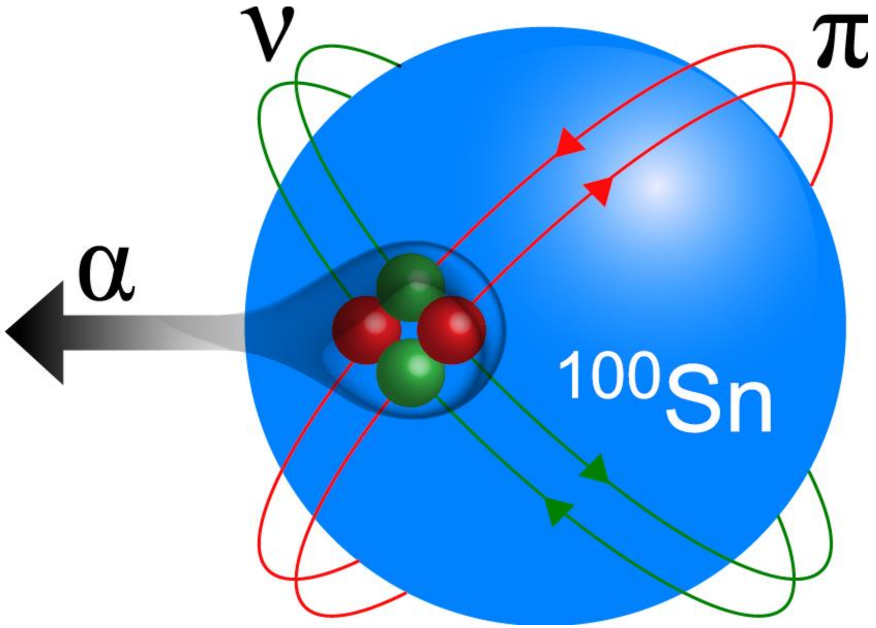
Superallowed alpha decay to doubly-magic ^{100}Sn

Darek Seweryniak

Argonne National Laboratory



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

Editors' Suggestion | Featured in Physics

Superallowed α Decay to Doubly Magic ^{100}Sn

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

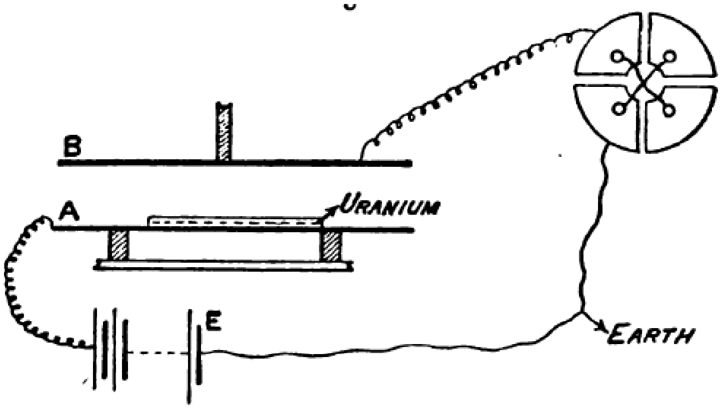
[1]*Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Lemont, Illinois 60439, USA*
[2]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[3]*Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[4]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[5]*Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA*
[6]*Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA*
[7]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*
[8]*University of Surrey, Guildford GU2 7XH, United Kingdom*
[9]*Department of Physics, University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*

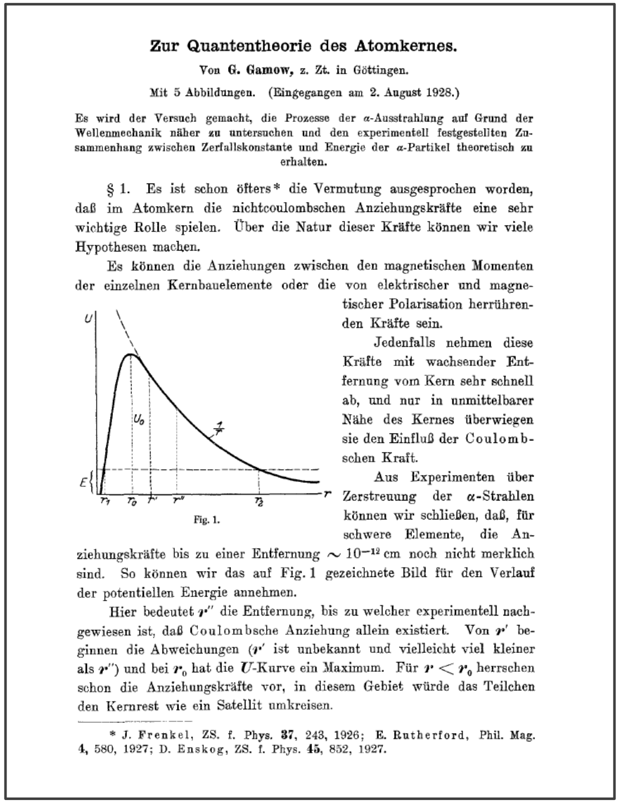
Outline

- Alpha decay, past and present
- Theoretical description of alpha decay
- Observation of the ^{108}Xe-^{104}Te-^{100}Sn alpha decay chain
- Discussion of alpha-decay reduced widths
  - ^{208}Pb region vs ^{100}Sn region
  - theoretical calculations for ^{104}Te
- Summary and Outlook

Alpha decay - early days

- **Becquerel** discovers first radioactivity (1896)
- **Rutherford** characterizes "alpha rays" (1899)
  - Identification of alpha rays as He ions (1907)
- **Geiger-Nuttall** law (1911)
  - $\log(T_{1/2}) = AQ_{\alpha}^{-1/2}+B$
- **Gamow** theory of alpha decay (1928)
  - tunneling through a Coulomb/centrifugal barrier
  - probabilistic interpretation of quantum mechanics
- **Geiger-Marsden** experiment (1909)
  - α scattering on Au foil
  - Rutherford proposes small/heavy atomic nucleus
- First nuclear reactions with α particles as beams
  - $\alpha+^{14}N$, discovery of **proton** (1920)
  - α+Be, discovery of **neutron** (1932)





Zur Quantentheorie des Atomkernes.

Von **G. Gamow,** z. Zt. in Göttingen.

Mit 5 Abbildungen. (Eingegangen am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund der Wellenmechanik näher zu untersuchen und den experimentell festgestellten Zusammenhang zwischen Zerfallskonstante und Energie der α-Partikel theoretisch zu erhalten.

§ 1. Es ist schon öfters* die Vermutung ausgesprochen worden, daß im Atomkern die nichtcoulombschen Anziehungskräfte eine sehr wichtige Rolle spielen. Über die Natur dieser Kräfte können wir viele Hypothesen machen.

Es können die Anziehungen zwischen den magnetischen Momenten der einzelnen Kernbauelemente oder die von elektrischer und magnetischer Polarisation herrührenden Kräfte sein.

Fig. 1.

Jedenfalls nehmen diese Kräfte mit wachsender Entfernung vom Kern sehr schnell ab, und nur in unmittelbarer Nähe des Kernes überwiegen sie den Einfluß der Coulombschen Kraft.

Aus Experimenten über Zerstreuung der α-Strahlen können wir schließen, daß, für schwere Elemente, die Anziehungskräfte bis zu einer Entfernung $\sim 10^{-12}$ cm noch nicht merklich sind. So können wir das auf Fig. 1 gezeichnete Bild für den Verlauf der potentiellen Energie annehmen.

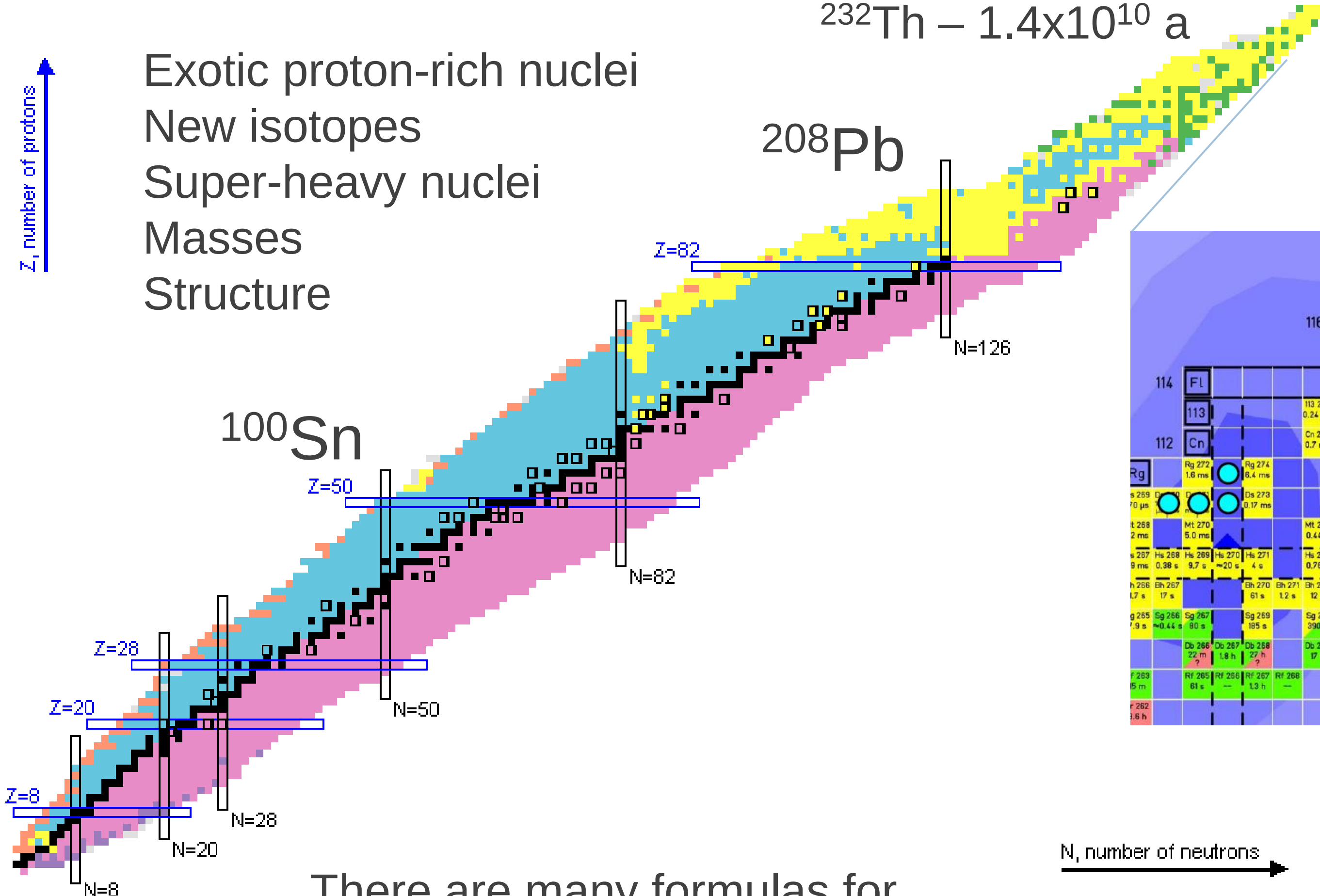
Hier bedeutet r'' die Entfernung, bis zu welcher experimentell nachgewiesen ist, daß Coulombsche Anziehung allein existiert. Von r' beginnen die Abweichungen (r' ist unbekannt und vielleicht viel kleiner als r'') und bei r_0 hat die U-Kurve ein Maximum. Für $r < r_0$ herrschen schon die Anziehungskräfte vor, in diesem Gebiet würde das Teilchen den Kernrest wie ein Satellit umkreisen.

* J. Frenkel, ZS. f. Phys. **37**, 243, 1926; E. Rutherford, Phil. Mag. **4**, 580, 1927; D. Enskog, ZS. f. Phys. **45**, 852, 1927.

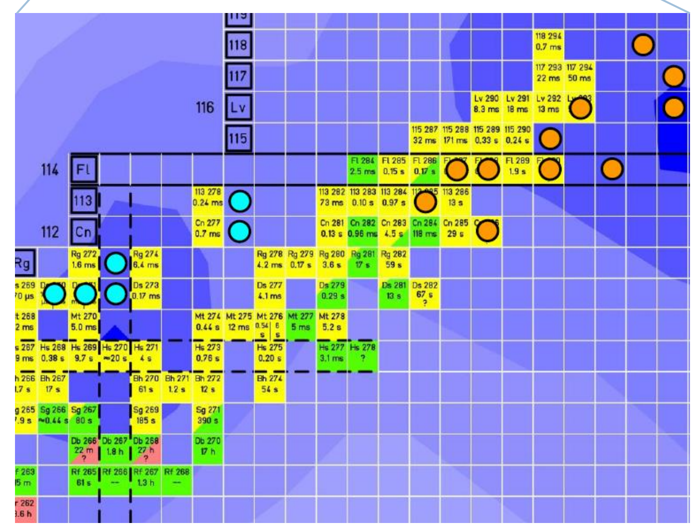
Alpha decay today

^{238}U – 4.5x10^9 a
^{232}Th – 1.4x10^{10} a

Exotic proton-rich nuclei
New isotopes
Super-heavy nuclei
Masses
Structure



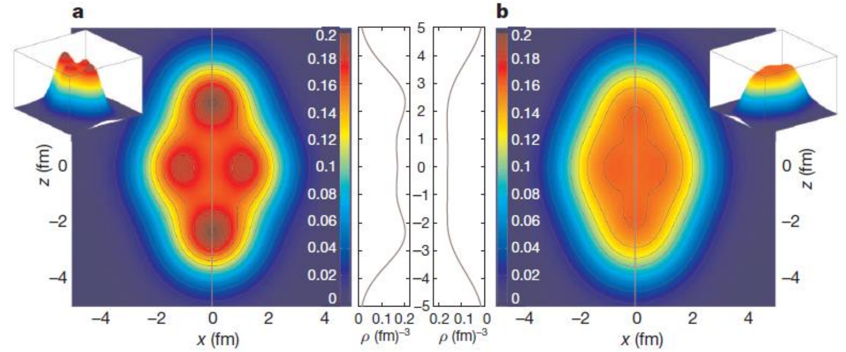
SHE



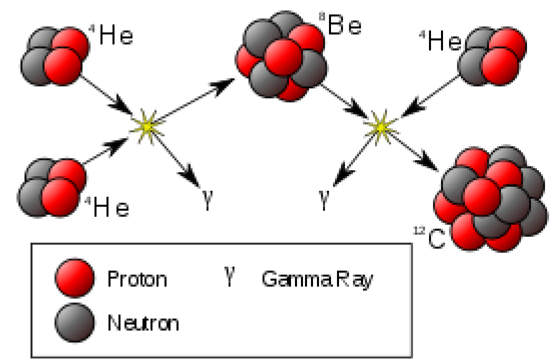
There are many formulas for calculating α-decay widths but **microscopic description** of α decay **remains challenging**

Significance of alpha decay

- Clustering in nuclei
  - Emission of heavy clusters
  - fission
- Astrophysics
  - $\alpha+\alpha+\alpha \rightarrow {}^{12}C$ creation in stars, Hoyle state
  - (p, α) reactions
  - (α, n) reactions
- Applications
  - Targeted radiation therapy
  - Thermo-electric engines
  - Smoke detectors
  - He from α decay of U and Th



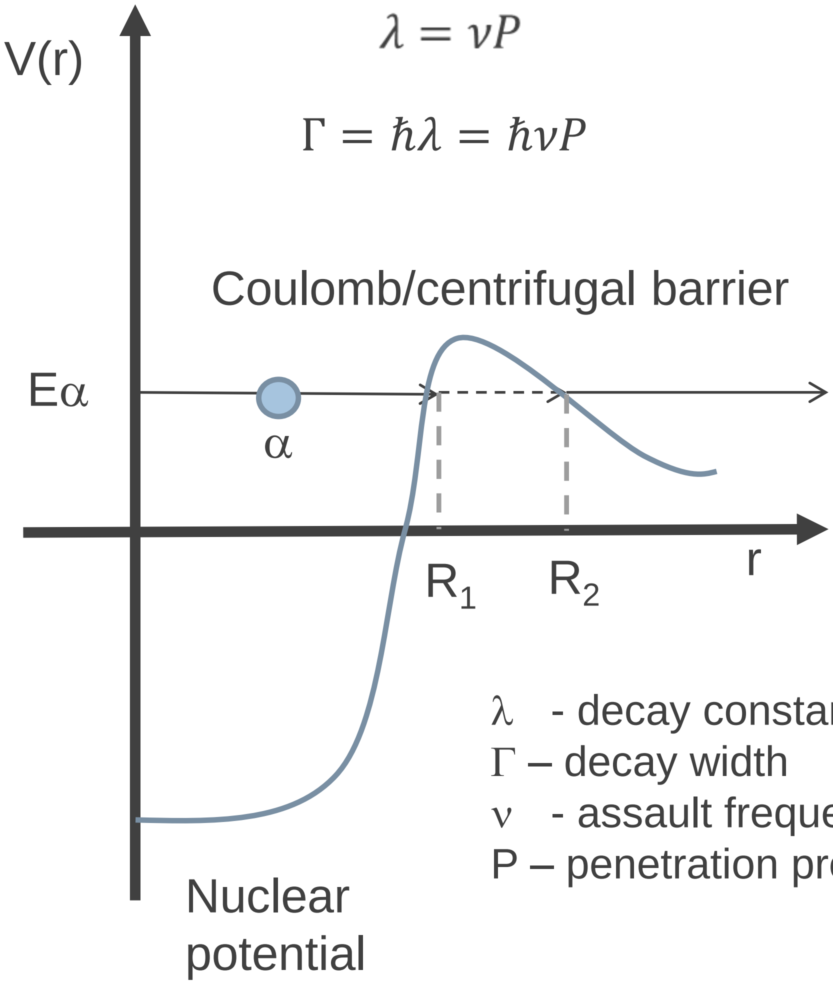
^{20}Ne EDF calculations, Nature 487, 341 (2012)



Uranium glass

Gamow alpha-decay model

G. Gamow, Z. Phys. 51, 204 (1928)



$$\lambda = \nu P$$

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

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

Can be readily calculated
Very steep function of Q-value

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

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

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

δ^2 - α preformation factor/
reduced α decay width

R-matrix expression of the alpha-decay width

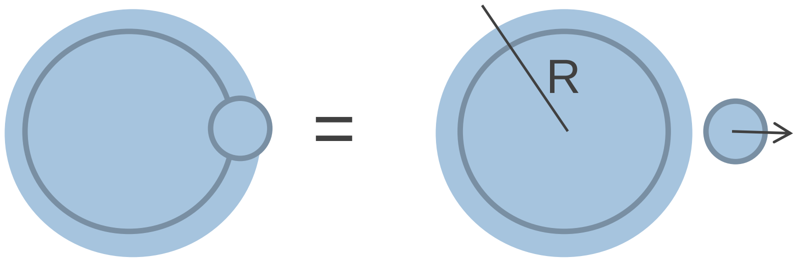
Decay width:

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

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

Reduced width amplitude:

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



Formation amplitude:

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

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

Challenges of microscopic α-decay width calculations

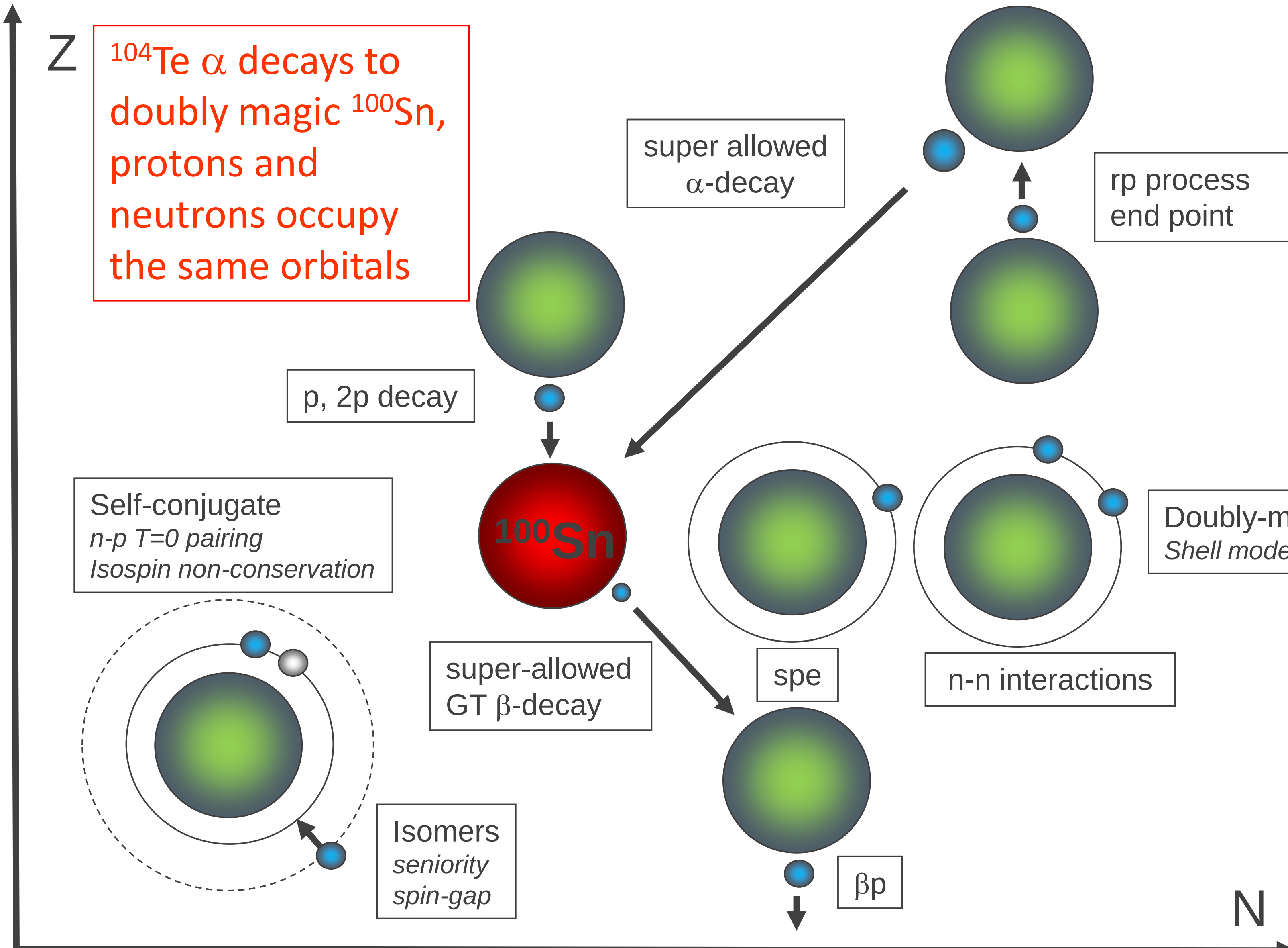
- Microscopic description using **the shell model**
  - Underestimates experimental values by about 2 orders of magnitude
  - Only Shell Model+Cluster Model reproduces ^{212}Po

  K. Varga et al., PRL 69, 37 (1992)
- Large configuration space
- Antisymmetrization
- Normalization
- Configuration mixing (nucleon-nucleon residual interaction)
  - pairing, **proton-neutron interaction**
- Contribution from the continuum

α decay of ^{212}**Po** to doubly-magic ^{208}Pb is the simplest case and serves as a benchmark for the calculations

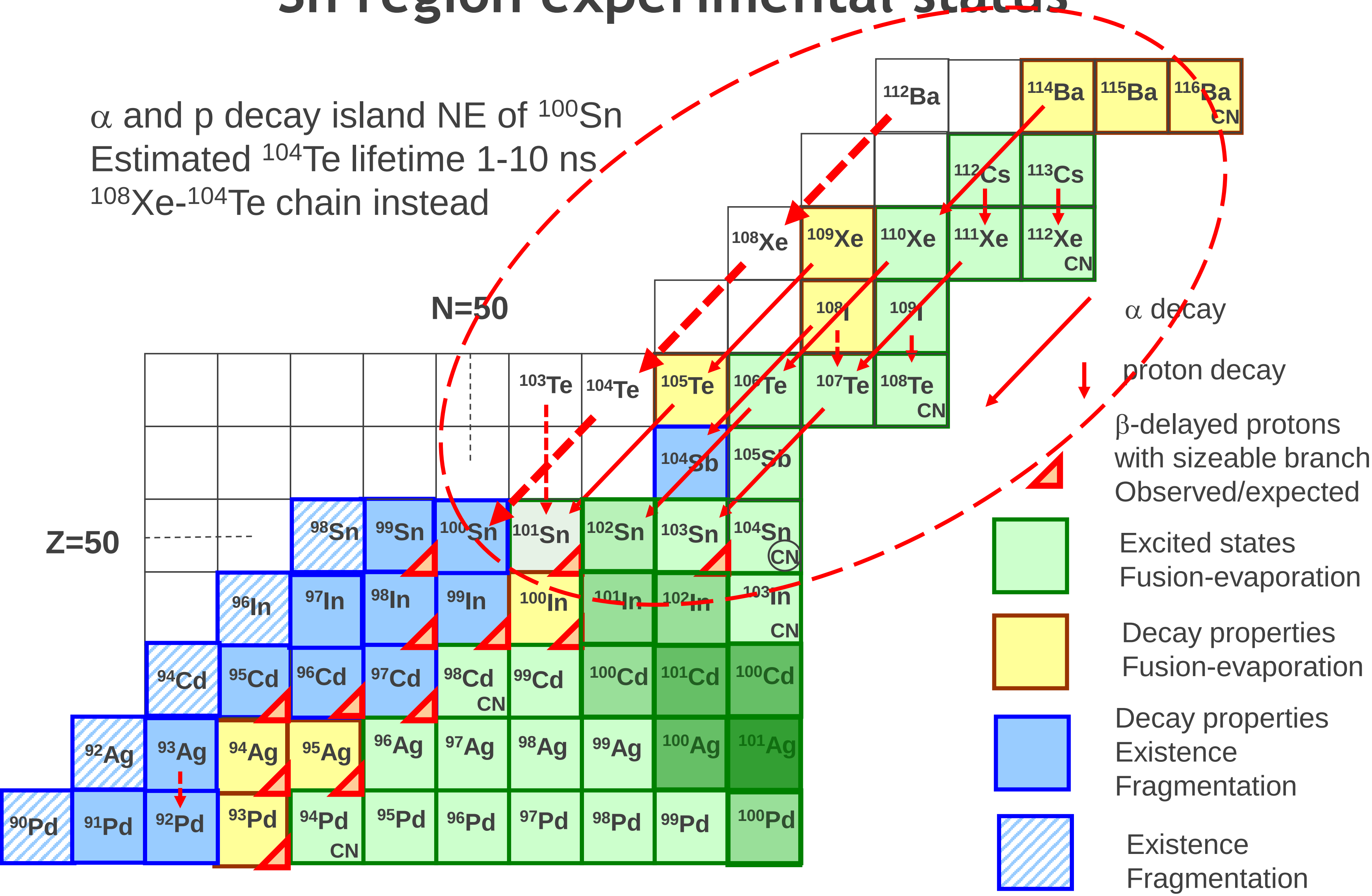
^{100}Sn physics

^{104}Te α decays to doubly magic ^{100}Sn, protons and neutrons occupy the same orbitals

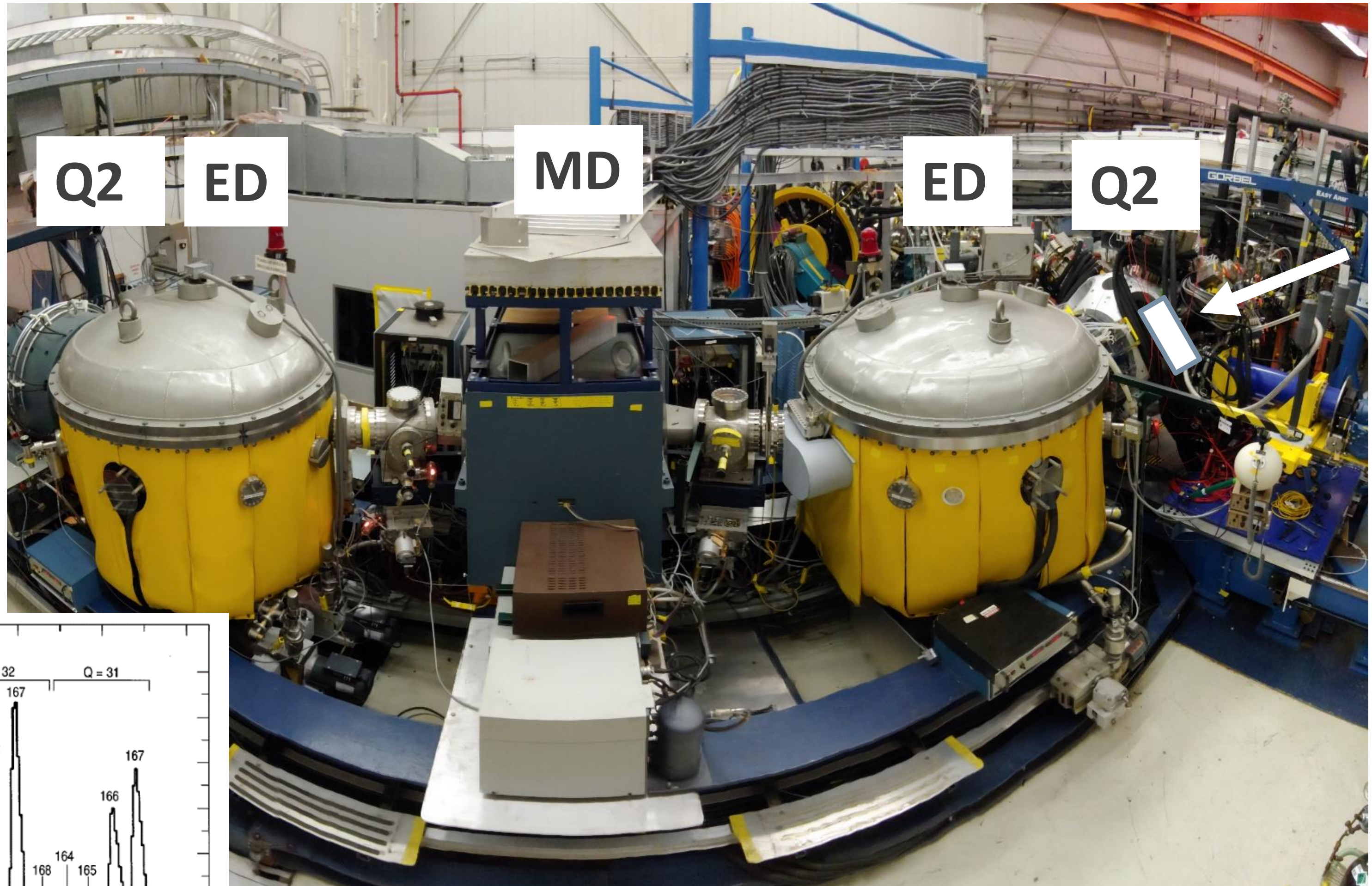


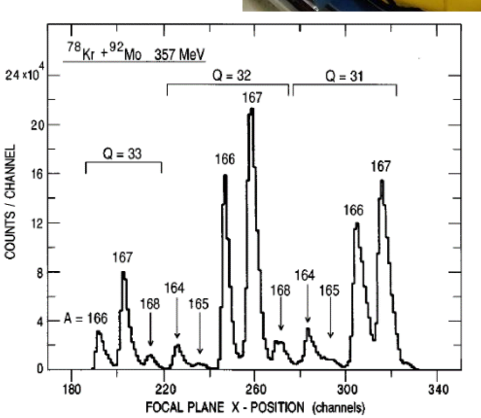
^{100}Sn region experimental status

α and p decay island NE of ^{100}Sn
Estimated ^{104}Te lifetime 1-10 ns
^{108}Xe-^{104}Te chain instead

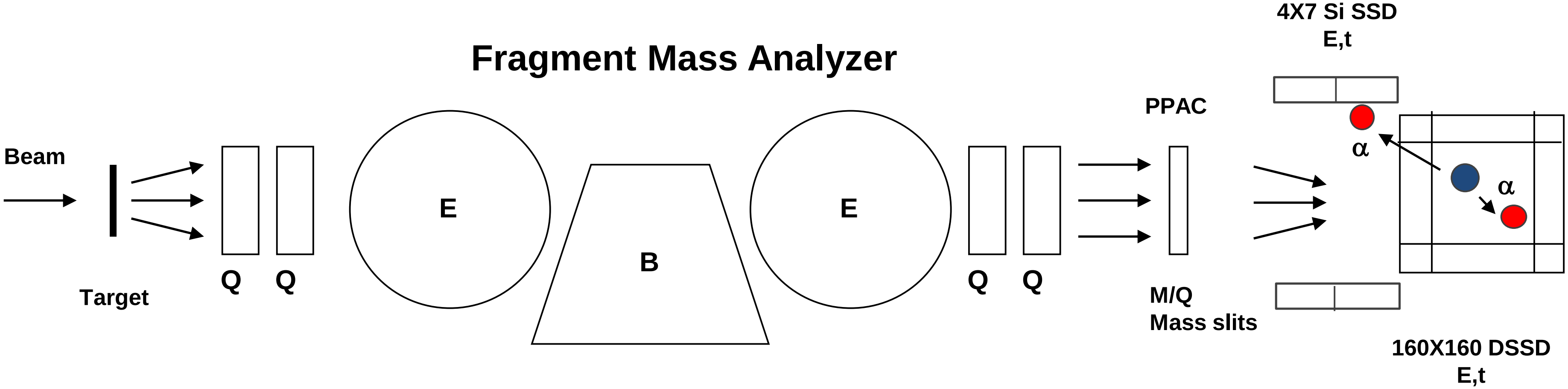


Argonne Fragment Mass Analyzer



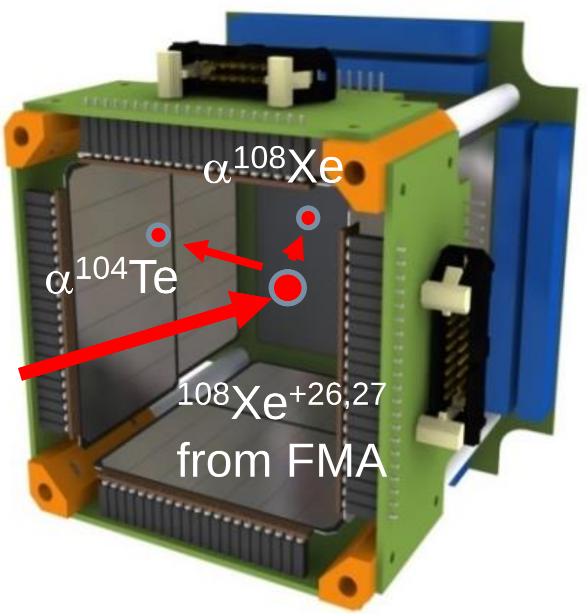


Recoil-Decay Correlations

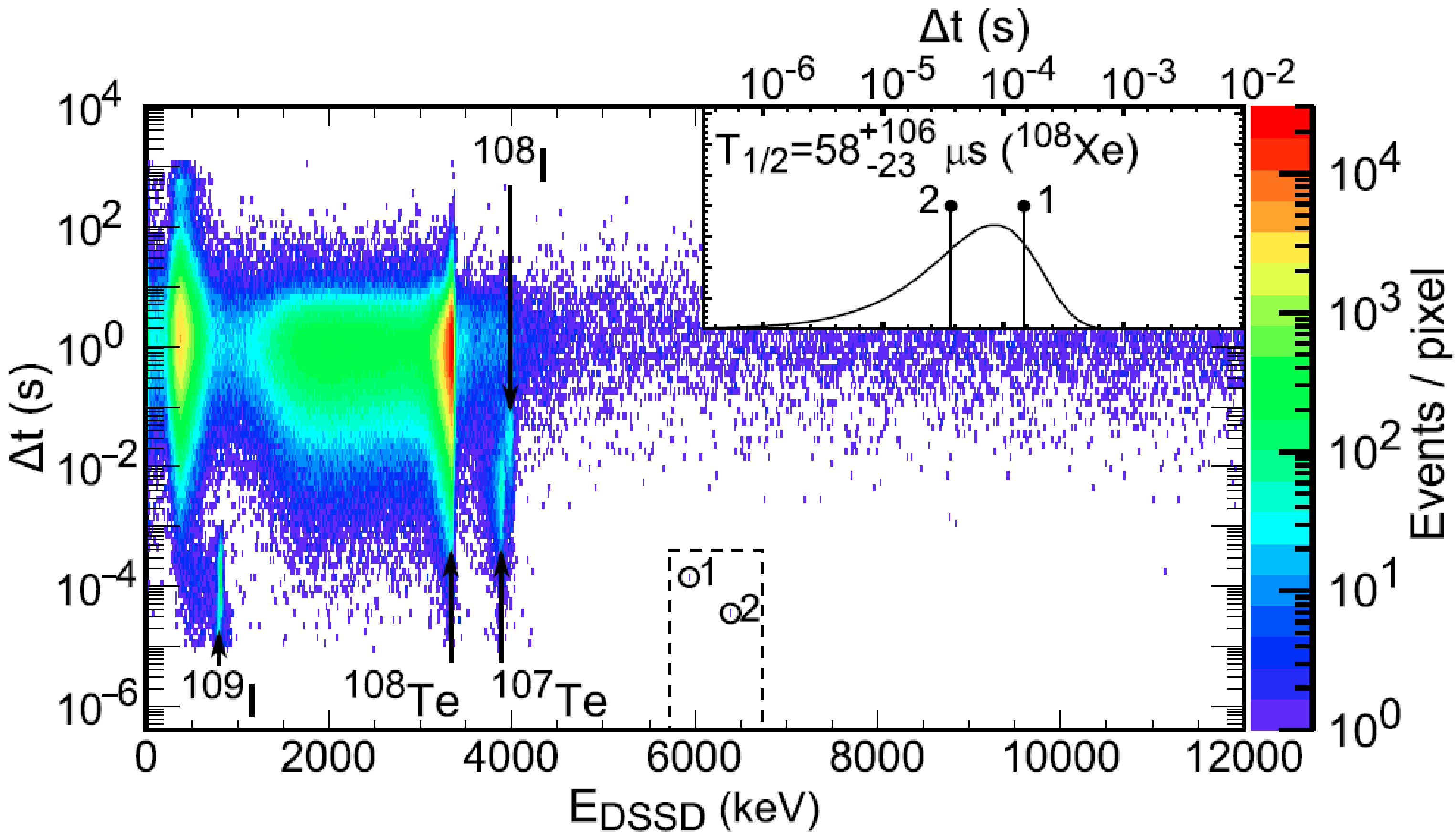


- Implant-decay spatial and time correlations in DSSD
- Digital DAQ to detect PU waveforms
- Si box to catch escaping alphas

^{58}Ni(^{54}Fe,4n)^{108}Xe reaction
~5 days , ~30 pnA
FMA set to A=108, charge states Q=+26,+27

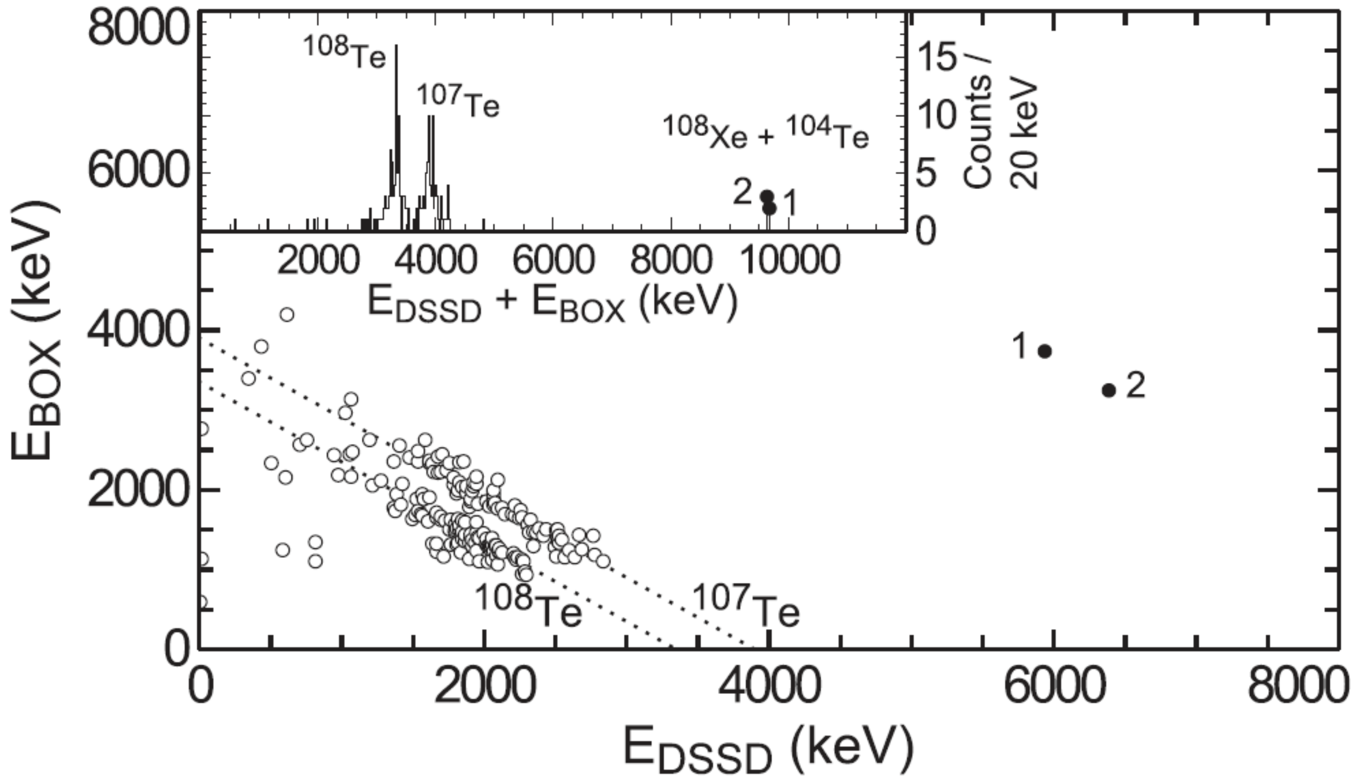


Recoil-decay correlations



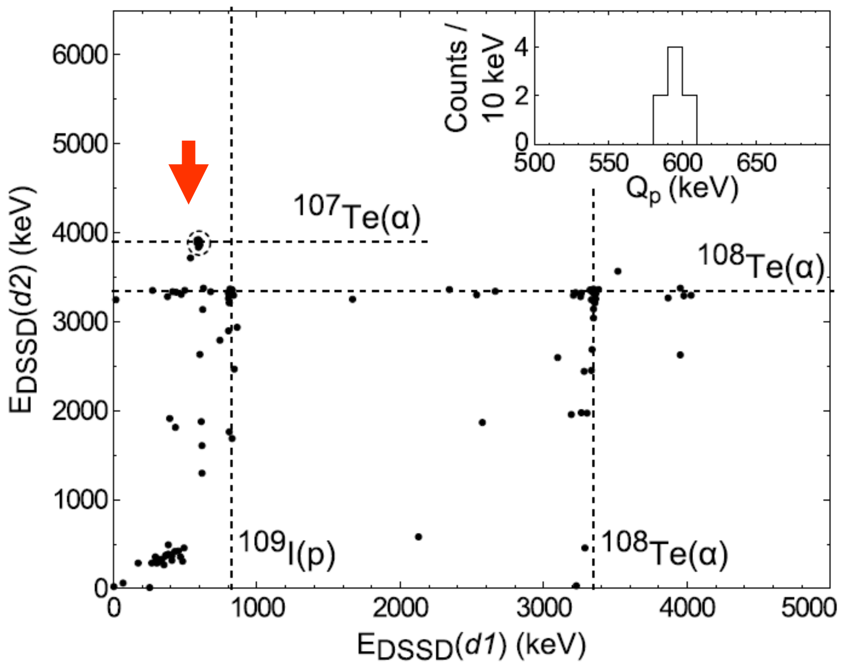
TWO fast high energy decay events
Expected **0.09** random events

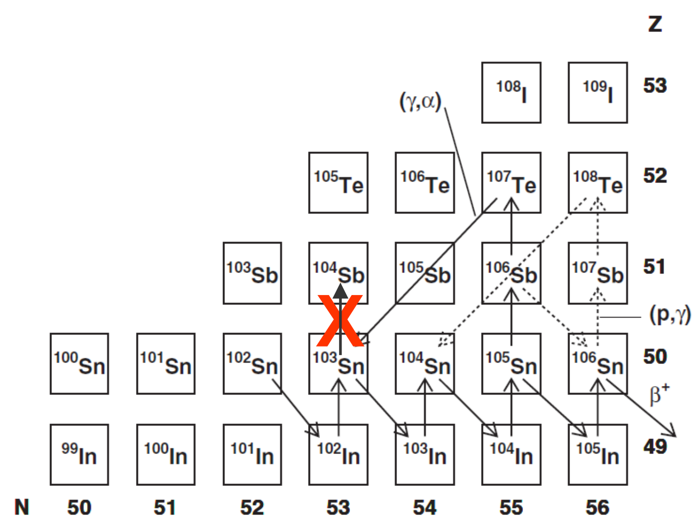
DSSD-Si box coincidences



- Both events where in coincidence with the Si box (only 1 out of 400 events were coincidences)
- The same total energy for both events
- Compared to α emitters different energy split
- Estimated cross section **~200 pb** (extrapolated 1-5 nb for ^{100}Sn)

Observation of weak proton branch in ^{108}I



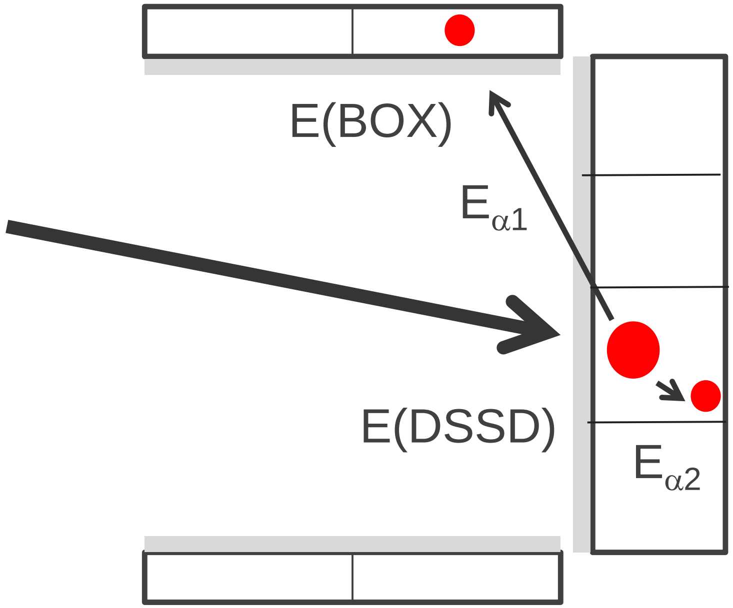


8 events followed by ^{107}Te decay

Q_p=597(13) keV
b_p=0.5(3)%
$T_{1/2}$=26.4(8) ms

Sn-Sb-Te cycle
at the termination of the rp-process

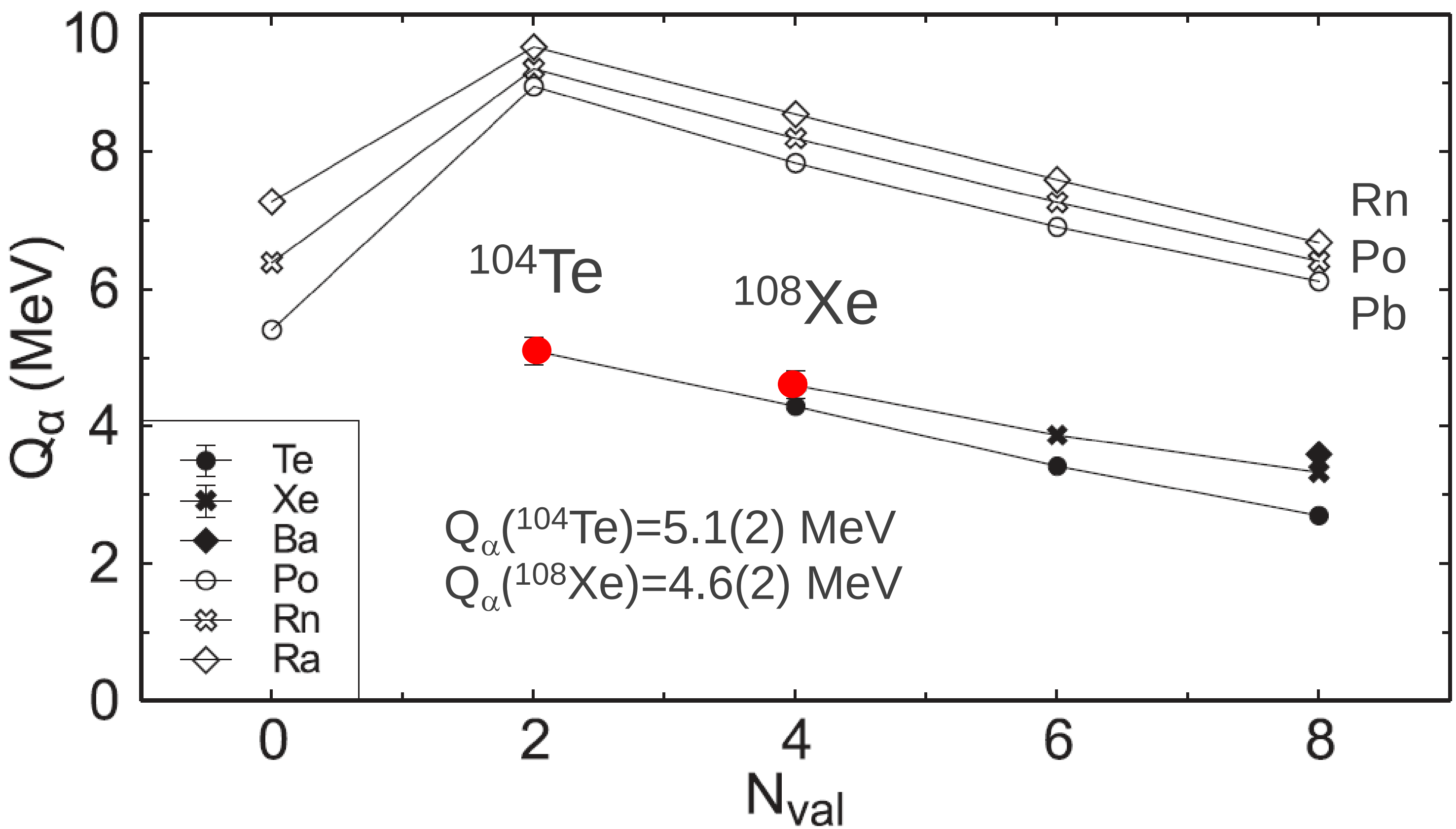
^{108}Xe/^{104}Te α-particle energy determination



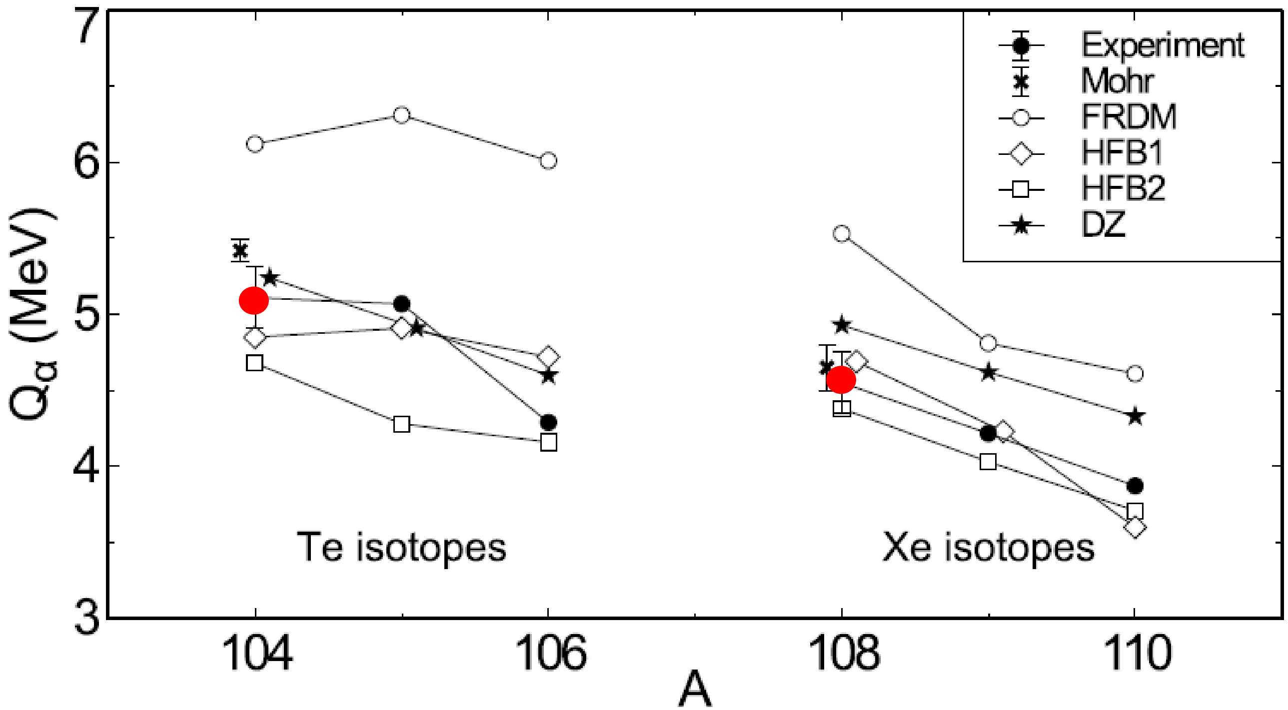
E_{α}(^{104}Te)=4.9(2) MeV
E_{α}(^{108}Xe)=4.4(2) MeV
ΣE_{α}=9.3(1) MeV

- Measured implantation depth and escape angle allow to determine energies of both α particles
- Sum of energies is much better constrained

Alpha-decay Q value systematics



Comparison with mass models

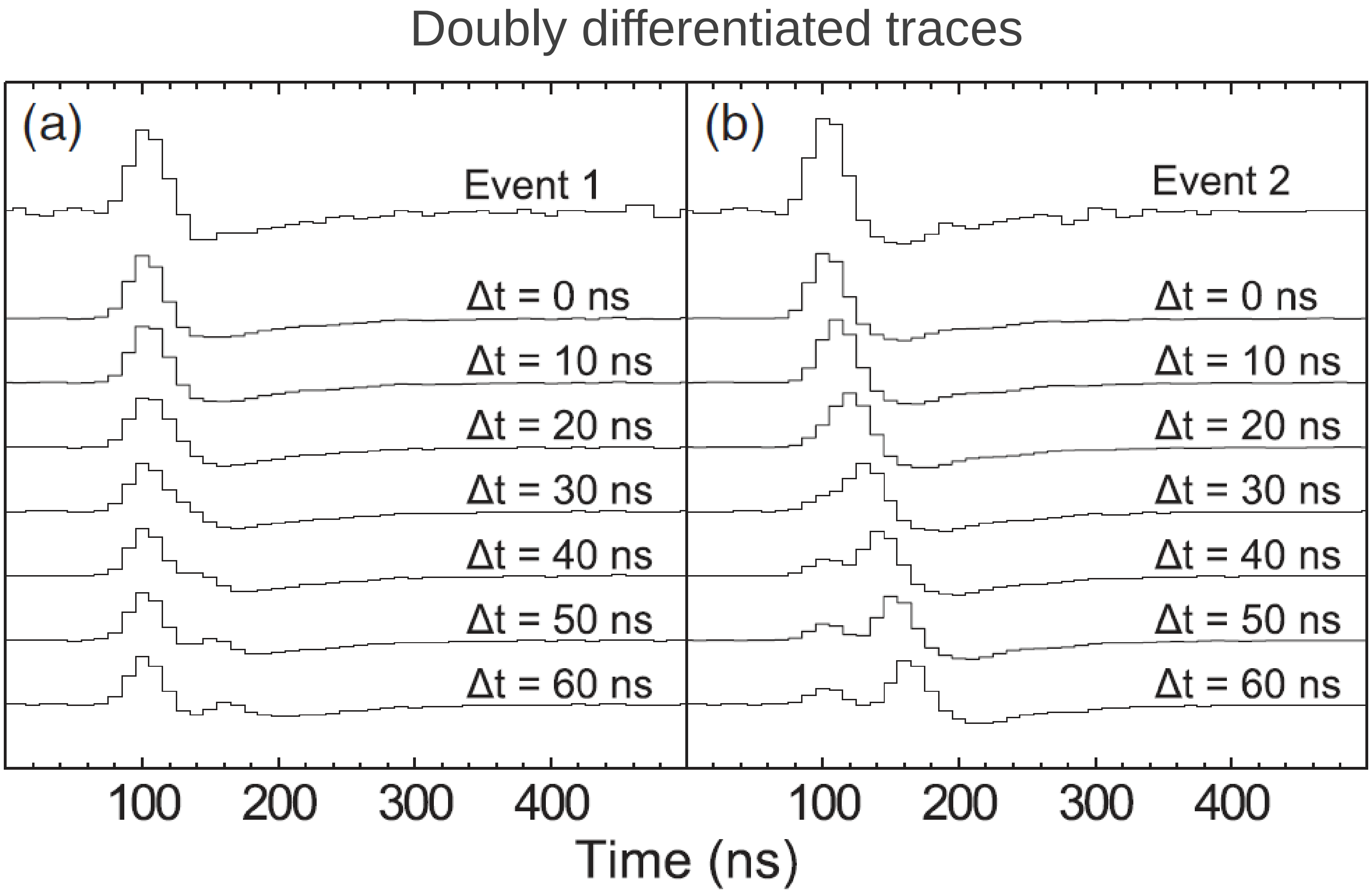


Locally adjusted double-folding potential

P. Mohr, Eur. Phys. J. A 31, 23 (2007)

$Q\alpha(^{104}Te)$=5.42(0.07) MeV, $T_{1/2}$ (^{104}Te) = 5 ns (assumed P=10%)
$Q\alpha(^{108}Xe)$=4.65(0.15), $T_{1/2}$ (^{108}Xe) = 60 μs (assumed P=5%)

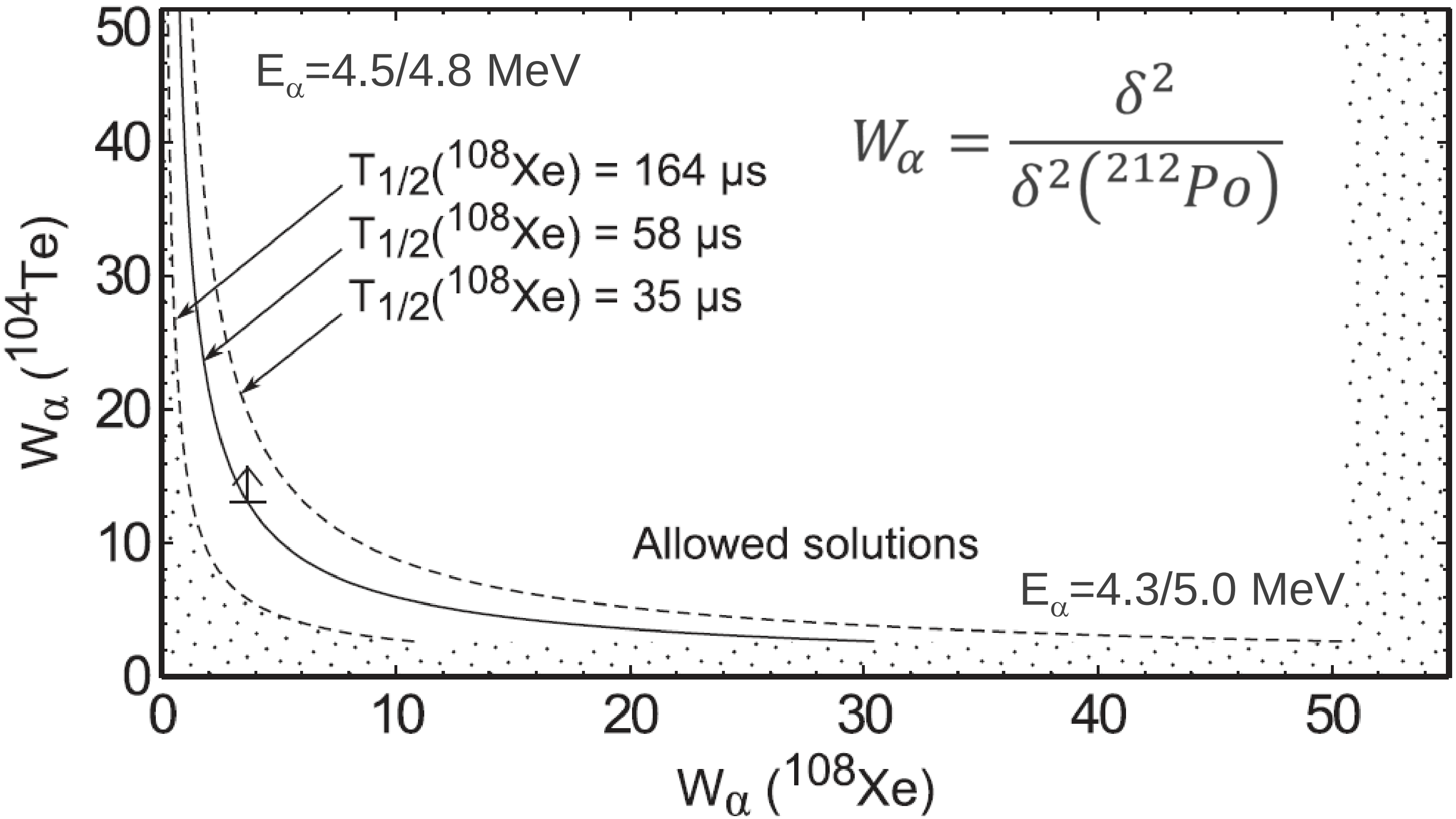
DSSD traces for the ^{108}Xe-^{104}Te pile-up events



NO noticeable delay

TWO decays faster than 20 ns each imply **$T_{1/2}$<18 ns**

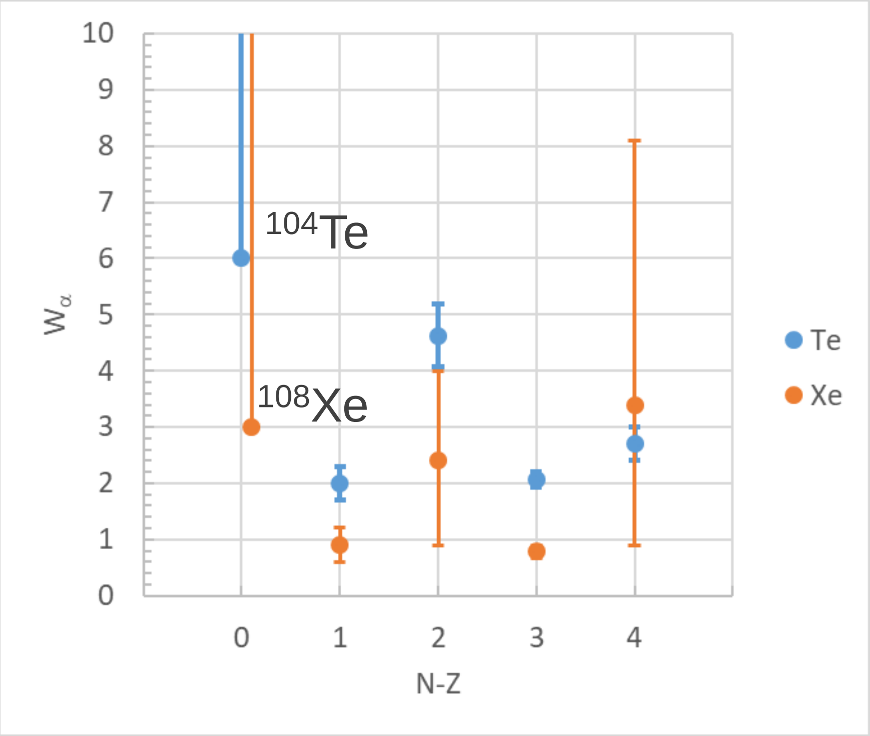
^{108}Xe-^{104}Te reduced width limits



$W\alpha(^{104}Te)W\alpha(^{108}Xe)>25$

At least one W_α greater than 5

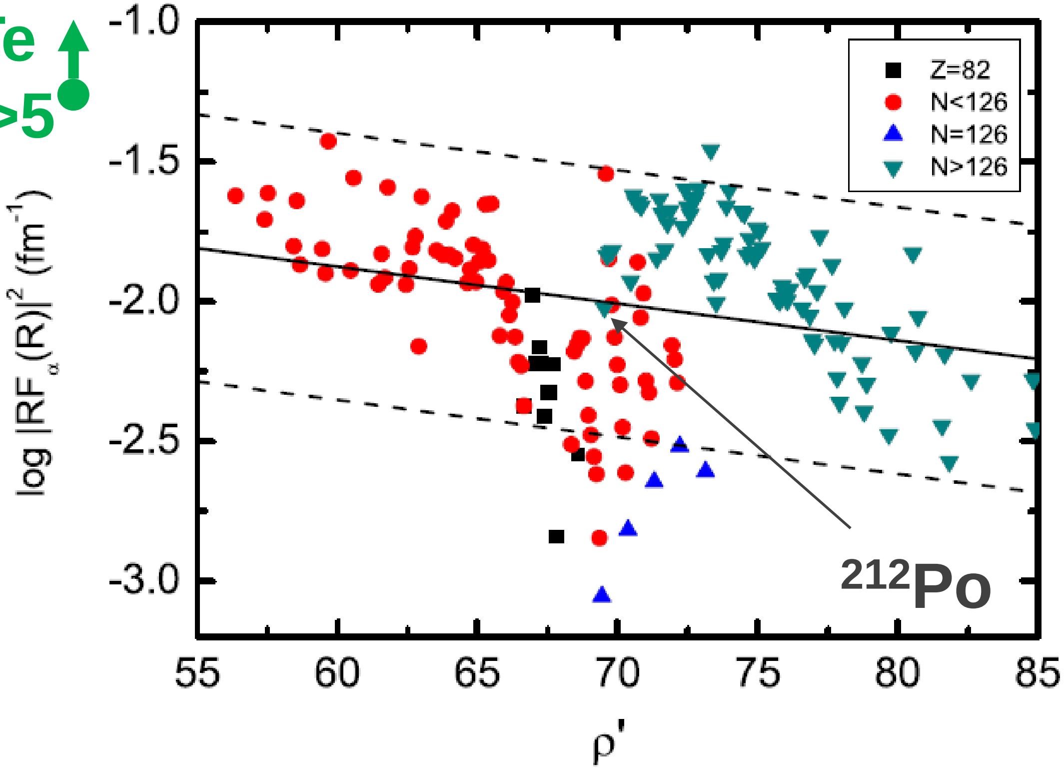
Reduced α-decay widths near ^{100}Sn



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

Reduced α-decay width global systematics

^{104}Te $W_\alpha>5$

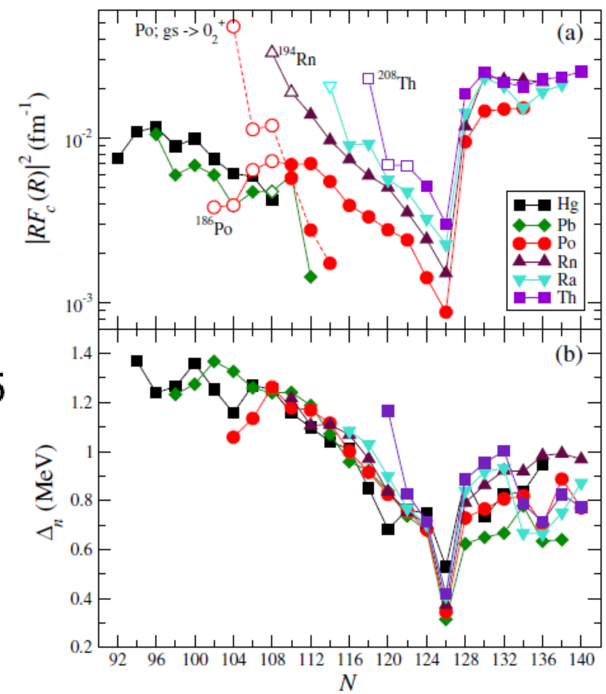


$$\rho' = \sqrt{A_{\alpha d} Z_\alpha Z_d (A_d^{\frac{1}{3}} + A_\alpha^{\frac{1}{3}})}$$

● ^{104}Te

ρ'~50

$\log_{10}|R\ F(R)|^2$>-1.3



C. Qi et al., Phys. Rev. C ***81****, 064319 (2010)*

Multistep shell model

Monika Patial, R. J. Liotta, and R. Wyss, Phys. Rev. C 93, 054326 (2016)

R-matrix

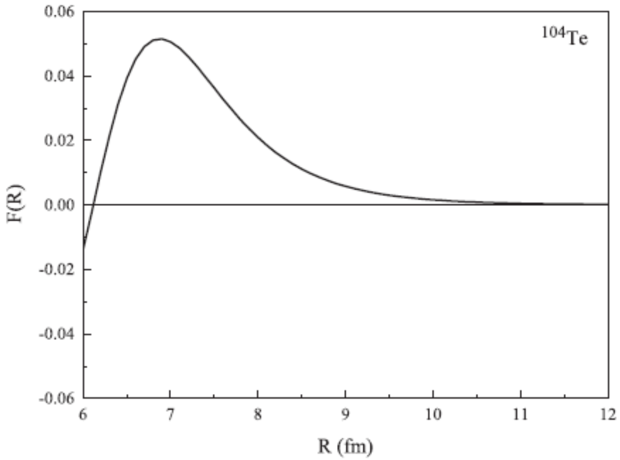
^{212}Po

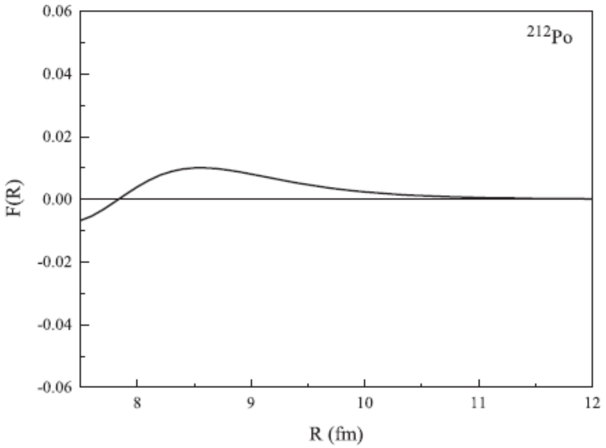
Calculated $T_{1/2}$=15 μs, experiment 298 ns

^{104}Te

Calculated $T_{1/2}$=1.5 μs, assuming $Q\alpha$=5.06 MeV, experiment $T_{1/2}$<15 ns

α-particle formation probability **4.85 times larger** in ^{104}Te compared to ^{212}Po





Complex-energy shell model

R. Id Betan and W. Nazarewicz, Phys. Rev. C 86, 034338 (2012)

R-matrix

^{212}Po

- Calculated $T_{1/2}$ is 36 times too long (R-matrix)
- Too small configuration space

^{104}Te

- No convergence
- $T_{1/2}$<500 ns, assuming $Q\alpha$=5.15 MeV
- Need to add proton-neutron interaction
- Better treatment of continuum

Summary and Outlook

- First observation of ^{108}Xe-^{104}Te-^{100}Sn chain
  - Enhanced alpha preformation
- Theoretical description of α decay still work in progress
  - ^{104}Te, ^{108}Xe important for the role of neutron-proton interaction
- Future measurements (more beam, larger efficiency)
  - ^{104}Te lifetime (~1 ns)
  - more precise α-decay widths for ^{108}Xe and other N~Z α emitters
  - ^{112}Ba N=Z α emitter
  - alpha emitters "north-east" ^{100}Sn can be studied at the new generation fragmentation facilities