Enhanced fission stability of K isomers in superheavy nuclei: the case of ^{254}Rf

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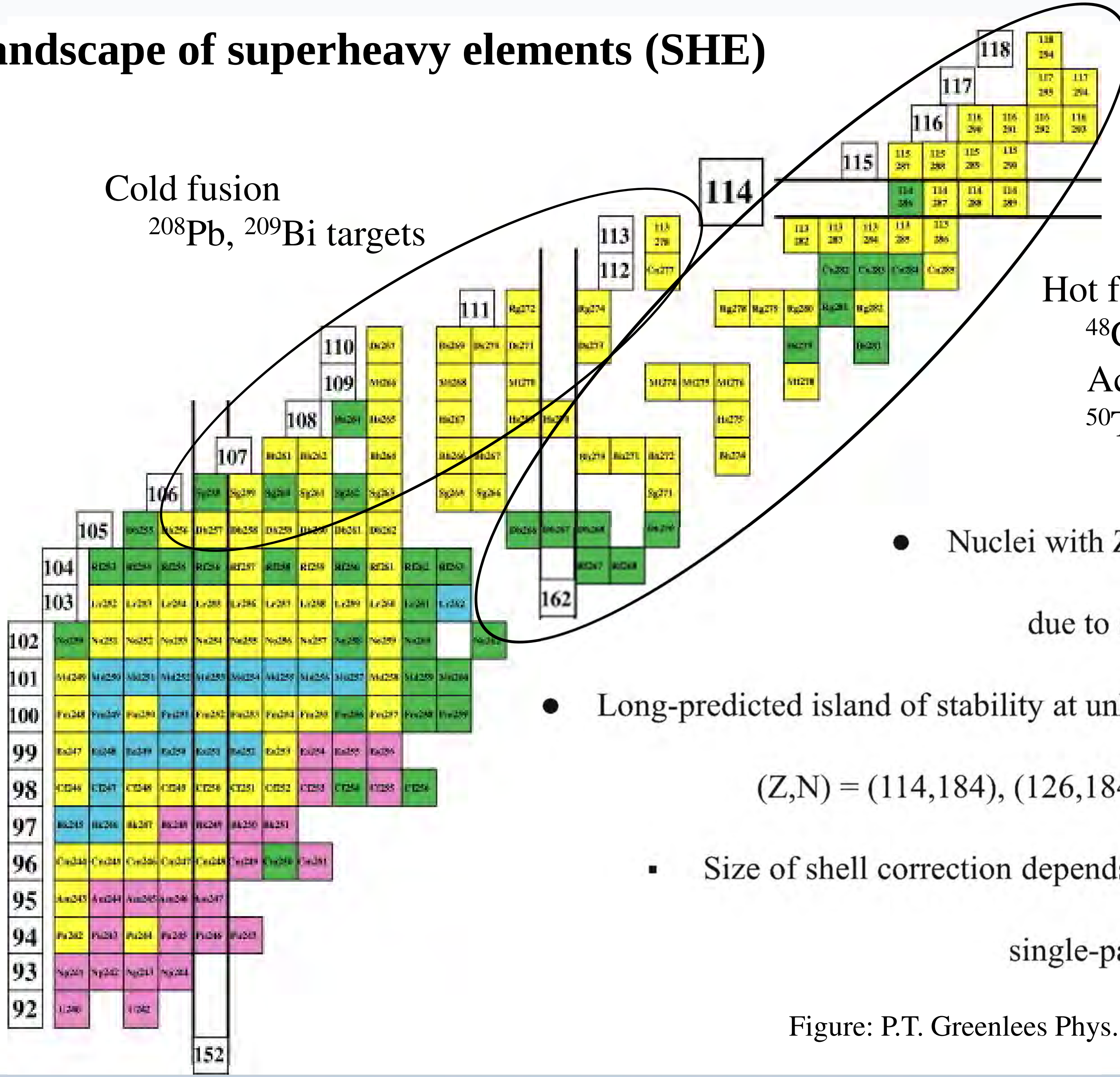
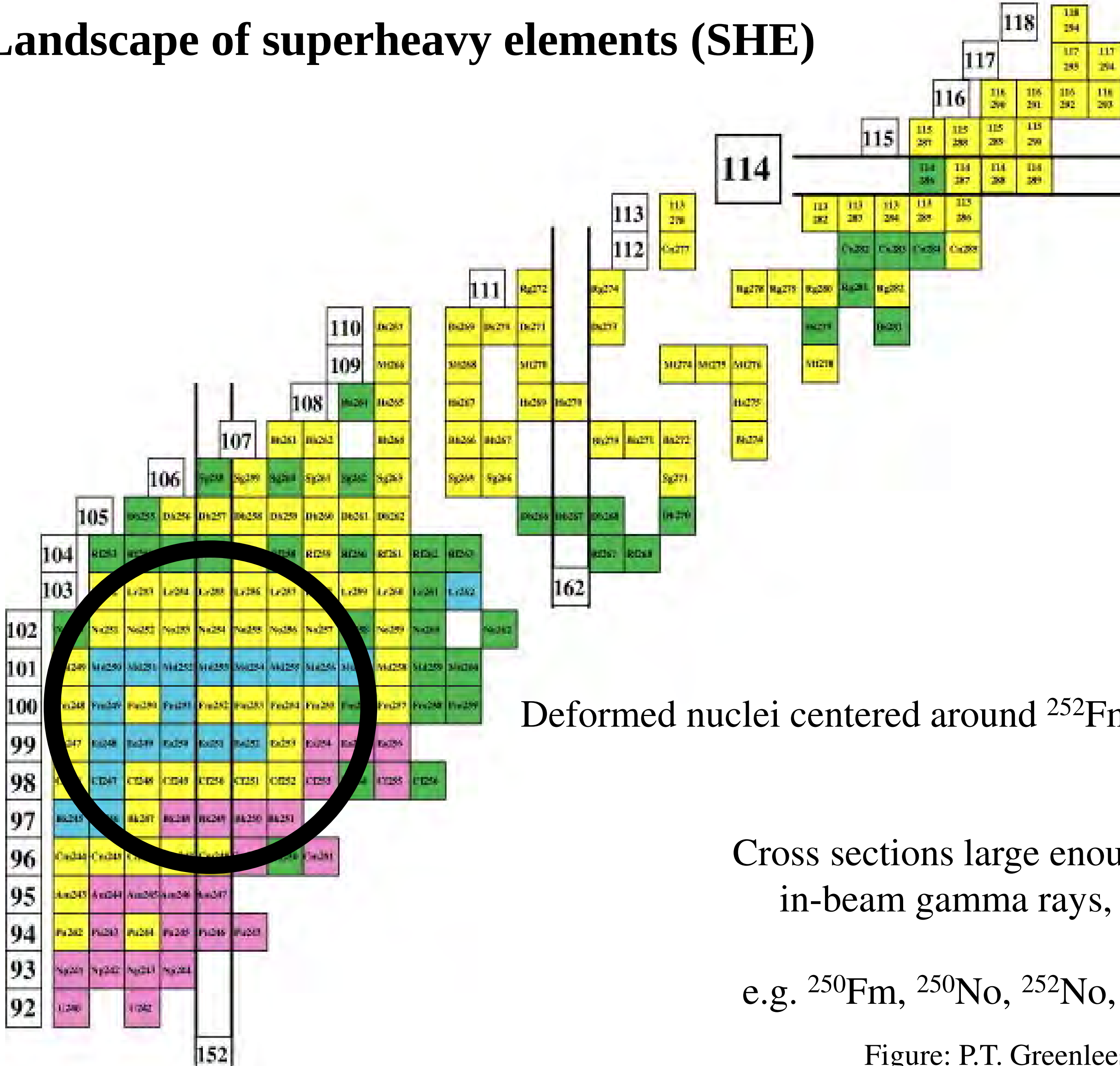
Landscape of superheavy elements (SHE)



- Nuclei with Z > 100 survive due to shell correction
- Long-predicted island of stability at unknown location (Z,N) = (114,184), (126,184), (120,172)…
  - Size of shell correction depends on underlying single-particle structure

Figure: P.T. Greenlees Phys. Scr. 2013 014016

Landscape of superheavy elements (SHE)



Deformed nuclei centered around ^{252}Fm (Z = 100, N = 152)

$\beta_2 \approx 0.25$

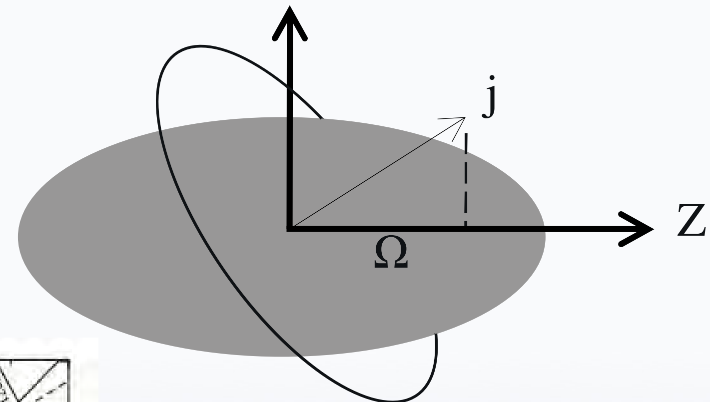
Cross sections large enough for spectroscopy:
in-beam gamma rays, isomers, α decay, SF

e.g. ^{250}Fm, ^{250}No, ^{252}No, ^{242}No, ^{256}Rf, ^{257}Rf…

Figure: P.T. Greenlees Phys. Scr. 2013 014016

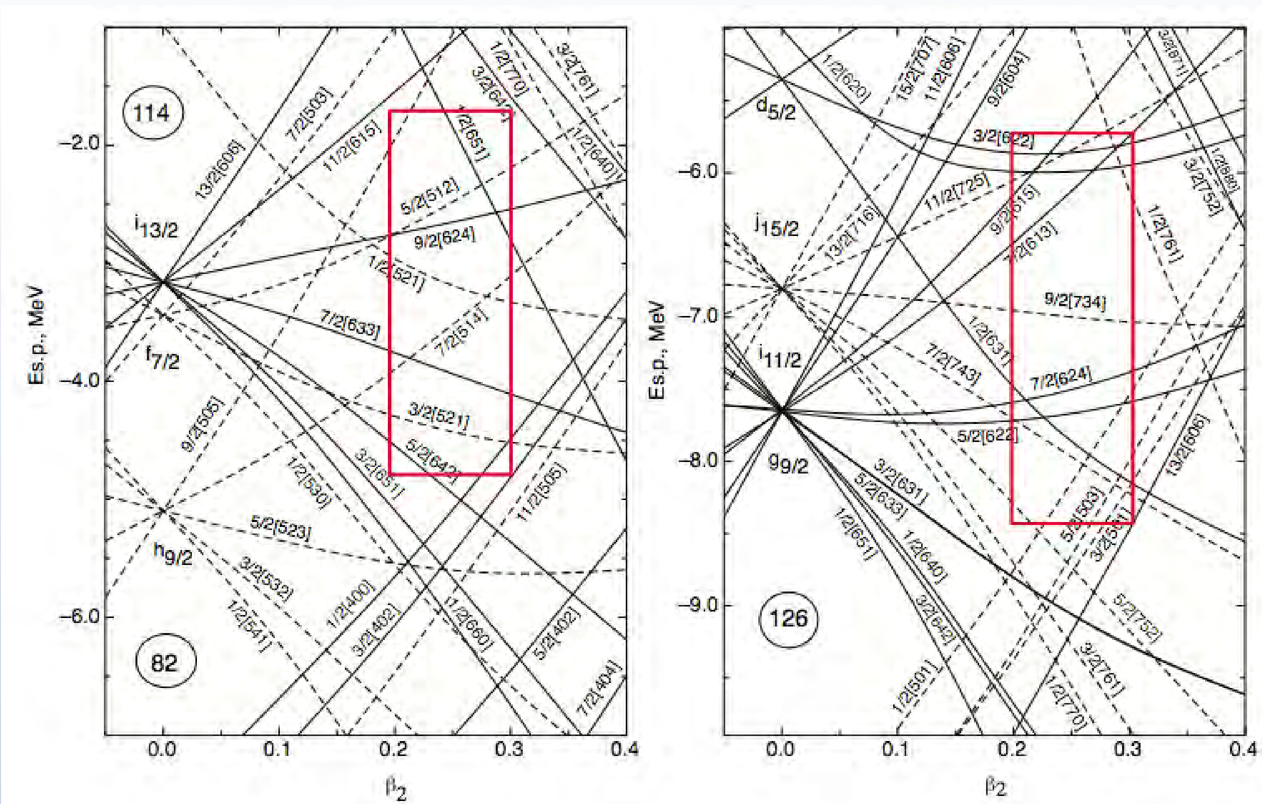
K isomerism in transfermium nuclei

- Region of prolate-deformed nuclei around Z = 100, N = 152
- High-K orbitals close to Fermi surface



$$K = \Sigma_i \Omega_i$$

sum of nucleon Ω: projection of angular momentum onto symmetry axis

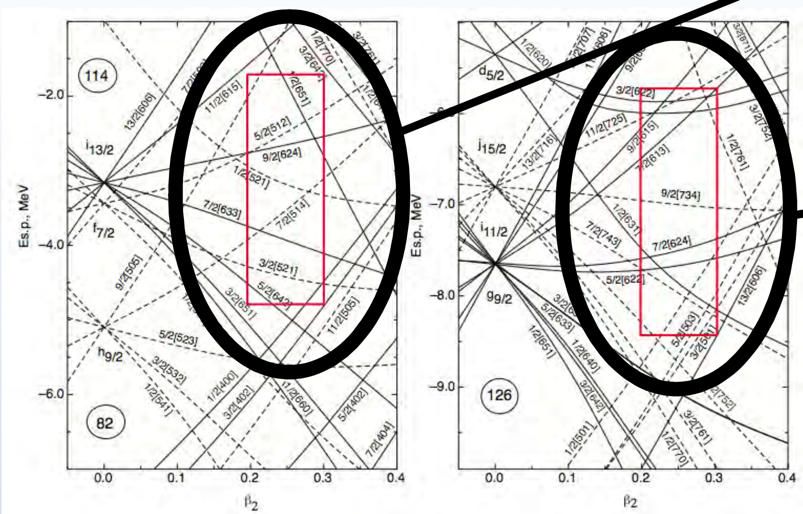


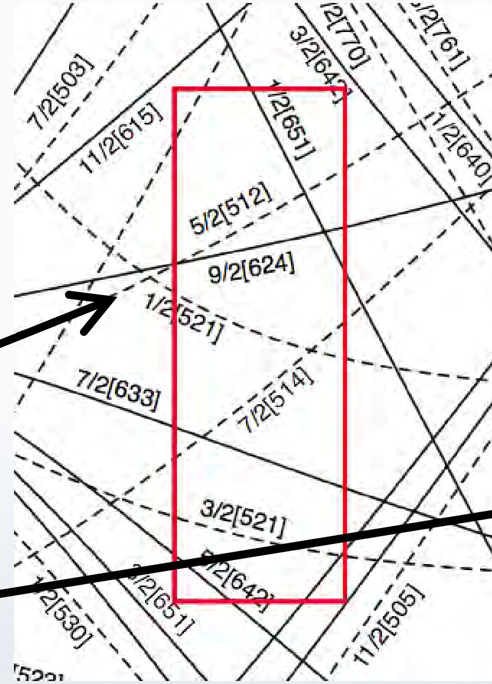
Nilsson levels for protons (left) and neutrons (right) with A~250 [1]

[1] Kondev, Dracoulis and Kibédi, At. Data Nucl. Data Tables 103-104, 50 (2015)

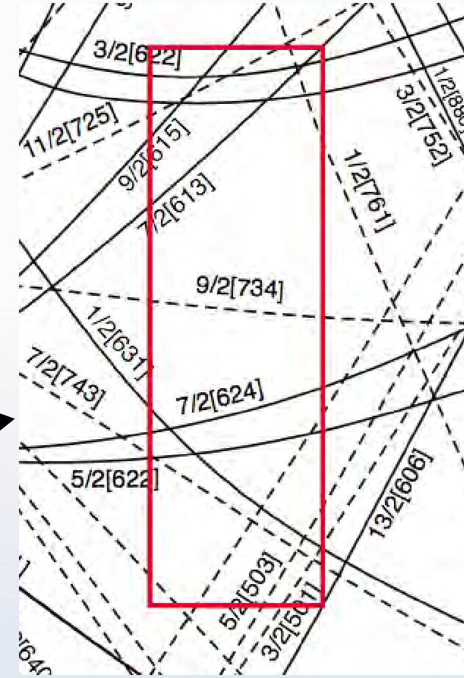
K isomerism in transfermium nuclei

- High-K states are often isomeric as transitions with **large ΔK** required





protons



neutrons

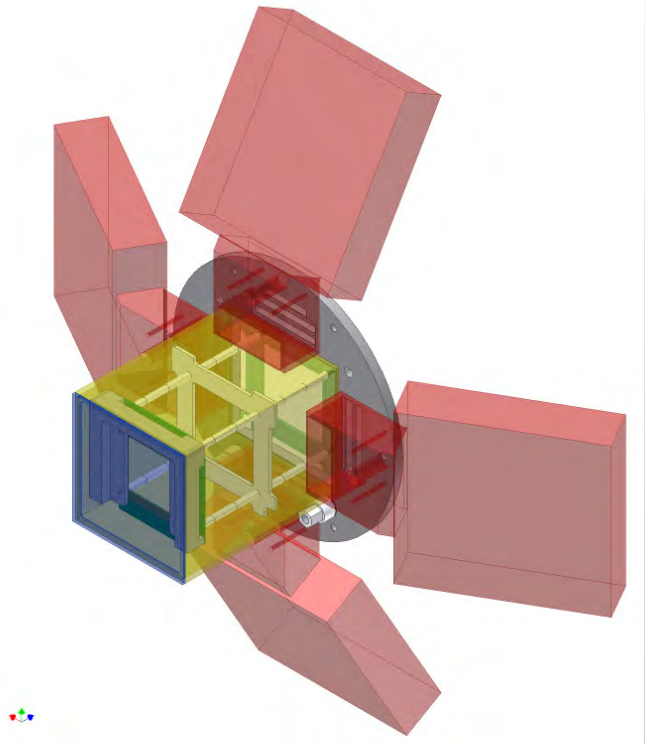
- High-K orbitals couple to make two and four quasi particle (qp) states:

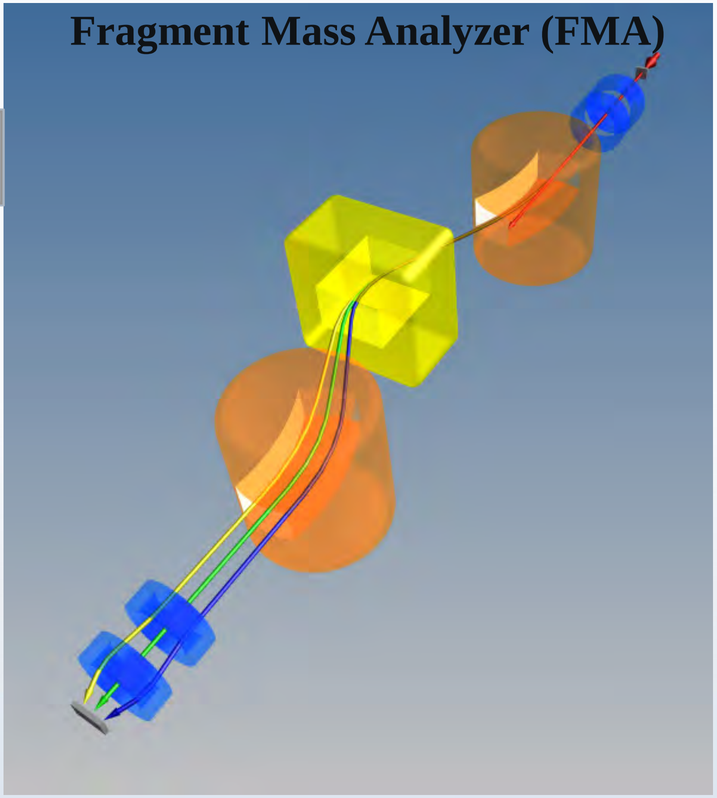
2qp:	$K^\pi = 8^-$	$\nu^2(9/2[734] \otimes 7/2[624])$
2qp:	$K^\pi = 8^-$	$\pi^2(7/2[514] \otimes 9/2[624])$
4qp:	$K^\pi = 16^+$	$\nu^2(9/2[734] \otimes 7/2[624]) \otimes (7/2[514] \otimes 9/2[624])$

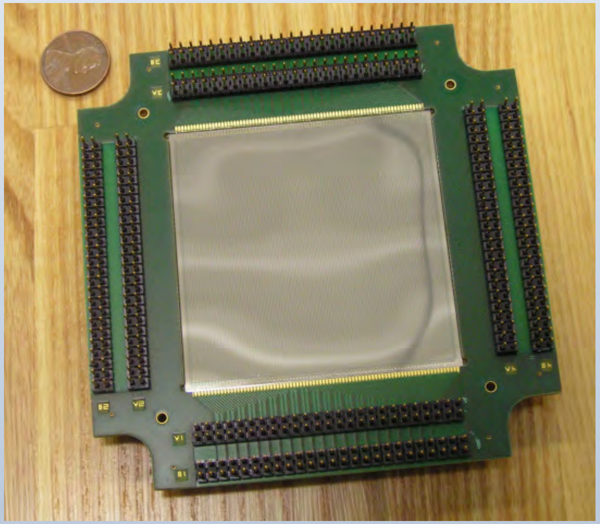
- 2qp isomers known in N=150 isotones from ^{244}Pu to ^{252}No
- ^{254}Rf heaviest known N=150 isotone – no spectroscopic information known
- Ground-state fissions with $T_{1/2}$ ~ 20μs

ANL experiment 2012

- $^{50}Ti + ^{206}Pb$ **@ 242.5 MeV; 2.4 nb** [1]; **~5 days; ~150 pnA**
- Reaction products dispersed by M/q at focal plane of Fragment Mass Analyzer (FMA)
- 160x160 DSSD served as implantation detector



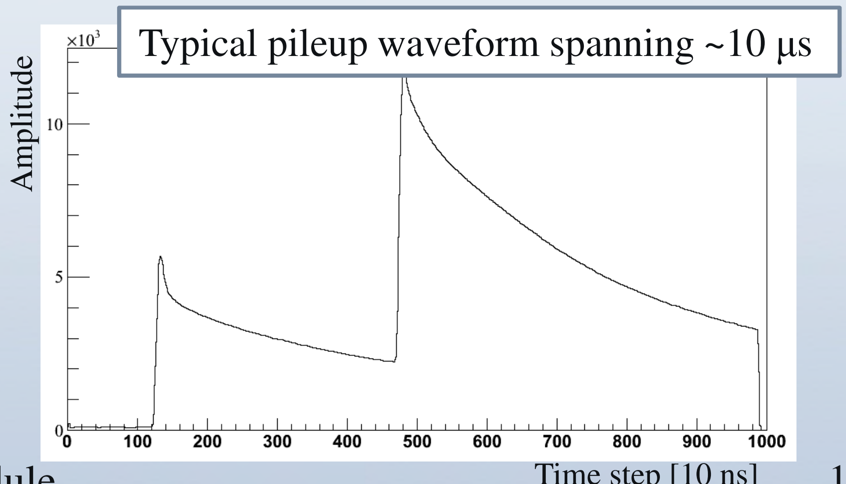




[1] Heβberger *et al.*, Z. Phys. A **359**, (1997) 415

Digital acquisition system

- Development of **new digital DAQ** at ANL
- Based on GRETINA system
  new ANL firmware written by J. Anderson
- Fully instrumented by 100 MHz, 14-bit digitizers [1,2]
- Especially large impact for cases with short-lived activity (~10s μs)
- Sensitive to very fast decays (~100s ns)
- Allows detailed analysis of waveforms



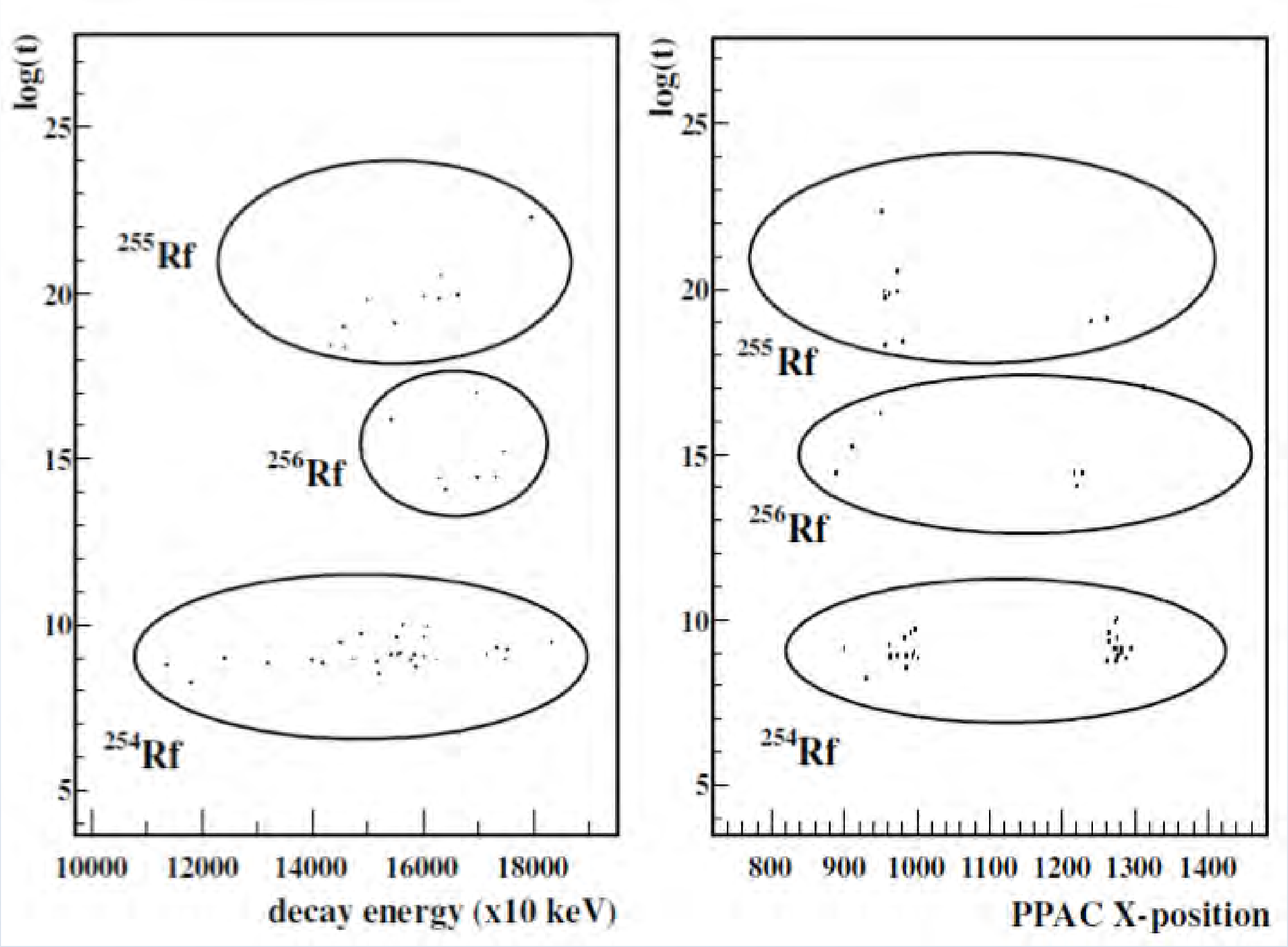
Trigger and Time control module

[2] Anderson *et al.*, 2007, IEEE Nuclear Science Symposium Conference Record, p. 1751

100 MHz, 14-bit Digitizer

[1] Cromaz *et al.*, A **597** (2008) 233–237

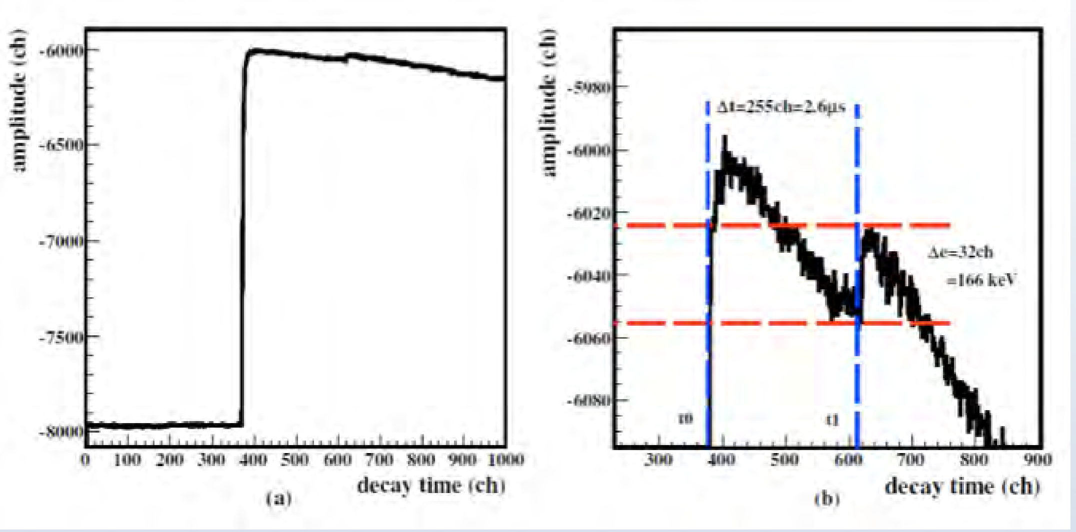
ANL results



- ^{254,255,256}Rf identified at the focal plane
- 28 fission events associated with ^{254}Rf implants

ANL results

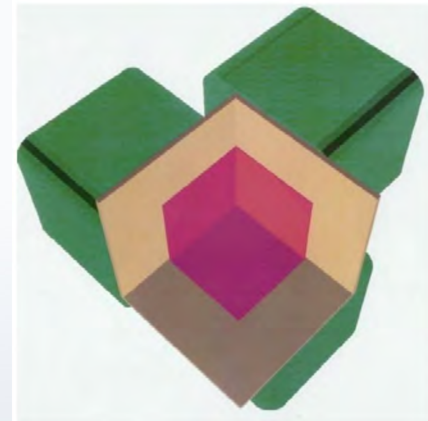
- Signature of isomeric state is emission of conversion electrons followed by GS fission
- 4 conversion-electron cascades detected within 10 μs of ^{254}Rf implantation
- A single electron cascade observed with much longer decay time (515 μs), followed by fission 38 μs later
- Evidence for two distinct isomeric states in ^{254}Rf



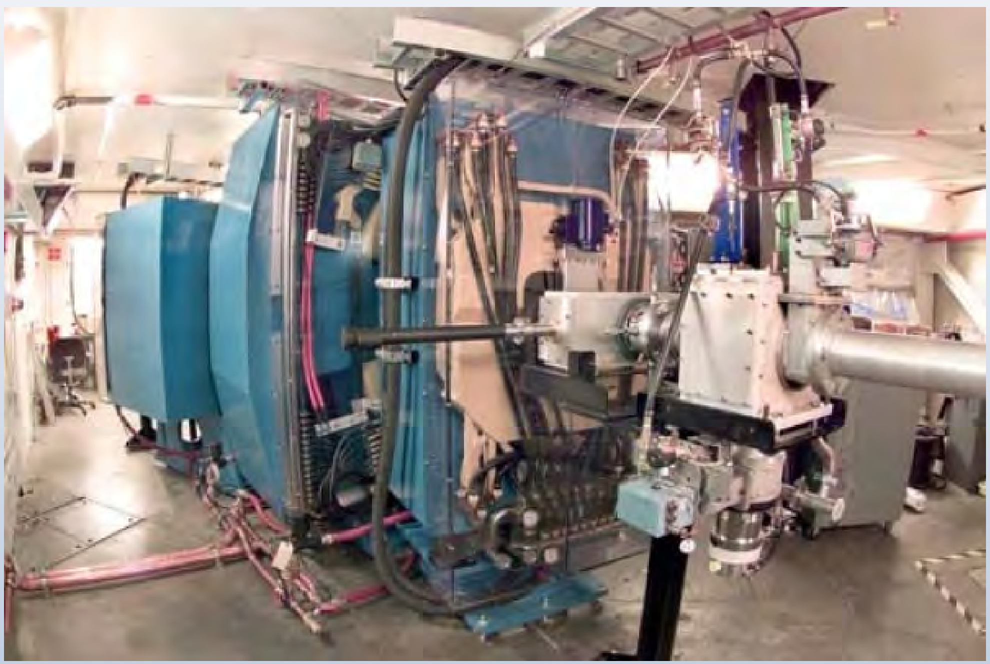
- But… the digital DAQ did not perform as expected
  - Unexpected deadtime up to ~40 μs

LBNL experiment 2014

- **88-inch cyclotron; $^{50}Ti + ^{206}Pb$ @ 244 MeV; 2.4 nb; ~5 days; 250 pnA**
- Reaction products separated from unreacted beam ions by Berkeley Gas-filled Separator (BGS)
- No mass separation but high transmission efficiency



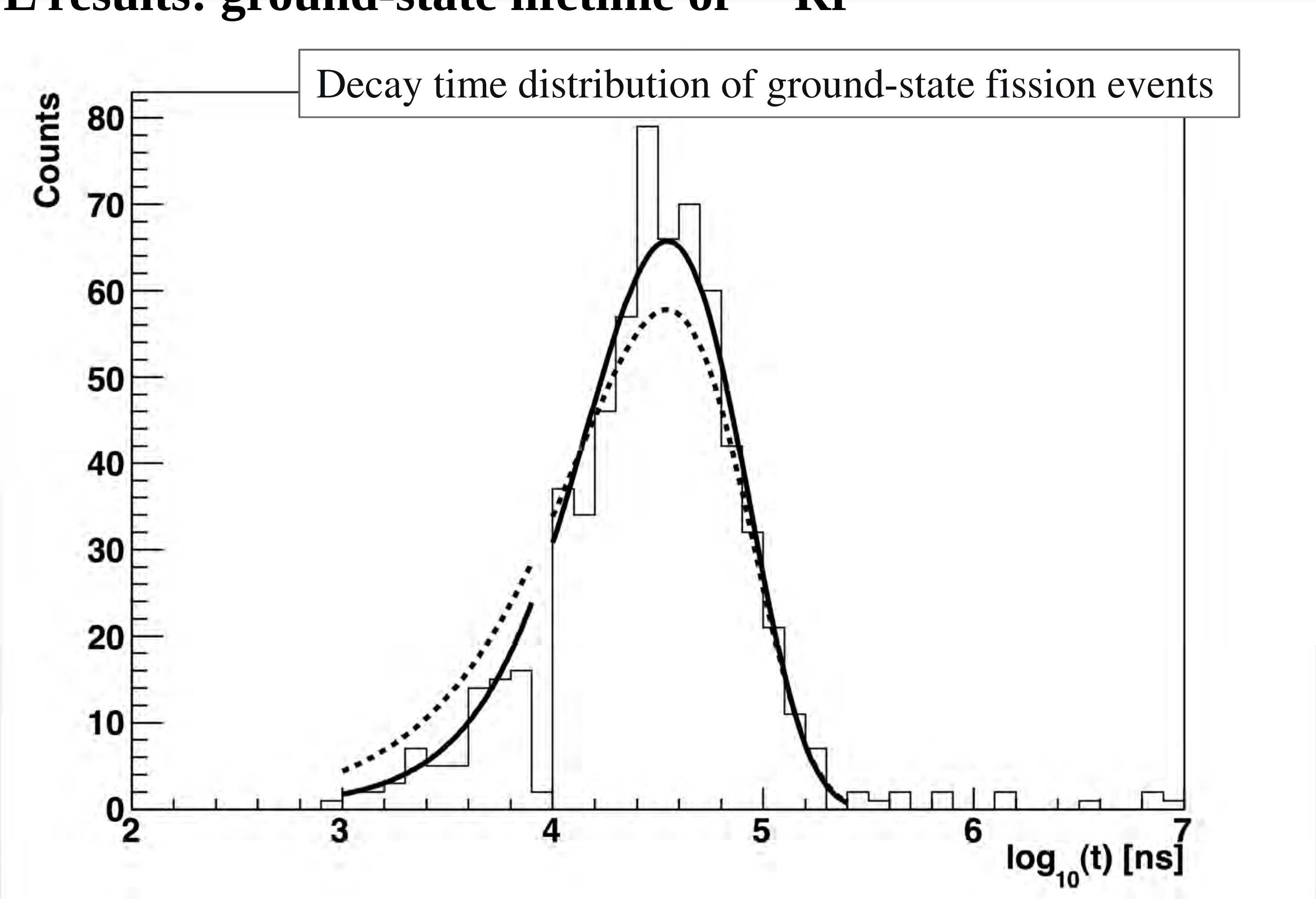
"corner-cube" configuration



Berkeley Gas-filled Separator (BGS)

- Three 32x32 DSSDs in "corner-cube" configuration as implantation detectors with three clovers ~4 mm behind each
- Digital DAQ for all channels using ANL system, bugs fixed

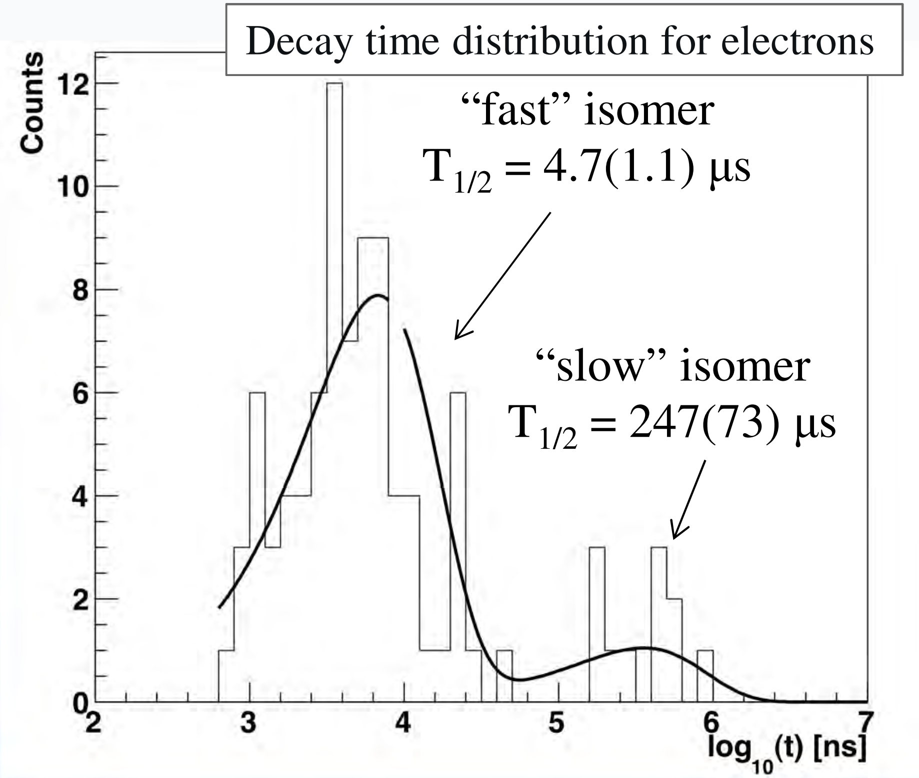
LBNL results: ground-state lifetime of ^{254}Rf

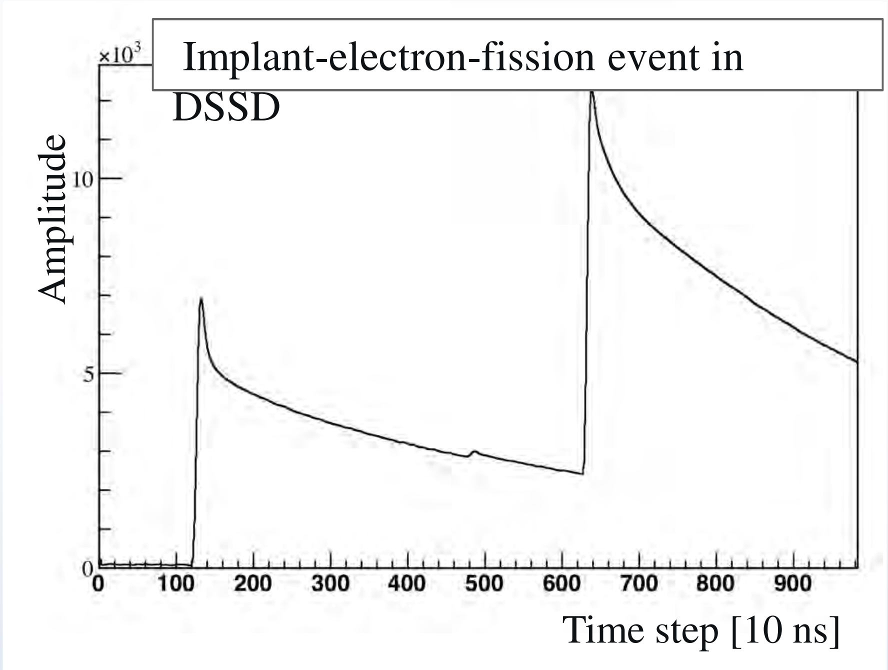


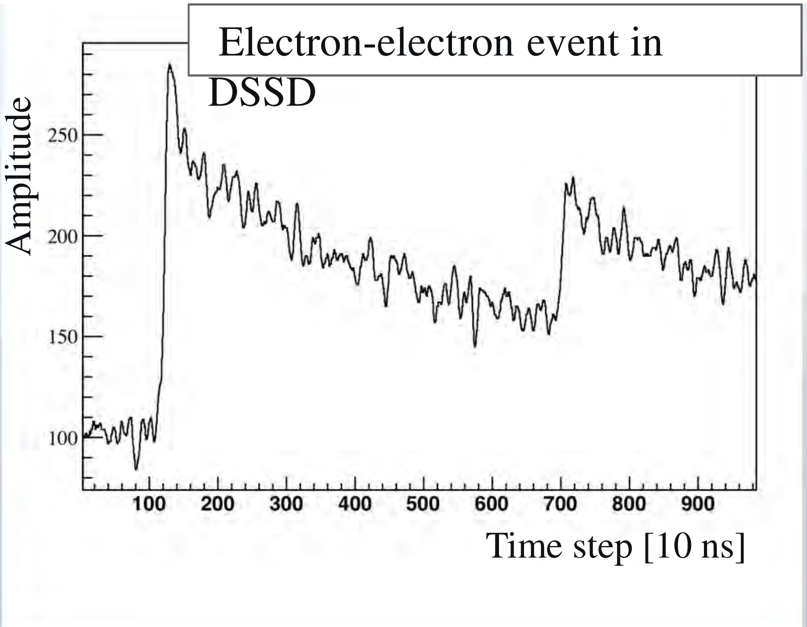
- Dashed line: exponential fit
- Solid line: includes undetected feeding from 2qp isomer
- Measured halflife of 23.2(1.1) µs

cf: 23(3) µs	F.P. Heßberger *et al.*, (1997, GSI)
29.6(+0.7-0.6) µs	I. Dragojević *et al.*, (2008, LBNL)

Two isomeric states



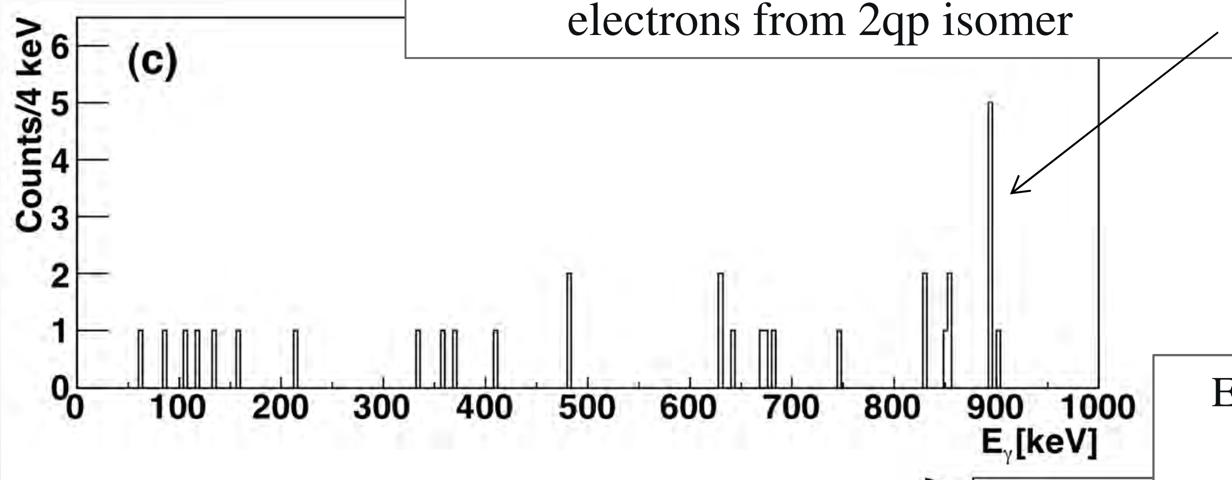




- Conversion electron cascades detected in between implant and spontaneous fission
- Two distinct isomers observed
- Seven event chains of implant-electron-electron-fission: slow isomer feeds fast isomer

Isomer spectroscopy

Gamma rays in prompt coincidence with electrons from 2qp isomer



- Five counts at 893 keV
- Three counts at 853 keV
- Two counts at 829 keV

- Isomer population probabilities:

fast isomer: ~25 %
slow isomer: ~2 %

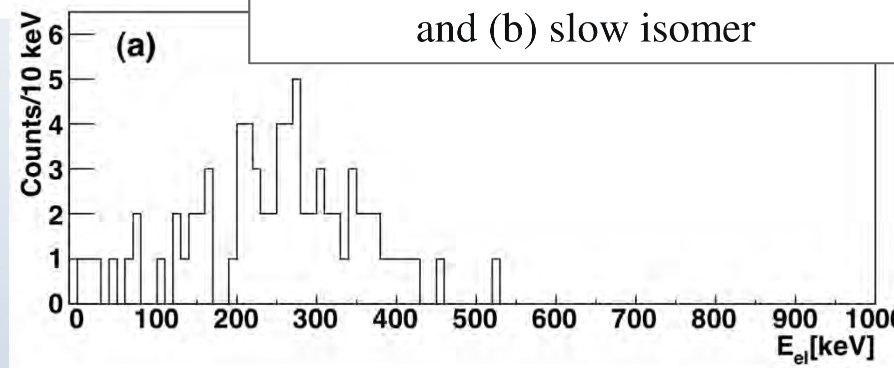
Fast isomer **2qp**:

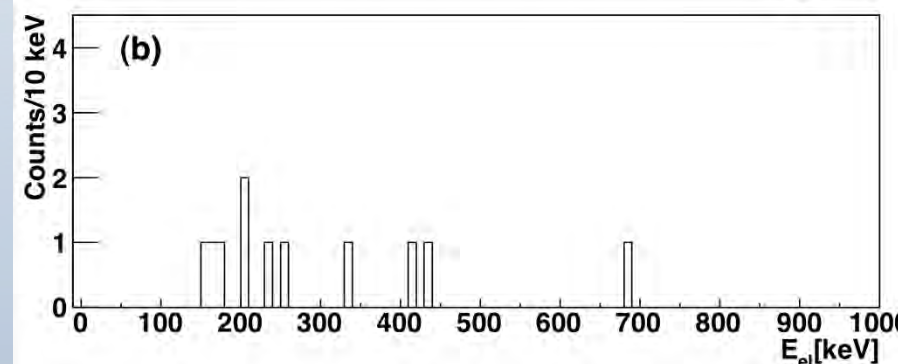
$8^- \nu^2(9/2[734] \otimes 7/2[624])$

Slow isomer **4qp**:

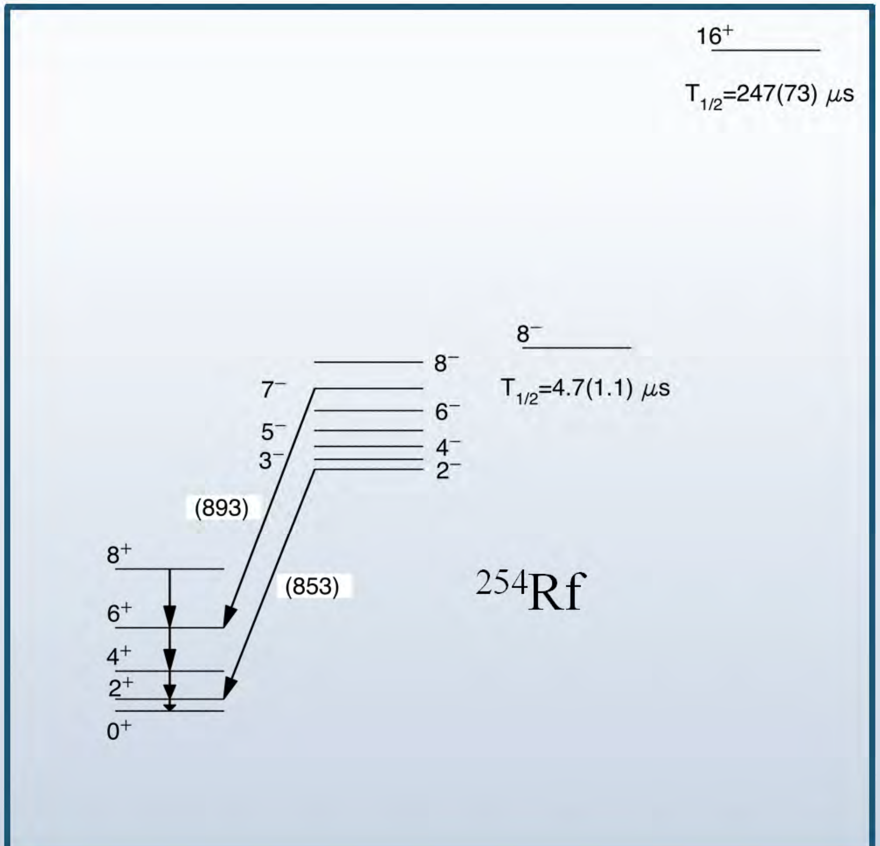
$16^+\{\nu^2(9/2[734] \otimes 7/2[624]) \otimes \pi^2 (7/2[514] \otimes 9/2[624])\}$

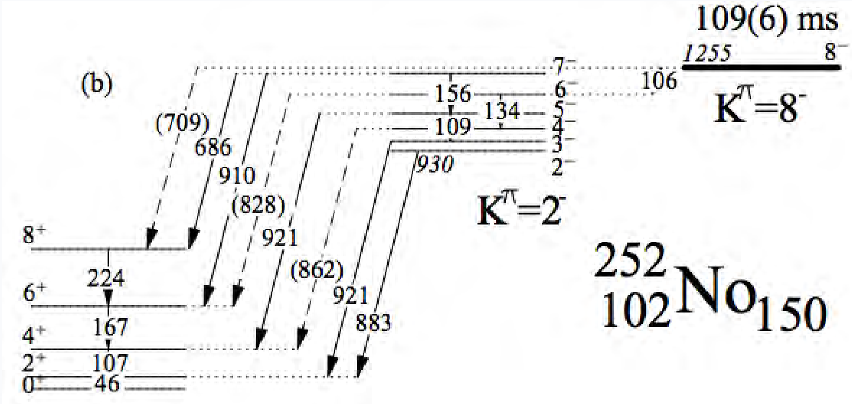
Energy distribution for electrons from the (a) fast and (b) slow isomer





Possible level scheme of ^{254}Rf





Robinson *et al.*, Phys Rev C **78** (2008) 034308

Two quasineutron, $K^{\pi} = 8^{-}$

$8^{-}\nu^{2}(9/2[734] \otimes 7/2[624])$

Four quasiparticle, $K^{\pi} = 16^{+}$

$16^{+}\{\nu^{2}(9/2[734] \otimes 7/2[624]) \otimes$
$\pi^{2}(7/2[514] \otimes 9/2[624])\}$

- 2qp halflife **4-5 orders of magnitude shorter** than that of neighbouring isotones
- Could be attributed to accidental mixing between 8^{-} 2qp isomer and 8^{-} member of octupole band

Fission hindrance

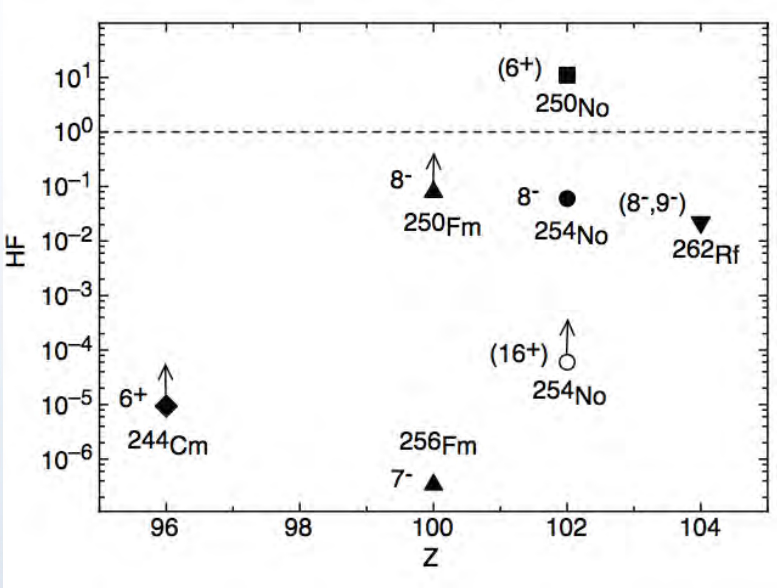
- No definite evidence for fission branches observed from either isomer

Two quasiparticle isomer

Obscured by ground-state fission
~10 % upper limit on fission branch
~50 µs lower limit on partial fission lifetime
Estimated **factor of at least 2** hindrance wrt ground-state fission

Four quasiparticle isomer

Six fission events consistent with 4qp halflife
Likely these events due to missed electrons
~40 % upper limit on fission branch
~600 µs lower limit on partial fission lifetime
Estimated **factor of at least 25** hindrance wrt ground-state fission



Fission hindrances for 2 and 4qp isomers relative to unity for ground-state fission [1]

[1] Kondev, Dracoulis and Kibédi, At. Data Nucl. Data Tables 103-104, 50 (2015)

PRL **115,** 132502 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

Decay and Fission Hindrance of Two- and Four-Quasiparticle *K* Isomers in ^{254}Rf

H. M. David,[1] J. Chen,[1,‡] D. Seweryniak,[1,†] F. G. Kondev,[1] J. M. Gates,[2] K. E. Gregorich,[2] I. Ahmad,[1] M. Albers,[1,§] M. Alcorta,[1,‖] B. B. Back,[1] B. Baartman,[2] P. F. Bertone,[1,¶] L. A. Bernstein,[3] C. M. Campbell,[2] M. P. Carpenter,[1] C. J. Chiara,[4,1] R. M. Clark,[2] M. Cromaz,[2] D. T. Doherty,[5,**] G. D. Dracoulis,[6,*] N. E. Esker,[2] P. Fallon,[2] O. R. Gothe,[2] J. P. Greene,[1] P. T. Greenlees,[7] D. J. Hartley,[8] K. Hauschild,[9] C. R. Hoffman,[1] S. S. Hota,[10,††] R. V. F. Janssens,[1] T. L. Khoo,[1] J. Konki,[7] J. T. Kwarsick,[2] T. Lauritsen,[1] A. O. Macchiavelli,[2] P. R. Mudder,[2] C. Nair,[1] Y. Qiu,[10] J. Rissanen,[2] A. M. Rogers,[1,‡‡] P. Ruotsalainen,[7,‡‡] G. Savard,[1] S. Stolze,[7] A. Wiens,[2] and S. Zhu[1]

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Summary

- Two high-K isomers in ^{254}Rf observed at ANL and LBNL

- 2qp isomer, $T_{1/2}$ = 4.7(1.1) μs,
  $8^{-} \nu^2(9/2[734] \otimes 7/2[624])$

- 4qp isomer, $T_{1/2}$ = 247(73) μs,
  $16^{+}\{\nu^2(9/2[734] \otimes 7/2[624]) \otimes \pi^2 (7/2[514] \otimes 9/2[624])\}$

- Observation of “fast” isomer only possible due to new digital acquisition system

- A few surprises in ^{254}Rf:

  2qp isomer decays four orders of magnitude faster than in neighboring isotones
  No evidence of fission branches implies fission hindrances of >1 for both isomers

Thank you

J. Chen[1], D. Seweryniak[1], F.G. Kondev[1], J. Gates[3], K. Gregorich[3], I. Ahmad[1], M. Albers[1], M. Alcorta[2], B. Back[1], B. Baartman[3], P. Bertone[1], L. Bernstein[4], C. Campbell[3], M.P. Carpenter[1], C.J. Chiara[5], M. Cromaz[3], R. Clark[3], D.T. Doherty[2], G. Dracoulis[6], N. Esker[3], O. Gothe[3], J.P. Greene[1], P.T. Greenlees[7], D.J. Hartley[8], K. Hauschild[9], P. Fallon[3], C.R. Hoffman[1], S.S. Hota[10], R.V.F. Janssens[1], J. Karwsik[3], T.L. Khoo[1], J. Konki[7], T. Lauritsen[1], A. Macchiavelli[3], P. Mudder[3], C. Nair[1], Y. Qiu[6], J. Rissanen[3], A.M. Rogers[1], P. Ruotsalainen[7], G. Savard[1], S. Stolze[7], A. Wiens[3], S. Zhu[1]

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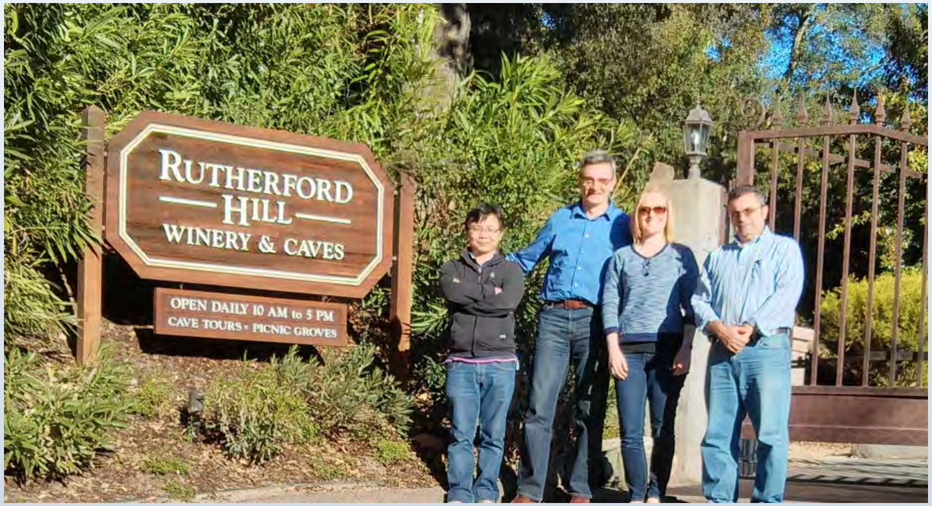
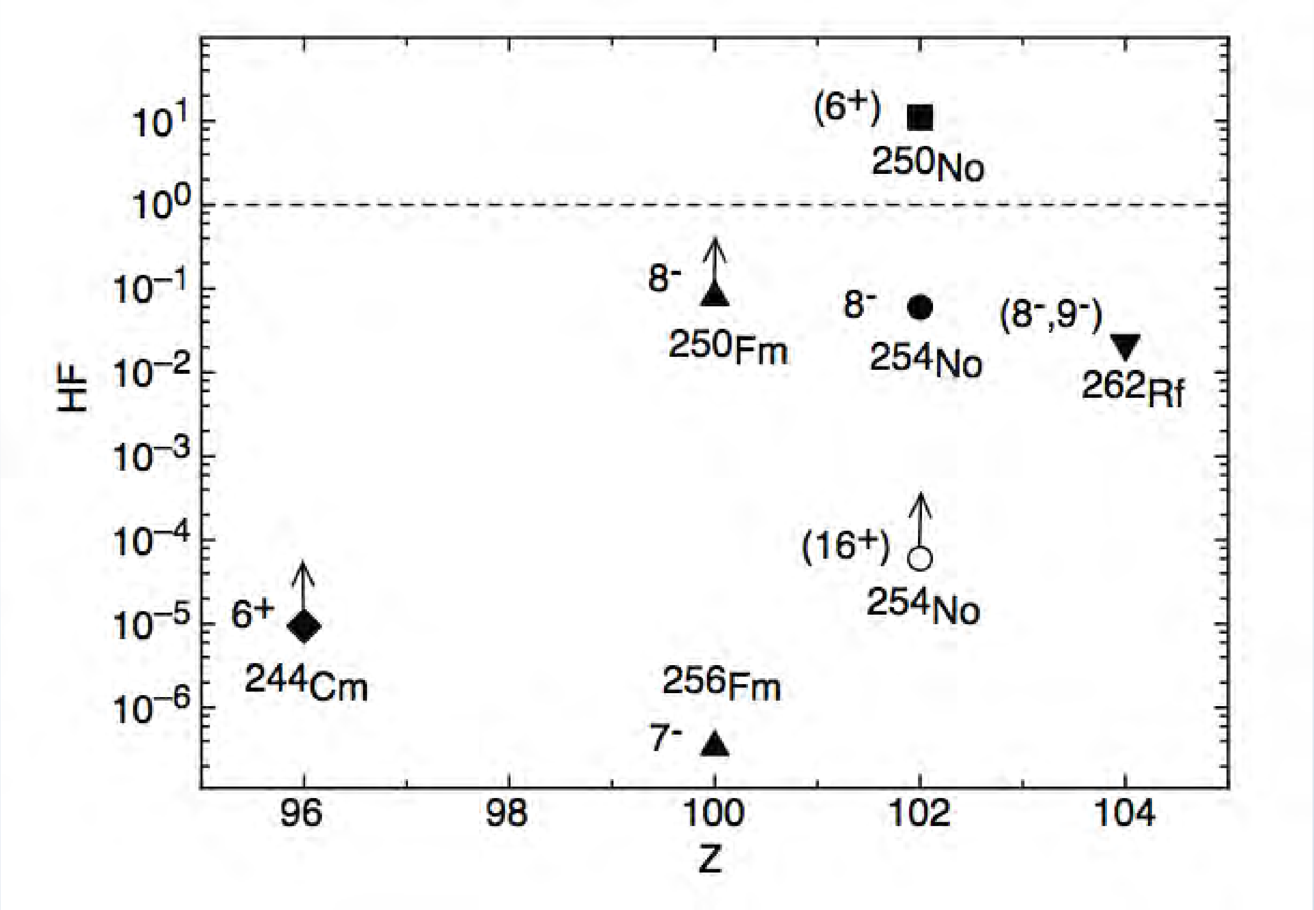


Known fission hindrances



Fission hindrances for 2 and 4qp isomers relative to unity for ground-state fission [1]

- 2qp K isomers found in several even-even N = 150 isotones from ^{244}Pu to ^{252}No

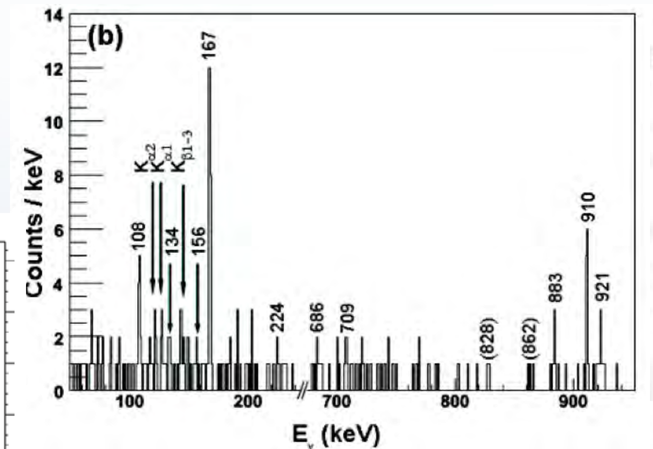
  $8^- \nu^2(9/2[734] \otimes 7/2[624])$ configuration

- ^{254}Rf heaviest known N=150 isotone. 2qp, $K^\pi = 8^-$ and 4qp, $K^\pi = 16^+$ isomers expected

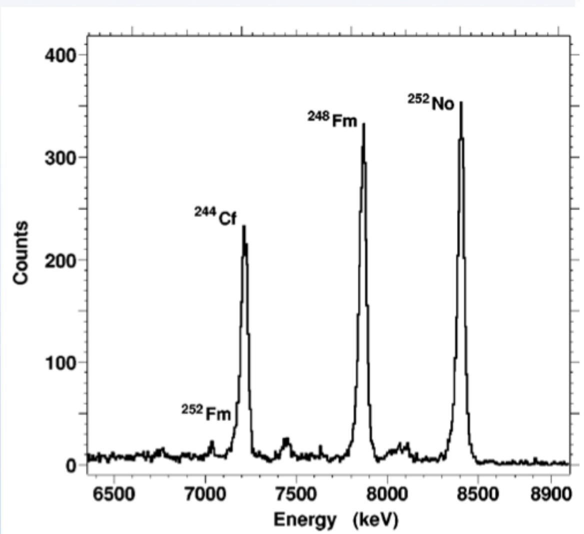
[1] Kondev, Dracoulis and Kibédi, ADNDT, in press

^{252}No (Z = 102, N = 150)

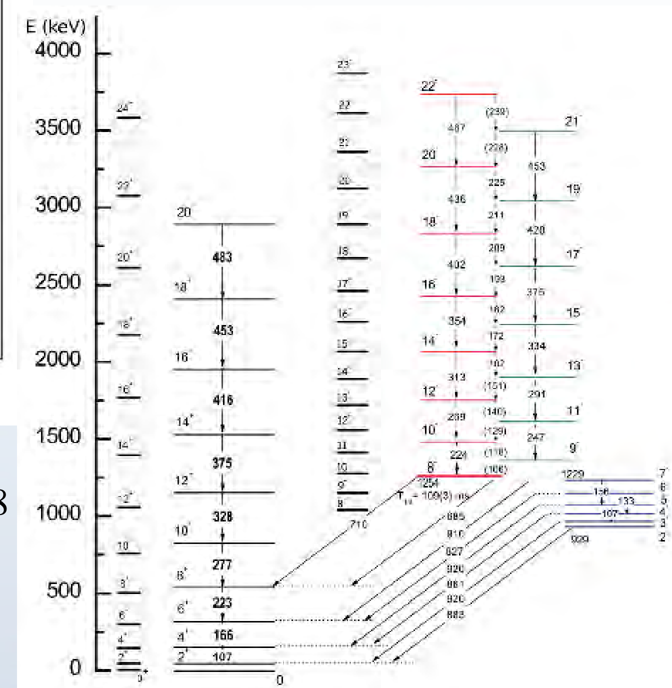
- Decay, delayed and in-beam spectroscopy of ^{252}No
- University of Jyvaskyla and at ANL
- Cross section ~220(nb)



Gamma-ray spectrum from 2qp isomer
Robinson *et al.*, PRC **78** (2008) 034308



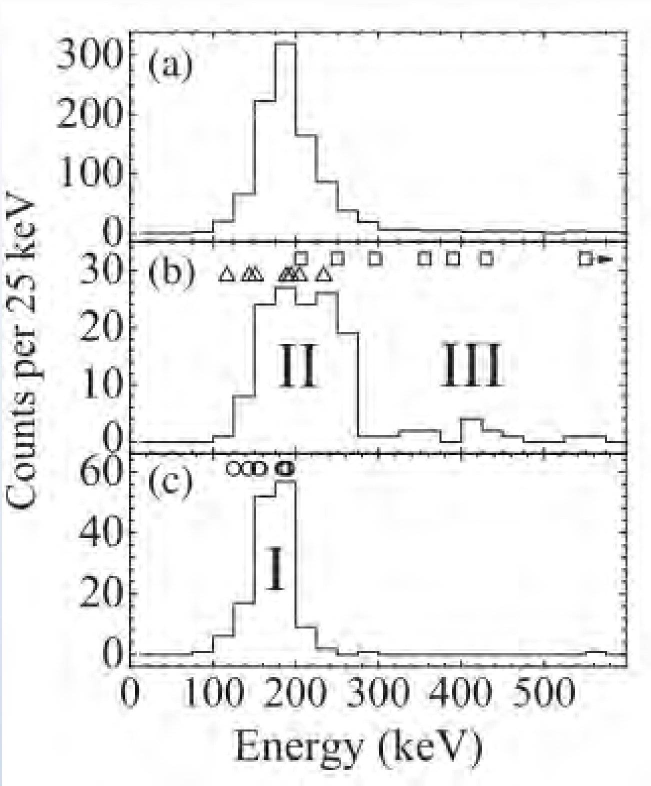
Energy spectrum of alpha particles
Herzberg *et al.*, PRC **65** (2001) 014303



^{252}No level scheme
Sulignano *et al.*, PRC **86**, 044318 (2012)

^{256}Rf (Z = 104, N = 152)

- Three isomeric states identified, interpreted as multi-quasiparticle isomers (LBNL) [1]
  Recoil-electron-electron-electron-fission events observed



Sum energy spectra of a) r-**e**-f, b) r-**e**-e-f
and c) r-e-**e**-f events [1]

Lowest isomer interpreted as K = 6 or 7,
second lowest K = 10-12

Third suggested as 4qp

Assignments reinterpreted after 3qp observed in ^{257}Rf, suggesting 2 quasiproton $K^{\pi} = 5^{-}$ for lowest state, decays to $K^{\pi} = 2^{-}$ octupole band [2]

[1] Jeppesen *et al.*, Phys Rev C **79** (2009) 031303(R)
[2] Rissanen *et al.*, PRC **88** (2013) 044313

Recoil-decay technique

Heavy-ion fusion evaporation reactions

In-beam gamma-rays detected at target position

Separator to disperse recoiling reaction products

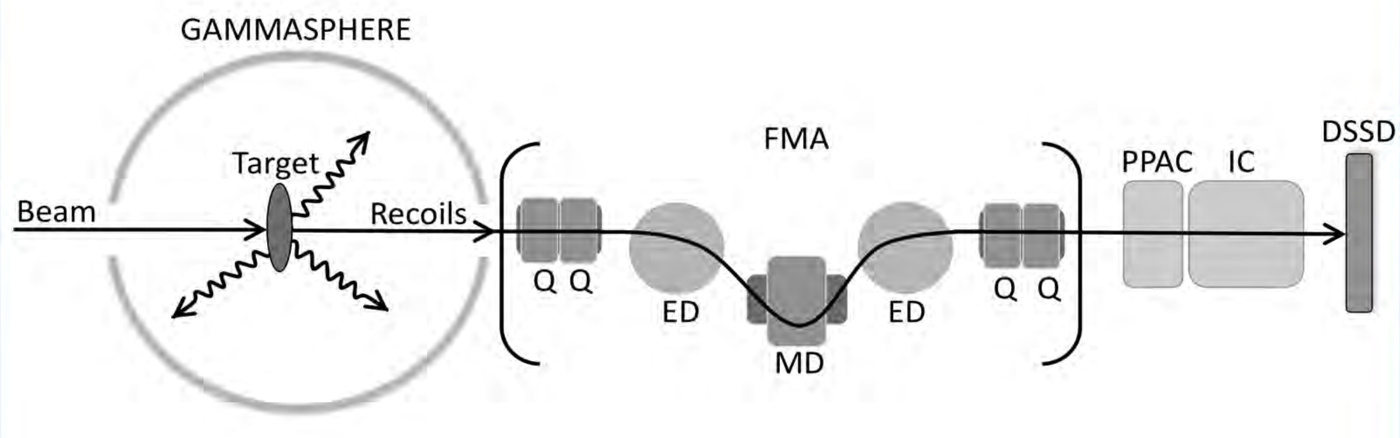
Recoils implanted into segmented Si detector

Position and time of subsequent decay recorded

Correlations between implanted recoils and decay

Developed to provide selectivity on weak reaction channels [1,2]

- α and p decay, β-delayed particle emission
- Later development of recoil-beta-tagging (RBT) [3,4]
- Recoil-fission correlations used extensively as spectroscopic tool



[1] Simon *et al*., Z. Phys. A **325** (1986) 197-202
[2] Paul *et al.*, Phys. Rev. C **51** (1995) 1
[3] Steer *et al.*, NIM A **565** (2006) 630-636
[4] Nara Singh *et al.,* Phys. Rev. C **75** (2007) 061301(R)

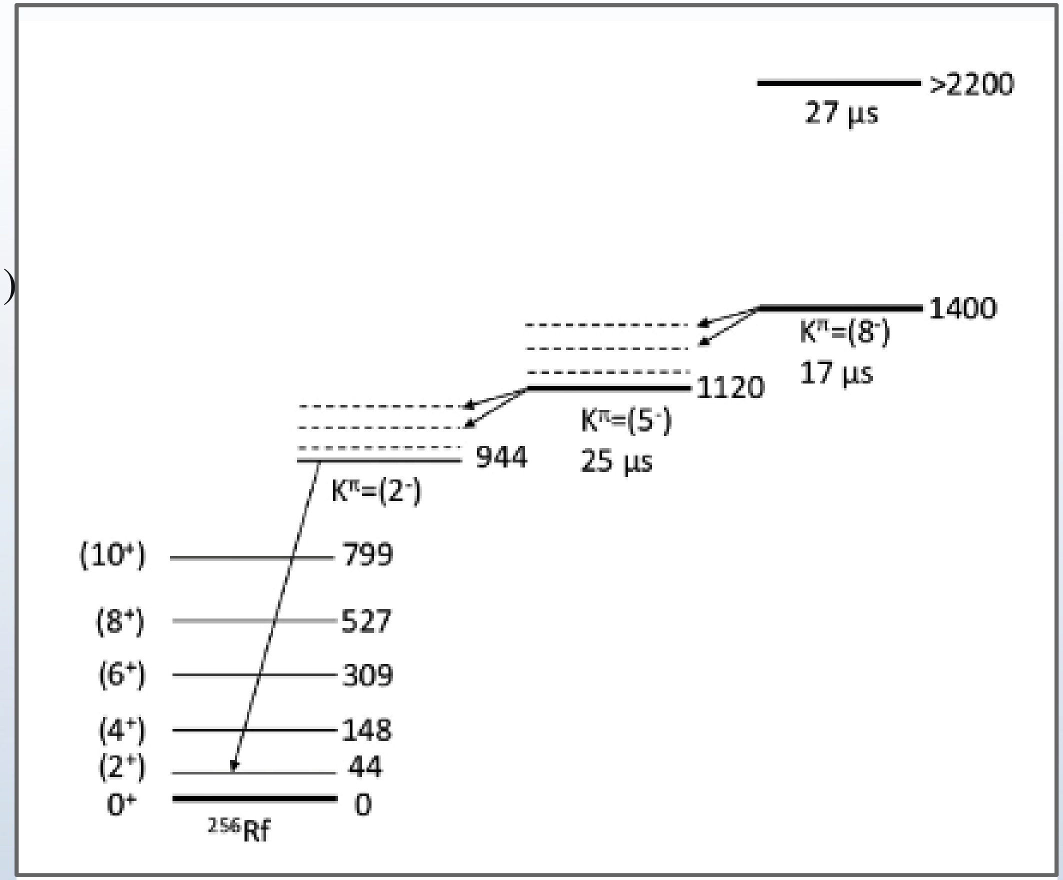
Lifetime of 2qp state

- 2qp isomer decays **four orders of magnitude** faster than those observed in N = 150 isotones (which decay to K = 2 octupole band)

- Possible explanation:
  - Fast isomer is $5^{-}\pi^{2}(1/2[521] \otimes 9/2[624])$

  This would result in a $\Delta K = 3$, not $\Delta K = 6$ transition

- Proposed explanation for a K isomer in ^{256}Rf [1] where an enhanced transition probability was observed

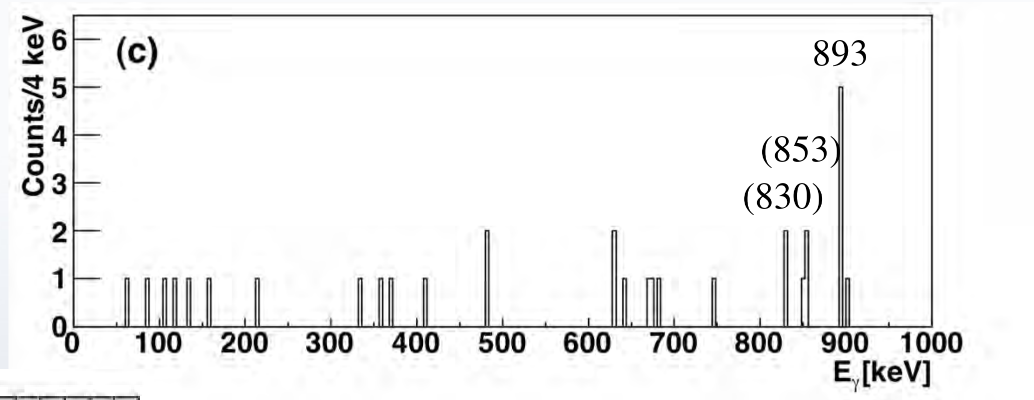


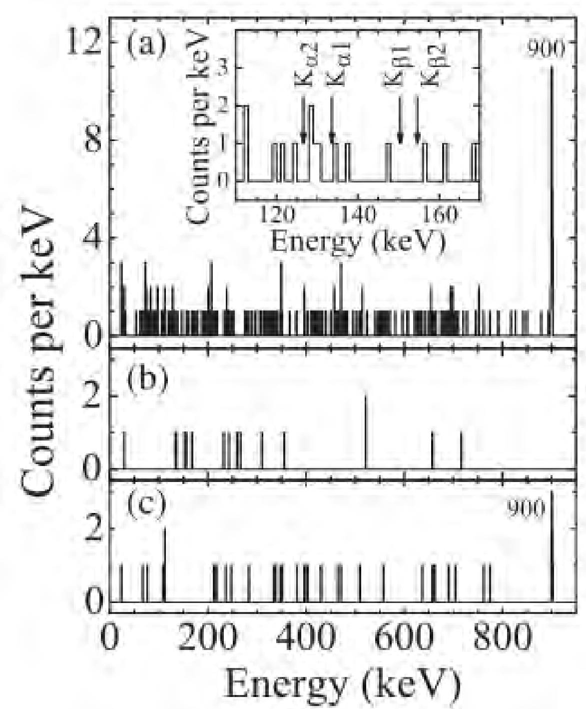
Level scheme of ^{256}Rf proposed in [1]

[1] Rissanen *et al.*, PRC **88**, (2013) 044313

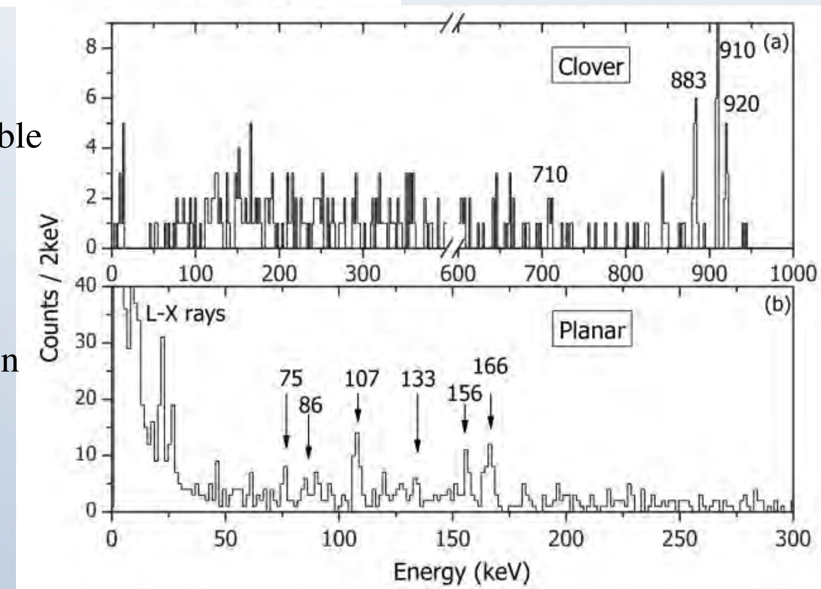
Lifetime of 2qp state

- Another possible explanation:
  - Accidental mixing between K = 8^-, 2qp isomer and 8- state of K = 2^- octupole band
  - Such bands identified in nearby N = 150 isotones ^{252}No and ^{250}Fm





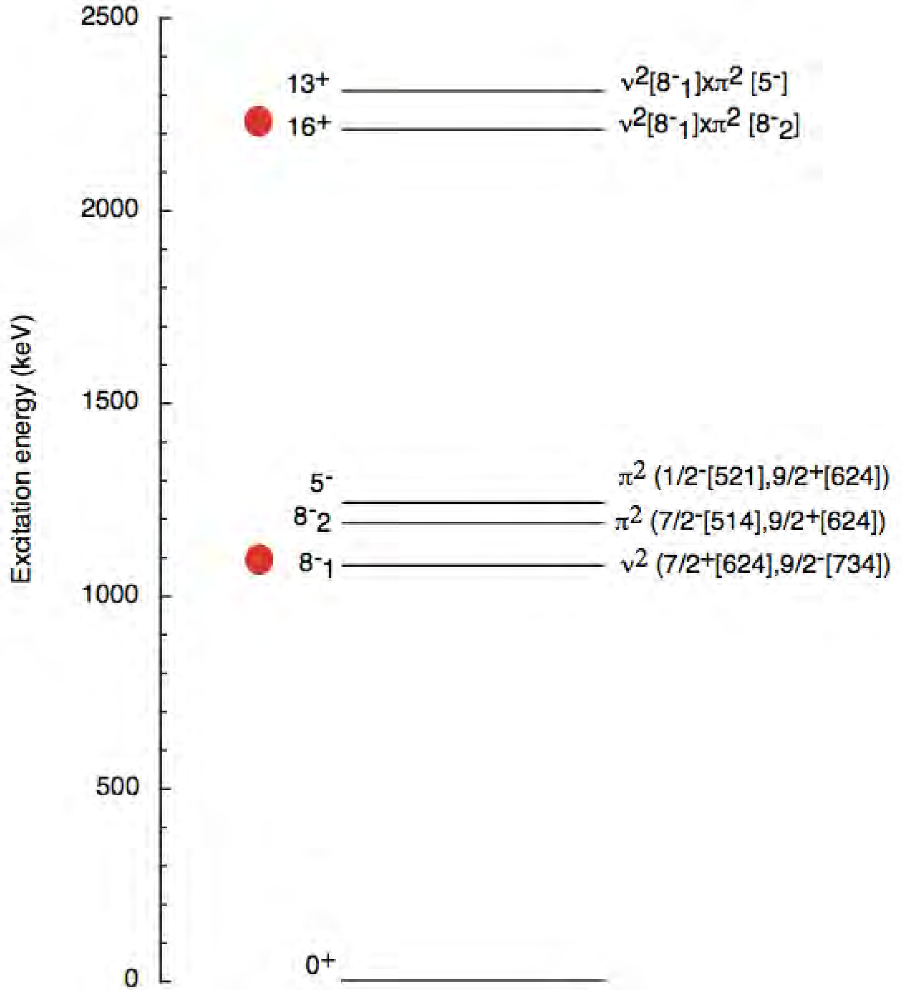
- Gamma-ray spectrum comparable to that of 2qp isomer in ^{252}No
- No single strong transition, as in ^{256}Rf
- Supports mixing scenario



Gamma rays coincident with electrons from 2qp isomer in ^{252}No

Jeppeson *et al.*, PRC **79**, (2009) 031303(R)

Sulignano *et al.*, PRC **86**, (2012) 044318



- Calculated multi-quasiparticle states in ^{254}Rf [1]
- Most likely candidate for 2qp isomer is two quasineutron configuration, in agreement with results
- $K^{\pi} = 5^{-}$ state predicted ~150 keV higher in energy than $K^{\pi} = 8^{-}$; would need to invoke sudden deformation change to invert the ordering

- Includes pairing-blocking, using Lipkin-Nogami approach
- Single-particle states adjusted to reproduce known 1qp states in neighbors
- Residual interaction accounted for as in [2]

[1] Kondev, Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, EDP Sciences, 2008 p. 61
[2] Jain *et al.*, Phys. Lett. B **322** (1994) 27