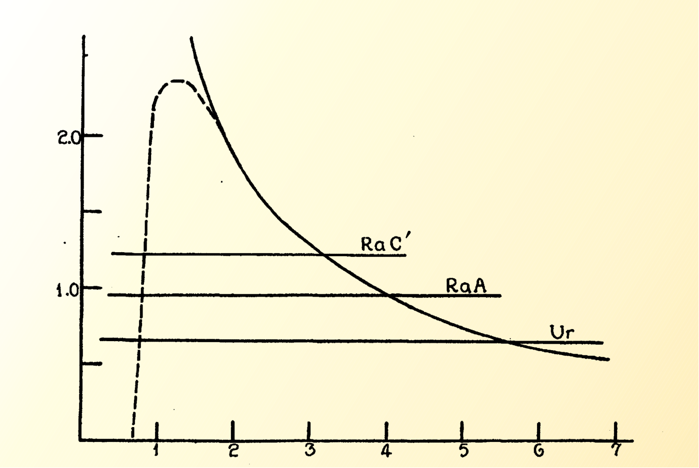
Superallowed Alpha Decay

Rod Clark

Wave Mechanics and Radioactive Disintegration

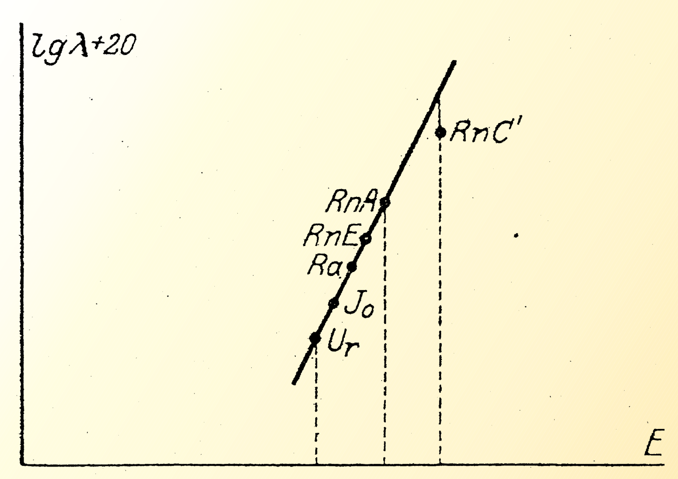
R. W. Gurney and E.U. Condon, Nature (London) 122, 439 (1928)



		E_α (MeV)	$T_{1/2}$
Radium C'	^{214}Po	7.7	160 μs
Radium A	^{218}Po	6.0	3 mins
Uranium	^{238}U	4.2	4.5 GYrs

Zur Quantentheorie des Atomkernes

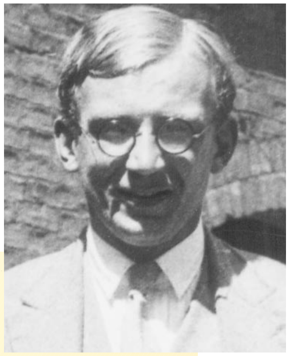
G. Gamow, Z. Phys. 51, 204 (1928)



Quantitative description of Geiger-Nuttall Rule:

$$\log(T_{1/2}) = a + bQ_\alpha^{-1/2}$$

H.Geiger and J.M.Nuttall, Phil. Mag. 22 613 (1911)



Superfluid Tunneling Model (STM)

The Schrödinger equation describing
the model is:

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

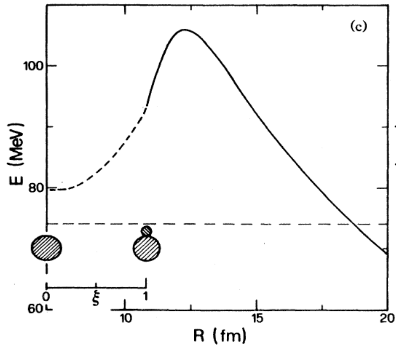
ξ = generalized deformation variable

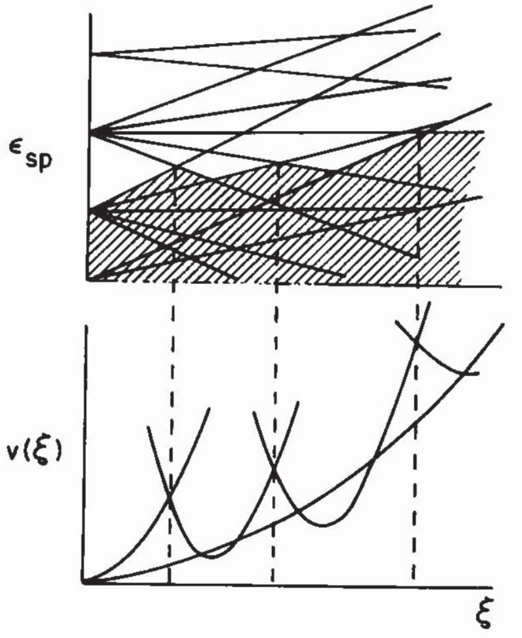
Calculation of decay constant:
λ = P . f . T

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)





Decay Constant

$$\lambda = P\,f\,T$$

Alpha-particle formation probability,

$$P = |\psi(\xi = 1)|^2 = \left(\frac{\alpha}{\sqrt{\pi}}\right) e^{-\alpha^2}, \qquad \alpha^2 = \sqrt{\frac{DC}{\hbar^2}}$$

Knocking frequency,

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{C}{D}}$$

Potential parameter, *C*, is dependent on *Q*-value

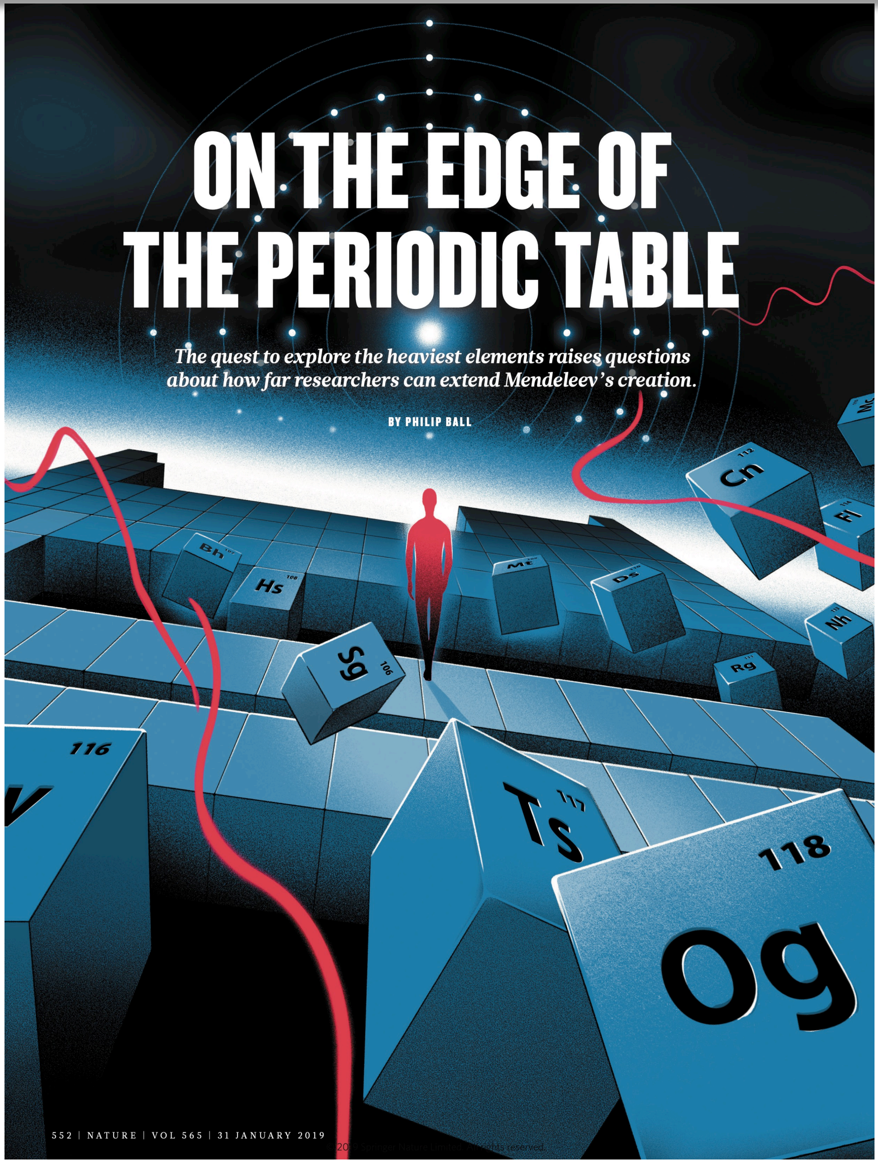
Inertial mass parameter, *D*, depends on pairing gap, *Δ*.

Transmission through barrier,

$$T_L = \frac{\rho}{F_L^2(\eta,\rho) + G_L^2(\eta,\rho)}$$

➔ Investigate dependencies on *Δ*, *Q*, *L*

Superheavy Nuclei



ON THE EDGE OF THE PERIODIC TABLE

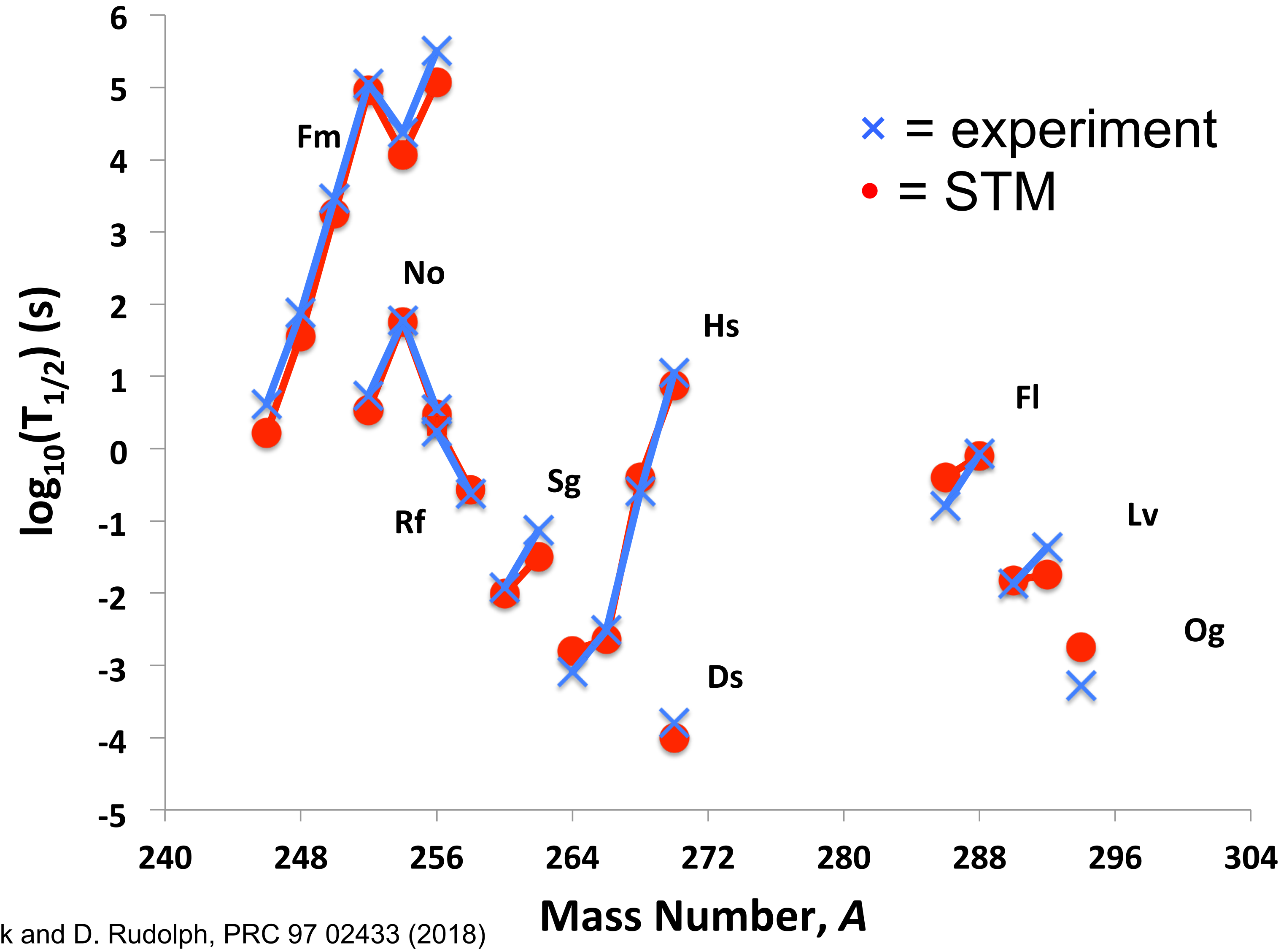
The quest to explore the heaviest elements raises questions about how far researchers can extend Mendeleev's creation.

BY PHILIP BALL

552 | NATURE | VOL 565 | 31 JANUARY 2019

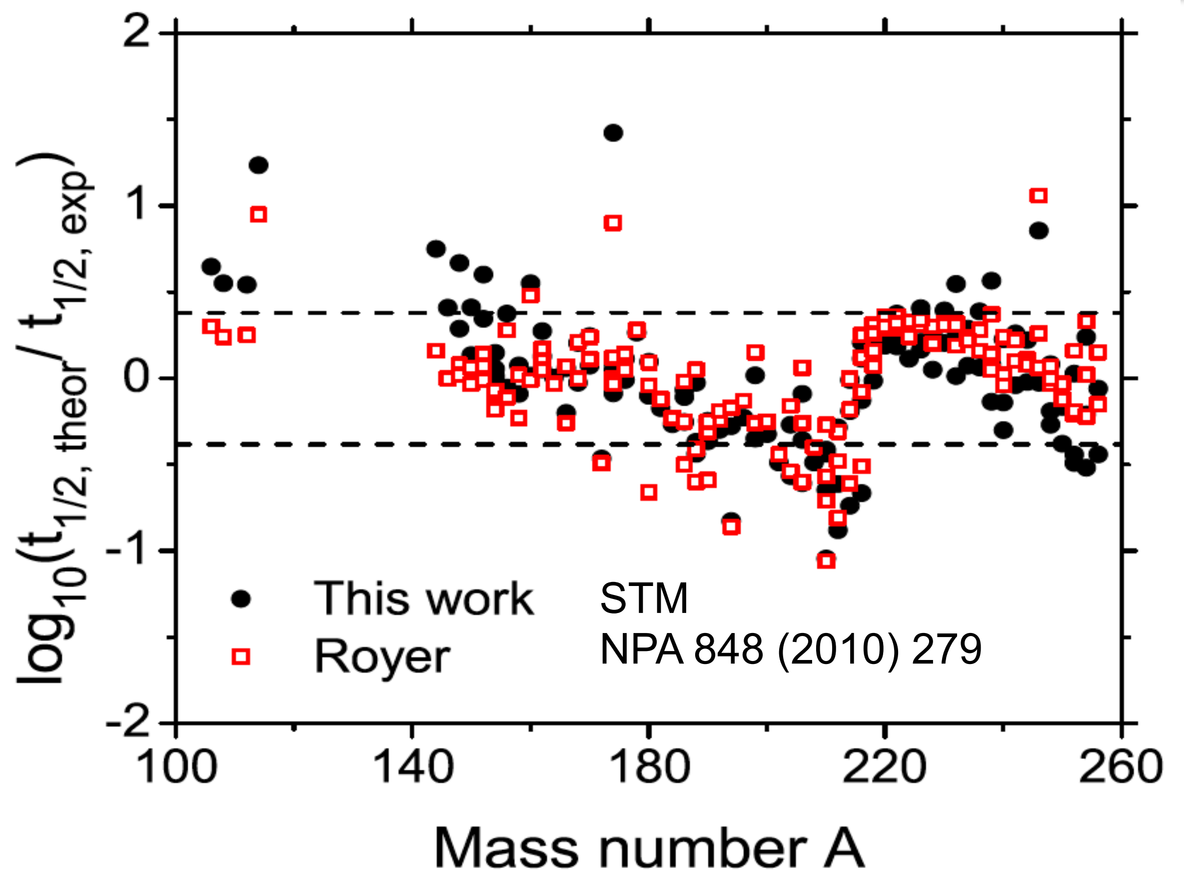
Nature **565**, 553 (2019).

Alpha Decay of Even-Even Isotopes: Fm to Og



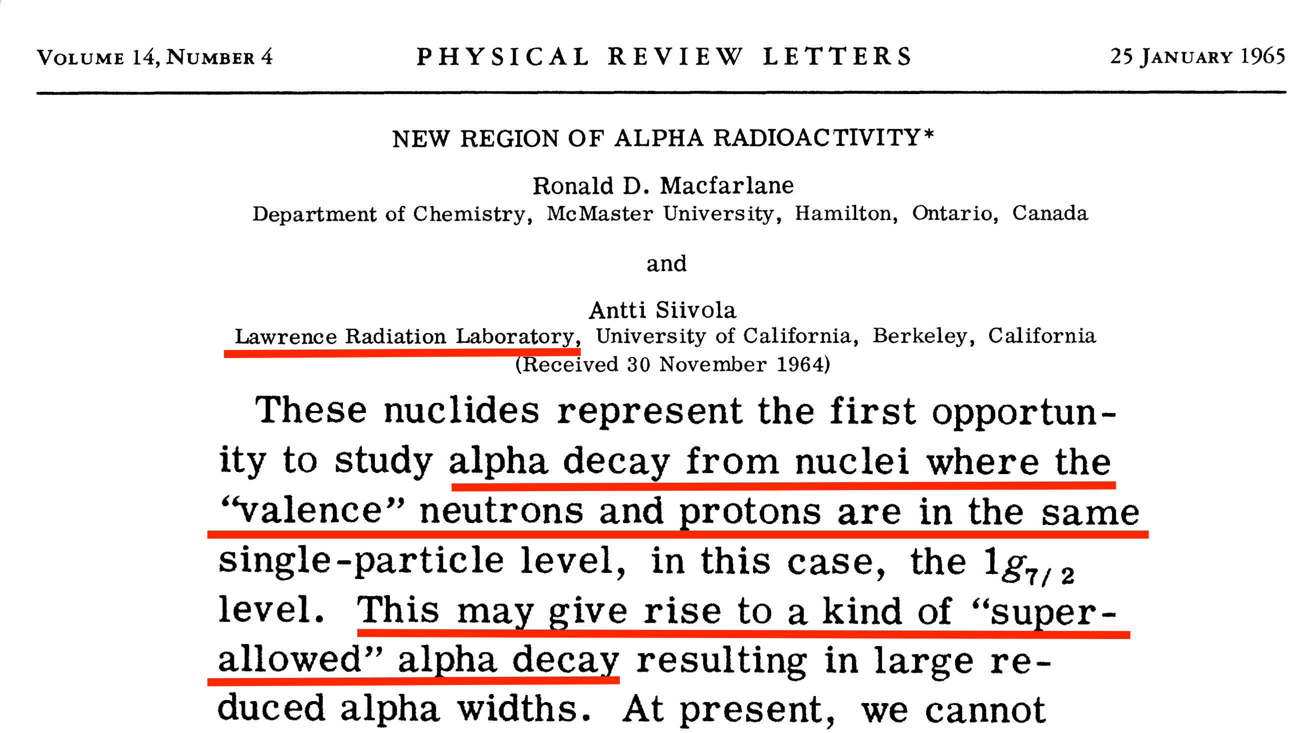
R.M. Clark and D. Rudolph, PRC 97 02433 (2018)

Modern “Geiger-Nuttall” Formula



$$\left.\begin{aligned}\log_{10}[T] &= -27.750 - 1.1138A^{\frac{1}{6}}\sqrt{Z} + \frac{1.6378Z}{\sqrt{Q}}\\ &\quad + \frac{1.7383\times 10^{-6}ANZ[l(l+1)]^{\frac{1}{4}}}{Q} + 0.002457A\left[1-(-1)^{l}\right]\end{aligned}\right\}\times 4\left\{\begin{array}{l}\text{even-odd}\\ \text{odd-even}\\ \text{odd-odd}\\ \text{even-even}\end{array}\right.$$

Superallowed Alpha Decay



VOLUME 14, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1965

NEW REGION OF ALPHA RADIOACTIVITY*

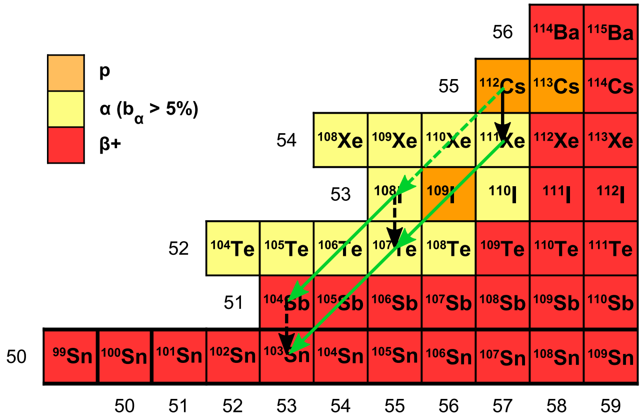
Ronald D. Macfarlane
Department of Chemistry, McMaster University, Hamilton, Ontario, Canada

and

Antti Siivola
Lawrence Radiation Laboratory, University of California, Berkeley, California

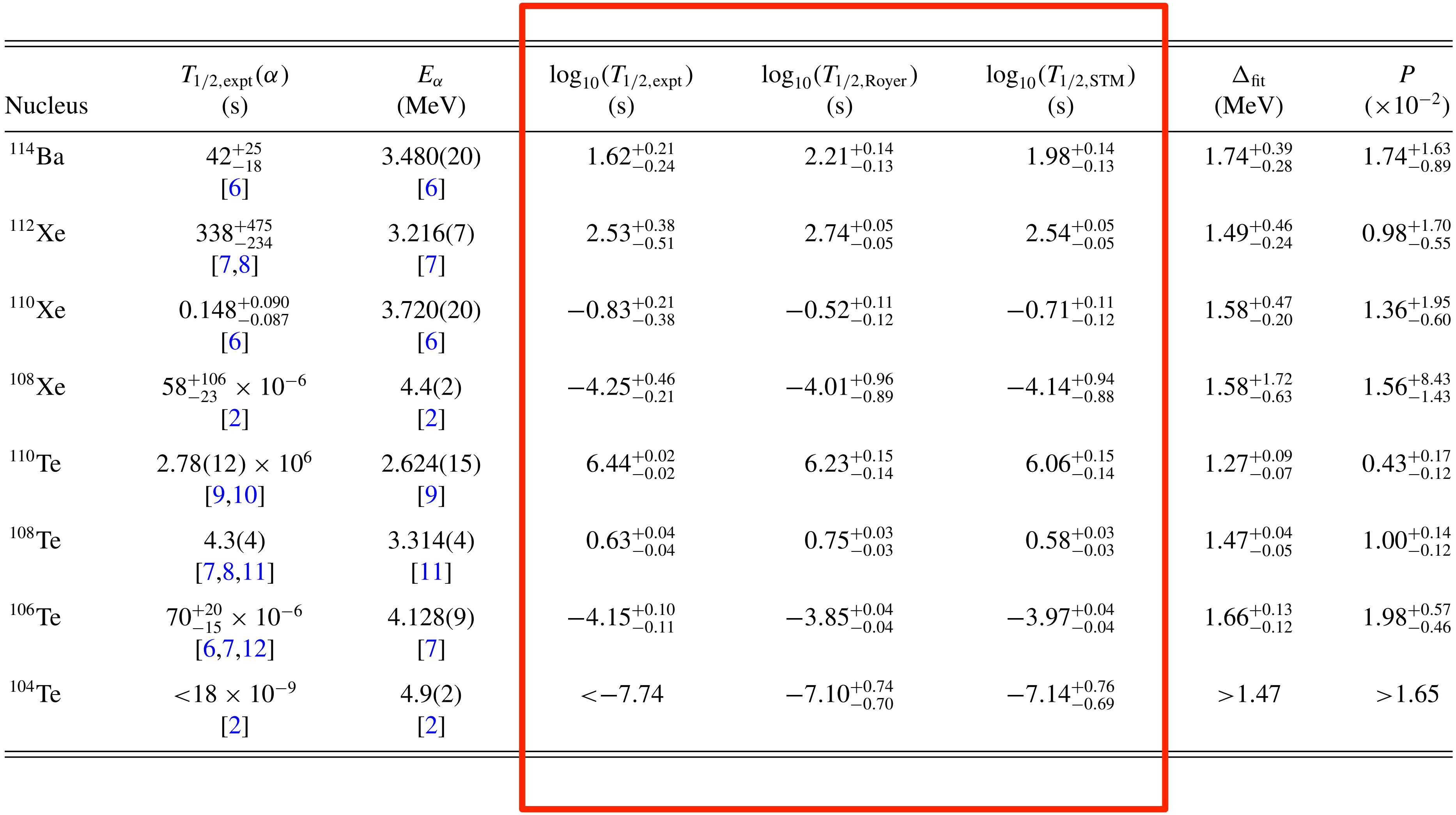
(Received 30 November 1964)

These nuclides represent the first opportunity to study alpha decay from nuclei where the "valence" neutrons and protons are in the same single-particle level, in this case, the $1g_{7/2}$ level. This may give rise to a kind of "superallowed" alpha decay resulting in large reduced alpha widths. At present, we cannot



K. Auranen et al., Phys. Lett. B 792 (2019) 187

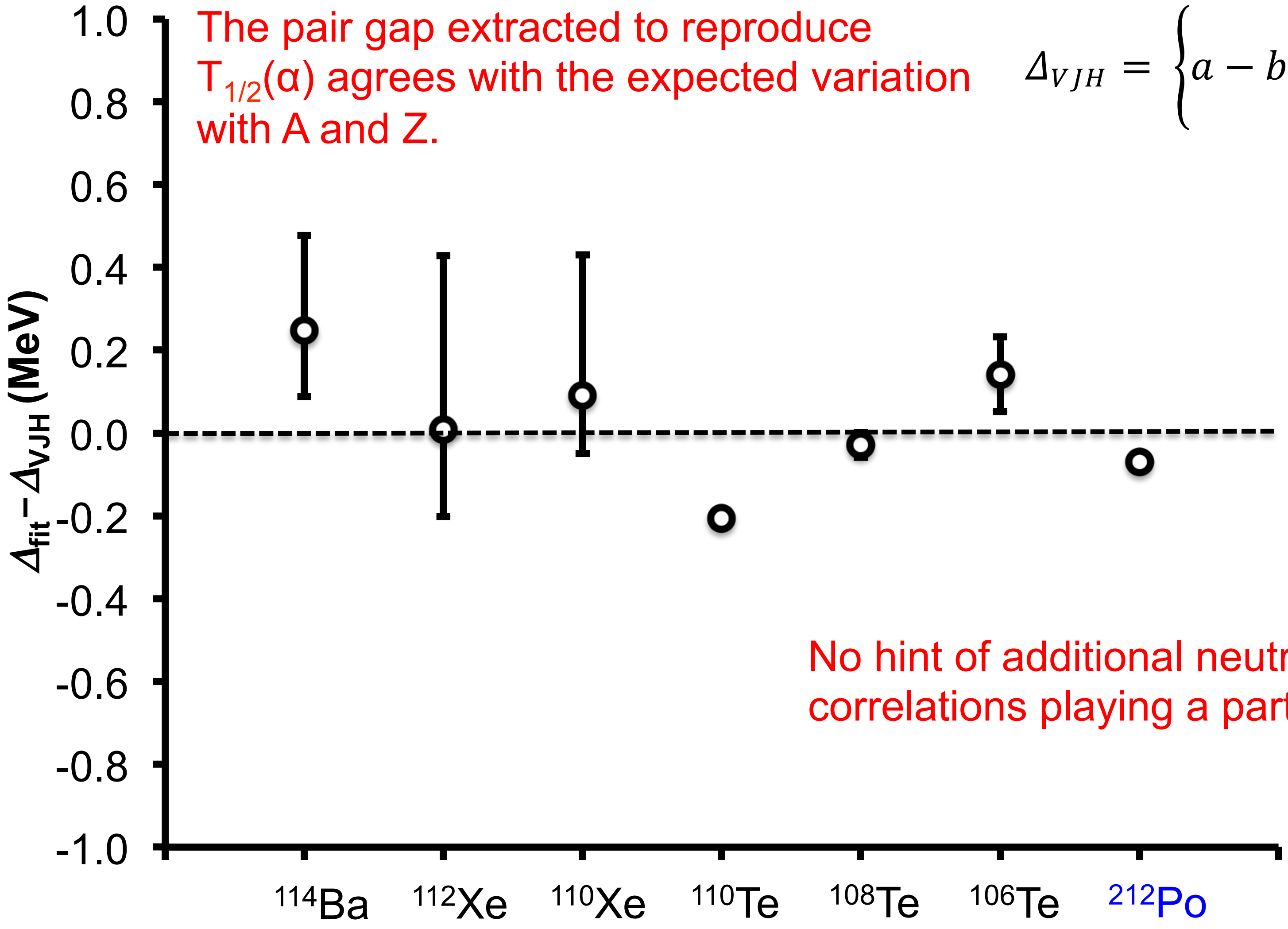
Experiment vs. Models



Nucleus	$T_{1/2,\text{expt}}(\alpha)$ (s)	E_α (MeV)	$\log_{10}(T_{1/2,\text{expt}})$ (s)	$\log_{10}(T_{1/2,\text{Royer}})$ (s)	$\log_{10}(T_{1/2,\text{STM}})$ (s)	Δ_fit (MeV)	P $(\times 10^{-2})$
^{114}Ba	42^{+25}_{-18} [6]	3.480(20) [6]	$1.62^{+0.21}_{-0.24}$	$2.21^{+0.14}_{-0.13}$	$1.98^{+0.14}_{-0.13}$	$1.74^{+0.39}_{-0.28}$	$1.74^{+1.63}_{-0.89}$
^{112}Xe	338^{+475}_{-234} [7,8]	3.216(7) [7]	$2.53^{+0.38}_{-0.51}$	$2.74^{+0.05}_{-0.05}$	$2.54^{+0.05}_{-0.05}$	$1.49^{+0.46}_{-0.24}$	$0.98^{+1.70}_{-0.55}$
^{110}Xe	$0.148^{+0.090}_{-0.087}$ [6]	3.720(20) [6]	$-0.83^{+0.21}_{-0.38}$	$-0.52^{+0.11}_{-0.12}$	$-0.71^{+0.11}_{-0.12}$	$1.58^{+0.47}_{-0.20}$	$1.36^{+1.95}_{-0.60}$
^{108}Xe	$58^{+106}_{-23} \times 10^{-6}$ [2]	4.4(2) [2]	$-4.25^{+0.46}_{-0.21}$	$-4.01^{+0.96}_{-0.89}$	$-4.14^{+0.94}_{-0.88}$	$1.58^{+1.72}_{-0.63}$	$1.56^{+8.43}_{-1.43}$
^{110}Te	$2.78(12) \times 10^{6}$ [9,10]	2.624(15) [9]	$6.44^{+0.02}_{-0.02}$	$6.23^{+0.15}_{-0.14}$	$6.06^{+0.15}_{-0.14}$	$1.27^{+0.09}_{-0.07}$	$0.43^{+0.17}_{-0.12}$
^{108}Te	4.3(4) [7,8,11]	3.314(4) [11]	$0.63^{+0.04}_{-0.04}$	$0.75^{+0.03}_{-0.03}$	$0.58^{+0.03}_{-0.03}$	$1.47^{+0.04}_{-0.05}$	$1.00^{+0.14}_{-0.12}$
^{106}Te	$70^{+20}_{-15} \times 10^{-6}$ [6,7,12]	4.128(9) [7]	$-4.15^{+0.10}_{-0.11}$	$-3.85^{+0.04}_{-0.04}$	$-3.97^{+0.04}_{-0.04}$	$1.66^{+0.13}_{-0.12}$	$1.98^{+0.57}_{-0.46}$
^{104}Te	$< 18 \times 10^{-9}$ [2]	4.9(2) [2]	< -7.74	$-7.10^{+0.74}_{-0.70}$	$-7.14^{+0.76}_{-0.69}$	> 1.47	> 1.65

R.M. Clark et al., Phys. Rev. C 101 034313 (2020)

STM Pair Gaps vs. Expectation



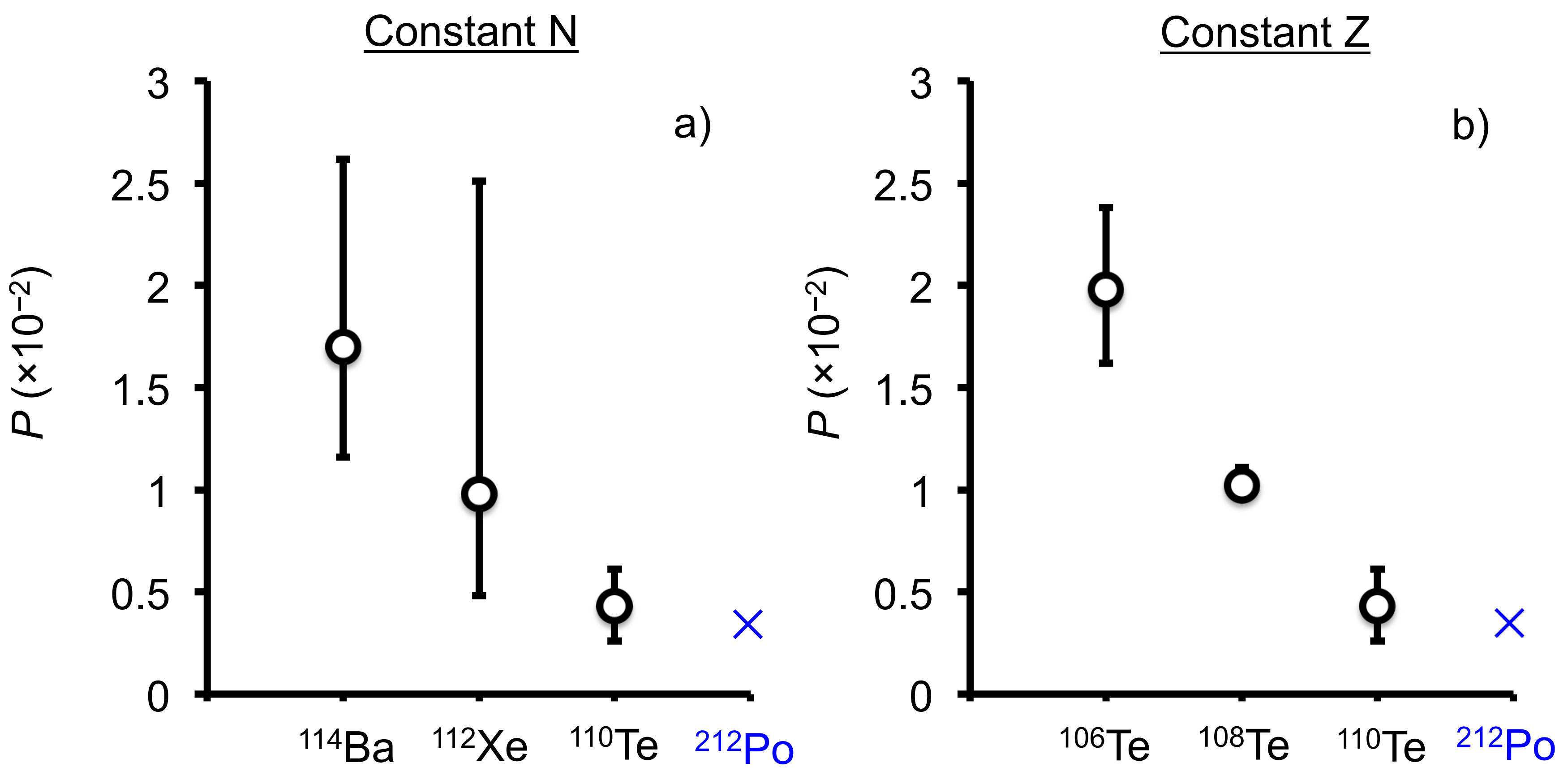
The pair gap extracted to reproduce $T_{1/2}(\alpha)$ agrees with the expected variation with A and Z.

$$\Delta_{VJH} = \left\{a - b\left[\frac{(N-Z)}{A}\right]^2\right\} A^{-1/3}$$

No hint of additional neutron-proton correlations playing a part.

P. Vogel, B. Jonson, and P.G. Hansen, Phys. Lett. B **139**, 227 (1984).

Extracted Alpha-Particle-Formation Probabilities, *P*

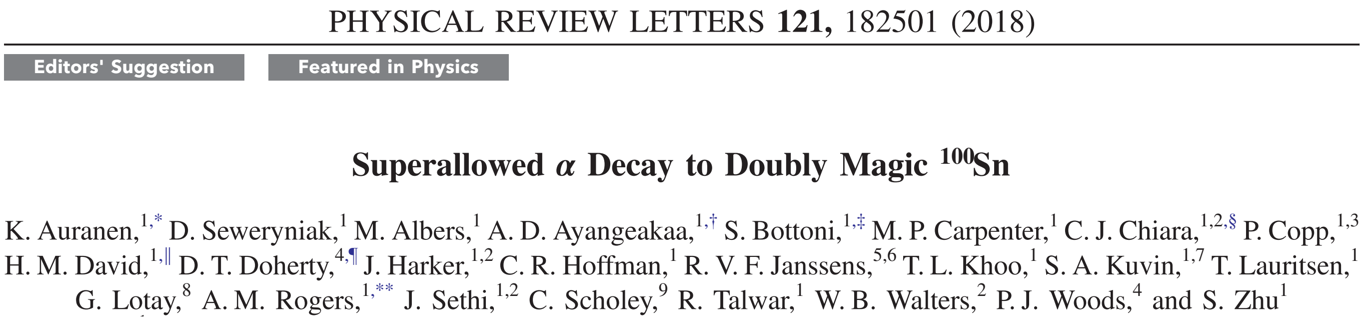


However, the "expected" variation of the pairing does lead to an increase in the formation probability of the alpha particle, *P*, as one approaches N=Z.

R.M. Clark et al., Phys. Rev. C 101 034313 (2020)

Alpha Decay Chain ^{108}Xe→^{104}Te→^{100}Sn

If extra proton-neutron correlations then the effect is likely to be biggest at N=Z. They would show up in unrealistically large values for the fitted pairing gaps.

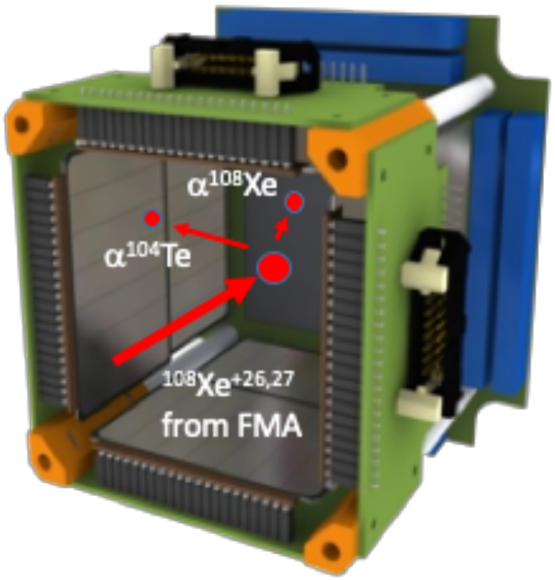


PHYSICAL REVIEW LETTERS **121,** 182501 (2018)

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]



Two events (!) with the average properties: ^{108}Xe

E_α=4.4(2) MeV

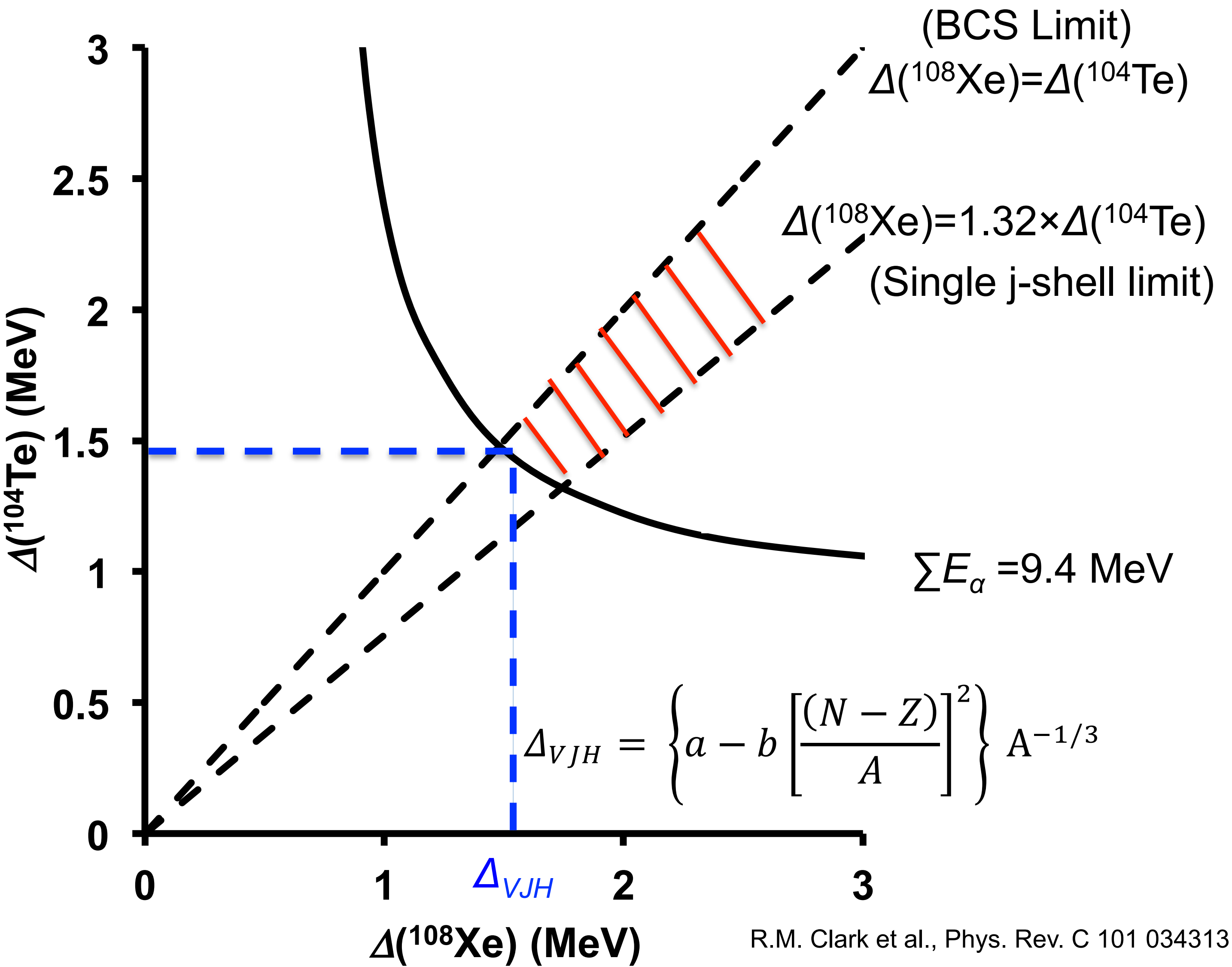
$T_{1/2} = 58^{+106}_{-23}$ μs

^{104}Te

E_α=4.9(2) MeV

$T_{1/2} < 18$ ns.

Exclusion Plot for Pairing Gaps



$$\Delta_{VJH} = \left\{a - b\left[\frac{(N-Z)}{A}\right]^2\right\} A^{-1/3}$$

R.M. Clark et al., Phys. Rev. C 101 034313 (2020)

Summary

Superfluid Tunneling Model

- Able to reproduce known data on alpha decay
- All ingredients (Q_α, L, Δ) essential to understanding

In the ^{100}Sn region

- Alpha preformation is larger near ^{100}Sn than ^{208}Pb
- Expected due to variation of pair gap
- Current data on N=Z nuclei ^{104}Te and ^{108}Xe still leave open possibility of superallowed alpha decay

Future Experiments at FRIB

	^{108}Xe		^{112}Ba	
FRIB Phase	Day 1	Max	Day 1	Max
Primary Beam	^{124}Xe	^{124}Xe	^{238}U	^{238}U
Rate	7.6×10^{-4}	3.0×10^{-2}	1.0×10^{-6}	3.0×10^{-3}
Per Day	65	2600	0.1	260

^{108}Xe should be feasible on Day One, ^{112}Ba comes into reach later

Thanks!

Extra Slides

Inertia

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

Inertial mass parameter,

$$D=-\frac{\hbar^2}{2v}n^2$$

n is the number of level crossings in rearrangement (n=4)

v is the interaction matrix element,

$$\begin{aligned}v &\approx -G\langle \mathrm{BCS}\left|P_{\mathrm{d}}^{\dagger}\right|\mathrm{BCS}\rangle\langle \mathrm{BCS}\,|P_{\mathrm{u}}|\,\mathrm{BCS}\rangle\\ &\approx -\frac{G}{4}\langle \mathrm{BCS}\,|P|\,\mathrm{BCS}\rangle^2=-\frac{1}{4}\frac{\Delta^2}{G},\end{aligned}$$

Inertial mass parameter, *D*, is dependent on pairing gap, *Δ*.

Potential Energy

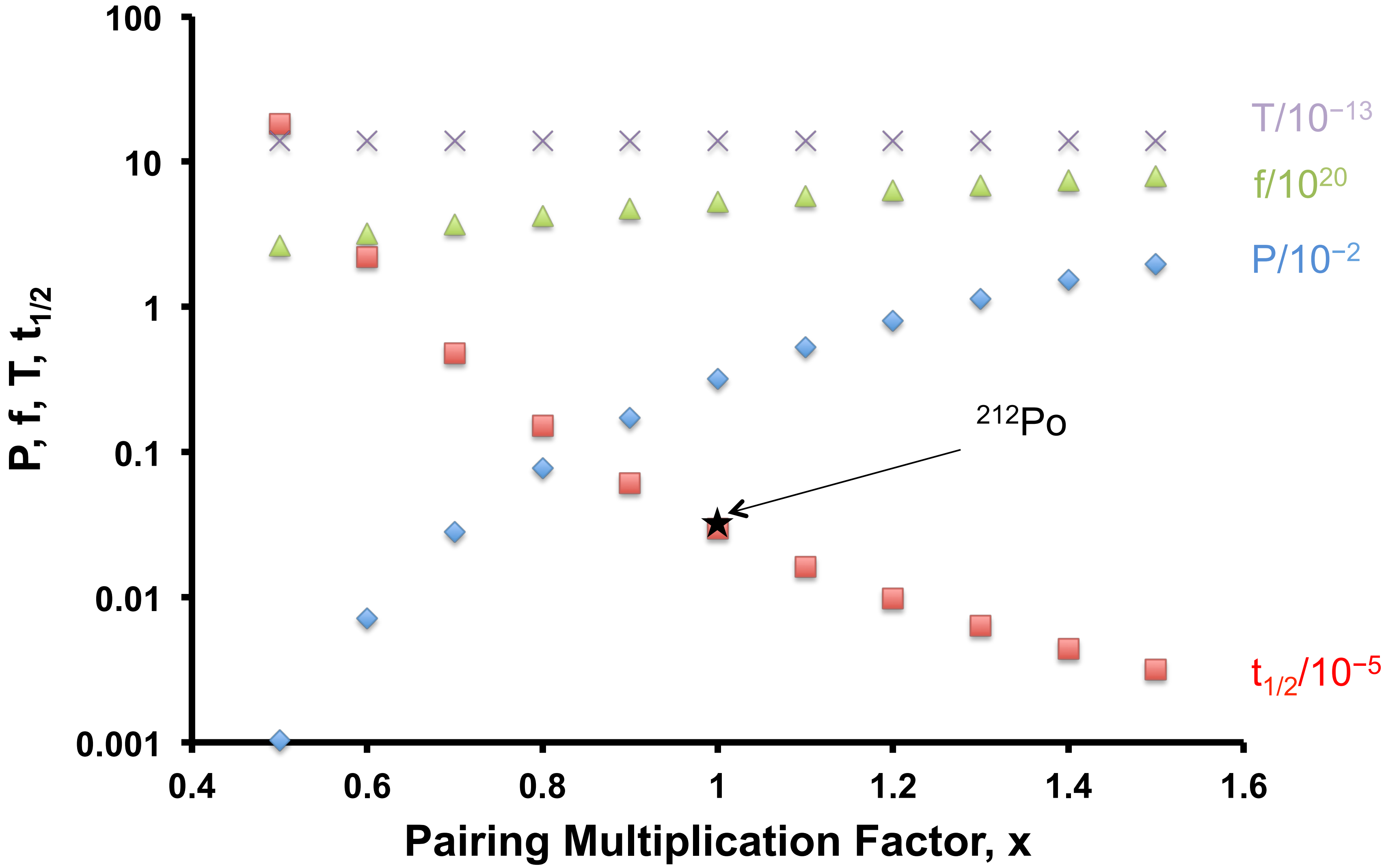
$$\left[-\frac{\hbar^2}{2D}\frac{\partial^2}{\partial\xi^2}+V(\xi)\right]\psi_n(\xi)=E_n\psi_n(\xi)$$

$$V(\xi)=\tfrac{1}{2}C\xi^2$$

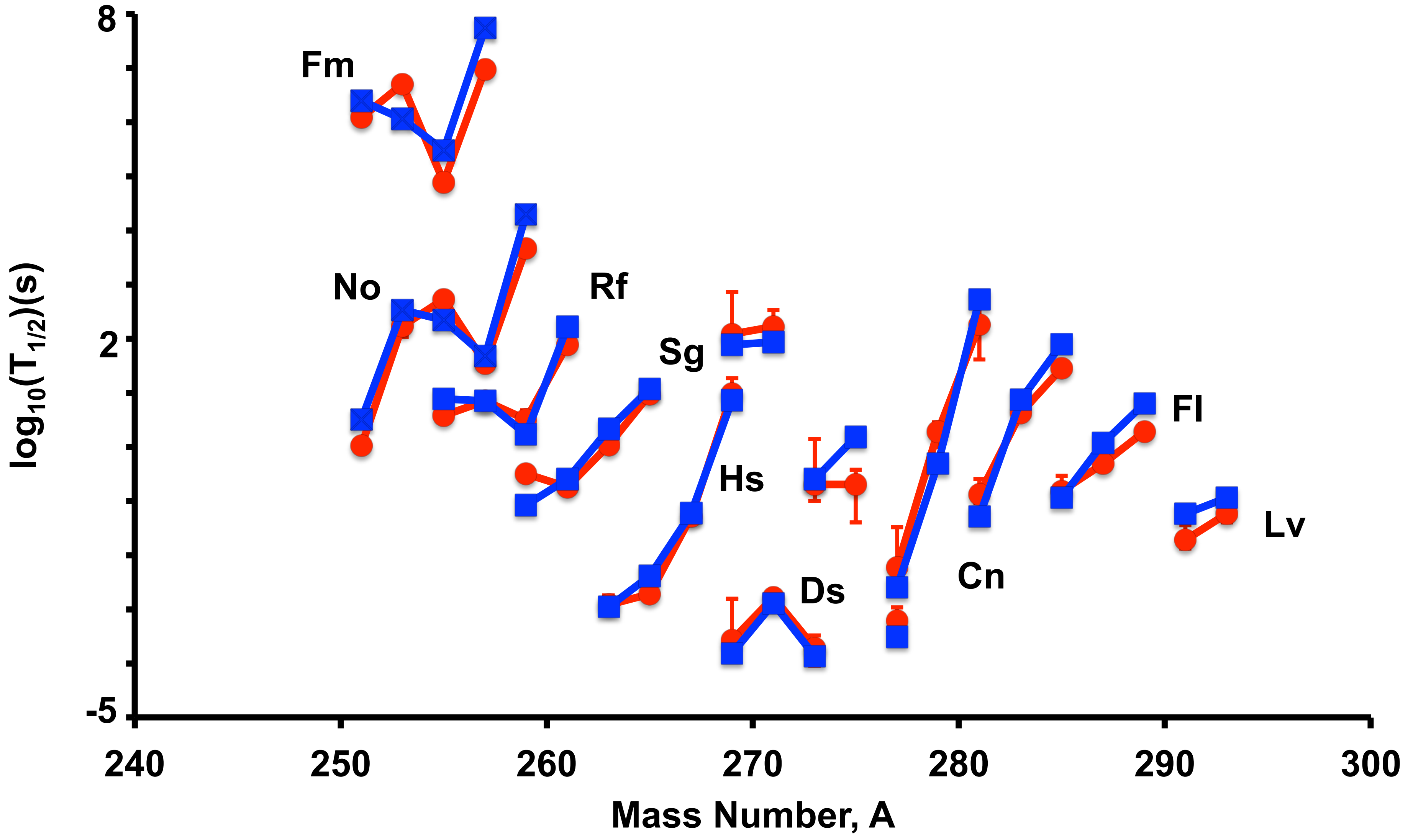
$$V(\xi=1) = V_n + V_c - Q = C/2$$

Potential energy parameter, *C*, is dependent on *Q*-value

Dependence on Pairing Gap, $\Delta = x\Delta_0$



Even-Z, Odd-N SHN



Using the STM: Variation of *Δ* with *A* and *Z*

Bohr and Mottelson:

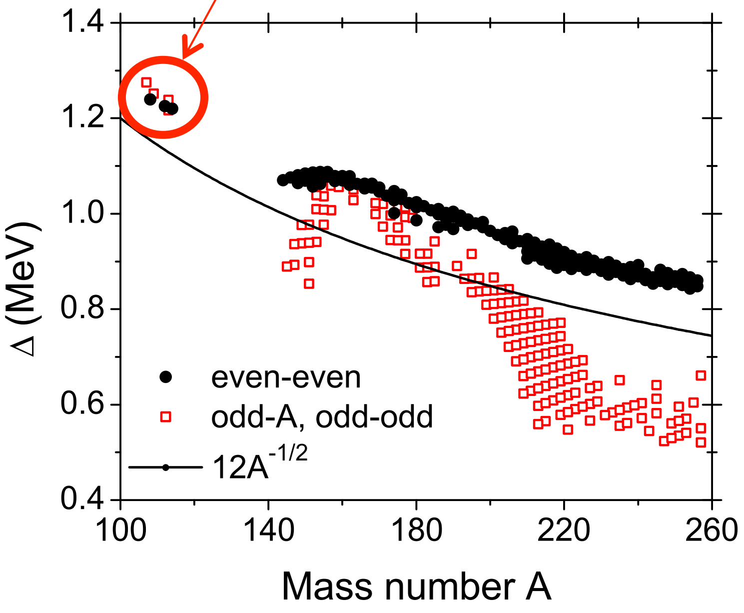
$$\Delta_{BM} = 12\ \mathrm{A}^{-1/2}\ MeV$$

Vogel, Jonson, Hansen:

$$\Delta_{VJH} = \left\{a - b\left[\frac{(N-Z)}{A}\right]^2\right\}\mathrm{A}^{-1/3}$$

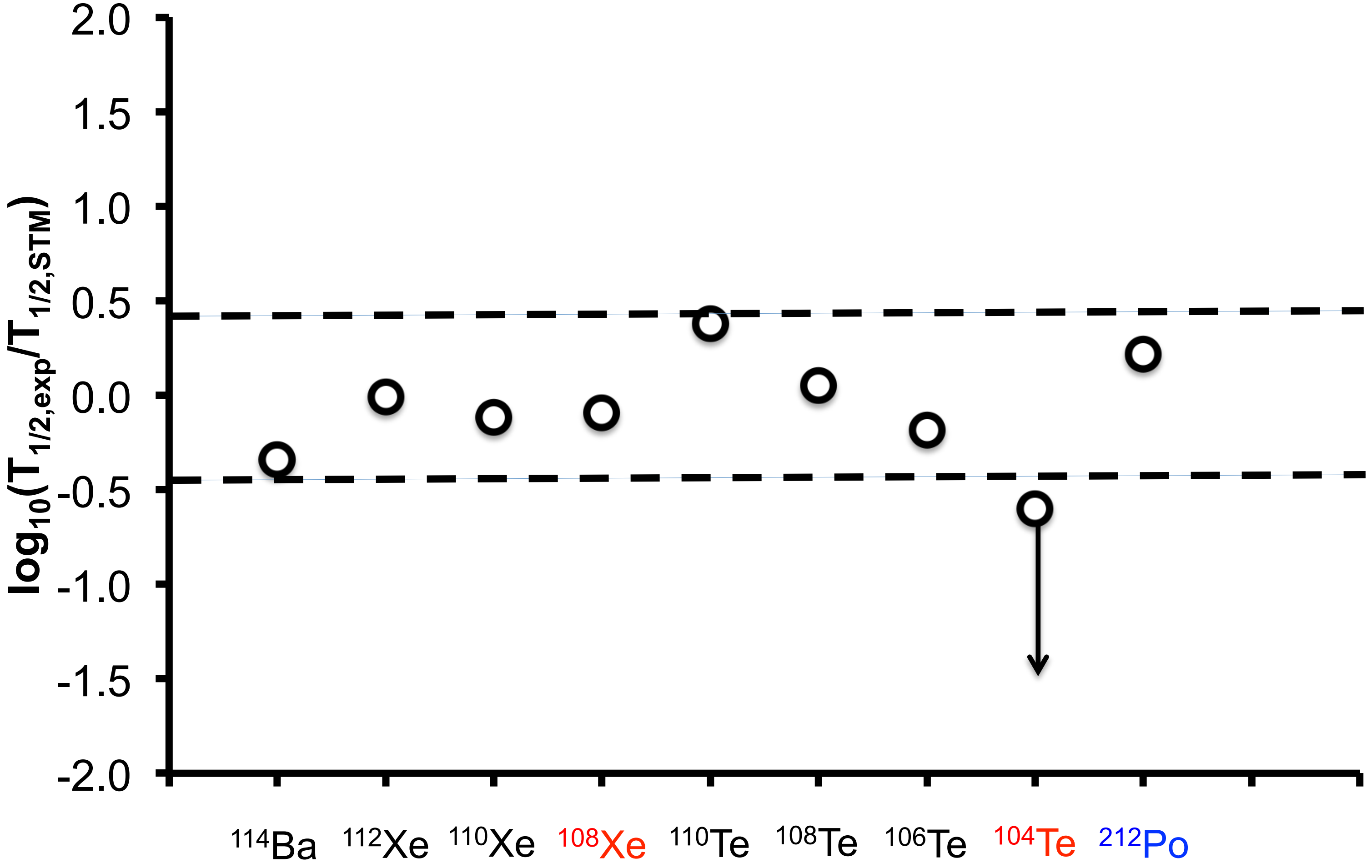
a=7.2 MeV and *b* =44MeV

First hint that nothing unusual about “superallowed” decay?

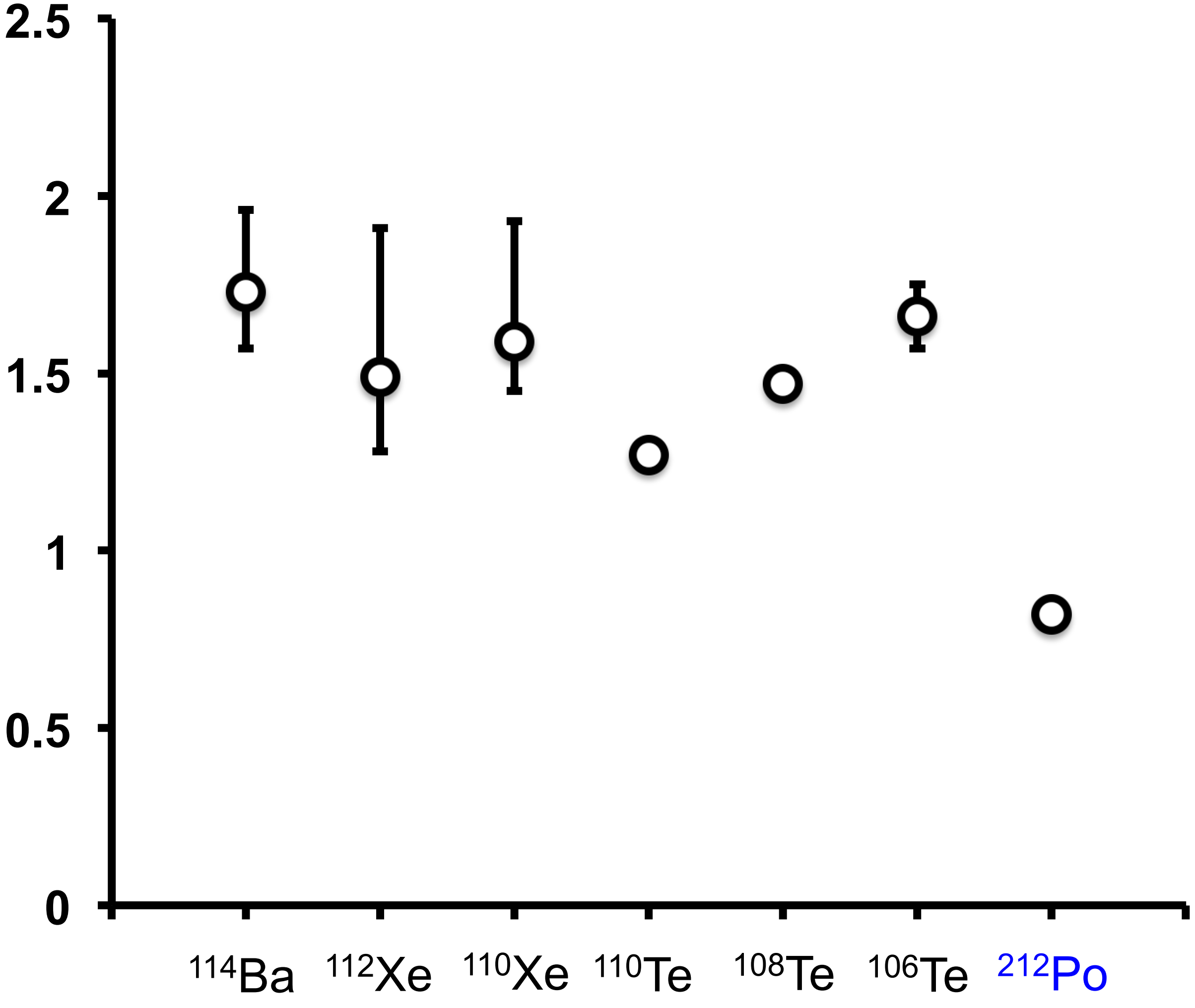


A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 1.
P. Vogel, B. Jonson, and P.G. Hansen, Phys. Lett. B **139**, 227 (1984).

STM vs. Experiment



Extracted Values of *Δ*



What About N=Z?

If extra proton-neutron correlations are contributing then the effect is likely to be biggest with the N=Z chain $^{108}\text{Xe} \rightarrow {}^{104}\text{Te} \rightarrow {}^{100}\text{Sn}$.

They would show up in unrealistically large values for the fitted pairing gaps.

^{108}Xe, E_α=4.4(2) MeV, $T_{1/2} = 58^{+106}_{-23}$ μs

^{104}Te, E_α=4.9(2) MeV, $T_{1/2} < 18$ ns.

The sum of the alpha energy is better constrained to value of 9.3(1)MeV

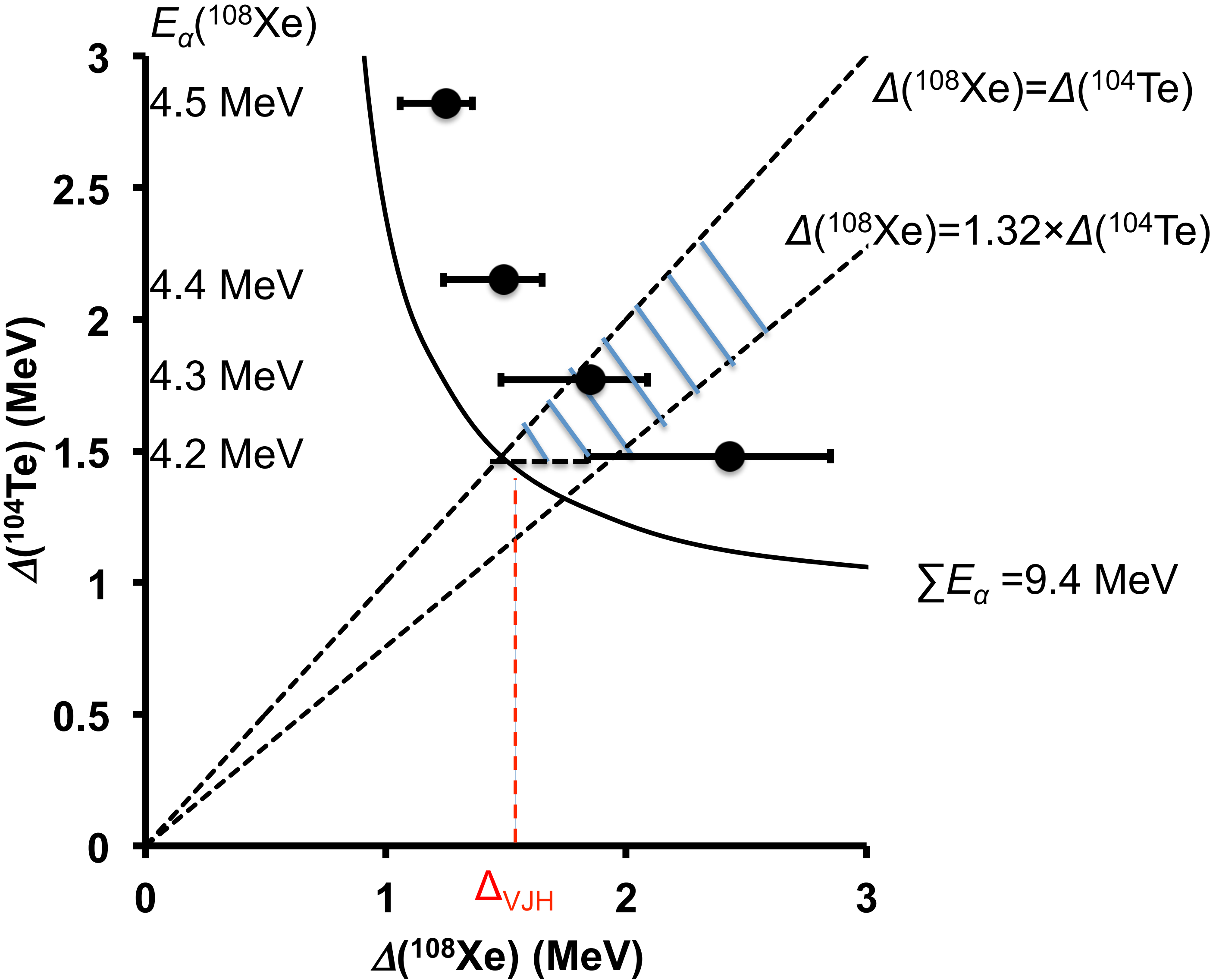
Also, assuming BCS applies, $\Delta(^{108}\text{Xe}) > \Delta(^{104}\text{Te})$

In case of pure pairing in single-j shell:

$$\Delta = G\sqrt{\frac{n}{2}\left(\Omega - \frac{n}{2}\right)}$$

Implying maximum of $\Delta(^{108}\text{Xe}) = 1.32 \times \Delta(^{104}\text{Te})$

Exclusion Plot for Pairing Gaps



New Results from JAEA

Search for α decay of 104 Te with a novel recoil-decay scintillation detector
Phys. Rev. C, Y. Xiao et al., Accepted16 August 2019

ABSTRACT

A search for super-allowed α decay of N=Z nuclei104Te and 108Xe was carried out using novel recoil-decay scintillator detector at the tandem accelerator facility at Japan Atomic Energy Agency (JAEA). Inorganic crystal scintillation material of YAP:Ce (Yttrium Aluminium Perowskite) coupled to position-sensitive photo-multiplier tube (PSPMT) was implemented for the first time in radioactive decay experiment. Residues from the fusion-evaporation reaction 58Ni+54Fe→ 112Xe∗ were separated by the JAEA Recoil Mass Separator (RMS) and implanted into the YAP:Ce crystal. α decays of neutron-deficient tellurium isotopes were identified and proton-emission of 109I was observed. The α decay chain 109Xe →105Te → 101Sn was recorded with time interval of 960 ns between two αpulses. Position localization in the crystal for decays and ions in the energy range from hundreds keV to 60 MeV was achieved with the accuracy of 0.67 mm, proving that this detector is capable of making temporal and spatial correlations for fast decay events. No conclusive evidence was found for the decay chain 108Xe → 104Te → 100Sn within 3 days experiment. However, two events were observed with properties consistent with the reported observation at Fragment Mass Analyzer (FMA) but with the separation between signals less than 4 ns. The cross section limit of 130 pb was obtained for production of two events of 108Xe, about an order of magnitude below the expectation based on earlier cross section measurements and HIVAP fusion-evaporation code.

$T_{1/2}(^{104}\mathrm{Te})<4\mathrm{ns}?$

Exclusion Plot for Pairing Gaps