Superheavies, Neutron-rich matter, Anti-matter, Strange matter

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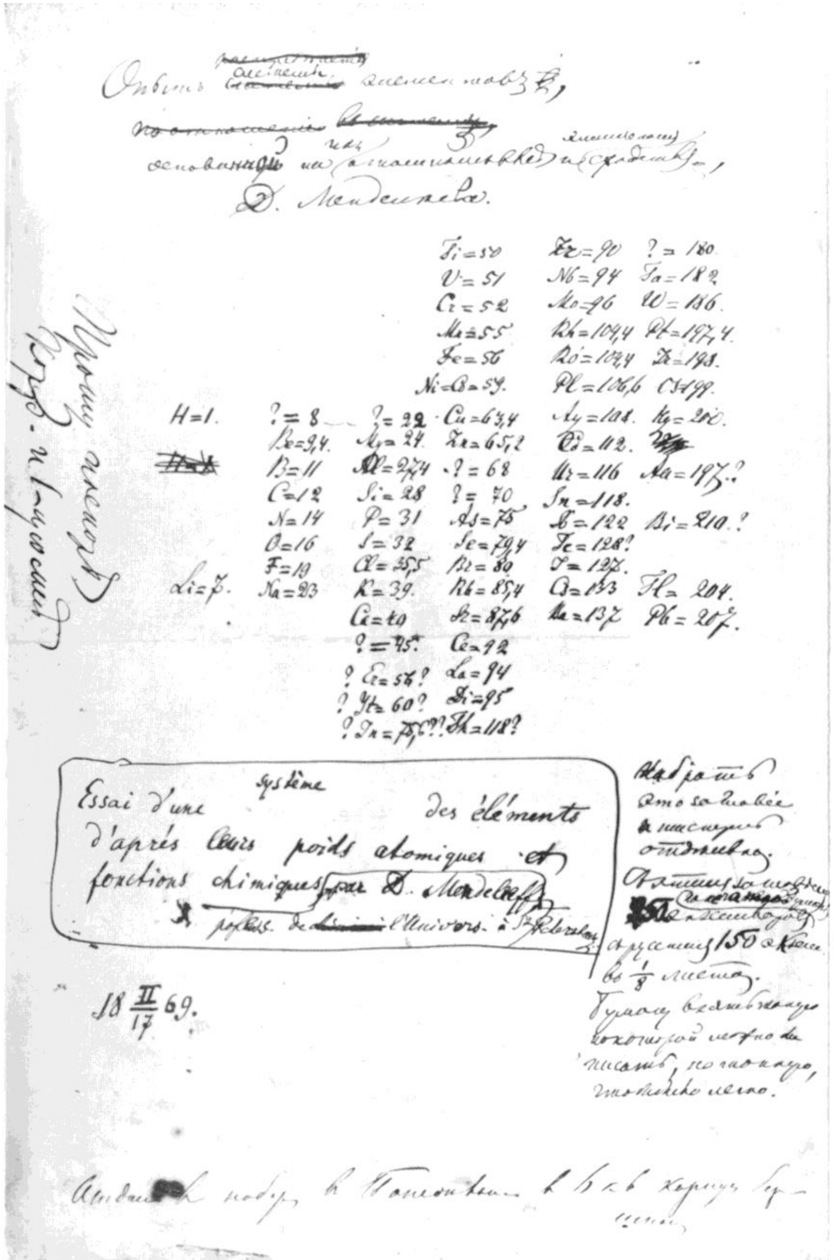
for TAN-2011, September 06, 2011, Sochi

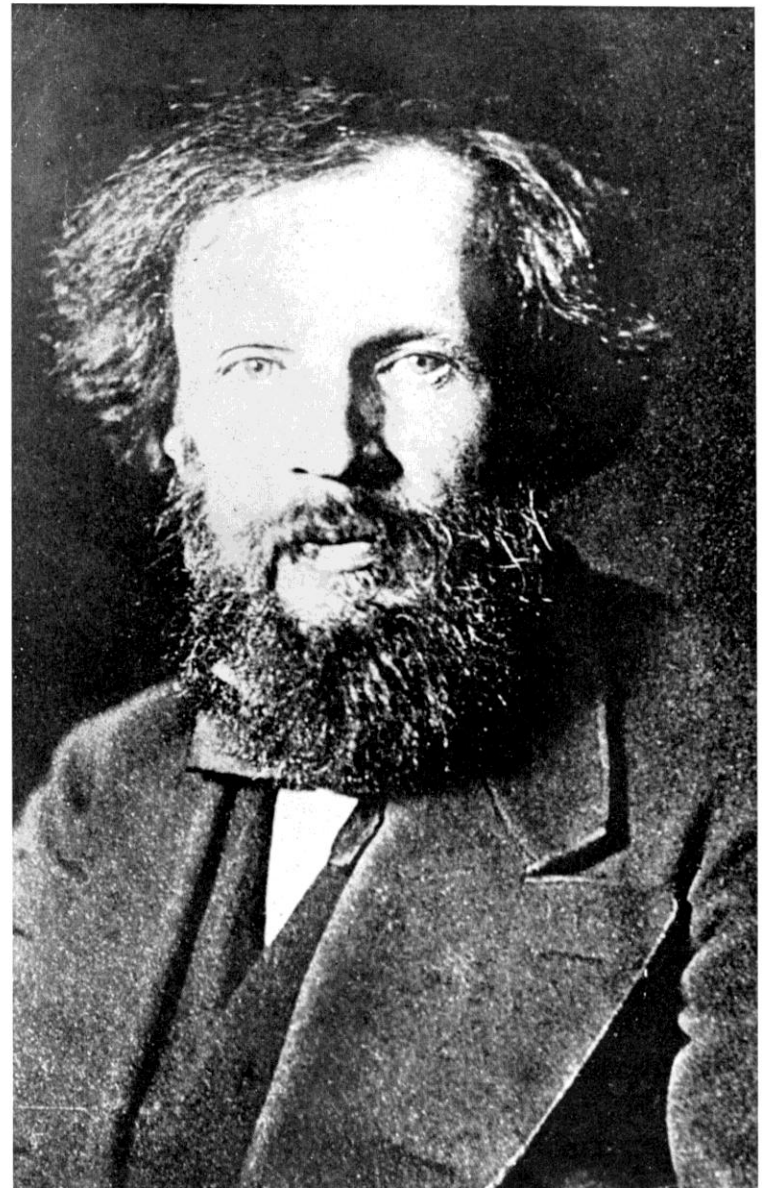
Frankfurt Institute for Advanced Studies

Prof. Senator E.h. Carlo Giersch

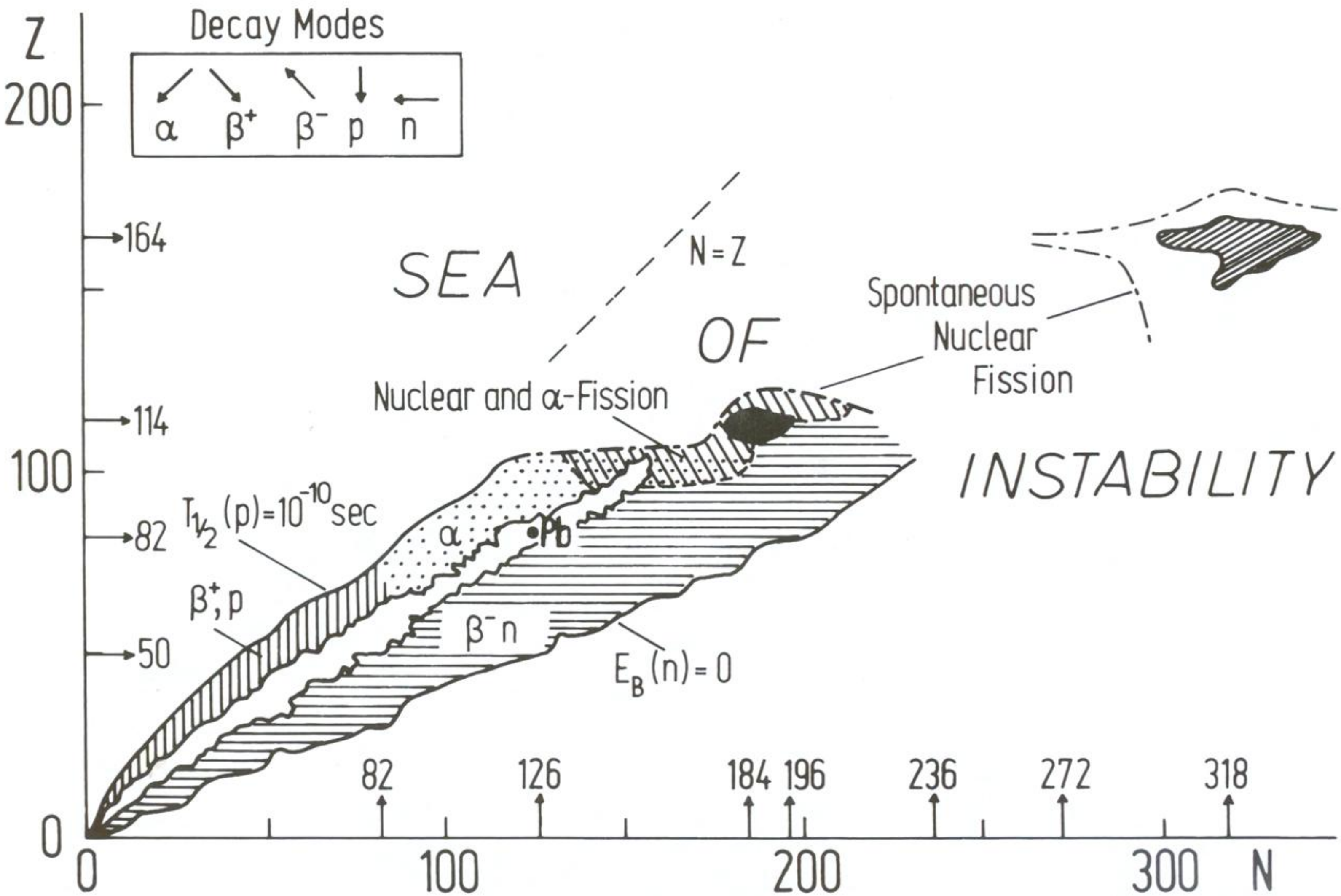
Senatorin E.h. Karin Giersch

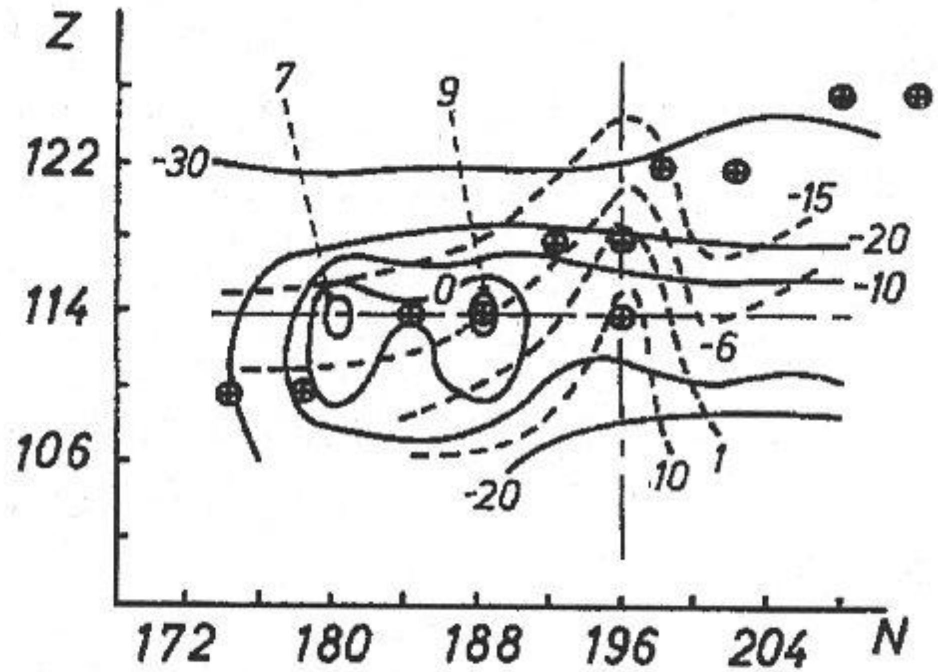
Mendeleev's Table 140 years ago





The idea about the “Islands of stability”





J. Grumann, U. Mosel, B. Fink, W. Greiner, Z. Physik 228, 371 (1969):
Investigation of the Stability of Superheavy Nuclei around Z=114 and Z=164

The QHD Lagrangian and structure of SHE

The interactions between baryons are mediated by mesons

name	Jπ	T	Mass (MeV)
σ	0^+	0	(520)
ω	1^-	0	780
ρ	1^-	1	763
(π)	0^-	1	138

σ: Medium range attraction. Simulates correlated 2π exchange (J=0, T=0).

ω: Short range repulsion.

ρ: Proton neutron asymmetry.

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{Baryon}} + \mathcal{L}_{\mathrm{Meson}} + \mathcal{L}_{\mathrm{BM}} + \mathcal{L}_{\mathrm{nonlin}} + \mathcal{L}_{\mathrm{em}},$$

where

$$\mathcal{L}_{\mathrm{Baryon}} = \bar{\psi}\,(i\gamma^{\mu}\partial_{\mu} - M)\psi$$

$$\mathcal{L}_{\mathrm{Meson}} = \frac{1}{2}\,\partial^{\mu}\sigma\,\partial_{\mu}\sigma - \frac{1}{2}\,m_{\sigma}^{2}\,\sigma^{2} - \frac{1}{4}\Omega^{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}\,m_{\omega}^{2}\,\omega^{\mu}\omega_{\mu} - \frac{1}{4}B^{\mu\nu}B^{\mu\nu} + \frac{1}{2}\,m_{\rho}^{2}\,R^{\mu}R_{\mu}$$

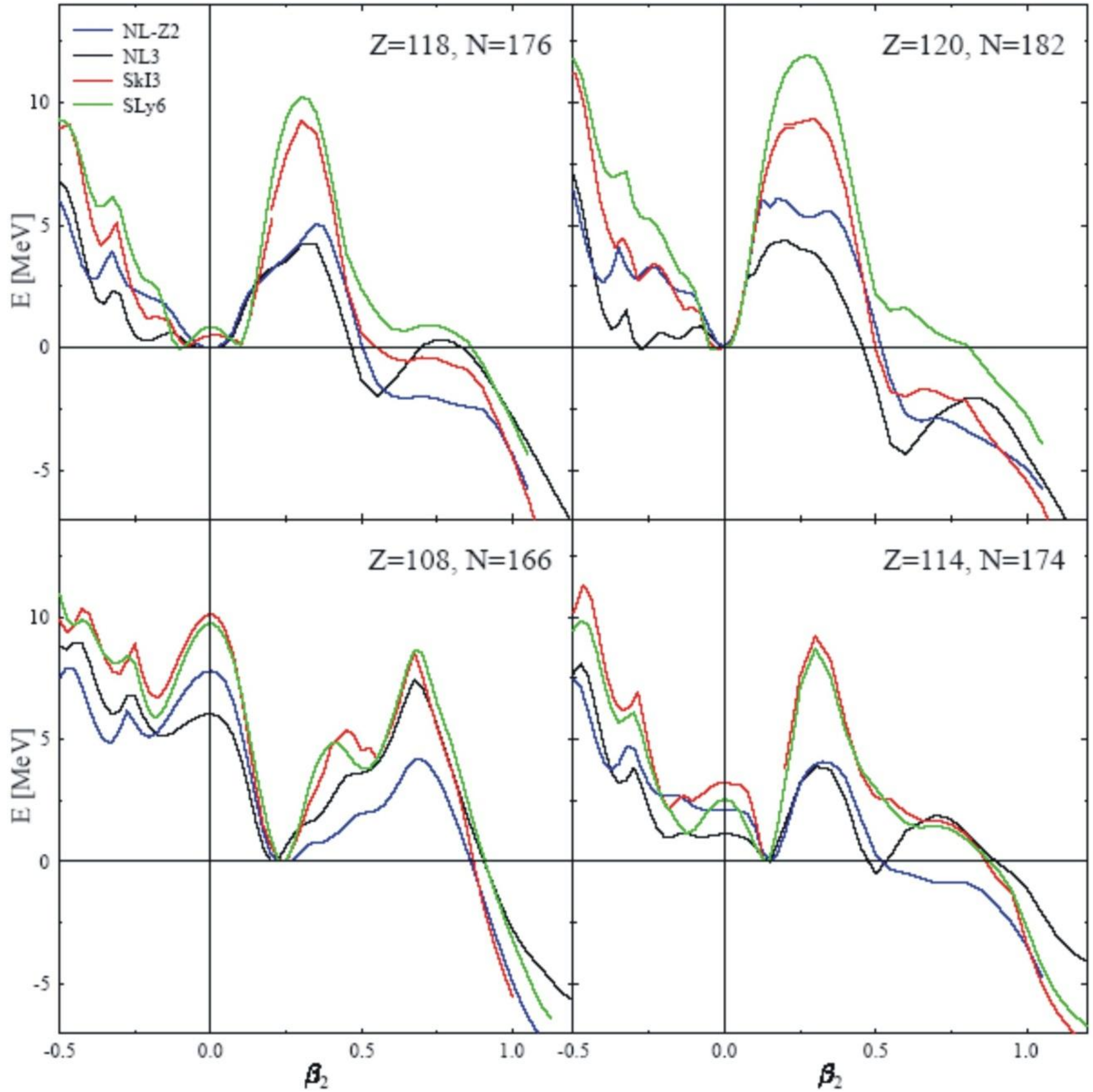
$$\mathcal{L}_{\mathrm{BM}} = -\,g_{\sigma}\bar{\psi}\,\psi\sigma - g_{\omega}\bar{\psi}\gamma^{\mu}\,\psi\omega_{\mu} - g_{\rho}\bar{\psi}\gamma^{\mu}\,\tau\psi R_{\mu}$$

$$\mathcal{L}_{\mathrm{nonlin}} = -\frac{1}{3}c_{2}\sigma^{3} - \frac{1}{4}\,c_{3}\,\sigma^{4} + \frac{1}{4}\,c_{4}\,(\omega^{\mu}\,\omega_{\mu})^{2}$$

$$\mathcal{L}_{\mathrm{em}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\bar{\psi}\,\gamma^{\mu}\,\frac{1-\tau_{3}}{2}\,\psi A_{\mu}$$

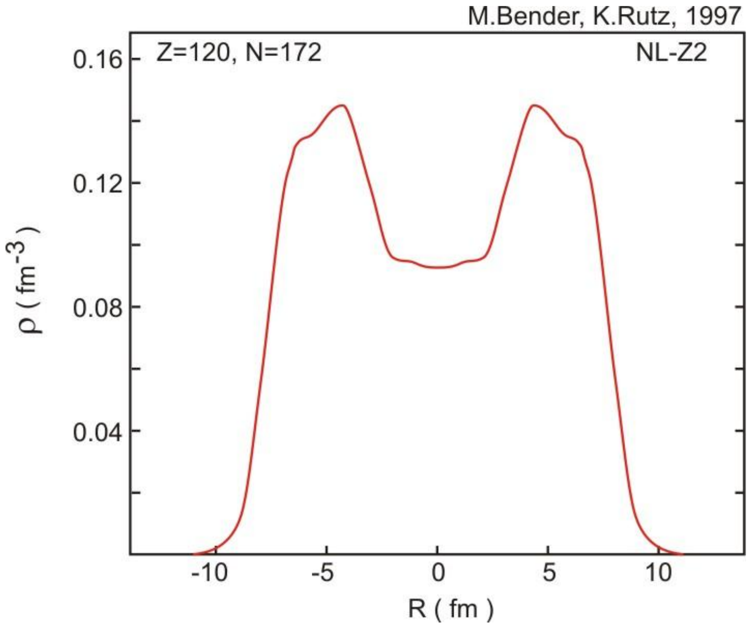
free parameters: g_{π}, g_{ω}, g_{ρ}, c_2, c_3, c_4

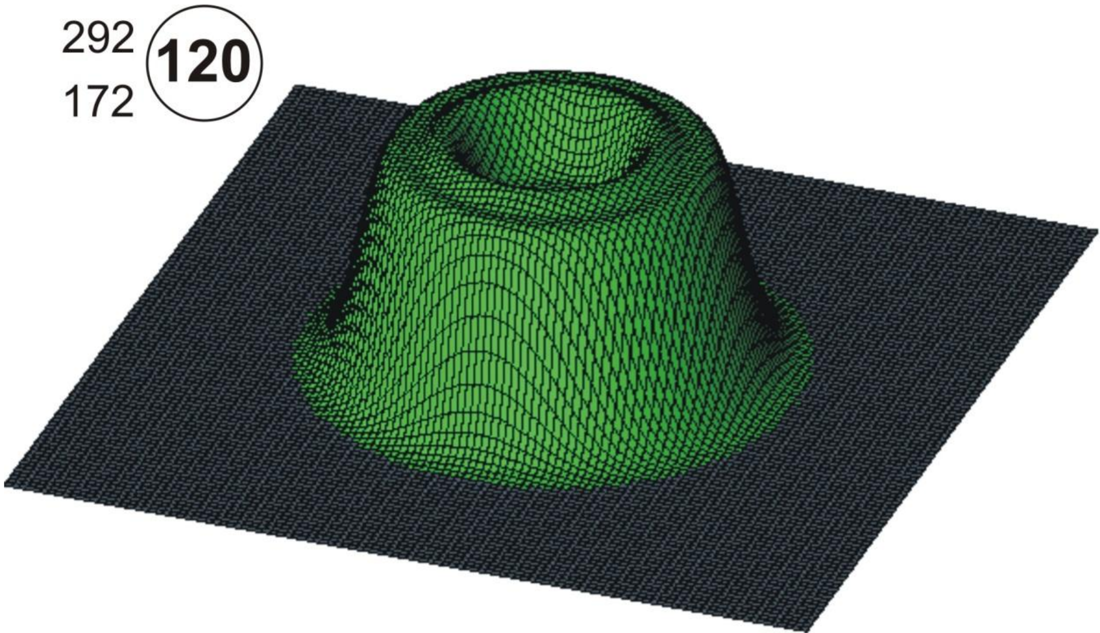
Fission barriers of superheavy nuclei

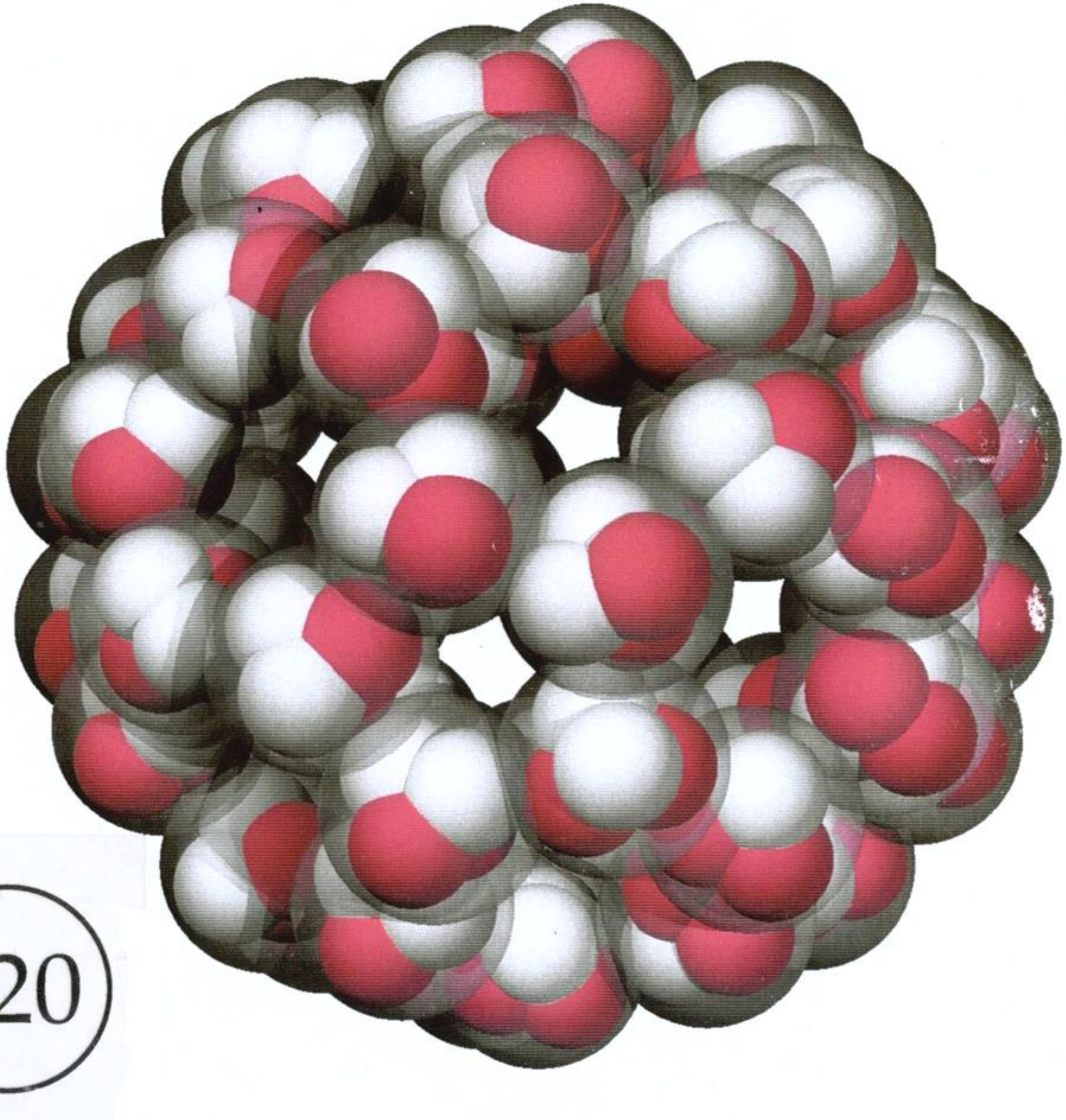


T. Bürvenich, M. Bender, A. Maruhn, and P.-G. Reinhard, Phys.Rev. C **69** (2004)

Matter density of superheavy nuclei





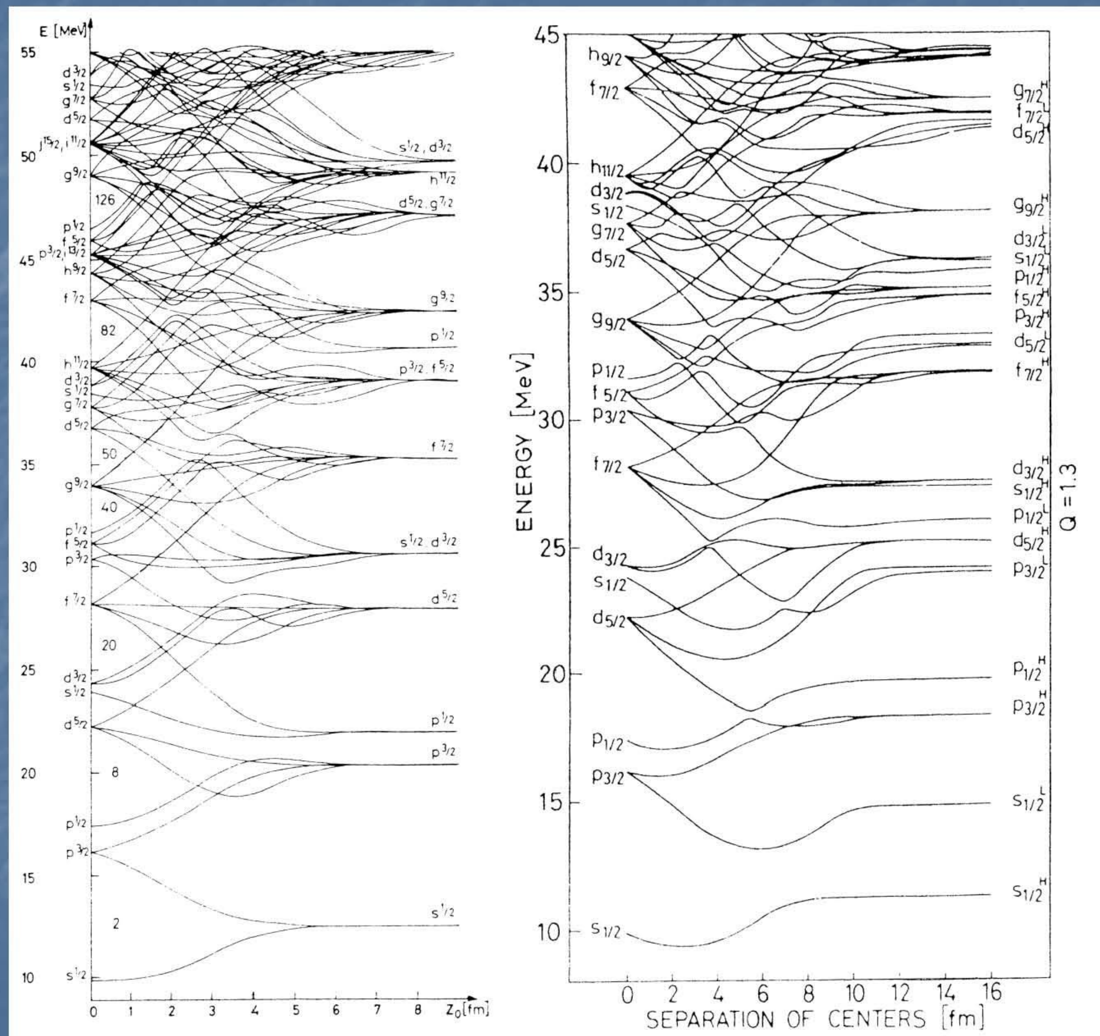


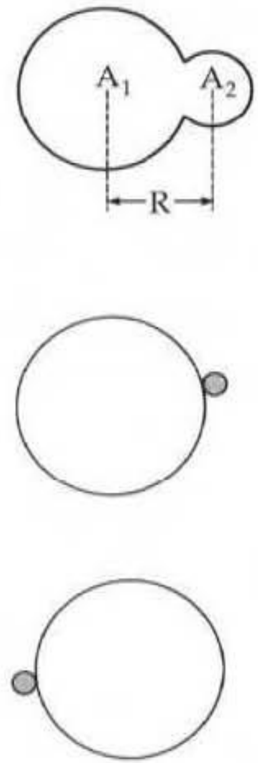
304

120

184

Neutron levels diagram in the two-center shell model (left: symmetric, right: asymmetric)



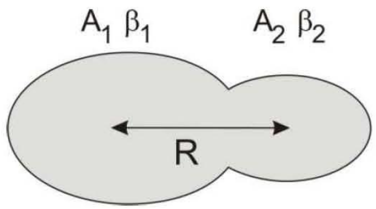


$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

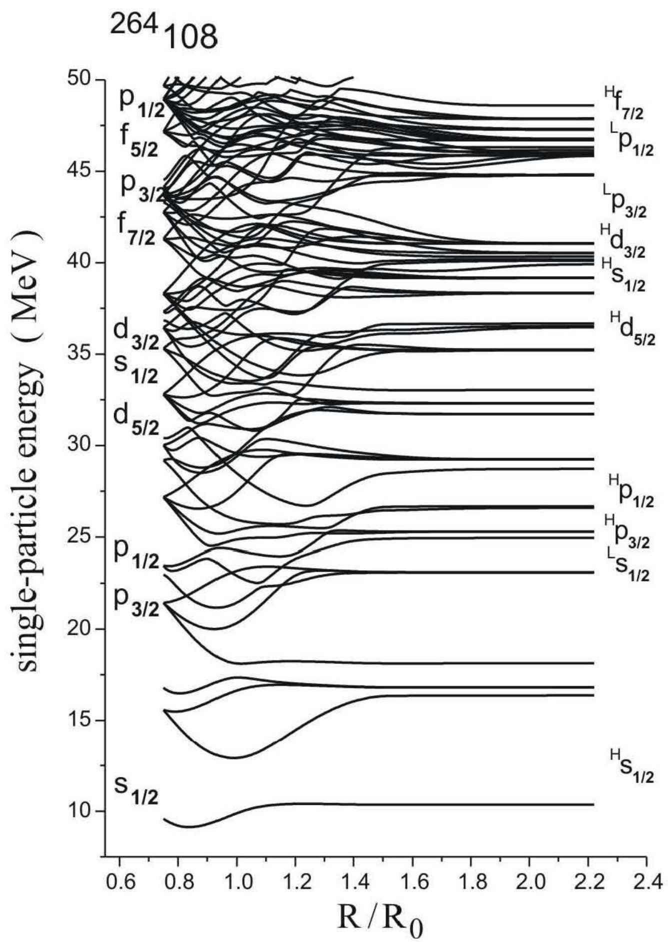
$$\eta = 1$$

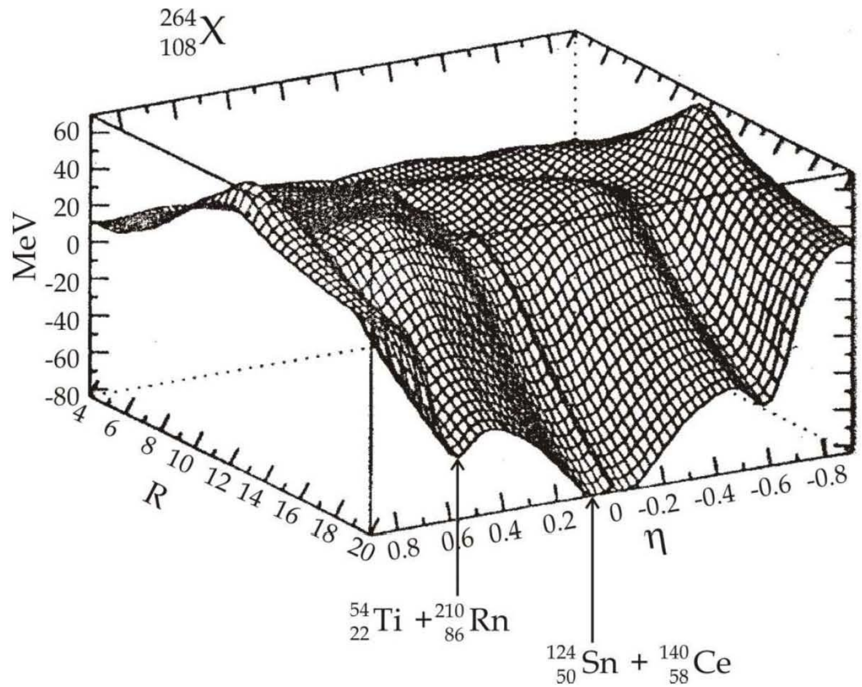
$$\eta = -1$$

Two-Center Shell Model



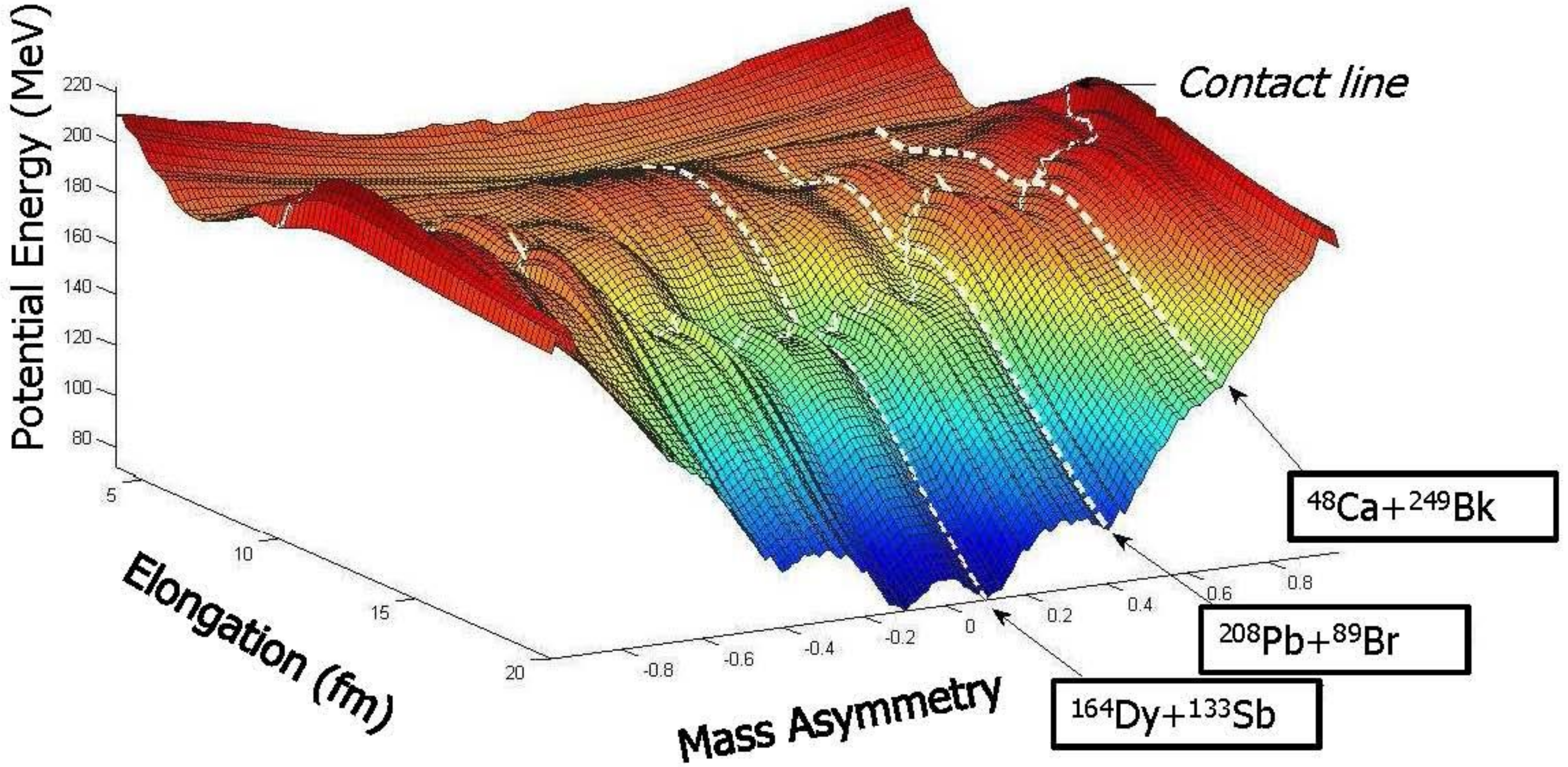
$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$





Mosel, Maruhn, Greiner, 1971

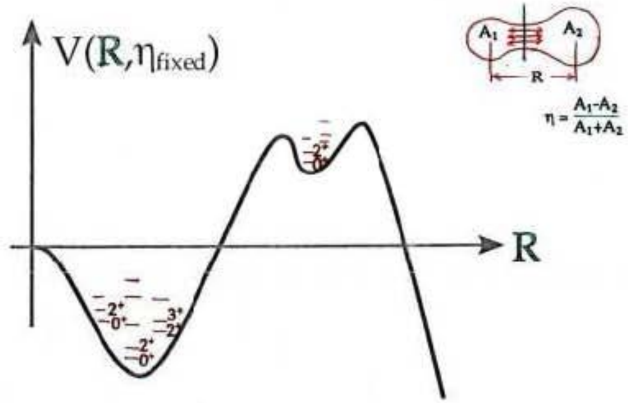
Potential Energy Surface (Z=117, A=297)

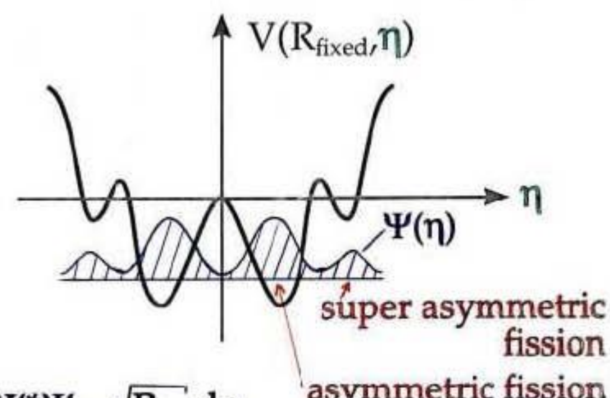


Alexander Karpov, Luis Ruiz, Yaser Martinez Palenzuela

$$H(R,\eta) = 1/2\ B_{RR}(R,\eta)\ \dot{R}^2 + B_{R\eta}(R,\eta)\ \dot{R}\dot{\eta}$$

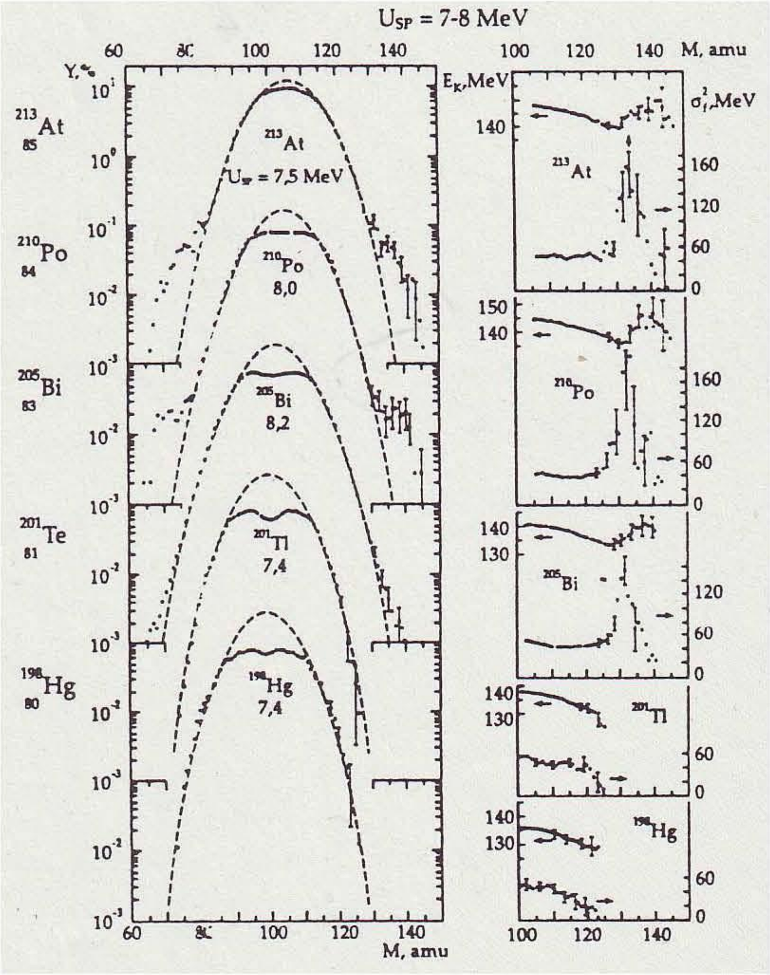
$$+\ 1/2\ B_{\eta\eta}(R\eta)\ \dot{\eta}^2 + V(R,\eta)$$





$$dP_{(\eta)} \sim \Psi^{*}\Psi_{(\eta)}\ \sqrt{B_{\eta\eta}}\ d\eta$$

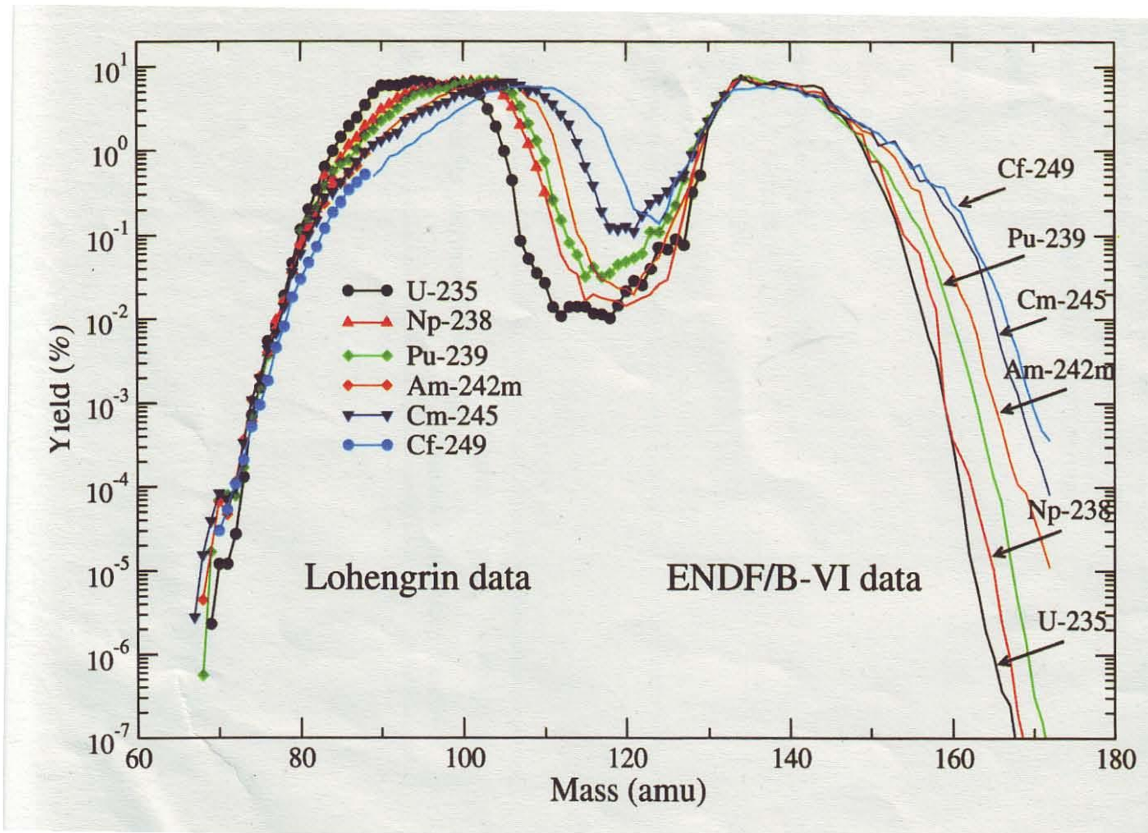
Fission of Nuclei with A = 200u.



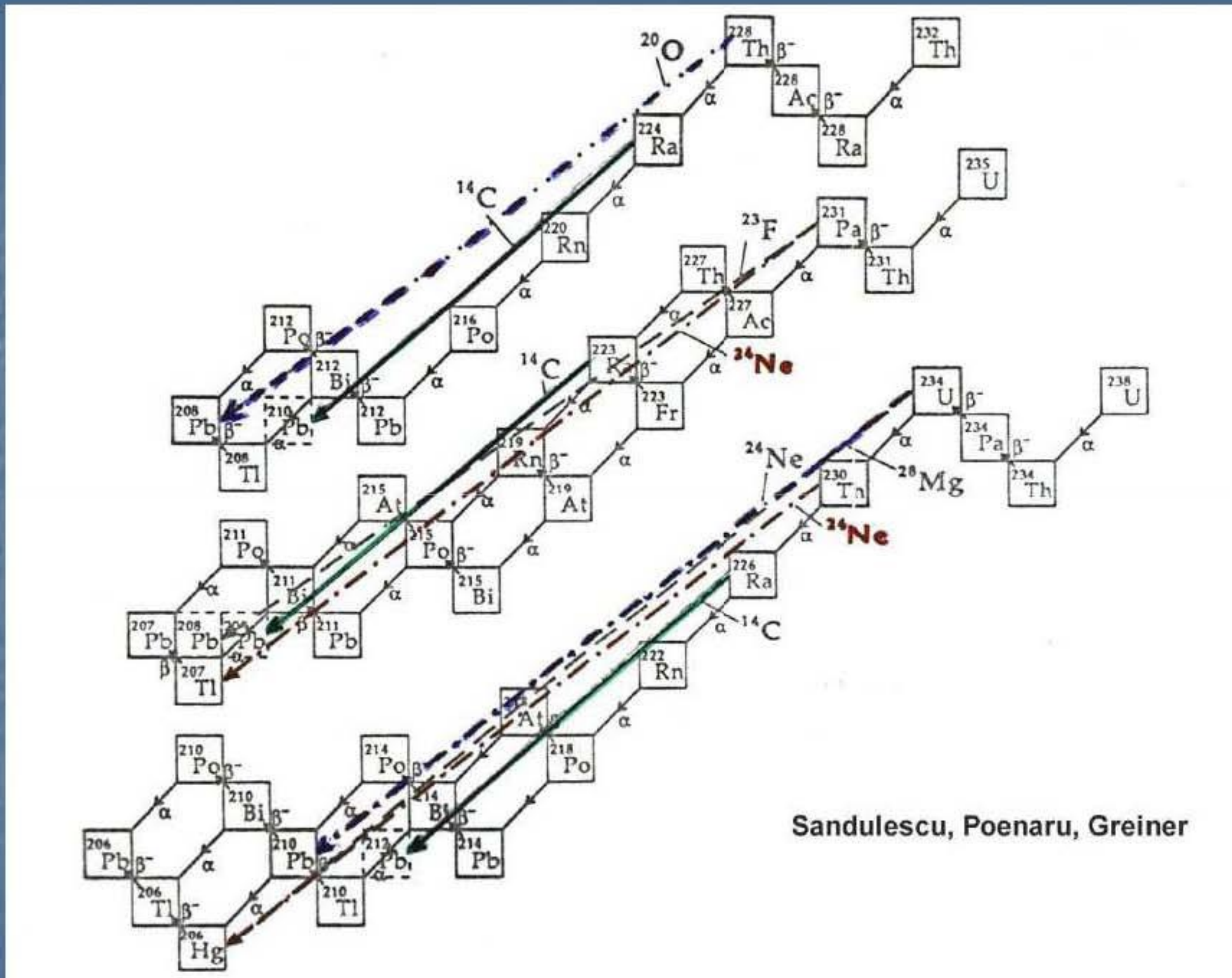
Shoulders on the sides from central peaks testify for asymmetric fission.

(M. Itkis 1990)

Systematics of Asymmetric and Superasymmetric Fission (Friedrich Gönnenwein, 2009)



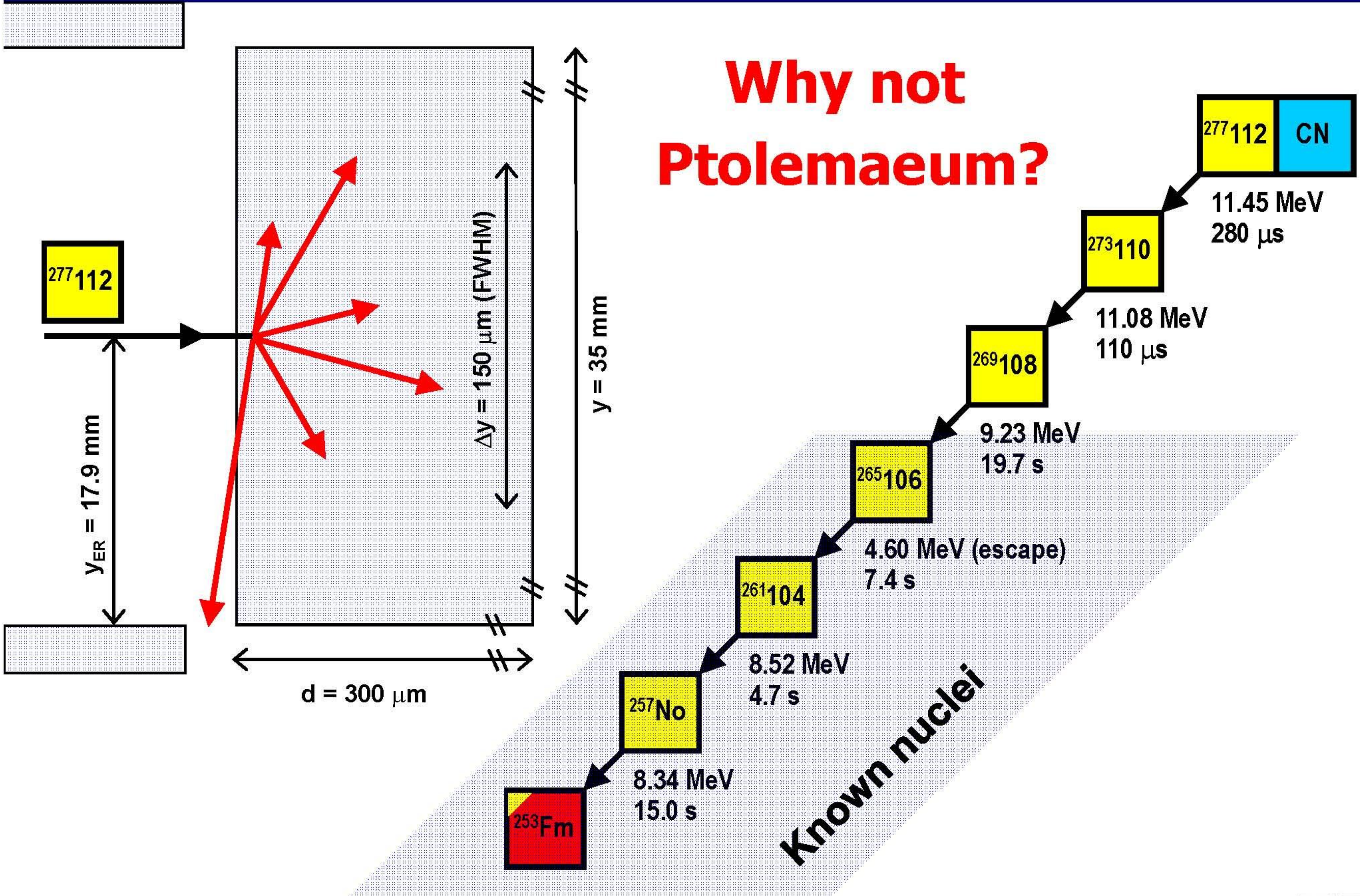
Cluster Radioactivity



Sandulescu, Poenaru, Greiner

Decay chain of $^{277}112$, now “copernicium”, ^{277}Cp

Why not Ptolemaeum?



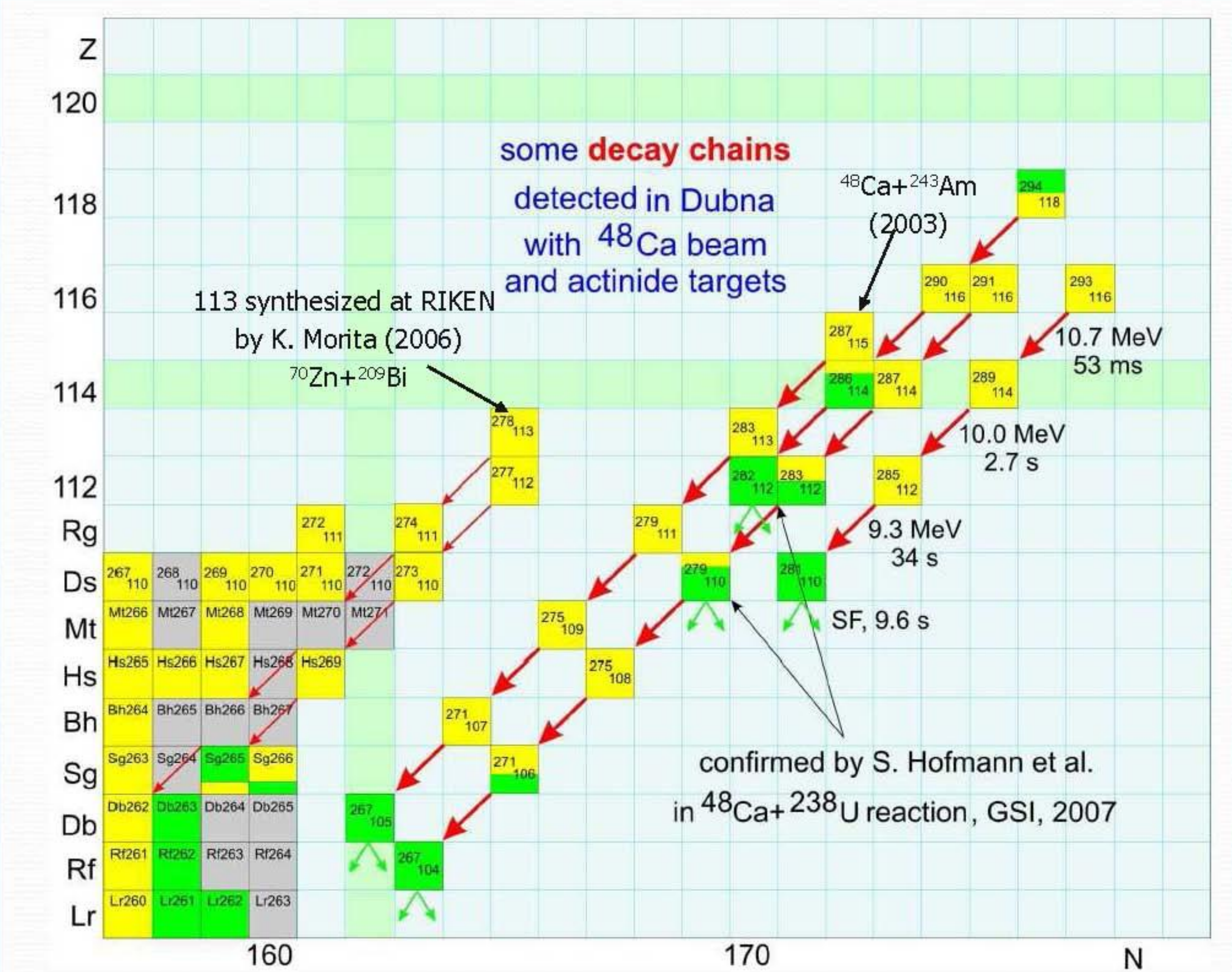
Epoche of 48Ca induced fusion reactions

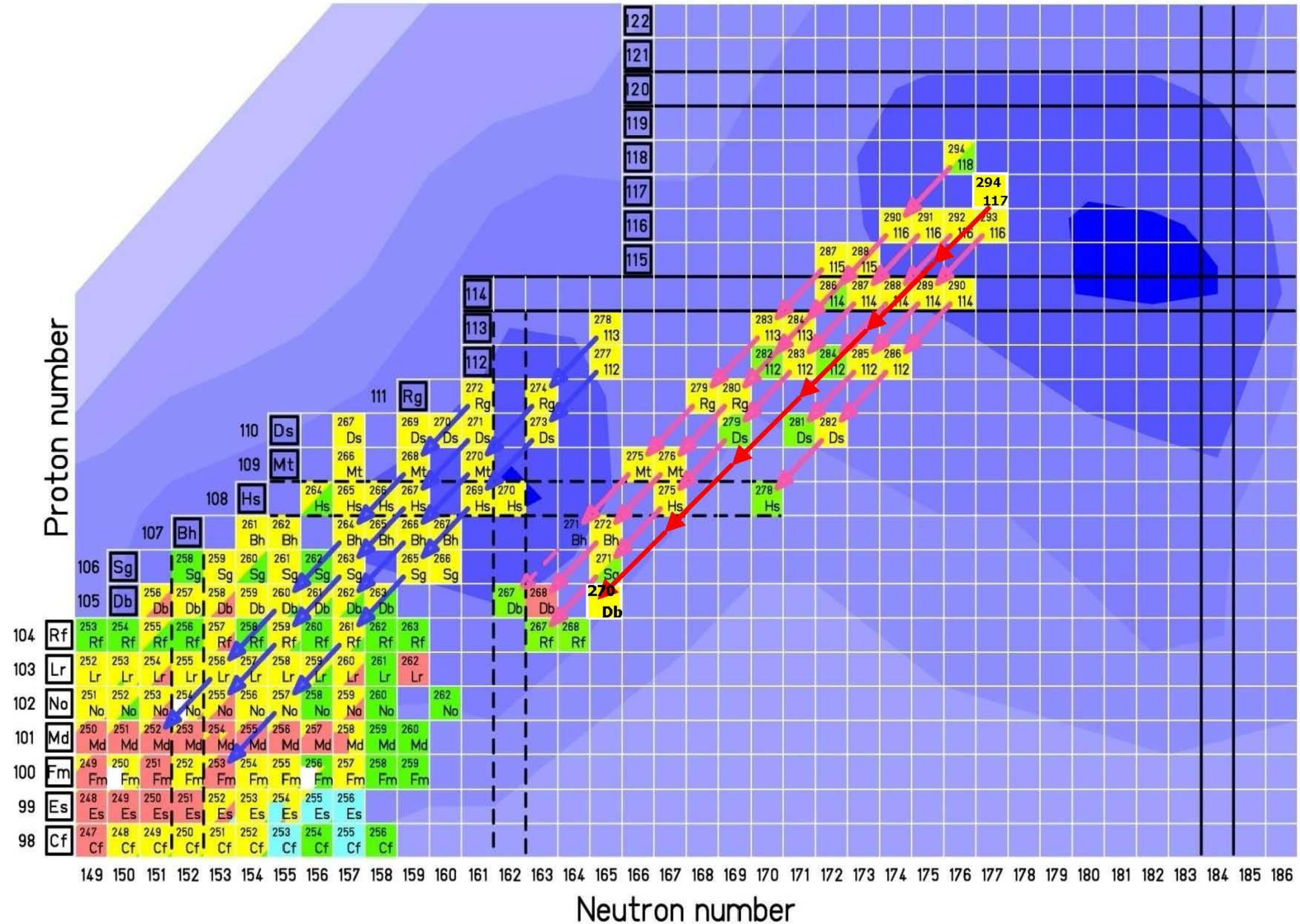
1964: G. Seaborg, $^{48}Ca+^{244}Pu \rightarrow 114$, $^{48}Ca+^{248}Pu \rightarrow 116$,…

1977: LBL, $^{48}Ca+^{248}Cm \rightarrow 116$, chemistry, no events

1985: GSI+LBL, $^{48}Ca+^{248}Cm \rightarrow 116$, <100 pb, no events

1999-2009: Dubna, Yu. Oganessian et al., full success,
^{48}Ca+actinides (U - Cf) $\rightarrow 112 - 118$, 1-10 pb


some decay chains
detected in Dubna
with 48Ca beam
and actinide targets
113 synthesized at RIKEN
by K. Morita (2006)
70Zn+209Bi
48Ca+243Am
(2003)
10.7 MeV
53 ms
10.0 MeV
2.7 s
9.3 MeV
34 s
SF, 9.6 s
confirmed by S. Hofmann et al.
in 48Ca+238U reaction, GSI, 2007
Z
120
118
116
114
112
Rg
Ds
Mt
Hs
Bh
Sg
Db
Rf
Lr
160
170
N


Proton number
Neutron number
294
117
270
Db

Mendeleev's Table today

период	ряд	группы элементов а I б	а II б	а III б	а IV б	а V б	а VI б	а VII б	а VIII б		
1	I	Водород H 1 $1s^1$ 1,00794 Hydrogen							Гелий He 2 $1s^2$ 4,0026 Helium		
2	II	Литий Li 3 $2s^1$ 6,941 Lithium	Бериллий Be 4 $2s^2$ 9,012182 Beryllium	Бор B 5 $2p^1$ 10,811 Boron	Углерод C 6 $2p^2$ 12,011 Carbon	Азот N 7 $2p^3$ 14,00674 Nitrogen	Кислород O 8 $2p^4$ 15,9994 Oxygen	Фтор F 9 $2p^5$ 18,9984032 Fluorine	Неон Ne 10 $2p^6$ 20,1797 Neon		
3	III	Натрий Na 11 $3s^1$ 22,989768 Sodium	Магний Mg 12 $3s^2$ 24,3050 Magnesium	Алюминий Al 13 $3p^1$ 26,981539 Aluminum	Кремний Si 14 $3p^2$ 28,0855 Silicon	Фосфор P 15 $3p^3$ 30,973762 Phosphorus	Сера S 16 $3p^4$ 32,066 Sulfur	Хлор Cl 17 $3p^5$ 35,4527 Chlorine	Аргон Ar 18 $3p^6$ 39,948 Argon		
4	IV	Калий K 19 $4s^1$ 39,0983 Potassium	Кальций Ca 20 $4s^2$ 40,078 Calcium	Скандий 21 $3d^1 4s^2$ Sc 44,955910 Scandium	Титан 22 $3d^2 4s^2$ Ti 47,88 Titanium	Ванадий 23 $3d^3 4s^2$ V 50,9415 Vanadium	Хром 24 $3d^5 4s^1$ Cr 51,9961 Chromium	Марганец 25 $3d^5 4s^2$ Mn 54,93805 Manganese	Железо 26 $3d^6 4s^2$ Fe 55,847 Iron	Кобальт 27 $3d^7 4s^2$ Co 58,93320 Cobalt	Никель 28 $3d^8 4s^2$ Ni 58,6934 Nickel
	V	Медь 29 $3d^{10} 4s^1$ Cu 63,546 Copper	Цинк 30 $3d^{10} 4s^2$ Zn 65,39 Zinc	Галлий Ga 31 $4p^1$ 69,723 Gallium	Германий Ge 32 $4p^2$ 72,61 Germanium	Мышьяк As 33 $4p^3$ 74,92159 Arsenic	Селен Se 34 $4p^4$ 9,75238 78,96 Selenium	Бром Br 35 $4p^5$ 79,904 Bromine	Криптон Kr 36 $4p^6$ 83,80 Krypton		
5	VI	Рубидий Rb 37 $5s^1$ 85,4678 Rubidium	Стронций Sr 38 $5s^2$ 87,62 Strontium	Иттрий 39 $4d^1 5s^2$ Y 88,90585 Yttrium	Цирконий 40 $4d^2 5s^2$ Zr 91,224 Zirconium	Ниобий 41 $4d^4 5s^1$ Nb 92,90638 Niobium	Молибден 42 $4d^5 5s^1$ Mo 95,94 Molybdenum	Технеций 43 $4d^5 5s^2$ Tc [98] Technetium	Рутений 44 $4d^7 5s^1$ Ru 101,07 Ruthenium	Родий 45 $4d^8 5s^1$ Rh 102,90550 Rhodium	Палладий 46 $4d^{10}$ Pd 106,42 Palladium
	VII	Серебро 47 $4d^{10} 5s^1$ Ag 107,8682 Silver	Кадмий 48 $4d^{10} 5s^2$ Cd 112,411 Cadmium	Индий In 49 $5p^1$ 114,818 Indium	Олово Sn 50 $5p^2$ 118,710 Tin	Сурьма Sb 51 $5p^3$ 121,757 Antimony	Теллур Te 52 $5p^4$ 127,60 Tellurium	Иод I 53 $5p^5$ 126,90447 Iodine	Ксенон Xe 54 $5p^6$ 131,29 Xenon		
6	VIII	Цезий Cs 55 $6s^1$ 132,90543 Cesium	Барий Ba 56 $6s^2$ 137,327 Barium	Лантан 57 $5d^1 6s^2$ La 138,9055 Lanthanum	Гафний 72 $5d^2 6s^2$ Hf 178,49 Hafnium	Тантал 73 $5d^3 6s^2$ Ta 180,9479 Tantalum	Вольфрам 74 $5d^4 6s^2$ W 183,84 Tungsten	Рений 75 $5d^5 6s^2$ Re 186,207 Rhenium	Осмий 76 $5d^6 6s^2$ Os 190,23 Osmium	Иридий 77 $5d^7 6s^2$ Ir 192,22 Iridium	Платина 78 $5d^9 6s^1$ Pt 195,08 Platinum
	IX	Золото 79 $5d^{10} 6s^1$ Au 196,96654 Gold	Ртуть 80 $5d^{10} 6s^2$ Hg 200,59 Mercury	Таллий Tl 81 $6p^1$ 204,3833 Thallium	Свинец Pb 82 $6p^2$ 207,2 Lead	Висмут Bi 83 $6p^3$ 208,98037 Bismuth	Полоний Po 84 $6p^4$ [209] Polonium	Астат At 85 $6p^5$ [210] Astatine	Радон Rn 86 $6p^6$ [222] Radon		
7	X	Франций Fr 87 $7s^1$ 4,073 [223] Francium	Радий Ra 88 $7s^2$ 226,025 Radium	Актиний 89 $6d^1 7s^2$ Ac [227] Actinium	Резерфордий 104 Rf [261] Rutherfordium	Дубний 105 Db [262] Dubnium	Сиборгий 106 Sg [266] Seaborgium	Борий 107 Bh [267] Bohrium	Хассий 108 Hs [269] Hassium	Мейтнерий 109 Mt [268] Meitnerium	Дармштадтий 110 Ds [269] Darmstadtium
	XI	Рентгений 111 Rg [269] Roentgenium	112	113	114	115	116	117	118		

атомный номер

Водород H 1 $1s^1$ 1,00794 Hydrogen

символ

электронная конфигурация

атомная масса

s-элементы

p-элементы

d-элементы

f-элементы

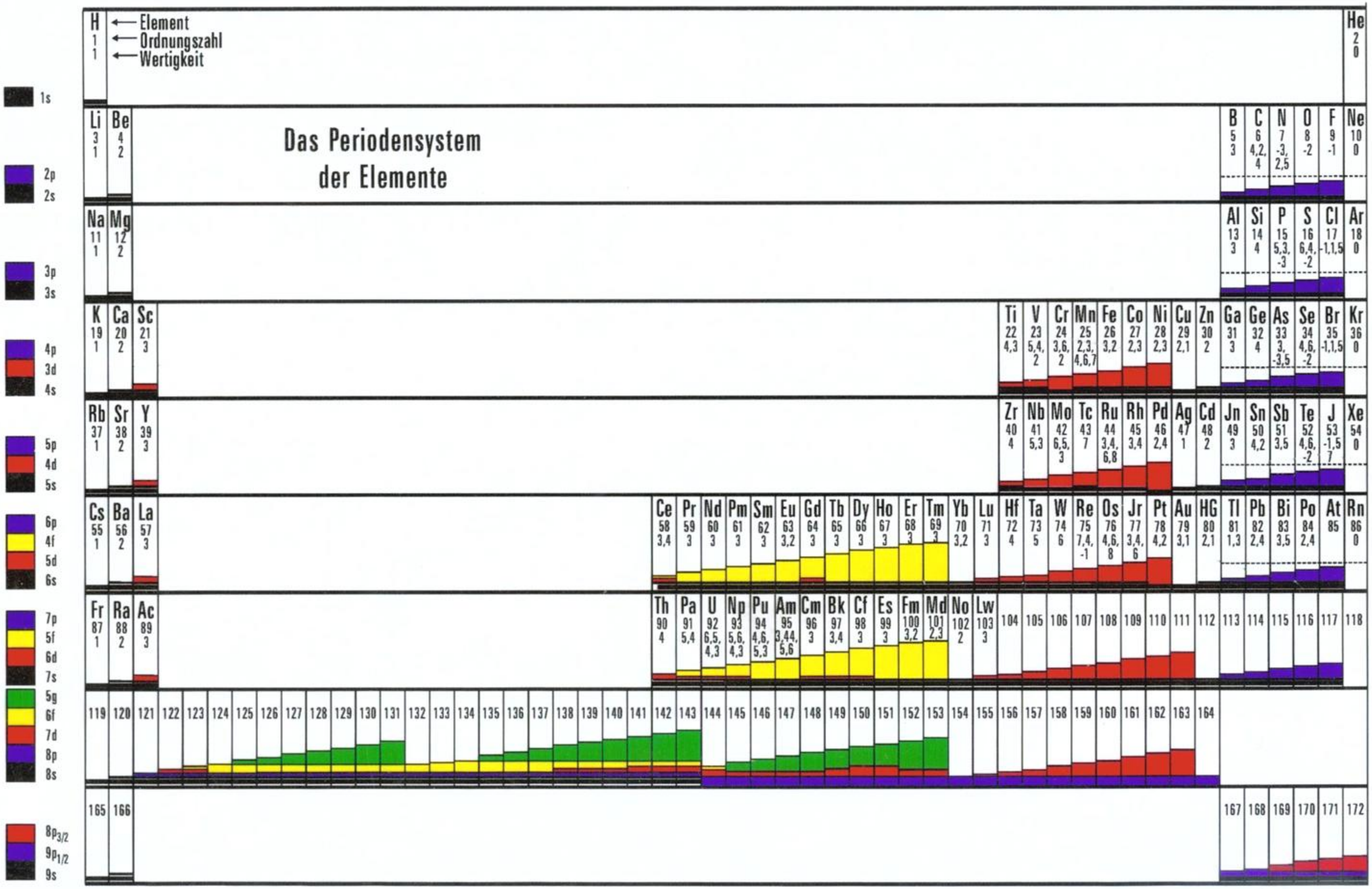
Лантаноиды Lanthanides

Церий	Празеодим	Неодим	Прометий	Самарий	Европий	Гадолиний	Тербий	Диспрозий	Гольмий	Эрбий	Тулий	Иттербий	Лютеций
Ce $4f^1 5d^1$	Pr $4f^3$	Nd $4f^4$	Pm $4f^5$	Sm $4f^6$	Eu $4f^7$	Gd $4f^7 5d^1$	Tb $4f^9$	Dy $4f^{10}$	Ho $4f^{11}$	Er $4f^{12}$	Tm $4f^{13}$	Yb $4f^{14}$	Lu $4f^{14} 5d^1$
140,115	140,90765	144,24	[145]	150,36	151,965	157,25	158,92534	162,50	164,93032	167,26	168,93421	173,04	174,967
Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium

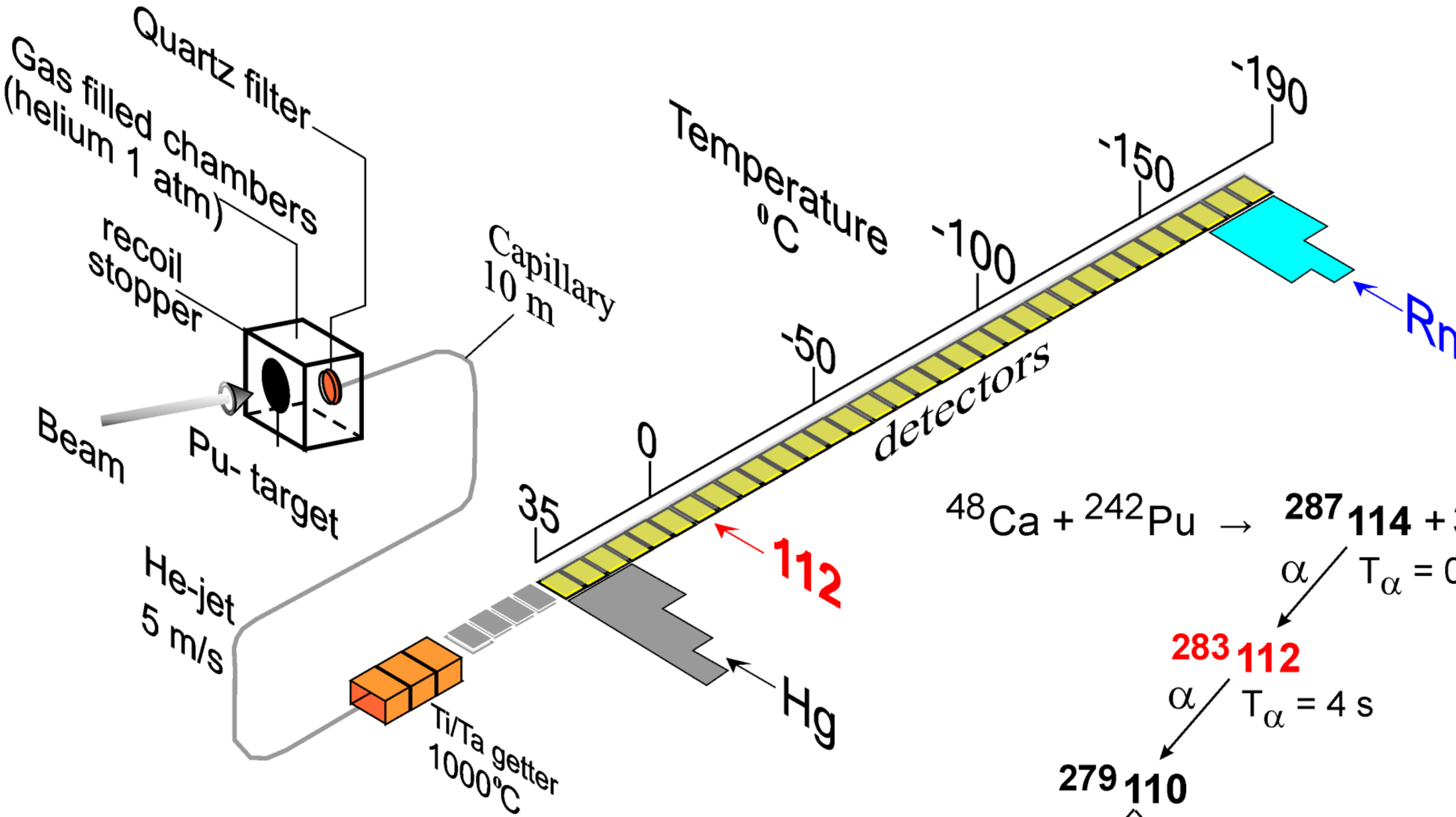
Актиноиды Actinides

Торий	Протактиний	Уран	Нептуний	Плутоний	Америций	Кюрий	Берклий	Калифорний	Эйнштейний	Фермий	Менделевий	Нобелий	Лоуренсий
Th $7s^2 6d^2$	Pa $5f^2 6d^1$	U $5f^3 6d^1$	Np $5f^4 6d^1$	Pu $5f^6$	Am $5f^7$	Cm $5f^7 6d^1$	Bk $5f^9$	Cf $5f^{10}$	Es $5f^{11}$	Fm $5f^{12}$	Md $5f^{13}$	No $5f^{14}$	Lr $5f^{14} 6d^1$
232,0381	231,03588	238,0289	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]	[262]
Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium

Electron shells in atoms (Fricke and Greiner, 1972)



Chemical properties of 112 element



$$^{48}Ca + {}^{242}Pu \rightarrow {}^{287}\mathbf{114} + 3n$$

α $T_\alpha = 0.6$ s

$^{283}\mathbf{112}$

α $T_\alpha = 4$ s

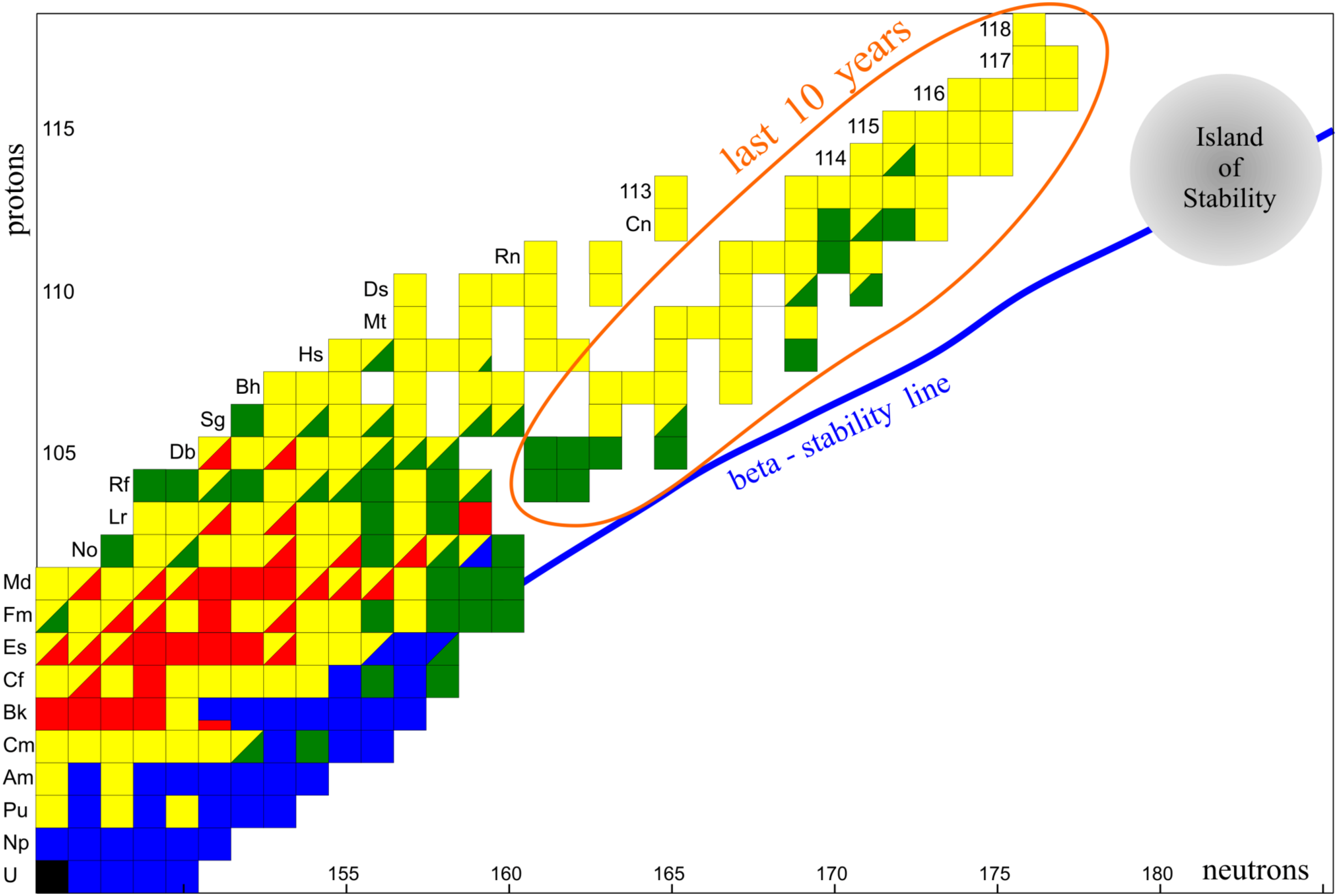
$^{279}\mathbf{110}$

Sf = 0.2 s

Dmitriev, Eichler et al., May 2006:

Volatility and adsorption properties of 112 are the same as of mercury

Great progress in synthesis of superheavy nuclei



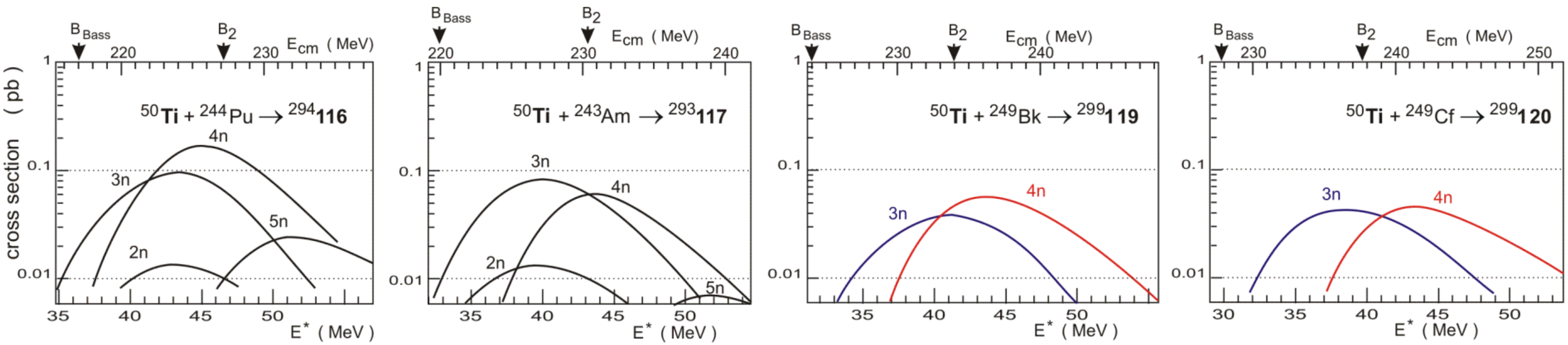
What is beyond 48Ca ?

All available targets have been already used:

^{238}U , ^{237}Np, ^{244}Pu, ^{243}Am, ^{248}Cm, ^{249}Bk, ^{249}Cf

+ ^{48}Ca

$\rightarrow$ ^{286}112 , ^{285}113, ^{292}114, ^{291}115 , ^{296}116 , ^{297}117, ^{297}118



How much Ti is worse ?

Factor $\frac{1}{20}$ as compared to ^{48}Ca

^{54}Cr ?

Factor $^{1}/_{2}$

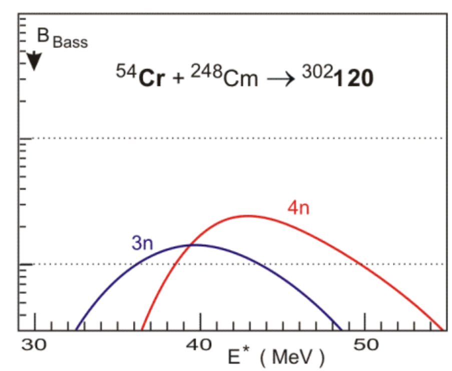
as compared to ^{50}Ti.

However

(1) beam is available,

(2) target is available,

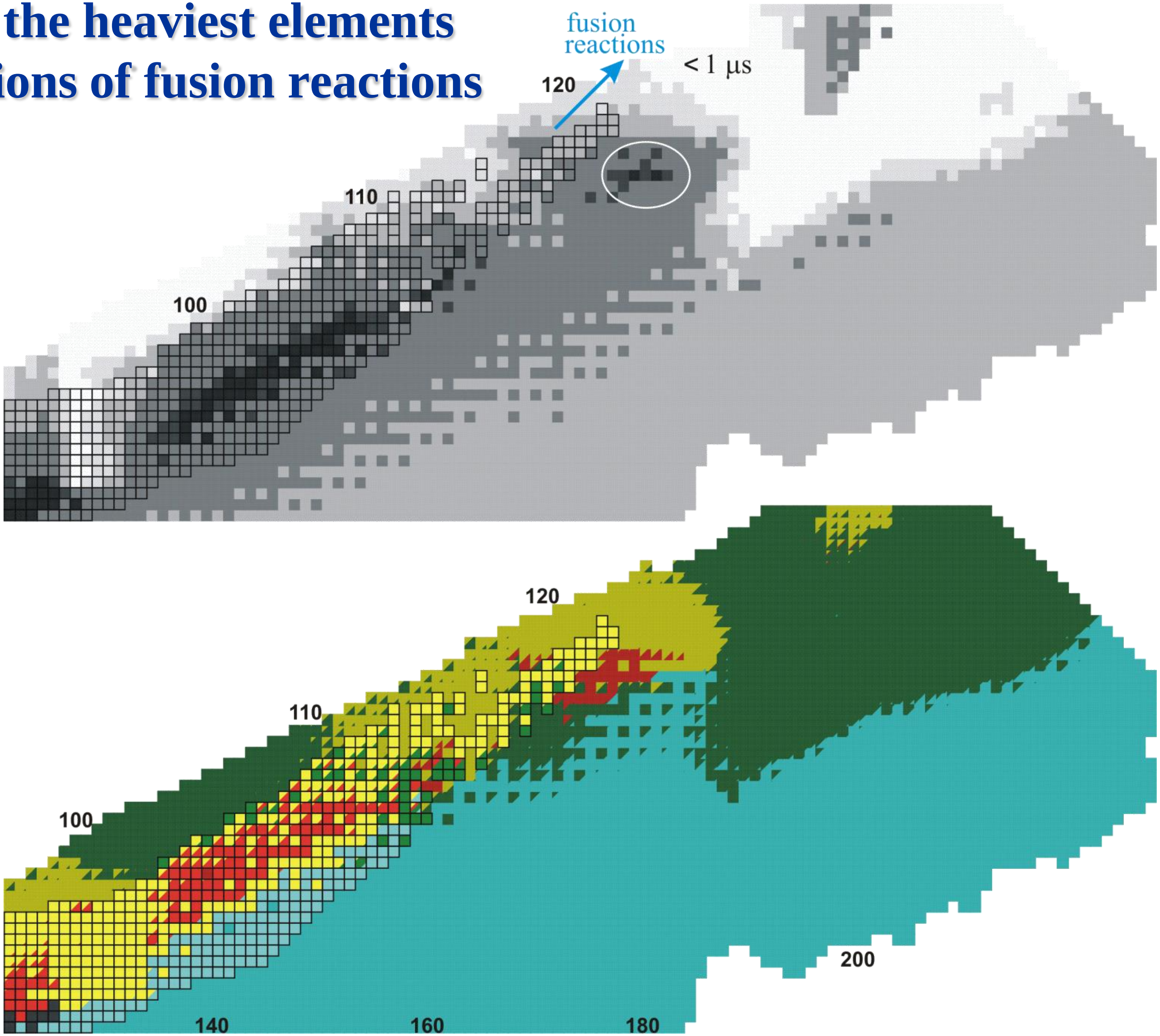
(3) decay chain is known.



The experiment started at GSI

(see talks of S. Hofmann and Ch. Duellman)

Stability of the heaviest elements and limitations of fusion reactions



See the talk of Alexander Karpov

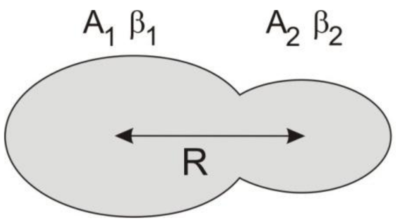
Multi-nucleon transfer reactions in low-energy heavy ion collisions

70-th and 80-th:
Hulet, Kratz, Schädel, Gäggeler, Freiesleben, Moody, Welch and others
(**talk of H. Gäggeler**)

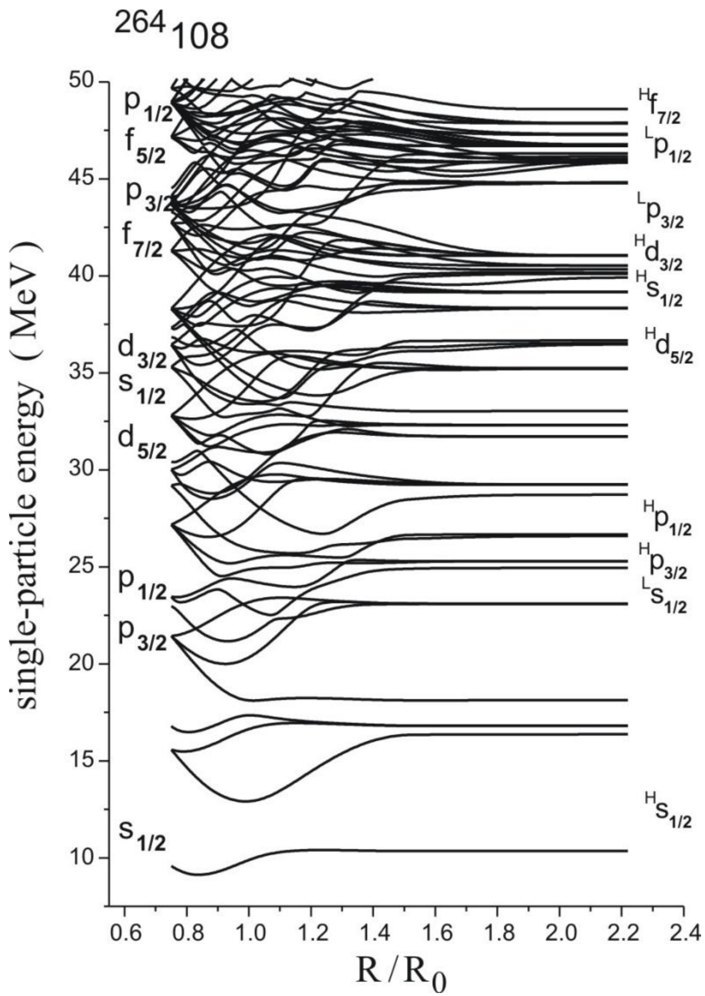
since 2005: renewed interest by Zagrebaev and Greiner

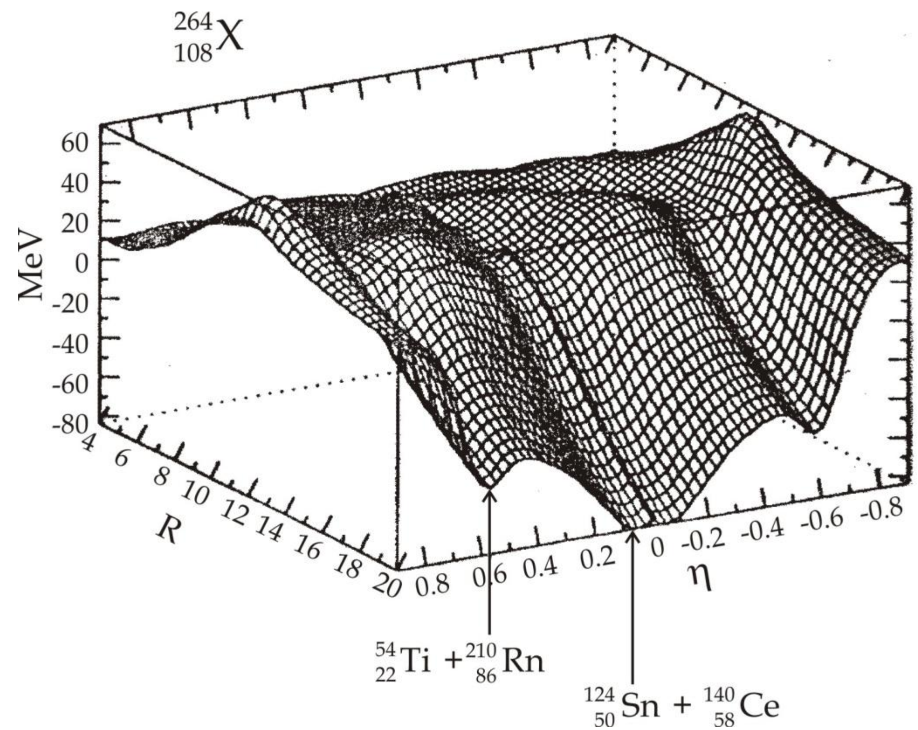
Our approach: (1) Two-center shell model
(2) Time-dependent driving potential
(3) Langevin type equations of motion

Two-Center Shell Model



$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

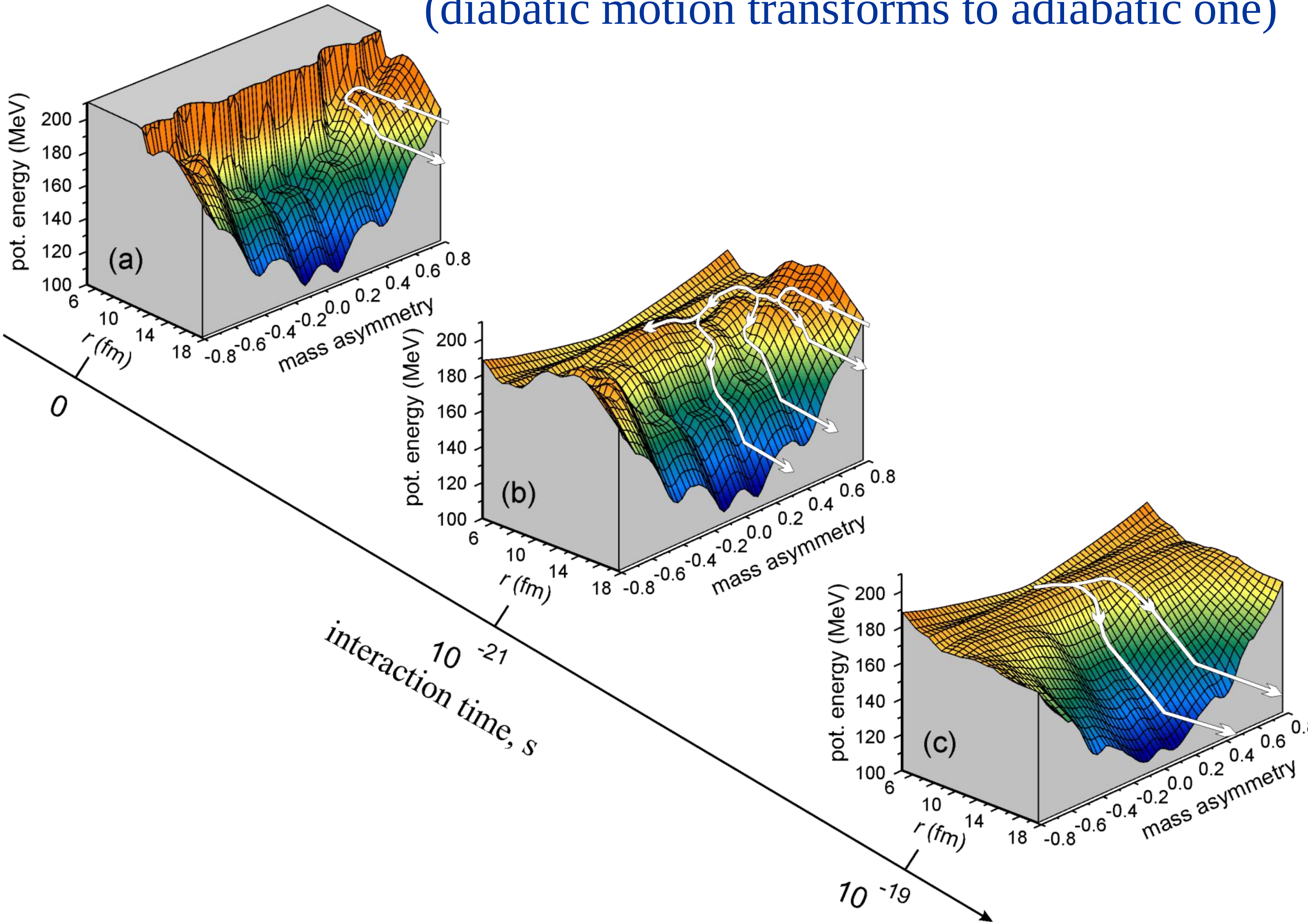




Maruhn and Greiner, 1971

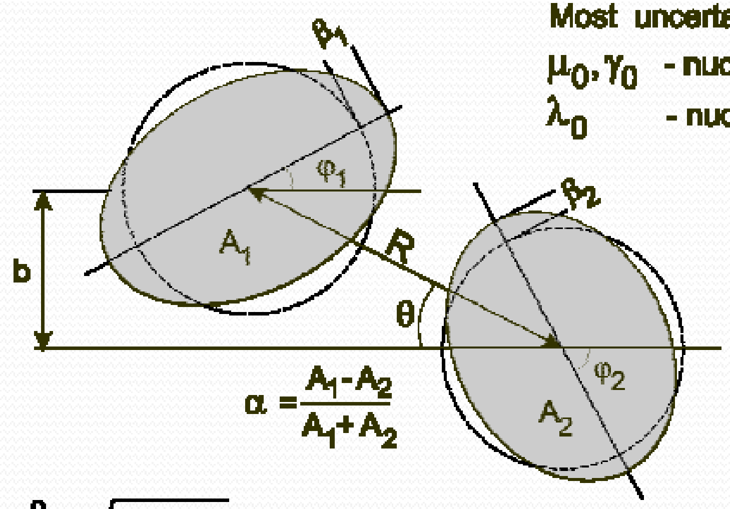
Time-dependent Driving Potential

(diabatic motion transforms to adiabatic one)



The system of coupled Langevin type Equations of Motion

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \alpha\}$



Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

$$\frac{d\vartheta}{dt} = \frac{\hbar\ell}{\mu_R R^2}$$

$$\frac{d\varphi_1}{dt} = \frac{\hbar L_1}{\Im_1}$$

$$\frac{d\varphi_2}{dt} = \frac{\hbar L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta_1}}{\mu_{\beta_1}}$$

$$\frac{d\beta_2}{dt} = \frac{p_{\beta_2}}{\mu_{\beta_2}}$$

$$\frac{d\alpha}{dt} = \frac{2}{A_{CN}} D_A^{(1)}(\alpha) + \frac{2}{A_{CN}} \sqrt{D_A^{(2)}(\alpha)}\Gamma_\alpha(t)$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\hbar^2\ell^2}{\mu_R R^3} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial R} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \vartheta} - \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)R + \frac{R}{\hbar}\sqrt{\gamma_{\rm tang} T}\Gamma_{\rm tang}(t)$$

$$\frac{dL_1}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \varphi_1} + \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_1 - \frac{a_1}{\hbar}\sqrt{\gamma_{\rm tang} T}\Gamma_{\rm tang}(t)$$

$$\frac{dL_2}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \varphi_2} + \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_2 - \frac{a_2}{\hbar}\sqrt{\gamma_{\rm tang} T}\Gamma_{\rm tang}(t)$$

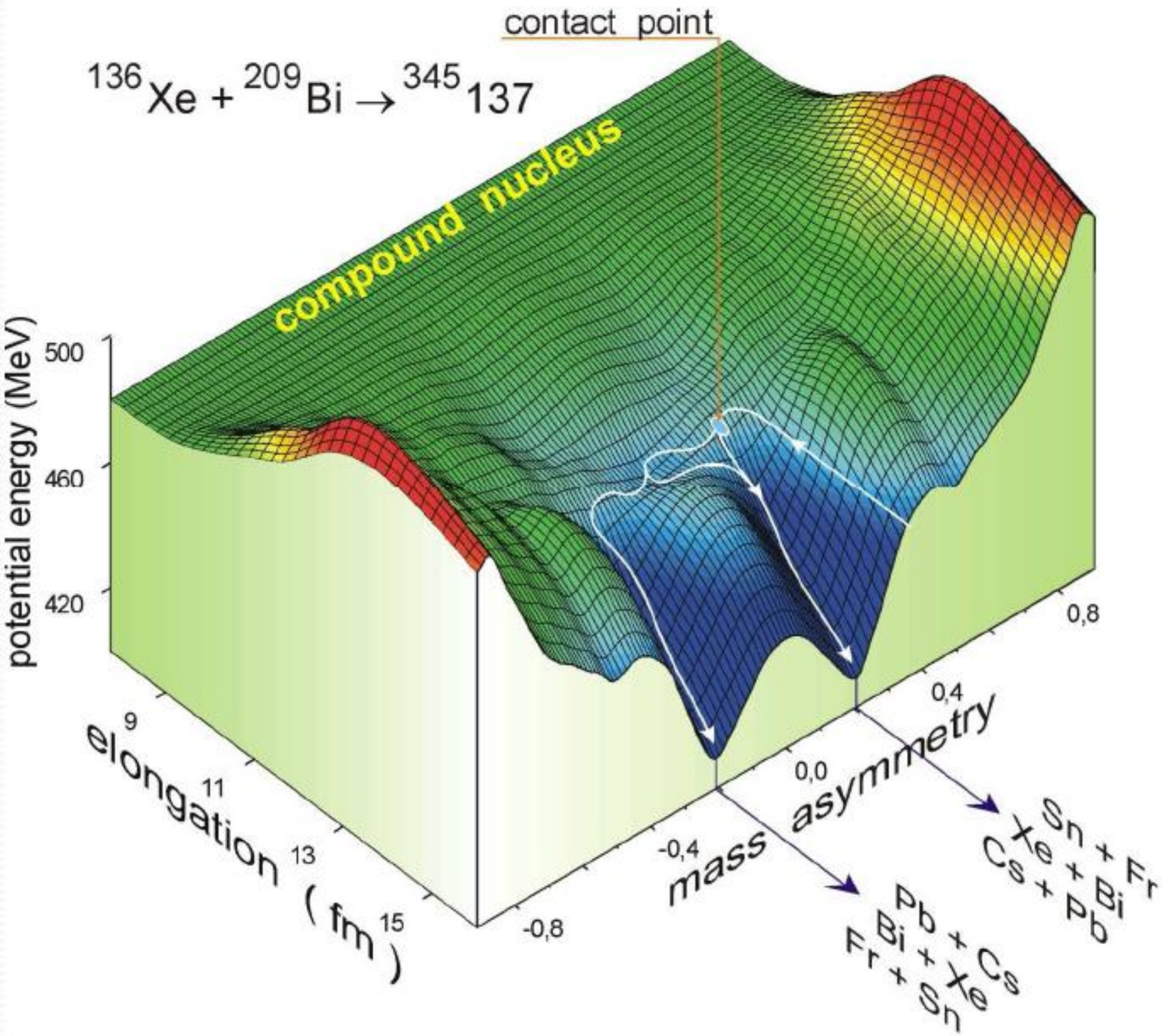
$$\frac{dp_{\beta_1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial \beta_1} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial \beta_1} + \frac{\hbar^2 L_1^2}{2\Im_1^2}\frac{\partial \Im_1}{\partial \beta_1} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_{\beta_1}\frac{p_{\beta_1}}{\mu_{\beta_1}} + \sqrt{\gamma_{\beta_1} T}\Gamma_{\beta_1}(t)$$

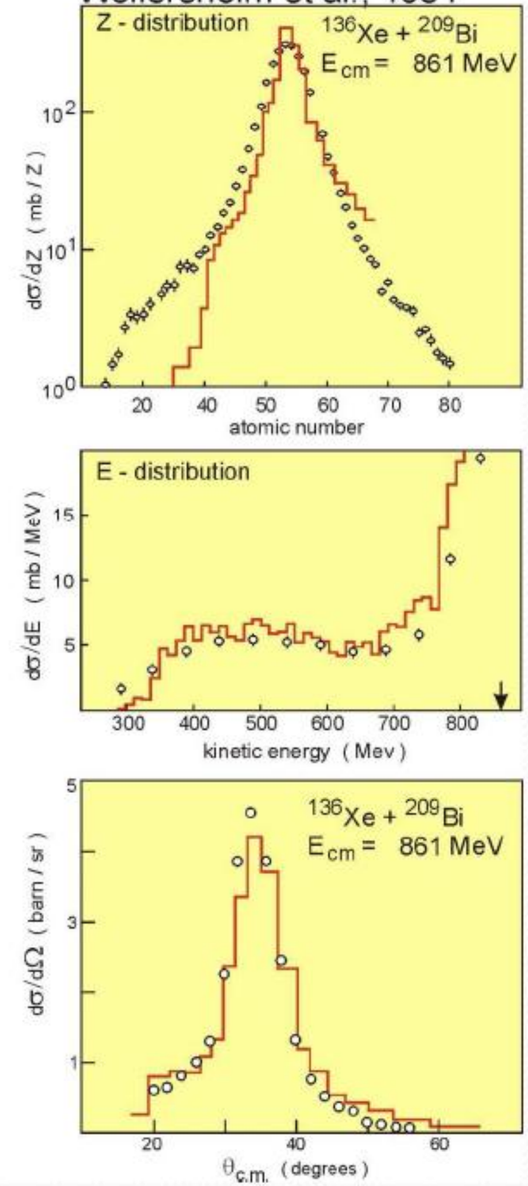
$$\frac{dp_{\beta_2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial \beta_2} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial \beta_2} + \frac{\hbar^2 L_2^2}{2\Im_2^2}\frac{\partial \Im_2}{\partial \beta_2} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_{\beta_2}\frac{p_{\beta_2}}{\mu_{\beta_2}} + \sqrt{\gamma_{\beta_2} T}\Gamma_{\beta_2}(t).$$

Collisions of heavy nuclei (no CN formation)

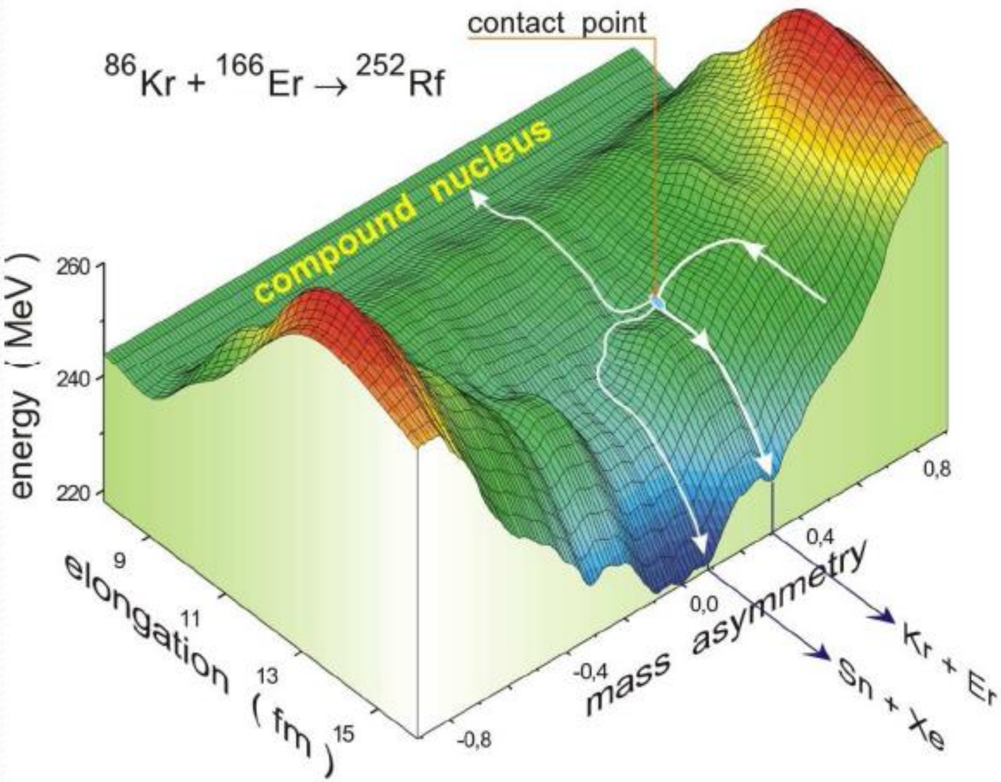
Freiesleben,

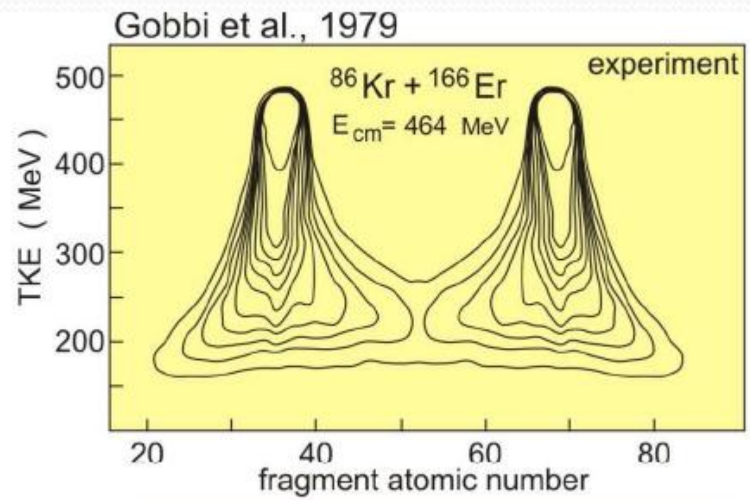
Wollersheim et al., 1981

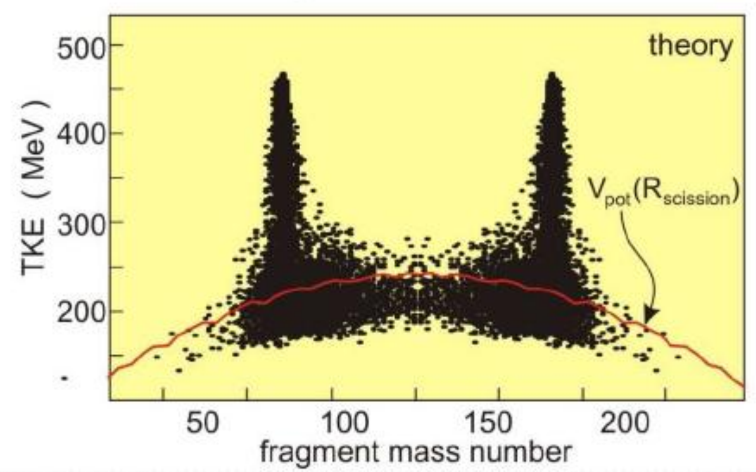




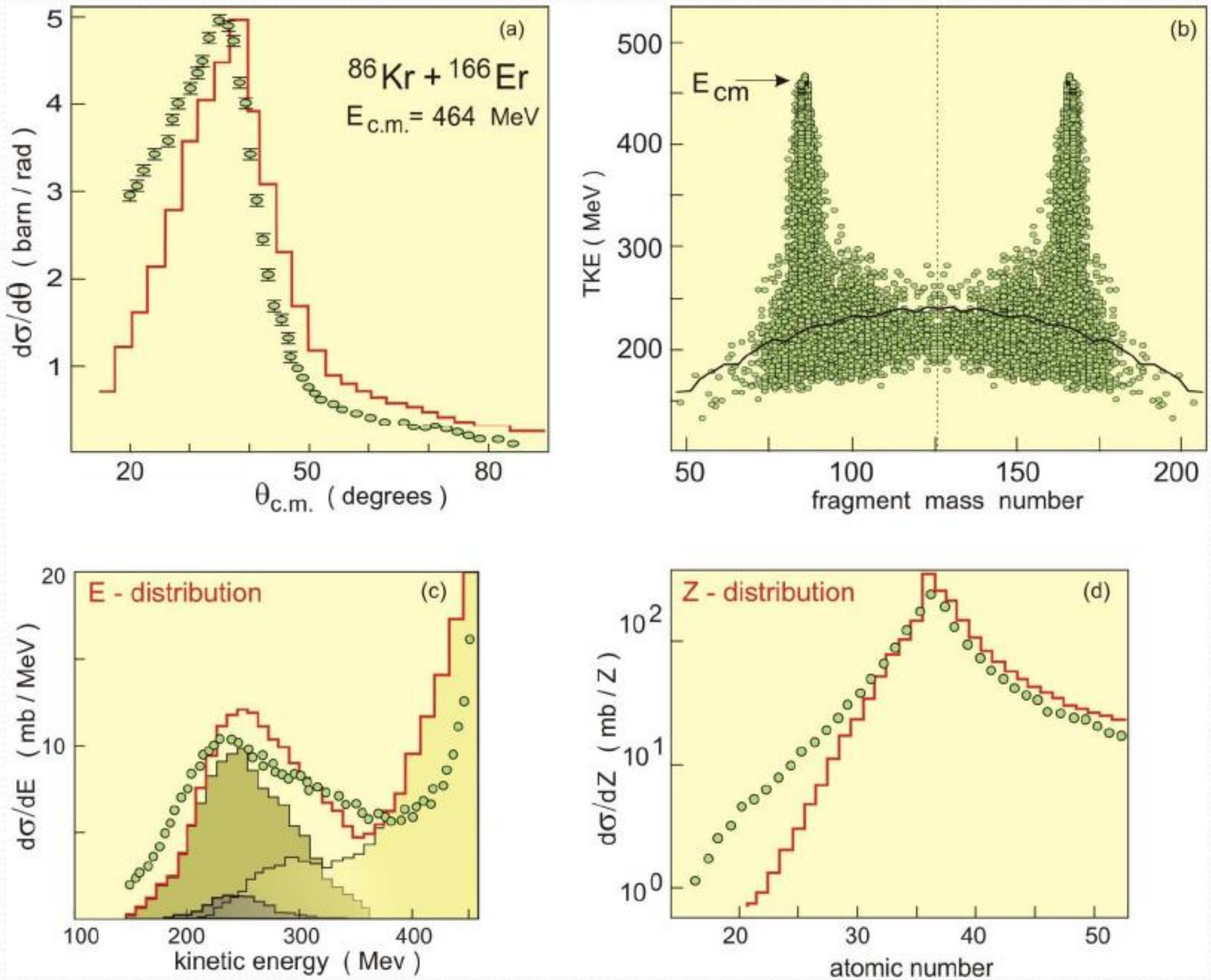
$^{86}Kr + ^{166}Er$ collision at E_{cm} = 464 MeV (Coulomb barrier = 260 MeV)



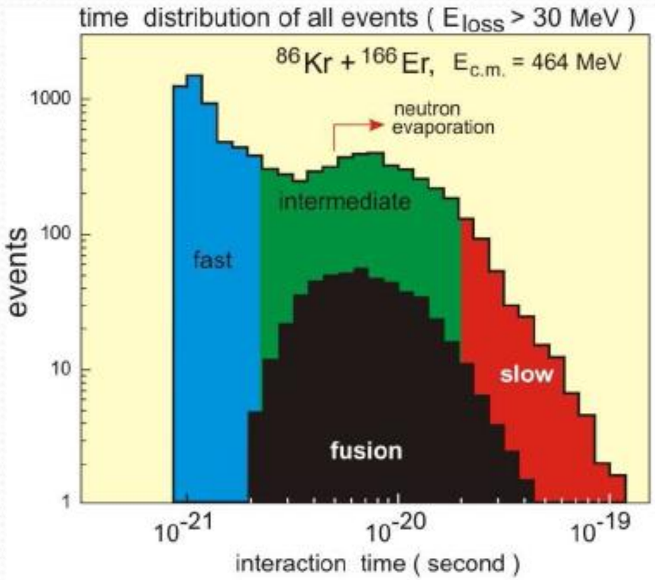


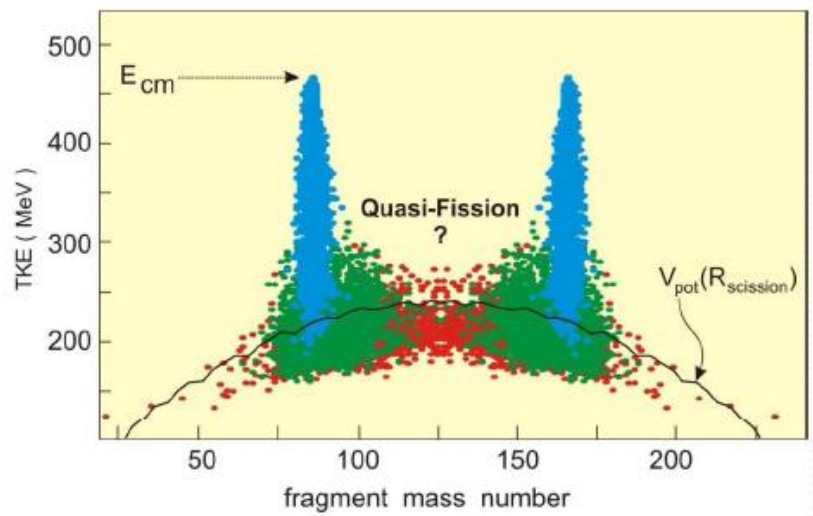


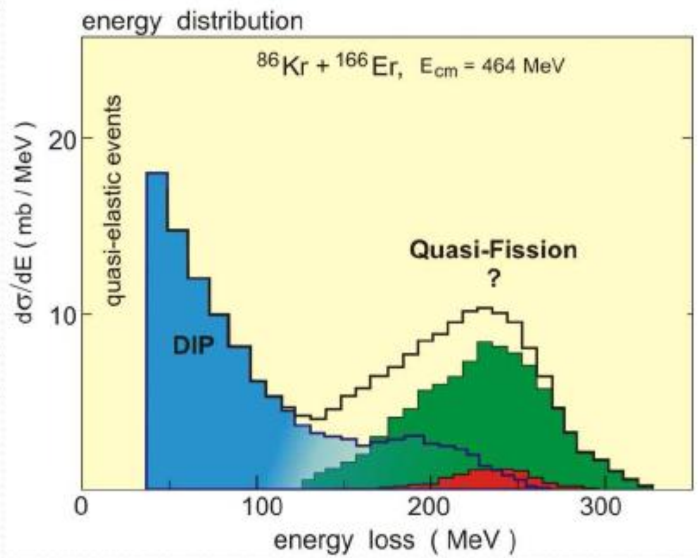
$^{86}Kr + ^{166}Er$ collision at E_{cm} = 464 MeV (Coulomb barrier = 260 MeV)



$^{86}Kr + ^{166}Er$ collision at E_{cm} = 464 MeV (time analysis)

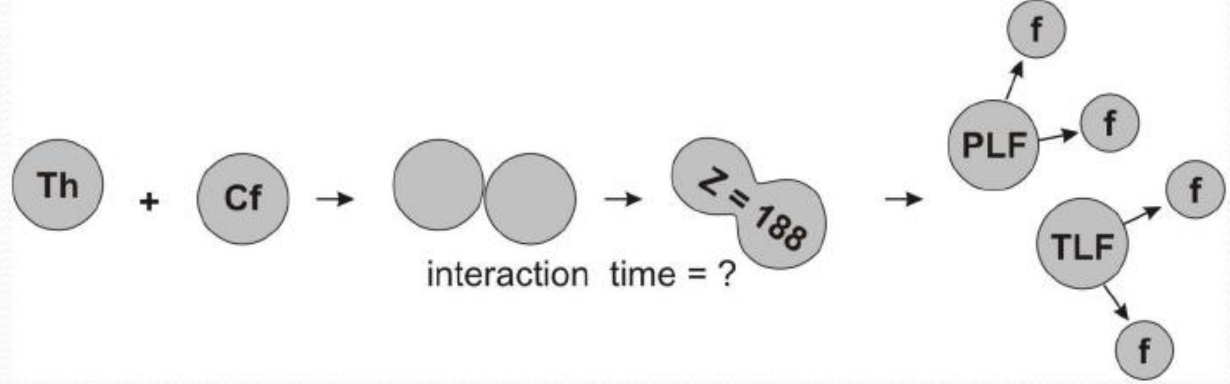


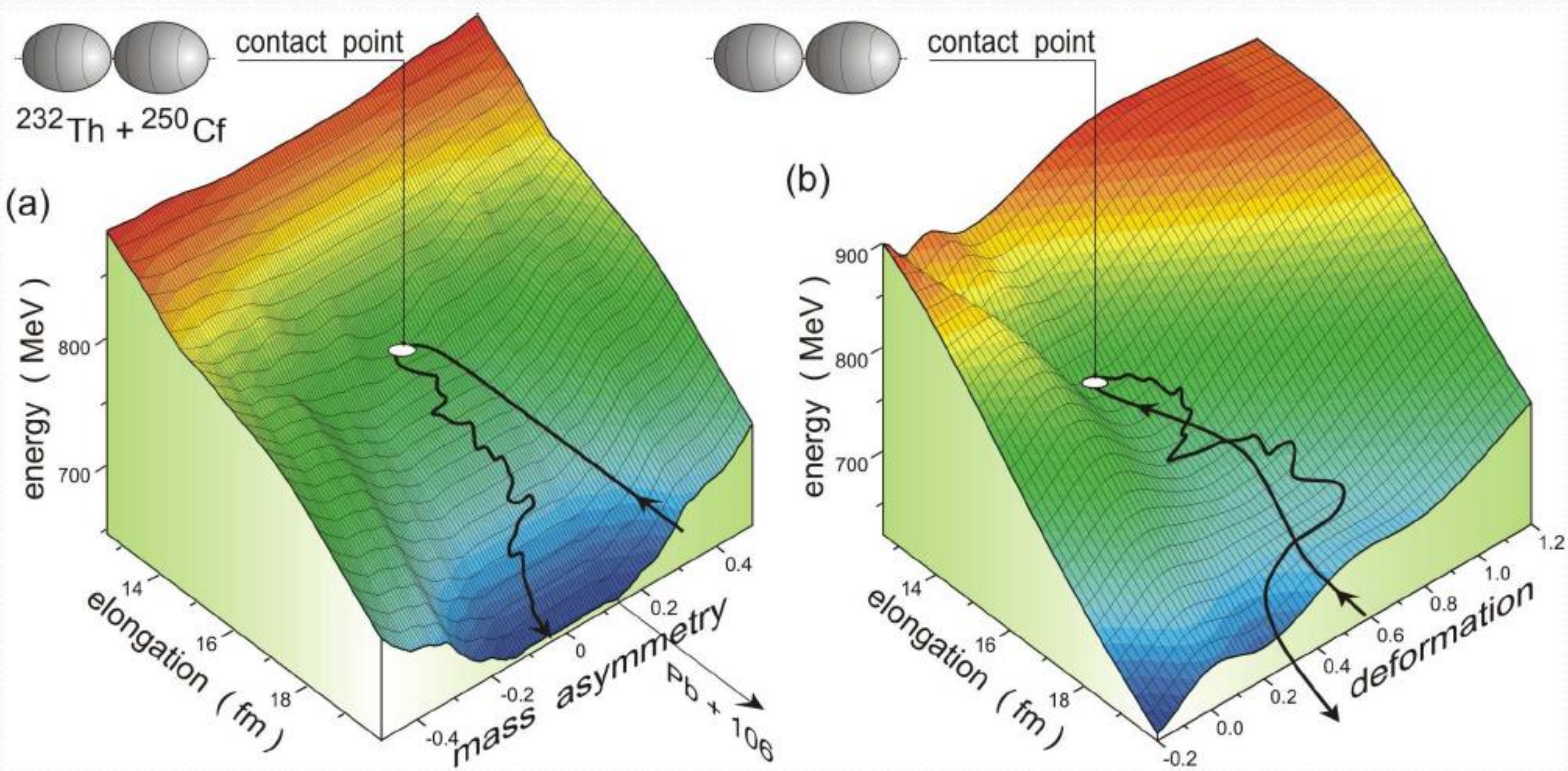




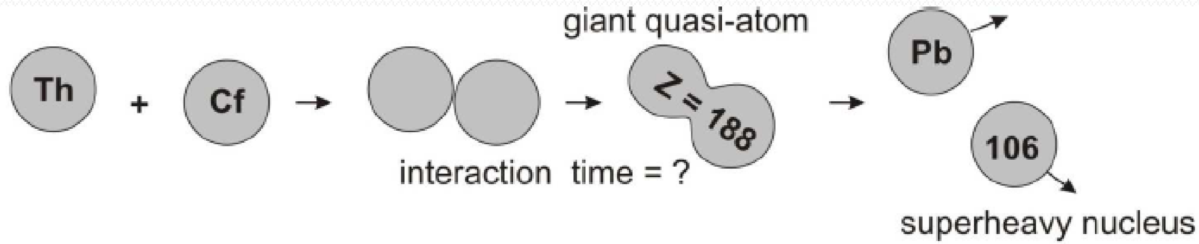
- $t_{int} < 2 \cdot 10^{-21}$ s
- $2 \cdot 10^{-21} < t_{int} < 2 \cdot 10^{-20}$ s
- $2 \cdot 10^{-20}$ s $< t_{int}$

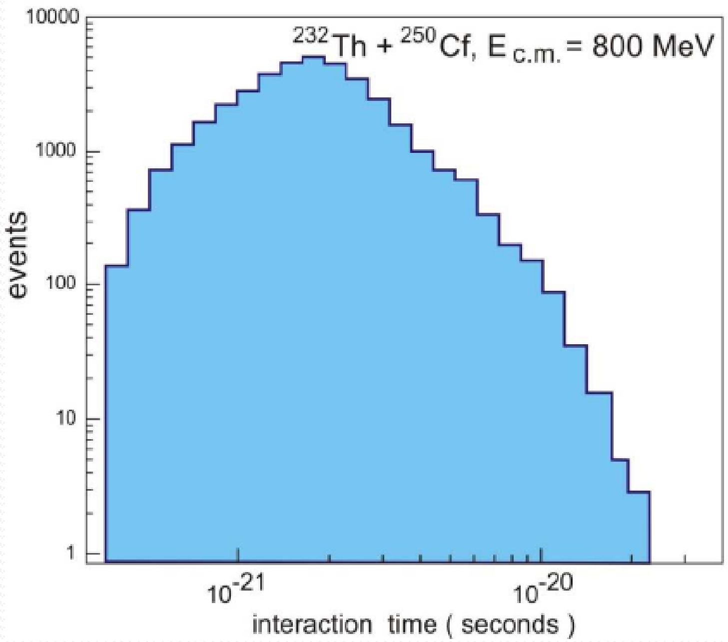
Collision of very heavy (transactinide) nuclei

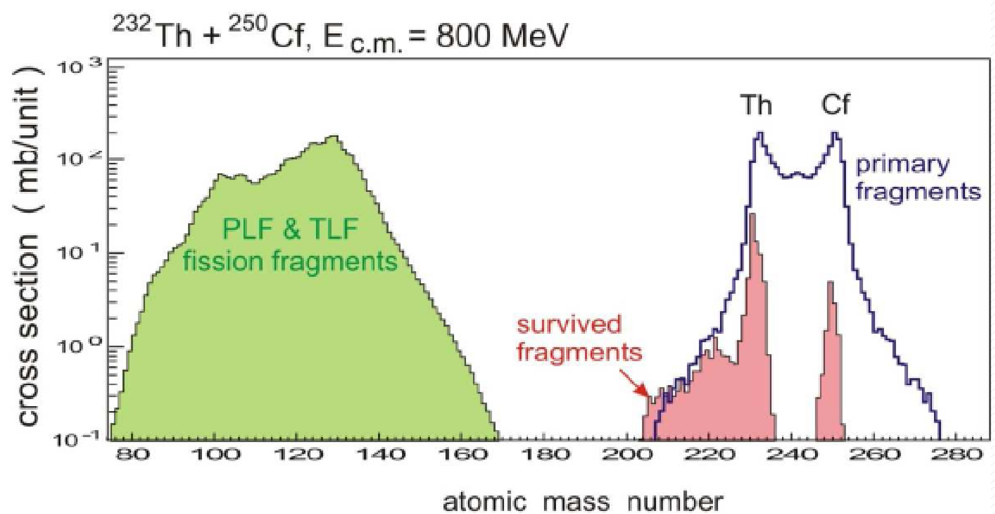




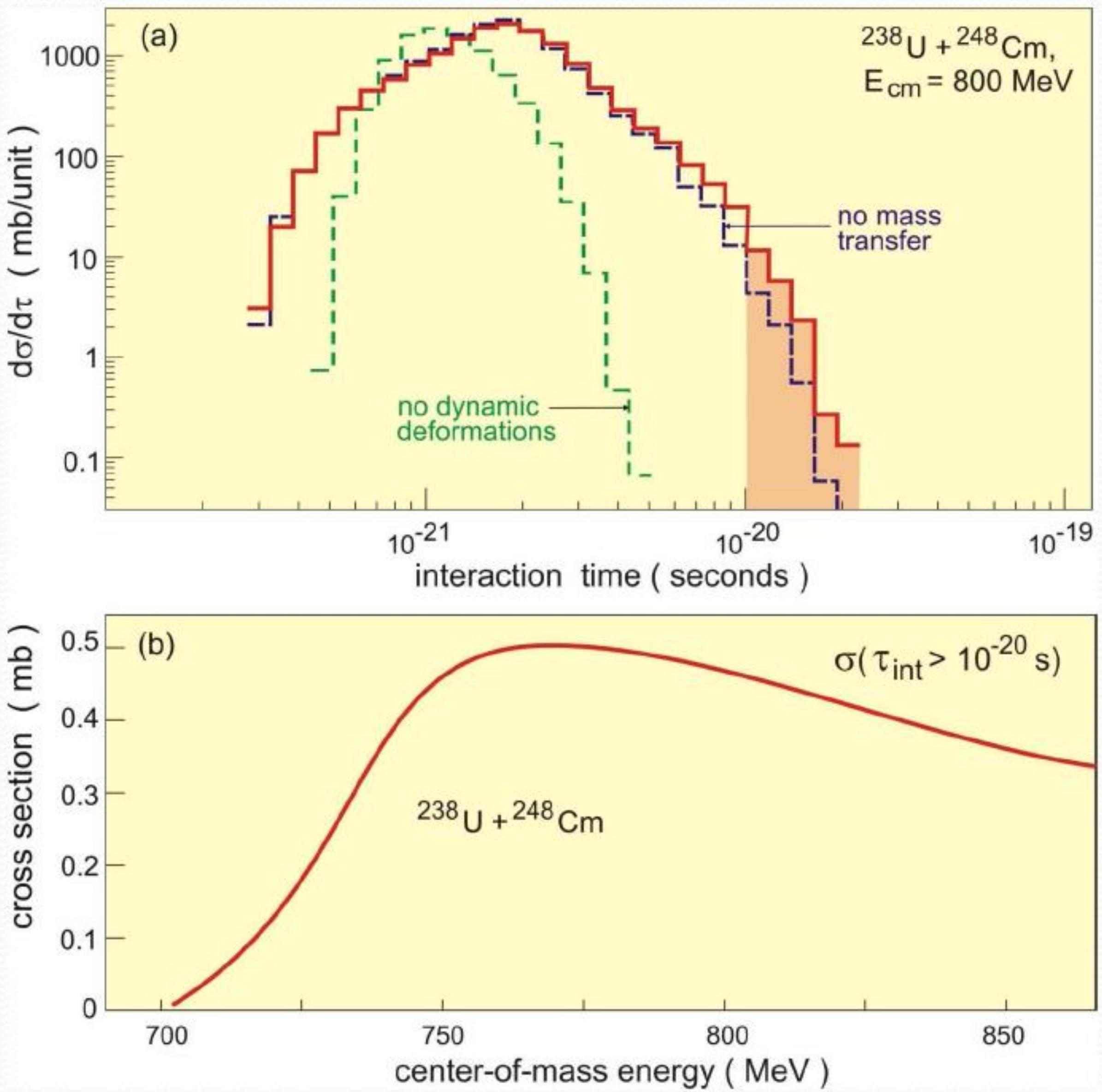
Giant quasi-atoms and neutron-rich superheavy nuclei



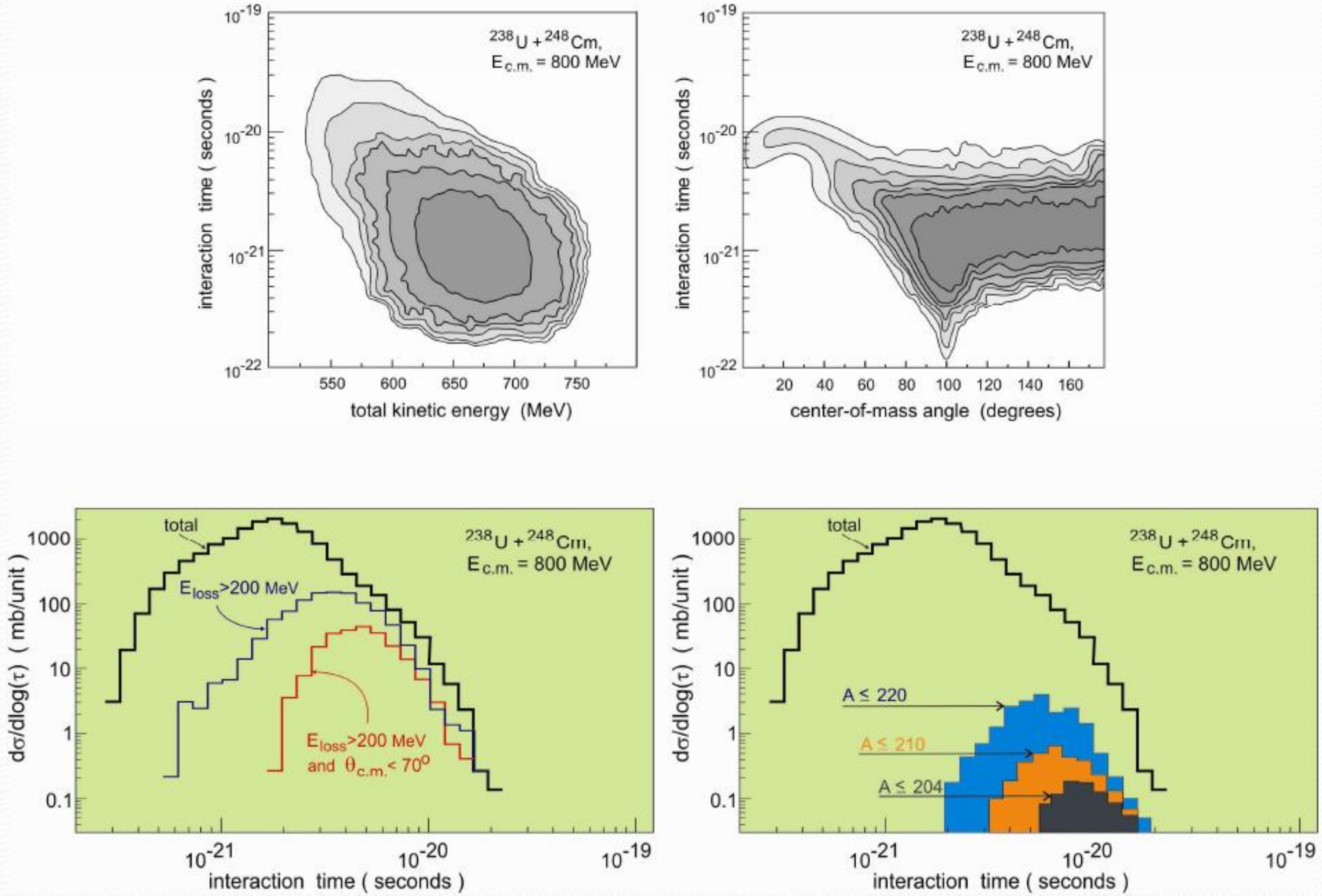




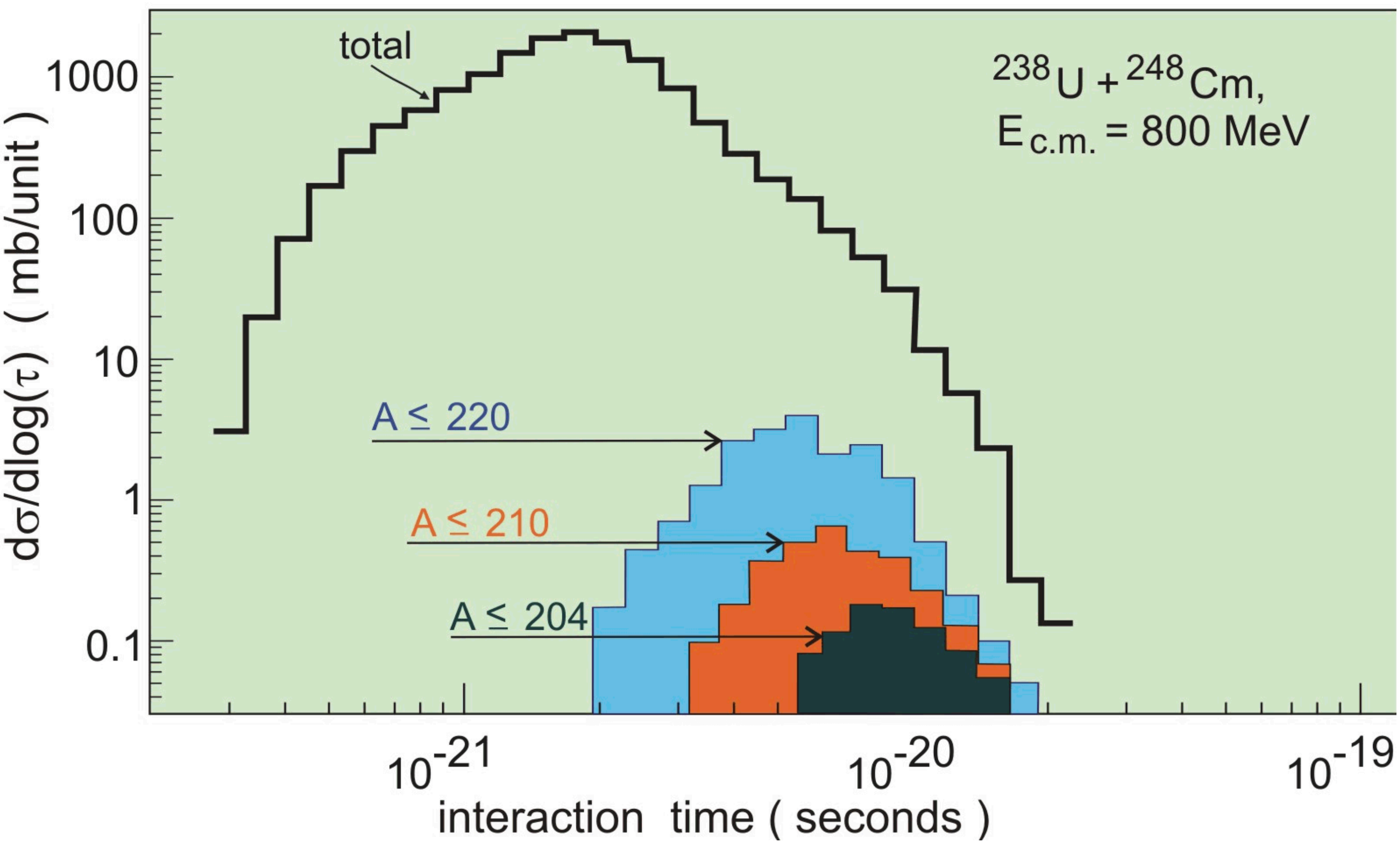
Interaction time at the U + Cm low-energy collision



What are the triggers for long reaction time ?

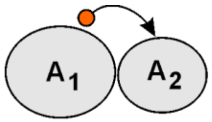


V.I. Zagrebaev, Yu.Ts. Oganessian, M.G. Itkis and W. Greiner,
*Phys. Rev. **C73**, 031602 (R) (2006)*



total
$^{238}U + ^{248}Cm$,
$E_{c.m.}$ = 800 MeV
1000
100
10
1
0.1
$d\sigma/d\log(\tau)$ (mb/unit)
A ≤ 220
A ≤ 210
A ≤ 204
10^{-21}
10^{-20}
10^{-19}
interaction time (seconds)

Nucleon Exchange: Langevin type equations



$A_1 \to A_1 - 1$
$A_2 \to A_2 + 1$

(L. Moretto, 1974)

Distribution function $\varphi(A_1, t)$ → Master equation $\dfrac{\partial \varphi}{\partial t} = \sum\limits_{A_1' = A_1 \pm 1} \lambda(A_1' \to A_1) \cdot \varphi(A_1') - \lambda(A_1 \to A_1') \cdot \varphi(A_1)$

$$\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial A_1}\left(D^{(1)}\varphi\right) + \frac{\partial^2}{\partial A_1^2}\left(D^{(2)}\varphi\right)$$

Fokker - Planck
(W. Nörenberg, 1974)

$$\frac{dA_1}{dt} = D^{(1)} + \sqrt{D^{(2)}}\,\Gamma(t)$$

Langevin type eq.

$$\eta = \frac{A_1 - A_2}{A_{CN}} = \frac{A_1 - (A_{CN} - A_1)}{A_{CN}} = \frac{2A_1 - A_{CN}}{A_{CN}}$$

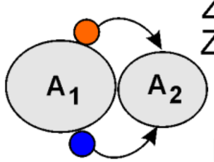
$$\frac{d\eta}{dt} = \frac{2}{A_{CN}} D_A^{(1)} + \frac{2}{A_{CN}} \sqrt{D_A^{(2)}}\,\Gamma(t)$$

at $A' = A \pm 1$

$$D^{(1)} = \lambda(A_1 \to A_1 + 1) - \lambda(A_1 \to A_1 - 1)$$

$$D^{(2)} = \frac{1}{2}[\lambda(A_1 \to A_1 + 1) + \lambda(A_1 \to A_1 - 1)]$$

transition probability $\lambda^{(\pm)} = \lambda_0 \sqrt{\dfrac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R; A \to A \pm 1)$, $\rho \sim exp(2\sqrt{aE^*})$, $E^* = E_{c.m.} - V(R, \beta_1, \beta_2, \eta)$



$Z_1 \to Z_1 - 1$
$Z_2 \to Z_2 + 1$

$N_1 \to N_1 - 1$
$N_2 \to N_2 + 1$

$$\eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

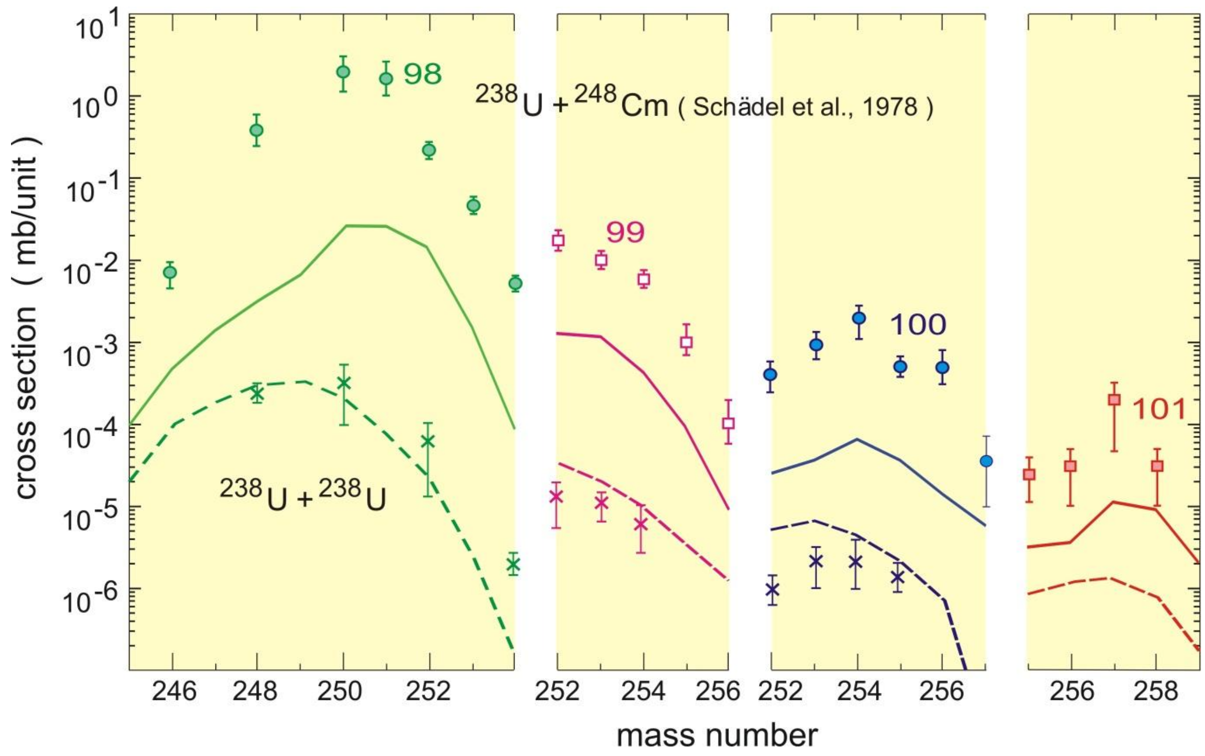
$$\eta_N = \frac{N_1 - N_2}{N_1 + N_2}$$

$$D_{N,Z}^{(1)} = \lambda_{N,Z}(A \to A + 1) - \lambda_{N,Z}(A \to A - 1)$$

$$D_{N,Z}^{(2)} = \frac{1}{2}[\lambda_{N,Z}(A \to A + 1) + \lambda_{N,Z}(A \to A - 1)]$$

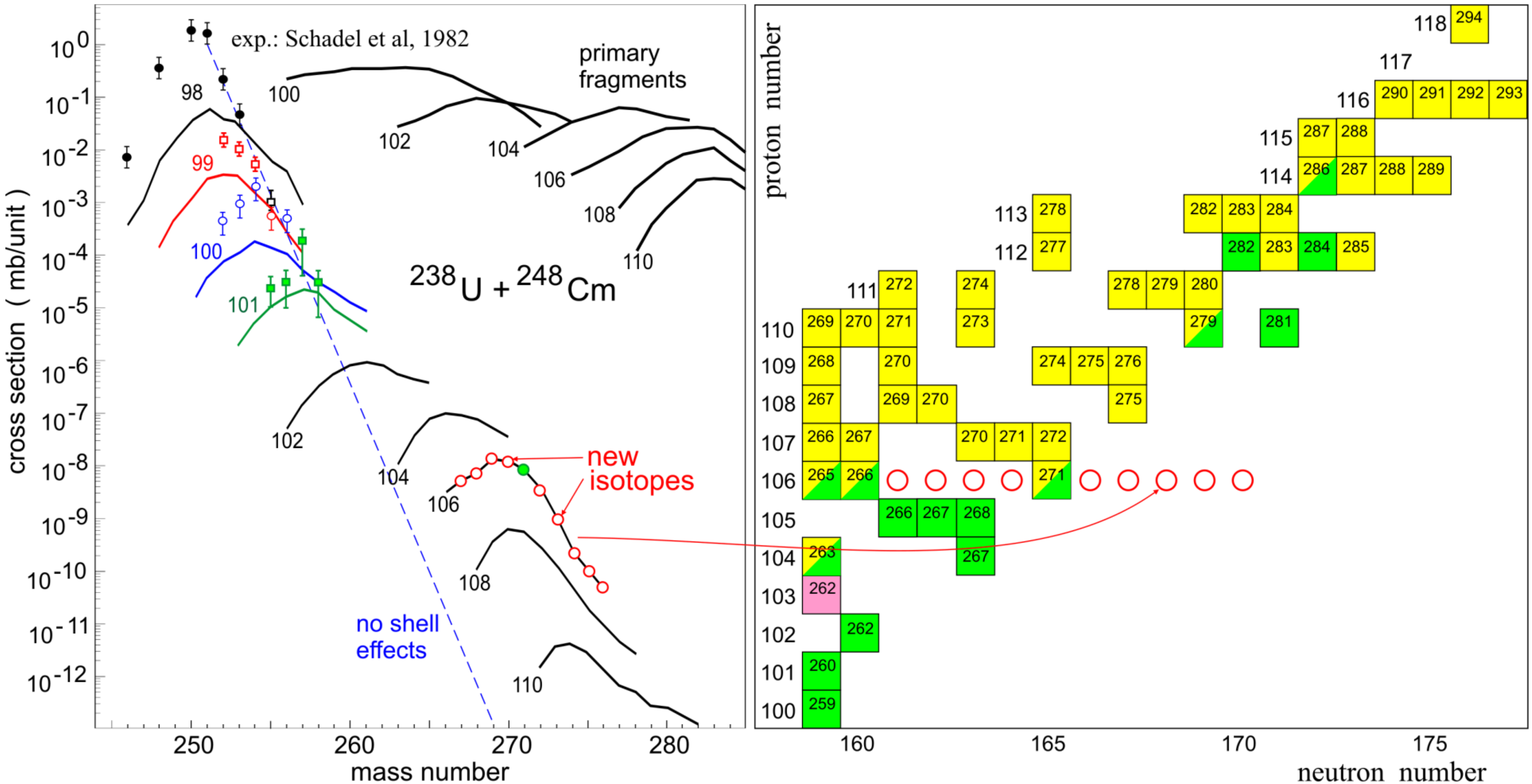
$$\lambda_{N,Z}^{(\pm)} = \lambda_{N,Z}^{0} \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R; A \to A \pm 1)$$

Comparison with available experimental data
(not so bad !)



Isotopic yield of SHE in collisions of heavy actinide nuclei

(wide area of the nuclear map may be populated)

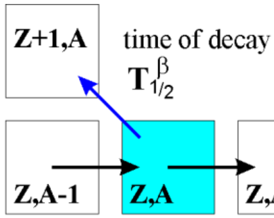


Production of neutron rich heavy and superheavy nuclei in neutron capture processes:

(1) Multiple nuclear explosions
(2) Pulsed nuclear reactors of next generation

Nucleogenesis in reactors and in nuclear explosions

(see talk of V. Zagrebaev)



time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

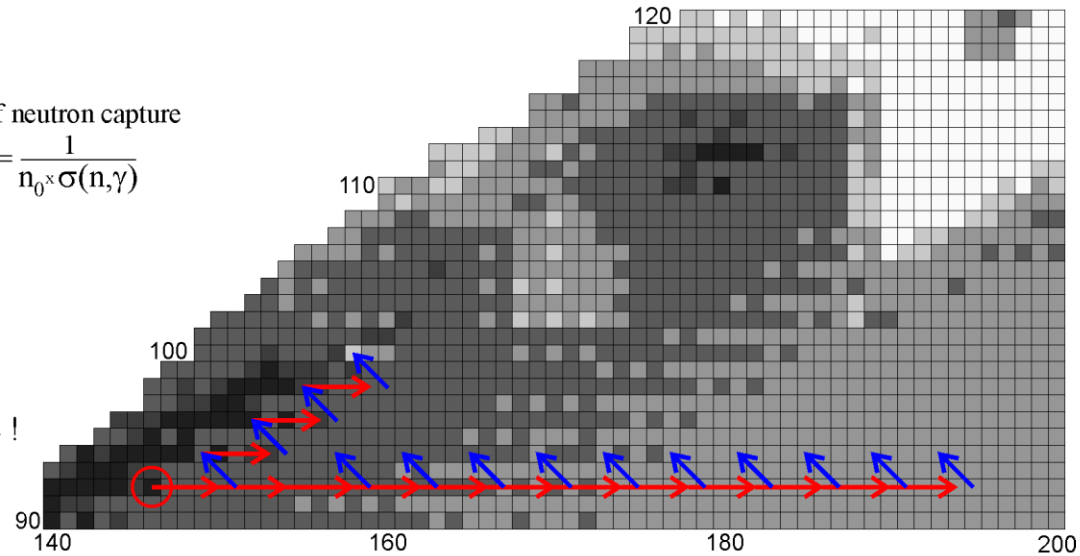
neutron capture stops

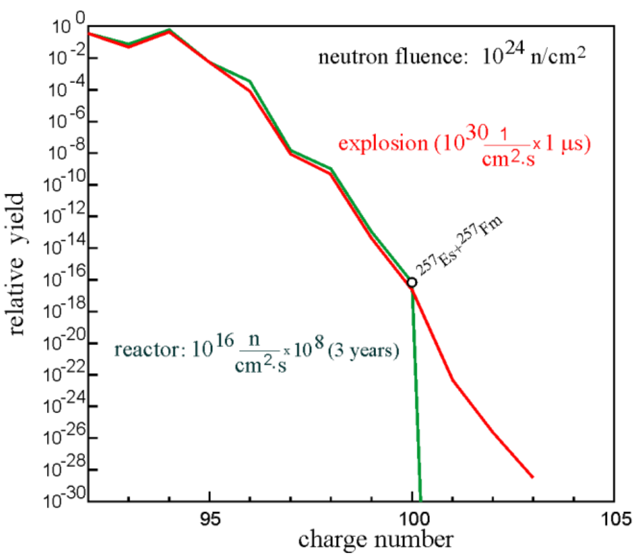
when $T^{\beta}_{1/2}(Z,A) < \tau_n^{cap}$

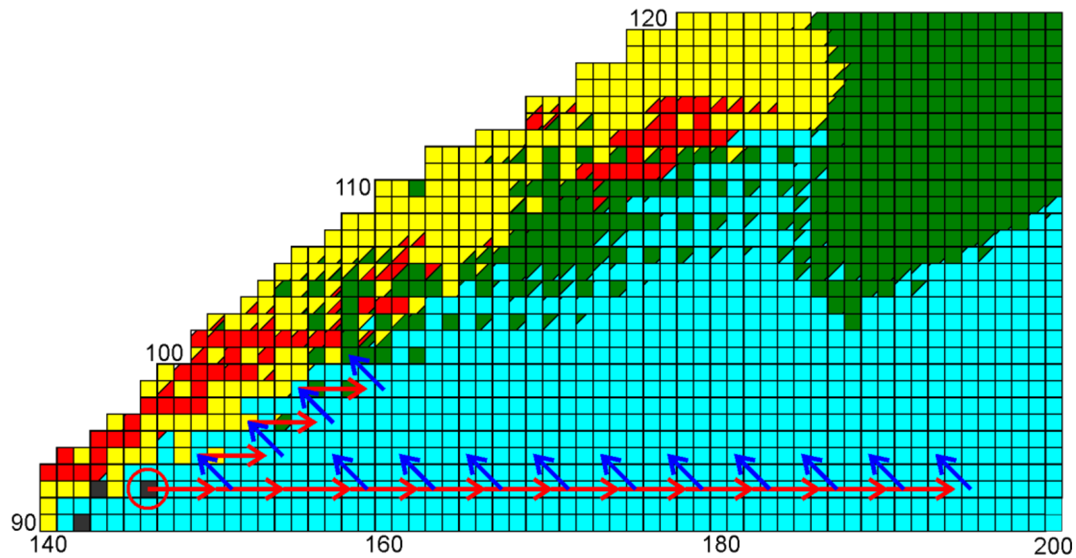
n_0 (reactor) $< 10^{19} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day),

but $T^{fis}_{1/2}$ ($^{258-260}$Fm) <= 1 sec !

n_0 (explosion) $\sim 10^{30} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} \sim 1\ \mu s$

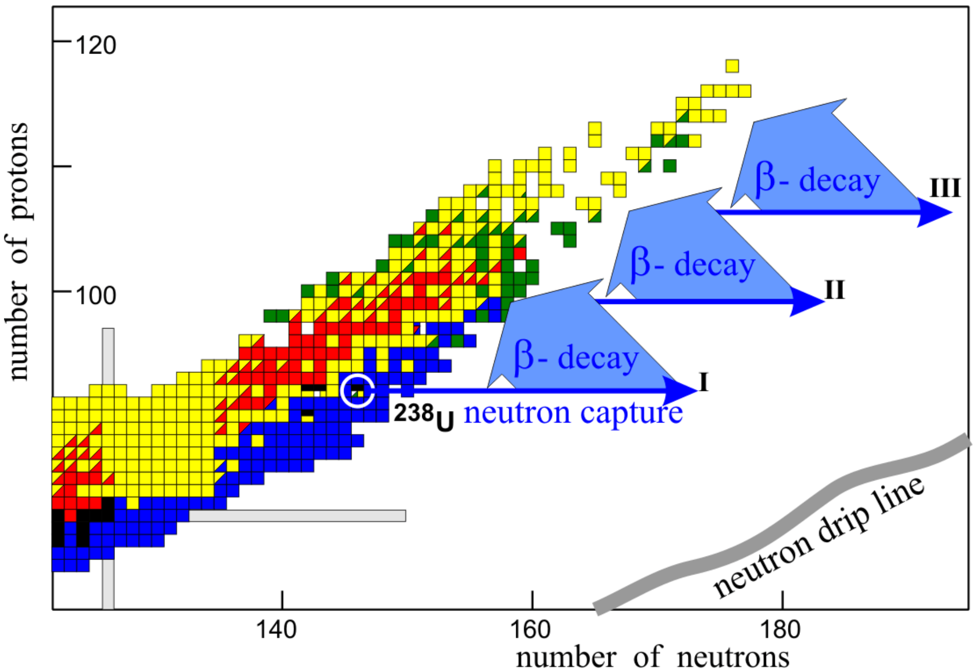


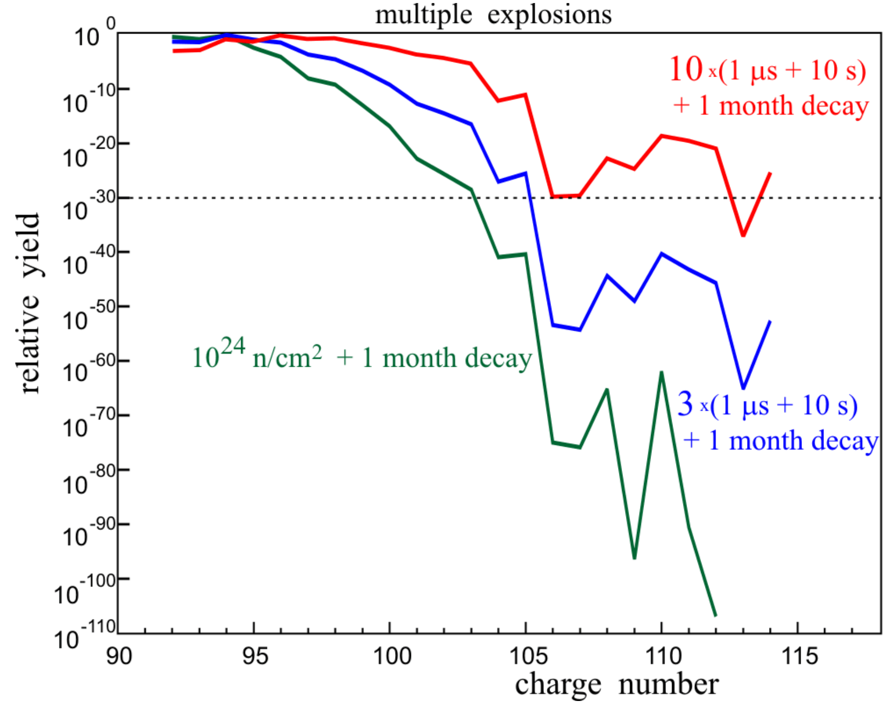




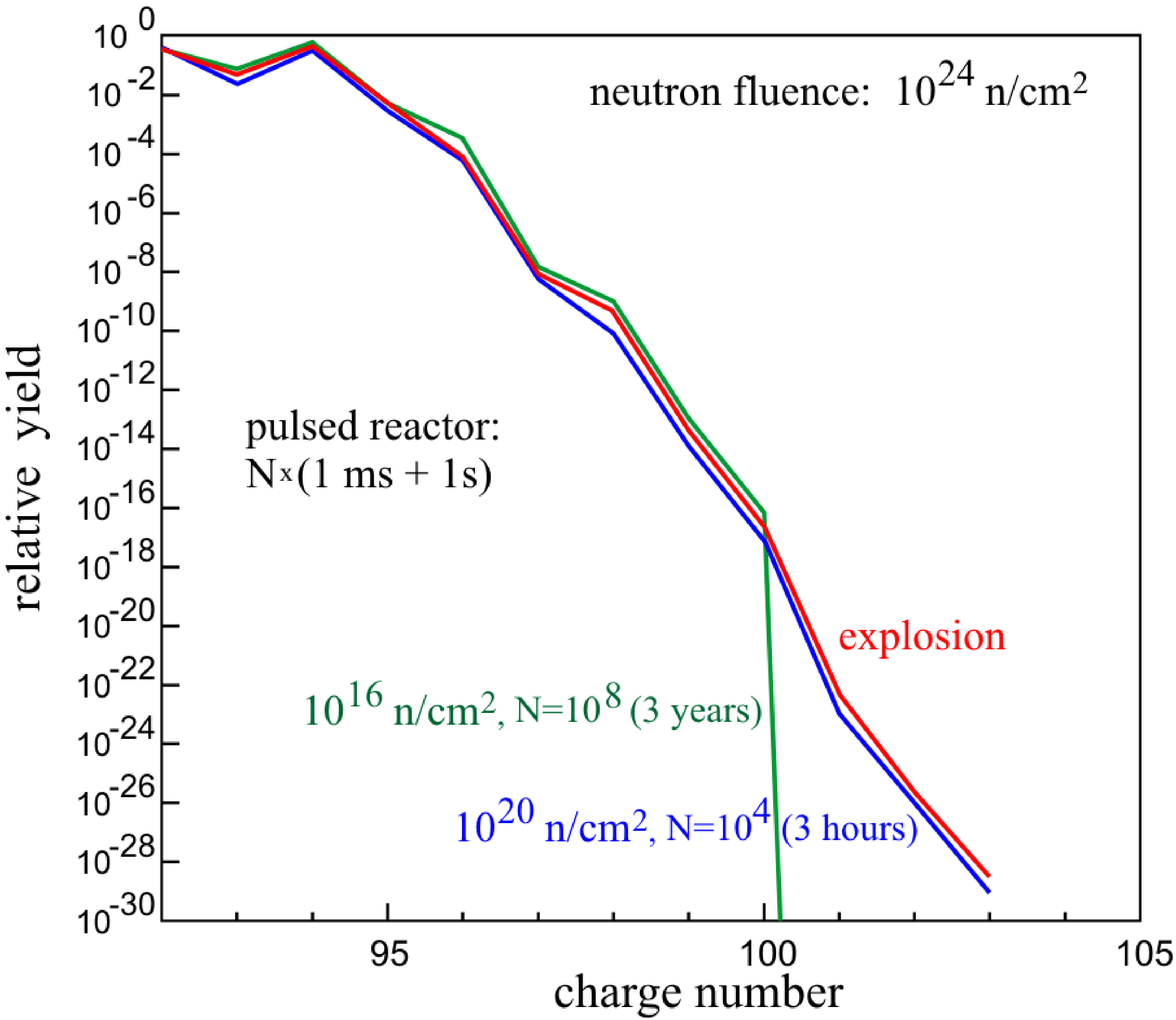
Multiple nuclear explosions

(Edward Teller: Technically it is quite possible)

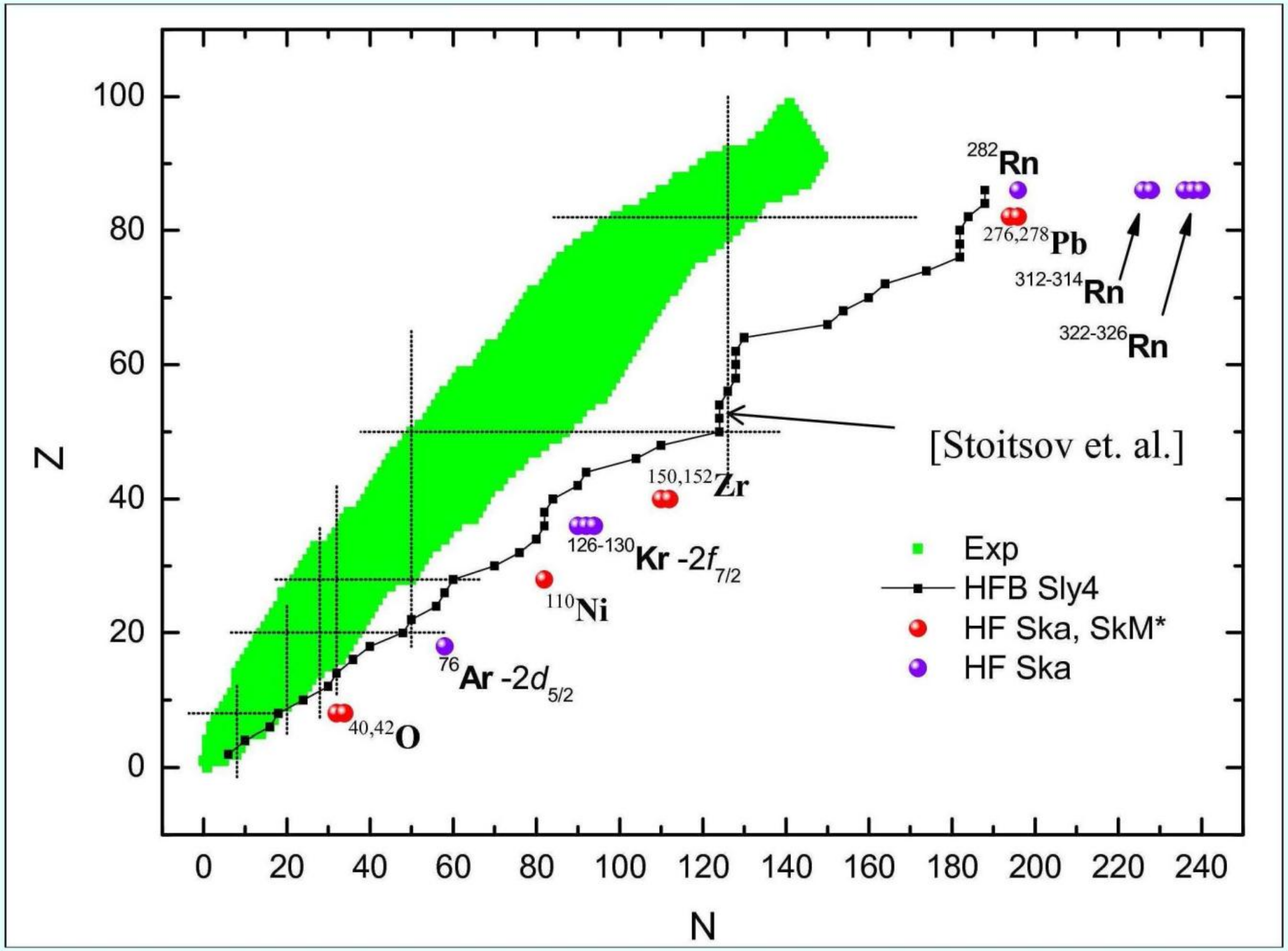




New generation of pulsed reactors (factor 1000 is needed at least)

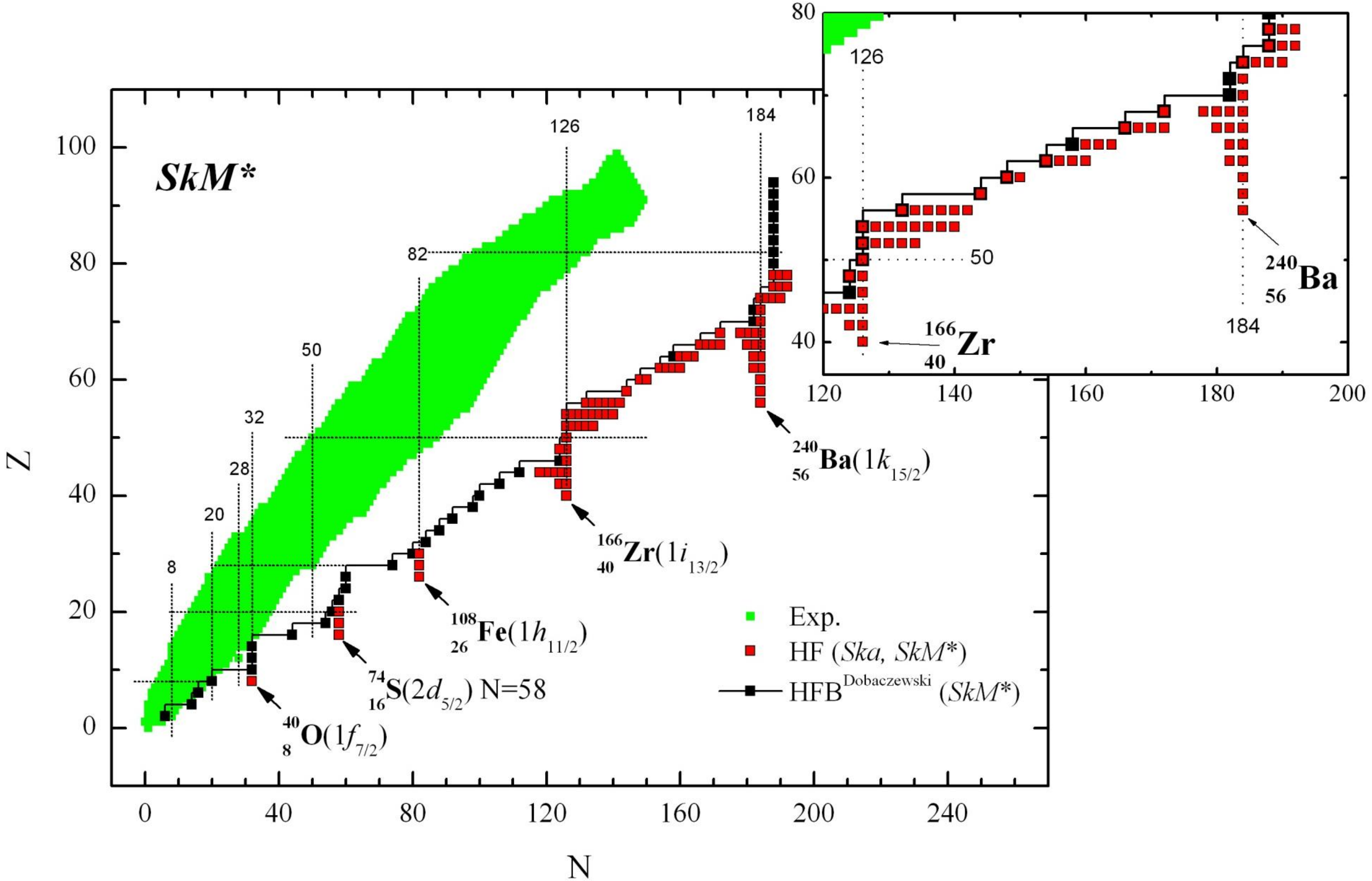


Revision of the Neutron Drip Line



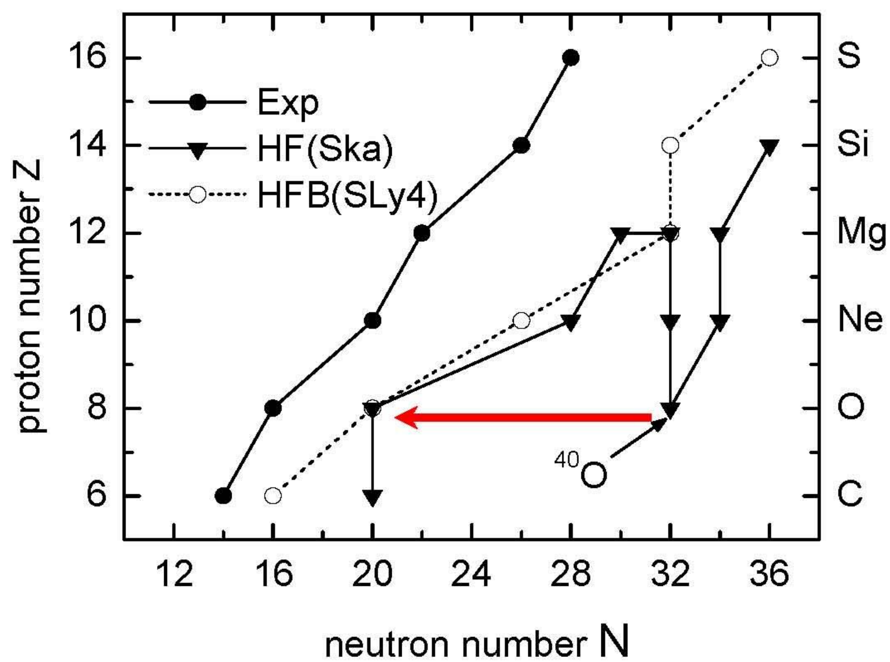
Rightmost circles denote edges (islands) of the drip line

Stability Enhancement near Magic Numbers

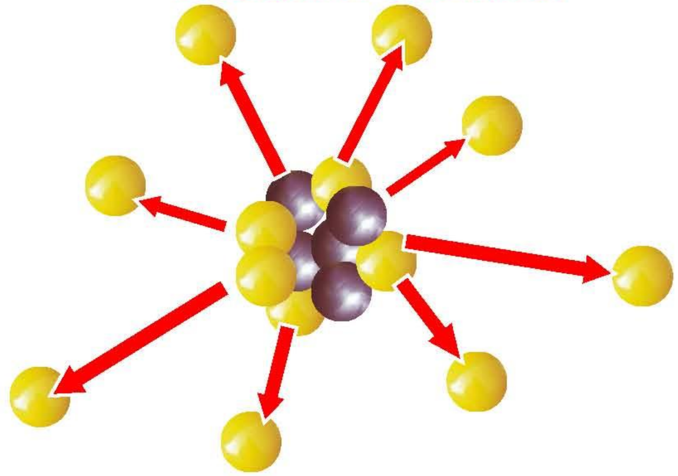


K. Gridnev, V. Tarasov, D. Gridnev, S. Schramm and W. Greiner

A new decay mode



Peninsulas on the drip line introduce a new decay mode: **neutron shower**

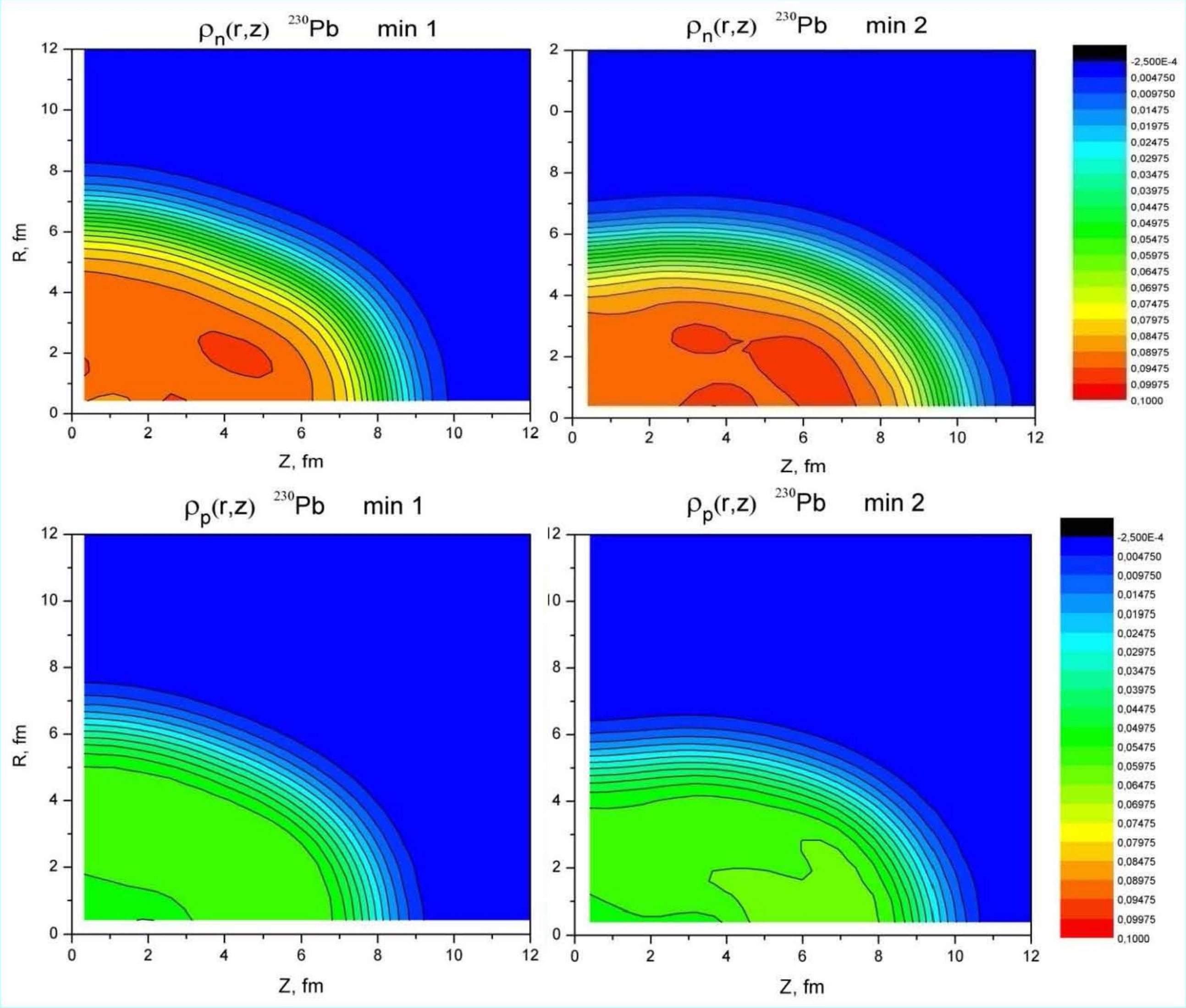


Analogy: A cluster of 24 atoms of 3He decays through a shower into 24 unbound atoms (the clusters with N<24 atoms are unstable)

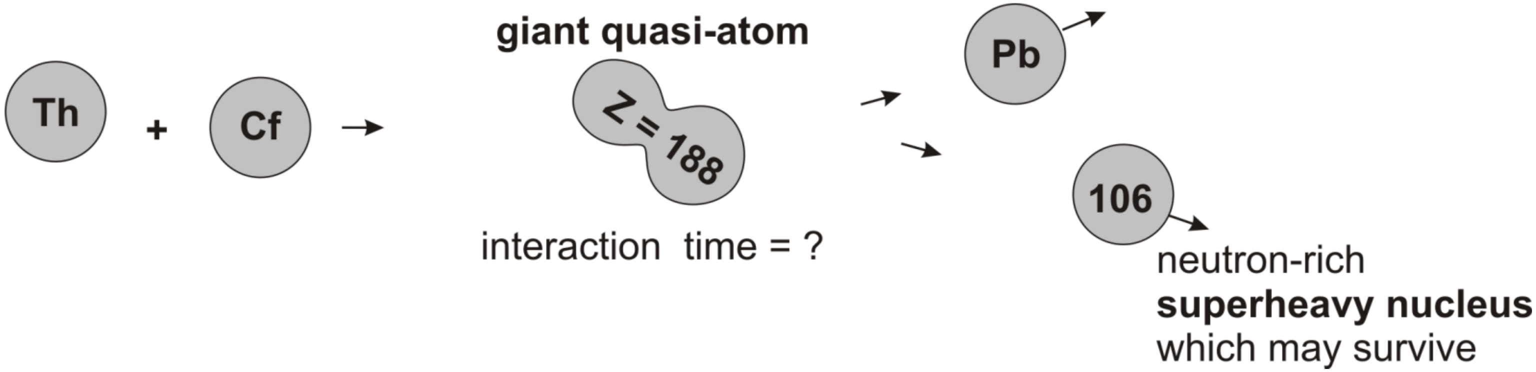
Pandharipande et al., Phys. Rev. 34, 4571 (1986)

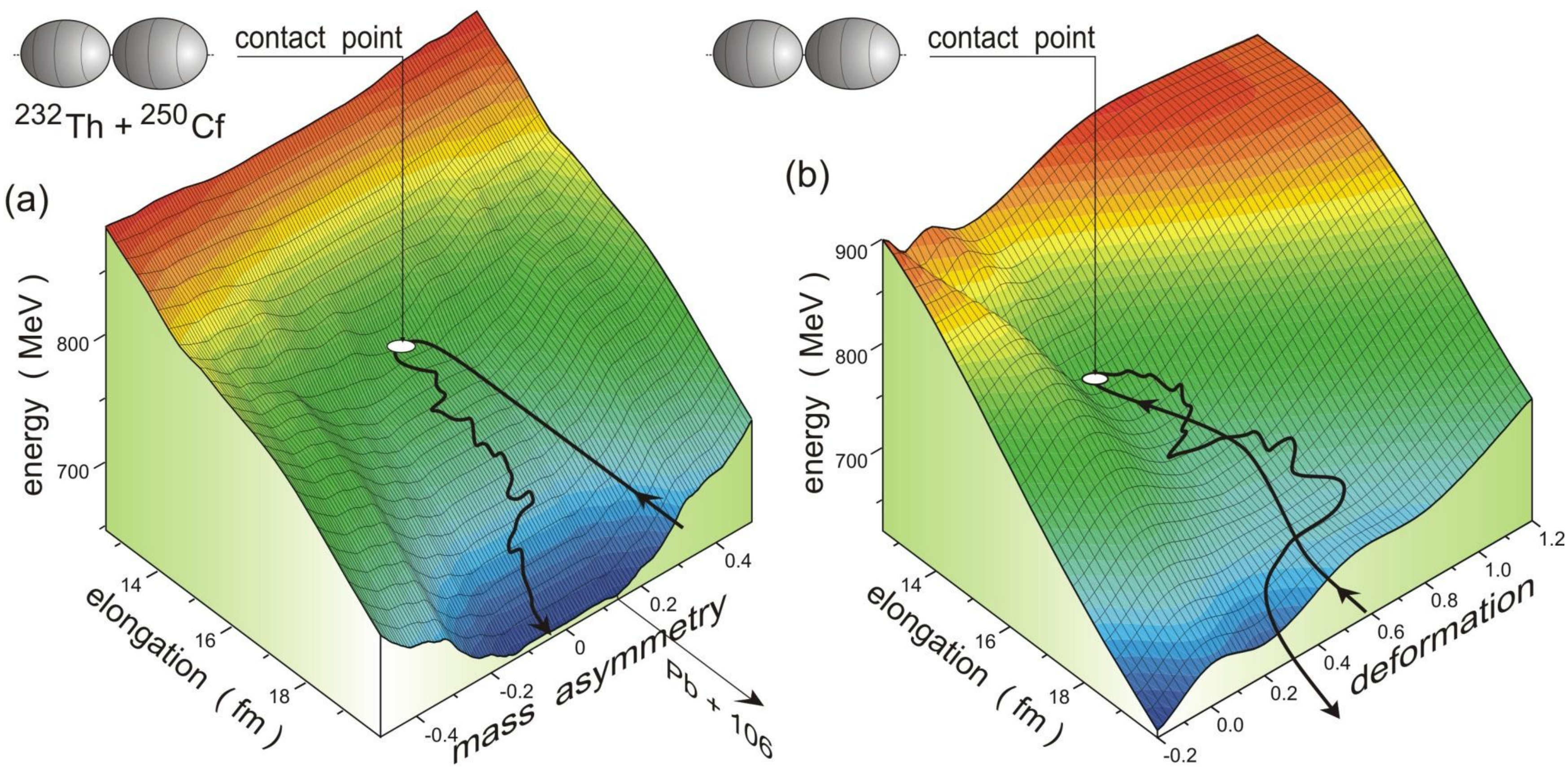
Density distribution in ^{230}Pb

Left: normally deformed Right: superdeformed

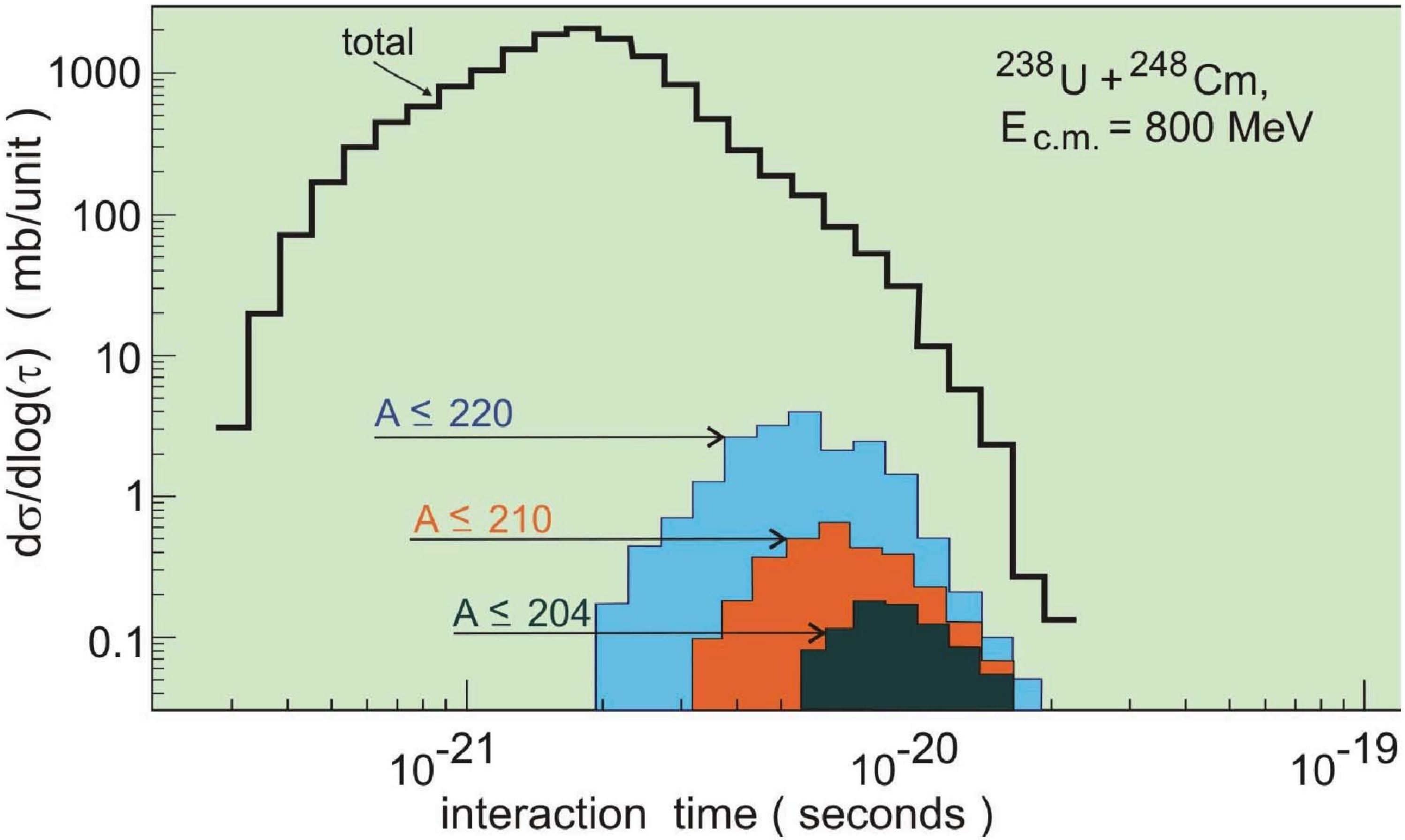


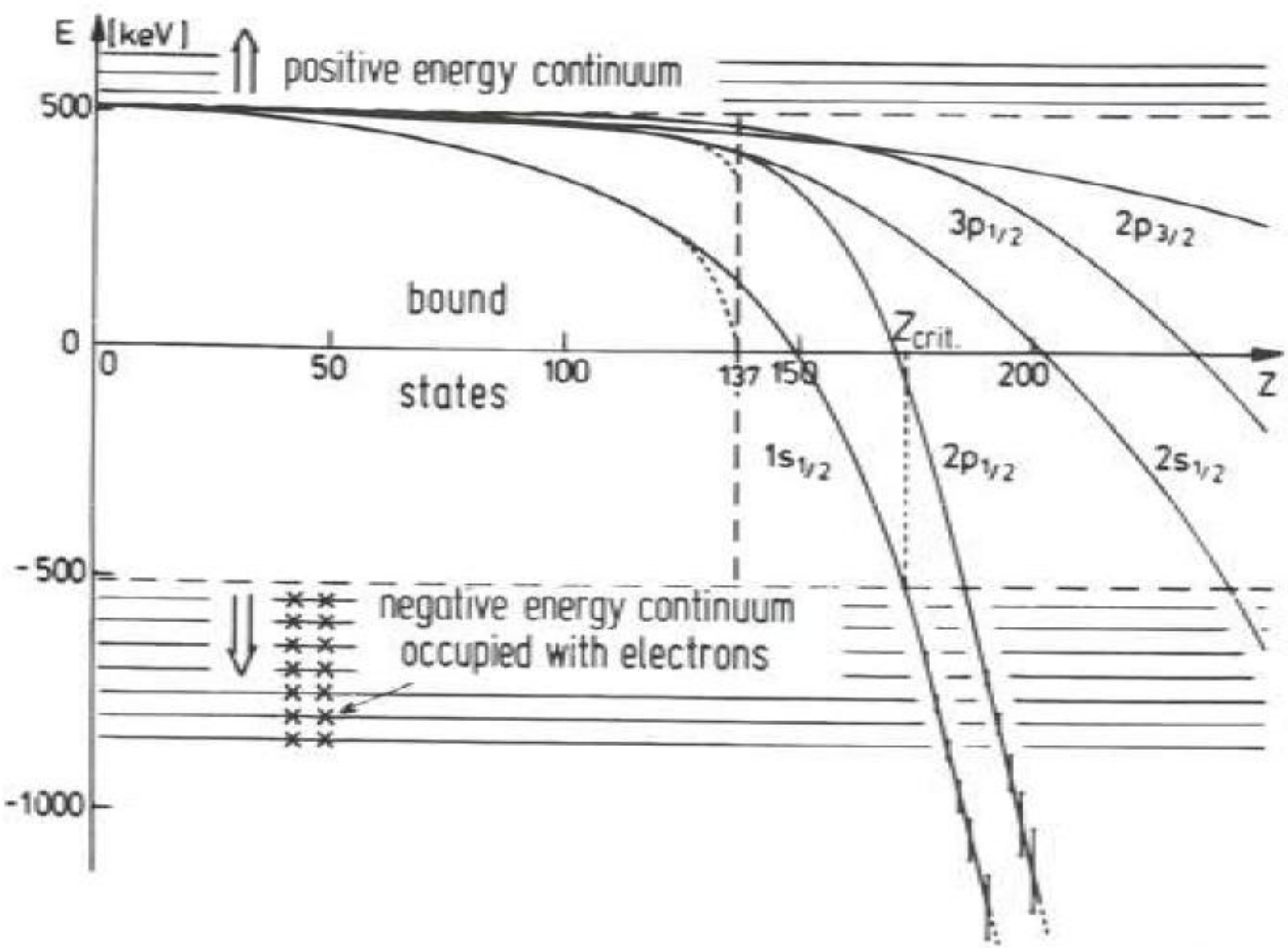
Collision of transactinide nuclei and giant quasi-atoms





Delay time distribution
and a possibility for spontaneous positron formation




E [keV]
positive energy continuum
500
0
-500
-1000
0
50
100
137
150
200
Z
bound
states
$Z_{crit.}$
$3p_{1/2}$
$2p_{3/2}$
$1s_{1/2}$
$2p_{1/2}$
$2s_{1/2}$
negative energy continuum
occupied with electrons

Positron creation in time-delayed heavy ion collisions
The effect of a continuous distribution of times

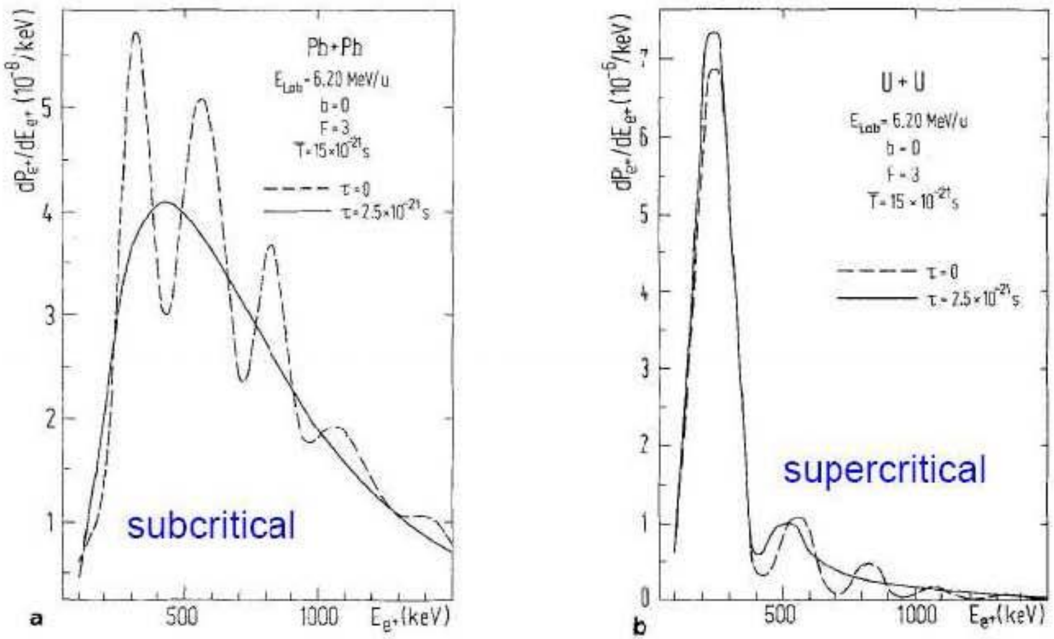
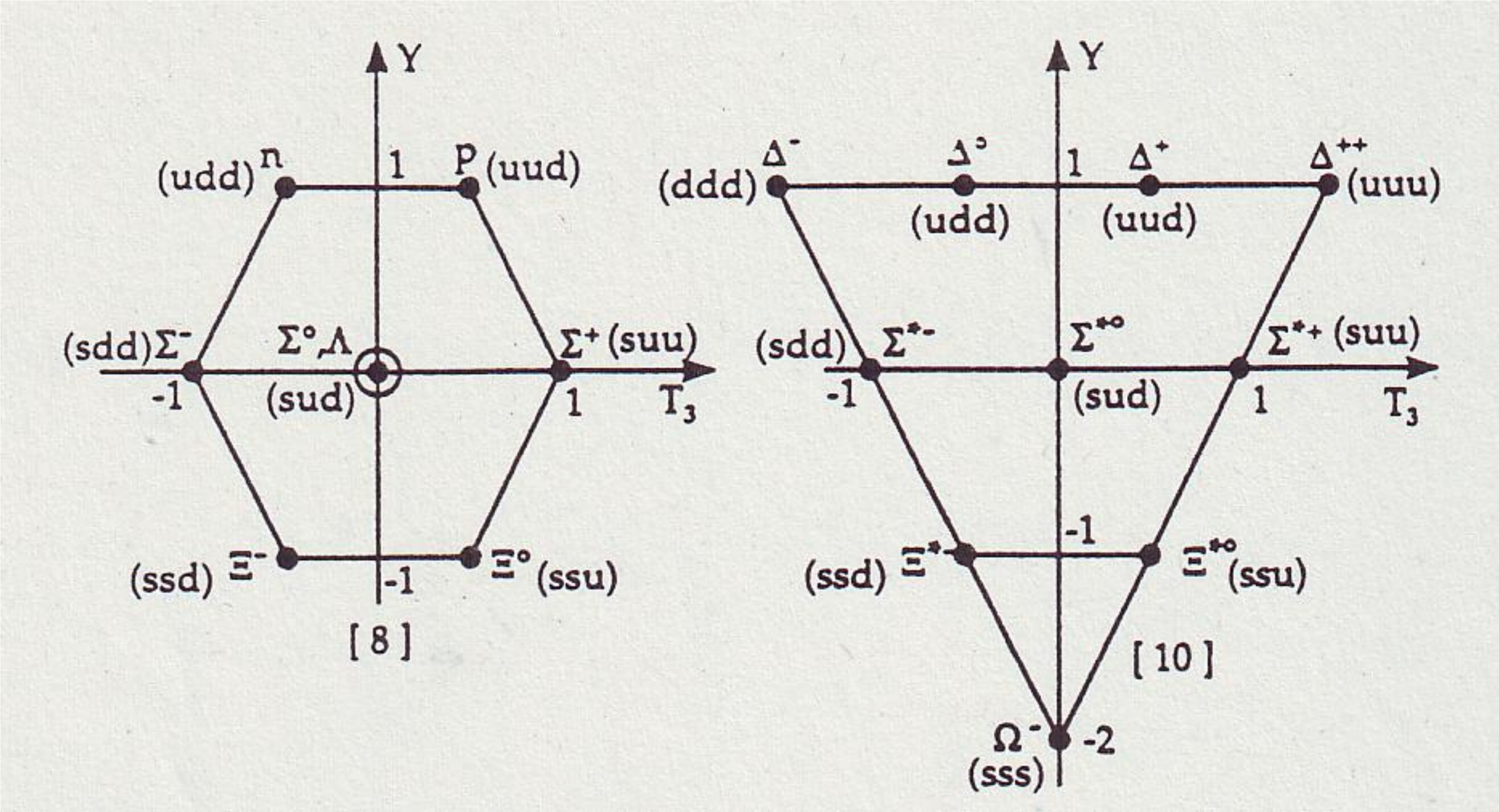


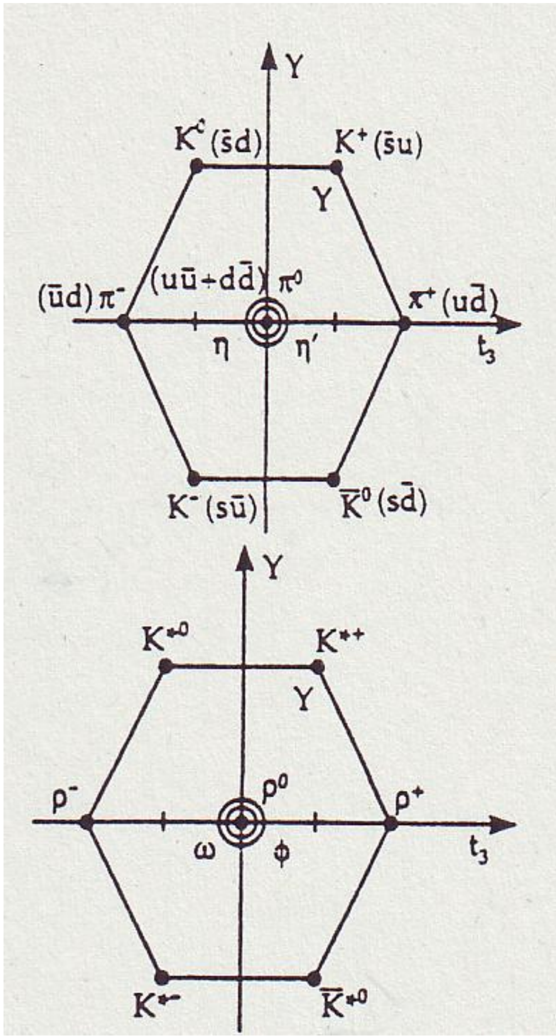
Fig. 7a and b. The effect of a nuclear time delay distribution $f(T)$, here a Gaussian distribution, on positron spectra. A mean time $\bar{T} = 15 \cdot 10^{-21}$ s and deviations $\tau = 0$ and $\tau = 2.5 \cdot 10^{-21}$ s have been assumed. **a** In the subcritical system Pb + Pb the interference pattern is damped out. **b** In the supercritical system U + U the spontaneous positron line is still present and will survive even larger deviations τ

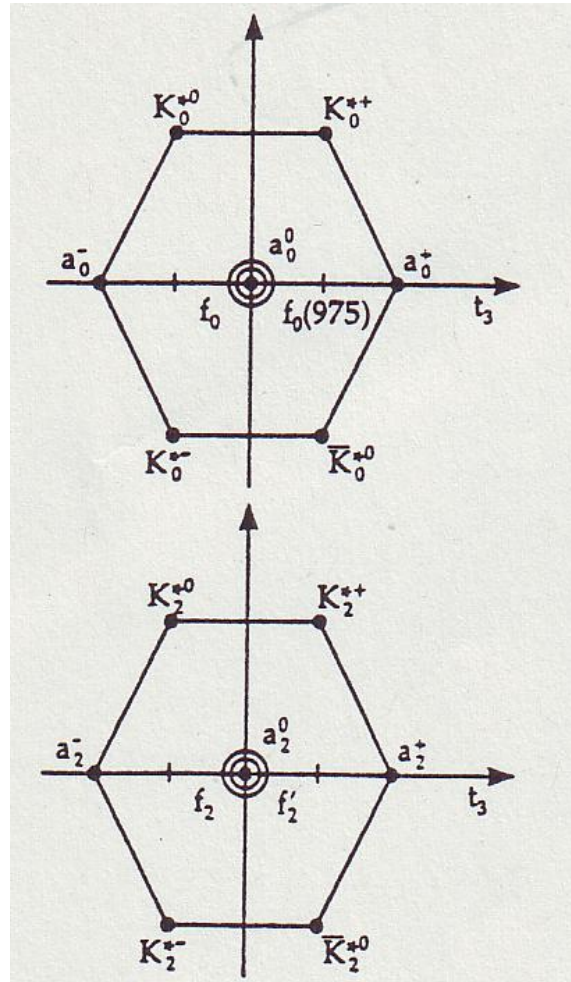
U. Müller, G. Soff, T. deReus, J. Reinhardt, B. Müller, W. Greiner, Z. Physik A313, 263 (1983)

Octet of spin 1/2 nucleons and hyperons (left)
Dekuplet of spin 3/2 baryons (right)

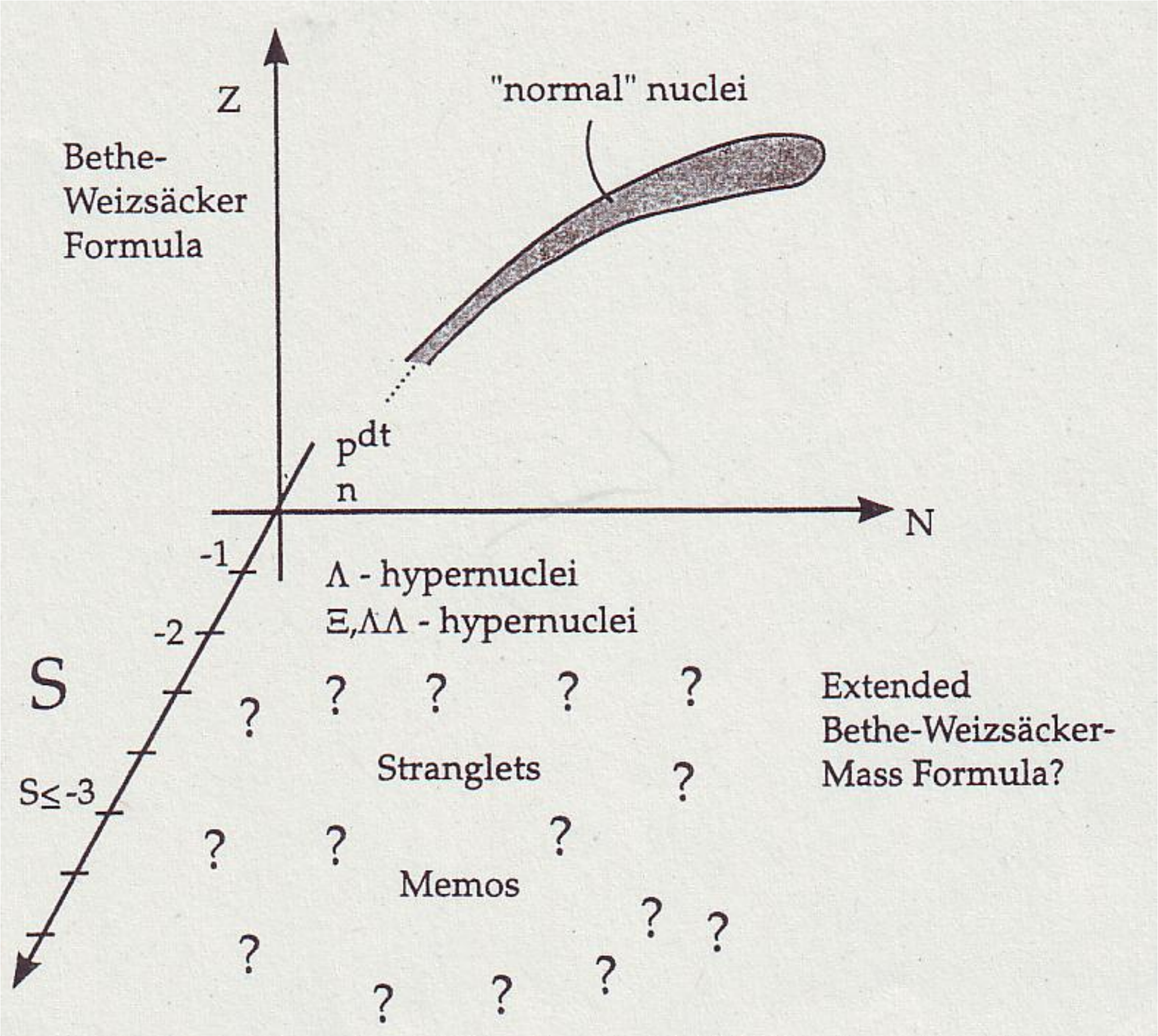


Multiplets of pseudoscalar (0^-), vector (1^+), scalar (0^+) and tensor (2^+) mesons

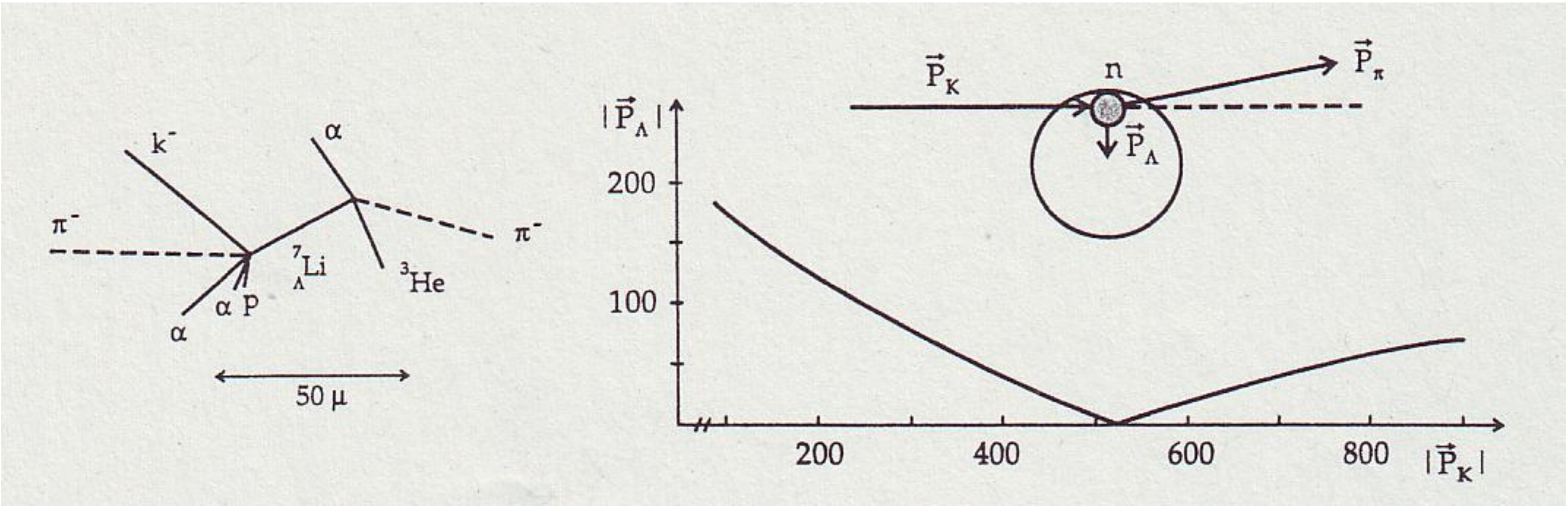




Extension of the Periodic System into the direction of the finite net strangeness

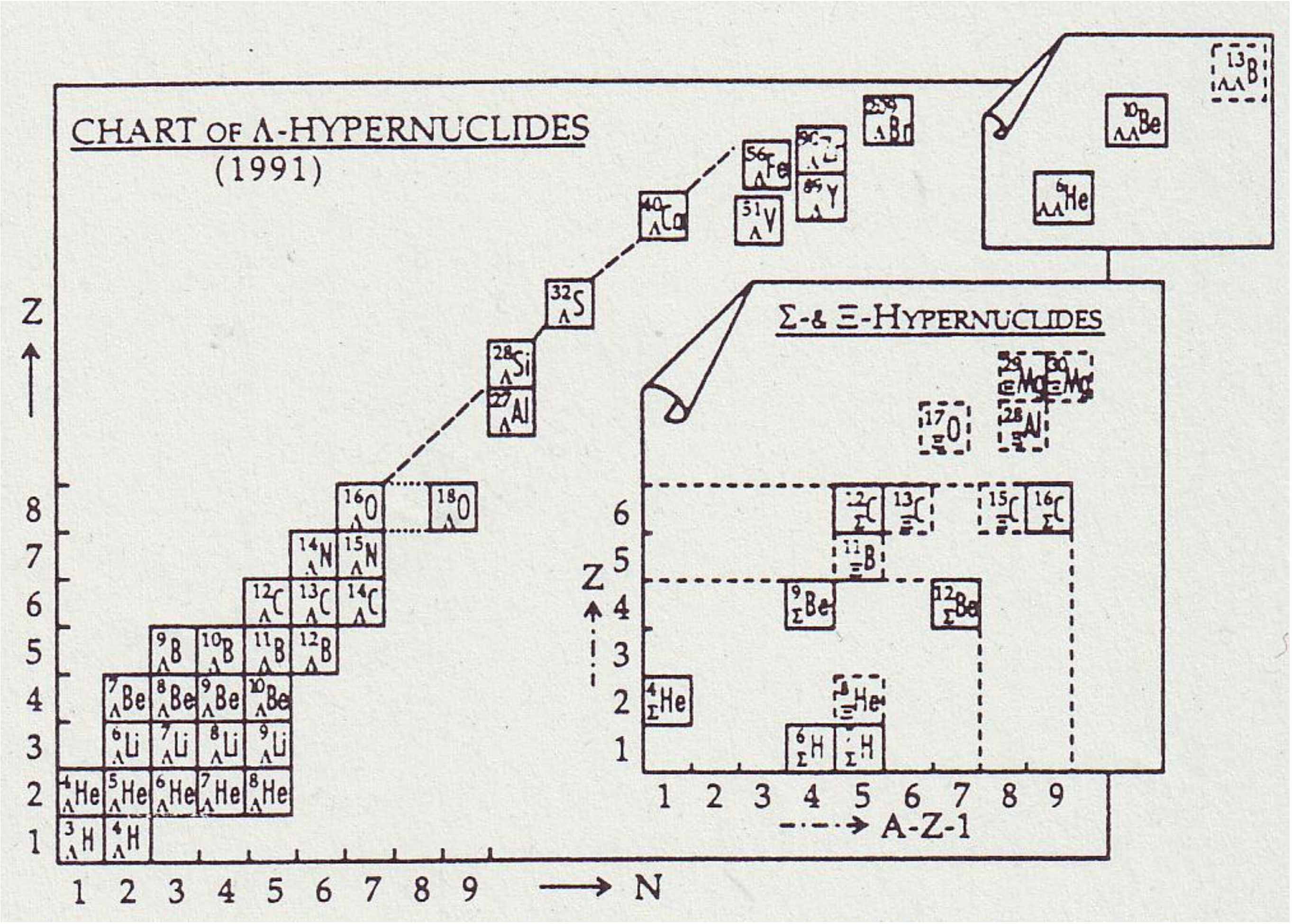


With recoilless Λ-production a Λ or a Σ substitutes a nucleon



Danisz and Pniewski, 1953

Chart of Λ-Hypernuclei. Only very few double Λ-nuclei are known



The Lagrangian according to the Relativistic Mean Field Theory

$$\mathcal{L} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Meson}} + \mathcal{L}_{\text{Coupling}} + \mathcal{L}_{\text{Coulomb}} ,$$

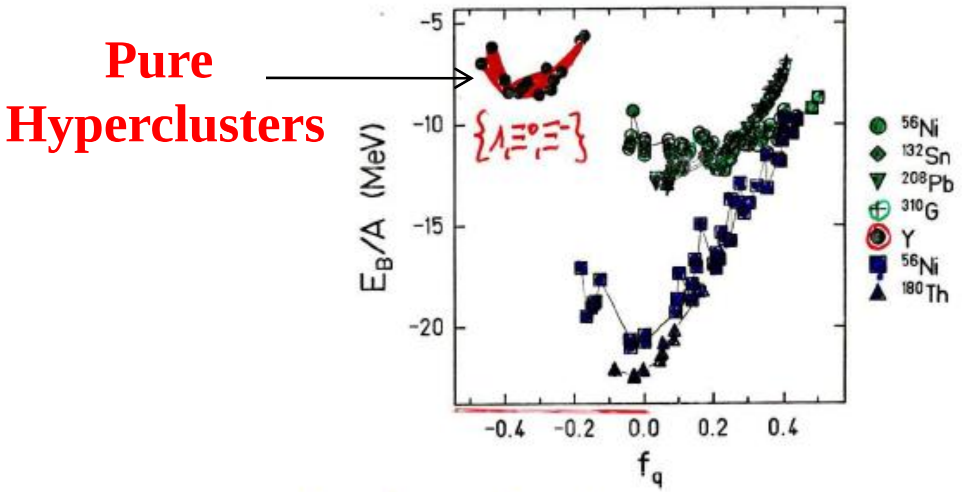
$$\mathcal{L}_{\text{Dirac}} = \overline{\Psi}_B (\mathrm{i}\gamma^\mu \partial_\mu - m_B) \Psi_B ,$$

$$\begin{aligned}\mathcal{L}_{\text{Meson}} = &\tfrac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - U(\sigma) - \tfrac{1}{4} G^{\mu\nu} G_{\mu\nu} + \tfrac{1}{2} m_\omega^2 V^\mu V_\mu \\ &- \tfrac{1}{4}\mathbf{B}^{\mu\nu}\mathbf{B}_{\mu\nu} + \tfrac{1}{2} m_\rho^2 \mathbf{R}^\mu \mathbf{R}_\mu ,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\text{Coupling}} = &-g_{\sigma B}\overline{\Psi}_B \Psi_B \sigma - g_{\omega B}\overline{\Psi}_B \gamma^\mu \Psi_B V_\mu - \tfrac{f_{\omega B}}{m_B}\overline{\Psi}_B \sigma_{\mu\nu} \Psi_B \partial^\mu V^\nu \\ &- g_{\rho B}\overline{\Psi}_B \gamma^\mu \boldsymbol{\tau}_B \Psi_B \mathbf{R}_\mu - \tfrac{f_{\rho B}}{2m_B}\overline{\Psi}_B \sigma_{\mu\nu} \boldsymbol{\tau}_B \Psi_B \partial^\mu \mathbf{R}^\nu ,\end{aligned}$$

$$\mathcal{L}_{\text{Coulomb}} = -\tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} - \tfrac{1}{2} e A^\mu \overline{\Psi}_B \gamma_\mu (1 + \tau_{0,B}) \Psi_B ,$$

Charge of $\{n, p, \Lambda, \Xi^0, \Xi^-\}$ systems



$f_q = \frac{Z}{A}$, $f_s = \frac{|S|}{A}$

- negatively charged composites possible
- purely hyperonic nuclei exist for $f_s \approx 1.8$ and $f_q \approx -0.3 \pm 0.1$

$$f_q^{\min} \approx \begin{cases} +0.1 & : \sigma + \omega \\ -0.05 & : \sigma + \omega + \sigma^* + \phi \\ 0.0 & : \text{strangelets} \end{cases}$$

striking similarities to strangelets

Jürgen Schaffner *Carsten Greiner*

Bethe - Weizsäcker Formula:

$$E_B(\{p,n\}) = -a_V \cdot A + a_S \cdot A^{2/3} + a_C \cdot \frac{Z^2}{A^{1/3}} + a_A \cdot \frac{(N-Z)^2}{A}$$

$a_V = 16\ \mathrm{MeV}$	Volume Term
$a_S = 18\ \mathrm{MeV}$	Surface Term
$a_C = 0.72\ \mathrm{MeV}$	Coulomb Term
$a_A = 23\ \mathrm{MeV}$	Asymmetrie Term

Extended Formula:

$$E_B(\{p,n,\Lambda,\Xi^0,\Xi^-\}) \approx E_B^{min} + c_S \cdot \left(\frac{|S|}{A} - \left(\frac{|S|}{A}\right)_{min}\right)^2 \cdot A$$

$c_S \approx 13\ \mathrm{MeV}$ Strangeness term

J. Schaffner, Carsten Greiner, H. Stöcker, A. Gal, C. Dover

Three-dimensional nuclear map

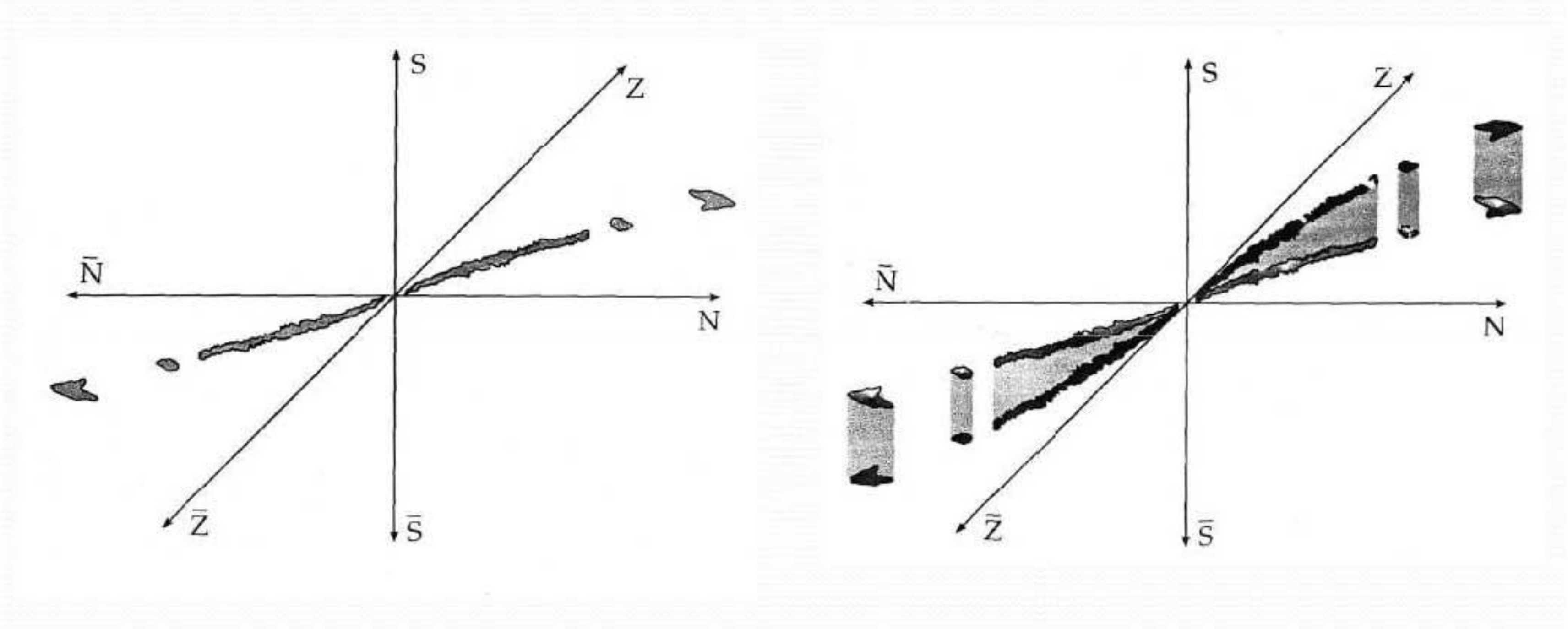
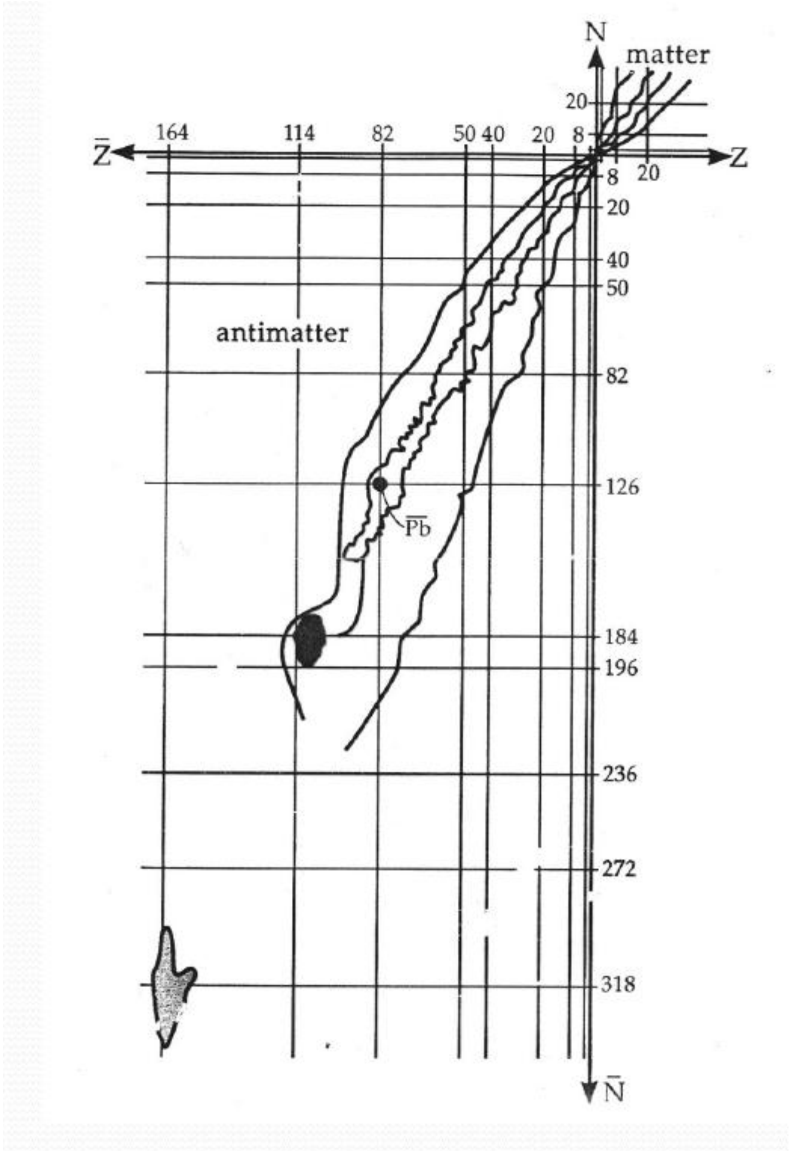
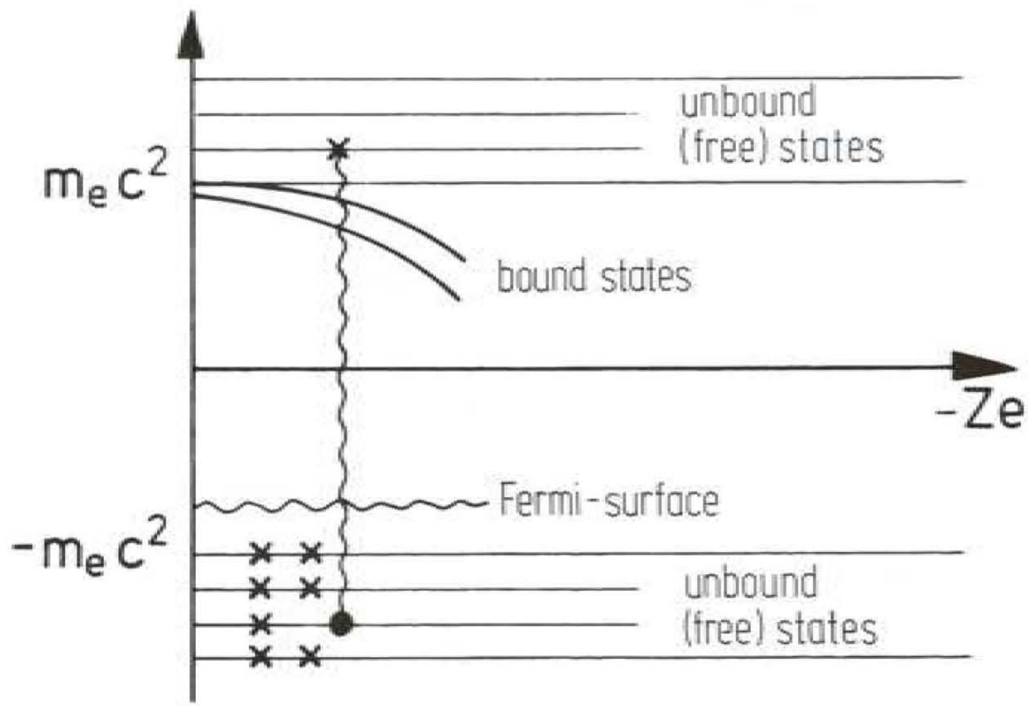


Chart of Anti-Nuclei





$$E = \pm\sqrt{c^2 p^2 + \left(m_e c^2\right)^2}$$

QHD Lagrangian and Structure of SHE

The interactions between baryons are mediated by mesons

name	Jπ	T	Mass (MeV)
σ	0^+	0	(520)
ω	1^-	0	780
ρ	1^-	1	763
(π)	0^-	1	138

σ: Medium range attraction. Simulates correlated 2π exchange (J=0, T=0).

ω: Short range repulsion.

ρ: Proton neutron asymmetry.

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{Baryon}} + \mathcal{L}_{\text{Meson}} + \mathcal{L}_{\text{BM}} + \mathcal{L}_{\text{nonlin}} + \mathcal{L}_{\text{em}},$$

where

$$\mathcal{L}_{\text{Baryon}} = \bar{\psi}\,(i\gamma^{\mu}\partial_{\mu} - M)\psi$$

$$\mathcal{L}_{\text{Meson}} = \frac{1}{2}\,\partial^{\mu}\sigma\,\partial_{\mu}\sigma - \frac{1}{2}\,m_{\sigma}^{2}\,\sigma^{2} - \frac{1}{4}\,\Omega^{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}\,m_{\omega}^{2}\,\omega^{\mu}\omega_{\mu} - \frac{1}{4}\,B^{\mu\nu}B^{\mu\nu} + \frac{1}{2}\,m_{\rho}^{2}\,R^{\mu}R_{\mu}$$

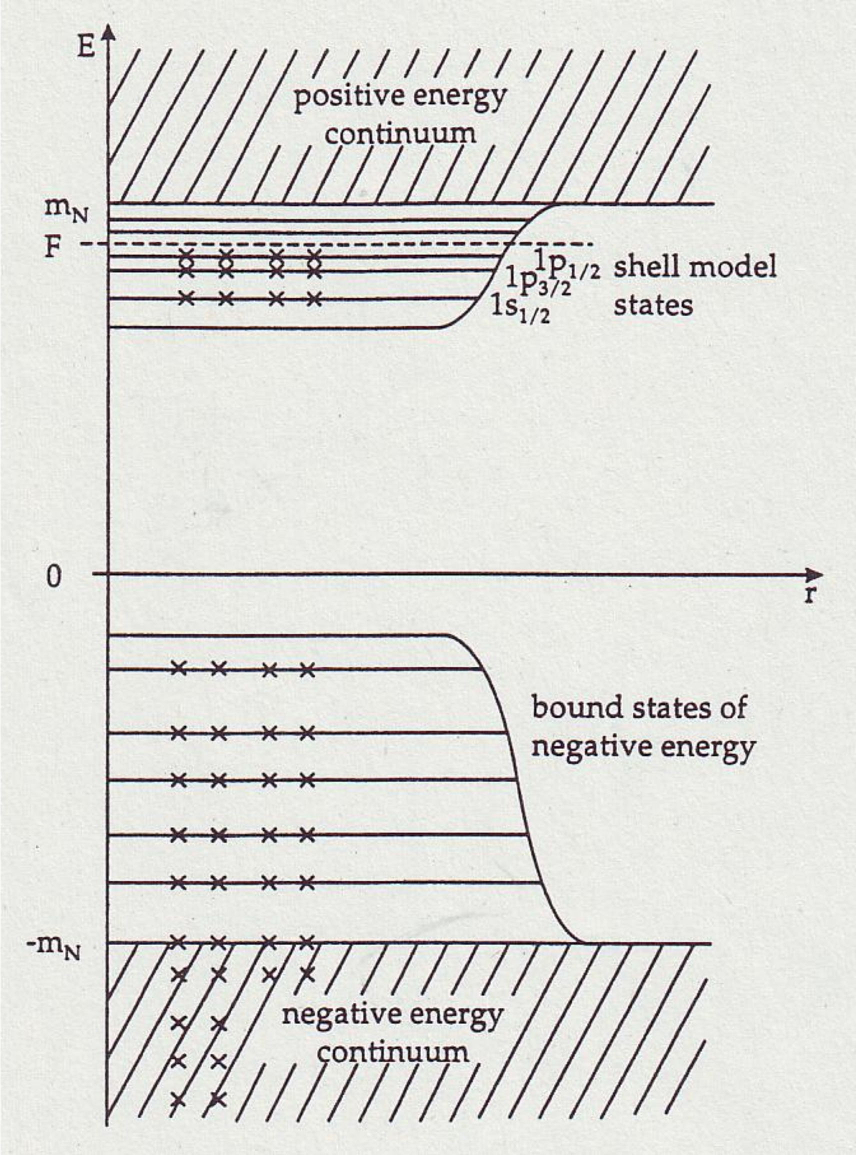
$$\mathcal{L}_{\text{BM}} = -\,g_{\sigma}\bar{\psi}\,\psi\sigma - g_{\omega}\bar{\psi}\,\gamma^{\mu}\,\psi\omega_{\mu} - g_{\rho}\bar{\psi}\,\gamma^{\mu}\,\tau\psi R_{\mu}$$

$$\mathcal{L}_{\text{nonlin}} = -\frac{1}{3}c_{2}\sigma^{3} - \frac{1}{4}\,c_{3}\,\sigma^{4} + \frac{1}{4}\,c_{4}\,(\omega^{\mu}\,\omega_{\mu})^{2}$$

$$\mathcal{L}_{\text{em}} = -\frac{1}{4}\,F^{\mu\nu}F_{\mu\nu} - e\bar{\psi}\,\gamma^{\mu}\,\frac{1-\tau_{3}}{2}\,\psi A_{\mu}$$

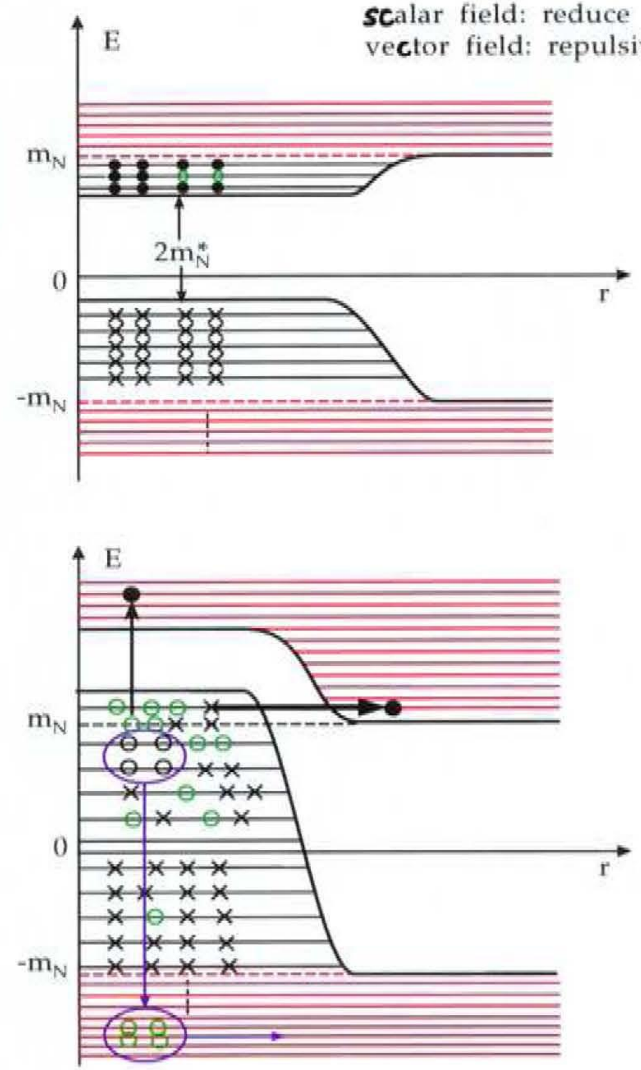
free parameters: g_{π}, g_{ω}, g_{ρ}, c_2, c_3, c_4

Positive and negative energy states of nucleons



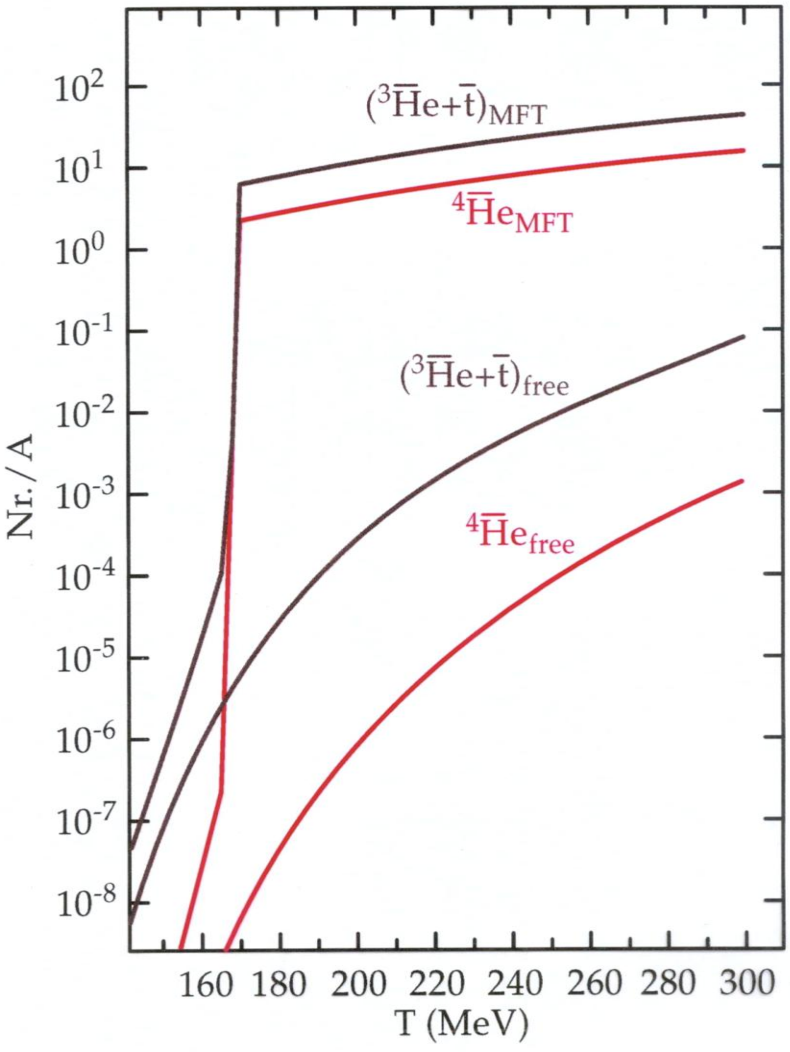
Mishustin , Satarov ,
Greiner 1990- 1992

scalar field: reduce nucleon mass (attr.)
vector field: repulsive potential ($\pm \bar{p}$)



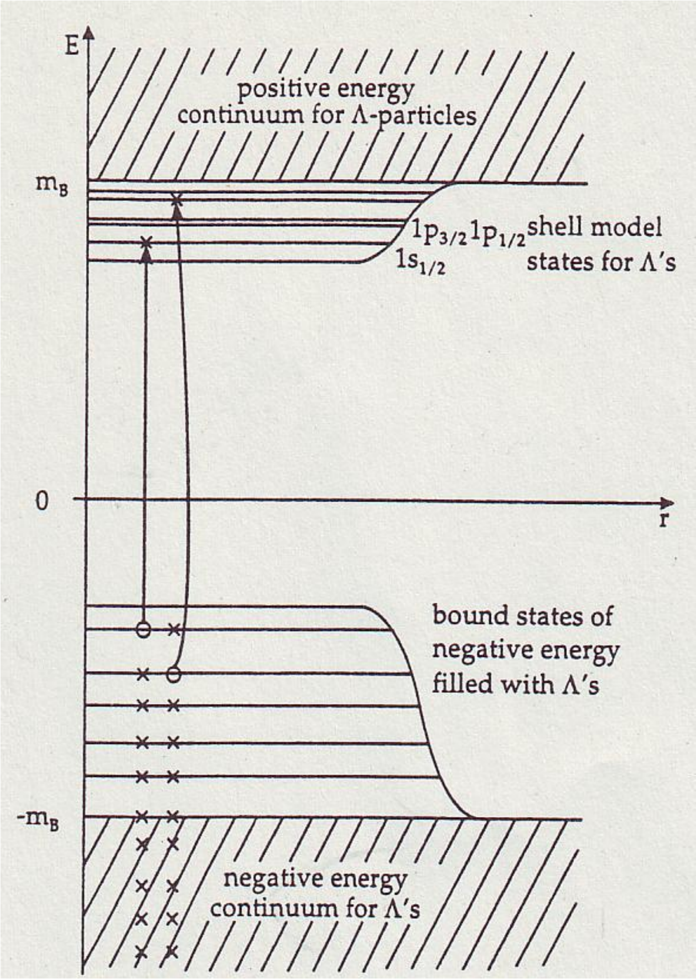
Antimatter - Cluster - Production out of the correlated vacuum!!

Composites in the strong MFT



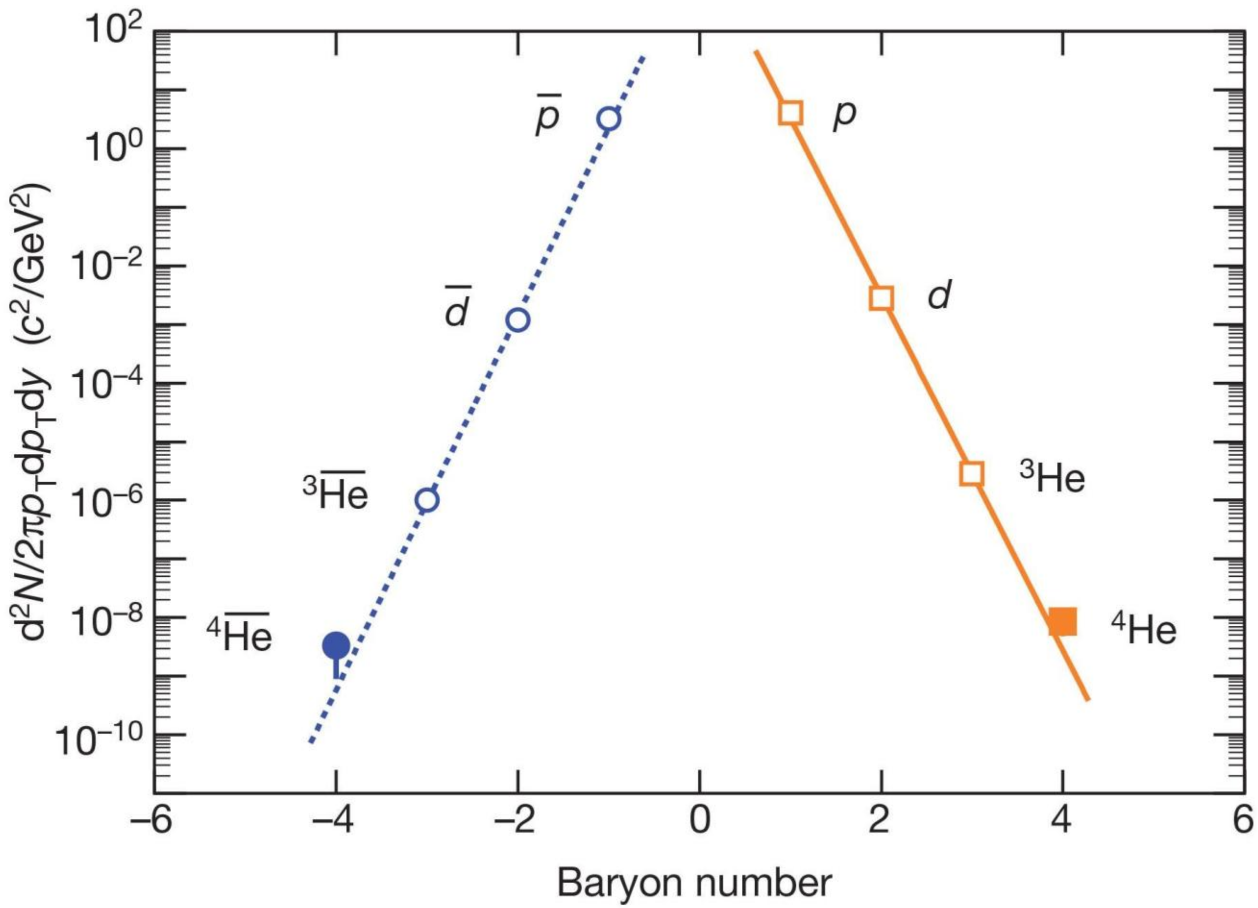
Temperature Model

Collective production mechanism of multi-Λ-Hypernuclei and multi-$\bar{\Lambda}$-Hypernuclei



Nuclei and Antinuclei Yields in the Experiment of STAR Collaboration

(J. W. Harris, T. Kollegger, R. Stock, et al.)



The lines are fits with the exponential e^{-rB}, where r is the reduction factor and B is the Baryon number