Shell-Structure and Pairing Interaction in SHE: Rotational Properties of the $Z = 104$ Nucleus ^{256}Rf

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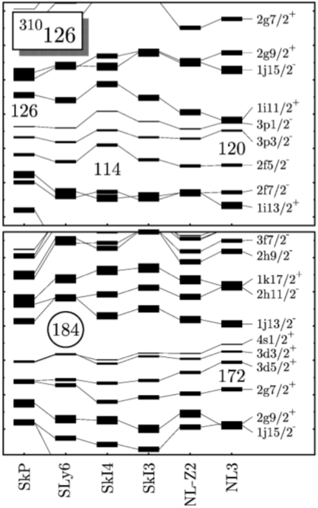
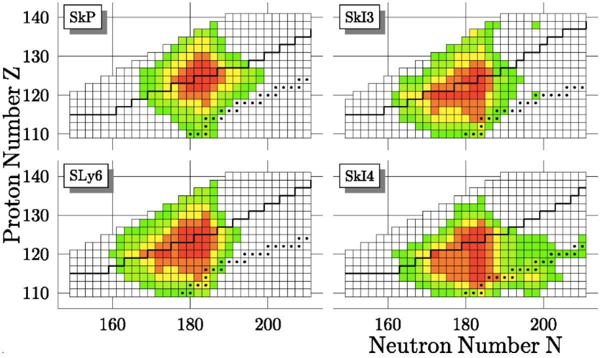
Nuclear Structure 2012
13.8.-17.8.2012
Argonne National Laboratory, U.S.A.

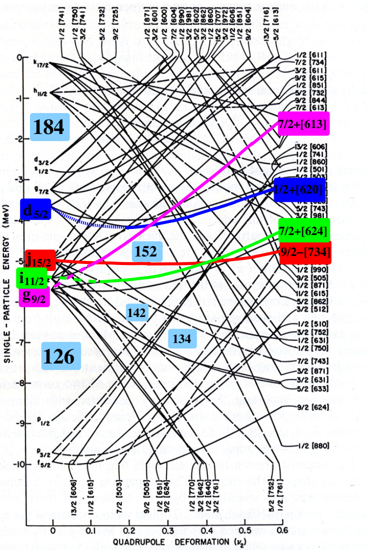
SHE - Shell Correction and Single-Particle Levels

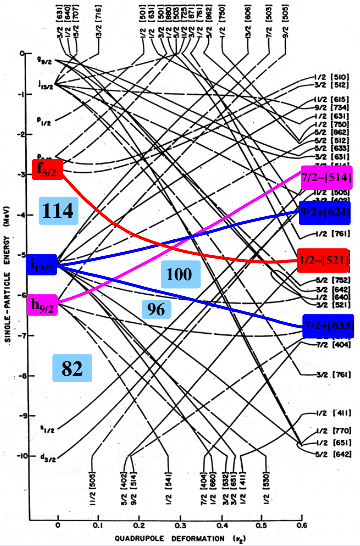




M. Bender, W. Nazarewicz, P.-G. Reinhard, PLB **515**, 42 (2001)

Single-Particle Orbitals in Region of ^{254}No



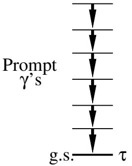


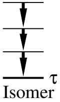
R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

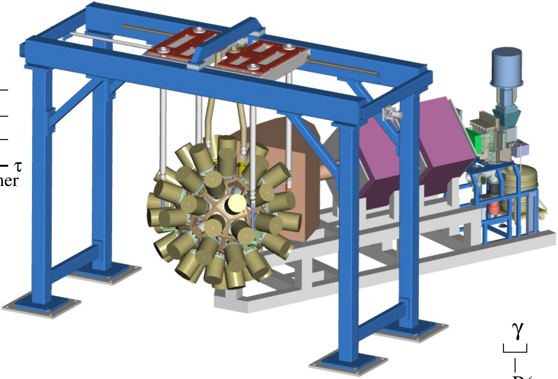
In-beam Spectroscopy: Principles of RDT

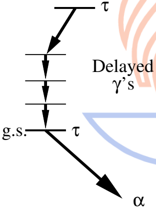
Tagging Techniques

Recoil, Recoil–Decay, Isomer

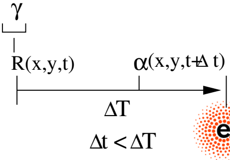






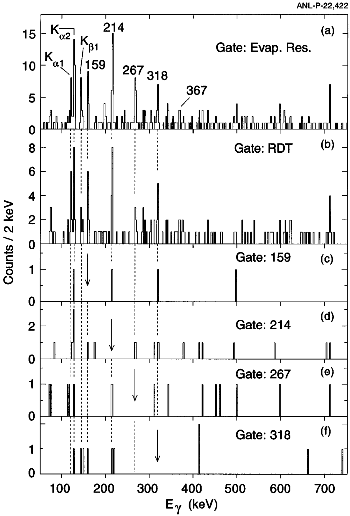


Time Line:



In-beam studies in 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]
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[2]*University of Liverpool, Liverpool L69 7ZE, England*
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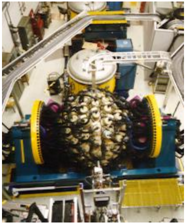
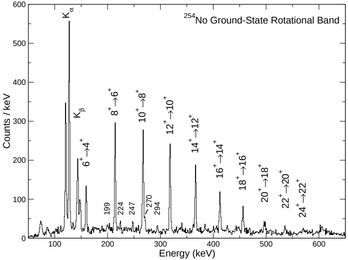
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[8]*University of Oslo, Oslo, Norway*
(Received 21 October 1998)

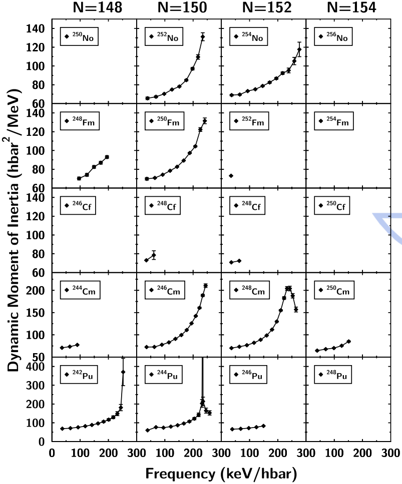
The ground-state band of the $Z = 1\ \ 2$ isotope ^{254}No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = \ .27$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible 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 studies in region of ^{254}No

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





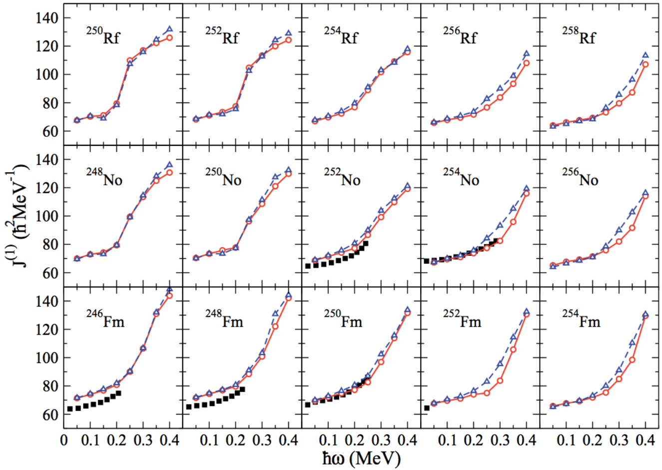
- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at N=150 compared to N=152 ($\pi i_{13/2}$, $\nu j_{15/2}$)
- Excellent testing ground for theory; e.g. Duguet et al., NPA **679**, 427 (2001), Bender et al., NPA **723**,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

Theory - N=150 vs. N=152

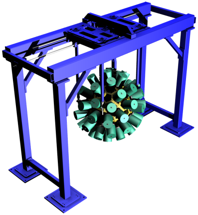
PHYSICAL REVIEW C **86**, 011301(R) (2012)

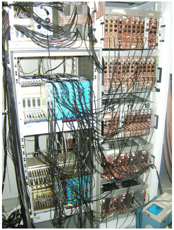
Understanding the different rotational behaviors of ^{252}No and ^{254}No

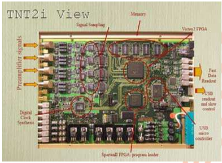
H. L. Liu,[1,*] F. R. Xu,[2] and P. M. Walker[3,4]



Recent history of JUROGAM







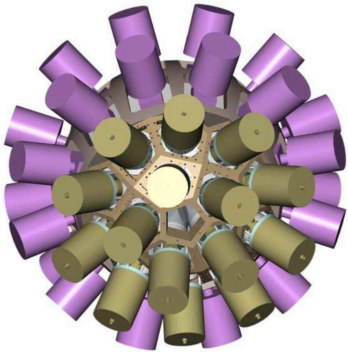
- Fifth and final campaign ended May 2008
- 2003 - 2008: 67 experiments, 11000 hours beam on target
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II

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

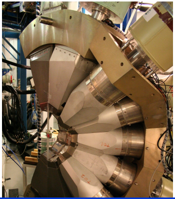
γ-Ray Spectroscopy at the Limits: First Observation of Rotational Bands in ^{255}Lr

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 ≃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

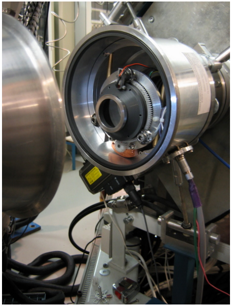
PHYSICAL REVIEW C **85**, 041301(R) (2012)

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

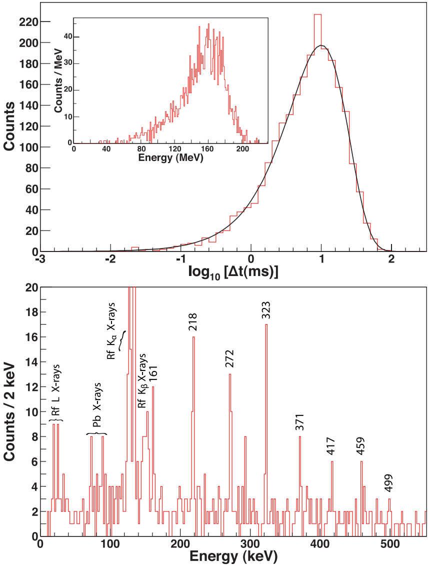
- Can produce ^{256}Rf using:
  ^{50}Ti + ^{208}Pb $\rightarrow$ ^{256}Rf + 2n
- Cross section below 20 nb
- Need high intensity ^{50}Ti beam
- Used up to 70 pnA in ^{246}Fm experiment
- Rotating target wheel built at IPHC Strasbourg



^{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}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

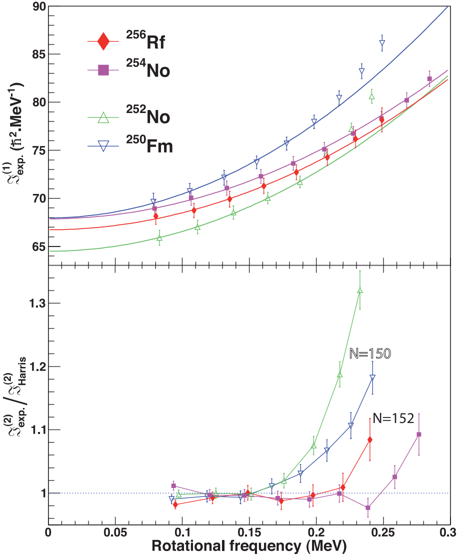


Experimental Details

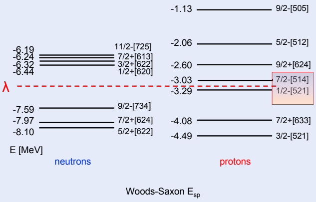
- ^{50}Ti + ^{208}Pb ⇒ ^{256}Rf + 2n
- JUROGAM II, RITU, GREAT
- Enriched ^{50}Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

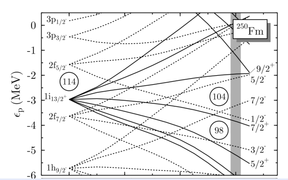
P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

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



Single-particle energies

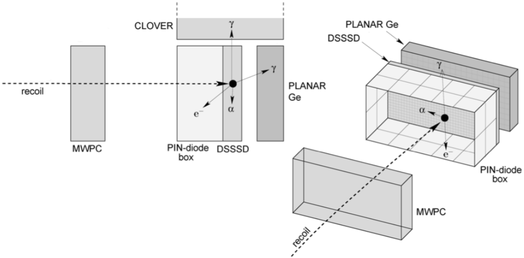


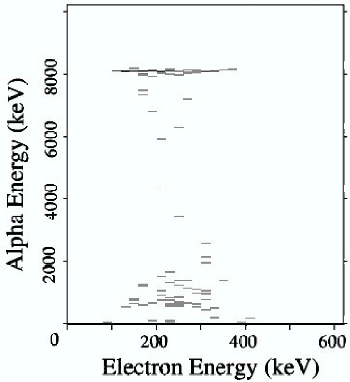


P.T.Greenlees, J.Rubert et al.,
PRL **109**, 012501 (2012)

Studies of K-Isomerism - Calorimetric Method

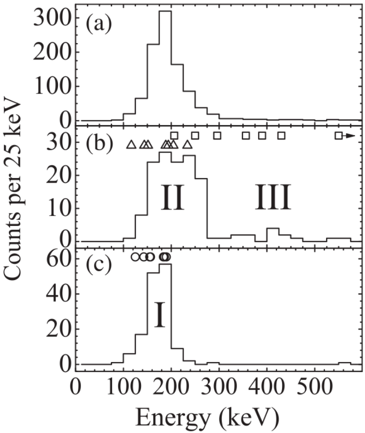
- Isomeric states in ^{250}Fm and ^{254}No first postulated by Ghiorso et al., PRC **7**, 2032 (1973)
- Powerful method proposed by Jones, NIM **A488**, 471 (2002)
- Low-energy transitions highly converted, look for Recoil-electron-α correlated chains in DSSSD

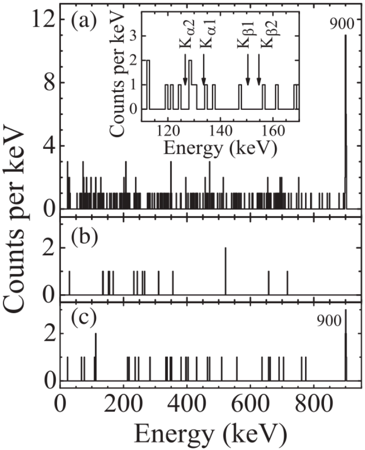




K-isomers in ^{256}Rf from Berkeley

H.B.Jeppesen et al., PRC **79**, 031303(R) (2009)





K-isomers in ^{256}Rf from Berkeley

H.B.Jeppesen et al., PRC **79**, 031303(R) (2009)

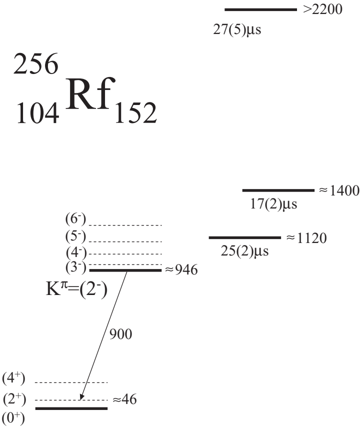


FIG. 3. Proposed decay scheme for ^{256}Rf. Energies are given in keV. Half-lives are written beneath each isomer.

Observed Decays

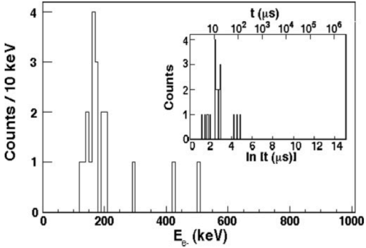
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	5400	6.67(9) ms
R-e-F	985 (18%)	25(2) μs
R-e-e-F	147 (2.7%)	17(2) μs
R-e-e-e-F	7 (0.13%)	27(2) μs

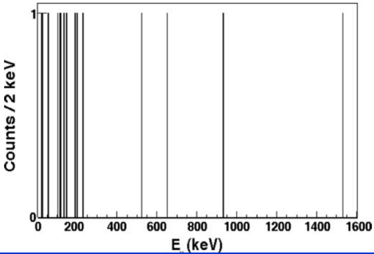
Interpretation

- Lowest isomer 2QP K=6,7
- Second isomer 2QP K=10-12: possibly 10^+ - $\nu[734]9/2^- \otimes \nu[725]11/2^-$
- Highest isomer? - not discussed

K-isomers in ^{256}Rf from ANL

A.P.Robinson et al., PRC **83**, 064311 (2011)





Observed Decays

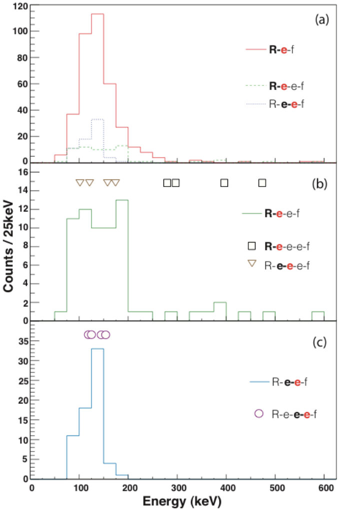
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	1322	6.9(4) ms
R-e-F	19 (1.4%)	17(5) μs

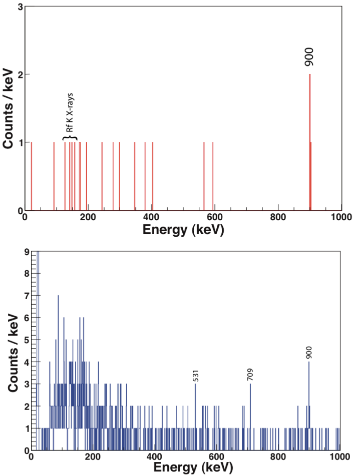
Interpretation

- Low population of isomer - similar to 4QP in ^{254}No, etc
- Conclude isomer is 4QP
- Non-observation of EM decay from 2QP suggests direct fission
  - fission half-life same as g.s.

K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

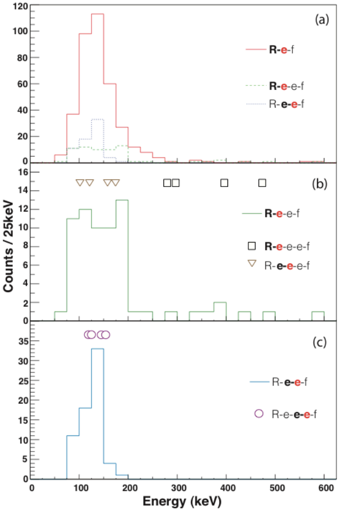
J.Rubert, P.T.Greenlees et al., to be published

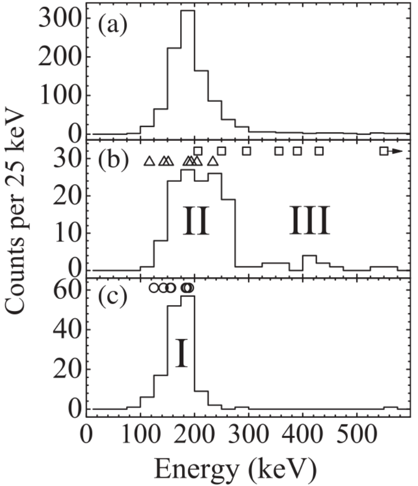




K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

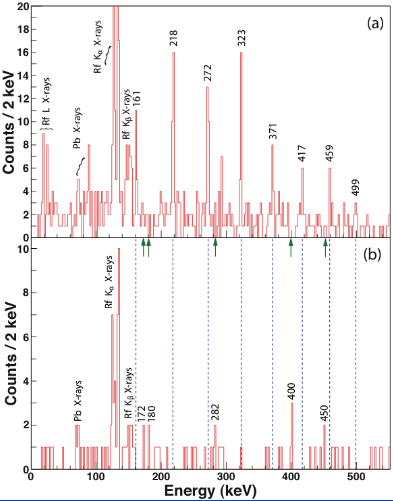
J.Rubert, P.T.Greenlees et al., to be published

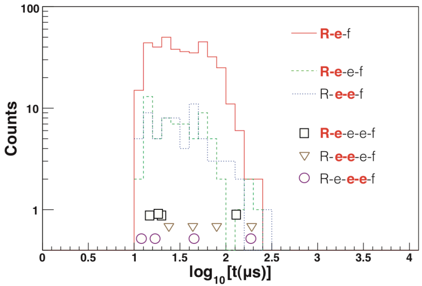




K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

J.Rubert, P.T.Greenlees et al., to be published





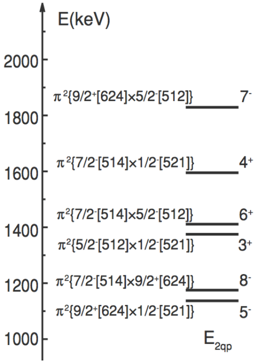
Observed Decays

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	2210	6.9(2) ms
R-e-F	382 (17%)	23 μs
R-e-e-F	67 (3.0%)	17 μs
R-e-e-e-F	4 (0.18%)	27 μs

Interpretation/Speculation

- Much improved data required to make firm assignments!
- Calculated ordering of 2QP states sensitive to deformation
- Many possibilities for 4QP:
  11^- - $\pi 5^- \otimes \pi 6^+$
  12^+ - $\pi 8^- \otimes \nu 4^-$
  9^+ - $\pi 5^- \otimes \nu 4^-$
- If 900 keV is $E1$ 8^- to 8^+
  900 keV E1 ΔK=8: f_ν = 37
  Excitation energy of 8^- too high, little/no sign of gsb transitions
- If 900 keV is $E1$ 5^- to 4^+
  900 keV E1 ΔK=5: f_ν = 565
  Observed electron energy possibly too high?
  Could be possible scenario with second isomer K=8^-

K^π	Configuration	$E_{2\text{-qp}}$ (MeV)[a]
8^-	π 7/2[514] π 9/2[624]	0.93
5^-	π 1/2[521] π 9/2[624]	1.06
6^+	π 7/2[514] π 5/2[512]	1.34
3^+	π 7/2[514] π 1/2[521]	1.34
4^-	ν 9/2[734] ν 1/2[620]	1.40
6^-	ν 9/2[734] ν 3/2[622]	1.49
10^+	ν 9/2[734] ν 11/2[725]	1.75
8^-	ν 9/2[734] ν 7/2[613]	1.80



Summary

- Developments in instrumentation now allow in-beam γ-ray spectroscopy at 10 nb level
- First observation of rotational states in the superheavy nucleus ^{256}Rf
- Differences in MoI reveal details about underlying shell structure and pairing
- Alignment effects in N=152 isotone ^{254}No delayed compared to ^{256}Rf
- New K-isomer data from JYFL seems to be consistent with data from Berkeley
- Interpretation still open, better spectroscopic data needed

Collaboration

Selected for a Viewpoint in *Physics*
PRL **109,** 012501 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

Shell-Structure and Pairing Interaction in Superheavy Nuclei: Rotational Properties of the $Z = 104$ Nucleus ^{256}Rf

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(Received 4 May 2012; published 3 July 2012)

Nuclear Instruments and Methods in Physics Research B 276 (2012) 33–37

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Contents lists available at SciVerse ScienceDirect
Nuclear Instruments and Methods in Physics Research B
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First intense isotopic titanium-50 beam using MIVOC method

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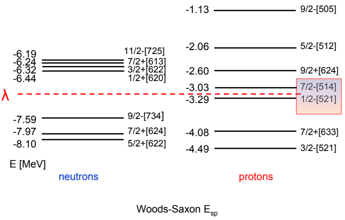
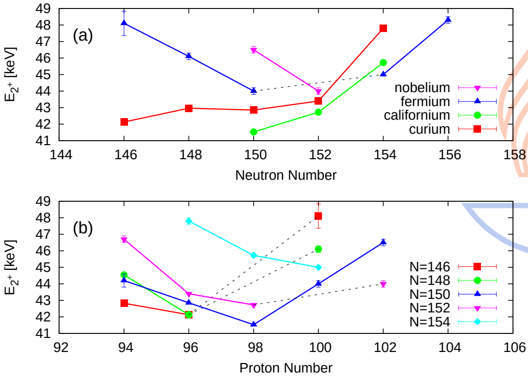
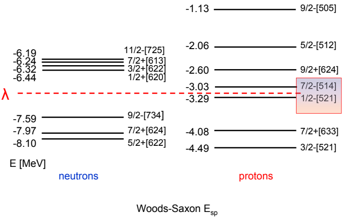
Experimental 2^+ Energies

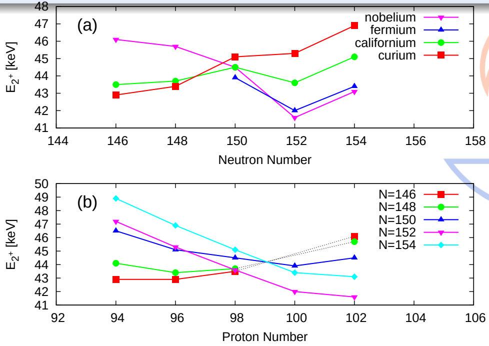




Theoretical 2^+ Energies

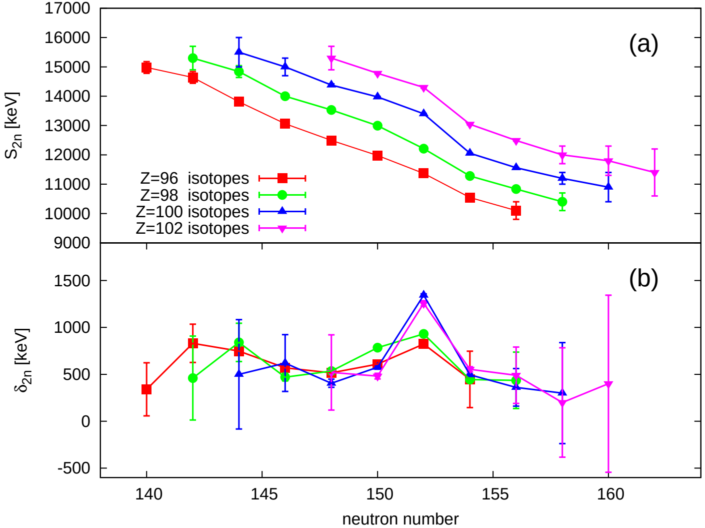


Sobiczewski, Muntian, Patyk. PRC **63**, 034306 (2001)



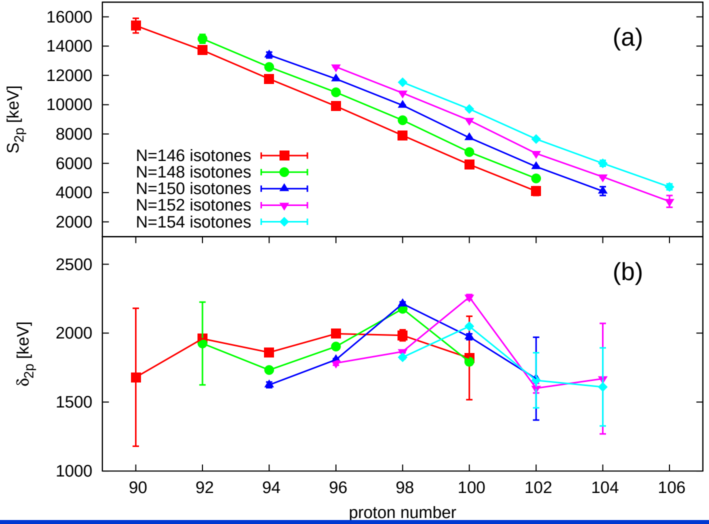
Correlation to Masses - Isotopes

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

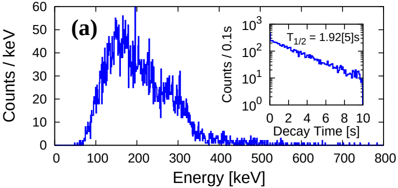


Correlation to Masses - Isotones

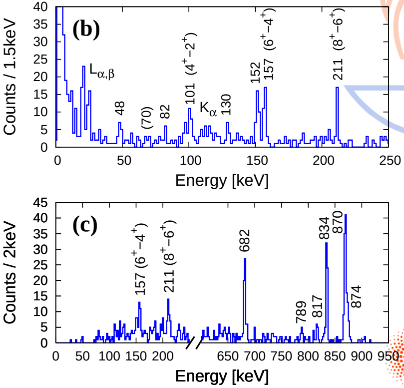
AME2003: $S_{2p}(Z,N) = B(Z,N) - B(Z-2,N)$, $\delta_{2p}(Z,N) = S_{2p}(Z,N) - S_{2p}(Z+2,N)$



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



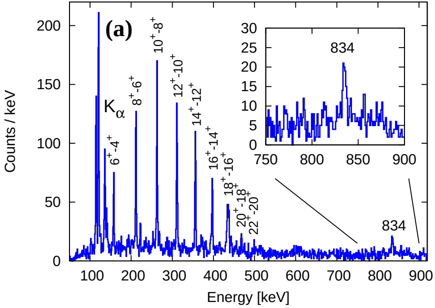
Focal Plane Gamma Rays



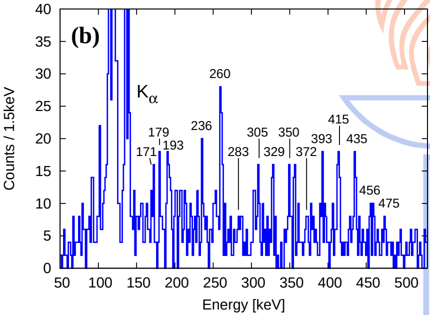
K-Isomerism in ^{250}Fm

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

Ground State Band

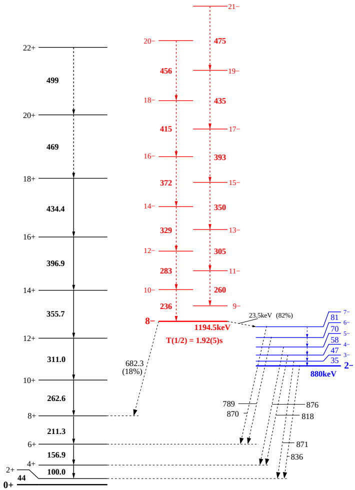


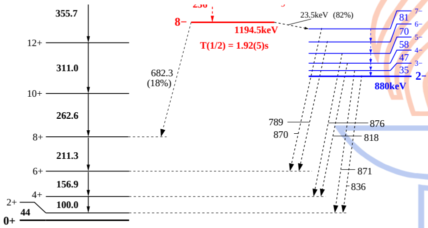
Isomer-Tagged Transitions



K-Isomerism in ^{250}Fm

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

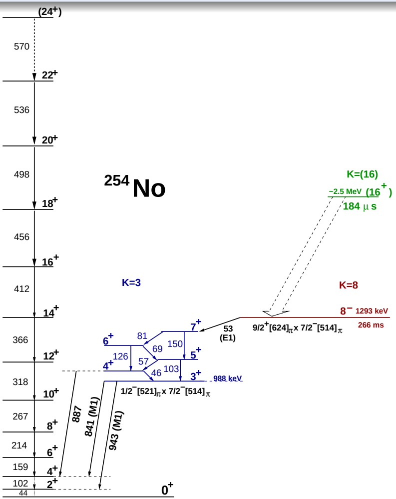




8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$
2^- - $\nu[622]5/2^+ \otimes \nu[734]9/2^-$ dominates
682 keV E1 $\Delta K=8$: $f_\nu = 213$
23.5 keV M1 $\Delta K=6$: $f_\nu = 192$

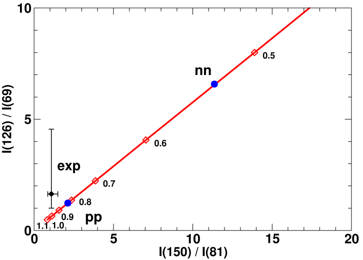
K-Isomerism in ^{254}No

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

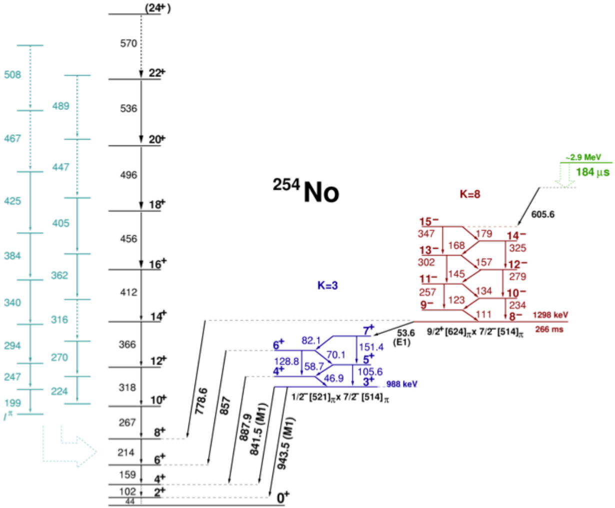


Determined Configurations:

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

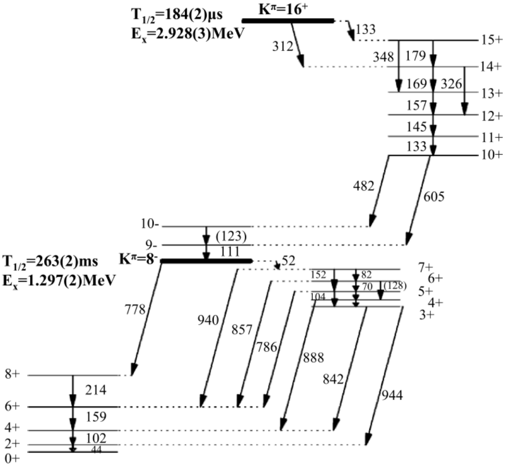


K-Isomerism in ^{254}No



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

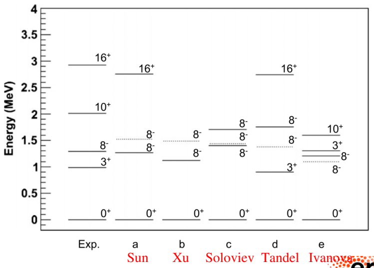
K-Isomerism in ^{254}No



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

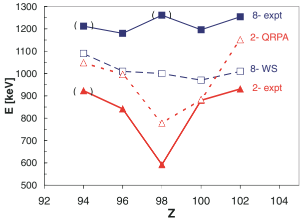
Determined Configurations:

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^+ - $(\pi[514]7/2^- \otimes \pi[624]9/2^+)$ + $(\nu[734]9/2^- \otimes \nu[613]7/2^+)$



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)