Alpha Decay and Fission of K-Isomers

Rod Clark

Outline

Introduction

Alpha Decay

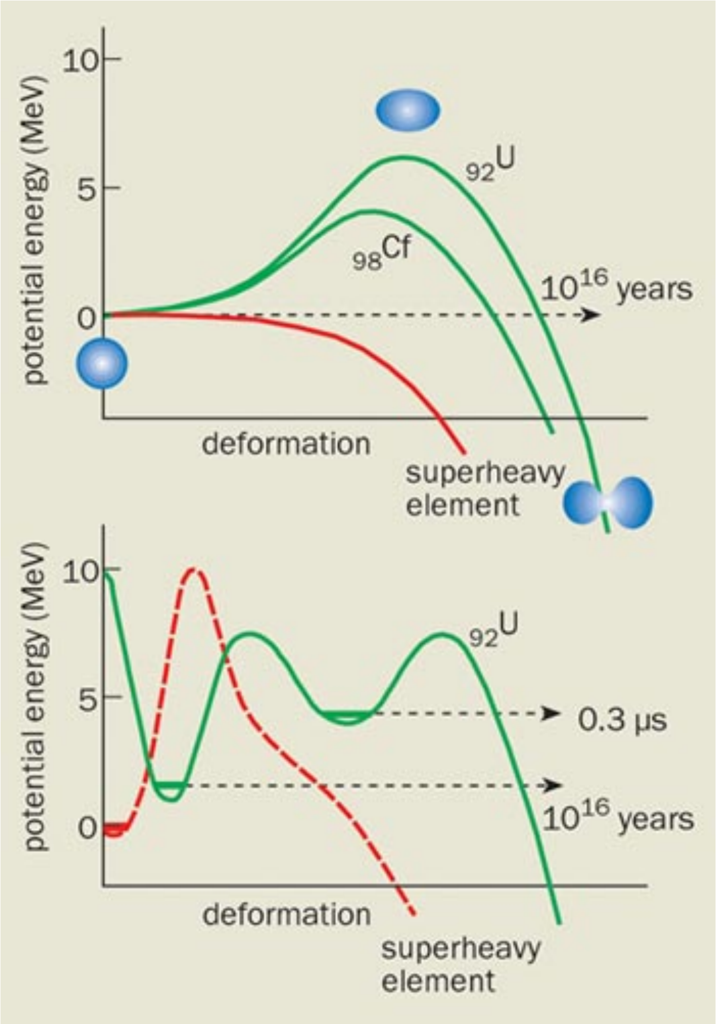
- stability of excited metastable states
- superfluid tunneling model
- role of pairing, excitation energy, angular momentum

Fission

- stability against fission
- hindrances of K-isomers
- expectations for hindrance factors

A look to the future

Super-heavy Nuclei



Y. Oganessian, Physics World, July 2004

1) What are the “magic numbers” for the spherical super-heavy nuclei?

➔ Locating the center of the “island of stability”

2) What are the magnitudes of the shell effects?

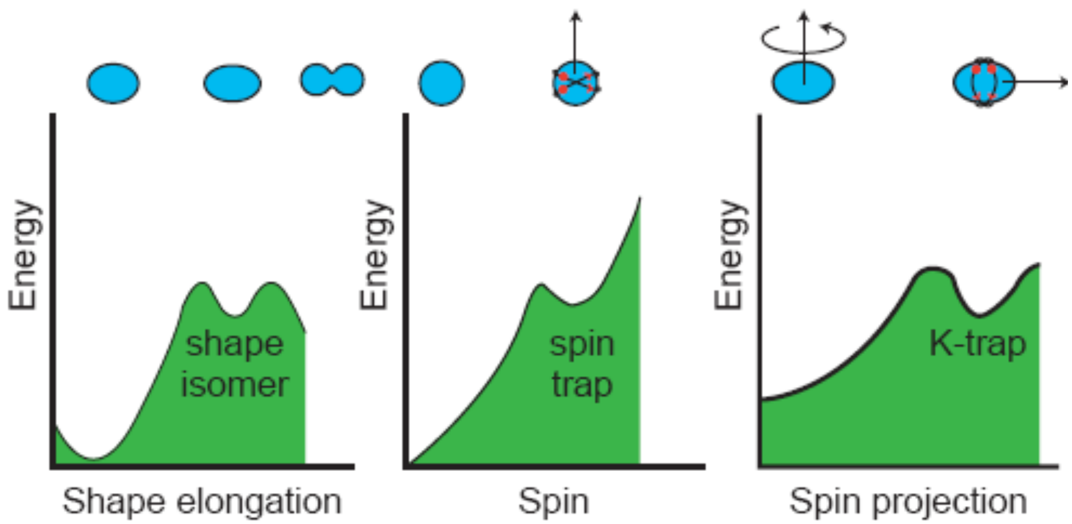
➔Extent and relative stability of island

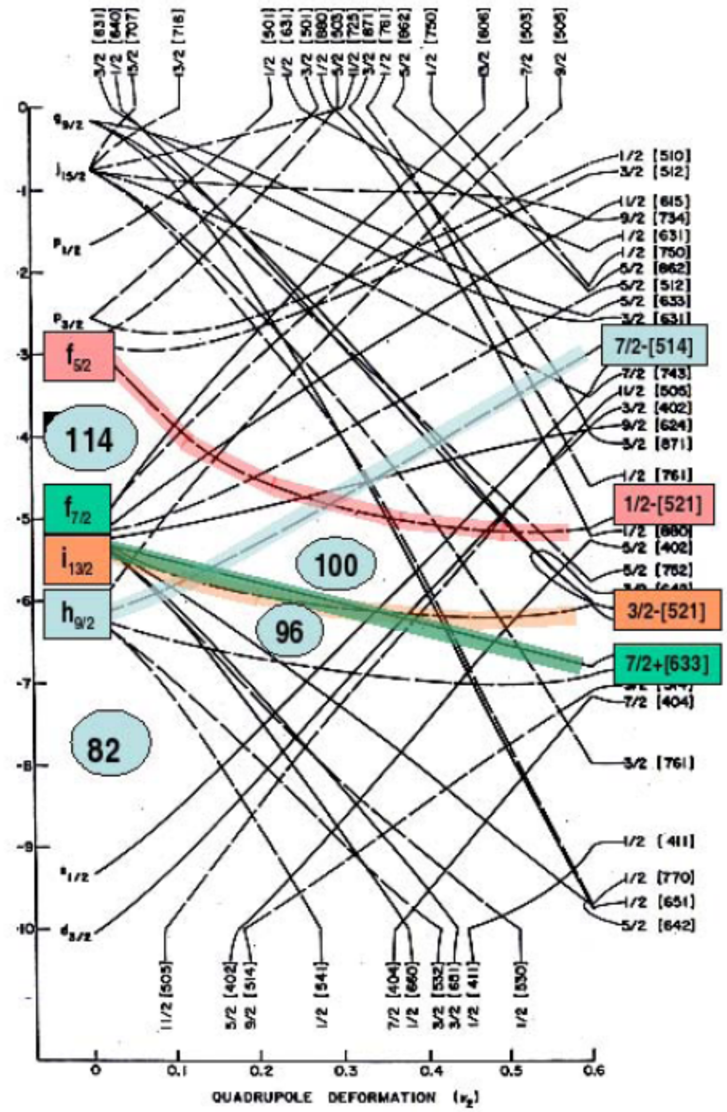
Key Experimental Information:

- single-particle structure
- stability against alpha decay
- stability against fission

Structure Studies of the Heaviest Nuclei

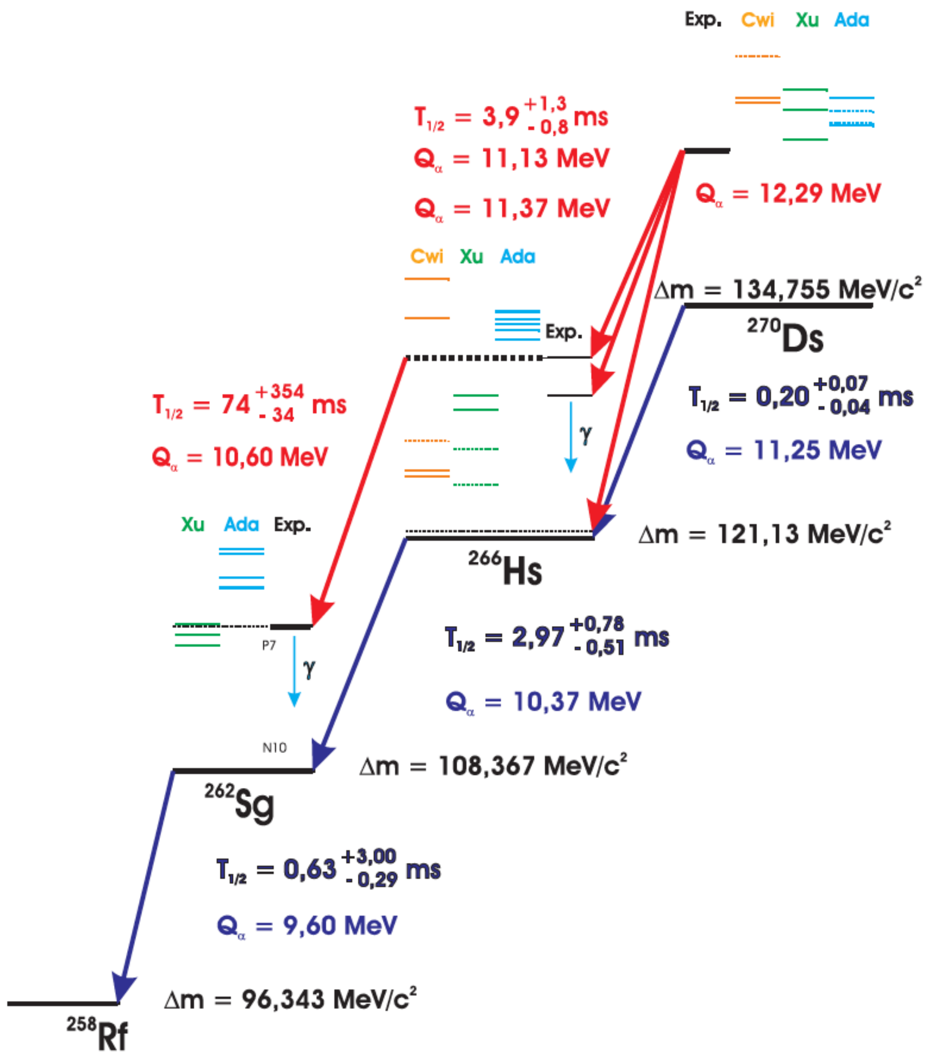
- Single-particle levels → shell structure
  - Next major spherical gaps
  - Deformed gaps
- Deformation and collectivity
  - Meta-stable states
  - Rotation and vibration
  - Pairing (superfluidity)





Alpha Decay

Alpha Decay of K-Isomers: ^{270}Ds



Observation of alpha-decaying K-isomers with half-lives significantly longer than the ground state.

Implications for stability/survivability

Three major factors influencing alpha decay multi-QP states:

- Larger Q_α means shorter $T_{1/2}$
- Large ΔL means longer $T_{1/2}$
- Reduced pairing means longer $T_{1/2}$

Superfluid tunneling model used to estimate influence of these factors on alpha decay of multi-QP states.

J. Rissanen et al., PRC 90 044324 (2014)
R.M. Clark and D. Rudolph, PRC 97 02433 (2018)

S. Hofmann et al., Eur. Phys. J. A 10 5 (2001), D. Ackermann, Prog. Theor. Phys. Suppl. 196 255 (2012)

Superfluid Tunneling Model (STM)

The Hamiltonian of the model is:

$$\left[-\frac{\hbar^2}{2D}\frac{\partial^2}{\partial\xi^2}+V(\xi)\right]\psi_n(\xi)=E_n\psi_n(\xi)$$

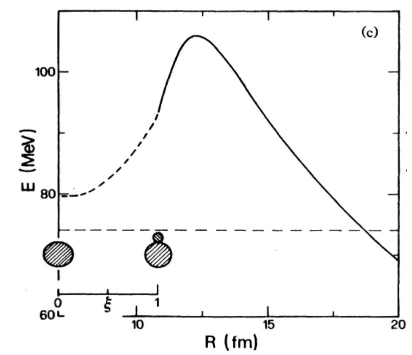
ξ = generalized deformation variable
D = inertial mass (depends on Δ)

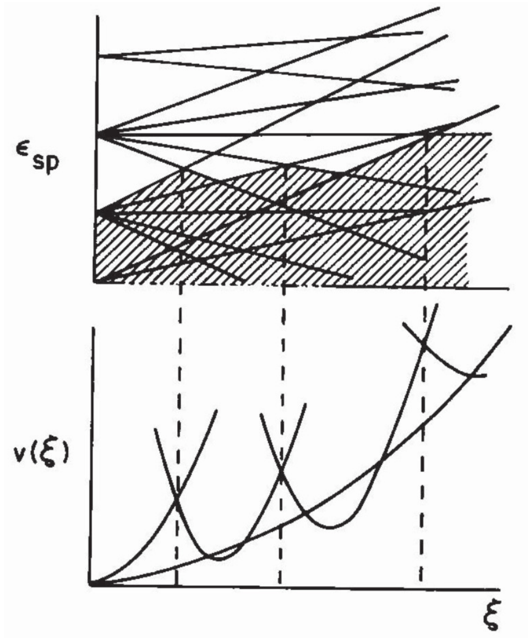
Calculation of decay constant:
λ = f . P . T

P= preformation of decay configuration
f = frequency of hitting barrier
T = transmission coefficient through barrier

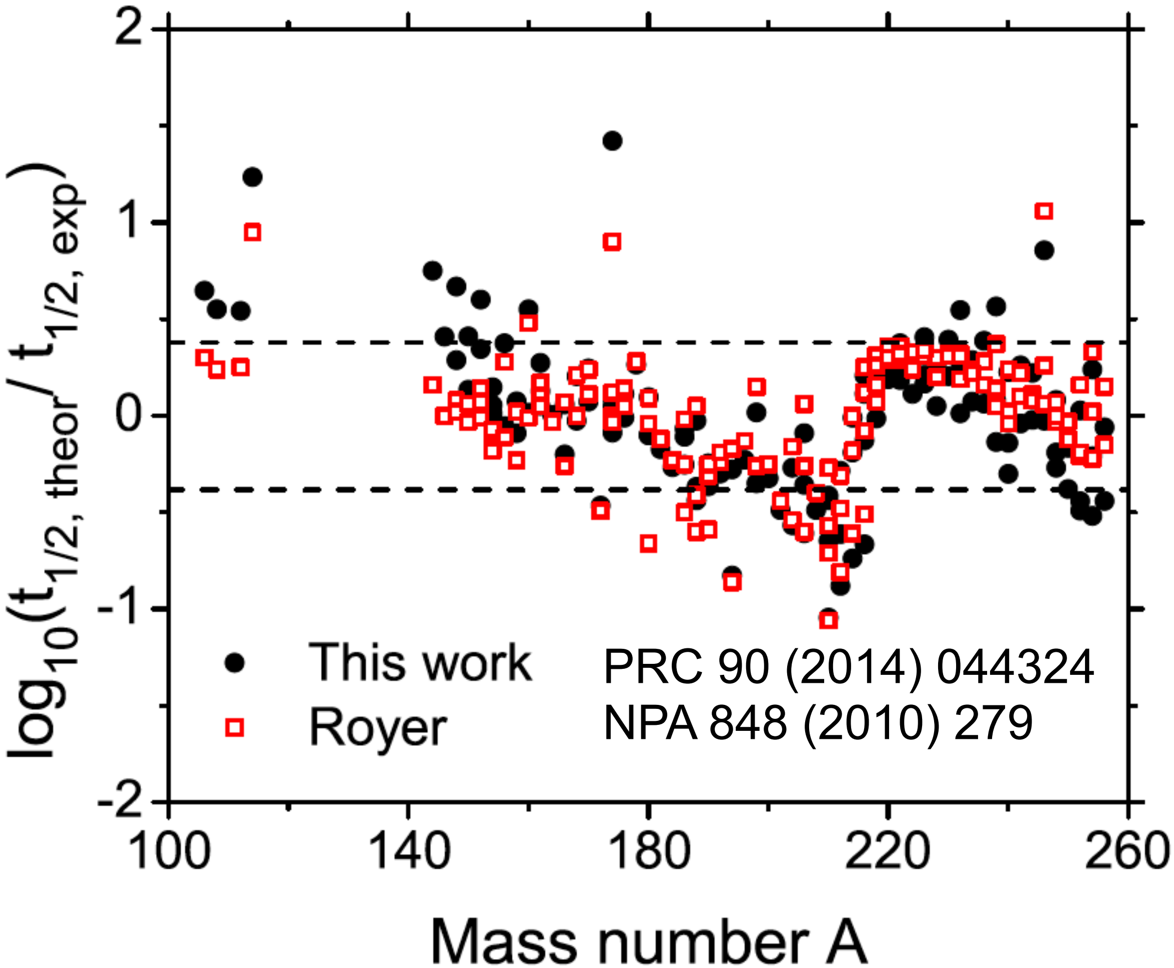
"Nuclear Superfluidity: Pairing in Finite Systems"
David M. Brink and Ricardo A. Broglia
Cambridge University Press, 2005

F. Barranco, G.F. Bertsch, R.A.Broglia, E.Vigezzi,
NPA 512 253 (1990)



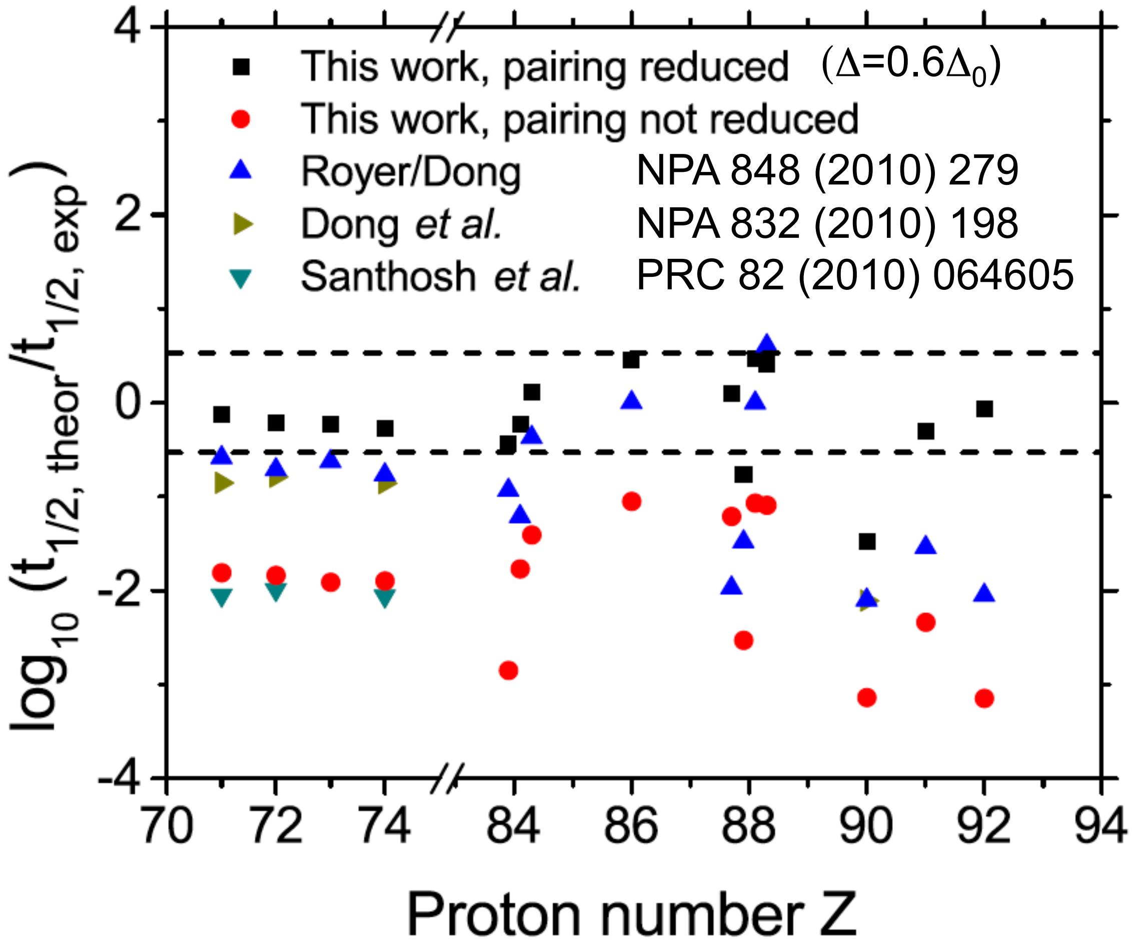


Reproducing Ground State Alpha Decays



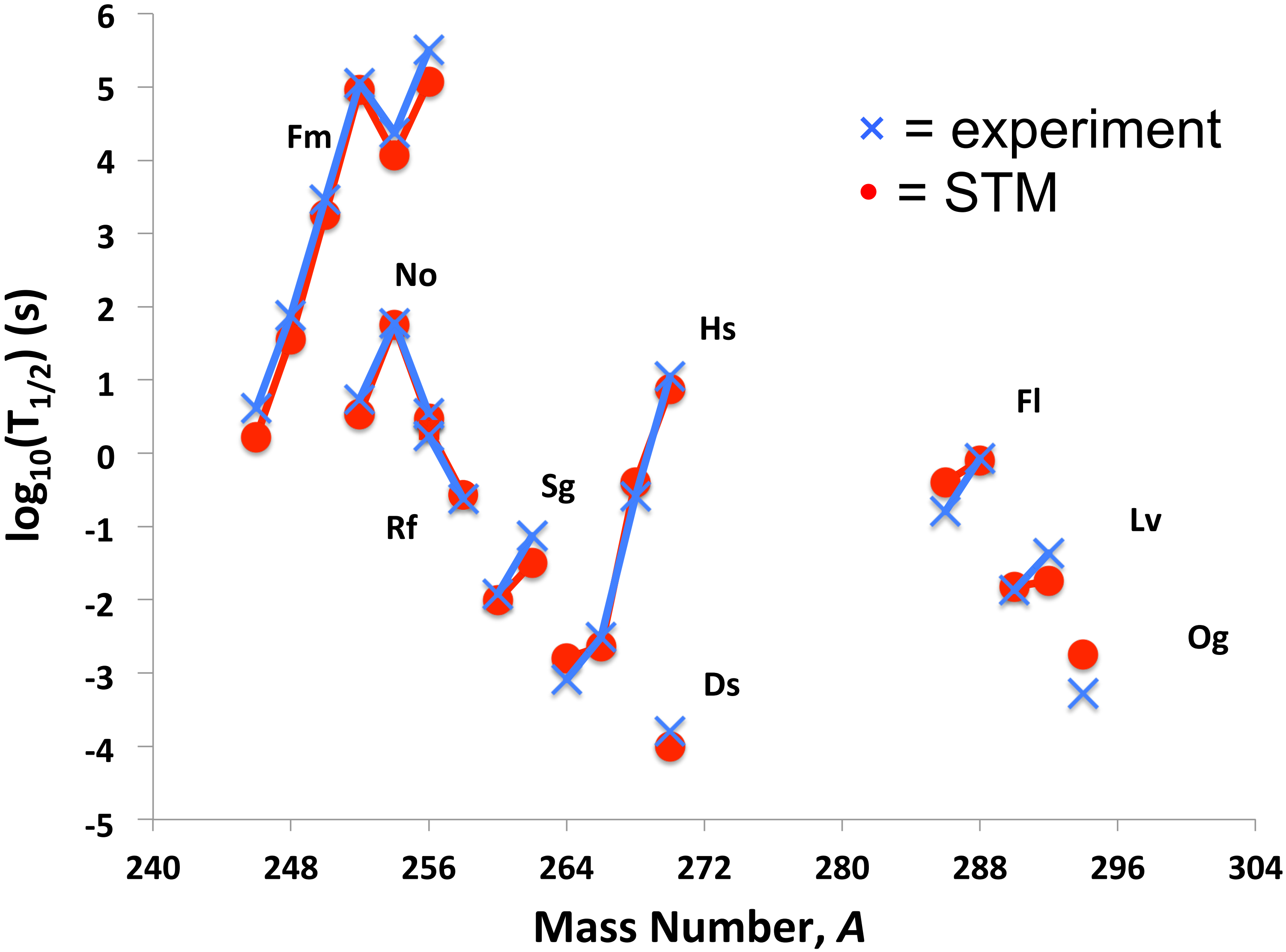
Pair gap, Δ, optimized to reproduce experimental half-lives of even-even ground-state to ground-state alpha decays. In red are the estimates from a semi-empirical formula.

Alpha Decay Half-lives for Multi-QP Isomers

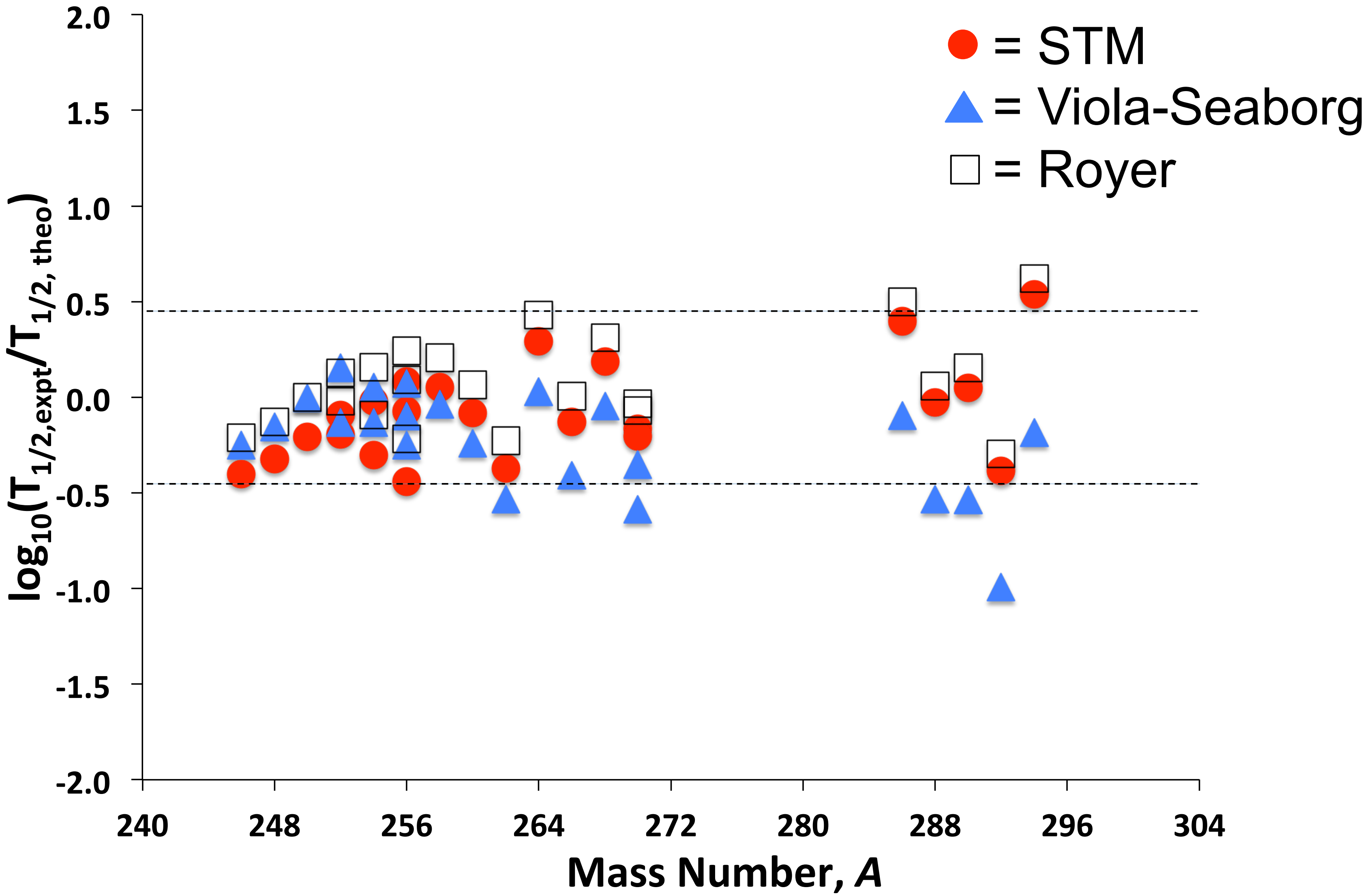


A single pairing reduction factor of 0.6 seems able to reproduce all of known data.

Alpha Decay of Even-Even Isotopes: Fm to Og

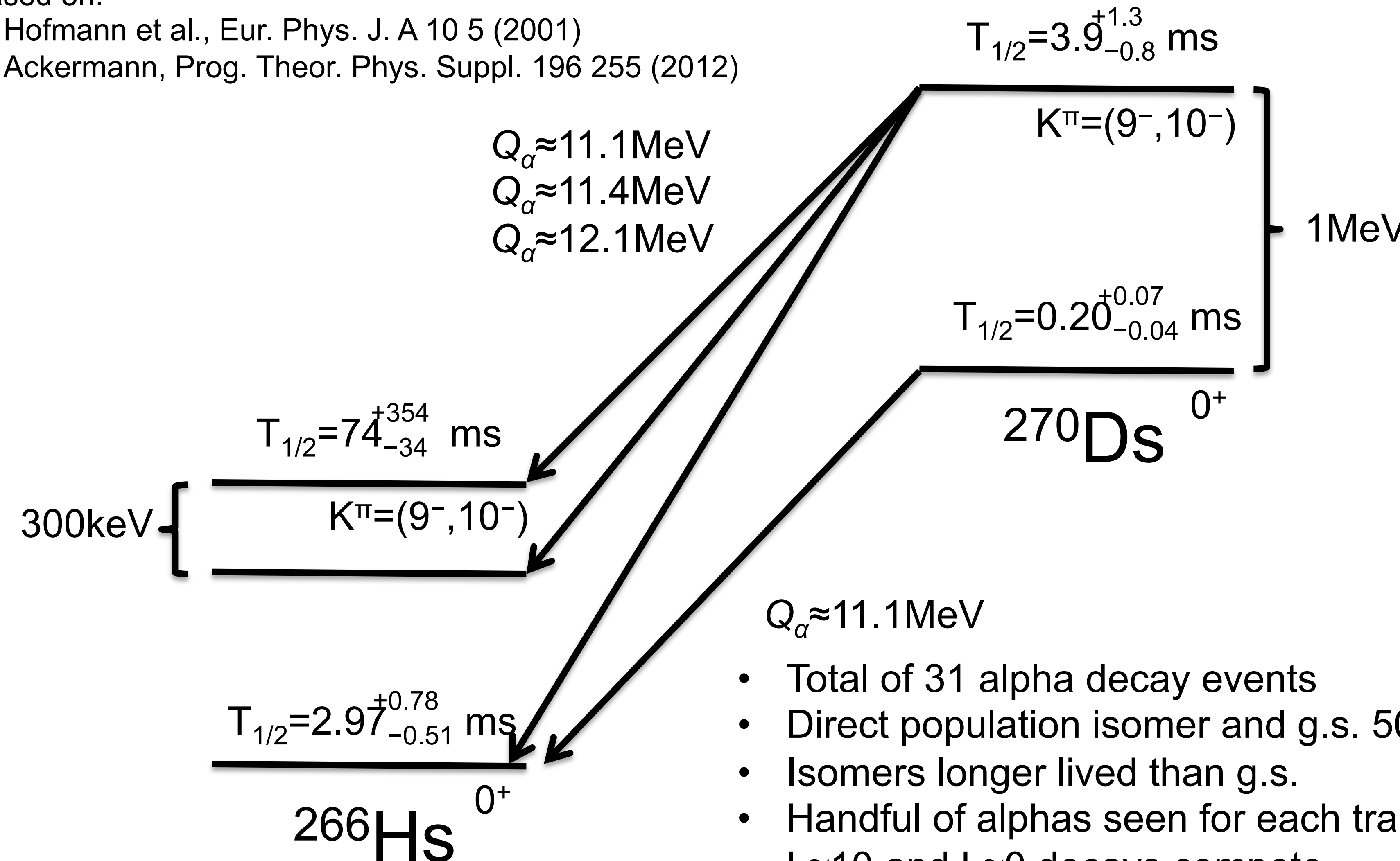


Reproducing Ground State Alpha Decays of SHN



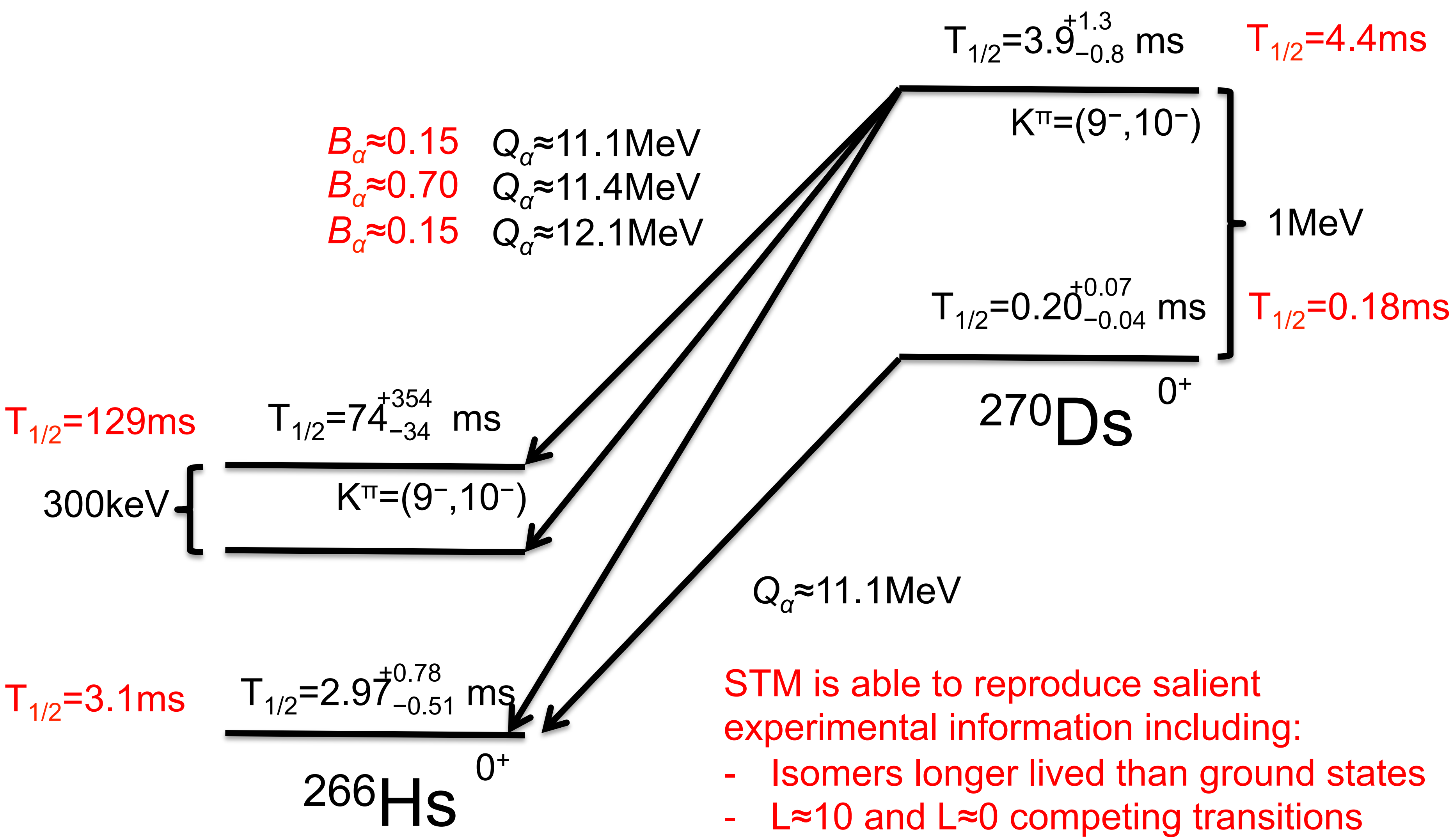
Alpha Decay of K Isomers in ^{270}Ds: Experiment

Based on:
S. Hofmann et al., Eur. Phys. J. A 10 5 (2001)
D. Ackermann, Prog. Theor. Phys. Suppl. 196 255 (2012)



- Total of 31 alpha decay events
- Direct population isomer and g.s. 50:50
- Isomers longer lived than g.s.
- Handful of alphas seen for each transition
- L≈10 and L≈0 decays compete

Reproducing Alpha Decays of K Isomers in ^{270}Ds

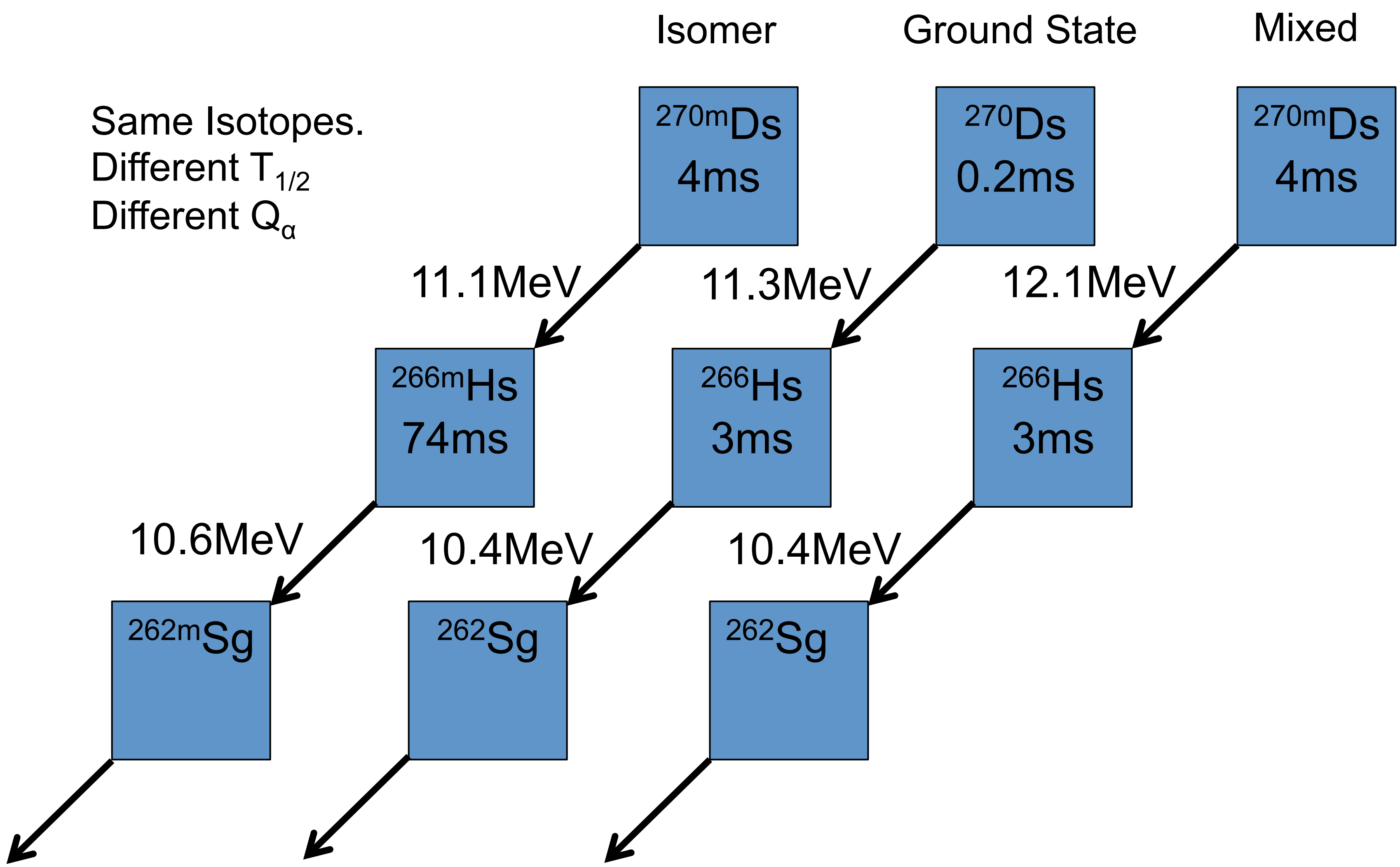


STM is able to reproduce salient experimental information including:

- Isomers longer lived than ground states
- L≈10 and L≈0 competing transitions

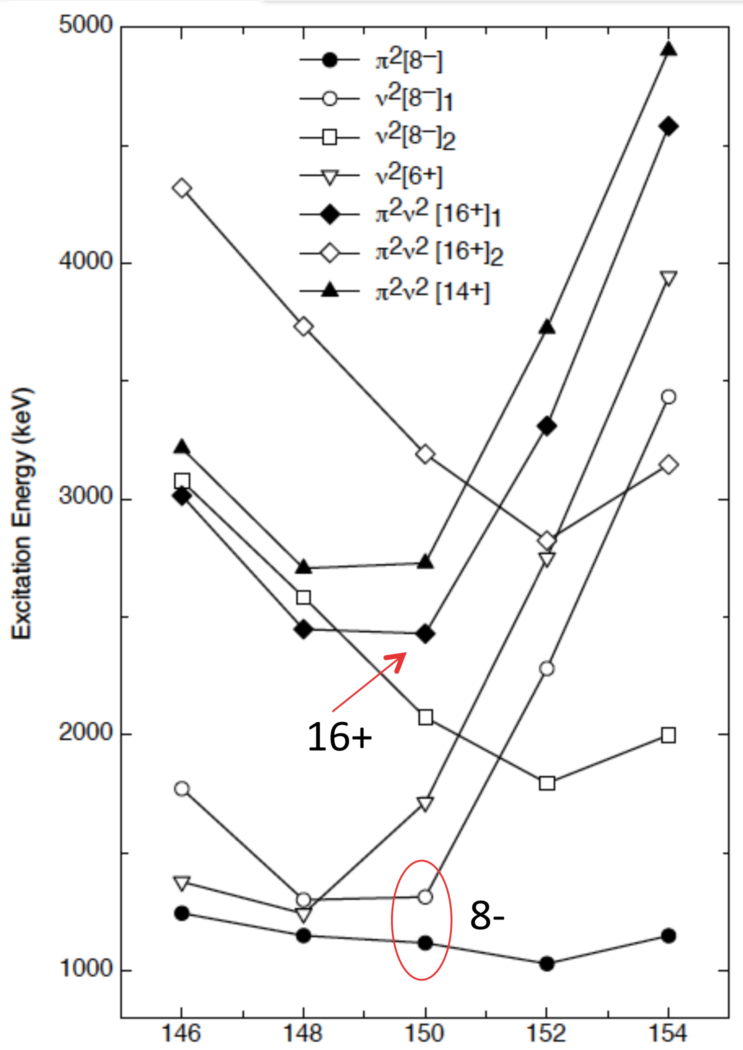
Ambiguities in Decay Chains

Same Isotopes.
Different $T_{1/2}$
Different Q_{α}



Fission

K-Isomers and Fission: ^{254}Rf



Ground-state decay mode is 100% SF with half-life of ~23μs.

Possibility of long-lived isomers that may also have significant SF branch?

Woods-Saxon calculations with universal parameterization.

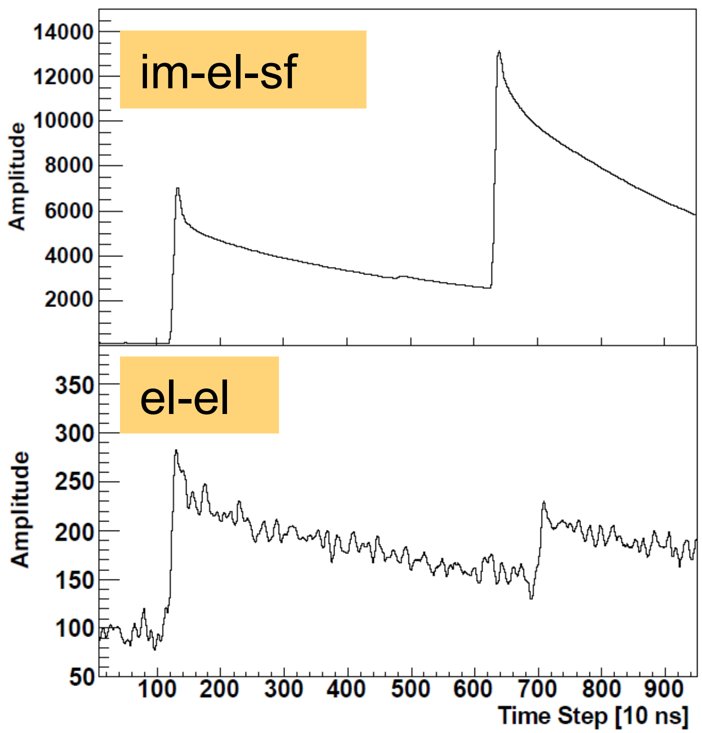
Lipkin-Nogami pairing method.

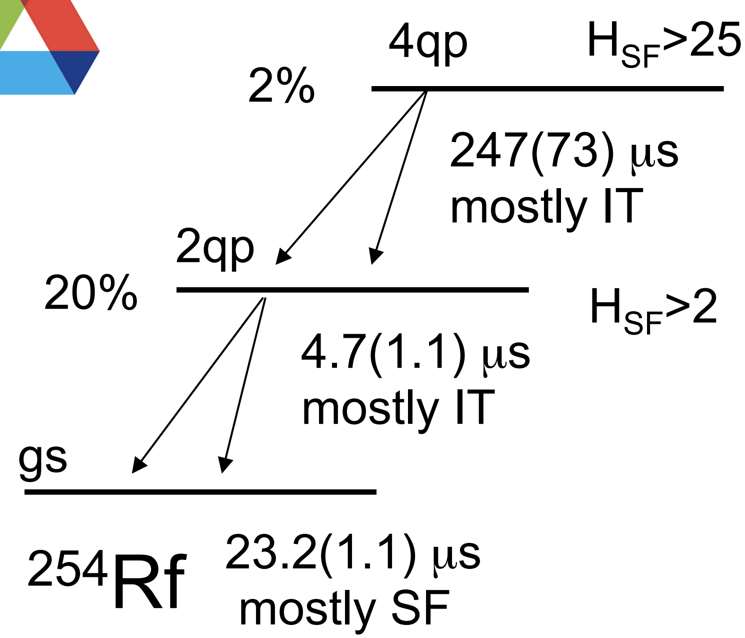
Prediction of competing $K^{\pi}=8^-$ 2 quasi-particle configurations:
$\nu^2 8^-_1$: ν^2(7/2[624]×9/2[734])
$\pi^2 8^-_2$: π^2(7/2[514]×9/2[624])

Low-lying $\nu^2 8^-_1 \times \pi^2 8^-_2$, $K^{\pi}=16^+$ 4qp state

F.G, Kondev et al., Int. Conf. Nuclear Data for Science and Technology, Nice, France, 2007

^{254}Rf Experiment at LBNL





- High Intensity ^{50}Ti beam from 88-Inch, high efficiency of BGS, ANL digital daq
- Compared to lighter N=150 isotones 2qp isomer decay is x10^4 faster
- No fission observed from the isomers: fission partial lifetimes are at least 2 and 25 longer for 2qp and 4qp isomers, respectively, relative to the gs

H.M.David et al., Phys. Rev. Lett. 115 132502 (2015)

^{254}Rf Results

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]

[1]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[4]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[5]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[6]*Department of Nuclear Physics, R.S.P.E., Australian National University, Canberra A.C.T. 2601, Australia*
[7]*Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*
[8]*United States Naval Academy, Annapolis, Maryland 21402, USA*
[9]*CSNSM, IN2P3-CNRS, F-91405 Orsay Campus, France*
[10]*Department of Physics, University of Massachusetts, Lowell, Massachusetts 01854, USA*

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Two isomers decaying by electromagnetic transitions with half-lives of 4.7(1.1) and 247(73) μs have been discovered in the heavy ^{254}Rf nucleus. The observation of the shorter-lived isomer was made possible by a novel application of a digital data acquisition system. The isomers were interpreted as the $K^\pi = 8^-, \nu^2(7/2^+[624], 9/2^-[734])$ two-quasineutron and the $K^\pi = 16^+, 8^-\nu^2(7/2^+[624], 9/2^-[734]) \otimes 8^-\pi^2(7/2^-[514], 9/2^+[624])$ four-quasiparticle configurations, respectively. Surprisingly, the lifetime of the two-quasiparticle isomer is more than 4 orders of magnitude shorter than what has been observed for analogous isomers in the lighter $N = 150$ isotones. The four-quasiparticle isomer is longer lived than the ^{254}Rf ground state that decays exclusively by spontaneous fission with a half-life of 23.2(1.1) μs. The absence of sizable fission branches from either of the isomers implies unprecedented fission hindrance relative to the ground state.

Expectations of Fission Hindrance

- The excitation energy of the high-K 2-qp isomer is ~1 MeV (or the fission barrier height, B_f, is ~ 1MeV less for the isomer relative to the ground state).

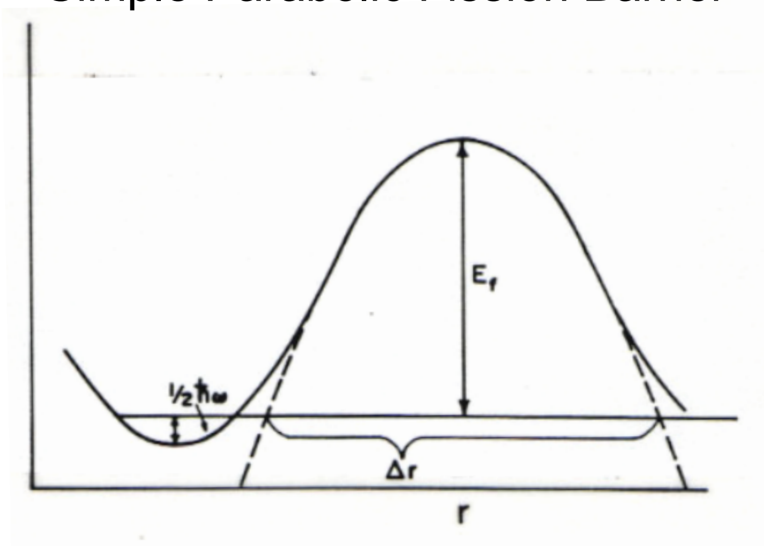
This will result in a shorter fission half-life

- The high-K state will involve broken pairs and it could “look” more like the configuration of the ground state of the odd-odd neighbor

This will result in a longer fission half-life

The Effect from Changing B_f

Simple Parabolic Fission Barrier



R. Vandenbosch and J.R. Huizenga, Nuclear Fission, Academic Press 1973

Loveland, Morrissey, and Seaborg, Nuclear Chemistry, Wiley and Sons 2006

The fission half life can be expressed as:

$$t_{1/2}=2.77\times10^{-21}\exp[2\pi(B_f)/\hbar\omega]$$

Barrier height, Bf = 6 MeV

Barrier curvature = 0.5 MeV

➔ $t_{1/2} = 1.5 \times 10^{12}$ s

Barrier height, Bf = 5 MeV

Barrier curvature = 0.5 MeV

➔ $t_{1/2} = 5.4 \times 10^{6}$ s

One expects the decay of the isomer to be ~3×10^{5} faster

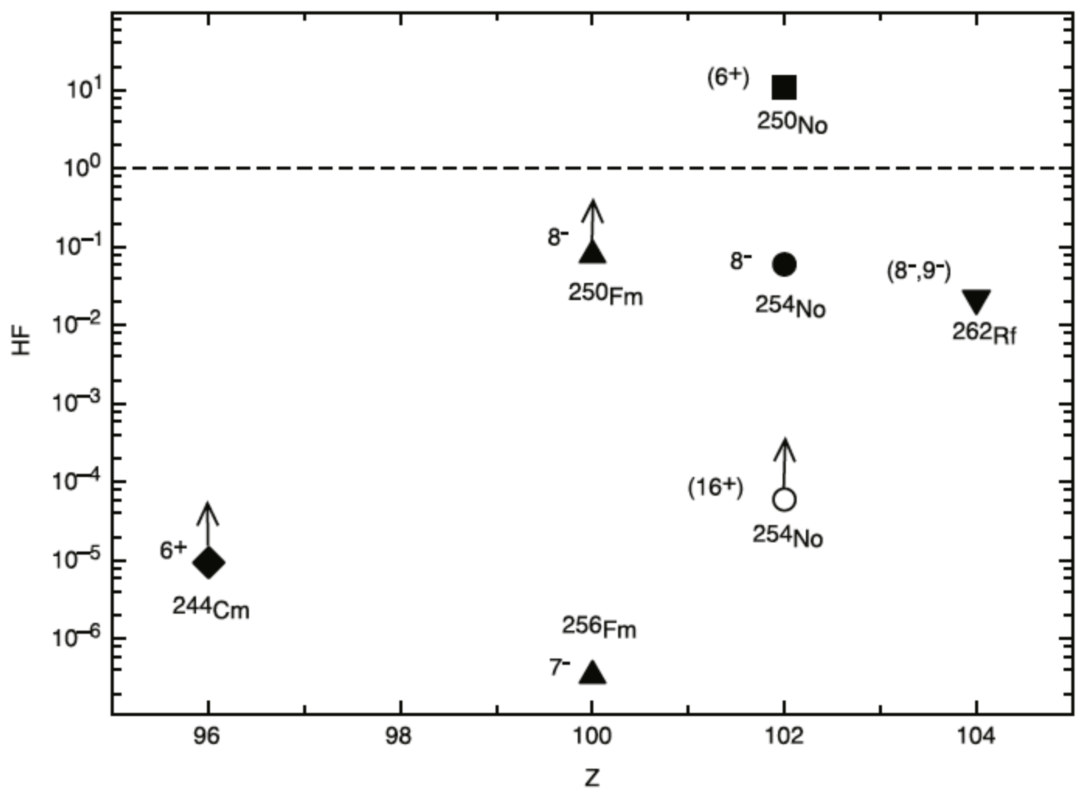
The Effect from Odd-Odd Character

$^{255}_{105}Db_{150}$ ~20% SF, $t_{1/2}$=1.6(5)s HF=3.5×10^5	$^{256}_{105}Db_{151}$ ~0.02% SF, $t_{1/2}$ = 1.9(4)s HF=4.1×10^8
$^{254}_{104}Rf_{150}$ ~100% SF, $t_{1/2}$=23(3)μs	$^{255}_{104}Rf_{151}$ ~48% SF, $t_{1/2}$=2.3(7)s HF=2.1×10^5

One expects the decay of the isomer to be ~4×10^8 slower due to odd particles

Fission Hindrances of Multi-QP Isomers

I'd expect K-isomer HF~10^3-10^5



F.G.Kondev, G.D.Dracoulis, T.Kibedi,
Atomic Data and Nuclear Data Tables 103-104 (2015) 50

Changing B_f by 1MeV gives HF of ~10^{-5}

Odd-Odd "character" gives HF of ~10^8-10^{10}

Available data does not indicate such hindrances

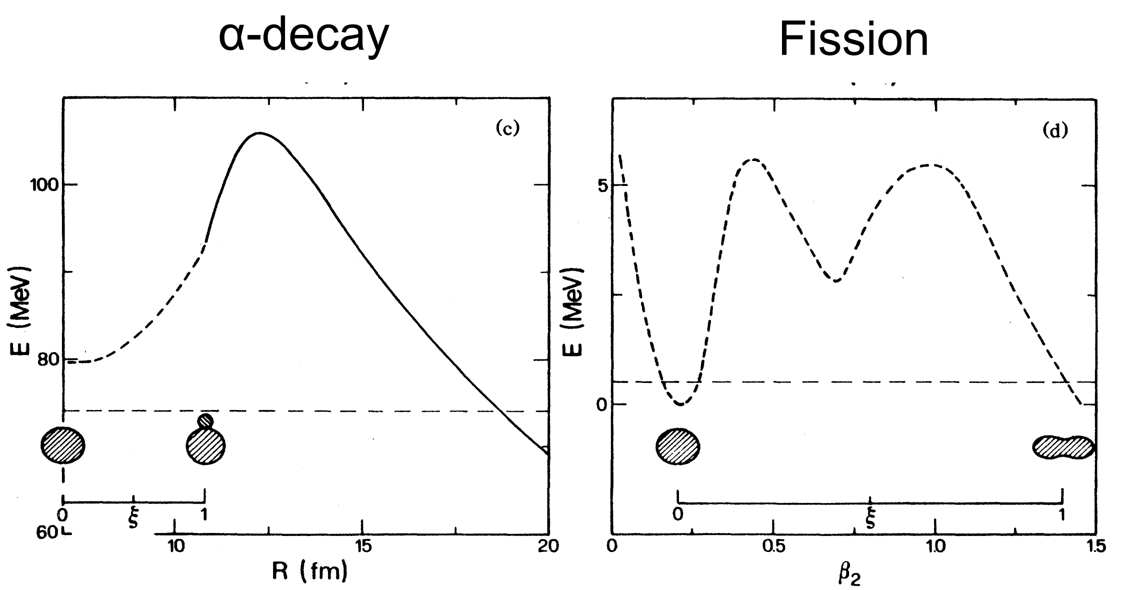
^{244}Cm, ^{250}Fm, ^{254}Rf all lower limits (no positive identification of a fission branch from isomer).

^{250}No story changing (EM-decay branch reported at TAN15)

^{262}Rf likely misassigned
(M. Murakami et al., PRC 88 (2013) 024618)

Leaves ^{256}Fm and ^{254}No cases needing to be confirmed

Description of Fission with STM



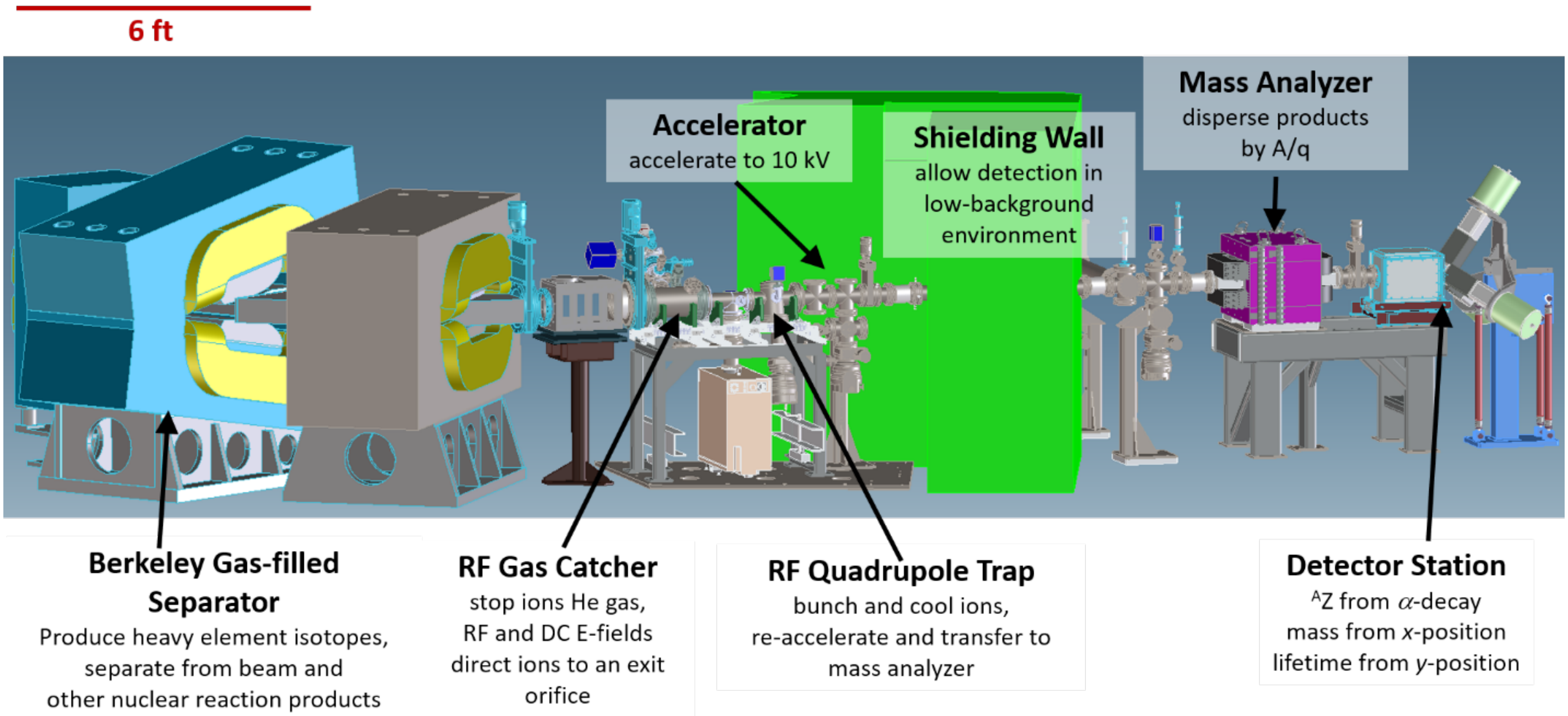
Decay	$\lambda_{exp}(s^{-1})$	$\lambda_{th}(s^{-1})$	n_{step}
^{4}He	9.0×10^{-14}	2.0×10^{-14}	4
^{24}Ne	6.3×10^{-26}	1.0×10^{-28}	19
^{28}Mg	2.0×10^{-26}	2.0×10^{-28}	23
Spontaneous fission	1.2×10^{-24}	5.0×10^{-24}	52

Decay modes of ^{234}U

F. Barranco, E. Vigezzi, R.A. Broglia, PRC 39 2101 (1989)

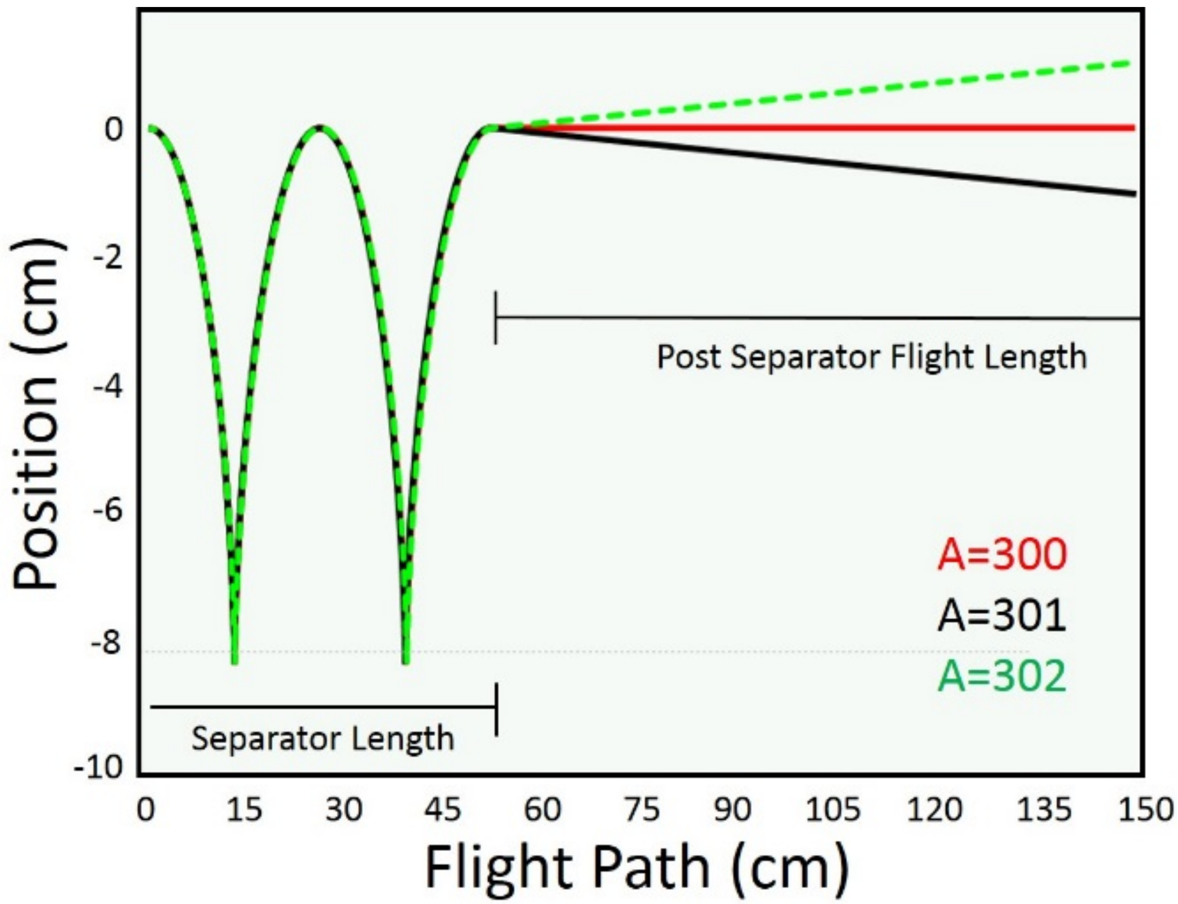
Experimental Prospects at LBNL: FIONA

Low energy (~ few keV), mass-separated isotopes delivered to low-background area on a timescale of ~10 ms.

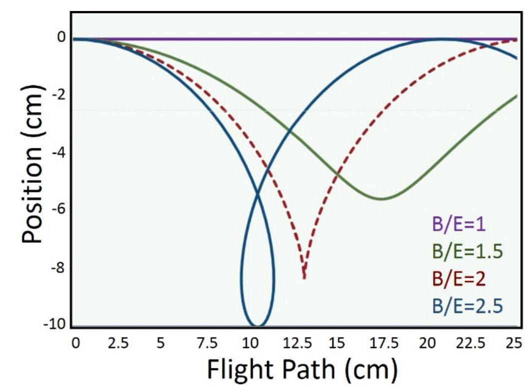


J.M.Gates, K.E.Gregorich et al., NIM A (to be published).

ExB Mass Analyzer



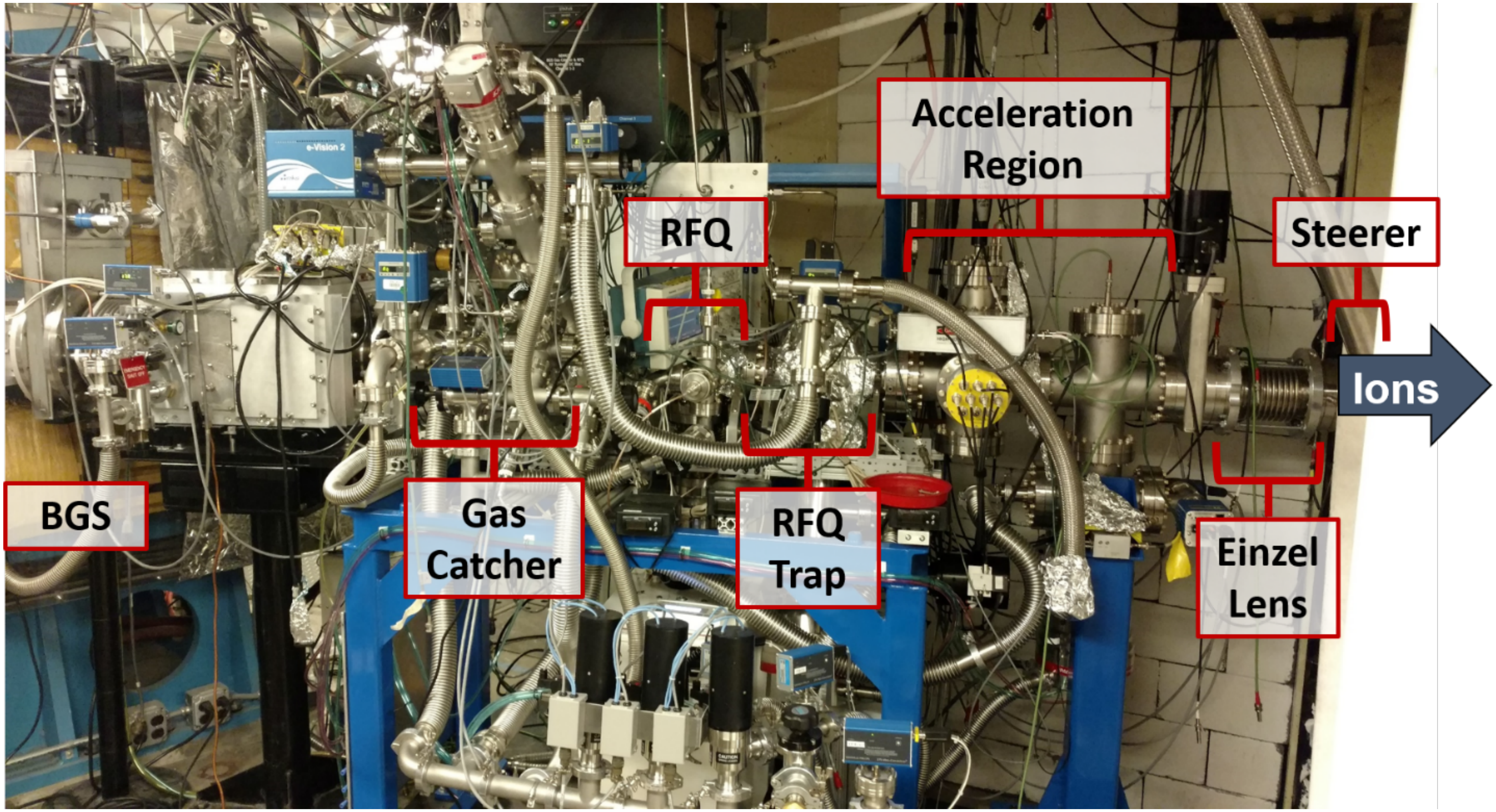
Trochoid spectrometer:
Perpendicular electric and magnetic fields that are unbalanced → ions take trochoidal trajectories



Pitch of each loop is related to *A/q*
Different *A/q* ratios exit with different angles and are separated after a short flight path

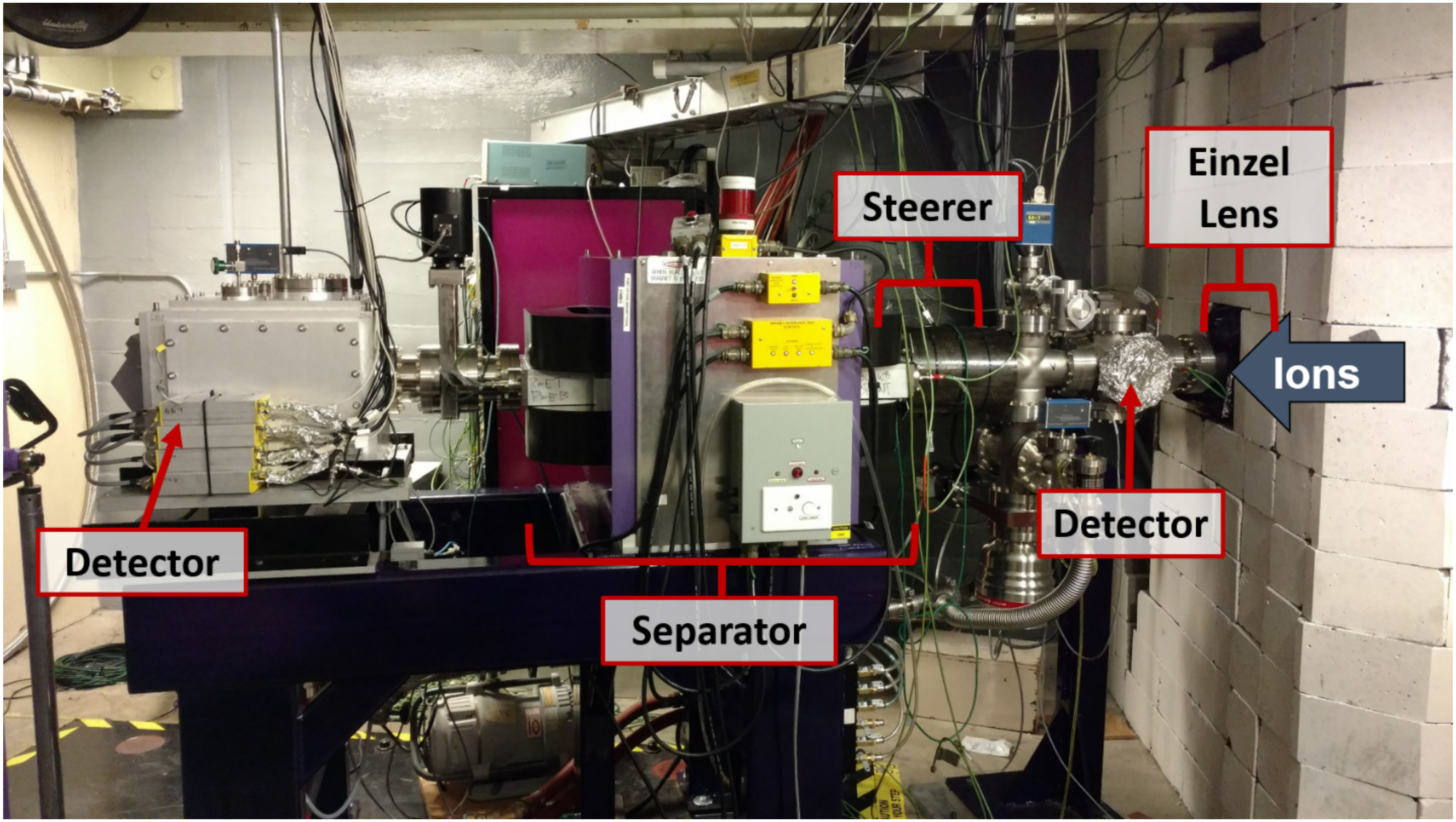
J.M.Gates, K.E.Gregorich et al., NIM A (to be published).

FIONA Status (1/2)



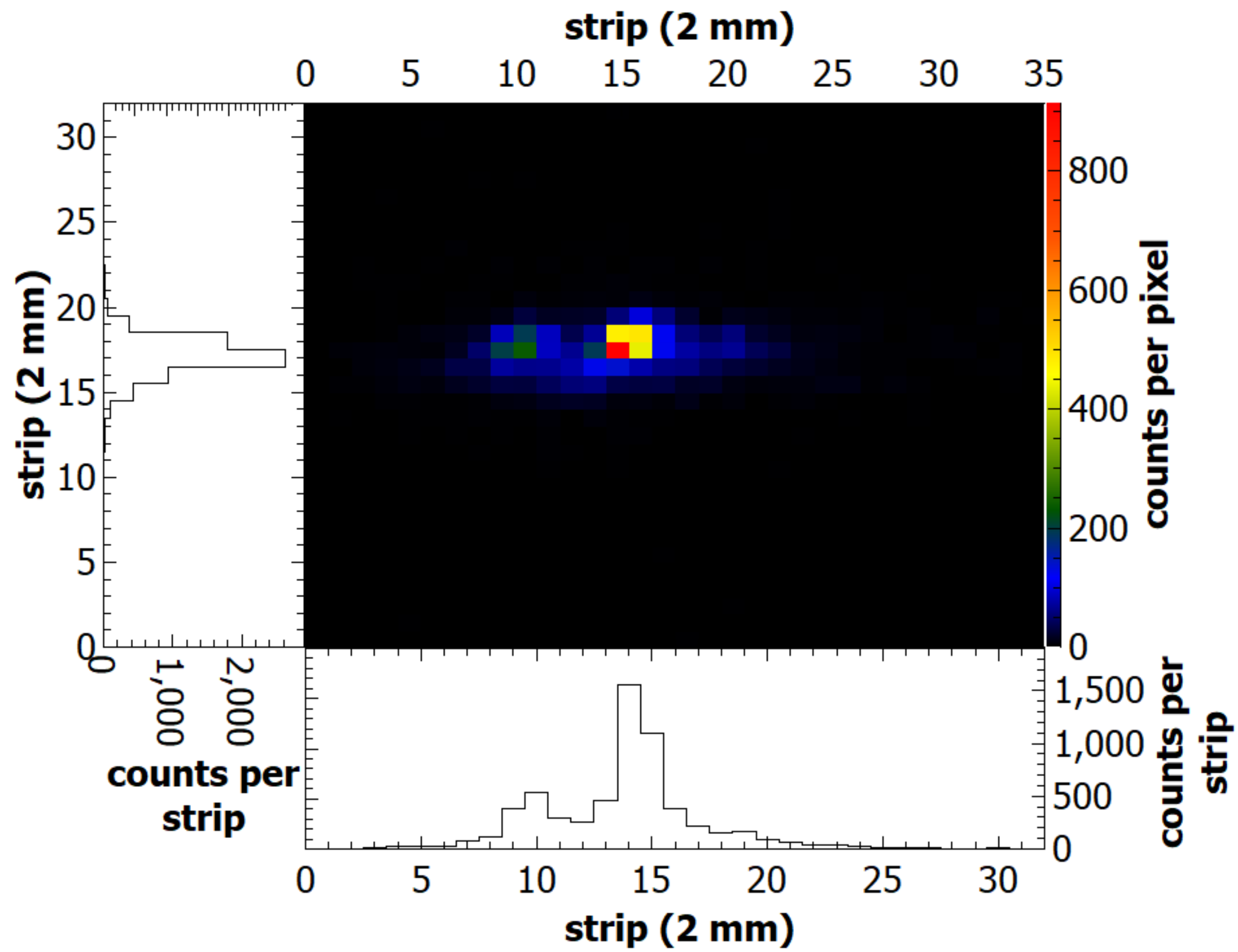
J.M.Gates, K.E.Gregorich et al., NIM A (to be published).

FIONA Status (2/2)



J.M.Gates, K.E.Gregorich et al., NIM A (to be published).

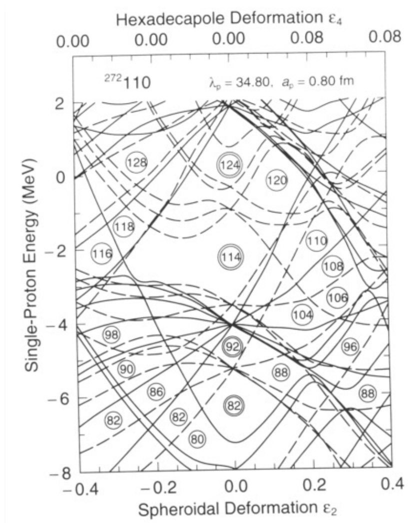
FIONA Commissioning Results

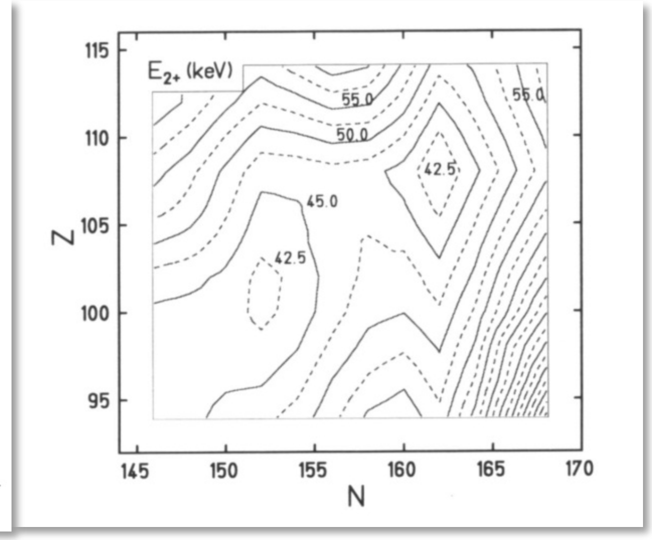


Experiment: $^{165}Ho(^{40}Ar,4\text{-}5n)^{201\text{-}200}At$, look for alpha decays

Science Program with FIONA

New capability for mass separated isotopes delivered to low-background counting area on time scale of 10ms



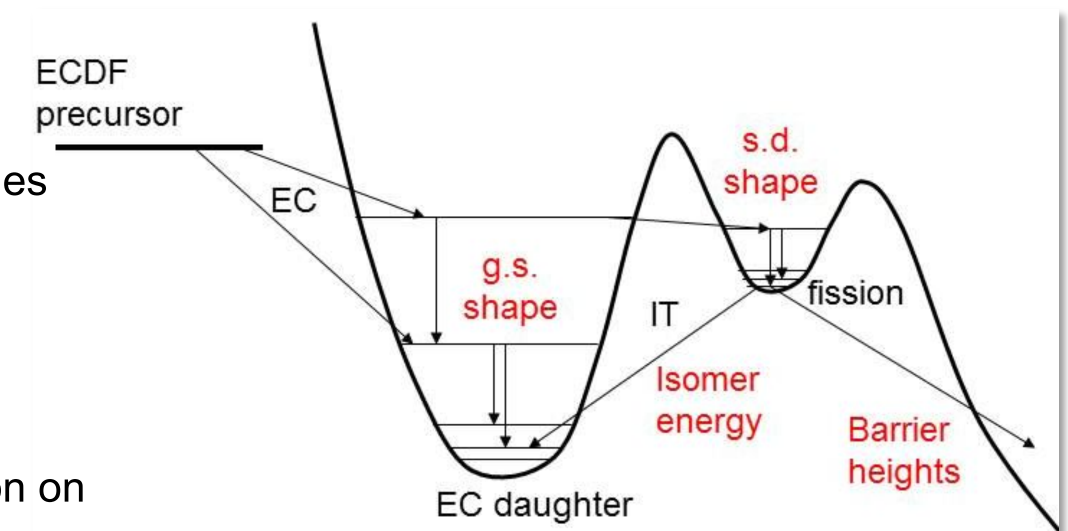


α-γ spectroscopy to study single-particle structure and collective behavior in heavy and super-heavy element isotopes

Isomer decay spectroscopy searching for electromagnetic, alpha, and fission decay modes to study stability of SHN

Identification of spontaneous fission activities in Z>90 to resolve ambiguities Z and A assignments for SF systematics including A and TKE distributions.

X-ray – γ coincidence measurements of electron-capture decay provides information on fission barriers and fission isomers



Summary

Isomer decay studies of the heaviest elements:

- Alpha decay is probing stability of states in heaviest nuclei
- Clear indications of isomers providing extra stability
- All ingredients (Q_α, L, pairing) essential to understanding
- Superfluid Tunneling Model is able to reproduce known data

- Fission decay from isomeric states has yet to be confirmed
- It will provide a new tool to understand fission process
- Pairing (dynamic), Specialization (role of odd particles, K purity)

- New experiments with FIONA at LBNL
- Decays of mass-separated isotopes in low-background environment
- Rare modes will be studied (isomer alpha decay and fission and ECDF...)

Grazie!

(With special thanks to: Jackie Gates, Ken Gregorich, Juho Rissanen, and Dirk Rudolph)