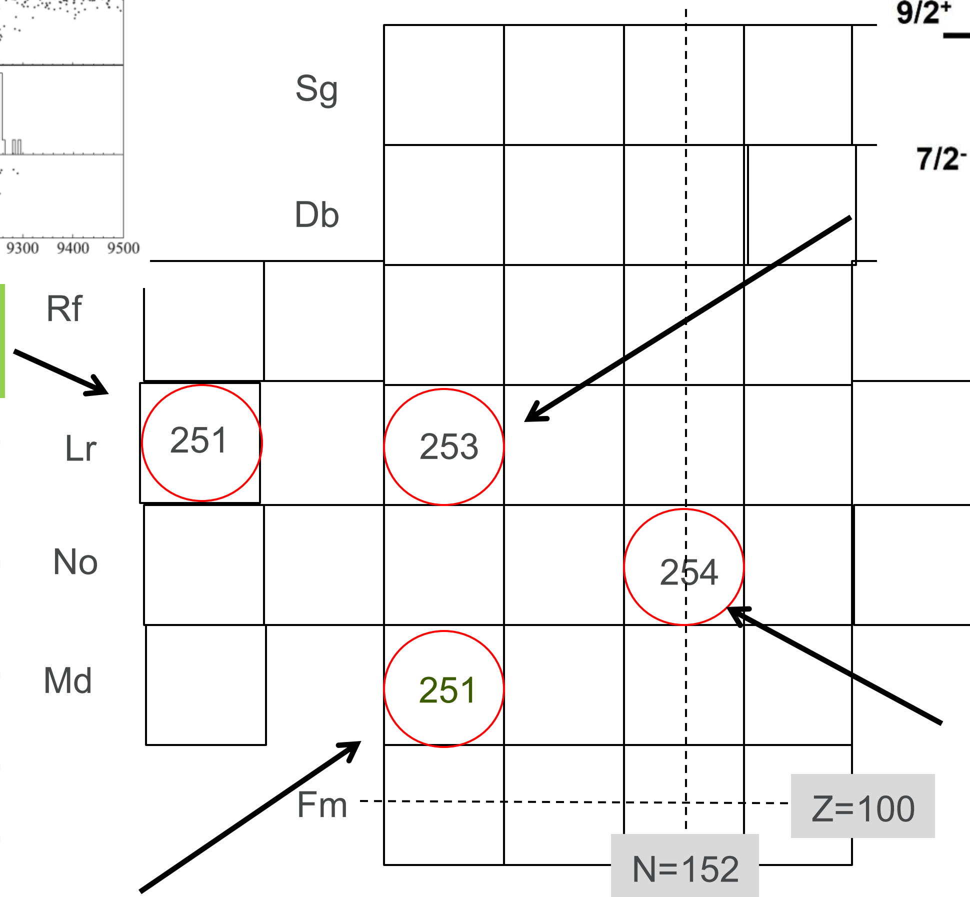
Two fast K-isomers in ^{253}Lr



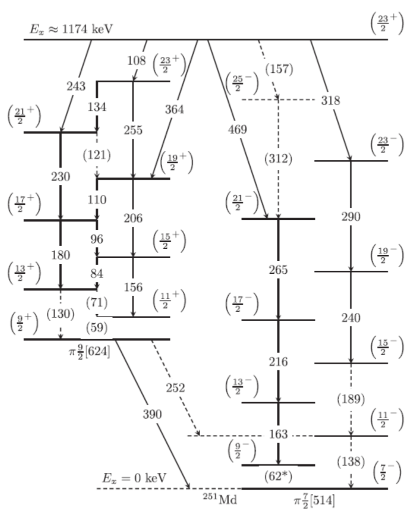


New isotope ^{251}Lr

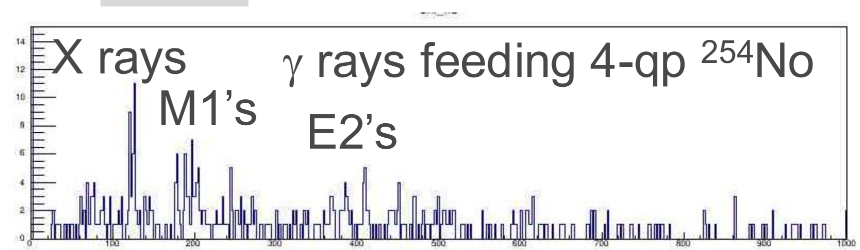
Single-proton energies



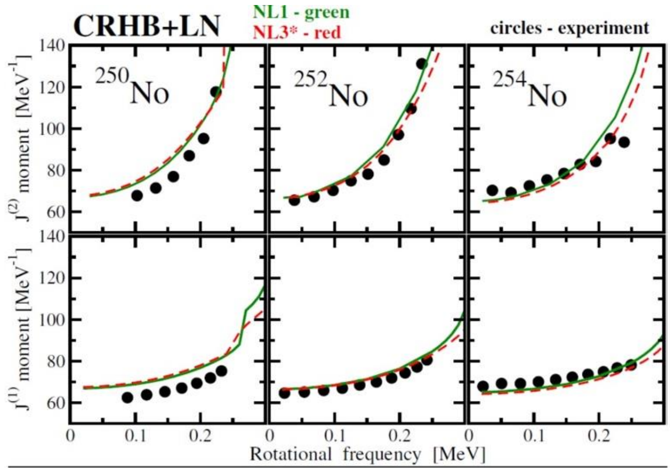
Rotational band feeding 4qp isomer, new 5-ns K-isomer in ^{254}No



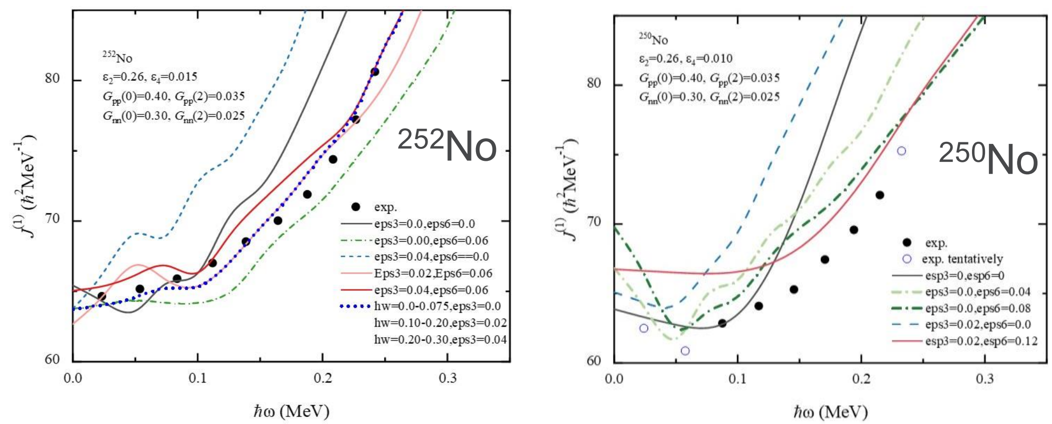
Detailed decay of K-isomer in ^{251}Md



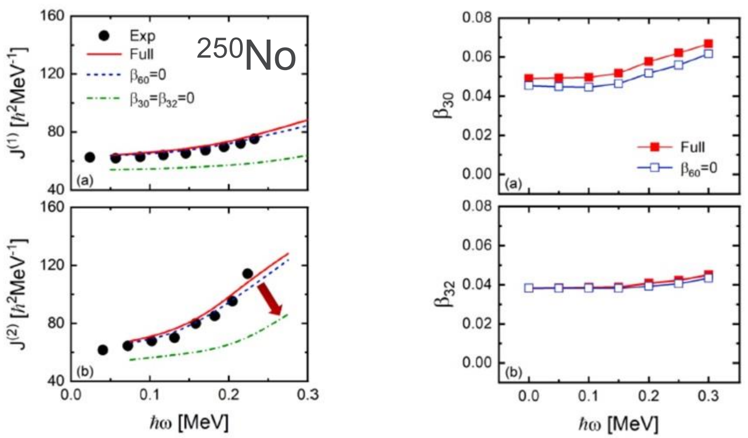
Moment of inertia calculations for No isotopes



Cranked Relativistic Hartree Bogoliubov theory
A.V. Afanasjev, Mississippi University



Particle-Number-Conserving Cranking Shell Model
Xiao-Tao He, Nanjing University



Cranking Covariant Density Functional Theory in 3D lattice space with a shell-model-like approach (SLAP)
P.W. Zhao, Peking University

CRHB and PNC CSM can explain data without octupole deformation
CDFT predicts octupole deformation already in the ground state in ^{250}No

We will propose an experiment to extend the ground state rotational band in ^{250}No to higher frequencies

Recent Gammasphere/AGFA campaigns

Fall 2022 – Spring 2024

~20 experiments in total

^{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

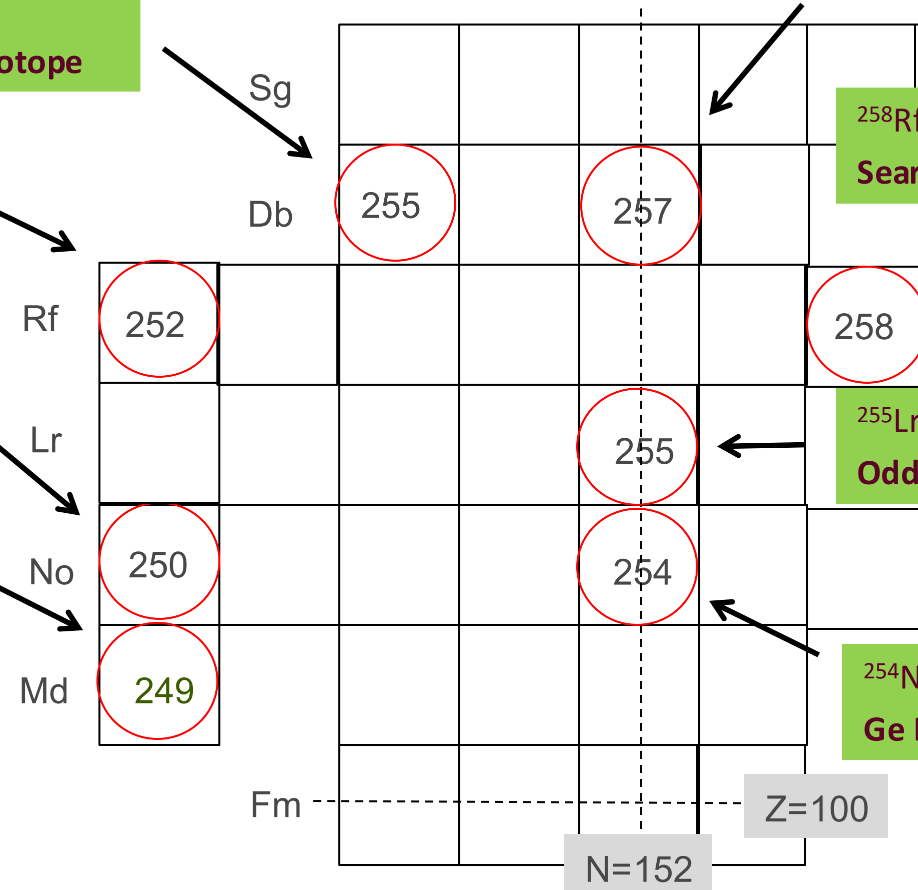
OTHER:
^{136}Xe+^{238}U MNT
^{196,197}Fr – proton drip line

^{257}Db
Search for K-isomers

^{258}Rf
Search for K-isomers

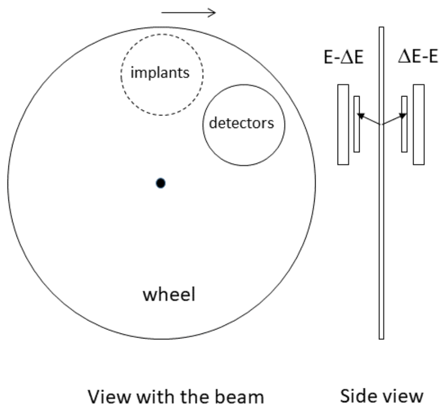
^{255}Lr – 200 nb
Odd-Z nucleus in beam

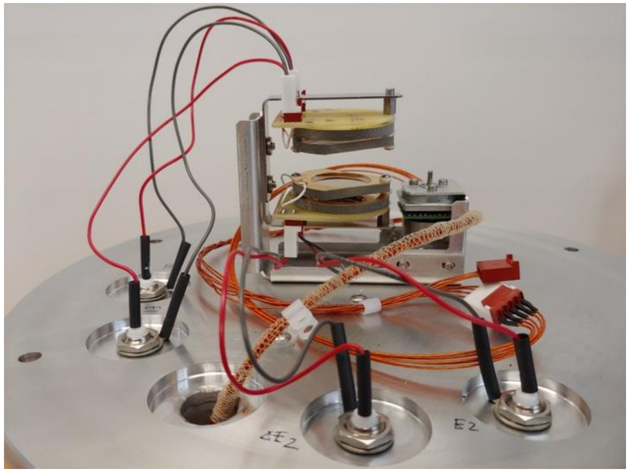
^{254}No – 2 μb
Ge DSSD



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

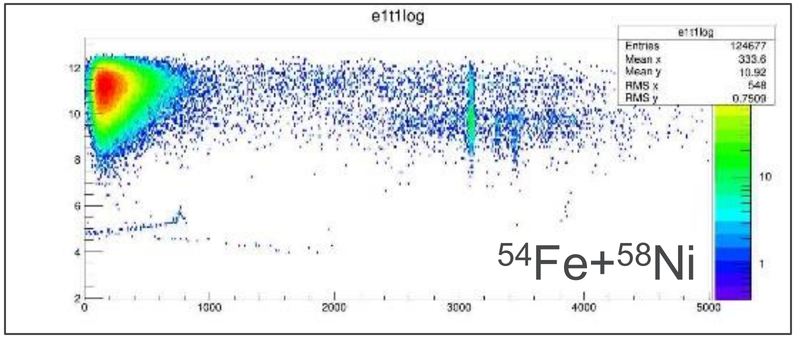
Rotating stopper at AGFA focal plane

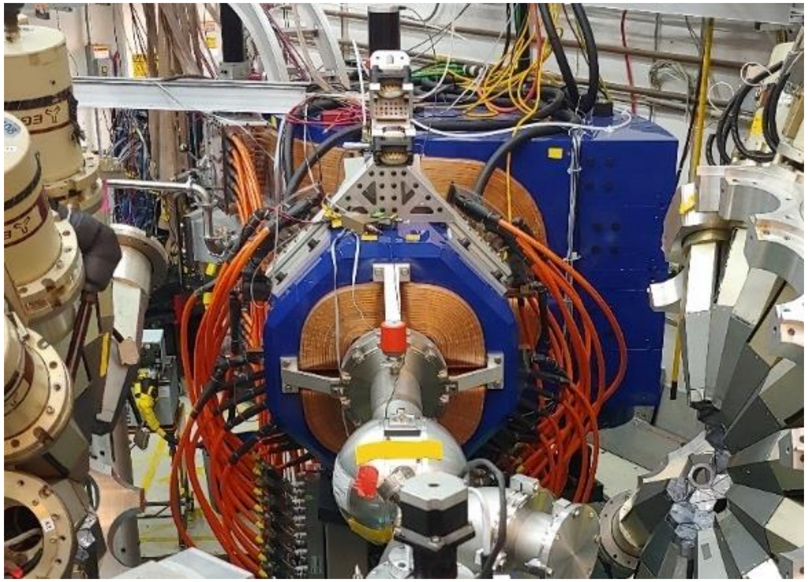




Search for triple α chains:
^{112}Ba-^{108}Xe-^{104}Te

Higher efficiency
Higher beam intensity
Δt~1 ns





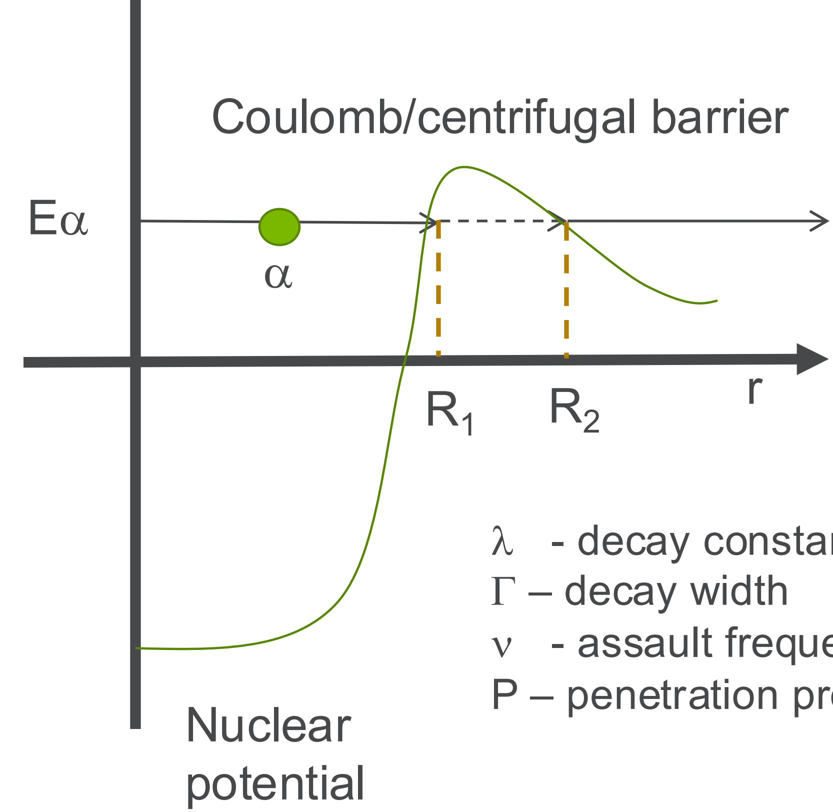
Argonne Gas-Filled Analyzer (AGFA)

Gamow alpha-decay model

G. Gamow, Z. Phys. 51, 204 (1928)
Probabilistic interpretation of quantum mechanics

$$\lambda = \nu P$$

$$\Gamma = \hbar\lambda = \hbar\nu P$$



λ - decay constant
Γ – decay width
ν - assault frequency
P – penetration probability

$$\lambda = \frac{\upsilon}{2R_0} exp\left[-2\int_{R_1}^{R_2}\sqrt{\frac{2\mu}{\hbar}}\,|Q_\alpha - V(r)|dr\right]$$

Can be readily calculated
Very steep function of Q-value

$$\Gamma = \delta^2 P$$

$$\delta^2 = \frac{\Gamma_{exp}}{P_{calc}}$$

δ^2 - reduced α decay width, often normalized to ^{212}Po (~α preformation factor)

R-matrix expression of the α-decay width

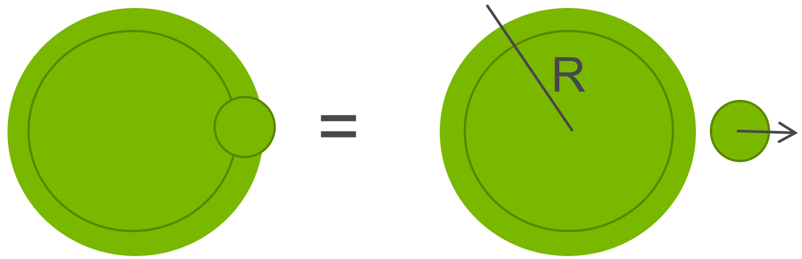
Decay width:

$$\Gamma_L(R) = 2\gamma_L^2(R)P_L(R)$$

$P_L(R)$ - penetrability
R – channel radius (outside of the nucleus)

Reduced width amplitude:

$$\gamma_L(R) = \left(\frac{\hbar^2 R}{2\mu}\right)^{1/2} F_L(R)$$



Formation amplitude:

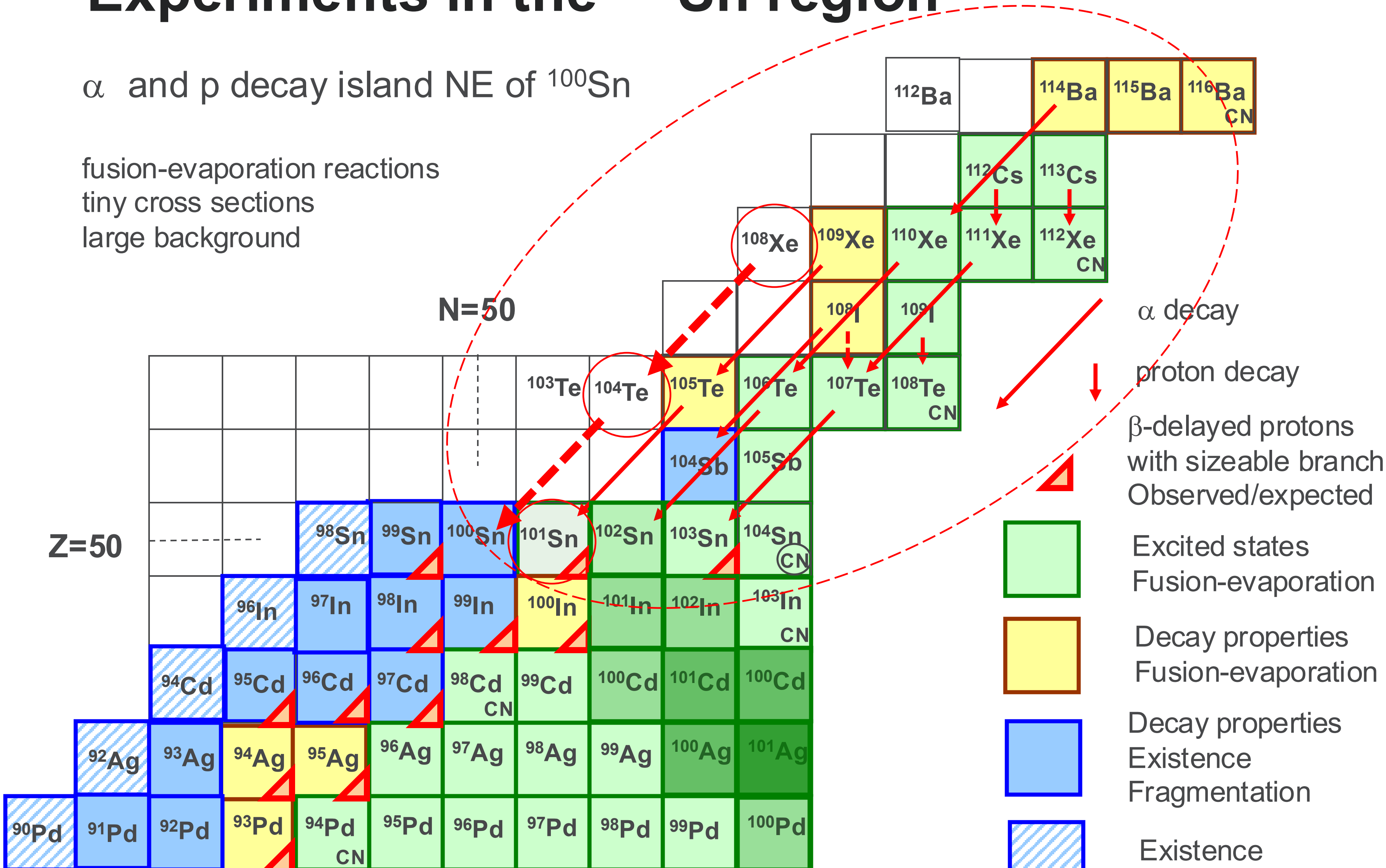
$$F_L(R) = \int d\xi_\alpha d\xi_D d\hat{R} [\underline{\phi_\alpha(\xi_\alpha)}\,\underline{\psi_D(\xi_D)}Y_L(\hat{R})]^*_{\alpha_4,\nu_4}\,\underline{\psi_P(\xi_\alpha\xi_D;R)}$$

Overlap between parent nucleus and daughter nucleus + alpha
at a distance R outside of nuclear interactions

Experiments in the ^{100}Sn region

α and p decay island NE of ^{100}Sn

fusion-evaporation reactions
tiny cross sections
large background



Single-neutron states in ^{101}Sn

PRL 99, 022504 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Single-Neutron States in ^{101}Sn

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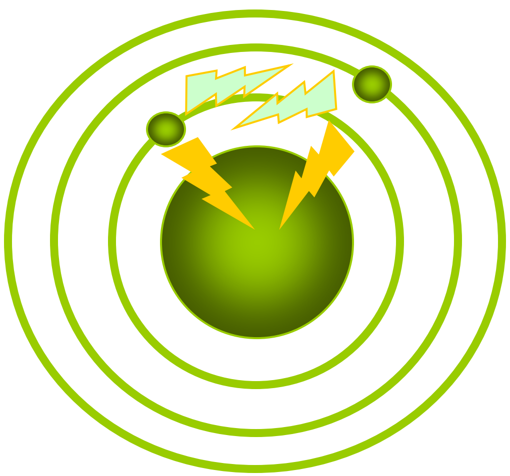
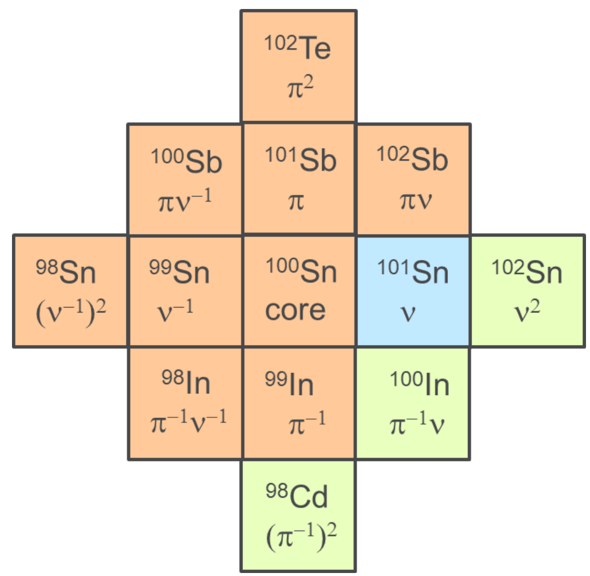
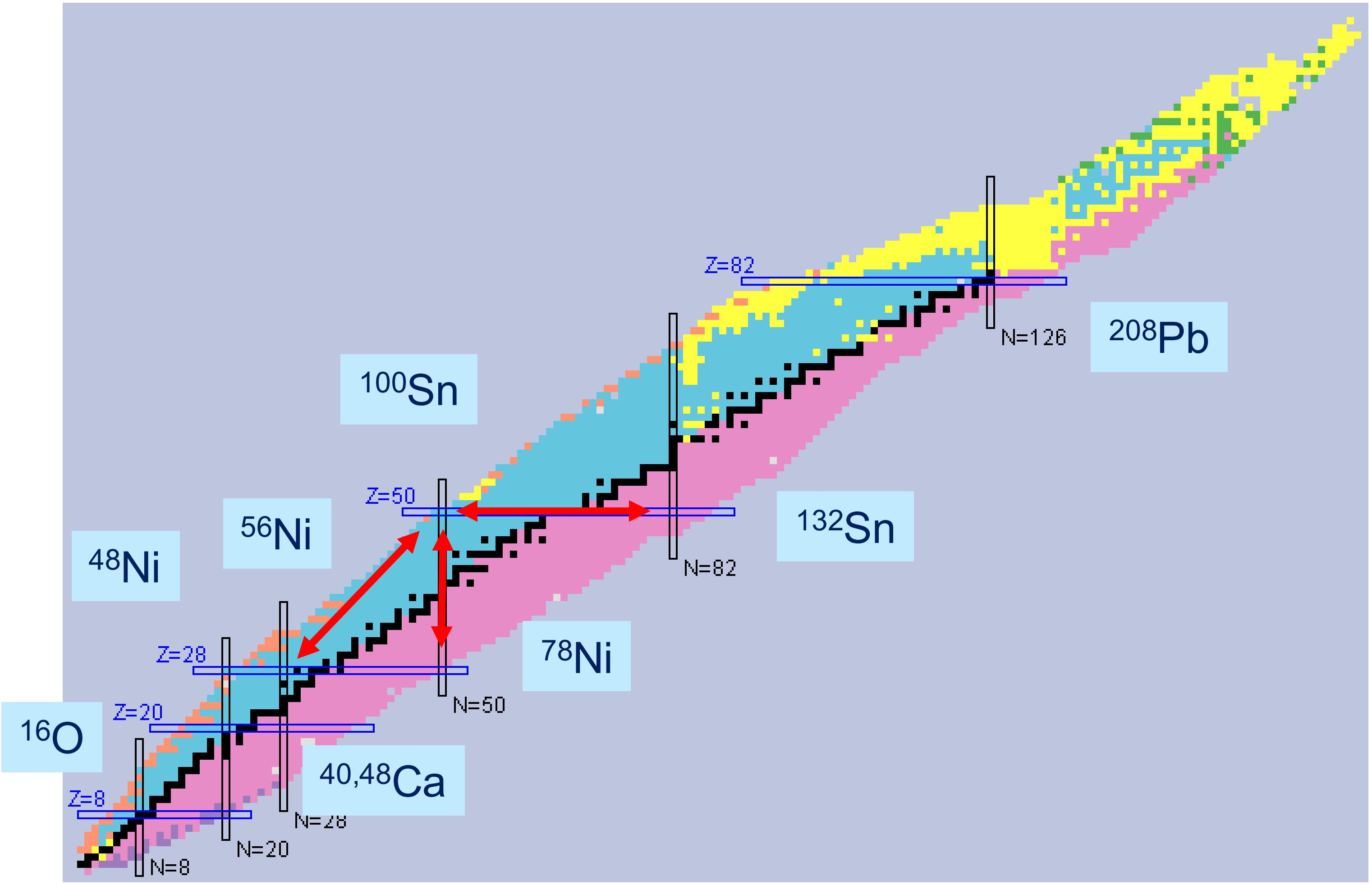
(Received 15 April 2007; published 12 July 2007)

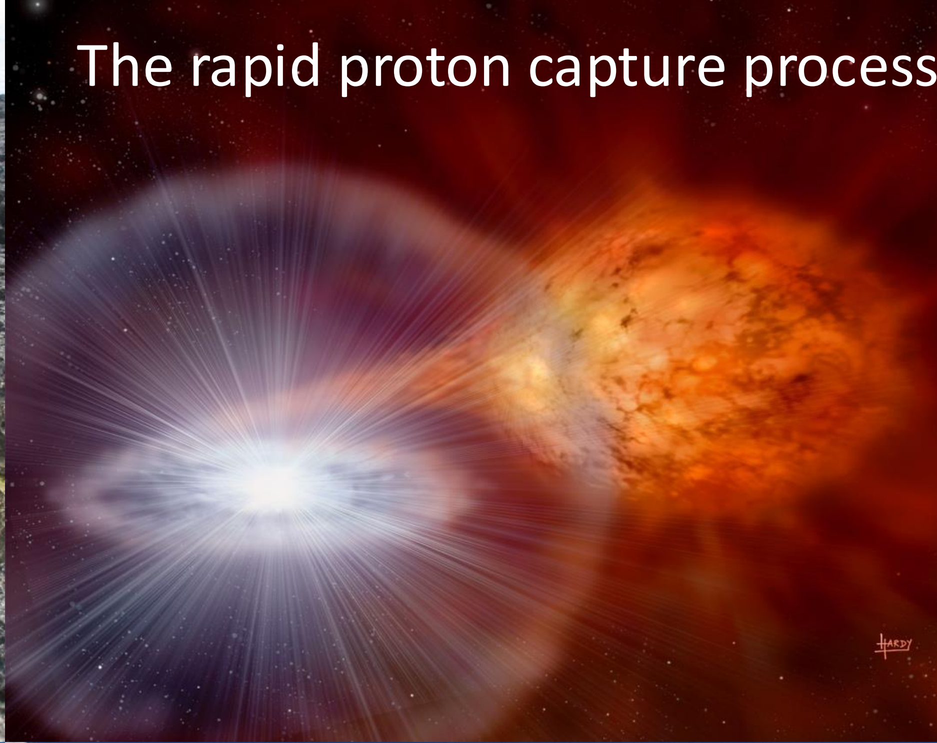


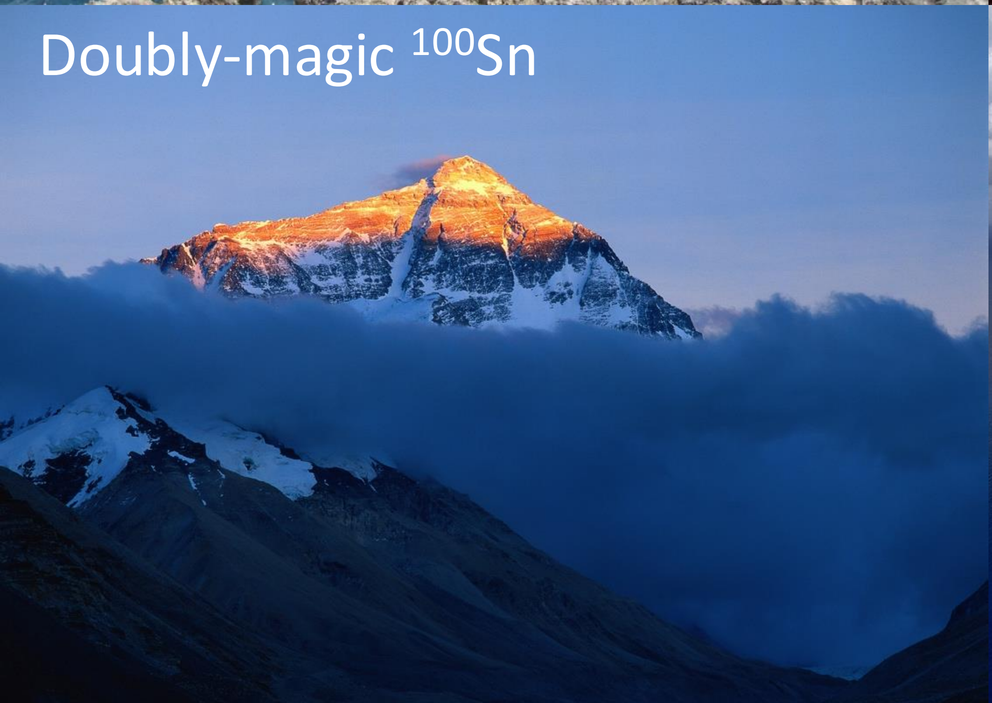


Doubly-magic nuclei far from stability



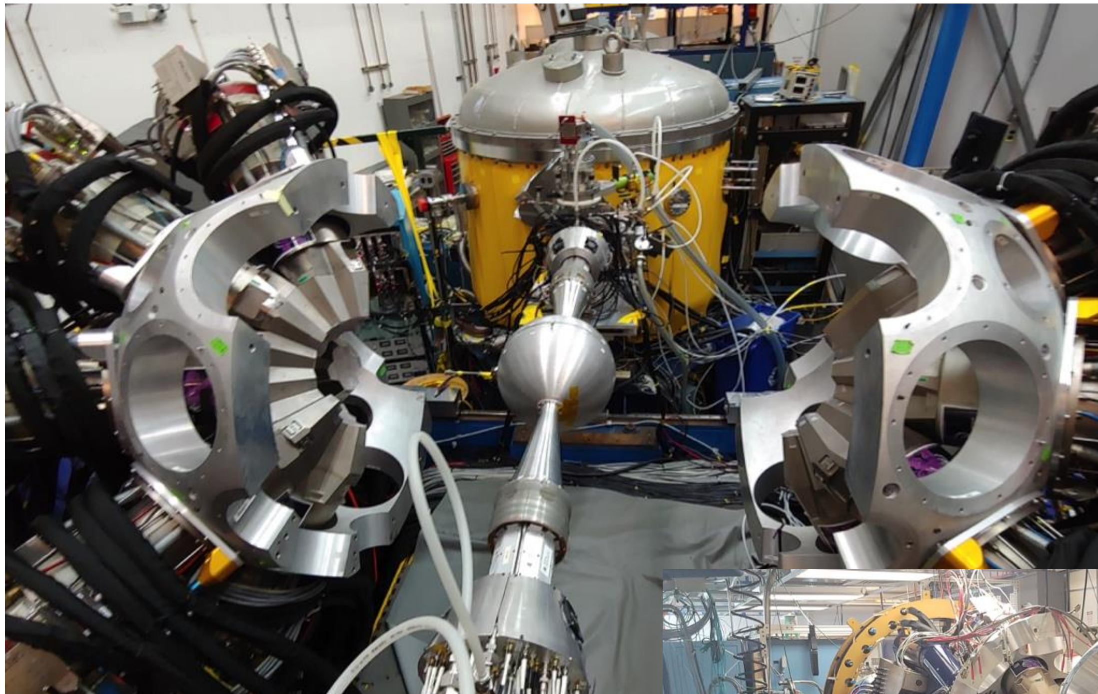

Proton drip-line

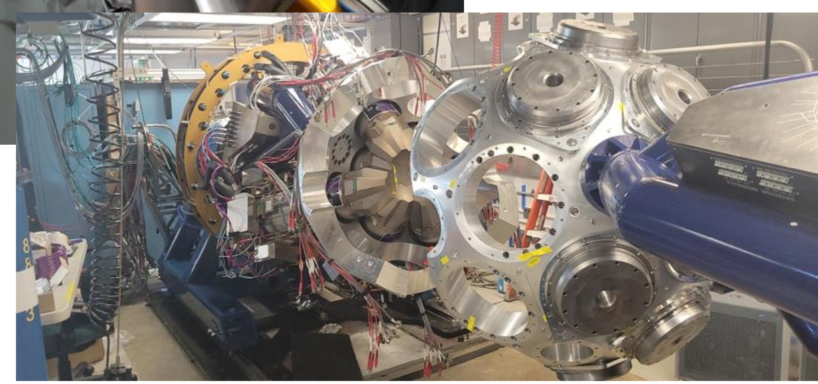

The rapid proton capture process
HARDY


Doubly-magic ^{100}Sn


Island of super-heavy nuclei

Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

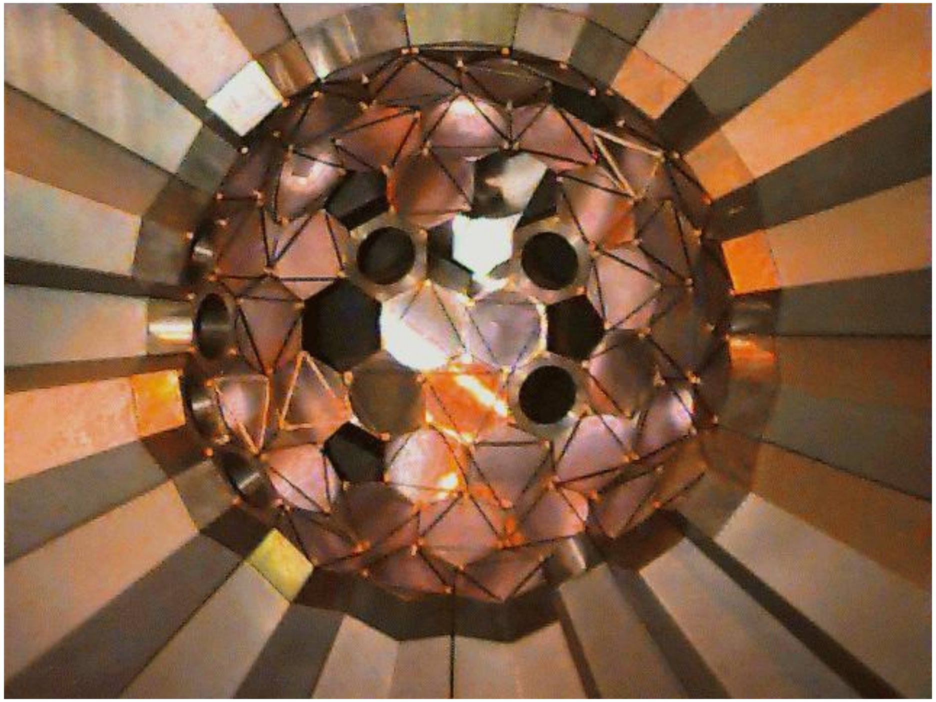




GRETA dedication – April 23, 2025

- 12 quad modules
- Each crystal divided into 36 segments
- Position resolution FWHM~5 mm
- Efficiency comparable to Gammasphere
- High-rate capability
- Transition into GRETA (30 modules, full 4π) starting this year

Gammasphere
4π array of Compton suppressed γ-ray detectors



Up to 110 HPGe detectors in BGO shields
γ-ray detection efficiency at 1.3MeV ~10%

Can be moved between FMA and AGFA

Argonne Gas-Filled Analyzer (AGFA)

D. Potterveld, ANL

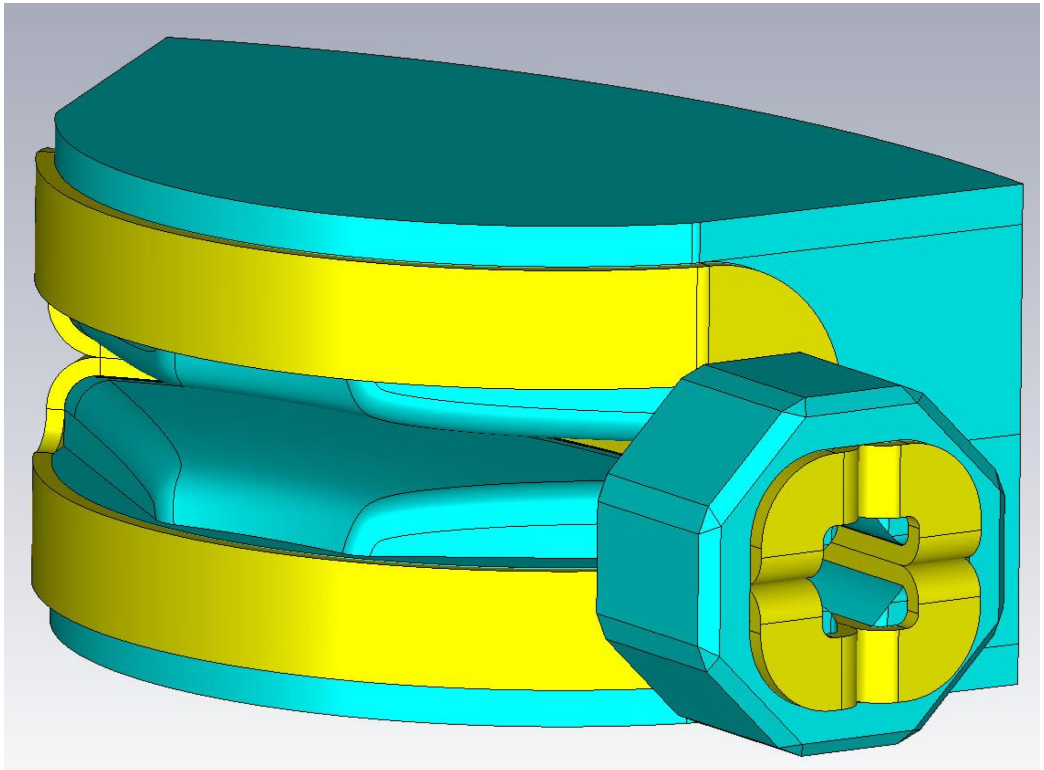
Use Combined Function bending magnet
- Overlapping bending, focusing fields
- Fewer magnets, ultra-compact design

$Q_v D_m$ design

2.5 Tm max Bρ
38° bend

22.5 msr @ 80 cm
(44 msr @ 40 cm)

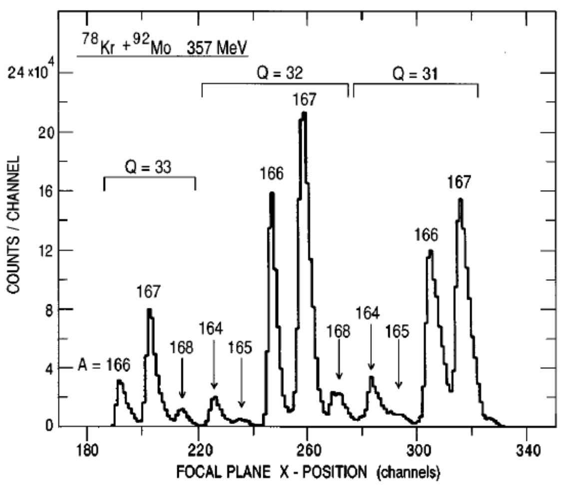
4.2 total length @ 80 cm
(3.9 m @ 40 cm)

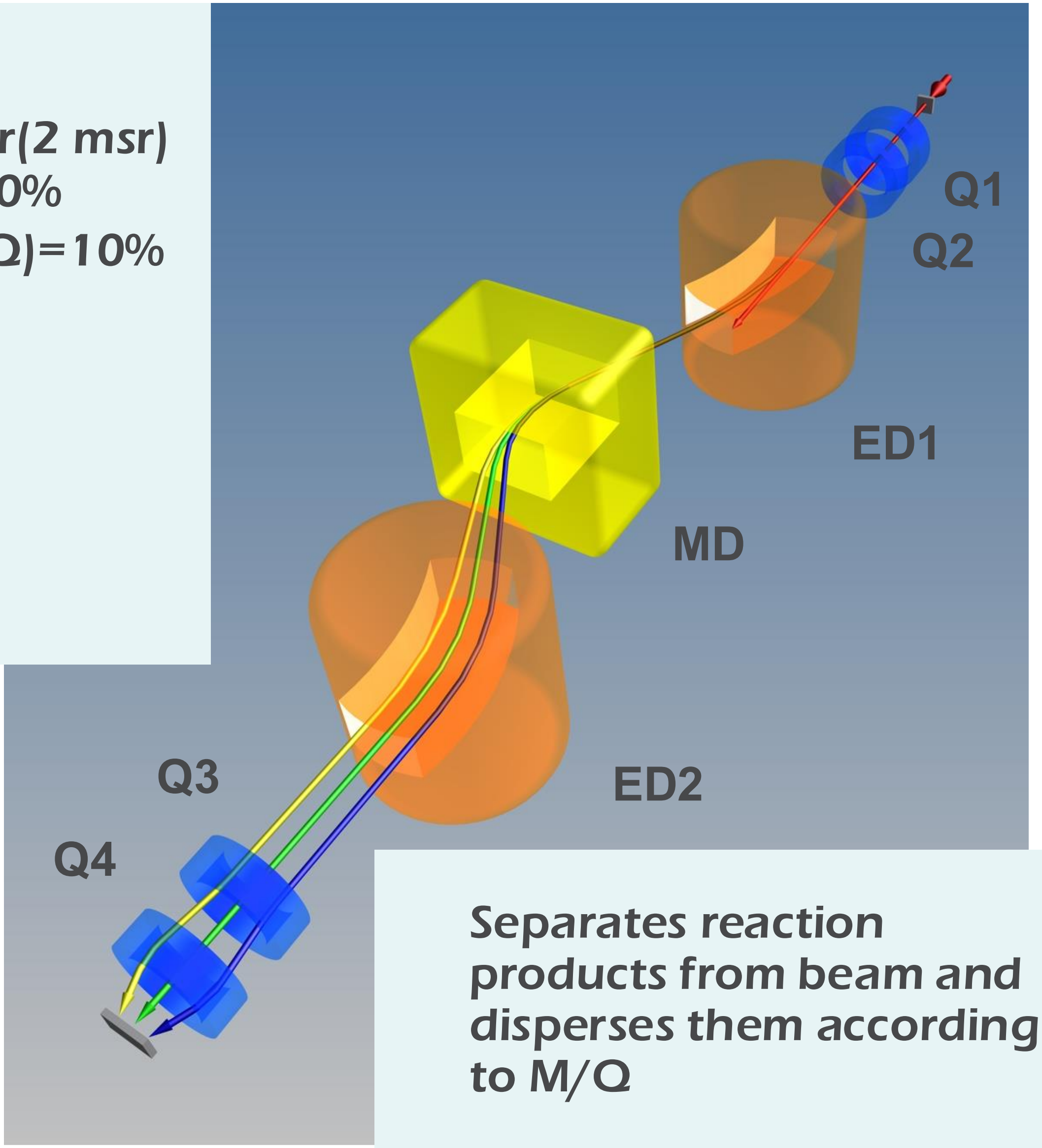


Optimized for spectroscopy, commissioned in late 2018

Argonne Fragment Mass Analyzer

Mass resolution: $\delta M/M \sim 1/350$
Angular acceptance: $\Delta\Omega$=8 msr(2 msr)
Energy acceptance: $\Delta\mathcal{E}/\mathcal{E}$=+/-20%
M/Q acceptance: $\Delta(M/Q)/(M/Q)$=10%
Flight path 8.2m
Max($B\rho$)=1.1Tm
Max($E\rho$)=20MV
Can be rotated off 0 degrees
Can be moved along the axis
Different focusing modes





Separates reaction products from beam and disperses them according to M/Q