Theoretical study of delayed neutron emission (and decay heat)

Hiroyuki Koura
Advance Science Research Center
Japan Atomic Energy Agency

Collaborate with:
S. Chiba (Tokyo Inst. Tech.,TIT), T. Yoshida (TIT) and T. Tachibana (Waseda Univ.)

東京工業大学 Tokyo Institute of Technology

WASEDA University Faculty of Science and Engineering

The 2nd BRIKEN Workshop, July 30-31, 2013 (Wako, Japan)

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- 3.5 year project of estimating and delayed neutron emission decay heat for U, Pu and minor actinides -

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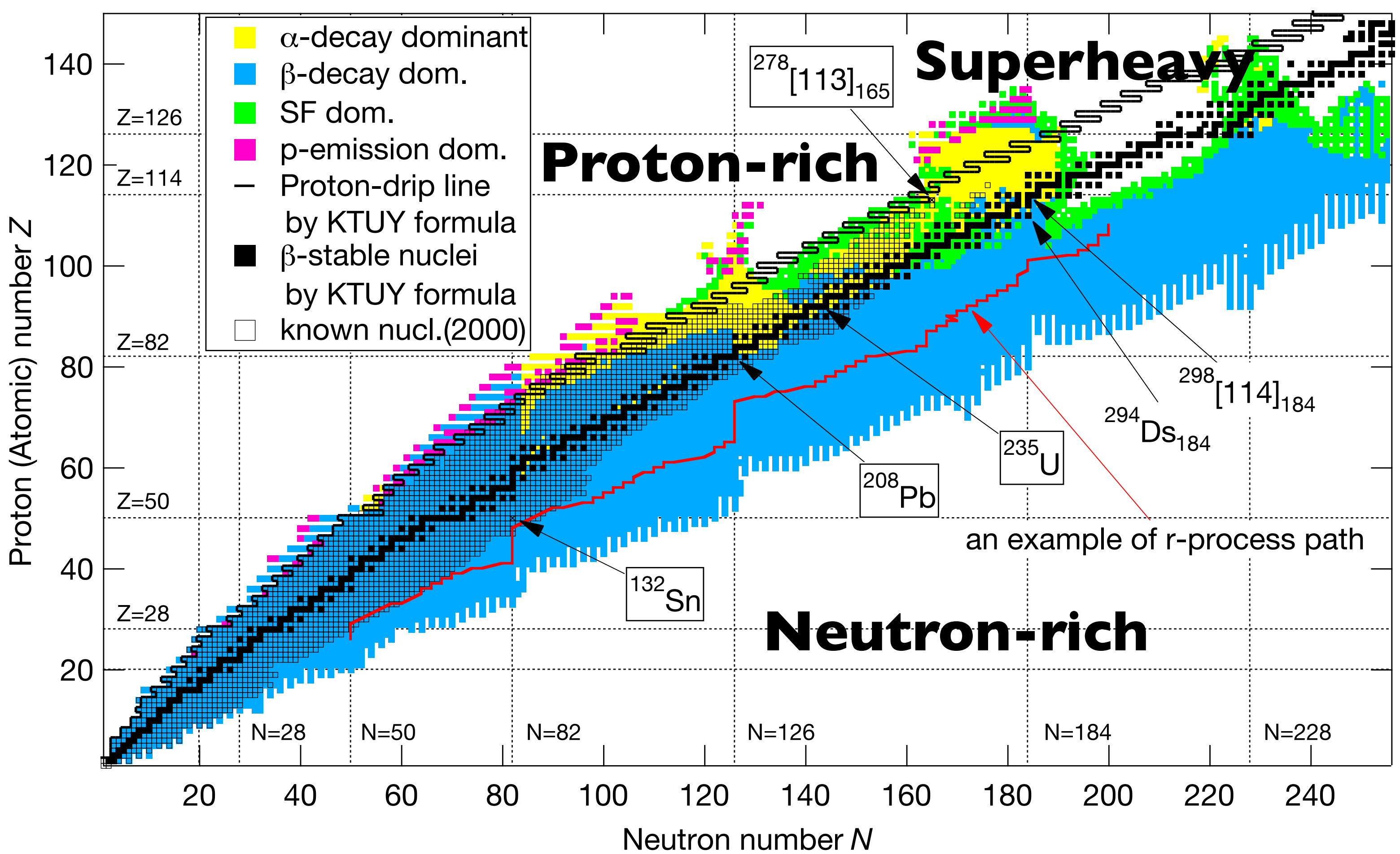
Understanding global properties of nuclei

Nuclear mass region

- (Extremely) Superheavy : Decay modes, Structure of superheavy double magic nuclei ^{298}[114] and its neighboring, and beyond
- Proton-rich : N=126 neutron-deficient nuclei (Unknown peninsula) : enhancement of existence due to the closed shell
- Neutron-rich : Change of closed shell, Fission in the superheavy, r-process nucleosynthesis



Prediction of decay modes (KTUY mass model)

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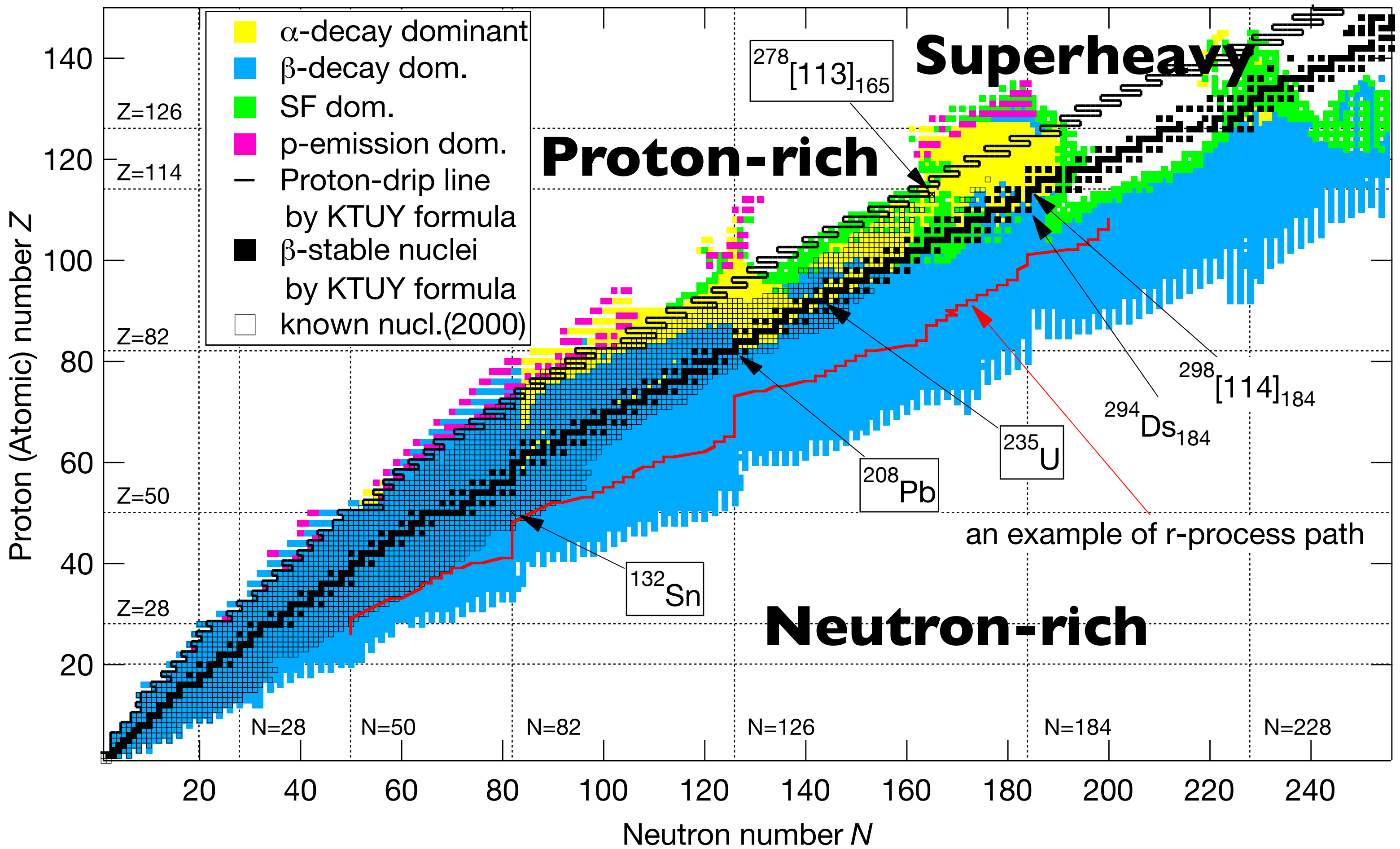

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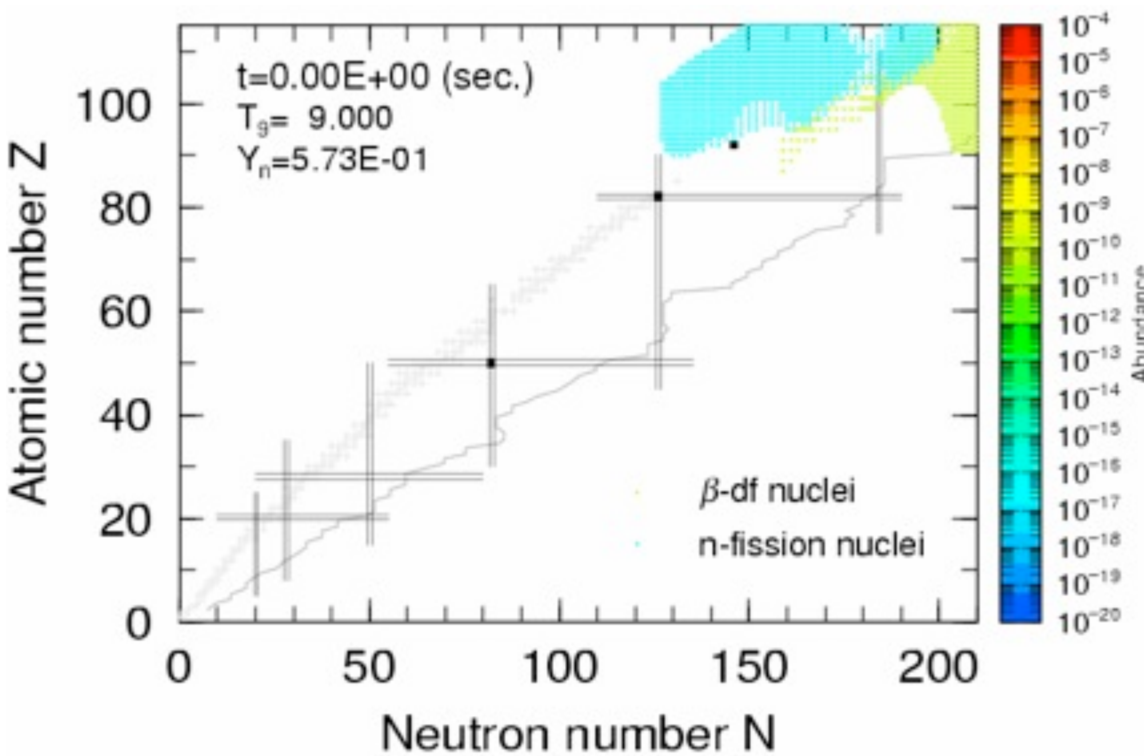

13年7月31日水曜日

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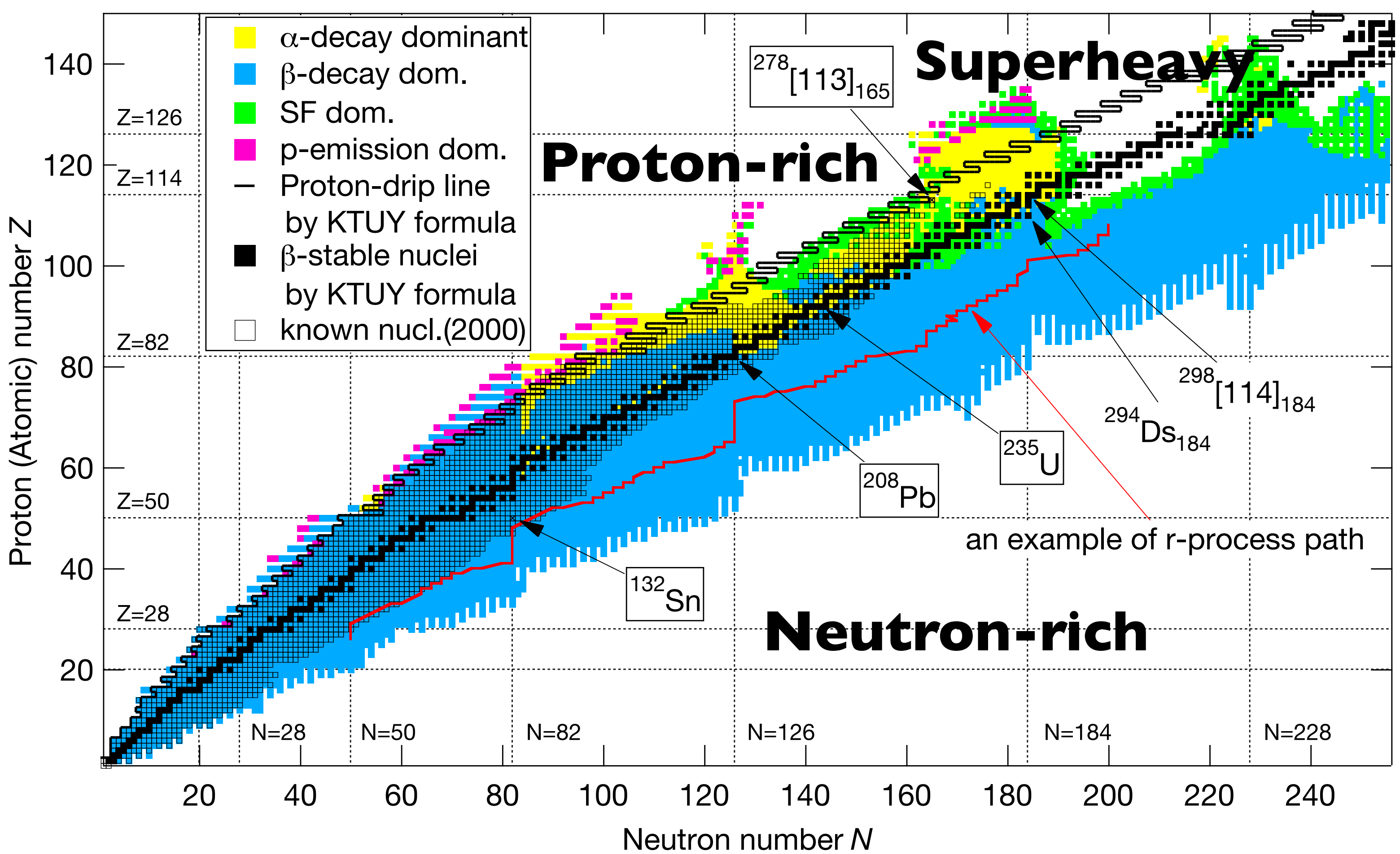

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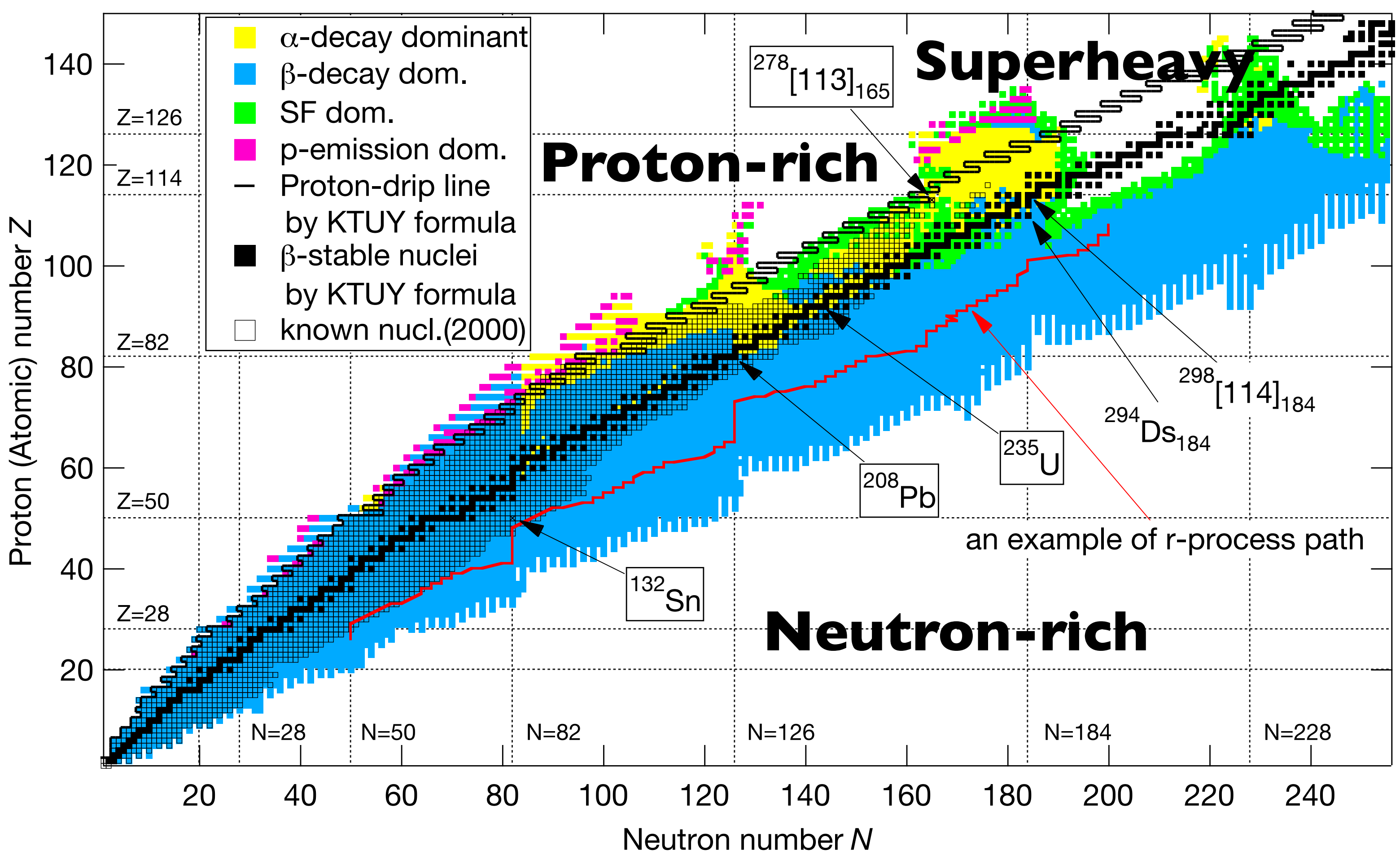

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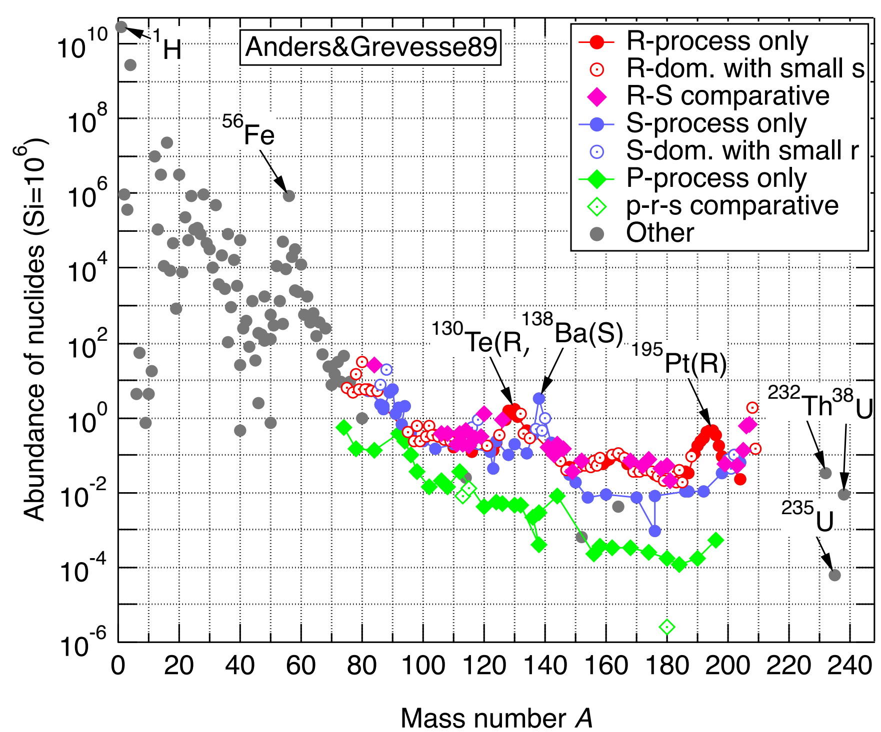

Solar abundances

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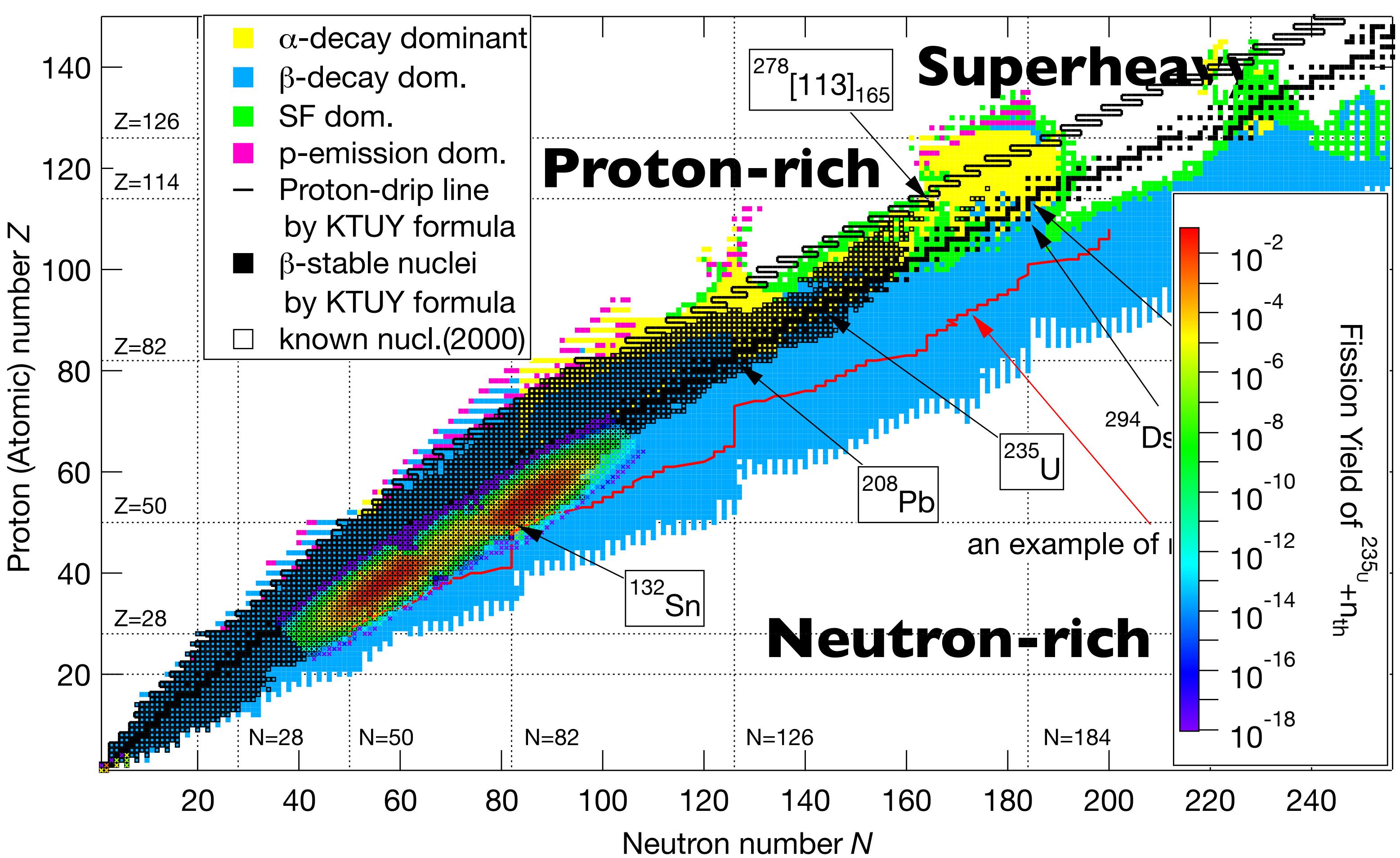

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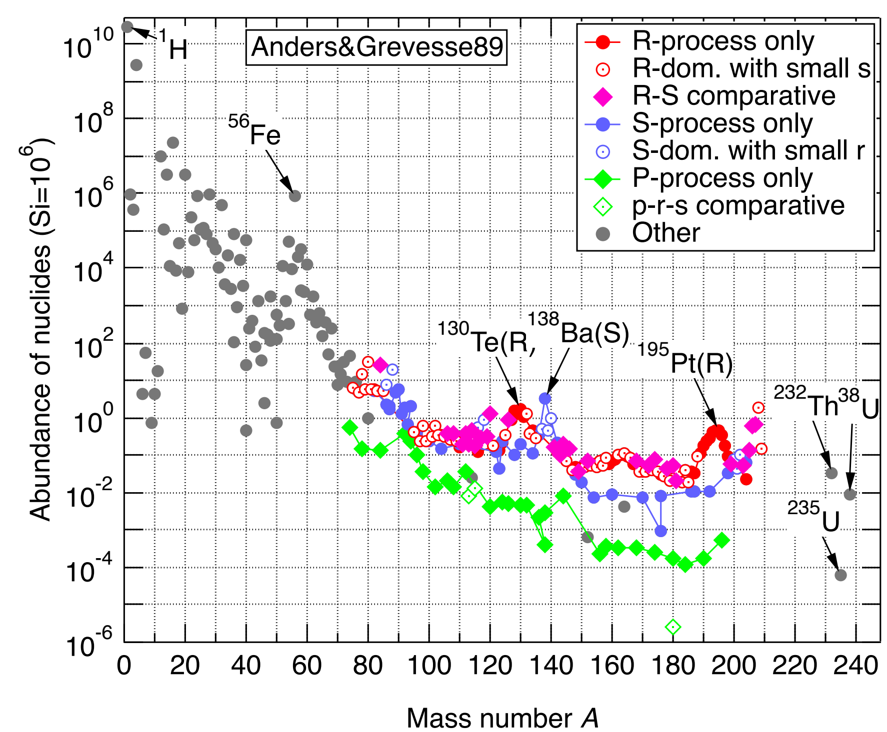

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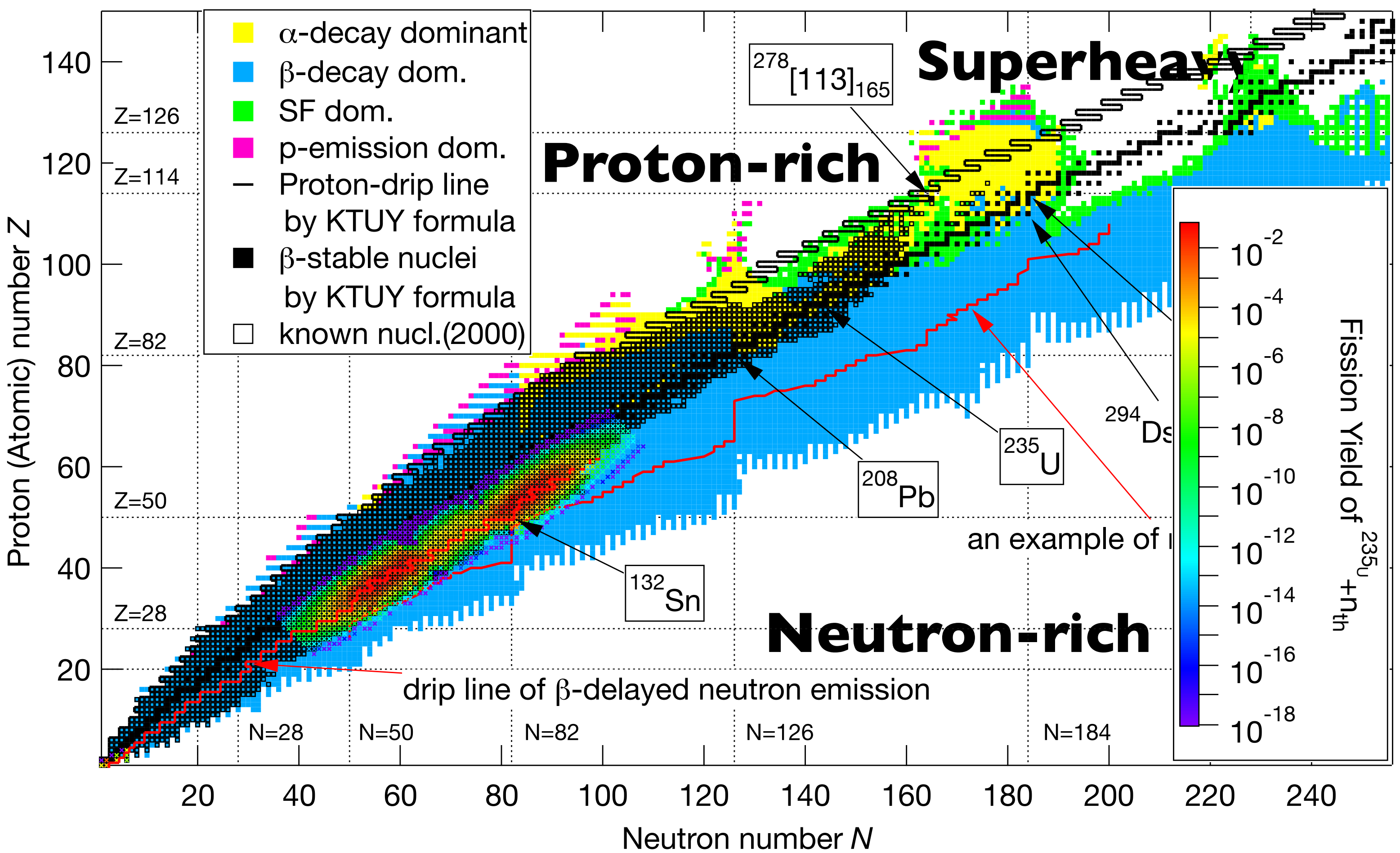

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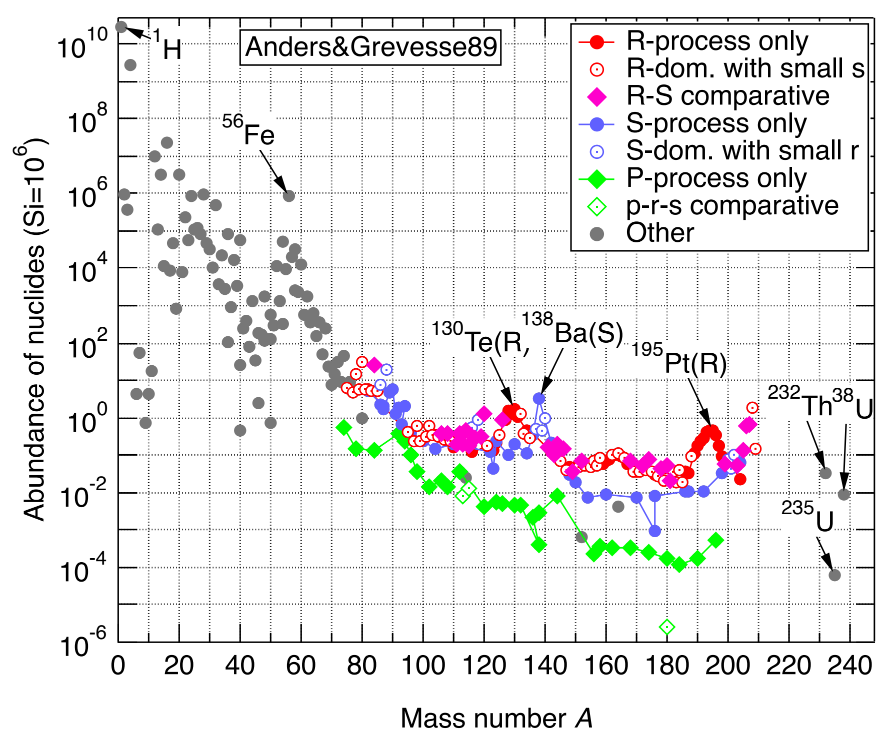

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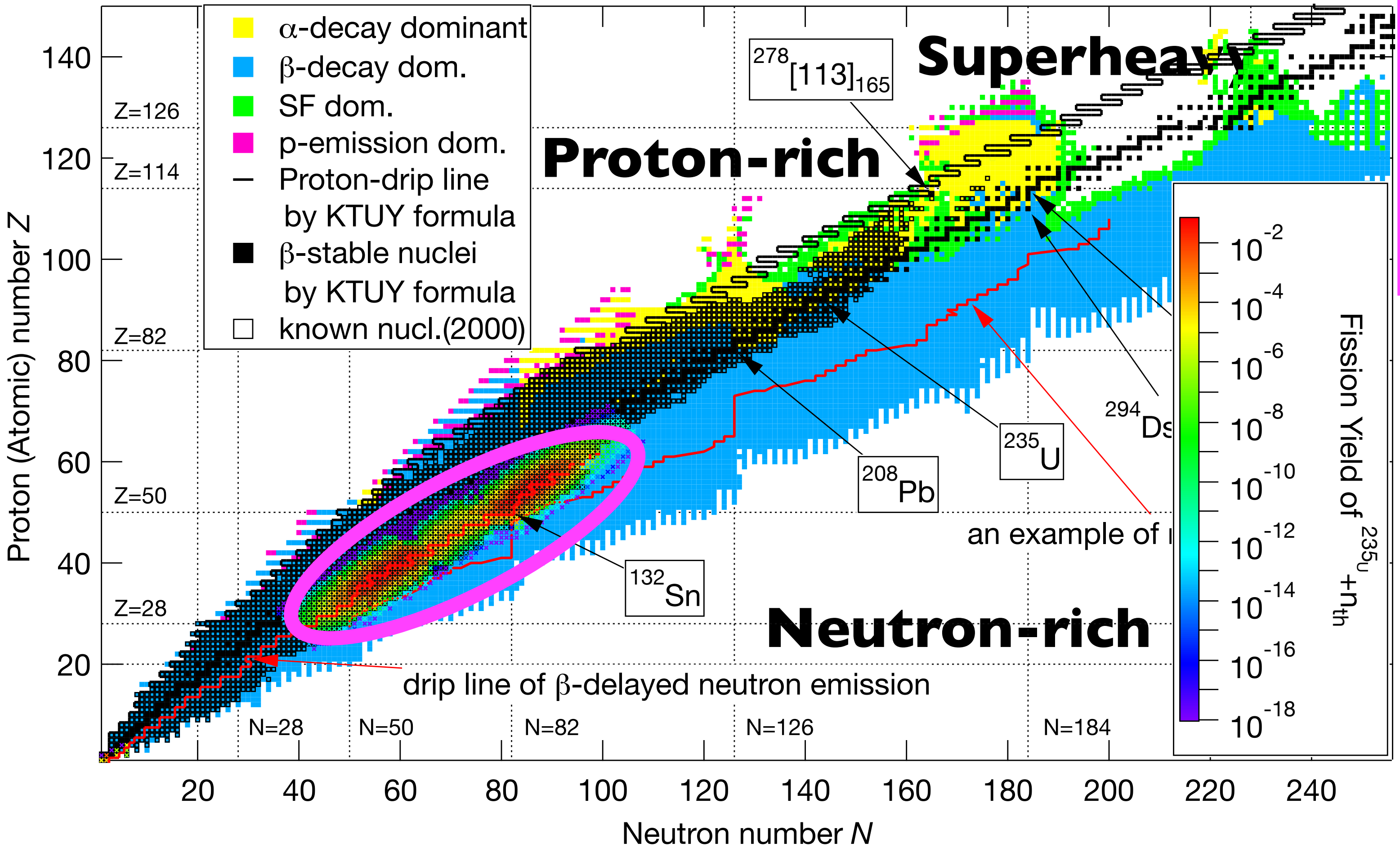

Prediction of decay modes (KTUY mass model)

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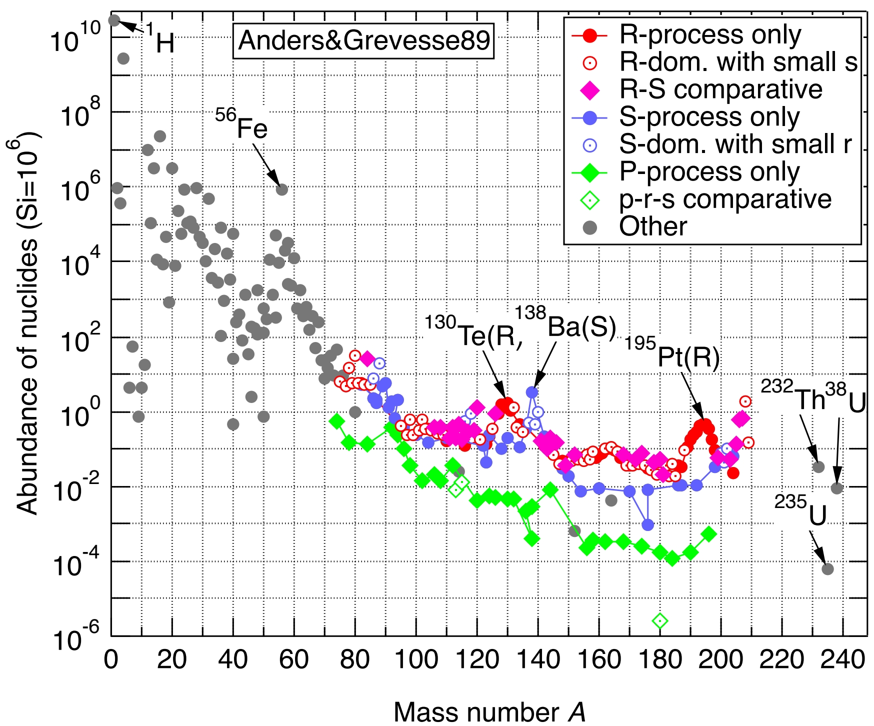
Medium-heavy n-rich region:

Astrophysics: r-process

Atomic Energy: Fission product from actinides



Solar abundances

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‘Development of High Precision of Delayed Neutron Rate for Evaluation of Operating Characteristic Properties of the Advanced Fast Reactors’

Entrusted project by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT)

Project Leader: S. Chiba (Tokyo Inst. Tech.),

Term: 2012.11-2016.3, Total budget: **200M yen (2M USD (1USD=100yen))**

Purpose: High-precision prediction of operating characteristic properties of highly-burn-up nuclear reactor and innovative nuclear reactor where **minor actinides accumulate**. We will do as the following way:

1. Measurement of **fission yield (FY) data** via surrogate reaction
2. Construction of method for obtaining delayed neutron rate and decay heat with gross theory of beta decay
3. Construction of theoretical method for obtaining **independent FY** with dynamical model (two-center shell model + Langevin eq.)
4. Nuclear data (including verification on reactor system)

Collaborate with:

Experiment(JAEA): **K. Nishio**, I. Nishinaka, H. Makii, T. Ishii, K. Tsukada, M. Asai, K. Furutaka

Beta-decay theory(JAEA): **H. Koura**, Y. Utsuno

Fission theory(TIT): **S. Chiba (TIT)** , Y. Aritomo (TIT)

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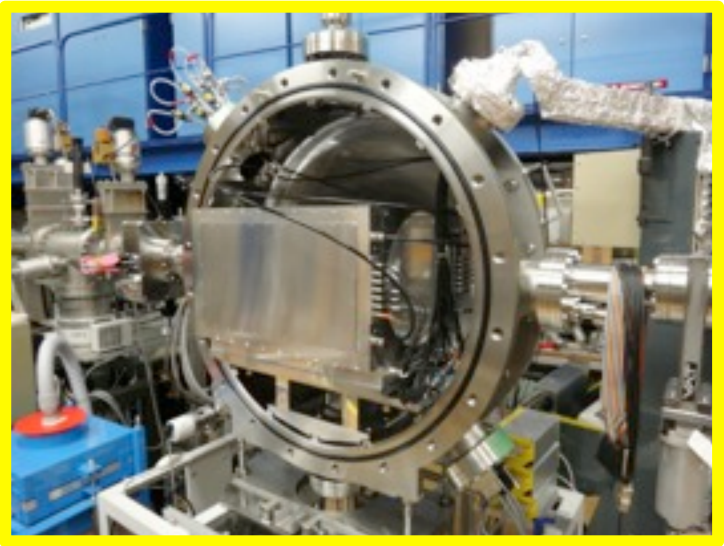

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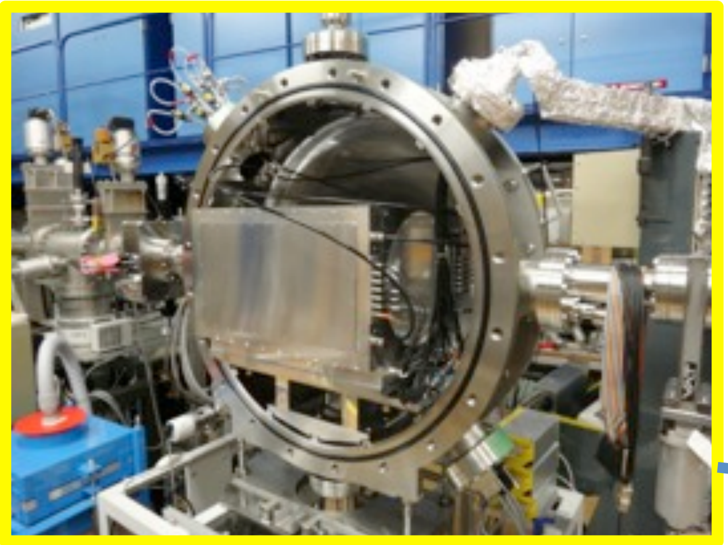
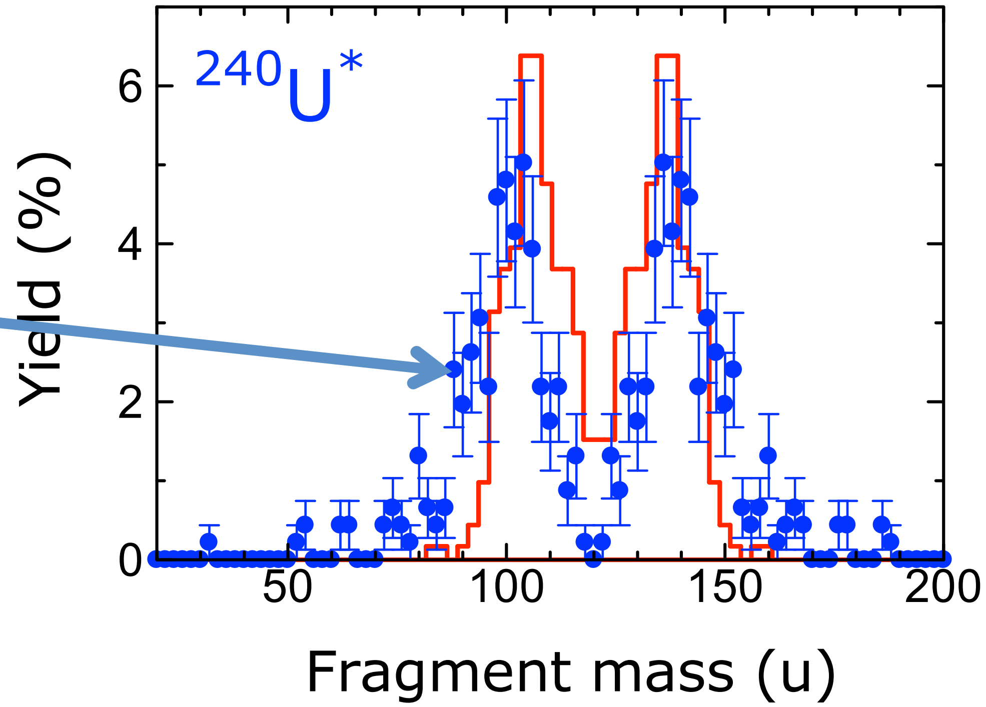


Fission fragment mass distr.



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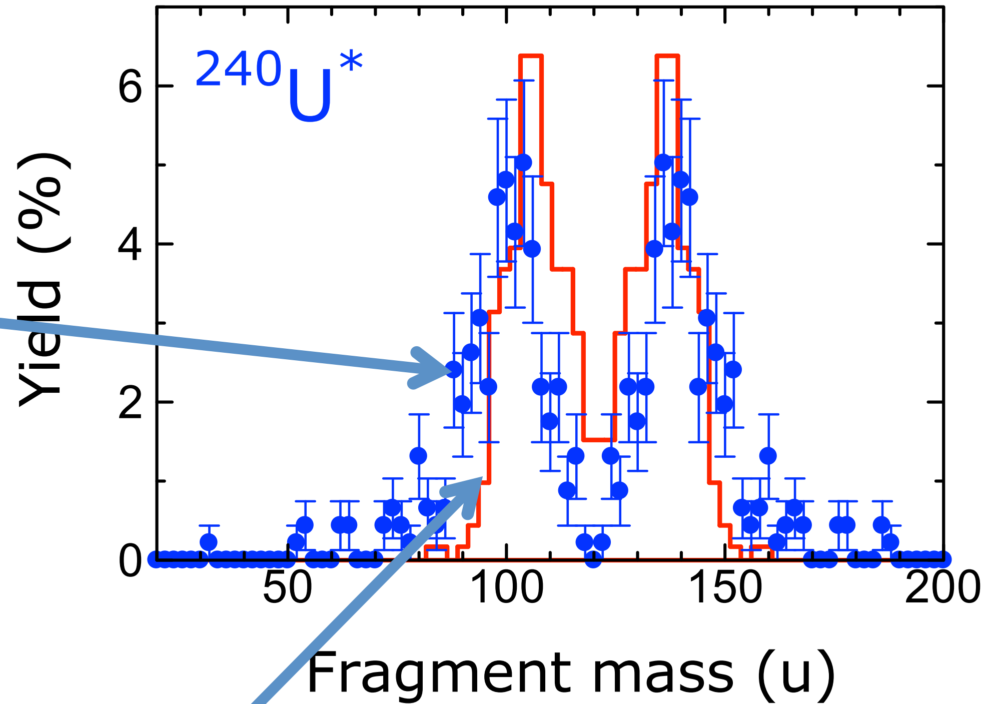
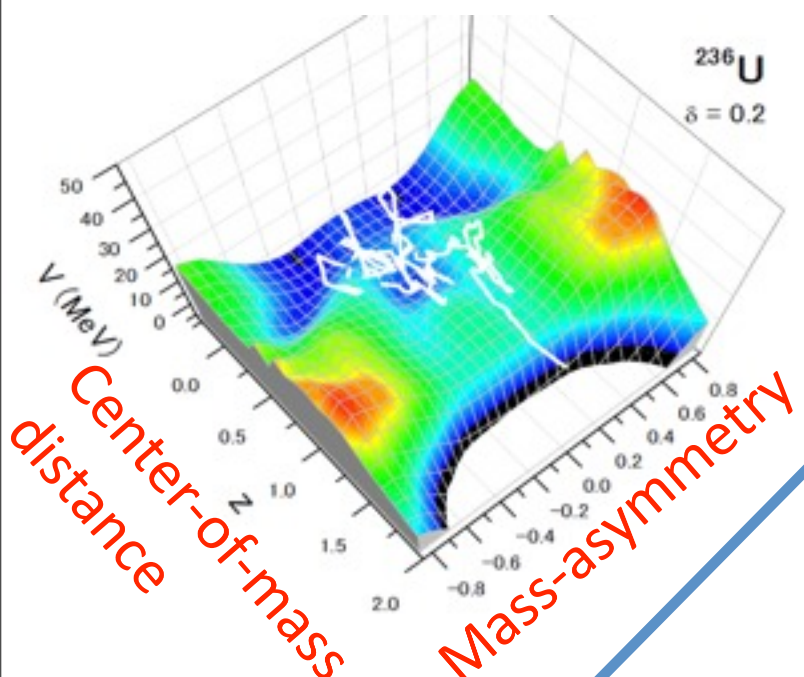


3. Multi-dimensional dynamics of
Fission (Langevin) model



- FP mass-number distr.
- FP independent Yield
- prompt neutron yield

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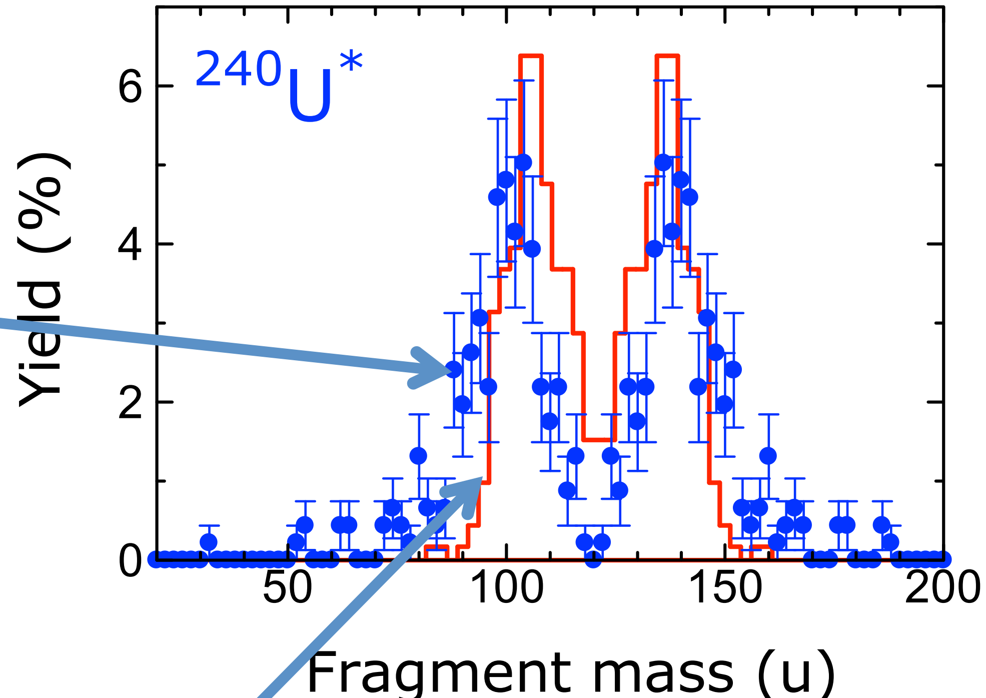

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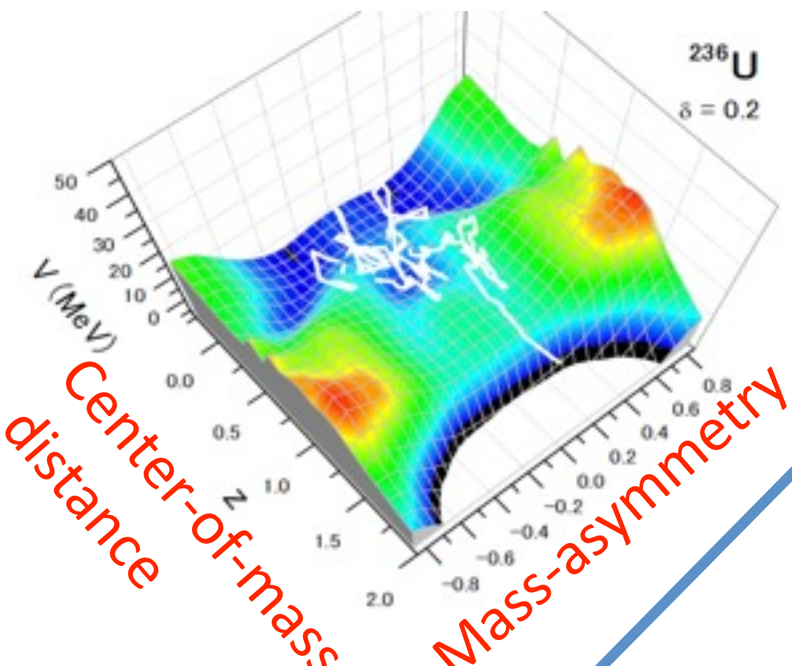

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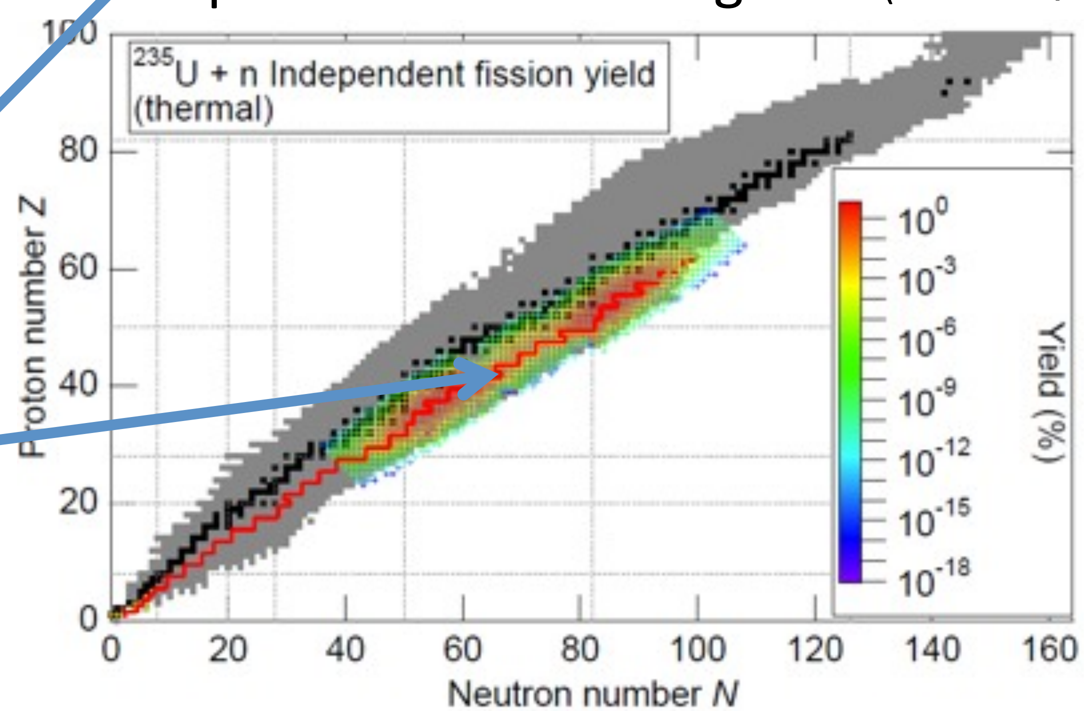
Independent Fission Fragment(N-Z distr.)



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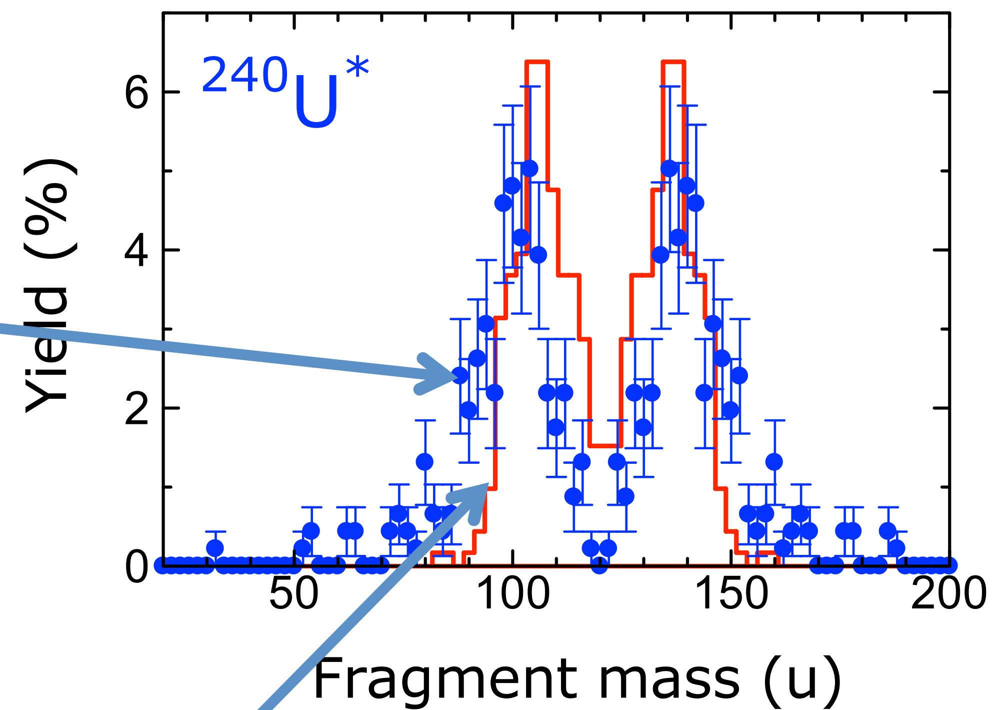
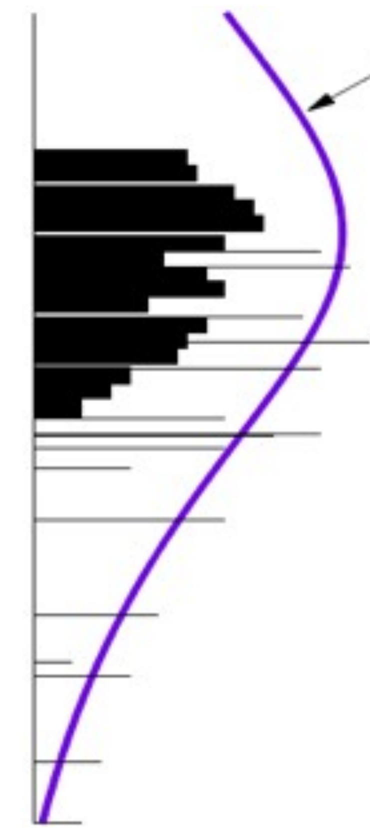


2. Gross theory of β decay



- β-ray spectra
- γ −ray spectra
- delayed neutron Yield, χ_d
- anti-neutrino spectra

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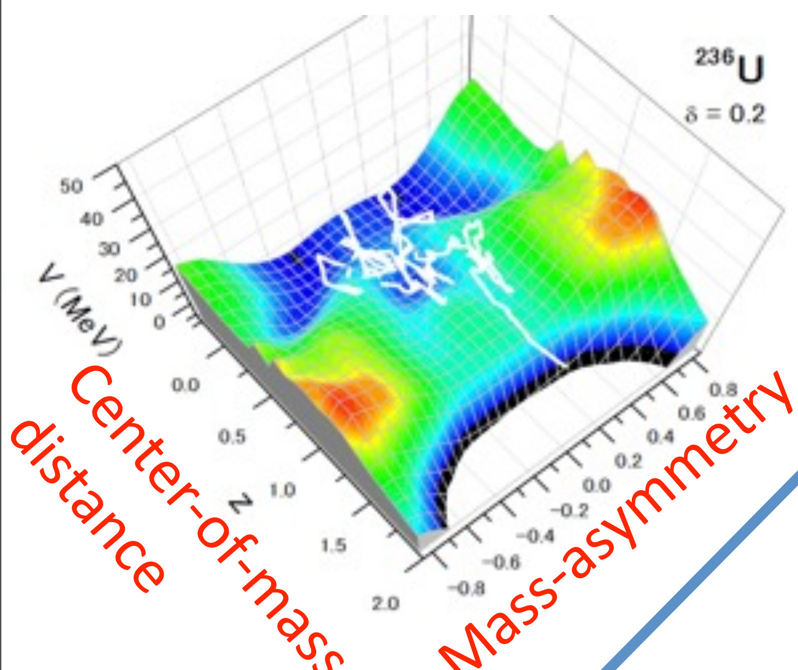

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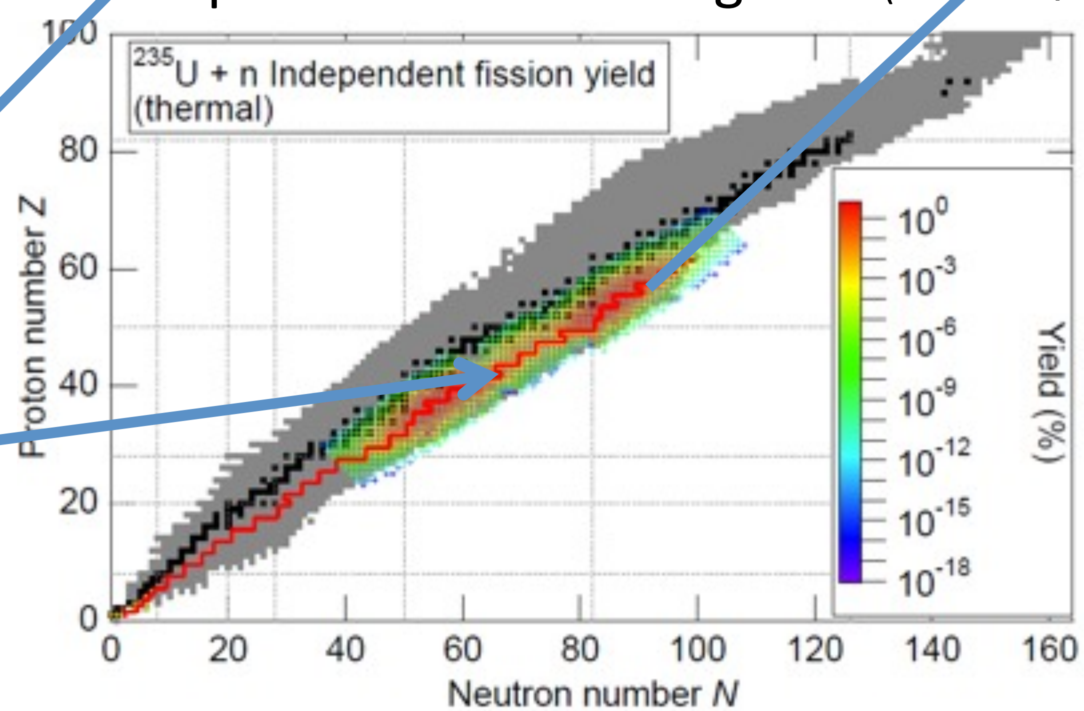

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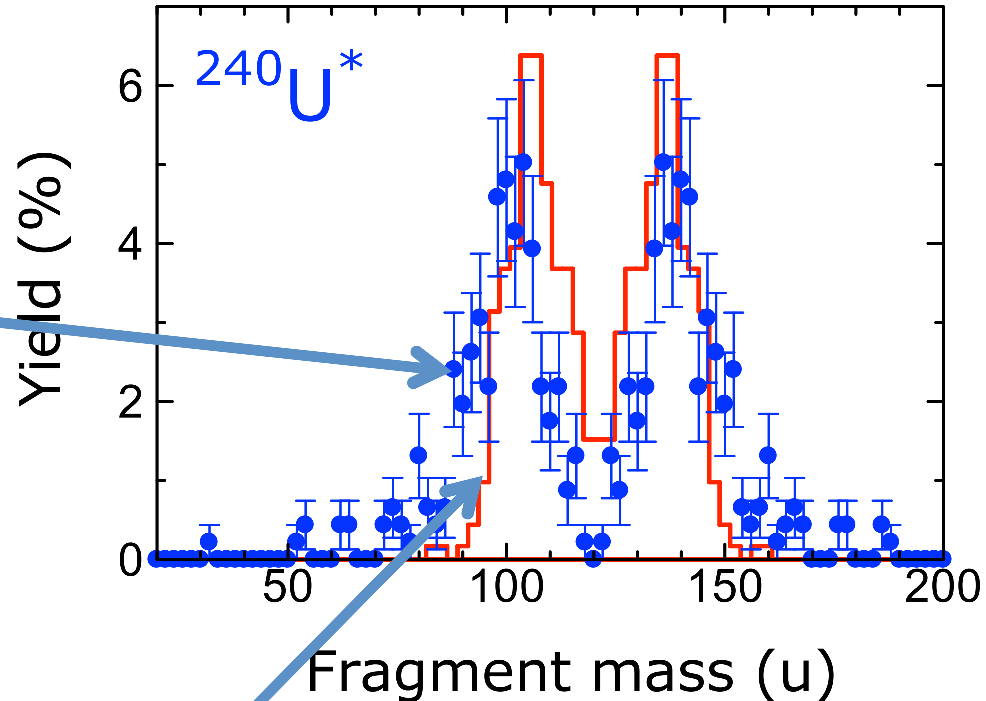

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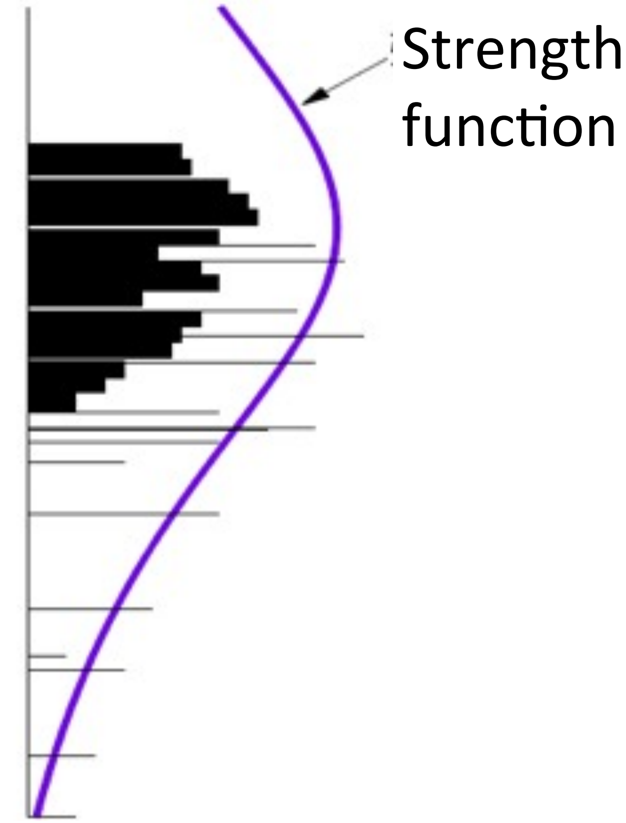

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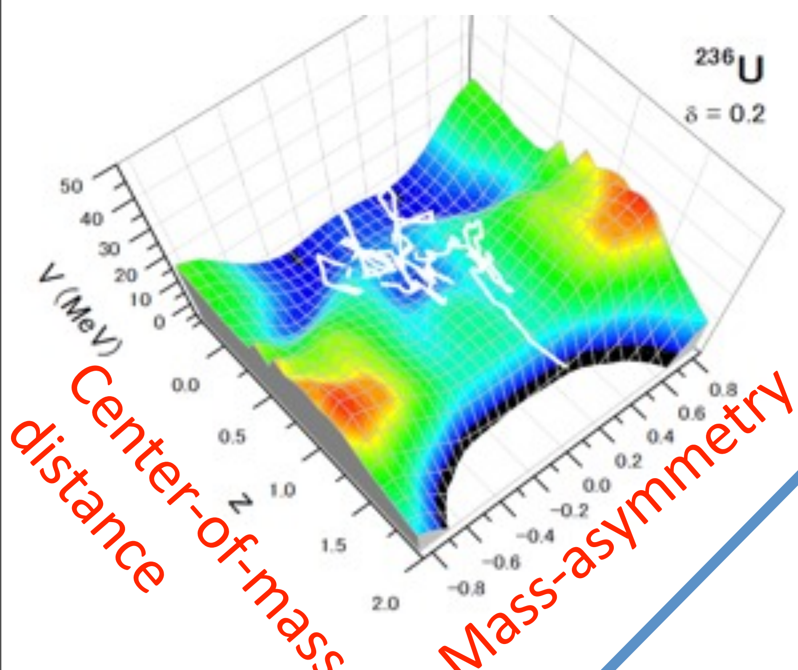

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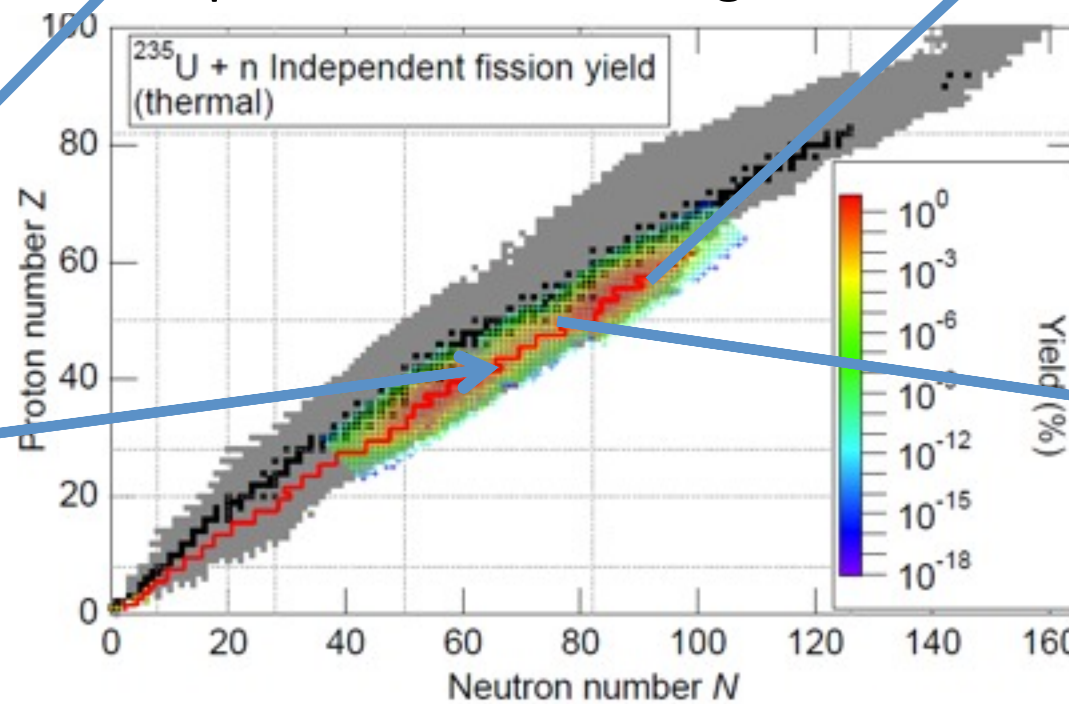

4. Library, Summation Calculation

- Analysis of decay heat data
- β_{eff} Analysis of Reactor Physics data
- Neutrino production

courtesy of S. Chiba

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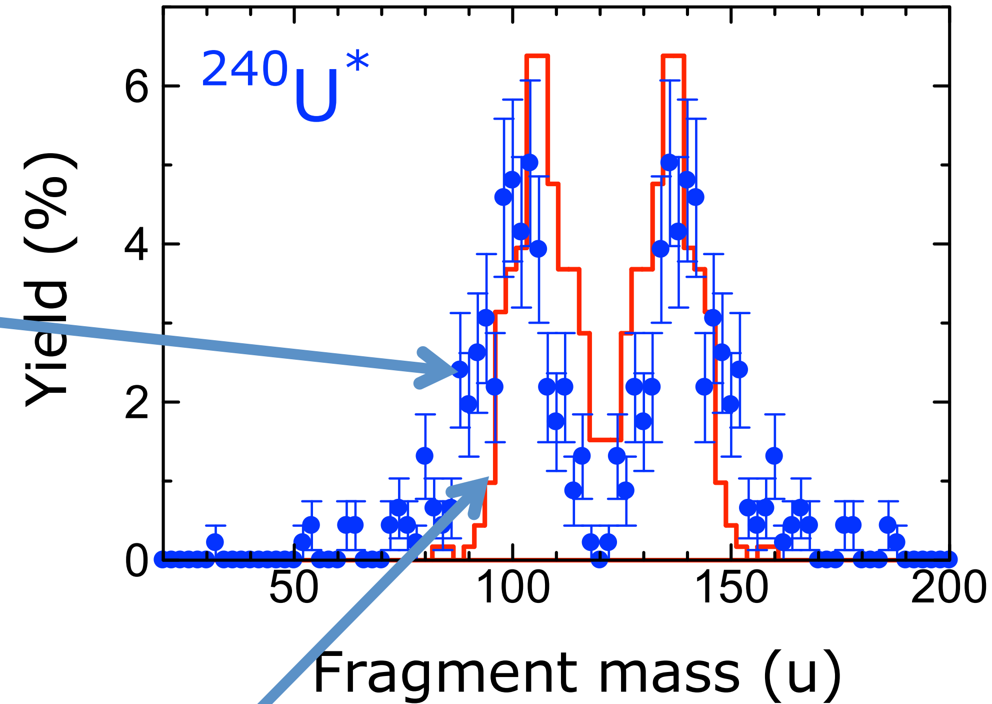

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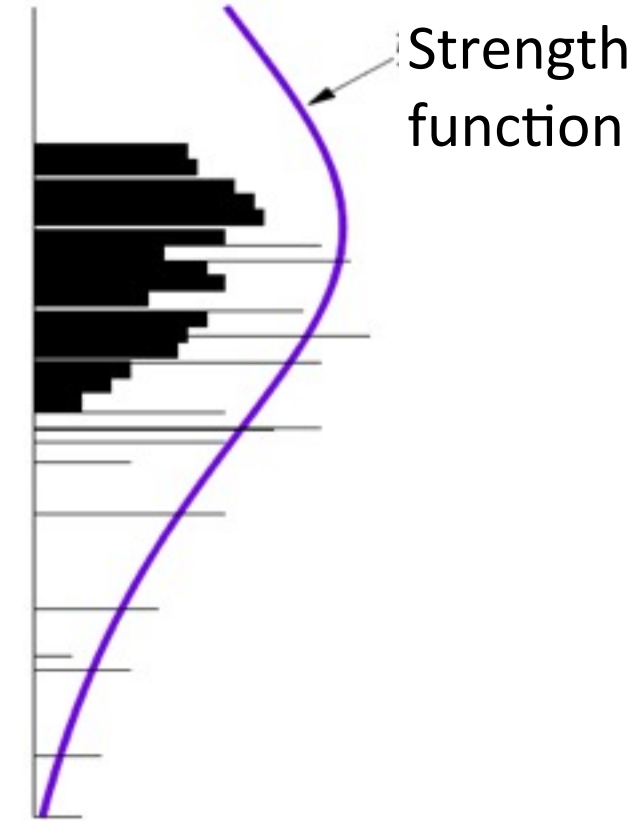

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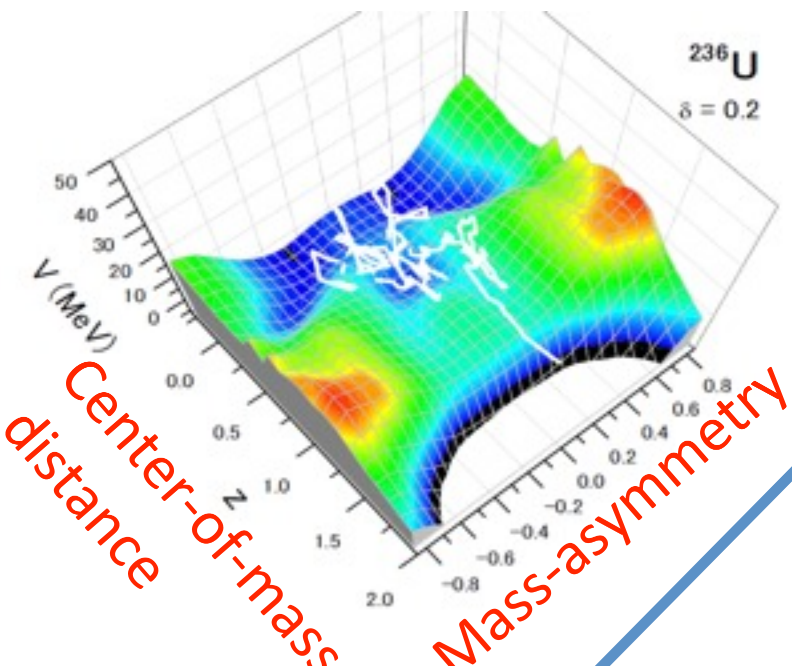

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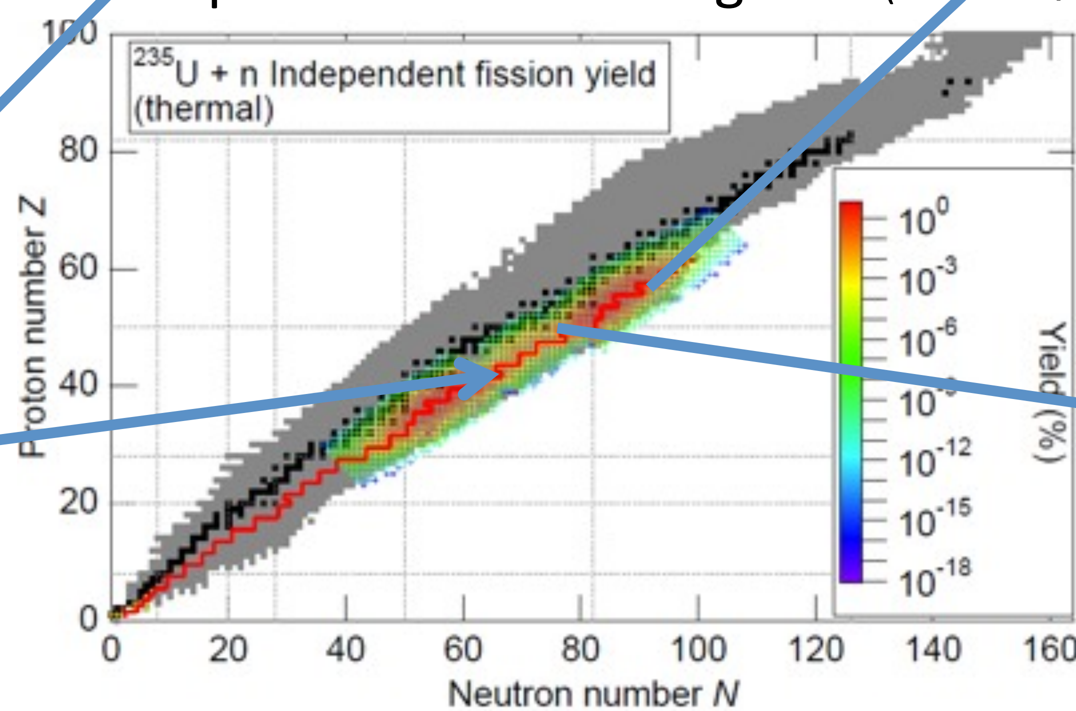

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Nuclear β-decay

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

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

(up to 1st forbidden)

Trans.	Type	ΔL	Parity ch.
Allowed	Fermi	0	+
	Gamow-Teller	0,±1 (0 -x-> 0)	+
1st forbid.	non-unique 1st	0,±1	-
	unique 1st	±2	-
2nd forbid.	non-unique 2nd	±2	+
	unique 2nd	±3	+
3rd forbid.	non-unique 3rd	±3	-
	unique 3rd	±4	-

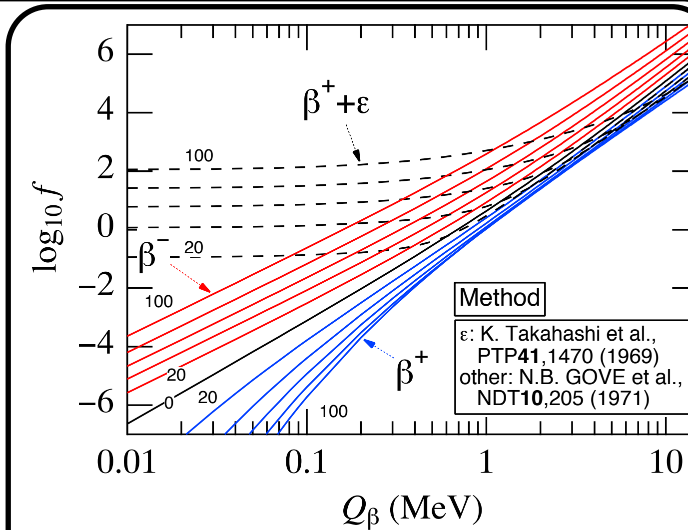
$$\lambda_{\mathrm{F}} = \frac{m_{\mathrm{e}}{}^5 c^4}{2\pi^3 \hbar^7} |g_{\mathrm{V}}|^2 \int_{-Q}^{0} |M_{\mathrm{F}}(E)|^2 f(-E) dE$$

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

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

$$\lambda_1^{(1)} = \frac{m_{\mathrm{e}}{}^5 c^4}{2\pi^3 \hbar^7} \left(\frac{m_{\mathrm{e}} c}{\hbar}\right)^2 \left[|g_{\mathrm{V}}|^2 \int_{-Q}^{0} |M_{\boldsymbol{r}}(E)|^2 f_{1\mathrm{V}}^{(1)}(-E) dE + |g_{\mathrm{A}}|^2 \int_{-Q}^{0} |M_{\boldsymbol{\sigma}\times\boldsymbol{r}}(E)|^2 f_{1\mathrm{A}}^{(1)}(-E) dE \right]$$

$$\lambda_1^{(0)} = \frac{m_{\mathrm{e}}{}^5 c^4}{2\pi^3 \hbar^7} \left(\frac{m_{\mathrm{e}} c}{\hbar}\right)^2 |g_{\mathrm{A}}|^2 \int_{-Q}^{0} |M_{\boldsymbol{\sigma}\cdot\boldsymbol{r}}(E)|^2 f_{1\mathrm{A}}^{(0)}(-E) dE$$



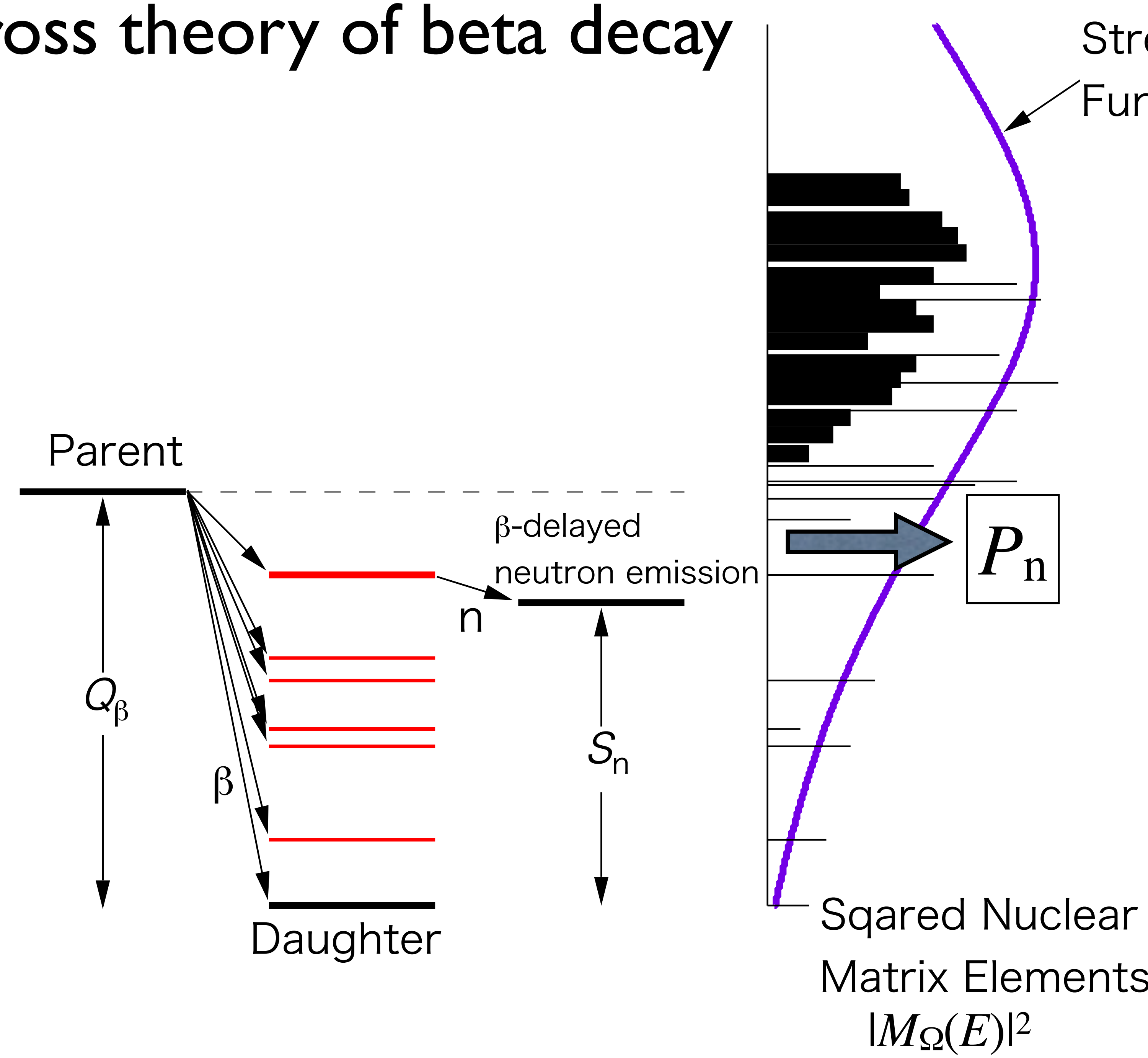
Integrated Fermi f (allowed)

Gross theory of beta decay

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

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

half-live, energy distribution,
delayed neutron probability

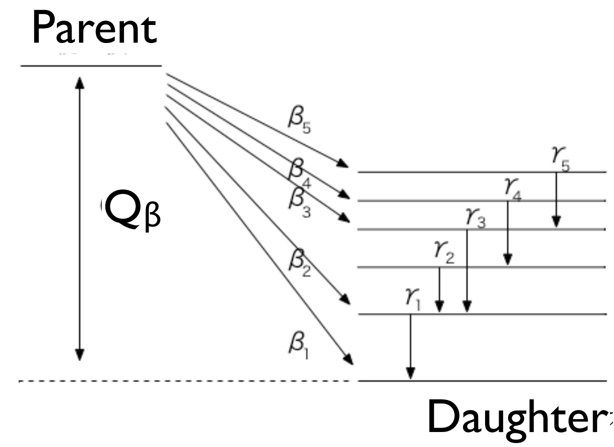


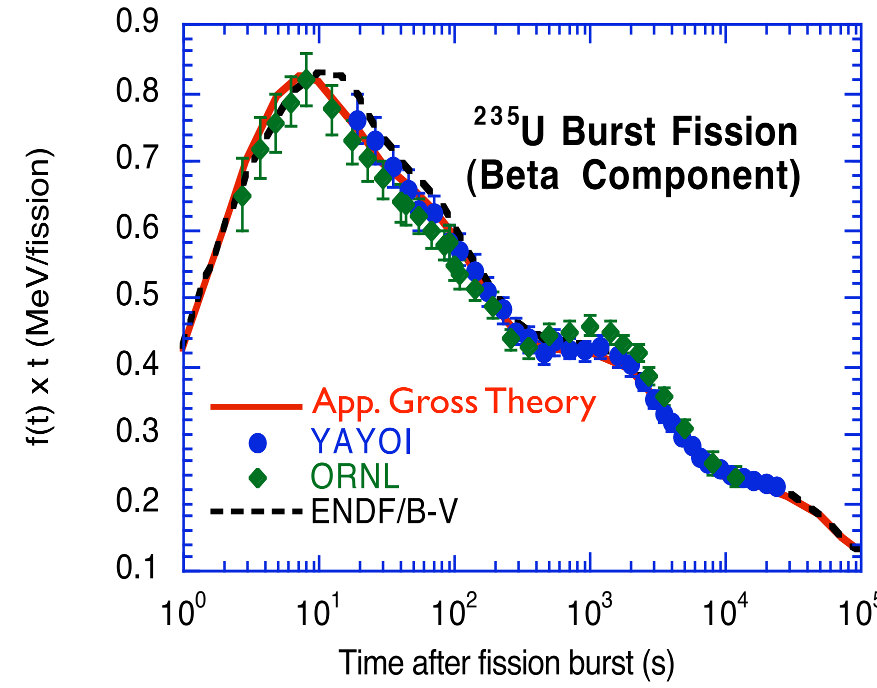
- Sum rules of the strength function are considered
- Fermi, Gamow-Teller and 1st forbidden transition are included

Decay heat and delayed neutron emission

Decay heat :

Fission products (FP) release energy through β-decay and γ decay. These sum of each energy release gives decay heat.





$$f(t) = \sum_i \lambda_i \cdot \overline{E_t^i} \cdot N_i(t) = \sum_i \lambda_i \cdot (\overline{E_\beta^i} + \overline{E_\gamma^i}) \cdot N_i(t)$$

$$\overline{E_\gamma} = \sum_j E_\gamma^j I_\gamma^j / \text{number}$$

$$\overline{E_\beta} = \sum_j E_\beta^j I_\beta^j / \text{number}$$

$N_i(t)$:Production Yield at time t

Delayed neutron rate:

Theory: $$\lambda_n = \sum_\Omega \int_{-Q+S_n}^{0} \frac{\Gamma_n}{\Gamma_n + \Gamma_\gamma} \lambda_\Omega(E)\, dE\,,$$

Ω:Type of β decay (Fermi, Gamow-Teller, forbidden,...)

Exp.: $$\lambda_n^{\mathrm{exp}} = \ln 2\, P_n^{\mathrm{exp}} / t_{1/2}^{\mathrm{exp}}\,,$$

P_n:Delayed neutron probability

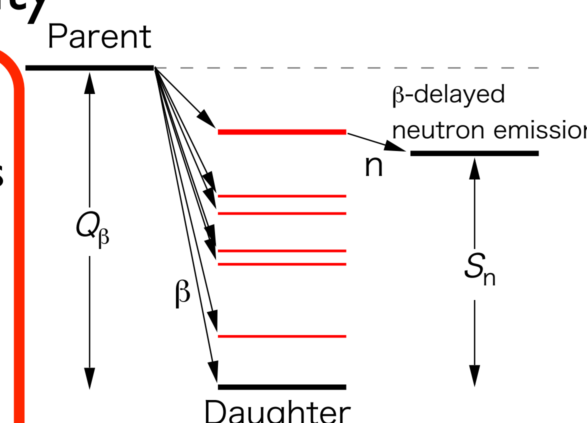
Delayed neutron yield: $$\overline{\nu_\mathrm{d}} = \sum_i P_{\mathrm{n}i} Y_i$$

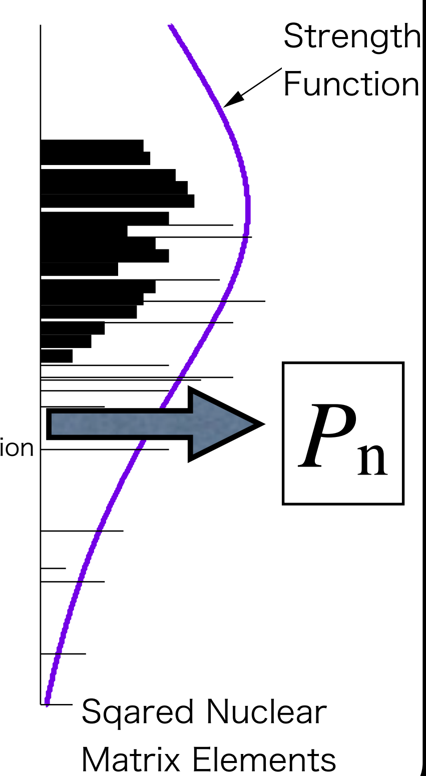
Y:Cumulative Fission Yield

i:all delayed neutron precursors

Time-dependency of delayed neutron emission : $$n_\mathrm{d}(t) = \sum_i P_{\mathrm{n}i} \lambda_i Y_i(t)$$

(6-Group Approx.: $$n_{\mathrm{d}6}(t) = \overline{\nu_\mathrm{d}} \sum_{i=1}^{6} \alpha_i \lambda_i \exp(-\lambda_i t)$$





Both phenomena accompany β decay.

Decay heat and delayed neutron emission

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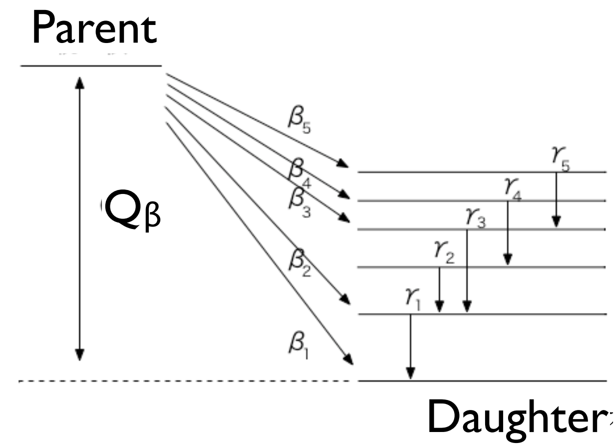
Fission products (FP) release energy through β-decay and γ decay. These sum of each energy release gives decay heat.

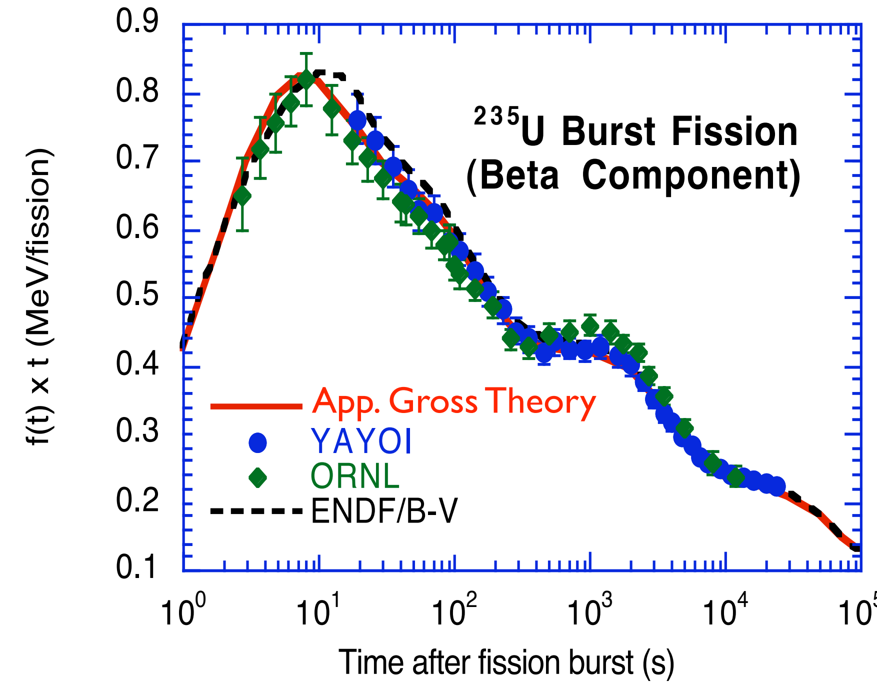


$$f(t) = \sum_i \lambda_i \cdot \overline{E_t^i} \cdot N_i(t) = \sum_i \lambda_i \cdot (\overline{E_\beta^i} + \overline{E_\gamma^i}) \cdot N_i(t)$$

$$\overline{E_\gamma} = \sum_j E_\gamma^j I_\gamma^j/\mathrm{number}$$

$$\overline{E_\beta} = \sum_j E_\beta^j I_\beta^j/\mathrm{number}$$

$N_i(t)$:Production Yield at time t



Delayed neutron rate:

From fission theory and exp.

Theory: $$\lambda_n = \sum_\Omega \int_{-Q+S_n}^{0} \frac{\Gamma_n}{\Gamma_n + \Gamma_\gamma} \lambda_\Omega(E)\, dE\,,$$

Ω:Type of β decay (Fermi, Gamow-Teller, forbidden,...)

Exp.: $$\lambda_n^{\exp} = \ln 2\, P_n^{\exp}/t_{1/2}^{\exp}\,,$$

P_n:Delayed neutron probability

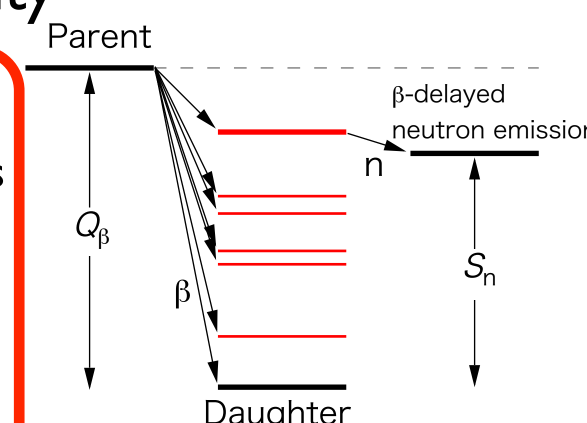
Delayed neutron yield: $$\overline{\nu_\mathrm{d}} = \sum_i P_{\mathrm{n}i} Y_i$$

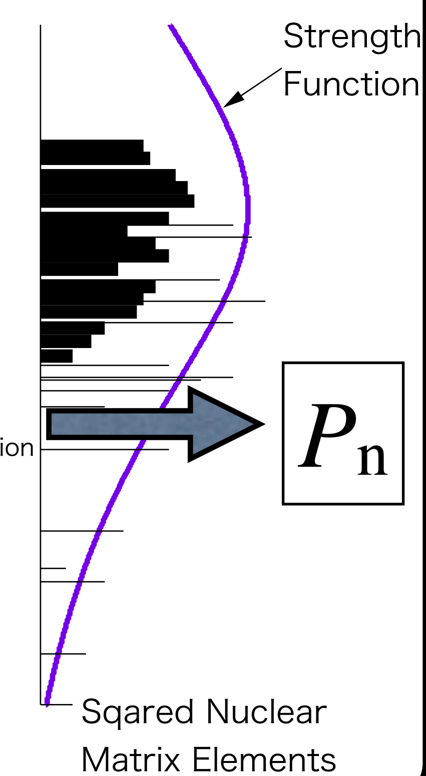
Y:Cumulative Fission Yield

i:all delayed neutron precursors

Time-dependency of delayed neutron emission : $$n_\mathrm{d}(t) = \sum_i P_{\mathrm{n}i} \lambda_i Y_i(t)$$

(6-Group Approx.: $$n_{\mathrm{d}6}(t) = \overline{\nu_\mathrm{d}} \sum_{i=1}^{6} \alpha_i \lambda_i \exp(-\lambda_i t)$$

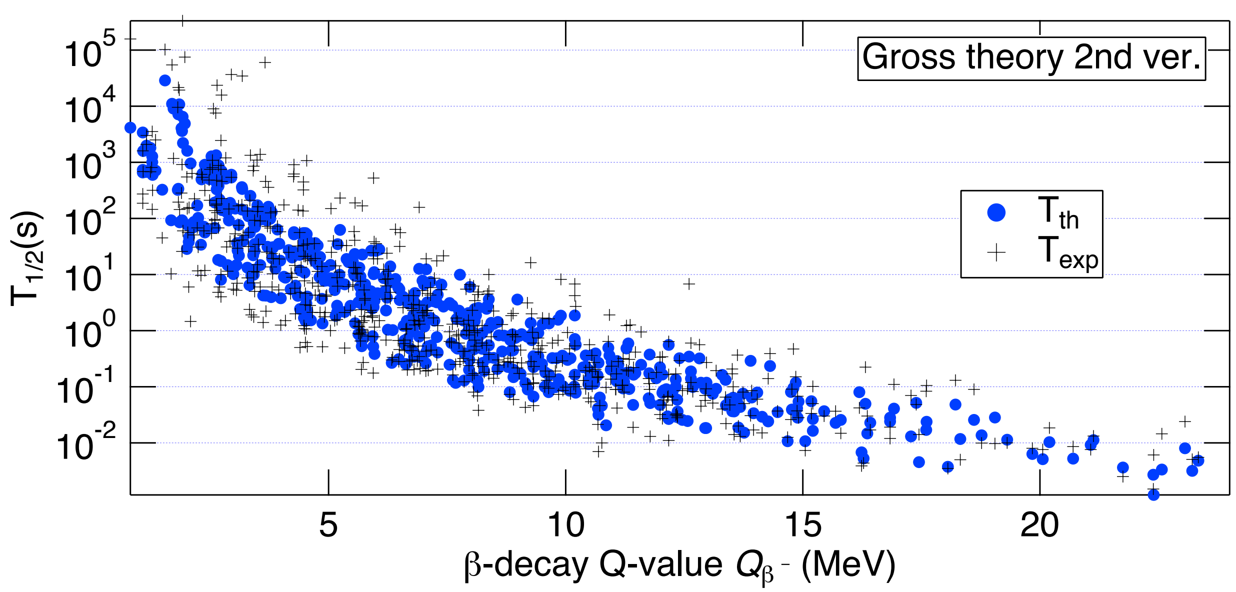


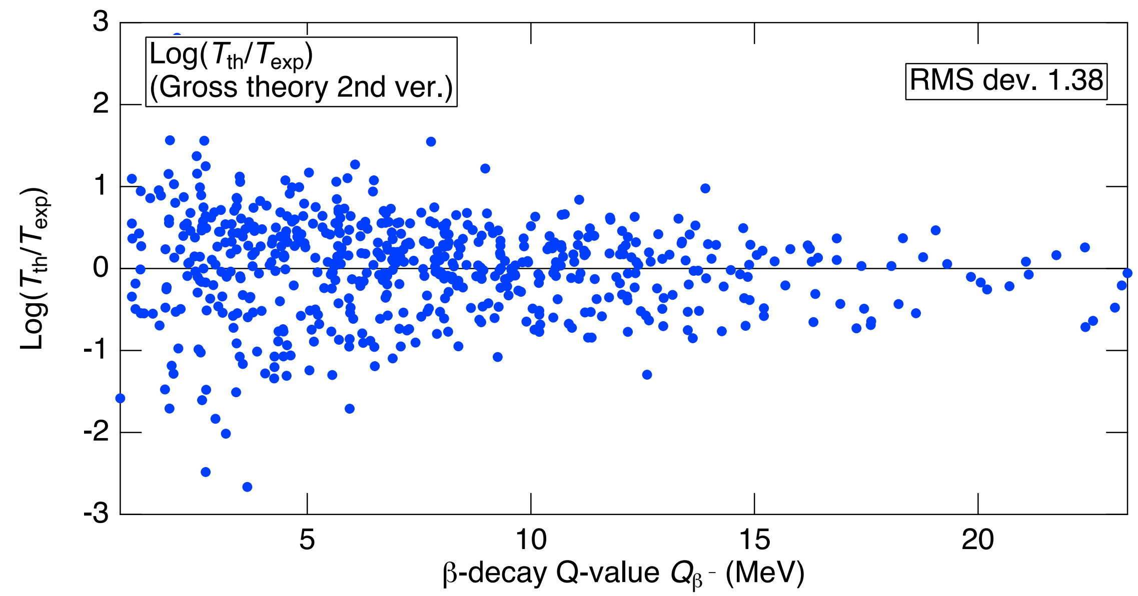


Both phenomena accompany β decay.

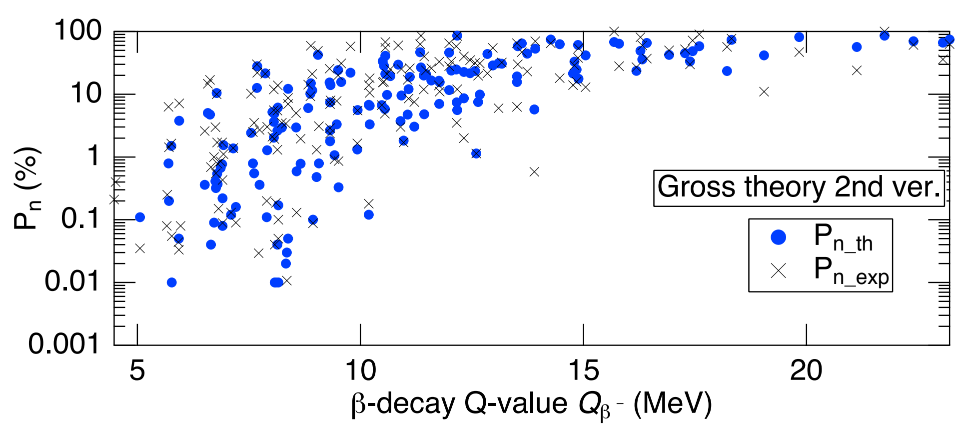
Exp vs Gross theory (2nd version)

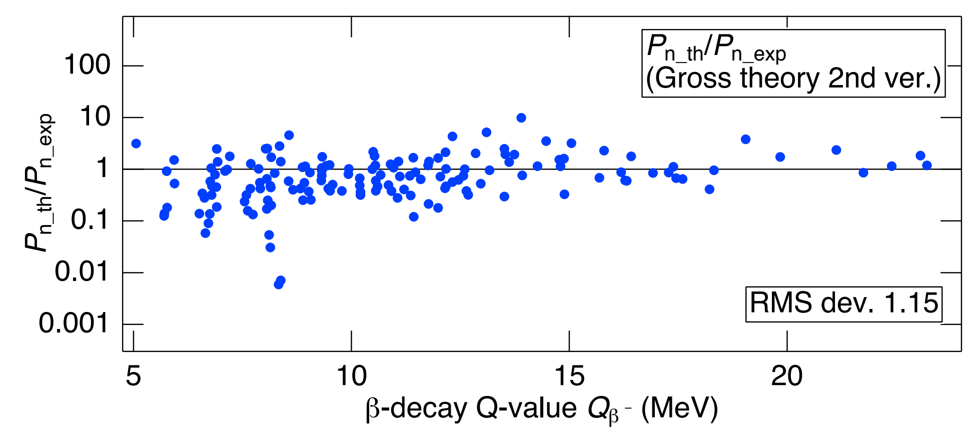
Half-lives $T_{1/2}$ (β^-)





Beta-delayed neutron P_n (%)





Download of theoretical data is available from http://wwwndc.jaea.go.jp/nucldata/index.html

Improvement of Gross theory from the 2nd version for <u>half-life, neutron emission and decay heat</u> (on going)

- <u>Spin-parity of g.s. odd-odd</u>

  (odd-odd nuclei (J^-, J is large in most case) → even-even nuclei (0^+)

  cf. H. Nakata, T. Tachibana and M. Yamada, NPA594 (1995): <u>only for half-lives</u>
- <u>Spin-parity dependency of low-energy excited states</u>
- <u>Re-consideration of sum rules of one-particle strength function in high-energy part</u>

  (Analysis of ^{90}Zr(p,n): broad distribution of strength function at 50MeV)
- ...

•Experimental Data (obtained in 2012-2013)

β decay half-life Delayed neutron prob. Spin-parity	← extracted	ENSDF (May 2012 version)
Decay heat	← extracted	Lowell(U-235, etc (3 nucl.) Oak Ridge (3 nucl.) Yayoi (Univ. Tokyo) (3 nucl.)
TAGS data	← extracted	collab. with T. Yoshida (TIT)

Summary

- We start a new project related to delayed neutron and decay heat based on nuclear theory and experiment for 3.5 year.
- In this project we will develop a comprehensive code to calculate beta-decay half-lives, delayed neutron emission prob., decay heat, and relevant quantities.
- Through this work, we will contribute to further understanding nuclear structure and decay, and will also apply to nuclear astrophysics as the r-process nucleosynthesis.

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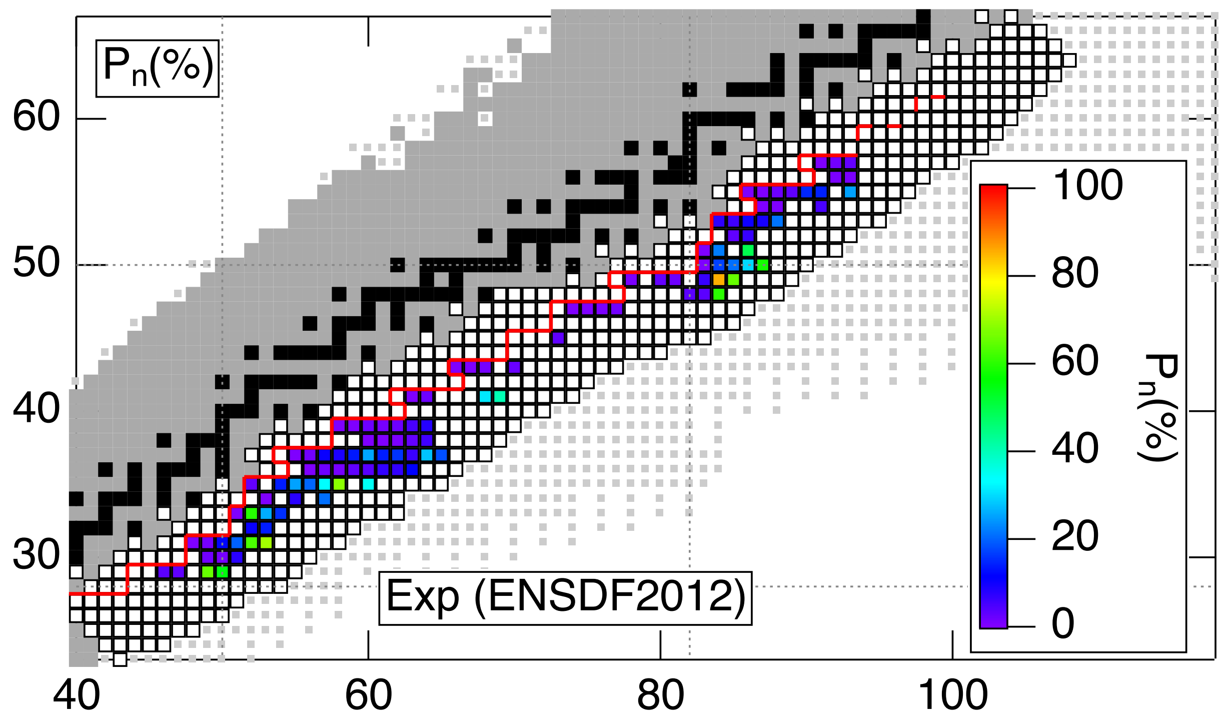
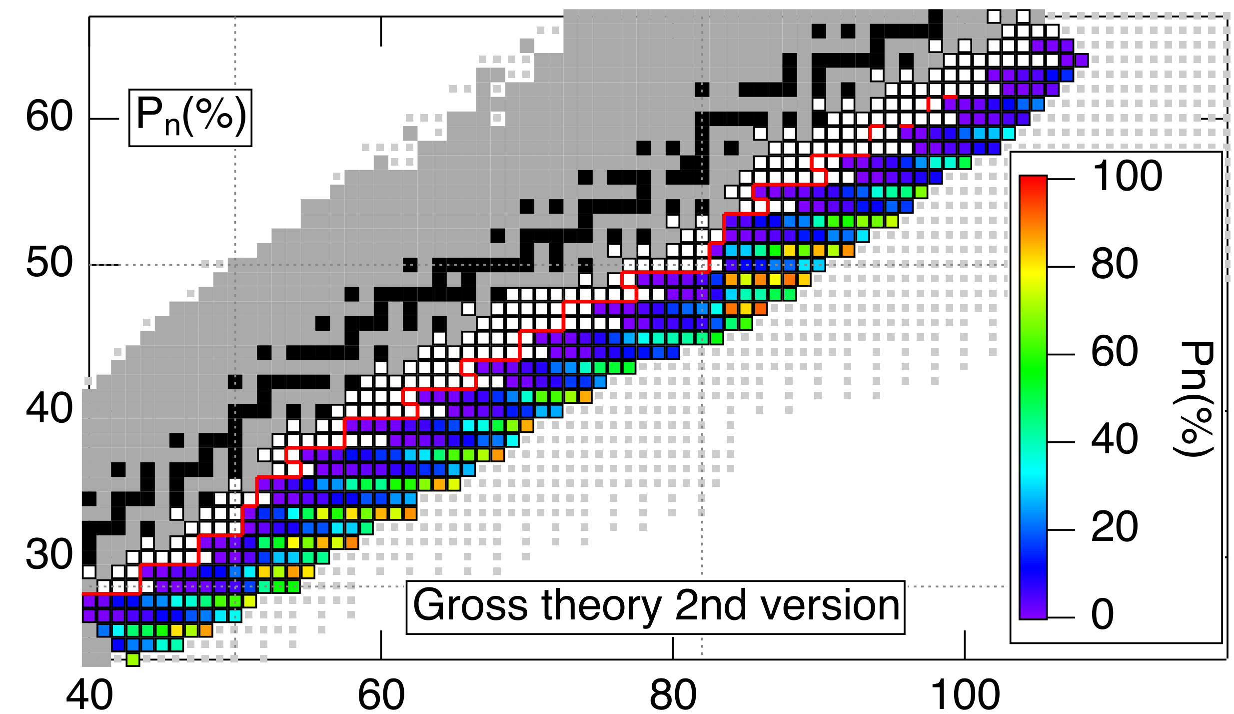
Accumulating experimental data is quite important for understanding of nuclei, and is also quite helpful for constructing nuclear theory (model).

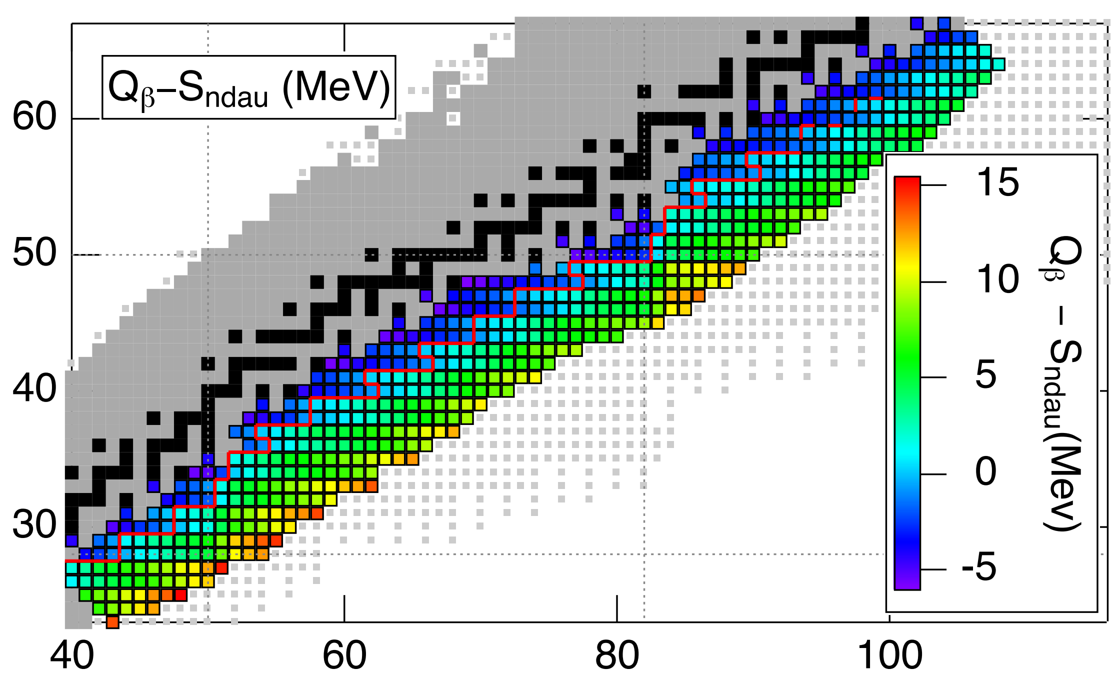
Pn(%)



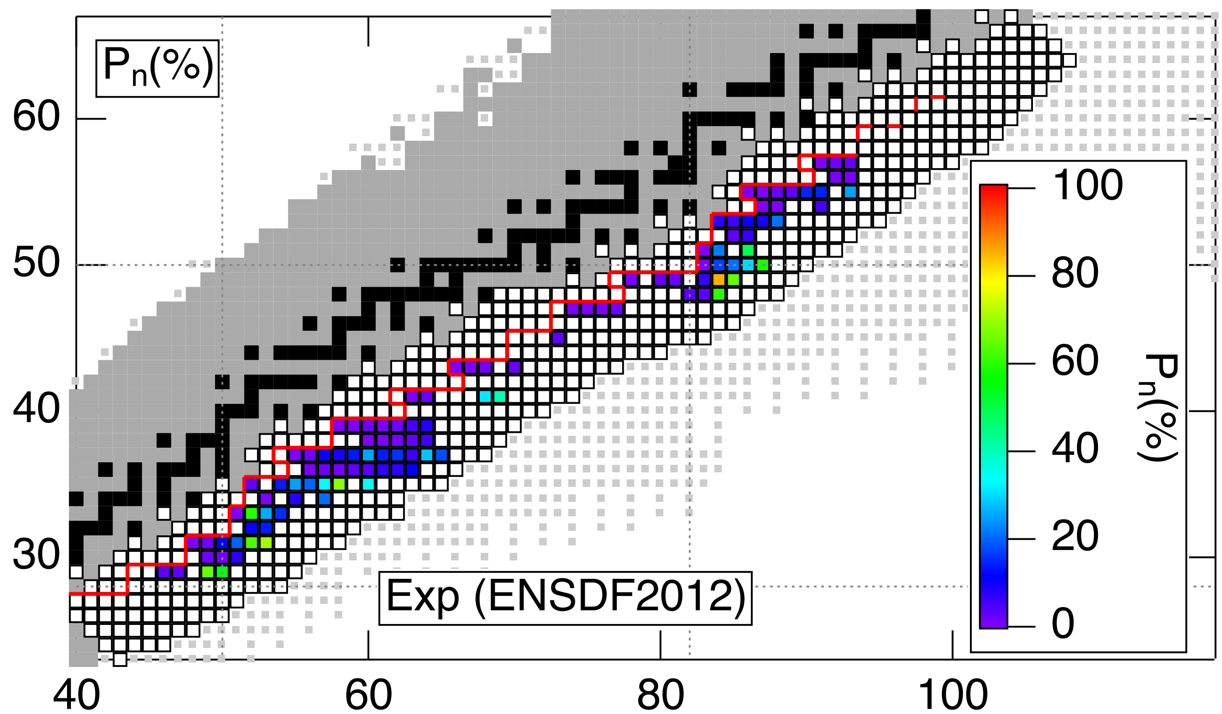


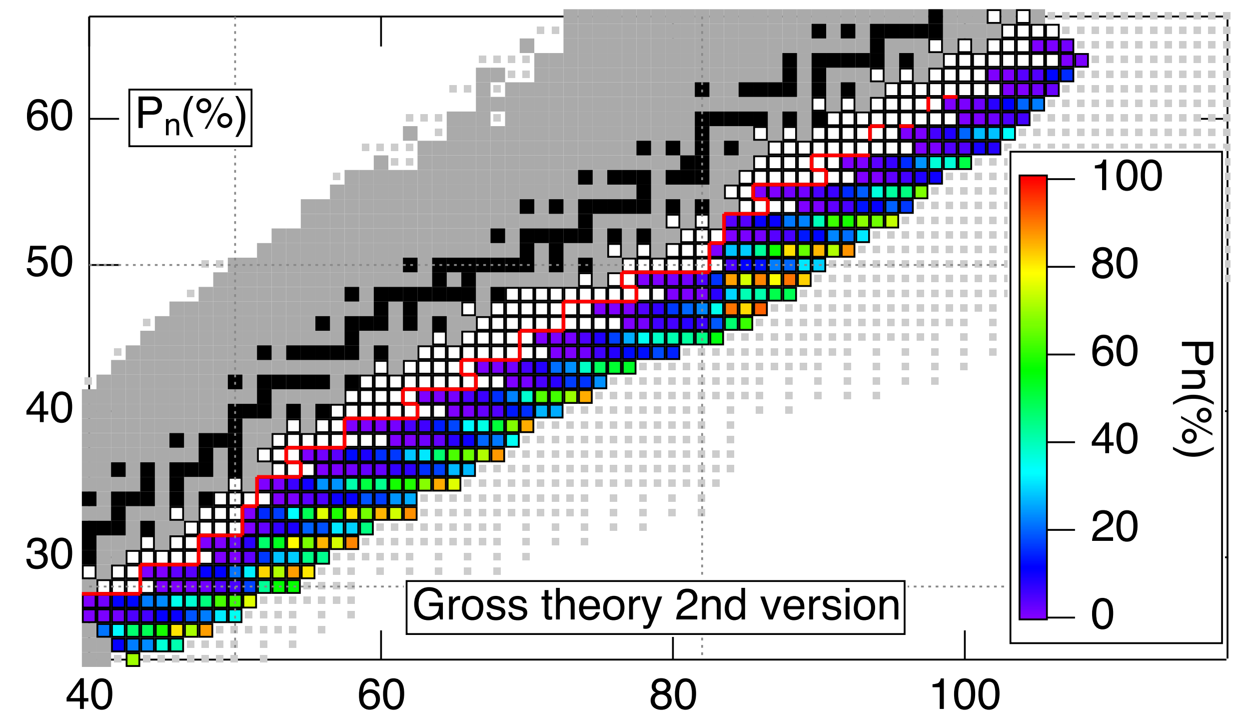
Pn has even-odd stagger for Z.

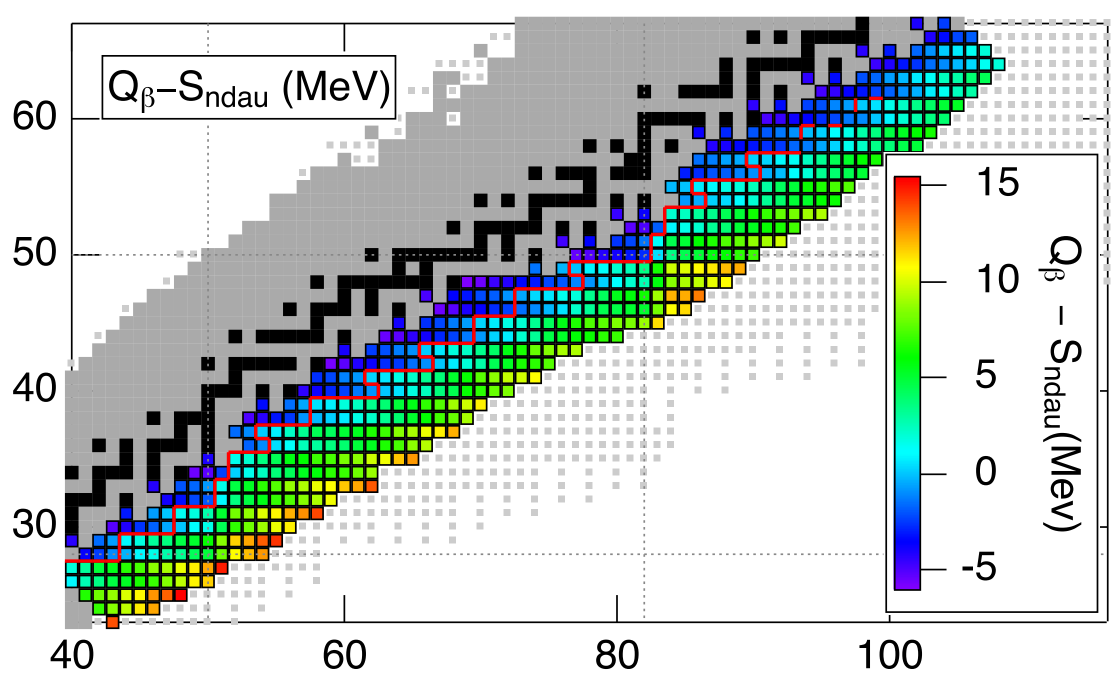
The stagger in the r-process abun. -> smoothness



Pn(%)







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