Superallowed α decay to doubly magic ^{100}Sn

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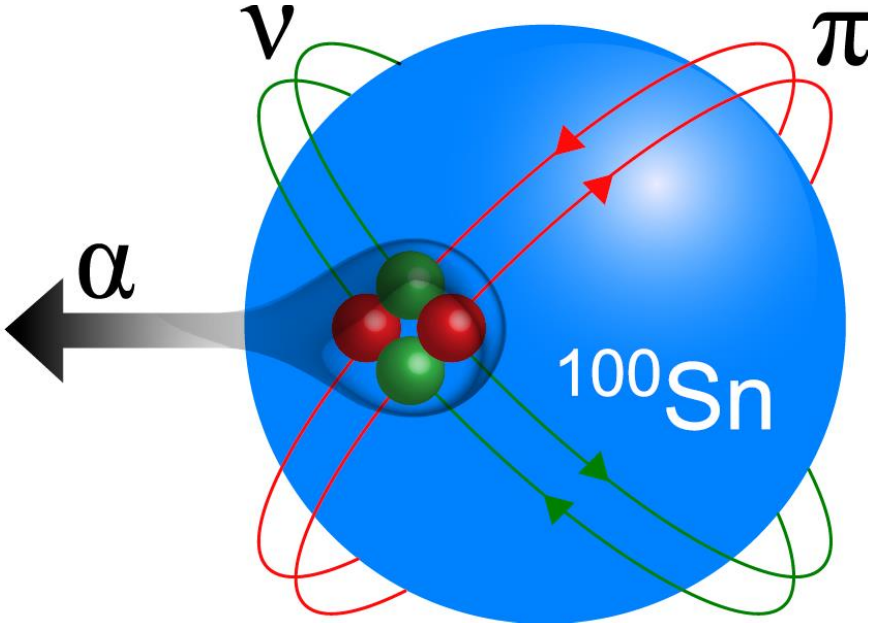


Symposium “Developments of Physics of Unstable Nuclei”

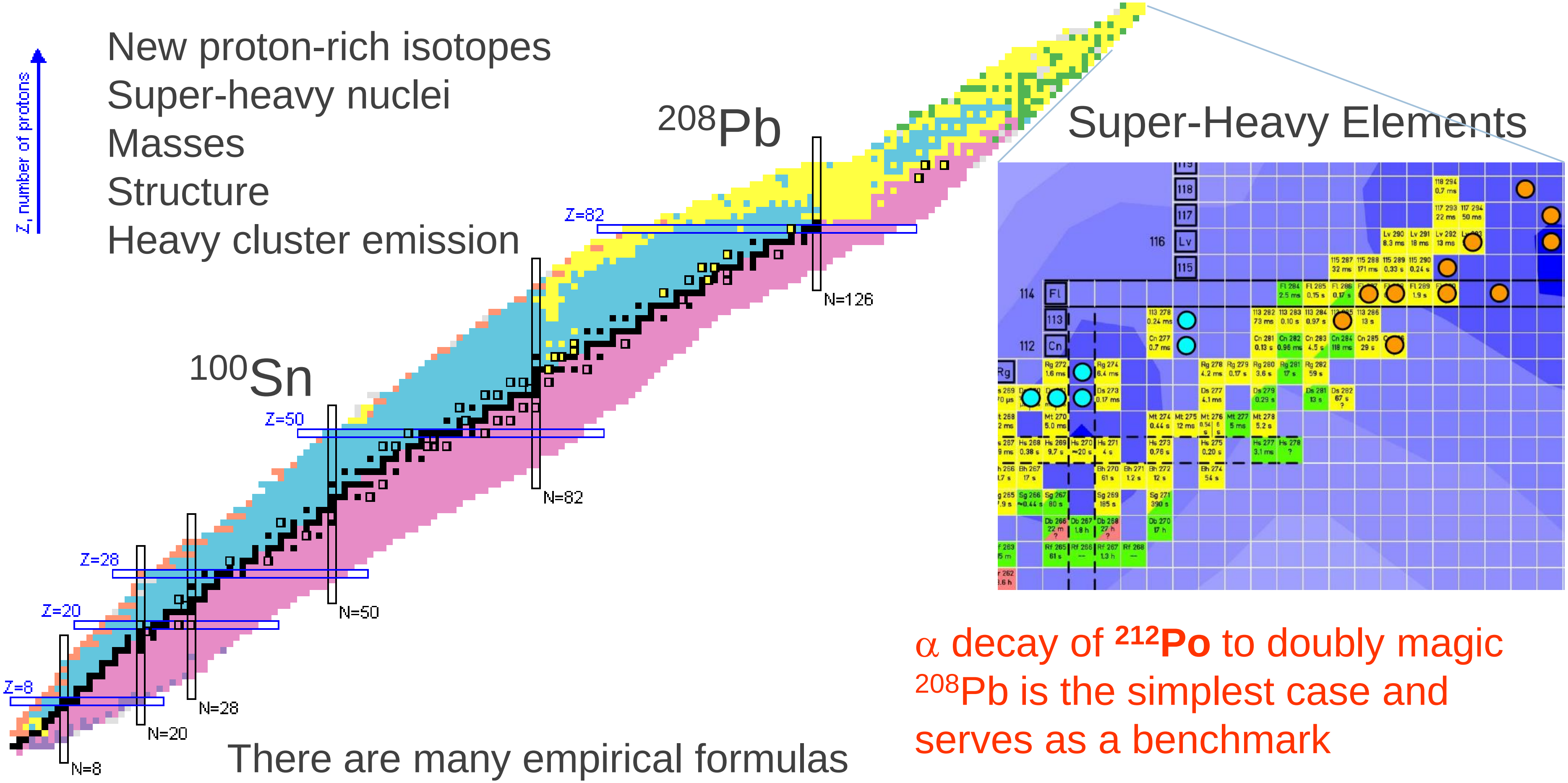
Yukawa International Seminar YKIS2022b

Outline

- Alpha decay landscape
- Microscopic description of α decay
- Doubly-magic ^{100}Sn
- Observation of the ^{108}Xe-^{104}Te-^{100}Sn α decay chain
- Discussion of α-decay reduced widths
  - ^{208}Pb region vs ^{100}Sn region
  - theoretical calculations for ^{104}Te
- Summary and Outlook

Alpha-decay landscape

New proton-rich isotopes
Super-heavy nuclei
Masses
Structure
Heavy cluster emission



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

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

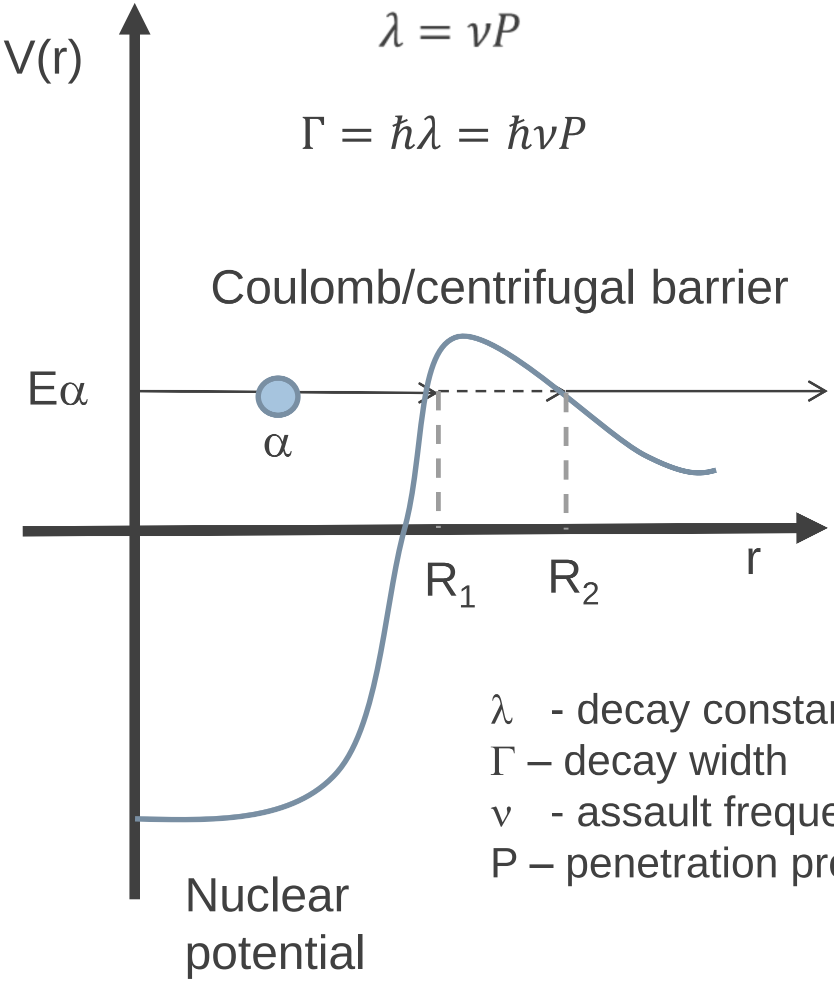
α decay of **^{104}Te** to doubly magic ^{100}Sn, enhanced α preformation factor due to strong π-ν interaction, **superallowed α decay**

Gamow alpha-decay model

G. Gamow, Z. Phys. 51, 204 (1928)
Probabilistic interpretation of quantum mechanics

$$\lambda = \nu P$$

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



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

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

Can be readily calculated
Very steep function of Q-value

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

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

δ^2 - reduced α decay width,
often normalized to ^{212}Po
(~α preformation factor)

R-matrix expression of the alpha-decay width

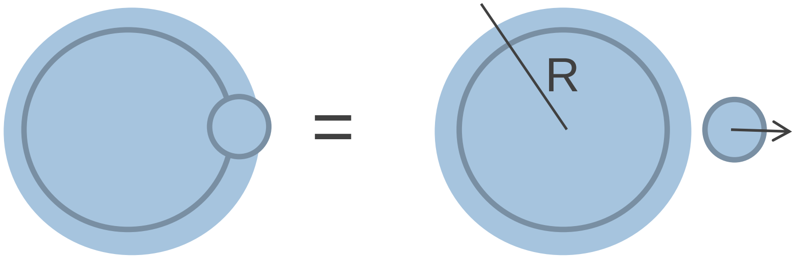
Decay width:

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

$P_L(R)$ - 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:

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

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

Spectroscopic factor formulation

Decay width:

$$\Gamma_L = S_L \Gamma_L^{sp}$$

Γ^{sp}_L – single-particle decay width
L – α angular momentum

Spectroscopic factor:

$$S_L = \left|\left\langle \mathcal{A}\left[\phi_\alpha(\xi_\alpha)\ \Psi_j^D(\xi_D)\ \psi_L(\boldsymbol{R})\right]_{JM} \middle| \Phi^P_{JM}\right\rangle\right|^2$$

α particle

daughter nucleus

relative motion

parent nucleus

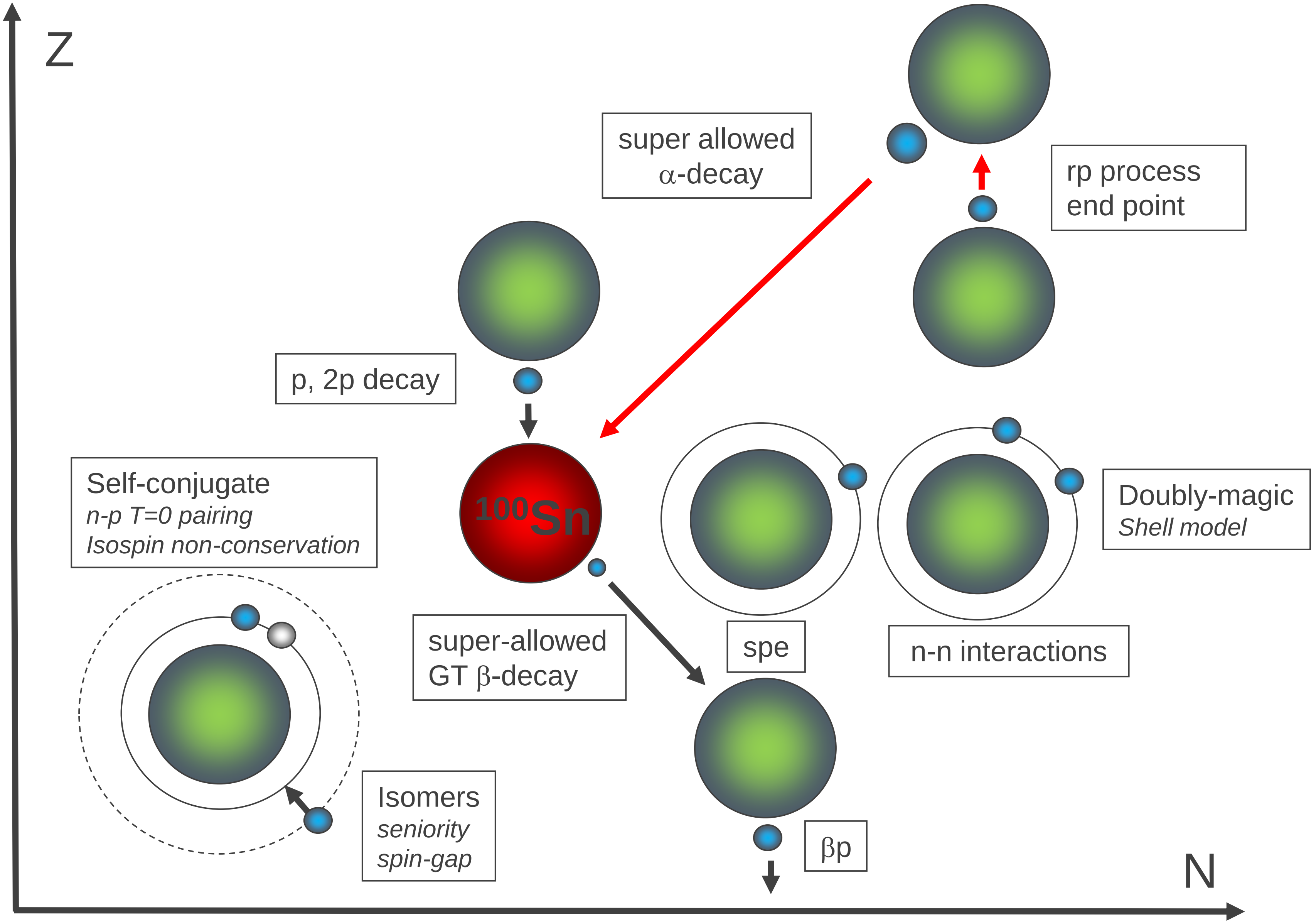
probability of finding α particle in the parent nucleus

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

^{100}Sn physics



super allowed
α-decay

rp process
end point

p, 2p decay

Self-conjugate
n-p T=0 pairing
Isospin non-conservation

super-allowed
GT β-decay

spe

n-n interactions

Doubly-magic
Shell model

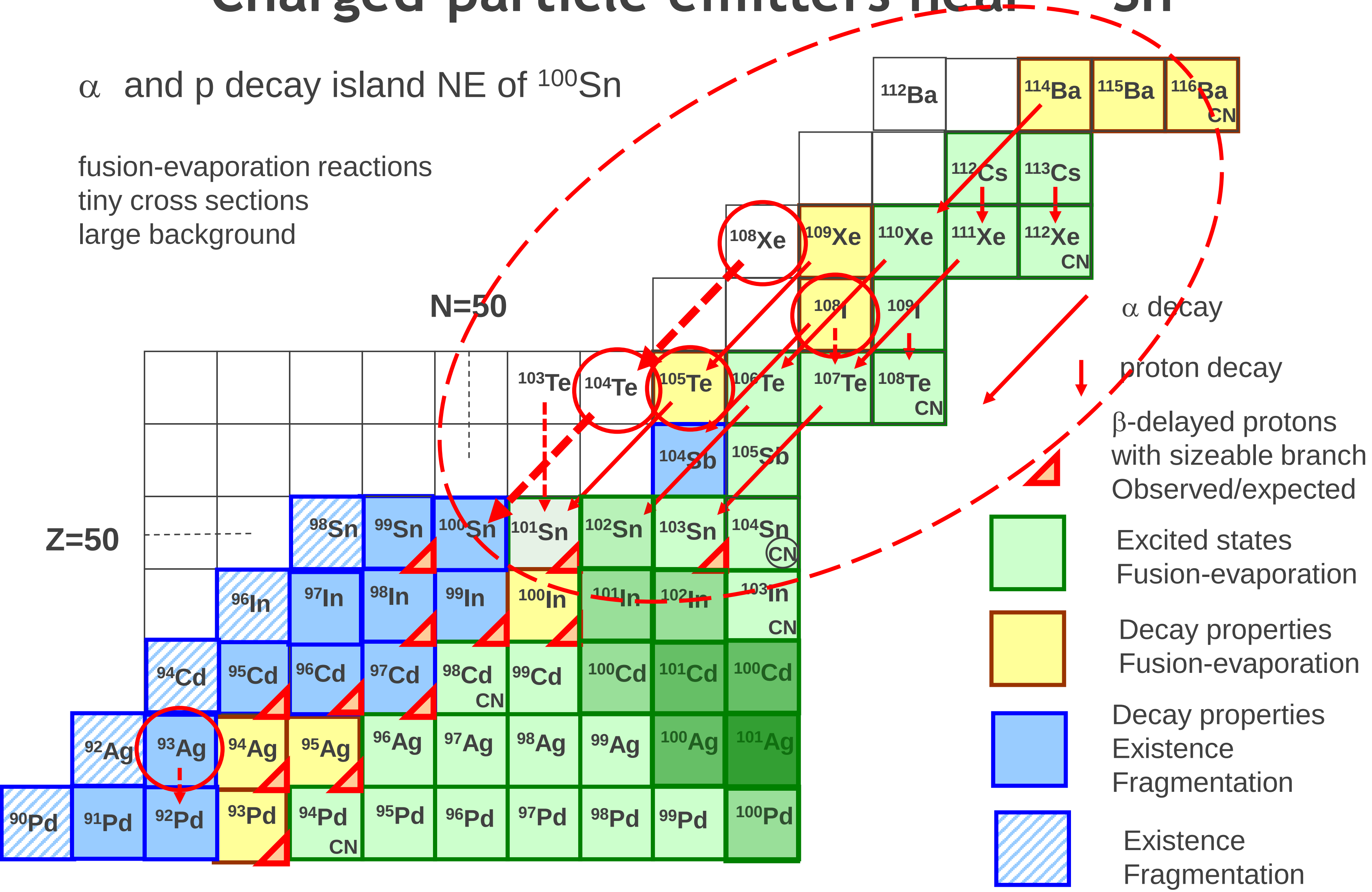
Isomers
seniority
spin-gap

βp

Charged-particle emitters near ^{100}Sn

α and p decay island NE of ^{100}Sn

fusion-evaporation reactions
tiny cross sections
large background



α decay

proton decay

β-delayed protons
with sizeable branch
Observed/expected

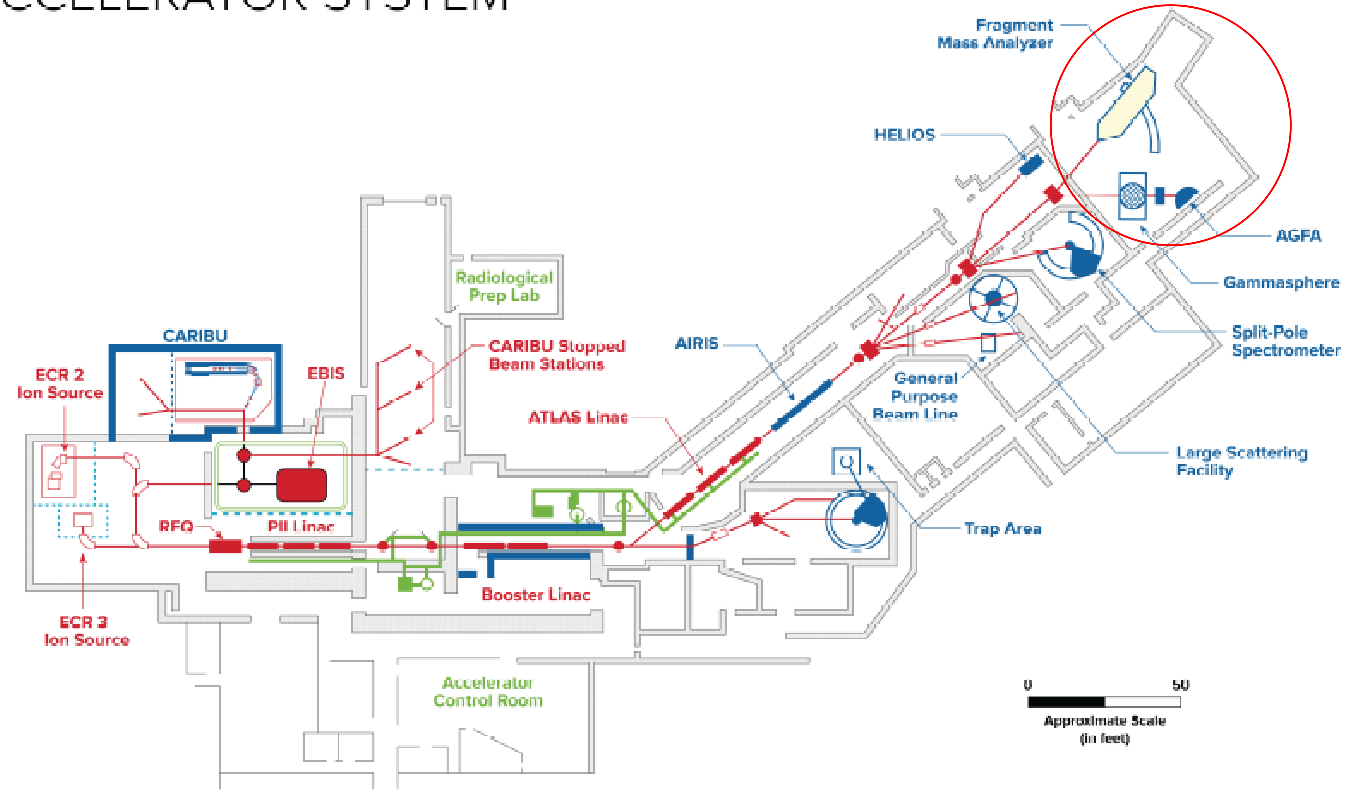
🟩 Excited states
Fusion-evaporation

🟨 Decay properties
Fusion-evaporation

🟦 Decay properties
Existence
Fragmentation

▨ Existence
Fragmentation

ATLAS
ARGONNE TANDEM LINEAR ACCELERATOR SYSTEM



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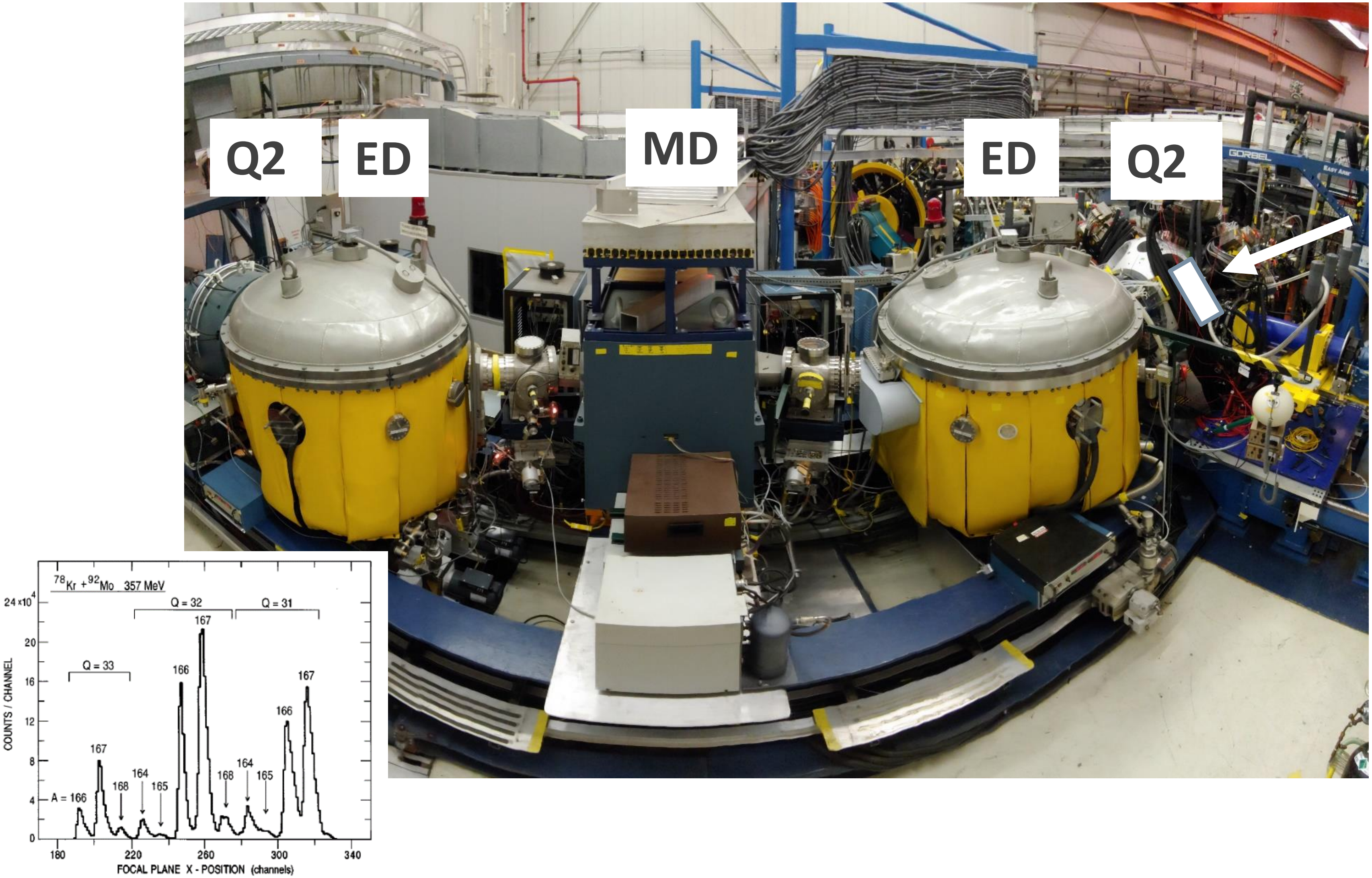
RP071701

Triple LINAC: beam from H to U up to 10 MeV/n

In-flight radioactive beams with RASOR separator

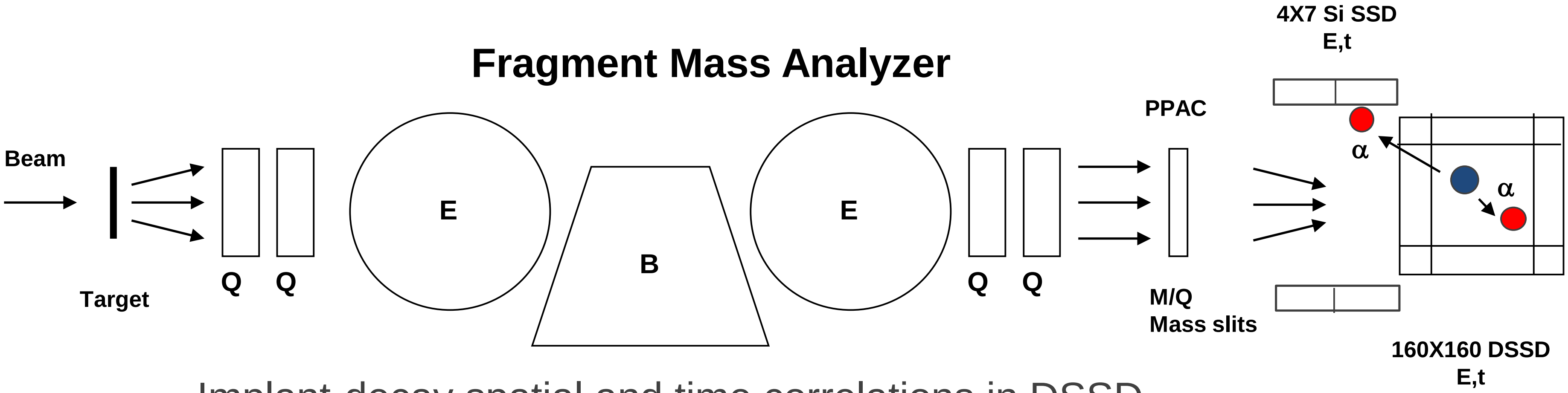
CARIBU - ^{252}Cf fission fragment beams

Argonne Fragment Mass Analyzer



YKIS2022b

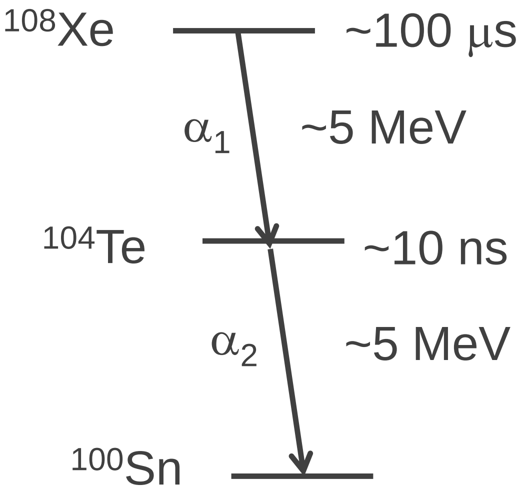
Super-allowed α decay ^{108}Xe-^{104}Te-^{100}Sn

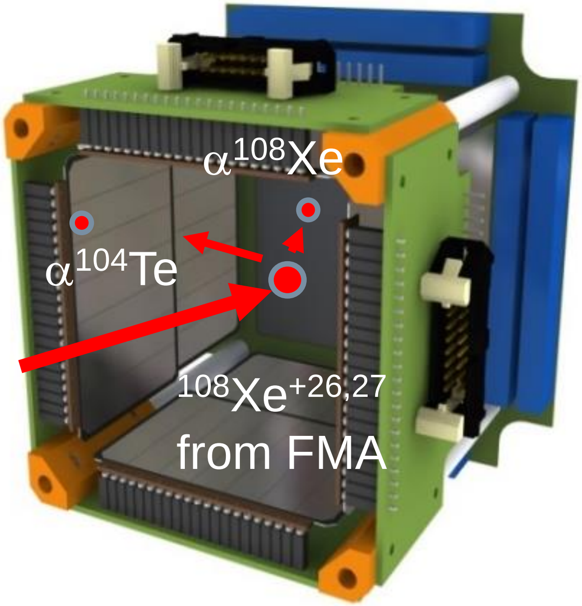


Fragment Mass Analyzer

Implant-decay spatial and time correlations in DSSD

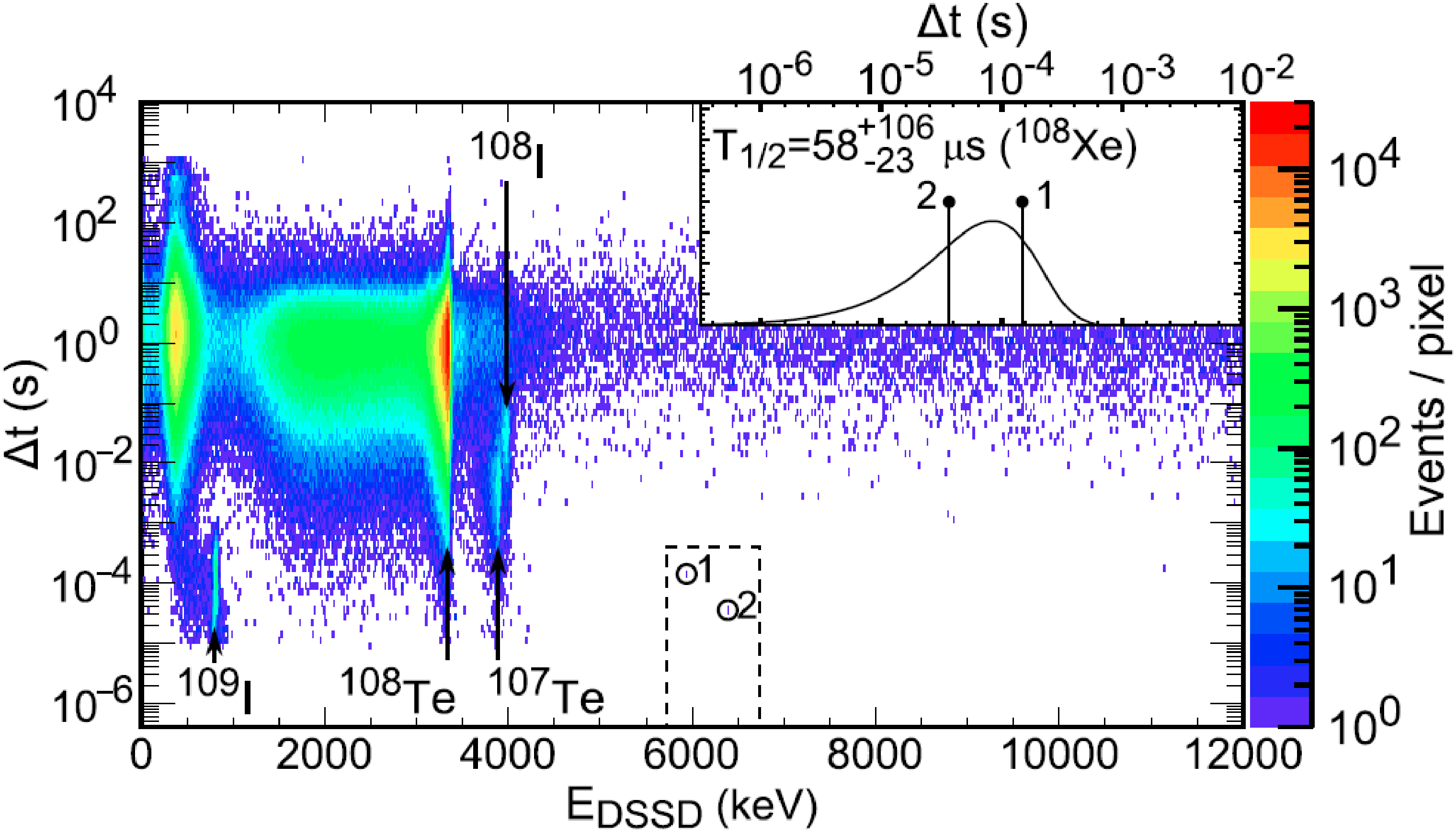
^{58}Ni(^{54}Fe,4n)^{108}Xe reaction, **cross section 100 pb out of 1b!**





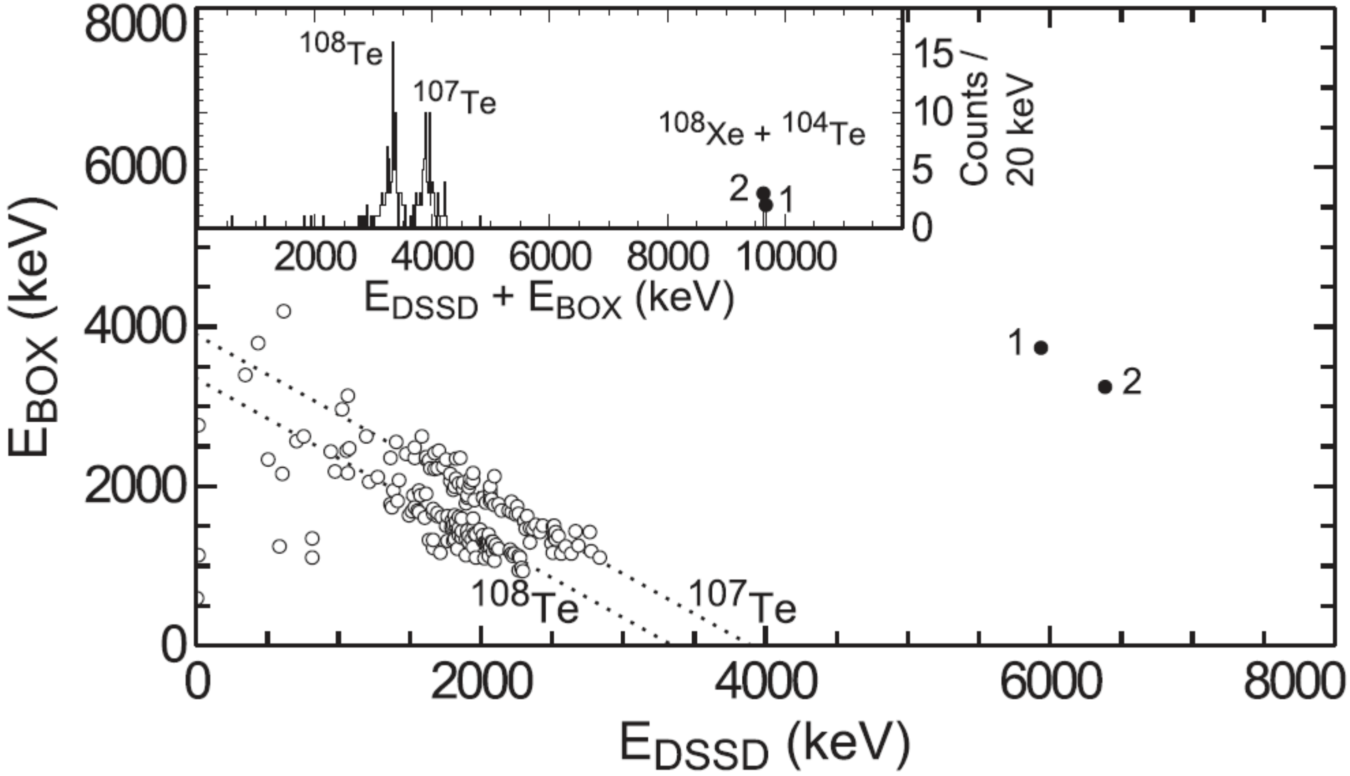
Digital DAQ to detect
$\alpha\,^{108}$Xe-$\alpha\,^{104}$Te pileup
Si box to catch
escaping alphas

Recoil-decay correlations



TWO fast high energy decay events
Expected **0.09** random events
BOTH events where in coincidence with the Si box (1 out of 400)

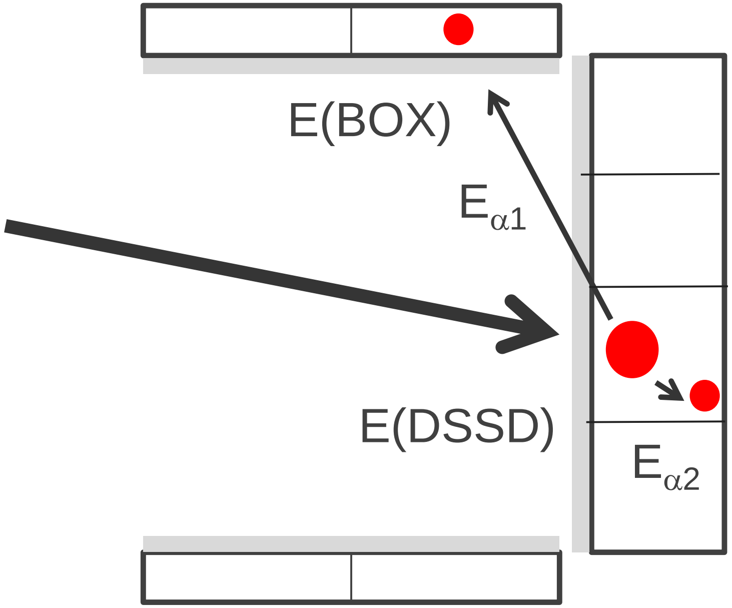
DSSD-Si box coincidences



- The same total energy for both events - **ΣE_α=9.3(1) MeV**
- Compared to α emitters different energy split

E_α(^{104}Te)=4.9(2) MeV, E_α(^{108}Xe)=4.4(2) MeV

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

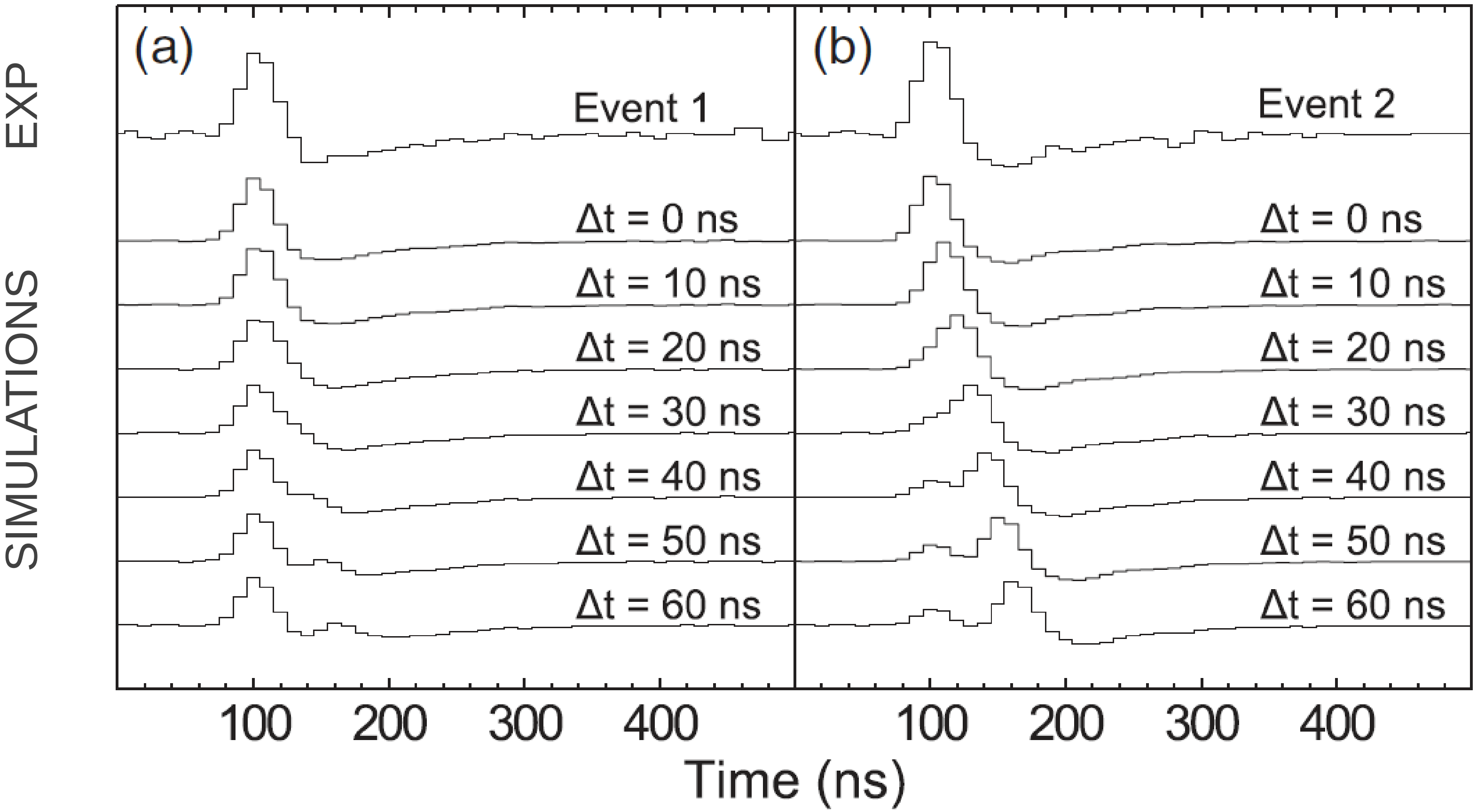


$E_{\alpha}(^{104}\text{Te})=4.9(2)$ MeV
$E_{\alpha}(^{108}\text{Xe})=4.4(2)$ MeV
$\Sigma E_{\alpha}=9.3(1)$ MeV

1. Implantation depth known from other α escapes
2. Emission angle know from detector geometry
3. Path in the DSSD calculated
4. Path in the box calculated from E(BOX)
5. Path in dead layers calculated
6. Total $E_{\alpha 1}$ calculated from total path
7. $E_{\alpha 1}$(DSSD) deposited in DSSD calculated
8. Total $E_{\alpha 2}$ calculated as E(DSSD)-$E_{\alpha 1}$(DSSD)

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

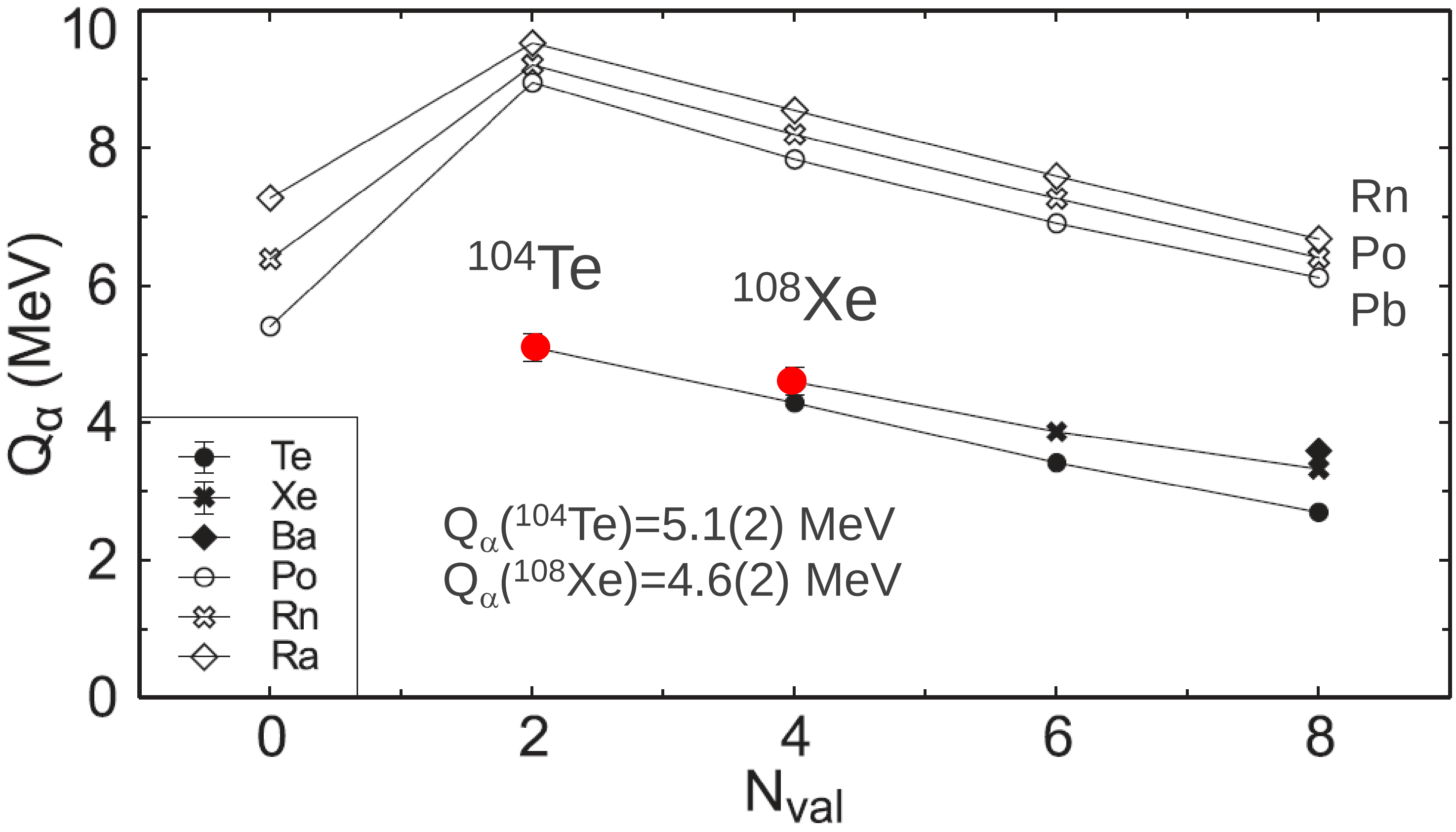
Doubly differentiated traces



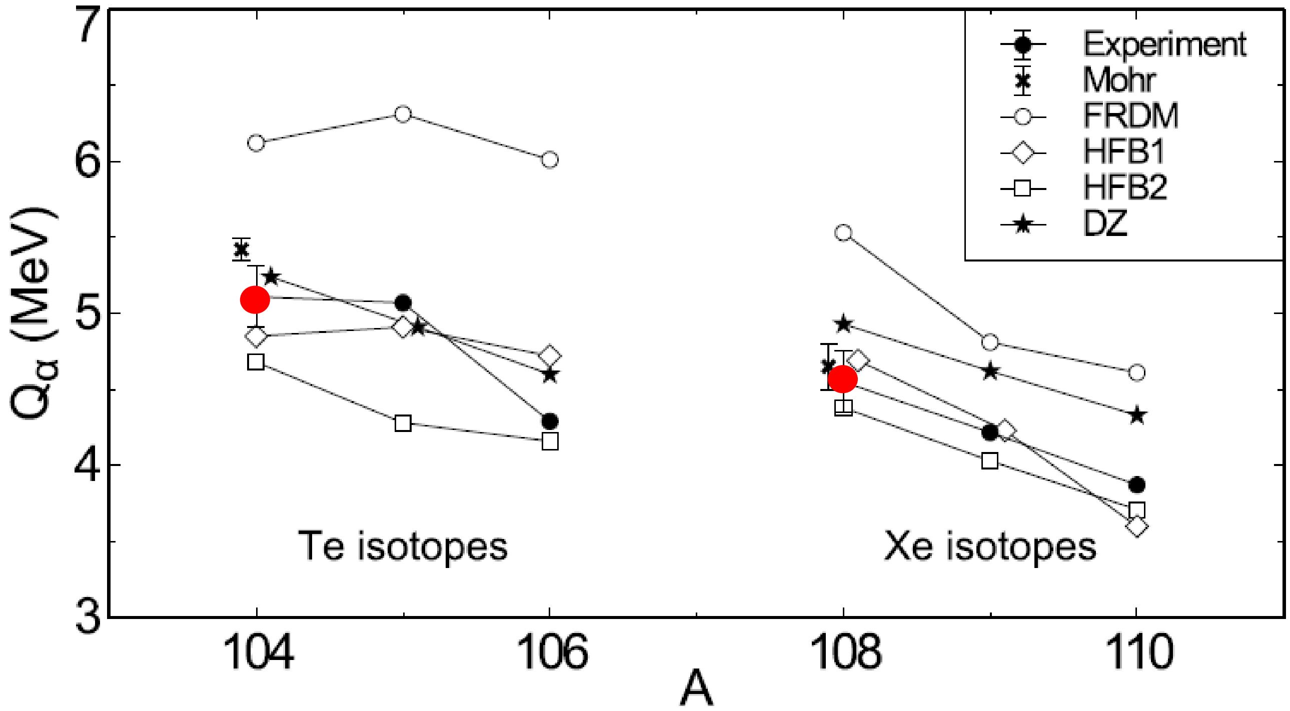
NO noticeable delay

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

Alpha-decay Q value systematics



Comparison with mass models

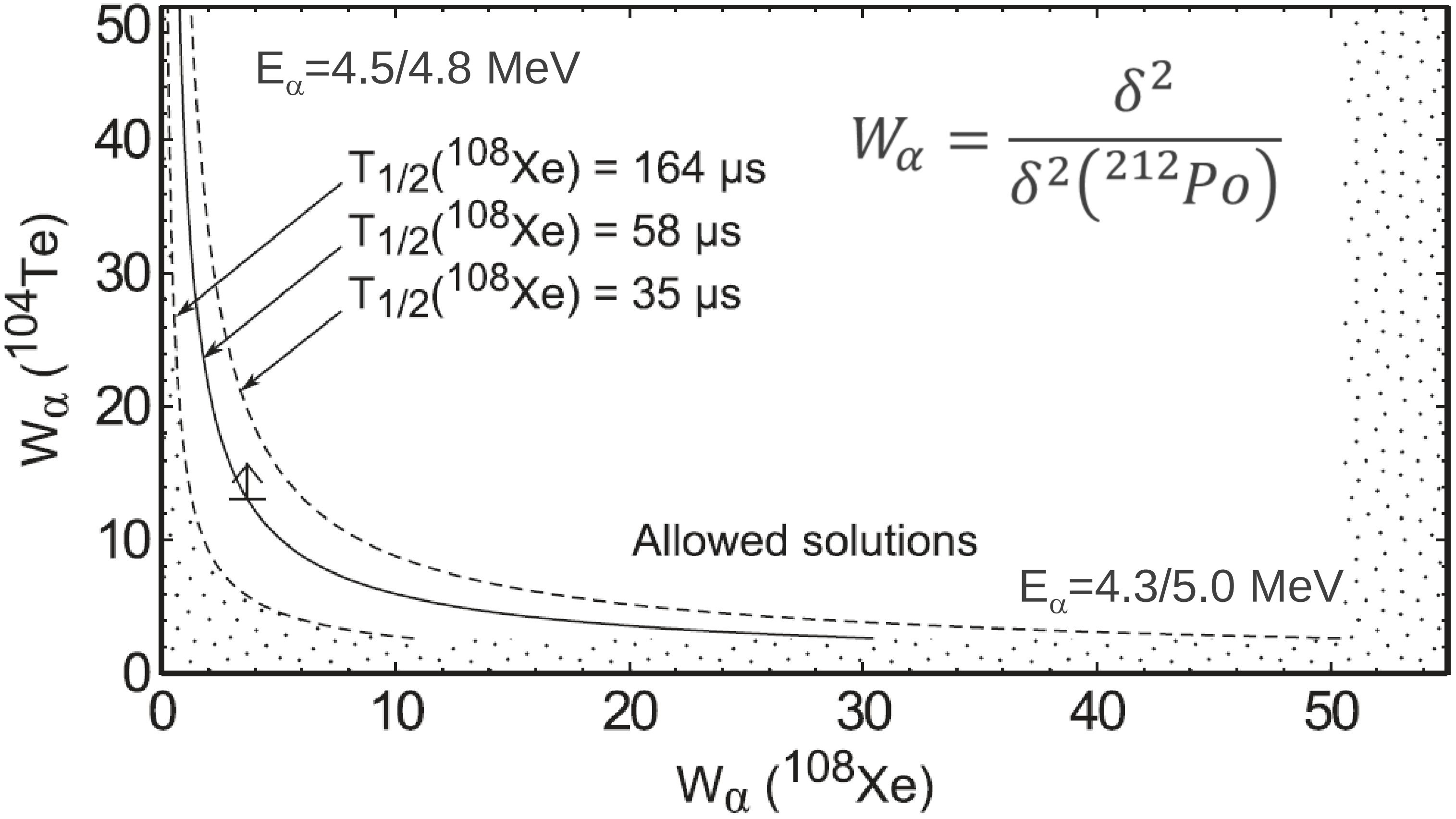


Locally adjusted double-folding potential

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

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

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

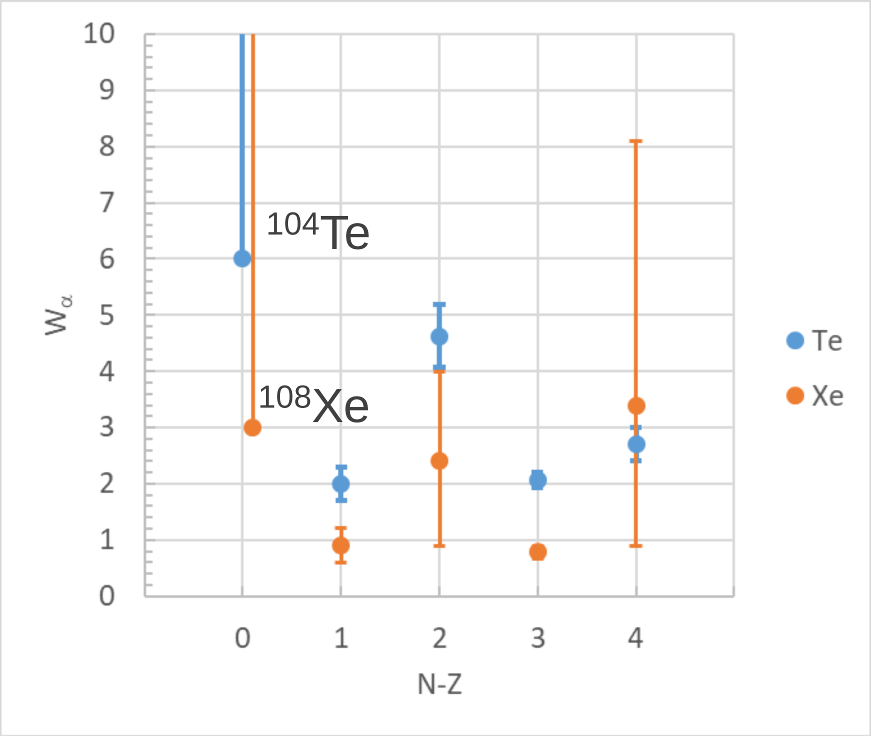


$$W_\alpha = \frac{\delta^2}{\delta^2(^{212}Po)}$$

$W_\alpha(^{104}\mathrm{Te})>13.1$
$W_\alpha(^{104}\mathrm{Te})>1.9$
$W_\alpha(^{108}\mathrm{Xe})=3.7(-3.5+41.6)$

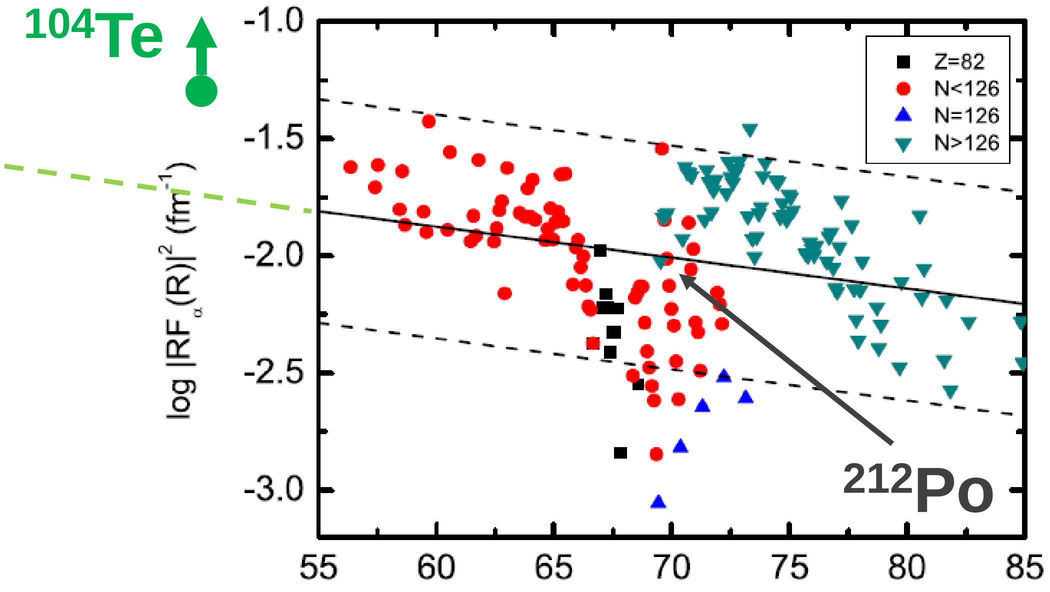
$W_\alpha(^{104}\mathrm{Te})W_\alpha(^{108}\mathrm{Xe})>25$
At least one W_α greater than 5

Reduced α-decay widths near ^{100}Sn

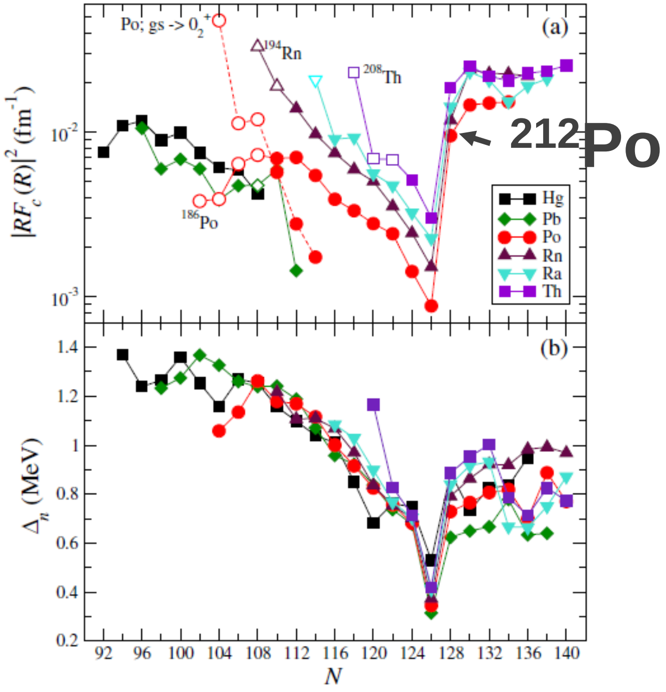


If **W_α(Te)/W_α(Xe)~2** as for ^{106}Te/^{110}Xe pair: **W_α(^{104}Te)>6, W_α(^{108}Xe)>3**

Reduced α-decay width global systematics



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



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

A.N. Andreev et al., PRL 110, 242502 (2013)

^{104}Te, ρ'~50, $\log_{10}$|R F(R)|^2>-1.3 (Wα>5)

Enhancement beyond pairing after size taken into account

Complex-energy shell model

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

Spectroscopic factor, R-matrix

^{212}Po

Half life reproduced (spectroscopic factor formulation)
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

Multistep shell model

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

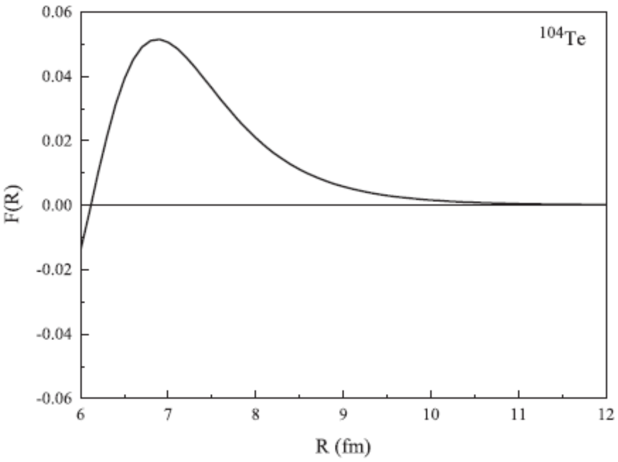
R-matrix

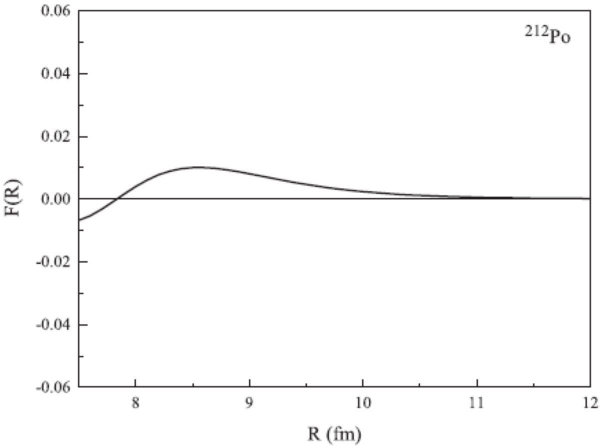
^{212}Po

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

^{104}Te

Calculated $T_{1/2}$=1.5 μs, assuming Qα=5.06 MeV, experiment $T_{1/2}$<15 ns
α-particle formation probability **4.85 times larger** in ^{104}Te compared to ^{212}Po





Recent calculations for ^{104}Te/^{108}Xe

Density-dependent cluster model plus two-potential approach
Dong Bai and Zhongzhou Ren, Eur. Phys. J. A 54, 220 (2018)

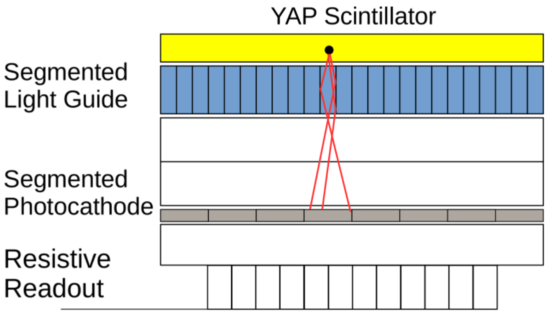
Relativistic Density Functional DD-PC1+separable pairing of finite range
Dynamical least-action paths from equilibrium deformation to scission
Assault frequency assumed
$T_{1/2}(^{108}\mathrm{Xe})=50\ \mu\mathrm{s}$, $T_{1/2}(^{104}\mathrm{Te})=197\mathrm{ns}$
F. Mercier et al., Phys. Rev. C **102**, 011301(R) (2020)

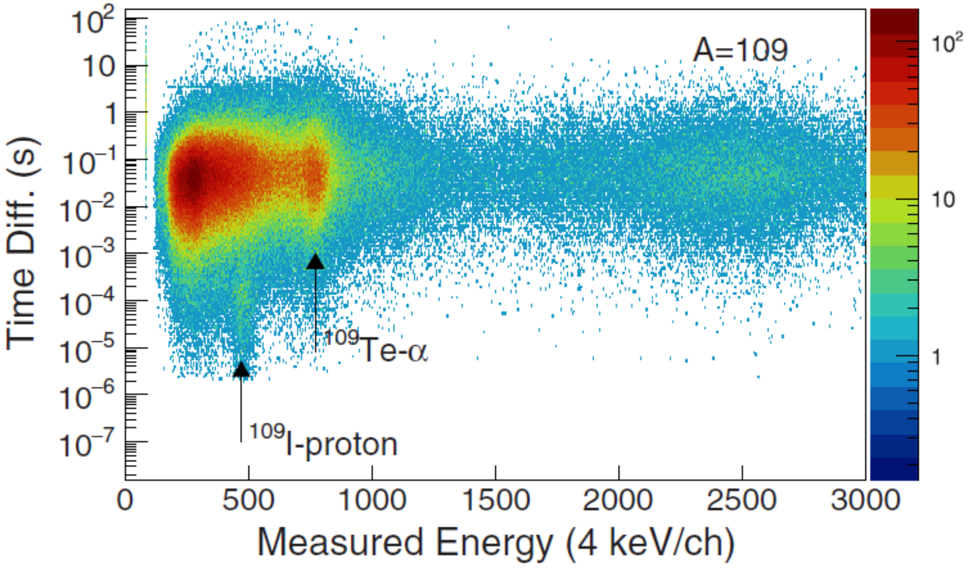
Quartetting wave function approach
$T_{1/2}(^{104}\mathrm{Te})=15\ \mathrm{ns}$, $P\alpha = 0.72$
$T_{1/2}(^{212}\mathrm{Po})=340\ \mathrm{ns}$, $P\alpha = 0.10$
Shuo Yang et al., Phys. Rev. C 101, 024316 (2020)

Cluster-Formation Model+DDCM
Niu Fan and Jingya Fan, Phys. Rev. C **104**, 064320 (2021)

Search for ^{108}Xe-^{104}Te-^{100}Sn with segmented scintillator

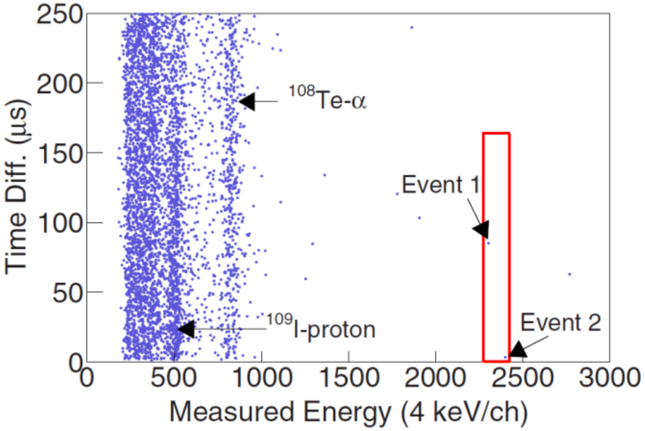
Tandem, Tokai





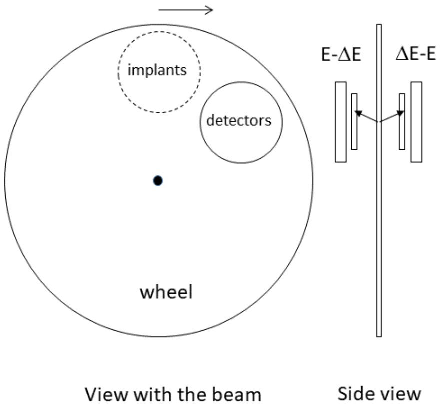
- YAP scintillator
  - faster detector
  - worse energy resolution
  - larger random background

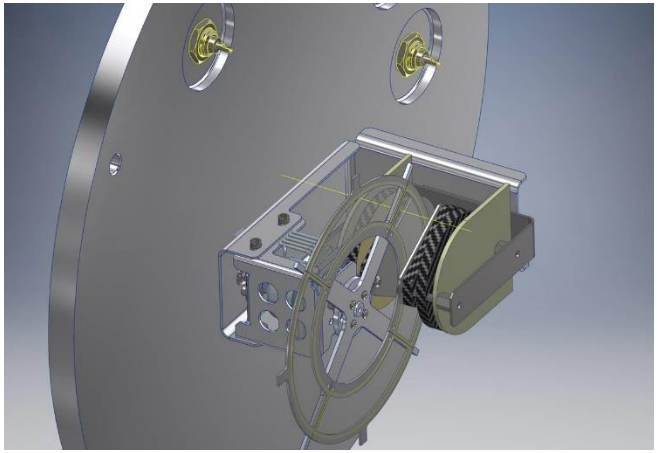
- Two candidate events, if real:
  - $T_{1/2}(^{108}Xe)=30(+57-12)$ μs
  - $T_{1/2}(^{104}Te) < 4$ ns, no pileup observed
  - Consistent with our paper
  - Even faster α decays?



Y. Xiao et al., Phys. Rev. C **100**, 034315 (2019)

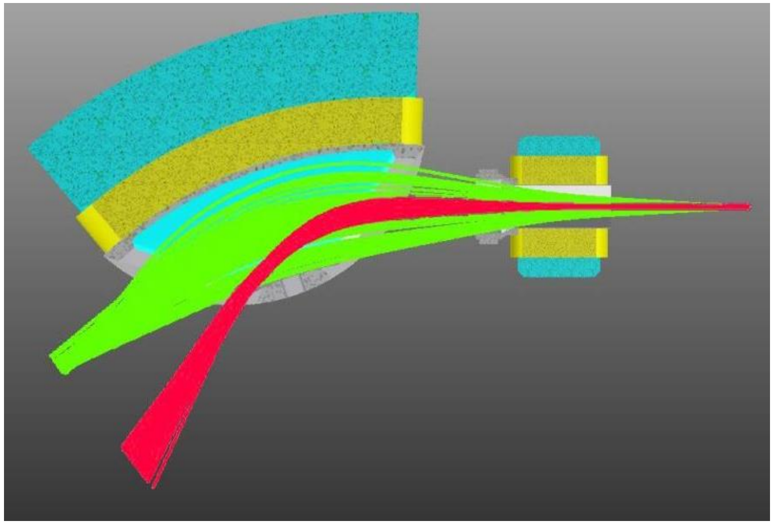
New approach - rotating stopper with AGFA





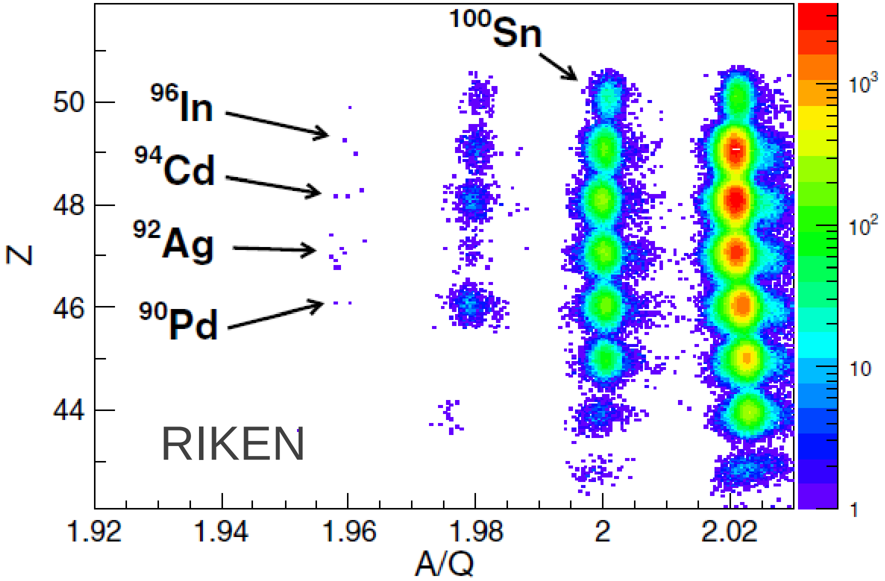
Search for triple α chains:
^{112}Ba-^{108}Xe-^{104}Te

Higher efficiency
Higher beam intensity
Δt~1 ns
No mass dispersion
Beam suppression?
Background?



Argonne Gas-Filled Analyzer (AGFA)

Possible α-decay studies "north-east" of ^{100}Sn at fragmentation facilities



No results reported "north-east" of ^{100}Sn so far

- ^{108}Xe
- ^{112}Ba
- ^{103}Te 2p emitter candidate (*E. Olsen et al., PRL 111, 139903 (2013)*)
- …

Summary and Outlook

- First observation of the ^{108}Xe-^{104}Te-^{100}Sn chain
  - Enhanced alpha preformation compared to ^{212}Po
- Microscopic description still work in progress
  - ^{104}Te, ^{108}Xe important for the role of neutron-proton interaction
- Future measurements
  - **More statistics**
  - ^{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

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

Editors' Suggestion | Featured in Physics

Superallowed α Decay to Doubly Magic ^{100}Sn

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Thank you for your attention!