

European Summer school
Super Heavy Elements,
Physics and Chemistry
at extremely low rate



Olivier DORVAUX
(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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- Nuclear stability and limits of existence
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What do we know about nuclear stability?

118 elements

some
are
not
stable

Tableau Périodique des Éléments

Auteur : M.S. Antony,
Docteur de l'Université de Lyon,
Docteur ès Sciences, Université de Strasbourg
Imprimé par : Patrick Moessner, Impressions François
103 route de Marienthal, 67500 Haguenau, FRANCE

1 H Hydrogène 1,007 84 (1) 1s ¹ -258,9 -252,9 0,0099 Ar. hydrog., eau gènes, générateur Cavendish 1785	2 He Hélium 4,002 602 (2) 1s ² -273,2 -268,93 5,1794 Ar. hélium, soléil Ramsay 1895	3 Li Lithium 6,941 (2) 1s ² 2s ¹ 1807 1342 5324 Gr. beryll., pierre Arfvedson 1817	4 Be Béryllium 9,012 182 (3) 1s ² 2s ² 1808 1401 2400 1,85 Gr. beryll., gypse, sucre Vauquelin 1798	5 B Bore 10,811 (7) 1s ² 2s ² 2p ¹ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	6 C Carbone 12,0107 (8) 1s ² 2s ² 2p ² 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	7 N Azote 14,00643 (3) 1s ² 2s ² 2p ³ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	8 O Oxygène 15,9994 (3) 1s ² 2s ² 2p ⁴ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	9 F Fluor 18,998 4032 (5) 1s ² 2s ² 2p ⁵ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	10 Ne Néon 20,1797 (6) 1s ² 2s ² 2p ⁶ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808
11 Na Sodium 22,989 770 (2) [Ne] 3s ¹ 1808 883 6,371 L. natron Ar. sodé Day 1807	12 Mg Magnésium 24,3050 (4) [Ne] 3s ² 1808 1200 1,738 Magnésia, distric Ar. sodé Day 1807	13 Al Aluminium 26,981 538 (2) [Ne] 3s ² 3p ¹ 1808 2690 2,70 Al. alum. Ar. sodé Day 1807	14 Si Silicium 28,0855 (3) [Ne] 3s ² 3p ² 1808 2808 2,35 L. carbo. Ar. sodé Day 1807	15 P Phosphore 30,973 761 (2) [Ne] 3s ² 3p ³ 1808 3097 2,29 L. carbo. Ar. sodé Day 1807	16 S Soufre 32,06 (2) [Ne] 3s ² 3p ⁴ 1808 3207 2,26 L. carbo. Ar. sodé Day 1807	17 Cl Chlore 35,453 (2) [Ne] 3s ² 3p ⁵ 1808 3545 3,16 L. fluo. fluo. Ar. sodé Day 1807	18 Ar Argon 39,948 (1) [Ne] 3s ² 3p ⁶ 1808 3994 3,84 L. fluo. fluo. Ar. sodé Day 1807	19 K Potassium 39,0983 (1) [Ar] 4s ¹ 1808 4039 2,26 L. calx. Ar. sodé Day 1807	20 Ca Calcium 40,078 (4) [Ar] 4s ² 1808 4008 2,20 L. calx. Ar. sodé Day 1807
21 Sc Scandium 44,955 910 (8) [Ar] 3d ¹ 4s ² 1808 4496 2,55 L. calx. Ar. sodé Day 1807	22 Ti Titane 47,867 (1) [Ar] 3d ² 4s ² 1808 4788 2,23 L. calx. Ar. sodé Day 1807	23 V Vanadium 50,9415 (1) [Ar] 3d ³ 4s ² 1808 5094 2,26 L. calx. Ar. sodé Day 1807	24 Cr Chrome 51,9961 (2) [Ar] 3d ⁵ 4s ¹ 1808 5199 2,23 L. calx. Ar. sodé Day 1807	25 Mn Manganèse 54,938 040 (3) [Ar] 3d ⁵ 4s ² 1808 5493 2,23 L. calx. Ar. sodé Day 1807	26 Fe Fer 55,845 (2) [Ar] 3d ⁶ 4s ² 1808 5585 2,23 L. calx. Ar. sodé Day 1807	27 Co Cobalt 58,933 195 (5) [Ar] 3d ⁷ 4s ² 1808 5893 2,23 L. calx. Ar. sodé Day 1807	28 Ni Nickel 58,6934 (2) [Ar] 3d ⁸ 4s ² 1808 5869 2,23 L. calx. Ar. sodé Day 1807	29 Cu Cuivre 63,546 (3) [Ar] 3d ¹⁰ 4s ¹ 1808 6355 2,23 L. calx. Ar. sodé Day 1807	30 Zn Zinc 65,409 (4) [Ar] 3d ¹⁰ 4s ² 1808 6538 2,23 L. calx. Ar. sodé Day 1807
31 Ga Gallium 69,723 (1) [Ar] 3d ¹⁰ 4s ² 4p ¹ 1808 6972 2,23 L. calx. Ar. sodé Day 1807	32 Ge Germanium 72,64 (1) [Ar] 3d ¹⁰ 4s ² 4p ² 1808 7264 2,23 L. calx. Ar. sodé Day 1807	33 As Arsenic 74,9216 (2) [Ar] 3d ¹⁰ 4s ² 4p ³ 1808 7492 2,23 L. calx. Ar. sodé Day 1807	34 Se Sélénium 78,96 (2) [Ar] 3d ¹⁰ 4s ² 4p ⁴ 1808 7896 2,23 L. calx. Ar. sodé Day 1807	35 Br Brome 79,904 (1) [Ar] 3d ¹⁰ 4s ² 4p ⁵ 1808 7990 2,23 L. calx. Ar. sodé Day 1807	36 Kr Krypton 83,798 (4) [Ar] 3d ¹⁰ 4s ² 4p ⁶ 1808 8380 2,23 L. calx. Ar. sodé Day 1807	37 Rb Rubidium 85,4678 (3) [Kr] 5s ¹ 1808 8547 2,23 L. calx. Ar. sodé Day 1807	38 Sr Strontium 87,62 (1) [Kr] 5s ² 1808 8762 2,23 L. calx. Ar. sodé Day 1807	39 Y Yttrium 88,905 85 (2) [Kr] 4d ¹ 5s ² 1808 8891 2,23 L. calx. Ar. sodé Day 1807	40 Zr Zirconium 91,224 (2) [Kr] 4d ² 5s ² 1808 9122 2,23 L. calx. Ar. sodé Day 1807
41 Nb Niobium 92,906 38 (2) [Kr] 4d ⁴ 5s ¹ 1808 9291 2,23 L. calx. Ar. sodé Day 1807	42 Mo Molybdène 95,96 (2) [Kr] 4d ⁵ 5s ¹ 1808 9594 2,23 L. calx. Ar. sodé Day 1807	43 Tc Technétium 98,0064 (1) [Kr] 4d ⁵ 5s ² 1808 9801 2,23 L. calx. Ar. sodé Day 1807	44 Ru Ruthénium 101,07 (2) [Kr] 4d ⁷ 5s ¹ 1808 1011 2,23 L. calx. Ar. sodé Day 1807	45 Rh Rhodium 102,905 50 (2) [Kr] 4d ⁸ 5s ¹ 1808 1029 2,23 L. calx. Ar. sodé Day 1807	46 Pd Paladium 106,42 (1) [Kr] 4d ¹⁰ 1808 1064 2,23 L. calx. Ar. sodé Day 1807	47 Ag Argent 107,8682 (2) [Kr] 4d ¹⁰ 5s ¹ 1808 1079 2,23 L. calx. Ar. sodé Day 1807	48 Cd Cadmium 112,411 (8) [Kr] 4d ¹⁰ 5s ² 1808 1124 2,23 L. calx. Ar. sodé Day 1807	49 In Indium 114,818 (3) [Kr] 4d ¹⁰ 5s ² 5p ¹ 1808 1148 2,23 L. calx. Ar. sodé Day 1807	50 Sn Étain 118,710 (7) [Kr] 4d ¹⁰ 5s ² 5p ² 1808 1187 2,23 L. calx. Ar. sodé Day 1807
51 Sb Antimoine 121,760 (1) [Kr] 4d ¹⁰ 5s ² 5p ³ 1808 1218 2,23 L. calx. Ar. sodé Day 1807	52 Te Tellure 127,60 (2) [Kr] 4d ¹⁰ 5s ² 5p ⁴ 1808 1276 2,23 L. calx. Ar. sodé Day 1807	53 I Iode 126,904 47 (2) [Kr] 4d ¹⁰ 5s ² 5p ⁵ 1808 1269 2,23 L. calx. Ar. sodé Day 1807	54 Xe Xénon 131,29 (2) [Kr] 4d ¹⁰ 5s ² 5p ⁶ 1808 1313 2,23 L. calx. Ar. sodé Day 1807	55 Cs Césium 132,905 45 (2) [Xe] 6s ¹ 1808 1329 2,23 L. calx. Ar. sodé Day 1807	56 Ba Baryum 137,327 (7) [Xe] 6s ² 1808 1373 2,23 L. calx. Ar. sodé Day 1807	57 La Lanthane 138,905 (3) [Xe] 5d ¹ 6s ² 1808 1389 2,23 L. calx. Ar. sodé Day 1807	58 Ce Cérium 140,12 (1) [Xe] 5d ¹ 6s ² 1808 1401 2,23 L. calx. Ar. sodé Day 1807	59 Pr Praseodyme 140,907 69 (2) [Xe] 5d ¹ 6s ² 1808 1409 2,23 L. calx. Ar. sodé Day 1807	60 Nd Néodyme 144,24 (3) [Xe] 5d ² 6s ² 1808 1442 2,23 L. calx. Ar. sodé Day 1807
61 Pm Prométhium 144,9127 (1) [Xe] 5d ⁴ 6s ² 1808 1449 2,23 L. calx. Ar. sodé Day 1807	62 Sm Samarium 150,36 (2) [Xe] 5d ⁶ 6s ² 1808 1504 2,23 L. calx. Ar. sodé Day 1807	63 Eu Europium 151,964 (1) [Xe] 5d ⁶ 6s ² 1808 1519 2,23 L. calx. Ar. sodé Day 1807	64 Gd Gadolinium 157,25 (3) [Xe] 5d ⁷ 6s ² 1808 1572 2,23 L. calx. Ar. sodé Day 1807	65 Tb Terbium 158,925 (2) [Xe] 5d ⁹ 6s ² 1808 1589 2,23 L. calx. Ar. sodé Day 1807	66 Dy Dysprosium 162,500 (1) [Xe] 5d ¹⁰ 6s ² 1808 1625 2,23 L. calx. Ar. sodé Day 1807	67 Ho Holmium 164,930 32 (2) [Xe] 5d ¹⁰ 6s ² 1808 1649 2,23 L. calx. Ar. sodé Day 1807	68 Er Erbium 167,259 (3) [Xe] 5d ¹⁰ 6s ² 1808 1672 2,23 L. calx. Ar. sodé Day 1807	69 Tm Thulium 168,934 21 (2) [Xe] 5d ⁹ 6s ² 1808 1689 2,23 L. calx. Ar. sodé Day 1807	70 Yb Ytterbium 173,054 (3) [Xe] 5d ¹⁰ 6s ² 1808 1730 2,23 L. calx. Ar. sodé Day 1807
71 Lu Lutécium 174,967 (1) [Xe] 5d ¹ 6s ² 1808 1749 2,23 L. calx. Ar. sodé Day 1807	72 Hf Hafnium 178,49 (2) [Xe] 5d ² 6s ² 1808 1785 2,23 L. calx. Ar. sodé Day 1807	73 Ta Tantale 180,9479 (1) [Xe] 5d ³ 6s ² 1808 1809 2,23 L. calx. Ar. sodé Day 1807	74 W Tungstène 183,84 (1) [Xe] 5d ⁴ 6s ² 1808 1838 2,23 L. calx. Ar. sodé Day 1807	75 Re Rhenium 186,207 (1) [Xe] 5d ⁵ 6s ² 1808 1862 2,23 L. calx. Ar. sodé Day 1807	76 Os Osmium 190,23 (3) [Xe] 5d ⁶ 6s ² 1808 1902 2,23 L. calx. Ar. sodé Day 1807	77 Ir Iridium 192,222 (1) [Xe] 5d ⁷ 6s ² 1808 1922 2,23 L. calx. Ar. sodé Day 1807	78 Pt Platine 195,078 (2) [Xe] 5d ⁹ 6s ¹ 1808 1950 2,23 L. calx. Ar. sodé Day 1807	79 Au Or 196,966 55 (2) [Xe] 5d ¹⁰ 6s ¹ 1808 1969 2,23 L. calx. Ar. sodé Day 1807	80 Hg Mercure 200,59 (2) [Xe] 5d ¹⁰ 6s ² 1808 2006 2,23 L. calx. Ar. sodé Day 1807
81 Tl Thallium 204,3832 (2) [Xe] 5d ¹⁰ 6s ² 6p ¹ 1808 2044 2,23 L. calx. Ar. sodé Day 1807	82 Pb Plomb 207,2 (1) [Xe] 5d ¹⁰ 6s ² 6p ² 1808 2072 2,23 L. calx. Ar. sodé Day 1807	83 Bi Bismuth 208,980 38 (2) [Xe] 5d ¹⁰ 6s ² 6p ³ 1808 2090 2,23 L. calx. Ar. sodé Day 1807	84 Po Polonium 209 (3) [Xe] 5d ¹⁰ 6s ² 6p ⁴ 1808 2090 2,23 L. calx. Ar. sodé Day 1807	85 At Astate 210 (3) [Xe] 5d ¹⁰ 6s ² 6p ⁵ 1808 2100 2,23 L. calx. Ar. sodé Day 1807	86 Rn Radon 222 (3) [Xe] 5d ¹⁰ 6s ² 6p ⁶ 1808 2220 2,23 L. calx. Ar. sodé Day 1807	87 Fr Francium 223 (1) [Rn] 7s ¹ 1808 2230 2,23 L. calx. Ar. sodé Day 1807	88 Ra Radium 226 (254) [Rn] 7s ² 1808 2260 2,23 L. calx. Ar. sodé Day 1807	89 Ac Actinium 227 (227) [Rn] 7s ² 1808 2270 2,23 L. calx. Ar. sodé Day 1807	90 Th Thorium 232,0377 (2) [Rn] 6d ² 7s ² 1808 2320 2,23 L. calx. Ar. sodé Day 1807
91 Pa Protactinium 231,036 89 (2) [Rn] 6d ¹ 7s ² 1808 2310 2,23 L. calx. Ar. sodé Day 1807	92 U Uranium 238,028 91 (3) [Rn] 6d ³ 7s ² 1808 2380 2,23 L. calx. Ar. sodé Day 1807	93 Np Neptunium 237,048 (1) [Rn] 6d ⁴ 7s ² 1808 2370 2,23 L. calx. Ar. sodé Day 1807	94 Pu Plutonium 244,0642 (1) [Rn] 6d ⁶ 7s ² 1808 2440 2,23 L. calx. Ar. sodé Day 1807	95 Am Américium 243,061 (1) [Rn] 6d ⁷ 7s ² 1808 2430 2,23 L. calx. Ar. sodé Day 1807	96 Cm Curium 247,07 (3) [Rn] 6d ⁸ 7s ² 1808 2470 2,23 L. calx. Ar. sodé Day 1807	97 Bk Berkélium 247,07 (3) [Rn] 6d ⁹ 7s ² 1808 2470 2,23 L. calx. Ar. sodé Day 1807	98 Cf Californium 251,083 (1) [Rn] 6d ¹⁰ 7s ² 1808 2510 2,23 L. calx. Ar. sodé Day 1807	99 Es Einsteinium 252,083 (1) [Rn] 6d ⁹ 7s ² 1808 2520 2,23 L. calx. Ar. sodé Day 1807	100 Fm Fermium 257,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2570 2,23 L. calx. Ar. sodé Day 1807
101 Md Mendelevium 258,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2580 2,23 L. calx. Ar. sodé Day 1807	102 No Nobelium 259,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2590 2,23 L. calx. Ar. sodé Day 1807	103 Lr Lawrencium 260,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2600 2,23 L. calx. Ar. sodé Day 1807	104 Rf Rutherfordium 261,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2610 2,23 L. calx. Ar. sodé Day 1807	105 Db Dubnium 262,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2620 2,23 L. calx. Ar. sodé Day 1807	106 Sg Seaborgium 266,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2660 2,23 L. calx. Ar. sodé Day 1807	107 Bh Bohrium 267,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2670 2,23 L. calx. Ar. sodé Day 1807	108 Hs Hassium 277,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2770 2,23 L. calx. Ar. sodé Day 1807	109 Mt Meitnerium 278,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2780 2,23 L. calx. Ar. sodé Day 1807	110 Ds Darmstadtium 281,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2810 2,23 L. calx. Ar. sodé Day 1807
111 Rg Roentgenium 282,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2820 2,23 L. calx. Ar. sodé Day 1807	112 Cn Copernicium 285,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2850 2,23 L. calx. Ar. sodé Day 1807	113 Nh Nihonium 286,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2860 2,23 L. calx. Ar. sodé Day 1807	114 Fl Flerovium 289,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2890 2,23 L. calx. Ar. sodé Day 1807	115 Lv Livermorium 293,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2930 2,23 L. calx. Ar. sodé Day 1807	116 Ts Tennessine 294,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2940 2,23 L. calx. Ar. sodé Day 1807	117 Og Oganesson 294,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2940 2,23 L. calx. Ar. sodé Day 1807	118 Uu Ununseptium 294,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2940 2,23 L. calx. Ar. sodé Day 1807	119 Uub Unbinilium 294,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2940 2,23 L. calx. Ar. sodé Day 1807	120 Uut Untrium 294,10 (3) [Rn] 6d ¹⁰ 7s ² 1808 2940 2,23 L. calx. Ar. sodé Day 1807

↑ Lanthanides

Actinides

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

























































































Les Leucodystrophies sont des maladies de la myéline, gaine isolante des nerfs du système central.
En mémoire de Dmitri Ivanovitch Mendéléev, auteur de la Classification Périodique des Éléments

13 B Bore 10,811 (7) 1s ² 2s ² 2p ¹ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	14 C Carbone 12,0107 (8) 1s ² 2s ² 2p ² 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	15 N Azote 14,00643 (3) 1s ² 2s ² 2p ³ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	16 O Oxygène 15,9994 (3) 1s ² 2s ² 2p ⁴ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	17 F Fluor 18,998 4032 (5) 1s ² 2s ² 2p ⁵ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	18 Ne Néon 20,1797 (6) 1s ² 2s ² 2p ⁶ 2075 3927 2,34 Ar. bauxit, blanc Gay-Lussac 1808	19 K Potassium 39,0983 (1) [Ar] 4s ¹ 1808 4039 2,26 L. calx. Ar. sodé Day 1807	20 Ca Calcium 40,078 (4) [Ar] 4s ² 1808 4008 2,20 L. calx. Ar. sod
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118 eleme

Tableau Périodique des Éléments

Elements & Country of Discovery

1 H																	2 He
																	
UK 23	Sweden 19		Germany 19		U.S.A. 17		France 17		Russia 6		Austria 2						
3 Li	4 Be																
																	
11 Na	12 Mg																
																	
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
							Known to ancestors			Known to ancestors				Known to ancestors			
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
										Known to ancestors			Known to ancestors	Known to ancestors			
55 Cs	56 Ba	57 La	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
										Known to ancestors	Known to ancestors		Known to ancestors	Known to ancestors			
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
																	
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				
																	
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				
																	

What do we know about nuclear stability ?

Chemical properties fixed by the number of electrons (Z)

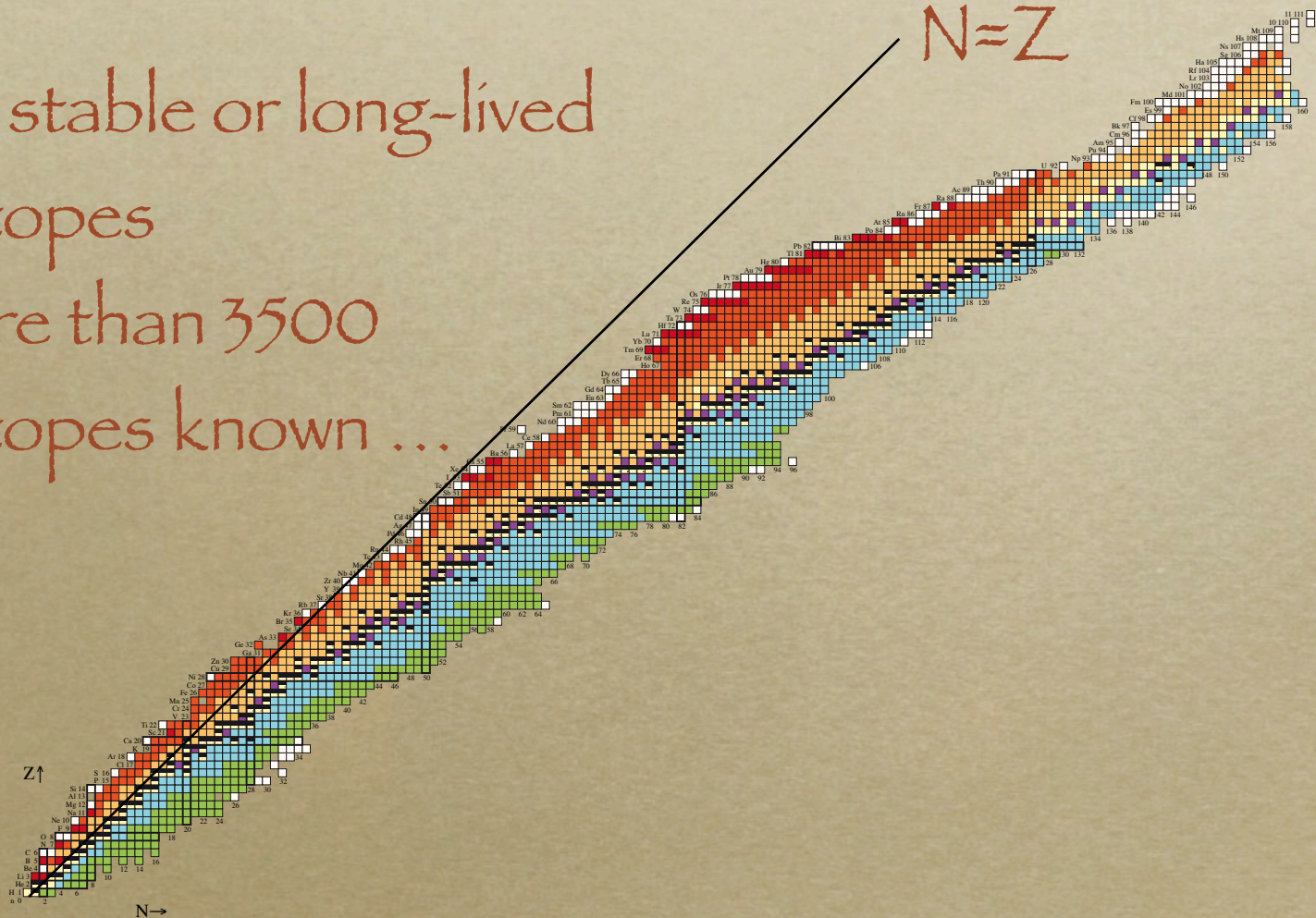
... but ... Several elements for each Z

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

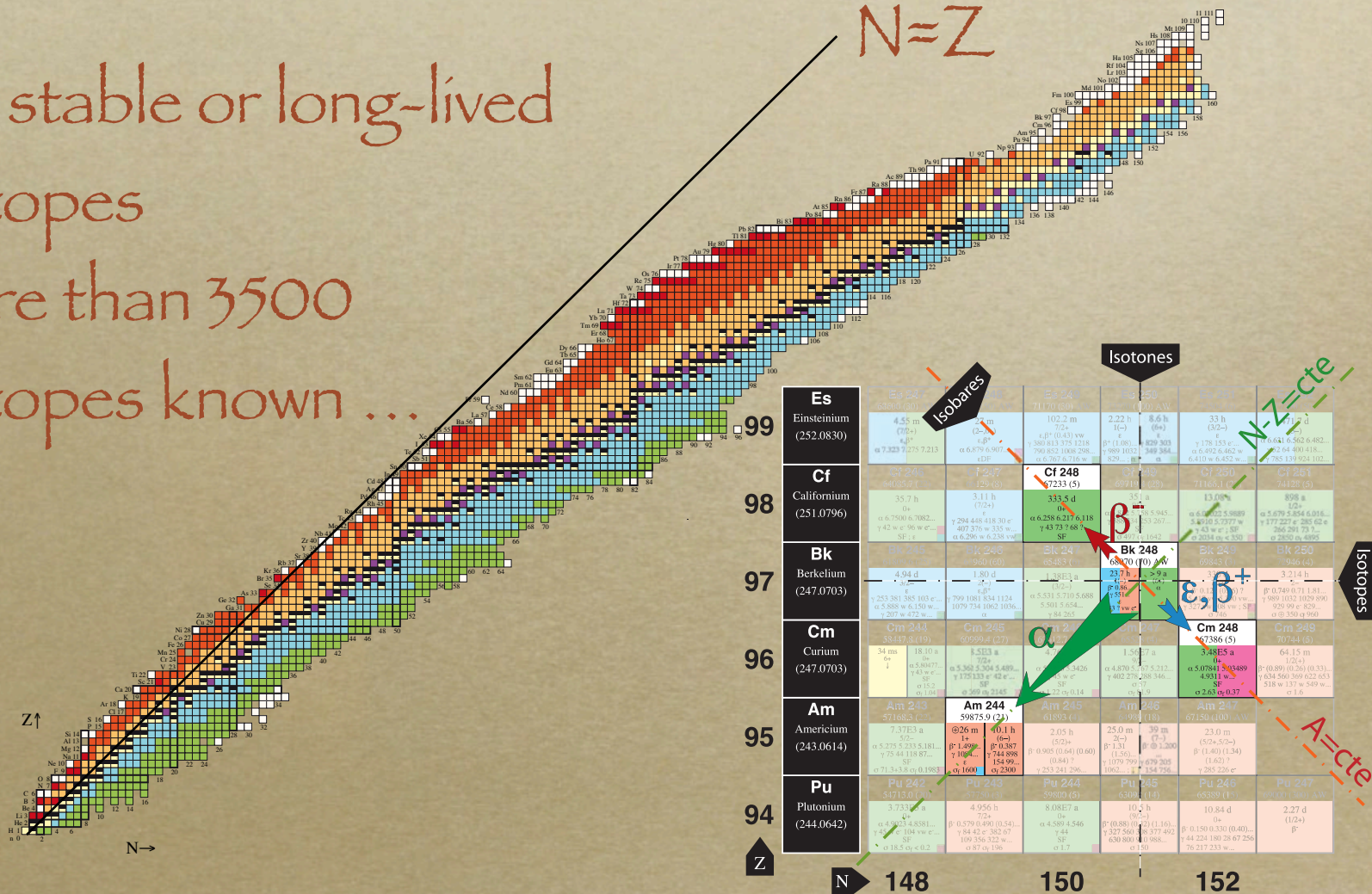
What do we know about nuclear stability ?

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



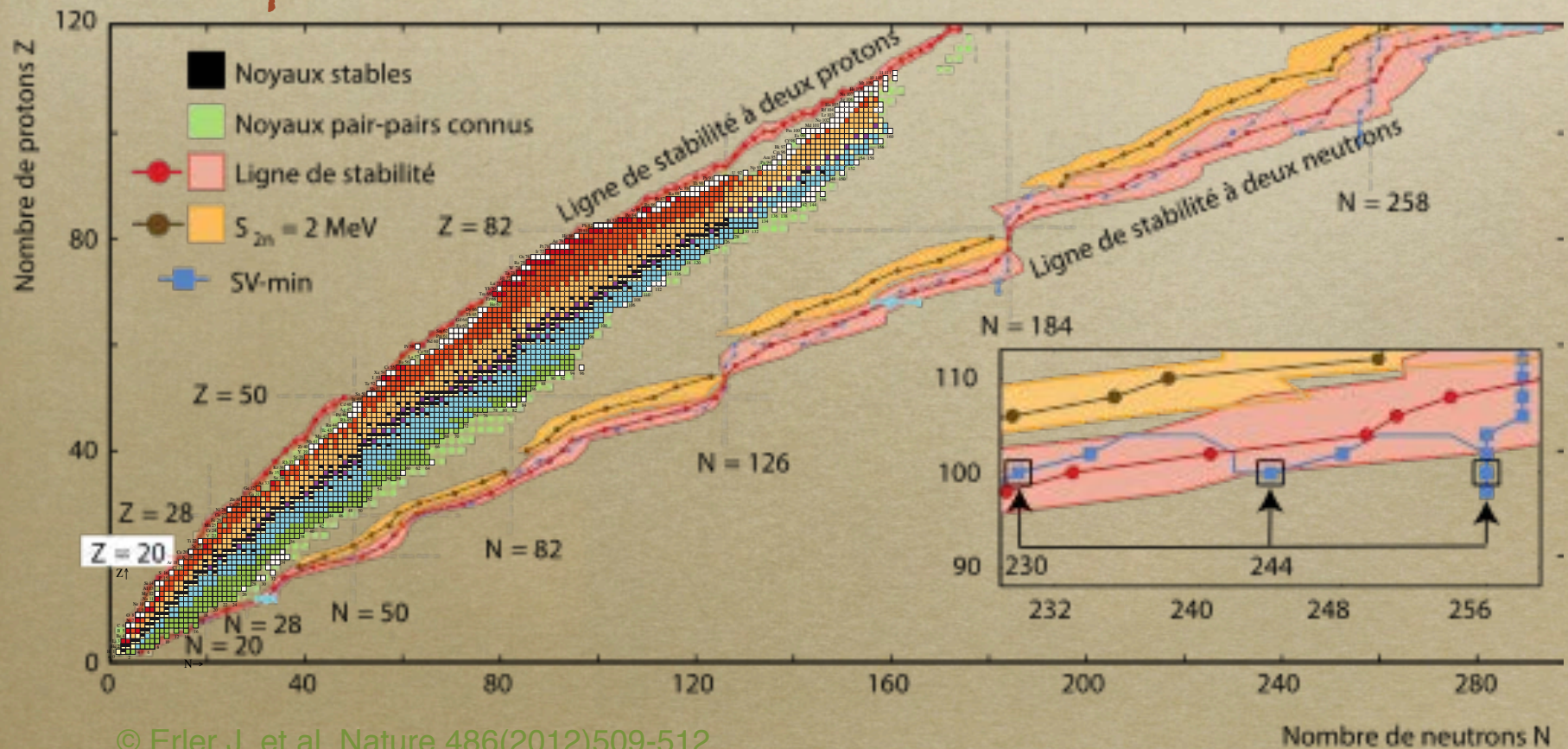
What do we know about nuclear stability ?

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



Limits of existence of nuclei ?

Drip lines



Nuclear binding energy ...

Aston curve

Binding energy per nucleon

B/A

as a function of

A

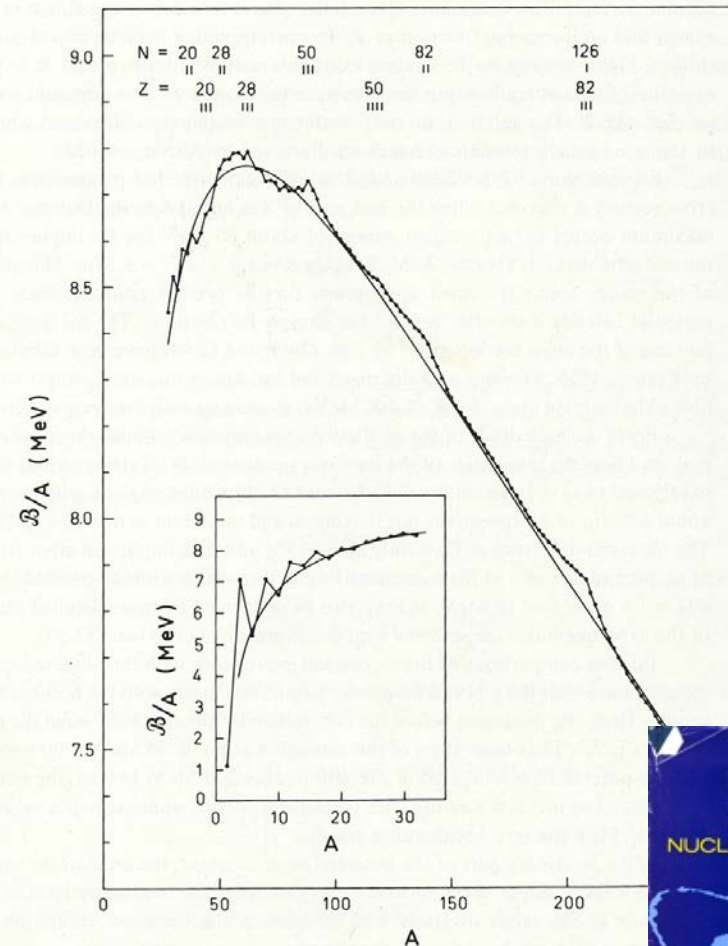
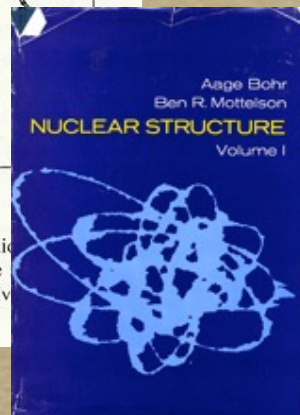
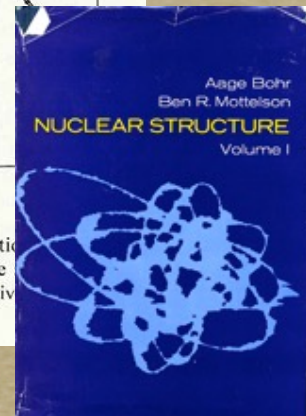
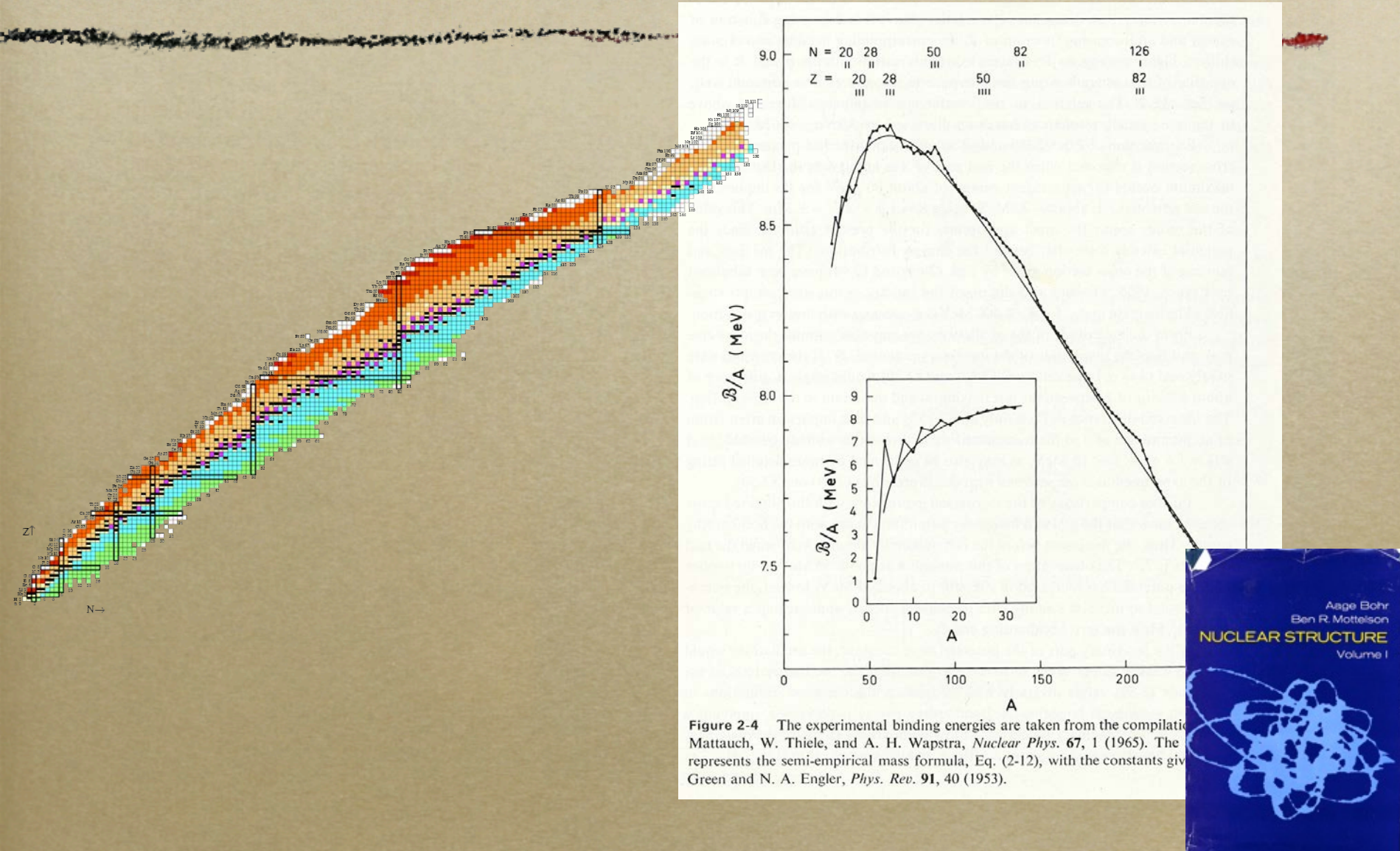


Figure 2-4 The experimental binding energies are taken from the compilation of Mattauch, W. Thiele, and A. H. Wapstra, *Nuclear Phys.* 67, 1 (1965). The smooth curve represents the semi-empirical mass formula, Eq. (2-12), with the constants given by Green and N. A. Engler, *Phys. Rev.* 91, 40 (1953).



Nuclear binding energy ... and radioactivity



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 ?

Liquid drop model

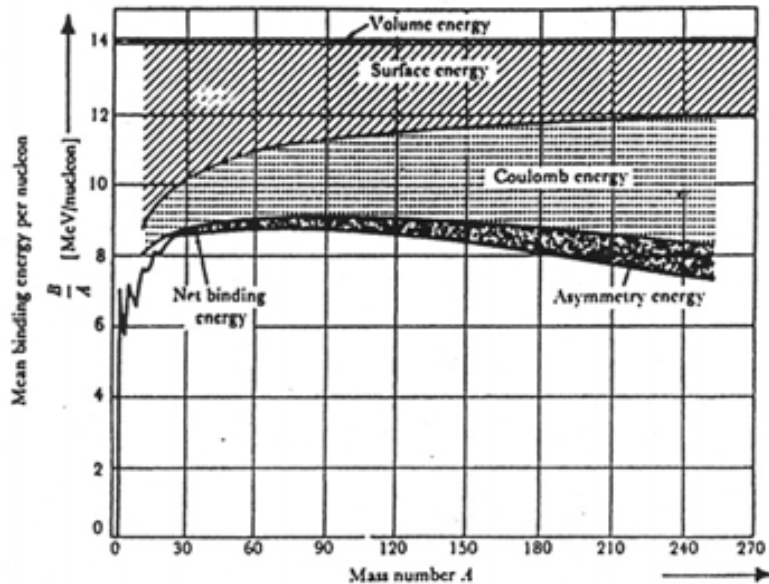


Fig. 2-9 Contribution des différents termes à la formule de masse.

$$m(Z, A) = Zm({}^1H) + Nm_n - a_v A + a_s A^{2/3} + a_c \frac{Z^2}{A^{1/3}} + a_{\text{sym}} \frac{(A - 2Z)^2}{A} - B_{\text{paire}}$$

$$a_v = 15.5 \text{ MeV} \quad a_s = 16.8 \text{ MeV}$$

$$a_c = 0.72 \text{ MeV} \quad a_{\text{sym}} = 23.0 \text{ MeV}$$

$$a_p = 34.0 \text{ MeV}$$

$$\hookrightarrow r_0 = 1.251 \text{ fm}$$

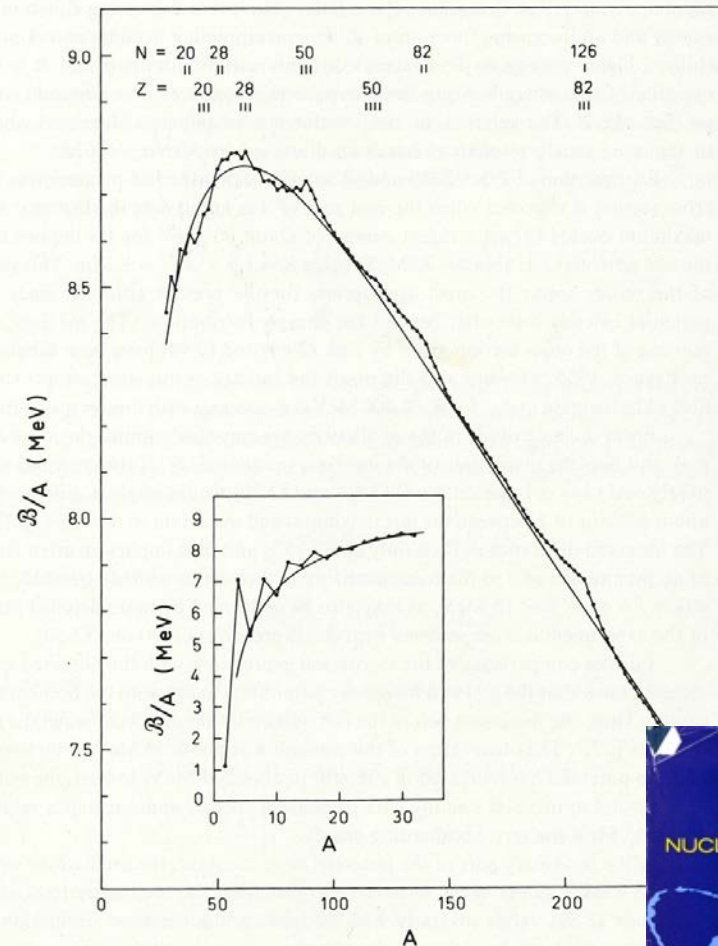
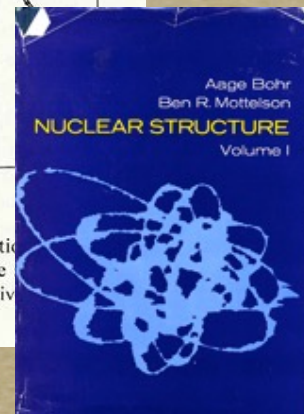
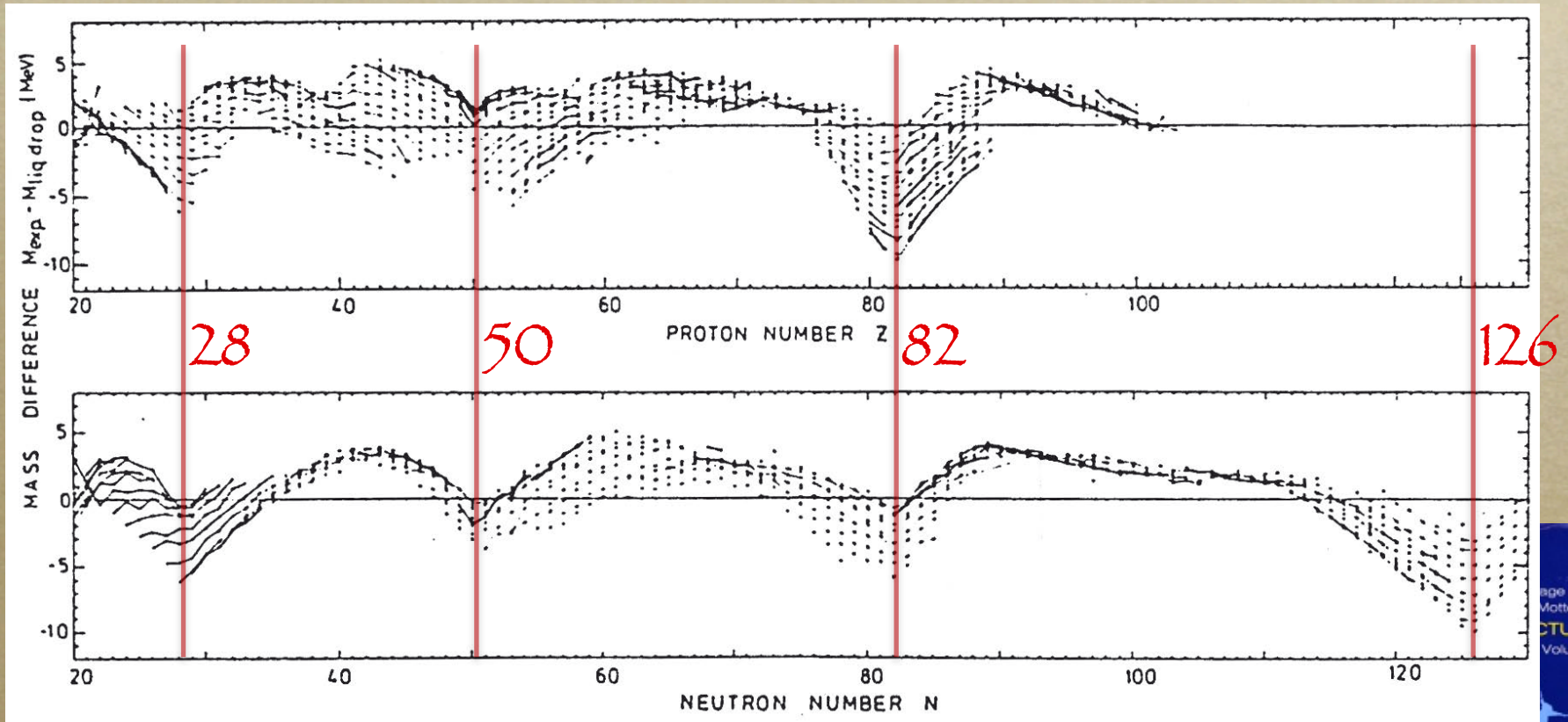
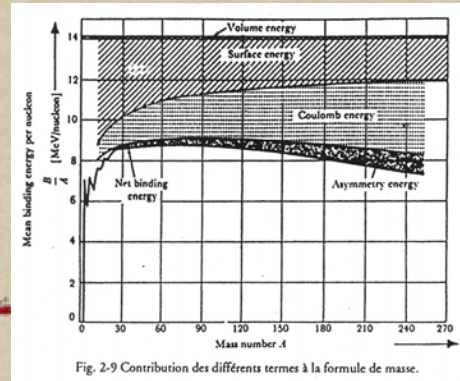


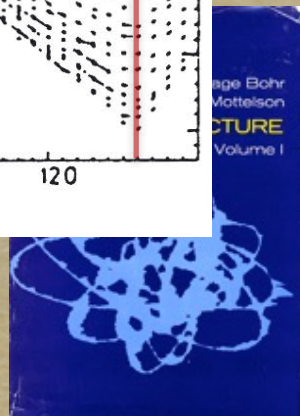
Figure 2-4 The experimental binding energies are taken from the compilation Mattauch, W. Thiele, and A. H. Wapstra, *Nuclear Phys.* 67, 1 (1965). The represents the semi-empirical mass formula, Eq. (2-12), with the constants given by Green and N. A. Englert, *Phys. Rev.* 91, 40 (1953).



Beyond liquid drop ...



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



Magic numbers ...

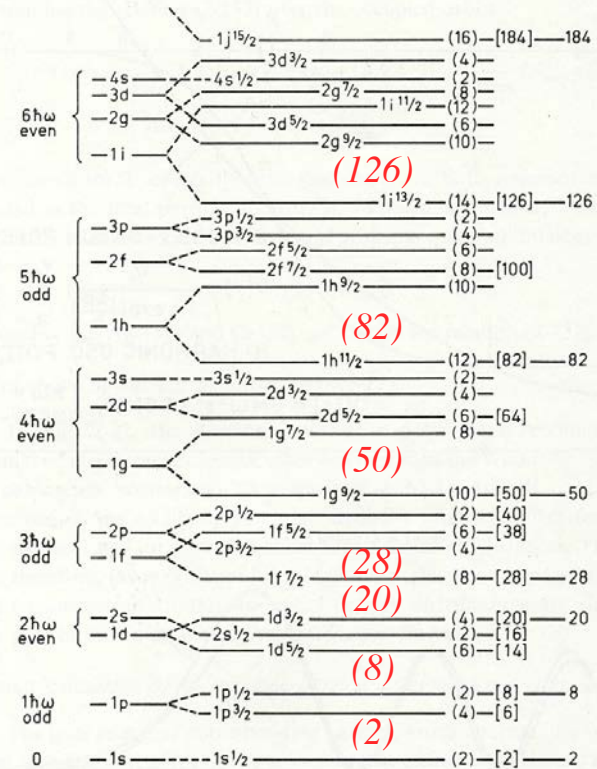
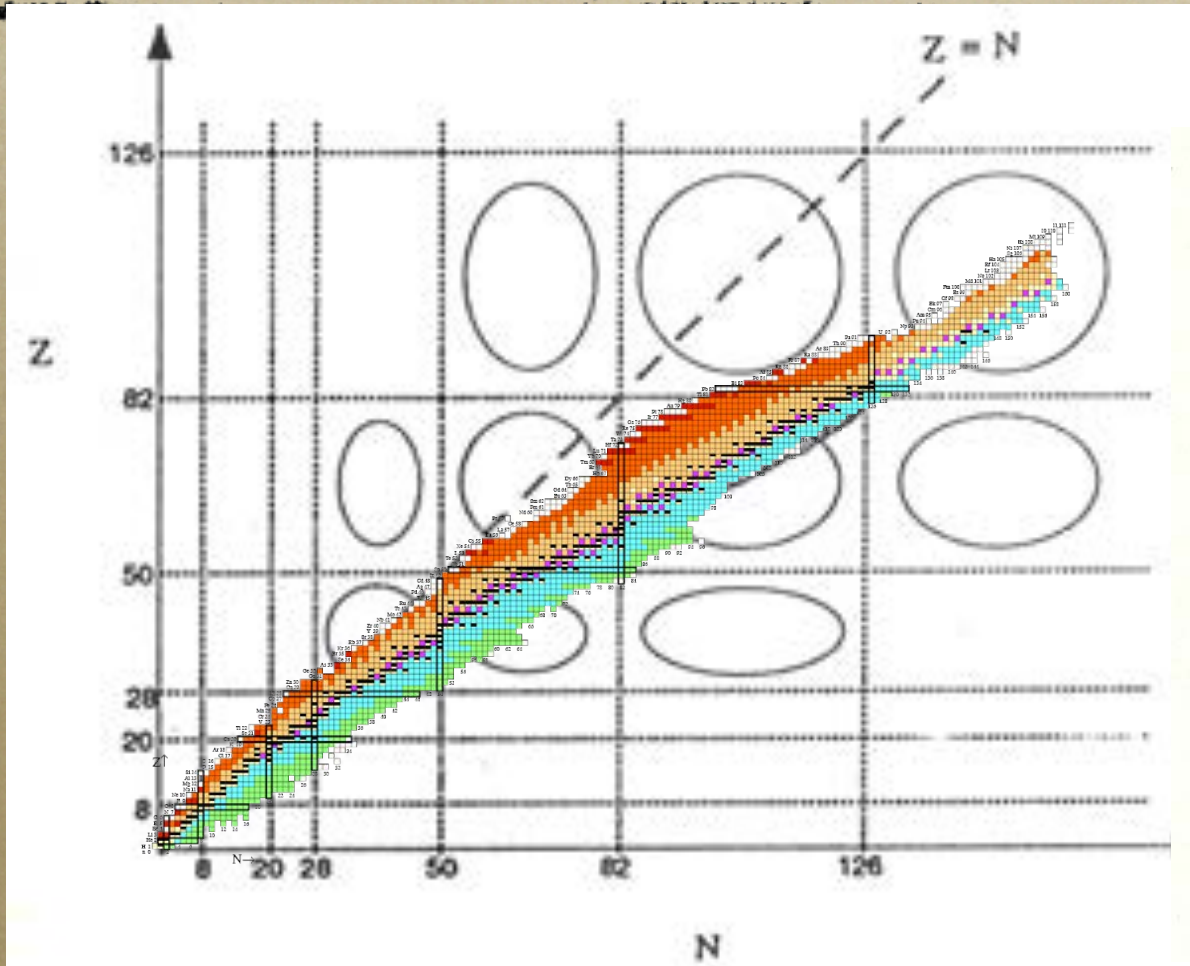
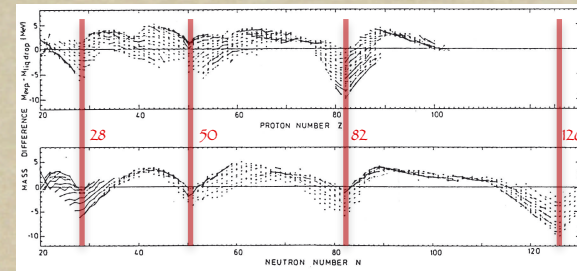


Figure 2-23 Sequence of one-particle orbits. The figure is taken from M. G. J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1960.

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

Magic numbers ...

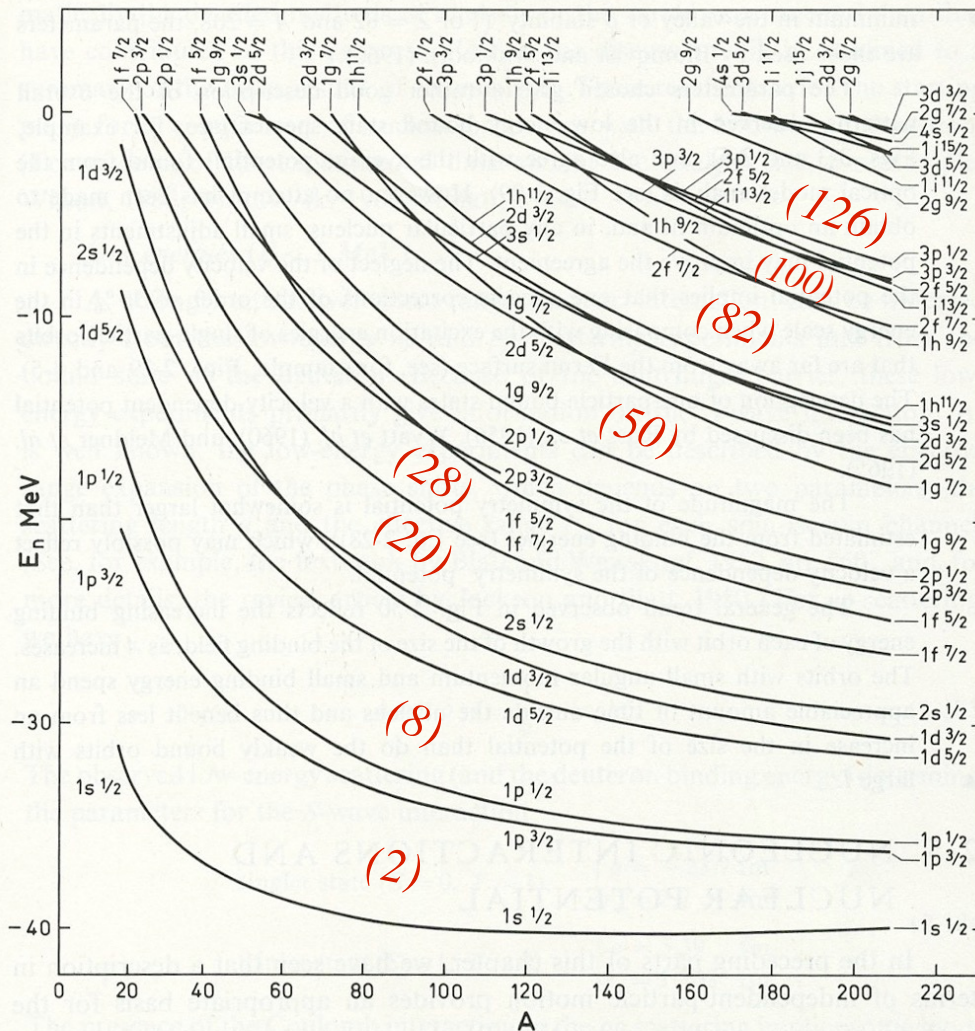
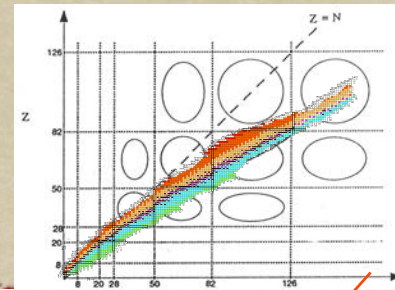


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

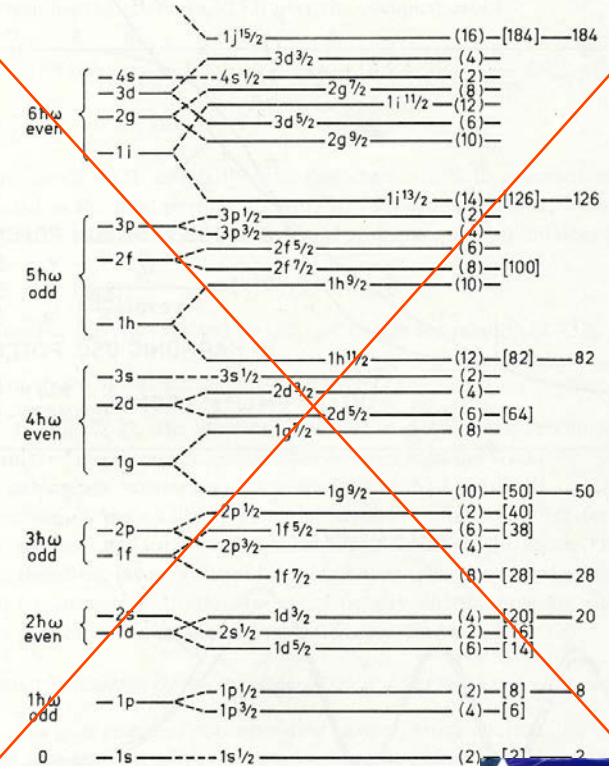
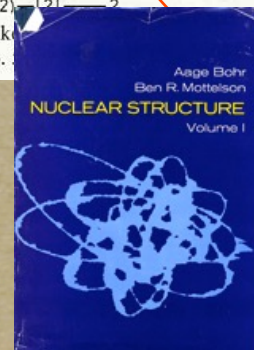
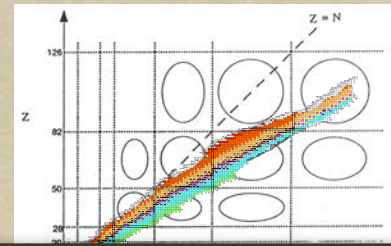


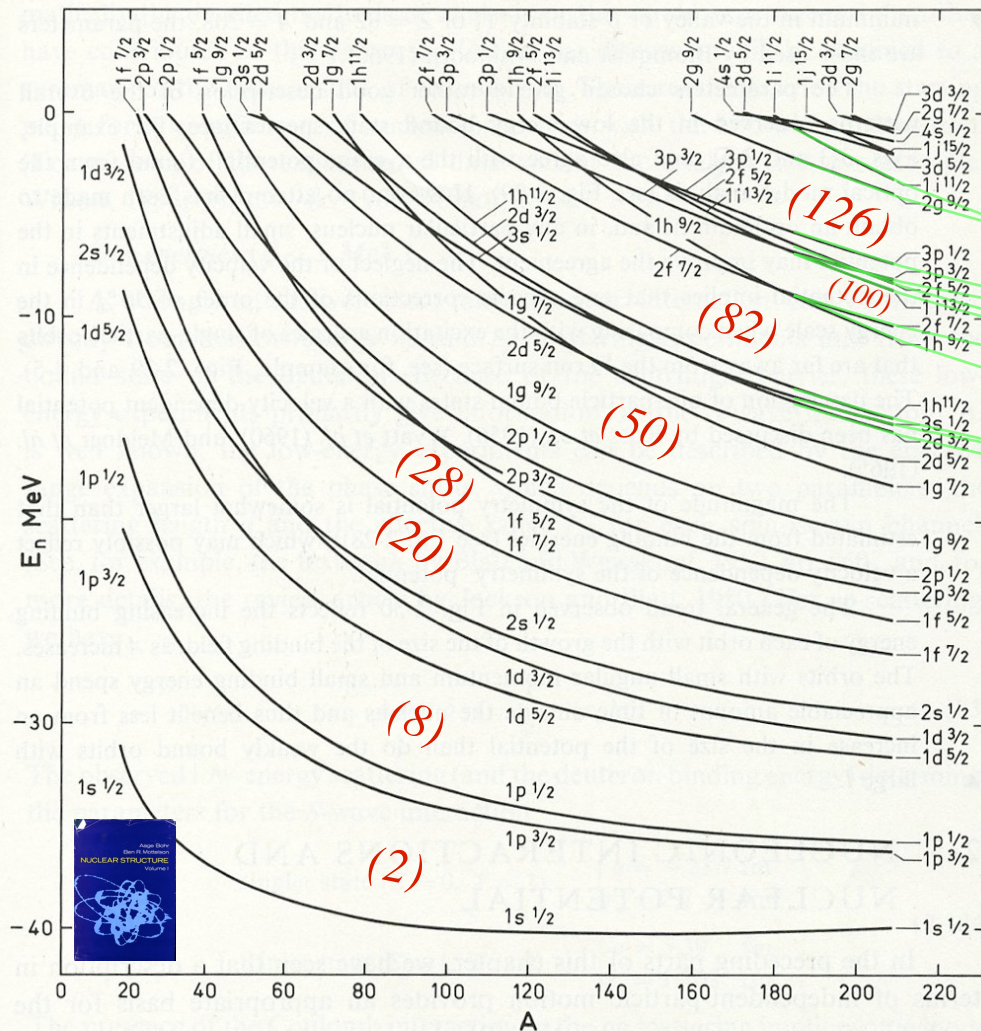
Figure 2-23 Sequence of one-particle orbits. The figure is taken from J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 10.



Magic numbers ...



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



VHE's -->

SHE's -->

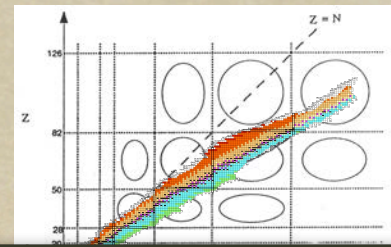
- 2g_{9/2}
- 1i_{11/2}
- 3p_{1/2}
- 3p_{3/2}
- 2f_{5/2}
- 1i_{13/2}
- 1h_{9/2}
- 3s_{1/2}
- 1h_{11/2}
- 2d_{3/2}

What are the
spherical magic
numbers for
SHE?

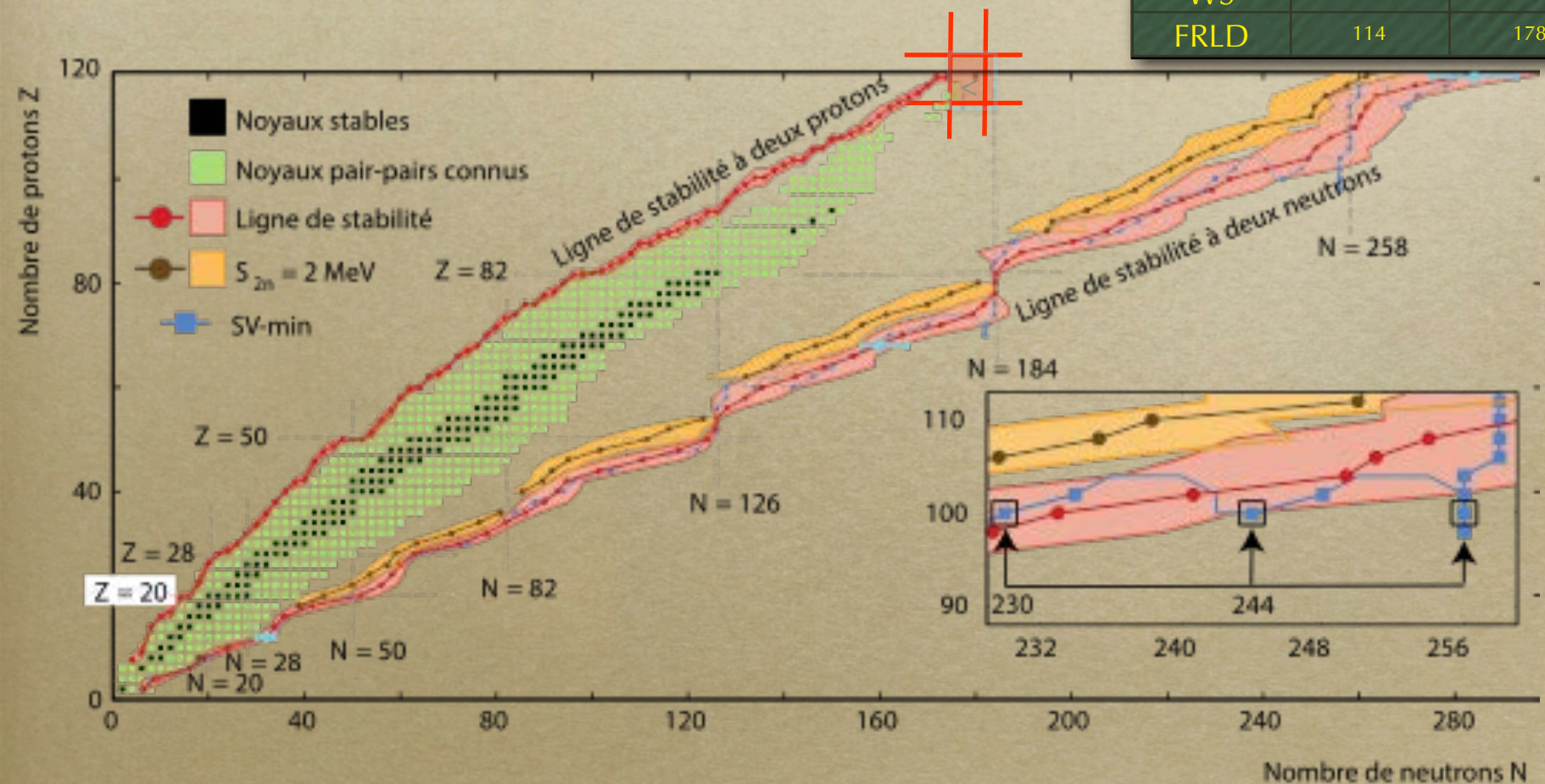
Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

Magic numbers ...

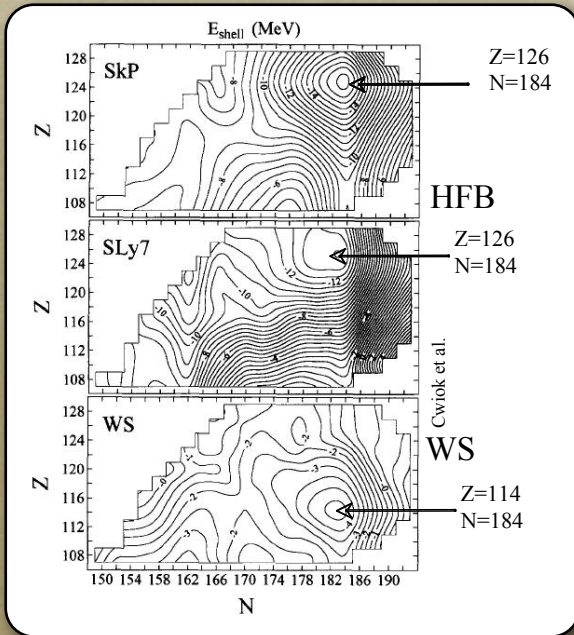
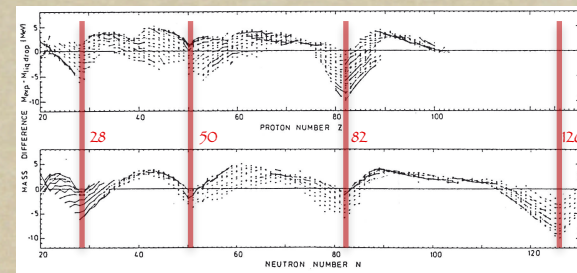
What are the magic numbers for SHE?



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



NEXT magic numbers ...



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

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

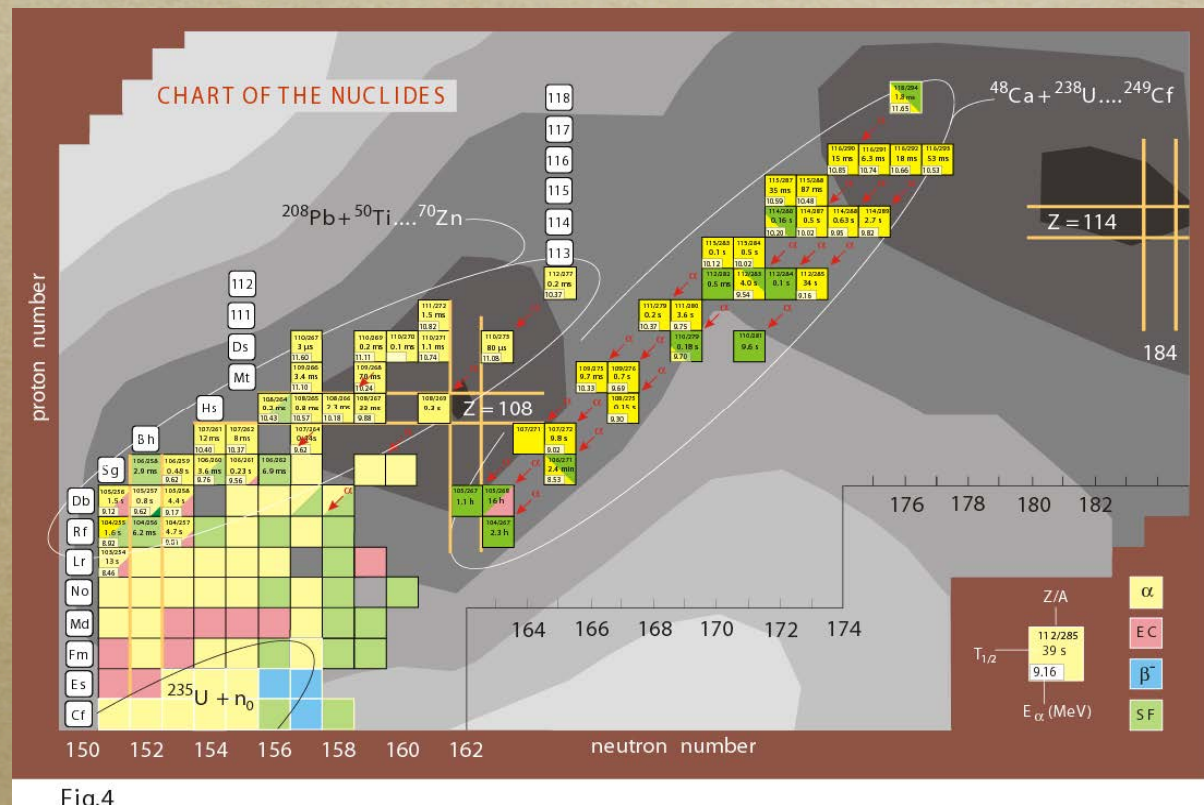


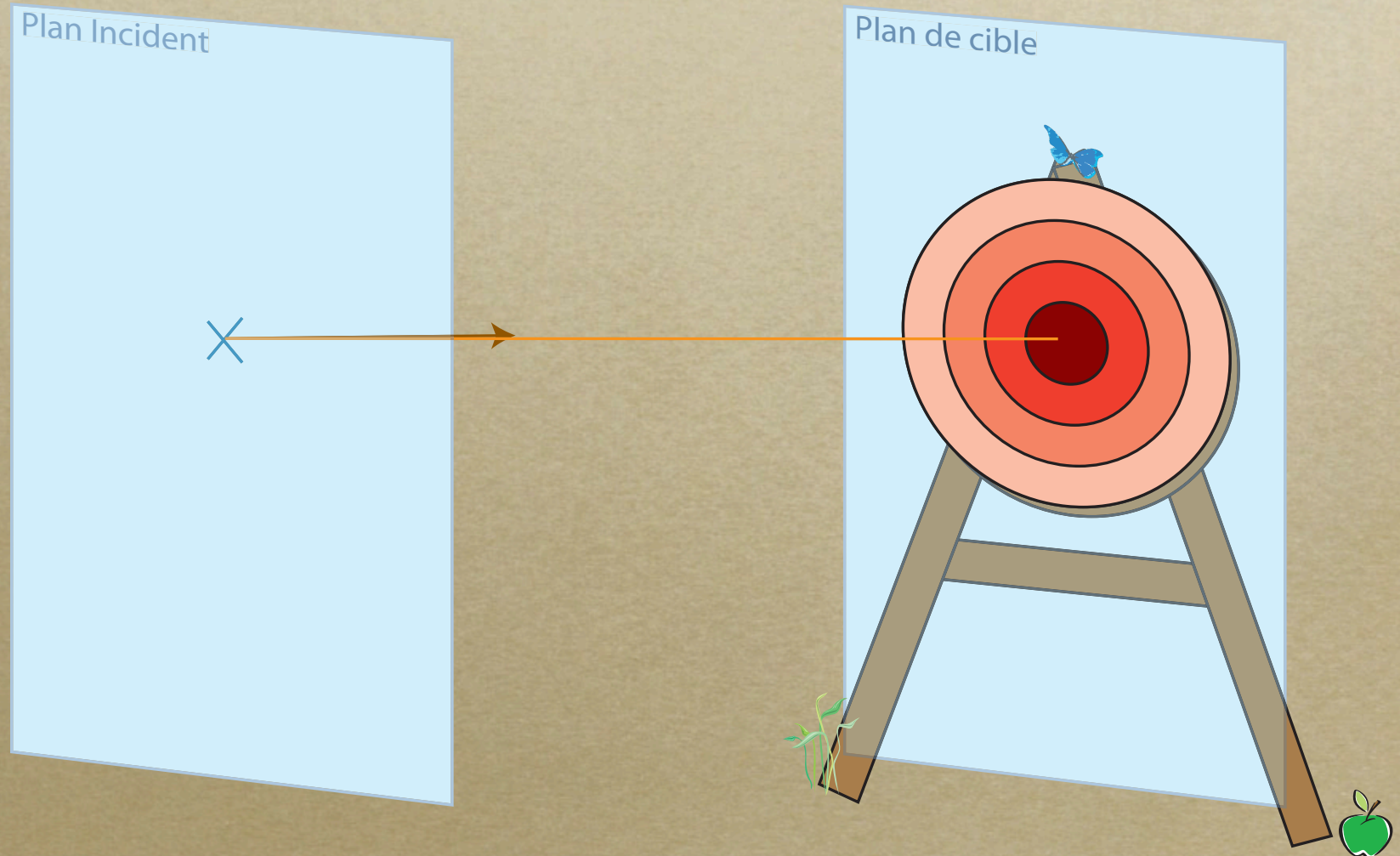
Fig.4

Super Heavy Elements (SHE)

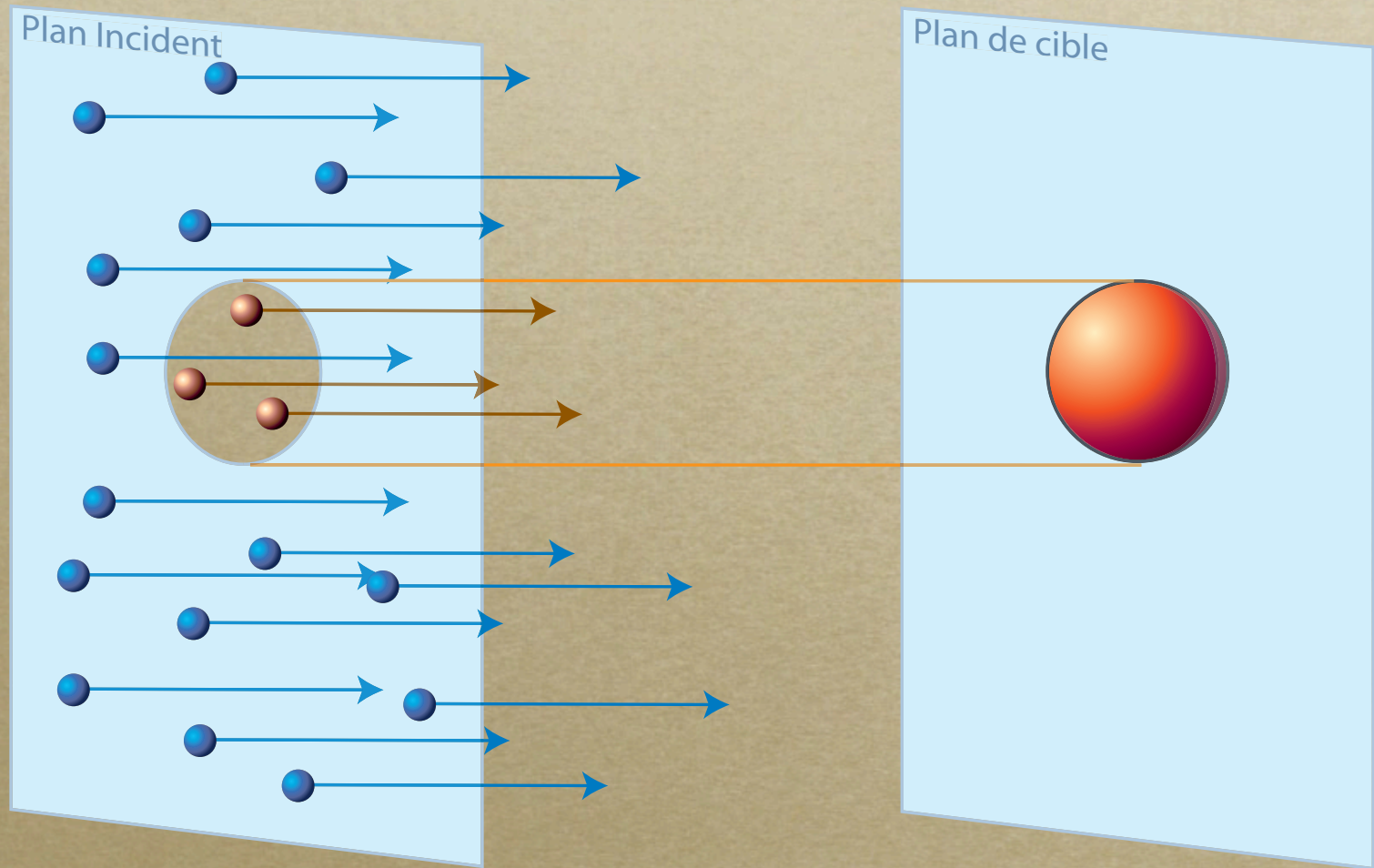
outline

- 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 ?

Femto - ballistics

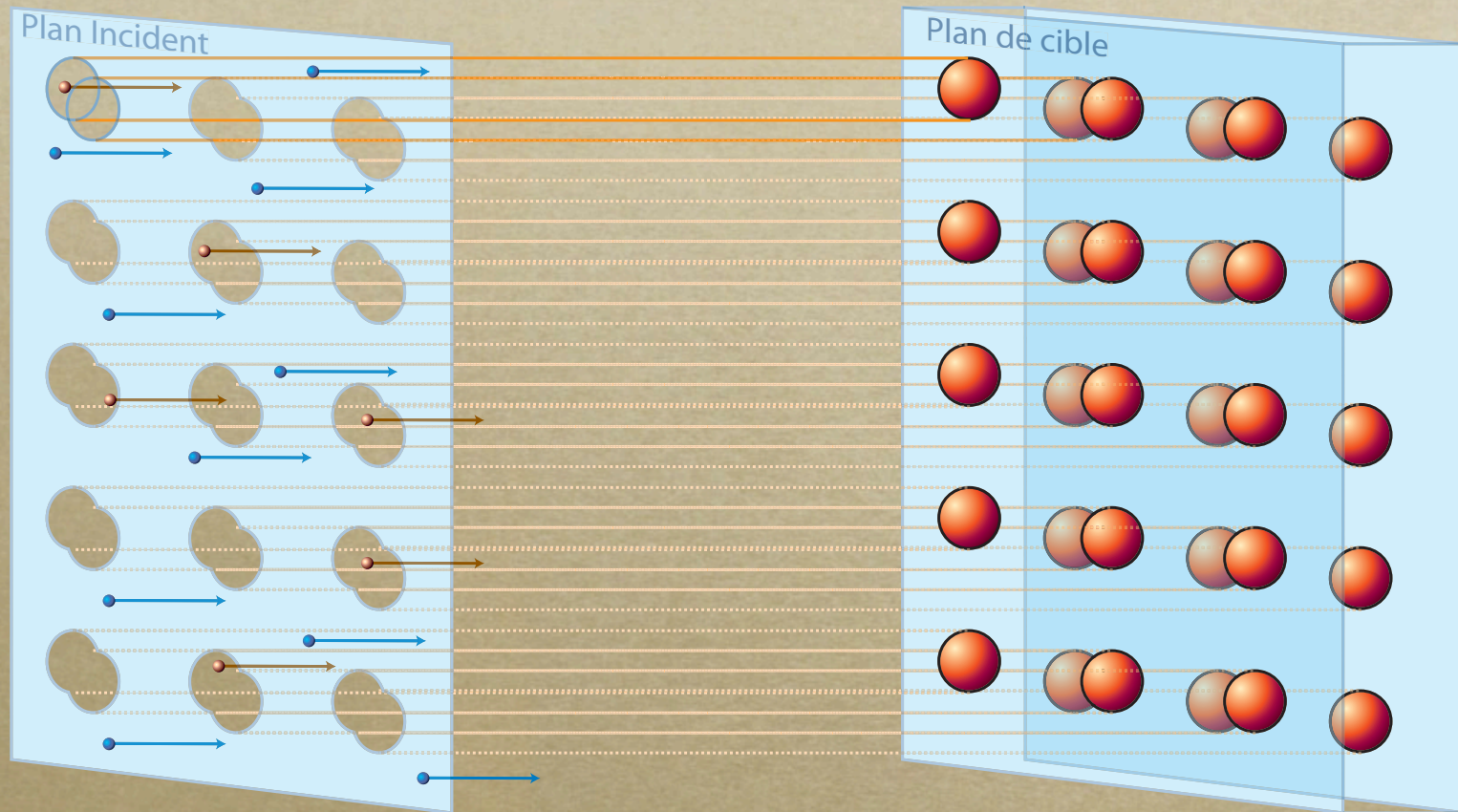


Incident plane \longrightarrow target plane



Cross section

$$S_{\text{total}} \approx N_{\text{target atoms}} \times S_{\text{efficient}}$$



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

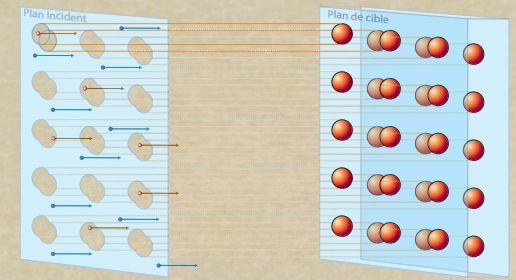
$$N_{\text{tot}} = N_i \cdot P_{\text{choc}} = N_i \cdot \sigma_{\text{geo}} \cdot N_C$$

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

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

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

Reaction flux calculation



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

...often in μA
 (1 $\mu\text{A} = 6 \cdot 10^{12}$ ions/s)

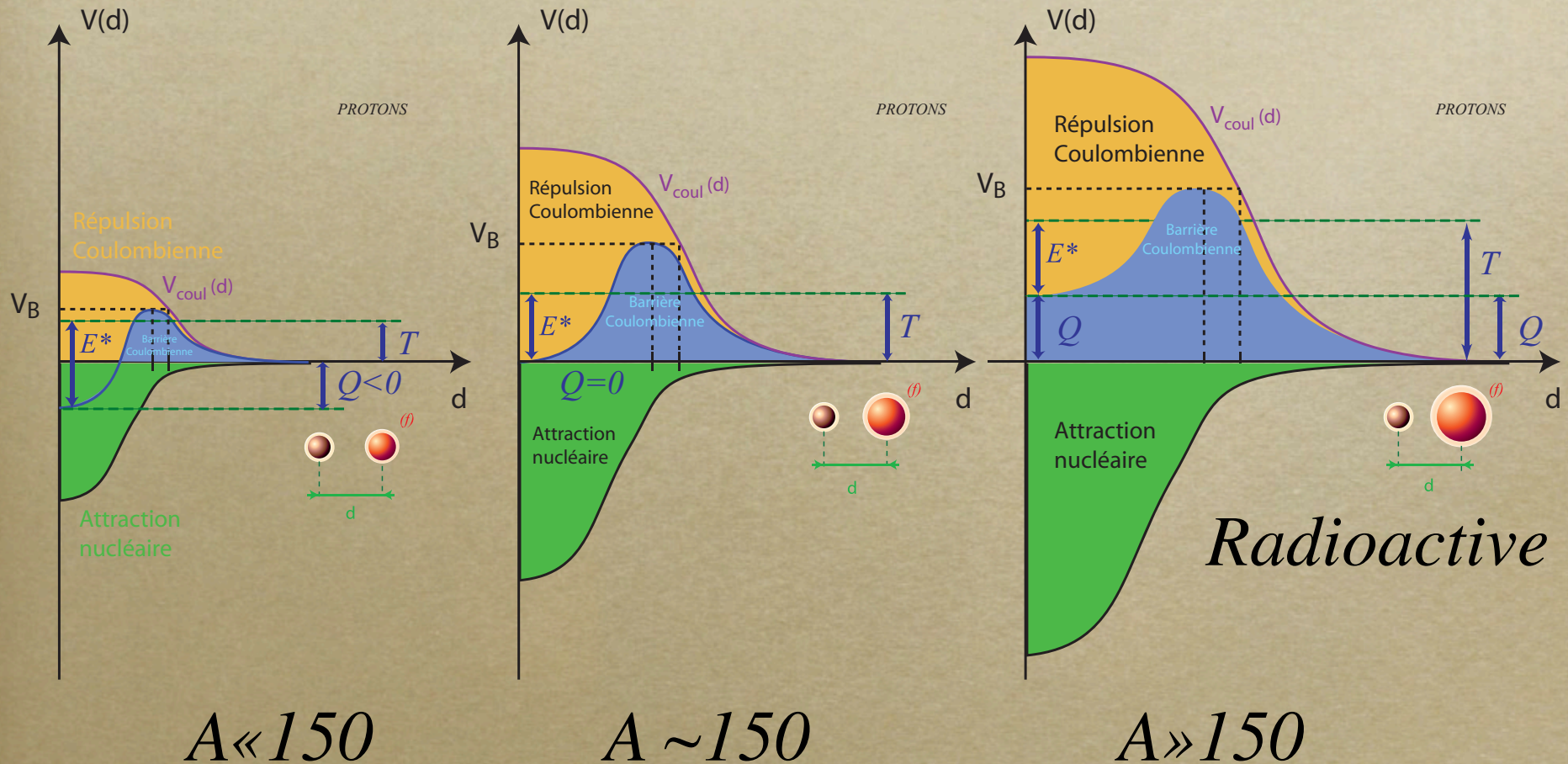
$$e' = e\rho = 500 \mu\text{g/cm}^2$$

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

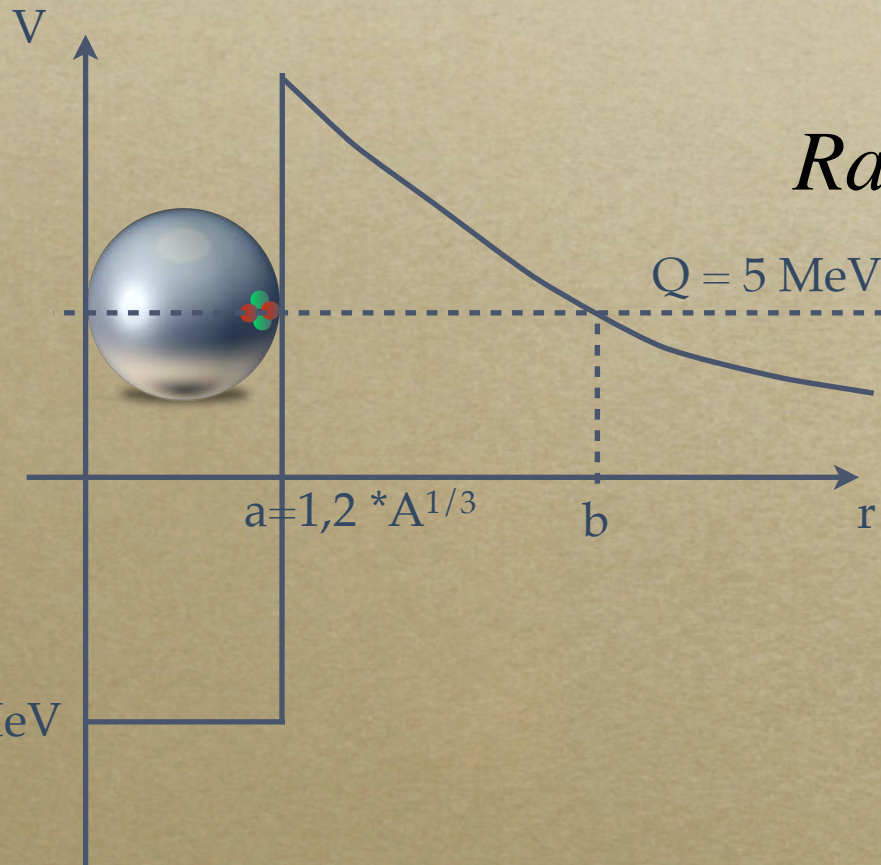
$$N_C (\text{atomes / cm}^2) = \frac{e \cdot \rho (\text{g/cm}^2)}{m_{at} (\text{g / atome})} = \frac{e \cdot \rho \cdot N_{Avogadro}}{M(A, Z)}$$

$$P_{choc} = \sigma_{geo} \cdot N_C \quad \rightarrow \quad \begin{cases} N_{tot} = N_i \cdot \sigma_{geo} \cdot N_C \\ \phi_{tot} = \phi_i \cdot \sigma_{geo} \cdot N_C \end{cases}$$

unstability of heavy nuclei ...



unstability of heavy nuclei ...



*Gamow Theory and
Tunnel effect*

Radioactive decay constant

$$\lambda = p \cdot f$$

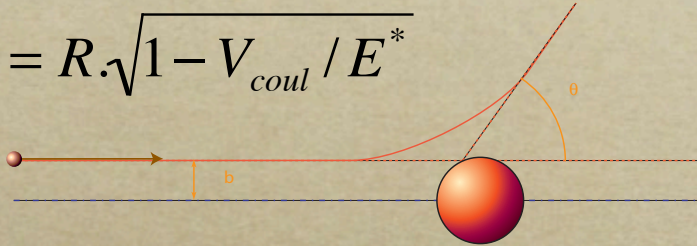
$$f \sim 10^{21} \text{ Hz}$$

Radioactive

$$A \gg 150$$

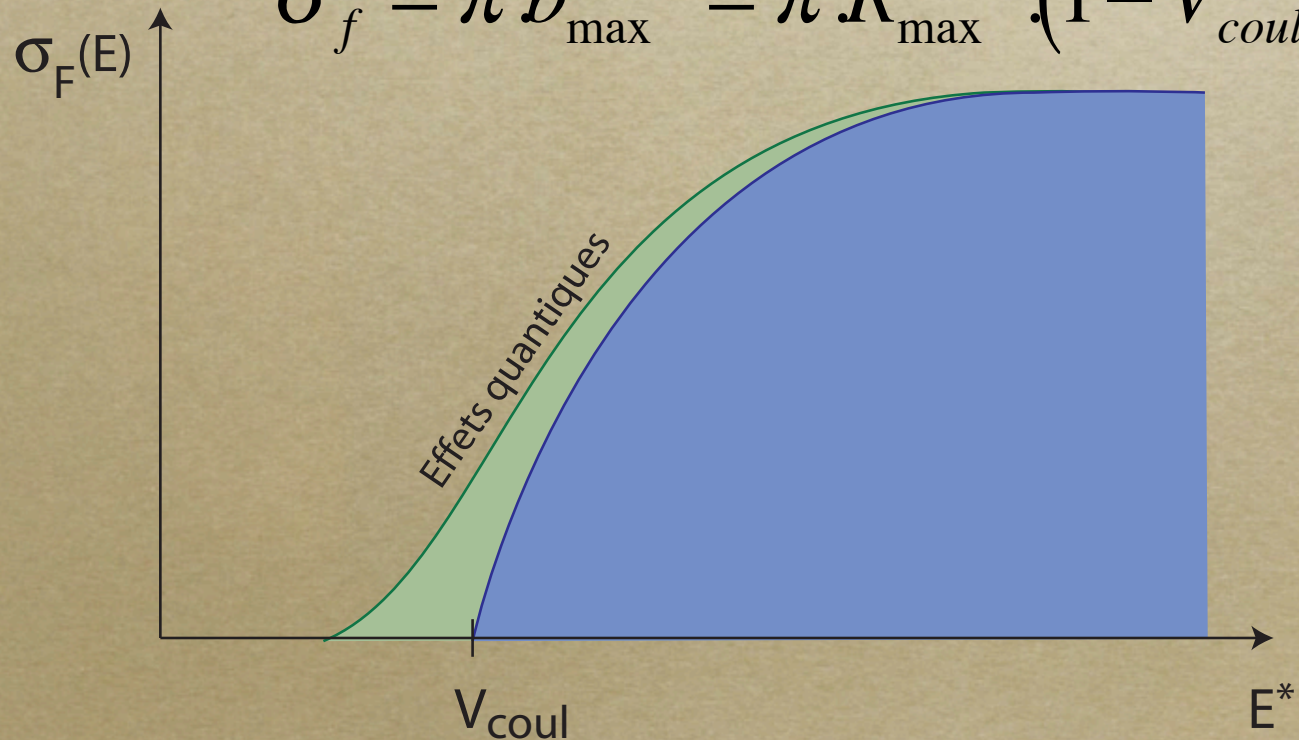
Fusion cross section

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



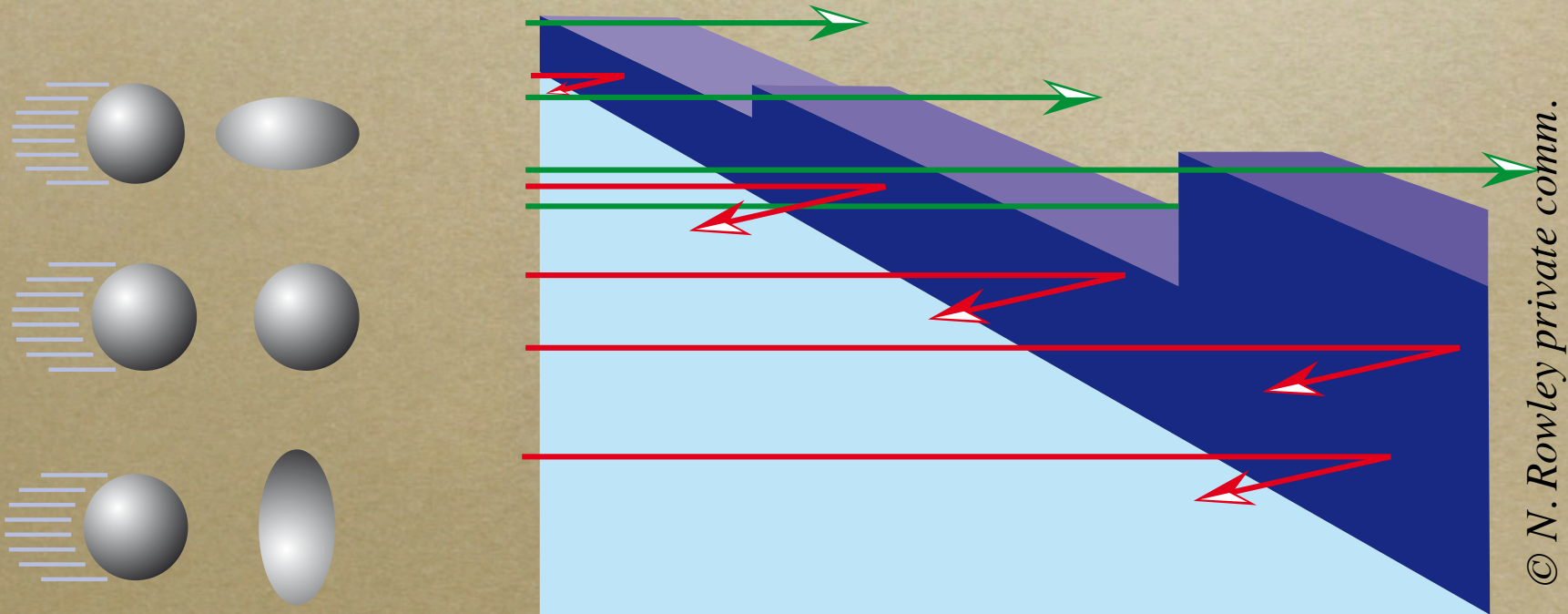
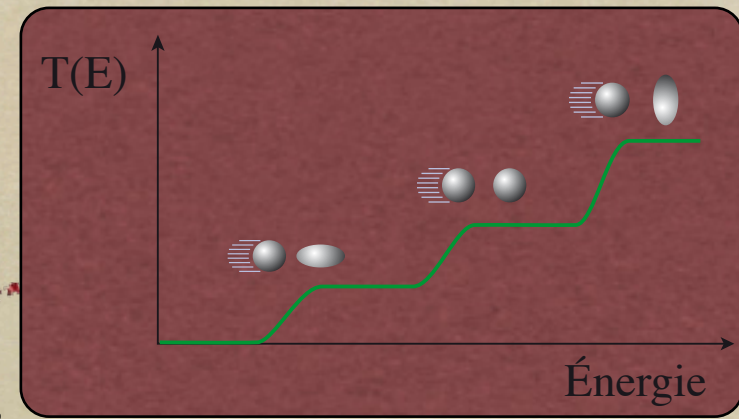
then

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

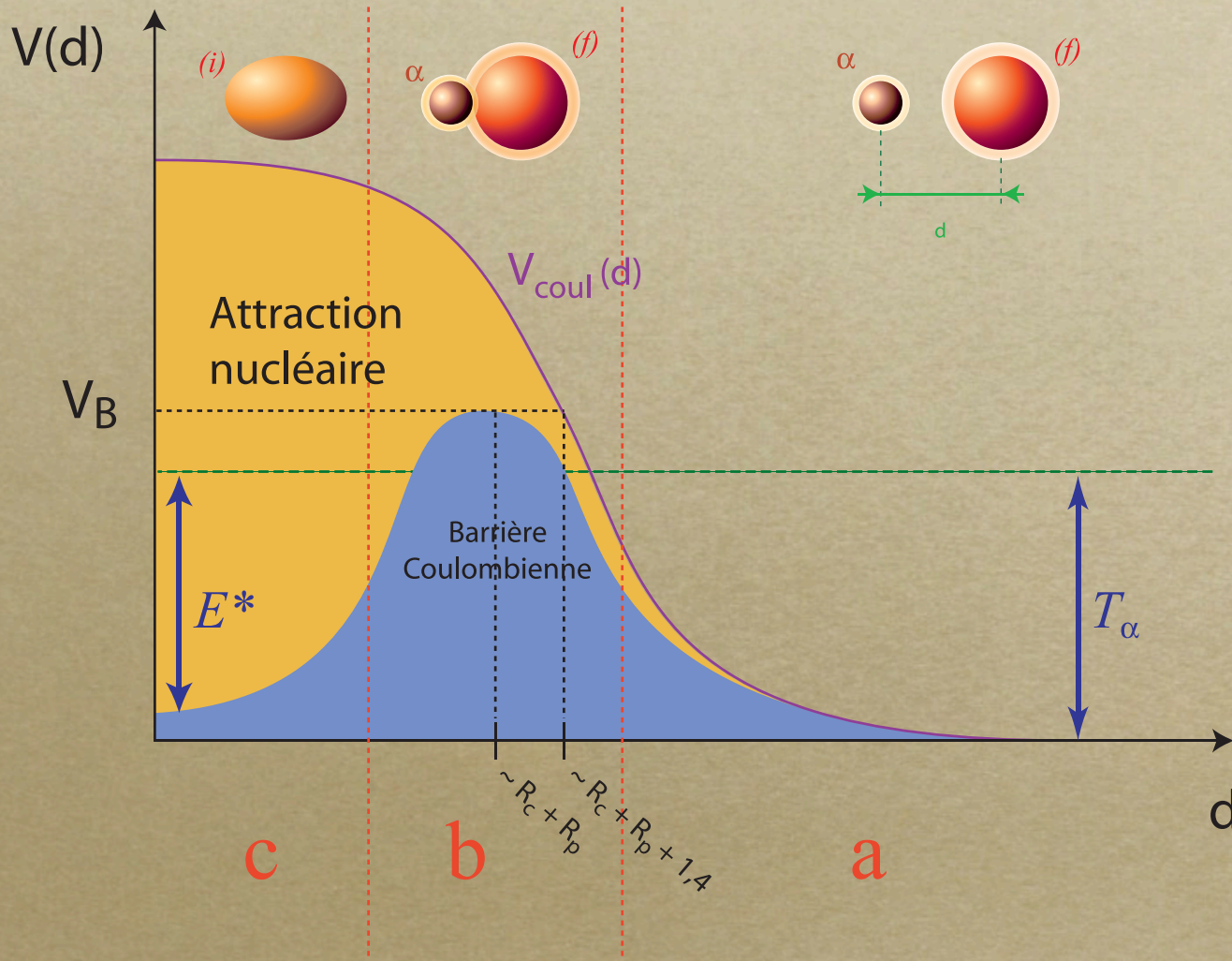


Effects of the entrance channel

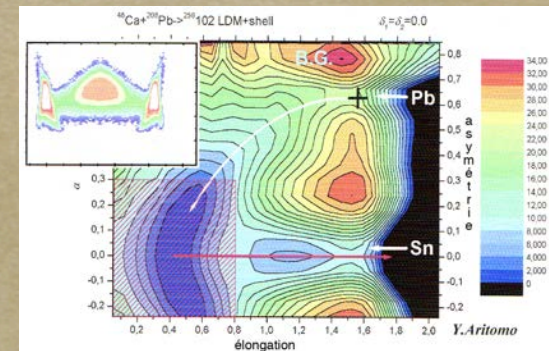
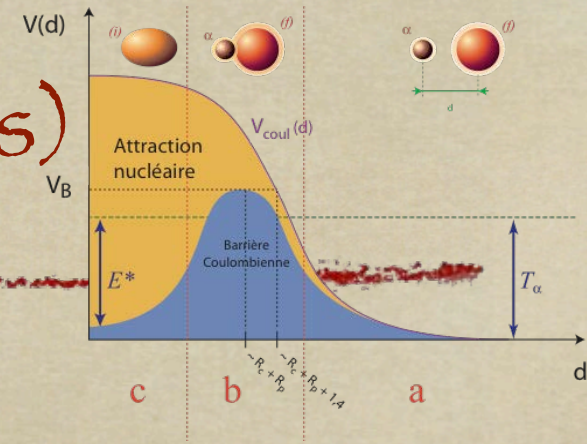
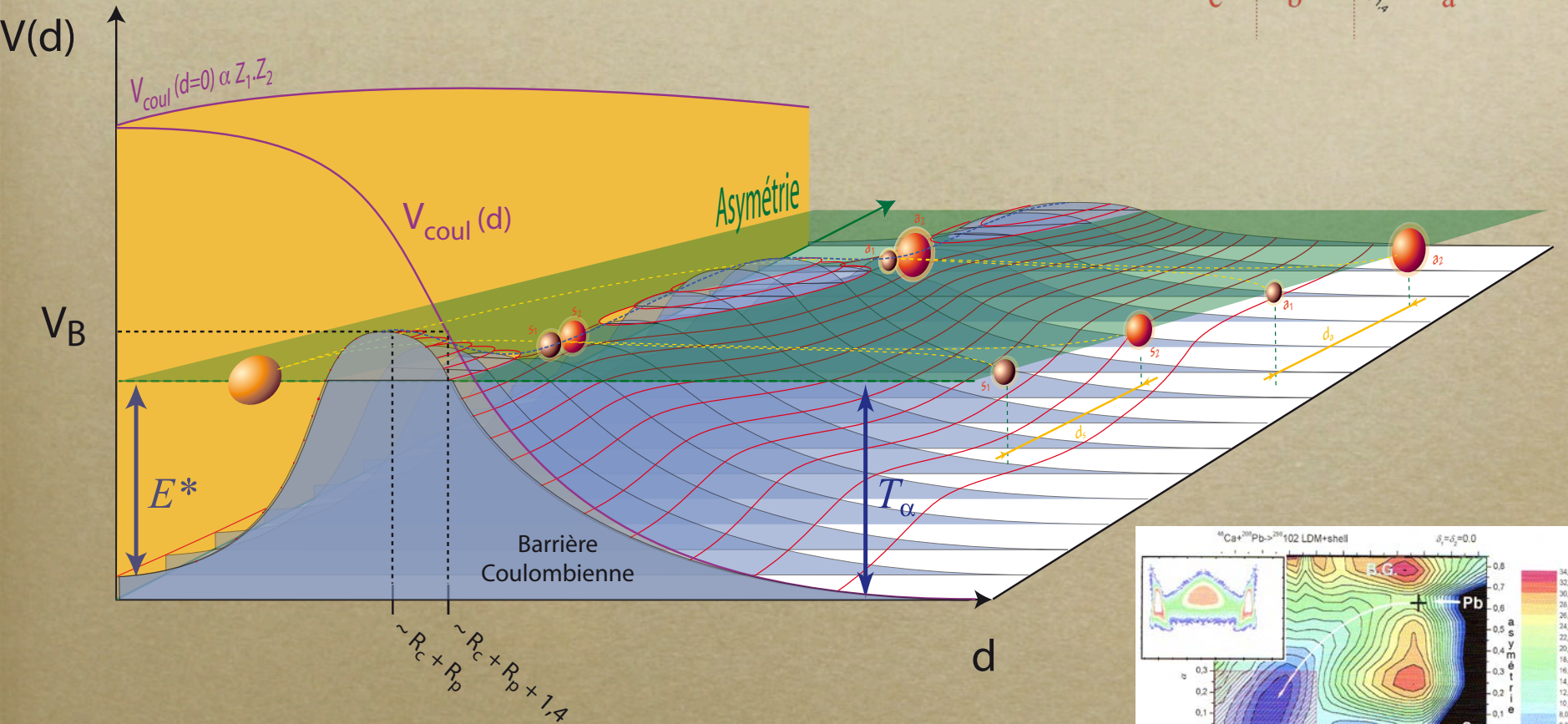
Coulomb force depends on the orientation of the target and the projectile



Coulomb barrier (1 dimension)



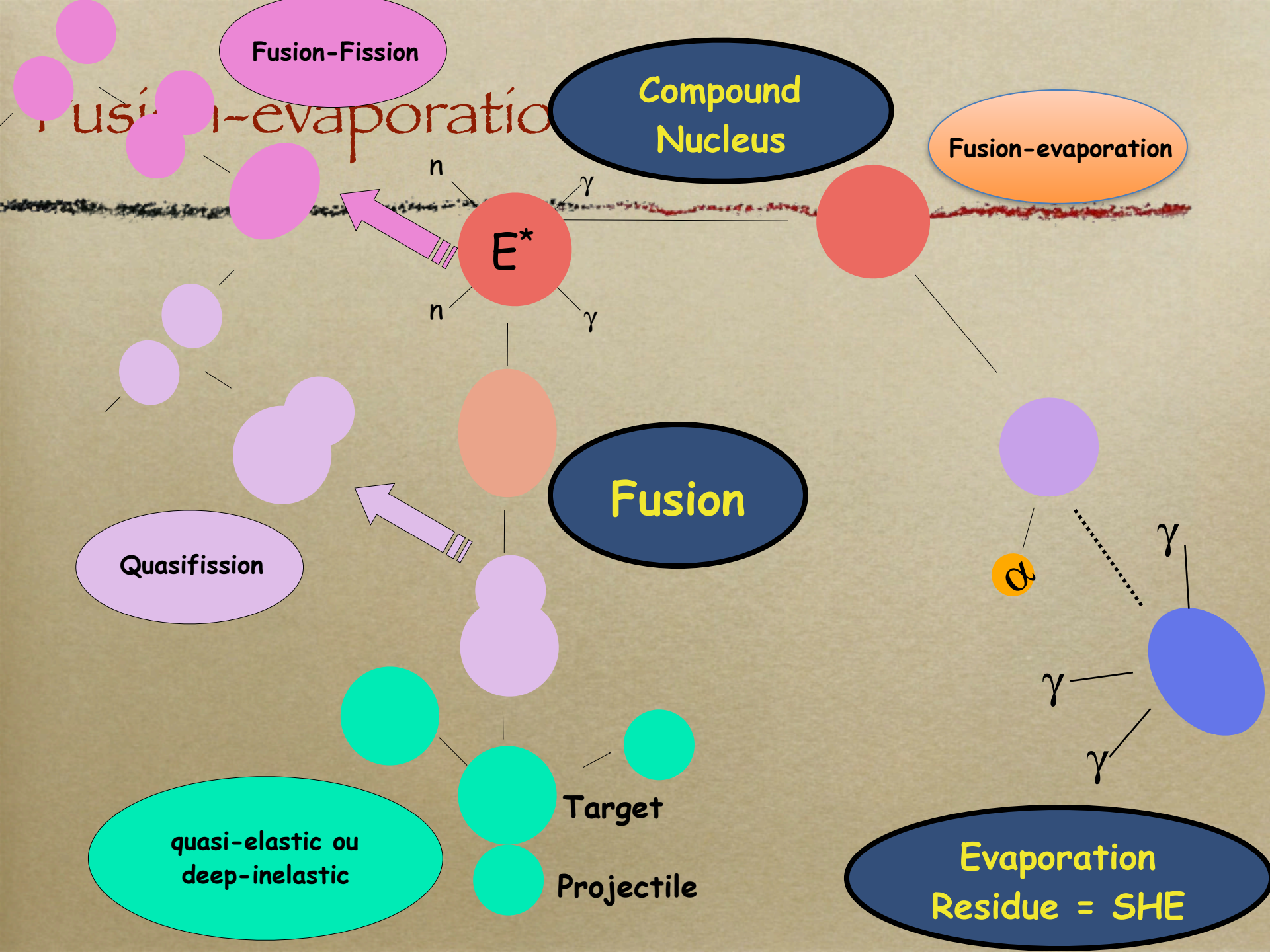
Coulomb barrier (2 dimensions)



Super Heavy Elements (SHE)

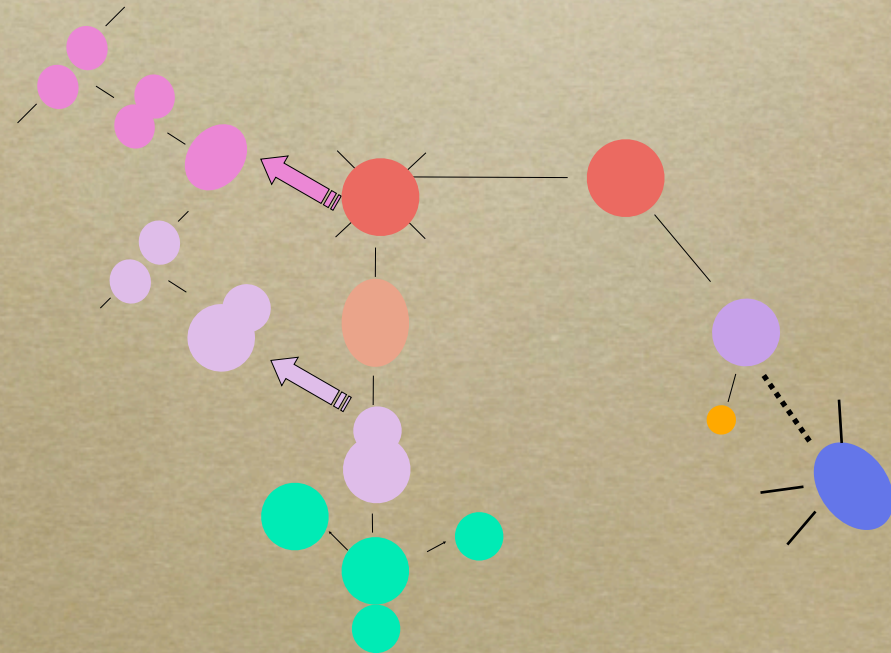
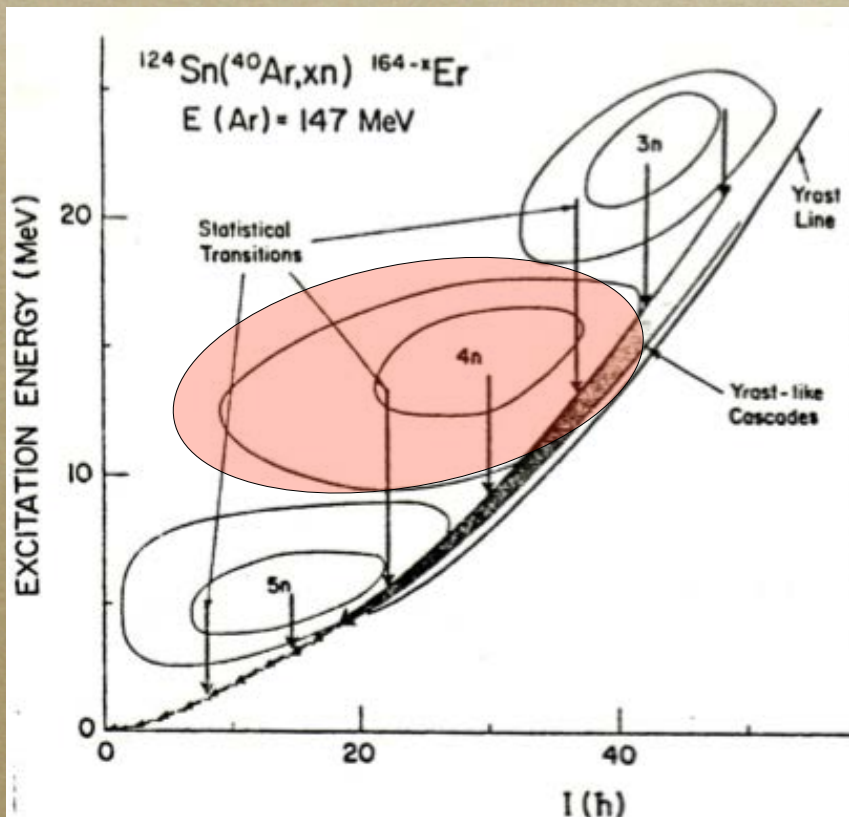
outline

- 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 ?



Fusion-evaporation reaction

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



Exit channel as a function of Energy

Statistical evaporation
of x neutrons

« xn » channel

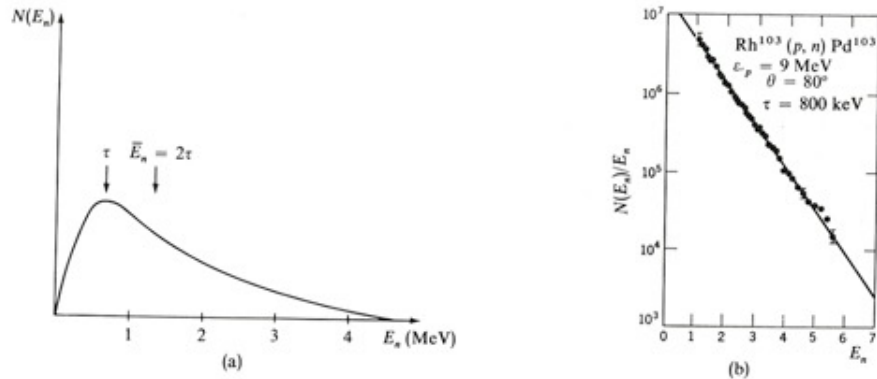


FIGURE XI.4

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 $E_n + dE_n$ ou où τ est la température nucléaire définie par la relation (XI.18), à savoir: $d(\text{Log } \omega)/dE_n = 1/\tau$. La figure (a) donne son allure caractéristique pour $\tau \approx 0.8$ 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 $\theta = 80^\circ$. L'accord avec la théorie est satisfaisant pour $\tau = 0.8$ MeV.

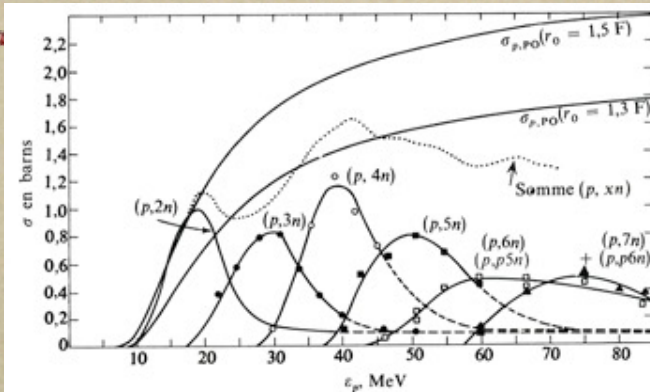
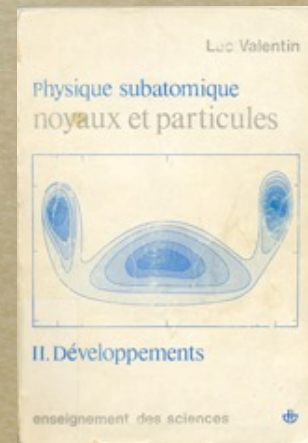


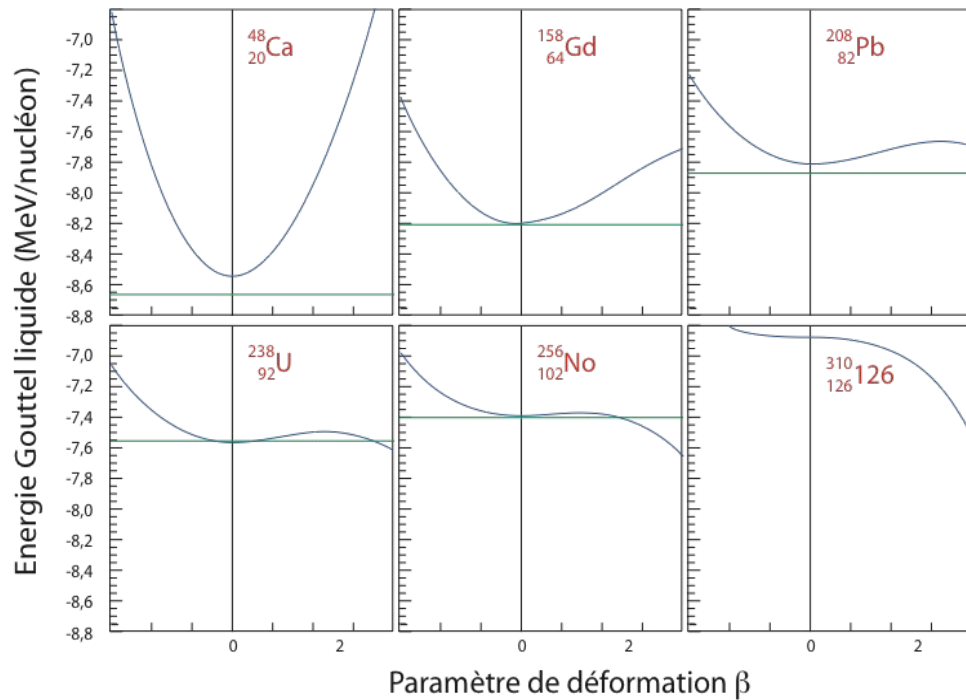
FIGURE XI.3

Fonctions d'excitation des réactions (p, xn) induites sur le noyau ^{209}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 $\sigma_{p,PO}$ sont les sections efficaces de formation du noyau composé ^{210}Po calculées dans l'hypothèse d'un noyau noir de rayon $R = r_0 A^{1/3}$ (avec $r_0 = 1.5 \text{ F}$ et $r_0 = 1.3 \text{ F}$), en tenant compte de la probabilité de franchir la barrière coulombienne (cf. exercice XI.2).

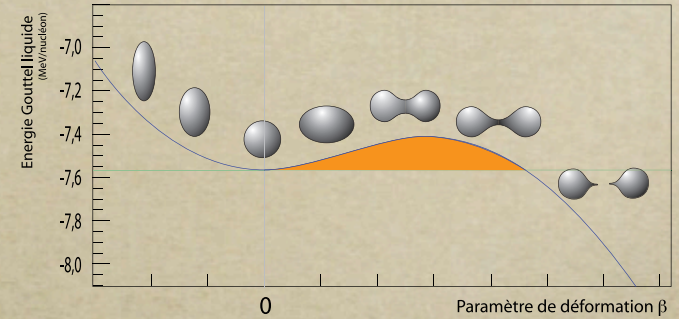
Maxwell Energy Distribution



Coulomb barrier (Z dependance)

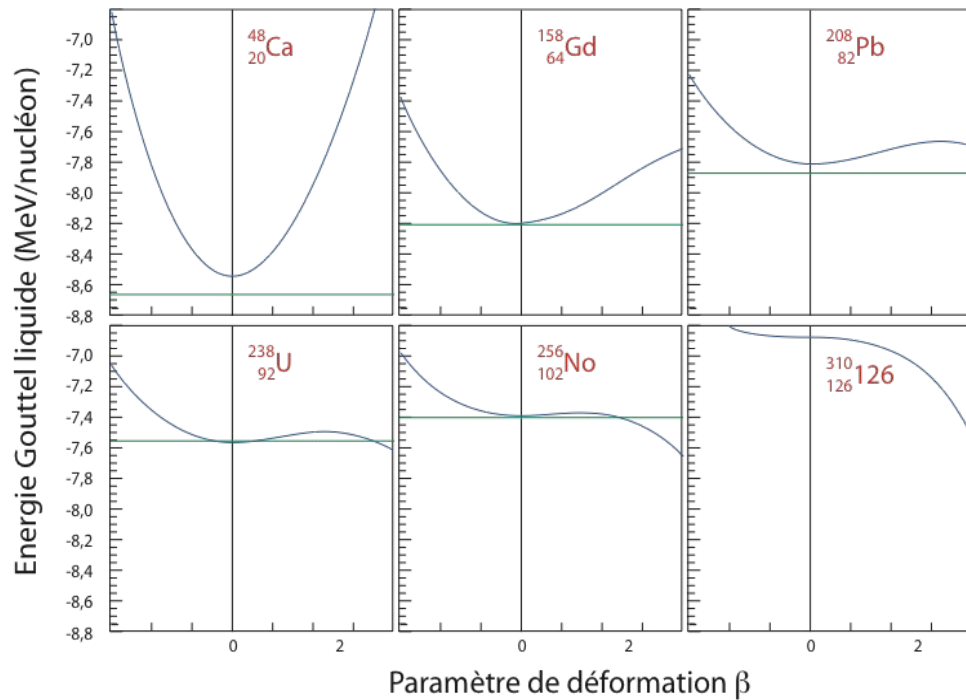


D'après : Myers - Swiatecki Nucl. Phys. A 81 (1966) 1.

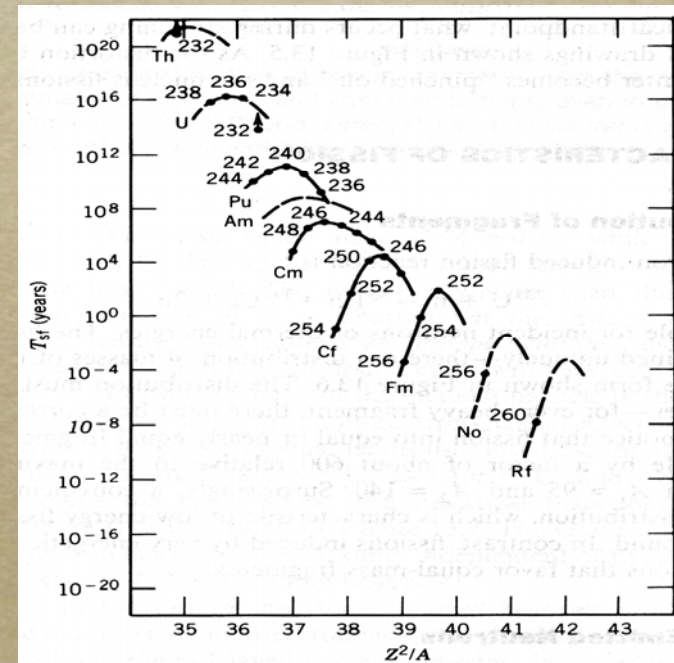
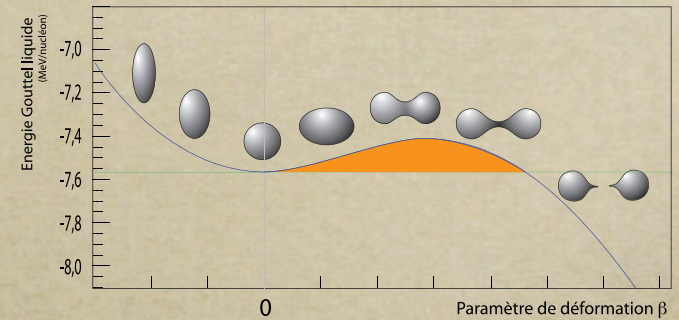


Coulomb barrier disappear progressively with Z

Coulomb barrier (Z dependance)

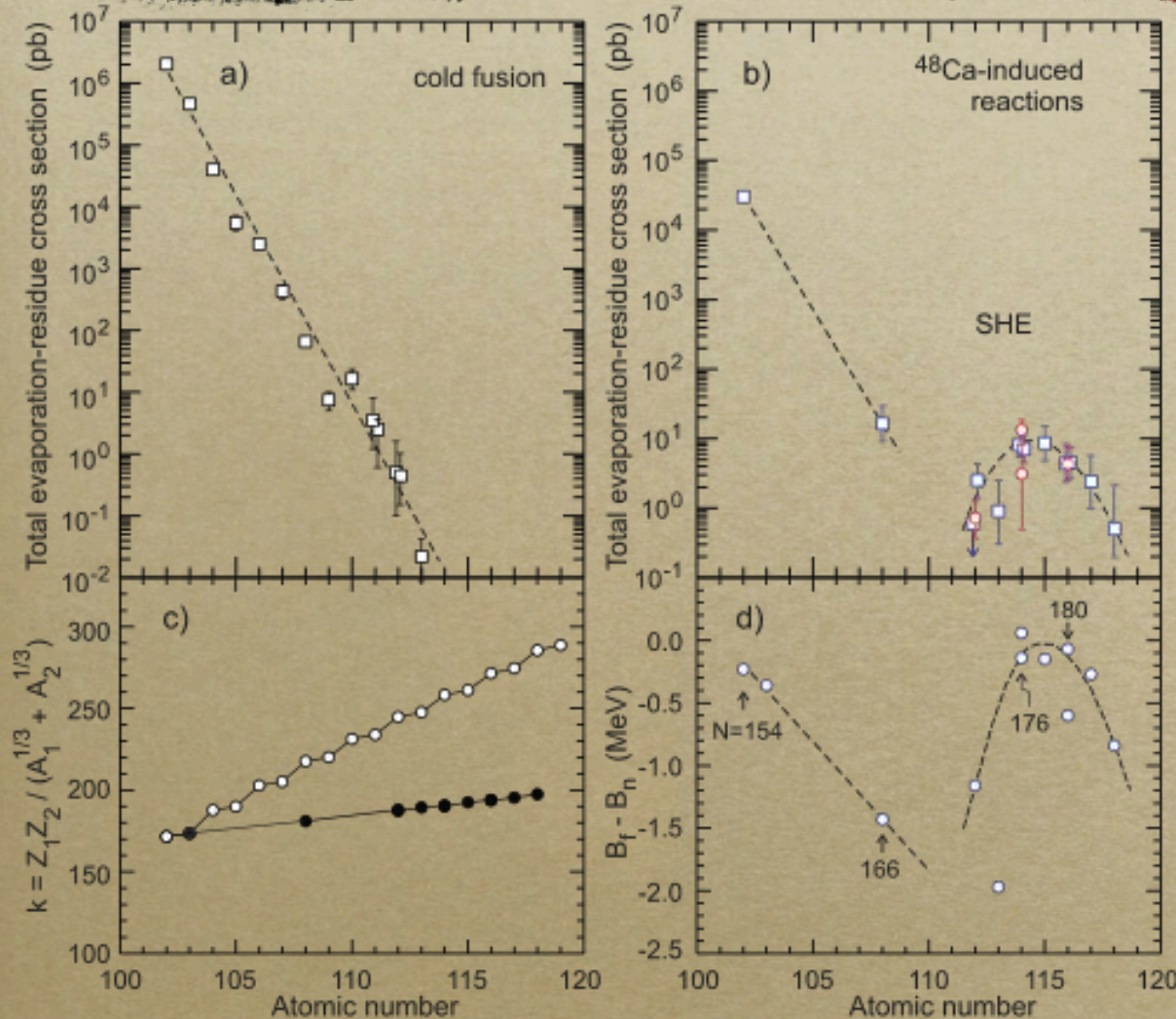


D'après : Myers - Swiatecki Nucl. Phys. A 81 (1966) 1.

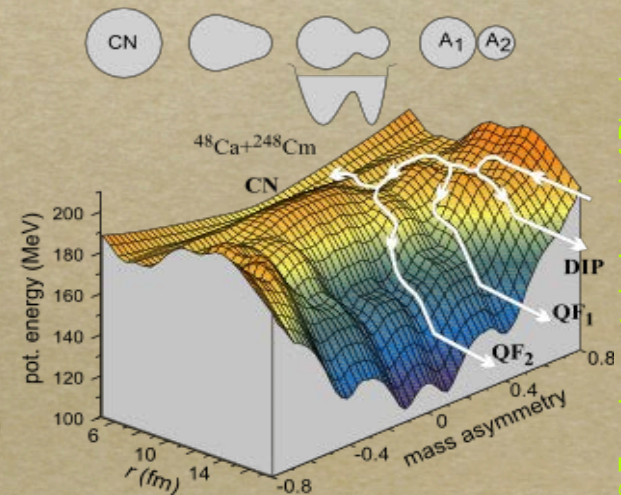


*Coulomb barrier disappear progressively with Z
... Fission is enhanced !*

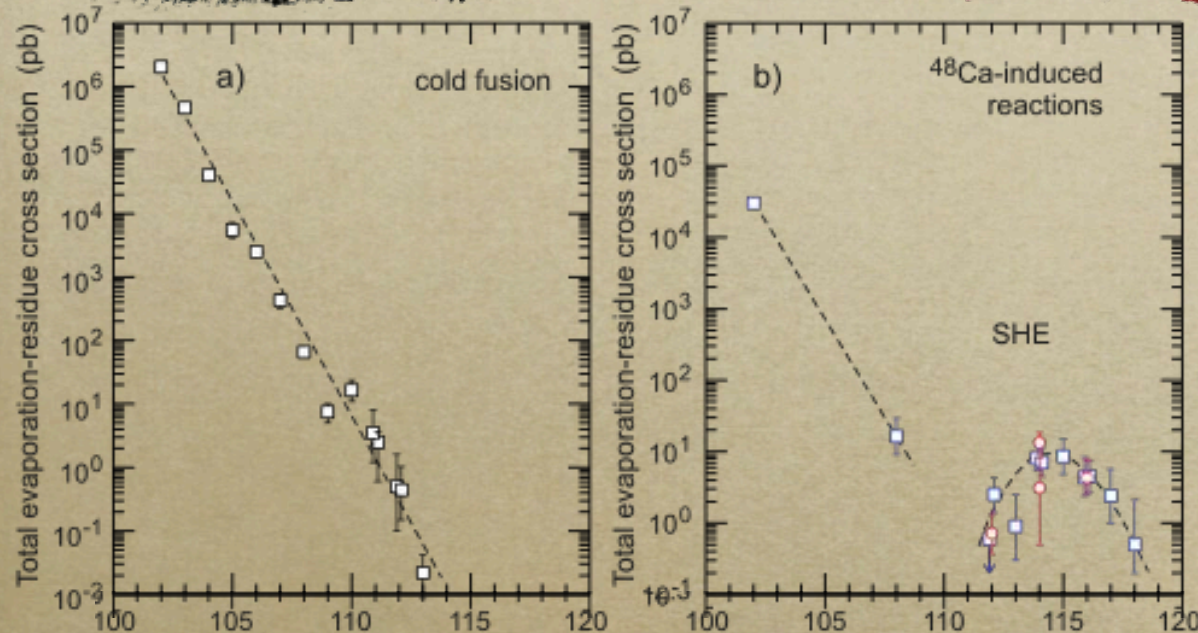
SHE production probability



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

500 μg/cm²

\Leftrightarrow 1 evt per month

Heaviest elements

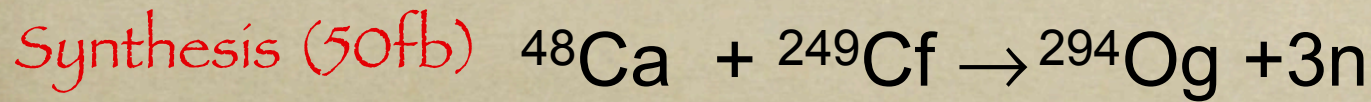
Only a few
events observed

in years of
study

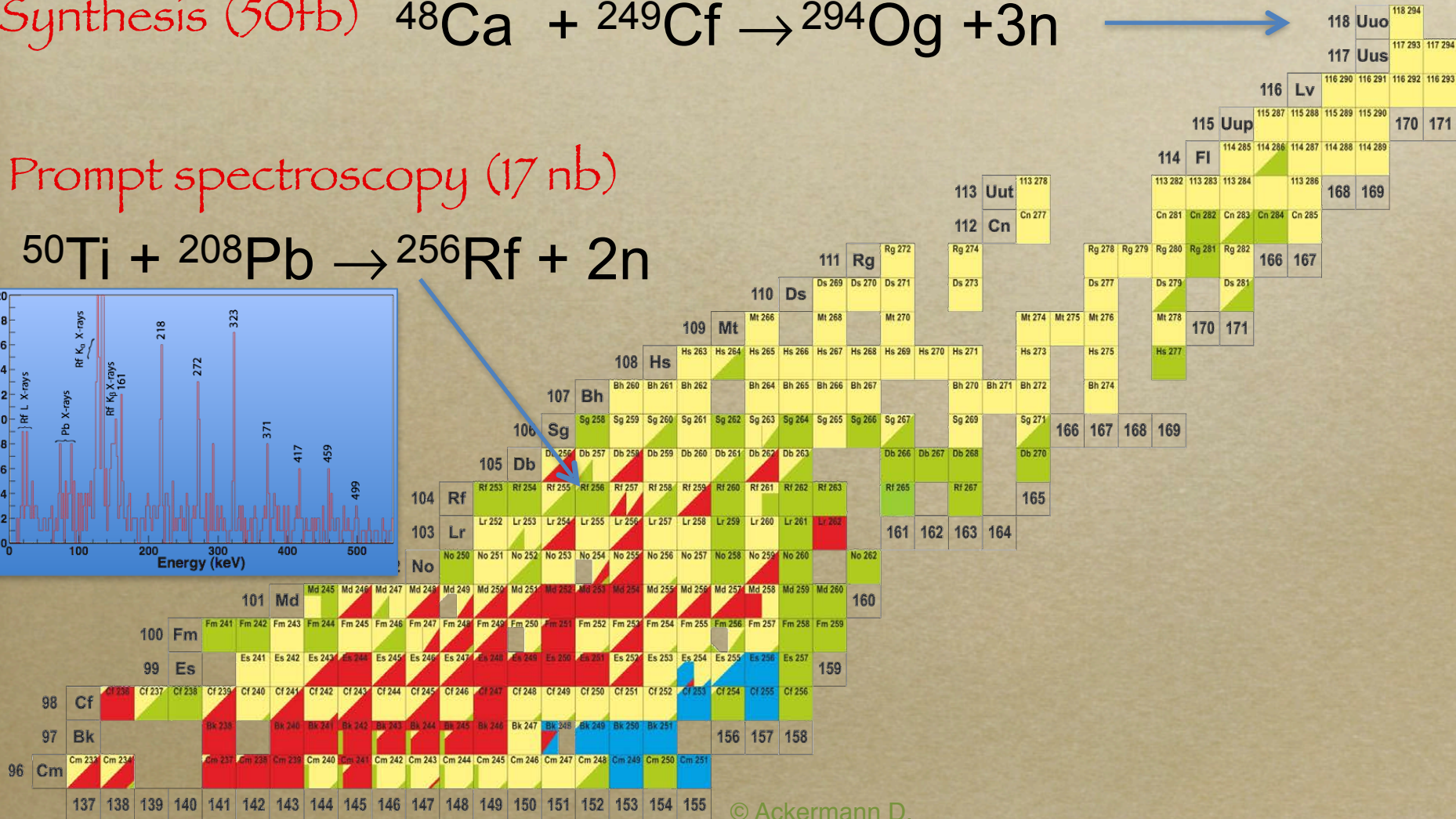
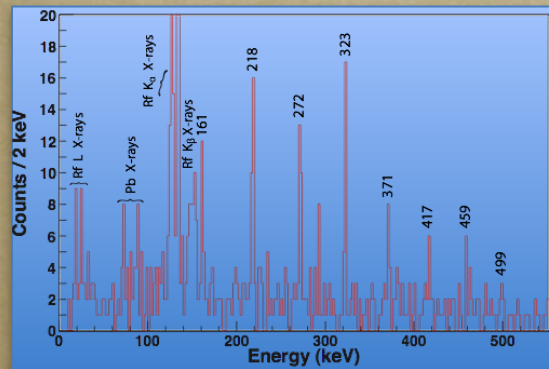
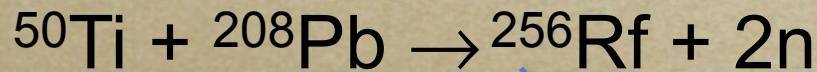
Table 1
Decay properties of nuclei.

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	$10.81\text{--}11.07$	11.18 ± 0.04	[74,86–89]
	176	293	d:15	α	22^{+8}_{-4} ms	$10.60\text{--}11.20$	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	$9.78\text{--}10.31$	10.41 ± 0.04	[74,86–89]
	174	289	d:16	α	330^{+120}_{-80} ms	$10.15\text{--}10.54$	10.49 ± 0.05	[74,80,81,86–88]
	173	288	d:27, t:19	α	164^{+30}_{-21} ms	$10.29\text{--}10.58$	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	$9.61\text{--}9.75$	9.79 ± 0.05	[74,86–89]
	172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	$9.47\text{--}10.18$	10.01 ± 0.04	[74,80,81,86–88]
	171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	$9.10\text{--}10.11$	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]

The experimental limits ?



Prompt spectroscopy (17 nb)



Limits for SHE production

beam intensity

- highest possible $\sim 1\text{p}\mu\text{A}$ ($6 \cdot 10^{12}$ pps)

- avoid target fusion

heaviest target available

249, 250, 251 Cf ($Z=98$)

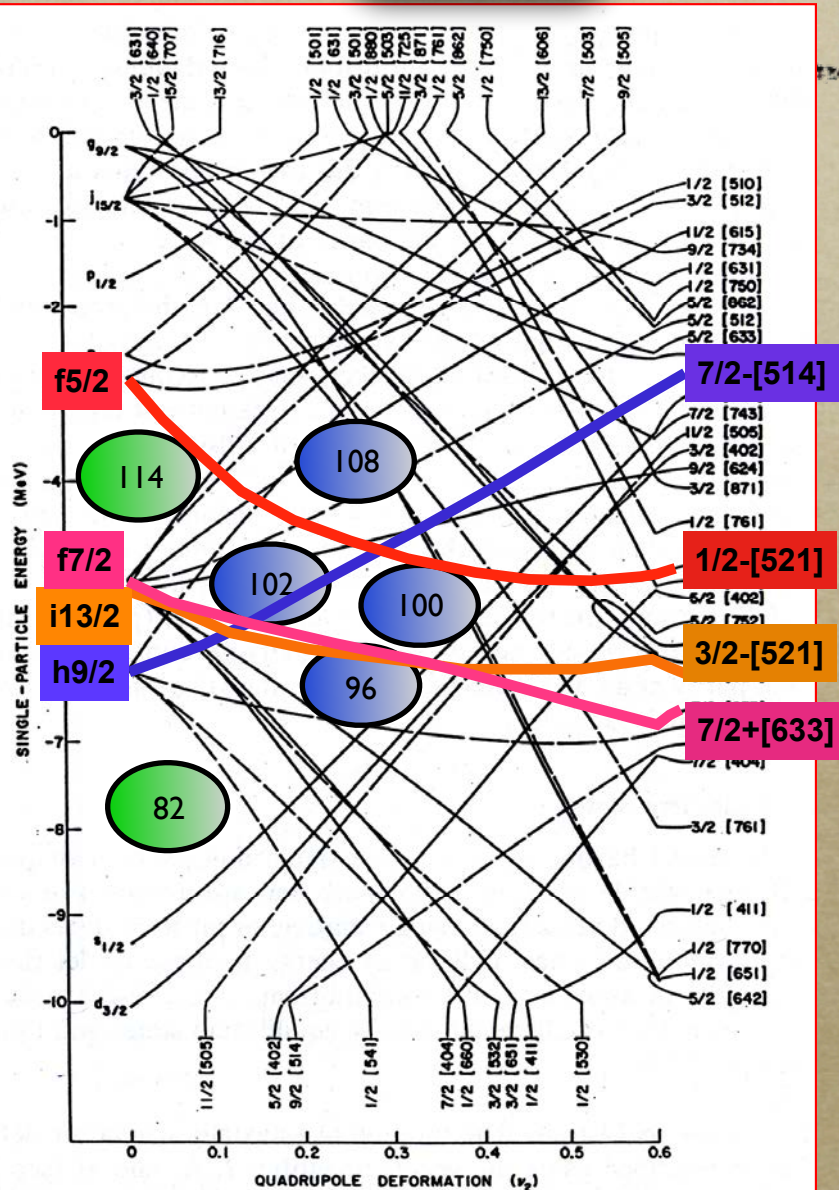
neutron-rich beams

 ^{48}Ca ($z=20$)

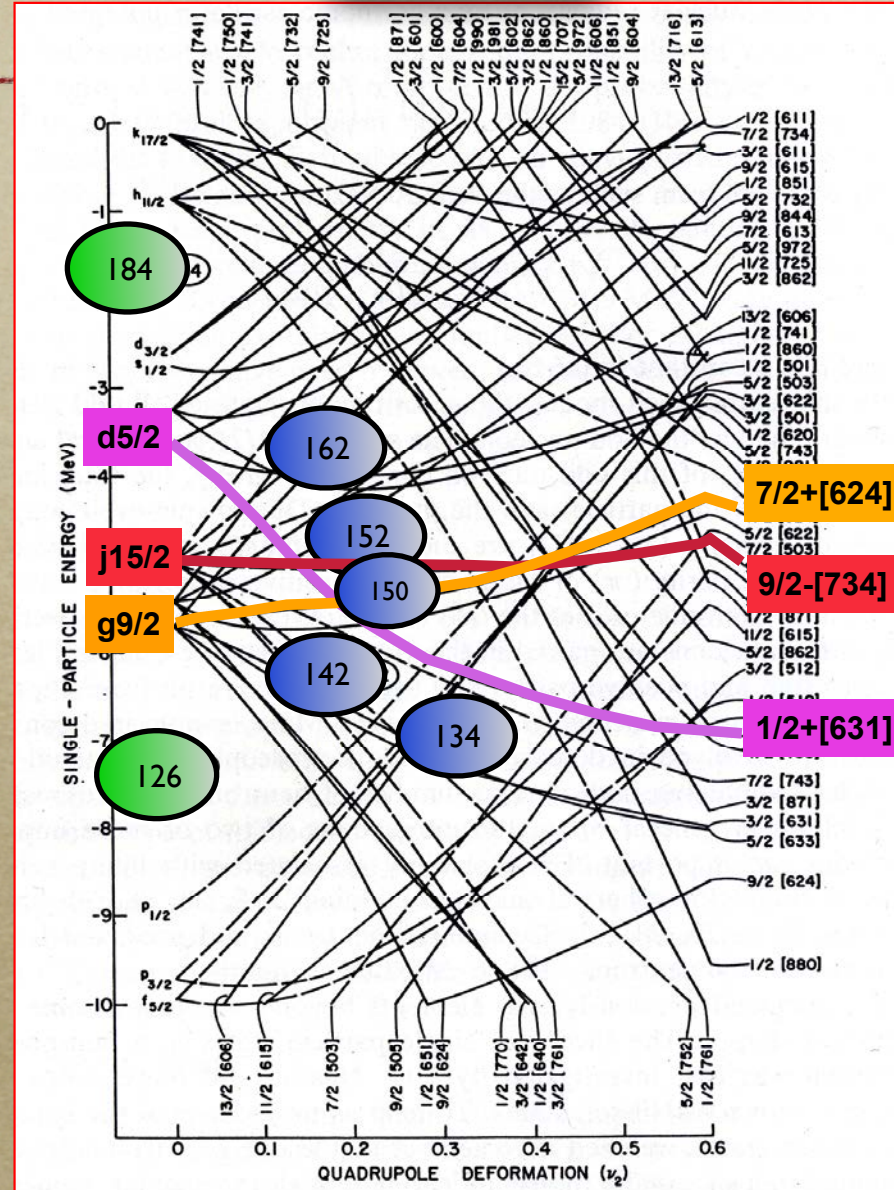
new intense
neutron-rich beam
 ^{50}Ti ($z=22$)

What can we learn from γ - e^- spectroscopy?

Protons

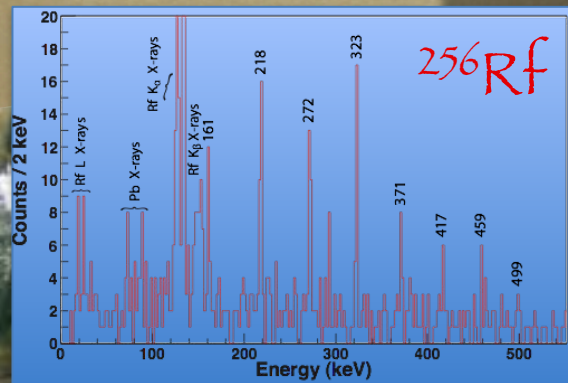
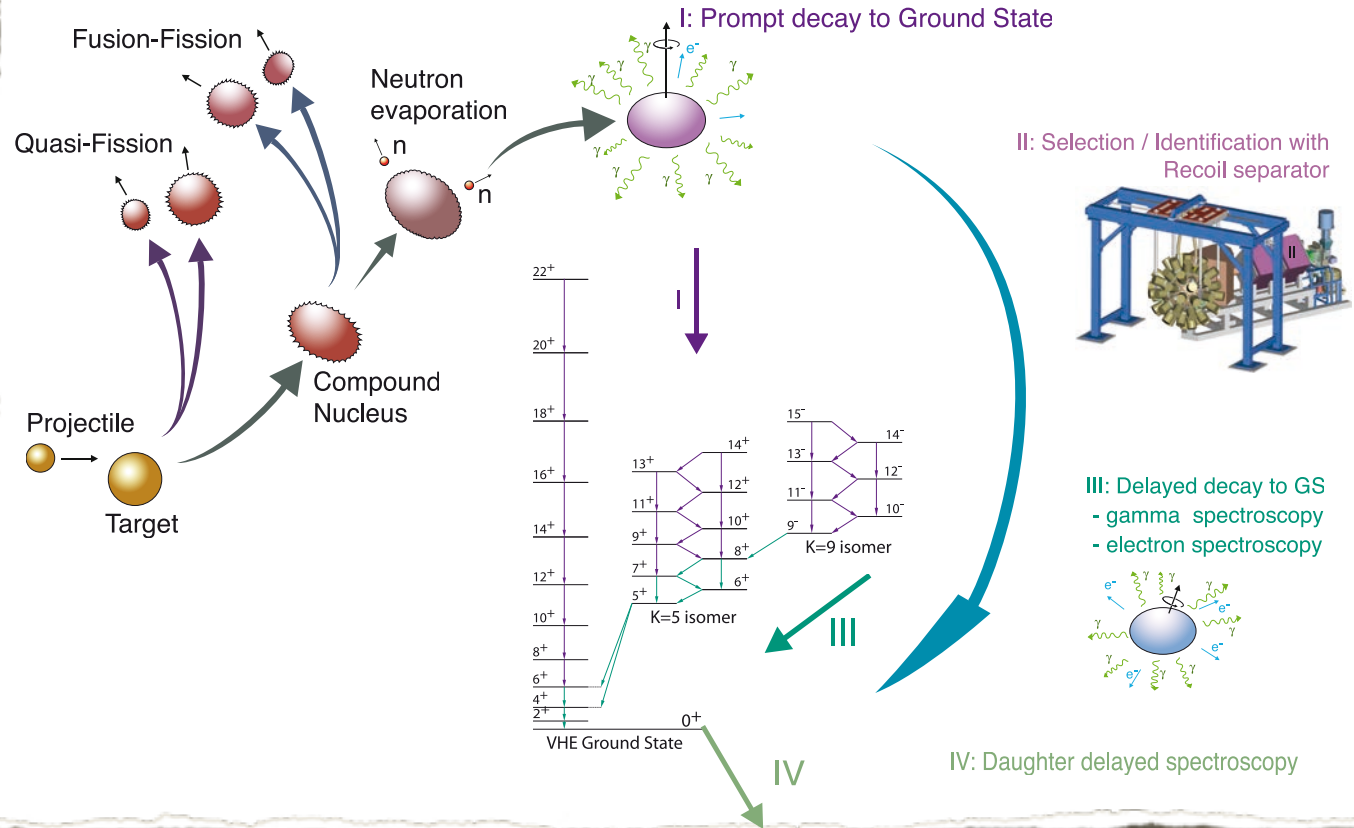


Neutrons



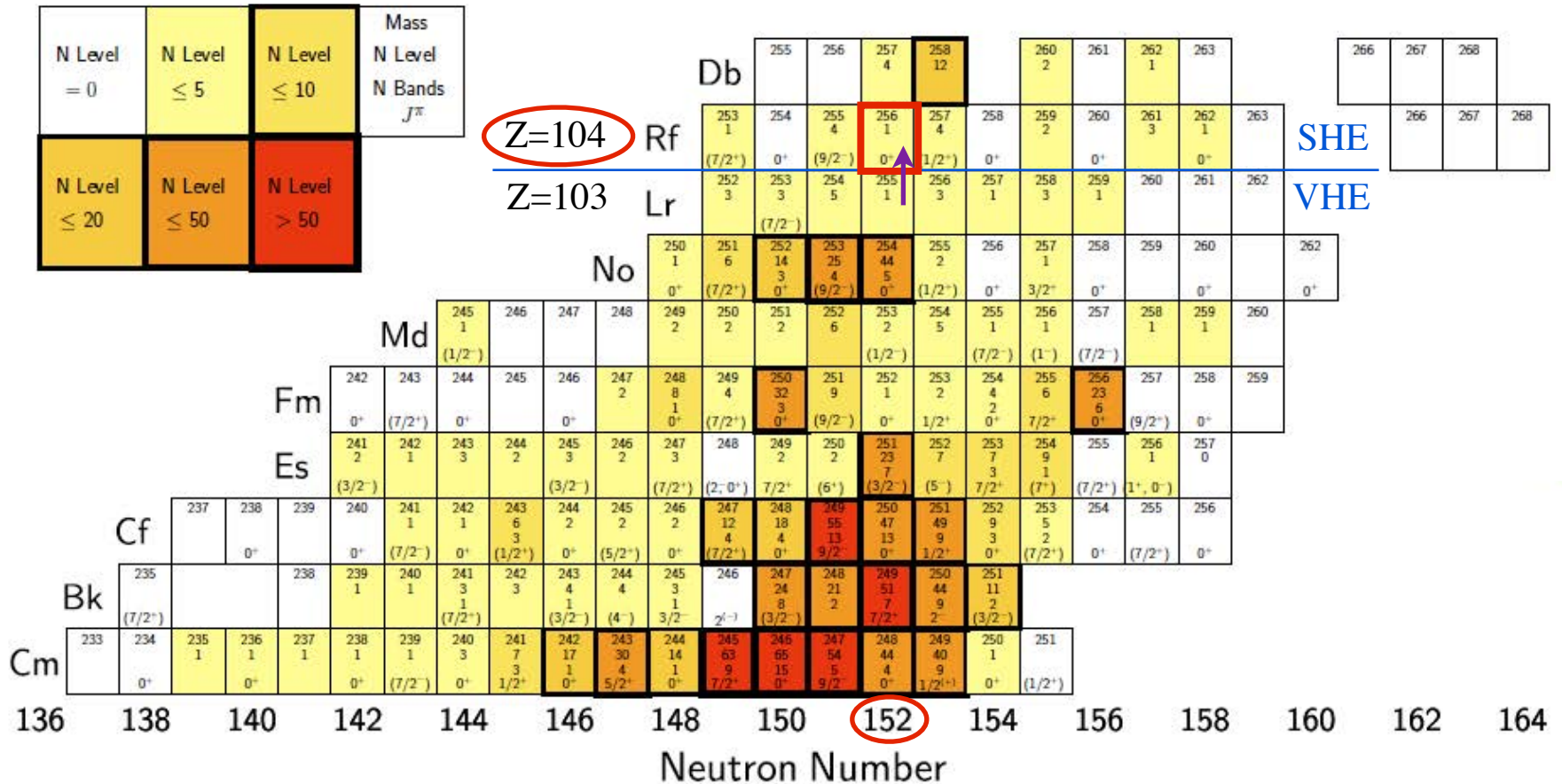
Limits for prompt spectroscopy

...counting rate in Ge detectors ...



Transfermium region spectroscopy

Proton Number

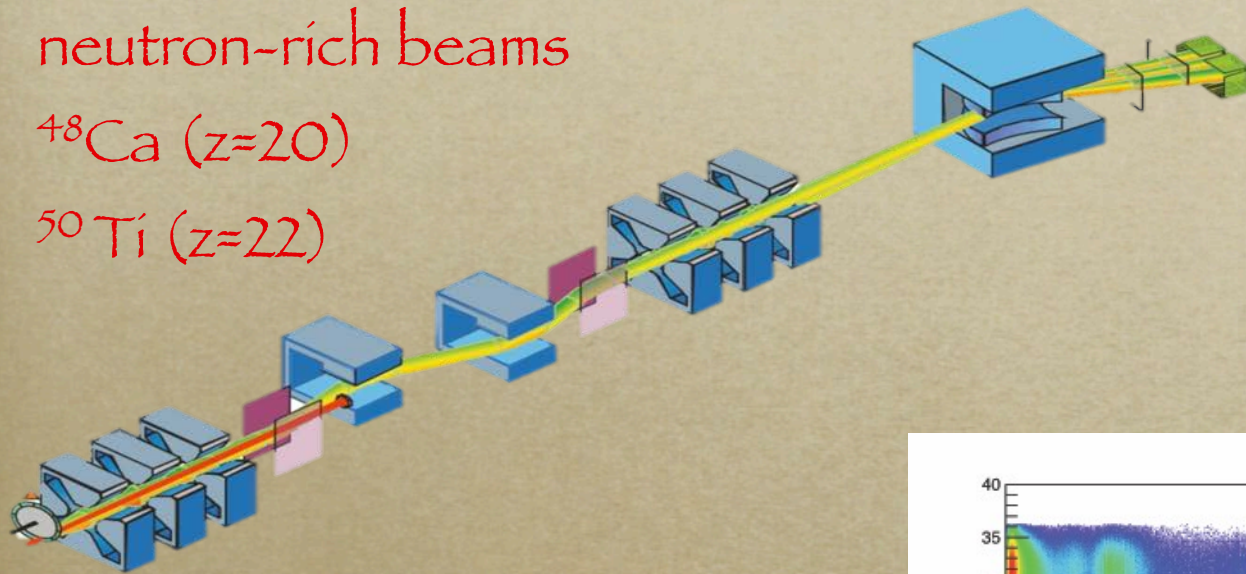


Limits for delayed spectroscopy

neutron-rich beams

^{48}Ca ($z=20$)

^{50}Ti ($z=22$)

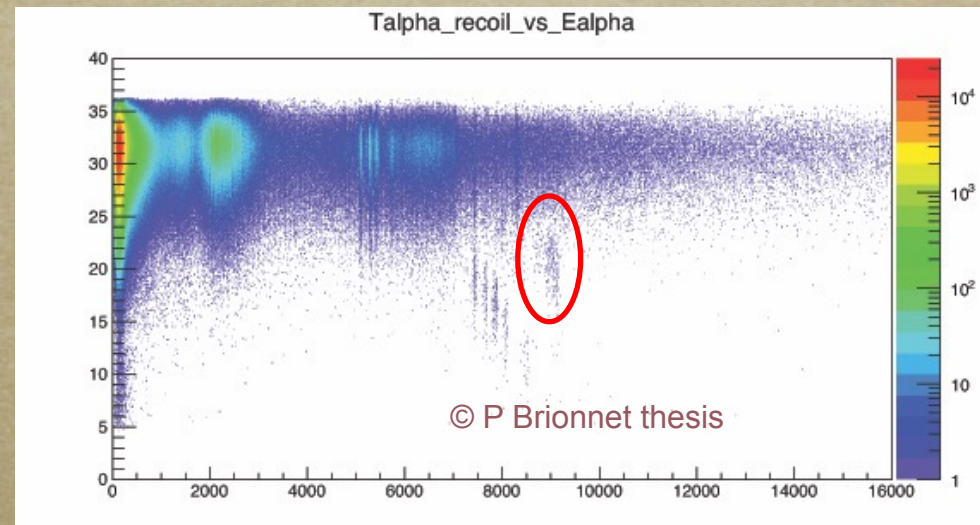


beam intensity

- highest possible $\sim 0.6 \text{ p}\mu\text{A}$

- avoid target fusion

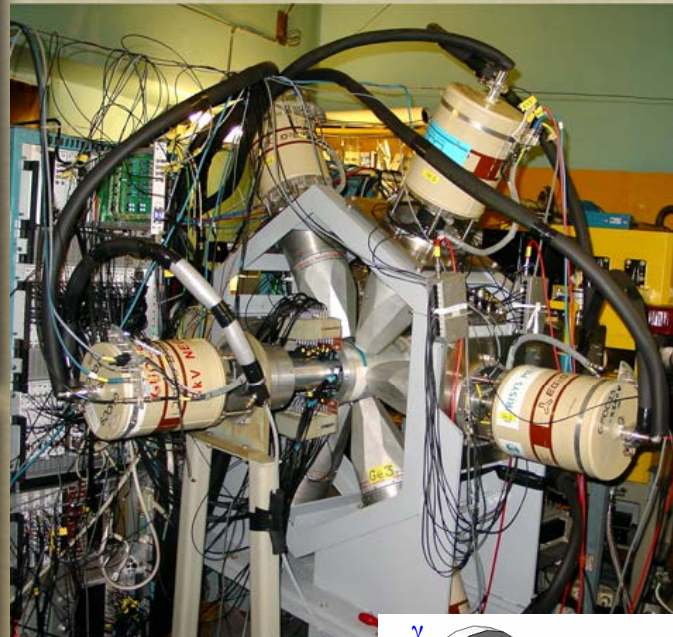
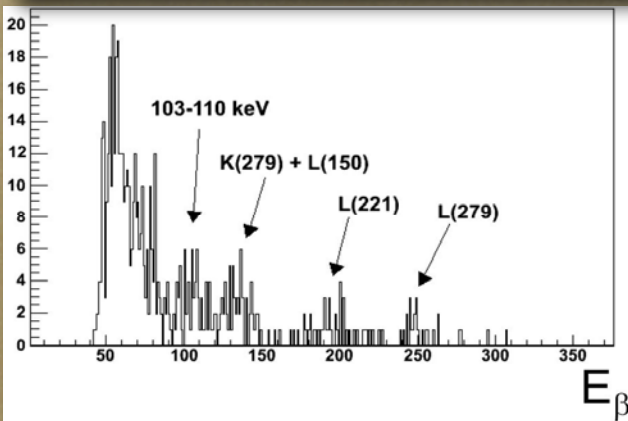
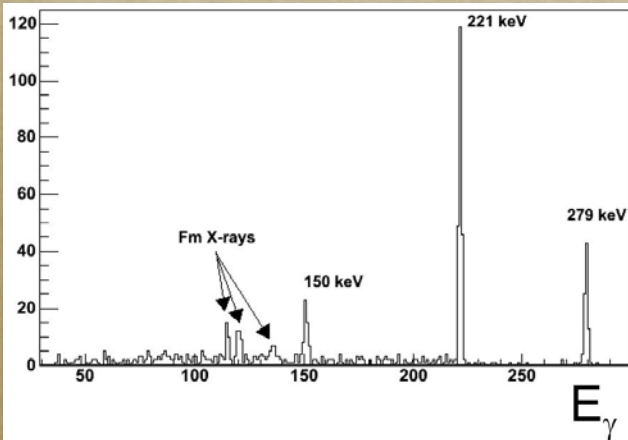
targets available



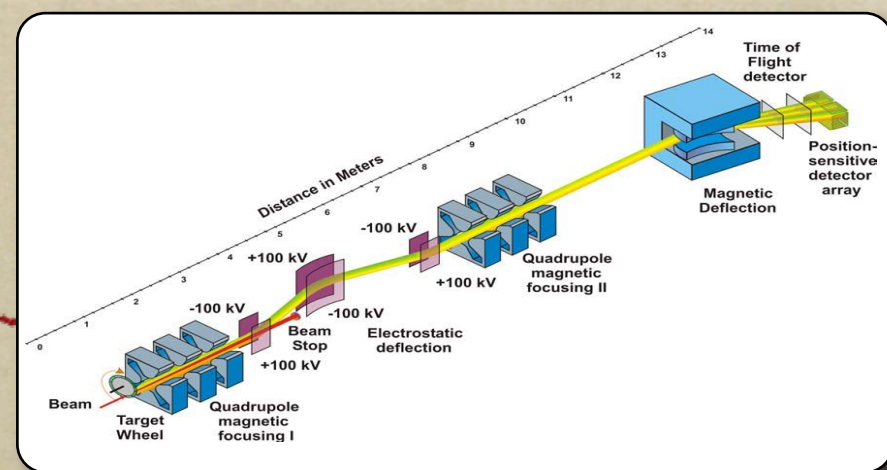
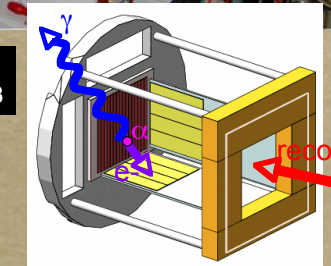
VASSILISSA - "VASSILISSA" electrostatic separator was put into operation in 1987. It's one of the FLNR's basic setups for synthesis of superheavy elements. In 2005 the experiments on study of decay properties of transfermium elements using gamma- and electron spectroscopy methods were performed for the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

Example with GABRIELA

Spectra of ^{249}Fm at focal plane



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



7 detectors Ge+BGO- AC (@IreS)

detection Gamma :

10% efficacité @200 keV

60x60 mm² 16 strips Si detector

SI at vassilissa focal plane de Vassilissa

implantation ER & alpha detection

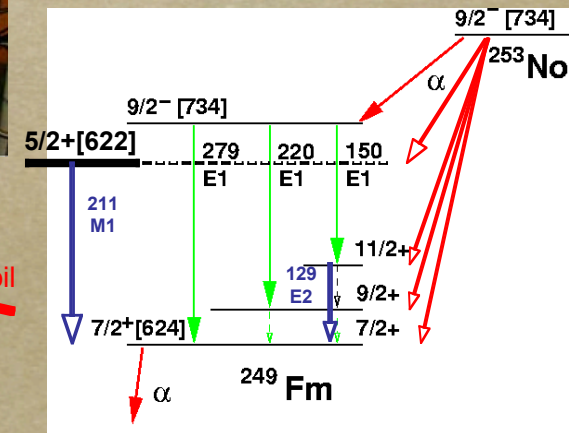
efficiency : 50%

Four 50x50 mm² 4-strip Si@IN2P3

Preamplifiers developed @GANIL

detection Electron & escape as

20% efficacité @200 keV



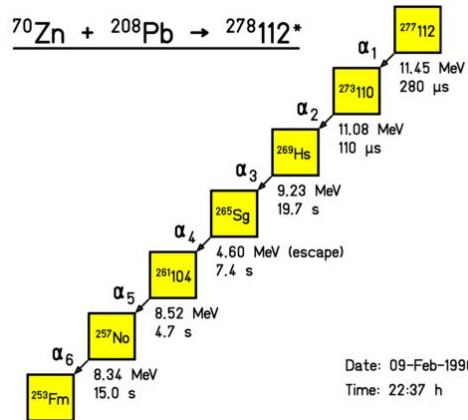
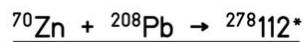
Spectroscopy of trans uranium (VHE)

Super Heavy Elements (SHE)

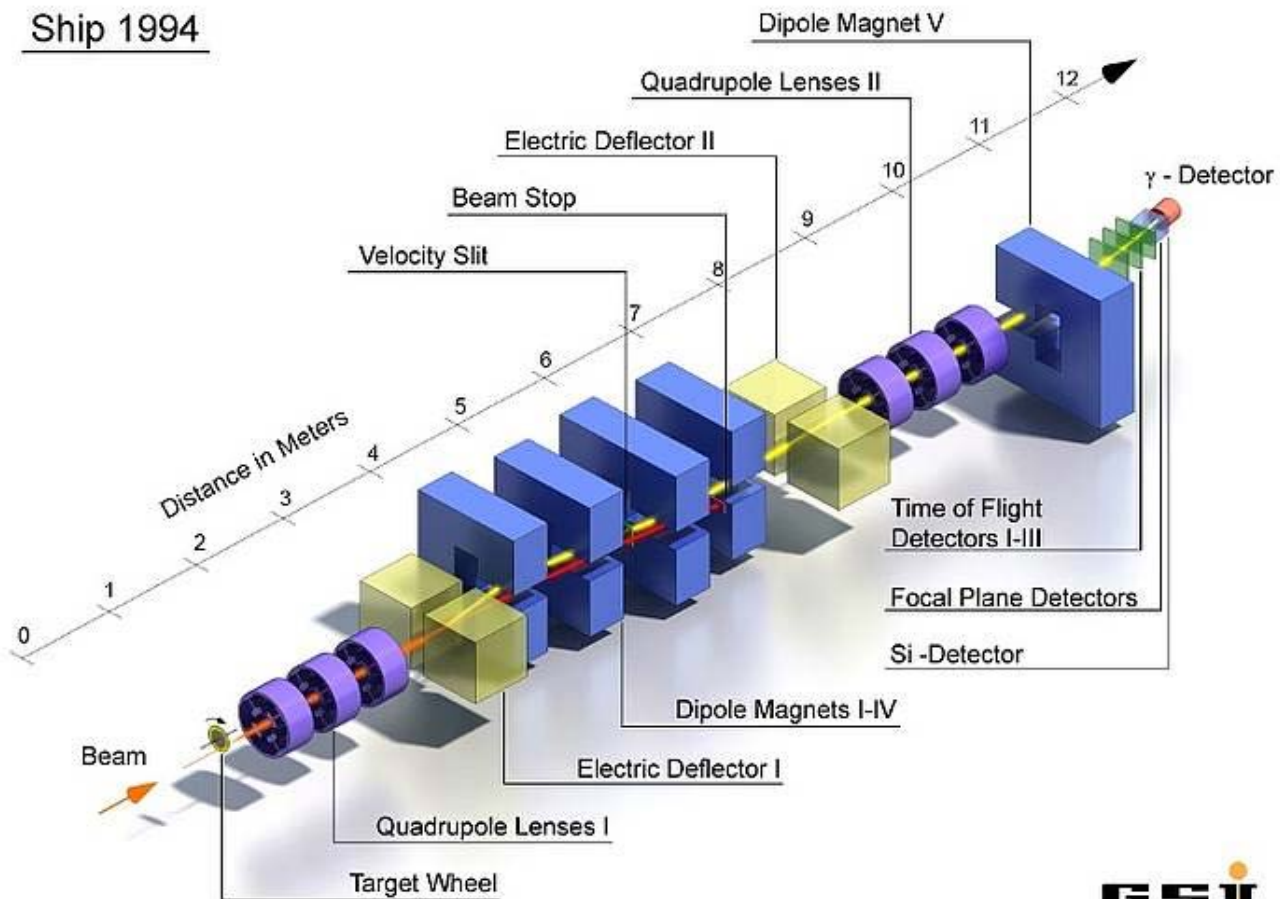
outline

- 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 1994



SHIP (@GSI) discovery of elements 107-112

Needs efficient separators

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

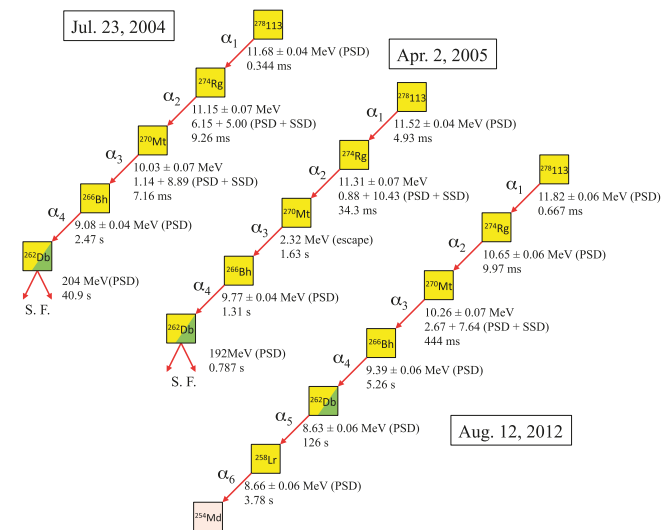


Fig. 3. (Color) Observed decay chain in the present work together with previously observed chains.^{1,2)}

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

Needs efficient separators

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

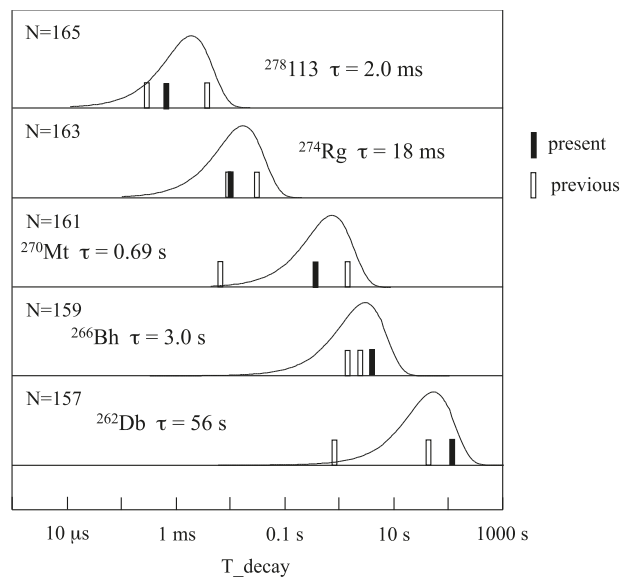


Fig. 2. Decay time (T_{decay}) distributions of the decay family originating from ^{278}Nh are indicated. The logarithm of the decay times is taken as the abscissa. Mean lifetimes τ determined from three decay chains are shown together with the symbols of the nuclides. Curves in the graphs correspond

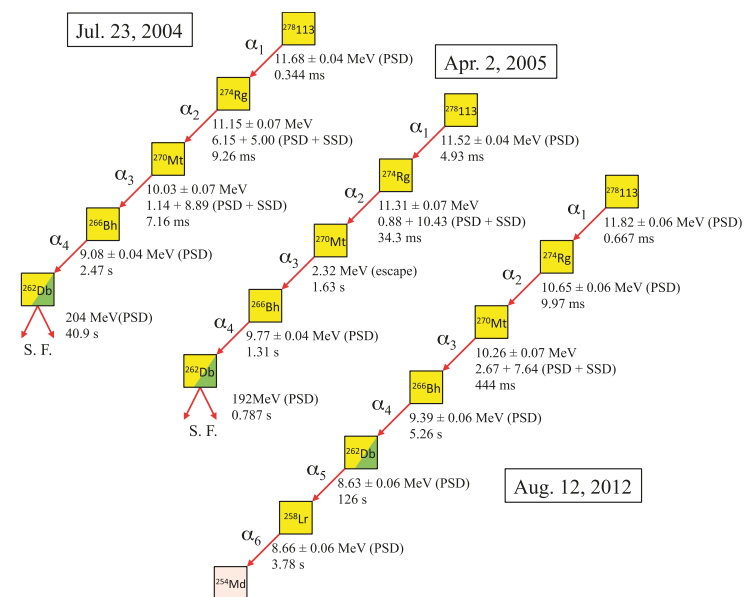


Fig. 3. (Color) Observed decay chain in the present work together with previously observed chains.^{1,2)}

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

Needs Intense beams & long runs (months)

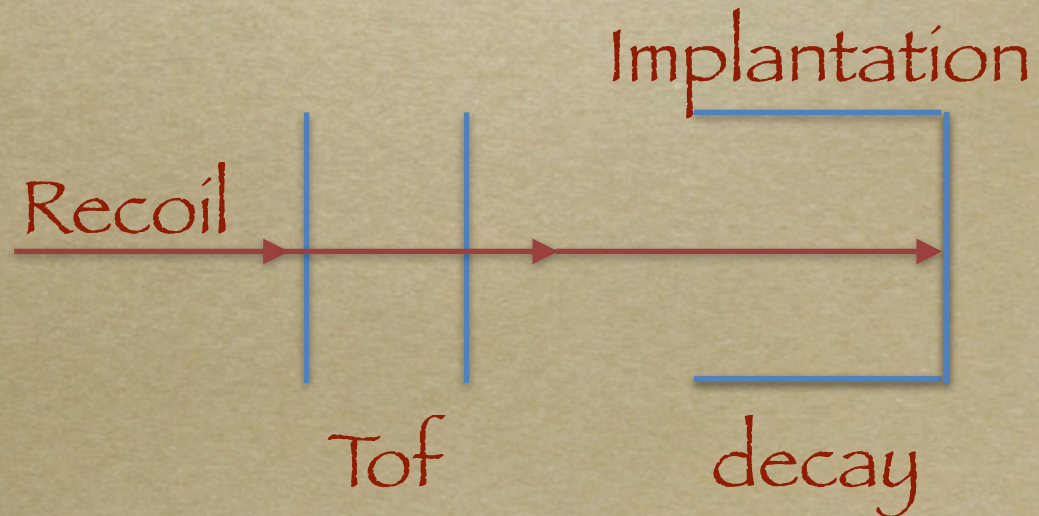
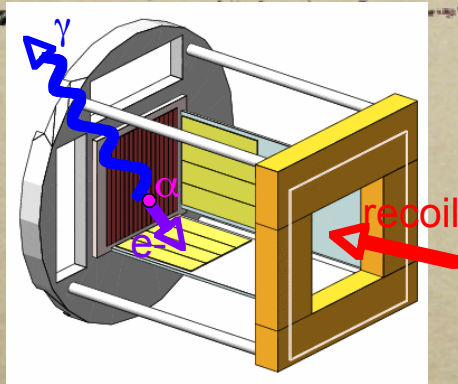
Five ^{294}Og ($Z=118$) observed



DGFRS (@FLNR Dubna)

DGFRS - 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

- 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 properties

Decay Properties of observed SHE

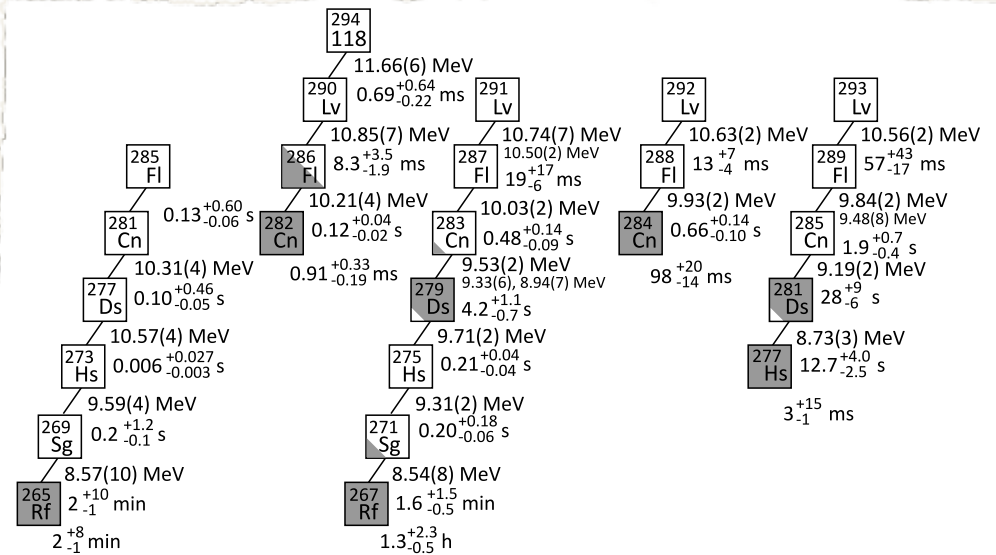
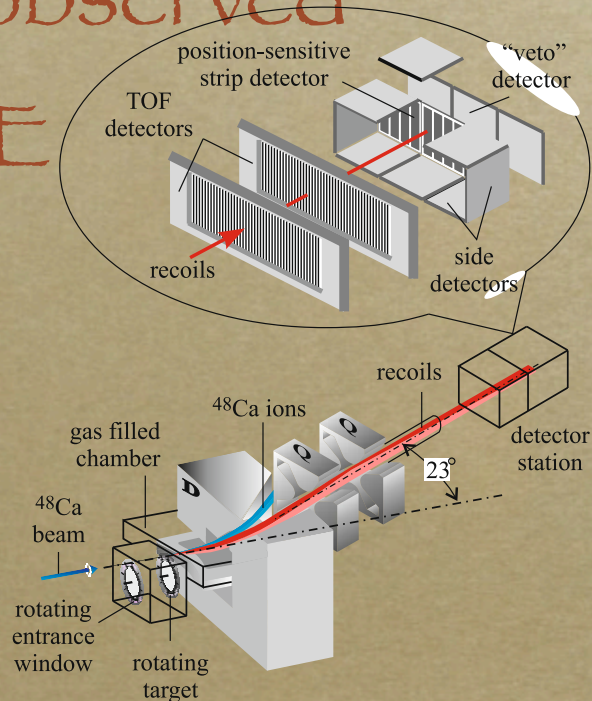


Fig. 3. Summary decay properties of the isotopes of even-Z elements synthesized in the reactions of ^{48}Ca with ^{238}U , $^{242,244}\text{Pu}$, $^{245,248}\text{Cm}$, and ^{249}Cf target nuclei. The average energies of α particles and half-lives are given for α emitters (open squares). The energies 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.

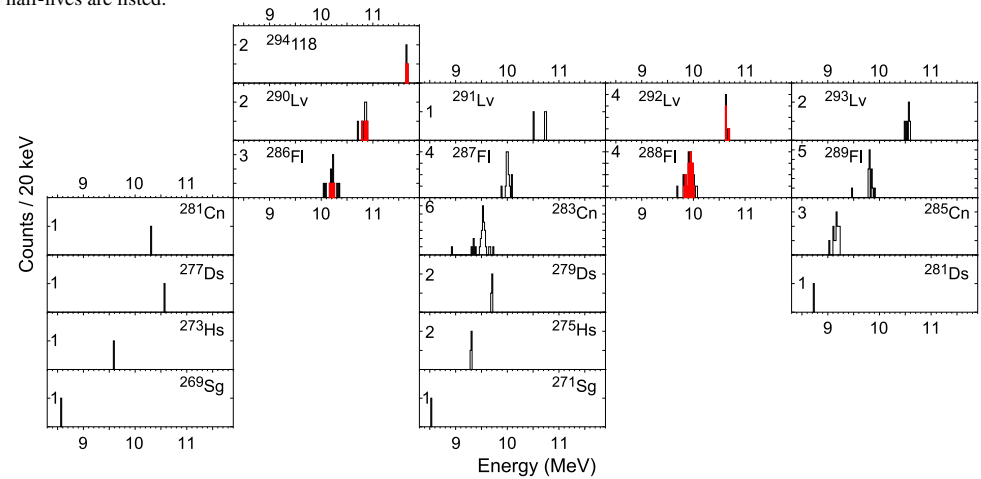


Fig. 7. α -particle energy spectra for even-Z nuclei registered by the focal-plane detector only or together with the side one at DGFRS [48,49,56,68–71,73,74], IVO + COLD [57–61], SHIP [63,72], BGS [46,47], and TASCA [45,65]. Note, the energy resolution of α -particles detected simultaneously by the 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.

SHE properties

Decay Properties of observed SHE

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	$10.81\text{--}11.07$	11.18 ± 0.04	[74,86–89]
	176	293	d:15	α	22^{+8}_{-4} ms	$10.60\text{--}11.20$	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	$9.78\text{--}10.31$	10.41 ± 0.04	[74,86–89]
	174	289	d:16	α	330^{+120}_{-80} ms	$10.15\text{--}10.54$	10.49 ± 0.05	[74,80,81,86–88]
	173	288	d:27, t:19	α	164^{+30}_{-21} ms	$10.29\text{--}10.58$	10.63 ± 0.01 ≈ 10.7 [83]	[75,76,80,81,83,84]
	172	287	d:2, t:1	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	$9.61\text{--}9.75$	9.79 ± 0.05	[74,86–89]
	172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	$9.47\text{--}10.18$	10.01 ± 0.04	[74,80,81,86–88]
	171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	$9.10\text{--}10.11$	10.12 ± 0.01 ≈ 10.3 [83]	[75,76,80,81,83,88,84]
	170	283	d:1, t:1	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]

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, t:1	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, t:1	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, t:1	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, t:1	SF ^e	$1.3^{+1.6}_{-0.5}$ h			[75,76,81,83, 84]

(continued on next page)

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.

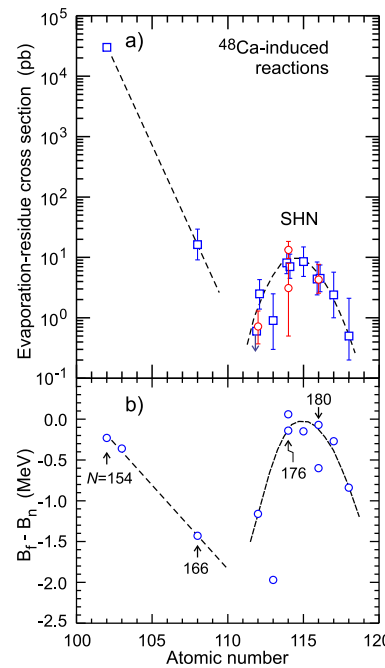


Fig. 6. (a) Maximum cross sections of the production of the isotopes of the heavy elements in hot fusion reactions: ^{208}Pb , ^{226}Ra , $^{233,238}\text{U}$, $^{242,244}\text{Pu}$, ^{243}Am , $^{245,248}\text{Cm}$, ^{249}Bk , and $^{249}\text{Cf} + ^{48}\text{Ca}$ ($E^* = 35\text{--}40$ MeV). Data 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.

SHE properties

Decay Properties of observed SHE

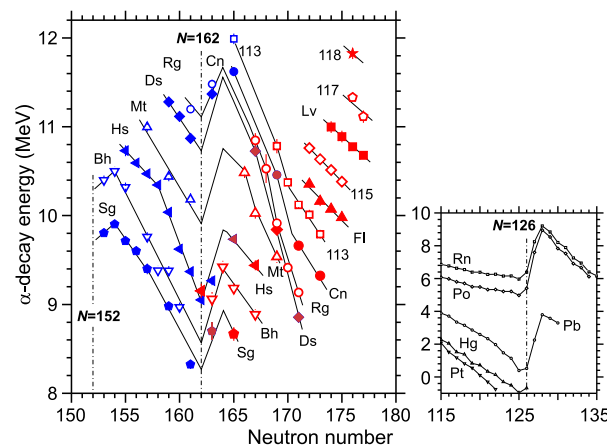


Fig. 10. Measured α -decay energy vs. neutron number for the isotopes of elements 106–118 (filled and open symbols refer to even- Z and odd- Z nuclei, respectively; Q_α values for nuclei produced in the Ra-Cf + ^{48}Ca reactions are shown in red; other data (blue symbols) are taken from [114,115]. The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

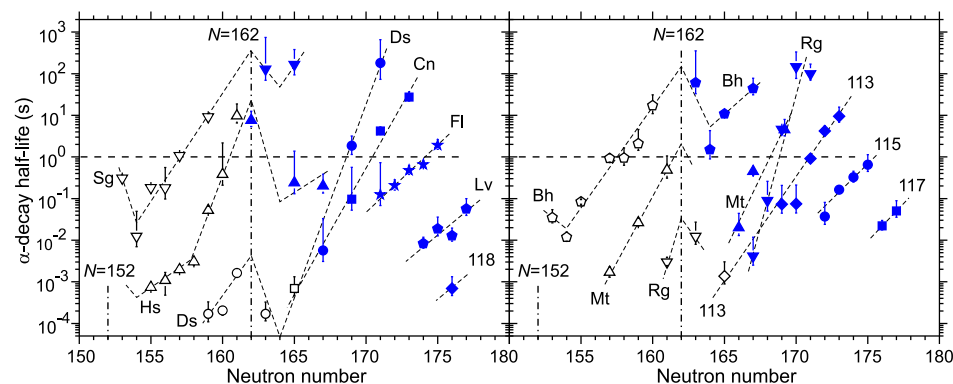


Fig. 11. Half-lives vs. neutron number for the isotopes of even- Z (left panel) and odd- Z (right panel) elements with $Z = 106$ –118 (results from Ra-Cf + ^{48}Ca reaction are shown by full blue symbols (see Figs. 3, 5 and Table 1); other data are taken from [116]. Lines are drawn to guide the eye.

SHE properties

Decay

Properties
of observed
SHE

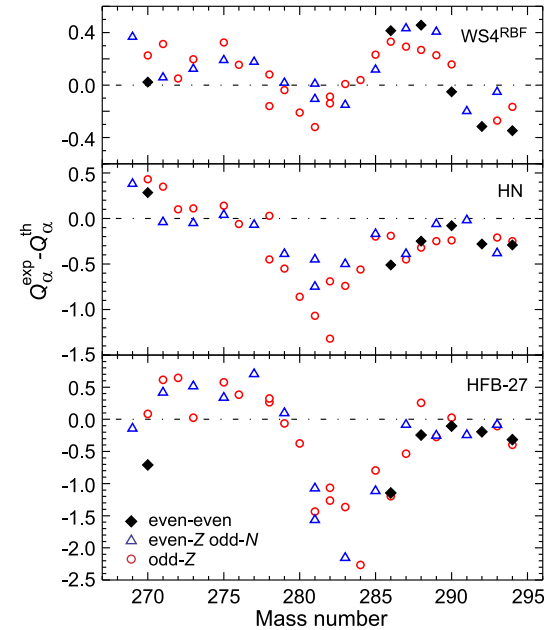
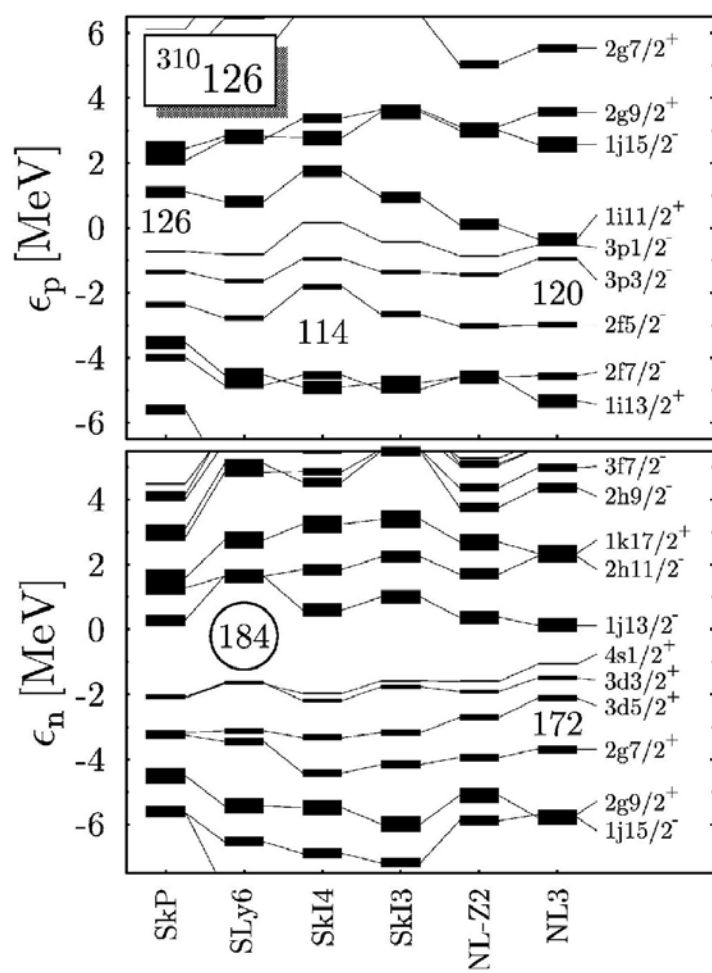
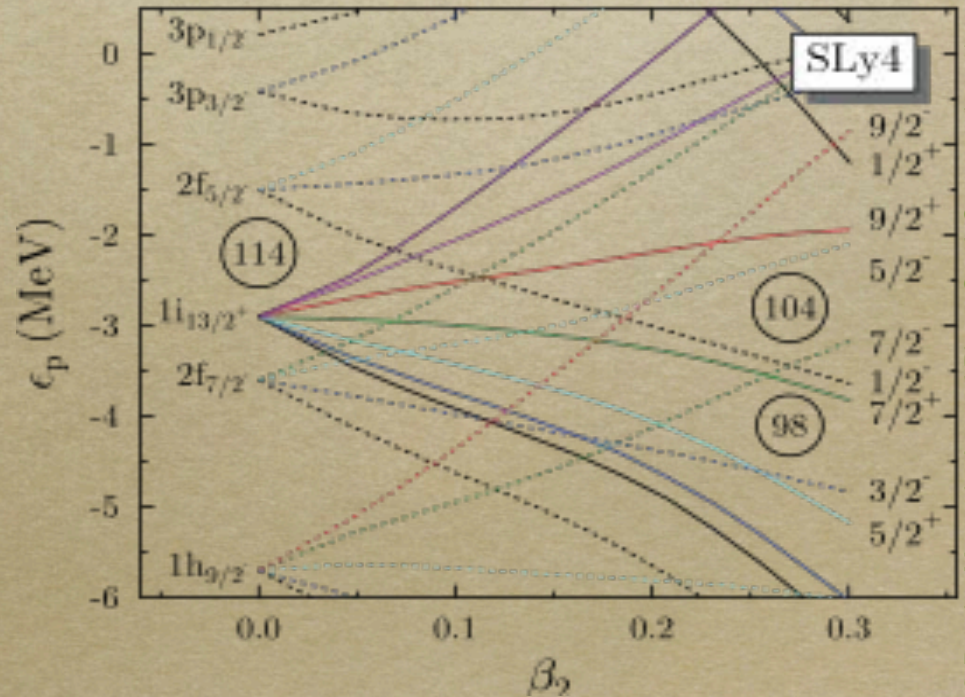
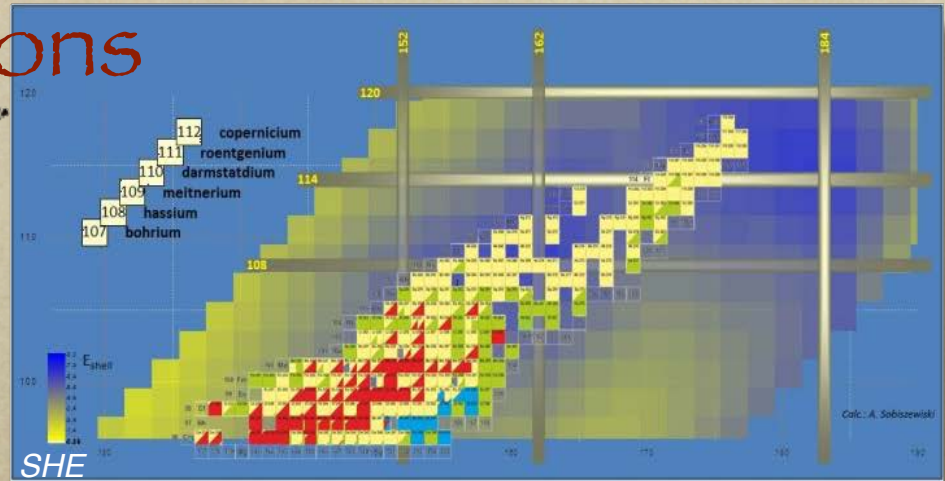


Fig. 12. Deviation between experimental and calculated α -decay energies for even-even, even- Z and odd- N , and odd- Z nuclei. Theoretical Q_α values were taken from [107,108] for macroscopic-microscopic model (HN, middle panel) and mass tables [117] (WS4^{RBF}, macroscopic-microscopic model, top panel)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

Comparison to theoretical predictions



© Bender M. et al., Phys. Lett. B515 (2001) 42-48



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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

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn		Fl				
												113		115	Lv	117	118
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Transactinide elements

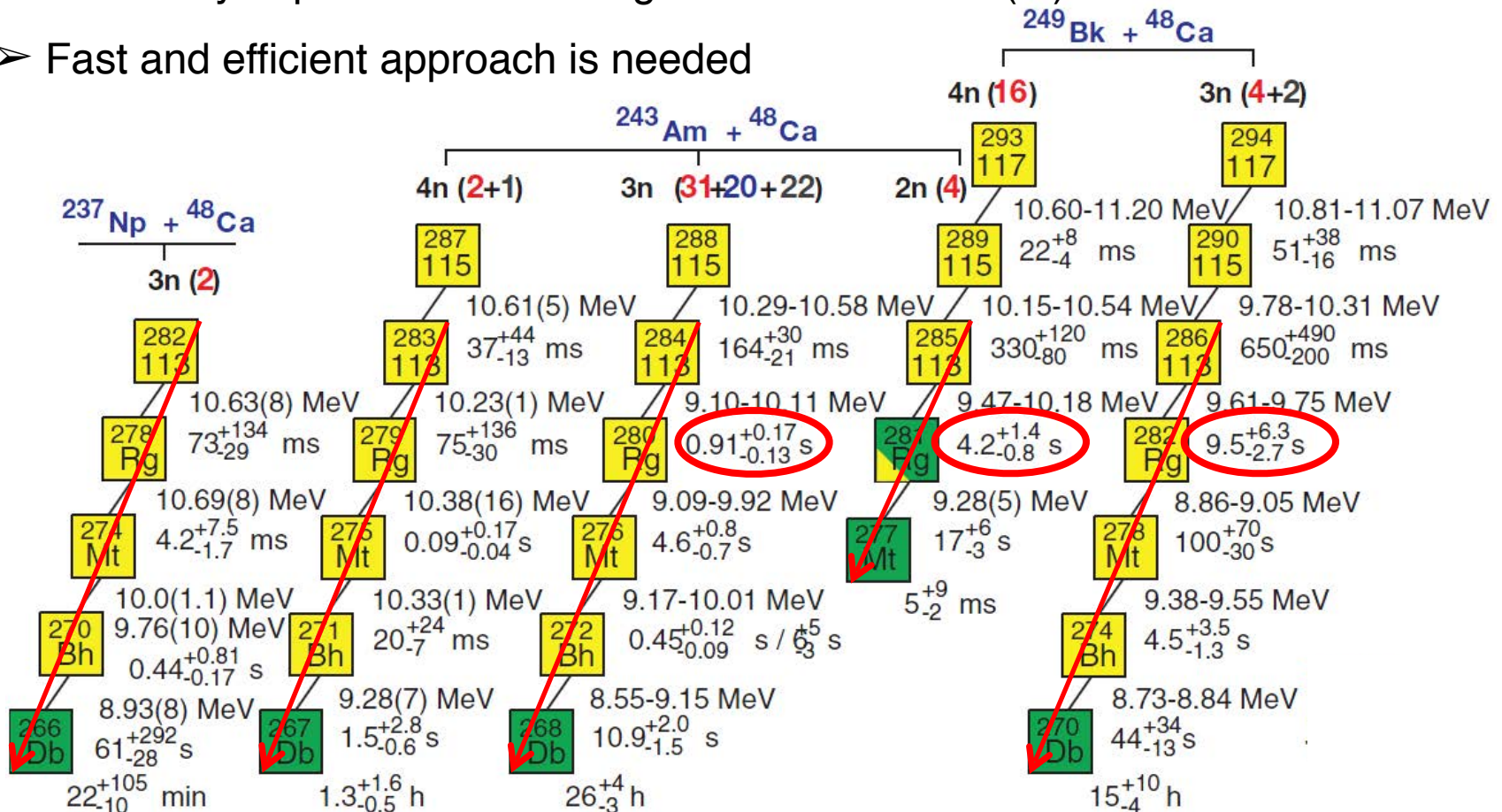


Protons and neutrons
Electron structure

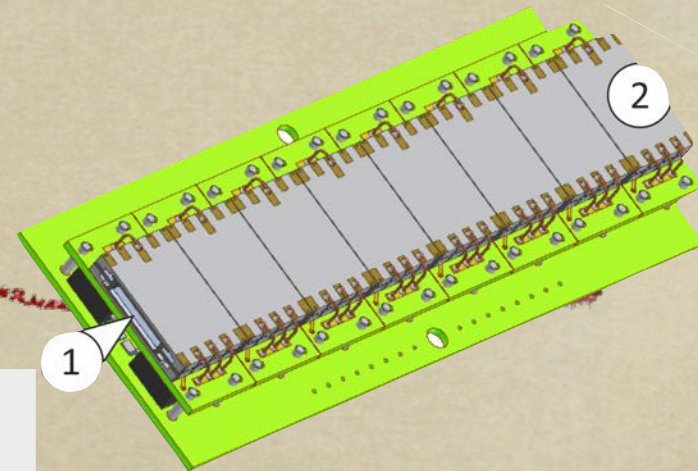


SHE chemical properties

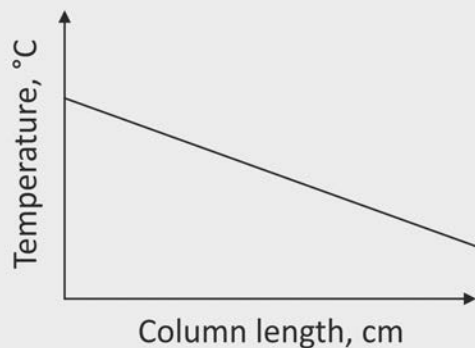
- Chemistry experiments with single atoms at a time (!)
- Fast and efficient approach is needed



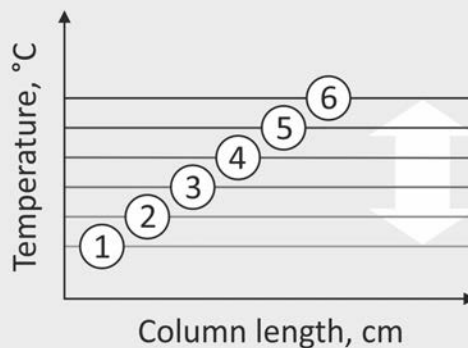
SHE chemical properties



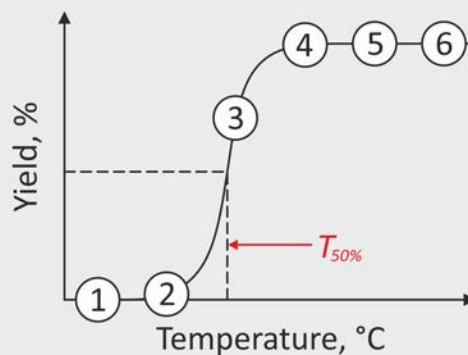
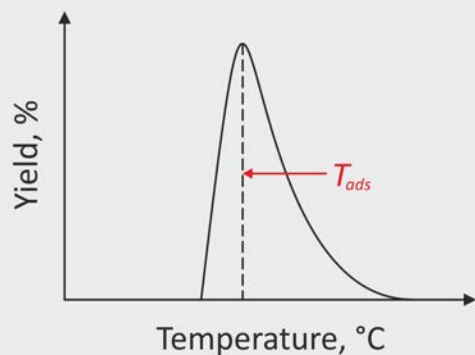
Thermochromatography



Isothermal Chromatography

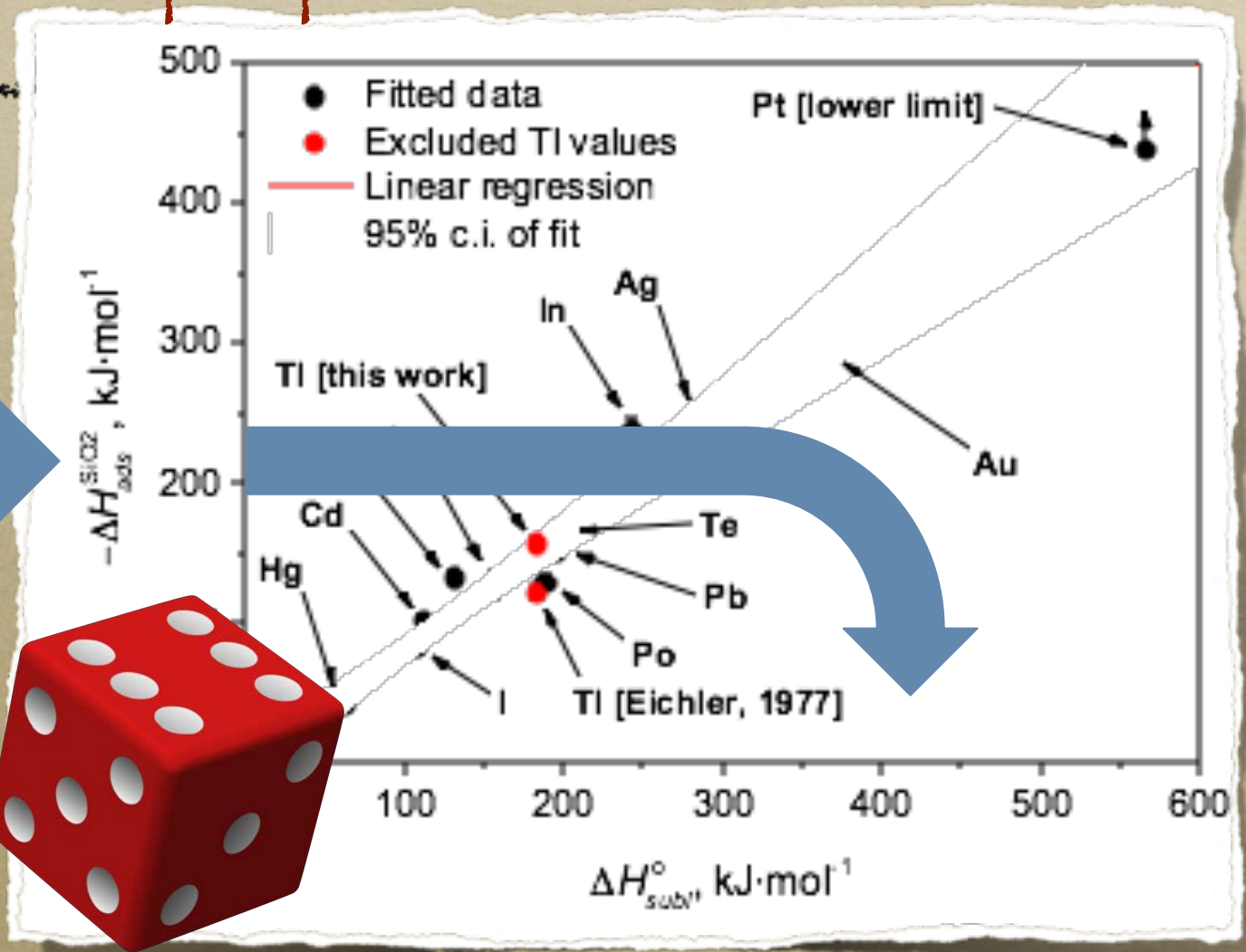


$$T_{ads} \approx T_{50\%}$$



SHE chemical properties

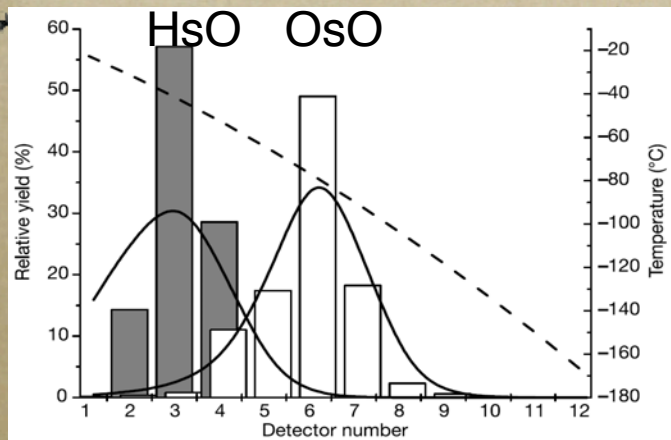
Monte Carlo
simulation



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 here —> SiO₂) and the corresponding sublimation enthalpy.

SHE chemical properties

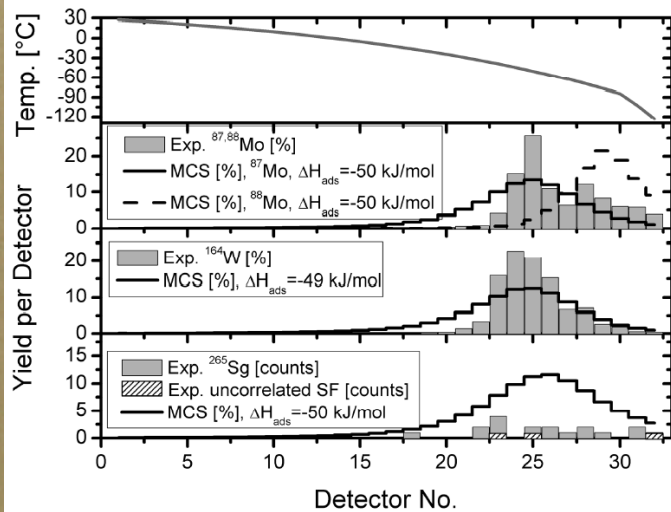
2002



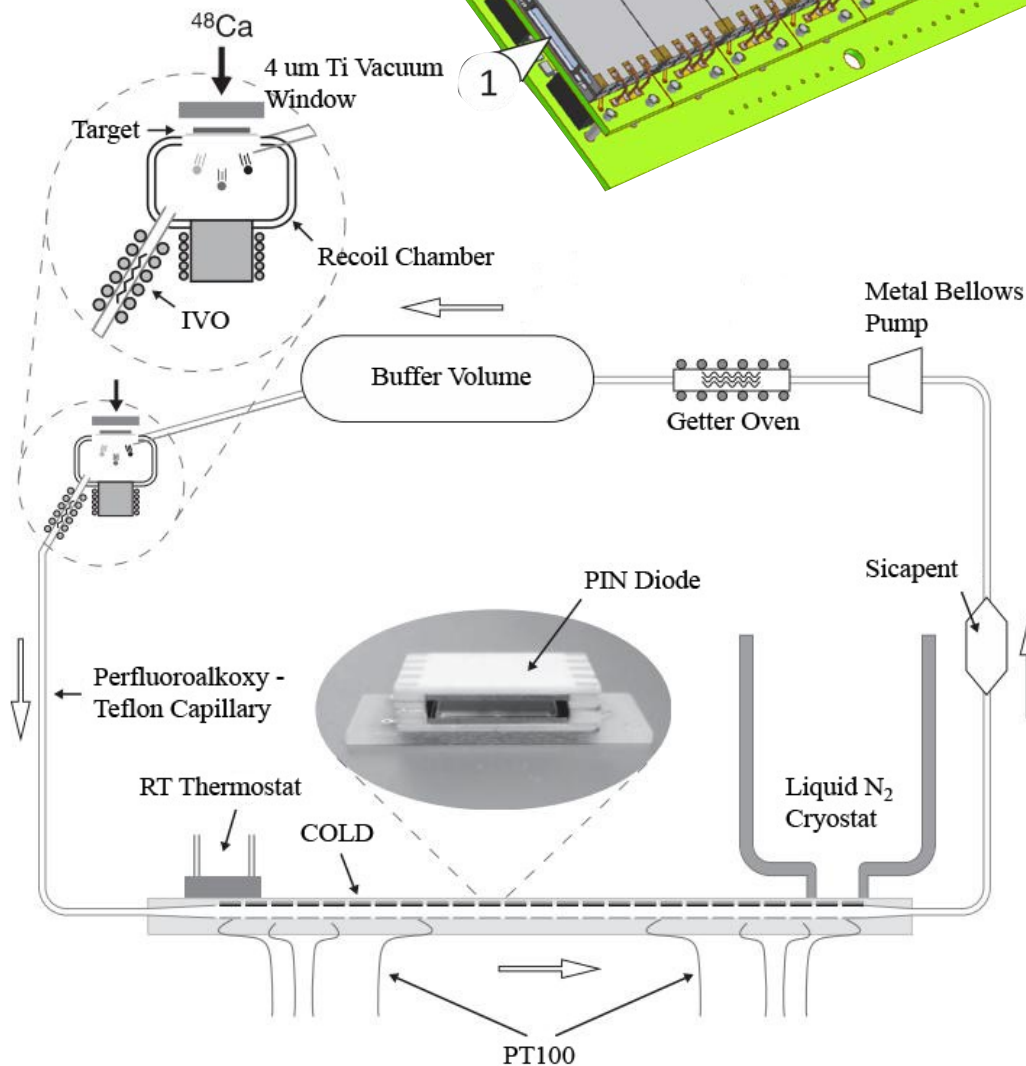
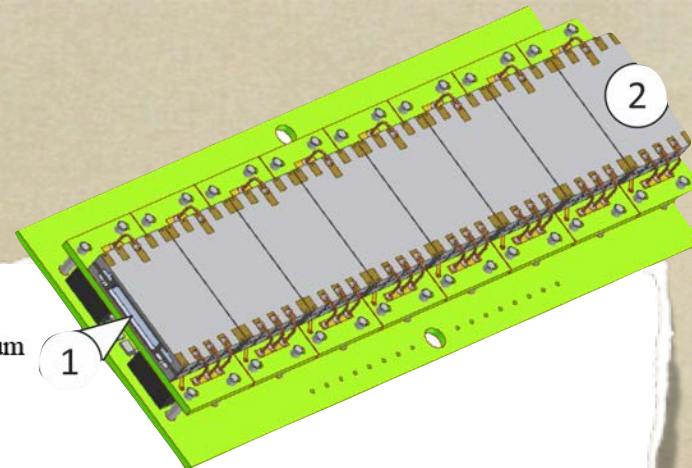
Ch. E. Düllmann et al., *Nature* **418** (2002), pp. 859 – 862

2014

Mo/W/Sg(CO)₆

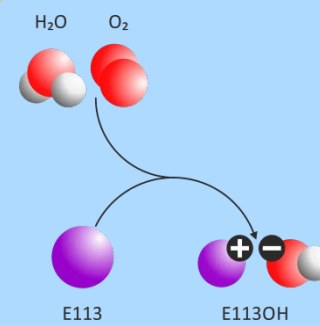
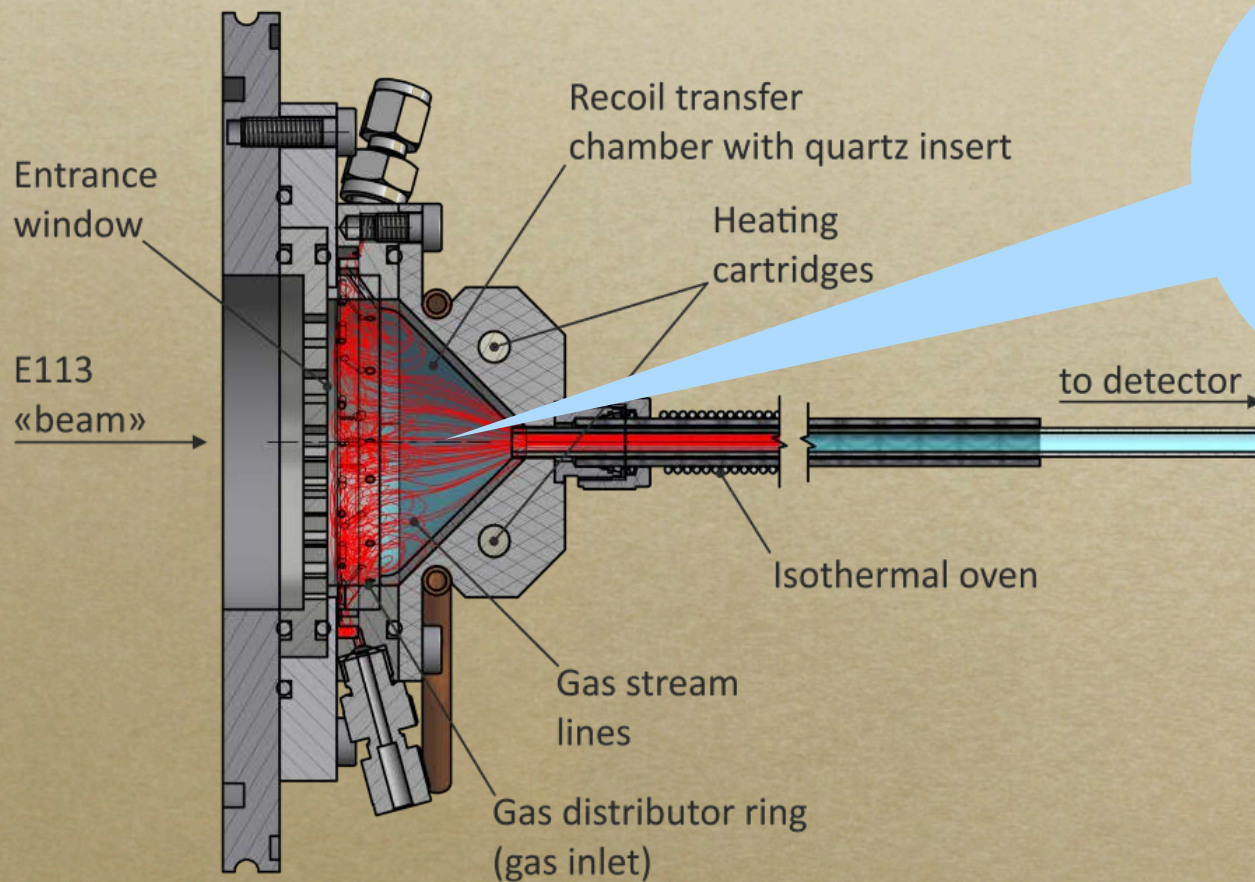


J. Even et al., *Science* **345** (2014), pp. 1491 – 1493



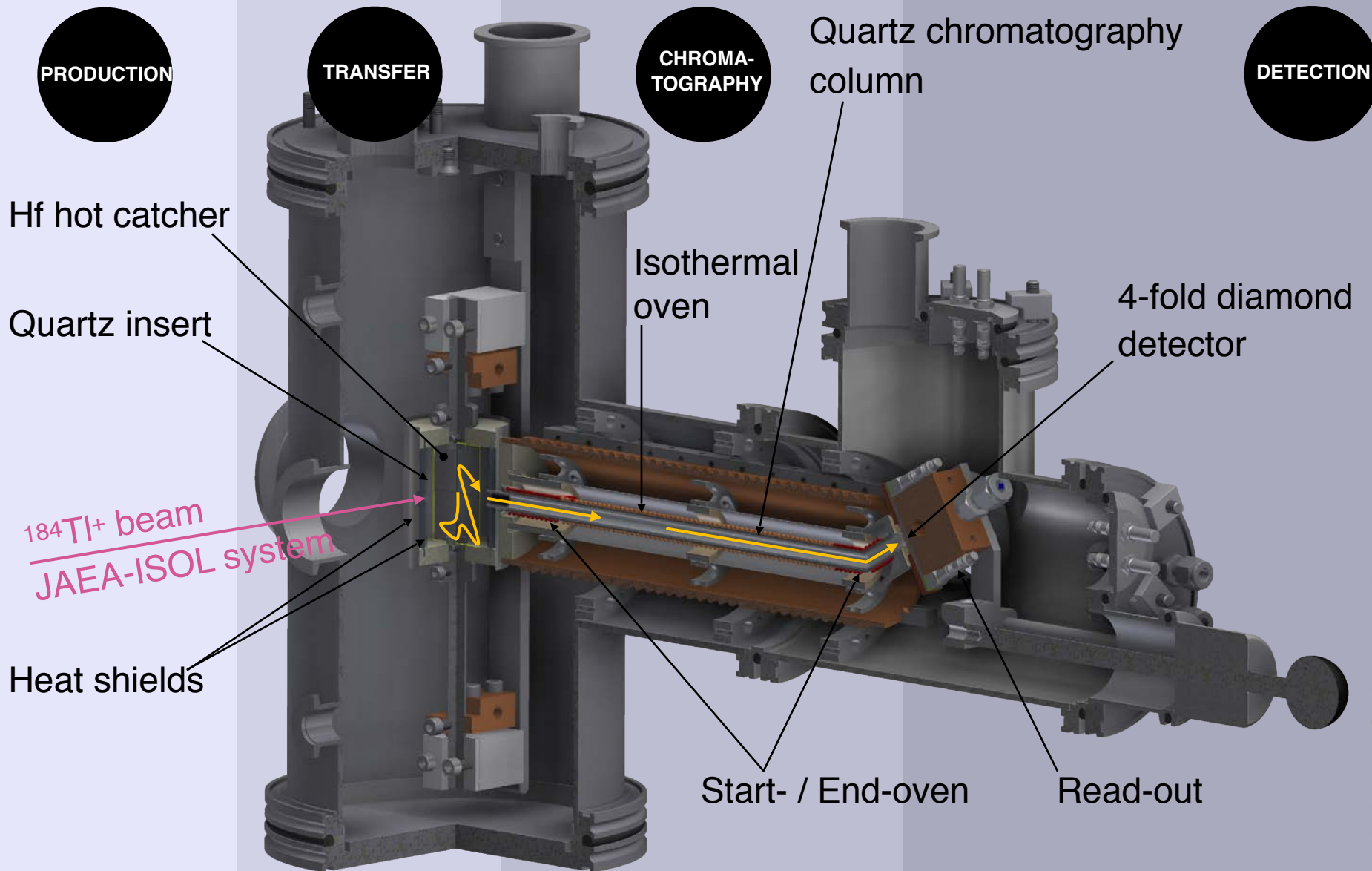
R. Eichler et al., *Nature* **447** (2007), pp. 72 – 75

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 or less the limit of current state-of-the-art gas phase experiments).

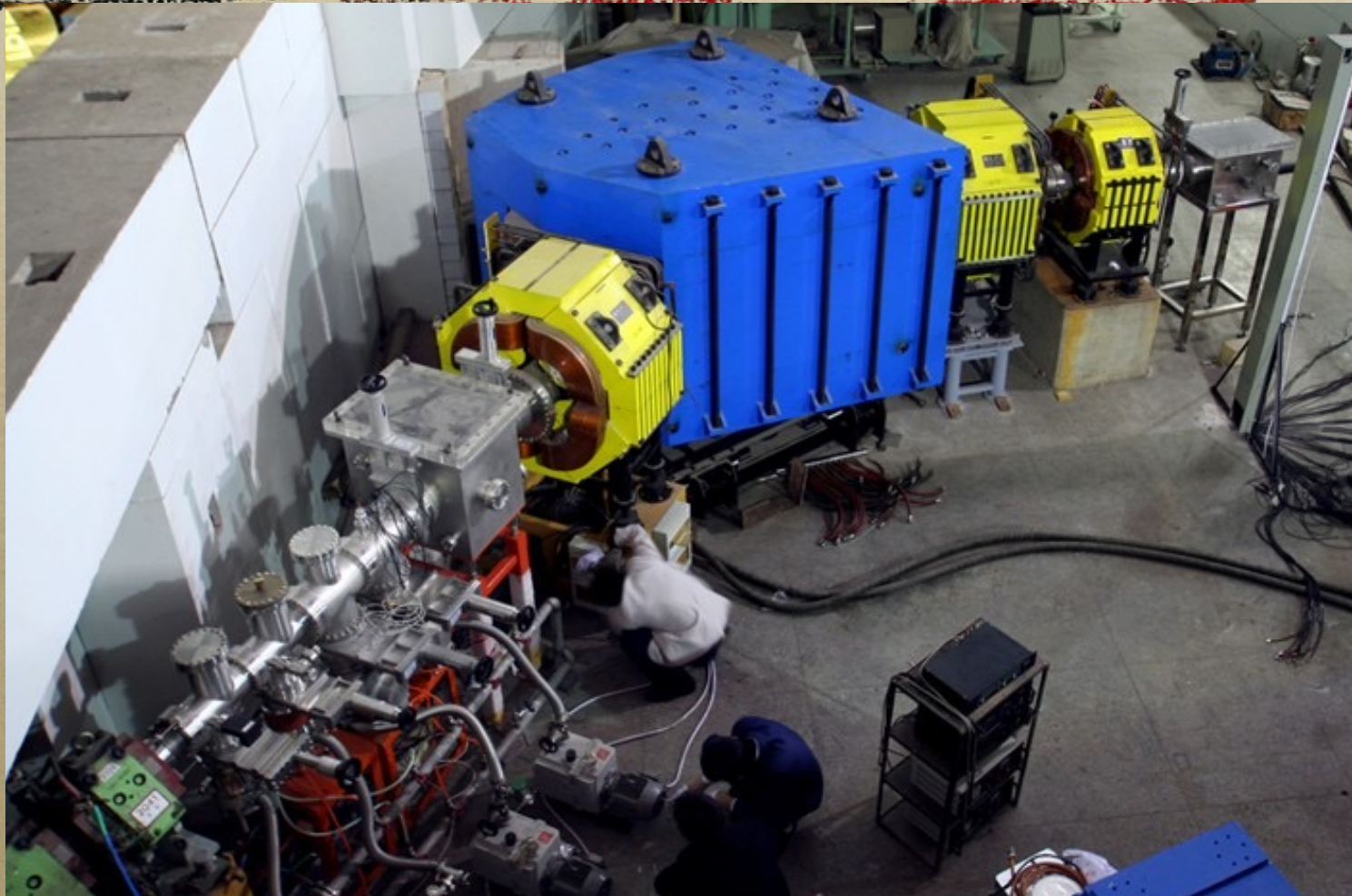


Super Heavy Elements (SHE)

Perspectives ...

Chinese separator for VHE : SHANS ?

Chinese
separator
for Heavy
elements
@ Lanzhou



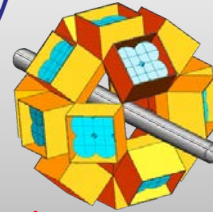
A new gas-filled recoil separator was installed in the HIRFL (Heavy Ion Research Facility, Lanzhou) to separate the evaporation residues (EVRs) from other beam ions and unwanted reaction products. It is filled with helium gas at the pressure of about 0.8mbar. The focal plane detector system consisting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

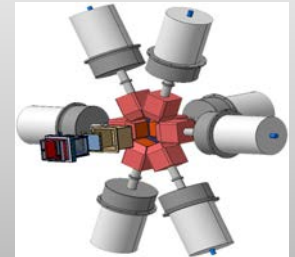


S3 Physics case (15 Lols)

- VHE – SHE elements
- Proton drip-line and $N=Z$
- Nuclear astrophysics
- Atomic physics

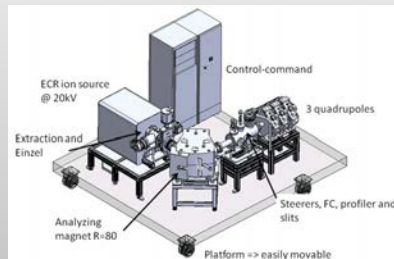
Delayed spectroscopy

SIRIUS setup
 Implantation-decay
 station at the mass
 dispersive plan

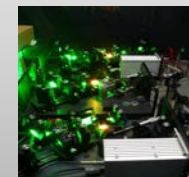


Atomic physics

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

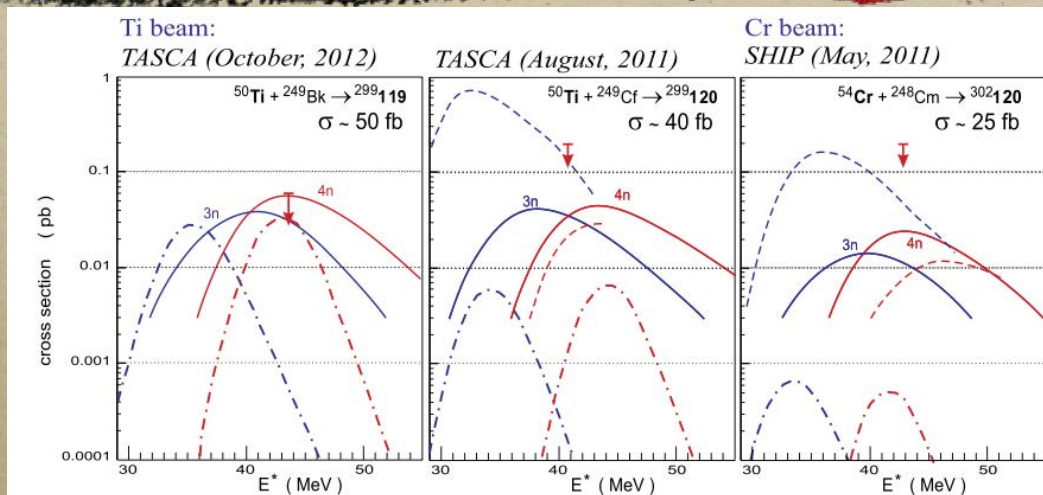
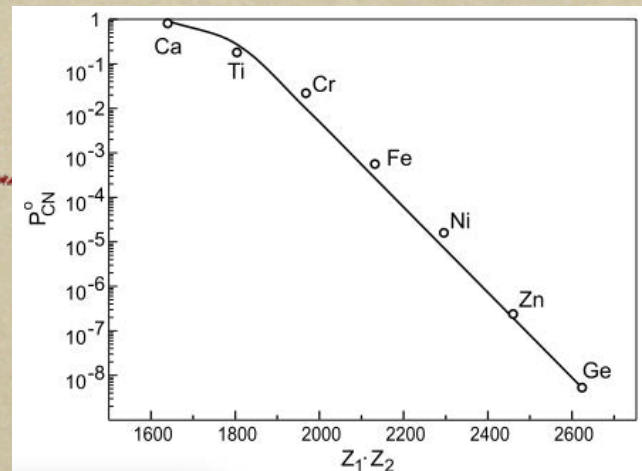
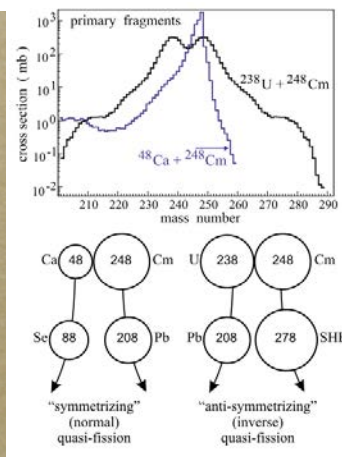
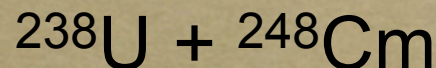
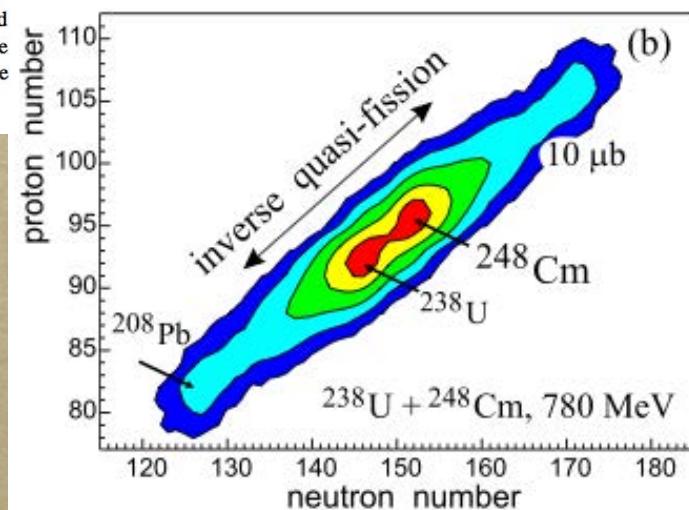


Fig. 31. Cross sections for the production of new elements 119 and 120 in the Ti and Cr induced fusion reactions predicted within the described above model (solid curves [71]) and by the “fusion-by-diffusion” model (dashed curves [91]). The latest calculations within the “fusion-by-diffusion” model [92] 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 !



Next SHE's ?

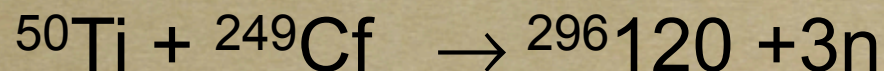
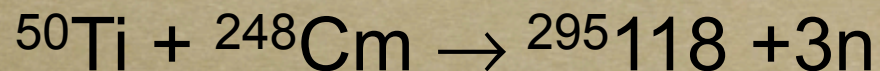
PERIODIC TABLE OF ELEMENTS

© Ackermann D.

120	Ubn				
119	Uue				
118	Uuo	118 294			
117	Uus	117 293	117 294		
116	Lv	116 290	116 291	116 292	116 293
115	Uup	115 287	115 288	115 289	115 290
				170	171



WITH INTENSE TITANIUM BEAM



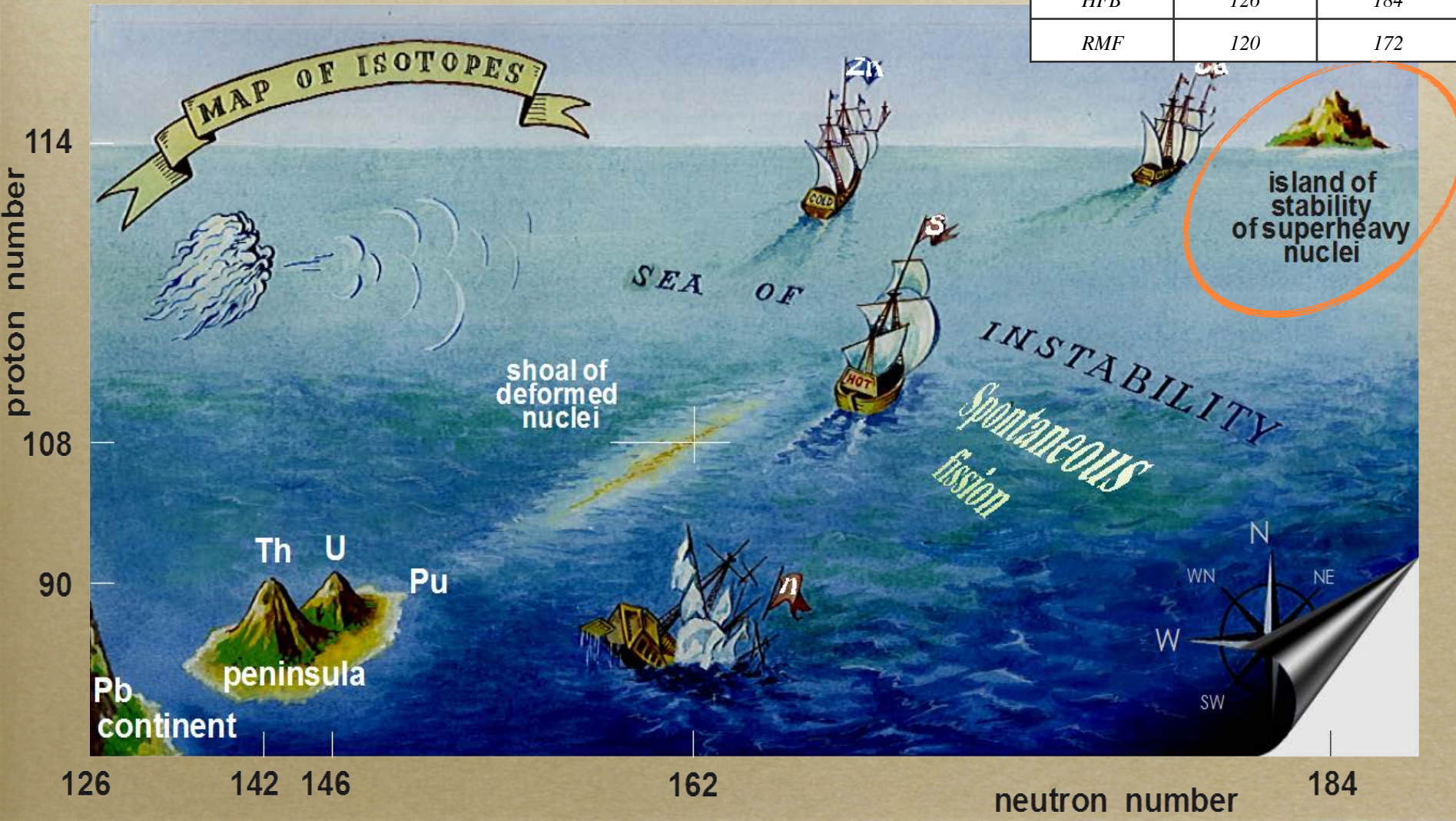
Mendeleev table ?

Period 1		Periodic Table 1-172																18 Orbitals		
1	1 H	2											13	14	15	16	17	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	3	4	5	6	7	8	9	10	11	12	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





L'installation U-400, à Dubna, en Russie. (IMB/FLEBOV)

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 nevanche 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 contiennent 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 !

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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.

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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.

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