Decay Properties and Stability of Heaviest Elements

- History of the problem and Motivation
- Details of half-lives calculations
- Results and Discussion
- Conclusions

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Motivation

- Californium is the heaviest element available as a target material. To synthesize superheavy SH elements with $Z > 118$ in fusion reactions, one should proceed to heavier than ^{48}Ca projectiles (^{50}Ti, ^{54}Cr, etc.).

- Center of stability island of SH elements was not yet reached. Reactions leading to the center of the stability island and neutron-rich SH nuclei are required.

- Search of SH nuclei in nature.

- Search of new regions of stability (next islands of stability) of SH elements.

History of half-lives study

α-decay

- *The most studied [V.E. Viola and G.T. Seaborg (1966);*
  A. Sobiczewski, , Z. Patyk, and S. Ćwiok (1989);
  Yu.Ts. Oganessian, V. K. Utyonkov, et al. (2004); ...]
- *All models are quite reliable (Geiger-Nuttall-type relations,*
  WKB approximation)

β-decay

- *Strongly depends on nuclear structure (allowed and forbidden decays)*
- *Systematic calculations were performed for allowed transitions only*
  [B.W. Sargent (1933); E.O. Fiset and J.R. Nix (1972); P. Möller, et al.(1997)]

Spontaneous fission (SF)

- *Mainly determined by the potential energy properties (fission barrier)*
- *Phenomenological relations reproduce main trends of SF half-lives*
  [W.J. Swiatecki (1955); D.W. Dorn (1961); C. Xu and Z. Ren (2005)]
- *Multidimensional dynamical approaches are the most accurate but rather complicated for systematic studies [R. Smolanczuk (1997);*
  A. Sobiczewski and K. Pomorski(2007)]

Macro-microscopical approach

g.s. masses:

$$M(Z,A) = M_{\mathrm{LDM}}(Z,A) + \delta U(Z,A)$$

M_{gs} *and* δU_{gs} *are from P. Möller et al., At. Data Nucl. Data Tables (1995)*

fission barrier:

$$B_f = B_f^{\mathrm{LDM}} - \delta U_{gs}$$

B_f^{LDM} *- A.J. Sierk, PRC (1986)*

α-decay

Empirical Viola-Seaborg formula (enough reliable):

$$\log_{10} T_\alpha(\mathrm{sec}) = \frac{aZ + b}{\sqrt{Q_\alpha(MeV)}} + cZ + d + h_{\log},$$

a, b, c, d - A. Sobiczewski, Z. Patyk, and S. Ćwiok (1989)

$h_{\log}$ - V.E. Viola and G.T. Seaborg (1966)

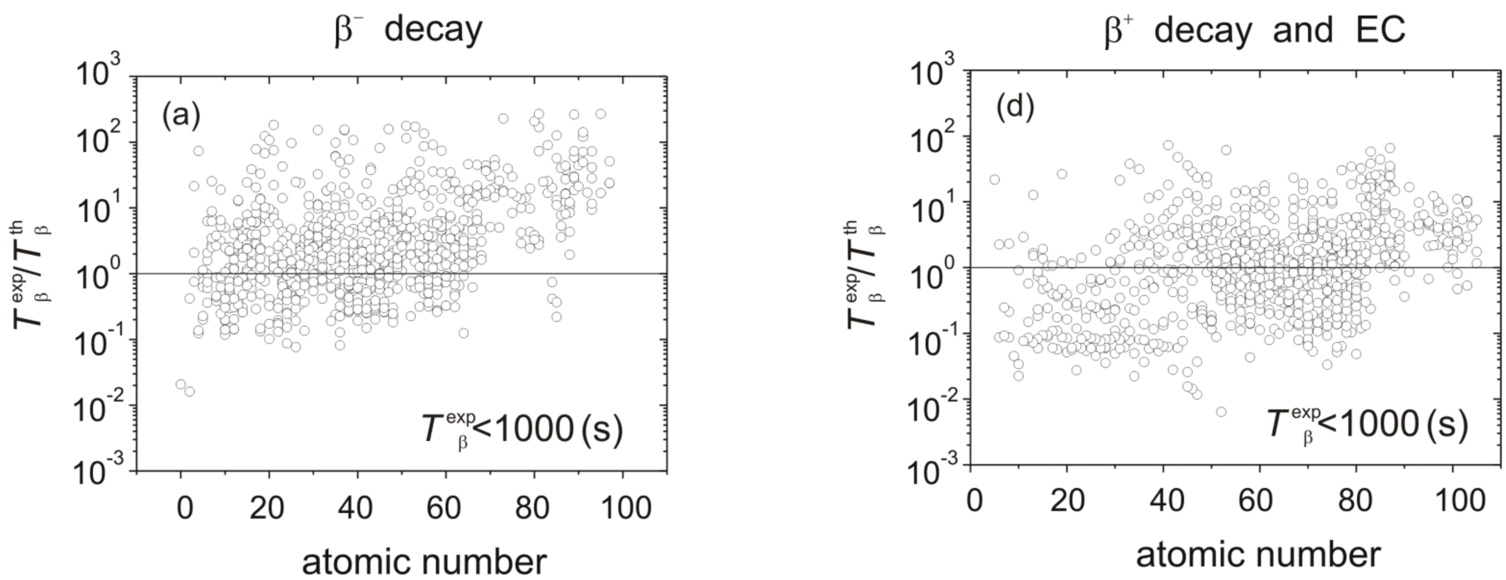
β-decay (β^-, β^+, EC)

$$1/T_\beta = 1/T_{\beta^-} + 1/T_{\beta^+} + 1/T_{EC}$$

allowed β-*transitions:*

$$\log_{10} f_0 T\,(\mathrm{sec}) \approx const = 4.7$$

f_0(Z,A,Q) - Fermi function is calculated by standard relations



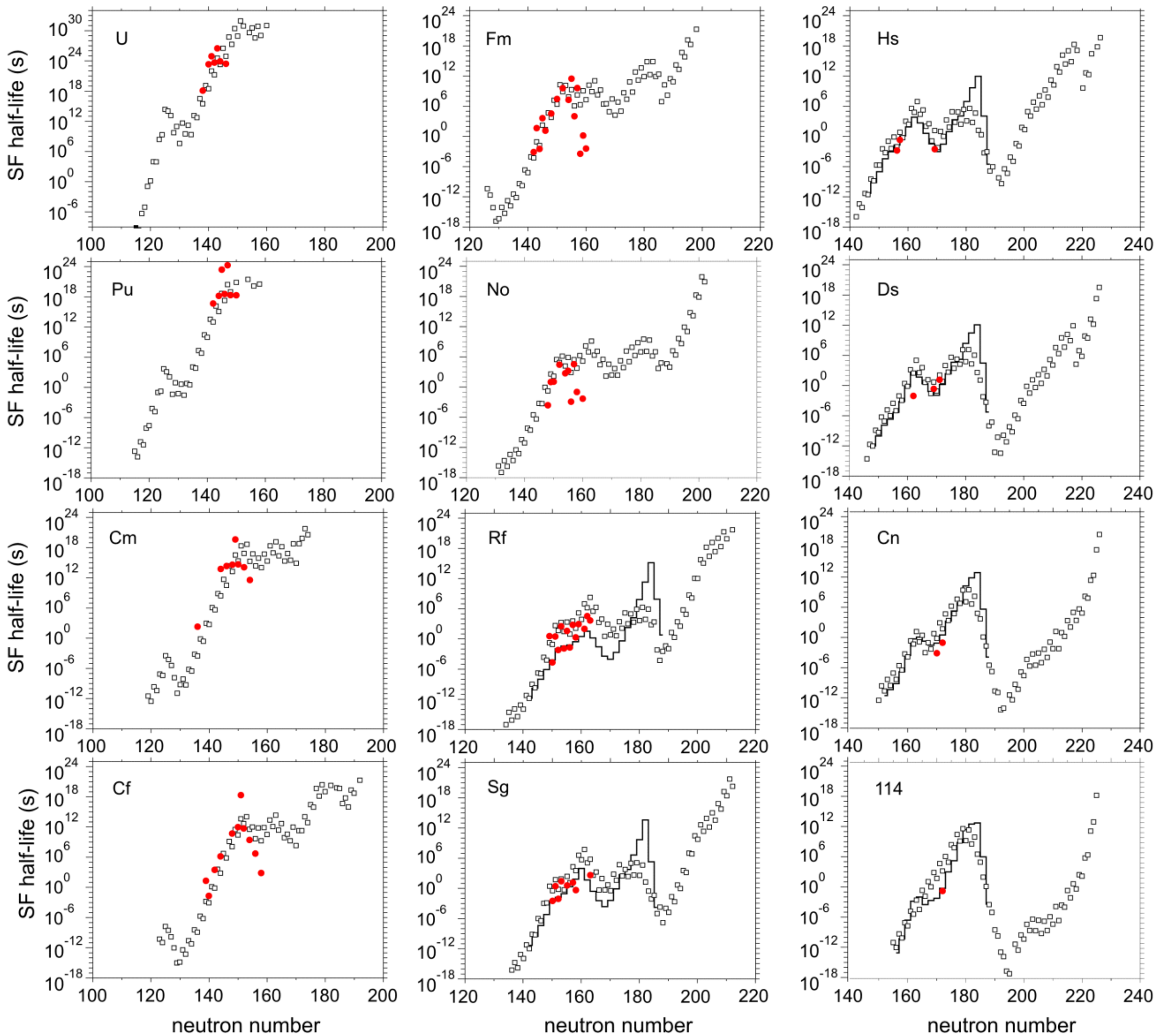
empirical relation based on the fission barrier:

$$B_f = B_f^{\mathrm{LDM}} - \delta U_{gs}$$

$$\log_{10} T_{SF}\left(\mathrm{sec}\right) = 1146.44 - 75.3153\frac{Z^2}{A} + 1.63792\left(\frac{Z^2}{A}\right)^2 - 0.0119827\left(\frac{Z^2}{A}\right)^3 +$$

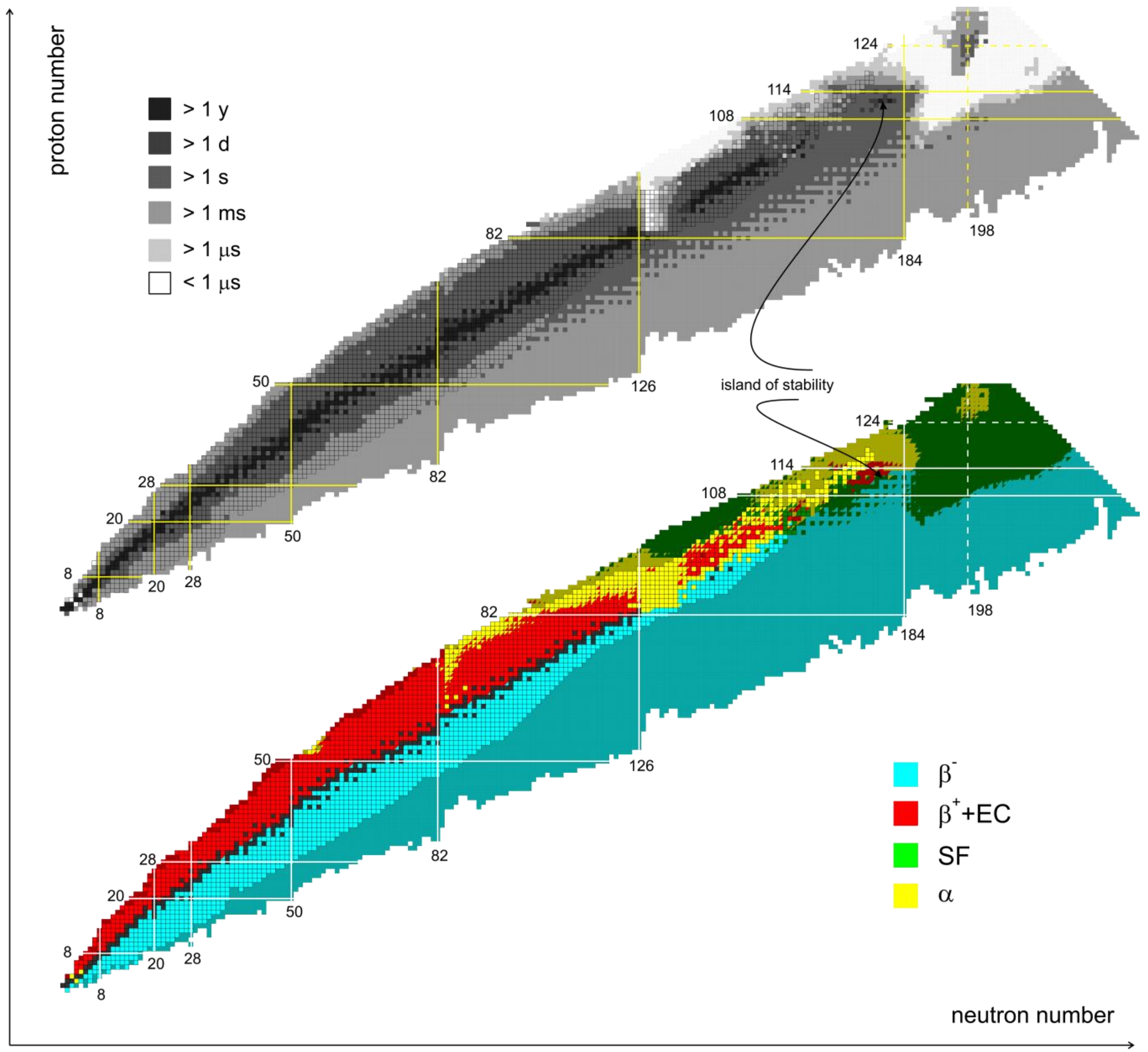
$$+ \quad B_f\left(7.23613 - 0.0947022\frac{Z^2}{A}\right) \quad + \begin{cases} 0, & \text{Z and N are even} \\ 1.53897, & \text{A is odd} \\ 0.80822, & \text{Z and N are odd} \end{cases}$$

Spontaneous fission

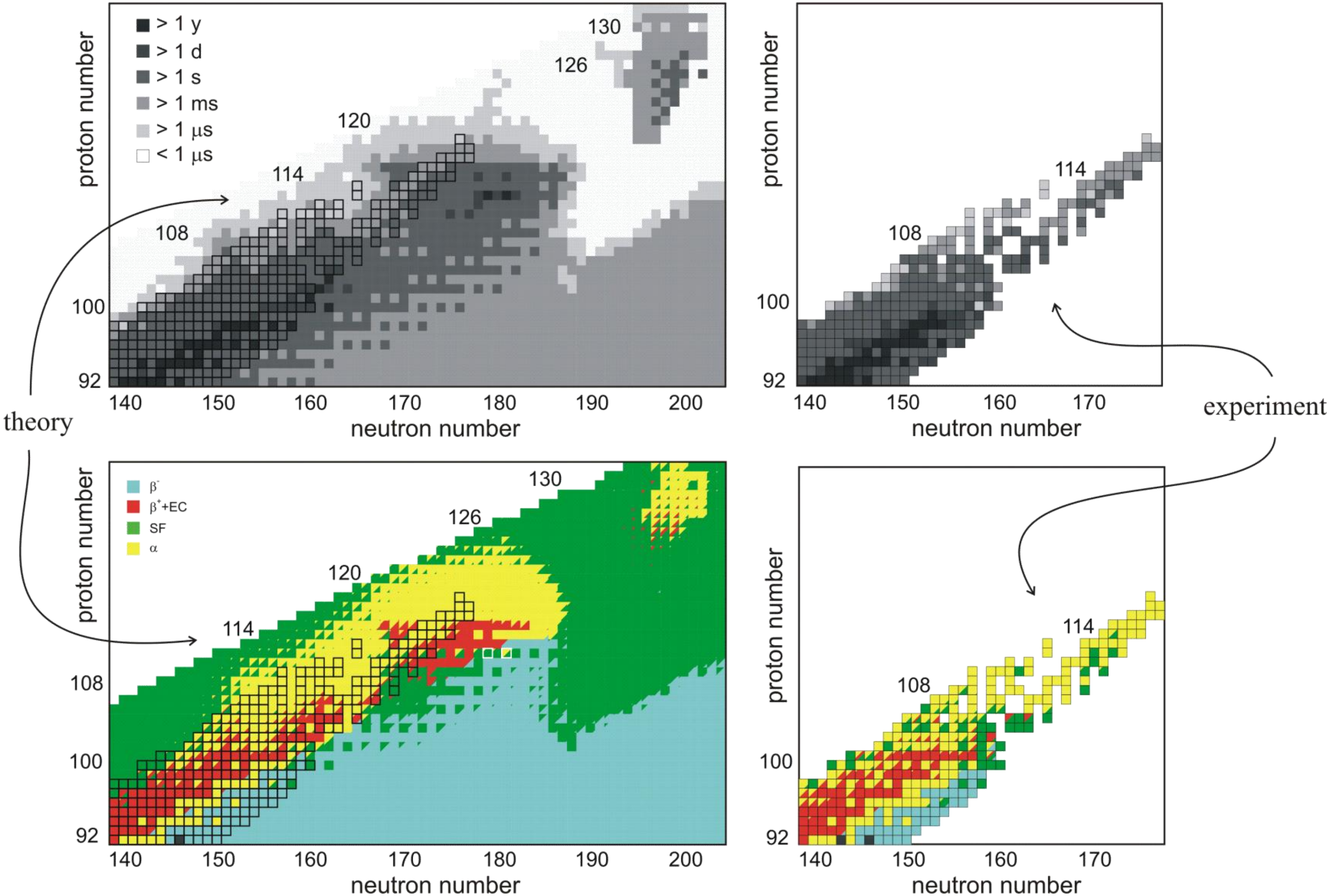


□ *this work* ▬ *R. Smolańczuk (1997)* ● *exp. data - N.E. Holden and D.C. Hoffman, (2000)*

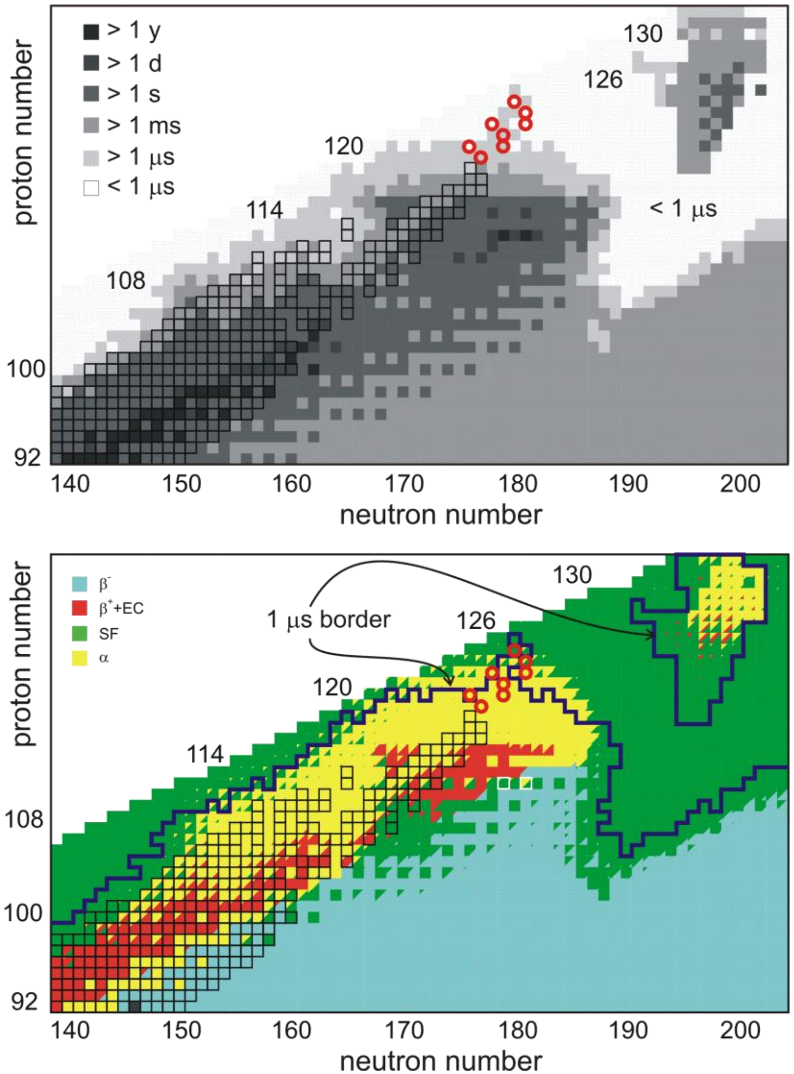
Chart of nuclei



Upper part of nuclear map (up to Z=132)



Perspectives of fusion reactions for SH (Z>118)



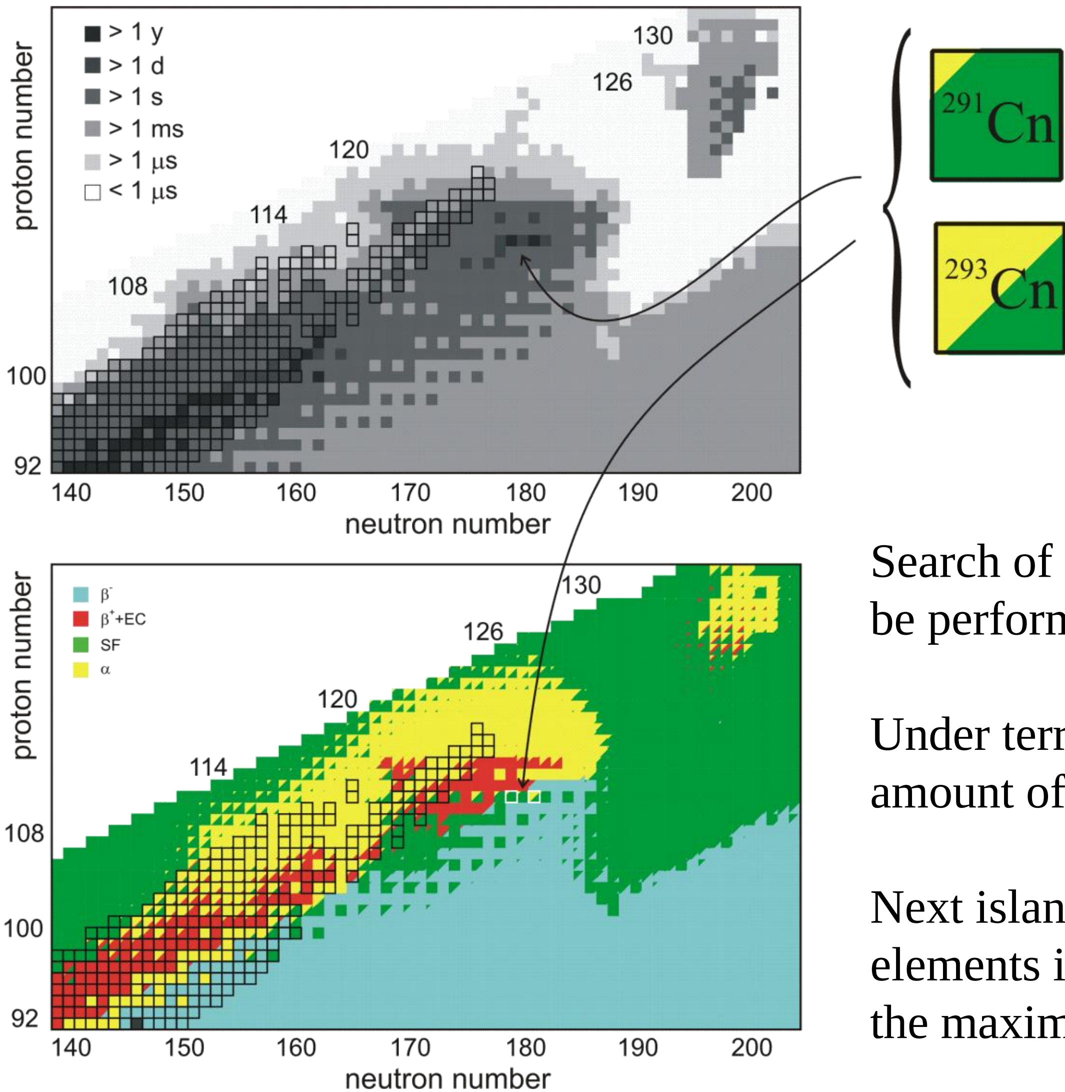
□ - ***known nuclei***

○ - *nuclei with **Z=119-124***
***3n channel** of the fusion reactions:*

$$^{50}Ti + {}^{249}Bk \rightarrow {}^{296}119 + 3n$$
$$^{50}Ti + {}^{249}Cf \rightarrow {}^{296}120 + 3n$$
$$^{54}Cr + {}^{248}Cm \rightarrow {}^{299}120 + 3n$$
$$^{54}Cr + {}^{249}Bk \rightarrow {}^{300}121 + 3n$$
$$^{54}Cr + {}^{249}Cf \rightarrow {}^{300}122 + 3n$$
$$^{58}Fe + {}^{248}Cm \rightarrow {}^{303}122 + 3n$$
$$^{58}Fe + {}^{249}Bk \rightarrow {}^{304}123 + 3n$$
$$^{58}Fe + {}^{249}Cf \rightarrow {}^{304}124 + 3n$$

Superheavy nuclei with Z>120 could be hardly detected due to their short half-lives!

Center of the Stability Island. Search of SH in Nature



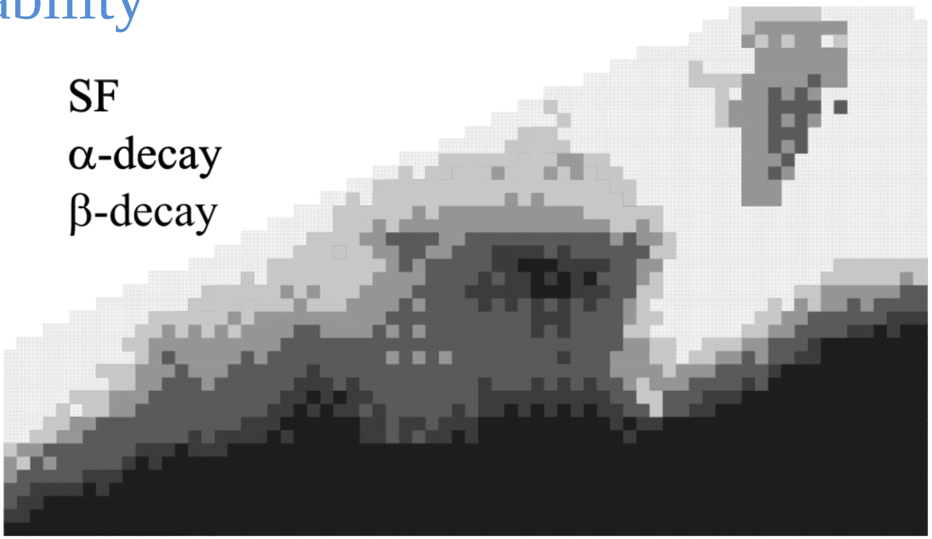
The most stable are **β-stable** isotopes of the element **112** with half-life ~ **100 years**

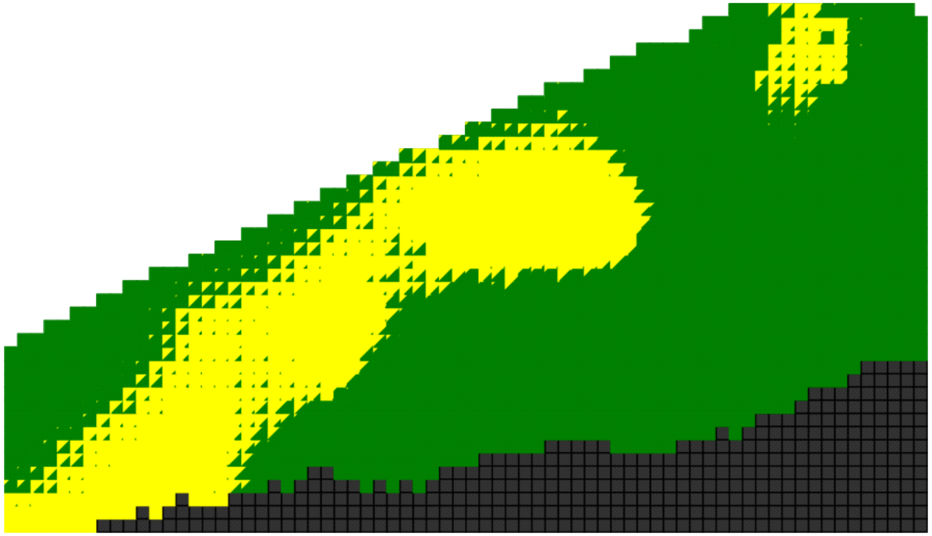
Search of superheavy nuclei in nature may be performed in cosmic rays.

Under terrestrial conditions a measurable amount of superheavies is unlikely to exist.

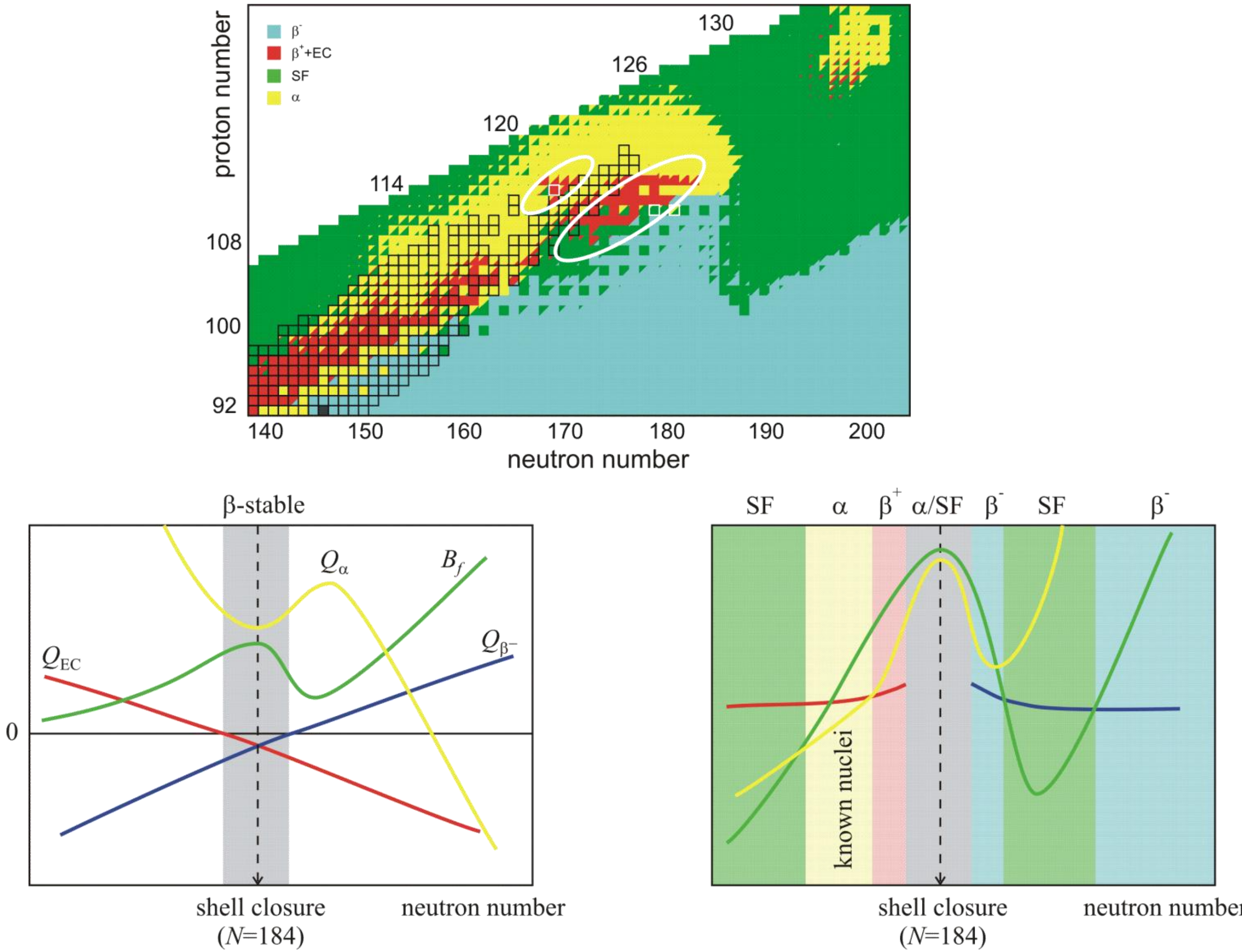
Next island of stability of superheavy elements is located at Z~124, N~198 with the maximum half-lives ~1 s

Islands of Stability

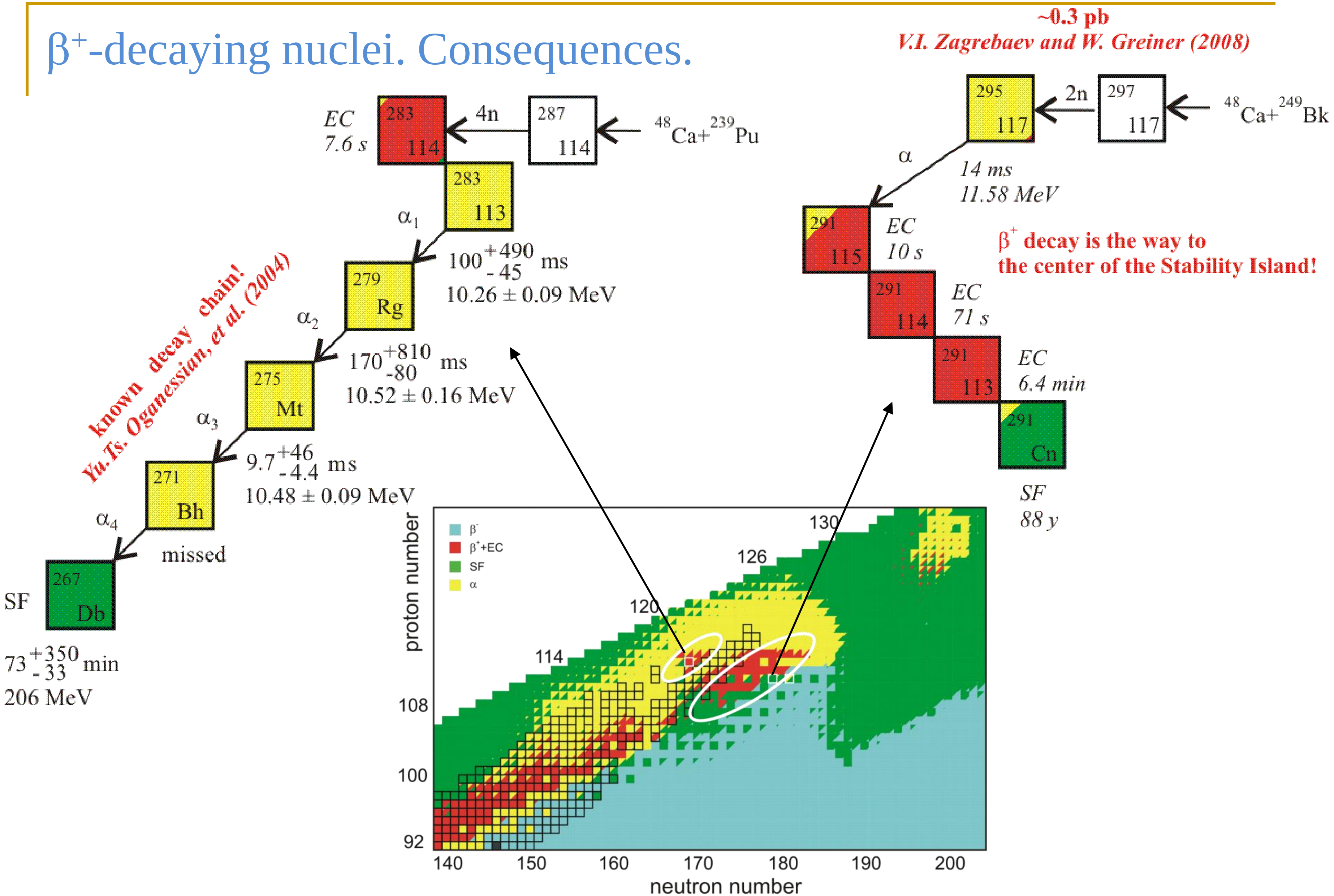




Decay modes in the vicinity of Stability Island



β⁺-decaying nuclei. Consequences.



Conclusions

- The island of stability of superheavy nuclei is centered at β-stable Copernicium isotopes ^{291}Cn and ^{293}Cn having the half-life of about 100 years.
- At existing experimental facilities the synthesis and detection of nuclei with $Z>120$ produced in fusion reactions may be difficult due to their short half-lives (shorter than 1 μs).
- The found area of β^+-decaying nuclei with $111<Z<115$ may significantly complicate their experimental discovery. In this region the α-decay dominates for the nuclei already discovered in the ^{48}Ca-induced fusion reactions.
- An existence of β^+-decaying isotopes of elements with $111<Z<115$ (located to the right of those synthesized in ^{48}Ca fusion reactions) gives us a chance to reach the center of the island of stability in fusion reactions via β^+-decay chains.
- The second island of stability of superheavy elements is located at Z~124, N~198 with the maximum half-lives ~1 s. It is separated from the “continent” by the “gulf” formed by nuclei with the half-lives shorter than 1 μs.
- Studies (both theoretical and experimental) of the structure of excited states in the region of superheavy nuclei are necessary for more accurate estimation of β-decay half-lives. Analysis of SF mode requires additional experimental information for neutron-rich isotopes of nuclei with Z=100-106.

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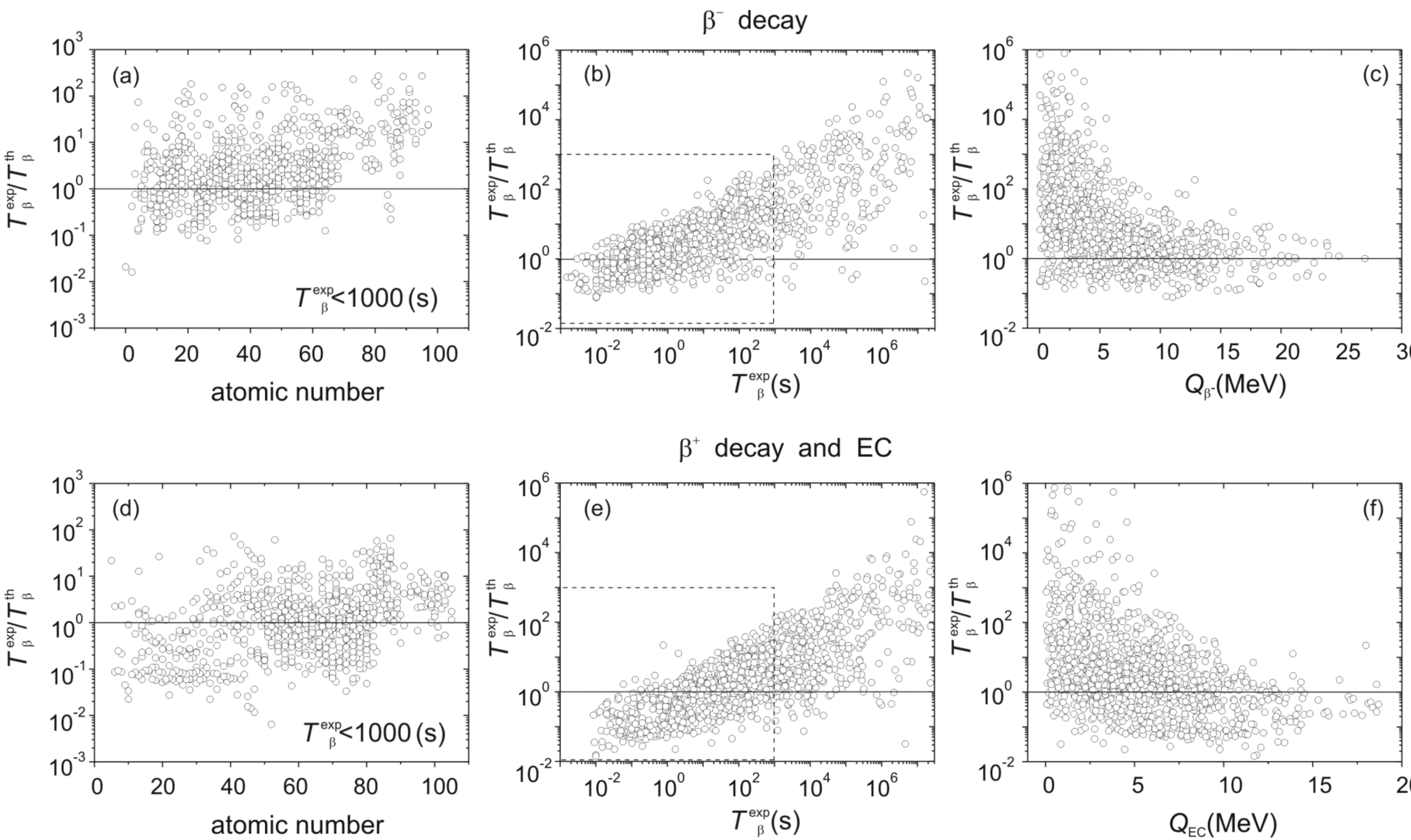
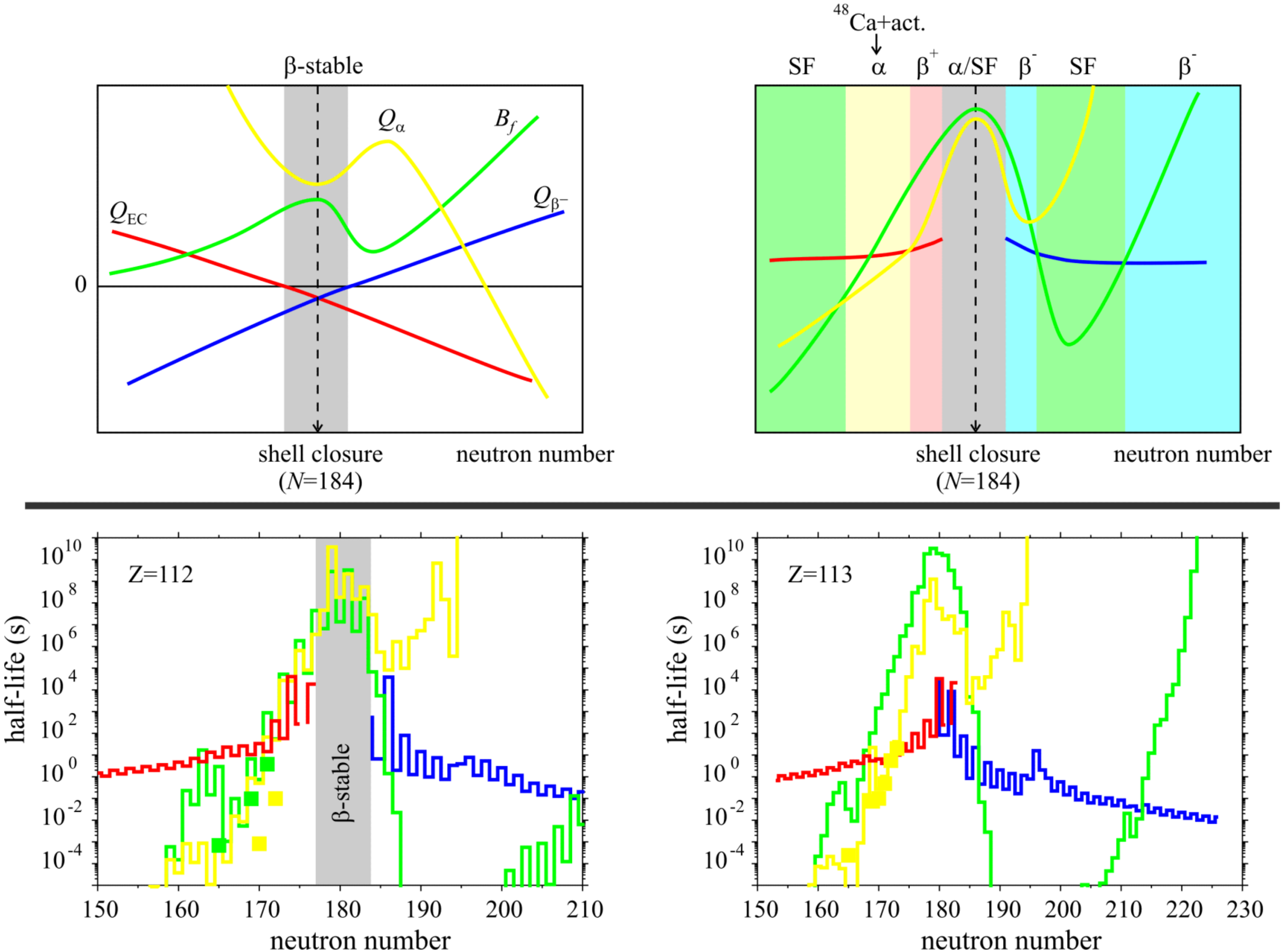

β⁻ decay
(a)
(b)
(c)
$T_\beta^{exp} < 1000$ (s)
atomic number
T_β^{exp}(s)
Q_{β^-}(MeV)
$T_\beta^{exp}/T_\beta^{th}$
β⁺ decay and EC
(d)
(e)
(f)
$T_\beta^{exp} < 1000$ (s)
atomic number
T_β^{exp}(s)
Q_{EC}(MeV)



β-stable
Q_α
B_f
Q_{EC}
Q_{β^-}
0
shell closure
(N=184)
neutron number
^{48}Ca+act.
SF
α
β^+
α/SF
β^-
SF
β^-
shell closure
(N=184)
neutron number
Z=112
half-life (s)
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
β-stable
150
160
170
180
190
200
210
neutron number
Z=113
half-life (s)
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
150
160
170
180
190
200
210
220
230
neutron number