Spectroscopy of Very Heavy Elements

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What is the link?

Outline

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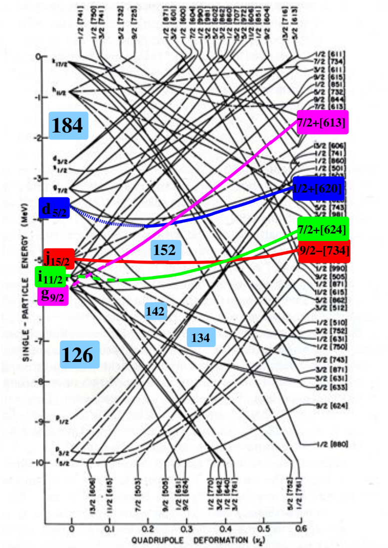
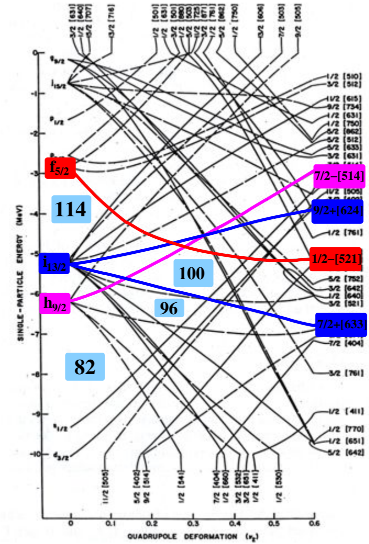
1. Introduction
2. Experimental Approaches
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. Structure of High-K States
6. Future Perspectives

What is the structure of SHE?





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1. Introduction
2. **Experimental Approaches**
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. Structure of High-K States
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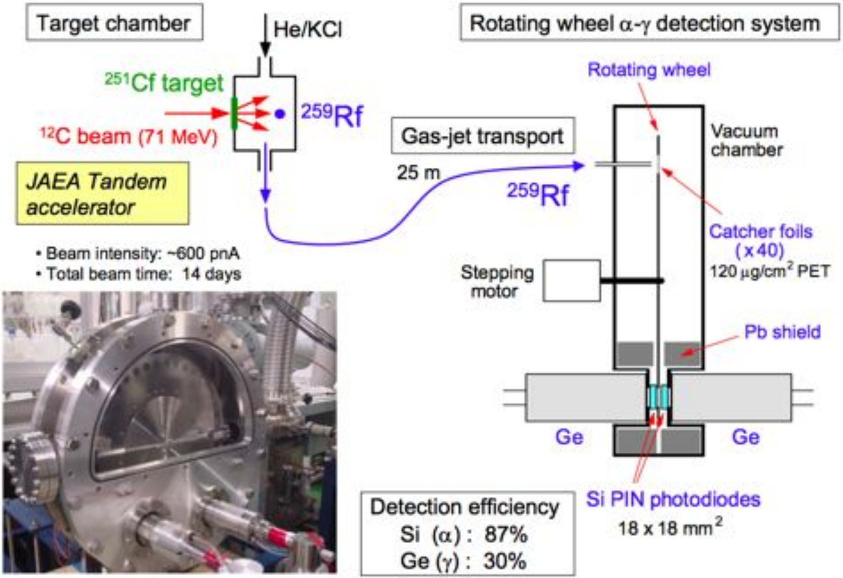
6. Future Perspectives

Decay Spectroscopy - Case Study ^{255}No



Target chamber

He/KCl

^{251}Cf target

^{12}C beam (71 MeV)

^{259}Rf

JAEA Tandem accelerator

- Beam intensity: ~600 pnA
- Total beam time: 14 days

Gas-jet transport

25 m

^{259}Rf

Rotating wheel α-γ detection system

Rotating wheel

Vacuum chamber

Catcher foils (x40)

120 μg/cm^2 PET

Stepping motor

Pb shield

Ge

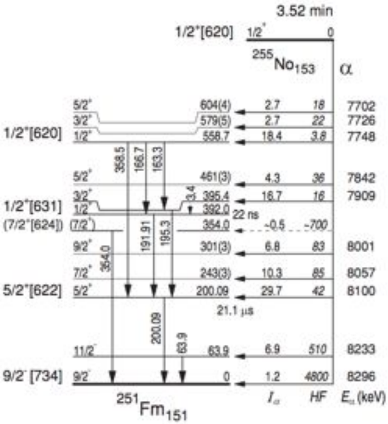
Ge

Si PIN photodiodes

18 x 18 mm^2

Detection efficiency
Si (α) : 87%
Ge (γ) : 30%

Decay Spectroscopy - Case Study ^{255}No



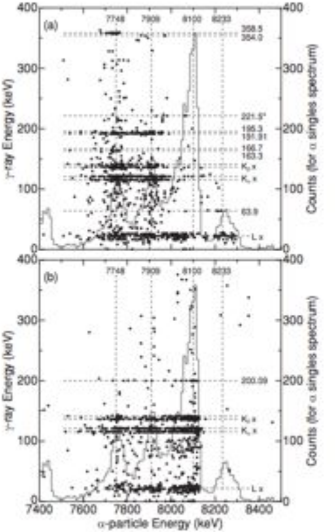
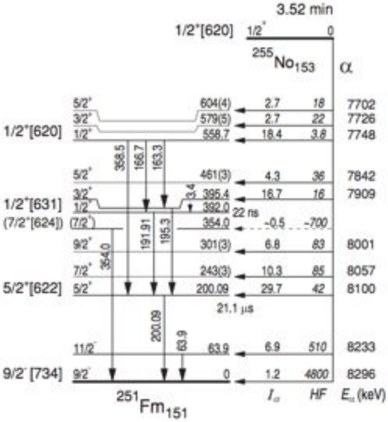


FIG. 2. Two-dimensional plots of α-γ coincidence events: (a) prompt coincidence events detected within the time interval

M.Asai et al., PRC **83**, 014315 (2011) and ARIS2011

Decay Spectroscopy - Case Study ^{255}No



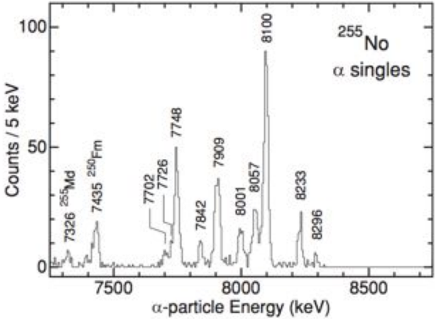
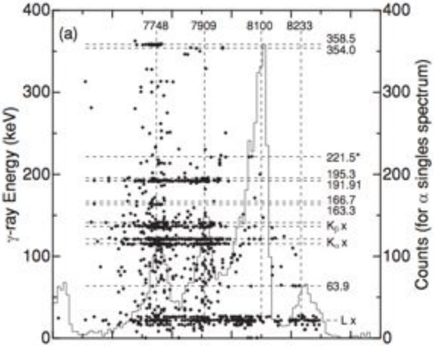


FIG. 6. α fine-structure spectrum of ^{255}No measured during the period of 90–360 s after the ends of the source depositions.

M.Asai et al., PRC **83**, 014315 (2011) and ARIS2011

Decay Spectroscopy - Case Study ^{255}No



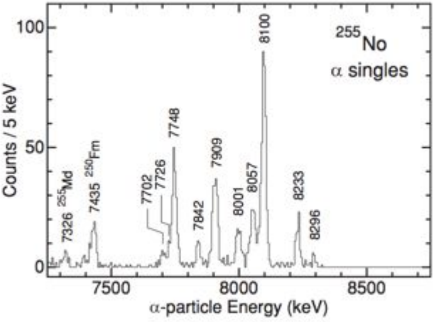


FIG. 6. α fine-structure spectrum of ^{255}No measured during the period of 90–360 s after the ends of the source depositions.

Decay Spectroscopy - Case Study ^{255}No

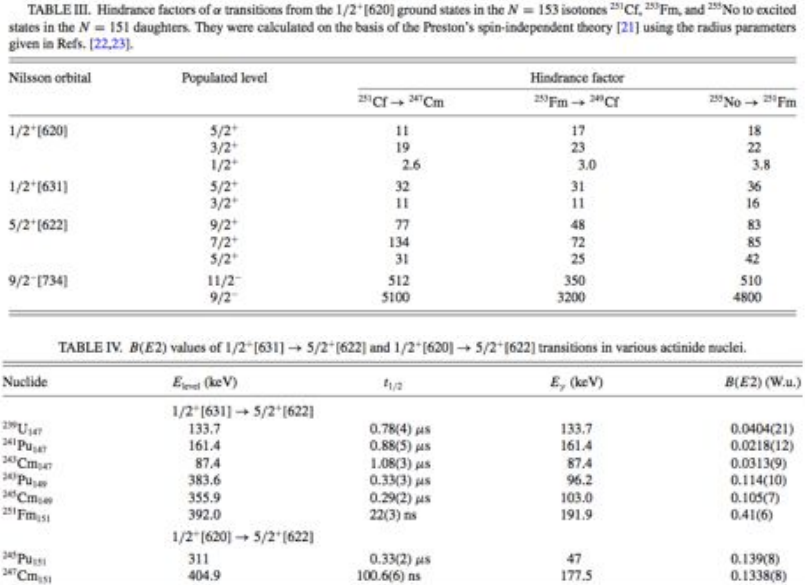


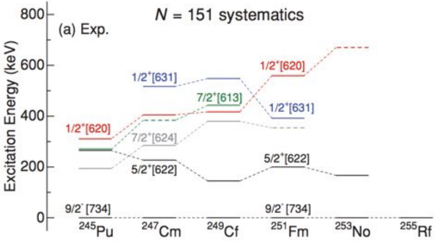
TABLE III. Hindrance factors of α transitions from the $1/2^+[620]$ ground states in the $N = 153$ isotones ^{251}Cf, ^{253}Fm, and ^{255}No to excited states in the $N = 151$ daughters. They were calculated on the basis of the Preston's spin-independent theory [21] using the radius parameters given in Refs. [22,23].

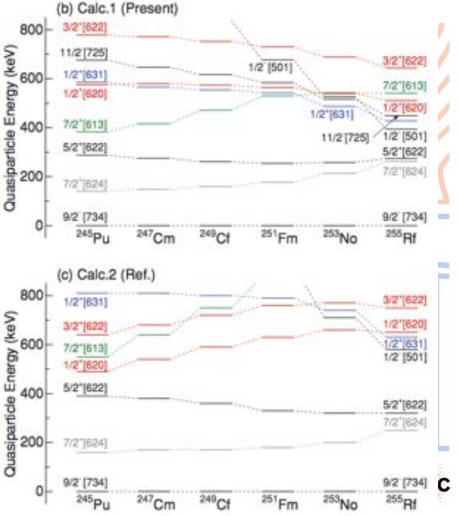
Nilsson orbital	Populated level	Hindrance factor		
		$^{251}\mathrm{Cf} \rightarrow {}^{247}\mathrm{Cm}$	$^{253}\mathrm{Fm} \rightarrow {}^{249}\mathrm{Cf}$	$^{255}\mathrm{No} \rightarrow {}^{251}\mathrm{Fm}$
$1/2^+[620]$	$5/2^+$	11	17	18
	$3/2^+$	19	23	22
	$1/2^+$	2.6	3.0	3.8
$1/2^+[631]$	$5/2^+$	32	31	36
	$3/2^+$	11	11	16
$5/2^+[622]$	$9/2^+$	77	48	83
	$7/2^+$	134	72	85
	$5/2^+$	31	25	42
$9/2^-[734]$	$11/2^-$	512	350	510
	$9/2^-$	5100	3200	4800

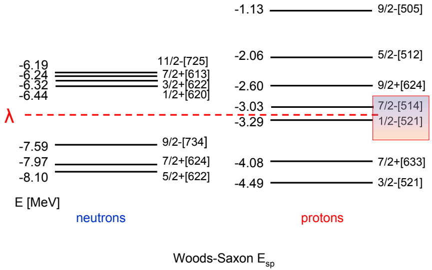
TABLE IV. $B(E2)$ values of $1/2^+[631] \rightarrow 5/2^+[622]$ and $1/2^+[620] \rightarrow 5/2^+[622]$ transitions in various actinide nuclei.

Nuclide	E_{level} (keV)	$t_{1/2}$	E_γ (keV)	$B(E2)$ (W.u.)
	$1/2^+[631] \rightarrow 5/2^+[622]$			
$^{239}\mathrm{U}_{147}$	133.7	0.78(4) μs	133.7	0.0404(21)
$^{241}\mathrm{Pu}_{147}$	161.4	0.88(5) μs	161.4	0.0218(12)
$^{243}\mathrm{Cm}_{147}$	87.4	1.08(3) μs	87.4	0.0313(9)
$^{243}\mathrm{Pu}_{149}$	383.6	0.33(3) μs	96.2	0.114(10)
$^{245}\mathrm{Cm}_{149}$	355.9	0.29(2) μs	103.0	0.105(7)
$^{251}\mathrm{Fm}_{151}$	392.0	22(3) ns	191.9	0.41(6)
	$1/2^+[620] \rightarrow 5/2^+[622]$			
$^{245}\mathrm{Pu}_{151}$	311	0.33(2) μs	47	0.139(8)
$^{247}\mathrm{Cm}_{151}$	404.9	100.6(6) ns	177.5	0.1338(8)

Decay Spectroscopy - Case Study ^{255}No







-1.13 9/2-[505]
-2.06 5/2-[512]
-6.19 11/2-[725]
-6.24 7/2+[613]
-6.32 3/2+[622]
-6.44 1/2+[620]
-2.60 9/2+[624]
-3.03 7/2-[514]
λ
-3.29 1/2-[521]
-7.59 9/2-[734]
-7.97 7/2+[624]
-8.10 5/2+[622]
-4.08 7/2+[633]
-4.49 3/2-[521]

E [MeV]

neutrons

protons

Woods-Saxon E_{sp}

Decay spectroscopy of ^{255}Lr

A.Chatillon et al., EPJA **30** 397 (2006)

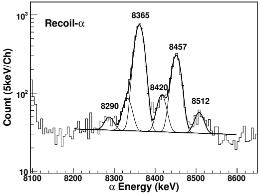


Fig. 4. Portion of the α-decay spectrum, resulting from recoil-α correlations, in the ^{255}Lr region. Data are taken from the JYFL experiment.

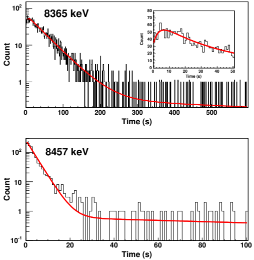


Fig. 5. Decay curves corresponding to the 8365 keV (upper panel) and 8457 keV (lower panel) α-decay lines.

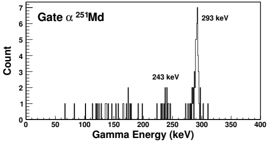


Fig. 9. Upper panel: matrix corresponding to prompt α-γ correlations. Lower panel: γ transition in coincidence with the ^{251}Md α line. Data are taken from the GANIL experiment.

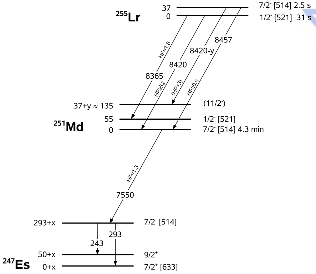
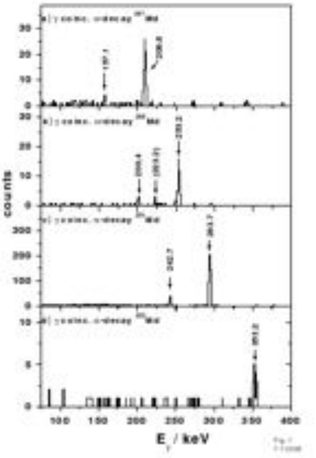
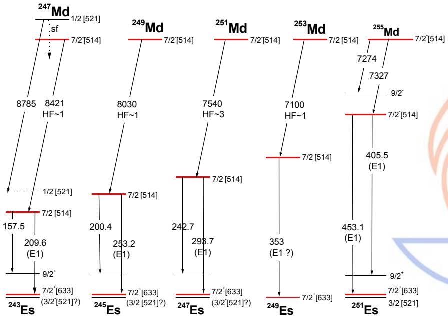


Fig. 13. Level scheme of ^{247}Es ^{251}Md and ^{255}Lr deduced from experimental data. The tentative 8290 keV line from ^{255}Lr is not shown.

Decay spectroscopy at SHIP

Courtesy of F.P.Heßberger





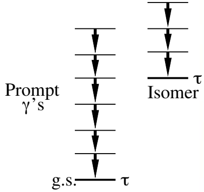
- Trace separation of states from 4 spherical shells:
- $\pi[521]1/2^-$ $(2f_{5/2})$
- $\pi[514]7/2^-$ $(1h_{9/2})$
- $\pi[633]7/2^+$ $(1i_{13/2})$
- $\pi[521]3/2^-$ $(2f_{7/2})$

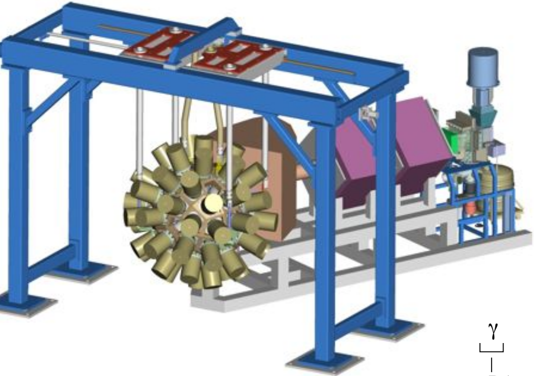
Outline

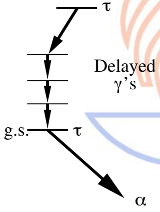
Principles of Recoil-Decay Tagging

Tagging Techniques

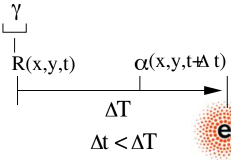
Recoil, Recoil–Decay, Isomer







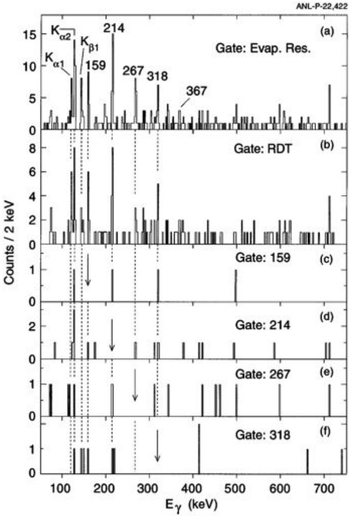
Time Line:

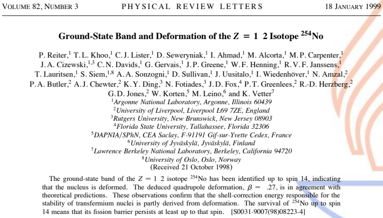


$\Delta t < \Delta T$

Over a decade of in-beam studies in the region of ^{254}No

P.Reiter et al., PRL **82**, 509 (1999)



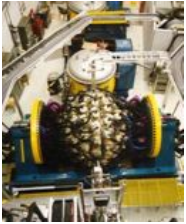


VOLUME 82, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1999

Ground-State Band and Deformation of the $Z = 1\ 2$ Isotope ^{254}No

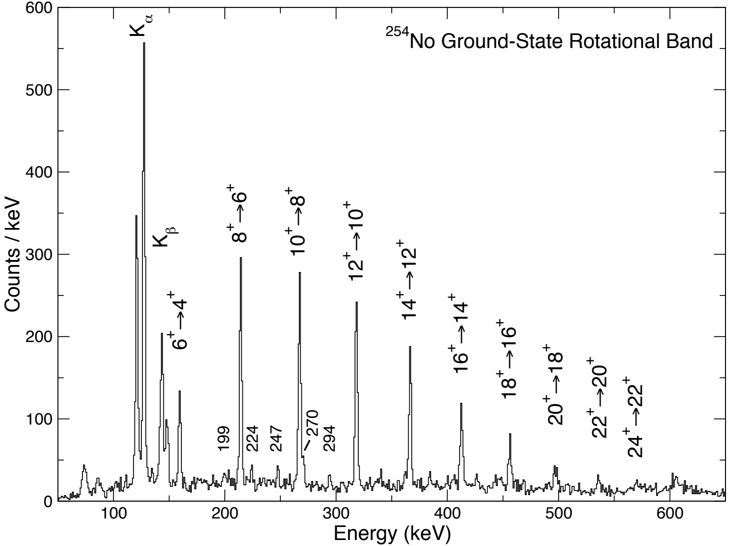
P. Reiter,[1] T. L. Khoo,[1] C. J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M. P. Carpenter,[1]
J. A. Cizewski,[1,3] C. N. Davids,[1] G. Gervais,[1] J. P. Greene,[1] W. F. Henning,[1] R. V. F. Janssens,[1]
T. Lauritsen,[1] S. Siem,[1,8] A. A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] 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)

The ground-state band of the $Z = 1\ 2$ isotope ^{254}No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = \ .27$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible for the stability of transfermium nuclei is partly derived from deformation. The survival of ^{254}No up to spin 14 means that its fission barrier persists at least up to that spin. [S0031-9007(98)08223-4]

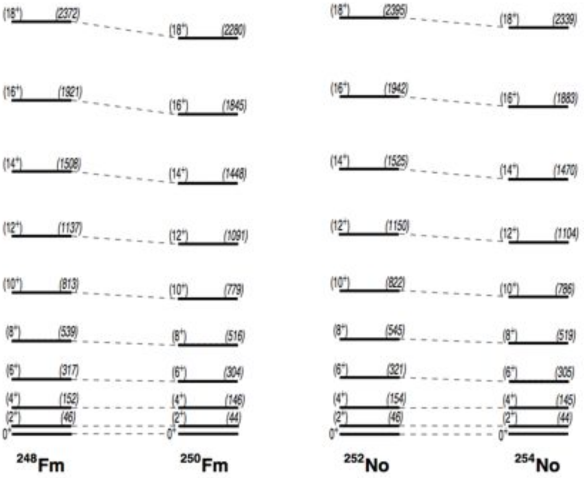


In-beam γ-ray Spectroscopy of ^{254}No

Unpublished spectrum,see also S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)



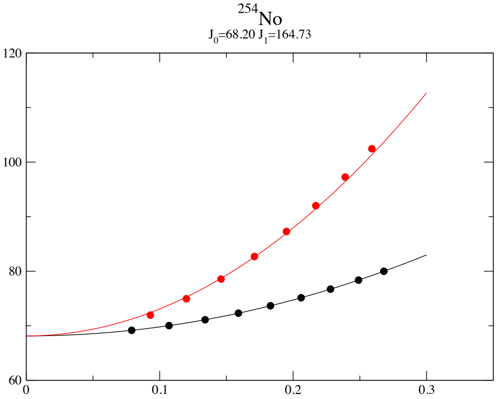
Rotational Bands



Harris Fits

- $\mathcal{J}^{(1)} = \hbar^2 \frac{2I-1}{E_{\gamma 1}}$
- $\mathcal{J}^{(2)} = \frac{4\hbar^2}{\Delta E_\gamma}$
- $\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2$
- $\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2$
- $I = \mathcal{J}_0\omega + \mathcal{J}_1\omega^3 + 1/2$

Rotational Bands



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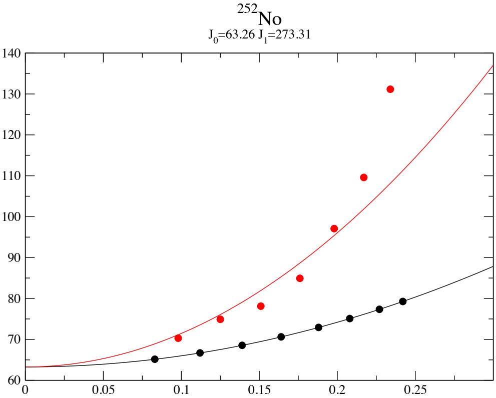
Rotational Bands



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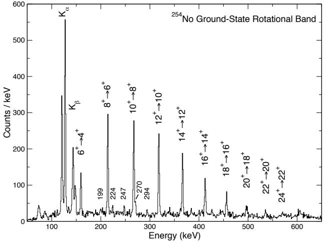
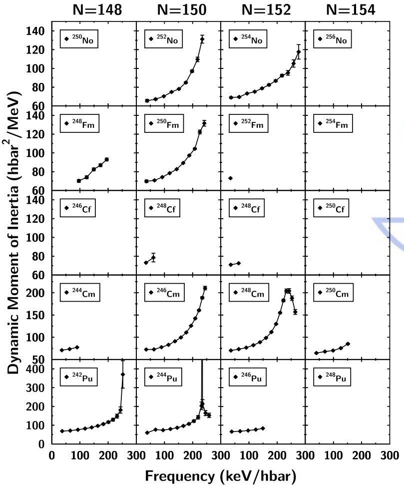
In-beam studies in region of ^{254}No

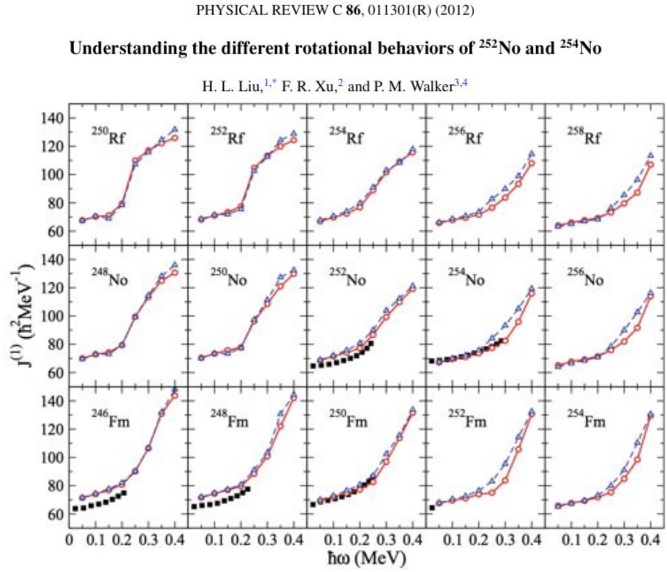
S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)





- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at N=150 compared to N=152 ($\pi i_{13/2}, \nu j_{15/2}$)
- Excellent testing ground for theory; e.g.
  Duguet et al., NPA **679**, 427 (2001),
  Bender et al., NPA **723**, 354 (2003),
  Afanasjev et al., PRC **67**, 024309 (2003),
  Egido and Robledo, PRL **85** 1198 (2000)

Theory - N=150 vs. N=152

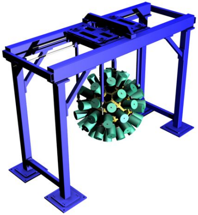


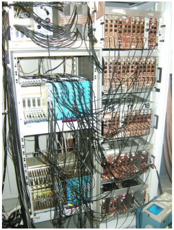
PHYSICAL REVIEW C **86**, 011301(R) (2012)

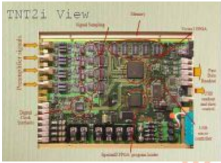
Understanding the different rotational behaviors of ^{252}No and ^{254}No

H. L. Liu,[1,*] F. R. Xu,[2] and P. M. Walker[3,4]

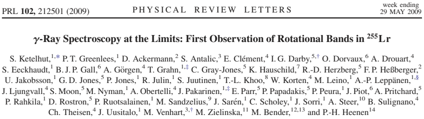
Recent history of JUROGAM







- Fifth and final campaign ended May 2008
- 2003 - 2008: 67 experiments, 11000 hours beam on target
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II

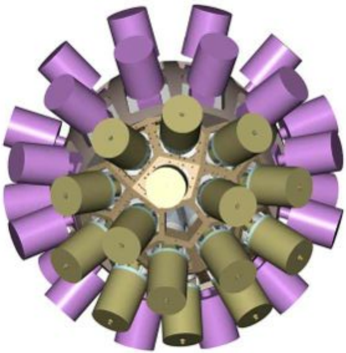


PRL **102,** 212501 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

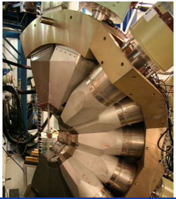
γ-Ray Spectroscopy at the Limits: First Observation of Rotational Bands in ^{255}Lr

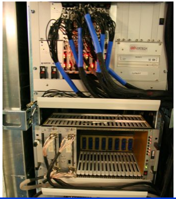
S. Ketelhut,[1,*] P. T. Greenlees,[1] D. Ackermann,[2] S. Antalic,[3] E. Clément,[4] I. G. Darby,[5,†] O. Dorvaux,[6] A. Drouart,[4] S. Eeckhaudt,[1] B. J. P. Gall,[6] A. Görgen,[4] T. Grahn,[1,‡] C. Gray-Jones,[5] K. Hauschild,[7] R.-D. Herzberg,[5] F. P. Heßberger,[2] U. Jakobsson,[1] G. D. Jones,[5] P. Jones,[1] R. Julin,[1] S. Juutinen,[1] T.-L. Khoo,[8] W. Korten,[4] M. Leino,[1] A.-P. Leppänen,[1,§] J. Ljungvall,[4] S. Moon,[5] M. Nyman,[1] A. Obertelli,[4] J. Pakarinen,[1,‡] E. Parr,[5] P. Papadakis,[5] P. Peura,[1] J. Piot,[6] A. Pritchard,[5] P. Rahkila,[1] D. Rostron,[5] P. Ruotsalainen,[1] M. Sandzelius,[9] J. Sarén,[1] C. Scholey,[1] J. Sorri,[1] A. Steer,[10] B. Sulignano,[4] Ch. Theisen,[4] J. Uusitalo,[1] M. Venhart,[3,†] M. Zielinska,[11] M. Bender,[12,13] and P.-H. Heenen[14]

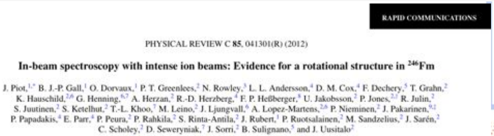
The JUROGAM II Germanium Array



- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resource
- Total Photopeak Efficiency $\simeq$6% @ 1.3 MeV
- Excellent γ-γ efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with TNT2 / Lyrtech digital electronics
- Higher counting rates, higher beam intensities
- 20,000 hours in-beam γ-ray spectroscopy passed in 2011







RAPID COMMUNICATIONS

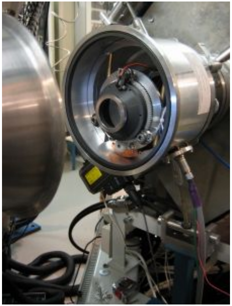
PHYSICAL REVIEW C **85**, 041301(R) (2012)

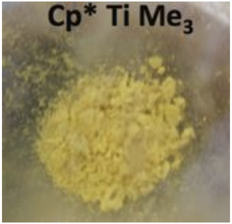
In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in ^{246}Fm

J. Piot,[1,*] B. J.-P. Gall,[1] O. Dorvaux,[1] P. T. Greenlees,[2] N. Rowley,[3] L. L. Andersson,[4] D. M. Cox,[4] F. Dechery,[5] T. Grahn,[2] K. Hauschild,[2,6] G. Henning,[6,7] A. Herzan,[2] R.-D. Herzberg,[4] F. P. Heßberger,[8] U. Jakobsson,[2] P. Jones,[2,†] R. Julin,[2] S. Juutinen,[2] S. Ketelhut,[2] T.-L. Khoo,[7] M. Leino,[2] J. Ljungvall,[6] A. Lopez-Martens,[2,6] P. Nieminen,[2] J. Pakarinen,[9,‡] P. Papadakis,[4] E. Parr,[4] P. Peura,[2] P. Rahkila,[2] S. Rinta-Antila,[2] J. Rubert,[1] P. Ruotsalainen,[2] M. Sandzelius,[2] J. Sarén,[2] C. Scholey,[2] D. Seweryniak,[7] J. Sorri,[2] B. Sulignano,[5] and J. Uusitalo[2]

Next step - push to Rutherfordium Z=104

- Can produce ^{256}Rf using:
  $^{50}\mathrm{Ti} + {}^{208}\mathrm{Pb} \rightarrow {}^{256}\mathrm{Rf} + 2\mathrm{n}$
- Cross section below 20 nb
- Need high intensity ^{50}Ti beam
- Used up to 70 pnA in ^{246}Fm experiment
- Rotating target wheel built at IPHC Strasbourg

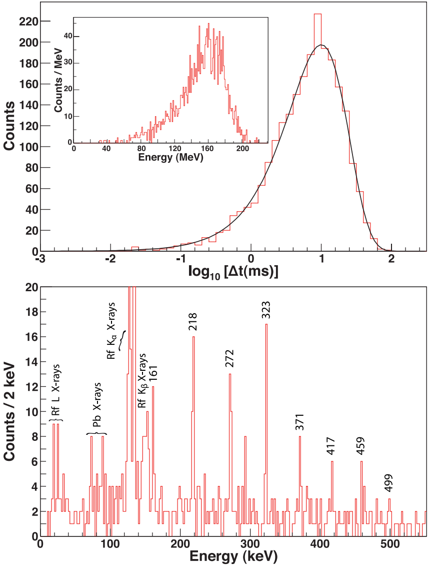




^{50}Ti MIVOC beam development

- Metallic Ions from VOlatile Compounds
- Method developed at JYFL
- Synthesis of enriched ^{50}Ti compound led by IPHC Strasbourg
- Several years of hard work!
- 19 μA of $^{50}\mathrm{Ti}^{11+}$ from ECR
- 490 enA on target
- Low consumption - 0.2 mg/hr
- See J.Rubert et al., NIMB **276**, 33 (2012)

In-beam spectroscopy of SHE: ^{256}Rf

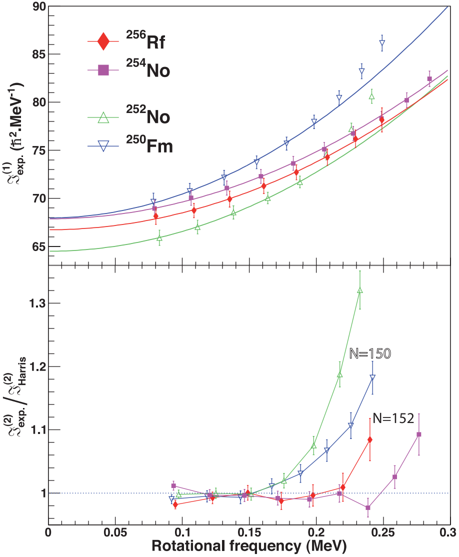


Experimental Details

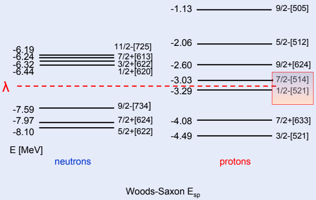
- ^{50}Ti + ^{208}Pb ⇒ ^{256}Rf + 2n
- JUROGAM II, RITU, GREAT
- Enriched ^{50}Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

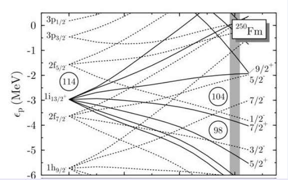
P.T.Greenlees, J.Rubert et al.,
PRL **109**, 012501 (2012)

In-beam spectroscopy of SHE: ^{256}Rf



Single-particle energies

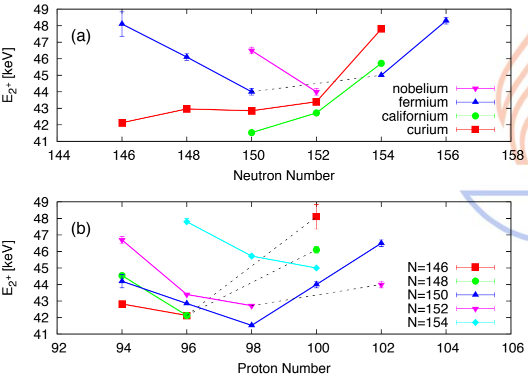




P.T.Greenlees, J.Rubert et al.,
PRL **109**, 012501 (2012)

Experimental 2^+ Energies

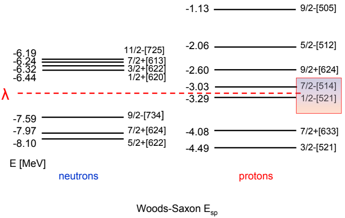
Woods-Saxon E_{sp}



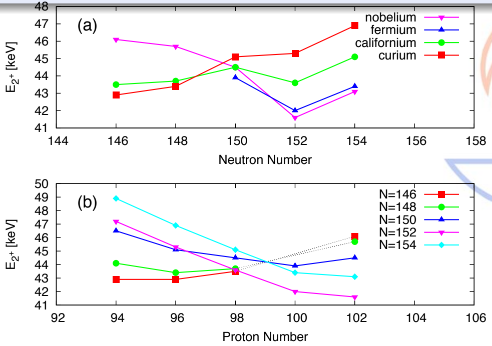
Harris Fits

- $\mathcal{J}^{(1)} = \hbar^2 \frac{2I-1}{E_{\gamma 1}}$
- $\mathcal{J}^{(2)} = \frac{4\hbar^2}{\Delta E_\gamma}$
- $\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1 \omega^2$
- $\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1 \omega^2$
- $I = \mathcal{J}_0 \omega + \mathcal{J}_1 \omega^3 + 1/2$

Theoretical 2^+ Energies

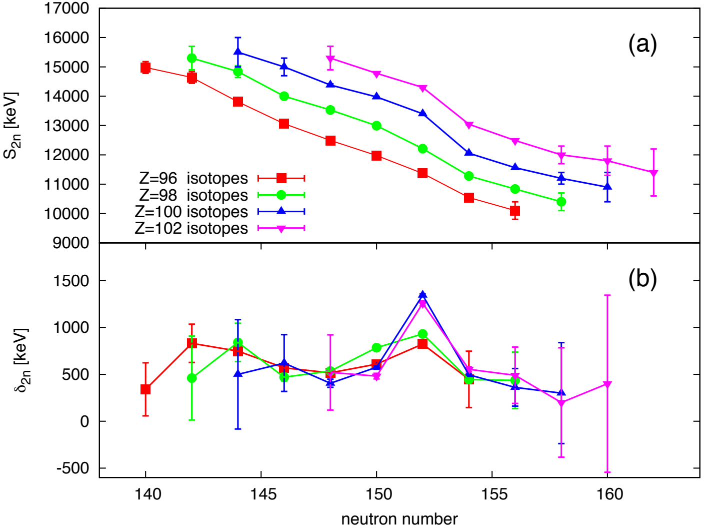


Sobiczewski, Muntian, Patyk. PRC **63**, 034306 (2001)



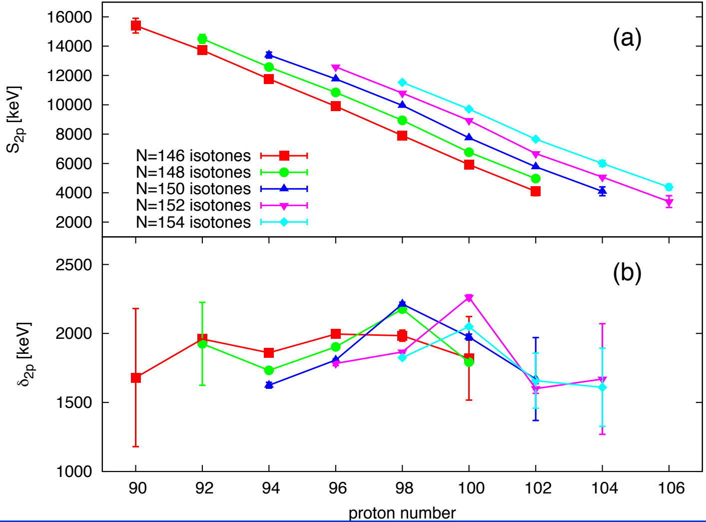
Correlation to Masses - Isotopes

AME2003: $S_{2n}(Z,N) = B(Z,N) - B(Z,N-2)$, $\delta_{2n}(Z,N) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$



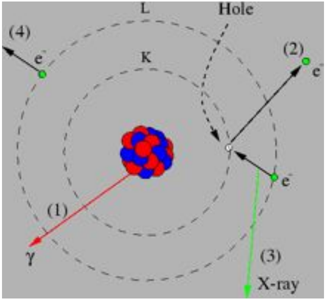
Correlation to Masses - Isotones

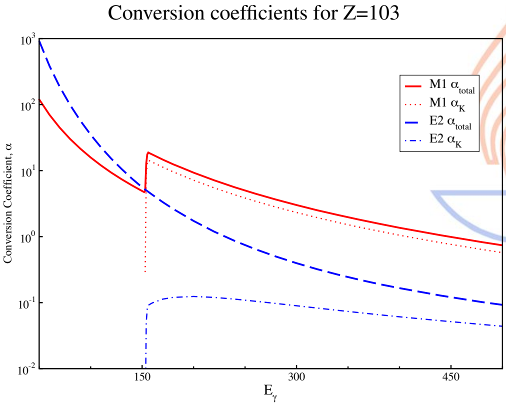
AME2003: $S_{2p}(Z,N) = B(Z,N) - B(Z-2,N)$, $\delta_{2p}(Z,N) = S_{2p}(Z,N) - S_{2p}(Z+2,N)$



Internal Conversion

- $E_i = E_\gamma - B_i$;
  $i = K, L_I, L_{II}, .., M_V, ..$
- $\alpha_{tot} = \frac{N_e}{N_\gamma} = \alpha_K + \alpha_L + \ldots$
- $\alpha \propto \frac{Z^3}{n^3 E_\gamma^{2.5}}$
- α increases strongly with multipolarity
- α larger for magnetic transitions

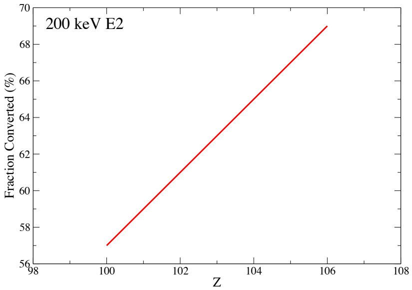


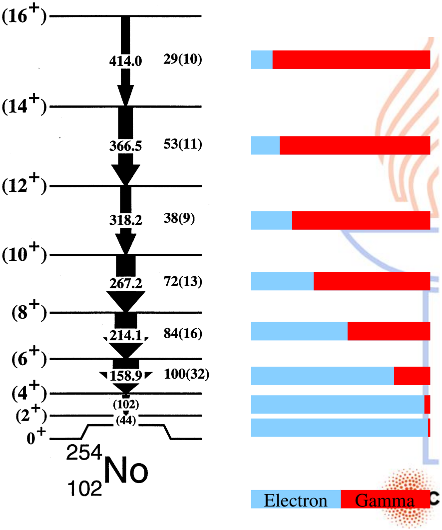


Internal Conversion

Fraction of 200 keV E2 converted

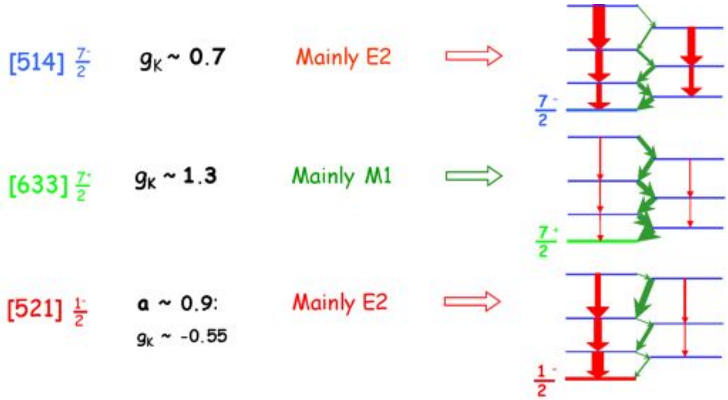
$$f = \frac{\alpha}{1+\alpha}$$





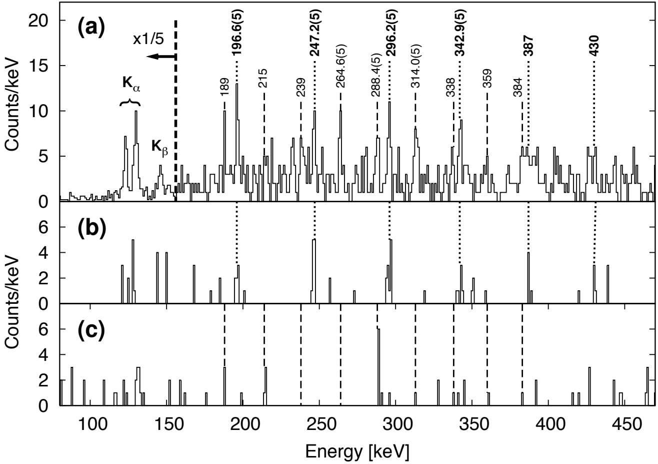
Electromagnetic Properties

- Odd-proton orbitals in ^{251}Md
- B(M1)/B(E2) depends on (g_K - g_R / Q_0)



In-beam γ-ray Spectroscopy of ^{255}Lr

^{48}Ca + ^{209}Bi $\Rightarrow$ ^{255}Lr + 2n, $\sigma \simeq 300$ nb, S. Ketelhut et al., PRL **102** 212501 (2009



Spectrometer Design Considerations

Efficiency

Broad Range
Typically 0-1 MeV
Backscattering - normal incidence

Magnetic Field

Profile
Strength

Detector

Thickness
Size
Granularity

Resolution

Intrinsic
Doppler Broadening

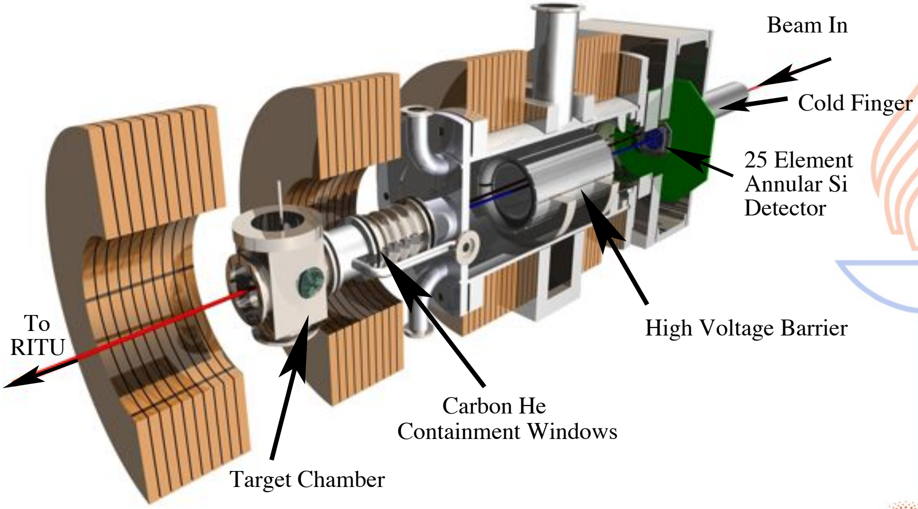
Delta Electron Suppression

Kinematics
Biased Target
Physical Block
HV Barrier
High Counting Rate Capability
Tagging Techniques

Combination with Ge

Maintain Ge Efficiency
Maintain P/T
Effect of stray field

The SACRED Electron Spectrometer

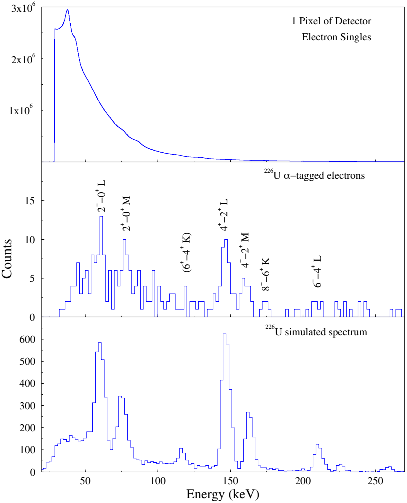


H. Kankaanpää et al., NIM A534, 503 (2004)
P. A. Butler et al., NIM A381, 433 (1996)

THE UNIVERSITY of LIVERPOOL

UNIVERSITY OF JYVÄSKYLÄ

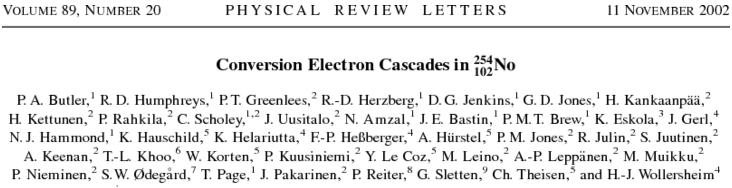
Recoil-Decay Tagging with SACRED



δ electrons produced with atomic cross sections!

H. Kankaanpää et al., NIM A534, 503 (2004)
see also:
R.D. Humphreys et al., PRC69, 064324 (2004)

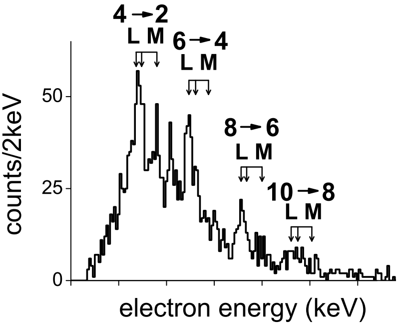
Conversion-Electron Spectroscopy of ^{254}No

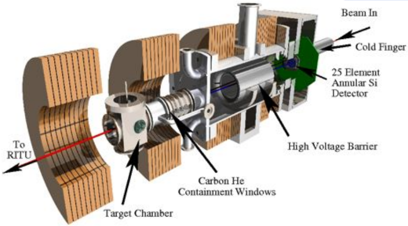


VOLUME 89, NUMBER 20 PHYSICAL REVIEW LETTERS 11 NOVEMBER 2002

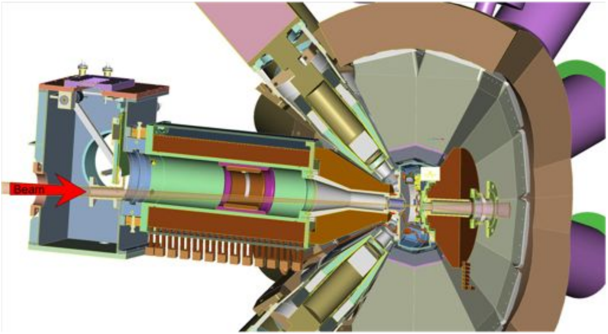
Conversion Electron Cascades in $^{254}_{102}$No

P. A. Butler,[1] R. D. Humphreys,[1] P. T. Greenlees,[2] R.-D. Herzberg,[1] D. G. Jenkins,[1] G. D. Jones,[1] H. Kankaanpää,[2] H. Kettunen,[2] P. Rahkila,[2] C. Scholey,[1,2] J. Uusitalo,[2] N. Amzal,[1] J. E. Bastin,[1] P. M. T. Brew,[1] K. Eskola,[3] J. Gerl,[4] N. J. Hammond,[1] K. Hauschild,[5] K. Helariutta,[4] F.-P. Heßberger,[4] A. Hürstel,[5] P. M. Jones,[2] R. Julin,[2] S. Juutinen,[2] A. Keenan,[2] T.-L. Khoo,[6] W. Korten,[5] P. Kuusiniemi,[2] Y. Le Coz,[5] M. Leino,[2] A.-P. Leppänen,[2] M. Muikku,[2] P. Nieminen,[2] S. W. Ødegård,[7] T. Page,[1] J. Pakarinen,[2] P. Reiter,[8] G. Sletten,[9] Ch. Theisen,[5] and H.-J. Wollersheim[4]

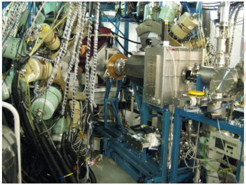


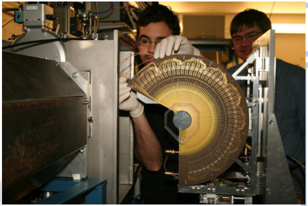


The SAGE Spectrometer



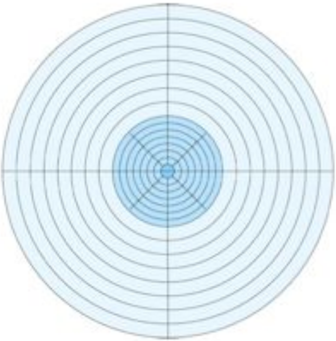
P. Papadakis et al., AIP Conf. Proc. **1090**, 14 (2009)



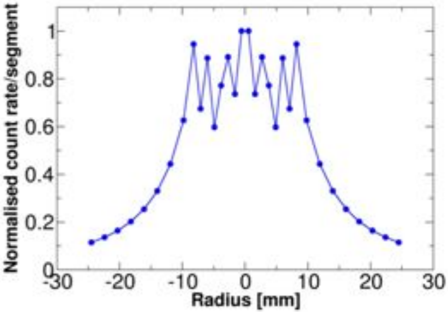


SAGE - Silicon Detector

- 90 segments
- 51 mm diameter
- 1 mm thick



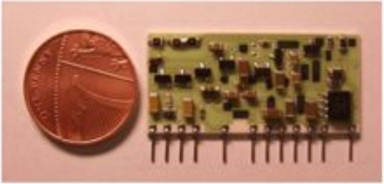
Simulated normalised count rate distribution using data from SACRED experiments

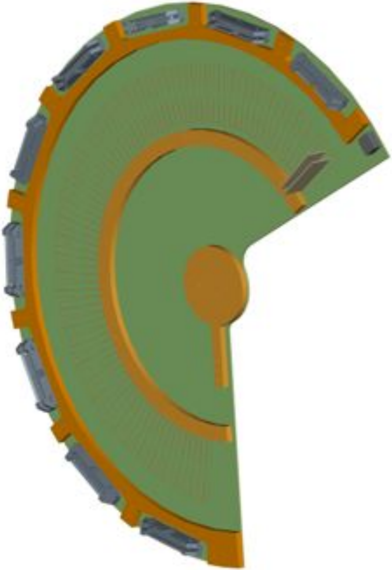


SAGE - Silicon Detector

C.A.E.N. A1422 charge sensitive hybrid preamplifiers

- 400 mV/MeV
- Low noise
- Suitable for high count-rates

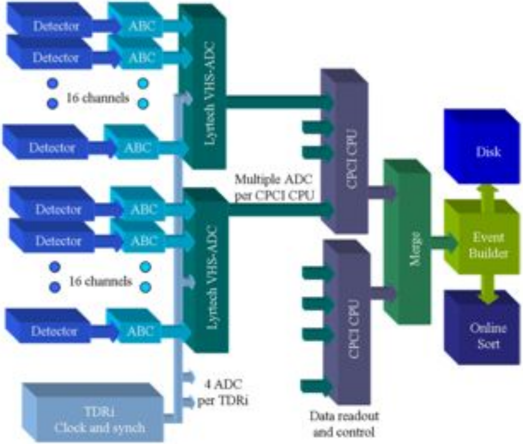




SAGE - Electronics

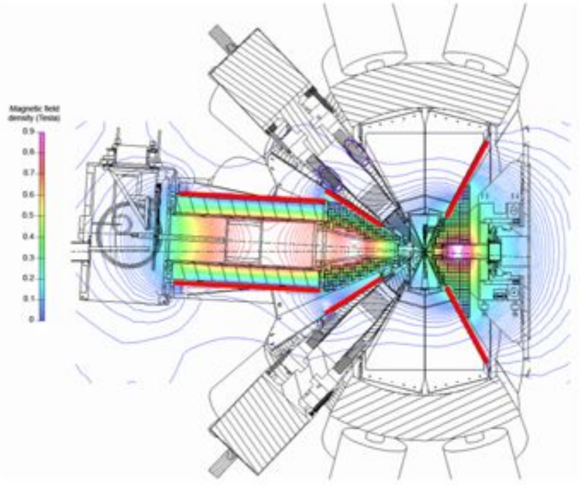
201 Fully digital channels
90 Si channels
111 Ge channels

Lyrtech VHS-ADC

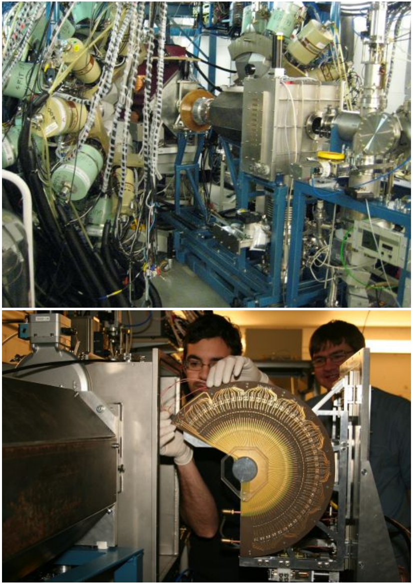


SAGE - Shielding

- Photomultiplier tubes are sensitive to magnetic fields
- Shields: Weaken and redirect stray magnetic field



The SAGE Spectrometer



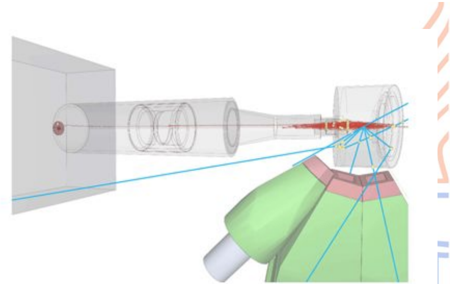
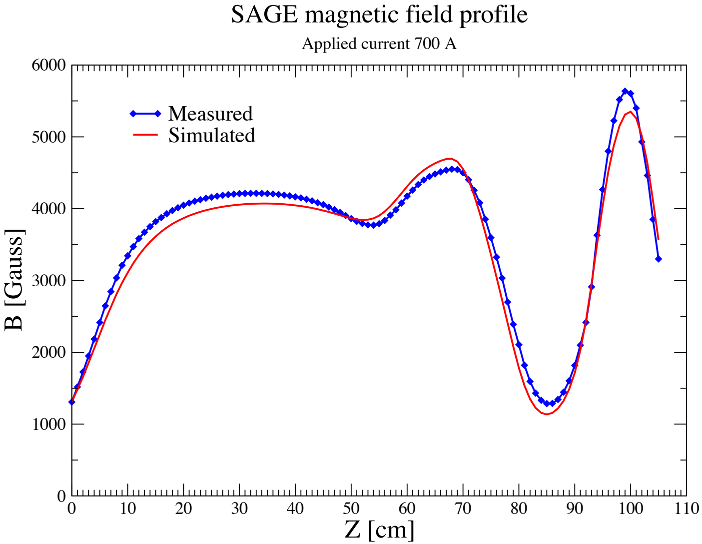


Figure 4.5: An example drawing of simulated events visualised in Geant4. Electrons are presented with red lines and gamma rays with blue. Only some of the electrons reach the detector while the others either interact with the surrounding materials (open circles) or are reflected back by the HV barrier. Note also the magnetic bottle effect of electrons being trapped in the magnetic field.

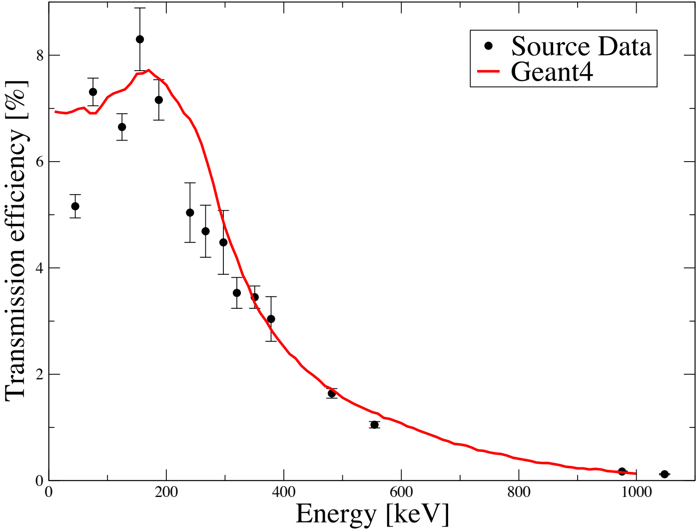
Full Geant4 Simulation

P.Papadakis, D.Cox, J.Konki, K.Hauschild, P. Rahkila

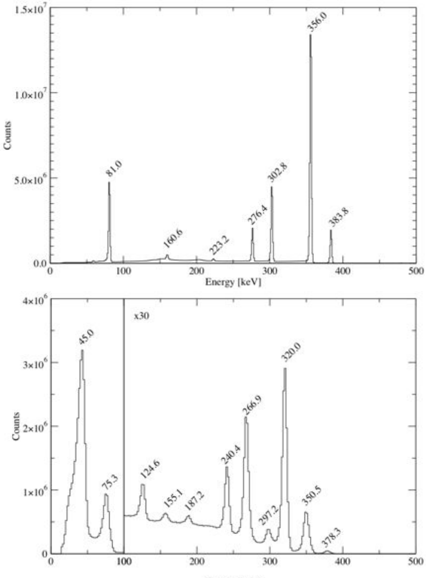
SAGE - Field Profile

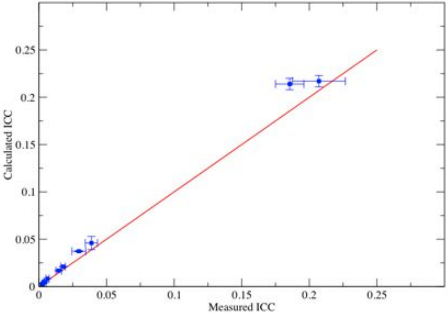


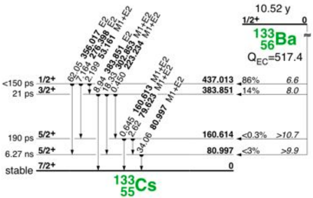
SAGE- efficiency



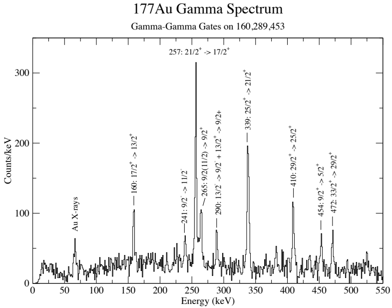
ICC determination with SAGE- ^{133}Ba



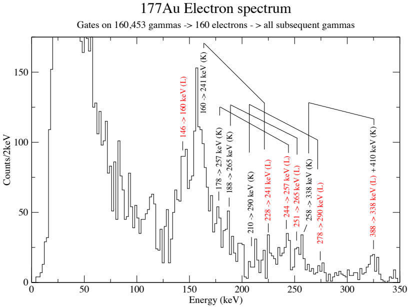




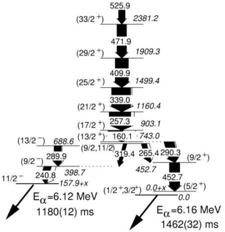
ICC determination with SAGE- ^{177}Au Preliminary!


177Au Gamma Spectrum

Gamma-Gamma Gates on 160,289,453


177Au Electron spectrum

Gates on 160,453 gammas -> 160 electrons - > all subsequent gammas



265 keV **9/2,11/2->9/2+**
K:182.5keV **L:254keV**

ICC	Value	Error
K ICC Exp	0.132	0.037
K ICC BRICC	0.090	0.007
L ICC Exp	0.082	0.002
L ICC BRICC	0.050	0.001
K/L Exp	1.610	0.400
K/L BRICC	1.82	0.04

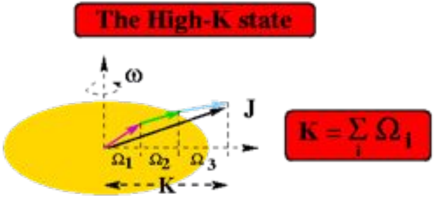
257 keV **21/2->17/2+**
K: 176.5keV **L: 243keV**

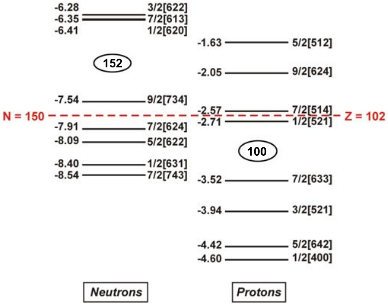
ICC	Value	Error
K ICC Exp	0.088	0.024
K ICC Theo	0.091	0.004
L ICC Exp	0.062	0.014
L ICC BRICC	0.051	0.001
K/L Exp	1.421	0.508
K/L BRICC	1.644	0.04

Outline

1. Introduction
2. Experimental Approaches
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. **Structure of High-K States**
6. Future Perspectives

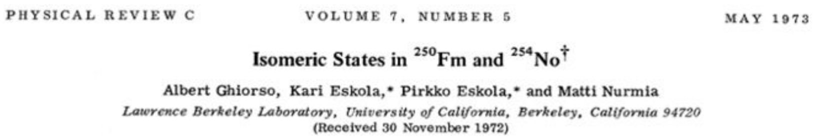
K-Isomerism in ^{254}No and ^{250}Fm





- Transition forbidden if: $\Delta K \leq L$
- Degree of forbiddenness $\nu = \Delta K - L$
- Information on pairing gap, Δ and single-particle energies, ϵ_i
- $E = \sqrt{(\epsilon_i - \lambda)^2 + \Delta^2} + \sqrt{(\epsilon_j - \lambda)^2 + \Delta^2}$
- Studies at focal plane - clean environment
- Often full decay path to ground state can be delineated

K-Isomerism in ^{254}No and ^{250}Fm



PHYSICAL REVIEW C VOLUME 7, NUMBER 5 MAY 1973

Isomeric States in ^{250}Fm and ^{254}No†

Albert Ghiorso, Kari Eskola,* Pirkko Eskola,* and Matti Nurmia
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 30 November 1972)

- Isomeric states in ^{254}No and ^{250}Fm first postulated by Ghiorso et al., PRC7 (1973) 2032
- *The transfer of the* ^{250}*Fm atoms from the wheel onto the movable detectors must then be caused by the feeble recoil resulting from the isomeric transition or other accompanying* γ *rays and conversion electrons in the cascade that leads to the ground state. For a 500 keV* γ *ray the recoil energy of a* ^{250}*Fm atom is about 0.5 eV.*

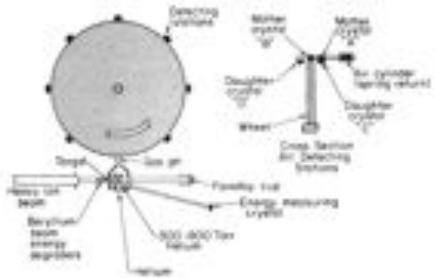
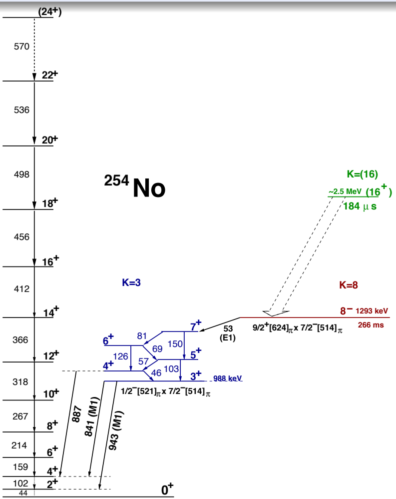


FIG. 1. A schematic diagram of the seven-detector-station system. The cross section at right shows the arrangement of the two movable mother detectors and the two stationary daughter detectors.

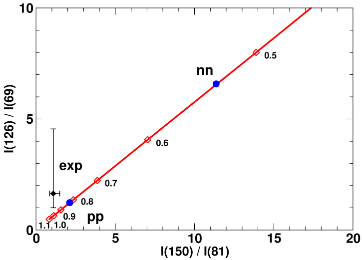
K-Isomerism in ^{254}No

R.-D. Herzberg et al., Nature **442**, 896-899 (2006)
S.K. Tandel et al., PRL **97**, 082502 (2006)

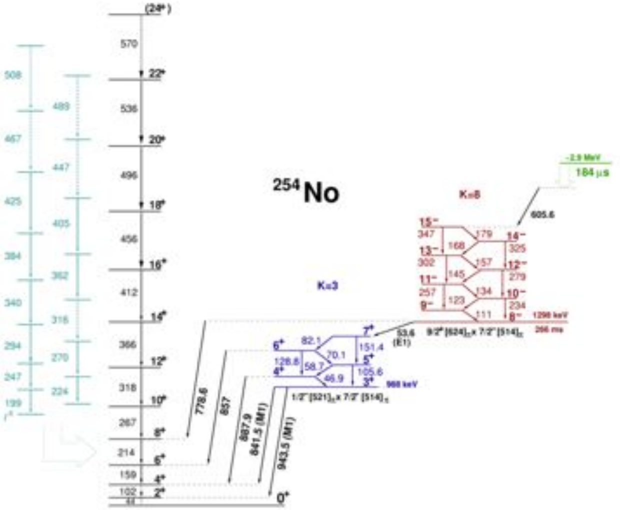


Determined Configurations:

3^+ - $(\pi[514]7/2^- \otimes \pi[521]1/2^-)$
8^- - $(\pi[514]7/2^- \otimes \pi[624]9/2^+)$
53keV E1 ΔK=5: f_ν = 804

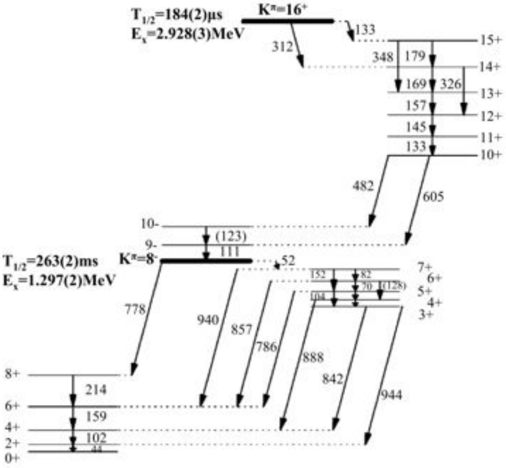


K-Isomerism in ^{254}No



F.P. Hessberger et al., EPJA **43**, 55 (2010) / C.Gray-Jones, Thesis, University of Liverpool

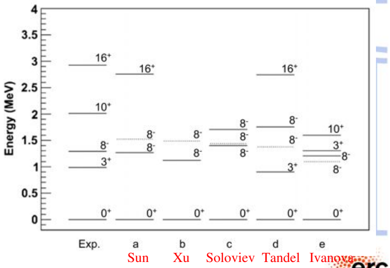
K-Isomerism in ^{254}No



R.M.Clark et al., PLB **690**, 19 (2010)

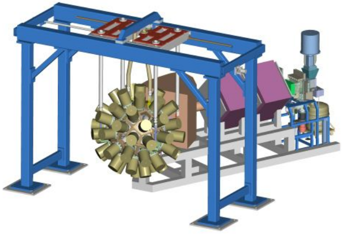
Determined Configurations:

3^+ - $(\pi[514]7/2^- \otimes \pi[521]1/2^-)$
8^- - $(\nu[734]9/2^- \otimes \nu[624]7/2^+)$
or 8^- - $(\nu[734]9/2^- \otimes \nu[613]7/2^+)$
10^+ - $(\nu[734]9/2^- \otimes \nu[725]11/2^-)$
16^+ - $(\pi[514]7/2^- \otimes \pi[624]9/2^+)$ +
$(\nu[734]9/2^- \otimes \nu[613]7/2^+)$

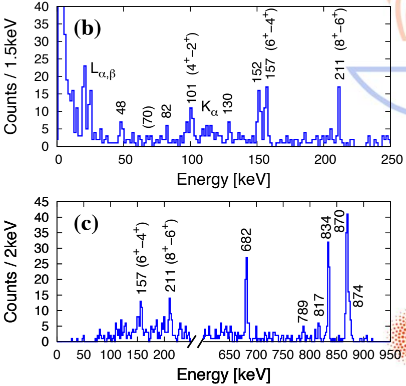


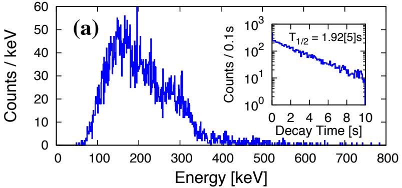
K-Isomerism in ^{250}Fm

^{48}Ca + ^{204}HgS ⇒ ^{250}Fm + 2n,JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC **78**, 021301(R) (2008)



Focal Plane Gamma Rays

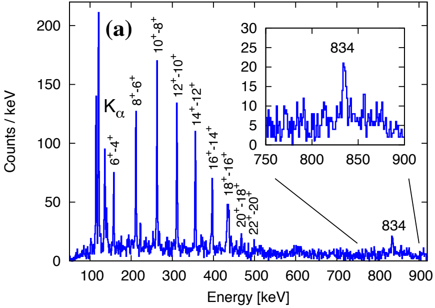




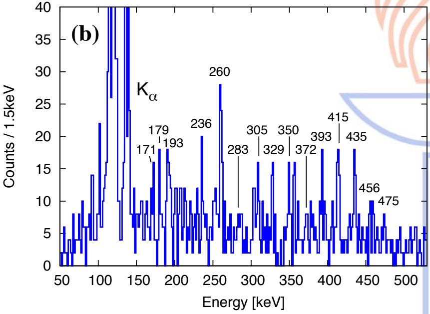
K-Isomerism in ^{250}Fm

^{48}Ca + ^{204}HgS ⇒ ^{250}Fm + 2n,JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC **78**, 021301(R) (2008)

Ground State Band

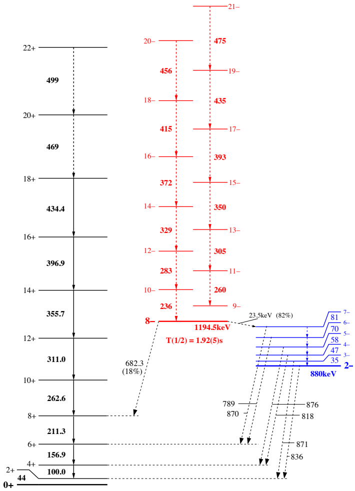


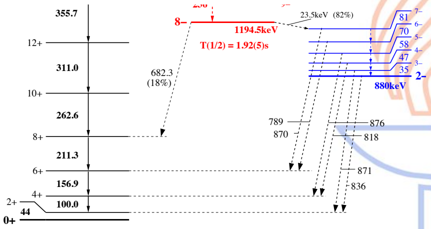
Isomer-Tagged Transitions



K-Isomerism in ^{250}Fm

^{250}Fm: P.T. Greenlees et al. PRC **78**, 021301(R) (2008)





8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$

2^- - $\nu[622]5/2^+ \otimes \nu[734]9/2^-$ dominates

682 keV E1 $\Delta K=8$: $f_\nu = 213$

23.5 keV M1 $\Delta K=6$: $f_\nu = 192$

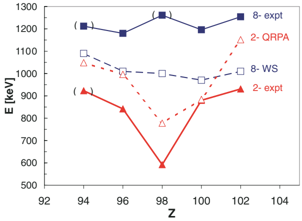
Known 2QP K-Isomers in Region

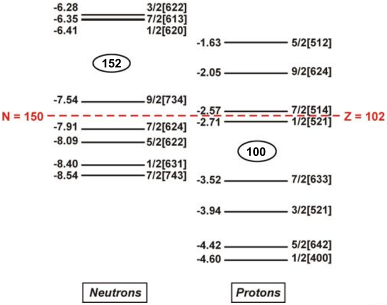
Nucleus	K^π	$T_{1/2}$	E_x	Decay Mode	Configuration
^{270}Ds	$9^-,10^-$	6 ms	$\simeq$1.13 MeV	α	9^- - $\nu[725]11/2^- \otimes \nu[613]7/2^+$ 10^- -$\nu[725]11/2^- \otimes \nu[615]9/2^+$
^{256}Rf	6,7?	25 μs	$\simeq$1.120 MeV	γ	??
^{256}Rf	10-12?	17 μs	$\simeq$1.400 MeV	γ	??
^{254}No	8^-	266 ms	1.293 MeV	γ	8^- - $\pi[514]7/2^- \otimes \pi[624]9/2^+$
^{252}No	8^-	110 ms	1.254 MeV	γ	8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$
^{250}No	6^+?	42 μs	??	SF,γ?	6^+ - $\nu[622]5/2^+ \otimes \nu[624]7/2^+$
^{256}Fm	7^-	70 ns	1.425 MeV	γ,SF	7^- - $\pi[633]7/2^+ \otimes \pi[514]7/2^-$
^{250}Fm	8^-	1.92 s	1.195 MeV	γ	8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$
^{248}Fm	??	$\simeq$8 ms	??	γ	??
^{246}Cm	8^-	??	1.179 MeV	γ	8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$
^{244}Cm	6^+	34 ms	1.040 MeV	γ	6^+ - $\nu[622]5/2^+ \otimes \nu[624]7/2^+$

- References: See R.-D.Herzberg and P.T.Greenlees, Prog. Part. Nuc. Phys. 61, 674 (2008)
- ^{256}Rf: H.B.Jeppesen et al., PRC **79**, 031303(R) (2009)
- 3QP isomer in ^{255}Lr (Dubna/GSI/JYFL/Berkeley). Also in ^{253}No

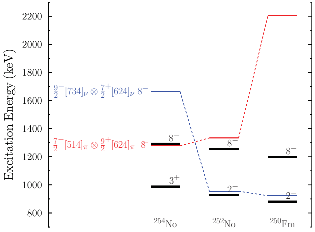
Systematics of 2 quasi-particle states

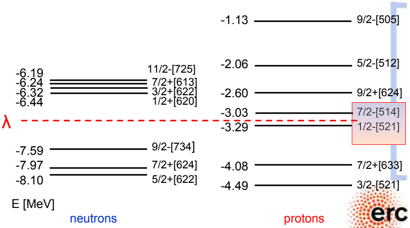
N=150: A.Robinson et al., PRC **78**, 034308 (2008)





N=150/152: P.T.Greenlees et al., PRC **78**, 021303(R) (2008)

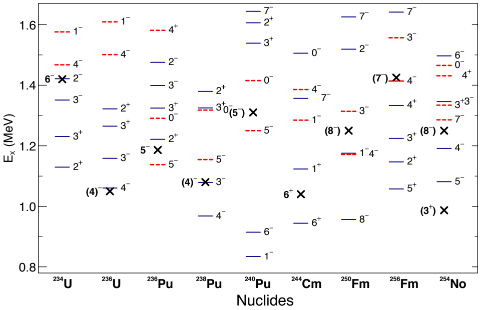




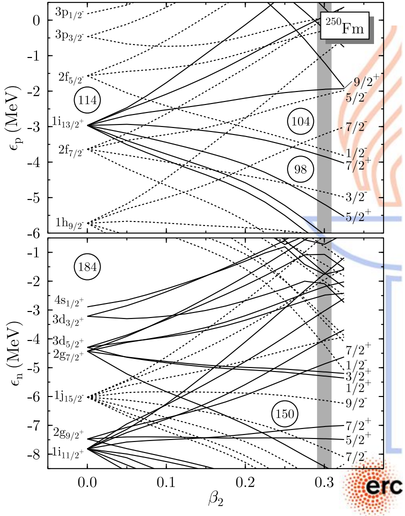
Woods-Saxon E_{sp}

Self-Consistent Calculations

HFB Gogny D1S
J.-P. Delaroche et al., Nucl. Phys. **A771**, 103 (2006)

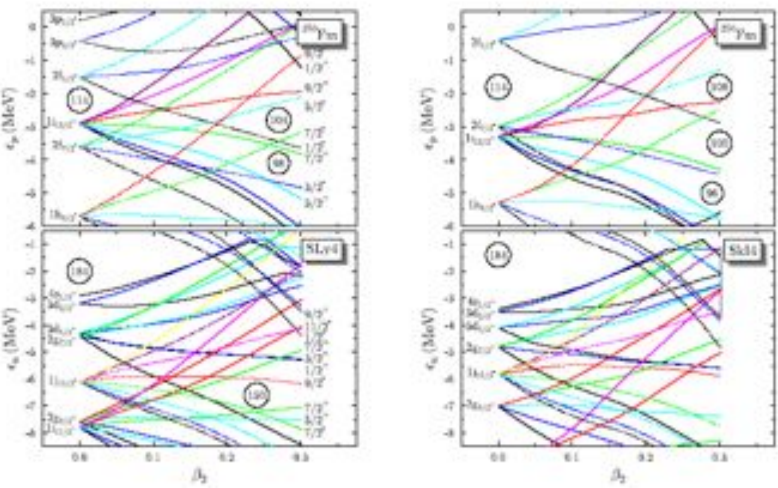


HFB SLy4 - from A.Chatillon et al., EPJA **30** 397 (20



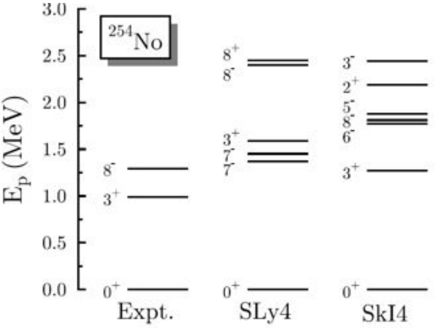
Self-Consistent Calculations

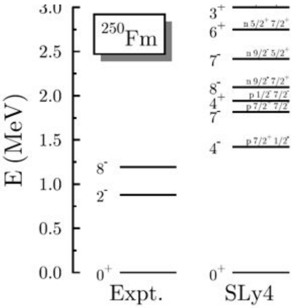
Taken from Talk of Paul-Henri Heenen (http://nuclear1.paisley.ac.uk/SHEworkshop/)



Self-Consistent Calculations

Taken from Talk of Paul-Henri Heenen (http://nuclear1.paisley.ac.uk/SHEworkshop/)



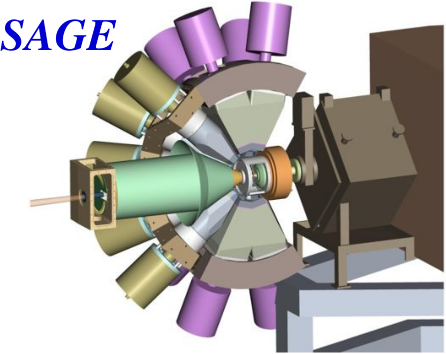


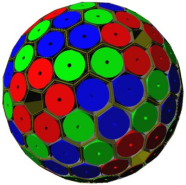
Outline

1. Introduction
2. Experimental Approaches
3. Alpha Decay (Fine Structure) Spectroscopy
4. In-Beam Spectroscopy
5. Structure of High-K States
6. Future Perspectives

In-beam spectroscopy: Future

SAGE





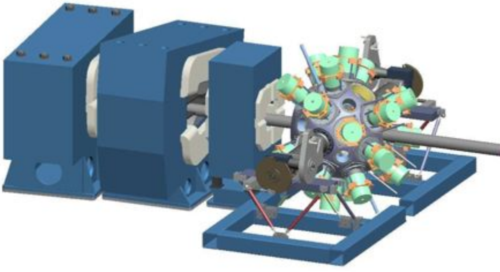
AGATA
ADVANCED GAMMA
TRACKING ARRAY

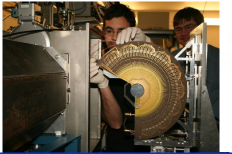
UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

UNIVERSITY OF JYVÄSKYLÄ

erc



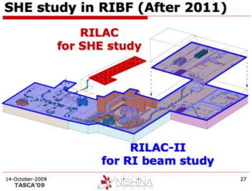


Future with Stable Beams: Upgrades / New Devices

REC SEP @ SHE CHEM

IRiS HEAVY ELEMENTS

TASISpec



SHE study in RIBF (After 2011)

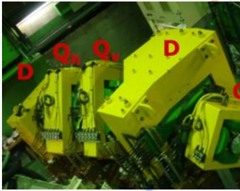
RILAC for SHE study

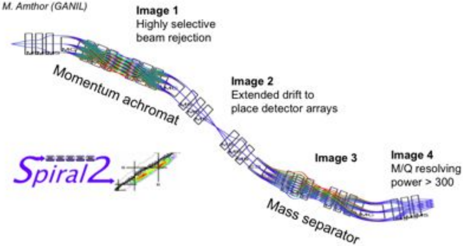
RILAC-II for RI beam study

14-October-2009 TASCA'09

NISHINA

27





M. Amthor (GANIL)

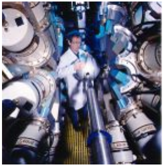
Image 1 Highly selective beam rejection

Image 2 Extended drift to place detector arrays

Image 3

Image 4 M/Q resolving power > 300

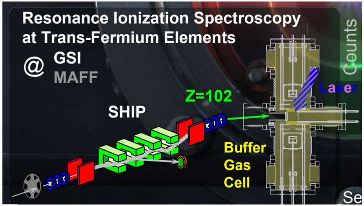
Spiral2

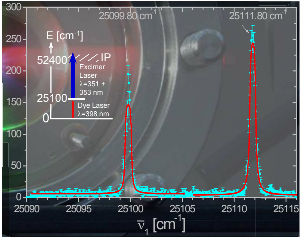


Argonne NATIONAL LABORATORY

erc

Optical spectroscopy of heaviest elements

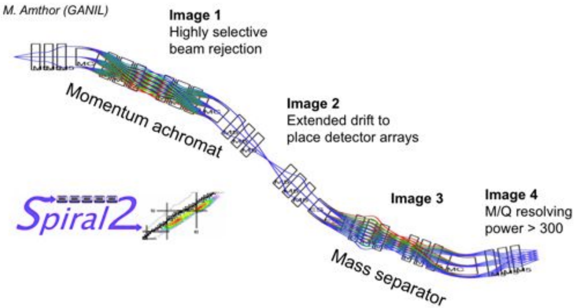


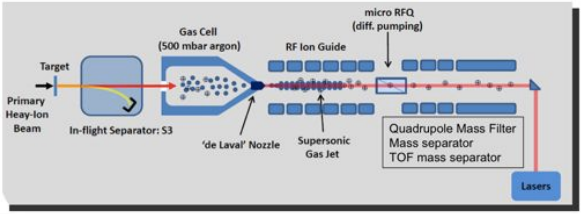


- Sample of ^{255}Fm produced at ORNL
- Breeding of ^{255}Es from ^{246}Cm
- Sample transported to Germany (about 10^{11} atoms)
- Two-step RIS, Fm confirmed with QMS
- Determined location of atomic levels for first time
- Heavily dependent on atomic theory

M. Sewtz et al., PRL **90**, 163002 (2003)

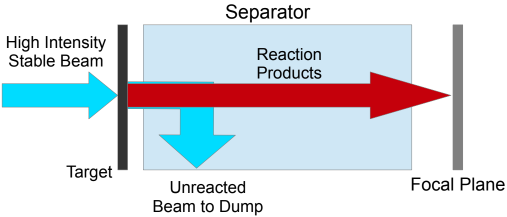
Optical spectroscopy of heaviest elements





P.Van Duppen et al., LoI for SPIRAL2

Production of heavy radioactive "beams"



Separator

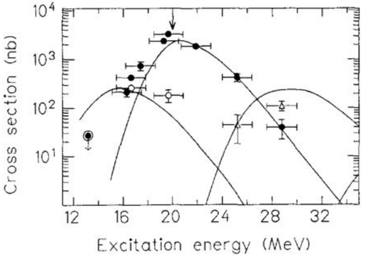
High Intensity Stable Beam

Reaction Products

Target

Unreacted Beam to Dump

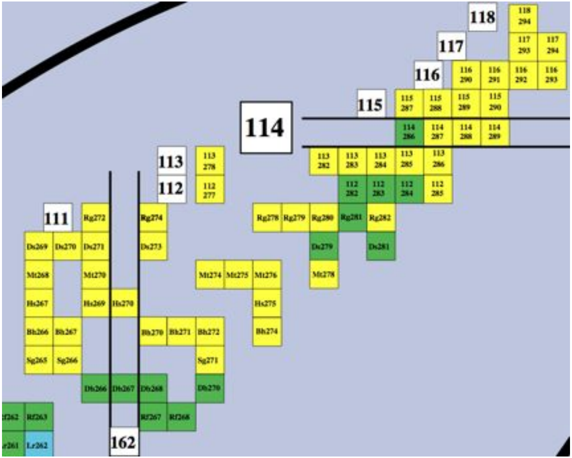
Focal Plane



- Typical separator efficiency 50%
- Primary beam suppression e.g. 10^{12}
- 10 pμA beam ^{48}Ca
- 0.5 mg/cm^2 ^{208}Pb target
- $\rightarrow$ 150pps ^{254}No

- Only one reaction product
- Narrow excitation function (10 MeV in lab)
- No increase in yield with thick target
- Energy $\simeq$ 0.2 MeV/u
- Could use inverse kinematics

Possibilities with RIBs



Around N=152/162

$^{90-94}\mathrm{Kr} + {}^{164}\mathrm{Dy} \rightarrow {}^{254-258}\mathrm{No}^*$

$^{90-94}\mathrm{Kr} + {}^{160}\mathrm{Gd} \rightarrow {}^{250-254}\mathrm{Fm}^*$

$^{132}\mathrm{Sn} + {}^{137}\mathrm{Cs} \rightarrow {}^{267}\mathrm{Db}^*$

$^{132}\mathrm{Sn} + {}^{132,134,136}\mathrm{Xe} \rightarrow {}^{264,266,268}\mathrm{Rf}^*$

$^{132}\mathrm{Sn} + {}^{138}\mathrm{Ba} \rightarrow {}^{270}\mathrm{Sg}^*$

$^{132}\mathrm{Sn} + {}^{139}\mathrm{La} \rightarrow {}^{271}\mathrm{Bh}^*$

$^{132}\mathrm{Sn} + {}^{140,142}\mathrm{Ce} \rightarrow {}^{272,274}\mathrm{Hs}^*$

$^{132}\mathrm{Sn} + {}^{142-150}\mathrm{Nd} \rightarrow {}^{274-282}\mathrm{Ds}^*$

$^{90-96}\mathrm{Kr} + {}^{181}\mathrm{Ta} \rightarrow {}^{271-277}\mathrm{Mt}^*$

$^{90-96}\mathrm{Kr} + {}^{186}\mathrm{W} \rightarrow {}^{276-282}\mathrm{Ds}^*$

$^{90-96}\mathrm{Kr} + {}^{180}\mathrm{Hf} \rightarrow {}^{270-276}\mathrm{Hs}^*$

$^{90-96}\mathrm{Kr} + {}^{175,176}\mathrm{Lu} \rightarrow {}^{265-272}\mathrm{Bh}^*$

$^{90-96}\mathrm{Kr} + {}^{176}\mathrm{Yb} \rightarrow {}^{266-272}\mathrm{Sg}^*$

Towards N=184?

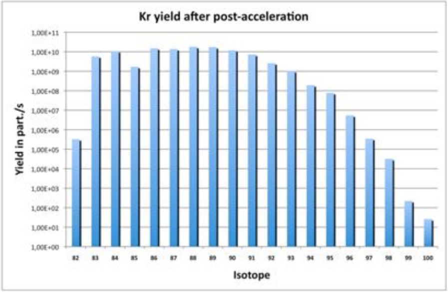
Difficult even with radioactive beams

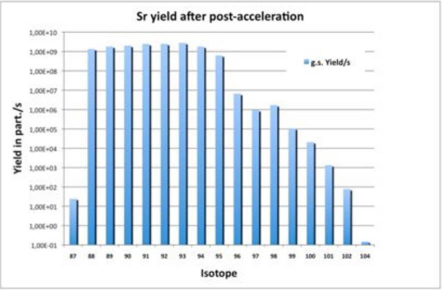
$^{90-95}\mathrm{Kr} + {}^{208}\mathrm{Pb} \rightarrow {}^{298-303}118^*$

$^{132}\mathrm{Sn} + {}^{170}\mathrm{Er} \rightarrow {}^{302}118^*$

$^{132}\mathrm{Sn} + {}^{176}\mathrm{Yb} \rightarrow {}^{308}120^*$

SPIRAL2 Predicted Intensities





- Figures assume 5×10^{13} fissions/sec
- Phase2 Day1, 50 kW d beam: e.g. ^{92}Kr 6.2MeV/u 2.6×10^{8} pps

EURISOL Predicted Intensities

EURISOL

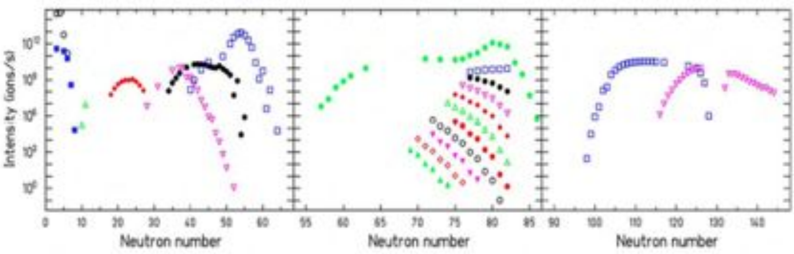


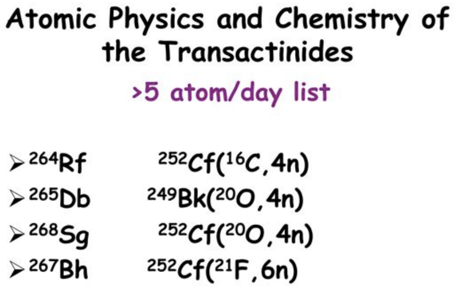
Fig. 13: Predicted EURISOL intensities of several nuclides:

Left: *Be (black open dots),*
Li (blue filled squares),
Mg (open green triangles),
Ar (red filled rhomboids),
Ni (magenta open triangles),
Ga (black filled dots),
Kr (open blue squares);

Centre: *Zr (filled green triangles),*
Nb (open red diamonds),
Mo (magenta filled triangles),
Tc (black open dots),
Ru (red filled dots)
Rh (green open triangles),
Pd (red filled diamonds)
Ag (magenta open triangles)
Cd (filled black dots),

Right: *Hg (squares)*
Fr (triangles)

Possibilities with RIBs

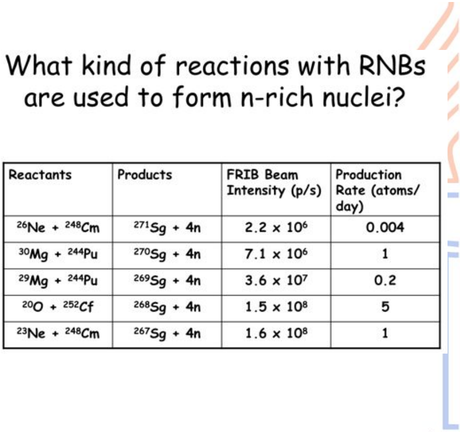


Atomic Physics and Chemistry of the Transactinides

>5 atom/day list

➢ ^{264}Rf	^{252}Cf(^{16}C,4n)
➢ ^{265}Db	^{249}Bk(^{20}O,4n)
➢ ^{268}Sg	^{252}Cf(^{20}O,4n)
➢ ^{267}Bh	^{252}Cf(^{21}F,6n)

W. Loveland, FUSHE2012
See also W.Loveland PRC **76** 014612 (2007)
N.B. Does not include detection efficiency



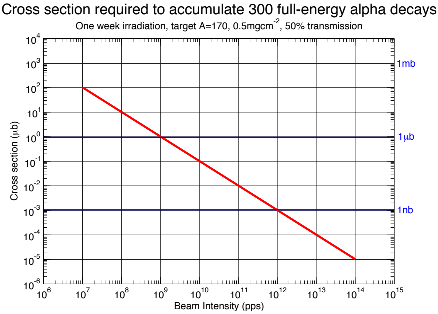
What kind of reactions with RNBs are used to form n-rich nuclei?

Reactants	Products	FRIB Beam Intensity (p/s)	Production Rate (atoms/ day)
^{26}Ne + ^{248}Cm	^{271}Sg + 4n	2.2×10^6	0.004
^{30}Mg + ^{244}Pu	^{270}Sg + 4n	7.1×10^6	1
^{29}Mg + ^{244}Pu	^{269}Sg + 4n	3.6×10^7	0.2
^{20}O + ^{252}Cf	^{268}Sg + 4n	1.5×10^8	5
^{23}Ne + ^{248}Cm	^{267}Sg + 4n	1.6×10^8	1

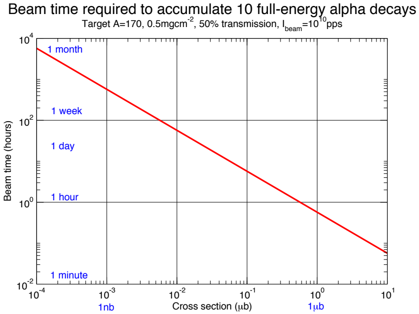
The Limits

Minimum requirement for in-beam studies

Minimum requirement for decay/ reaction mechanism studies


Cross section required to accumulate 300 full-energy alpha decays

One week irradiation, target A=170, 0.5mgcm^{-2}, 50% transmission


Beam time required to accumulate 10 full-energy alpha decays

Target A=170, 0.5mgcm^{-2}, 50% transmission, $I_{beam}=10^{10}$pps

10^{12} pps, XS 1pb → 0.3 events/week

Summary

- Detailed spectroscopy of heavy elements can provide high quality data and level assignments
- In-beam spectroscopy at 10 nb level
- Decay spectroscopy at sub-nb level
- Data is providing challenges for theory
- Hopefully will lead to a better understanding of the structure of SHE
- Laser and Mass Measurements will bring much-needed new information
- Many new facilities being built and upgrades going on
- Some opportunities to produce new isotopes from secondary reactions with RIBs
- Still much to be done (for both experiment and theory)