THEORY AND EXPERIMENTS ON HEAVY-ION RADIOACTIVITIES

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and

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OUTLINE

- Historical milestones
- Macroscopic-microscopic method
- Unified approach of cold fission, α-decay and heavy ion radioactivities within ASAF model
- Experimental confirmations
- Fine structure
- Extensions
  - saddle-point shapes obtained as solution of an Euler-Lagrange equation
  - α-decay of superheavies (ASAF, universal curve, semi-empirical formula)
  - multicluster fission (true ternary, quaternary, etc)
  - atomic cluster on a surface (with A. Solov'yov and R. A. Gherghescu)

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.

Historical milestones (I)

- 1878 John William Strutt (Lord Rayleigh): LDM
- 1895 Wilhelm Conrad Roentgen: X-rays
- 1896 Antoine Henri Becquerel: U rays
- 1898 Marie Sklodowska Curie and Pierre Curie: Ra, Po much stronger. Coined the name *radioactivity*
- 1899-1900 Ernest Rutherford and Paul Villard: α, β, γ rays
- 1911 Ernest Rutherford: atomic nucleus
- 1928 G. Gamow explained α-decay — quantum tunnelling
- 1935 Carl F. von Weizsäcker: Mass formula (binding energy)

Historical milestones (II)

- 1939 O. Hahn, Lise Meitner, F. Strassmann: induced fission. Explained with N. Bohr's LDM
- 1939 N. Bohr & J.A. Wheeler: mechanism of fission (LDM), Phys. Rev.
- 1940 G.N. Flerov & K.A. Petrzhak: spontaneous fission
- 1946 Tsien San-Tsiang, Ho Zah-Wei, L. Vigneron, R. Chastel: α accompanied (ternary) fission
- 1960 V. Goldansky predicted various kinds of proton rad.
- 1962 V. Karnaukhov: β-delayed proton radioactivity
- 1962 S.M. Polikanov: fissioning shape isomers

Historical milestones (III)

- 1963-1967 G. N. Flerov et al.: synthesis of SHelements, e.g. 102-105
- 1967 V.M. Strutinsky: shell & pairing corrections
- 1969 U. Mosel & W. Greiner: two-center shell model, prediction of superheavy nuclei, initiated creation of GSI
- 1973 V.V. Volkov: deep inelastic transfer reactions
- 1976-1996 S. Hofmann, G. Münzenberg, P. Armbruster: synthesis of SHelements Cold Fusion: 107-112
- 1980 A. Sandulescu, D.N. Poenaru, W. Greiner: prediction of cluster radioactivities.
- 1980 S. Hofmann: proton radioactivity

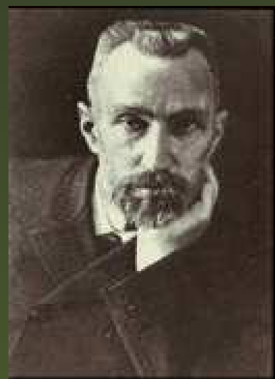
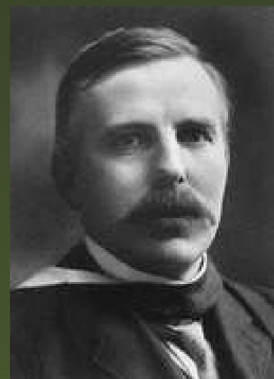
Historical milestones (IV)

- 1981 C. Signarbieux: cold fission
- 1984 H.J. Rose and G.A. Jones detected ^{14}C cluster radioactivity
- 1989 Fine structure of ^{14}C decay, SOLENO at IPN Orsay
- 1998 Vanderbilt Uni.-Dubna: α and ^{10}Be accompanied (ternary) cold fission
- 1999-2010 Yu. Ts. Oganessian et al.: SHelements 113-120 fusion with ^{48}Ca projectile
- 2002 GSI and GANIL: 2p radioactivity
- 2004 K. Morita et al. RIKEN: SHelement 113 Cold Fusion

The dawn of the Nuclear Age

Wilhelm Conrad Roentgen (Nobel prize 1901) discovered the X-rays in December 1895. **Radioactivity (coined by Marie Curie)** of an uranium salt was discovered by Antoine Henri Becquerel in March 1896. Marie Sklodowska Curie and Pierre Curie realized it is an atomic property of matter. Th is also emitter. Ra and Po are million times much stronger. Becquerel, Marie and Pierre Curie shared the Nobel prize 1903. In 1911 Marie Curie received the 2nd Nobel prize for discovery of Ra and Po.



Ernest Rutherford (1871-1937, 1908 Nobel prize) gave the names α and β radioactivity. From scattering experiments (1911) he deduced that atomic particles consisted primarily of empty space surrounding a central core called nucleus. He transmuted one element into another, elucidated the concepts of the half-life and decay constant. By bombarding N with α-particles produced oxygen. The atomic nucleus was discovered around 1911.

LDM and Quantum Tunneling

John William Strutt (Lord Rayleigh) (Nobel Prize, 1904)
Book *Theory of Sound*. On the equilibrium of liquid conducting masses charged with electricity.

Niels Bohr (Nobel Prize, 1922)



Lord Rayleigh, Phil. Mag. **14** (1878) 184
G. Gamow, Proc. Roy. Soc. A **51** (1930) 632
C.F. von Weizsäcker, Z. Phys. **96** (1935) 431
N. Bohr, Nature **137** (1936) 344. N. Bohr and J. Wheeler, Phys. Rev. **56** (1939) 426

B & W 1939: fission was more likely to occur with ^{235}U than ^{238}U.
We use LDM: W.D. Myers and W.J. Swiatecki, Nucl. Phys. **A 81** (1966) 1
Y+EM: H.J. Krappe, J.R. Nix and A.J. Sierk, Phys. Rev. **C 20** (1979) 992

Tunneling, first application of quantum theory to nuclei: G. Gamow, Z. Phys. **51** (1928) 204. Explained α-decay.

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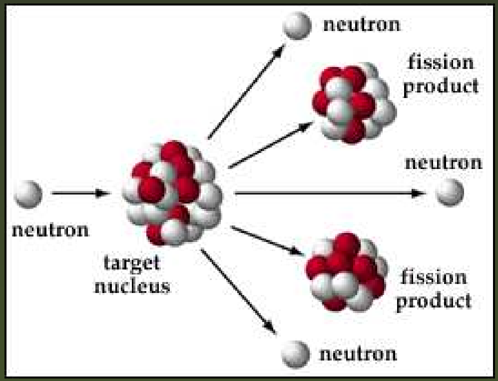
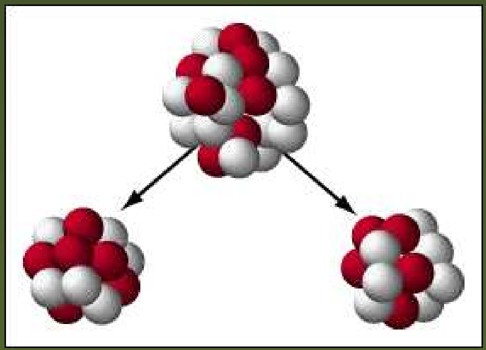
Discovery of nuclear fission (1939)

Induced fission: Otto Hahn (Nobel prize 1944), Lise Meitner and Fritz Strassmann — E. Fermi Award 1966.

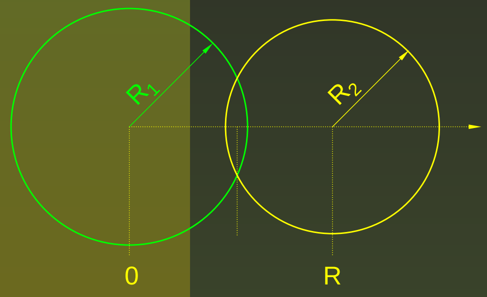
O. Frisch, Lise Meitner's nephew, borrowed the name FISSION from biology (cell division).



Spontaneous fission (1940): G.N. Flerov and K.A. Petrzhak



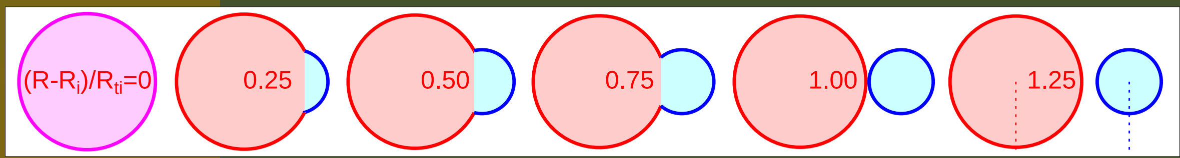
Intersected spheres



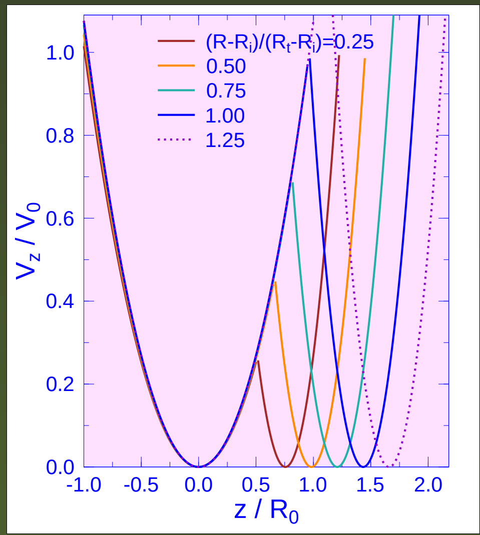
Two intersected spheres. Volume conservation and $R_2 = \text{const}$. One deformation parameter: separation distance R. Surface equation $\rho = \rho(z)$. Initial $R_i = R_0 - R_2$. Touching point $R_t = R_1 + R_2$.

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

Two center shell model (Frankfurt) potential



Sequence of shapes



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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

Shape dependent B_s and B_C

B_s is proportional with surface area $B_s = \frac{d^2}{2}\int_{-1}^{+1}\left[y^2 + \frac{1}{4}\left(\frac{dy^2}{dx}\right)^2\right]^{1/2} dx$

In cylindrical coordinates with -1, +1 intercepts on the symmetry axis $y = y(x)$ or $y_1 = y(x')$ is the surface equation. $d = (z'' - z')/2R_0$ – seminuclear length in units of R_0. Assume uniform charge density, $\rho_{0e} = \rho_{1e} = \rho_{2e}$. D.N. Poenaru et al., Comp. Phys. Comm. **16** (1978) 85, **19** (1980) 205. K, K' – complete elliptic integrals of the 1st and 2nd kind. $D = (K - K')/k^2$.

$$B_c = \frac{5d^5}{8\pi}\int_{-1}^{+1} dx \int_{-1}^{+1} dx' F(x, x')$$

$$\begin{aligned} F(x, x') \quad = \quad & \{yy_1[(K - 2D)/3] \cdot \\ & \left[2(y^2 + y_1^2) - (x - x')^2 + \frac{3}{2}(x - x')\left(\frac{dy_1^2}{dx'} - \frac{dy^2}{dx}\right)\right] + \\ & K\left\{y^2 y_1^2/3 + \left[y^2 - \frac{x - x'}{2}\frac{dy^2}{dx}\right]\left[y_1^2 - \frac{x - x'}{2}\frac{dy_1^2}{dx'}\right]\right\}\}a_\rho^{-1} \end{aligned}$$

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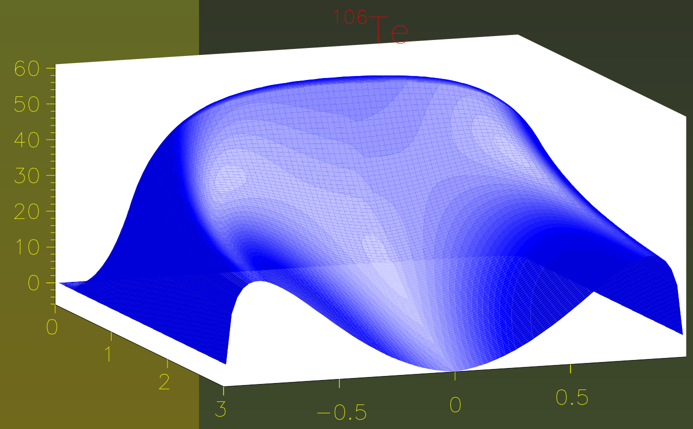
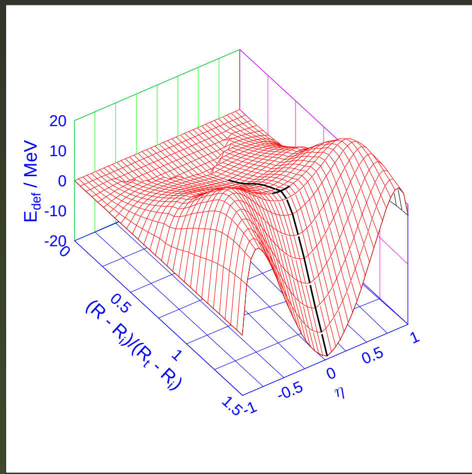
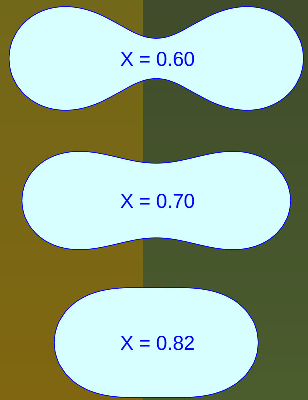
LDM PES and saddle-point shapes





Potential energy surfaces (PES) for ^{106}Te (left) and ^{232}Th (right)



Saddle point shapes for fissility parameter $X = 0.60, 0.70, 0.82$ (^{170}Yb, ^{204}Pb, ^{252}Cf nuclei) obtained by solving an integro-differential equation.

D.N. Poenaru, R.A. Gherghescu, W. Greiner, *Nucl. Phys.* **A 747** (2005) 182–205.

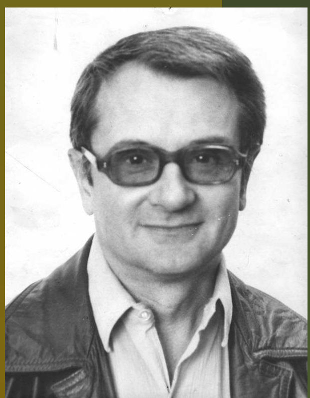
Macroscopic-microscopic method

$E_{def} = E_{LDM} + \delta E$.

V.M. Strutinsky (*Nucl. Phys.* **A 95** (1967) 420

microscopic calculation of shell and pairing corrections,

$\delta E = \delta U + \delta P$, based on the deformed shell models.



V.M. Strutinsky & S. Polikanov, APS 1978 Tom Bonner Prize *"For their significant contributions to the discovery and elucidation of isomeric fission. Their work has vastly expanded our understanding of the role of the single particle states on the total energy of heavy deformed nuclei. Their discoveries have had a crucial impact on the possible stability of very heavy nuclei."*

Also extended to atomic cluster physics.

Two center shell model (I)

Developed by the Frankfurt school since 1969, firstly a symmetric model [e.g. P. Holzer, U. Mosel, W. Greiner, *Nucl. Phys.* **138** (1969) 241], then the asymmetric one [J.A. Maruhn, W. Greiner, *Z. Phys.* **251** (1972) 431, R.A. Gherghescu and W. Greiner, *Phys. Rev.* **68** (2003) 044314.]

The Hamiltonian, H, is a sum of the kinetic energy, $-(\hbar^2/2M)\Delta$, and two potential terms: along the axis perpendicular to the symmetry axis is an harmonic oscillator $V_\rho = (m\omega_\rho^2/2)\rho^2$, and along the symmetry axis has two-centers $-z_1$ and $+z_1$, hence $V_z =$

$$\frac{m\omega_z^2}{2}\begin{cases}(z-z_1)^2 & , \quad z>0\\ (z+z_1)^2 & , \quad z<0\end{cases}$$

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Two center shell model (II)

One can separate the variables in the Schrödinger equation $H\Psi = E\Psi$ as $\Psi(\rho,\varphi,z) = R(\rho)\Phi(\varphi)Z(z)$, where $\Phi = e^{im\varphi}/\sqrt{2\pi}$, $R = \eta^{|m|/2}e^{-\eta/2}L_{n_r}^{|m|}(\eta)$, with $\eta = \rho^2/\alpha_\perp^2$ and the quantum numbers $m = (n_\perp - 2i)$ with $i = 0, 1, ...$ up to $(n_\perp - 1)/2$ for an odd $n_\perp$ or to $(n_\perp - 2)/2$ for an even $n_\perp$. $L_n^m(x)$ is the associated Laguerre polynomial and $\alpha_\perp = \sqrt{\hbar/m\omega_\rho}$ has the dimension of a length. The wave function in the dimension-less variable is given in terms of a Hermite function, with ν_n nonintegers.

$$\langle z|\nu_n\rangle = \begin{cases} c_n e^{-x^2/2} H_{\nu_n}\left(\frac{z-z_1}{\alpha}\right) & , \quad z > 0 \\ (-1)^n c_n e^{-x^2/2} H_{\nu_n}\left(-\frac{z+z_1}{\alpha}\right) & , \quad z < 0 \end{cases}$$

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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:

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

$k_i = Z/2 - n + 1, \;\; k_f = Z/2 + n', \;\; \frac{2}{G} \simeq 2\tilde{g}(\tilde{\lambda}) \ln\left(\frac{2\Omega}{\tilde{\Delta}}\right).$

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 $\tilde{p} = -(\tilde{g}\tilde{\Delta}^2)/2 = -(\tilde{g}_s\tilde{\Delta}^2)/4$. 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 $\delta e = \delta u + \delta p$.

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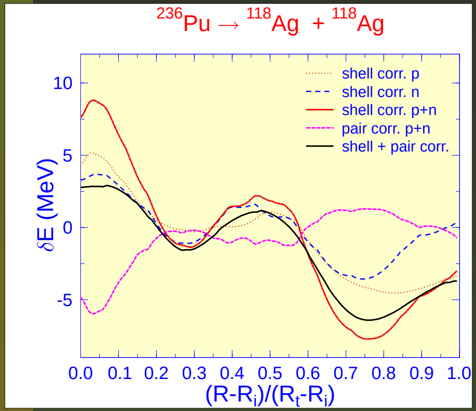
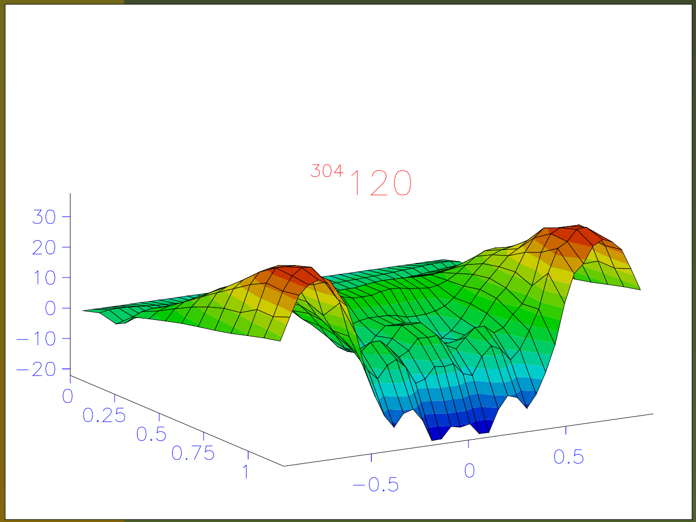
Results for ^{236}Pu and ^{304}120



Shell corrections for ^{236}Pu. Two-center shell model. Remark the smoothing due to the pairing correction.



PES vs R and η for a superheavy nucleus with $Z = 120$ and $A = 304$. The valleys due to the doubly magic fragments ^{208}Pb and ^{132}Sn are shown. Such cold valleys were used in the sixtieth by Walter Greiner to motivate the search for SHs, and the development of Heavy Ion Physics worldwide and in Germany, where GSI was built. Itkis et al. exp. confirmed the superasymmetric shoulder of fission fragment mass distributions.

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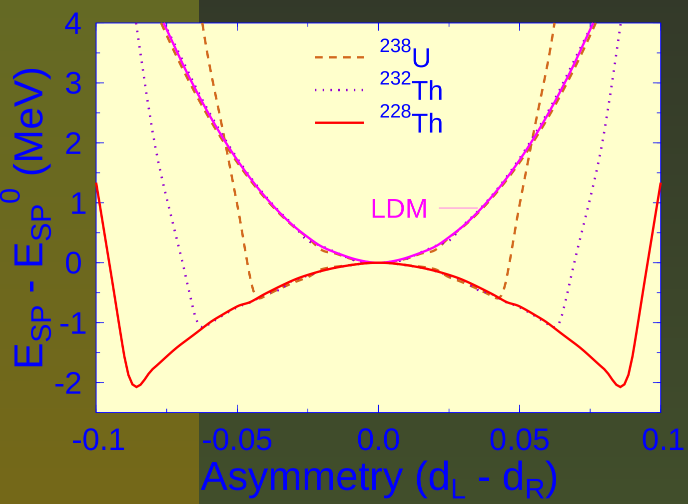
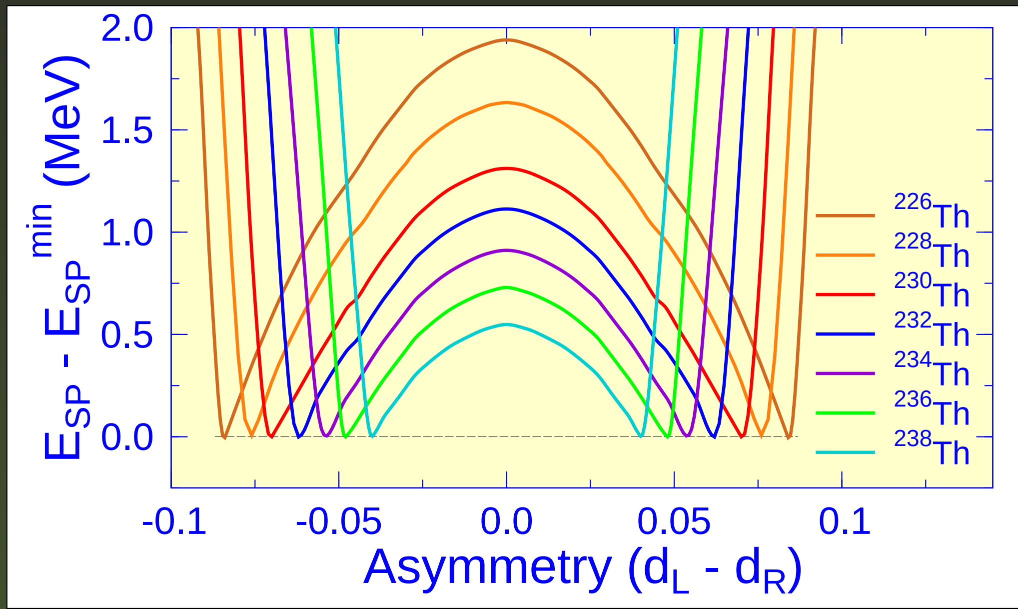
Mass asymmetry





Shell effects explain the mass asymmetry. Nuclear shape obtained as a solution of integro-differential equation.

D.N. Poenaru, R.A. Gherghescu, W. Greiner, *Nucl. Phys.* **A 747** (2005) 182–205.

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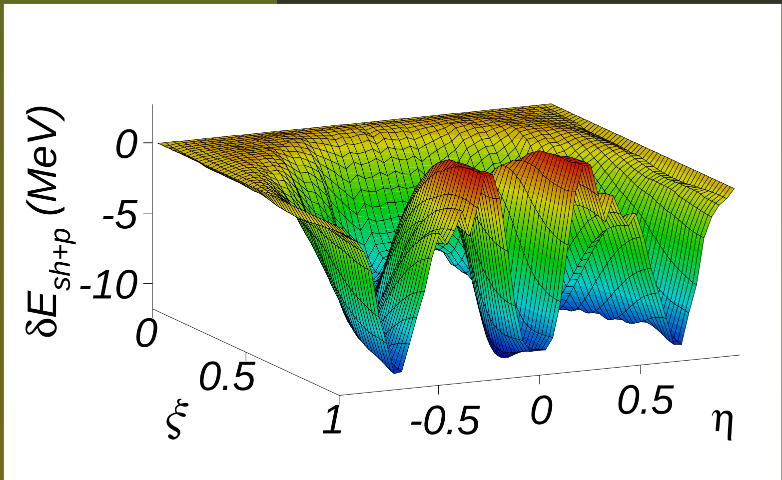
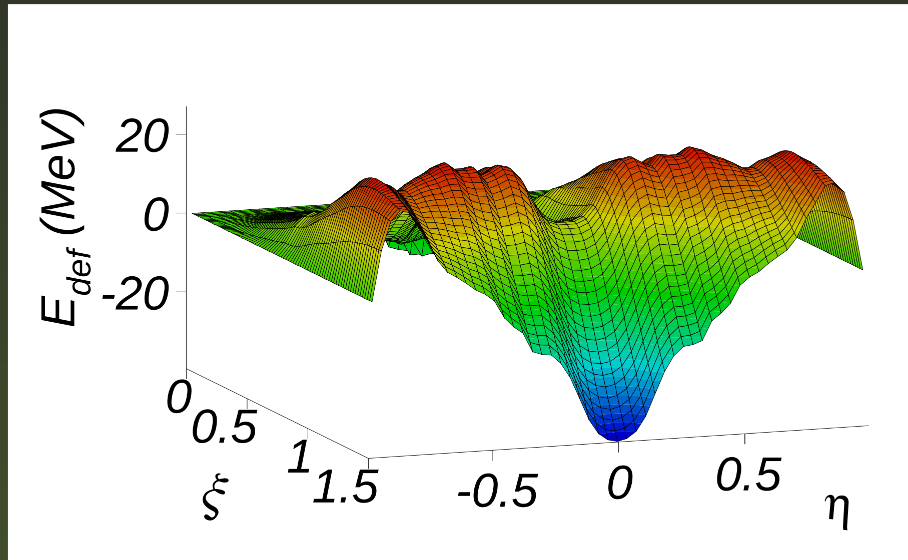
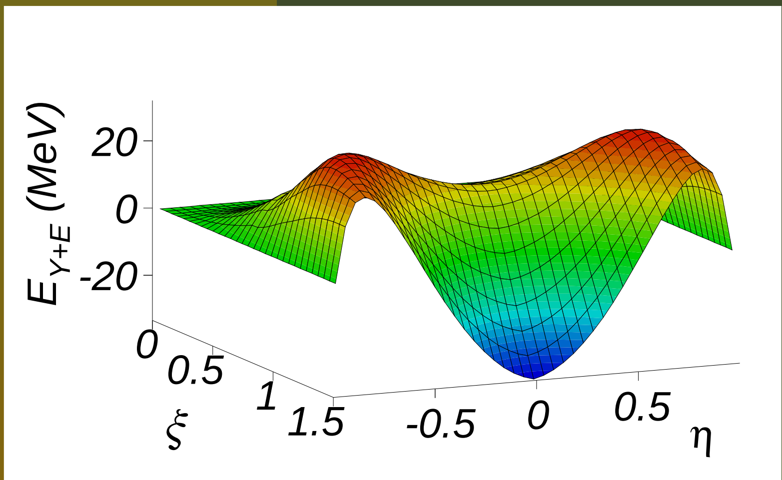
^{242}Cm E_{Y+EM}, $\delta E_{shell+pair}$, E_{def} PES







separation distance

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

mass asymmetry

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

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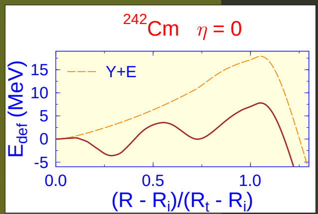
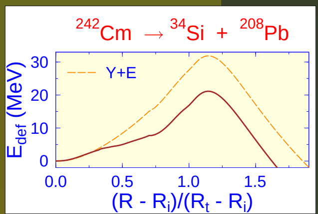
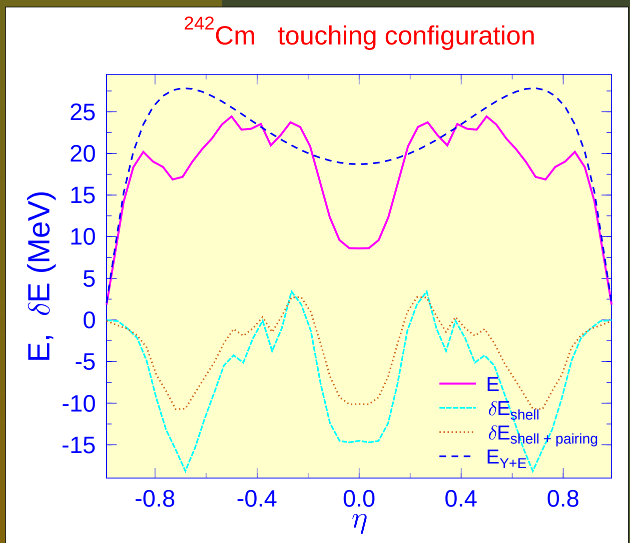
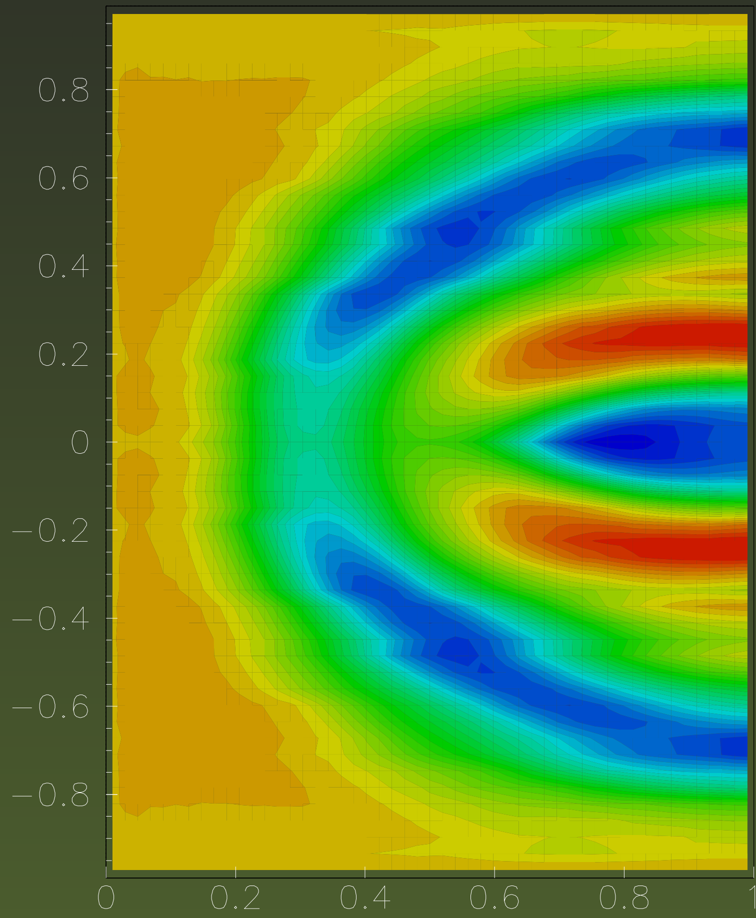
^{242}Cm barrier, touching, contour









$\delta E_{shell+pairing}$ contour plot

in the plane $(R - R_i)/(R_t - R_i), \eta$

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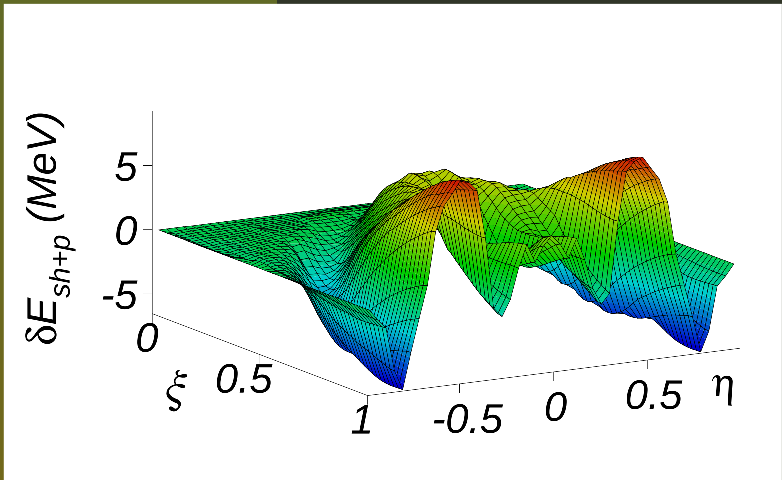
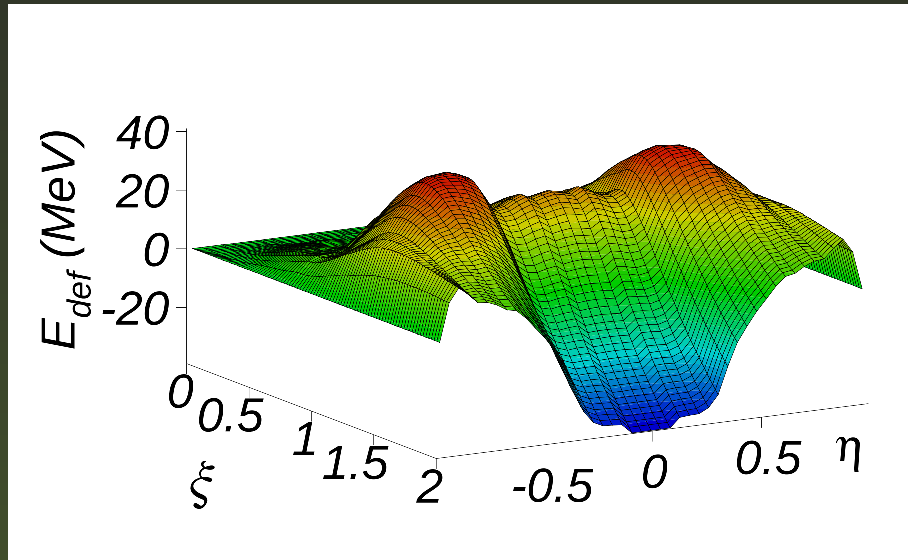
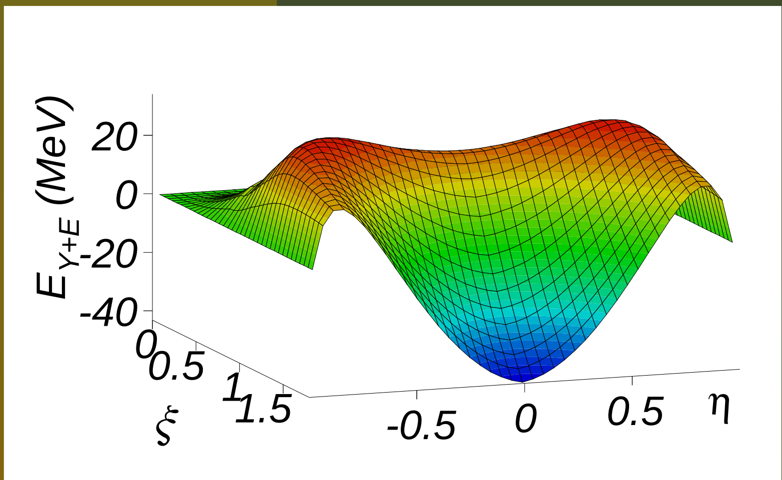
^{222}Ra E_{Y+EM}, $\delta E_{shell+pair}$, E_{def} PES







separation distance

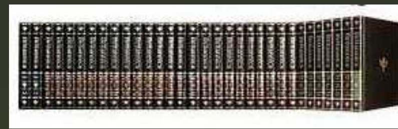
$$\xi = (R - R_i)/(R_t - R_i)$$

mass asymmetry

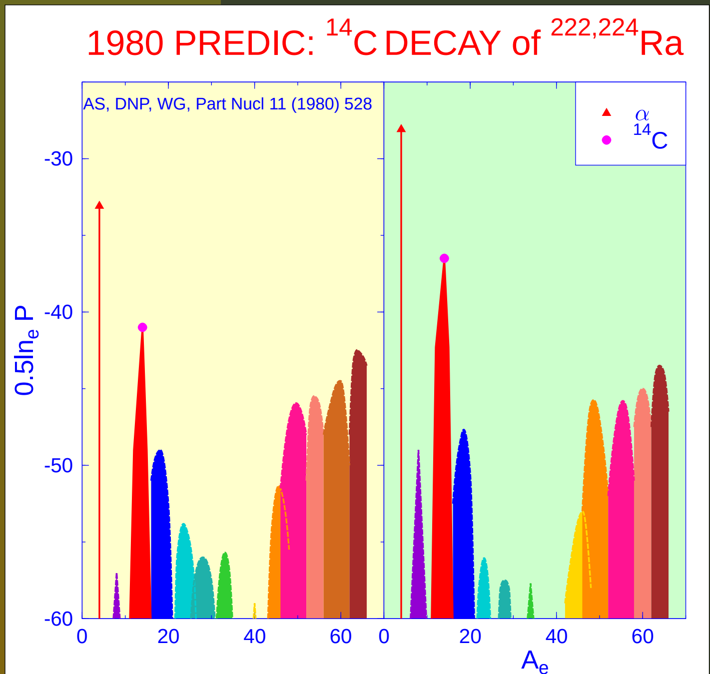
$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

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

Prediction of heavy ion radioactivity



The New Encyclopaedia Britannica: **"Heavy-ion radioactivity.** *In 1980 A. Sandulescu, D.N. Poenaru, and W. Greiner described calculations indicating the possibility of a new type of decay of heavy nuclei intermediate between alpha decay and spontaneous fission. The first observation of heavy-ion radioactivity was that of a 30-MeV carbon-14 emission from radium-223 by H.J. Rose and G.A. Jones in 1984."*



http://www.britannica.com/EBchecked/topic/465998/

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Our models

- Fragmentation and the asymmetric two center shell model
- Alpha-decay like theory
- Numerical superasymmetric fission (NuSAF) model
- Analytical superasymmetric fission (ASAF)

W. Greiner et al., in *Treatise on Heavy Ion Science*, Vol. 8 (Plenum, New York, 1989) 641.

D. N. Poenaru, M. Ivaşcu, W. Greiner, in *Particle Emission from Nuclei*, Vol. 3 (CRC, Boca Raton, 1989) 203.

D. N. Poenaru, W. Greiner (Eds):

Handbook of Nuclear Properties, (Clarendon Press, Oxford, 1996).

Nuclear Decay Modes, (IOP, Bristol, 1996).

Experimental Techniques in Nuclear Physics, (Walter de Gruyter, Berlin, 1997).

Cluster Radioactivity Ch. 1 in *Clusters in Nuclei. Lecture Notes in Physics 1* **Vol 818** (Springer, Berlin, 2010) Ed. C. Beck, pp. 1-56.

Basic relationships

Parent $\longrightarrow$ 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 $R \geq R_t$

Dorin N. POENARU, IFIN-HH

Analytical SuperAsymmetric Fission

Systematic search for cluster emitters: 10^5 combinations parent - emitted cluster. WKB approximation.

$$T = [(h \ln 2)/(2E_v)] exp(K_{ov} + K_s)$$

$$K_{ov} = 0.2196(E_b^0 A_e A_d/A)^{1/2}(R_t - R_i)\left[\sqrt{1-b^2} - b^2 \ln \frac{1+\sqrt{1-b^2}}{b}\right]$$

$$K_s = 0.4392[(Q+E_v)A_e A_d/A]^{1/2} R_b J_{rc} \; ; \; b^2 = E_v/E_b^0$$

$$\begin{aligned} J_{rc} &= (c) \arccos \sqrt{(1-c+r)/(2-c)} - [(1-r)(1-c+r)]^{1/2} \\ &+ \sqrt{1-c} \ln \left[\frac{2\sqrt{(1-c)(1-r)(1-c+r)} + 2 - 2c + cr}{r(2-c)}\right] \end{aligned}$$

$r = R_t/R_b$; $c = rE_c/(Q+E_v)$; $E_v = a_i(A_e)Q$; $R_i = R_0 - R_e, R_t = R_e + R_d$
$i = 1, 2, 3, 4$ for even-even, odd-even, even-odd, and odd-odd parent nuclei.
$R_b = R_t E_c \{1/2 + [1/4 + (Q+E_v)E_l/E_c^2]^{1/2}\}/(Q+E_v)$
$E_b^0 = E_i - Q$; $E_i = E_c + E_l = e^2 Z_e Z_d/R_t + \hbar^2 l(l+1)/(2\mu R_t^2)$

CLUSTER DECAYS

Experimental masses

2931 nuclei, measured or det. from Systematics. G. Audi et al., *Nucl. Phys.* **A 729** (2003) 337.

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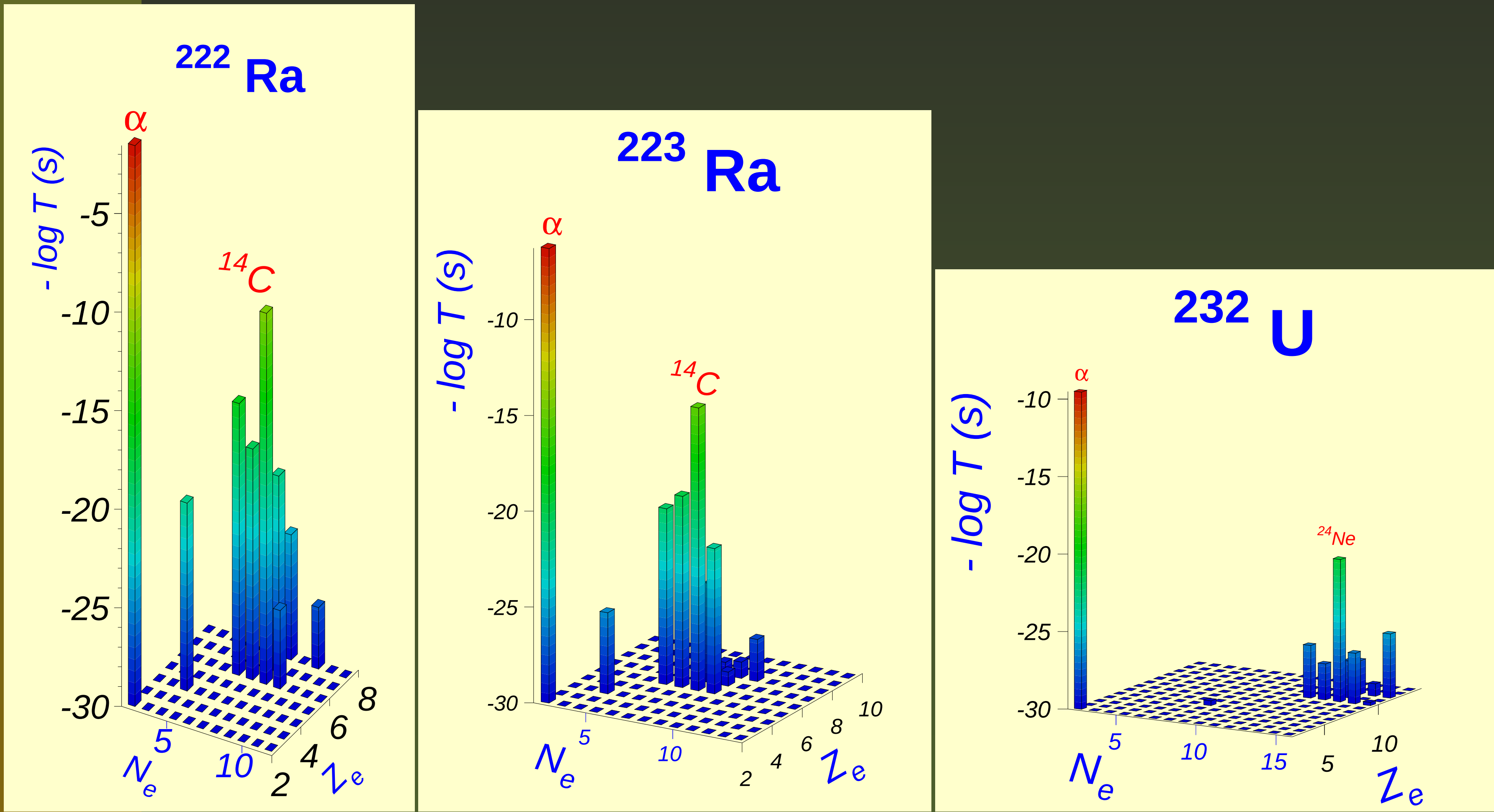
Examples of time spectra



CLUSTER DECAYS

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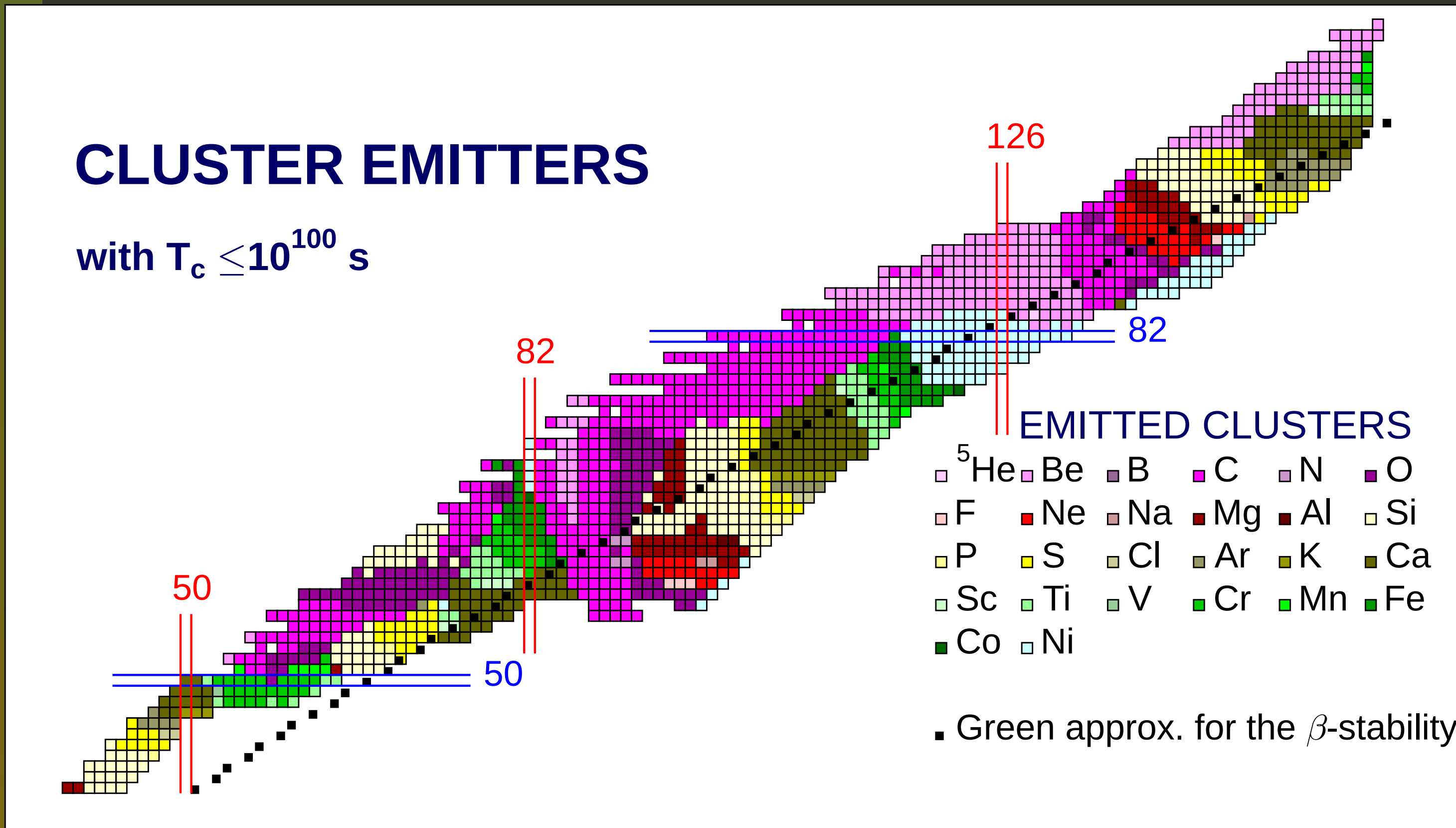
Cluster emitters



Most probable emitted clusters with different colors.

Comprehensive tables: DNP, WG, RAG et al. *Atomic Data Nucl. Data Tab.* **34**(1986)423;**48**(1991)231.

CLUSTER DECAYS

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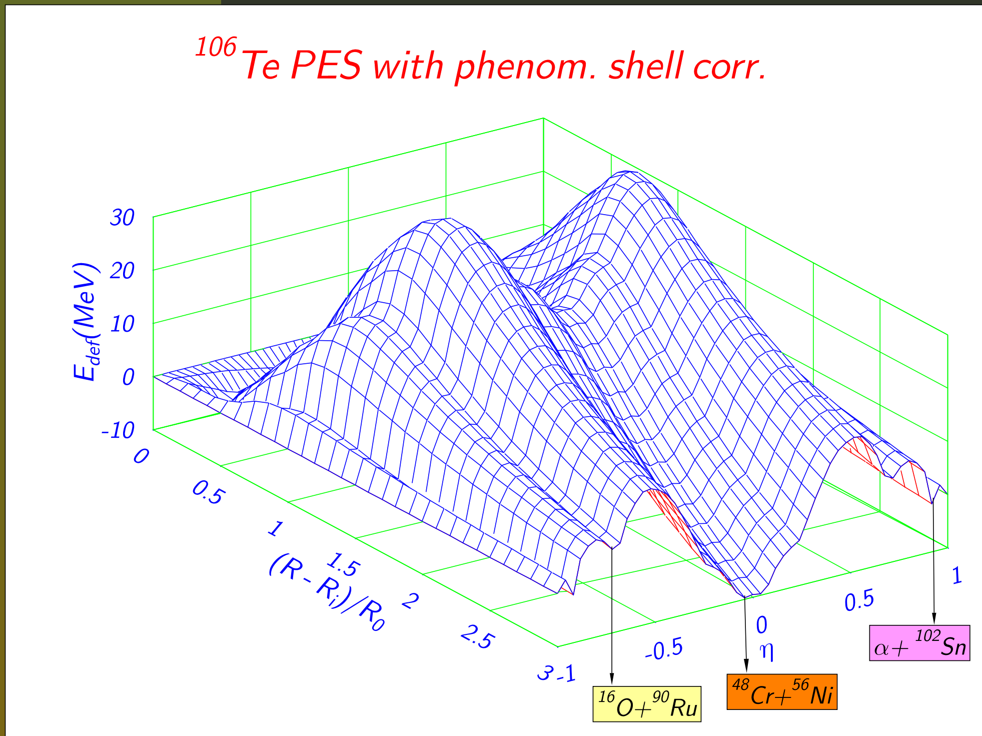
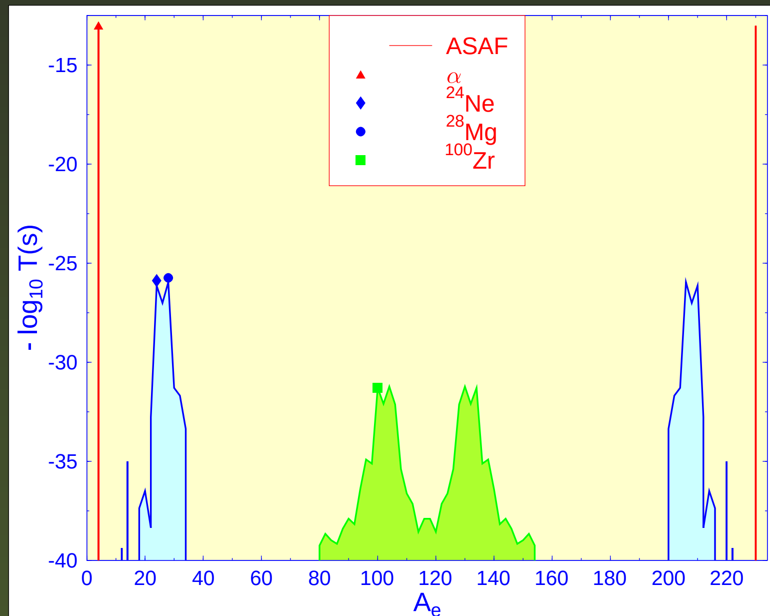
Unified approach: CF; HPR, and α-d





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.

Experiments performed in Dubna

Solid state nuclear track detectors (SSNTD).

Svetlana Tretyakova, V.L. Mikheev, Yu.Ts. Oganessian, A.A. Ogloblin *et al.*

Positive results or upper limits. Study of the following sources: ^{231}Pa; ^{233}U; ^{230}Th; ^{237}Np; ^{241}Am; ^{234}U; ^{236}Pu; ^{236}U; ^{114}Ba.

Coop. with R. Bonetti et al. from Univ. of Milano, Italy: ^{232}Th; ^{242}Cm; ^{223}Ac.

REVIEWS: D. Haşegan, S.P. Tretyakova, Spontaneous Emission of ^{24}Ne and Heavier Ions, Ch.9 in Particle Emission from Nuclei, Vol. II (CRC Press, Boca Raton, 1990) pp. 234-257

S.P. Tretyakova, Solid-state nuclear track detectors and their use in experimental nuclear physics, Sov. J. Part. Nucl. **23** (1992) 156-186

CLUSTER DECAYS

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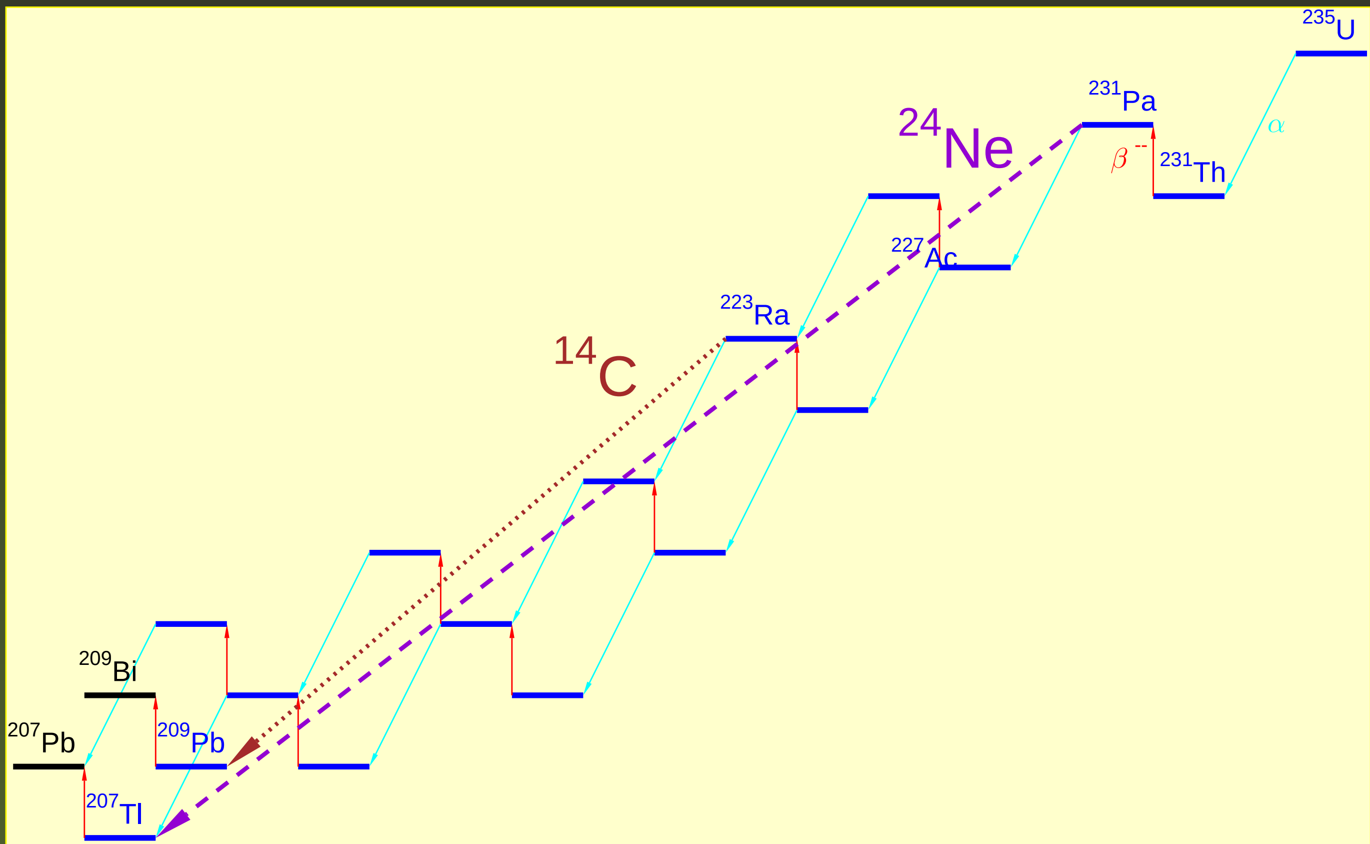
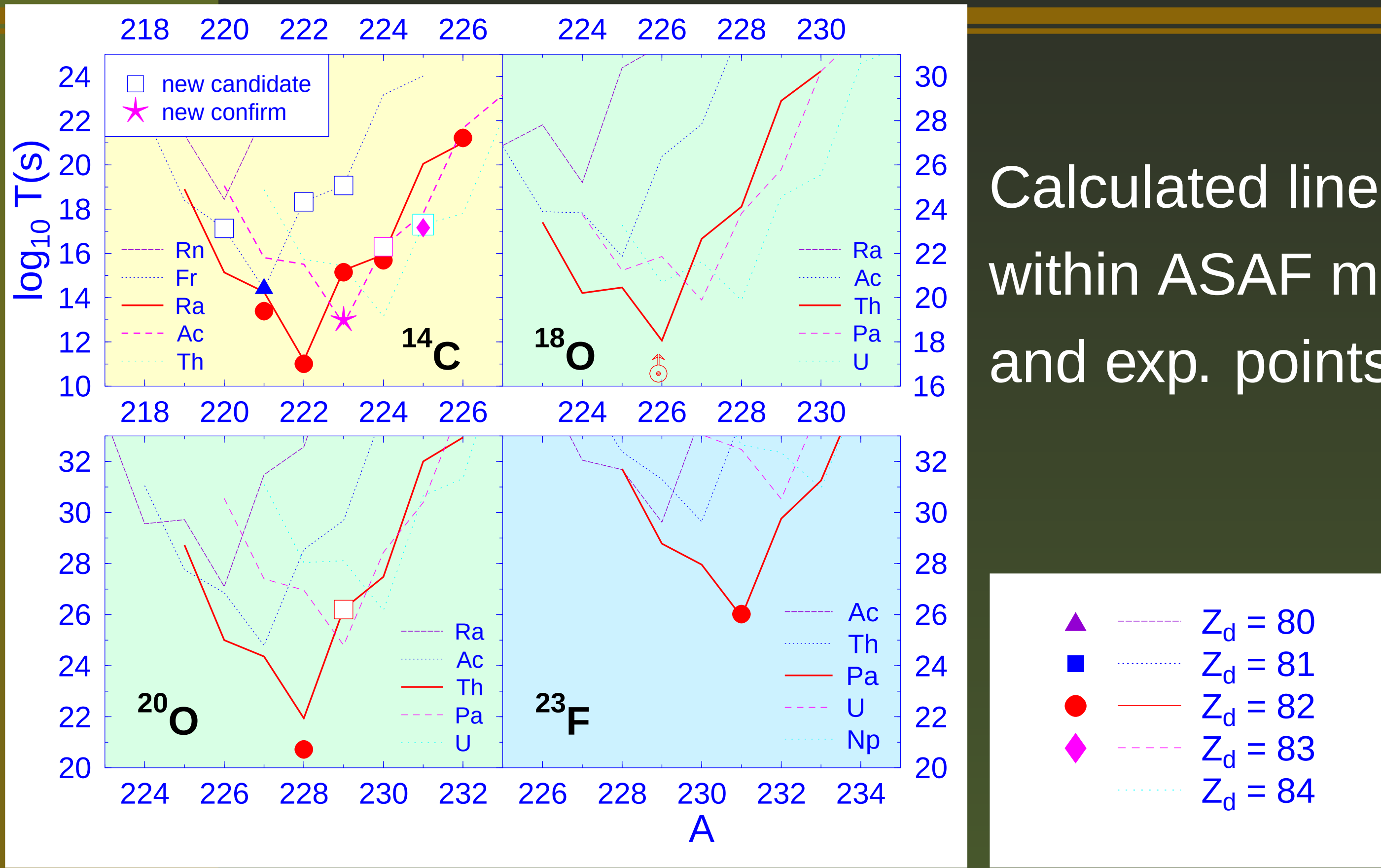
Natural radioactive family

Compare α and β^- to ^{14}C and ^{24}Ne decays



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

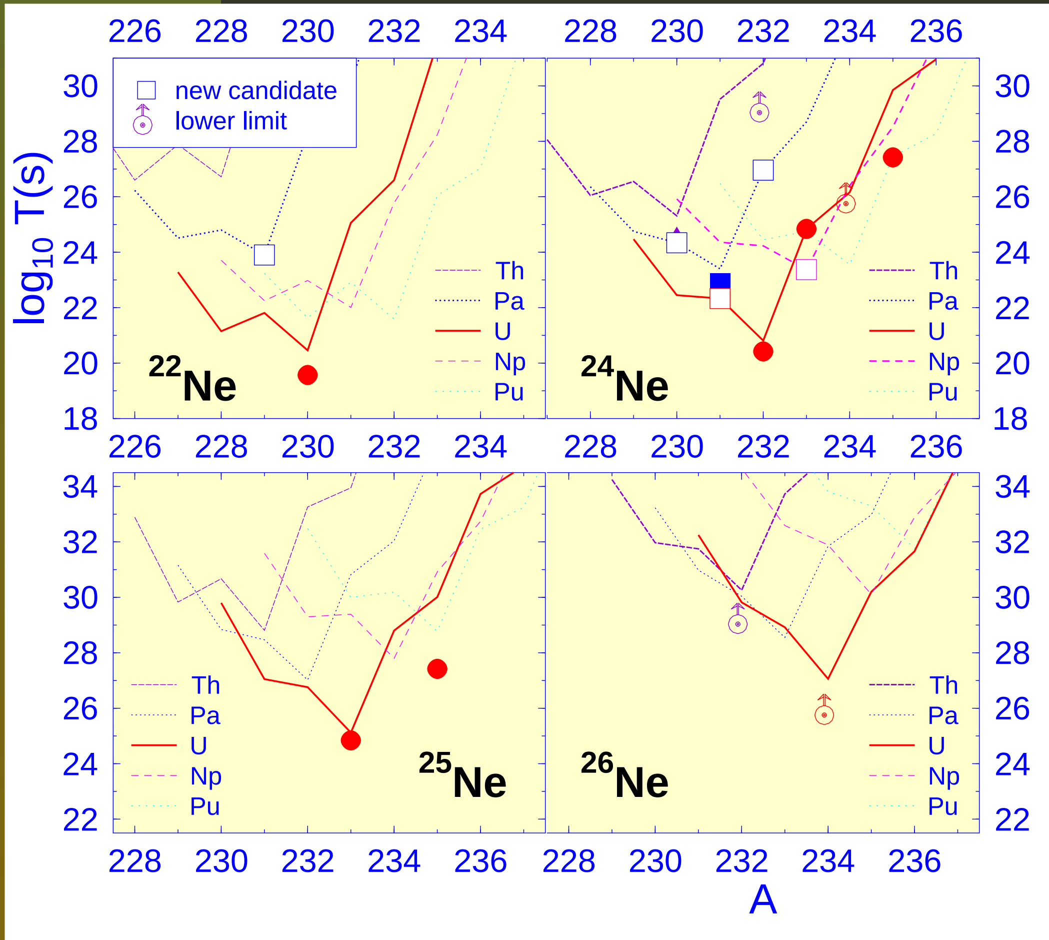


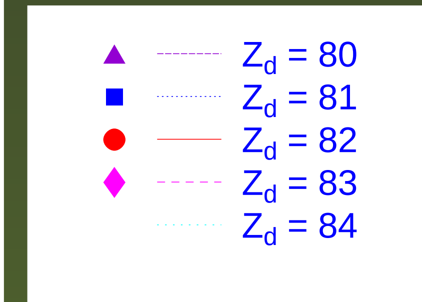
Calculated lines within ASAF model and exp. points

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.*

Dorin N. POENARU, IFIN-HH

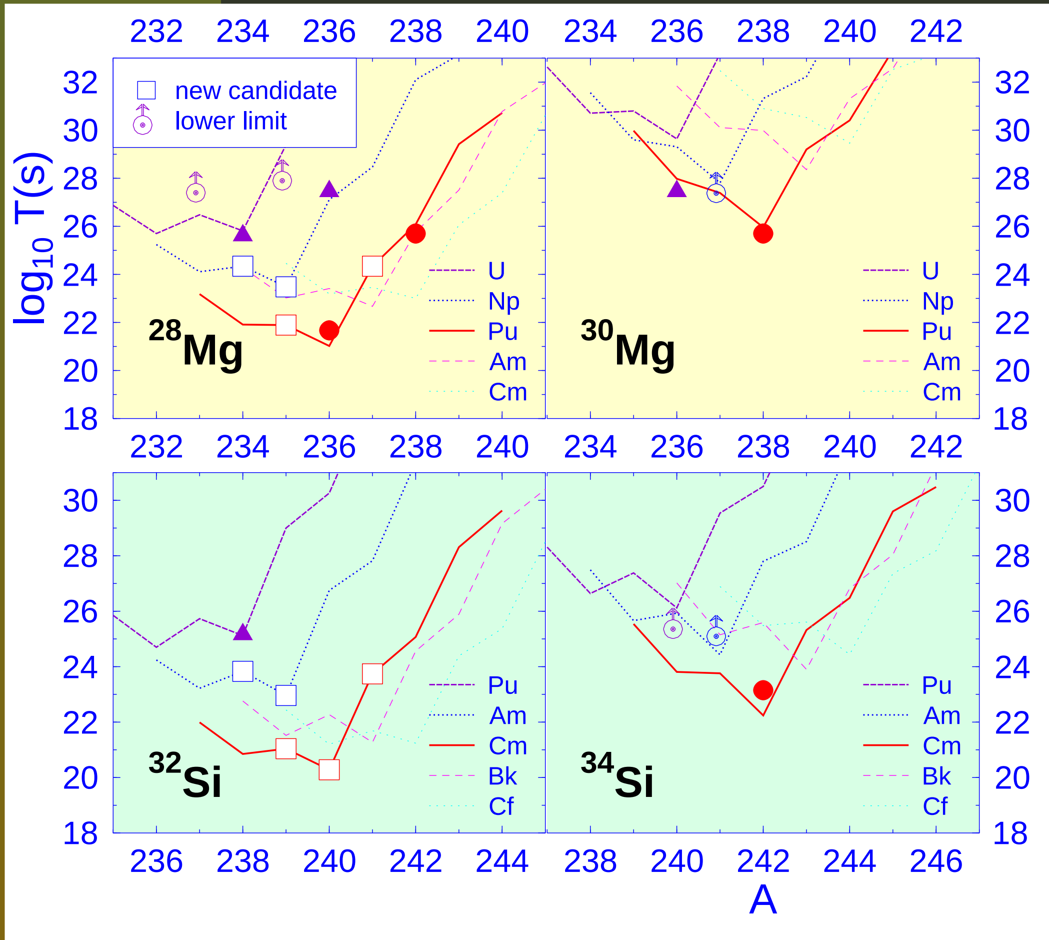
Systematics $T_{1/2}$: ^{22,24,25,26}Ne rad.





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

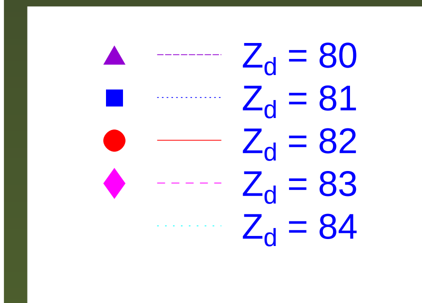
Systematics $T_{1/2}$: ^{28,30}Mg, ^{32,34}Si rad.



Minima at $N_d = 126$

Strong shell effect

Even-odd staggering



Strong shell effects

Cluster	Z_e	N_e	Parent - Daughter	Z_d	N_d	Cluster	Z_e	N_e	Parent - Daughter	Z_d	N_d
^{14}C	6	8	^{221}Fr	81	126	^{14}C	6	8	^{221}Ra	82	125
			^{222}Ra	82	126				^{223}Ra	82	127
			^{224}Ra	82	128				^{226}Ra	82	130
			^{223}Ac	83	126				^{225}Ac	83	128
^{20}O	8	12	^{228}Th	82	126	^{23}F	9	14	^{231}Pa	82	126
^{22}Ne	10	12	^{230}U	82	126	^{24}Ne	10	14	^{231}Pa	81	126
^{24}Ne	10	14	^{232}U	82	126				^{233}U	82	127
			^{234}U	82	128				^{235}U	82	129
^{25}Ne	10	15	^{233}U	82	128	^{25}Ne	10	15	^{235}U	82	128
^{26}Ne	10	16	^{234}U	82	126	^{28}Mg	12	16	^{234}U	80	126
^{28}Mg	12	16	^{236}U	80	128				^{236}Pu	82	126
			^{238}Pu	82	128	^{30}Mg	12	18	^{236}U	80	126
^{30}Mg	12	18	^{238}Pu	82	126	^{32}Si	14	18	^{238}Pu	80	126
^{34}Si	14	20	^{242}Cm	82	126						

Candidates for future experiments

^{220,222,223}Fr, ^{224}Ac, and ^{225}Th as ^{14}C emitters
(^{223}Ac emitter already measured)
^{229}Th for ^{20}O radioactivity
^{229}Pa for ^{22}Ne decay mode
^{230,232}Pa, ^{231}U, and ^{233}Np for ^{24}Ne radioactivity
^{234}Pu for ^{26}Mg decay mode
^{234,235}Np and ^{235,237}Pu as ^{28}Mg emitters
^{238,239}Am and $^{239-241}$Cm for ^{32}Si radioactivity
^{33}Si decay of ^{241}Cm

D.N. Poenaru, Y. Nagame, R.A. Gherghescu, W. Greiner, *Phys. Rev.* **C 65** (2002) 054308.

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

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}.

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

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

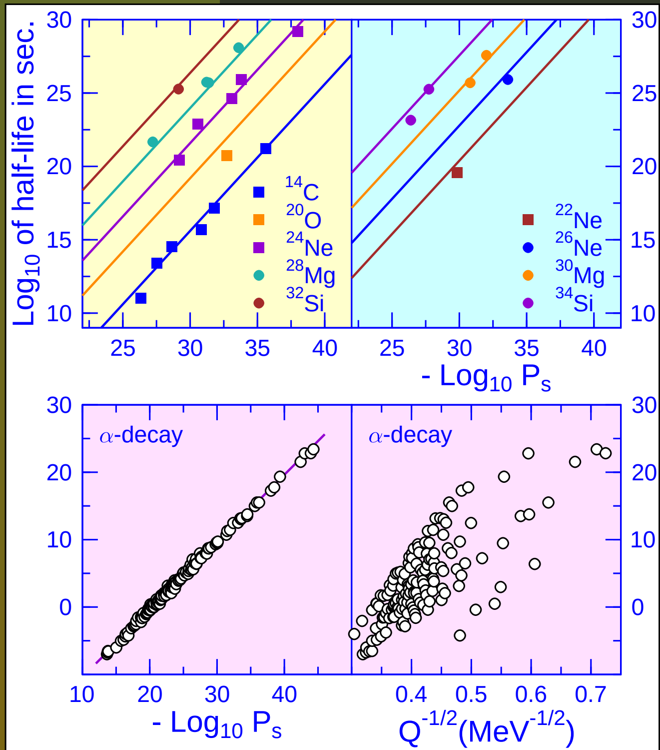
$c_{AZ} = 0.22873(\mu_A Z_d Z_e R_b)^{1/2}$, $r = R_t/R_b$, $R_t = 1.2249(A_d^{1/3} + A_e^{1/3})$, $R_b = 1.43998 Z_d Z_e/Q$, and $\mu_A = A_d A_e/A$.

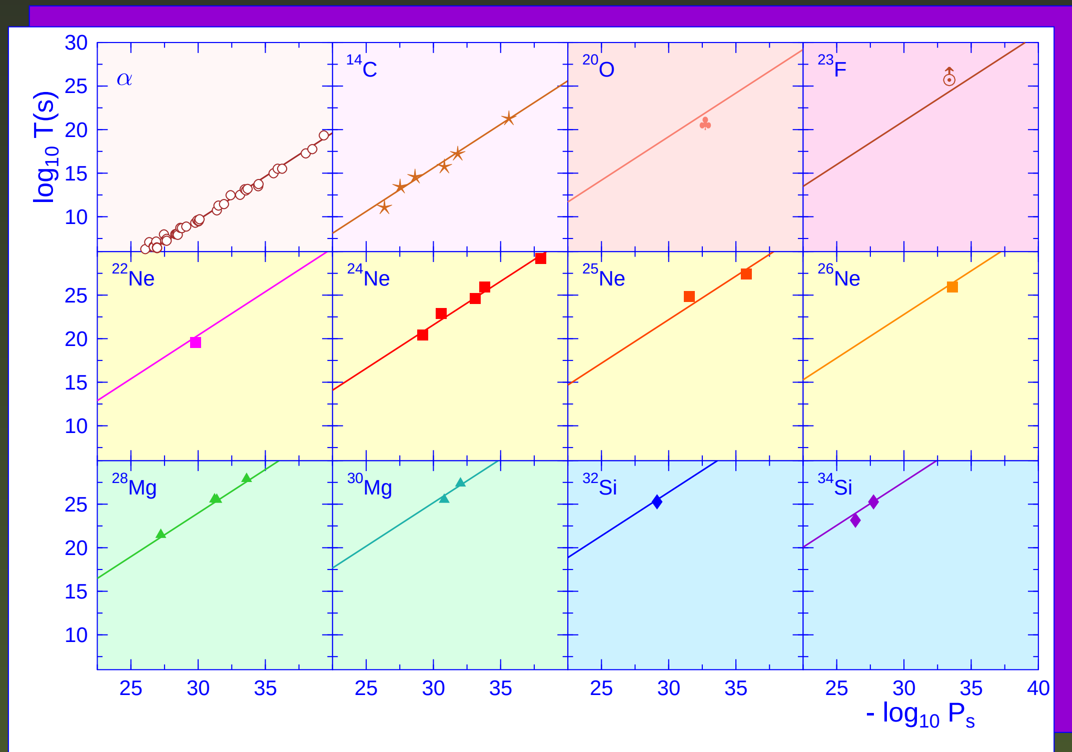
DN Poenaru, W Greiner, *Physica Scripta* **44** (1991) 427.

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

Universal curves (II)





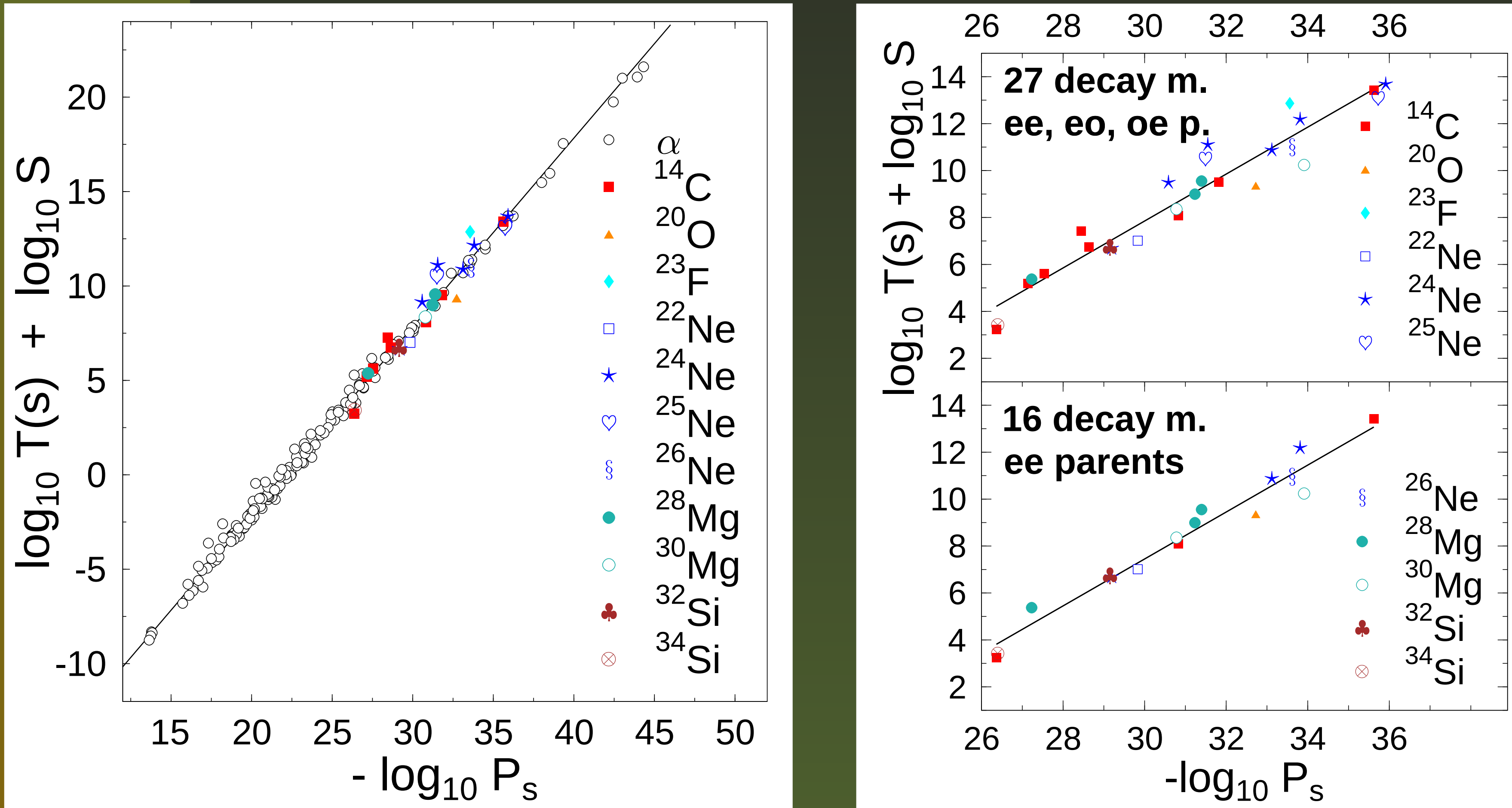
Geiger-Nuttal plot $T_\alpha = f(\text{range of } \alpha \text{ in air})$

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

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

Single Universal curve for α and HIR

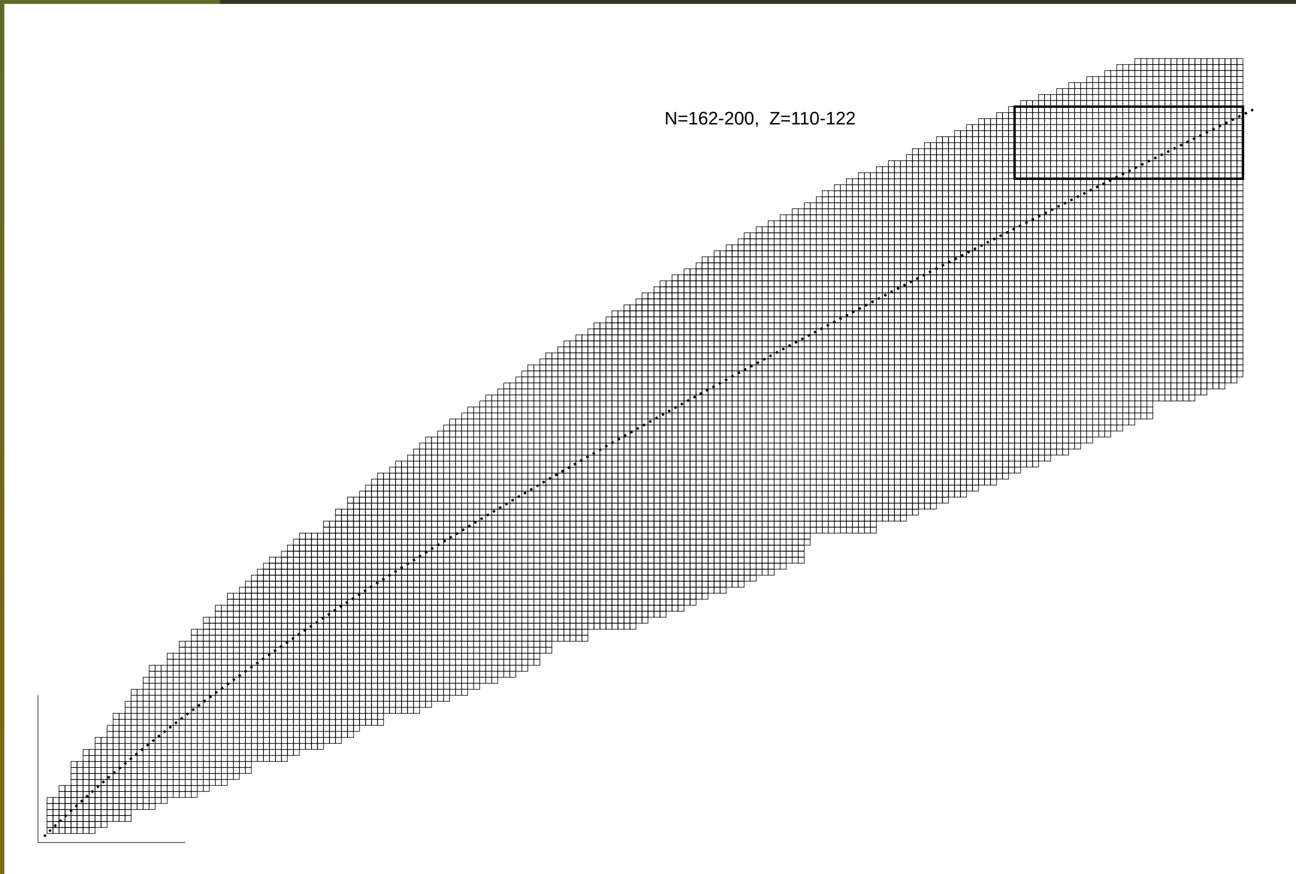


D.N. Poenaru, R.A. Gherghescu, W. Greiner, Phys. Rev. C, **83** (2011) 014601.

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

KTUY05 Calculated Masses

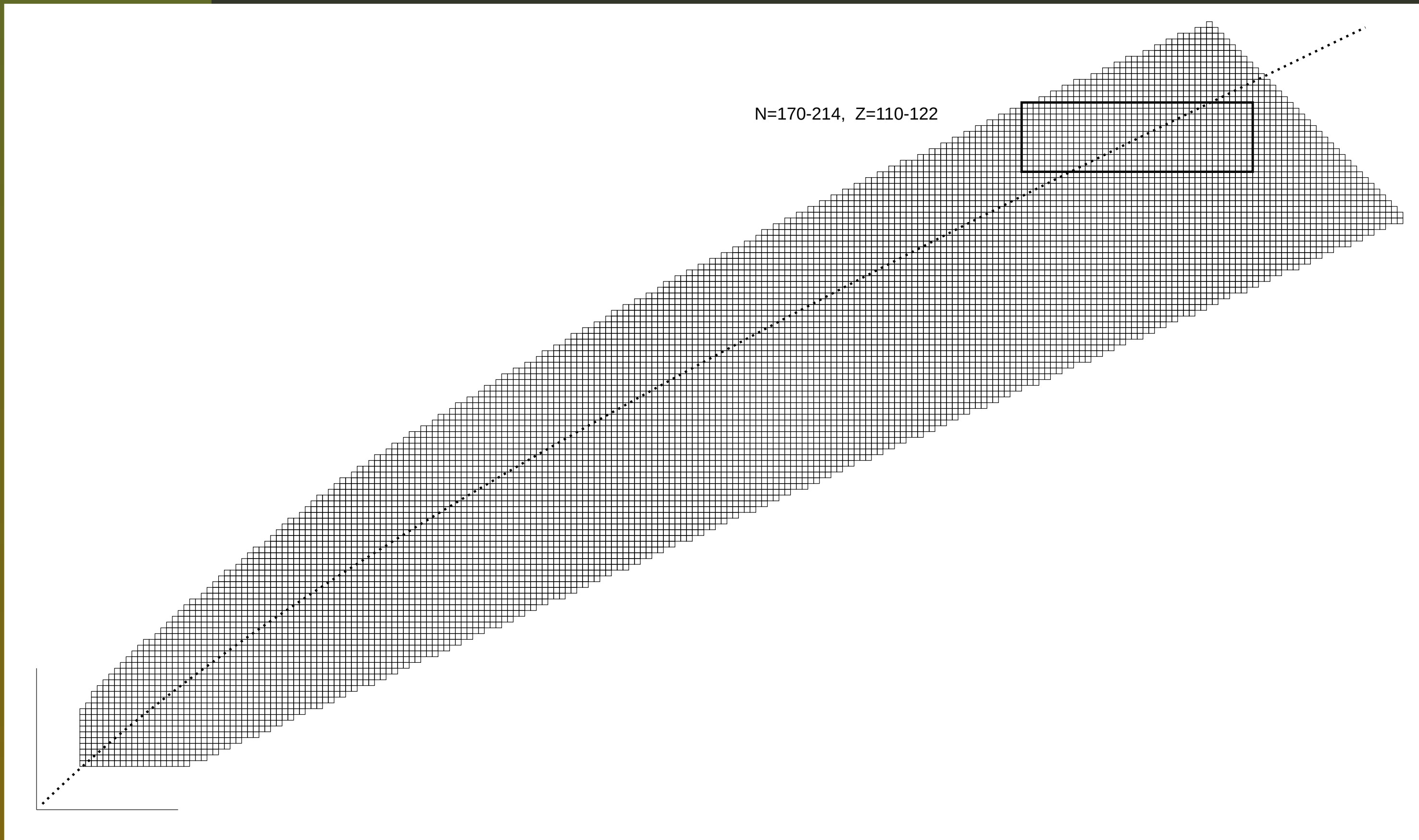


9441 nuclei with Z=2-130 and N=2-200. H. Koura, T. Tachibana, M. Uno and M. Yamada, *Prog. Theor. Phys.* **113** (2005) 305.

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

FRDM95 Calculated Masses

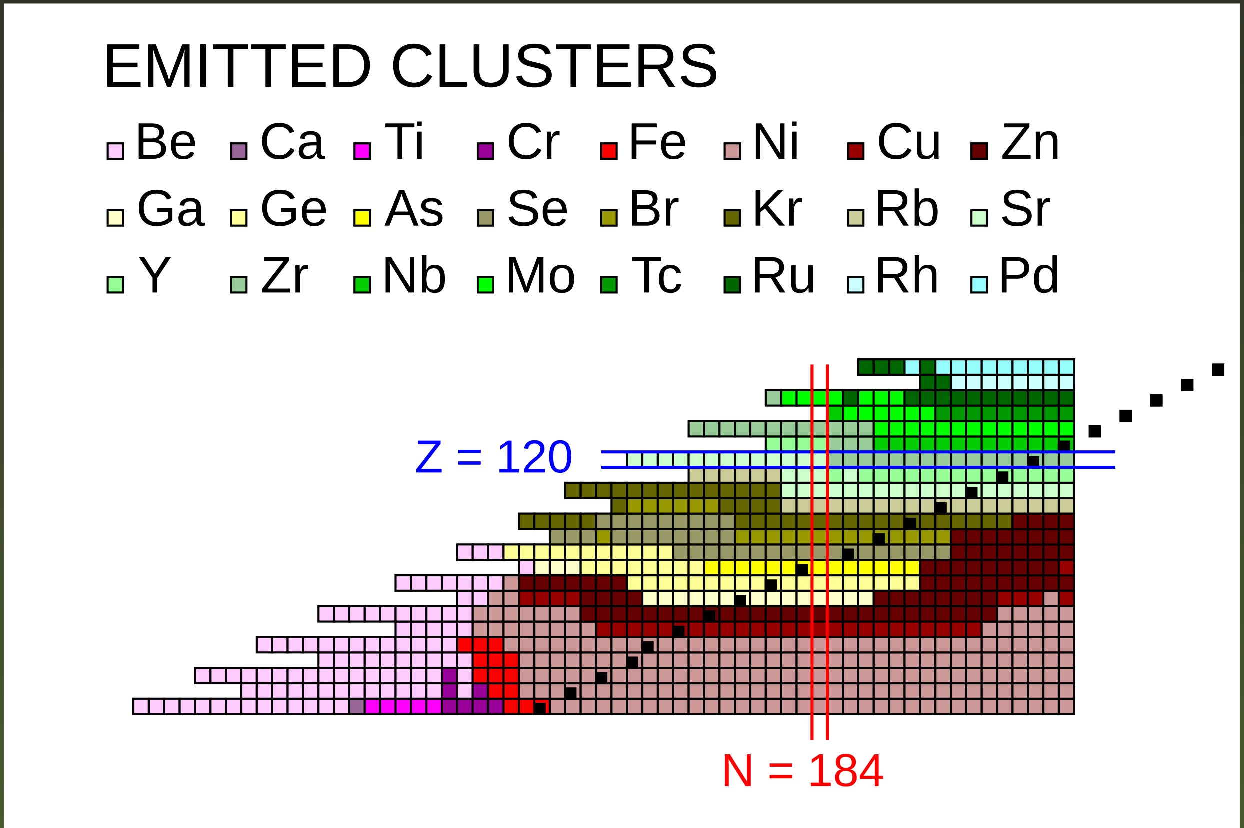


8979 nuclei with Z=8-136 and N=8-236. P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, *At. Data Nucl.Data Tables* **59** (1995) 185.

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

SH nuclei as cluster emitters (I)

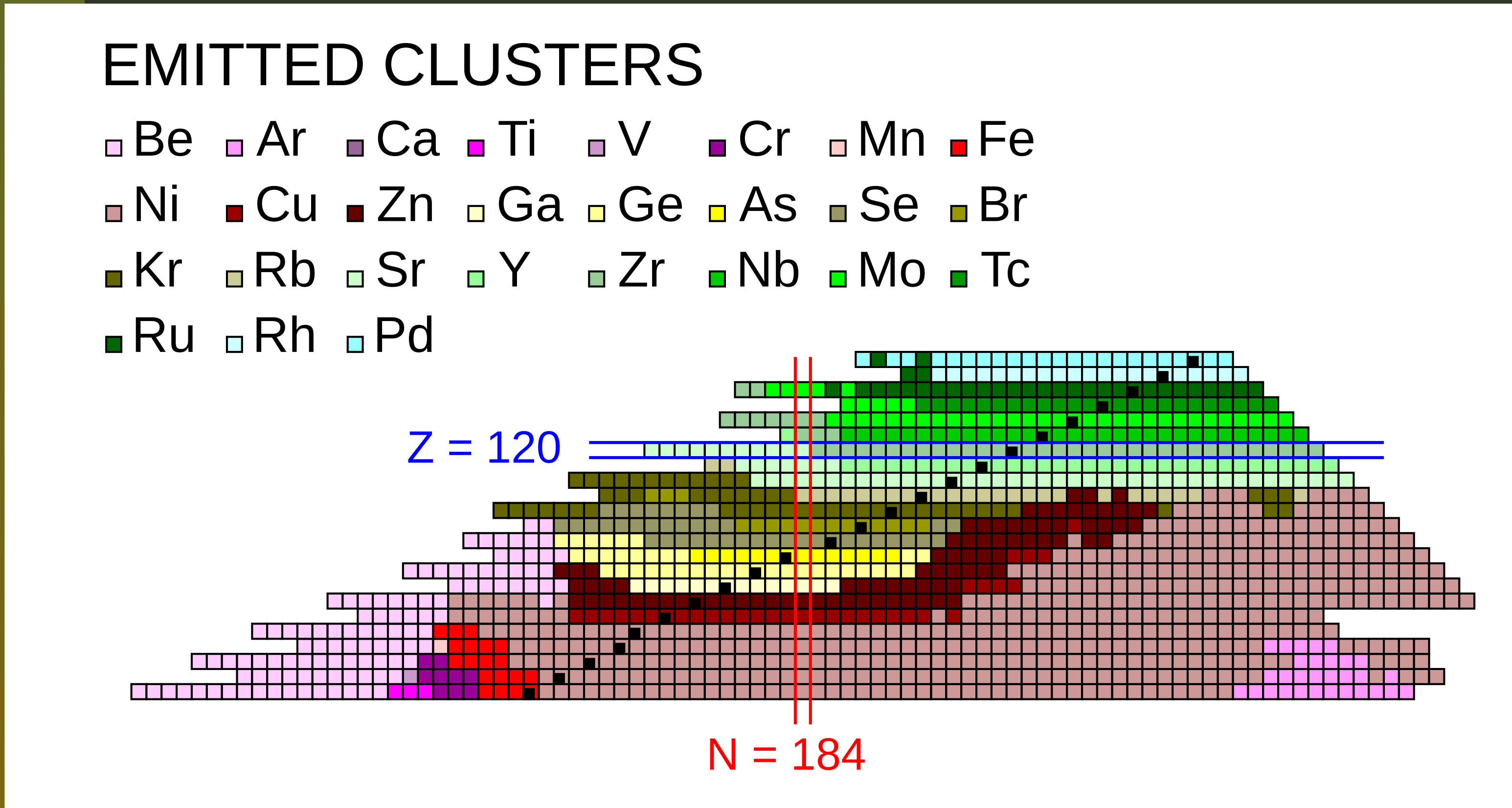


KTUY05 $Z_e \leq Z - 80$ (freq. daughter around ^{208}Pb)

Most probable emitted clusters with different colors.

Dorin N. POENARU, IFIN-HH

SH nuclei as cluster emitters (II)

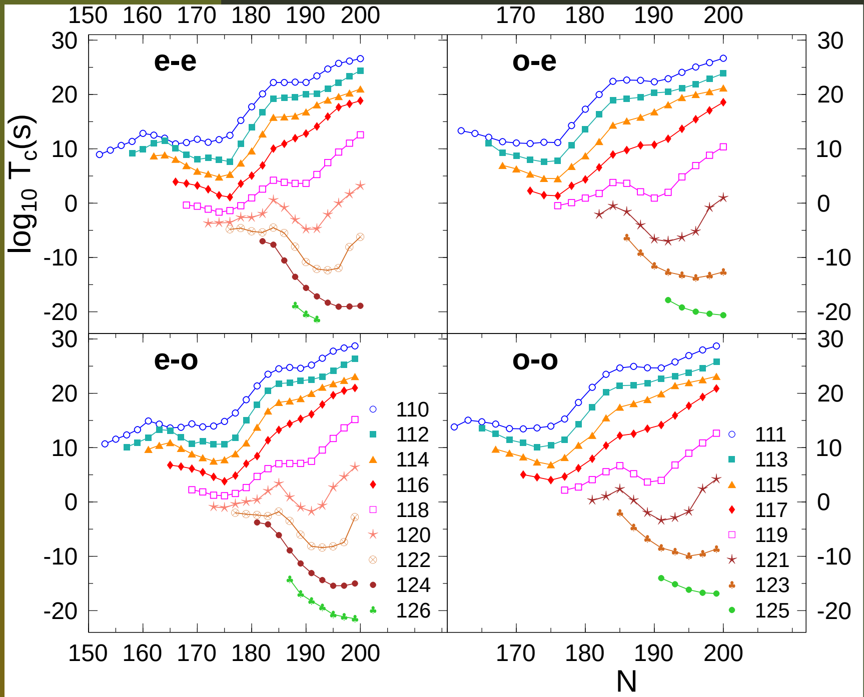


FRDM95 $Z_e \leq Z - 80$ (freq. daughter around ^{208}Pb)

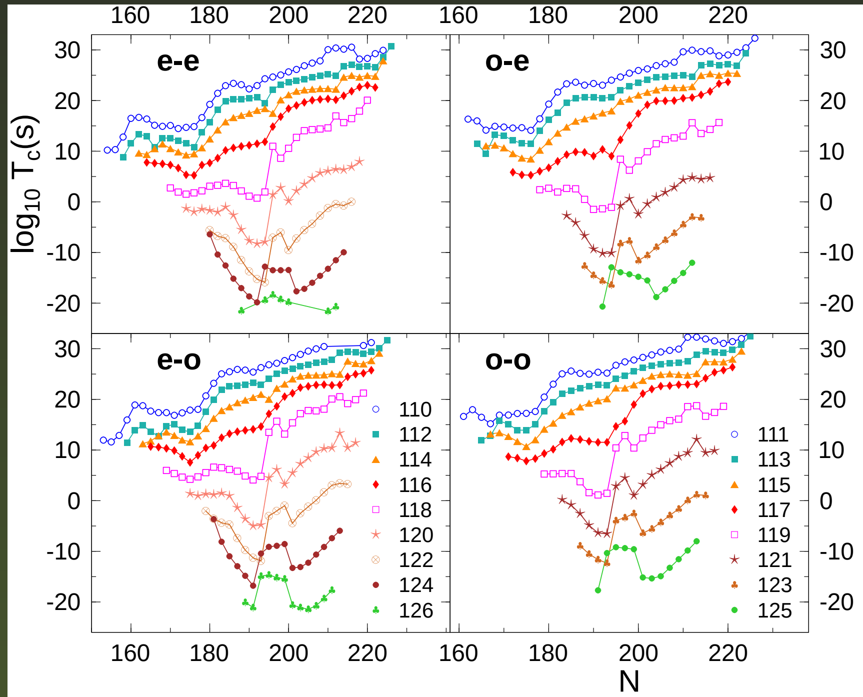
Most probable emitted clusters with different colors.

Dorin N. POENARU, IFIN-HH

HIR of SH nuclei (I)



KTUY05

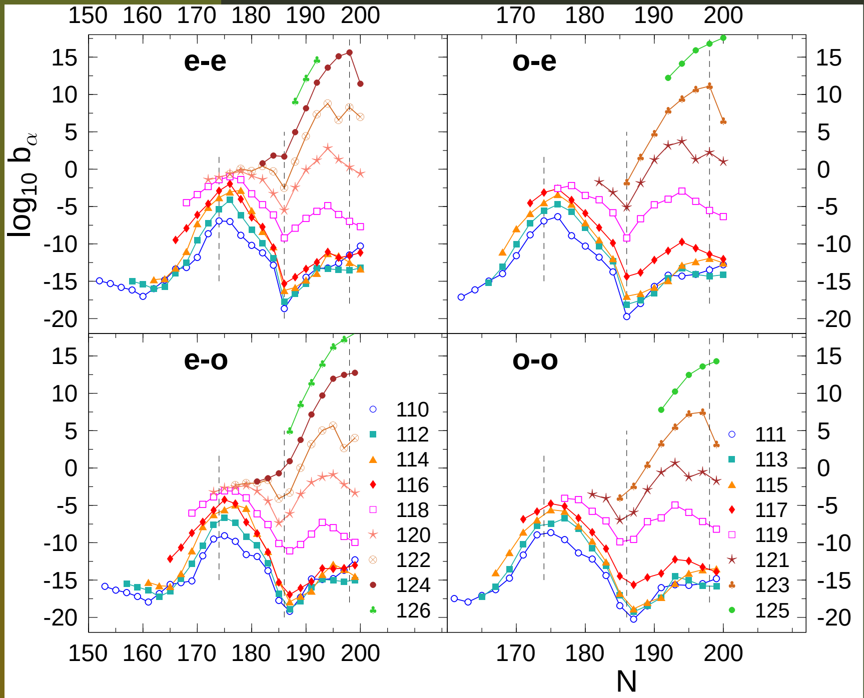


FRDM95

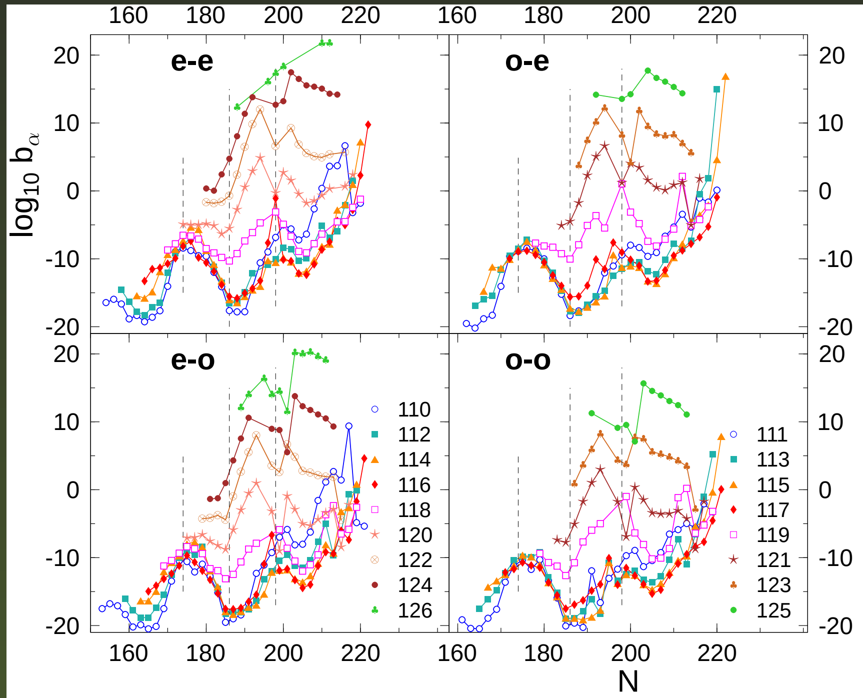
CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

HIR of SH nuclei (II)



KTUY05



FRDM95

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

Usually $b_\alpha << 1$.

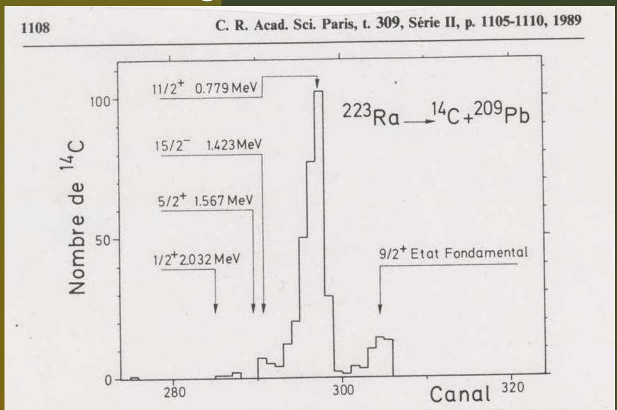
CLUSTER DECAYS

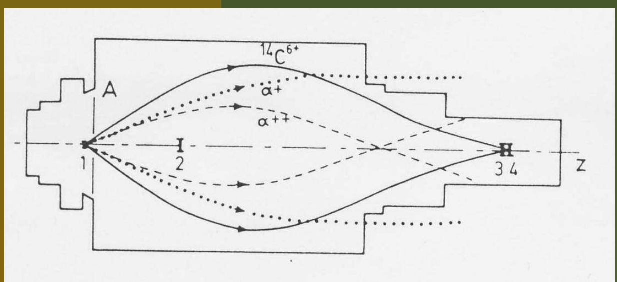
Dorin N. POENARU, IFIN-HH

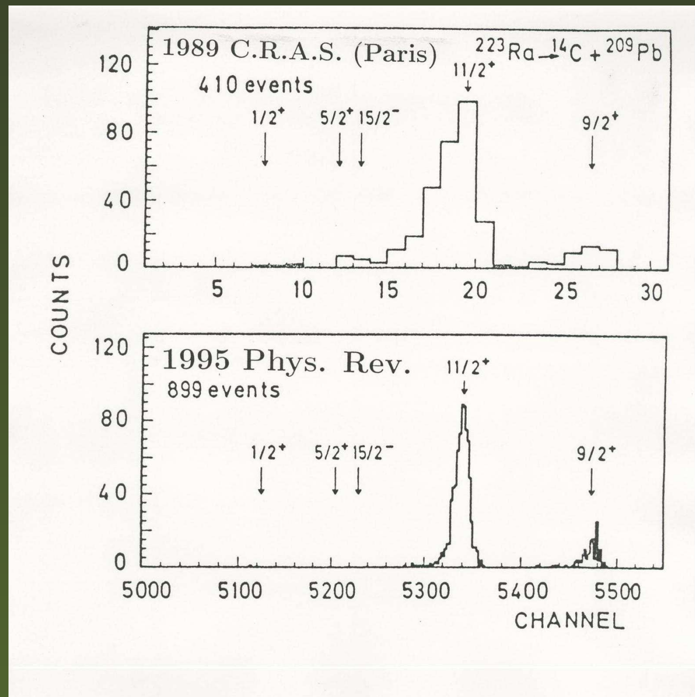
Fine structure of ^{14}C radioactivity

Martin Greiner and Werner Scheid, Radioactive decay into excited states via heavy ion emission, *J. Phys. G: Nucl. Phys.* **12** (1986) L229.

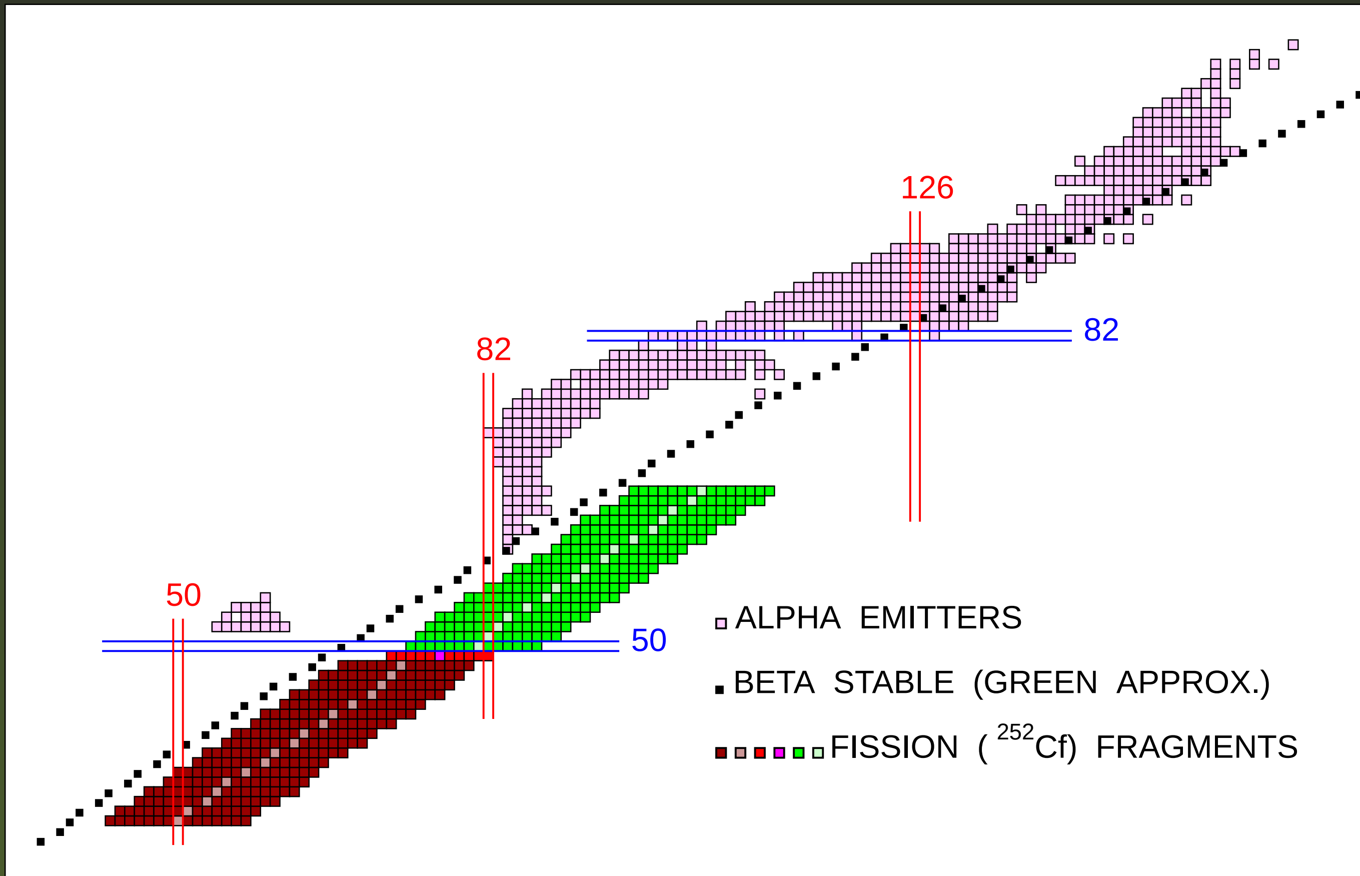
Experiments with SOLENO spectrometer at Orsay, France: E. Hourany, M. Hussonnois *et al.*, *C. R. Acad. Sci. Paris* **309** (1989) 1105. E. Hourany *et al.*, *Phys. Rev.* **C 52** (1995) 267: the transition from the gs of ^{223}Ra to the first excited state of the daughter ^{209}Pb is stronger than that to its gs. A transition with an excited state of ^{14}C was not observed.







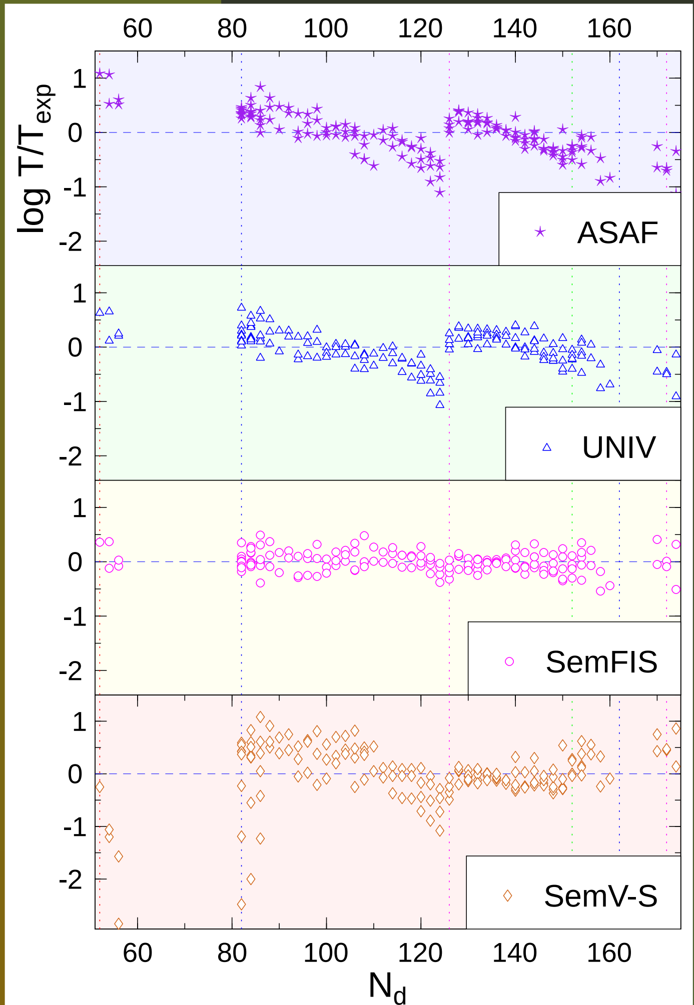
Experimentally det. α emitters



Fission fragments of ^{252}Cf are neutron-rich nuclei with $Q_\alpha < 0$, hence they are not α emitters.

CLUSTER DECAYS
Dorin N. POENARU, IFIN-HH

α-decay, ASAF, semiemp & univ

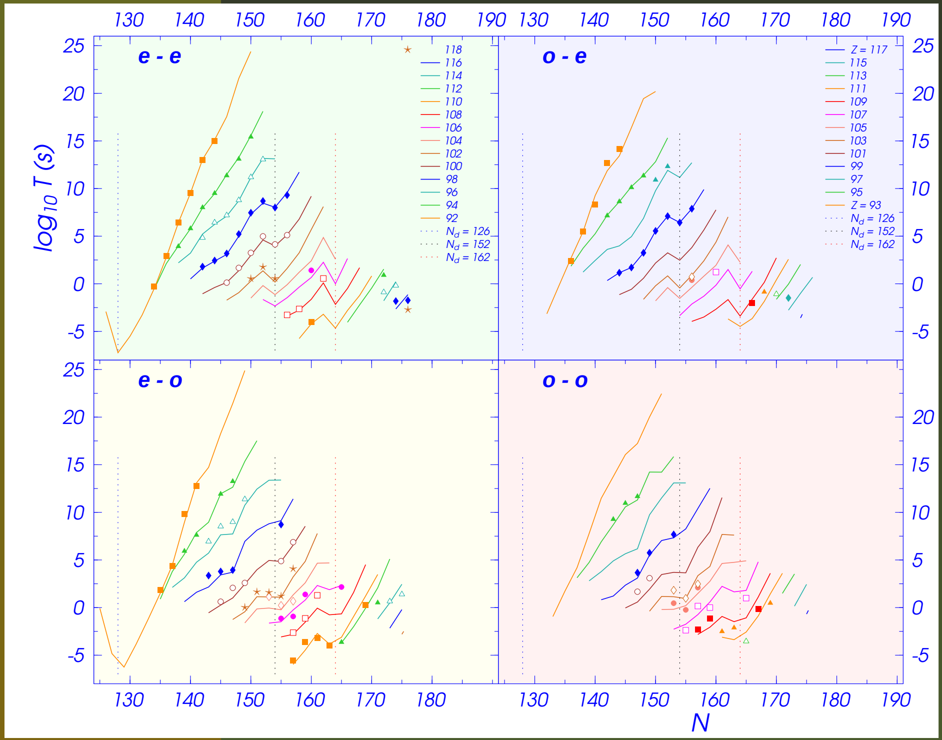


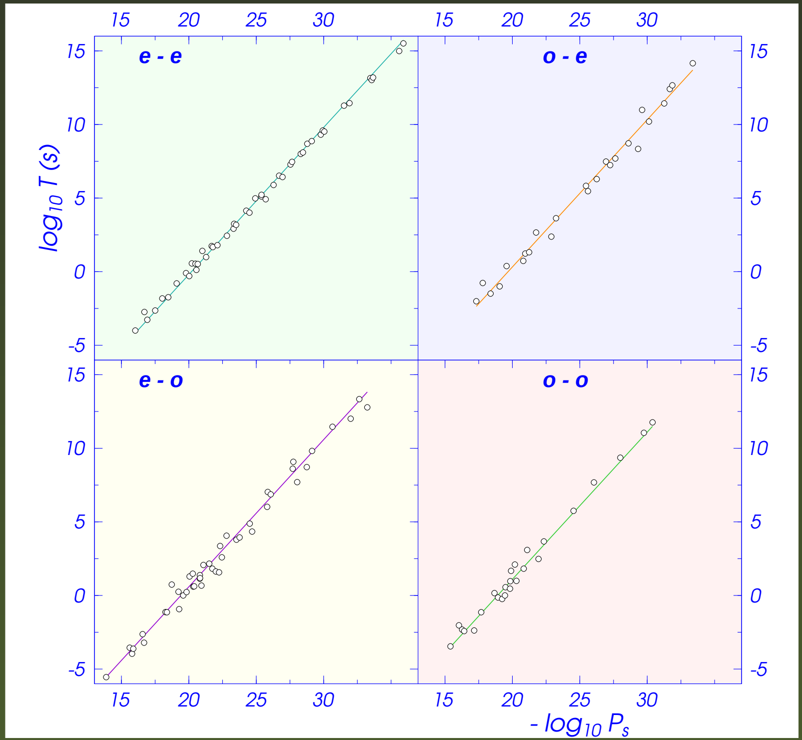
STANDARD DEVIATION

Group	σ-ASAF	σ-univ	σ-semiem
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

$Z = 92 - 118$, ASAF, semiemp & univ





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

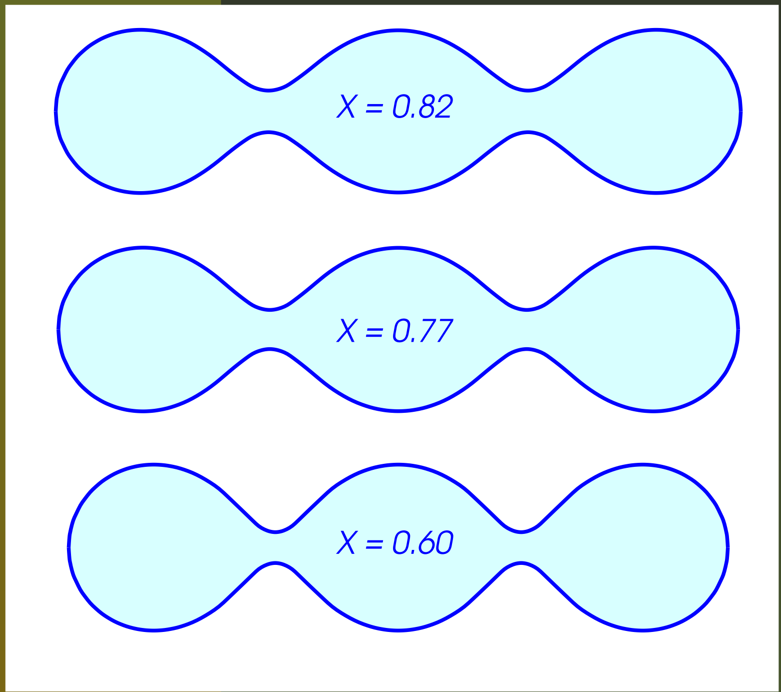
Poenaru, D.N., Plonski, I.H., and Greiner, W., *Phys. Rev.* **C 74** (2006) 014312

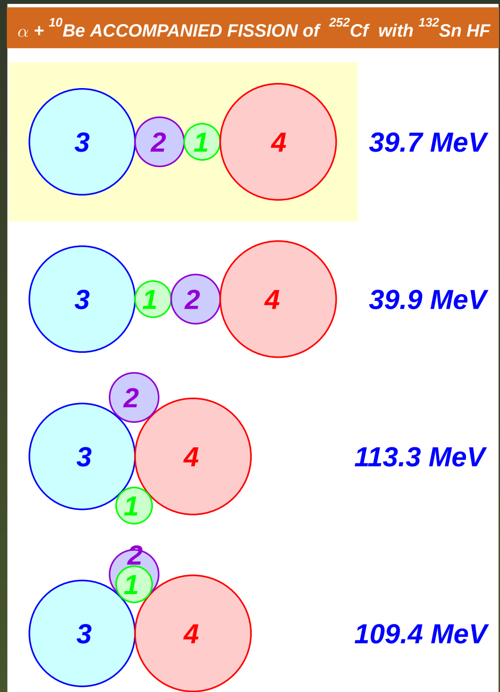
CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

Multicluster fission (I)

True-ternary and 2 particle-accompanied fission (quaternary)





D.N. Poenaru and W. Greiner, *J. Phys. G: Nucl. Part. Phys.* **25** (1999) L7

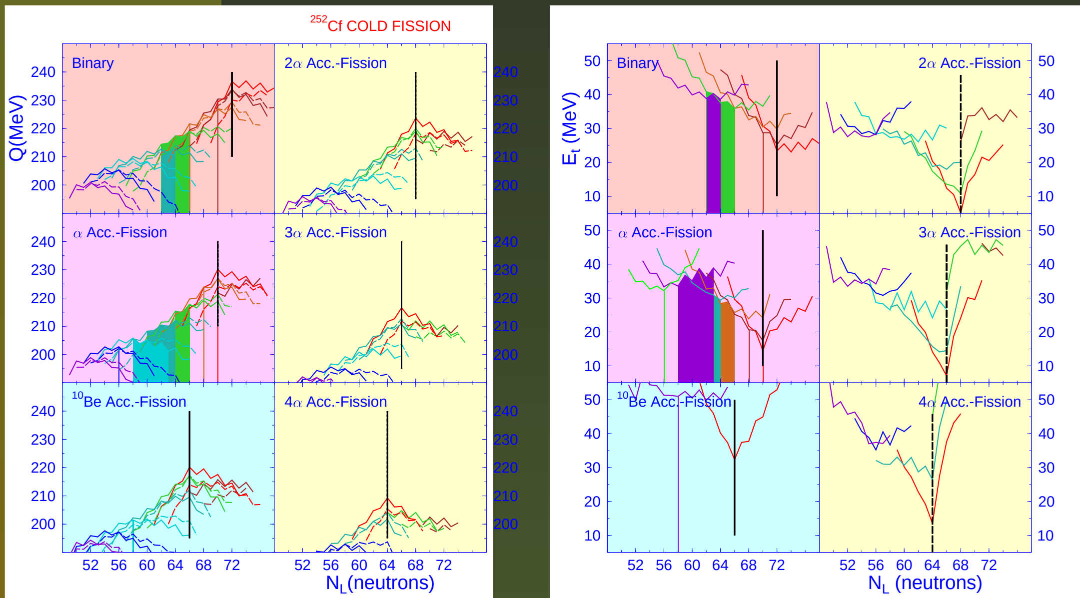
D.N. Poenaru, W. Greiner, J.H. Hamilton, A.V. Ramayya, E. Hourany and R.A. Gherghescu, *Phys. Rev.* **C 59** (1999) 3457

CLUSTER DECAYS

Dorin N. POENARU, IFIN-HH

Multicluster fission (II)

Good chance to be detected: 2α-, 3α-, and 4α-accompanied fission. Q-value and pot. barrier of 2α-accompanied fission is similar to ^{8}Be-accompanied fission.

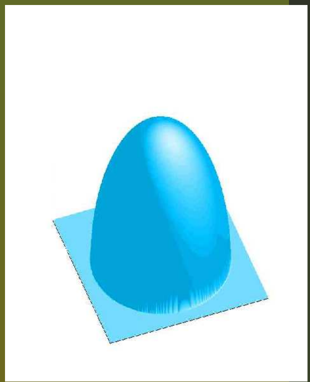


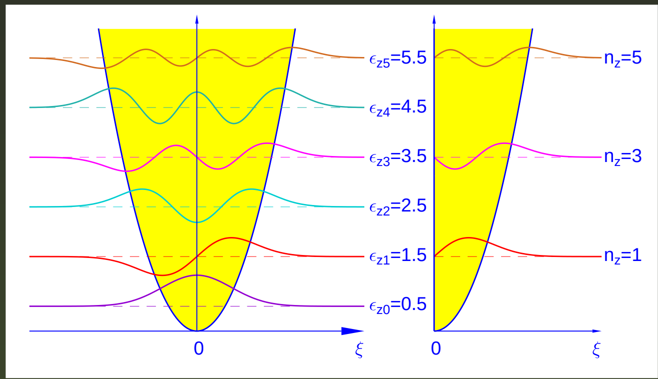
EXPERIMENTS: F. Gönnenwein, P. Jesinger, M. Mutterer, W.H. Trzaska, G. Petrov, A.M. Gagarski, V. Nesvizhevski and P. Geltenbort, *Heavy Ion Physics* **18** (2003) 419.

F. Gönnenwein, M. Mutterer and Yu. Kopatch, *Europhysics News* **36** (2005) 11.

Yu.V. Pyatkov, D.V. Kamanin, W.H. Trzaska, W. von Oertzen *et al. Rom. Rep. Phys.* **59** (2007) 569.

Appl. in scission and Nanoscience





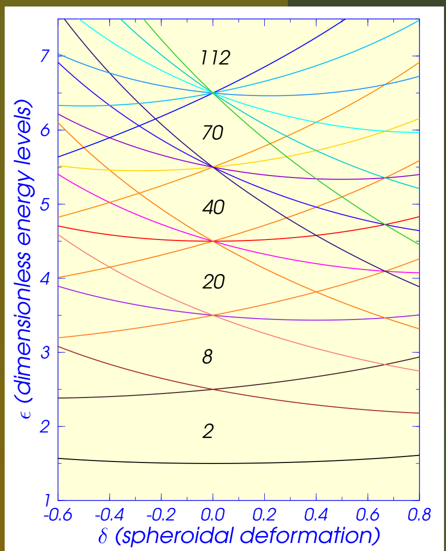
Hemispheroidal atomic cluster

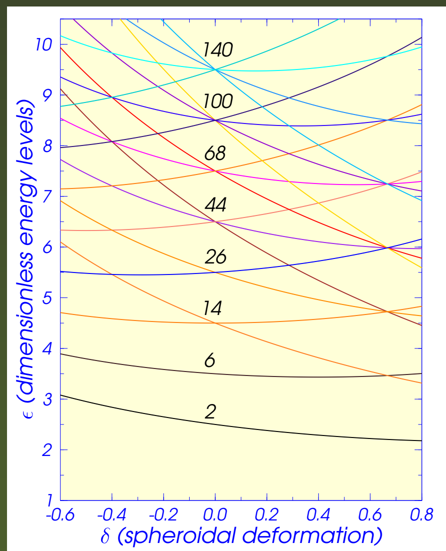
$a^2c = 1$ — volume conservation

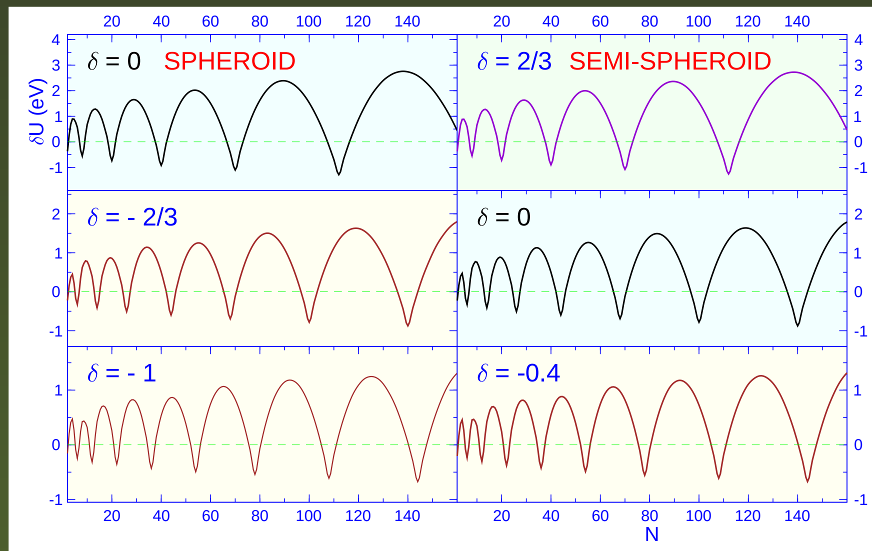
$a = [(2-\delta)/(2+\delta)]^{1/3}$

New shell model with striking properties of symmetry.

Maximum degeneracy at $\delta = 2/3$

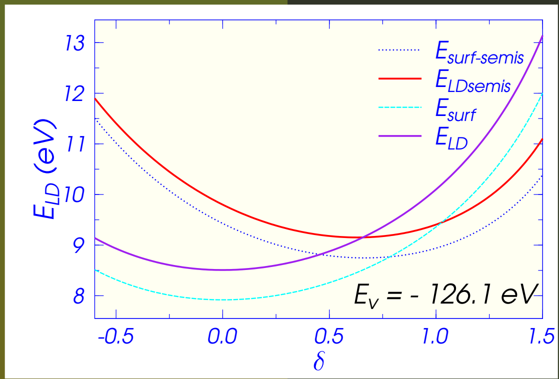






D.N. Poenaru, R.A. Gherghescu, A.V. Solov'yov, W. Greiner, Phys. Lett. **A 372** (2008) 5448; EPL **79** (2007) 63001; **88** (2009) 23002

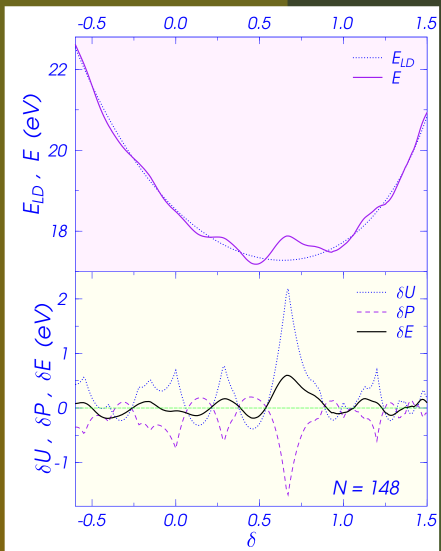
Hemispheroidal atomic cluster

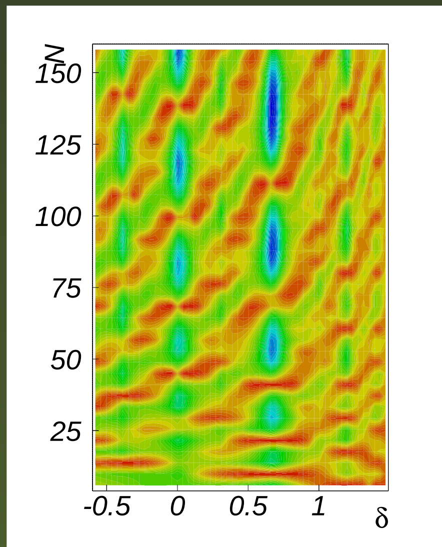


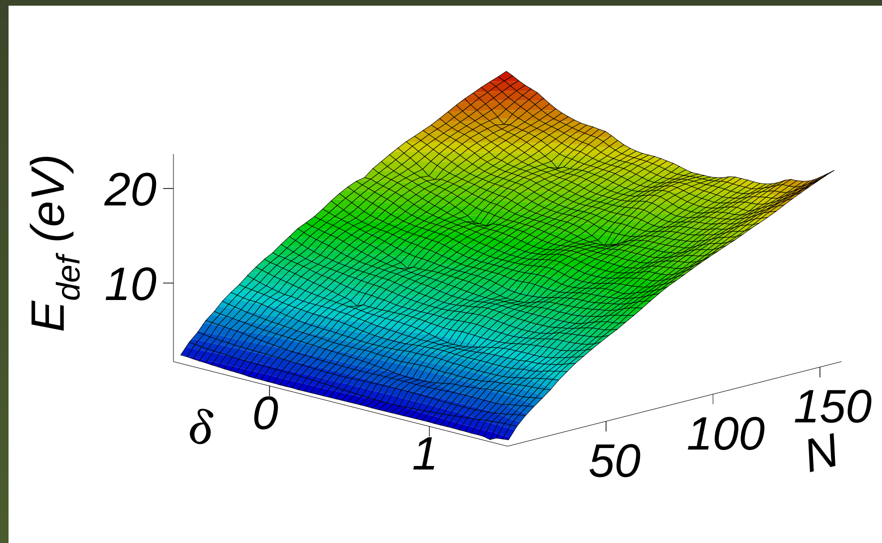
Figures, TOP: LDM (surface + curvature) energy of Na_{56} semi-spheroidal cluster compared to the spheroidal one.

BOTTOM: Na_{148} cluster, pairing corrections, total deformation energy (LDM + shell and pairing corrections).

Within LDM the most stable shape is a superdeformed prolate semi-spheroid ($\delta \approx 0.66$).







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CLUSTER DECAYS

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Summary

- The ASAF model predictions have been confirmed
- The magicity of the daughter ^{208}Pb was not fully exploited
- New experimental searches can be performed
- The universal curves provide good estimation of half-lives
- For some superheavies HIR half-lives could be shorter than that of α decay
- For atomic cluster on a surface
  - The maximum degeneracy of the new shell model occurs at a superdeformed prolate semi-spheroidal shape
  - Within LDM the most stable shape is a superdeformed prolate semi-spheroid

CLUSTER DECAYS

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