European Summer school

Super Heavy Elements, Physics and Chemistry at extremely low rate

UNIVERSITÉ DE STRASBOURG

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(on behalf of Benoît GALL)

Foreword

This lecture aims at understanding

-> the context of SHE studies

-> the state of art in SHE studies
(in physics and chemistry...)

Unfortunately 1.5 hour is rather short and I have to skip some of the results ... sorry !

Super Heavy Elements (SHE)

outline

- Nuclear stability and limits of existence
- Manifestation of quantum world
- Production probability
- How to produce SHE
- How to identify SHE
- What physical properties can we measure ?
- What chemical properties can we measure ?

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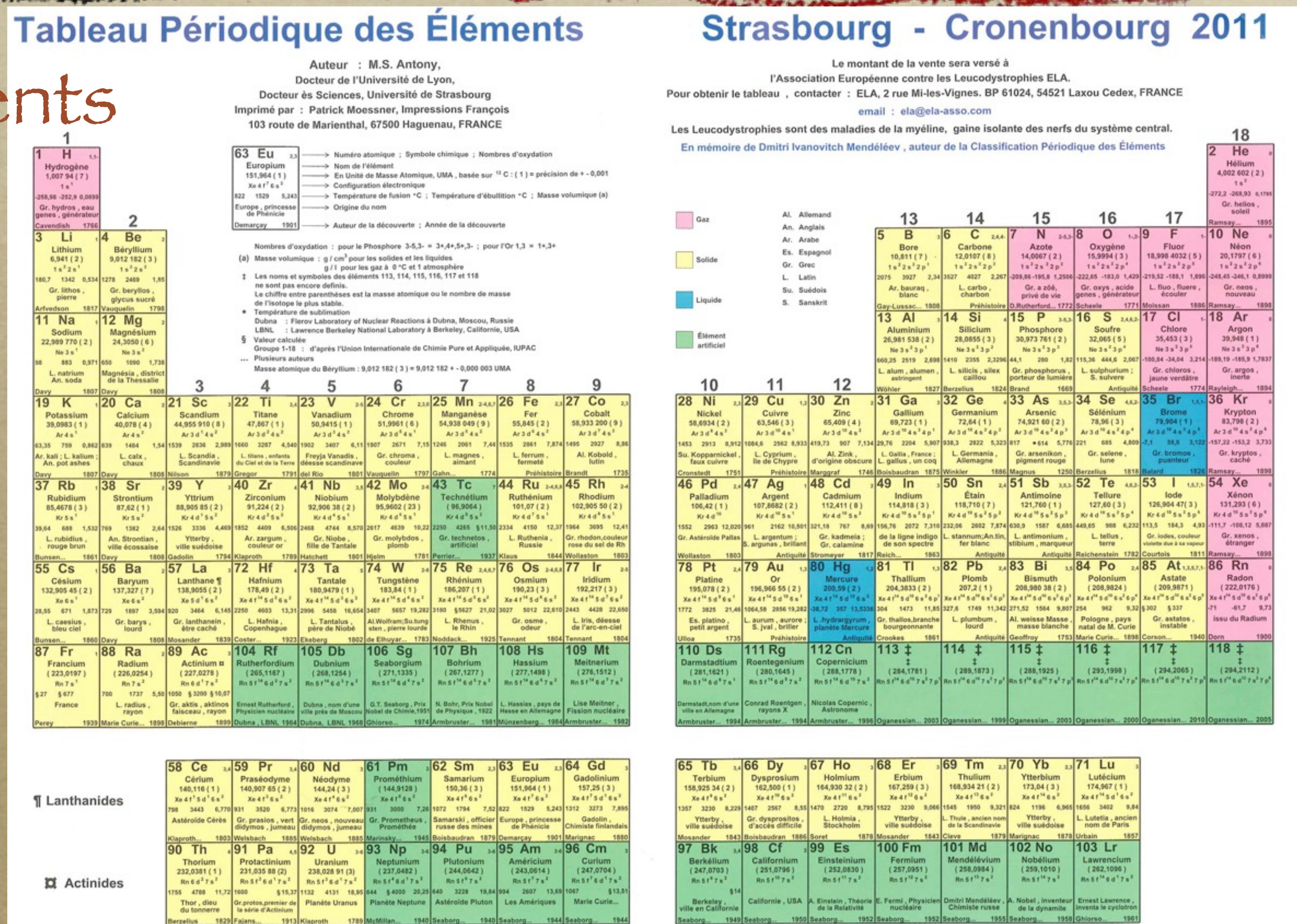
What do we know about nuclear stability ?

118 elements

some
are
not
stable



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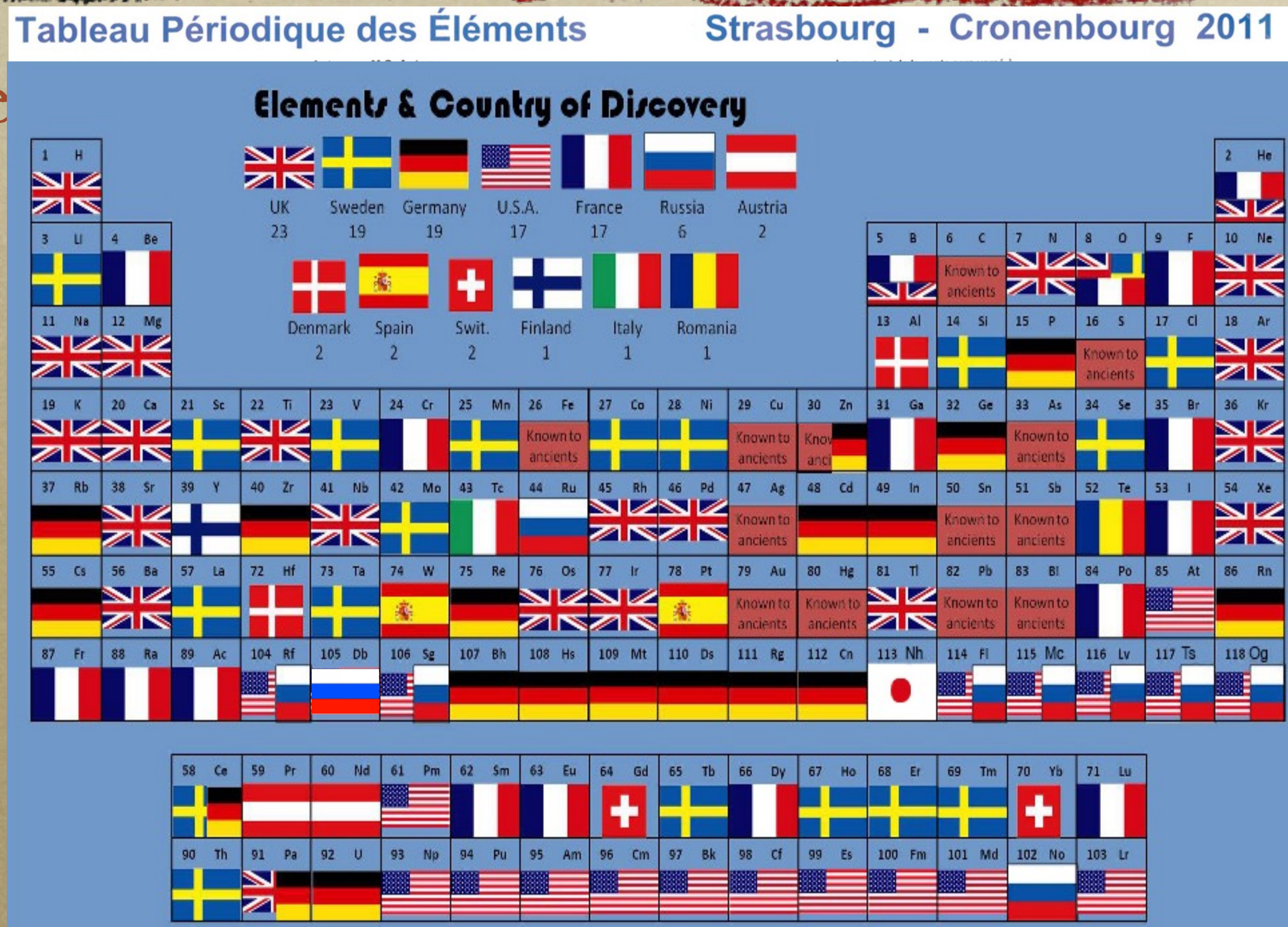


What do we know about nuclear stability ?

Chemical properties fixed by the number of electrons (Z)

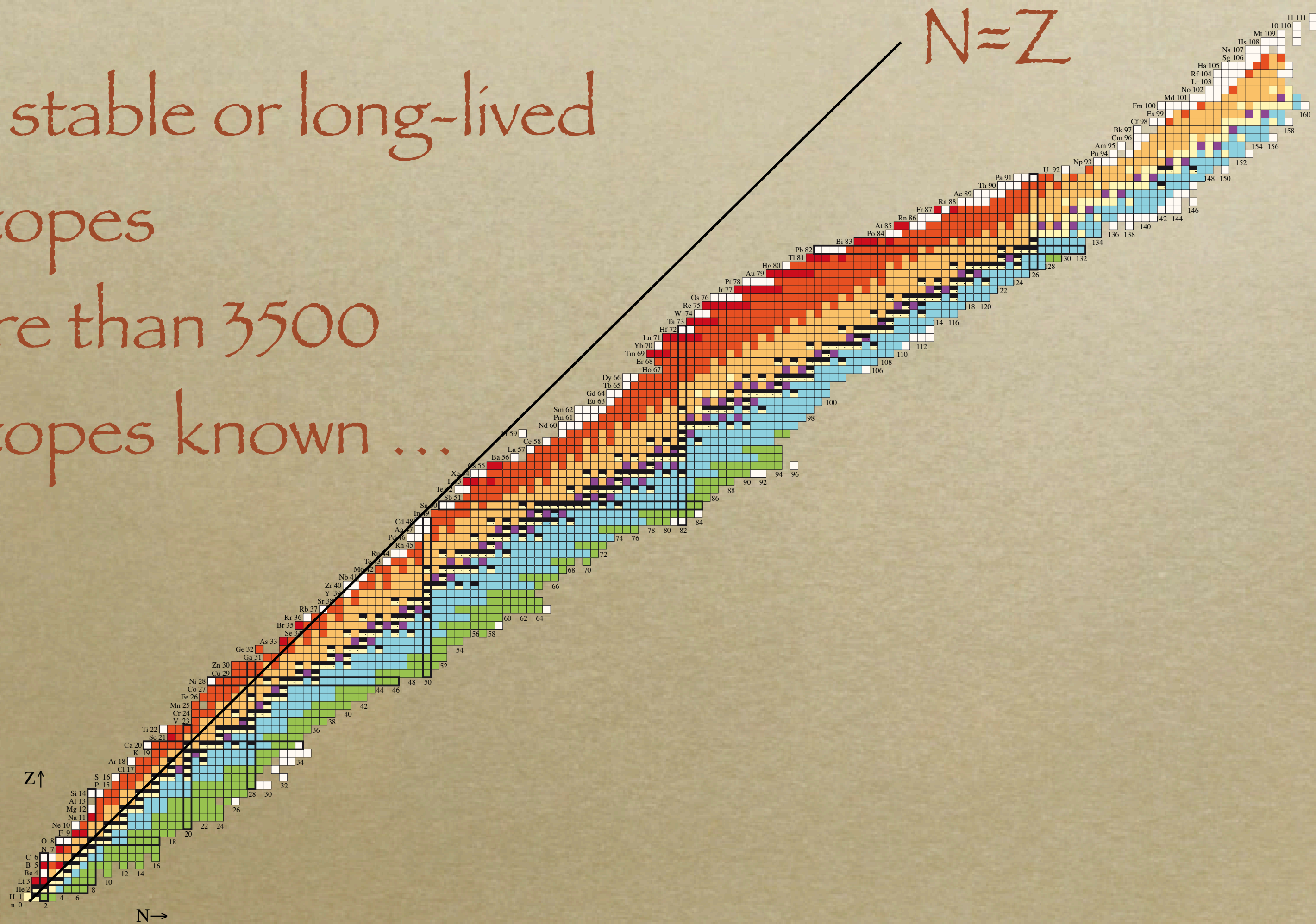
... but ... Several elements for each Z

Z=22	**Ti** Titanium 47.867 σ 6.09	...	**Ti 44** -37548.3 (8) 59.2 a 0+ ε γ 78* 68* 146 w σ 1.1	**Ti 45** -39006.9 (12) 184.8 m 7/2– β^+ 1.044 (0.32) w...,ε γ 720 1408 w 1661 w 425 w 1236 w...	**Ti 46** -44125.3 (11) 0+ 8.25% σ 0.59	**Ti 47** -44931.7 (10) 5/2– 7.44% σ 1.7	**Ti 48** -48487.0 (10) 0+ 73.72% σ 7.84	**Ti 49** -48558.0 (10) 7/2– 5.41% σ 2.2	**Ti 50** -51425.8 (10) 0+ 5.18% σ 0.179	**Ti 51** -49726.9 (13) 5.76 m 3/2– β^- (2.15) (1.54) γ 320 929 609	**Ti 52** -49464 (7) 1.7 m 0+ β^- 1.834 γ 124 17	...
		N=	22		24		26		28		30	

isotopes

What do we know about nuclear stability ?

- 285 stable or long-lived isotopes
- More than 3500 isotopes known ...



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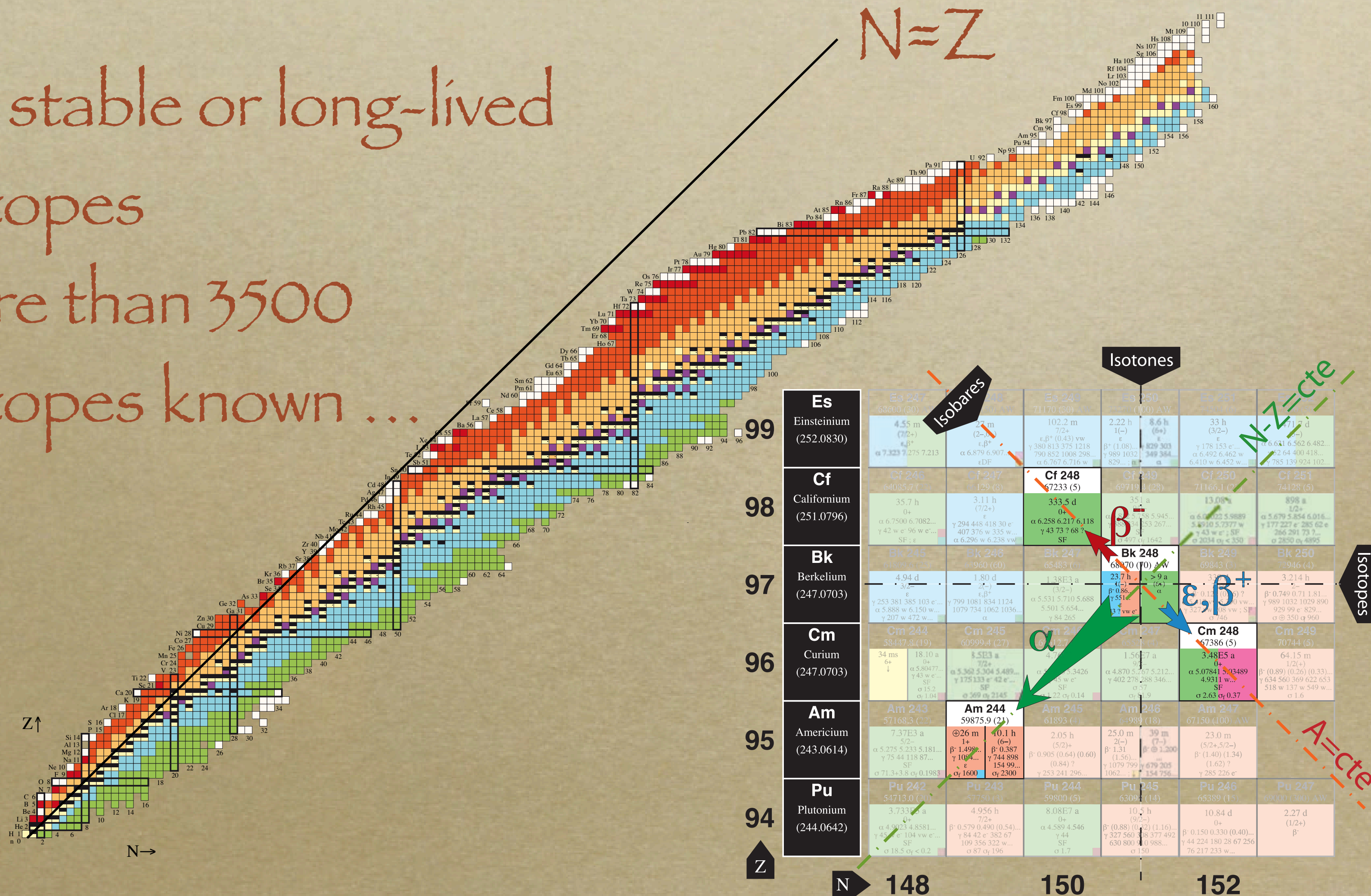
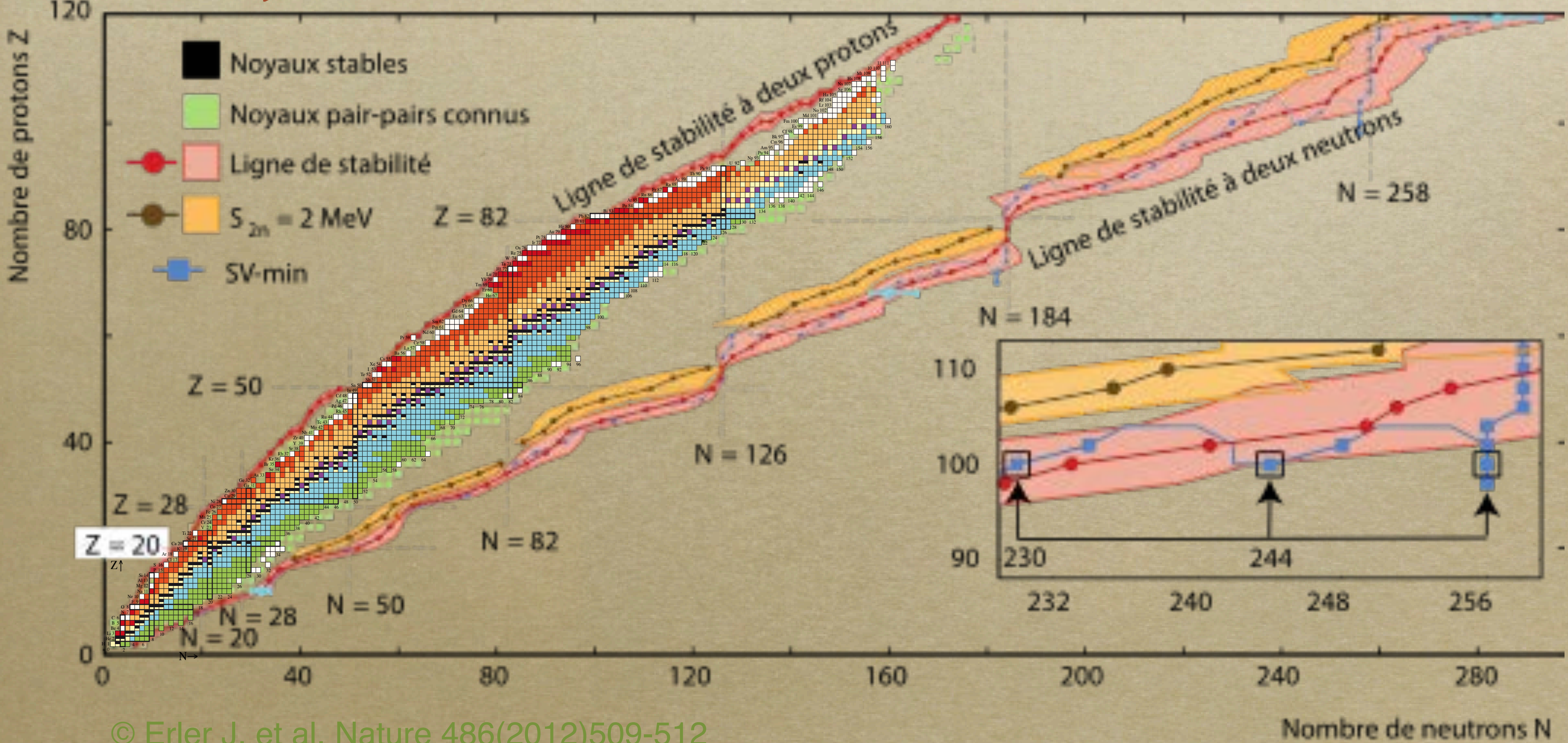


Limits of existence of nuclei ?

Drip lines



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Nuclear binding energy …

Aston curve

Binding energy per nucleon

B/A

as a function of

A

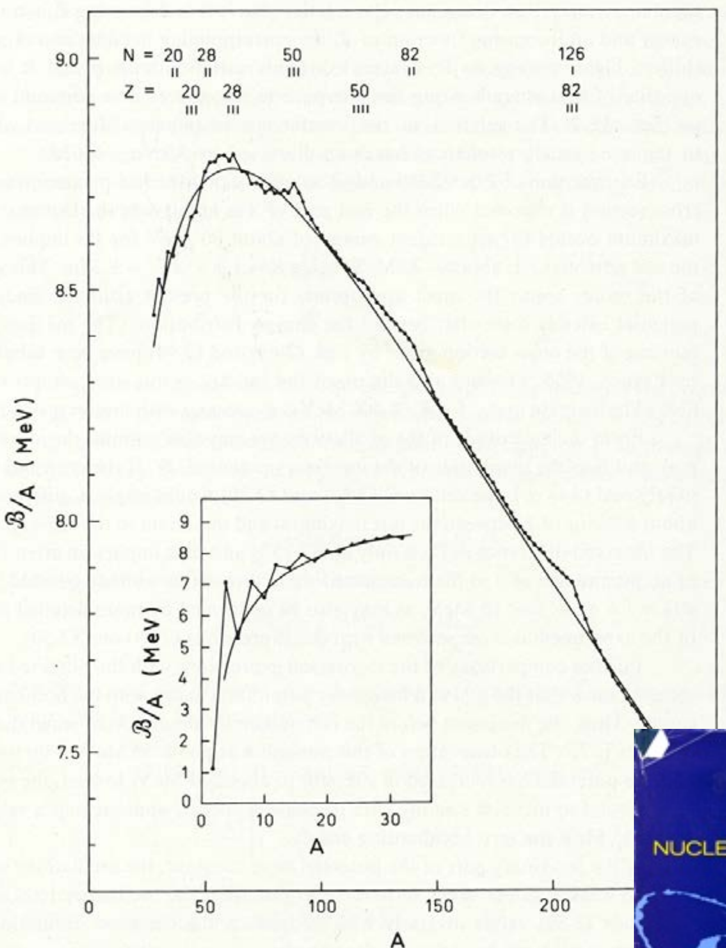
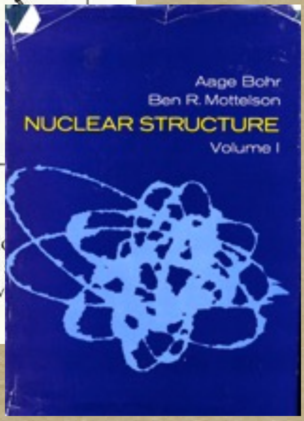
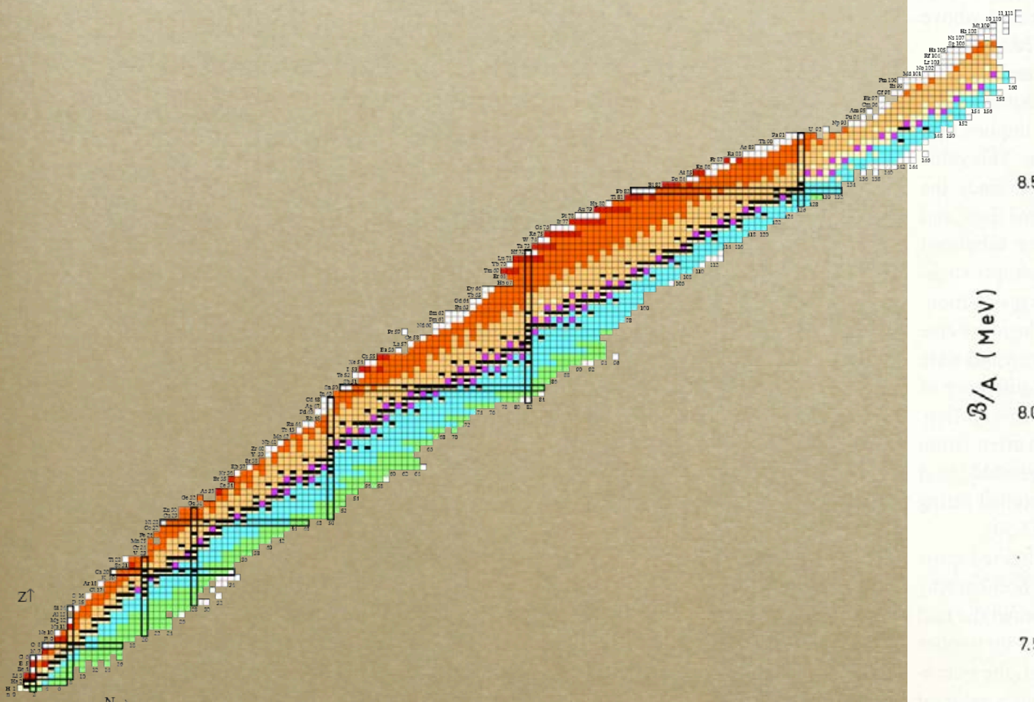
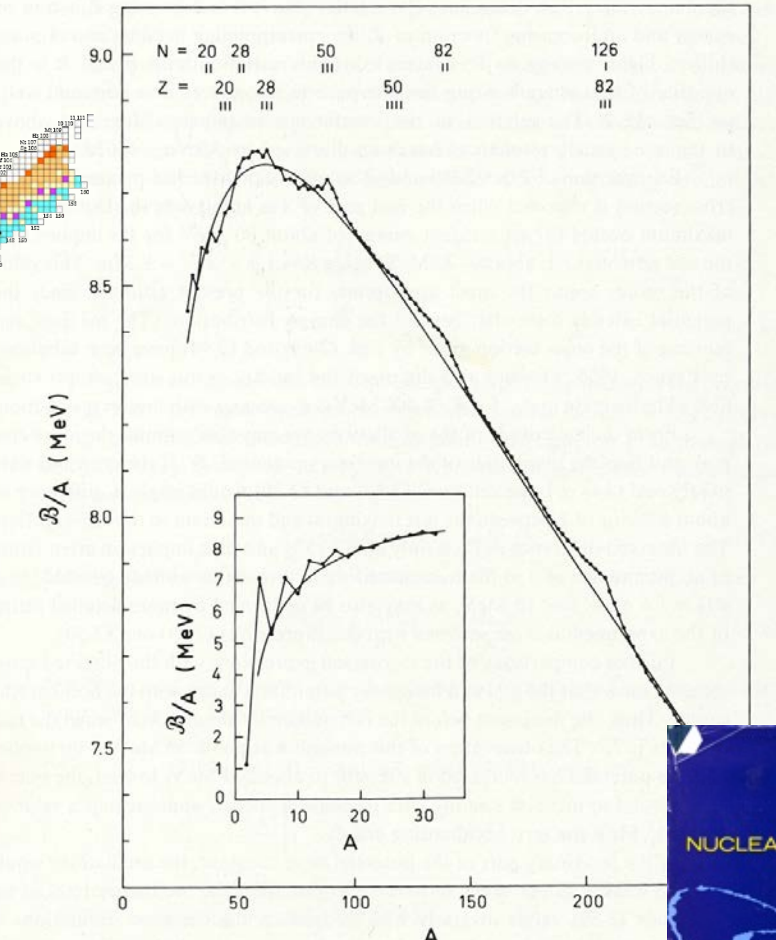


Figure 2-4 The experimental binding energies are taken from the compilatic Mattauch, W. Thiele, and A. H. Wapstra, *Nuclear Phys.* **67**, 1 (1965). The represents the semi-empirical mass formula, Eq. (2-12), with the constants giv Green and N. A. Engler, *Phys. Rev.* **91**, 40 (1953).



Nuclear binding energy … and radioactivity





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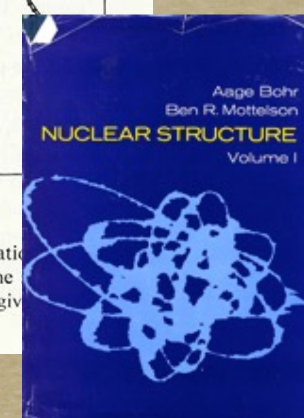

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Liquid drop model

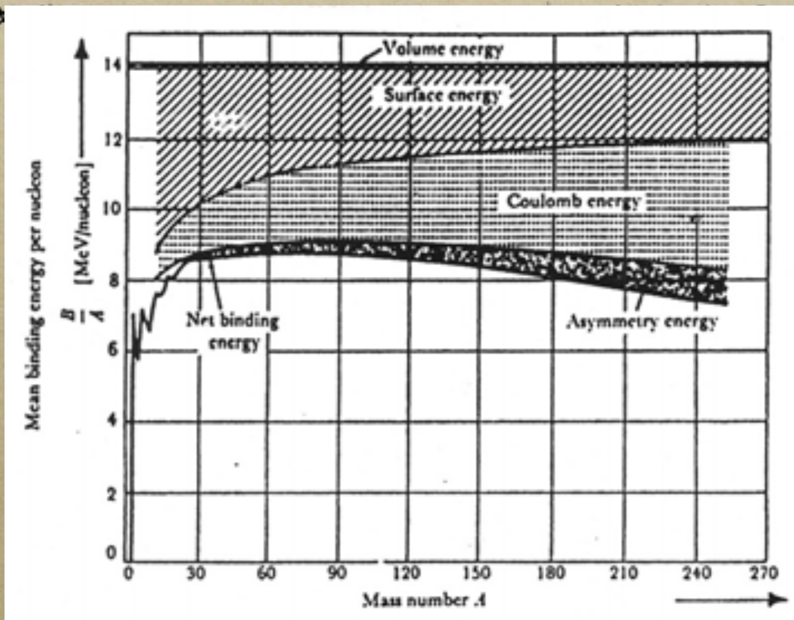


Fig. 2-9 Contribution des différents termes à la formule de masse.

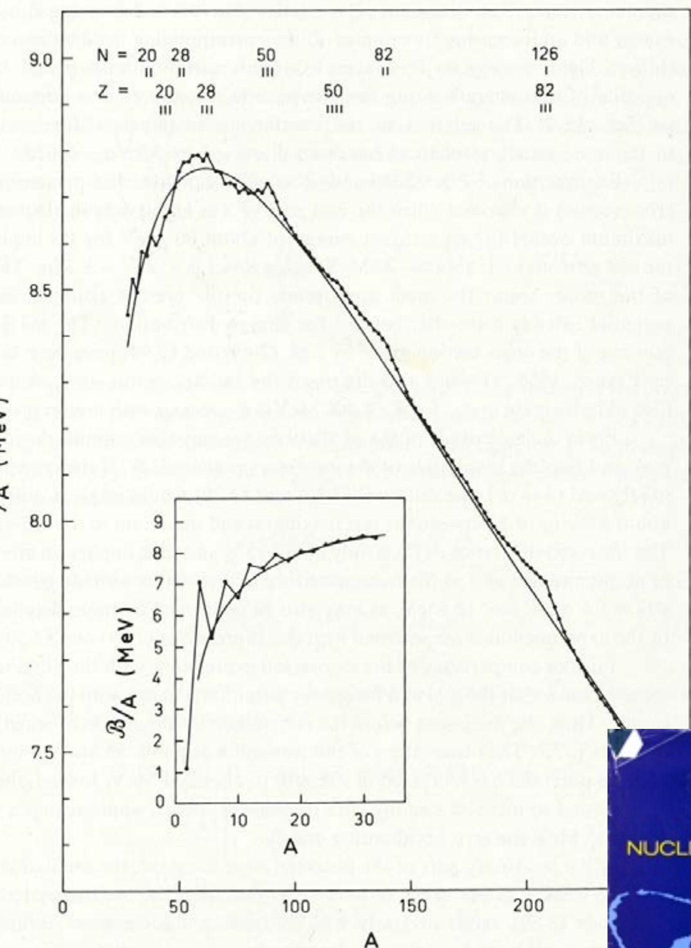
$$m(Z,A) = Zm(^1H) + Nm_n - a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_{sym} \frac{(A-2Z)^2}{A} - B_{paire}$$

$a_V = 15.5$ MeV $\quad a_S = 16.8$ MeV

$a_C = 0.72$ MeV $\quad a_{sym} = 23.0$ MeV

$a_p = 34.0$ MeV

LD $r_0 = 1{,}251$ fm



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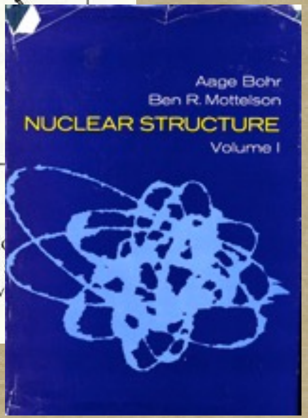
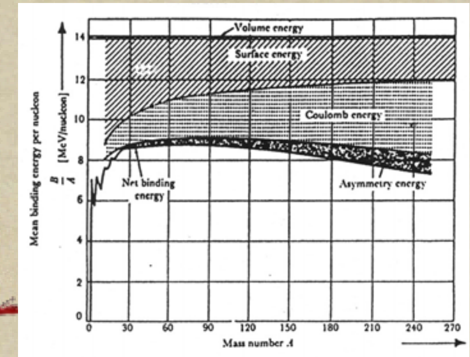


Beyond liquid drop …



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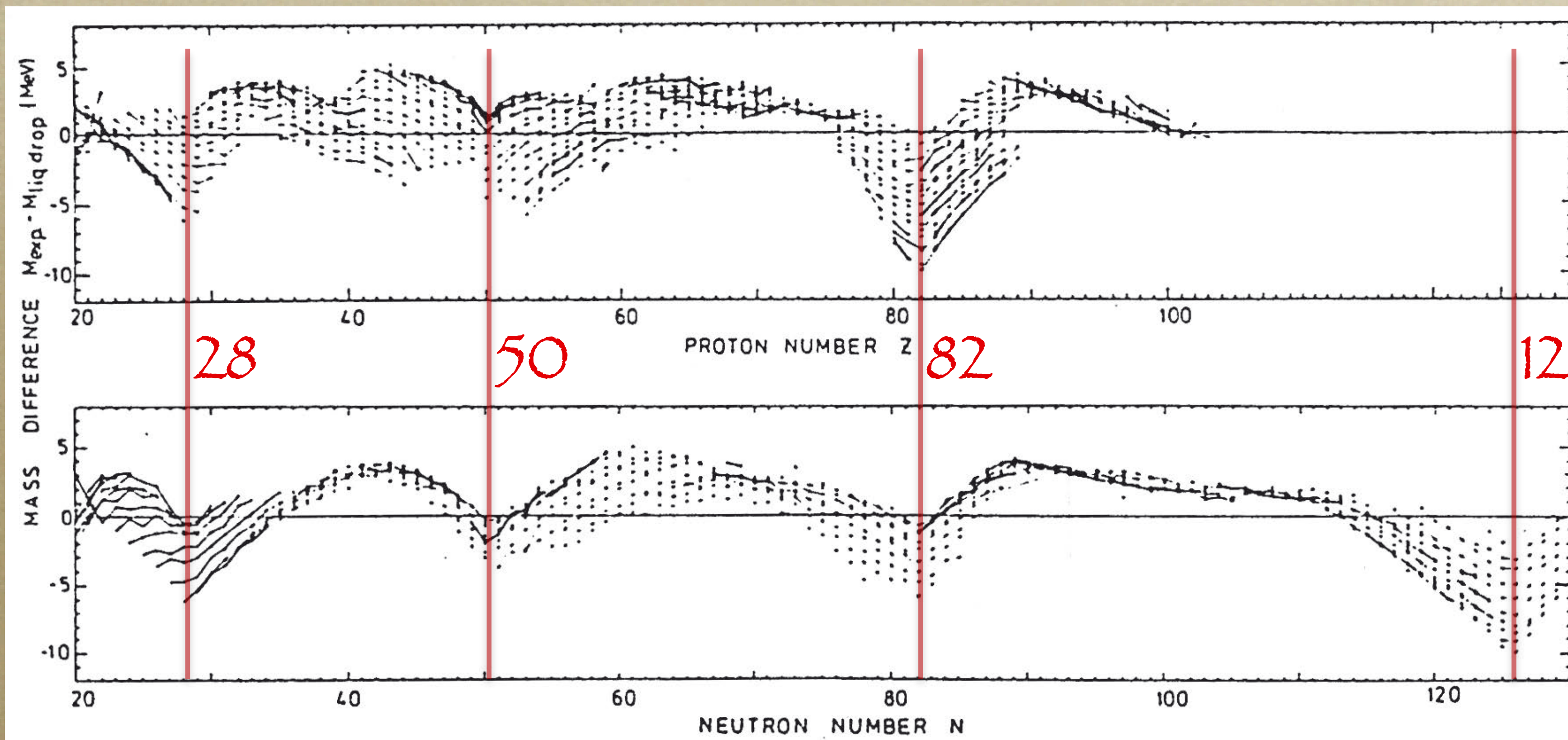
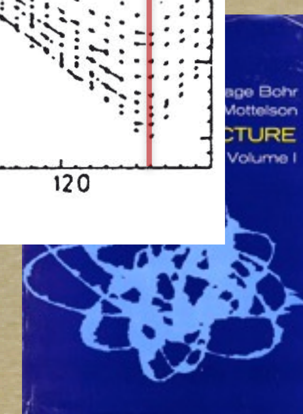
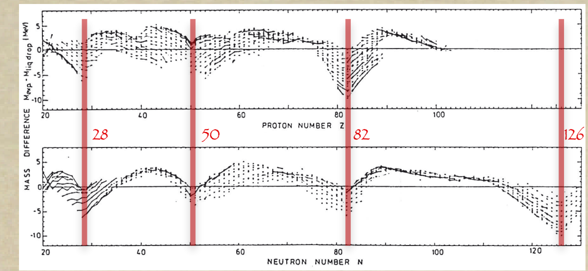
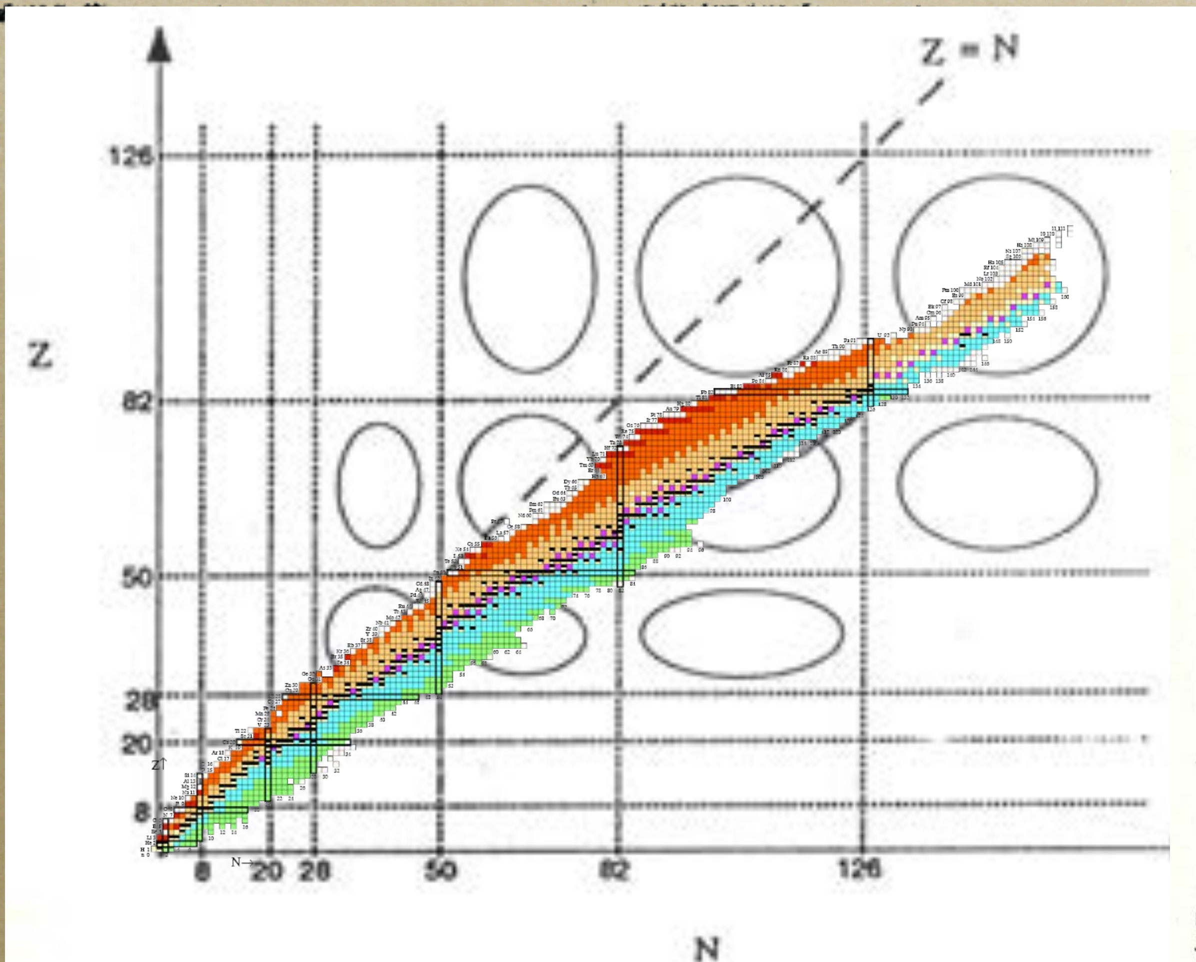




Magic numbers 2, 8, 20, 28, 50, 82, 126

Magic numbers ...





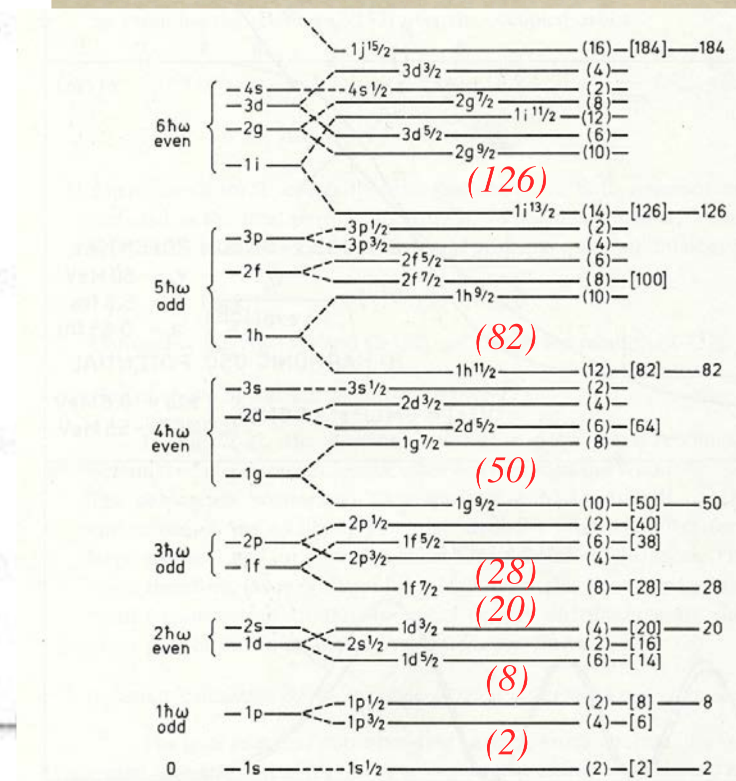


Figure 2-23 Sequence of one-particle orbits. The figure is taken from M. G... J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New...

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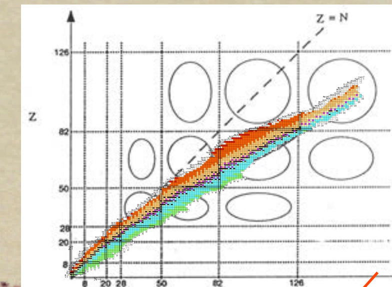


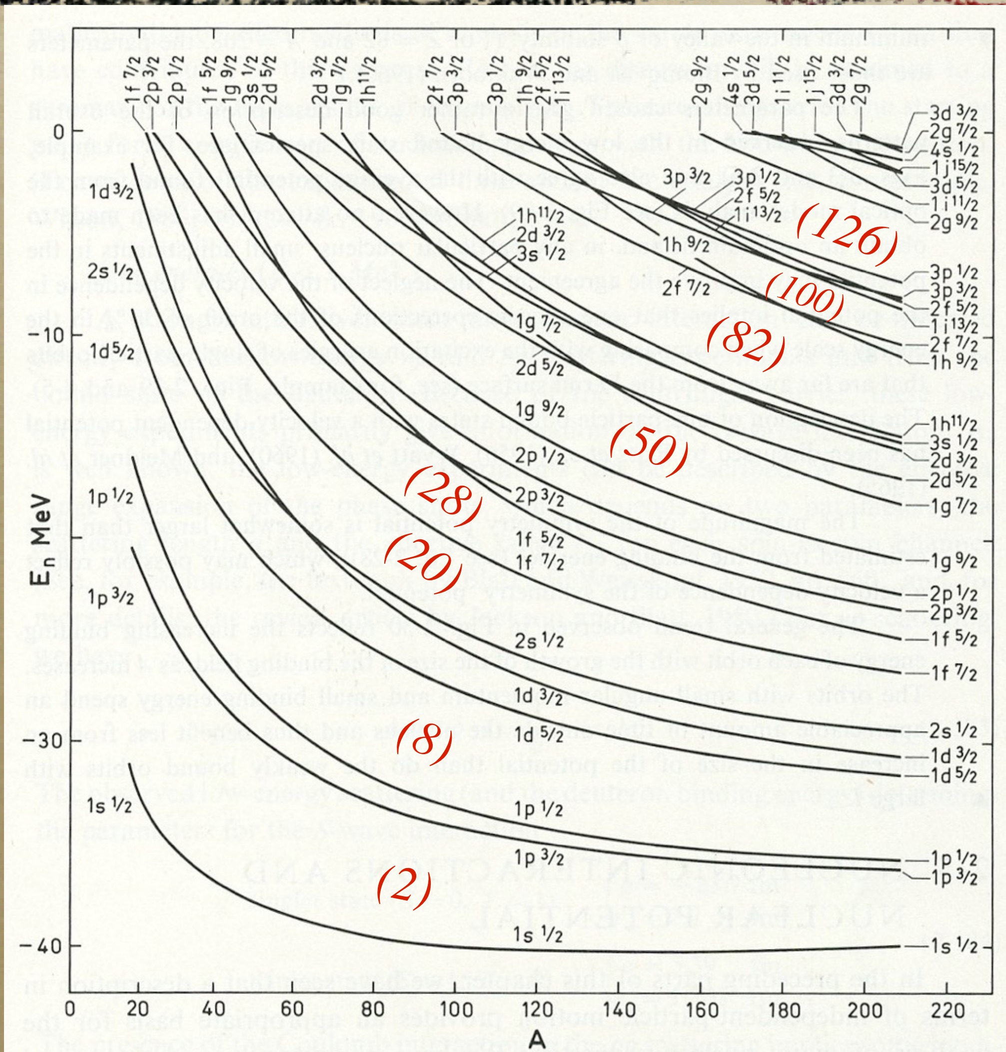
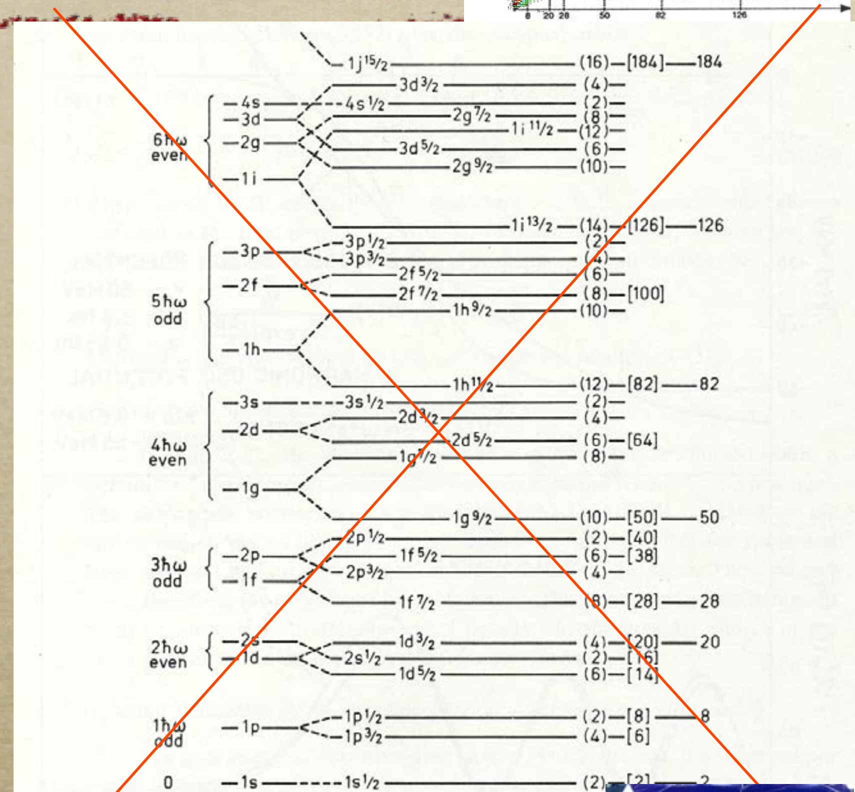


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).



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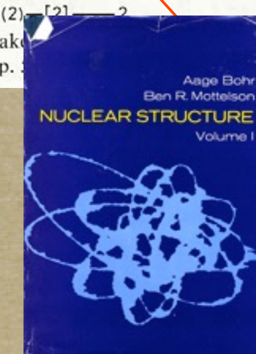
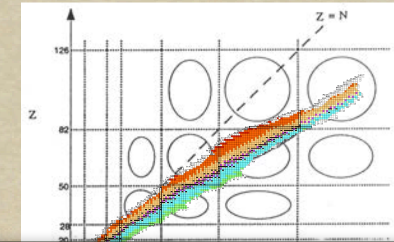
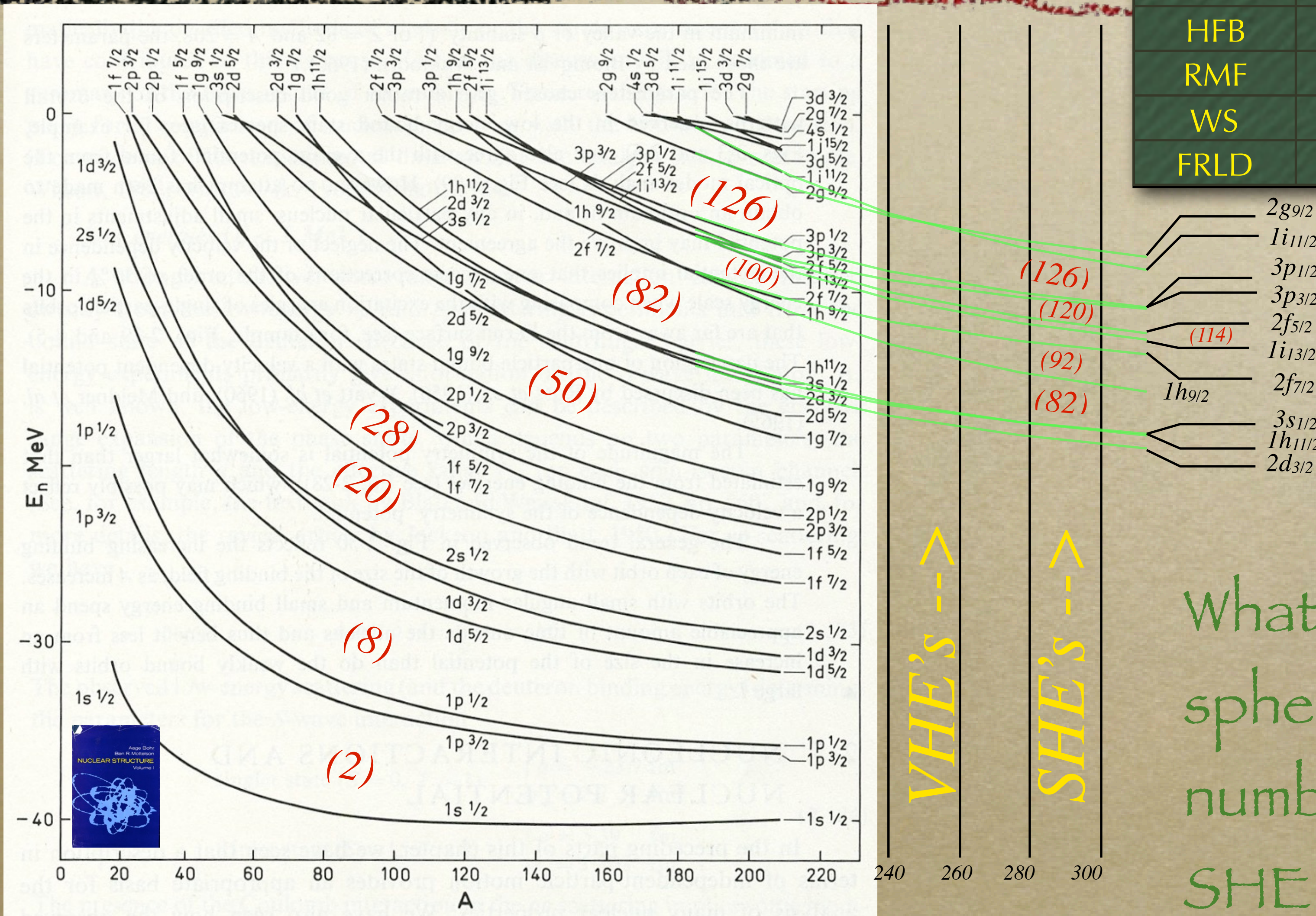


Magic numbers ...



	Z	N
HFB	126	184
RMF	120	172
WS	114	184
FRLD	114	178



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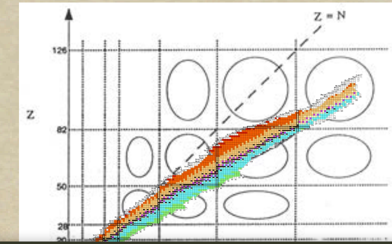
What are the spherical magic numbers for SHE ?

Magic numbers ...

What are the a magic numbers for SHE ?



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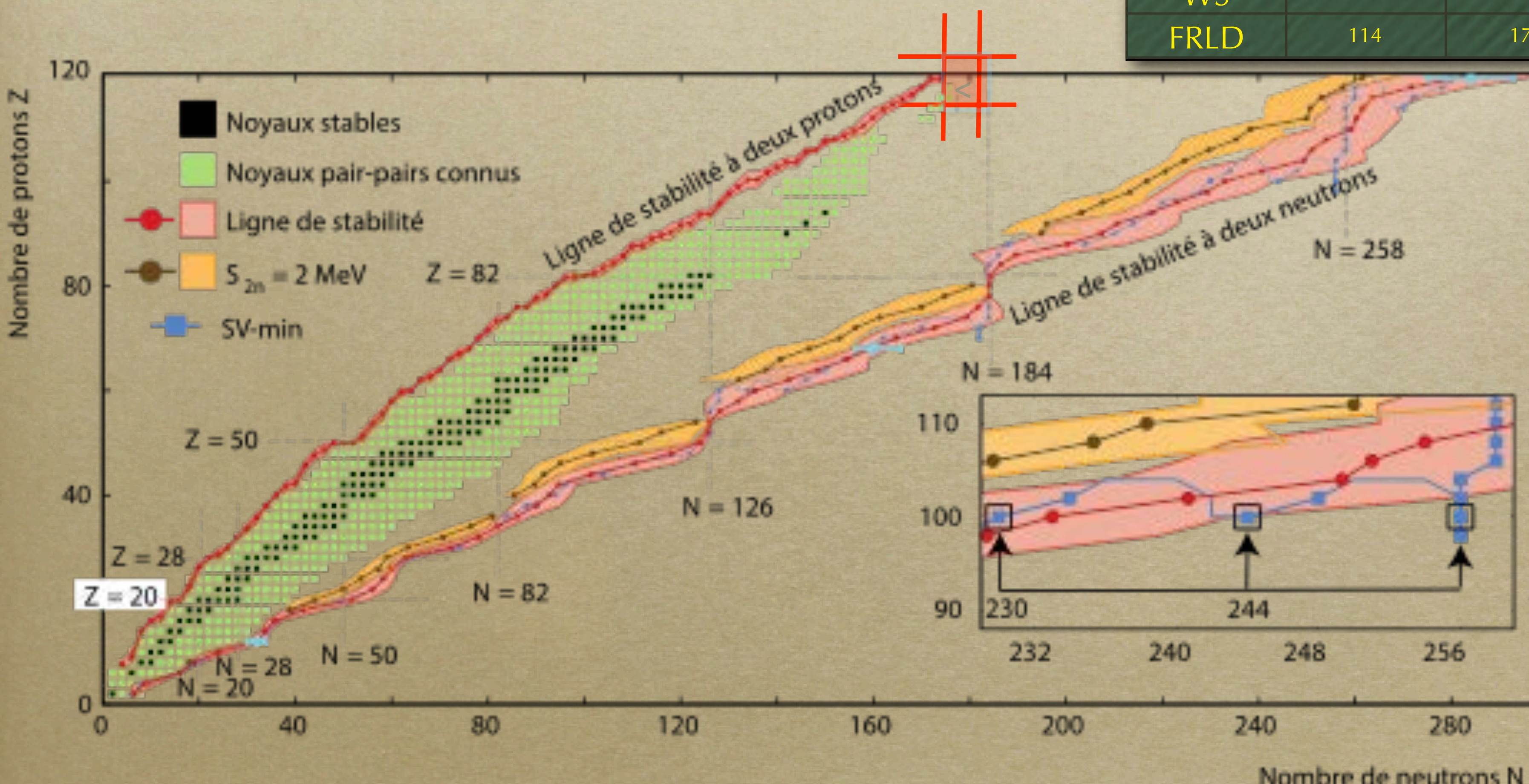
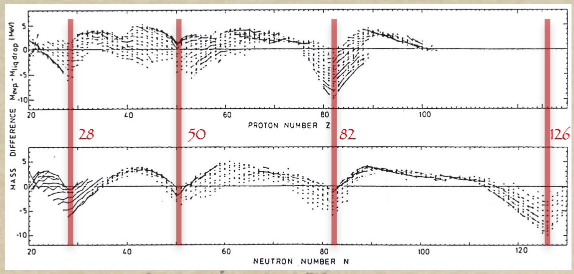
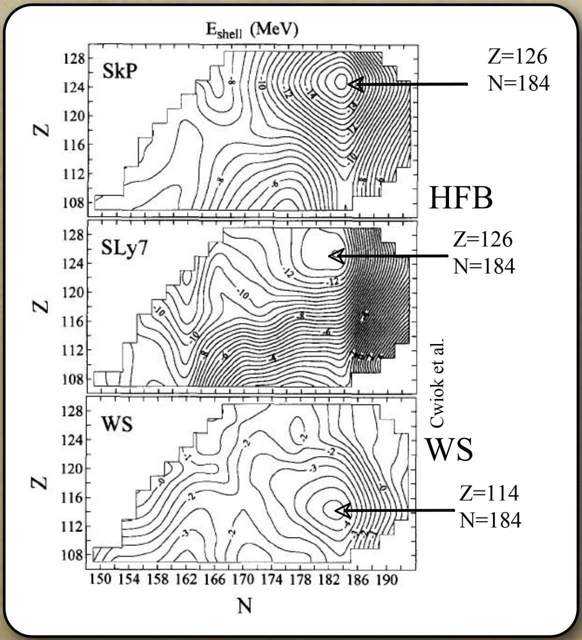


NEXT magic numbers ...



- Where is the ultimate island of stability ?
- What is the limit of nucleus stability ?
- What are the influences on nuclear forces ?



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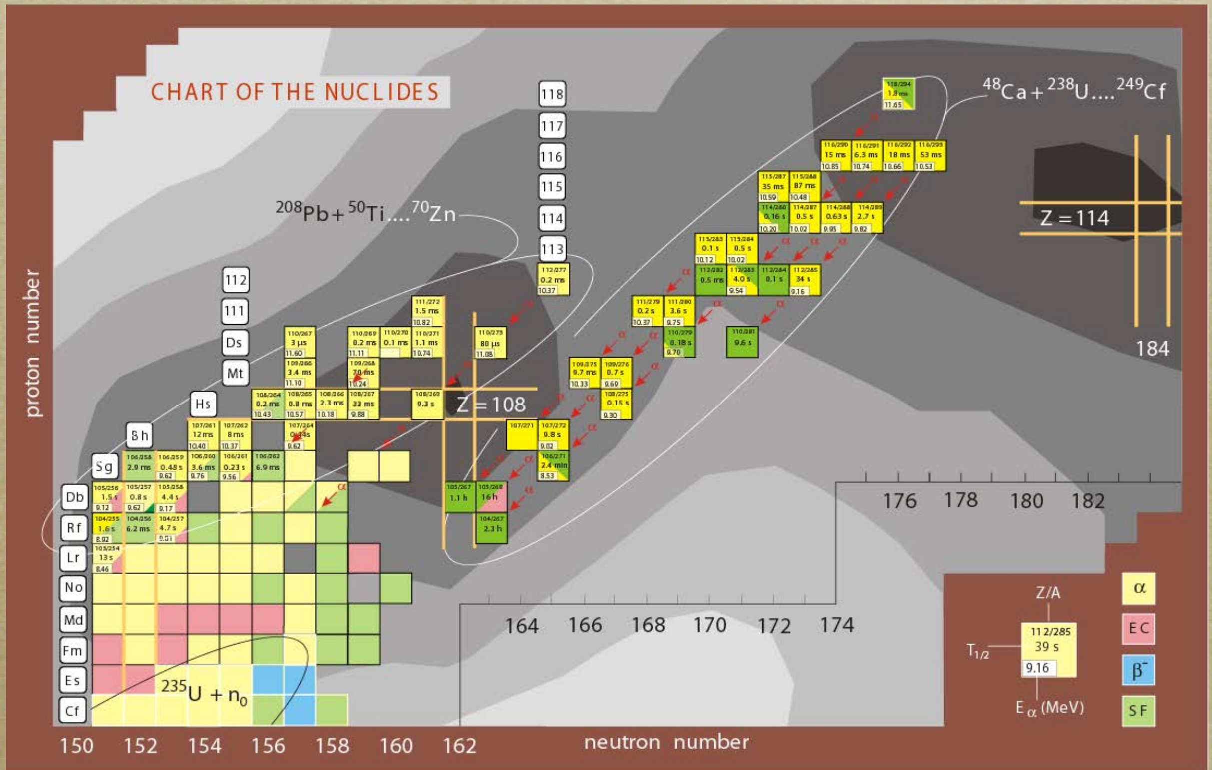

Fig.4

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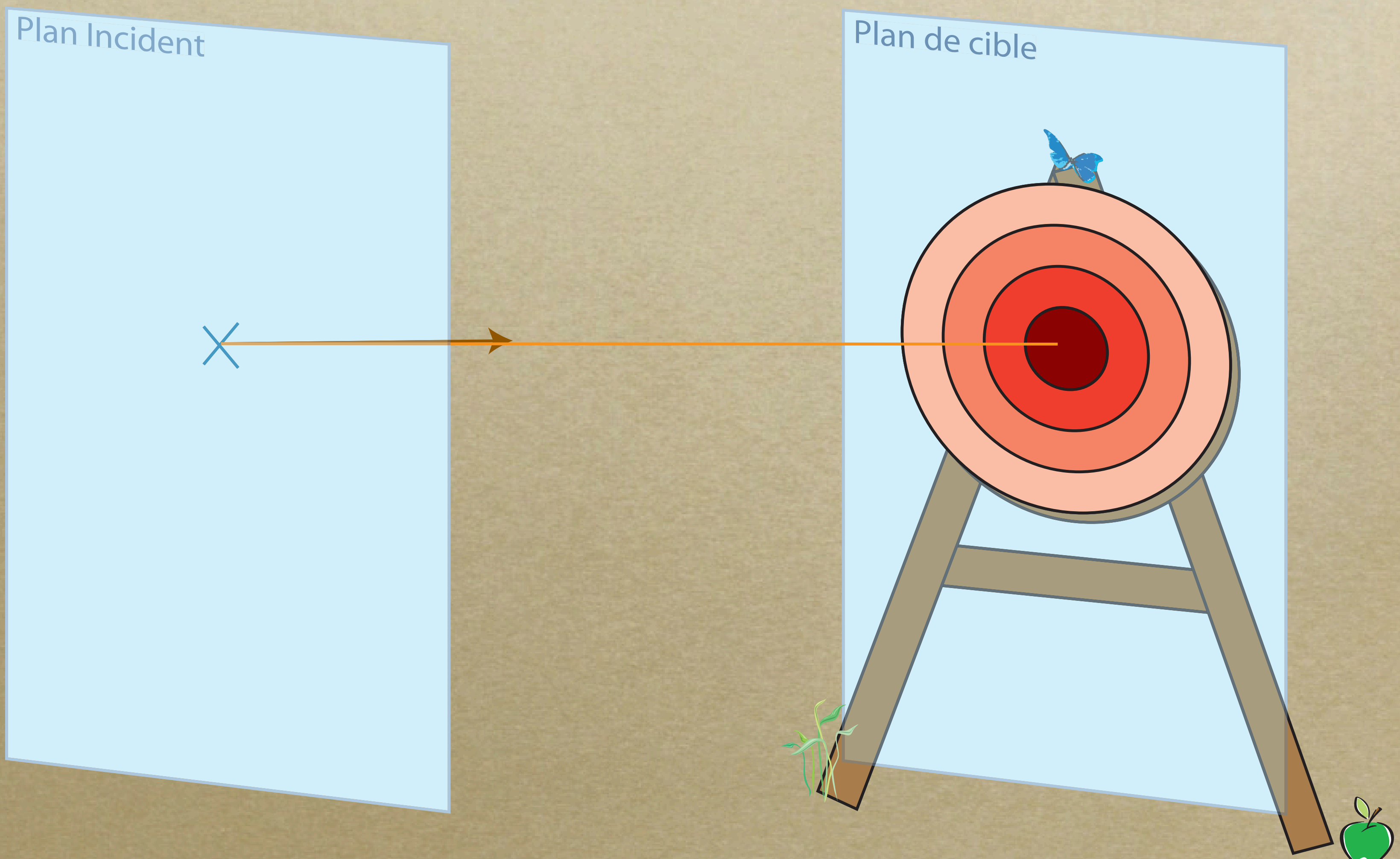
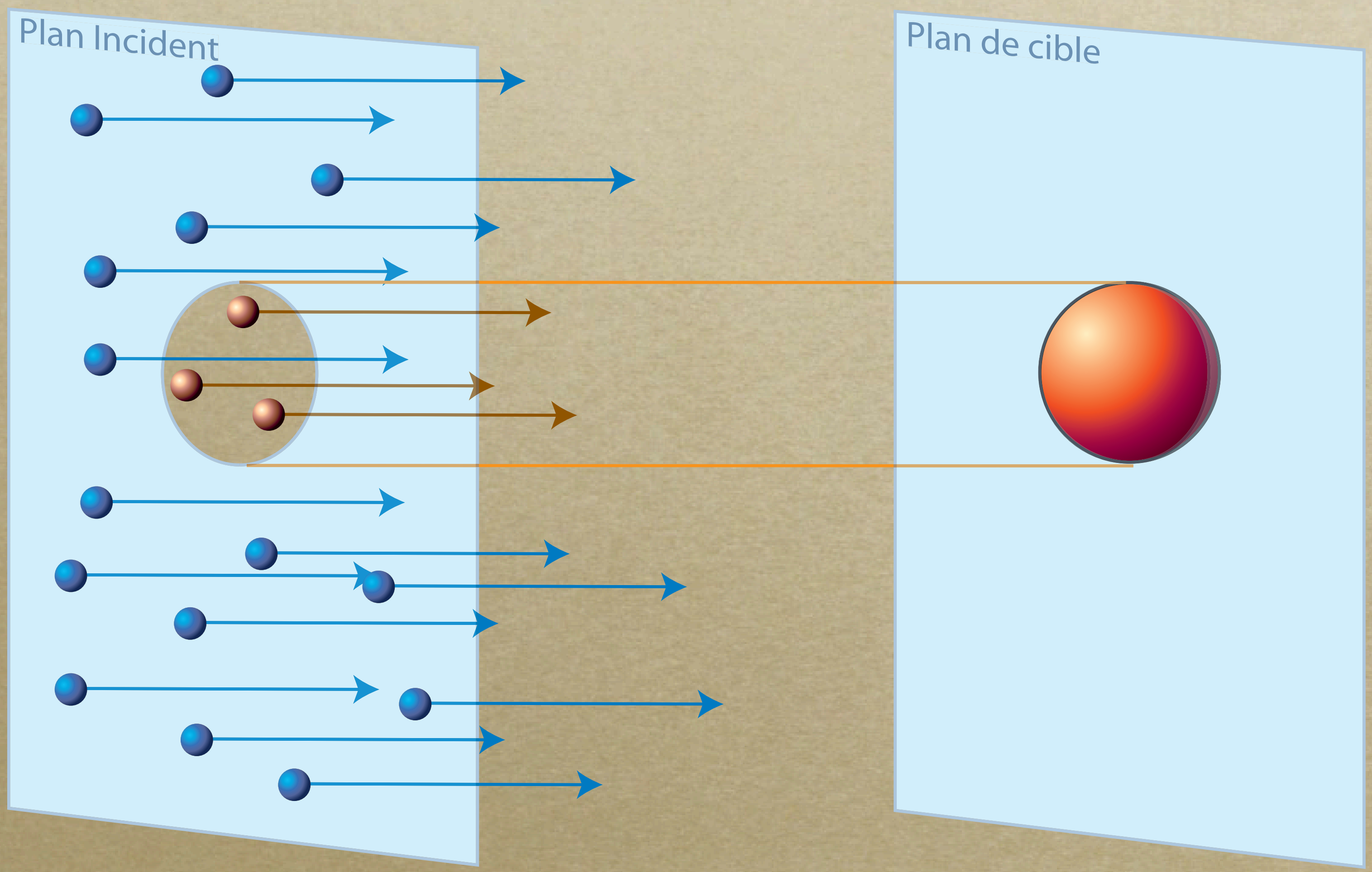
Femto - ballistics

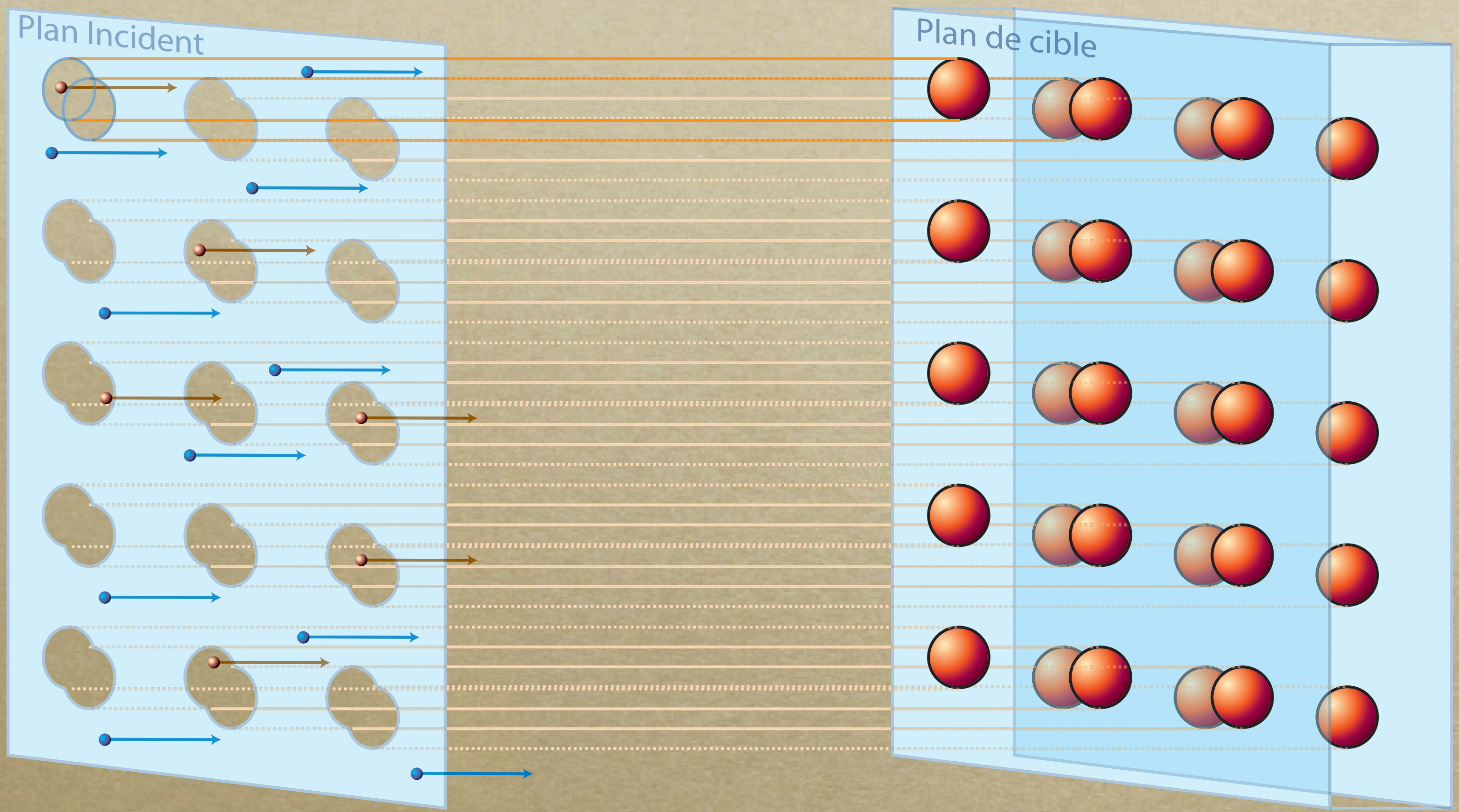


Incident plane —> target plane



Cross section

$S_{total} = N_{target\ atoms} \times S_{efficient}$



$$P_{choc} = \sigma_{geo} \cdot N_C$$

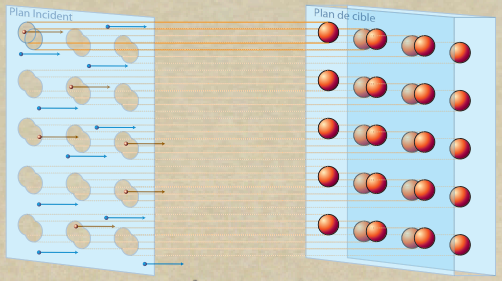
$$N_{tot} = N_i \cdot P_{choc} = N_i \cdot \sigma_{geo} \cdot N_C$$

$$N_{tot} = N_i \cdot \sigma_{geo} \cdot N_C$$

$$\phi_{tot} = \phi_i \cdot \sigma_{geo} \cdot N_C$$

$$N_C = \frac{e.\rho}{m_{at}(A,Z)} = \frac{e.\rho.N_A}{M(A,Z)}$$

Reaction flux calculation



$I = 2.\ 10^{11}$ ions / s

…often in pμA
(1 pμA = 6 10^{12} ions/s)

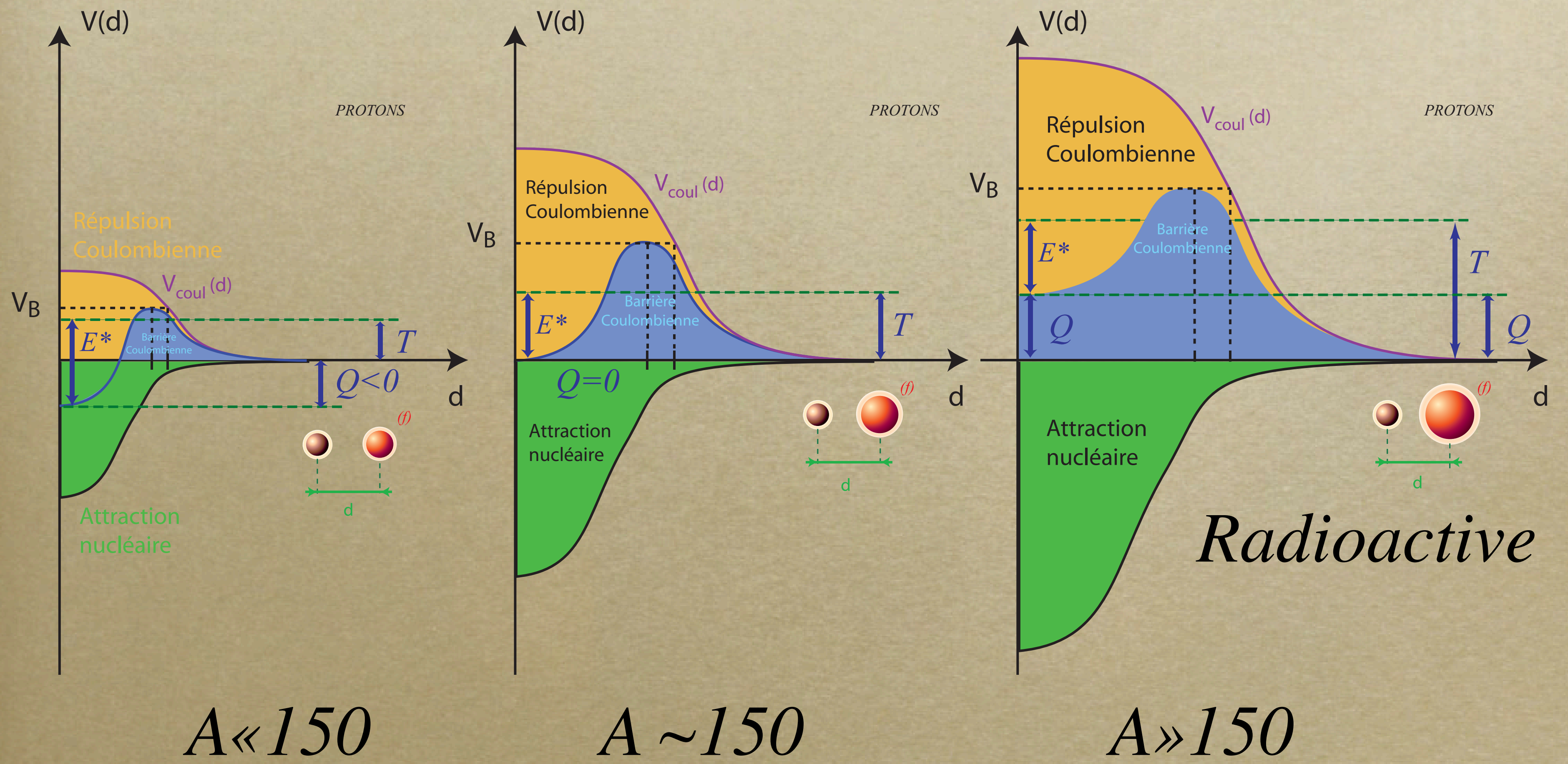
$e' = e\rho = 500\ \mu g/cm^2$

$\sigma = 1\ \mu b\ (1b = 100\ fm^2 = 10^{-24} cm^2)$

$$\mathrm{N_C}(atomes / cm^2) = \frac{\mathrm{e}.\rho(\mathrm{g/cm^2})}{m_{at}(g / atome)} = \frac{\mathrm{e}.\rho.N_{Avogadro}}{M(A,Z)}$$

$$P_{choc} = \sigma_{geo}.\mathrm{N_C} \quad \rightarrow \quad \begin{cases} \mathrm{N}_{tot} = \mathrm{N}_i.\sigma_{geo}.\mathrm{N_C} \\ \phi_{tot} = \phi_i.\sigma_{geo}.\mathrm{N_C} \end{cases}$$

unstability of heavy nuclei ...



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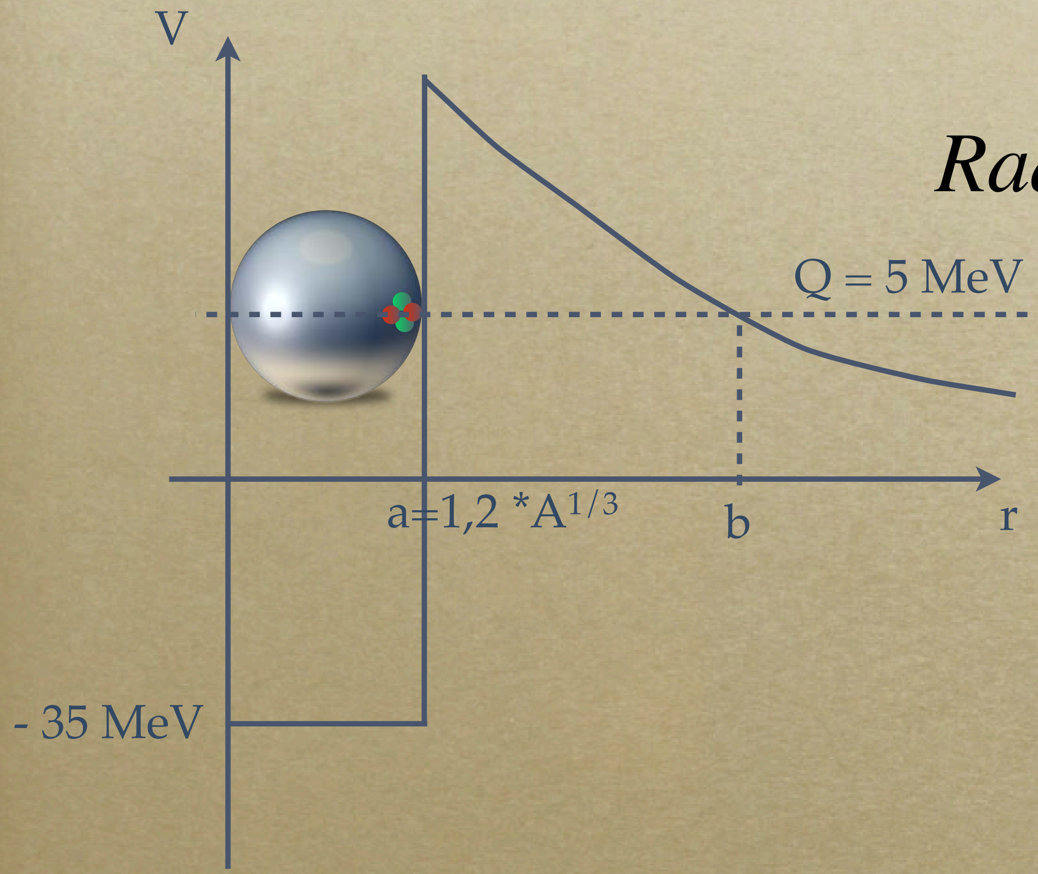


Gamow Theory and
Tunnel effect
Radioactive decay constant

$$\lambda = p.f$$

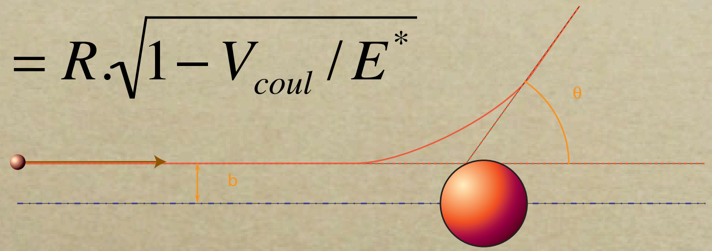
$$f \sim 10^{21} Hz$$

Radioactive

A»150

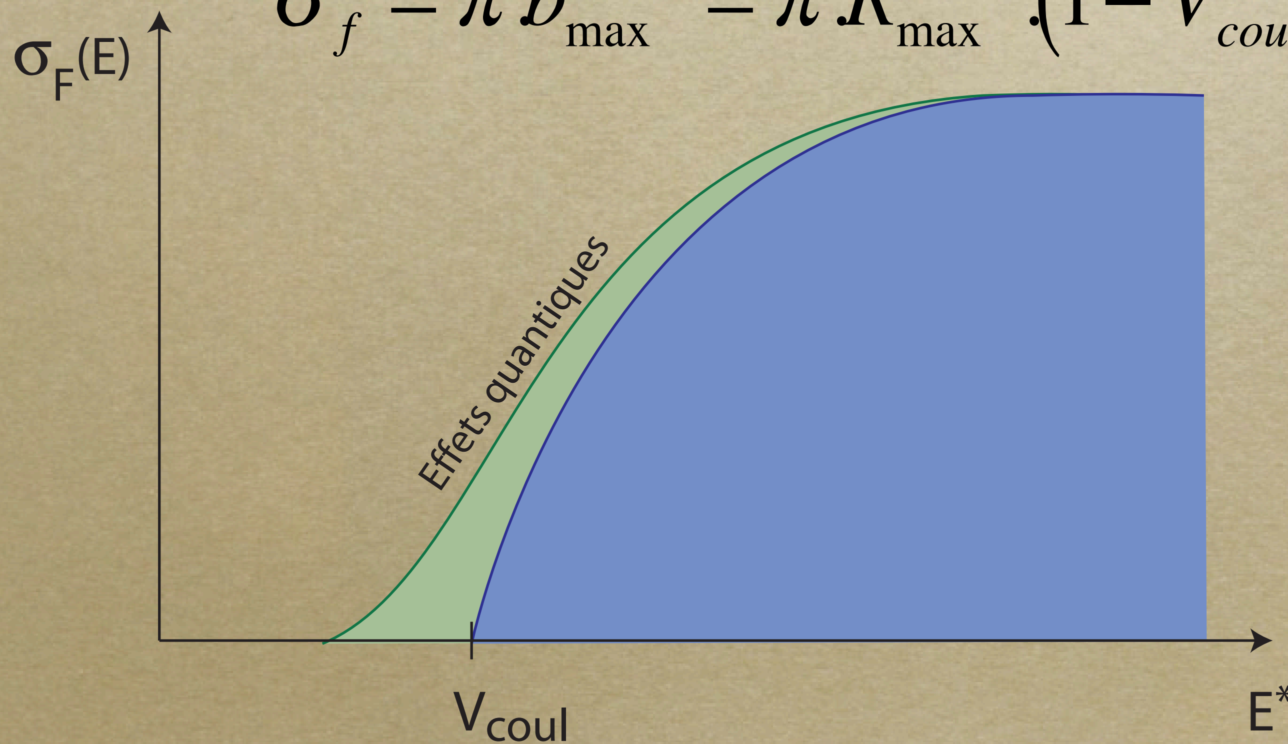
Fusion cross section

$$b = R.\sqrt{1 - V_{coul} / E^*}$$

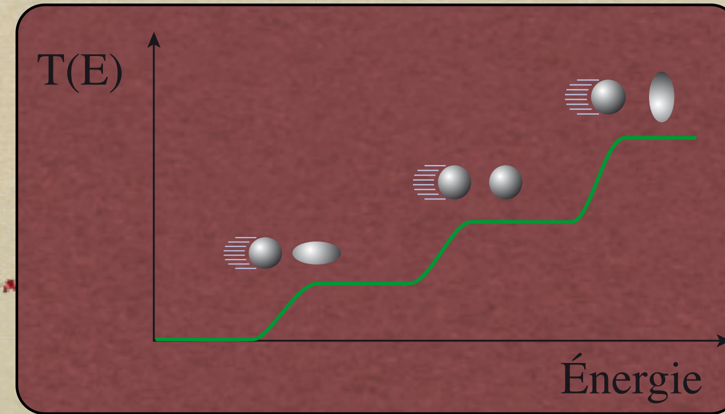


then

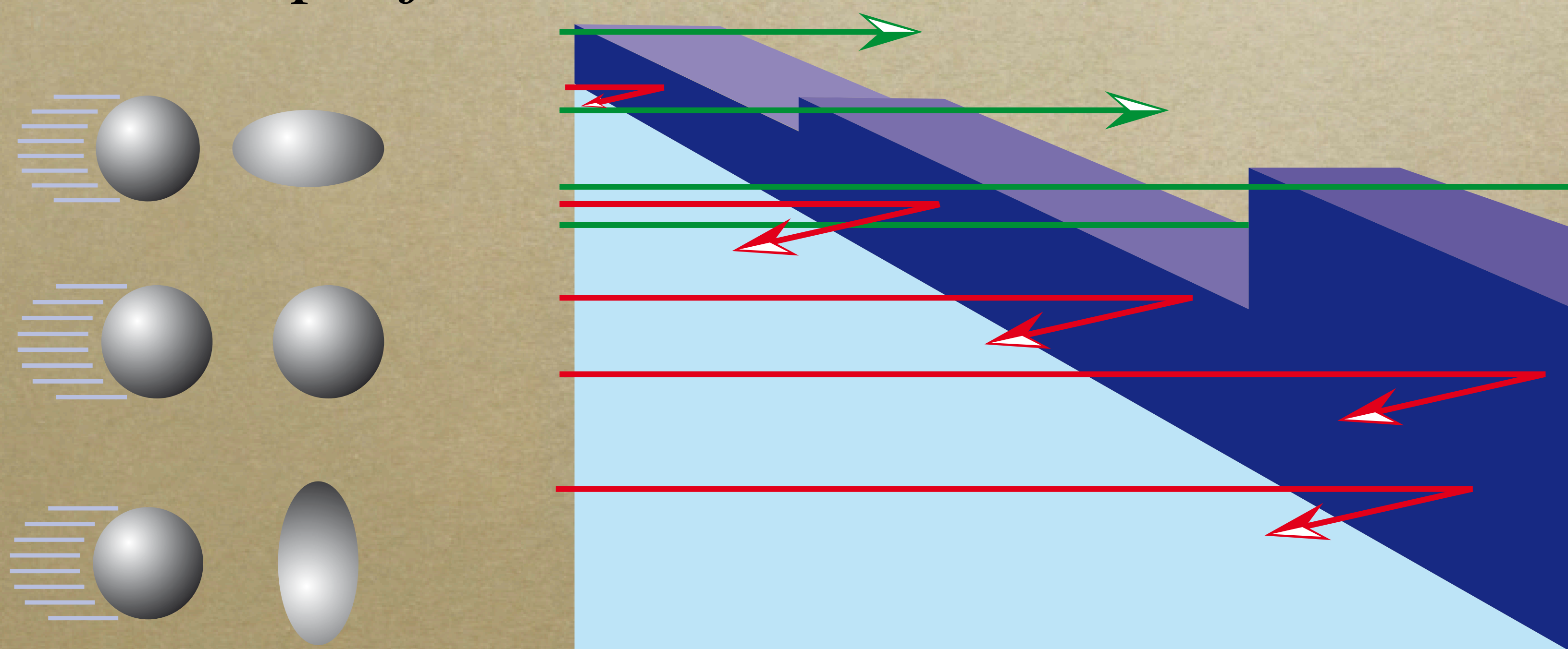
$$\sigma_f = \pi b_{max}^2 = \pi . R_{max}^2 . \left(1 - V_{coul} / E^*\right)$$



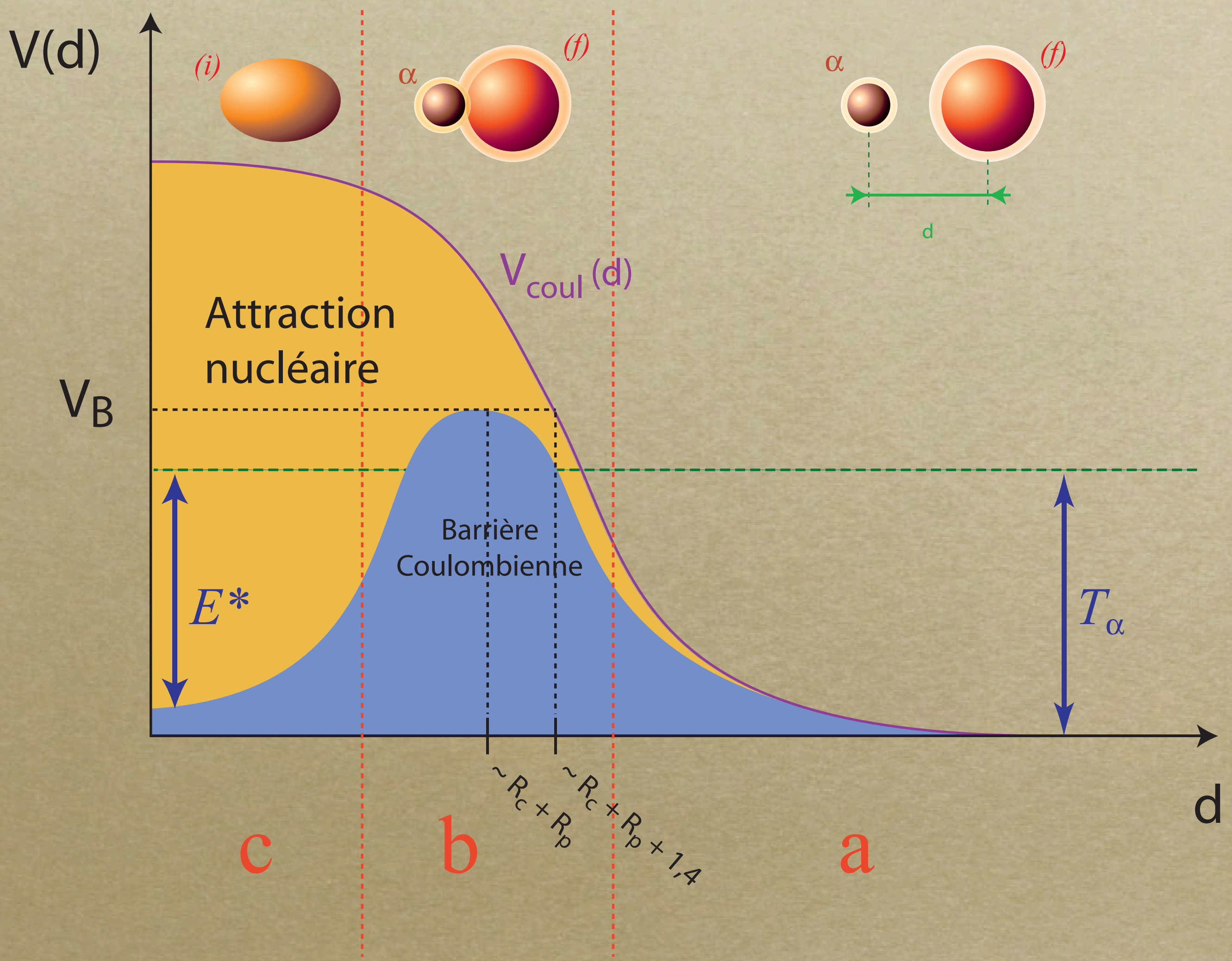
Effects of the entrance channel



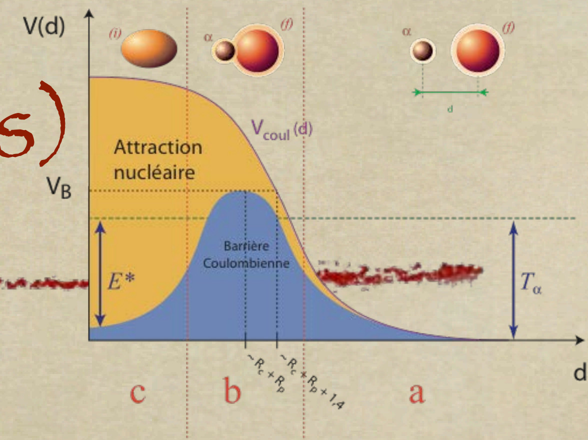
Coulomb force depends on the orientation of the target and the projectile

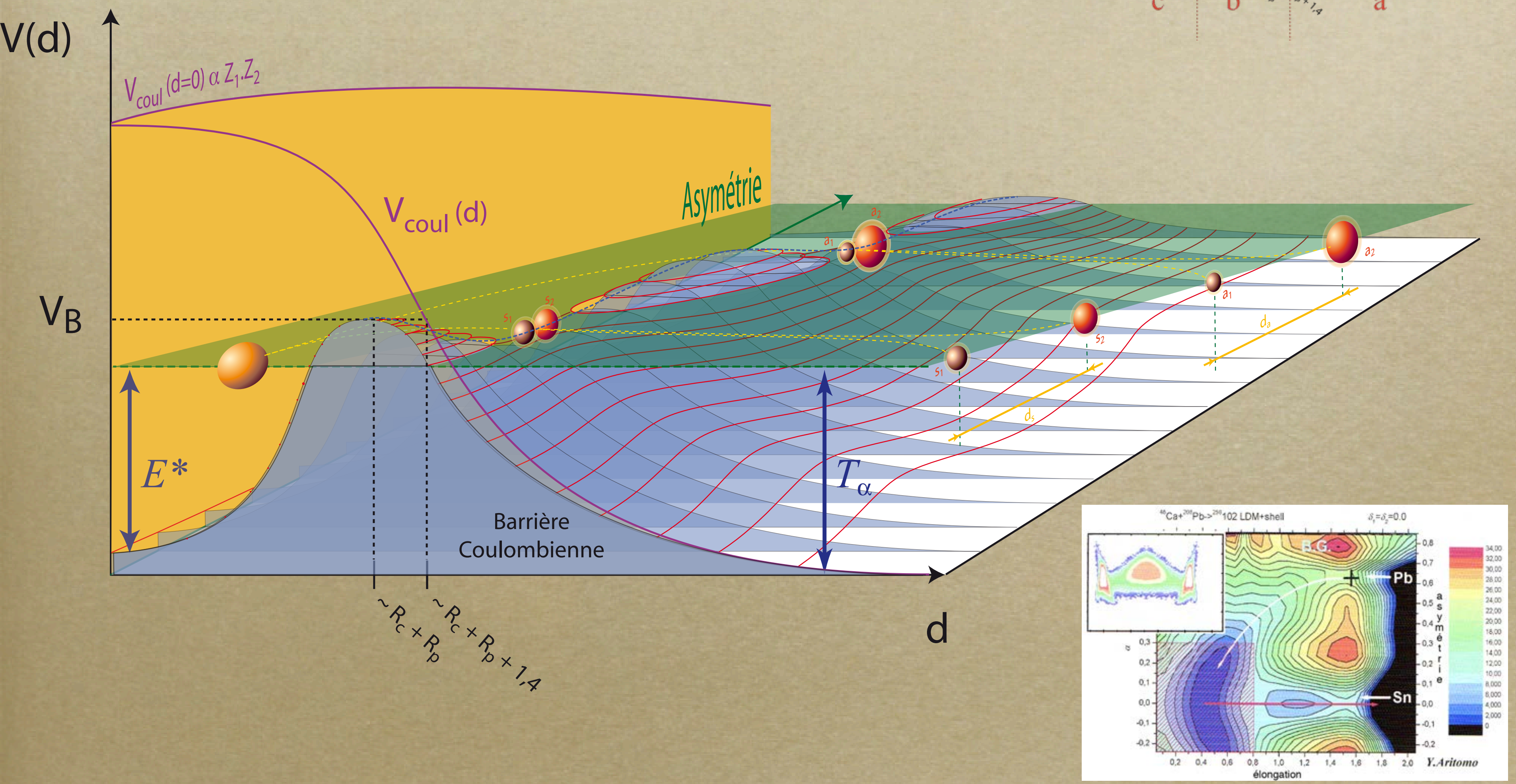


Coulomb barrier (1 dimension)



Coulomb barrier (2 dimensions)





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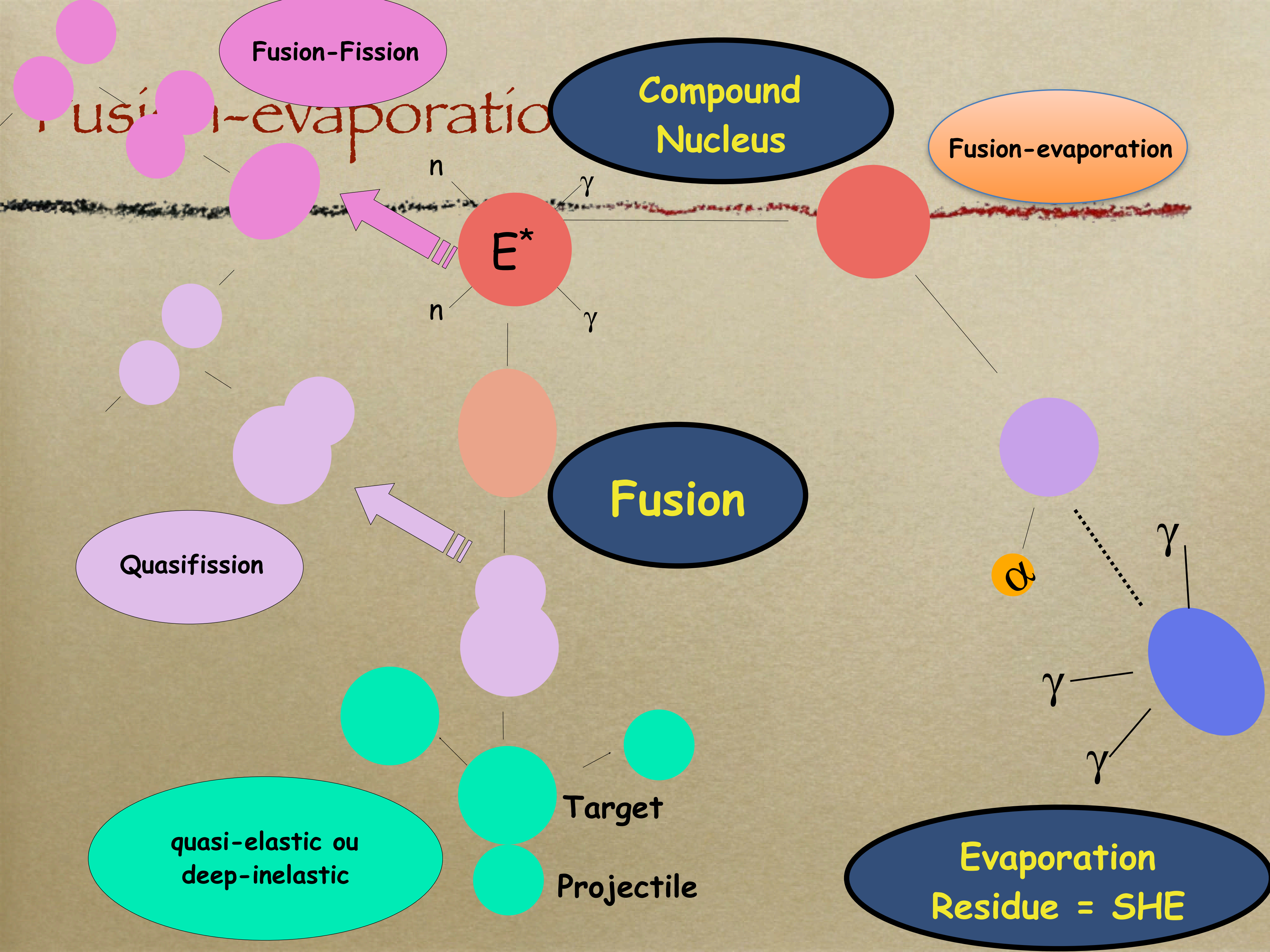
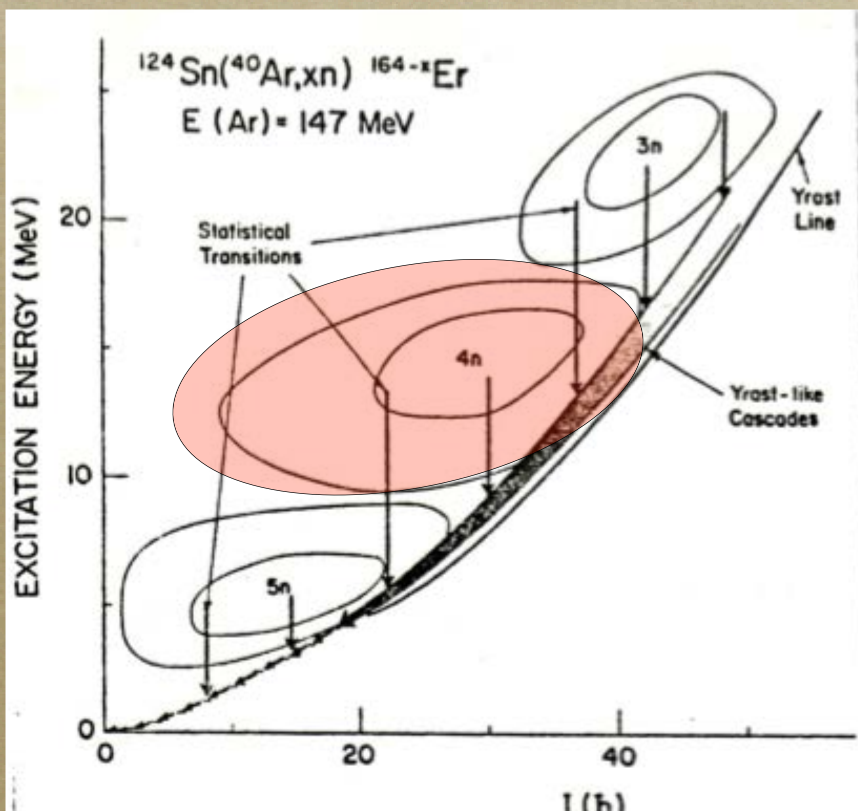
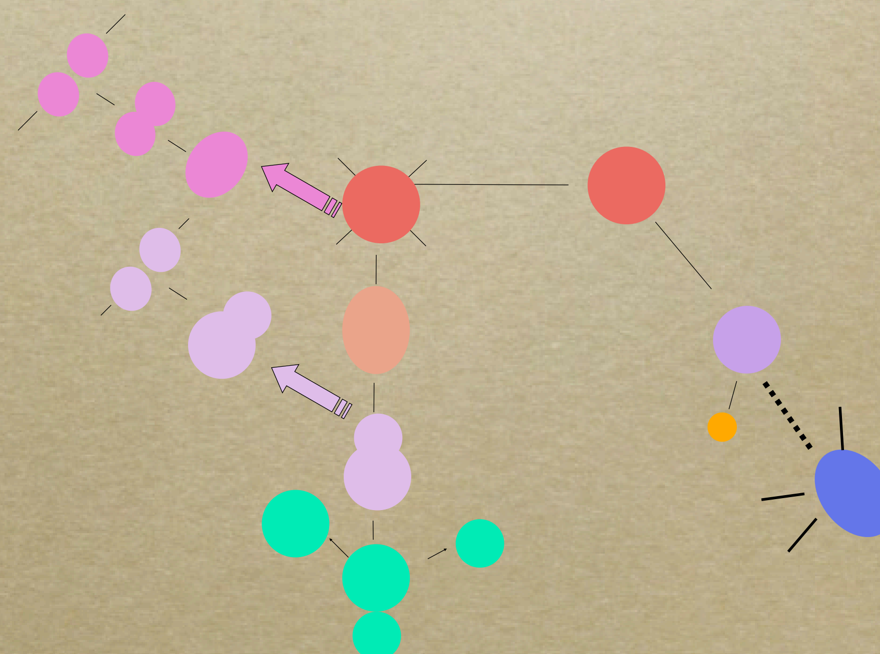

Fusion-Fission
Compound Nucleus
Fusion-evaporation
n
γ
E*
n
γ
Fusion
Quasifission
γ
α
γ
γ
Target
quasi-elastic ou deep-inelastic
Projectile
Evaporation Residue = SHE

Fusion-evaporation reaction

$$\sigma_{ER} = \frac{\pi}{k^2} \Sigma(2L+1)\, T_L(E)\, P_{fusion}(E,L)\, W_{survival}(E^*,L)$$





Exit channel as a function of Energy

Statistical evaporation of x neutrons

« xn » channel

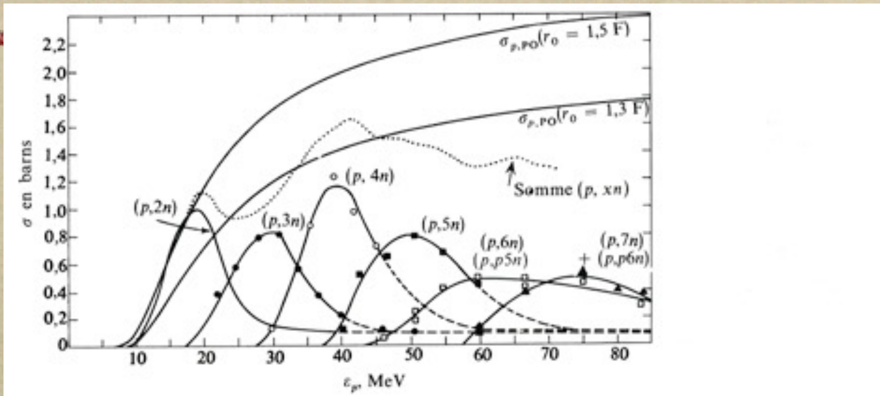


FIGURE XI.3

Fonctions d'excitation des réactions (p, xn) induites sur le noyau $^{209}_{83}$Bi (pour x variant de 2 à 7). Les sections efficaces des réactions $(p, 6n)$ et $(p, 7n)$ ne peuvent être obtenues que de façon cumulative avec celles des réactions $(p, p5n)$ et $(p, p6n)$ respectivement, car les nuclides formés par ces dernières se désintègrent vers les nuclides caractéristiques des réactions $(p, 6n)$ et $(p, 7n)$ avant que l'on puisse commencer les mesures d'activité. Les courbes notées $\sigma_{p,\mathrm{PO}}$ sont les sections efficaces de formation du noyau composé $^{210}_{84}$Po calculées dans l'hypothèse d'un noyau noir de rayon $R = r_0 A^{1/3}$ (avec $r_0 = 1{,}5$ F et $r_0 = 1{,}3$ F), en tenant compte de la probabilité de franchir la barrière coulombienne (cf. exercice XI.2).

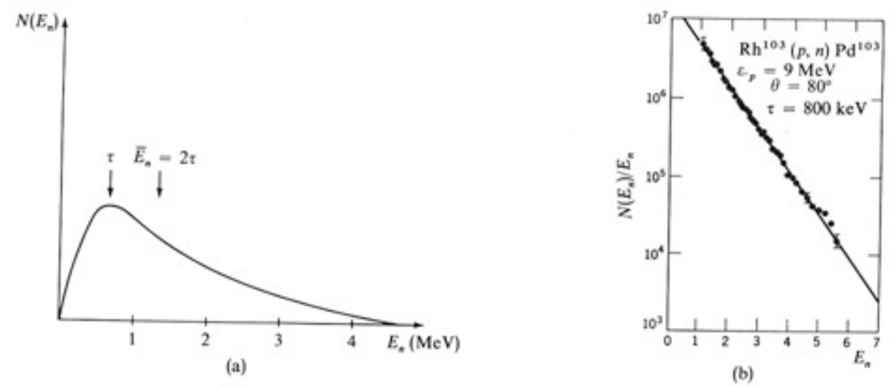
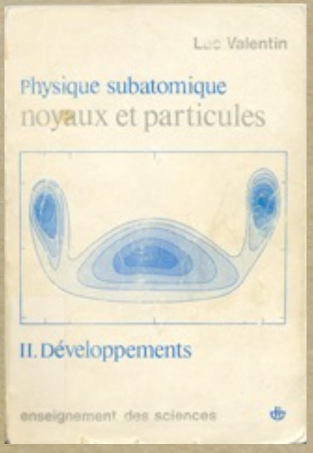


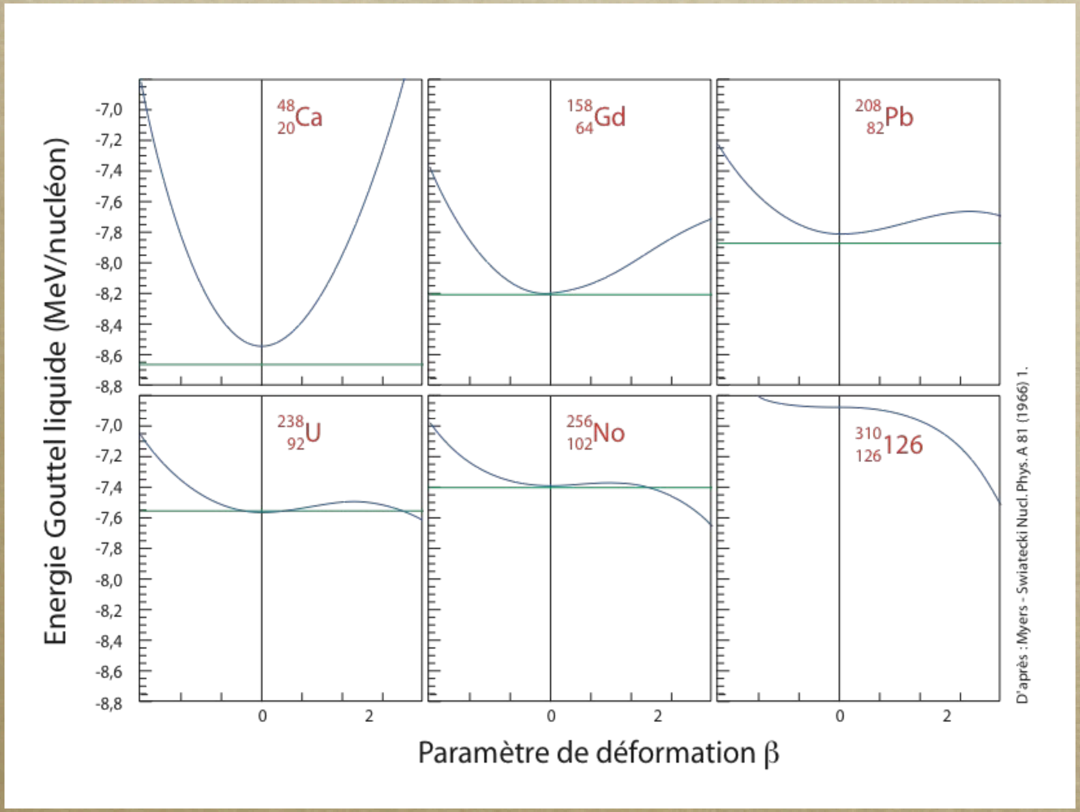
FIGURE XI.4

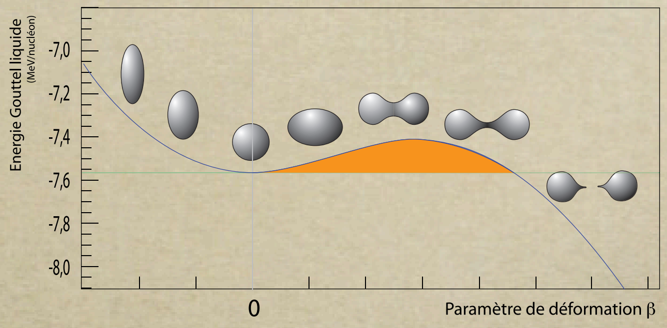
Le spectre d'évaporation de neutron est en première approximation une distribution de Maxwell de la forme $N(E_n) \propto (E_n/\tau^2)\,e^{-E_n/\tau}$ où $N(E_n)$ est le nombre de neutrons émis avec une énergie cinétique comprise entre E_n et $E_n + dE_n$ et où τ est la température nucléaire définie par la relation (XI.18), à savoir : $d(\mathrm{Log}\,\omega)/dE_n = 1/\tau$. La figure (a) donne son allure caractéristique pour $\tau \simeq 0{,}8$ MeV. Il est préférable de présenter les résultats en traçant directement la quantité $N(E_n)/E_n$ à l'échelle logarithmique en fonction de E_n. La pente de la droite ainsi obtenue fournit $1/\tau$ dont on déduit $\omega(E_n)$. La figure (b) montre un résultat expérimental typique. Le spectre des neutrons d'évaporation émis par le noyau composé ^{104}Pd a été détecté à l'angle $\theta = 80°$. L'accord avec la théorie est satisfaisant pour $\tau = 0{,}8$ MeV.

Maxwell Energy Distribution



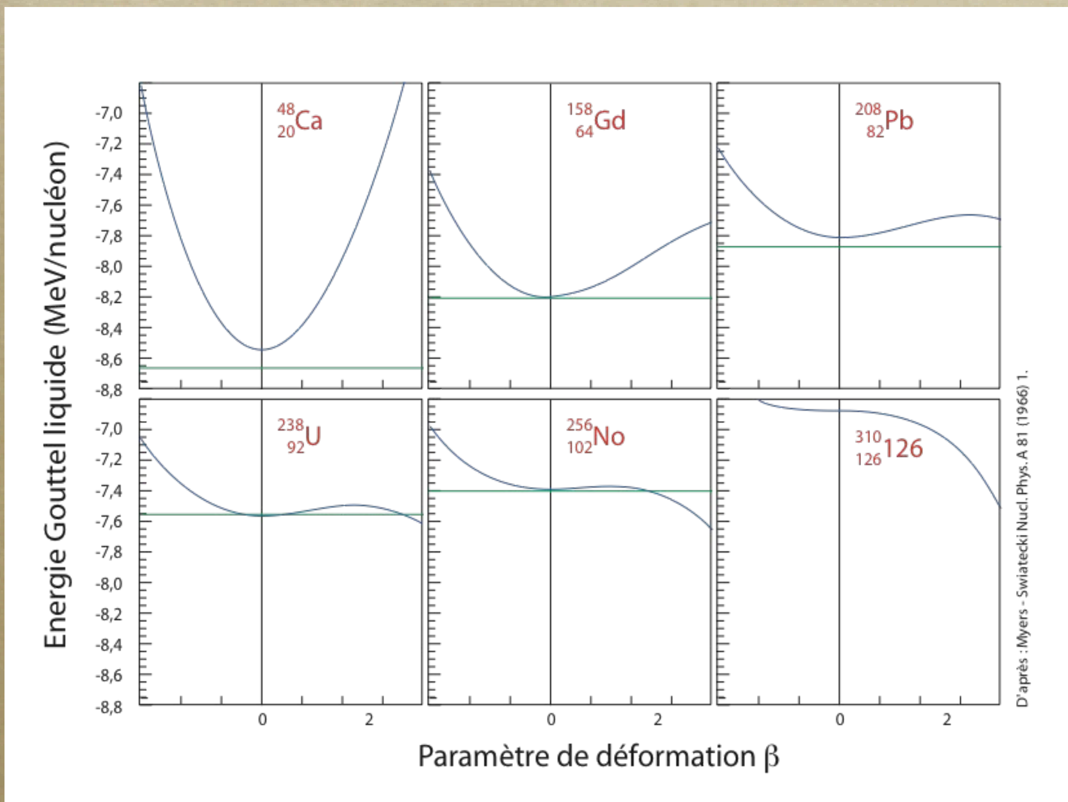
Coulomb barrier (Z dependance)

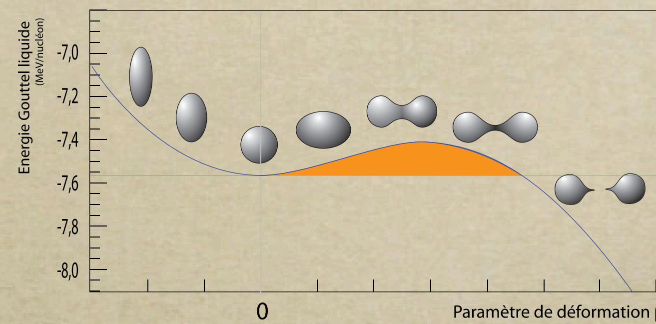


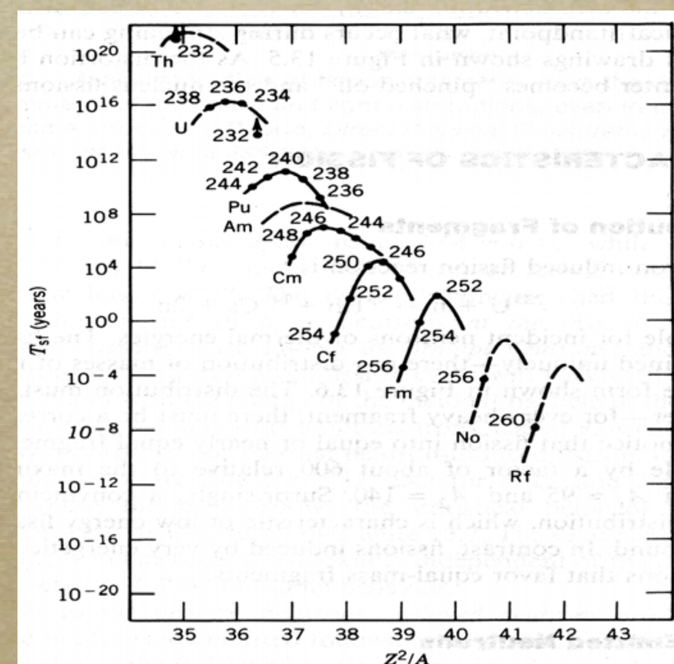


Coulomb barrier disappear progressively with Z

Coulomb barrier (Z dependance)



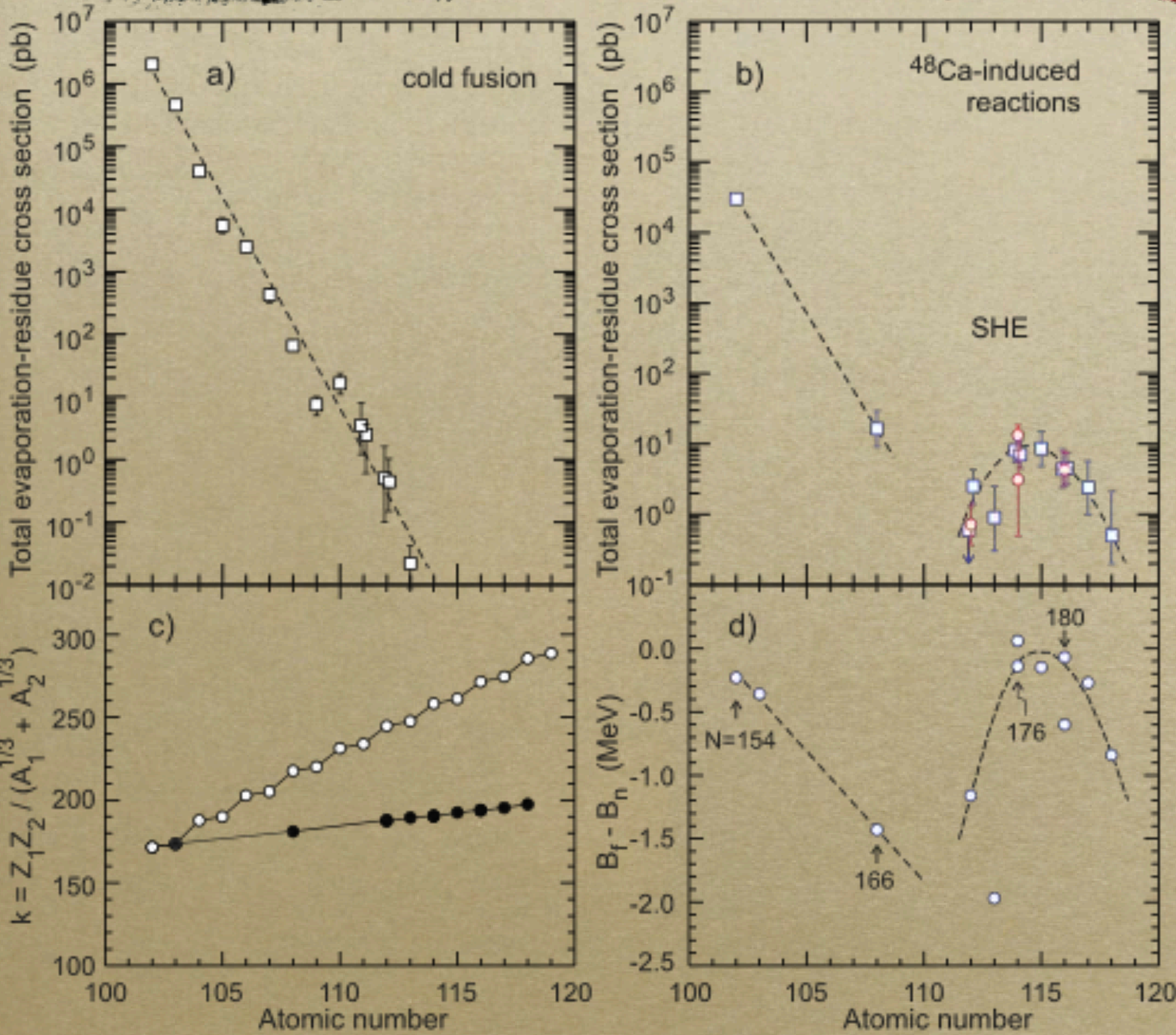




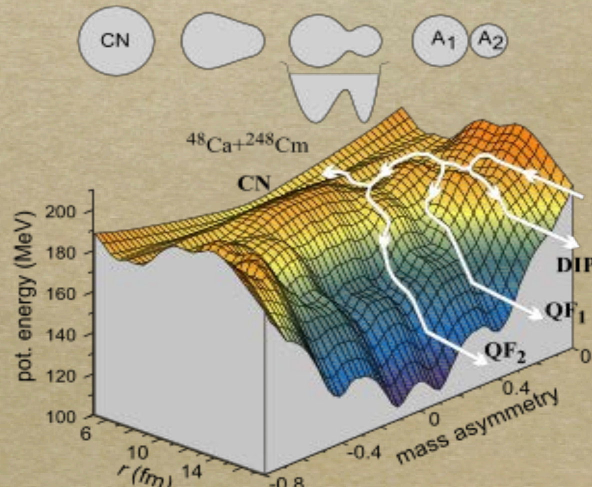
Coulomb barrier disappear progressively with Z

… Fission is enhanced !

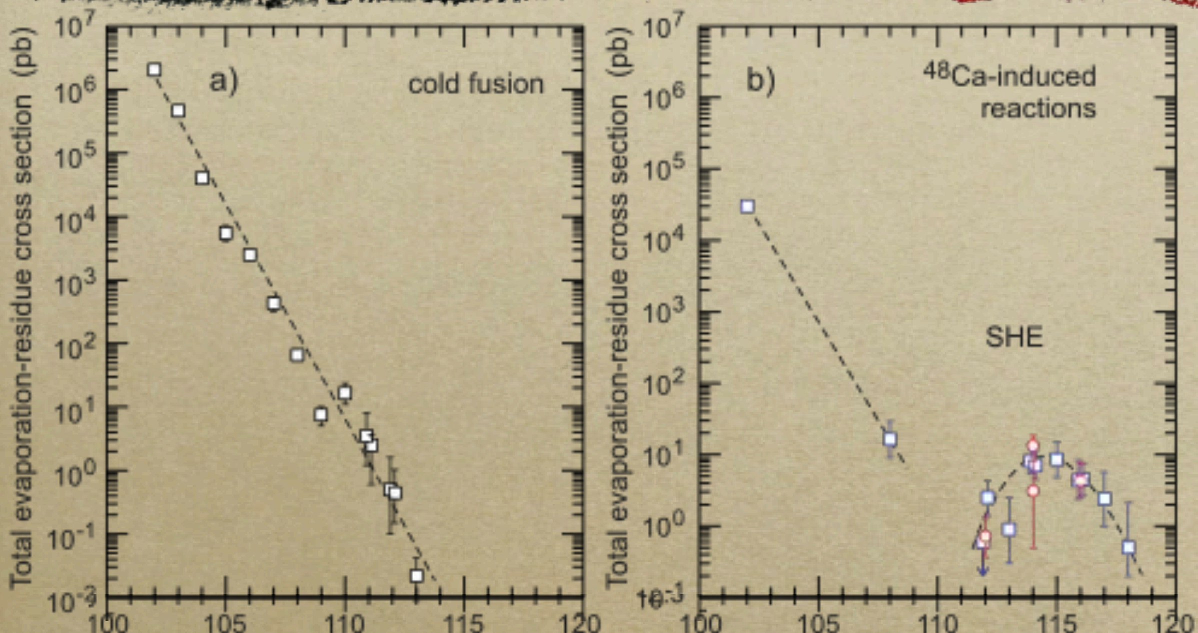
SHE production probability



Cross-section drop one decade down each 2 Mass unit !



SHE production probability



© Y Oganessian et al. Rep. Prog. Phys. 78 (2015) 036301

Cross-section drops one decade down each 2 Mass unit !

75 fb

1 pμA <=> 1 evt per month

500 μg/cm^2

Heaviest elements

Only a few events observed

in years of study

Table 1
Decay properties of nuclei.

Z	N	A	No. observed[a]	Decay mode, branch (%)[b,c]	Half-life[c]	E_α (MeV)	Q_α^{exp} (MeV)	Refs.
118	176	294	d:4	α	$0.69^{+0.64}_{-0.22}$ ms	11.66 ± 0.06	11.82 ± 0.06	[71,73,74]
117	177	294	d:3, t:2	α	51^{+38}_{-16} ms	10.81–11.07	11.18 ± 0.04	[74,86–89]
	176	293	d:15	α	22^{+8}_{-4} ms	10.60–11.20	11.32 ± 0.05	[74,86–88]
116	177	293	d:4, s:1	α	57^{+43}_{-17} ms	10.56 ± 0.02	10.71 ± 0.02	[68–70,72]
	176	292	d:5, s:4	α	13^{+7}_{-4} ms	10.63 ± 0.02	10.78 ± 0.02	[70,72]
	175	291	d:3, s:1	α	19^{+17}_{-6} ms	10.74 ± 0.07 10.50 ± 0.02	10.89 ± 0.07	[49,71,72]
	174	290	d:11	α	$8.3^{+3.5}_{-1.9}$ ms	10.85 ± 0.07	11.00 ± 0.07	[49,71,73, 74]
115	175	290	d:4, t:2	α	650^{+490}_{-200} ms	9.78–10.31	10.41 ± 0.04	[74,86–89]
	174	289	d:16	α	330^{+120}_{-80} ms	10.15–10.54	10.49 ± 0.05	[74,80,81, 86–88]
	173	288	d:27, t:19	α	164^{+30}_{-21} ms	10.29–10.58	10.63 ± 0.01 ≈ 10.7 [83]	[75,76,80,81, 83,84]
	172	287	d:2, t1	α	37^{+44}_{-13} ms	10.61 ± 0.05	10.76 ± 0.05	[75,76,81,83, 84]
114	175	289	d:10, s:1, t:4, tc:1	α	$1.9^{+0.7}_{-0.4}$ s	9.84 ± 0.02 9.48 ± 0.08	9.98 ± 0.02	[45,48,49,62, 65,68–70,72]
	174	288	d:17, s:4, t:11, ic:2, tc:1	α	$0.66^{+0.14}_{-0.10}$ s	9.93 ± 0.03	10.07 ± 0.03	[45,49,56,61, 62,65,70,72]
	173	287	d:16, s:1, b:1, ic:1	α	$0.48^{+0.14}_{-0.09}$ s	10.03 ± 0.02	10.17 ± 0.02	[46,49,56,61, 70–72]
	172	286	d:25, b:2	α: 60^{+10}_{-11}	$0.12^{+0.04}_{-0.02}$ s	10.21 ± 0.04	10.35 ± 0.04	[46,47,49,56, 70,71,73,74]
	171	285	b:1	α	$0.13^{+0.60}_{-0.06}$ s			[47]
113	173	286	d:4, t:2	α	$9.5^{+6.3}_{-2.7}$ s	9.61–9.75	9.79 ± 0.05	[74,86–89]
	172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	9.47–10.18	10.01 ± 0.04	[74,80,81, 86–88]
	171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	9.10–10.11	10.12 ± 0.01 ≈ 10.3 [83]	[75,76,80,81, 83,88,84]
	170	283	d:1, t1	α	75^{+136}_{-30} ms	10.23 ± 0.01	10.38 ± 0.01	[75,76,81,83, 84]
	169	282	d:2	α	73^{+134}_{-29} ms	10.63 ± 0.08	10.78 ± 0.08	[82]
112	173	285	d:10, s:1, t:4, ic:1, tc:1	α	28^{+9}_{-6} s	9.19 ± 0.02	9.32 ± 0.02	[45,48,49,60, 62,65,68–70, 72]
	172	284	d:19, s:4, t:11, ic:2, tc:1	SF	98^{+20}_{-14} ms			[45,49,56,61, 62,65,70,72]
	171	283	d:22, s:4, b:1, ic:6	α: ≥ 93	$4.2^{+1.1}_{-0.7}$ s	9.53 ± 0.02 9.33 ± 0.06 8.94 ± 0.07	9.66 ± 0.02	[46,49, 56–59,61,63, 70,71]

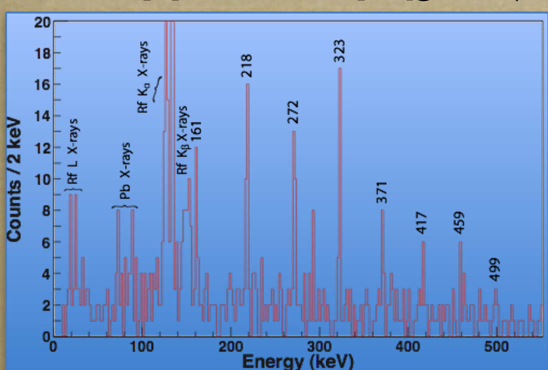
Yu.Ts.Oganessian*, V.K.Utyonkov Nuclear Physics A 944 (2015) 62–98

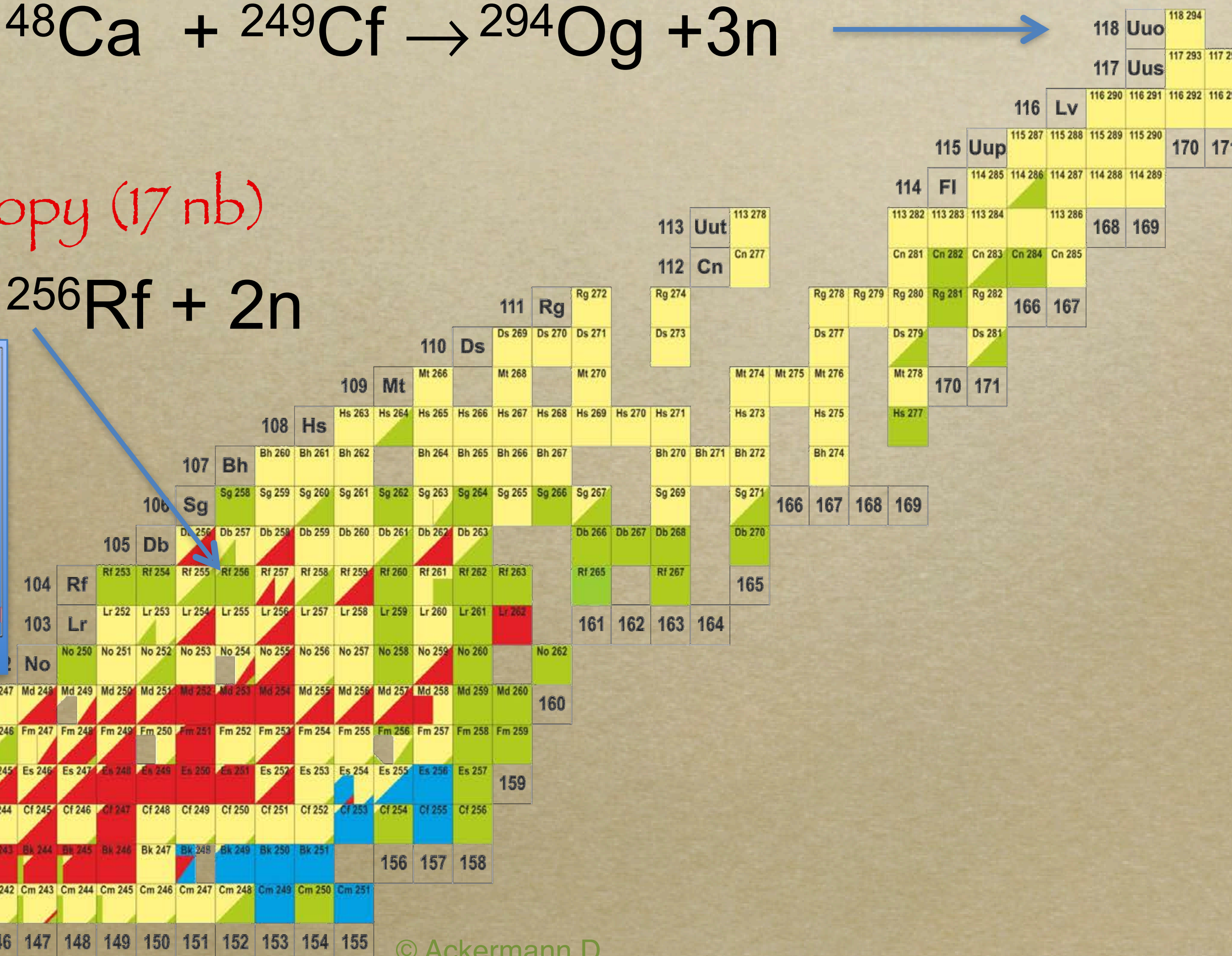
The experimental limits ?

Synthesis (50fb) $^{48}Ca + ^{249}Cf \rightarrow ^{294}Og + 3n$

Prompt spectroscopy (17 nb)

$^{50}Ti + ^{208}Pb \rightarrow ^{256}Rf + 2n$





© Ackermann D.

Limits for SHE production

beam intensity

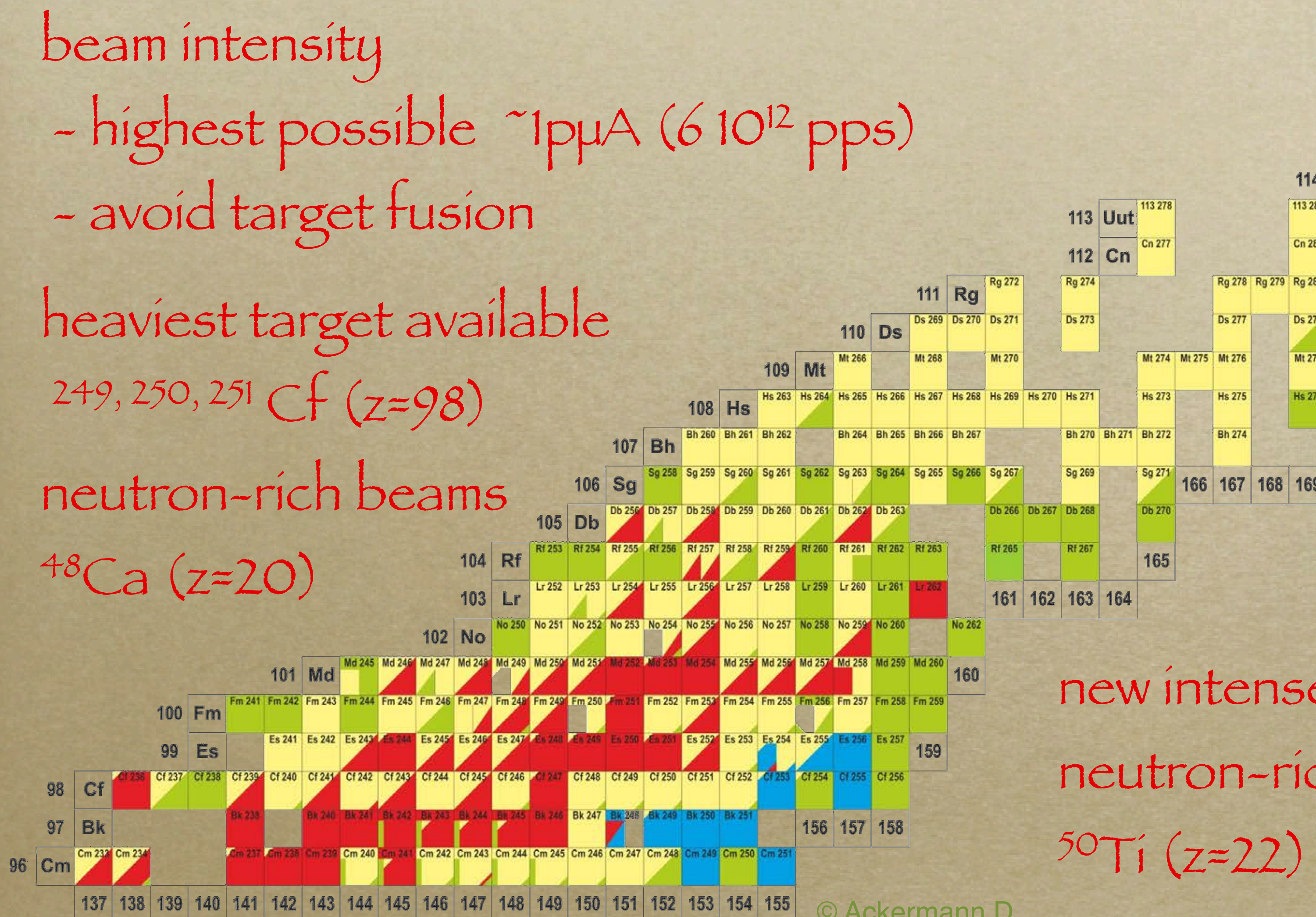
- highest possible ~1pμA (6 10^{12} pps)
- avoid target fusion

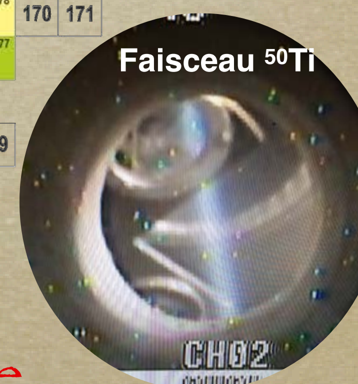
heaviest target available

$^{249, 250, 251}$Cf (z=98)

neutron-rich beams

^{48}Ca (z=20)





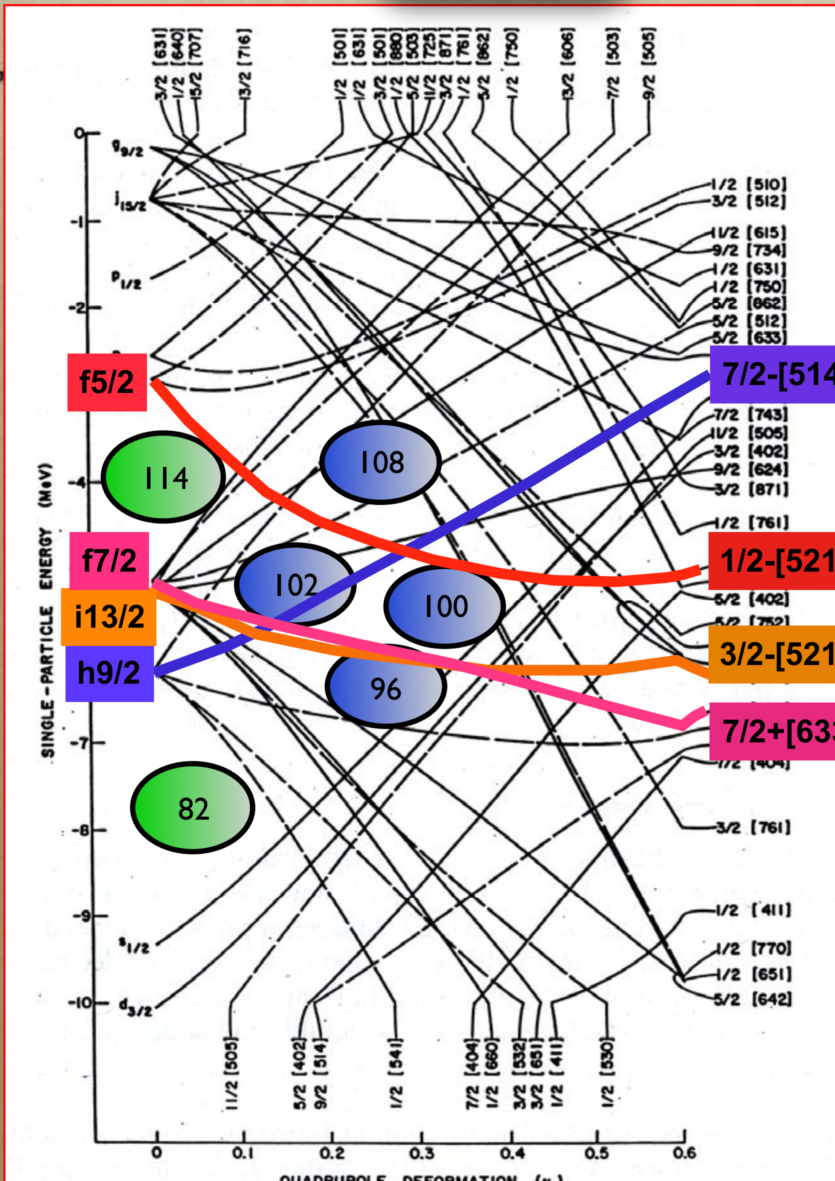
new intense

neutron-rich beam

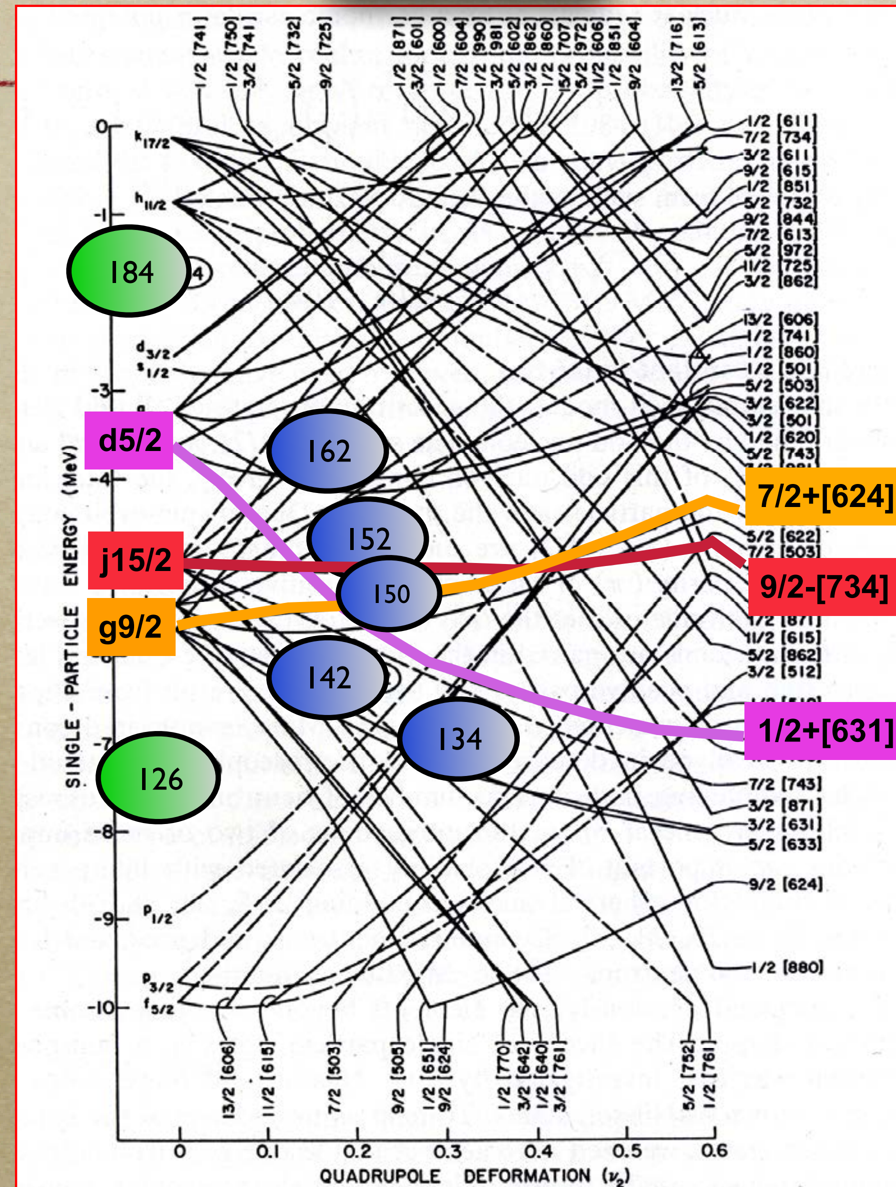
^{50}Ti (z=22)

What can we learn from γ-e⁻ spectroscopy ?

Protons

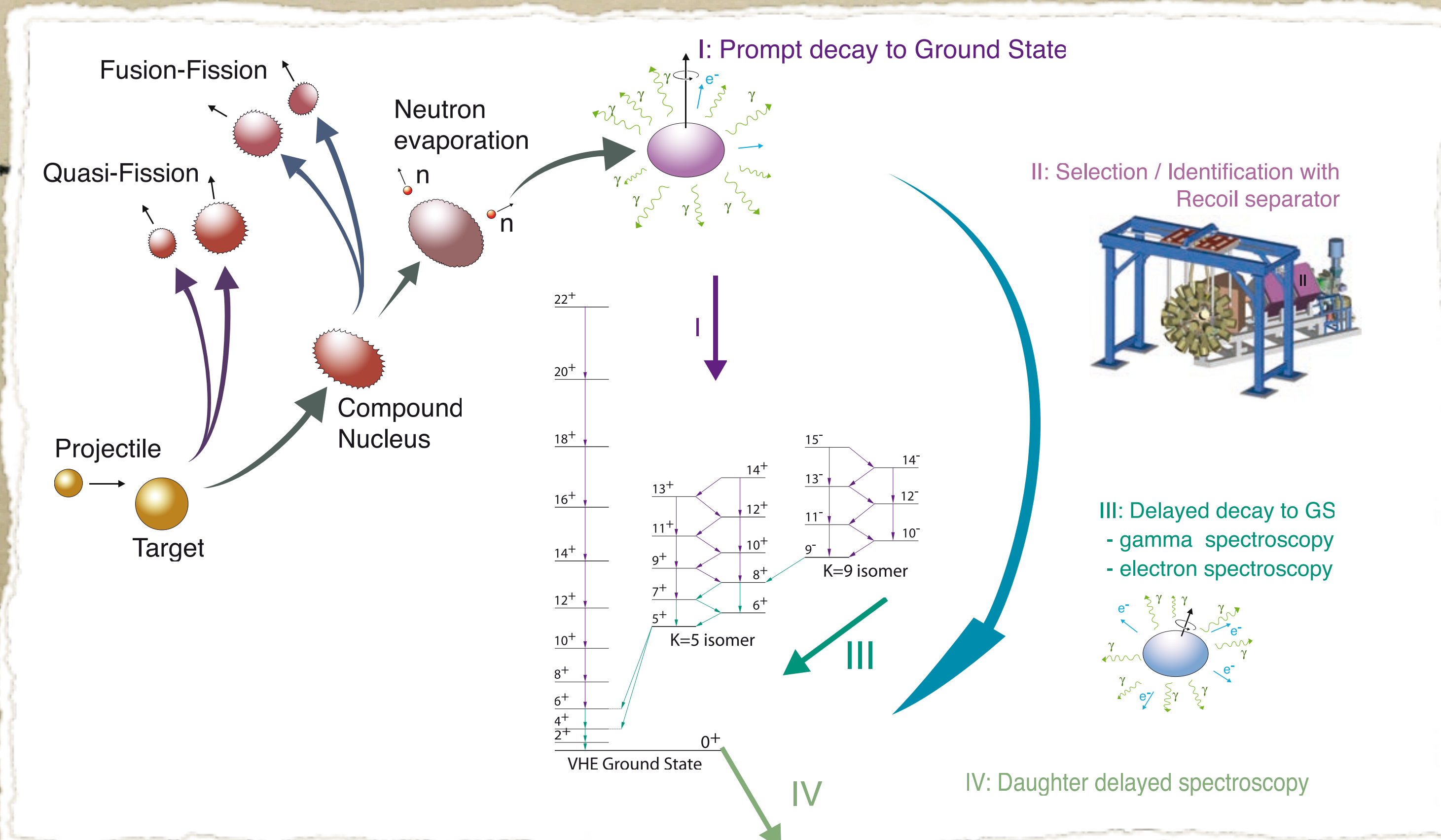


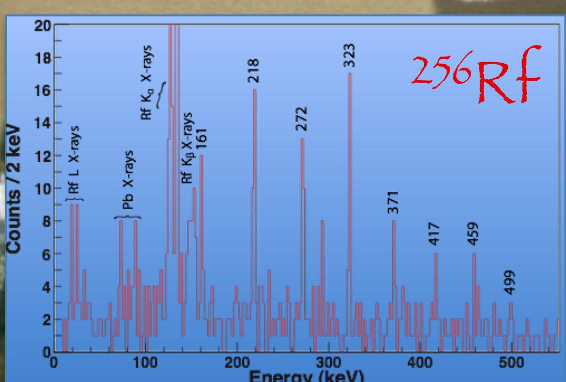
Neutrons



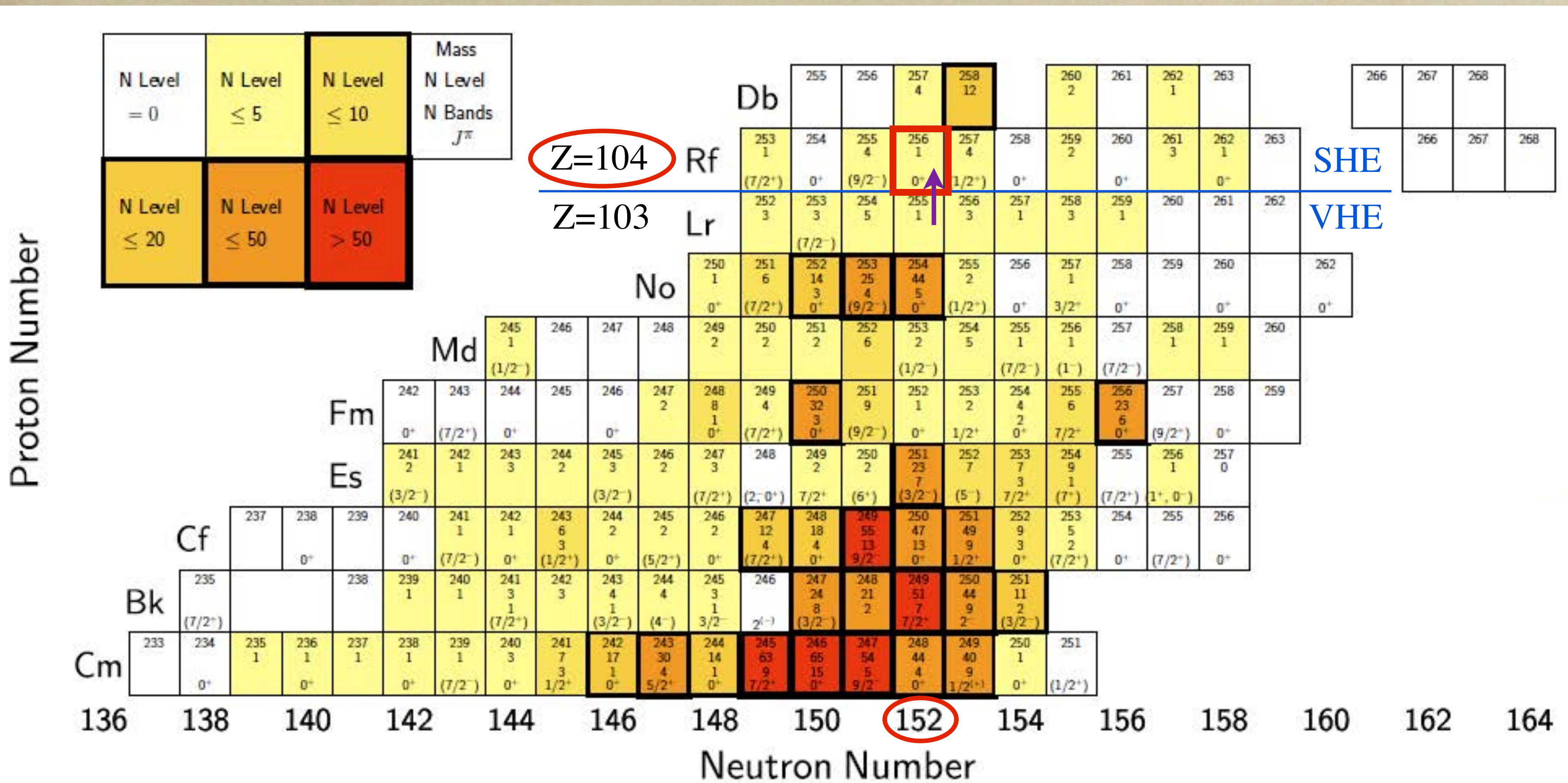
Limits for prompt spectroscopy

...counting rate in Ge detectors ...





Transfermium region spectroscopy



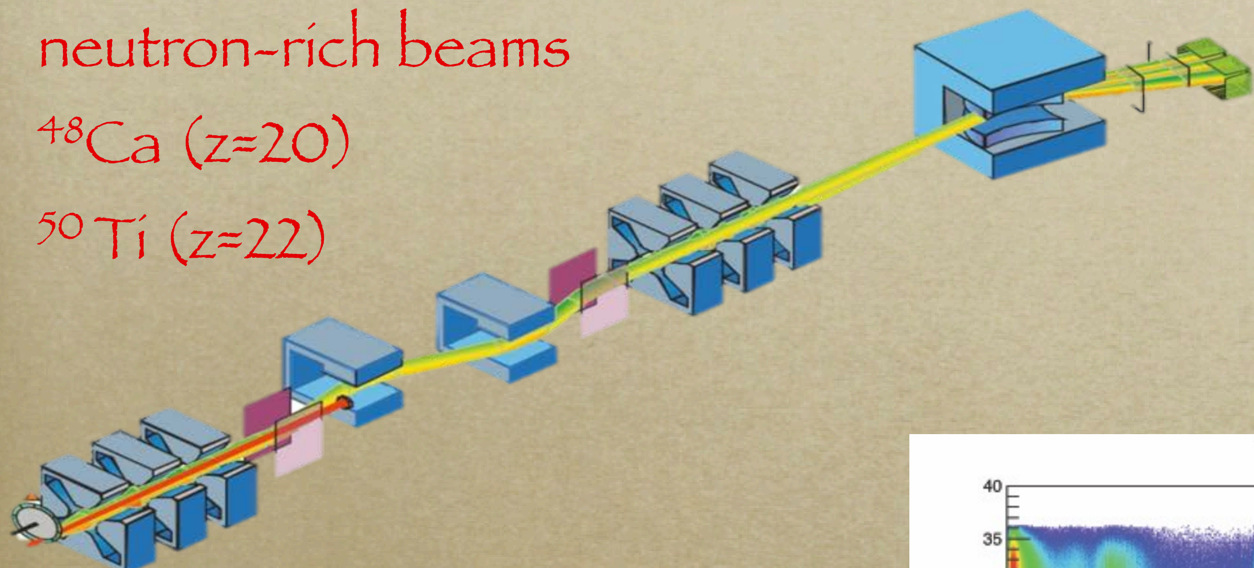
P. Greenlees, R.D. Herzberg, PPNP 61 (2008), 674

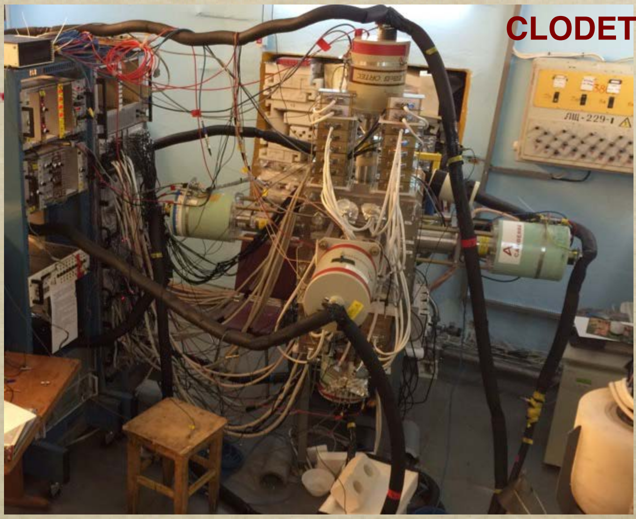
Limits for delayed spectroscopy

neutron-rich beams

^{48}Ca (z=20)

^{50}Ti (z=22)

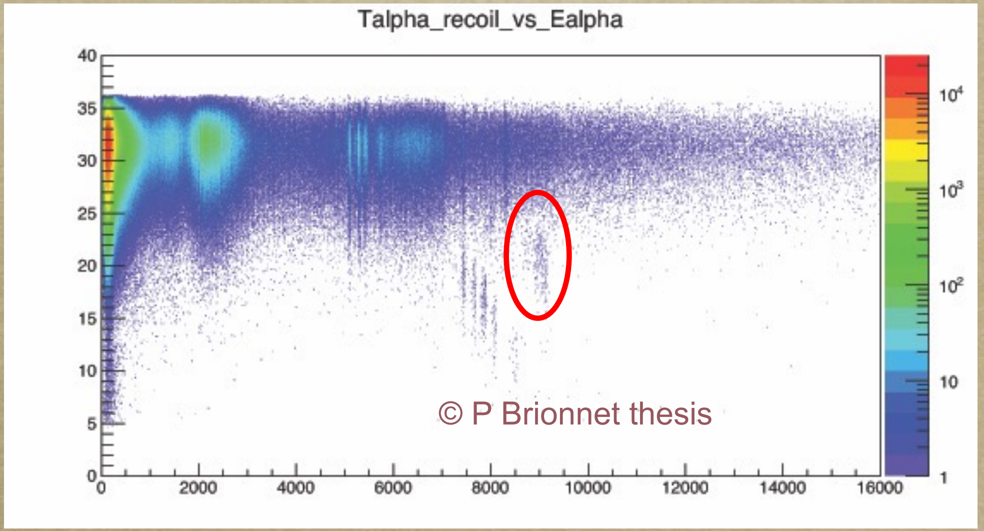




beam intensity

- highest possible ~0.6 pμA
- avoid target fusion

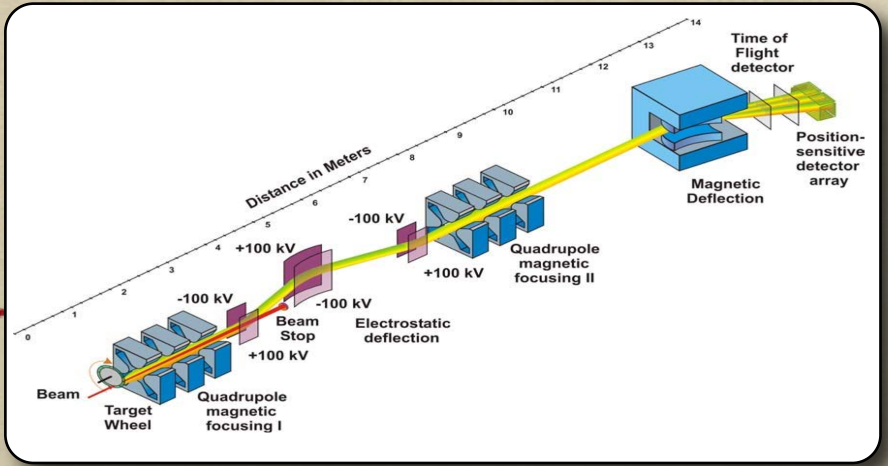
targets available

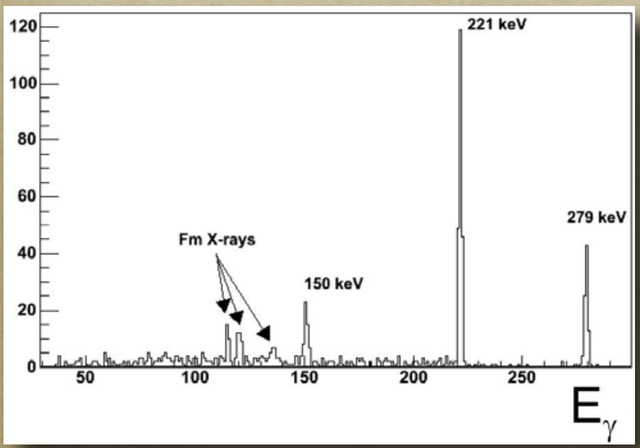


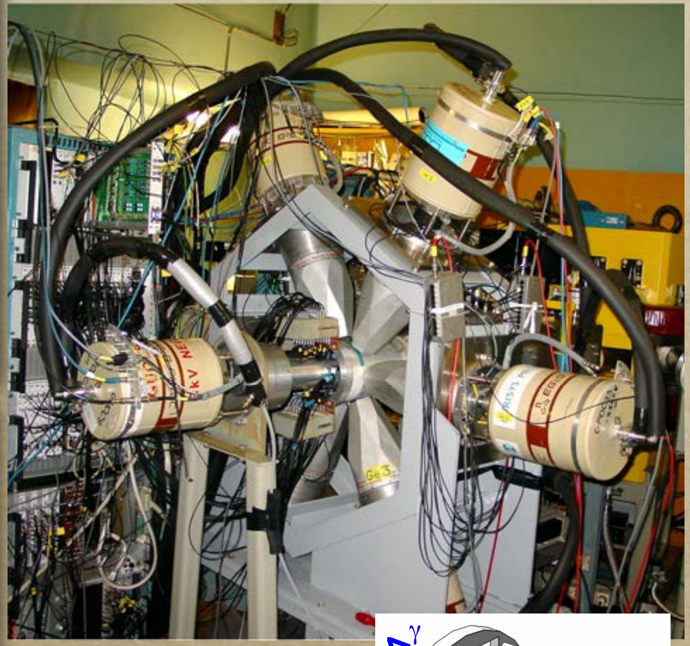
VASSILISSA - "VASSILISSA" electrostatic separator was put into operation in 1987. It's one of the FLNR's basic setups for synthesis of superheavy elements. In 2005 the experiments on study of decay properties of transfermium elements using gamma- and electrton spectroscopy methods were performed for the first time. This work has become feasible thanks to cooperation with French scientists.

Example with GABRIELA

Spectra of ^{249}Fm at focal plane



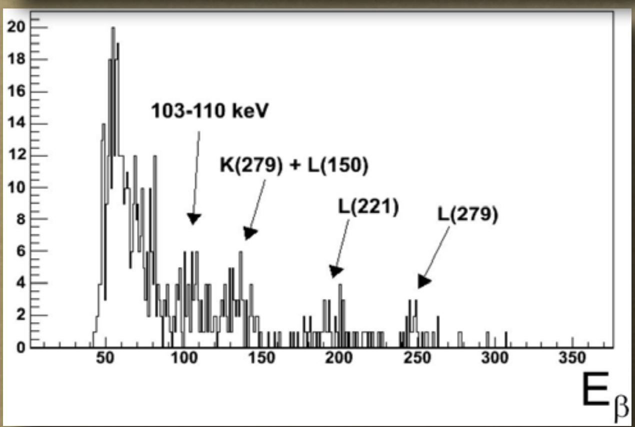




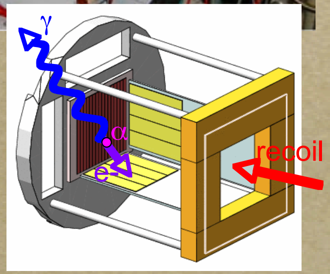
7 detectors Ge+BGO- AC (@IreS)
detection Gamma :
10% efficacité @200 keV

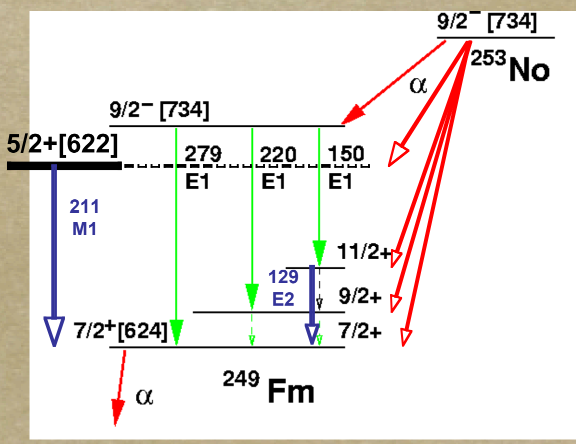
60x60 mm^2 16 strips Si detector
SI at vassilissa focal planede Vassilissa
implantation ER & alpha detection
efficiency : 50%

Four 50x50 mm^2 4-strip Si@IN2P3
Preamplifiers developed @GANIL
detection Electron & escape as
20% efficacité @200 keV



K. Hauschild, A.V. Yeremin et al., Nucl. Instr. Meth. A 560 (2006) 388





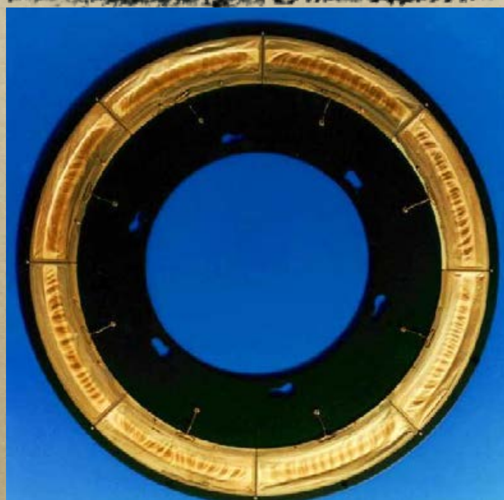
Spectroscopy of trans uranium (VHE)

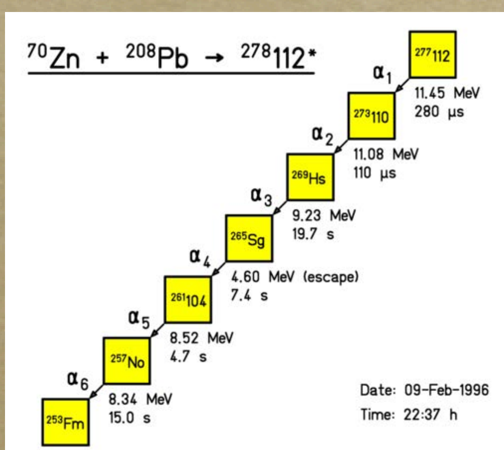
Super Heavy Elements (SHE)

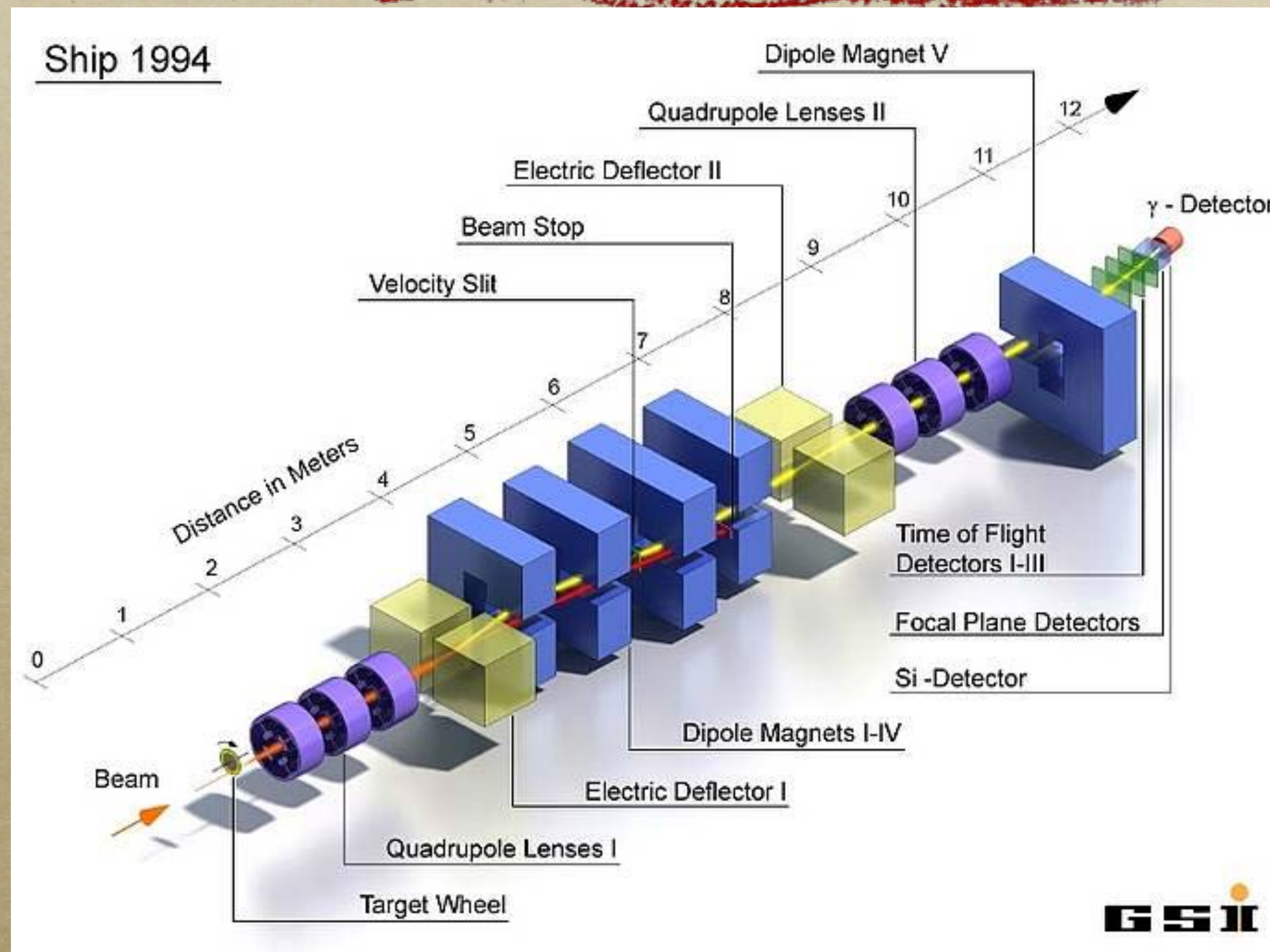
outline

- Nuclear stability and limits of existence
- Manifestation of quantum world
- Production probability
- How to produce SHE
- How to identify SHE
- What physical properties can we measure ?
- What chemical properties can we measure ?

Needs efficient separators

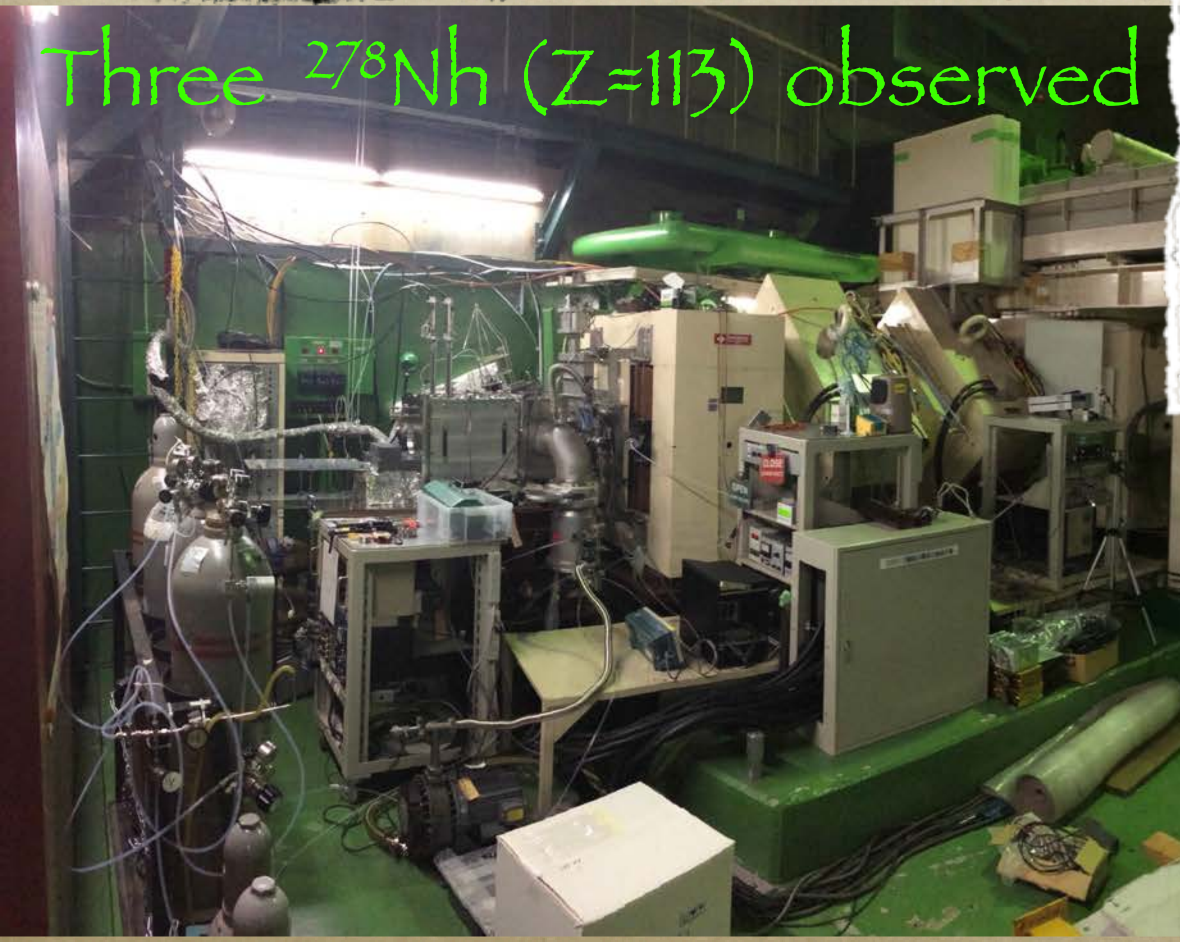






SHIP (@GSI) discovery of elements 107-112

Needs efficient separators



Three ^{278}Nh (Z=113) observed

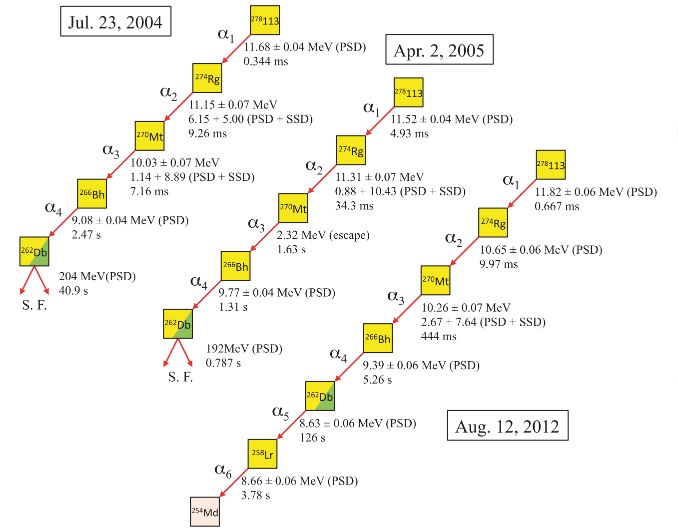


Fig. 3. (Color) Observed decay chain in the present work together with previously observed chains.[1,2)]

GARIS I (@RIKEN) Nh in 3 years of beam time)

Needs efficient separators

Three ^{278}Nh (Z=113) observed

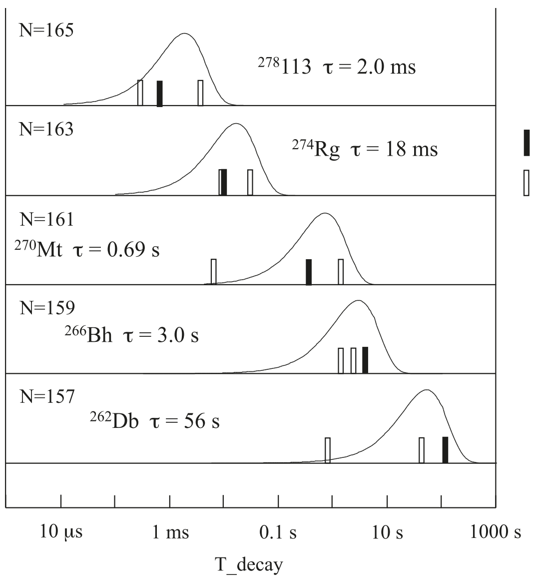


Fig. 2. Decay time (T_decay) distributions of the decay family originating from ^{278}113 are indicated. The logarithm of the decay times is taken as the abscissa. Mean lifetimes τ determined from three decay chains are shown together with the symbols of the nuclides. Curves in the graphs correspond

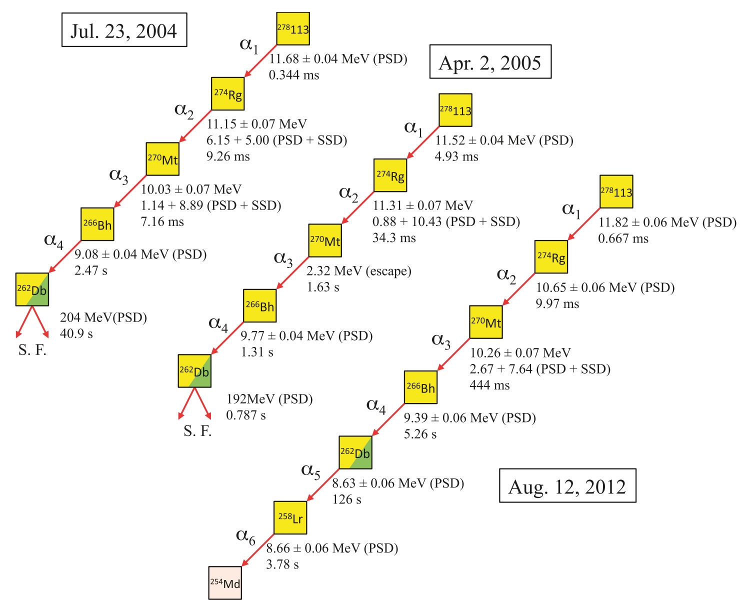
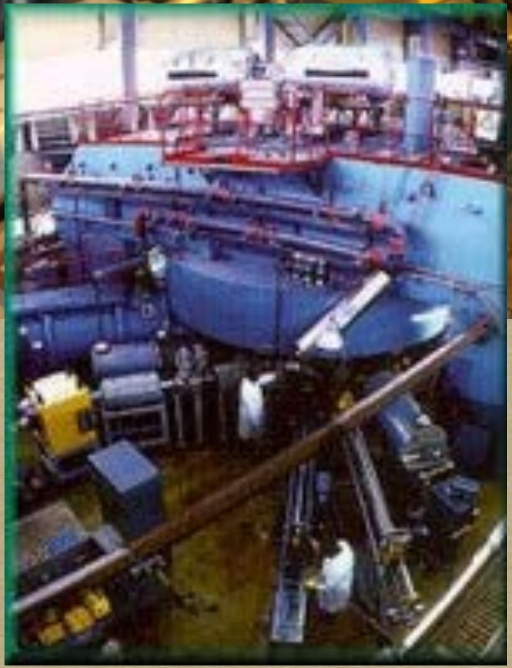


Fig. 3. (Color) Observed decay chain in the present work together with previously observed chains.[1,2]

GARIS I (@RIKEN) Nh in 3 years of beam time)

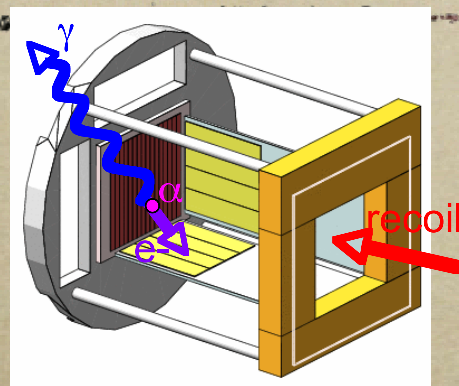
Needs Intense beams & long runs (months)

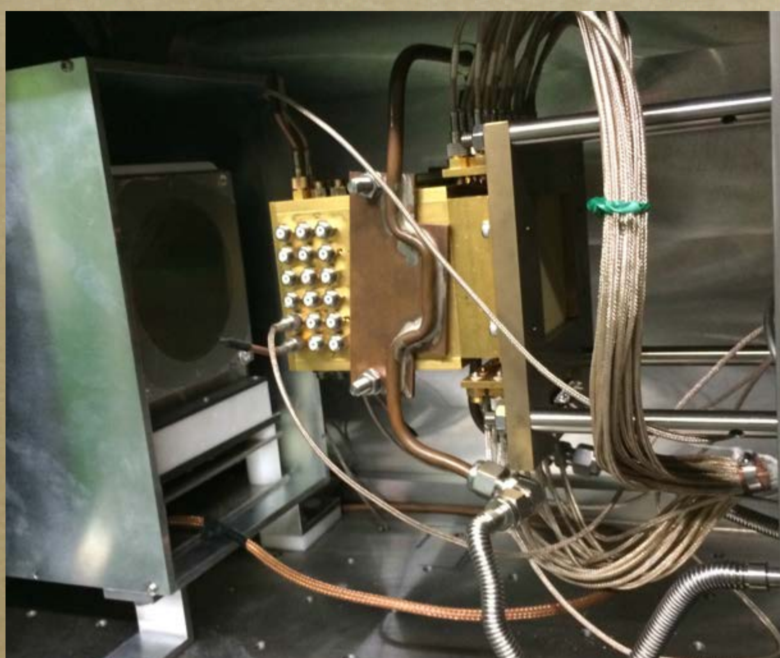


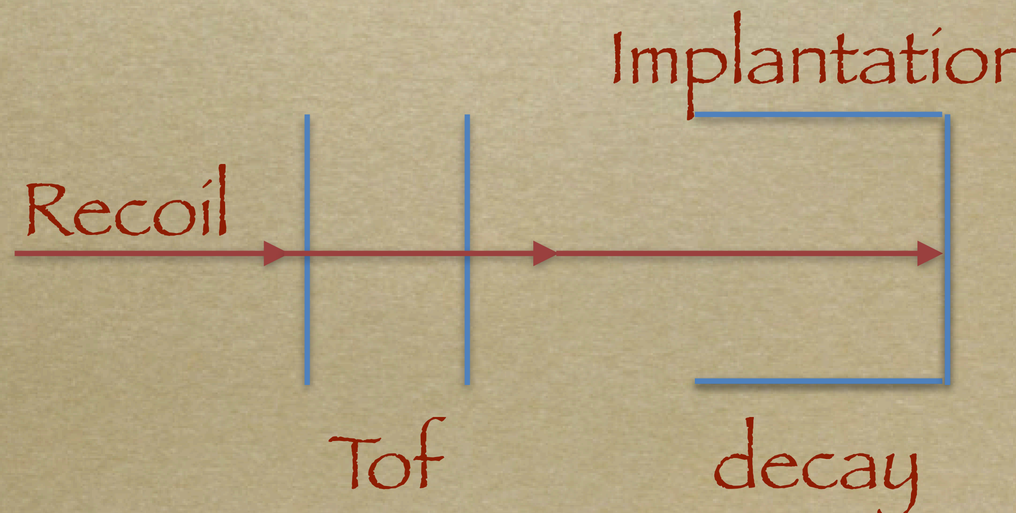
DGFRS (@FLNR Dubna)

GFRS - Dubna gas-filled separator of recoil nuclei was put into operation in 1989. The separator is one of the FLNR basic research setups. A number of unique experiments on synthesis of new superheavy elements, among them Elements 112, 113, 114, 115, 116 and 118 of the Periodic Table, were performed here.

Efficient focal plane detection systems







Super Heavy Elements (SHE)

outline

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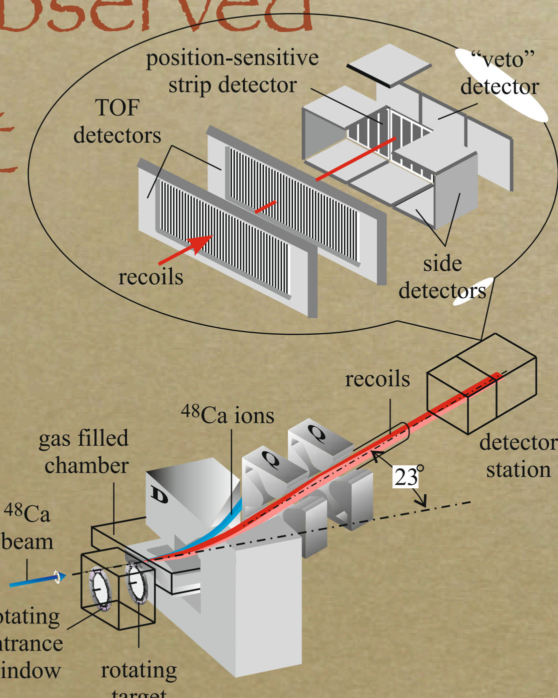
- What chemical properties can we measure ?

SHE properties

Decay Properties of observed SHE



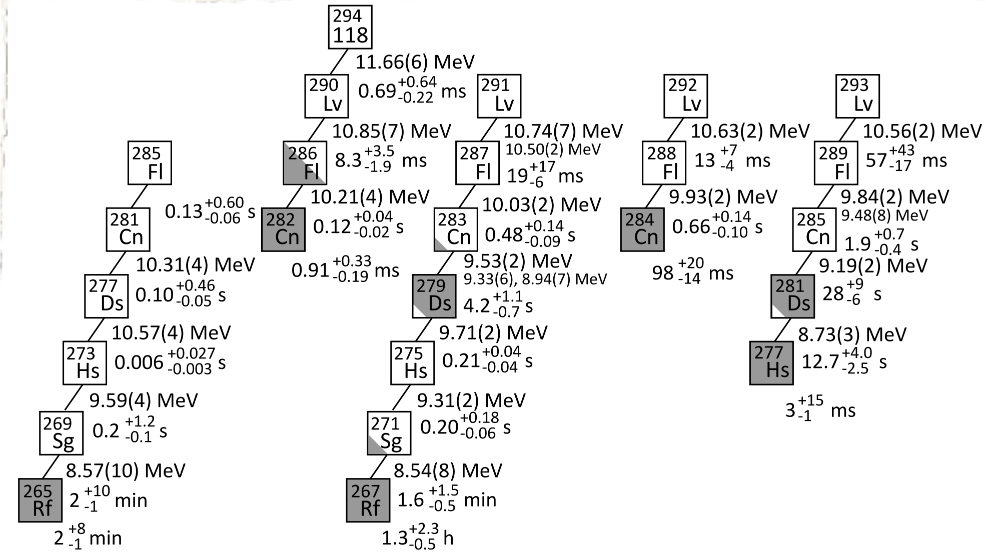


Fig. 3. Summary decay properties of the isotopes of even-Z elements synthesized in the reactions of ^{48}Ca with ^{238}U, ^{242,244}Pu, ^{245,248}Cm, and ^{249}Cf target nuclei. The average energies of α particles and half-lives are given for α emitters (open squares). The energies of rare α lines are given by smaller font. The energy uncertainties given in parenthesis correspond to the data with the best energy resolution. For spontaneously fissioning nuclei marked by grey squares the half-lives are listed.

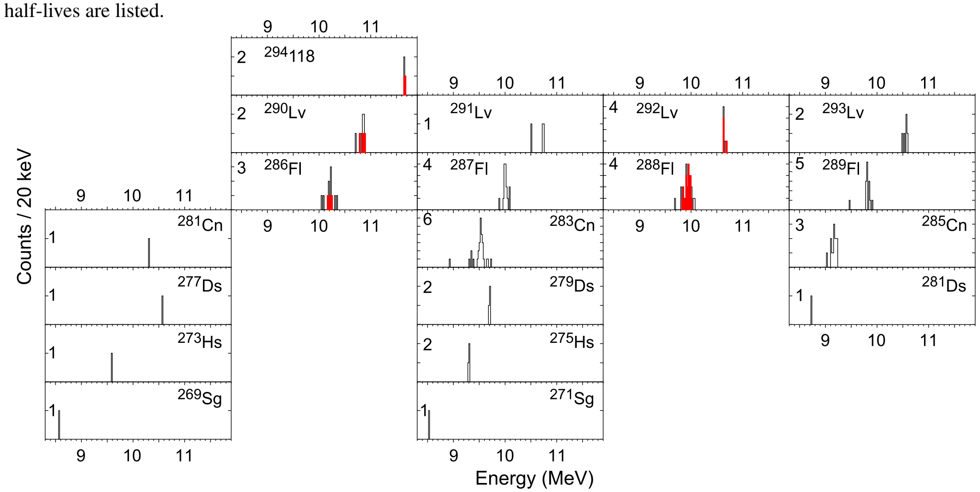


Fig. 7. α-particle energy spectra for even-Z nuclei registered by the focal-plane detector only or together with the side one at DGFRS [48,49,56,68–71,73,74], IVO + COLD [57–61], SHIP [63,72], BGS [46,47], and TASCA [45,65]. Note, the energy resolution of α-particles detected simultaneously by the focal-plane and side detectors was up to 0.20 MeV (spectra for events with energy resolution better than 0.1 MeV shown in red). The data from the IVO + COLD are included if ΔE_α are published.

Yu.Ts.Oganessian*, V.K.Utyonkov Nuclear Physics A 944 (2015) 62–98

SHE properties

Decay Properties of observed SHE

Table 1
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	175	291	d:3, s:1	α	19^{+17}_{-6} ms	10.74 ± 0.07 10.50 ± 0.02	10.89 ± 0.07	[49,71,72]
	174	290	d:11	α	$8.3^{+3.5}_{-1.9}$ ms	10.85 ± 0.07	11.00 ± 0.07	[49,71,73,74]
115	175	290	d:4, t:2	α	650^{+490}_{-200} ms	9.78–10.31	10.41 ± 0.04	[74,86–89]
	174	289	d:16	α	330^{+120}_{-80} ms	10.15–10.54	10.49 ± 0.05	[74,80,81,86–88]
	173	288	d:27, t:19	α	164^{+30}_{-21} ms	10.29–10.58	10.63 ± 0.01 ≈ 10.7 [83]	[75,76,80,81,83,84]
	172	287	d:2, t1	α	37^{+44}_{-13} ms	10.61 ± 0.05	10.76 ± 0.05	[75,76,81,83,84]
114	175	289	d:10, s:1, t:4, tc:1	α	$1.9^{+0.7}_{-0.4}$ s	9.84 ± 0.02 9.48 ± 0.08	9.98 ± 0.02	[45,48,49,62,65,68–70,72]
	174	288	d:17, s:4, t:11, ic:2, tc:1	α	$0.66^{+0.14}_{-0.10}$ s	9.93 ± 0.03	10.07 ± 0.03	[45,49,56,61,62,65,70,72]
	173	287	d:16, s:1, b:1, ic:1	α	$0.48^{+0.14}_{-0.09}$ s	10.03 ± 0.02	10.17 ± 0.02	[46,49,56,61,70–72]
	172	286	d:25, b:2	α: 60^{+10}_{-11}	$0.12^{+0.04}_{-0.02}$ s	10.21 ± 0.04	10.35 ± 0.04	[46,47,49,56,70,71,73,74]
	171	285	b:1	α	$0.13^{+0.60}_{-0.06}$ s			[47]
113	173	286	d:4, t:2	α	$9.5^{+6.3}_{-2.7}$ s	9.61–9.75	9.79 ± 0.05	[74,86–89]
	172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	9.47–10.18	10.01 ± 0.04	[74,80,81,86–88]
	171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	9.10–10.11	10.12 ± 0.01 ≈ 10.3 [83]	[75,76,80,81,83,88,84]
	170	283	d:1, t1	α	75^{+136}_{-30} ms	10.23 ± 0.01	10.38 ± 0.01	[75,76,81,83,84]
	169	282	d:2	α	73^{+134}_{-29} ms	10.63 ± 0.08	10.78 ± 0.08	[82]
112	173	285	d:10, s:1, t:4, ic:1, tc:1	α	28^{+9}_{-6} s	9.19 ± 0.02	9.32 ± 0.02	[45,48,49,60,62,65,68–70,72]
	172	284	d:19, s:4, t:11, ic:2, tc:1	SF	98^{+20}_{-14} ms			[45,49,56,61,62,65,70,72]
	171	283	d:22, s:4, b:1, ic:6	α: ≥ 93	$4.2^{+1.1}_{-0.7}$ s	9.53 ± 0.02 9.33 ± 0.06 8.94 ± 0.07	9.66 ± 0.02	[46,49,56–59,61,63,70,71]

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SHE properties

Decay Properties of observed SHE

Table 1 (*continued*)

Z	N	A	No. observed[a]	Decay mode, branch (%)[b,c]	Half-life[c]	E_α (MeV)	Q_α^{exp} (MeV)	Refs.
	170	282	d:12, b:2	SF	$0.91^{+0.33}_{-0.19}$ ms			[46,47,49,56,70,71]
	169	281	b:1	α	$0.10^{+0.46}_{-0.05}$ s	10.31 ± 0.04	10.46 ± 0.04	[47]
111	171	282	d:4, t:2	α	100^{+70}_{-30} s	8.86–9.05	9.16 ± 0.03	[74,86–89]
	170	281	d:20	SF: 88^{+7}_{-9}	17^{+6}_{-3} s	9.28 ± 0.05	9.41 ± 0.05	[74,80,81,86–88]
	169	280	d:27, t:18	α	$4.6^{+0.8}_{-0.7}$ s	9.09–9.92	9.91 ± 0.01 10.15 ± 0.01 [83]	[75,76,80,81,83,84]
	168	279	d:2, t1	α	90^{+170}_{-40} ms	10.38 ± 0.16	10.53 ± 0.16	[75,76,81,83,84]
	167	278	d:2	α	$4.2^{+7.5}_{-1.7}$ ms	10.69 ± 0.08	10.85 ± 0.08	[82]
110	171	281	d:10, s:1, t:4, ic:1, tc:1	SF: 93^{+5}_{-9}	$12.7^{+4.0}_{-2.5}$ s	8.73 ± 0.03	8.85 ± 0.03	[45,48,49,60,62,65,68–70,72]
	169	279	d:26, s:3, b:1, ic:6	SF: 89^{+4}_{-6}	$0.21^{+0.04}_{-0.04}$ s	9.71 ± 0.02	9.85 ± 0.02	[46,49,56–59,61,63,70–72]
	167	277	b:1	α	$0.006^{+0.027}_{-0.003}$ s	10.57 ± 0.04	10.72 ± 0.04	[47]
109	169	278	d:3, t:2	α	$4.5^{+3.5}_{-1.3}$ s	9.38–9.55	9.58 ± 0.03	[74,86–89]
	168	277	d:2	SF	5^{+9}_{-2} ms			[88]
	167	276	d:27, t:16	α	$0.45^{+0.12}_{-0.09}$ s 6^{+5}_{-3} s	9.17–10.01	10.03 ± 0.01 10.10 ± 0.01 [83]	[75,76,80,81,83,84]
	166	275	d:2, t1	α	20^{+24}_{-7} ms	10.33 ± 0.01	10.48 ± 0.01	[75,76,81,83,84]
	165	274	d:2	α	440^{+810}_{-170} ms	10.0 ± 1.1 9.76 ± 0.10	10.2 ± 1.1	[82]
108	169	277	t:1	SF	3^{+15}_{-1} ms			[45,65]
	167	275	d:3, s:1	α	$0.20^{+0.18}_{-0.06}$ s	9.31 ± 0.02	9.45 ± 0.02	[56,70–72]
	165	273	b:1	α	$0.2^{+1.2}_{-0.1}$ s	9.59 ± 0.04	9.73 ± 0.04	[47]
107	167	274	d:4, t:2	α	44^{+34}_{-13} s	8.73–8.84	8.94 ± 0.03	[74,86–89]
	165	272	d:27, t:17	α	$10.9^{+2.0}_{-1.5}$ s	8.55–9.15	9.18 ± 0.01 9.21 ± 0.01 [83]	[75,76,80,81,83,84]
	164	271	d:1, t1	α	$1.5^{+2.8}_{-0.6}$ s	9.28 ± 0.07	9.42 ± 0.07	[81,83,84]
	163	270	d:1	α	61^{+292}_{-28} s	8.93 ± 0.08	9.06 ± 0.08	[82]
106	165	271	d:3, s:1	α: 58 ± 23	$1.6^{+1.5}_{-0.5}$ min	8.54 ± 0.08	8.67 ± 0.08	[56,70–72]
	163	269	b:1	α	2^{+10}_{-1} min	8.57 ± 0.10	8.70 ± 0.10	[47]
105	165	270	d:4, t:2	SF[e]	15^{+10}_{-4} h			[74,86–89]
	163	268	d:27, t:19, lc:20	SF[e]	26^{+4}_{-3} h[d]			[75–78,80,81,83,84]
	162	267	d:2, t1	SF[e]	$1.3^{+1.6}_{-0.5}$ h			[75,76,81,83,84]

(*continued on next page*)

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SHE properties

Decay Properties of observed SHE

Table 1 (*continued*)

Z	N	A	No. observed[a]	Decay mode, branch (%)[b,c]	Half-life[c]	E_α (MeV)	Q_α^{exp} (MeV)	Refs.
	161	266	d:1	SF[e]	22^{+105}_{-10} min			[82]
104	163	267	d:2	SF	$1.3^{+2.3}_{-0.5}$ h			[56,70,71]
	161	265	b:1	SF	2^{+8}_{-1} min			[47]

[a] Number of observed decays at the separators DGFRS (d), SHIP (s), BGS (b), and TASCA (t) as well as in liquid-chemistry (lc) and gas-chemistry experiments at IVO + COLD (ic) and TASCA + COMPACT (tc) setups.
[b] Branch is given for the most probable decay mode (α or SF). It is not shown if only one decay mode was observed.
[c] Error bars correspond to 68%-confidence level.
[d] The value obtained combining the results of physical and chemical experiments.
[e] The SF mode was observed but EC/β^+ or α decay is not excluded.

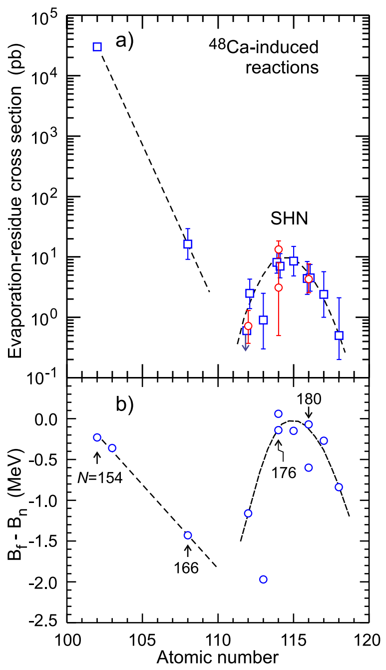

Fig. 6. (a) Maximum cross sections of the production of the isotopes of the heavy elements in hot fusion reactions: ^{208}Pb, ^{226}Ra, ^{233,238}U, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk, and ^{249}Cf + ^{48}Ca ($E^* = 35$–40 MeV). Data measured at DGFRS are shown by blue squares, results obtained at SHIP, BGS, and TASCA are shown by red circles. (b) Difference of fission barrier heights (involving nonaxial shapes) and neutron binding energies of the compound nuclei in ^{48}Ca-induced reactions calculated in the macroscopic–microscopic nuclear model [7,8,103,107,108] and corrected for the odd–even effect are shown. Arrows show number of neutrons in the compound nucleus with the given atomic number. Lines are drawn to guide the eye.

Yu.Ts.Oganessian*, V.K.Utyonkov Nuclear Physics A 944 (2015) 62–98

SHE properties

Decay Properties of observed SHE

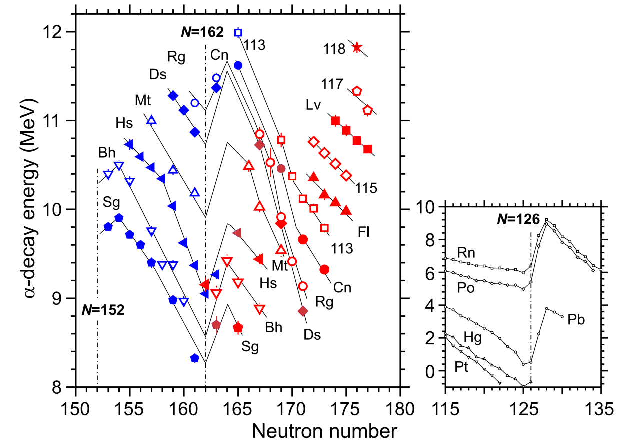

Fig. 10. Measured α-decay energy vs. neutron number for the isotopes of elements 106–118 (filled and open symbols refer to even-Z and odd-Z nuclei, respectively; Q_α values for nuclei produced in the Ra–Cf + ^{48}Ca reactions are shown in red; other data (blue symbols) are taken from [114,115]. The lines are drawn to guide the eye (left panel). The Q_α values for isotopes of even-Z elements Pt–Rn [114,115] are shown for comparison (right panel).

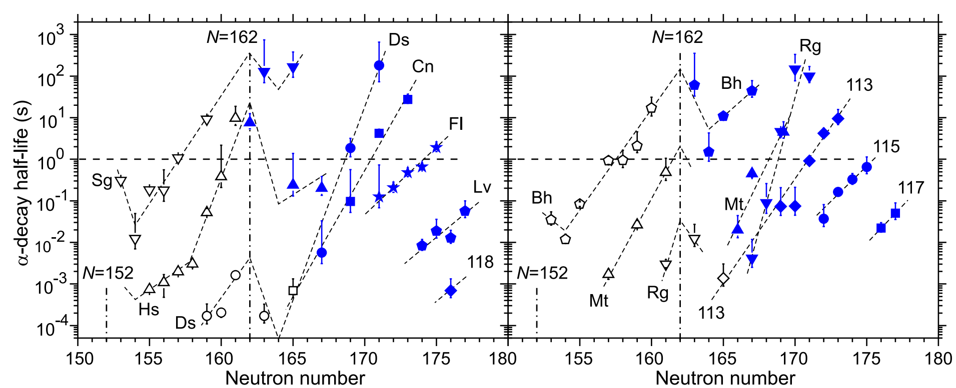

Fig. 11. Half-lives vs. neutron number for the isotopes of even-Z (left panel) and odd-Z (right panel) elements with $Z = 106$–118 (results from Ra–Cf + ^{48}Ca reaction are shown by full blue symbols (see Figs. 3, 5 and Table 1); other data are taken from [116]. Lines are drawn to guide the eye.

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SHE properties

Decay Properties of observed SHE

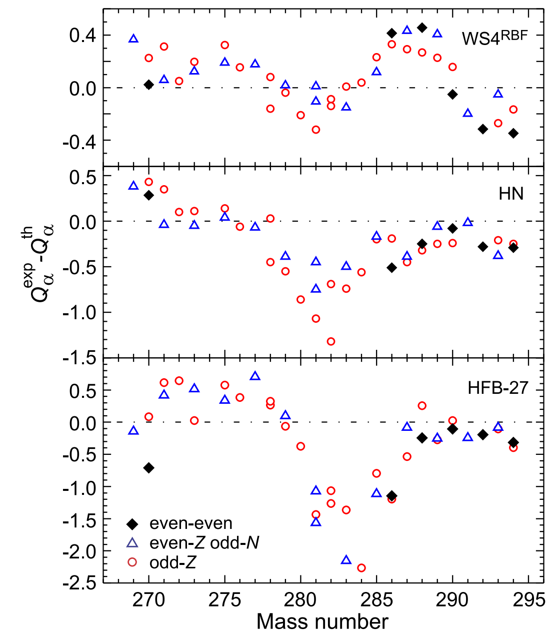
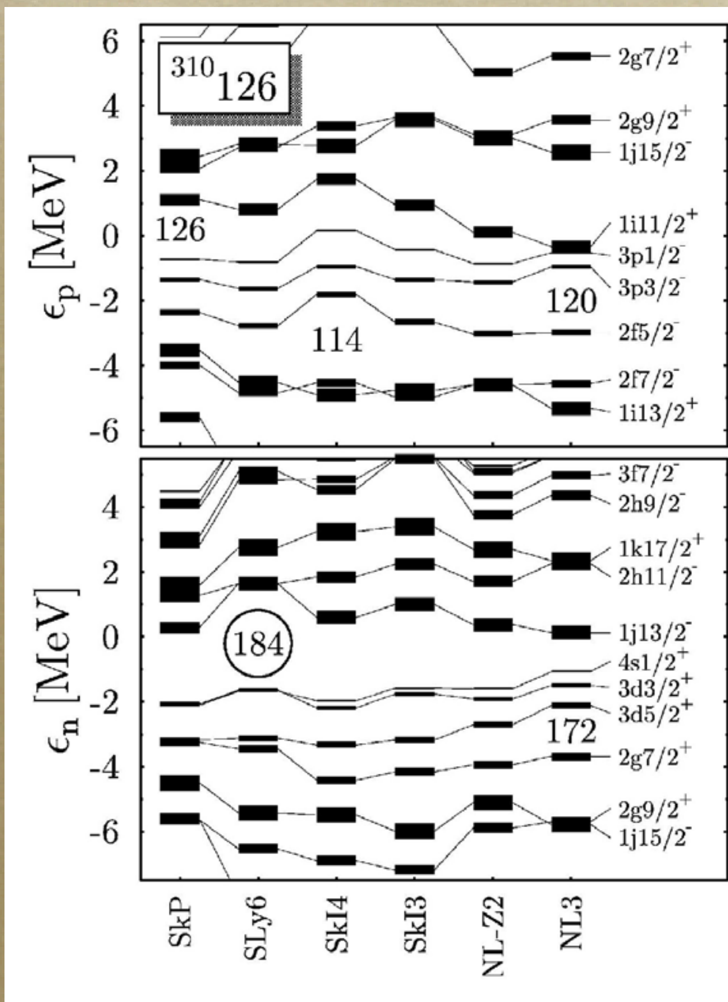
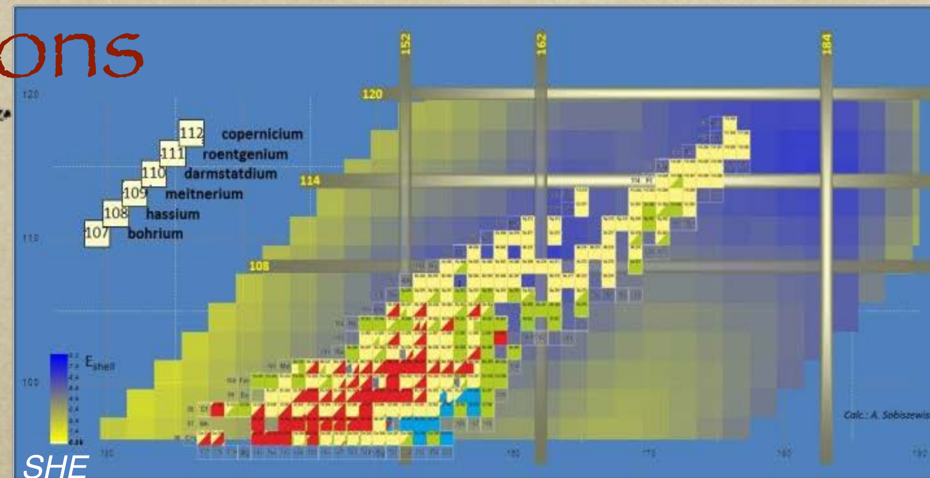


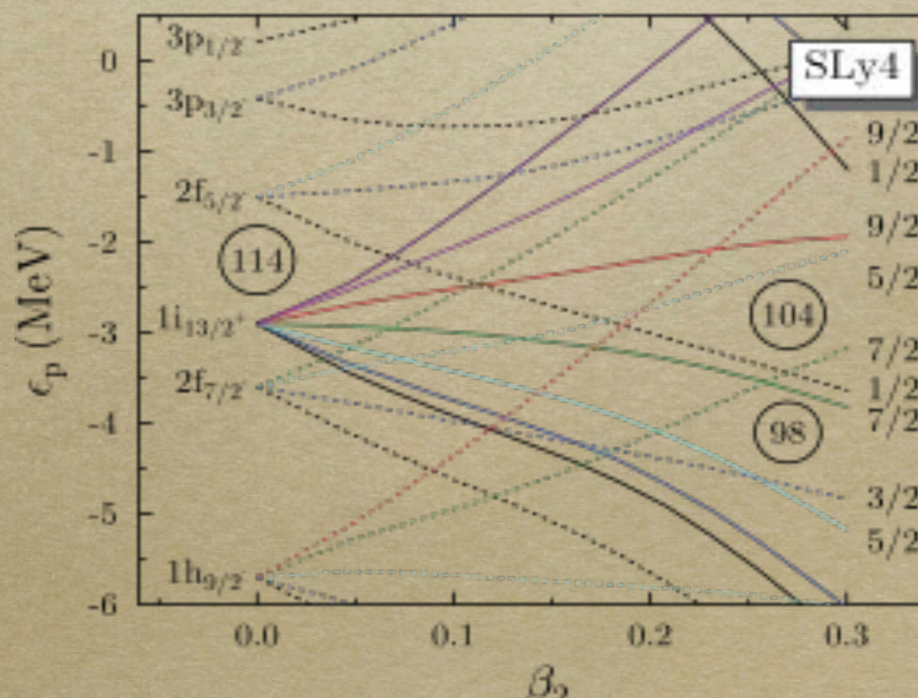
Fig. 12. Deviation between experimental and calculated α-decay energies for even–even, even-Z and odd-N, and odd-Z nuclei. Theoretical Q_α values were taken from [107,108] for macroscopic–microscopic model (HN, middle panel) and mass tables [117] ($WS4^{RBF}$, macroscopic–microscopic model, top panel) and [119] (HFB-27, Skyrme–Hartree–Fock–Bogoliubov model, bottom panel).

Yu.Ts.Oganessian*, V.K.Utyonkov Nuclear Physics A 944 (2015) 62–98

Comparison to theoretical predictions





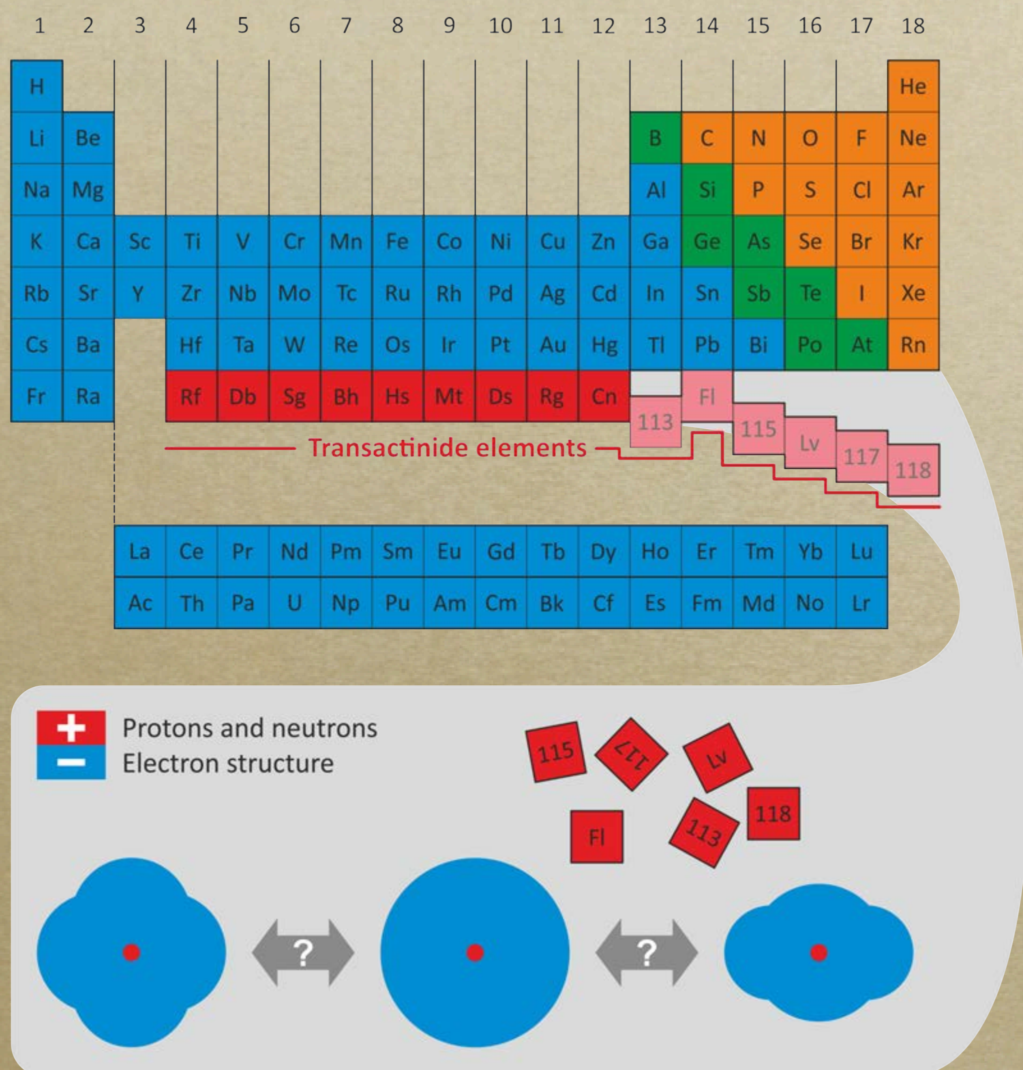


Super Heavy Elements (SHE)

outline

- Nuclear stability and limits of existence
- Manifestation of quantum world
- Production probability
- How to produce SHE
- How to identify SHE
- What physical properties can we measure ?
- What chemical properties can we measure ?

SHE chemical properties



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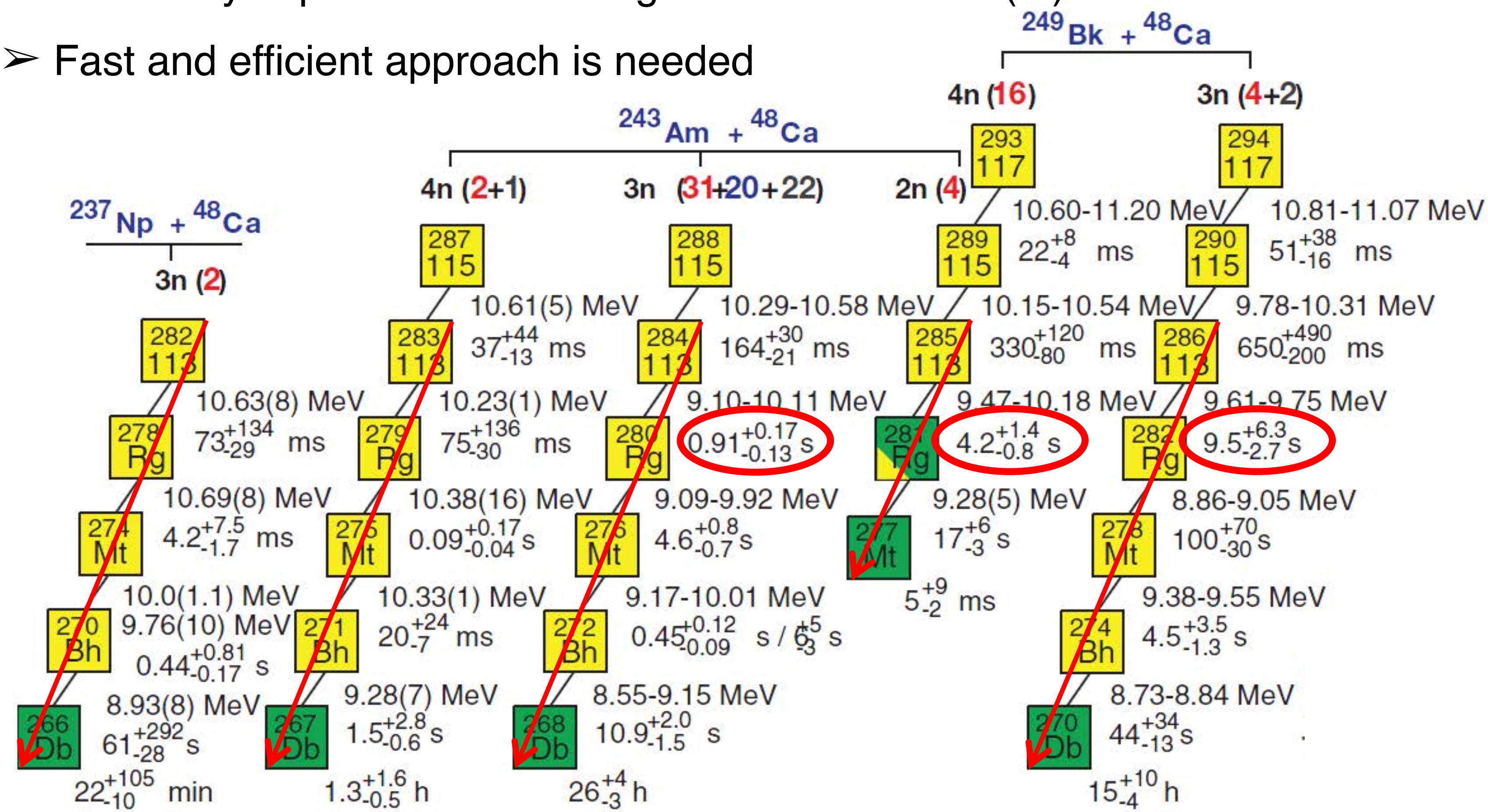
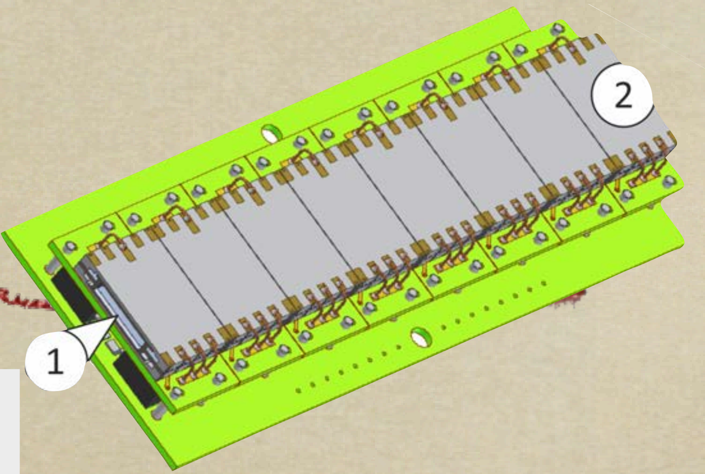
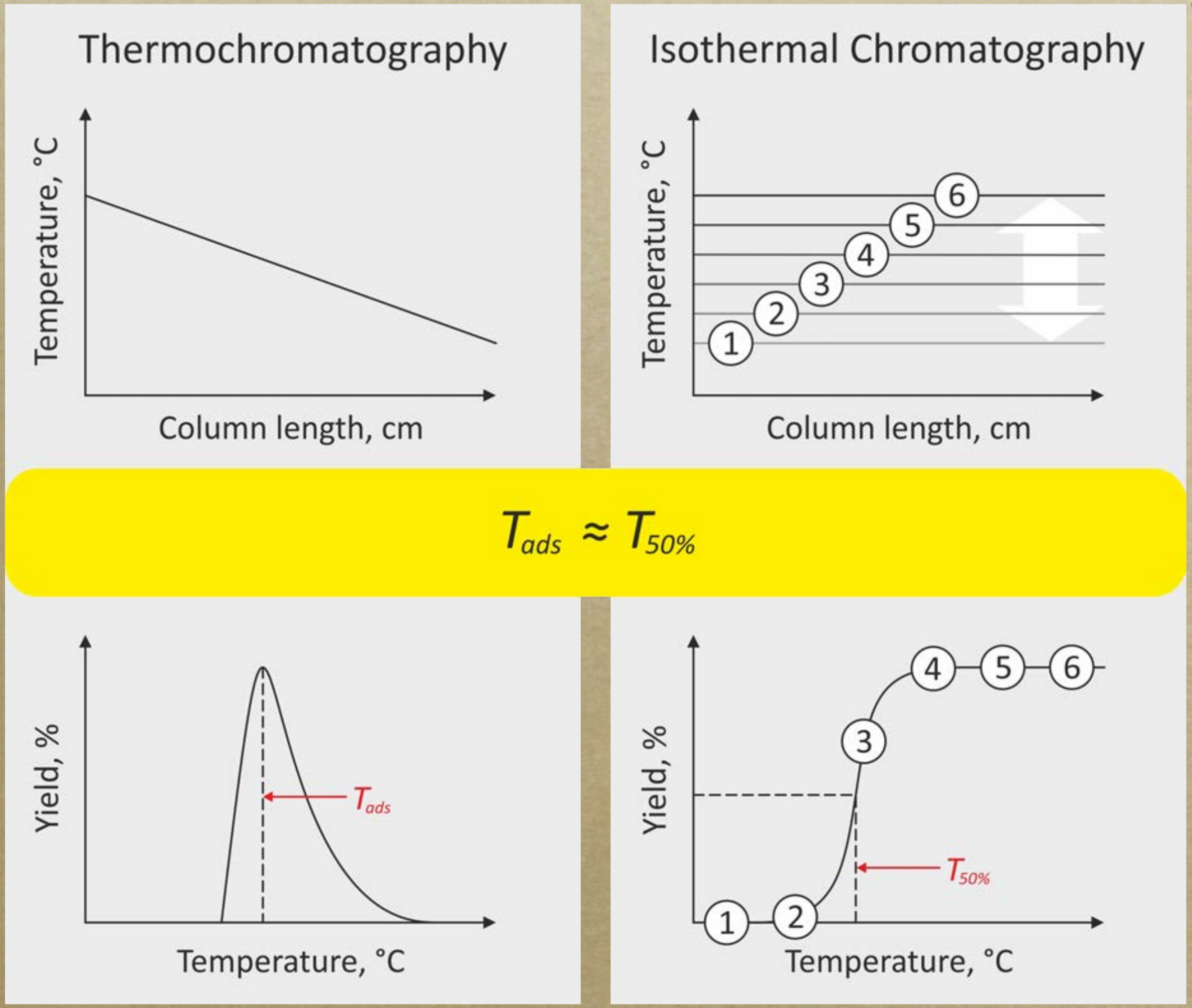
SHE chemical properties

- ➢ Chemistry experiments with single atoms at a time (!)
- ➢ Fast and efficient approach is needed



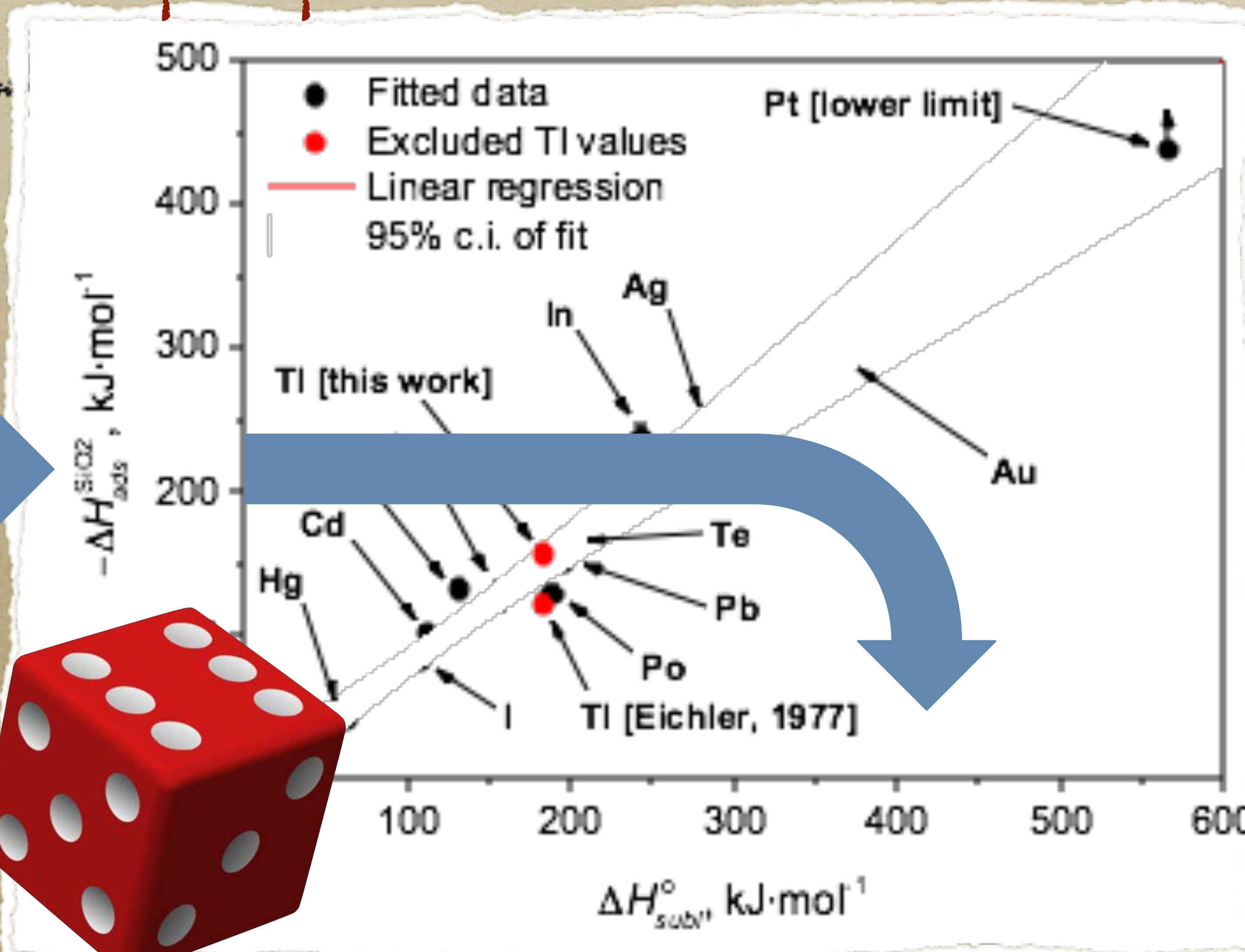
SHE chemical properties





SHE chemical properties

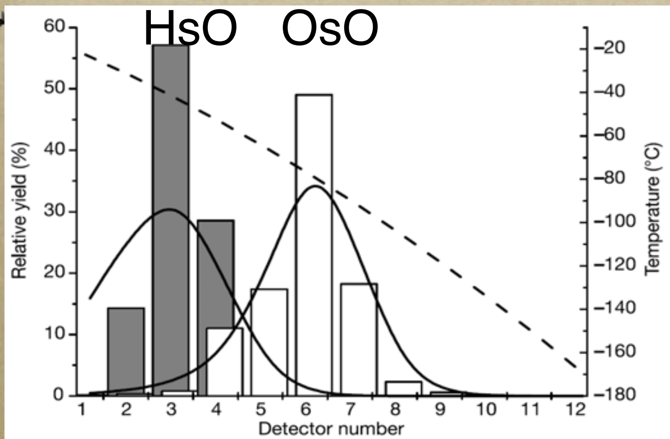
Monte Carlo simulation



Going from a single atom property (adsorption enthalpy, ordinate) to a macroscopic property (sublimation enthalpy, abscissa) —> semi-empirical correlations between the adsorption enthalpy for x elements in a certain chemical state (e.g., elemental form as shown here) on a certain surface (e.g., quartz as shown h —> SiO_2) and the corresponding sublimation enthalpy.

SHE chemical properties

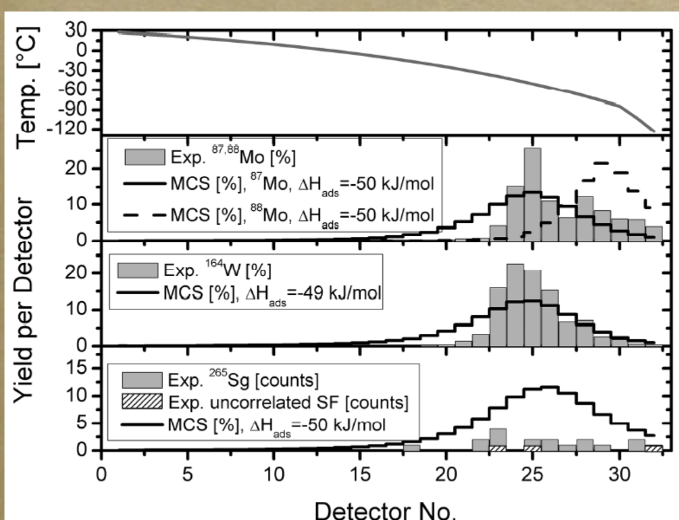
2002



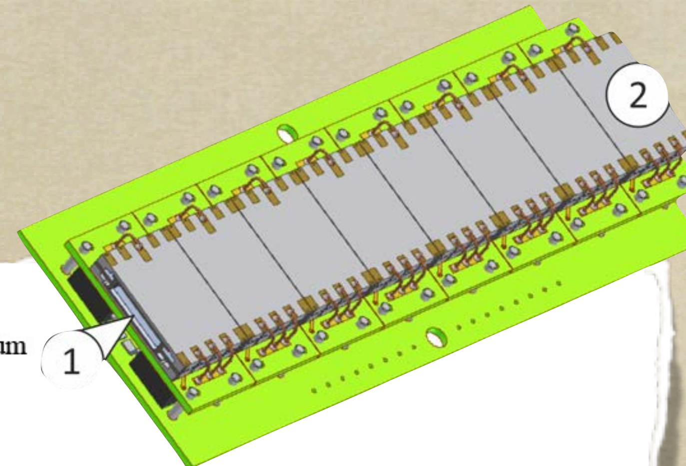
Ch. E. Düllmann et al., *Nature* **418** (2002), pp. 859 – 862

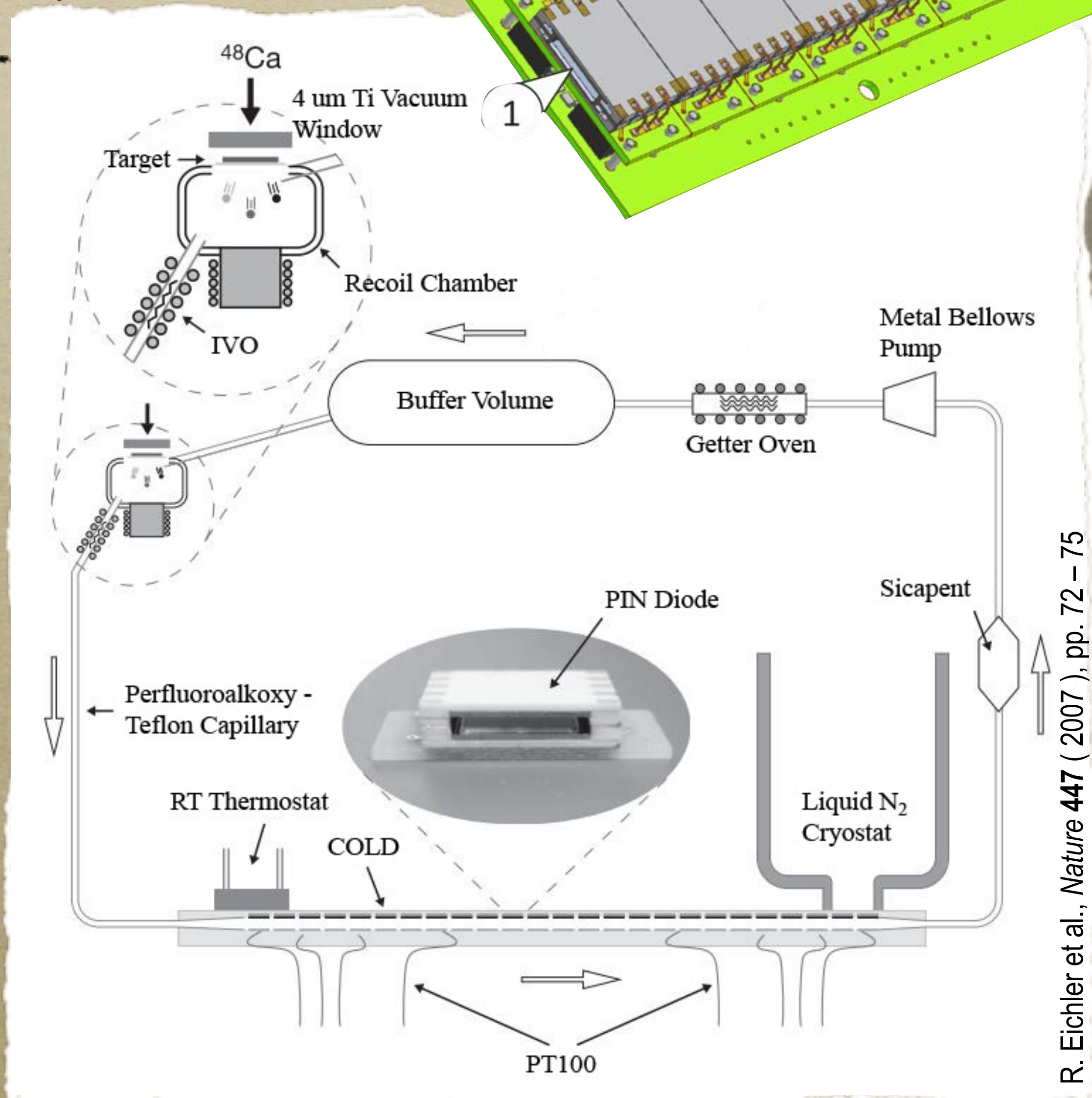
2014

Mo/W/Sg(CO)$_6$



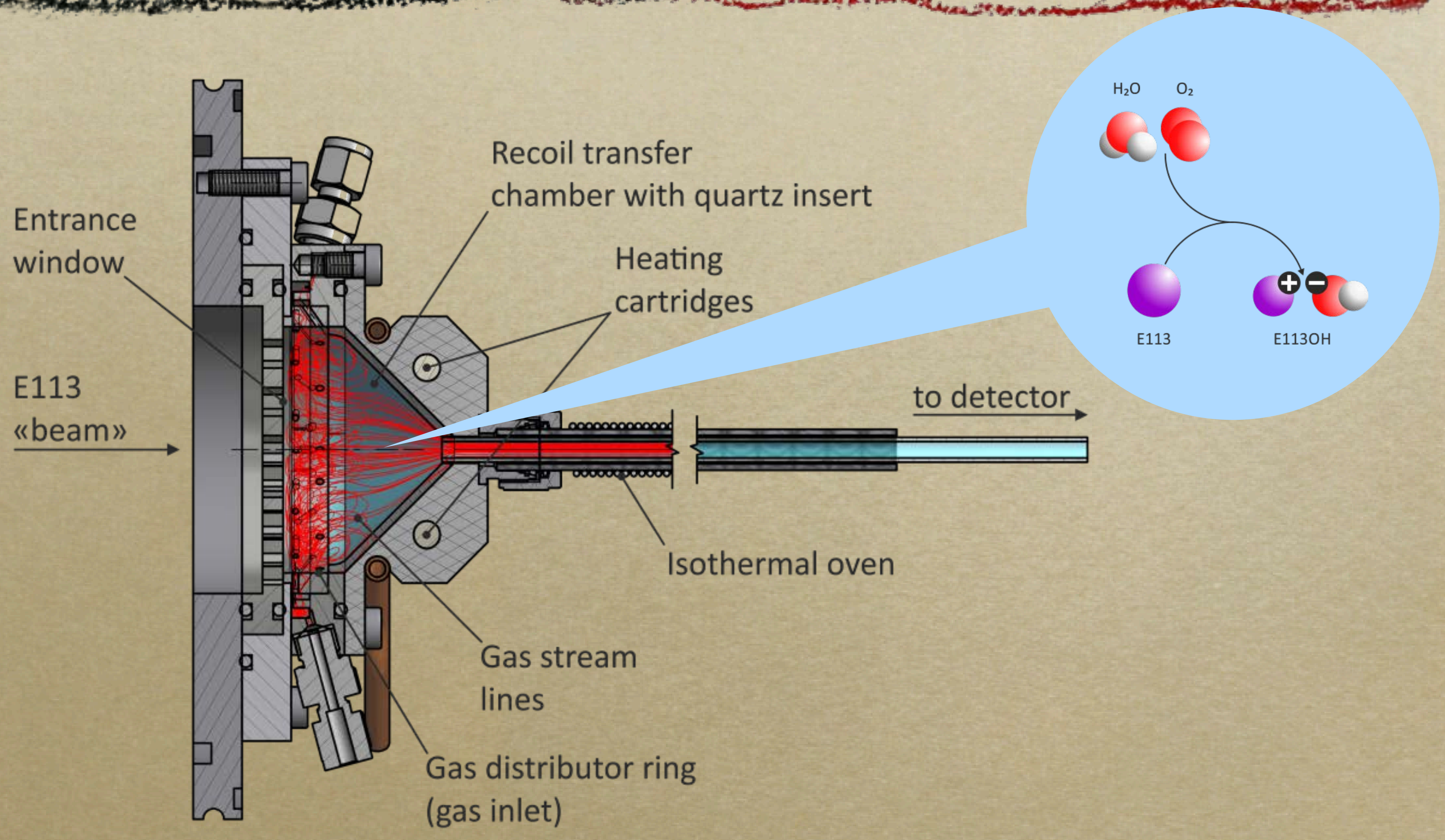
J. Even et al., *Science* **345** (2014), pp. 1491 – 1493





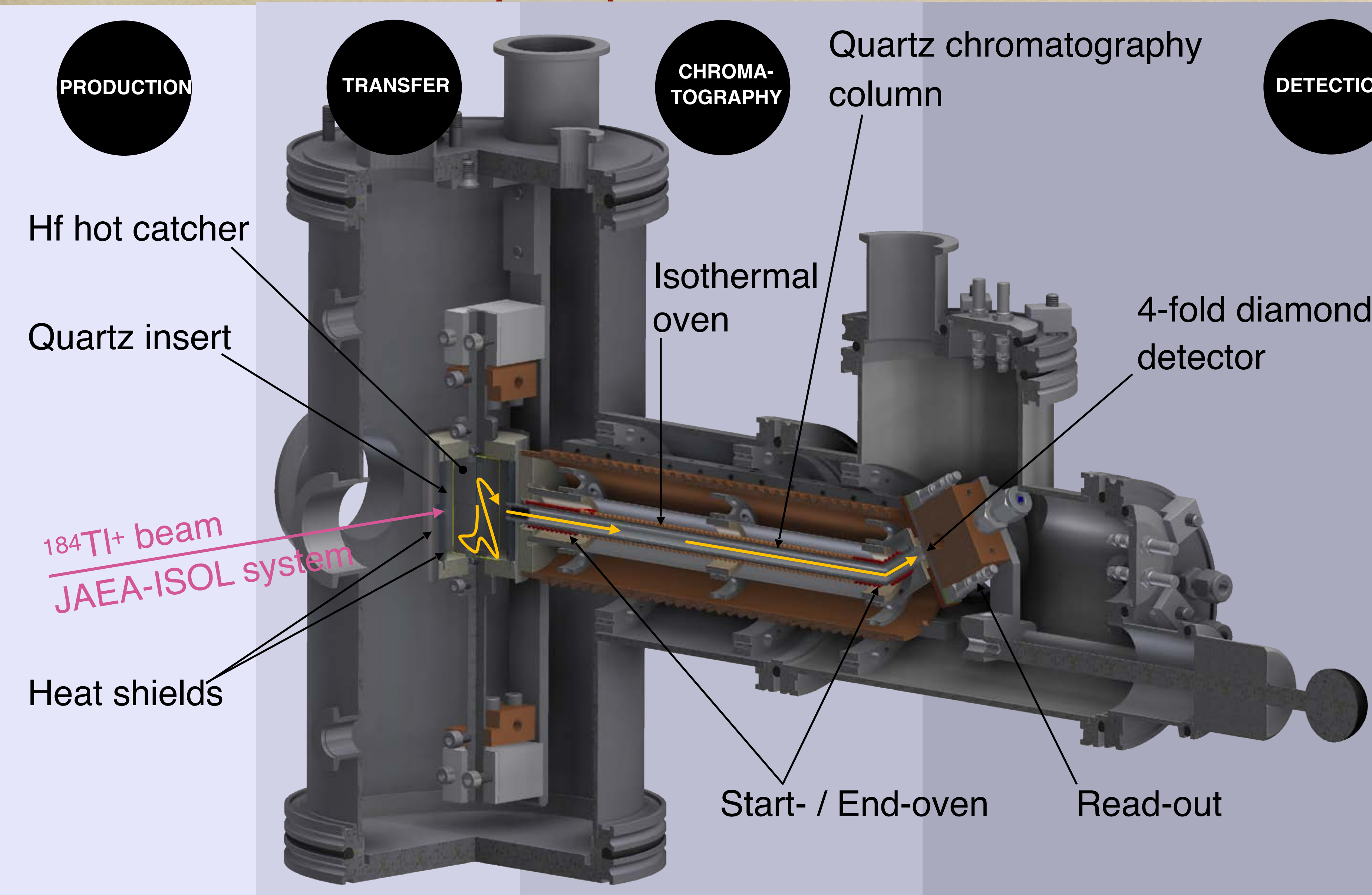
R. Eichler et al., *Nature* **447** (2007), pp. 72 – 75

SHE chemical properties



SHE chemical properties

Development of a faster "gas-phase" technique (actually vacuum) to go to half-lives below 1 s (this is more of less the limit of current state-of-the-art gas phase experiments).

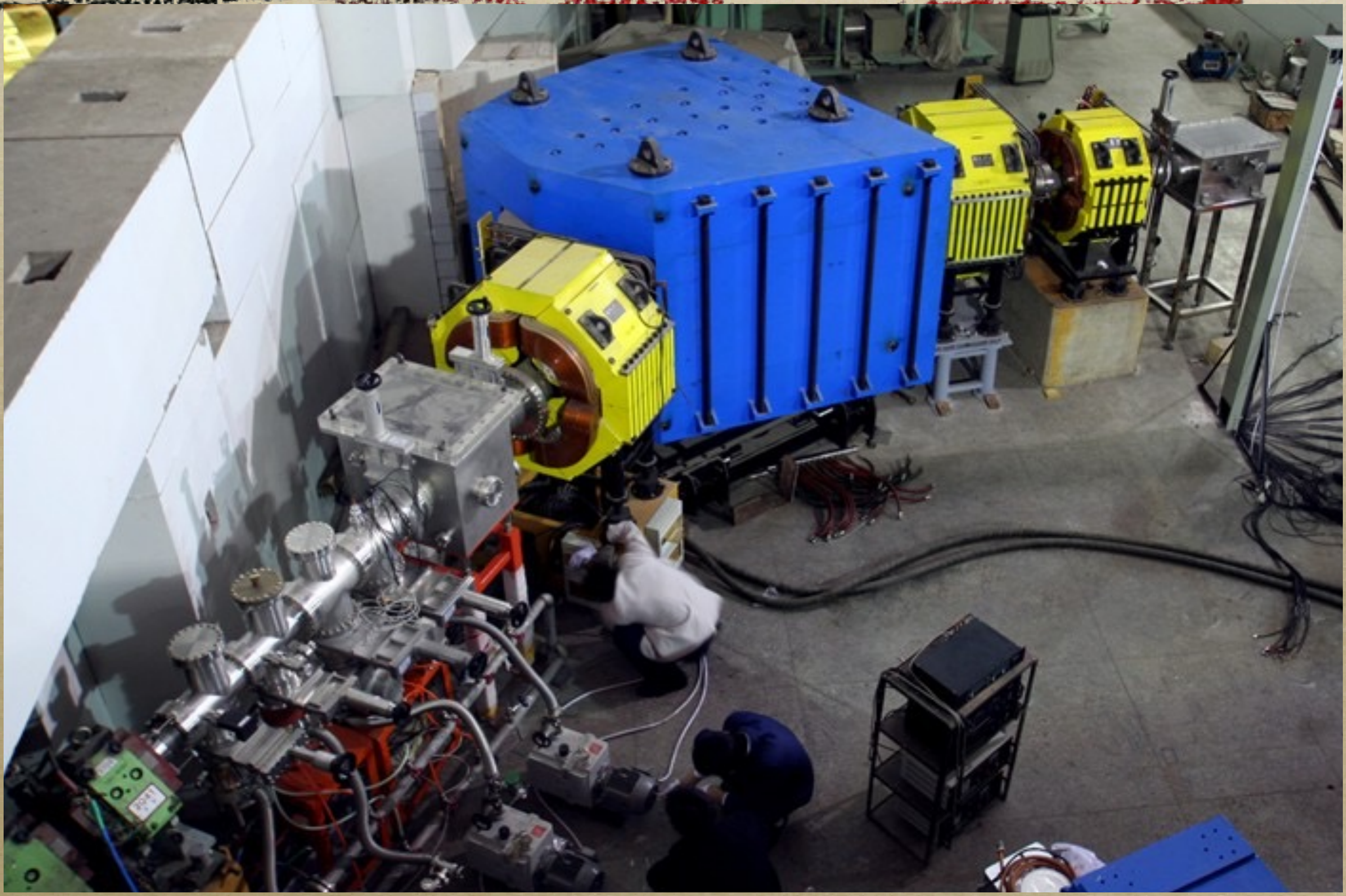


Super Heavy Elements (SHE)

Perspectives ...

Chinese separator for VHE : SHANS ?

Chinese separator for Heavy elements @ Lanzhou

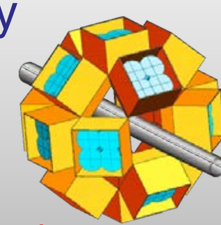


A new gas-filled recoil separator was installed in the HIRFL (Heavy Ion Research Facility, Lanzhou) to separate the evaporation residues (EVRs) from other beam ions and unwanted reaction products. It is filled with helium gas at the pressure of about 0.8mbar. The focal plane detector system consisting a silicon box and a time-of-flight detector was improved.

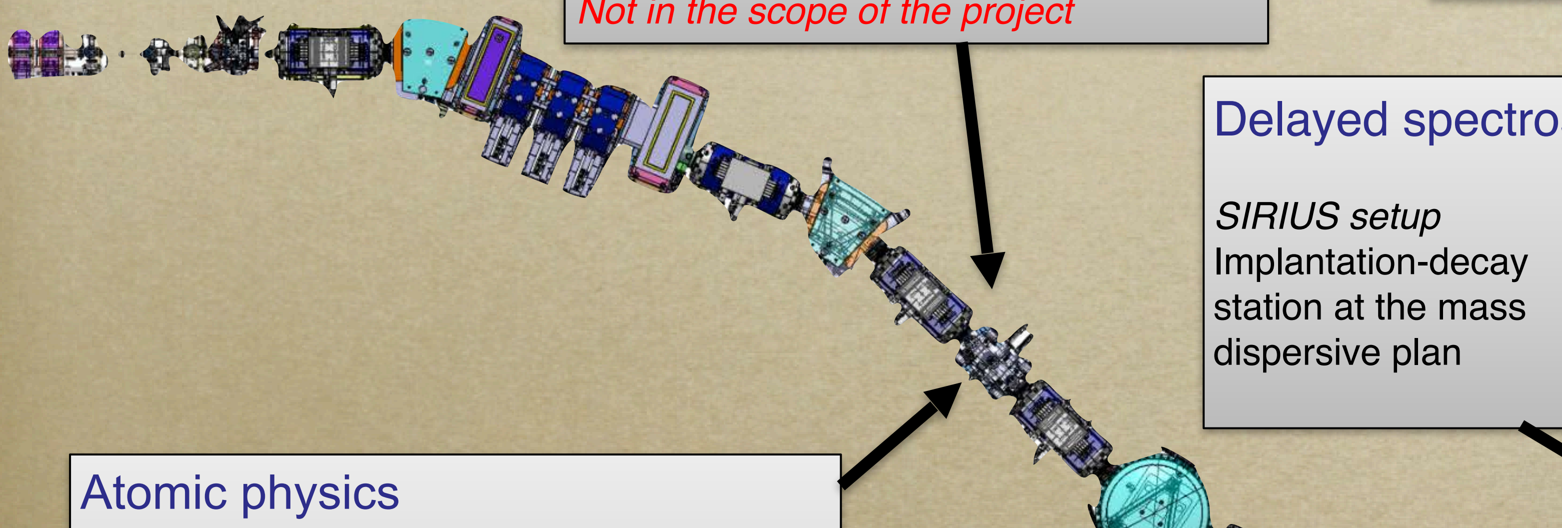
S3 in GANIL

In-beam spectroscopy

Two step reactions
EXOGAM2/AGATA
PARIS
MUST2/GASPARD
Not in the scope of the project

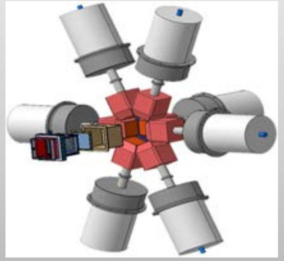


S3 Physics case (15 LoIs)
- VHE – SHE elements
- Proton drip-line and N=Z
- Nuclear astrophysics
- Atomic physics



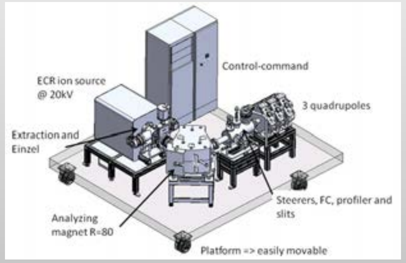
Delayed spectroscopy

SIRIUS setup
Implantation-decay station at the mass dispersive plan



Atomic physics

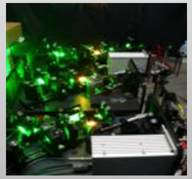
FISIC setup
Fast Ion Slow Ion Collisions Electron exchange



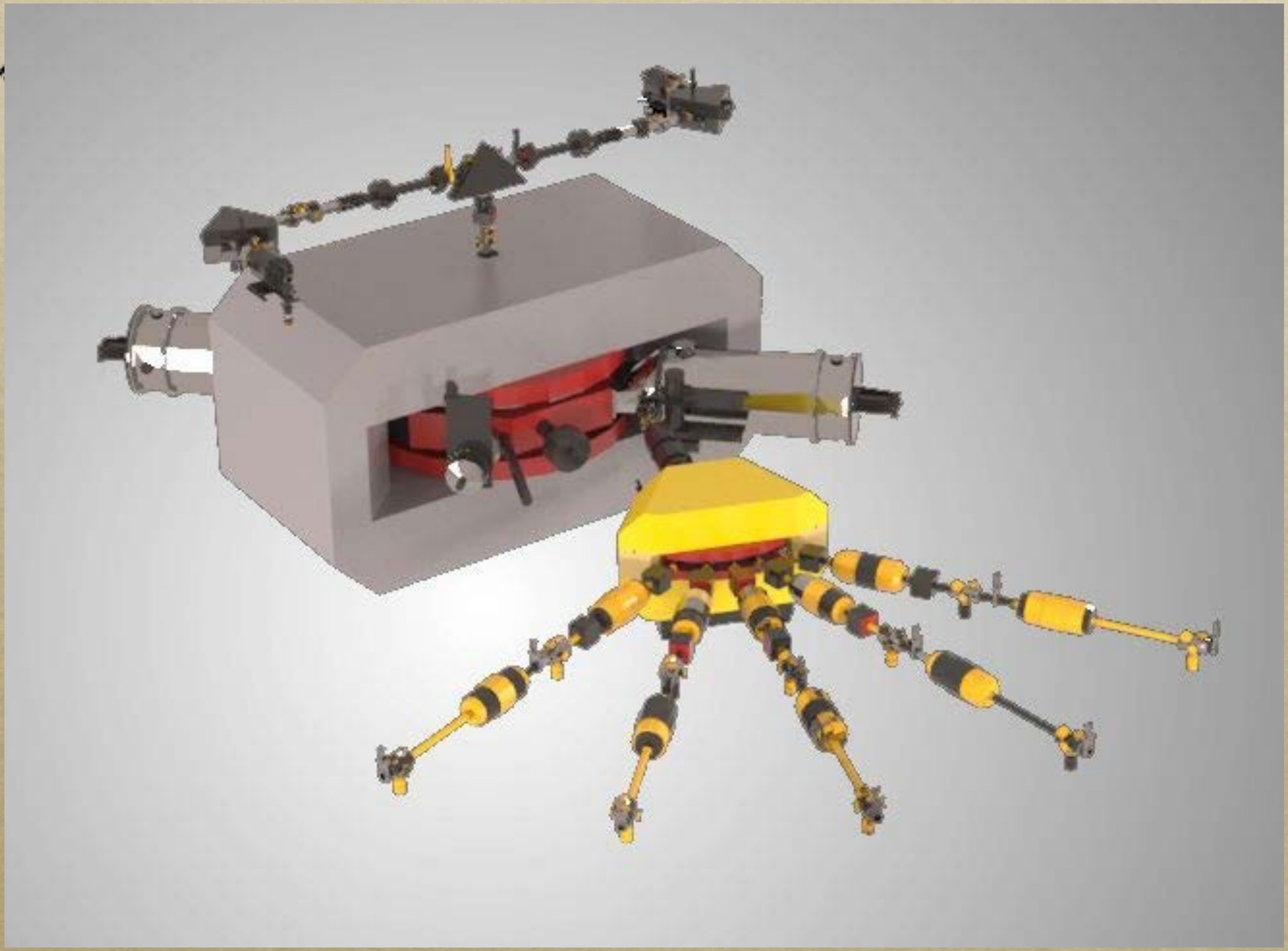
Ground state properties

(mass, size, moments, spins)

REGLIS³ setup
Low Energy Branch



The SHE Factory ?



Main setups:

- Gas-filled recoil separator (DGFRS-II);
- Preseparator for chemical investigations;
- Separator for Heavy Element Spectroscopy: velocity filter SHELS;
- Mass Analyzer of SuperHeavy Atoms (MASHA)
- Channels reserved for external users

The SHE Factory ?

Zagrebaev V.I. et al., Nucl. Phys. A 944 (2015) 257-307

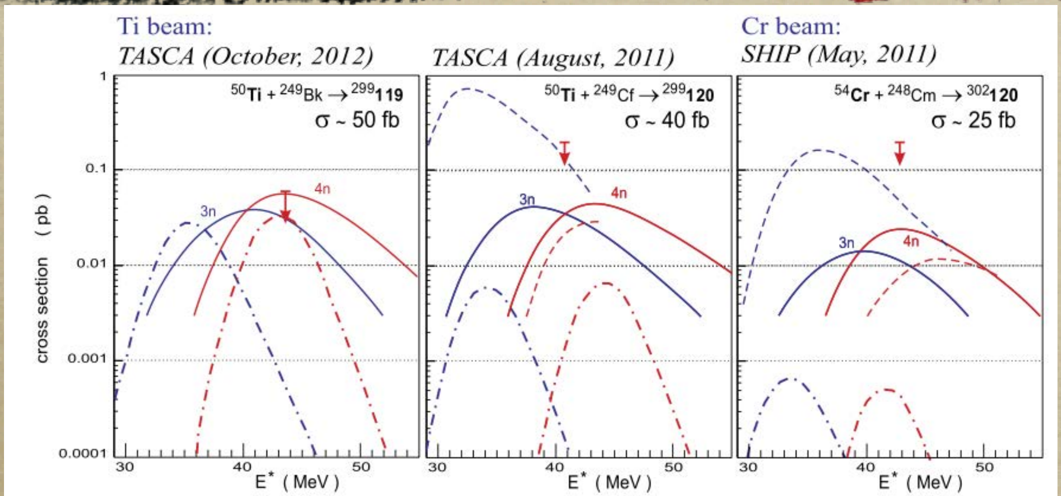
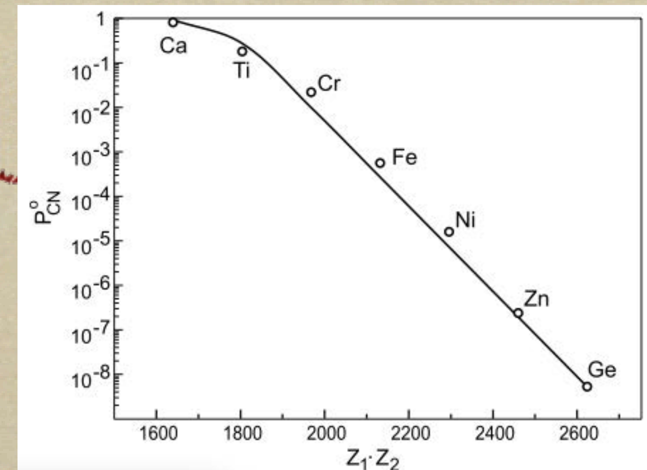
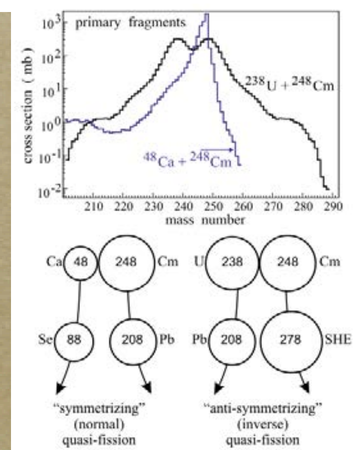


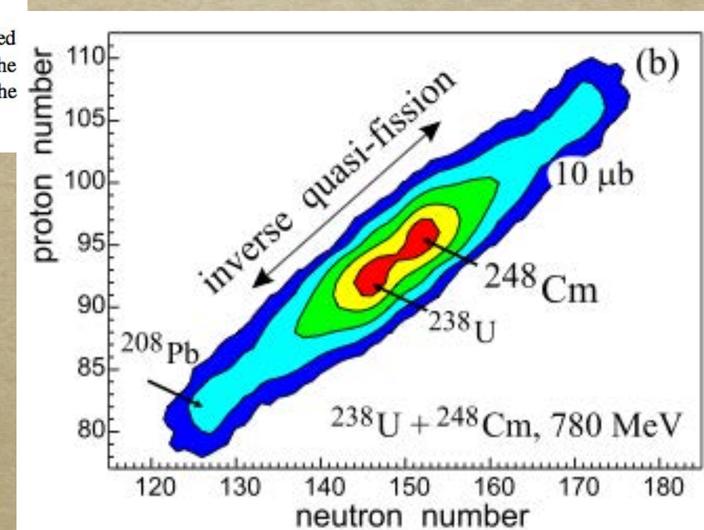
Fig. 31. Cross sections for the production of new elements 119 and 120 in the Ti and Cr induced fusion reactions predicted within the described above model (solid curves [71]) and by the "fusion-by-diffusion" model (dashed curves [91]). The latest calculations within the "fusion-by-diffusion" model [92] are shown by dash-dotted curves. The arrows indicate the upper limits reached in the corresponding experiments performed at GSI [93,94].



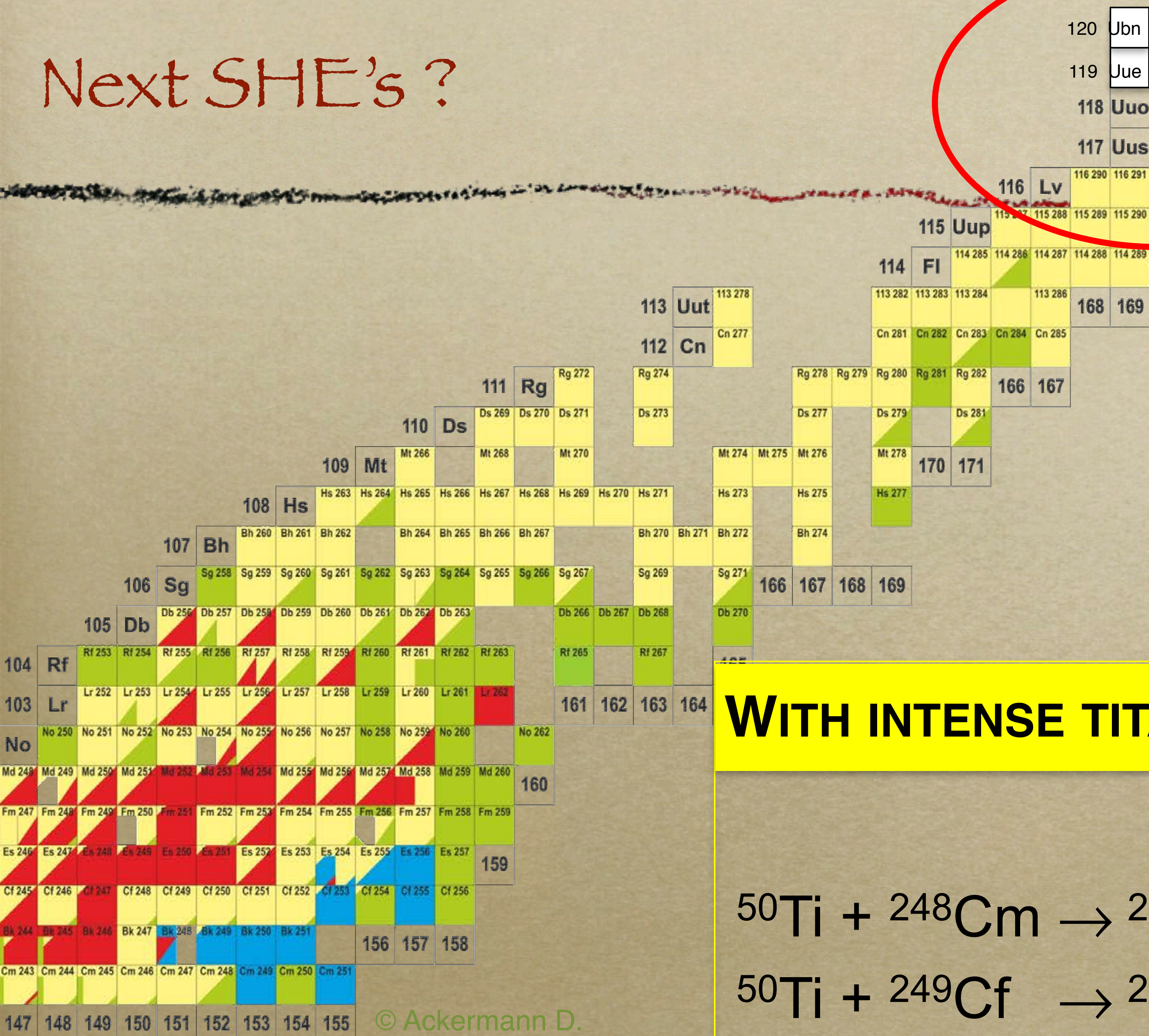
Need of very intense beams !

$^{238}U + ^{248}Cm$





Next SHE's ?



© Ackermann D.

WITH INTENSE TITANIUM BEAM

$$^{50}Ti + {}^{248}Cm \rightarrow {}^{295}118 + 3n$$

$$^{50}Ti + {}^{249}Cf \rightarrow {}^{296}120 + 3n$$

Mendeleev table ?

Periodic Table 1-172

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Orbitals
1	1 H																	2 He	1s
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2s2p
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3s3p
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4s3d4p
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	5s4d5p
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	6s5d6p
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113	114	115	116	117	118	7s6d7p
8	119	120	121-	156	157	158	159	160	161	162	163	164	139	140	169	170	171	172	8s7d8p
9	165	166											167	168					9s9p

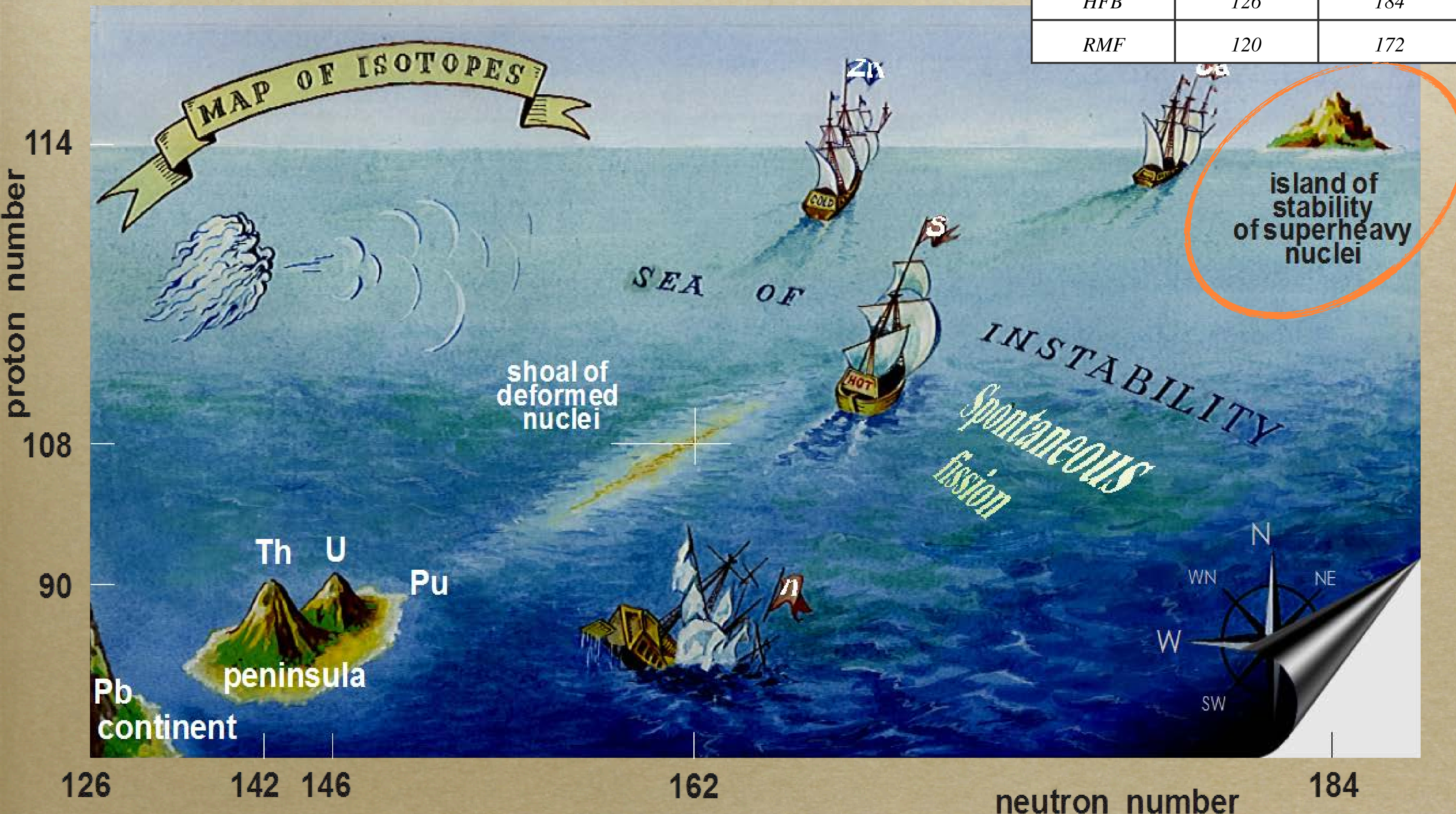
6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	4f
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	5f
8	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	6f

8	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	5g

Figure 1.10: Suggested periodic table up to $Z \leq 172$, based on Dirac-Fock calculations on atoms and ions [130].

Getting to the ultimate Island of stability

Model	Protons	Neutrons
Wood Saxon	*114*	*184*
HFB	*126*	*184*
RMF	*120*	*172*



Le Monde

science & médecine

L'installation U-400, à Dubna, en Russie. JINR/FLEROV

Chez les chasseurs russes des **nouveaux atomes**

Quatre nouveaux éléments, les plus lourds jamais produits, viennent d'être officiellement baptisés. Le plus massif, l'oganesson, qui compte 118 protons, a été obtenu à Dubna. Ce temple soviétique de la science explore depuis soixante ans les confins de la matière. Reportage

VAHÉ TER MINASSIAN
DUBNA (RUSSIE) - *envoyé spécial*

Au Centre international des conférences de Dubna, petite cité de 70 000 habitants aux allures de ville de vacances sur les rives du canal de la Volga, à 120 kilomètres de Moscou, les festivités du « banquet-anniversaire » des soixante ans du Laboratoire Flerov des réactions nucléaires (FLNR) battent leur plein. La vodka aidant, le brouhaha des conversations a rapidement augmenté. Et bientôt, en suivre une devient excessivement difficile. Sans regrets inutiles : il est déjà évident qu'on ne comprendra pas grand-chose. « Darmstadtium », « roentgenium », « copernicium », « dubnium »… les mots utilisés par ces physiciens et ces chimistes sont dénués de sens pour le commun des mortels. Et pour cause : ils font référence à des entités atomiques absentes, en principe, de notre planète ! Plus précisément à des éléments chimiques, créés artificiellement dans de grands accélérateurs, de même nature que l'hydrogène, l'hélium, le chrome, le plomb, l'or ou l'uranium détectables en quantités appréciables sur Terre, mais plus lourds, beaucoup plus lourds… *« Superlourds »*, dit-on même ici.

Heureusement, ce que le vocabulaire peine à faire saisir, le langage du corps l'exprime, aisément. Et il devient bientôt évident que la bonne humeur de l'assemblée ne s'explique ni par le large choix de zakouski mis à la disposition des convives, ni par la joie des retrouvailles entre spécialistes de toutes nationalités. Elle traduit un sentiment général de satisfaction qui, avec l'intensification des libations, prend des allures de revanche après des décennies de déboires et de désillusions…

C'est que l'année 2017 est celle d'une éclatante victoire pour cette discipline, si restreinte, mais ô combien prestigieuse et compétitive, qu'est la physique des éléments superlourds. En effet, le 2 mars, au cours d'une émouvante cérémonie organisée à Moscou, l'International Union of Pure and Applied Chemistry (Iupac), la seule instance habilitée pour une telle procédure, a solennellement achevé l'« inauguration » de quatre nouveaux éléments chimiques, officialisant ainsi leur existence dans le monde matériel. Et pas n'importe lesquels ! Mais précisément ceux qui, ajoutés à deux autres adoubés en 2012, permettront peut-être aux physiciens d'avoir enfin les moyens de résoudre un vieux problème relatif aux caractéristiques générales des corps simples.

L'exploit est de taille. Par convention, les éléments chimiques sont classés selon un ordre croissant en fonction du nombre de protons que contient le noyau de leurs atomes autour duquel tournent les électrons. Ainsi, l'atome d'hydrogène dont le noyau possède un seul proton est l'élément numéro un. L'hélium, qui a deux protons, l'élément numéro deux. Le lithium, le trois… etc. Les éléments dernièrement désignés correspondent, eux, aux numéros 113, 115, 117 et 118 !

➔ LIRE LA SUITE PAGES 4-5

Une sonde vers Mercure

BepiColombo vise l'orbite de la planète la plus proche du Soleil pour 2025. Un tour de force dont le compte à rebours a commencé.

PAGE 2

À NOS LECTEURS

Dès la semaine prochaine et jusqu'au numéro du 22 août daté 23 août, retrouvez les deux pages de la formule estivale du cahier « Science & médecine » dans le quotidien du mardi daté mercredi.

The ultimate Island of stability