COMPETITION OF ALPHA DECAY AND HEAVY PARTICLE DECAY IN SUPERHEAVY NUCLEI

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OUTLINE

- Macroscopic-microscopic method
- Unified approach of cold fission, α-decay and heavy particle radioactivities (HPR) within ASAF model
- Experimental confirmations
- New mass table Audi & Meng. KTUY05 and FRDM95
- α-decay and HPR of heaviest superheavies
- Results within ASAF, UNIV and semFIS
- Summary

Macroscopic-microscopic method

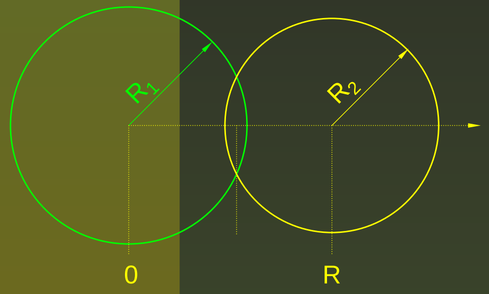
Accounting for quantum single-particle structure and classical collective properties.

- Liquid Drop Model: E_{LD}
- Single-particle shell model (SPSM): energy levels vs. deformation. *Two-center shell model for fission and fusion.*
- Shell correction method: $\delta E = \delta U + \delta P$
- Total deformation energy: $E_{def} = E_{LD} + \delta E$

The potential of SPSM Hamiltonian should admit the drop eq. $\rho = \rho(z)$ as an equipotential surface.

Semi-spheroidal shape, allows to obtain analytical results for atomic clusters on a surface.

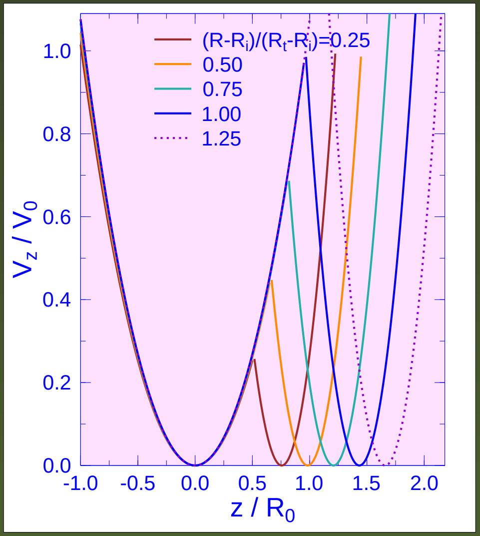
Intersected spheres

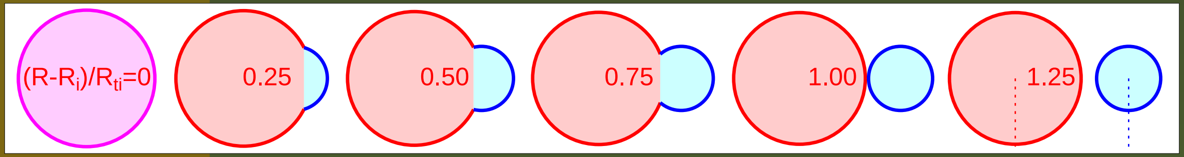


Two intersected spheres. Volume conservation and $R_2 = \text{const}$. One deformation parameter: separation distance R. Surface equation $\rho = \rho(z)$. Initial $R_i = R_0 - R_2$. Touching point $R_t = R_1 + R_2$.

Example: ${}^{232}\text{U} \rightarrow {}^{24}\text{Ne} + {}^{208}\text{Pb}$

Two center shell model (Frankfurt) potential





Sequence of shapes

Liquid drop model

Nucleus considered a uniformly charged drop. Two variants: LDM and Yukawa-plus-exponential (Y+EM).

LDM (surface + Coulomb) deformation energy

$$E_{LDM} = E - E^0 = (E_s - E_s^0) + (E_C - E_C^0)$$

$$= E_s^0(B_s - 1) + E_C^0(B_C - 1)$$

For spherical shapes $E_s^0 = a_s(1 - \kappa I^2)A^{2/3}$; $I = (N - Z)/A$; $E_C^0 = a_c Z^2 A^{-1/3}$. Nuclear fissility $X = E_c^0/(2E_s^0)$.

Parameters obtained by fit to experimental data on nuclear masses, quadrupole moments and fission barriers: $a_s = 17.9439$ MeV, $\kappa = 1.7826$, $a_c = 3e^2/(5r_0)$, $e^2 = 1.44$ MeV·fm, $r_0 = 1.2249$ fm.

W.D. Myers and W.J. Swiatecki, Nucl. Phys. **A 81** (1966) 1

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Shell corrections

The total energy of the uniform level distribution

$$\tilde{u} = \tilde{U}/\hbar\omega_0^0 = 2\int_{-\infty}^{\tilde{\lambda}} \tilde{g}(\epsilon)\epsilon d\epsilon$$

In units of $\hbar\omega_0^0$ the shell corrections are calculated for each deformation ε

$$\delta u(n,\varepsilon) = \sum_{i=1}^{n} 2\epsilon_i(\varepsilon) - \tilde{u}(n,\varepsilon)$$

$n = N_p/2$ particles. Then $\delta u = \delta u_p + \delta u_n$.

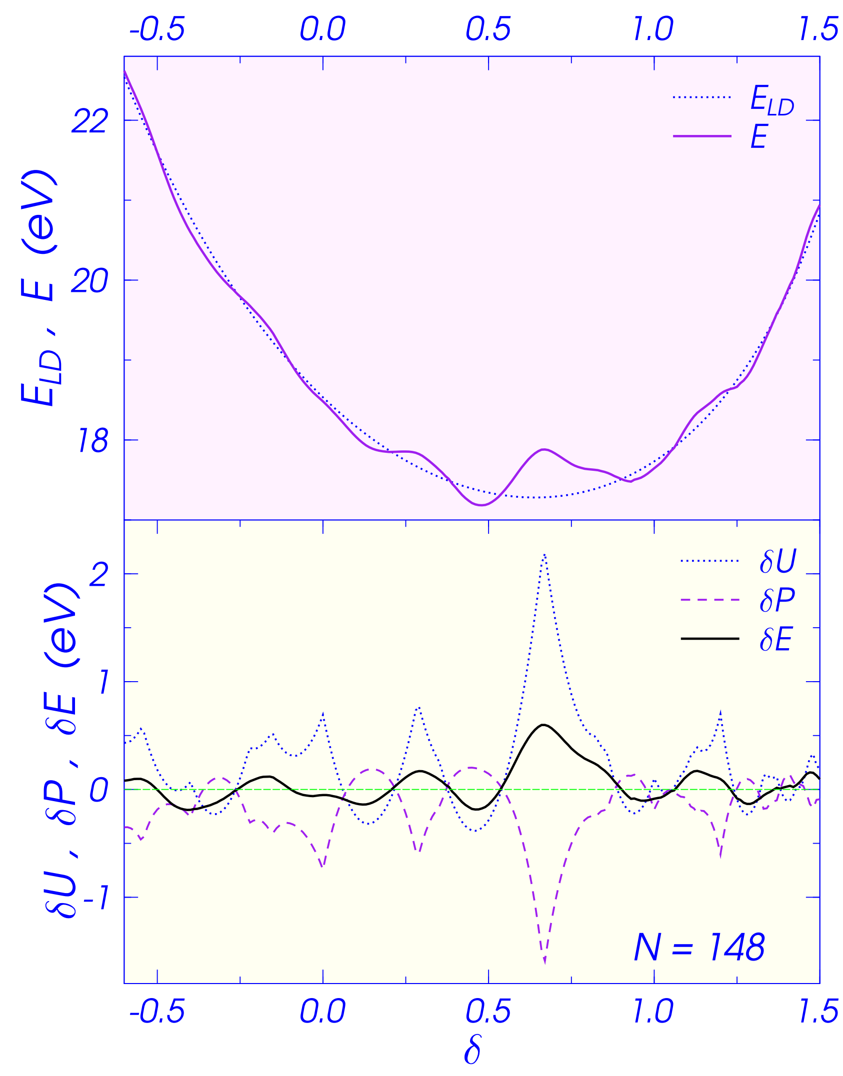
Pairing corrections

The gap Δ and Fermi energy λ are solutions of the BCS eqs:

$$0=\sum_{k_i}^{k_f}\frac{\epsilon_k-\lambda}{\sqrt{(\epsilon_k-\lambda)^2+\Delta^2}}\quad ; \quad \frac{2}{G}=\sum_{k_i}^{k_f}\frac{1}{\sqrt{(\epsilon_k-\lambda)^2+\Delta^2}}$$

$k_i = Z/2 - n + 1,\;\; k_f = Z/2 + n',\;\; \frac{2}{G} \simeq 2\tilde{g}(\tilde{\lambda}) \ln\left(\frac{2\Omega}{\tilde{\Delta}}\right).$
The pairing correction $\delta p = p - \tilde{p}$, represents the difference between the pairing correlation energies for the discrete level distribution $p = \sum_{k=k_i}^{k_f} 2v_k^2\epsilon_k - 2\sum_{k=k_i}^{Z/2}\epsilon_k - \frac{\Delta^2}{G}$ and for the continuous level distribution $\tilde{p} = -(\tilde{g}\widetilde{\Delta^2})/2 = -(\tilde{g}_s\widetilde{\Delta^2})/4$. Compared to shell correction, the pairing correction is out of phase and smaller. One has again $\delta p = \delta p_p + \delta p_n$, and $\delta e = \delta u + \delta p$.

Example: Na$_{148}$ atomic cluster



$E_v = -333$ eV was not included in E_{LD} and E. Liquid drop and total deformation energy (top). Shell plus pairing corrections for hemispheroidal harmonic oscillator energy levels (bottom).

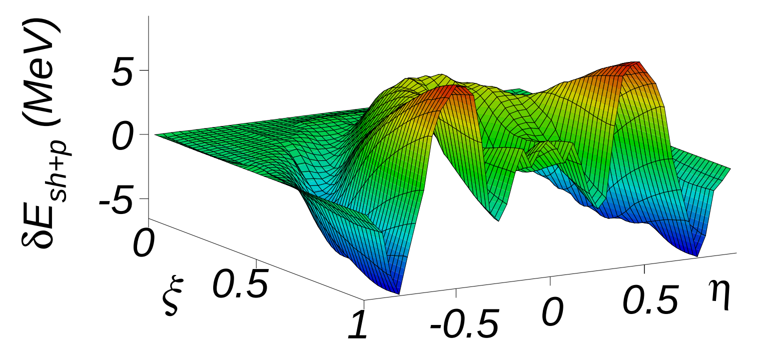
Smoothing effect of pairing.

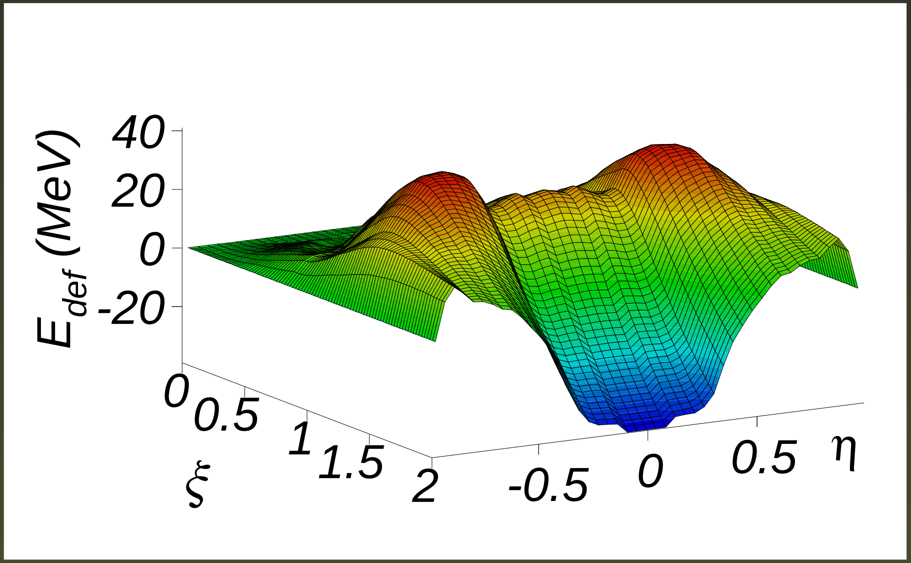
Ground state shape prolate

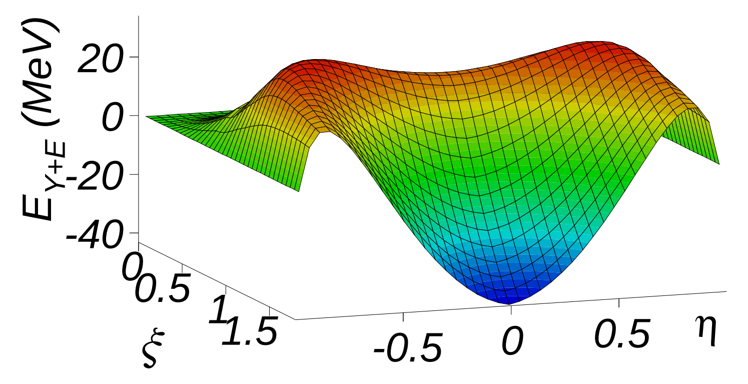
$\delta = 0.47$

Semiaxes ratio $\frac{a}{c} = \frac{2-\delta}{2+\delta}$

^{222}**Ra** $E_{Y+EM}, \delta E_{shell+pair}, E_{def}$ **PES**







separation distance

$$\xi = (R - R_i)/(R_t - R_i)$$

mass asymmetry

$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

Poenaru, Gherghescu, W.Greiner, *Phys. Rev.* **C 73** *(2006) 014608*

Basic relationships

Parent → emitted ion + daughter nucleus, ${}^{A}Z \rightarrow {}^{A_e}Z_e + {}^{A_d}Z_d$

Measurable quantities

- Kinetic energy of the emitted cluster $E_k = QA_1/A$ or the released energy $Q = M - (M_e + M_d) > 0$.
- Decay constant $\lambda = \ln 2/T$ or Half-life ($T < 10^{32}$ s) or branching ratio $b_\alpha = T_\alpha/T$ ($b_\alpha > 10^{-17}$)

Model dependent quantities ($\lambda = \nu S P_s$)

- ν frequency of assaults or $E_v = h\nu/2$
- S preformation probability
- P_s penetrability of external barrier

Fission theory

Shape parameters: fragment separation, R, and mass asymetry $\eta = (A_d - A_e)/A$.

Our method to estimate preformation as penetrability of internal barrier: $S = \exp(-K_{ov})$. DNP, WG, *Physica Scripta* **44** (1991) 427.

Similarly $P = \exp(-K_s)$ for external barrier.

Action integral calculated within Wentzel-Kramers-Brillouin (WKB) quasiclasical approximation

$$K_{ov} = \frac{2}{\hbar} \int_{R_i}^{R_t} \sqrt{2B(R)E(R)} dR$$

E – Potential barrier

$B = \mu$ – Nuclear inertia = reduced mass for $R \geq R_t$

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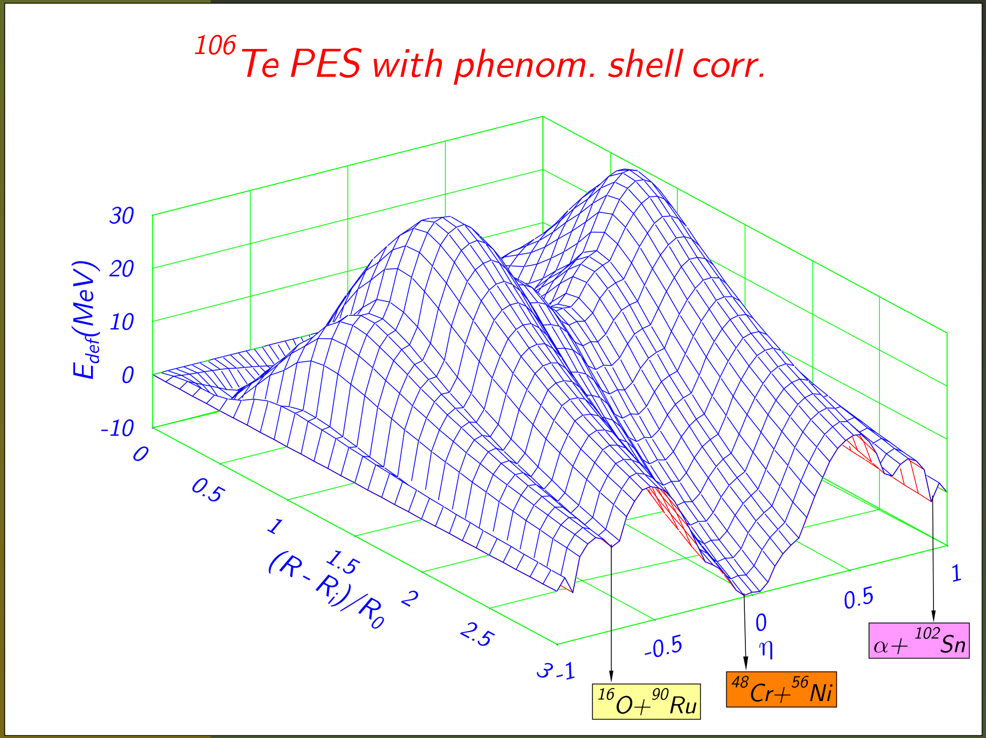
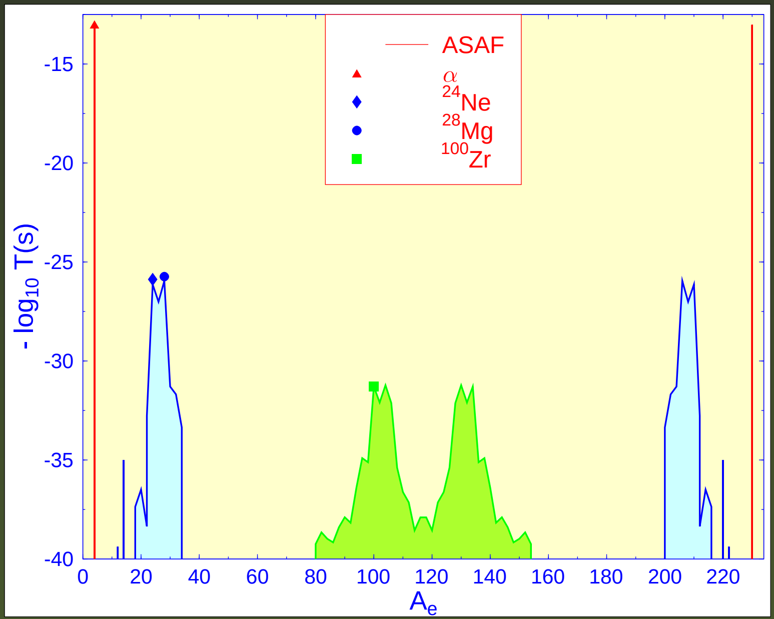
Unified approach: CF; HPR, and α-d





Three valleys: cold-fission (almost symmetrical); ^{16}O radioactivity, and α-decay

^{234}U half-lives spectrum (short T up)

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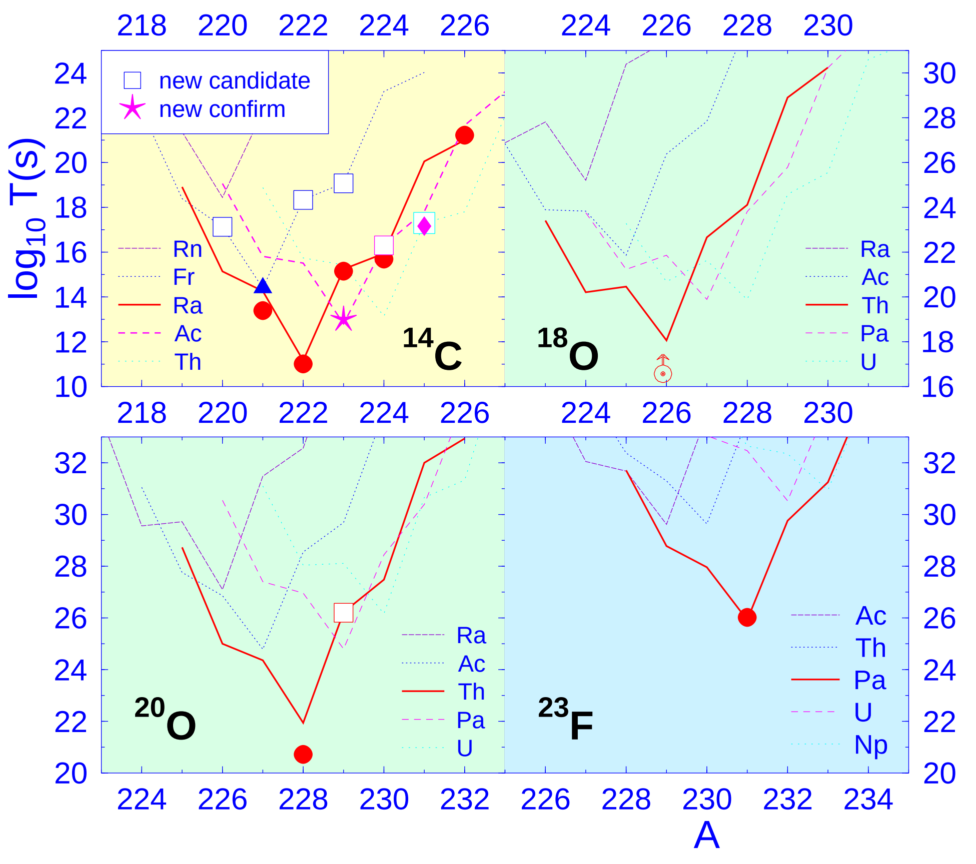
Experimental confirmations

Rare events in a strong background of α particles
Detectors:

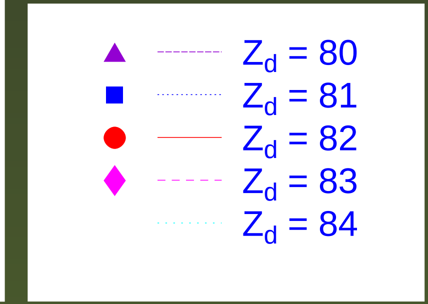
- Semiconductor telescope + electronics
- Magnetic spectrometers (SOLENO, Enge split-pole)
- Solid state nuclear track det. (SSNTD). Cheap and handy. Need to be chemically etched then follows microscope scanning

Experiments performed in Universities and Research Institutes from: Oxford; Moscow; Orsay; Berkeley; Dubna; Argonne; Livermore; Geneva; Milano; Vienna, and Beijing. Table: R. Bonetti and A. Guglielmetti, Rom. Rep. Phys. **59** (2007) 301.

Systematics $T_{1/2}$: ^{14}C, ^{18,20}O, ^{23}F rad.



Calculated lines within ASAF model and exp. points



new confirm — A. Guglielmetti et al., J Phys: Conf Ser **111** (2008) 012050 One of the new candidates from our paper: Poenaru, Nagame, Gherghescu, W. Greiner *Phys. Rev.* **C 65** *(2002) 054308.*

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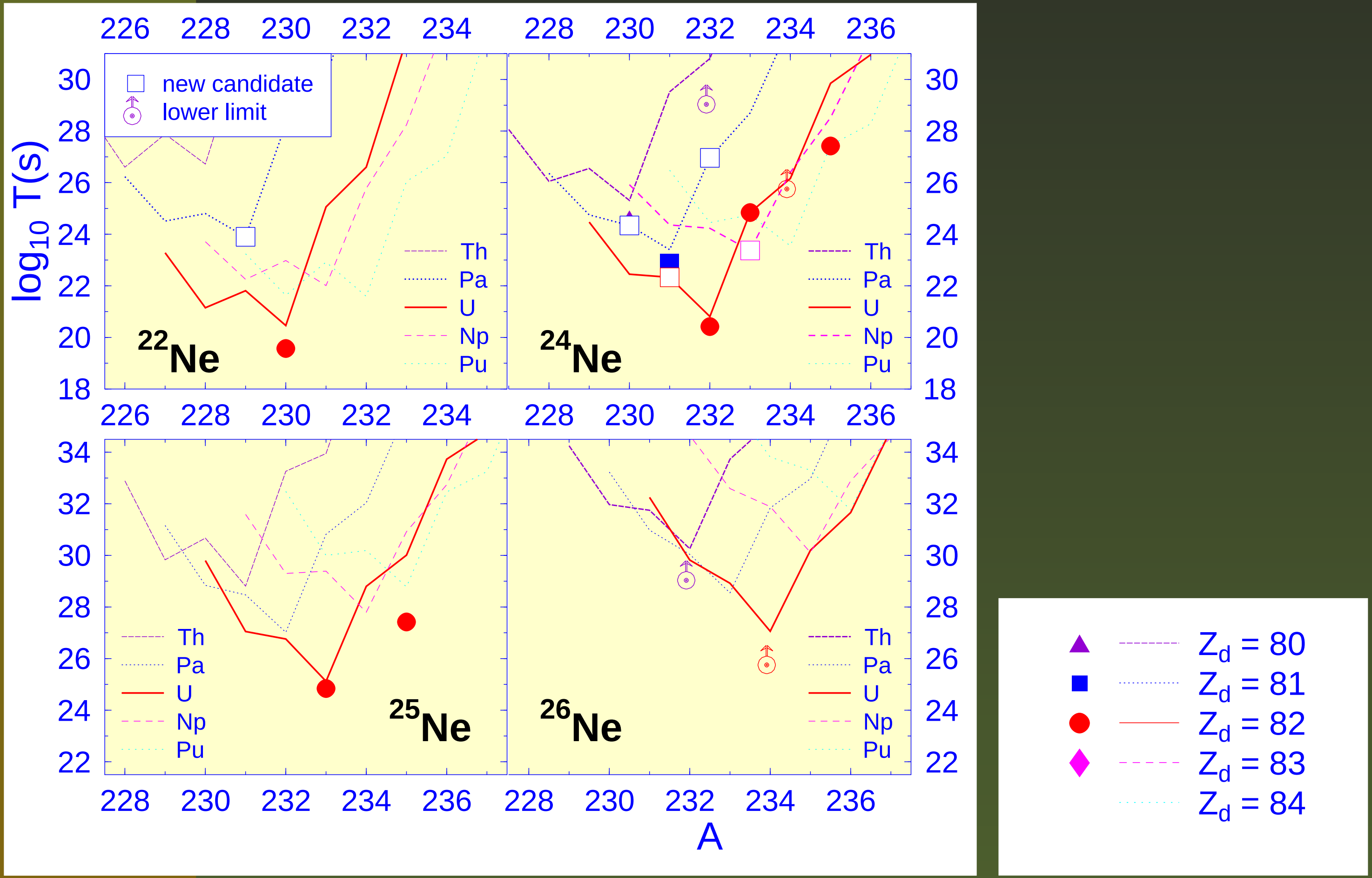
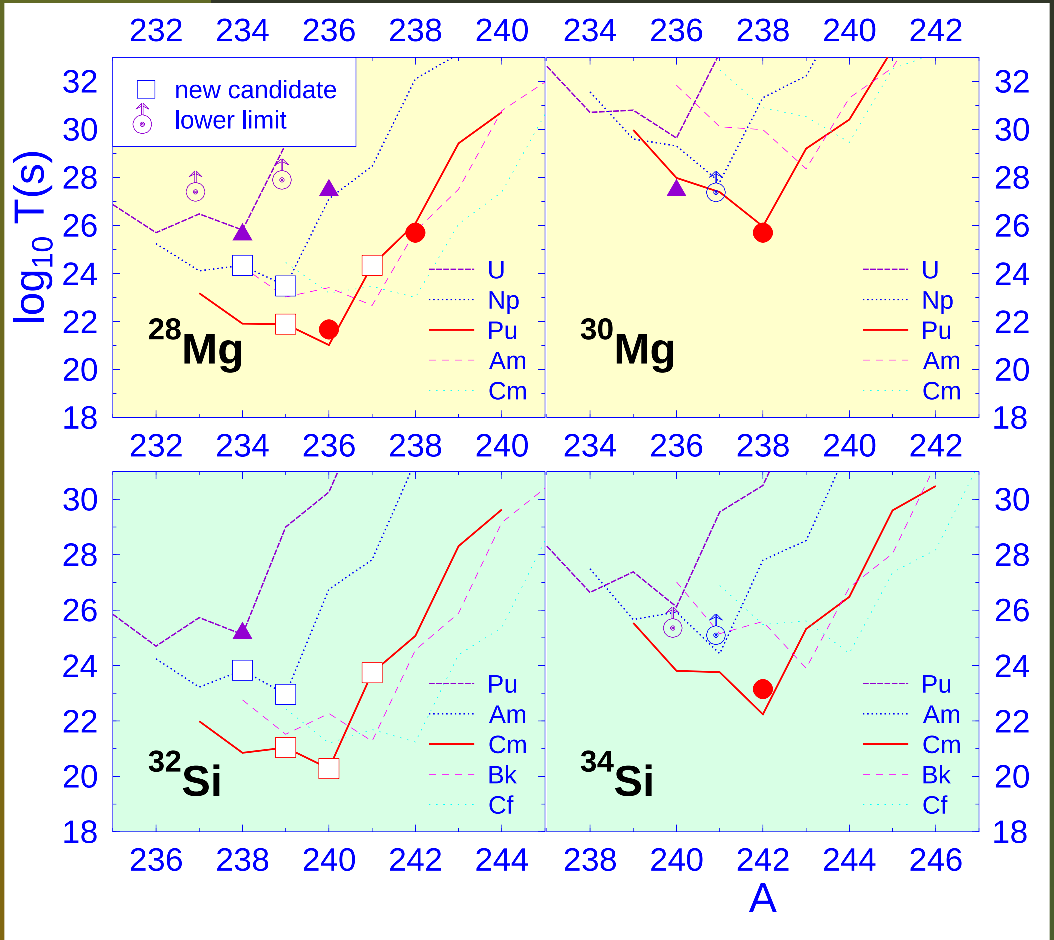
Systematics $T_{1/2}$: ^{22,24,25,26}Ne rad.



Only lower limits for ^{18}O and ^{26}Ne

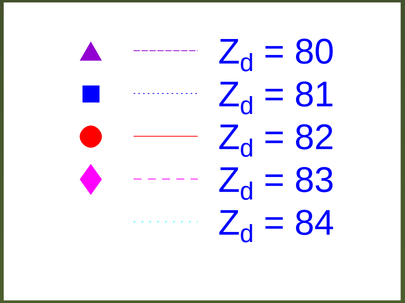
Systematics $T_{1/2}$: ^{28,30}Mg, ^{32,34}Si rad.



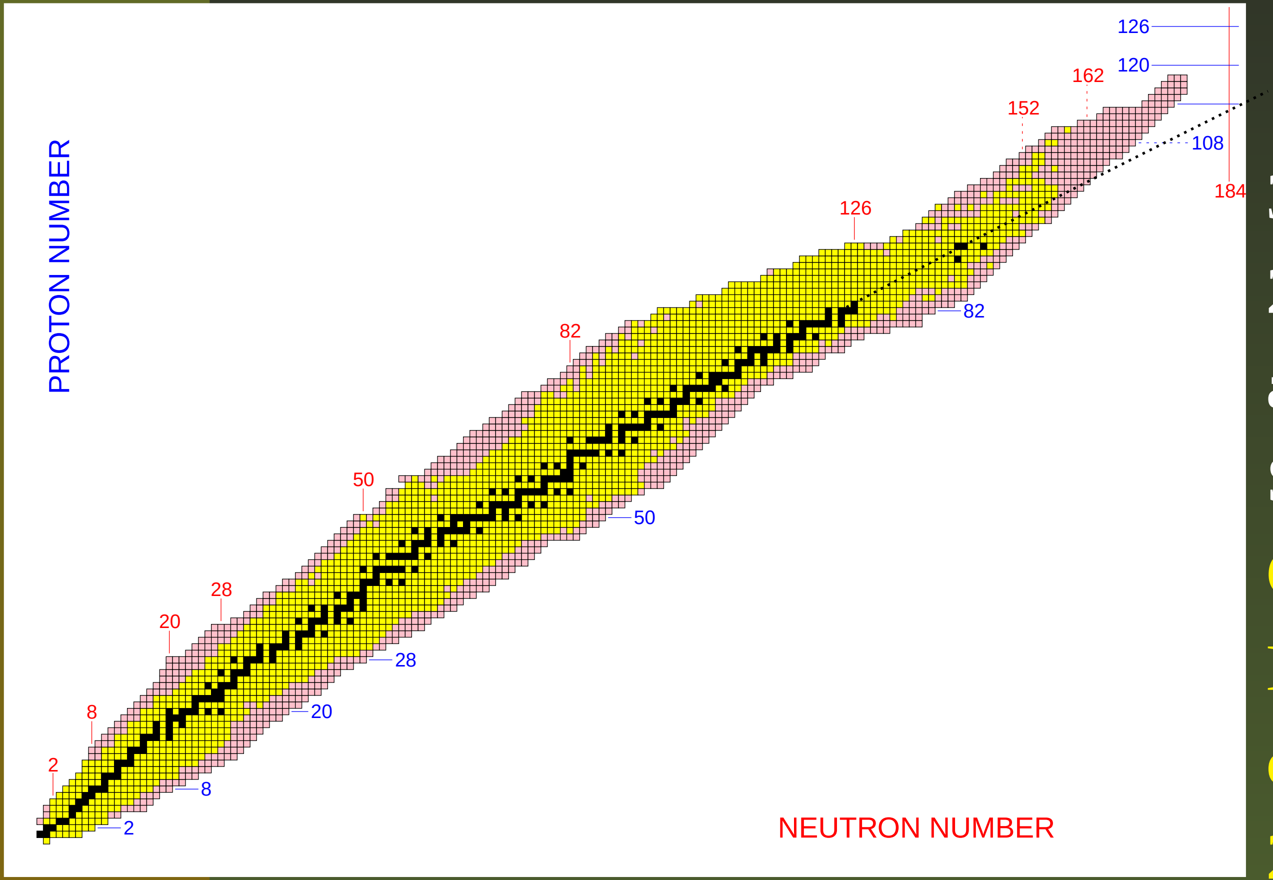
Minima at $N_d = 126$

Strong shell effect

Even-odd staggering



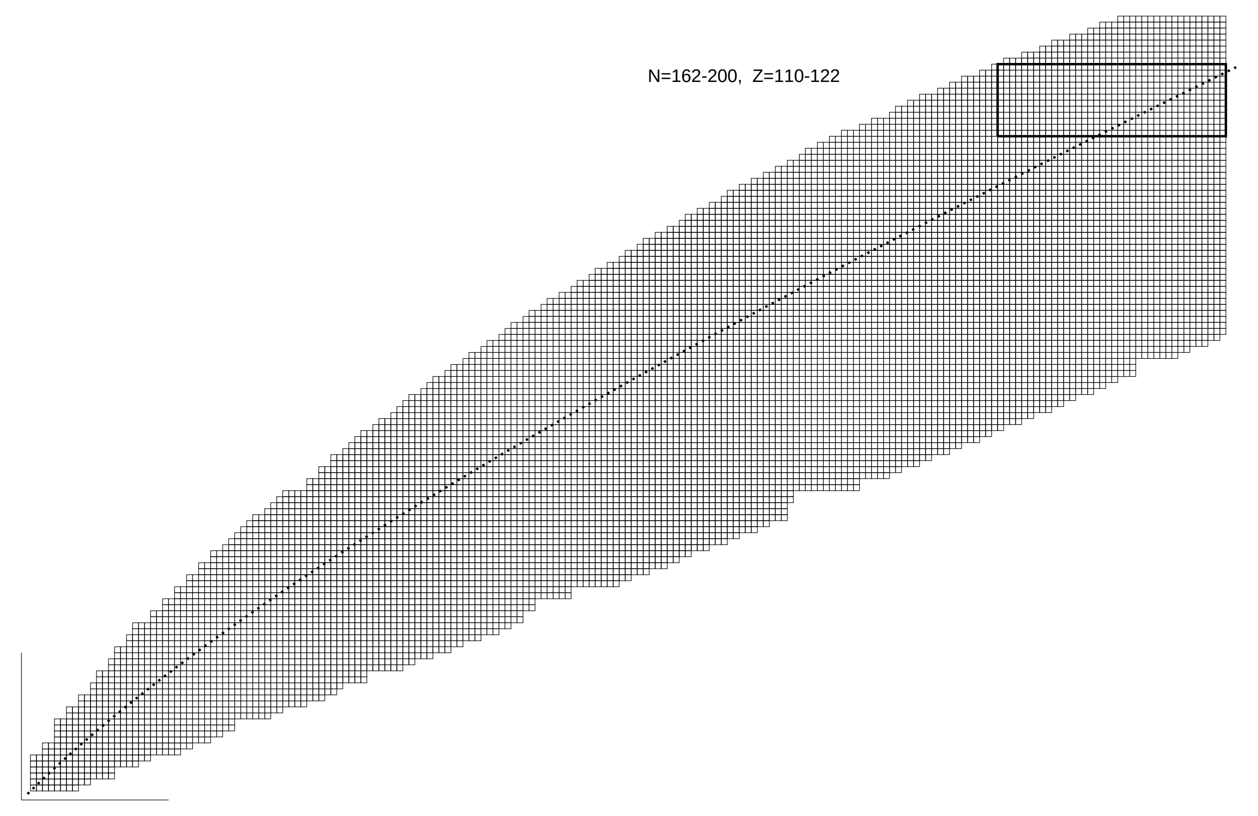
New table of experimental masses



3290 nuclei, 2377 measured and 913 det. from Systematics.

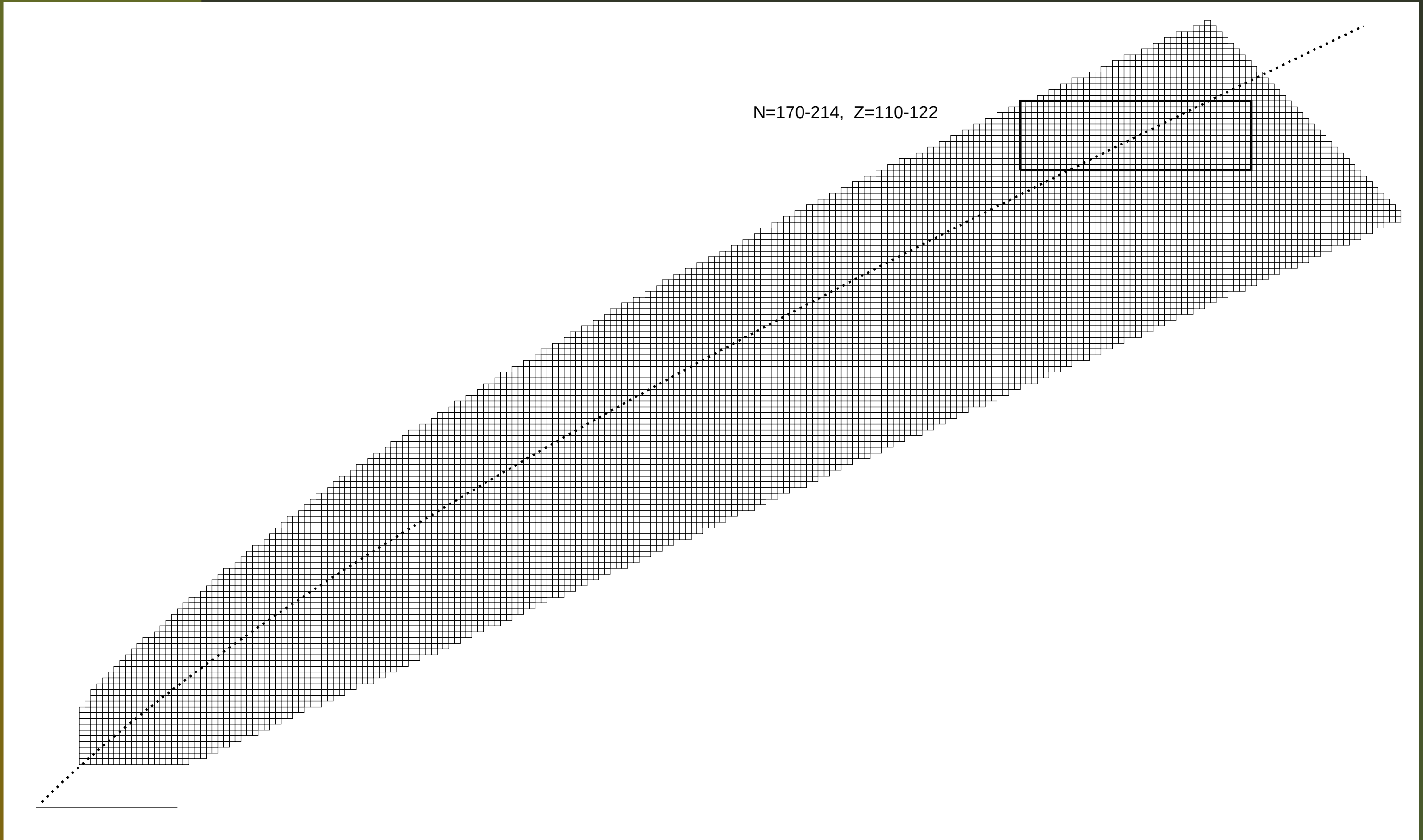
G. Audi, W. Meng, Private communication 2011.

KTUY05 Calculated Masses



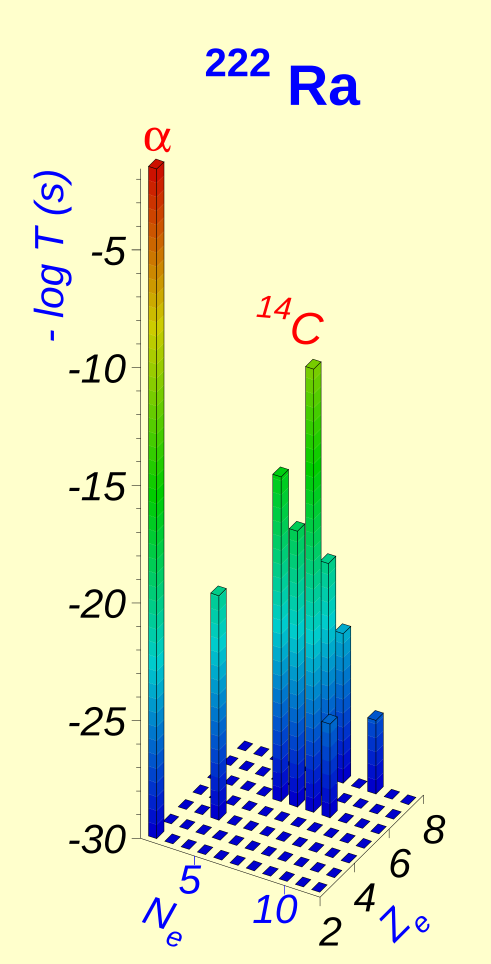
9441 nuclei with Z=2-130 and N=2-200. H. Koura, T. Tachibana, M. Uno and M. Yamada, *Prog. Theor. Phys.* **113** (2005) 305.

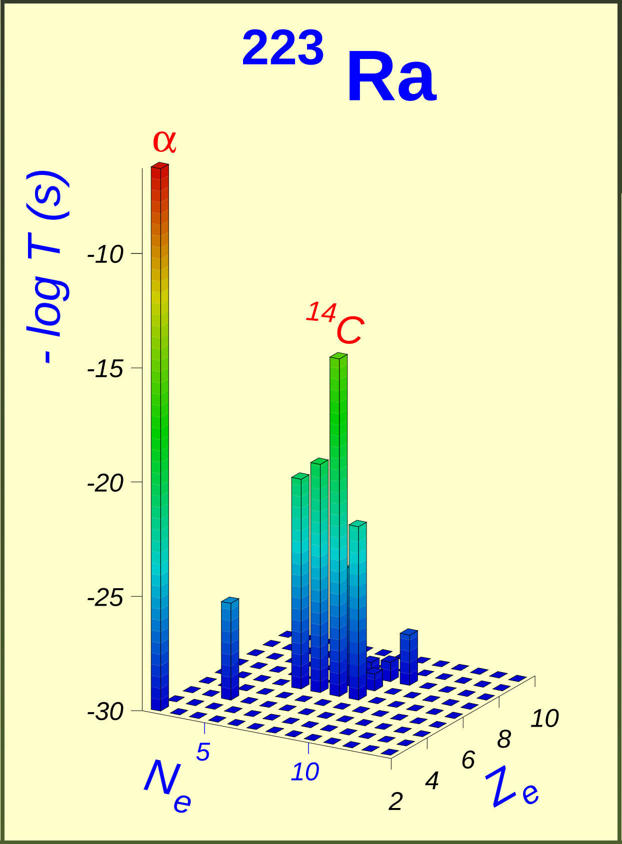
FRDM95 Calculated Masses

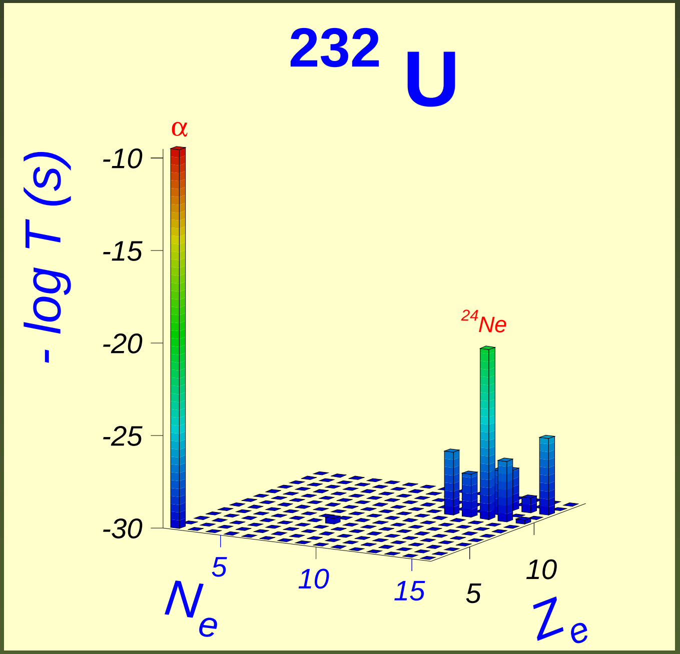


8979 nuclei with Z=8-136 and N=8-236. P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, *At. Data Nucl.Data Tables* **59** (1995) 185.

Examples of time spectra (I)







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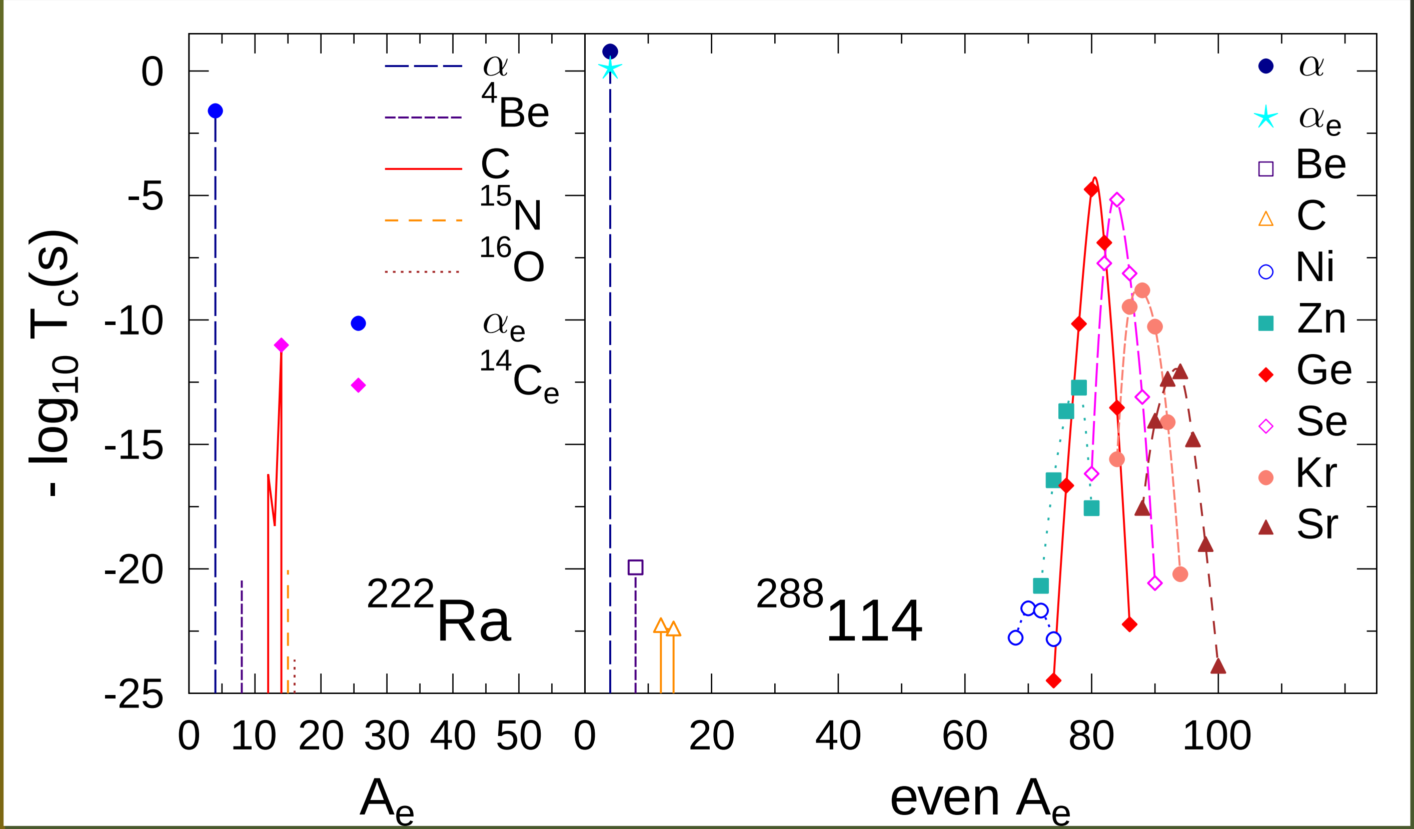
Examples of time spectra (II)



$^{288}114 \rightarrow \ ^{80}Ge \ + \ ^{208}$Pb. D.N. Poenaru, R.A. Gherghescu, W. Greiner, *Phys. Rev. Lett.* **107** (2011) 062503.

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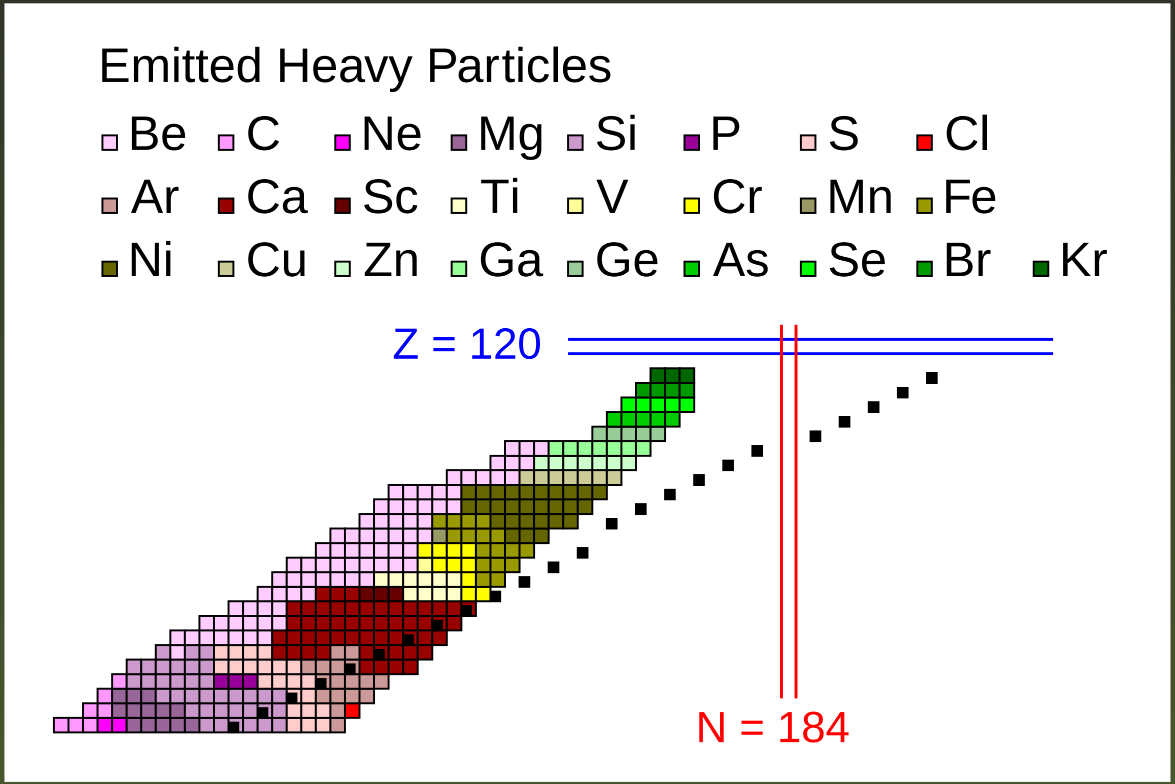
Superheavies as cluster emitters

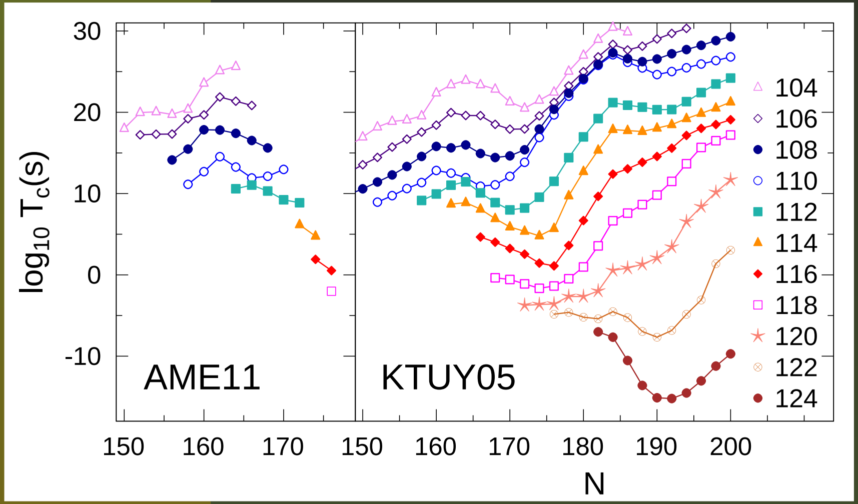


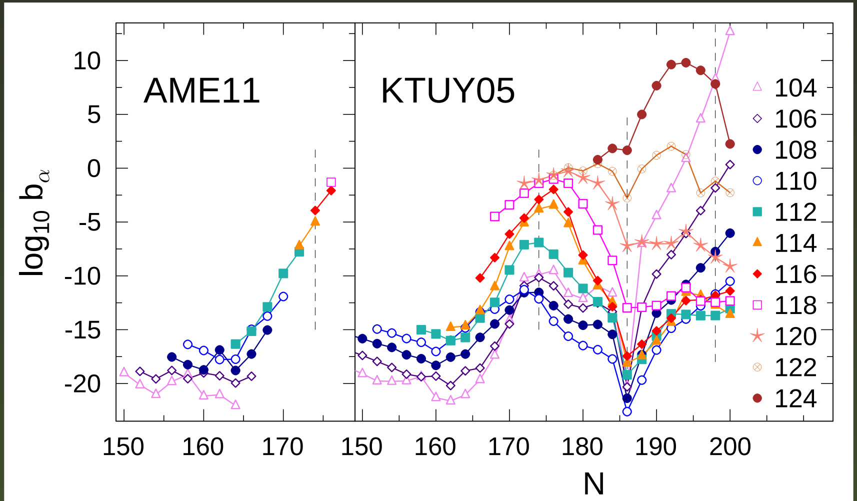
New concept: for $Z > 110$ $Z_e > 28$ to get a daughter around ^{208}Pb.

D.N. Poenaru, R.A. Gherghescu, W. Greiner,

Phys. Rev. Lett. **107** (2011) 062503.

HIR of SH nuclei (I)





Half-lives

Branching ratios

Branching ratio with respect to α decay: $b_\alpha = T_\alpha/T_c$.

Usually $b_\alpha << 1$.

Trend: shorter T_c and larger b_α.

For larger $Z > 120$ there are SHs with $T_c <$ 1 ns and $b_\alpha > 1$.

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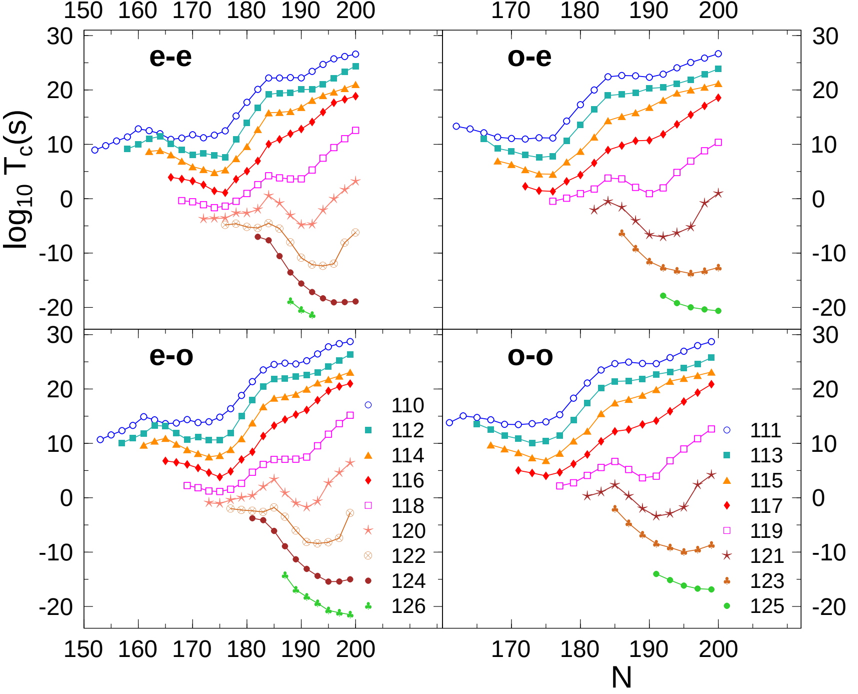
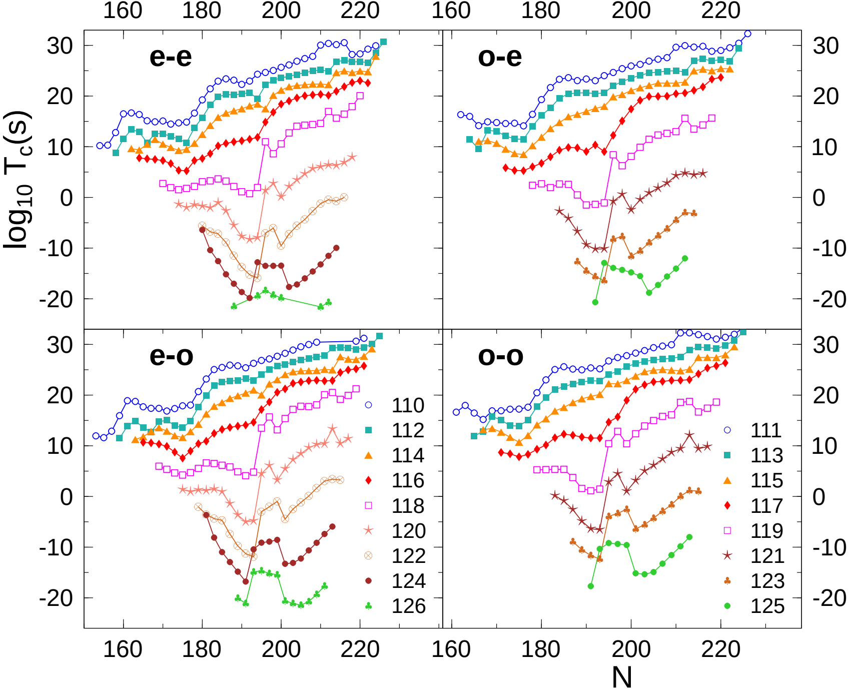
HIR of SH nuclei (II)

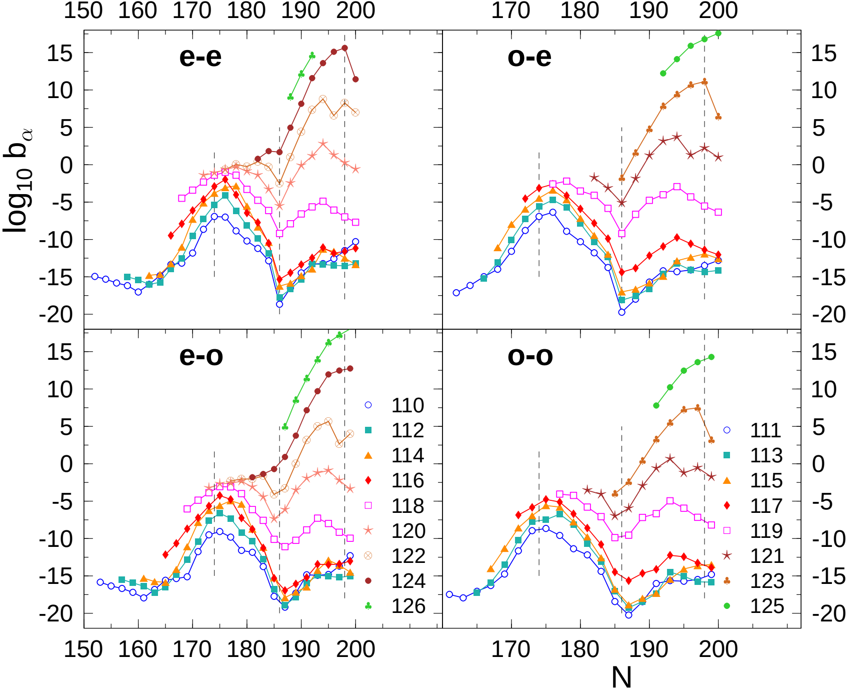


KTUY05

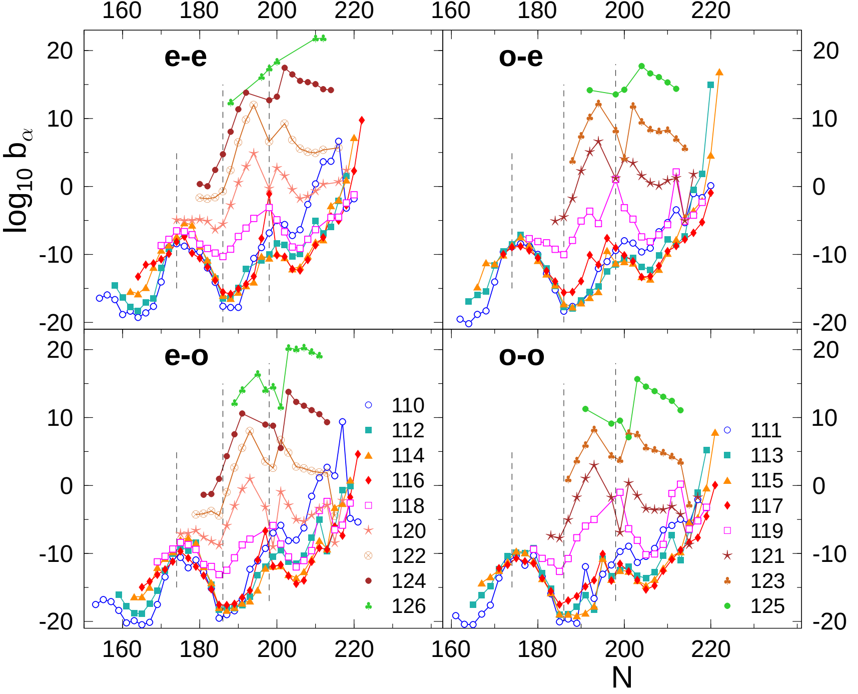


FRDM95

HIR of SH nuclei (III)

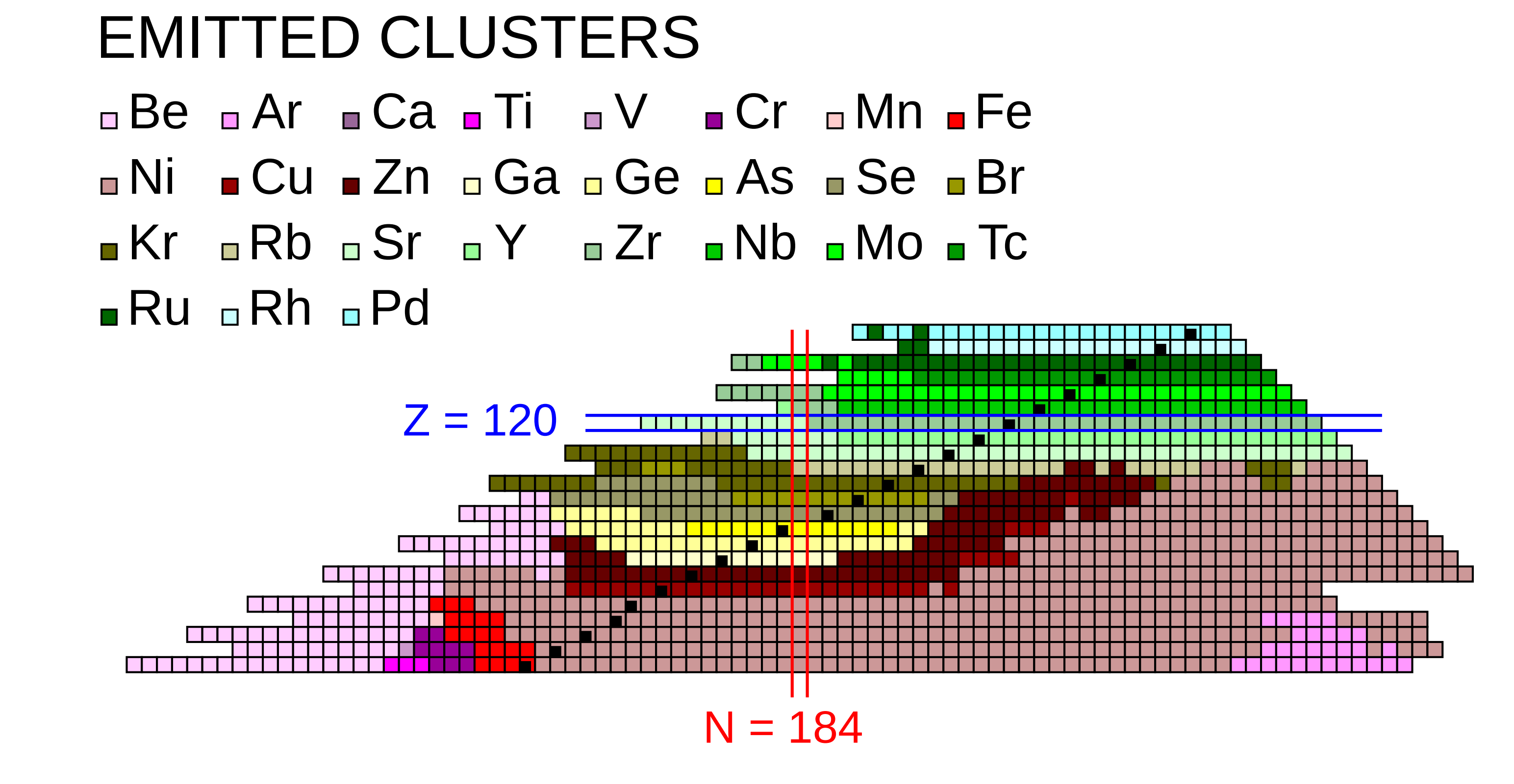


KTUY05



FRDM95

SH nuclei as cluster emitters



FRDM95 $Z_e \leq Z - 80$ (freq. daughter around ^{208}Pb)

Most probable emitted clusters with different colors.

Universal curves (I)

Approximations: $\log S = [(A_e - 1)/3] \log S_\alpha$, $\nu(A_e, Z_e, A_d, Z_d)$ = constant. From fit to α decay: $S_\alpha = 0.0160694$ and $\nu = 10^{22.01}$ s^{-1}.

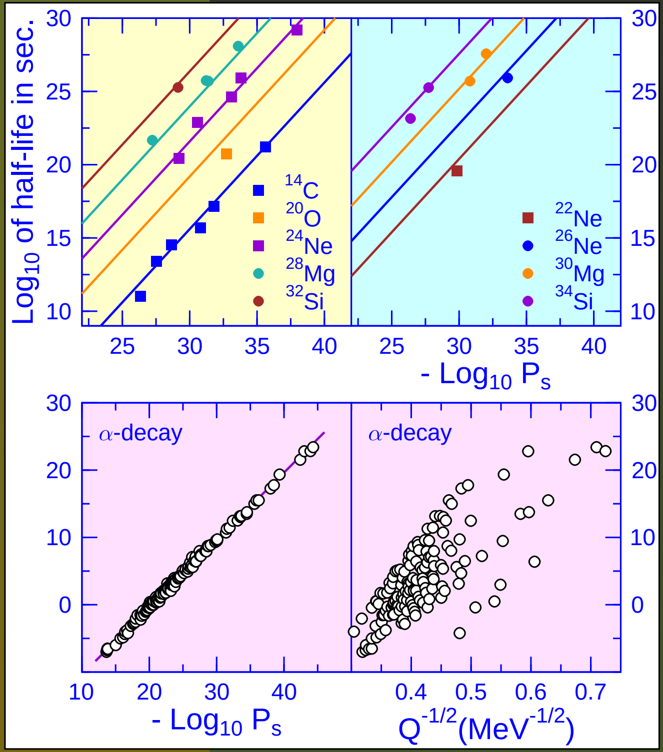
$$\boxed{\log T = -\log P - 22.169 + 0.598(A_e - 1)}$$

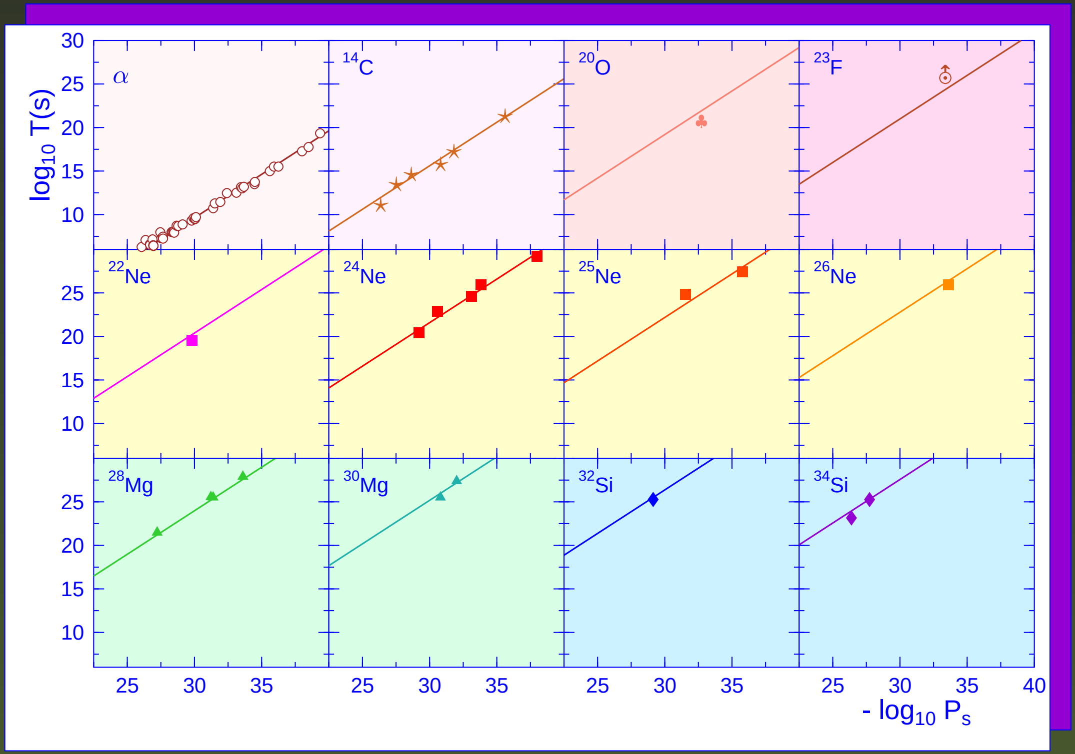
$$-\log P = c_{AZ} \left[\arccos \sqrt{r} - \sqrt{r(1-r)} \right]$$

$c_{AZ} = 0.22873(\mu_A Z_d Z_e R_b)^{1/2}$, $r = R_t/R_b$, $R_t = 1.2249(A_d^{1/3} + A_e^{1/3})$, $R_b = 1.43998 Z_d Z_e/Q$, and $\mu_A = A_d A_e/A$.

DN Poenaru, W Greiner, *Physica Scripta* **44** (1991) 427.

Universal curves (II)





Geiger-Nuttal plot $T_\alpha = f$(range of α in air)

$\log T = f(1/Q^{-1/2})$

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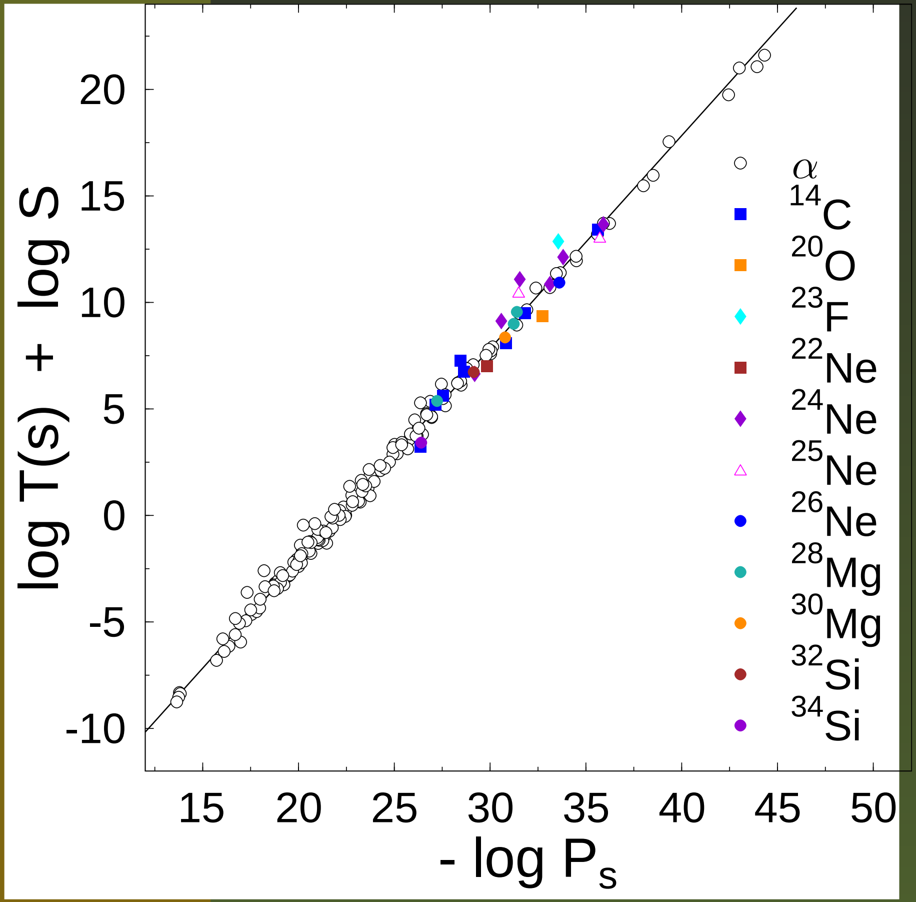
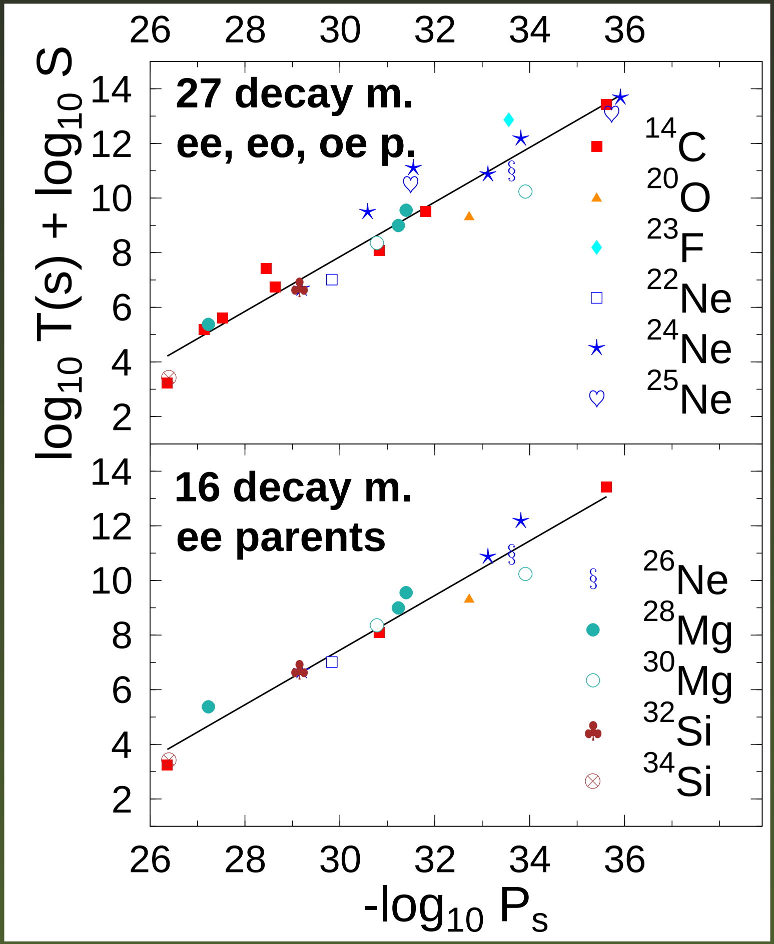
Single Universal curve: α and HIR





D.N. Poenaru, R.A. Gherghescu, W. Greiner, Phys. Rev. C, **83** (2011) 014601.

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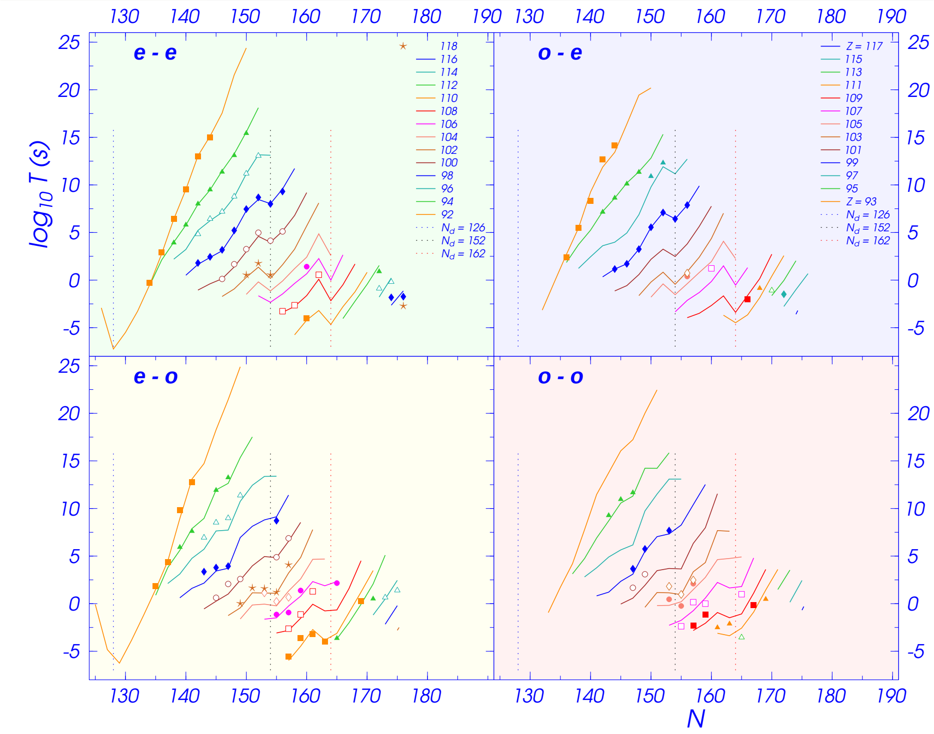
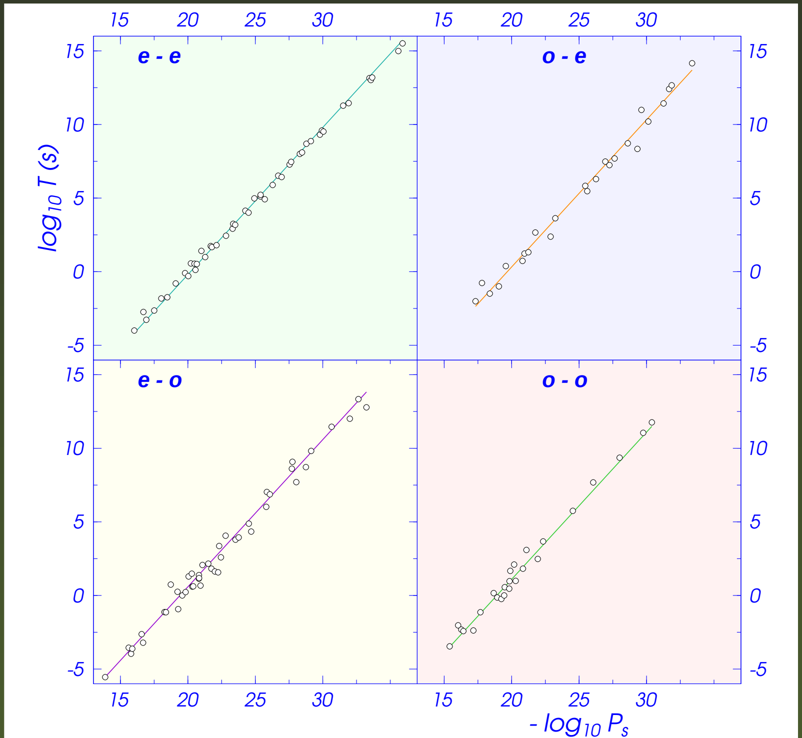
α-decay $Z = 92 - 118$, fission models

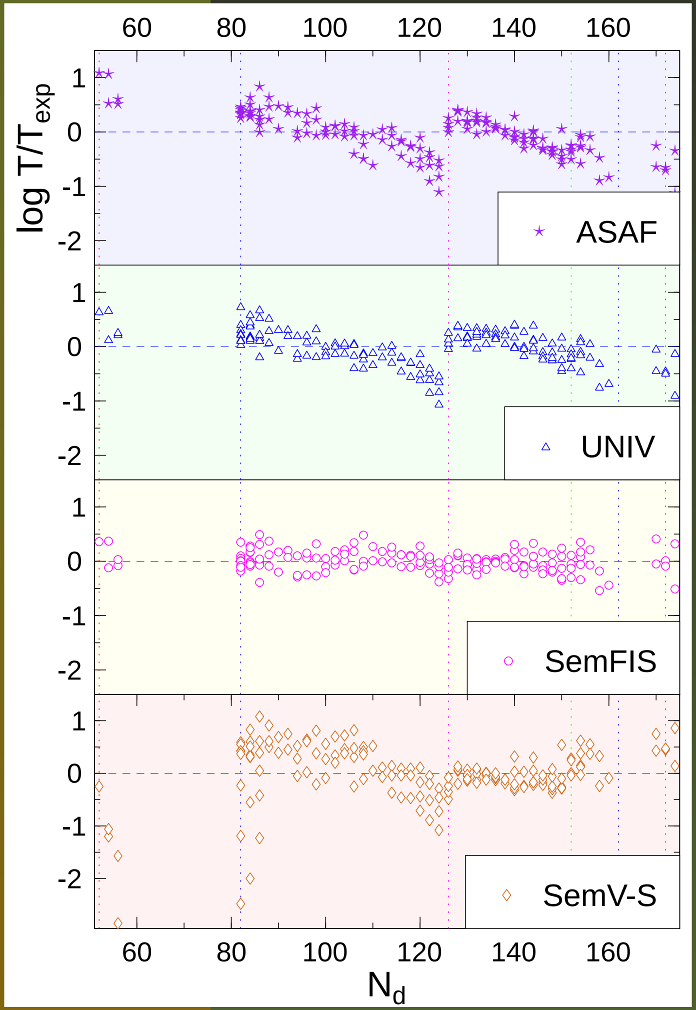




Vertical bars: $N_d = 126, 152, 162$

Poenaru, D.N., Plonski, I.H., and Greiner, W., *Phys. Rev.* **C 74** (2006) 014312

α-decay: ASAF, semFIS & UNIV

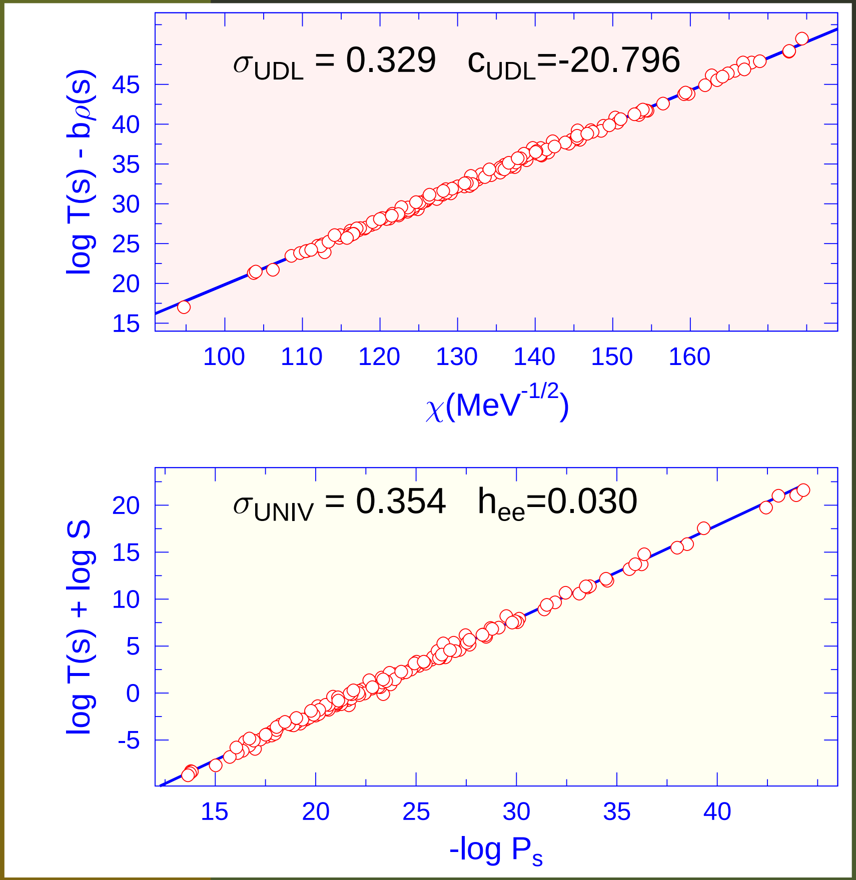


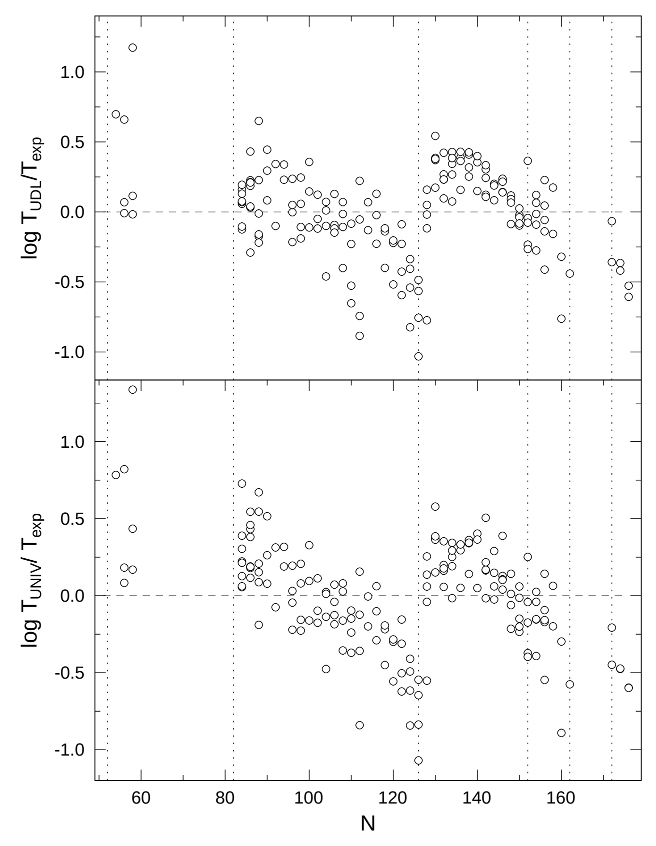
STANDARD DEVIATION

Group	σ-ASAF	σ-UNIV	σ-semFIS
47 e-e	0.402	0.267	0.164
45 e-o	0.615	0.554	0.507
25 o-e	0.761	0.543	0.485
25 o-o	0.795	0.456	0.451

Poenaru, D.N., Plonski, I.H.,
Gherghescu, R.A., Greiner, W.,
J. Phys. G **32** (2006) 1223

UNIV and UDL curve for e-e nuclei





Vertical bars: $N = 50, 82, 126, 152, 162, 172$

UDL: C. Qi, F.R. Xu, R.J. Liotta, R. Wyss Phys. Rev. Lett. **103** (2009) 072501.

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Compare UNIV, UDL, semFIS for α decay

Standard deviations of $\log T$ values of semFIS, UNIV and UDL formulae for 173 even-even, 134 even-odd, 123 odd-even, and 104 odd-odd α emitters with atomic numbers $Z = 52 - 118$.

n	σ_{UNIV}	h_{UNIV}	σ_{UDL}	c_{UDL}	σ_{SEM}
173	0.354	0.030	0.329	-20.796	0.222
134	0.640	0.528	0.606	-20.327	0.501
123	0.565	0.379	0.538	-20.481	0.434
104	0.826	0.961	0.804	-19.904	0.567

$$\sigma = \left\{\sum_{i=1}^{n}[\log(T_i/T_{exp})]^2/(n-1)\right\}^{1/2}$$

Summary

- ASAF model predictions have been confirmed for parent nuclei with $Z = 87 - 96$
- The magicity of the daughter ^{208}Pb was not fully exploited: new experimental searches can be performed
- The ASAF, semFIS and universal curves UNIV and UDL provide good estimation of half-lives
- For some superheavies HIR half-lives could be shorter than that of α decay