DECAY MODES AND A LIMIT OF EXISTENCE OF NUCLEI

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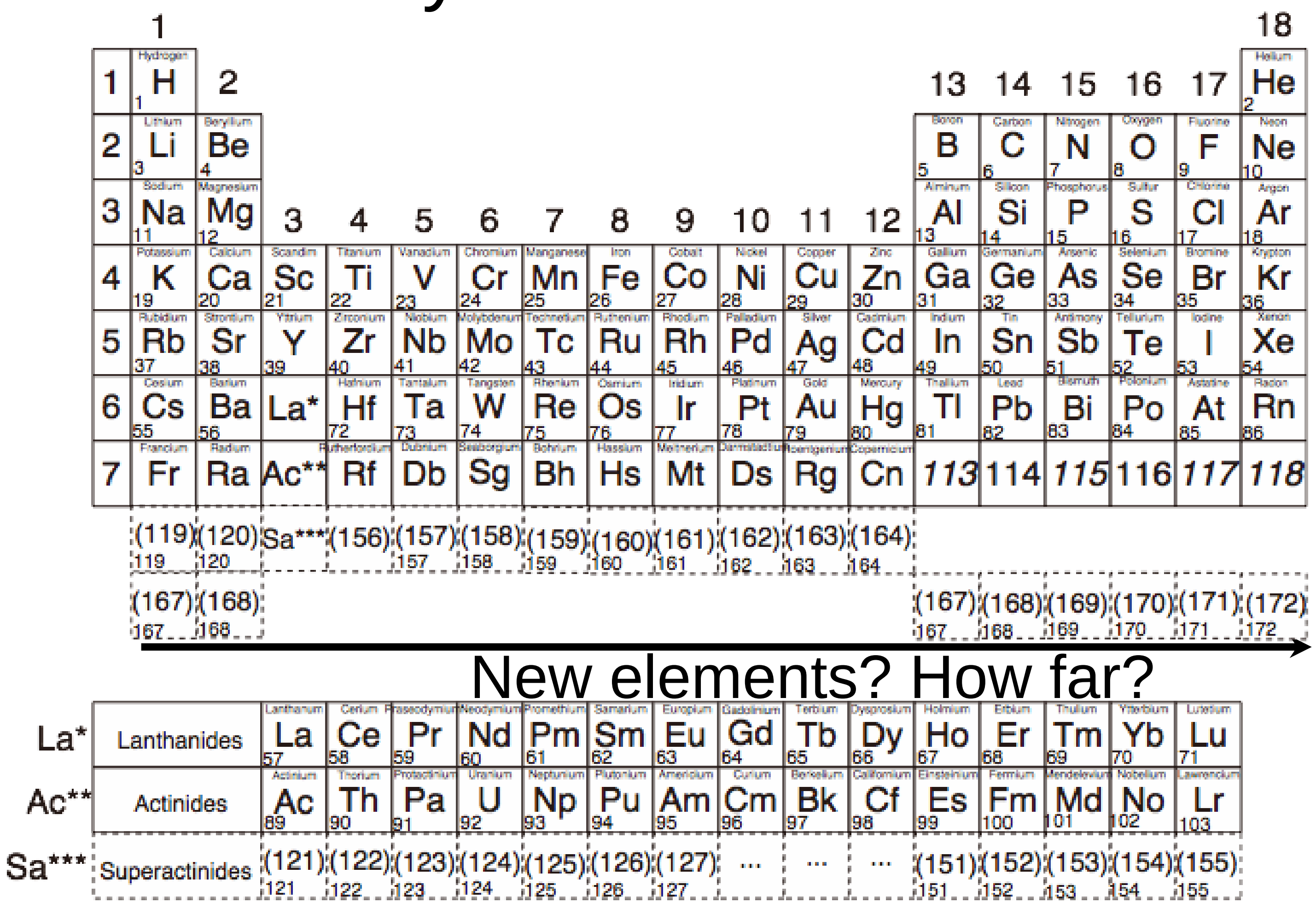
How is the limit of elements?

Chemistry



- In chemical study, elements up to Z~172 have been discussed.
- Are such elements can be existed?
- In other words, does the corresponding <u>nuclei</u> exist in certain <u>half-lives</u>?

P. Pyykko presented a more improved table.

How far does the area of nuclei extend? -some qualitative estimations-

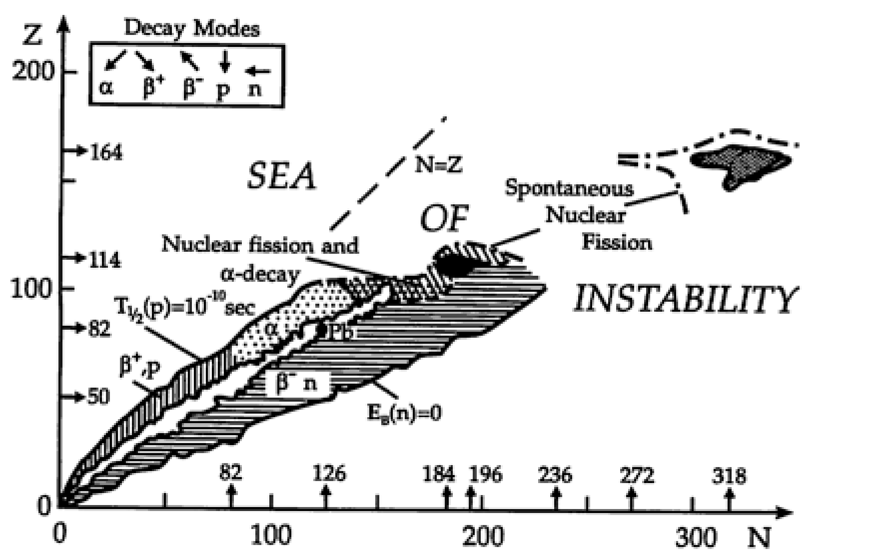


Fig. 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements ($Z = 114$, $N = 184$, 196 and $Z = 164$, $N = 318$) are shown as dark hatched areas.

Lecture Notes in Physics 581, p.317 (Greiner) 2001

also in talks of Kratz and Greiner himself

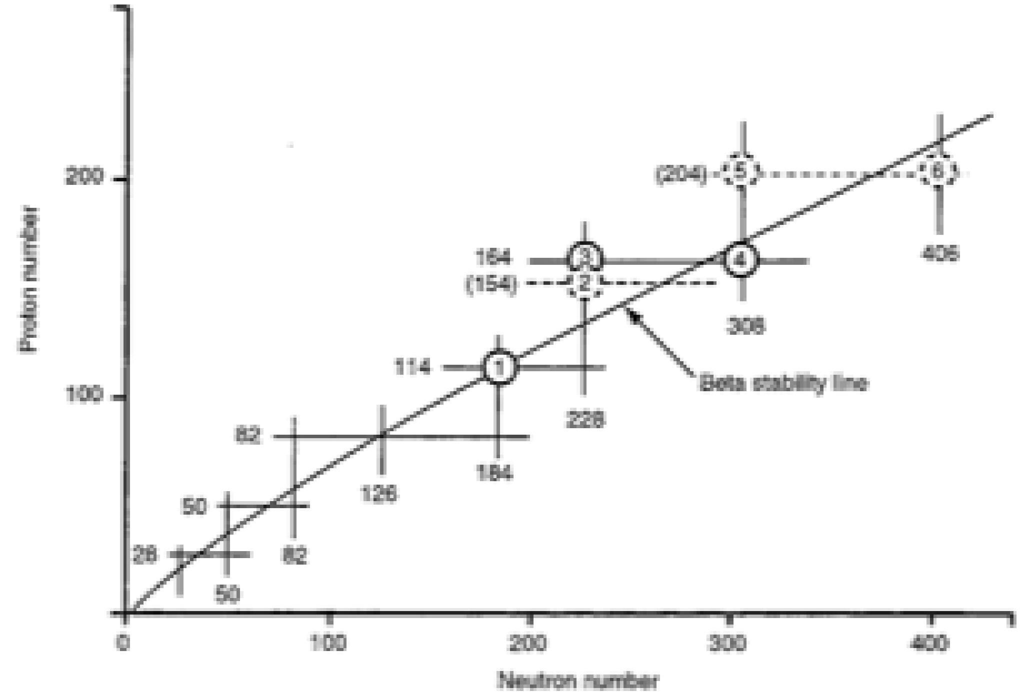


Figure 7.1 Calculated location of the islands of superheavy elements, 1, and super-superheavy elements, 2–6, in the nuclear chart. The figure was taken from Sobiczewski (1974).

On Beyond Uranium, p.66 (S, Hofmann) 2002.
Figure was taken from Sobiczewski (1974)

→ **Some qualitative estimation were studied, but rather quantitative estimation are required.**

→ **We estimate decay modes by using the KTUY mass formula.**

KUTY(KTUY) mass formula

(Koura Uno, Tachibana, Yamada, (00), **KTUY(05), PTP113, 305**)

$$M(Z,N)=M_{\mathrm{gross}}(Z,N)+M_{\mathrm{eo}}(Z,N)+E_{\mathrm{sh}}(Z,N)$$

Mass table (Z,N>1, Z<131,N<201) : available from the web site of Nuclear Data Center of JAEA

$M_{\mathrm{gross}}(Z,N)$: Gross term

$A^{-1/3}$ ***expansion term including*** $|N-Z|$, $(N-Z)^2$ + ***Coulomb term***

$E_{\mathrm{sh}}(Z,N)$: Shell term

Spherical nuclei: **Calculate from a modified Woods-Saxon potential (a function of Z, N) (NPA671(00)96)**

Spherical state of All nuclei are obtained.

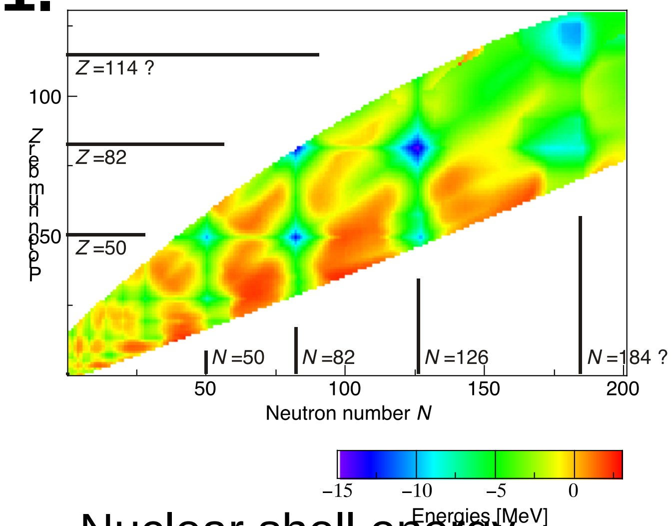
Deformed nuclei: **Mixing weight of the above spherical shell energies**
weight : determined by shapes of nuclei (NPA674(00)47)

$$E_{\mathrm{sh}}(Z,N)=\sum_{\mathrm{def.}}(<E_{\mathrm{sh}}^{\mathrm{sph}}(Z,N)>_{\mathrm{def.}}+\Delta E_{\mathrm{S}}(Z,N)-\Delta E_{\mathrm{C}}(Z,N)-\Delta E_{\mathrm{pro}}(Z,N))$$

Micro *Surface* *Coulomb*

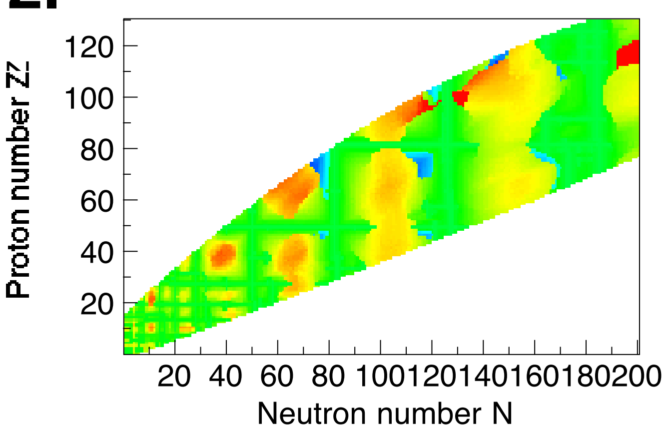
Results of the KTUY mass formula

1. Nuclear shell energies $E_{sh}(Z, N)$



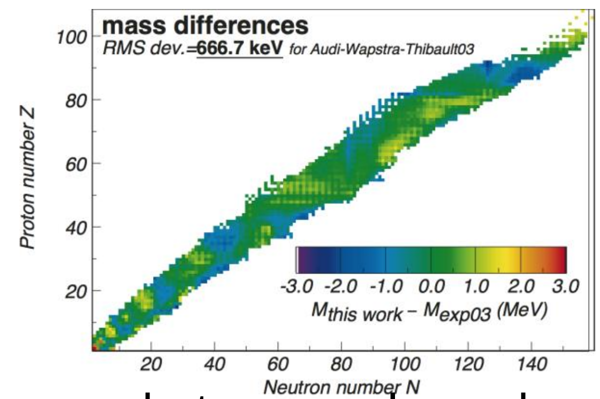
Nuclear shell energy

2. Deformation parameter alpha2 of KUTY



Deformation parameter α_2
(α_4 and α_6 are also obtained)

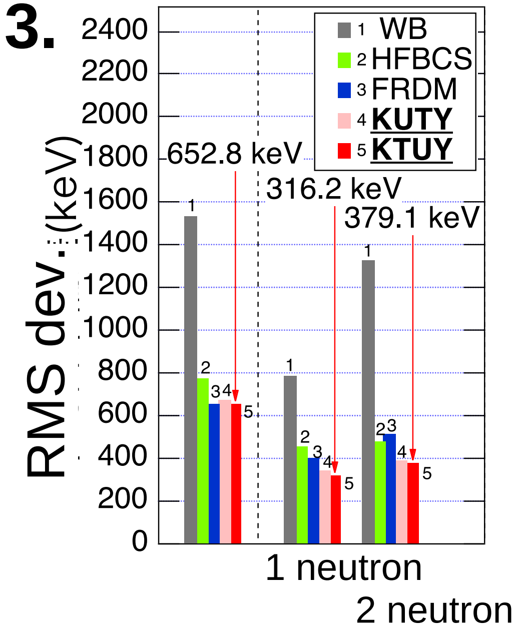
3.



Difference between calc. and exp. masses for 2219 nuclei ($Z, N \geq 2$)

1. **Nuclear shell energy**
2. **Nuclear shape**
3. **better mass-reproduction**
4. **Change of magicities in n-rich**
5. **Reproduction of n-drip line**
6. **etc.**

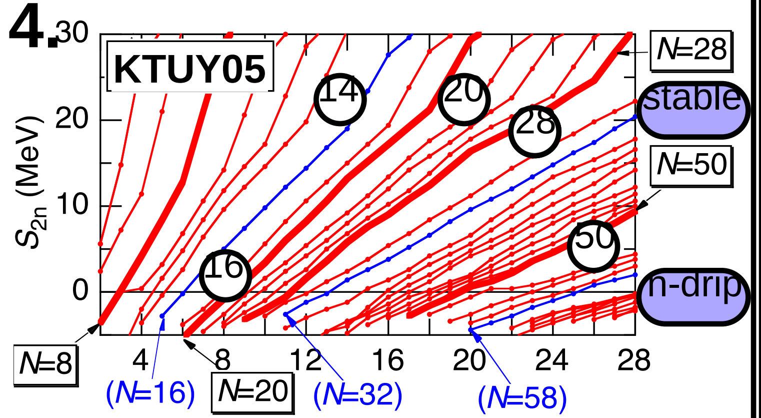
3.



RMS dev. from exp. mass

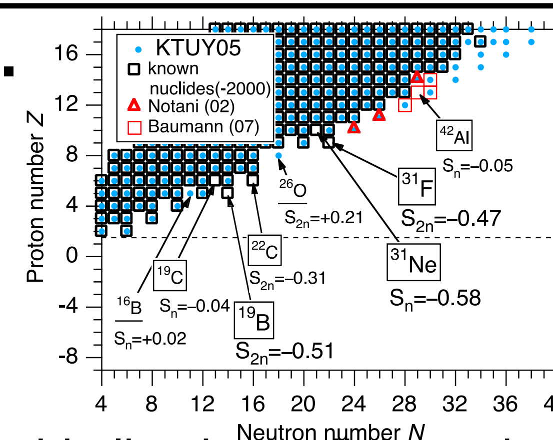
- ~10%better than other mass models in S_n, S_{2n},...

4.



N=14,20,28,50 gap -> <u>decreasing</u>

5.



N-drip line in the light region

Reproduction of the KTUY model

RMS deviation from experimental data in keV

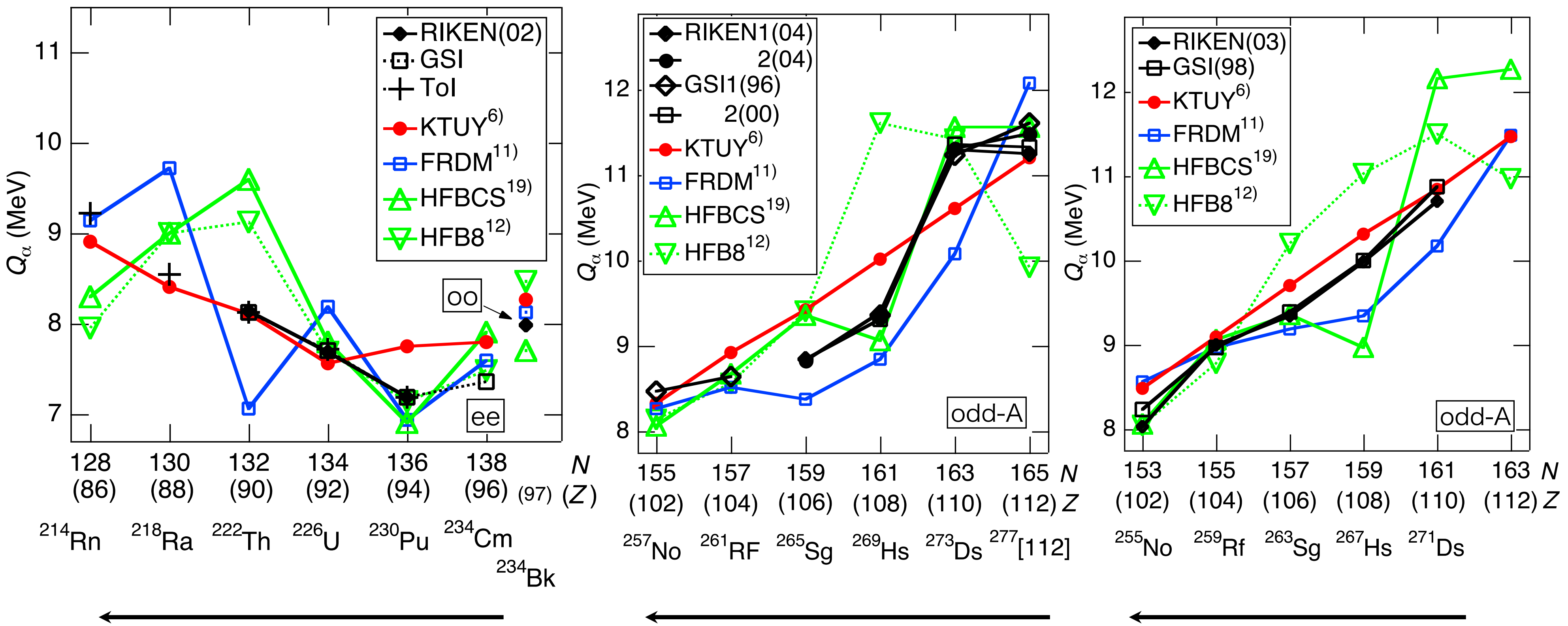
Mass formulas	Mass	Neutron	Proton	Alpha		Beta		
		S_n	S_p	Q_α	$Q_\alpha > 0$	Q_β	$Q_{\beta-} > 0$	$Q_{EC} > 0$
(n. of data)	(2149)	(1988)	(1948)	(1974)	(1860)	(1860)	(785)	(1073)
KTUY	**653**	**316**	**353**	**517**	**494**	**449**	**520**	**389**
FRDM	656	399	395	612	584	491	568	424
HBF2	659	470	490	550	521	581	636	541
HFB8	640	564	593	683	641	696	740	660

Exp. data: AME2003 by Audi et al.

- KTUY gives **Smallest RMS dev.** from exp. derivatives of masses by **10-20%**

α-decay Q-values from GSI and RIKEN

related to ^{234}Bk ^{277}Cn ^{271}Ds (^{275}Cn])



Experiment:
smoothness

Experiment:
steep at N≈ 162**,**
flat at N≈ 164

Experiment:
smoothness

KTUY: smooth property, but deformed shell is not clear

*All predictions are calculated as ground-to-ground-state

Estimation of nuclear decay modes

- Alpha-decay
- Beta-decay
- Proton emission
- Spontaneous fission

Sensitivity

Q-values from masses

Single-particle potential

Potential energy surface+
penetration probability

Alpha and beta decay half lives

Alpha decay: phenomenological relation between Q_α and $T_{\alpha 1/2}$.:

$$\log_{10} T_\alpha(\mathrm{s}) = 1.7195\sqrt{\frac{A-4}{A}} Z_{\mathrm{D}} / \sqrt{Q_\alpha(\mathrm{MeV})} - 1.2901\sqrt{\frac{A-4}{A}}\sqrt{R Z_{\mathrm{D}}}$$
$$+0.07466\sqrt{\frac{A-4}{A}} R^{3/2}/Z_{\mathrm{D}}^{1/2} \cdot Q_\alpha(\mathrm{MeV})$$
$$-\log_{10} N - 0.159175 + h_0 \delta_{\mathrm{eo}}.$$

$$R = r_0 A_{\mathrm{D}}^{1/3} + d_0, \ r_0 = 1.08 \ \mathrm{fm}.$$

- RMS dev.: **1/10~10 times** in partial half-lives if exp. Q-values are adopted.
- Uncertainty of estimated Q_α is ~500 keV. Typically, shift of 300 keV gives a change of $T_{1/2}$ in one order of magnitude in the superheavy mass region.
- Totally Uncertainty of 10^{-3}-10^{3} in $T_{\alpha 1/2}$

Beta decay: the Gross theory of beta decay

$$\lambda = \lambda_{\mathrm{F}} + \lambda_{\mathrm{GT}} + \lambda_1^{(0)} + \lambda_1^{(1)} + \lambda_1^{(2)}$$

$$\lambda_{\mathrm{F}} = \frac{m_{\mathrm{e}}{}^5 c^4}{2\pi^3 \hbar^7} |g_{\mathrm{V}}|^2 \int_{-Q}^{0} |M_{\mathrm{F}}(E)|^2 f(-E) dE$$:Fermi (allowed)

$$\lambda_1^{(2)} = \frac{m_{\mathrm{e}}{}^5 c^4}{2\pi^3 \hbar^7} \left(\frac{m_{\mathrm{e}} c}{\hbar}\right)^2 |g_{\mathrm{A}}|^2 \int_{-Q}^{0} \sum_{ij} |M_{ij}(E)|^2 f_1(-E) dE$$:1st forbidden

$$|M_\Omega(E)|^2 = \int_{\epsilon_{\min}}^{\epsilon_{\max}} D(E,\epsilon) W(E,\epsilon) \frac{dn_1}{d\epsilon} d\epsilon$$

$D(E,\epsilon)$:One particle strength function

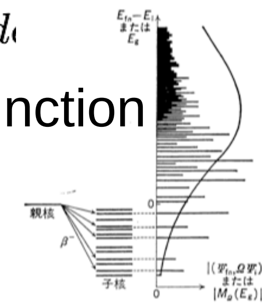
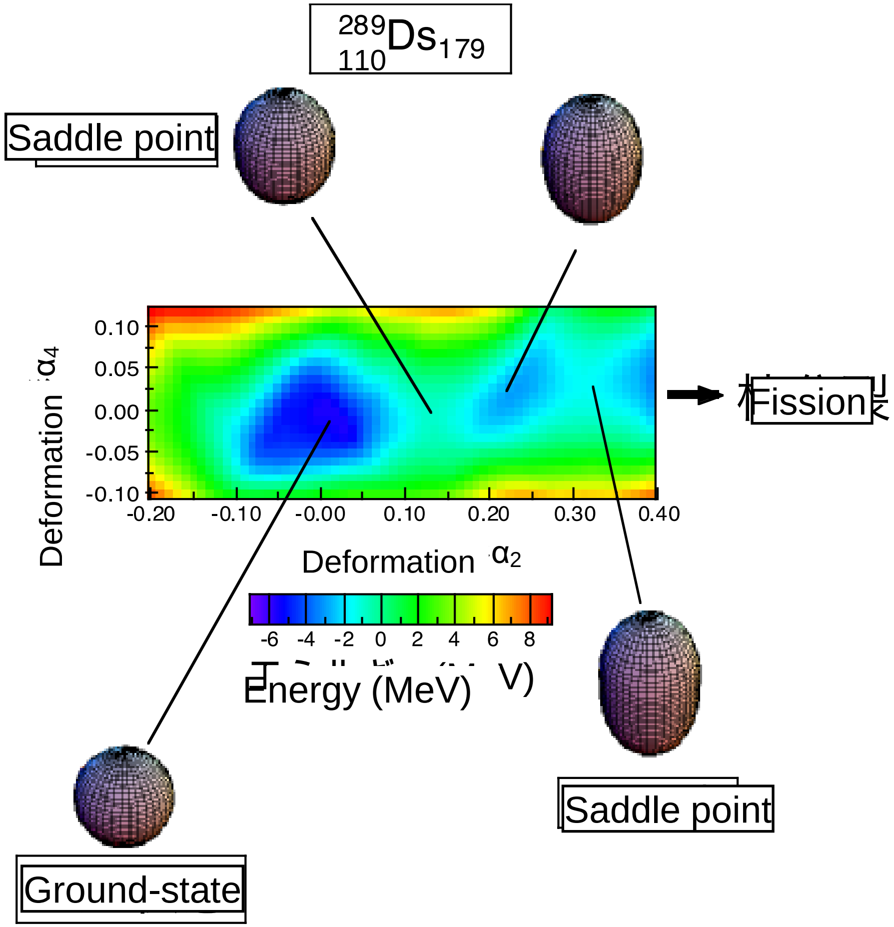


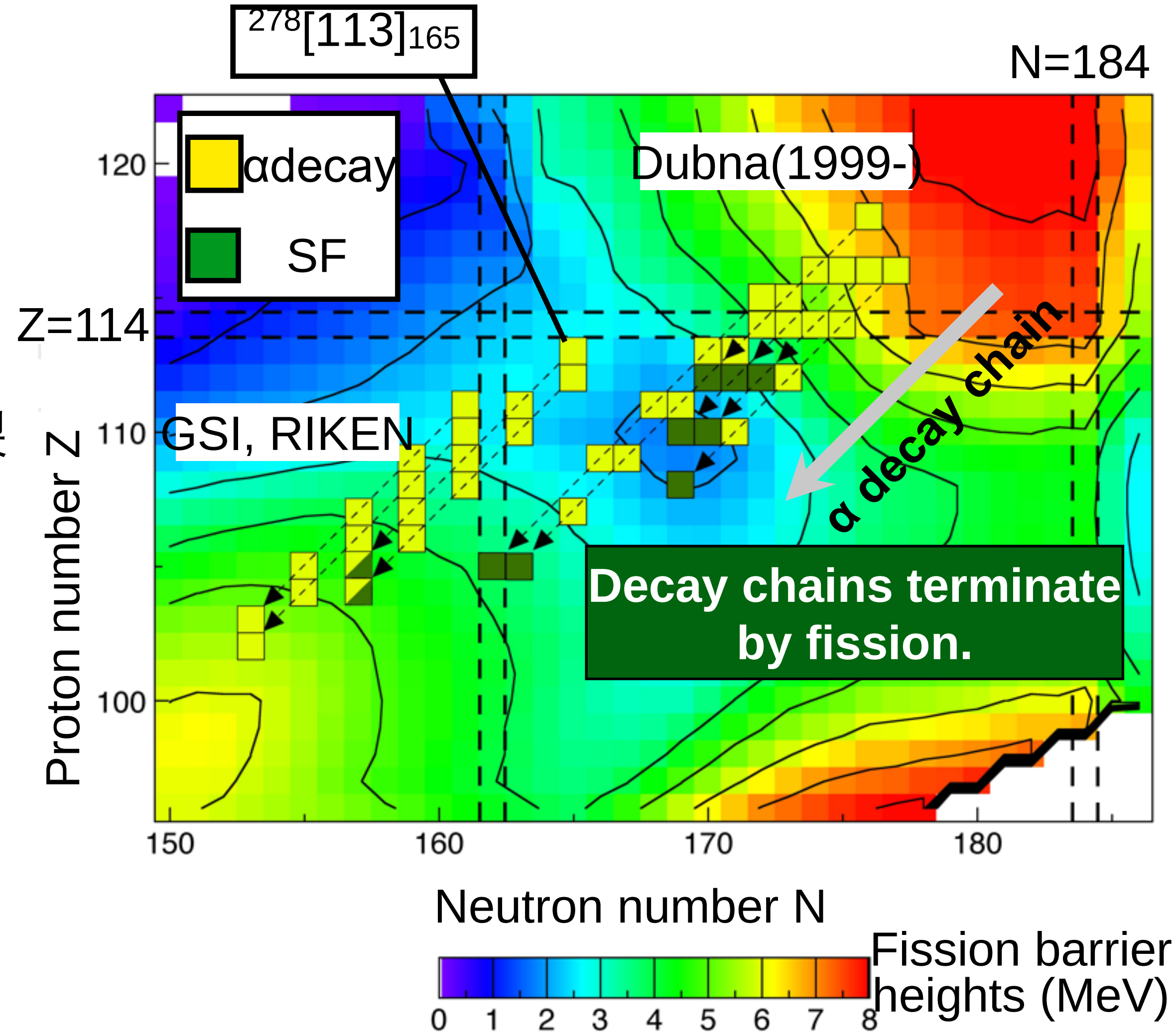
図 6·8 ベータ崩壊の強度関数の説明図

- Consider sum rules of beta-decay
- Not only allowed but also forbidden transition is treated:
- Averaged even-odd effect is introduced.

Spontaneous Fission half-lives



Potential energy surface

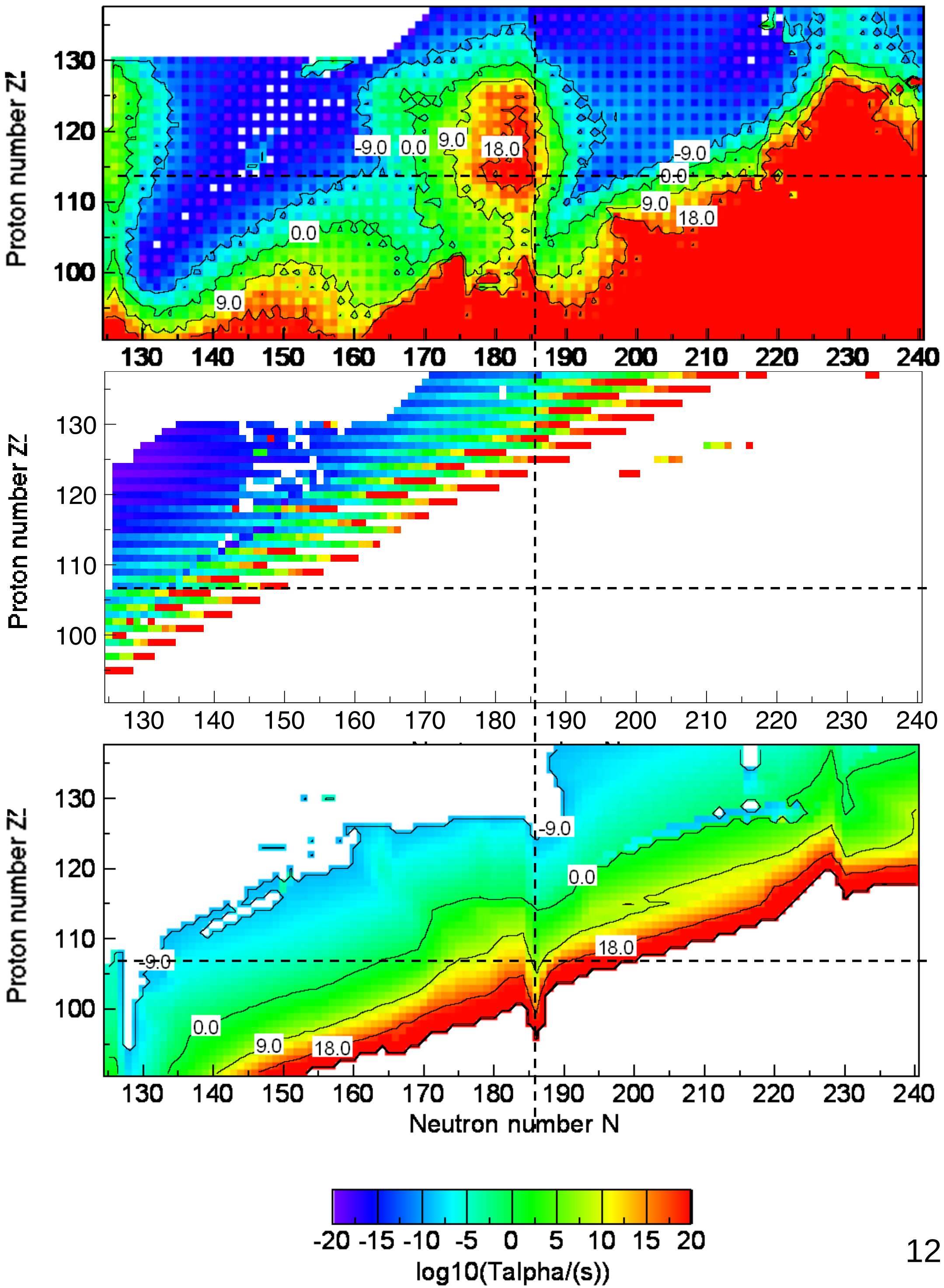


- Fission barrier height based on the KTUY mass calculation.

- SF-dominant region exists (N≈170) (in agreement with measured data)

<u>Spontaneous fission half-lives</u>: Penetration probability is calculated with 1-dim. WKB method (mass inertia is adjustable parameter)

Estimation of Partial half lives



Spontaneous fission

explained in previous page

Quite sensitive to the shell closure.

Proton emission

WKB method
Q_p, J^{π}: from **KTUY**

There has rather long partial half lives even outer proton-drip line

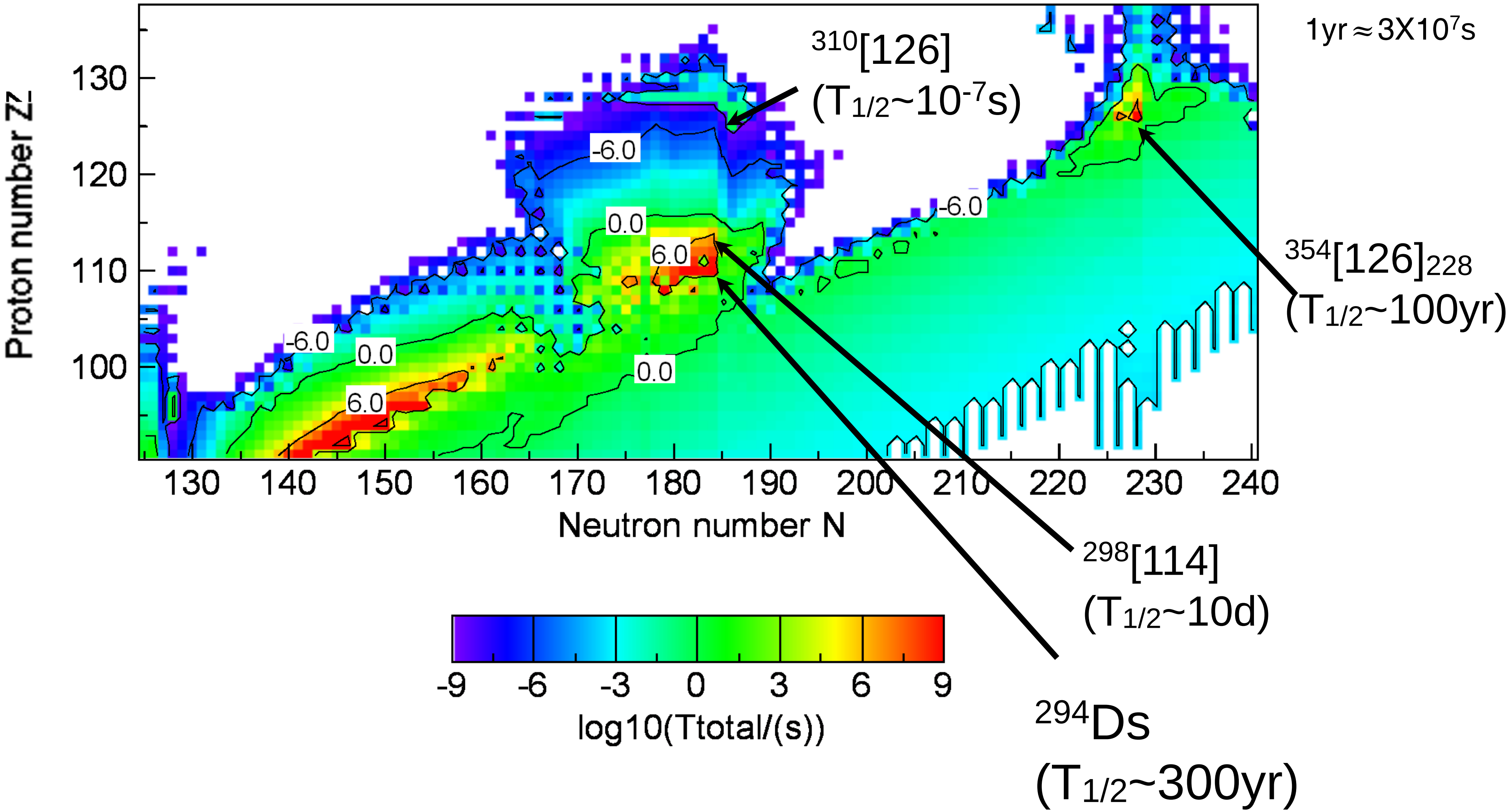
α decay

Phenom. formula
Q_{α}: from **KTUY**

Rather sensitive to the proton shell closure.

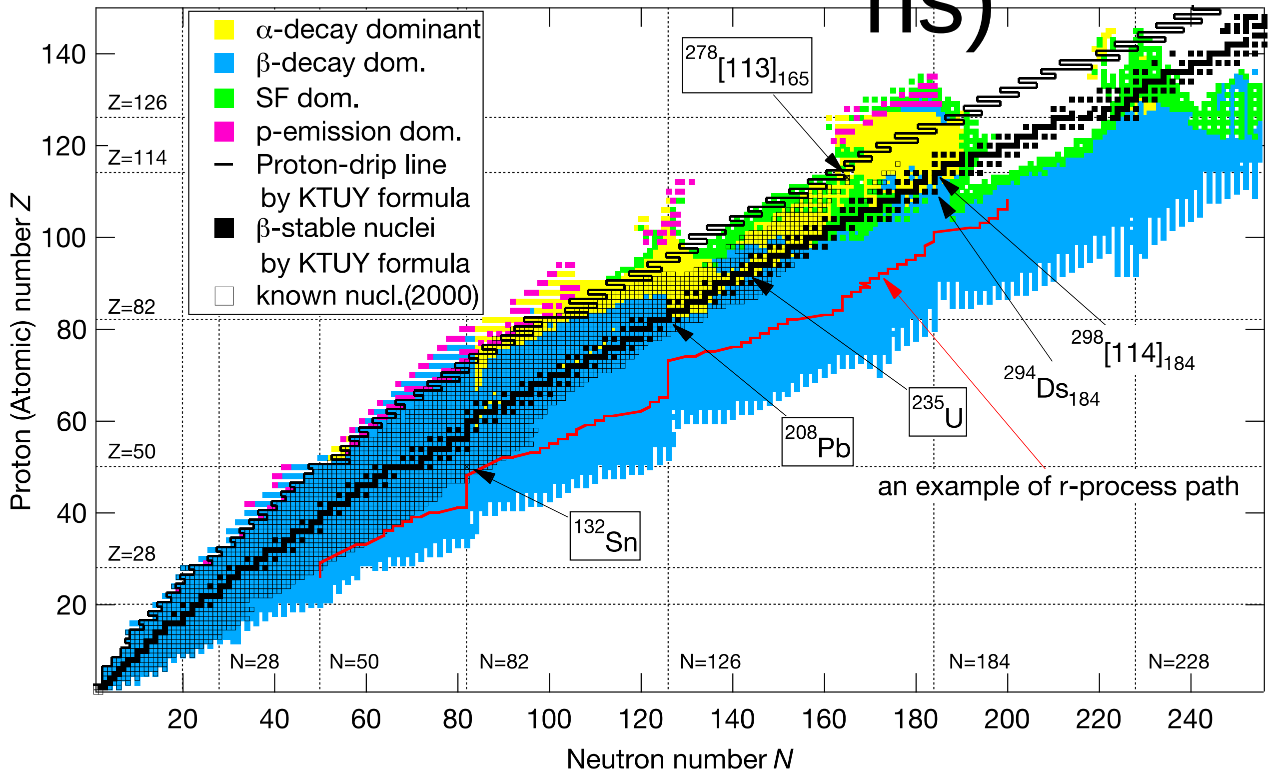
+ β-decay by using the gross theory of β-decay + KTUY

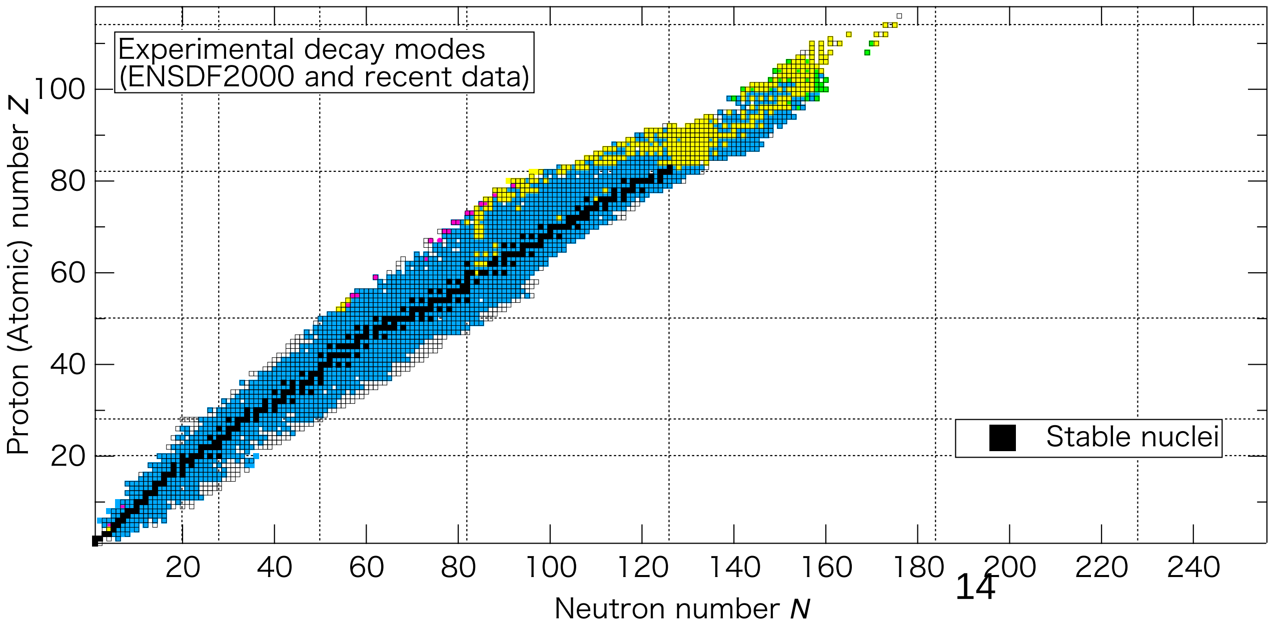
Total half-lives (α,β,p,sf)



(Long-lived superheavy nuclei distributes near the β-stability line)

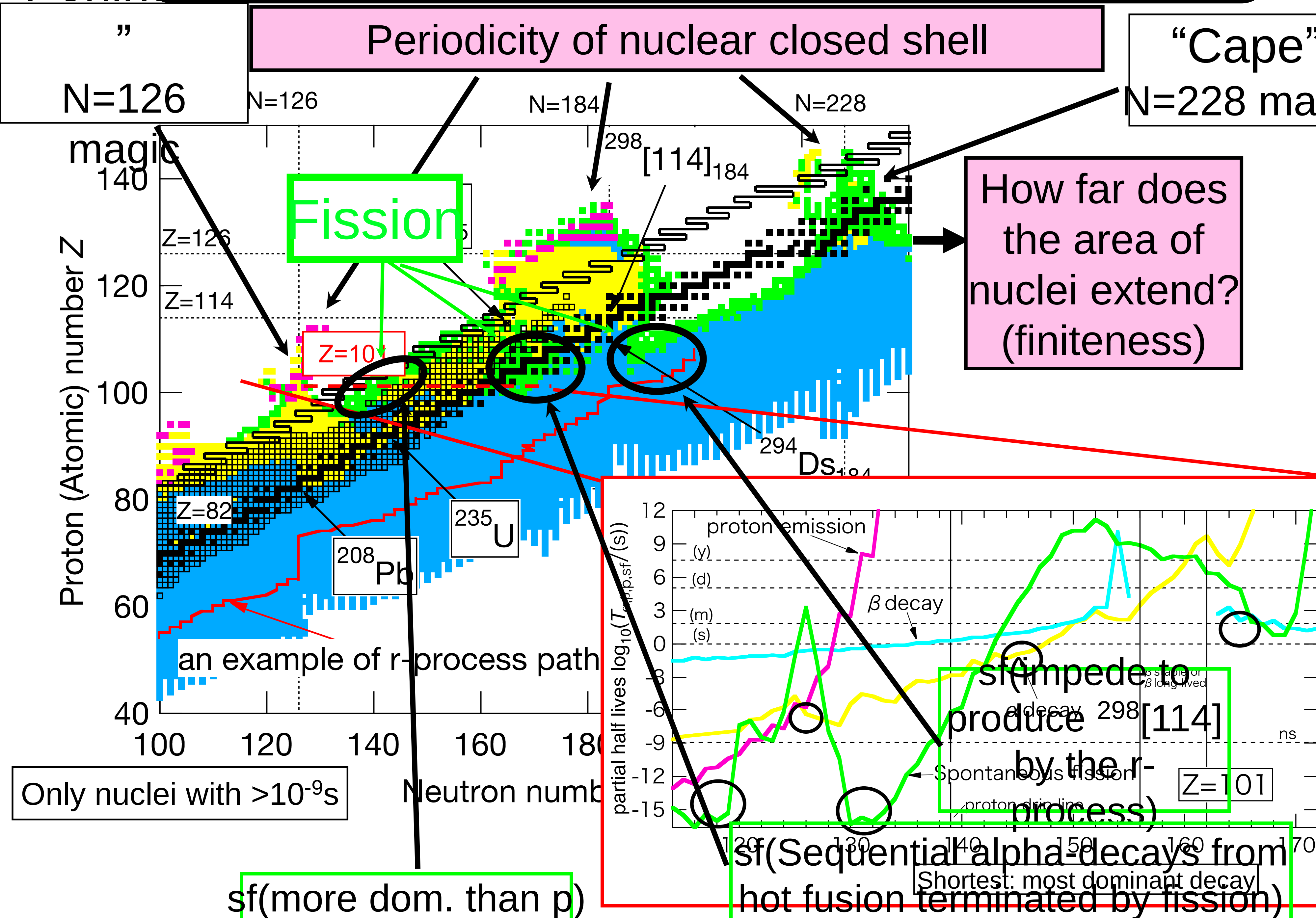
Most dominant decay (α, β, sf, p) ($T_{1/2} \geq 1$ ns)





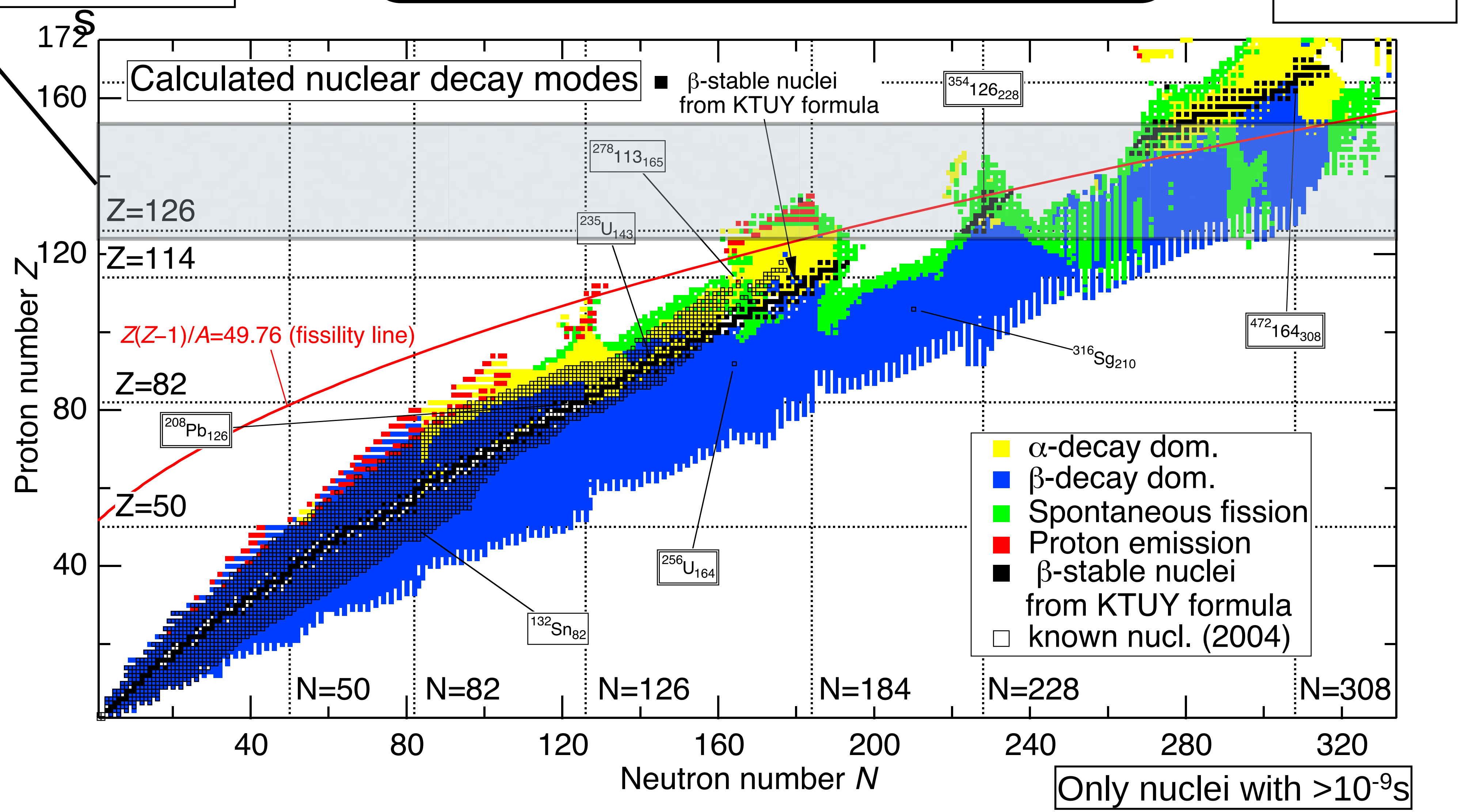
The bulletin of the Physical Society of Japan (BUTSURI), 60 (2005)

Decay modes in the superheavy region



Main decay modes

Superactinides

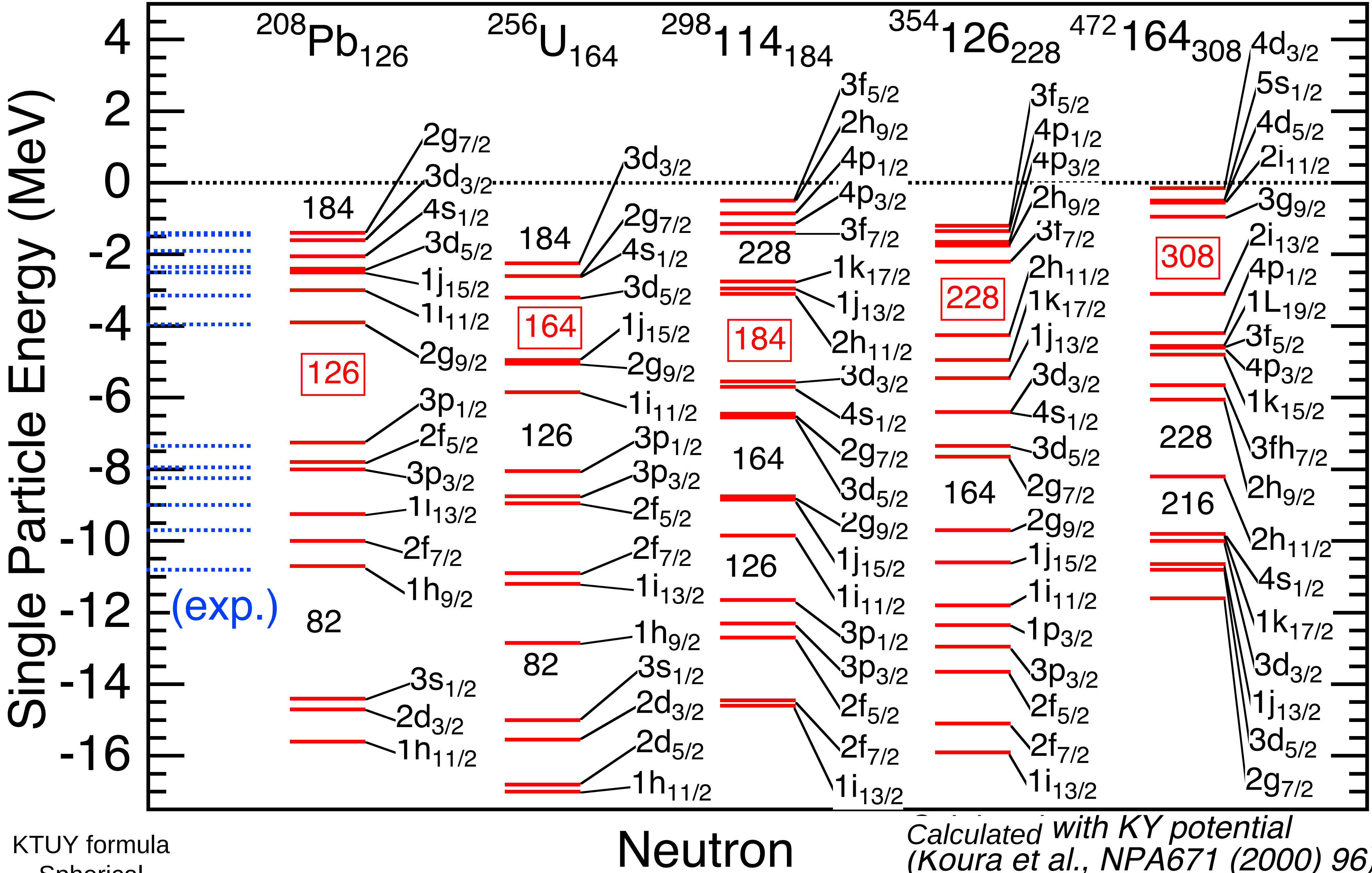


Spontaneous-fissioning nuclei is the border in the neutron-deficient side.

$T_{sf}=10^{-9}$ s line and neutron-drip line crosses near $N \approx 340$(cf. fissility line)

Islands of stability corresponding N = 228, 308, Z=164 magicity appear.

Spherical neutron magic:beyond 184

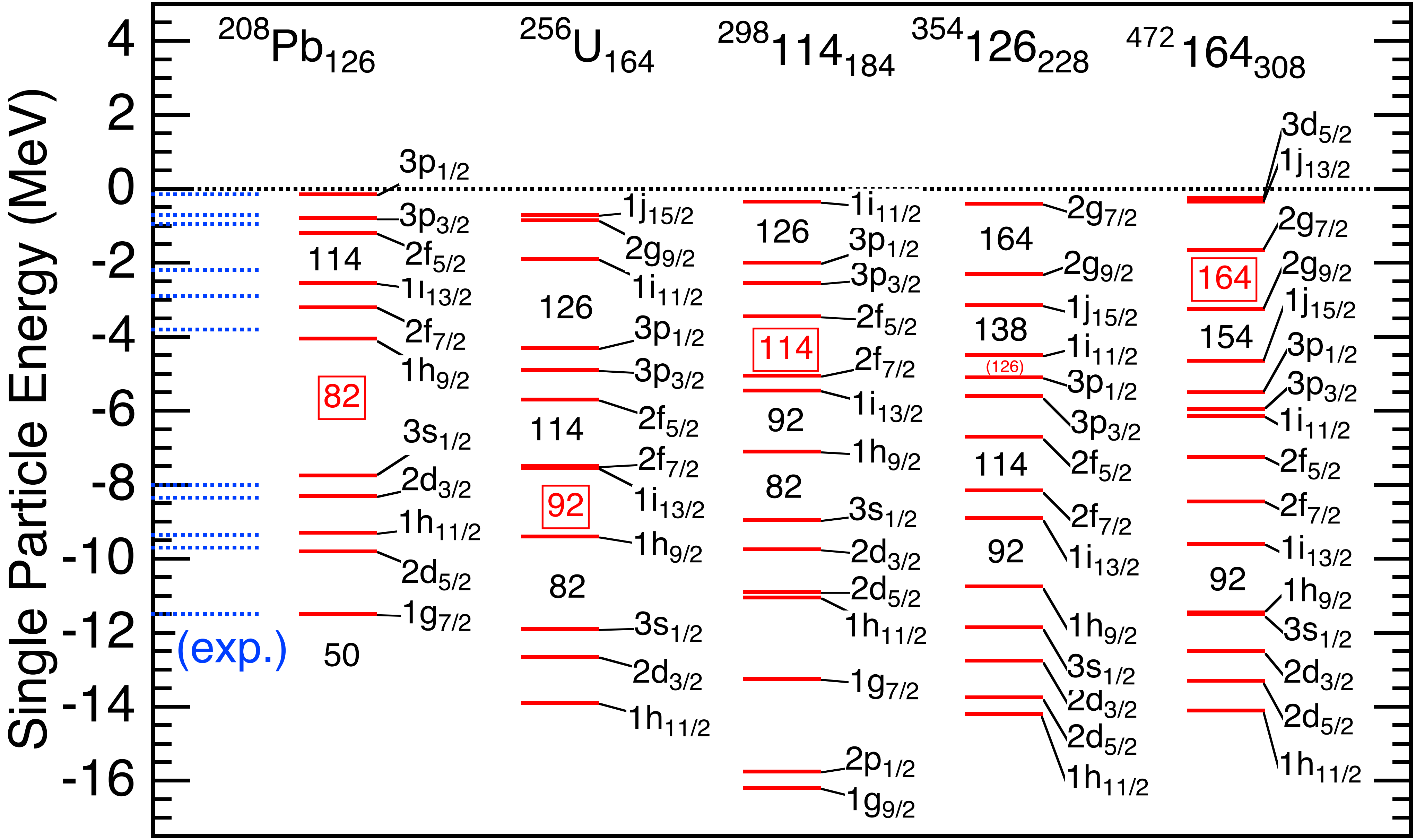


KTUY formula
Spherical

Calculated with KY potential (Koura et al., NPA671 (2000) 96)

Neutron:N=164, 184, 228, 308 gap appear clearly.

Spherical proton magic:beyond 114 (or 126)



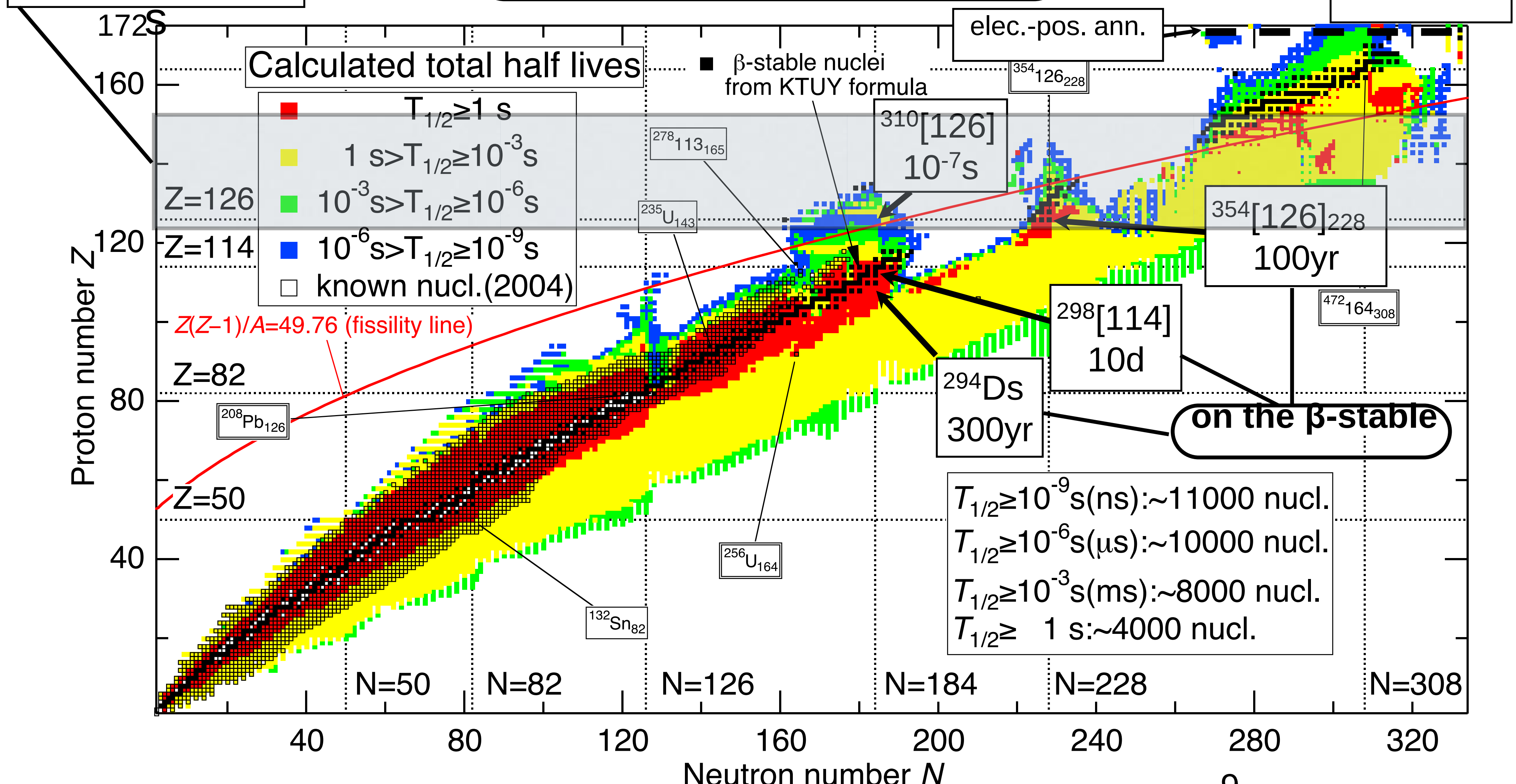
KTUY formula
Spherical

Proton

Calculated with KY potential
(Koura et al., NPA671 (2000) 96)

Proton:Z=114, 164 gap exist, but are no so remarkable.

Total half-lives



Upper limit of Atomic number with half-lives longer than 10^{-9} s:

$N \approx 184$ region => $Z \approx 136$,

$N \approx 228$ region => $Z \approx 142$,

$N \approx 308$ region => $Z \geq 175$

Uncertainty of half-lives : They may be in 3 order of magnitude. ex. ^{294}Ds:0.3 y~0.3 My

Conclusion

- We calculate **<u>nuclear decay modes</u>** and **<u>total half-lives</u>** in the (ultra) superheavy nuclear mass region by using **<u>the KTUY mass model</u>**.
- *<u>Nuclear decay mode of superheavy nuclei:</u>*
- **Other regions of "island of stability of superheavy nuclei"**

-"Peninsula" near the proton-drip region along N=126

-Next "island (cape) of stability" along N=228 (small) and also N=308 (large) <- due to the shell closure of the nuclear mean-field potential.

- *<u>Limit of Existence of nuclei:</u>*
- **A finiteness of region of (relatively) long-lived nuclei**

-Predicted number of nuclei:

-11,000 for nuclei with > 1 ns

-10,000 for nuclei with > 1 μs

- 8,000 for nuclei with > 1 ms

- 4,000 for nuclei with > 1 s

- Calculation region reaches the limit of macroscopic fissility line.

Спасибо!

Thank you for your attention!