重・超重核領域における原子核の崩壊様式の理論及びr過程元素合成への応用

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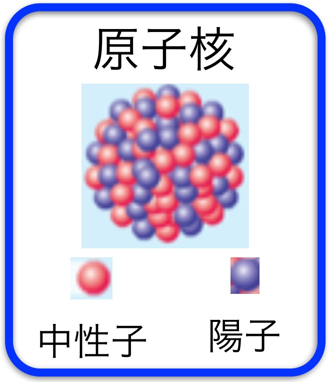
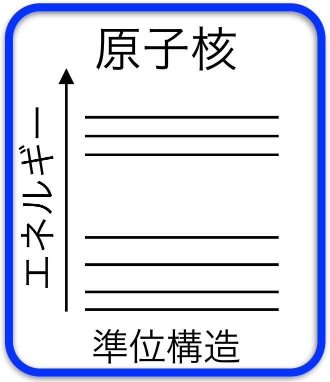
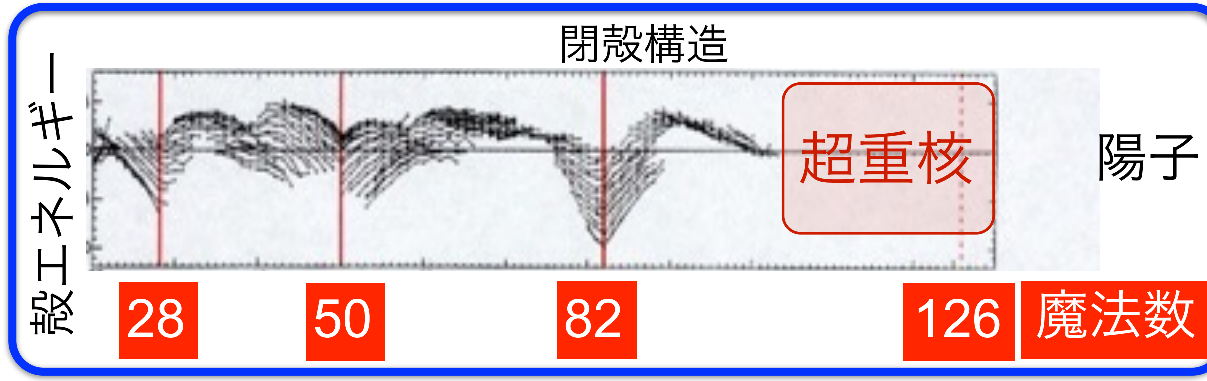
日本原子力研究開発機構
先端基礎研究センター

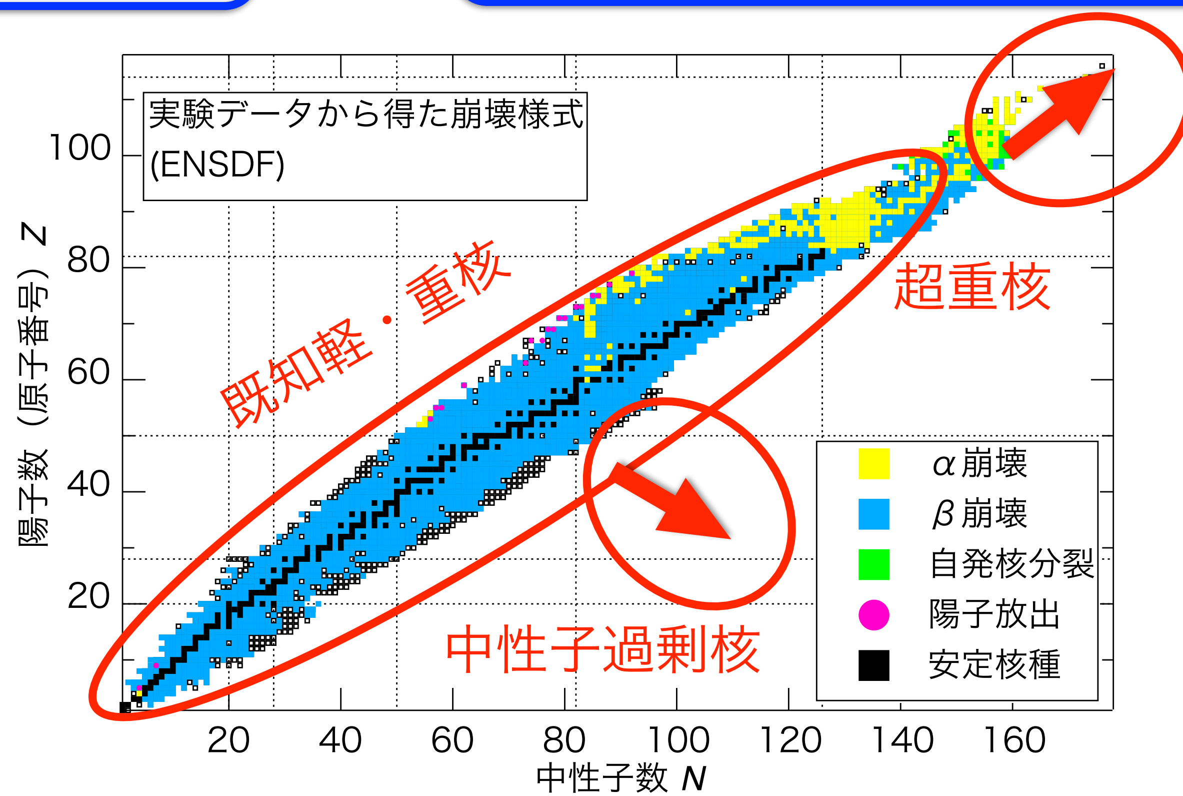
1. 原子核（同位体）探索の現状
2. 原子核質量模型及び原子核崩壊計算
3. 核分裂
4. r過程における核分裂の影響

目的：原子核構造・崩壊の（核図表上の）大域的理解





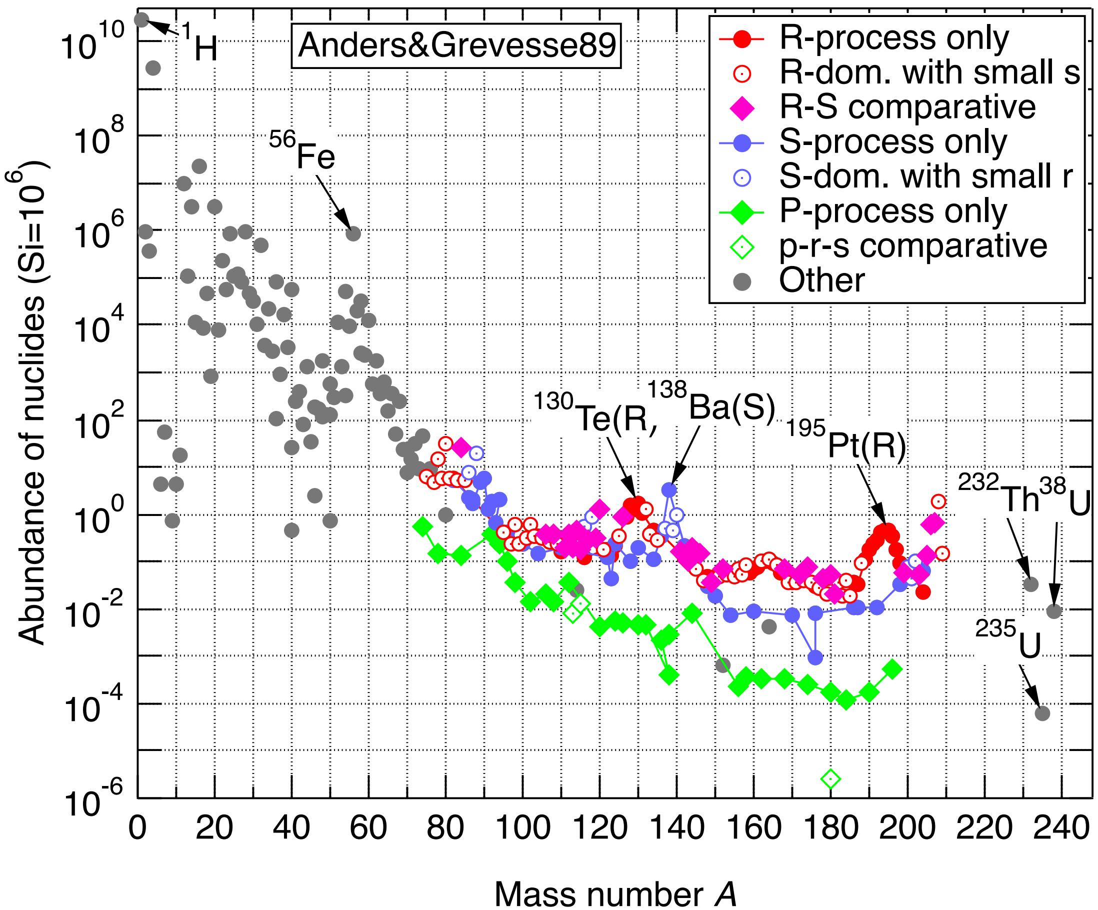




原子核の崩壊様式(小浦,
橘, 日本物理学会誌
60,717-724 (2005))

重・超重原子核の核構造、原子核崩壊を理論的に研究

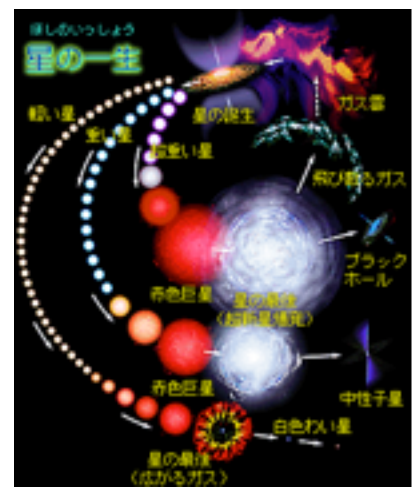
目的：原子核の起源の理論的探求　ー星の元素合成ー

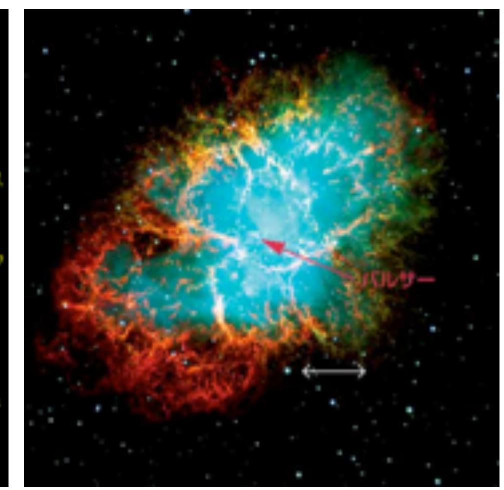


小浦、核データニュース101, (2012)

太陽系における同位体の存在比（観測値）

- S-process:遅中性子捕獲過程。赤色巨星などで数千年程度かけて中性子捕獲反応が進む。
- R-process:速中性子捕獲過程。超新星爆発などで数秒で中性子捕獲反応が進む。



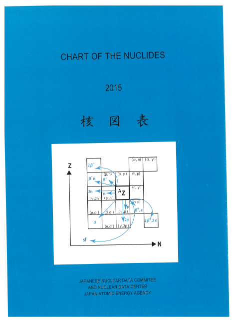


鉄(Fe)より重い原子核の現在の理解

- Fe-Bi：赤色巨星によって作られた(s過程(slow process))
- **Fe-U：超新星爆発によって作られた(r過程(rapid process))**

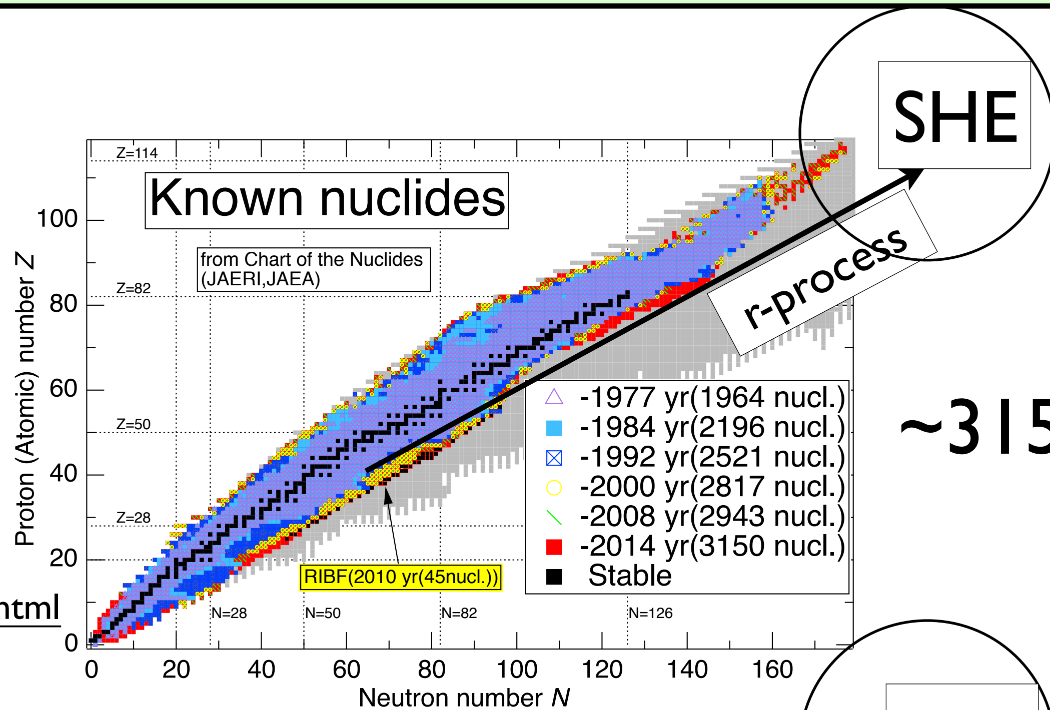
Search of nuclei: current understandings

Identified



taken from Chart of the nuclides by JAERI and JAEA (HK, et al., 2015)

wwwndc.jaea.go.jp/CN14/index.html



We know now

~3150 nuclei

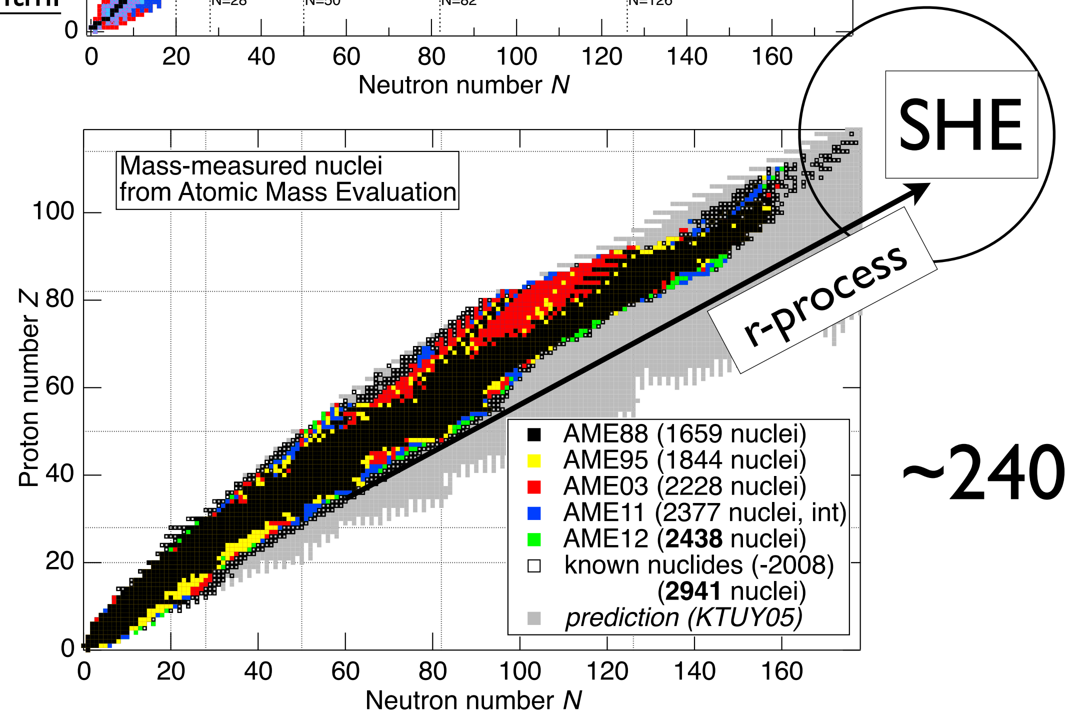
and

Mass-measured

AMDC Atomic Mass Data Center

AME2012 is updated three years ago

amdc.in2p3.fr/mastables/filel.html

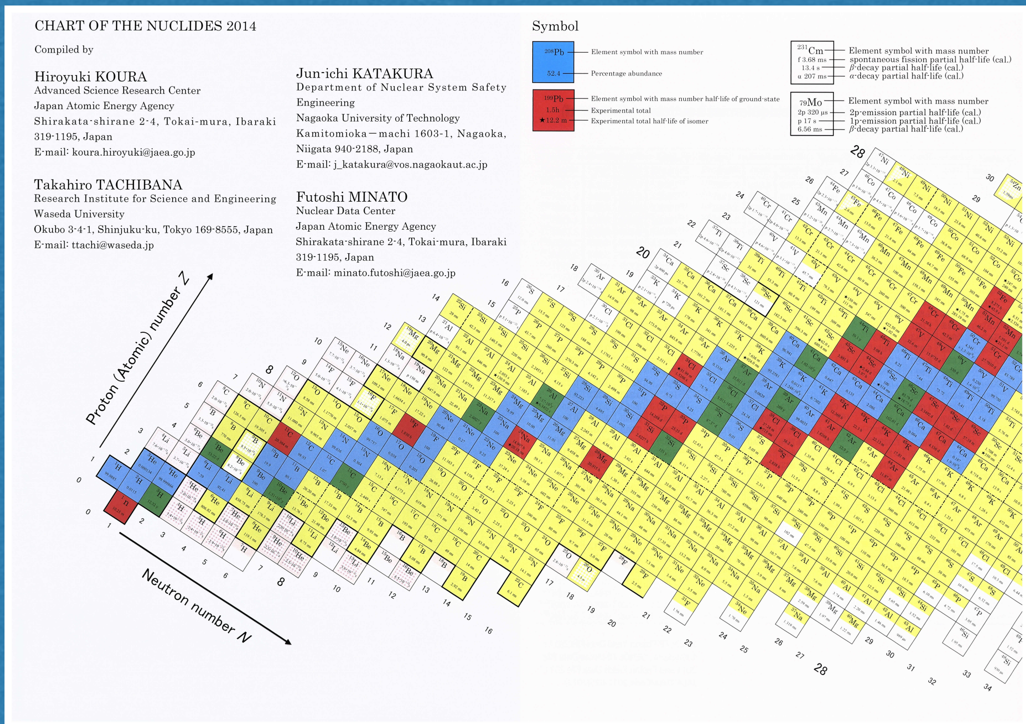


We know now masses of

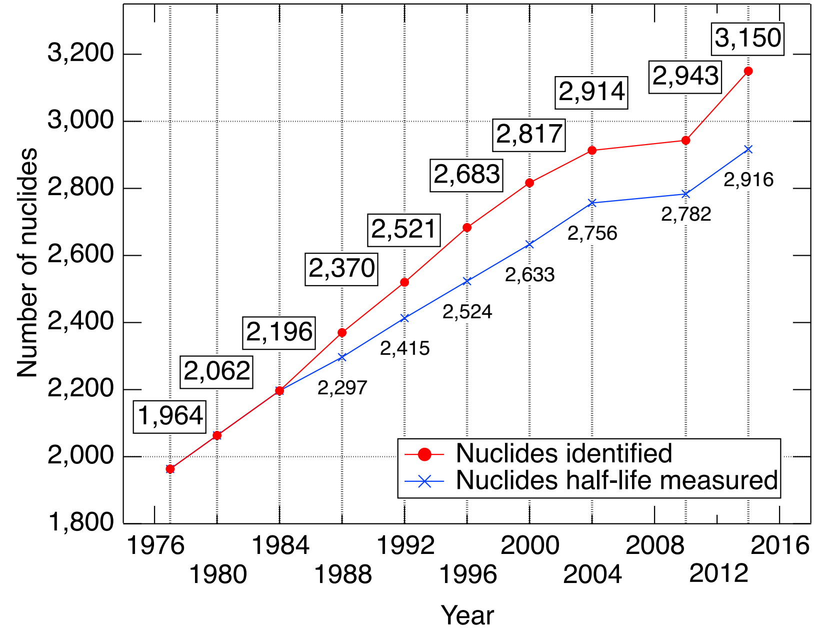
~2400 nuclei

JAEA Chart of the Nuclides 2014

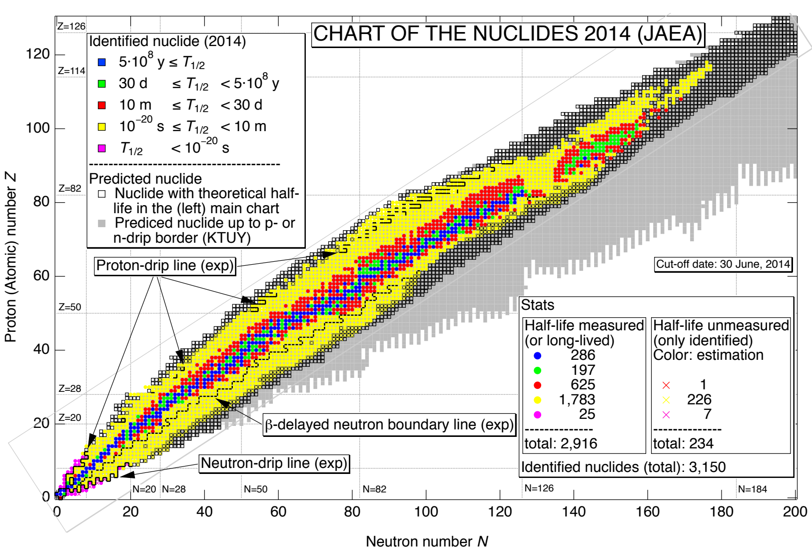
A tool to understand overview of nuclear decay

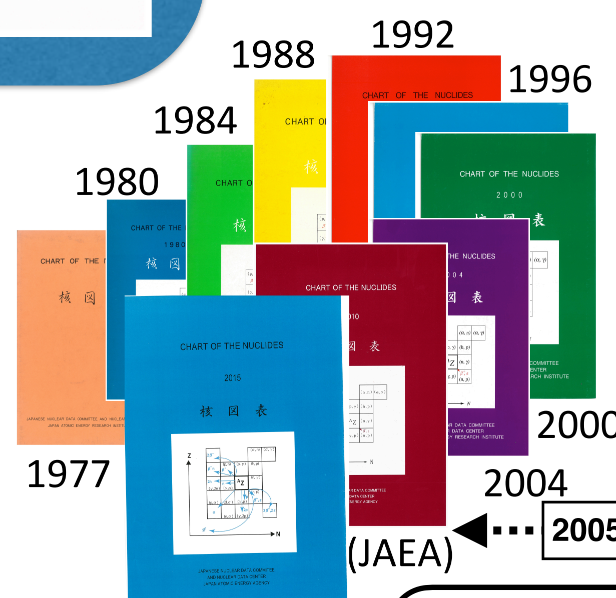


A4-size, folded in 16 pages



Identified isotopes





2005: JAERI to JAEA

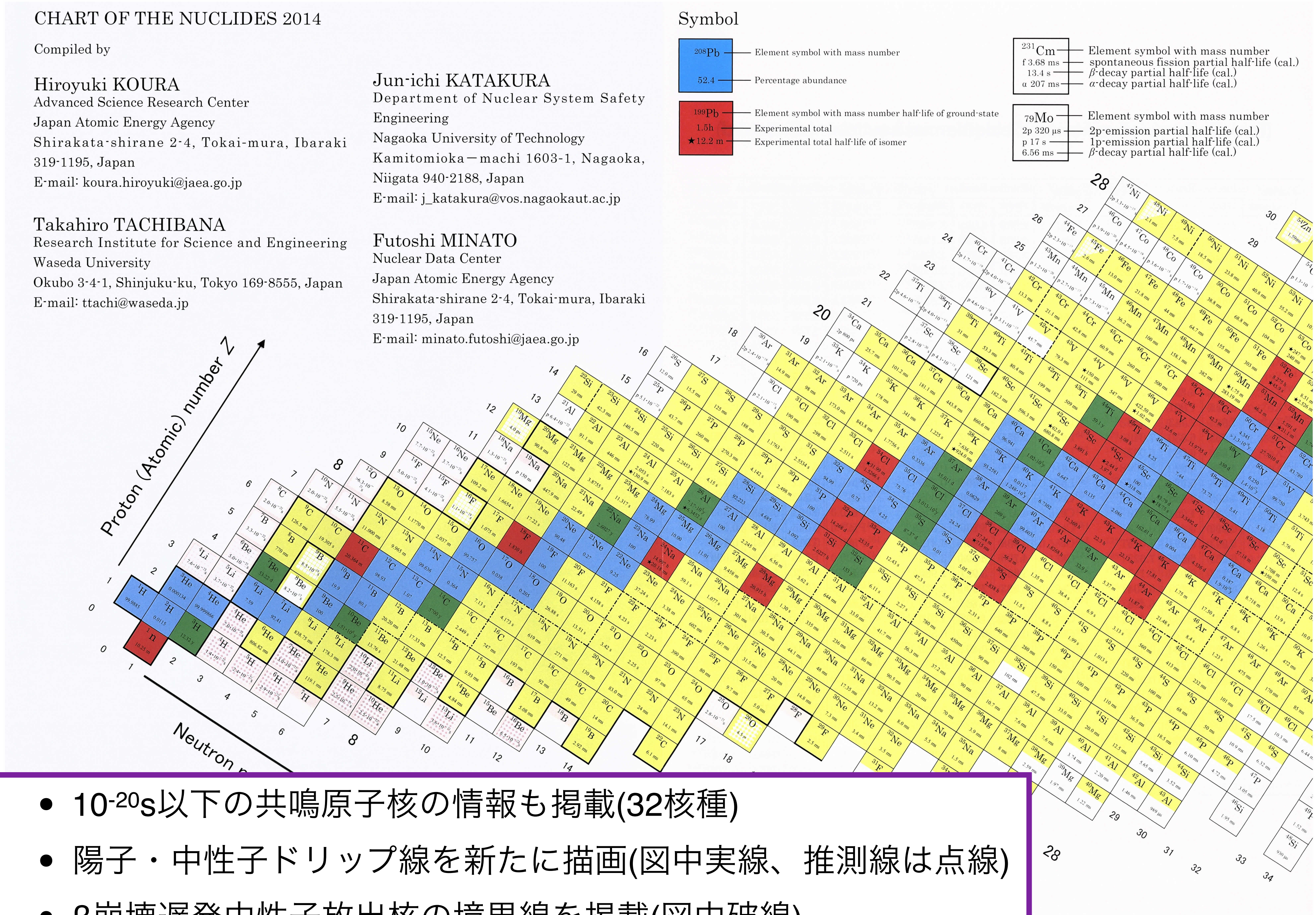
Compilers:

Y. Yoshizawa	(1977 - 1988)
T. Horiguchi	(1977 - 2004)
M. Yamada	(1977 - 1988)
T. Tamura	(1992)
J. Katakura	**(1992 -)**
T. Tachibana	**(1992 -)**
H. Koura	**(2000 -)**
F. Minato	**(2014 -)**

Person: current compiler

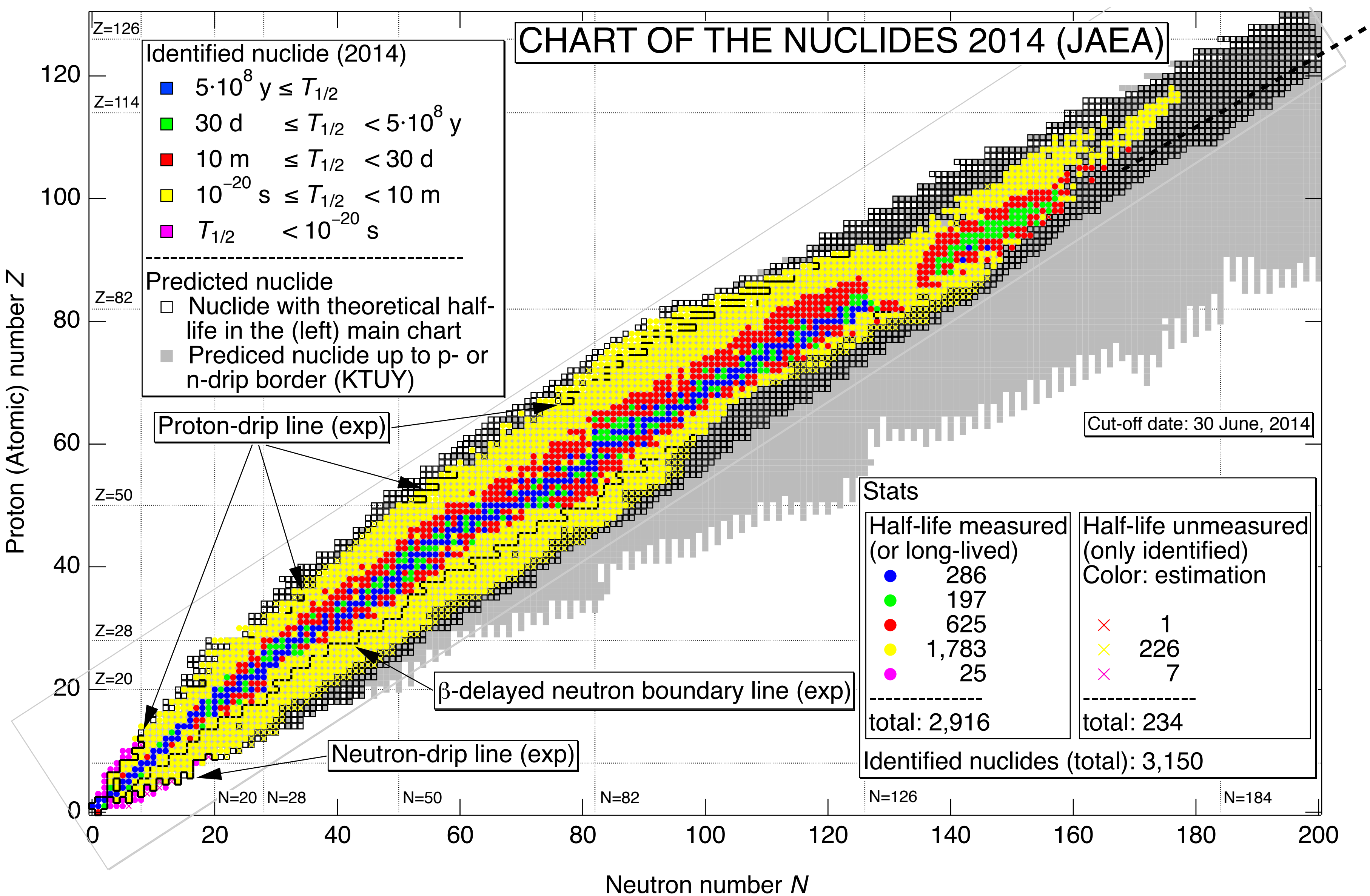
Press release
http://www.jaea.go.jp/02/press2014/p15031202/

核図表2014：軽核領域（表側p.1-2）



- 10^{-20}s以下の共鳴原子核の情報も掲載(32核種)
- 陽子・中性子ドリップ線を新たに描画(図中実線、推測線は点線)
- β崩壊遅発中性子放出核の境界線を掲載(図中破線)

Overview of identified nuclei from Chart of the Nuclides 2014



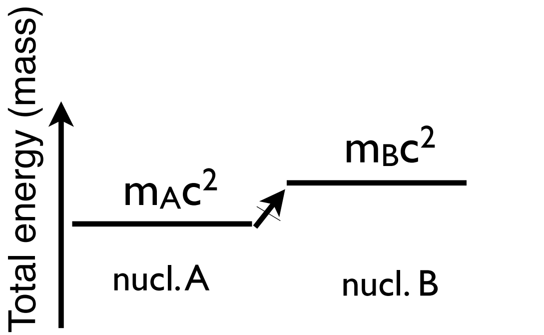
I. Introduction

Why nuclear mass?

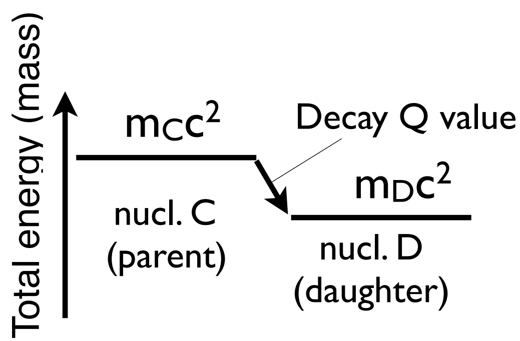
- Equivalence to **total energy** of nucleus: E = mc^2

  ➡ Governing nuclear reaction and decay modes

$E=mc^2$

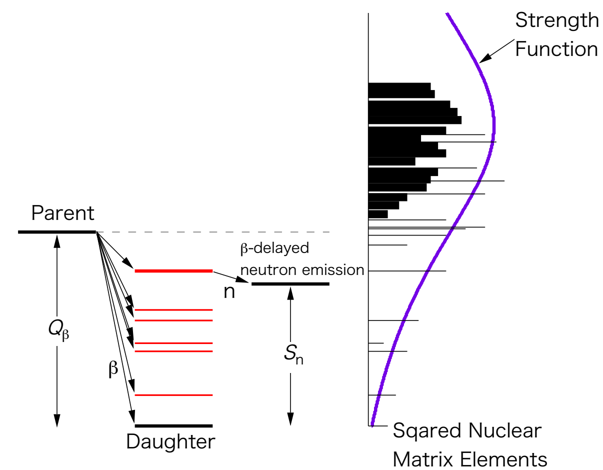


Nucleus A can not decay.



Nucleus C can decay.

Diff. of mass(total energy) determine the direction of nuclear decay.



$$\lambda = \frac{1}{2\pi^3}\int_{-Q}^{0}\sum_{\Omega}|g_\Omega|^2\cdot|M_\Omega(E_g)|^2 f(-E_g+1)dE_g$$

Decay rate of beta-decay

Prediction of nuclear decays

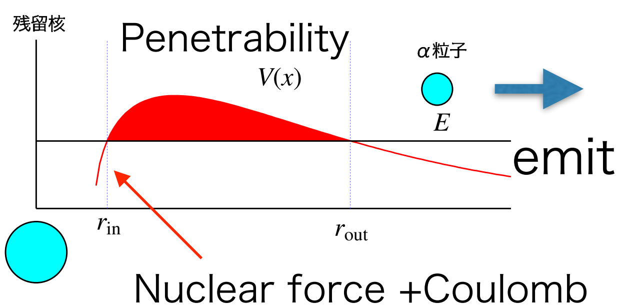
Nucleus

α-decay

β-decay

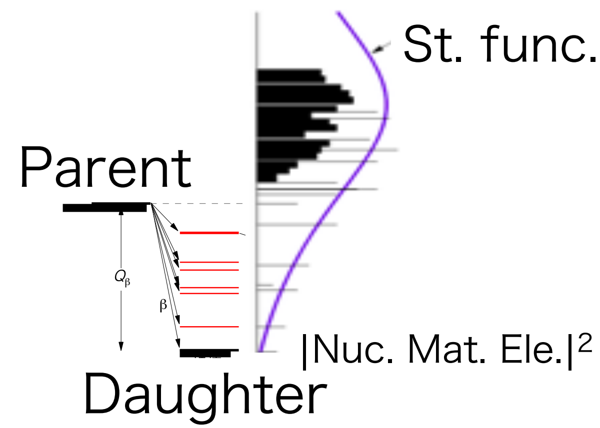
Fission

α-decay : tunneling



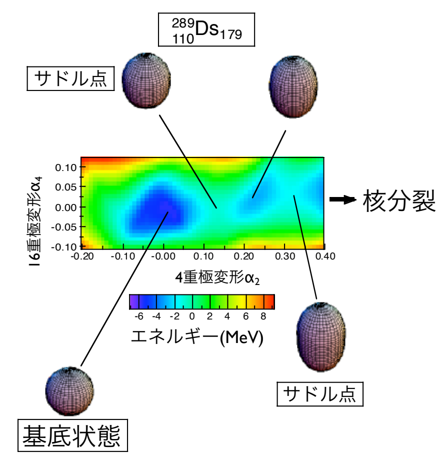
Req.: Mass diff. (Q-value)

β-decay : weak int.



Req.: Mass diff. (Q-value)

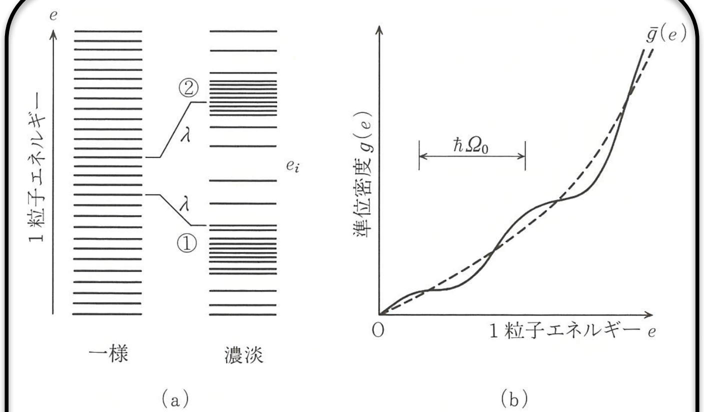
Fission : Potential ag. shape



Req.: Description of shape

Nuclear masses (and description of nuclear shape) are required.

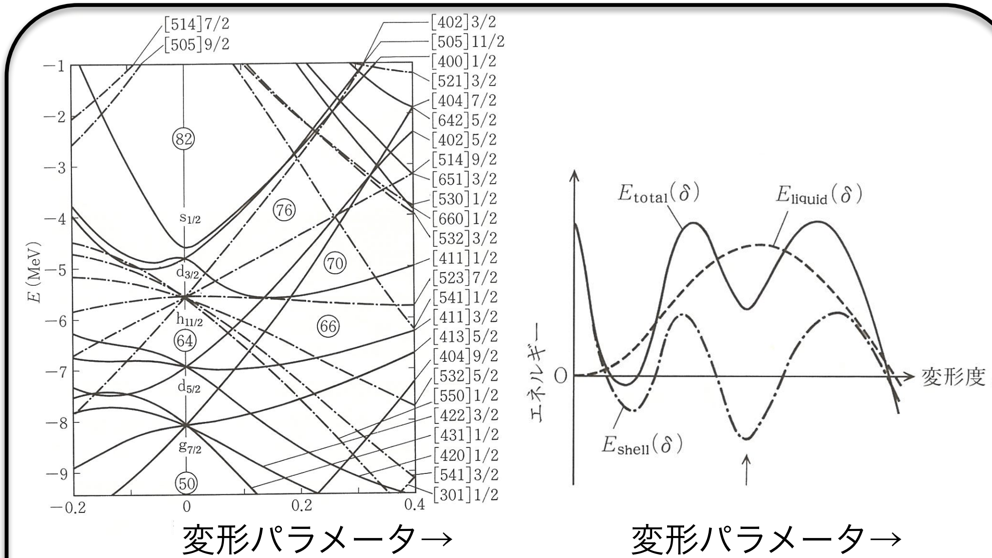
Mass model: Spherical-basis method (KTUY)



殻構造の概念図

Nilsson-Strutinsky 法

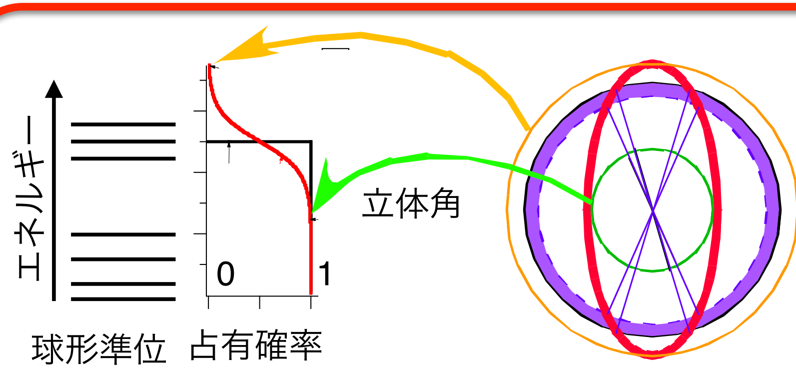
変形単一粒子ポテンシャルより準位を得、
それに粒子を積み上げることにより求める

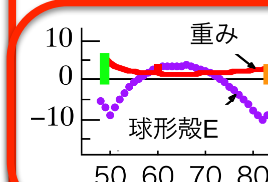


変形ポテンシャルで変形度を与えて、縮退が
解かれた準位に対して適用

球形基底の方法(今回用いた方法)

球形単一粒子ポテンシャルより準位を得、
変形状態を球形状態の配位混合として扱う





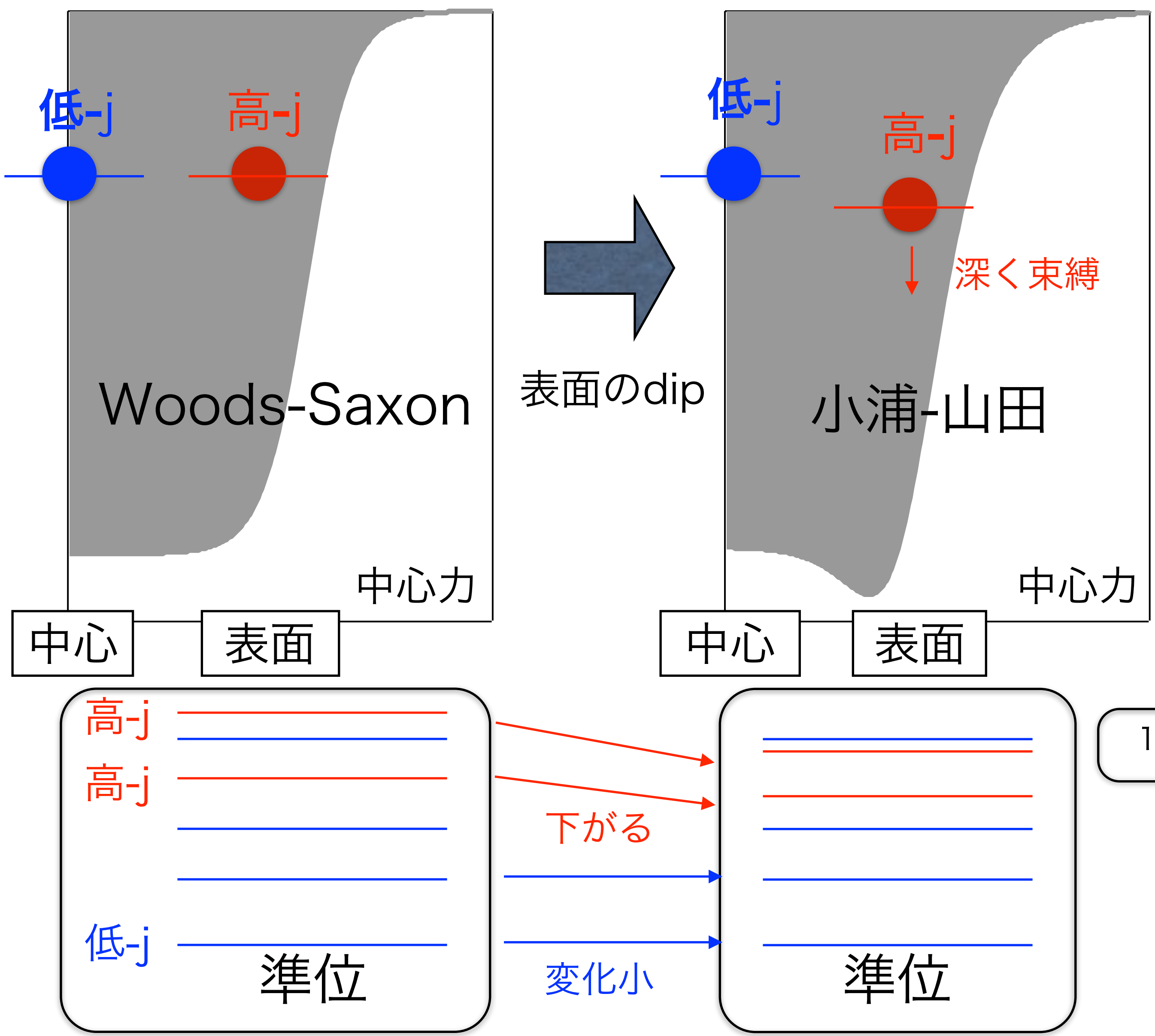
実際の計算：球形殻Eの重み付き和

球形殻E：球形準位の積分
重み：立体角(占有確率)の微分

H. Koura et al. NPA **671**, 96 (2000)
H. Koura et al. NPA **674**, 47 (2000)
H. Koura et al. PTP **113**, 305 (2004)

球形単一粒子準位

高スピン軌道(j)の核子に対する役割



低-j:原子核の**中心**に分布
高-j:原子核の**表面**に分布

↓ 表面のdip

高-j核子:**より深い準位へ**
→実験準位をW-Sよりよく再現することに成功

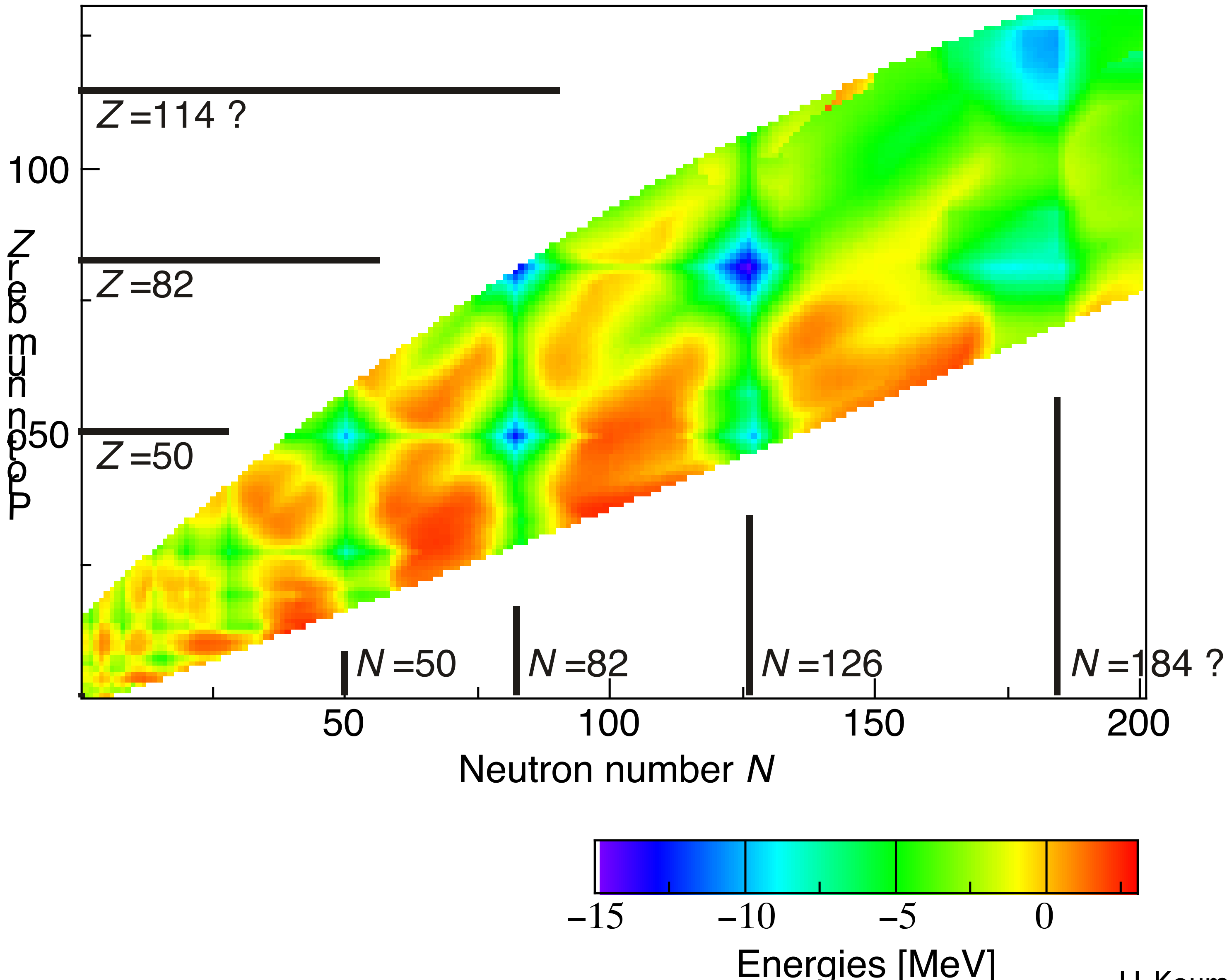
↓

^{132}Sn, ^{208}Pb等の２重球形閉殻

H. Koura et al. NPA **671**, 96 (2000)

Nuclear shell energy

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



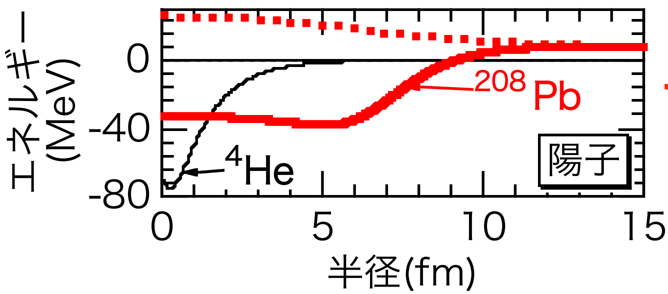
H. Koura et al. NPA **674**, 47 (2000)

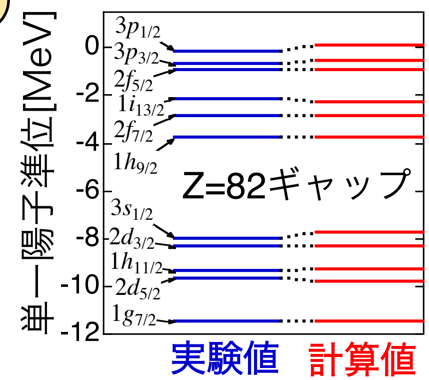
KTUY質量公式

(まとめ)

(1) 球形単一粒子ポテンシャル

- 5パラメータ,Z,Nの関数



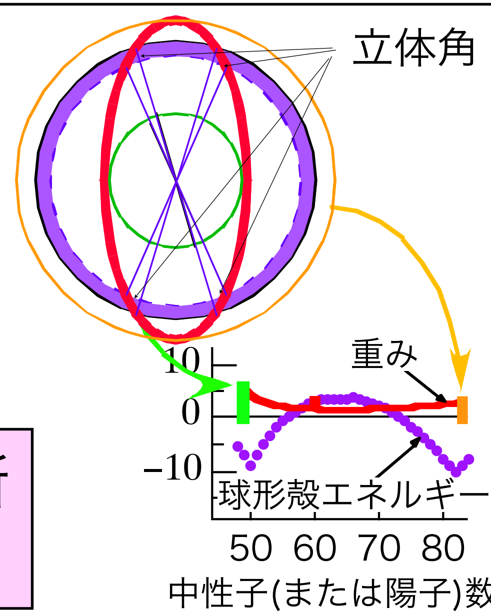


単一陽子準位 (^{208}Pb)

^{4}Heから^{208}Pbにわたり精度の高い単一粒子準位の再現を実現

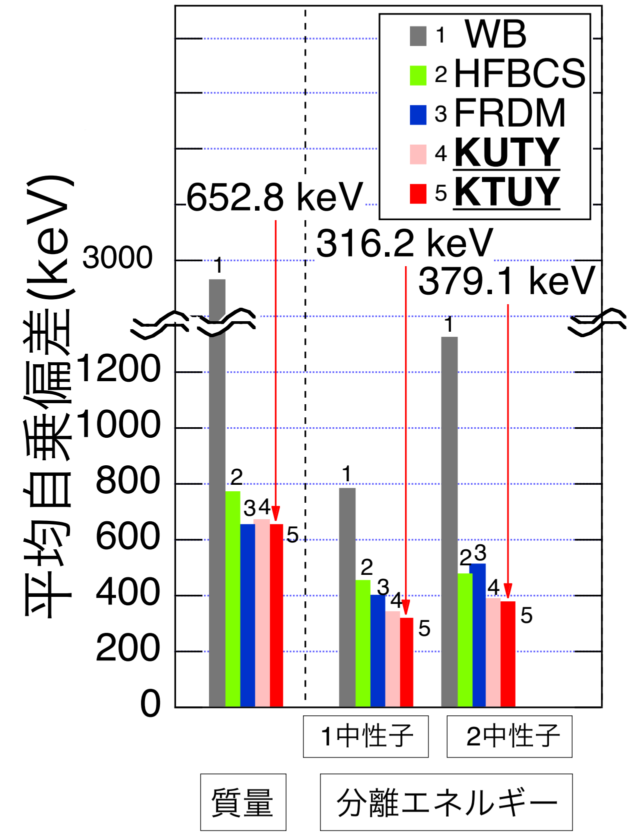
(2) 変形殻エネルギー計算

- (1) の球形ポテンシャルを使用
- <u>変形原子核の殻エネルギーを**球形殻エネルギーの重み付き和**として与える</u>
- <u>重み:分割球形核が占める立体角の微係数</u>



原子核質量の殻エネルギーの新たな計算方法

(3) 質量再現性

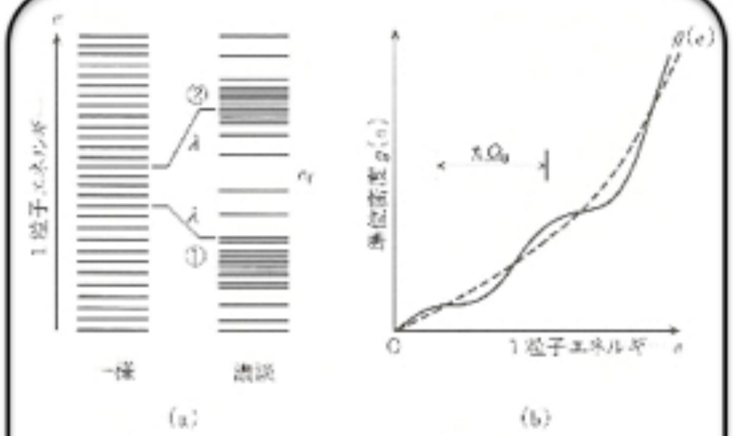


実験値との平均自乗偏差 (2149核種)

他モデルと比べて高い質量値再現性を実現

Fission

核分裂障壁の理論計算



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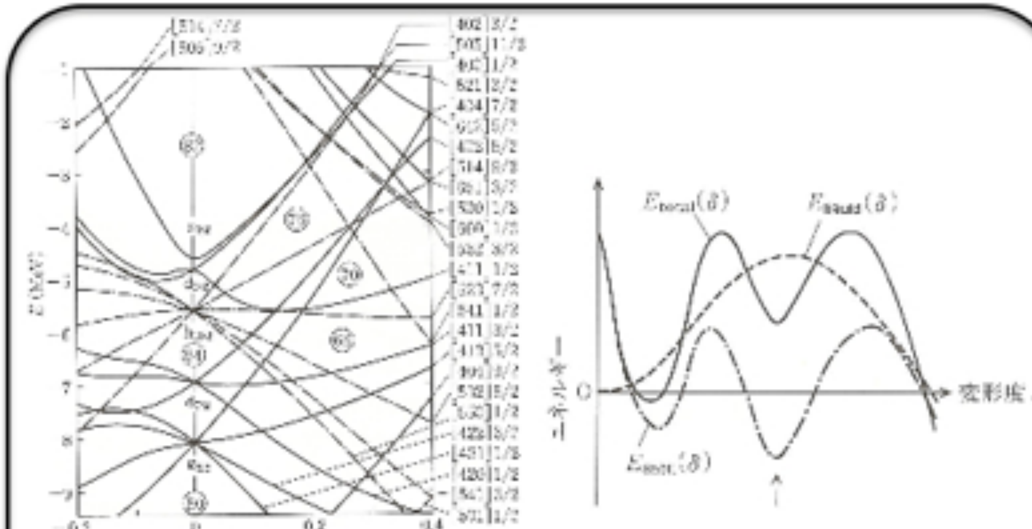

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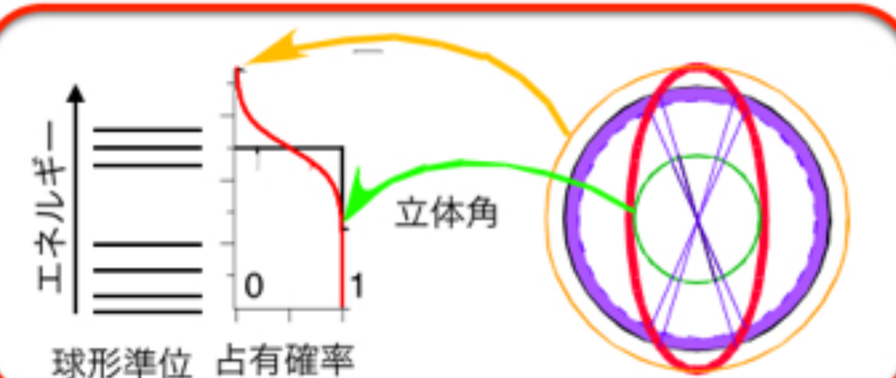

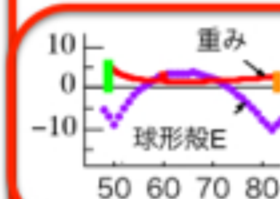

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球形殻E：球形準位の積分

重み：立体角(占有確率)の微分

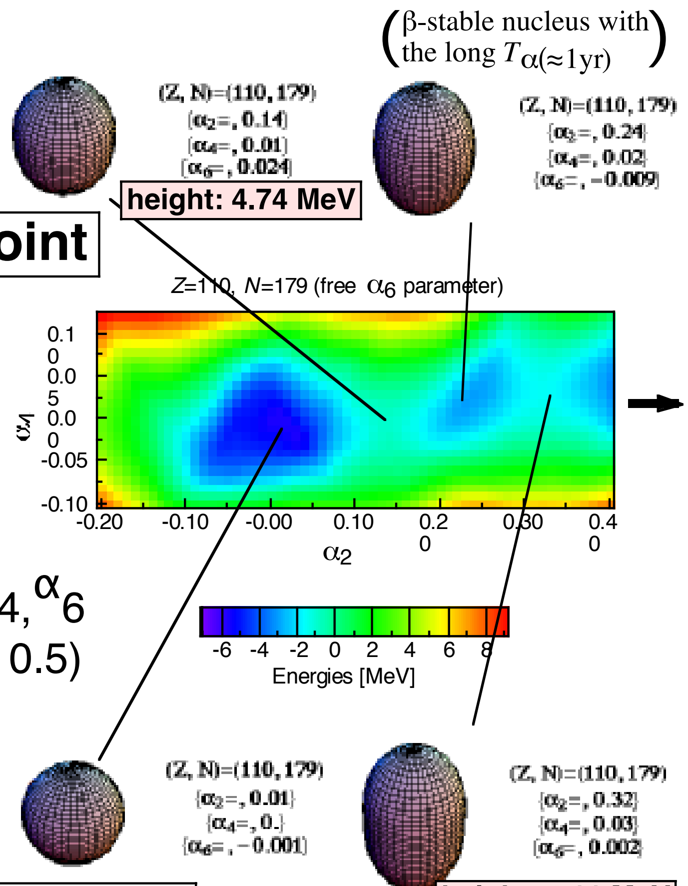
H. Koura, PTEP **113D02** (2014)

核分裂(1)：核分裂障壁

Fission-barrier height is defined
as **the highest saddle point**
measured from the ground-state energy.
(the saddle-point must be prolate)

$^{289}110_{179}$

saddle point



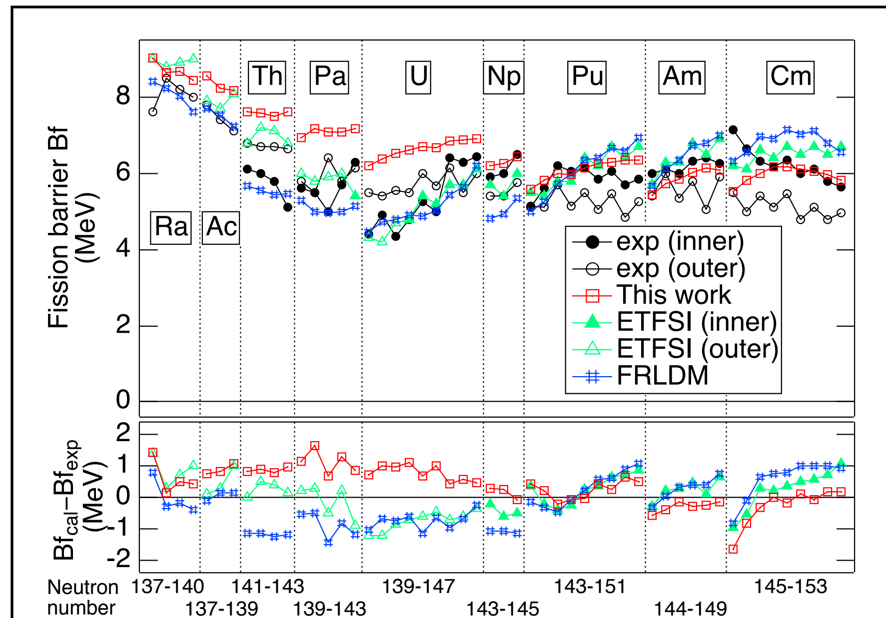
→ Fission

shape: $\alpha_2, \alpha_4, \alpha_6$

$(-0.2 \le \alpha_2 \le 0.5)$

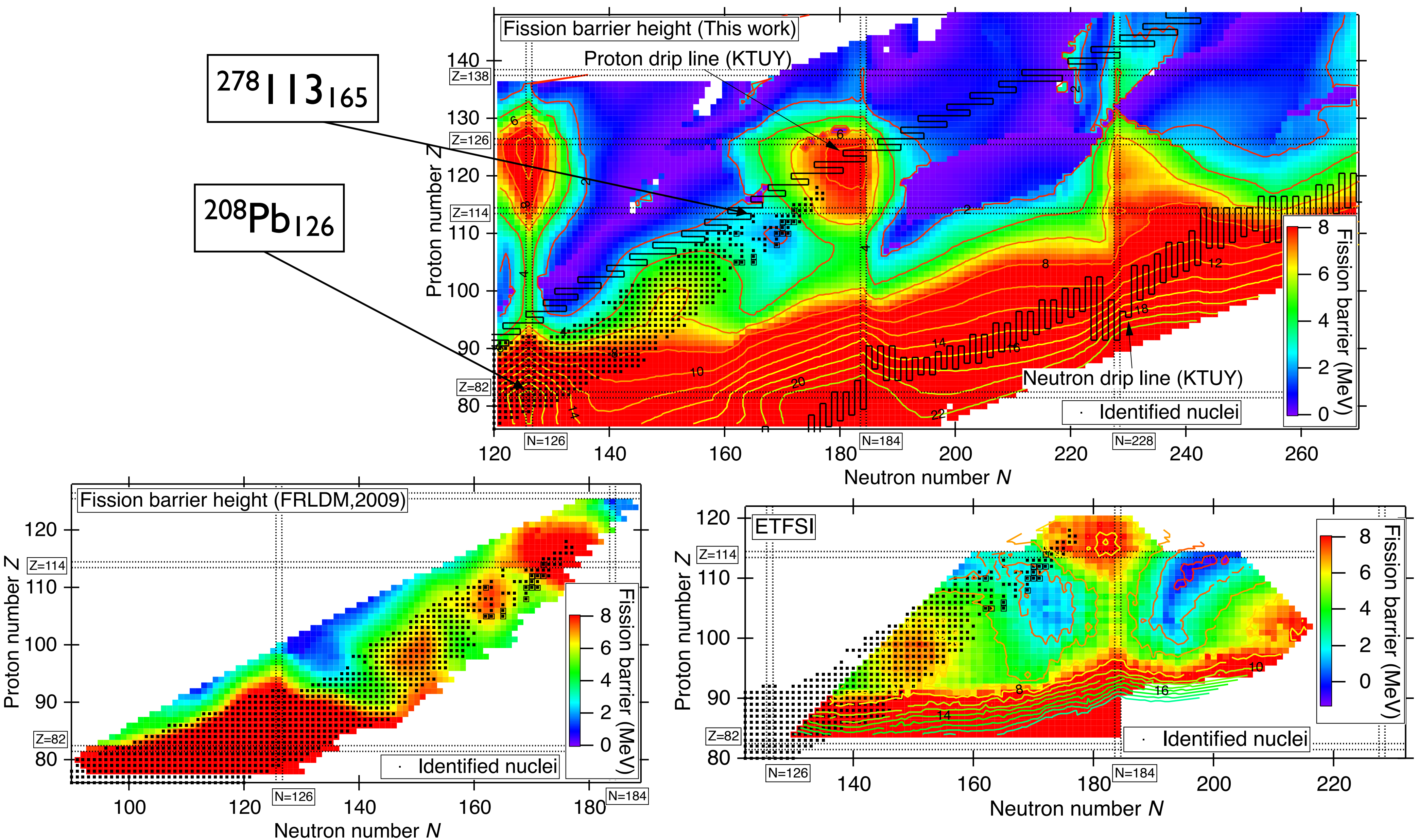
ground state

Energy surface (KUTY)



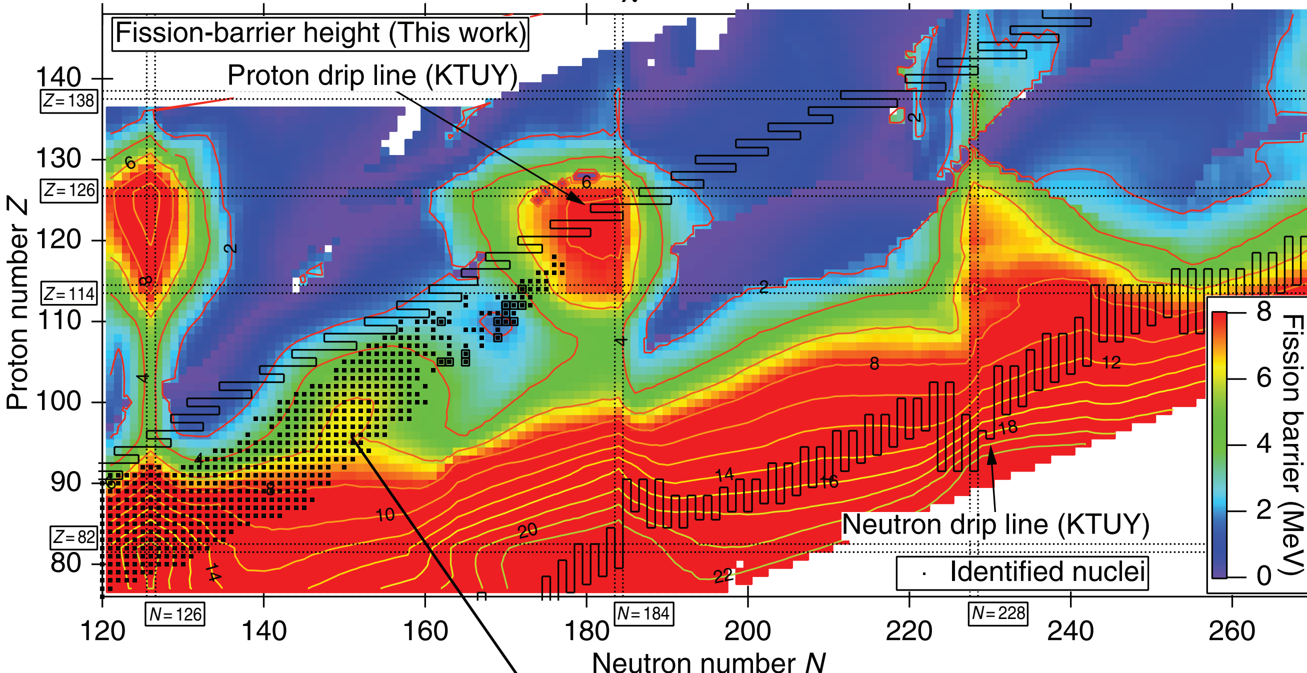
RMS dev.≈1MeV

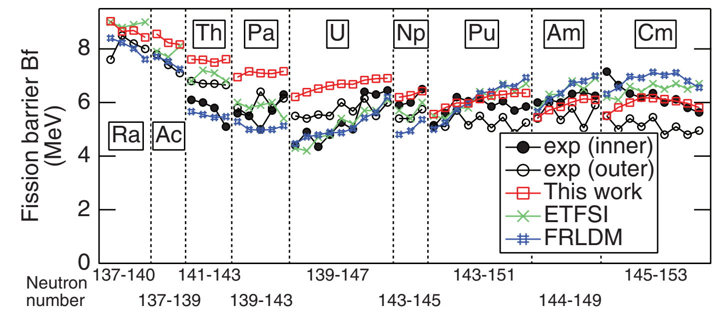
Fission barrier height

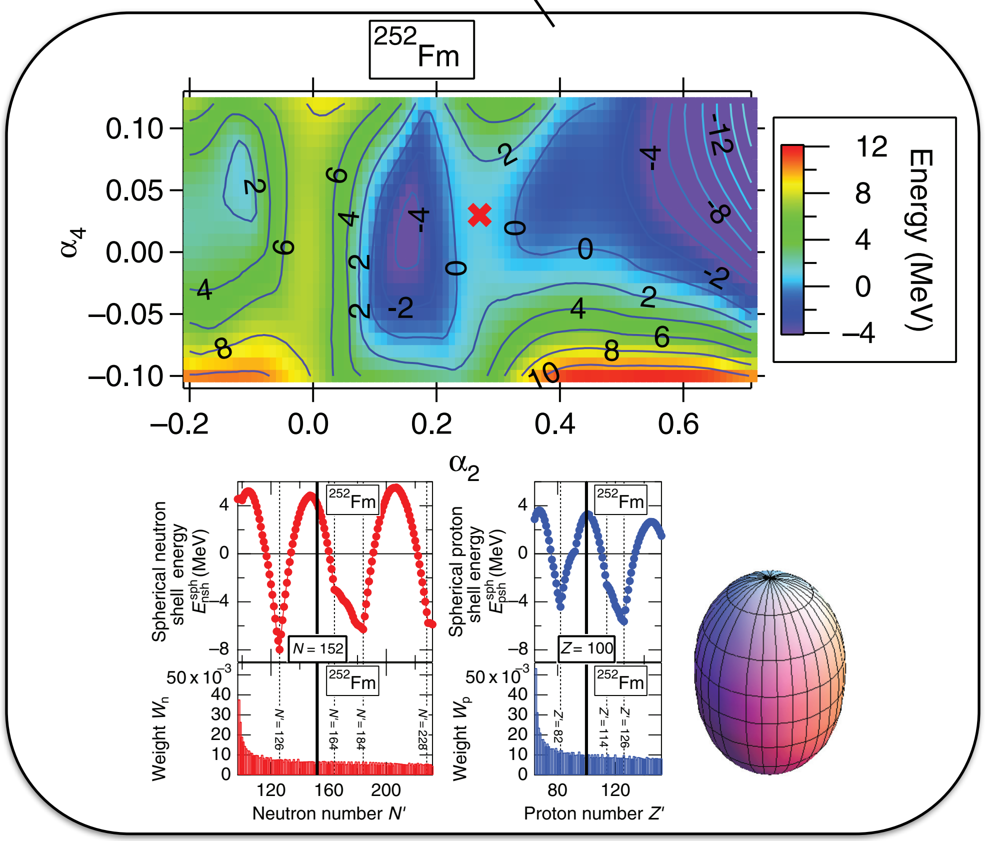


Koura

$$R(\theta) = \frac{R_0}{\lambda}\left[1 + \alpha_2 P_2(\cos\theta) + \alpha_4 P_4(\cos\theta) + \alpha_6 P_6(\cos\theta)\right],$$

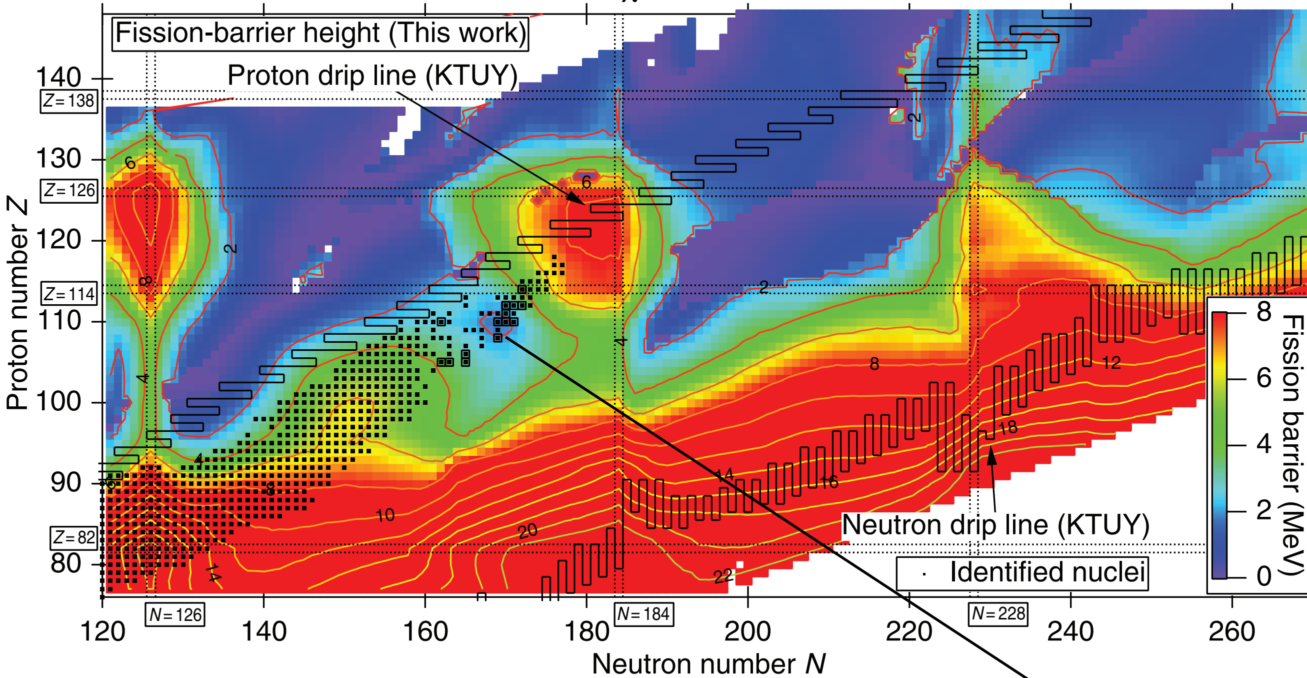


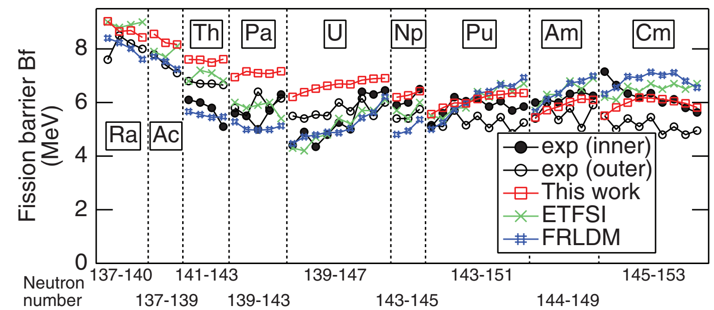


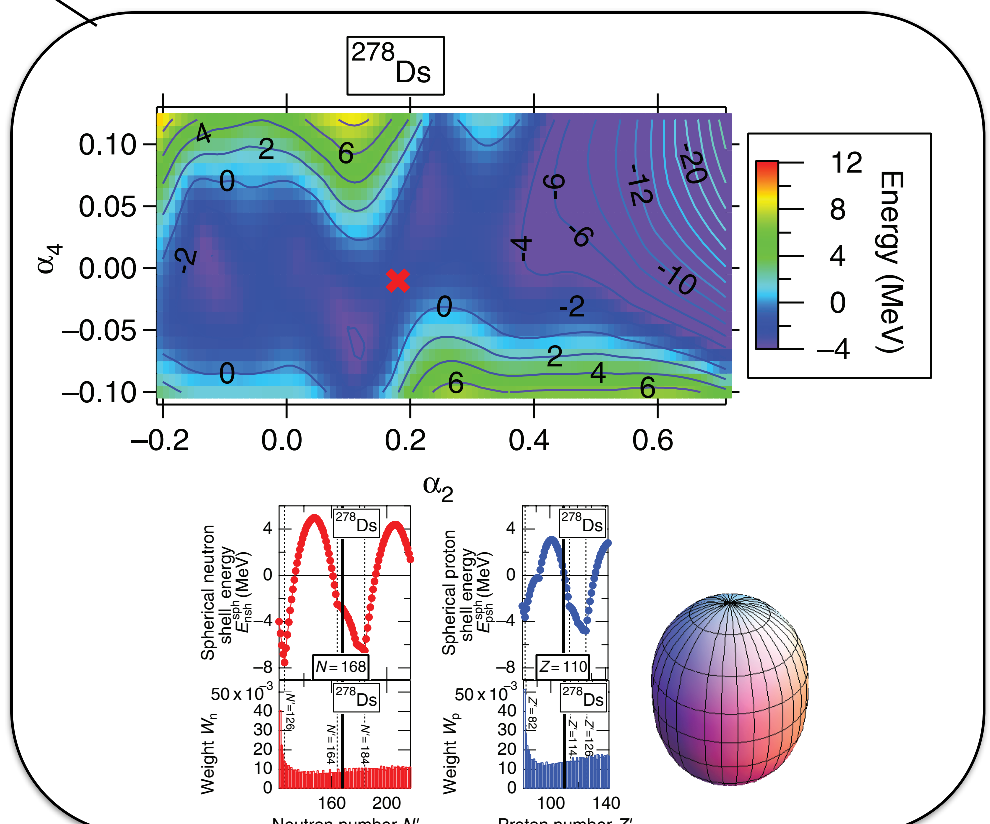


Neutron mixing weight reaches N=228 shell energy (left panel) : the saddle configuration of 252Fm is contributed to by only one shell closure of N=228.

$$R(\theta) = \frac{R_0}{\lambda}\left[1 + \alpha_2 P_2(\cos\theta) + \alpha_4 P_4(\cos\theta) + \alpha_6 P_6(\cos\theta)\right],$$



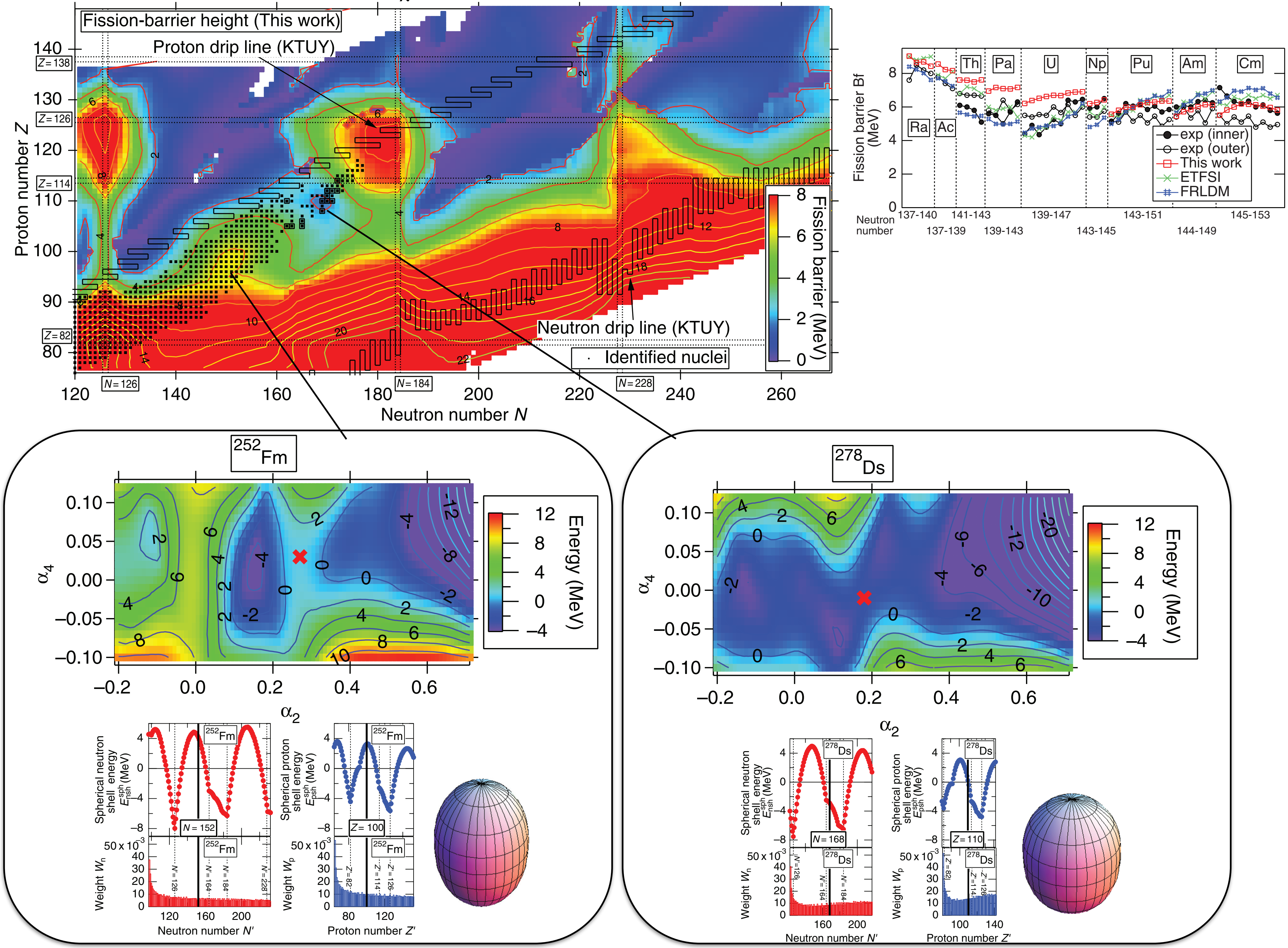




Neutron mixing weight reaches N=126 shell energy (left panel) and Proton mixing weight reaches Z=82 shell energy (right panel) : the saddle configuration of 278Fm is contributed to by two shell closures of Z=82. N=126.

=> **208Pb plus (collective) valence nucleons.**

$$R(\theta) = \frac{R_0}{\lambda}\left[1 + \alpha_2 P_2(\cos\theta) + \alpha_4 P_4(\cos\theta) + \alpha_6 P_6(\cos\theta)\right],$$



核分裂(2)：自発核分裂部分半減期の推定

- **原子核の形状:$\alpha_2,\alpha_4,\alpha_6$(軸対称・反転対称)**
- **１次元WKB法で透過確率を計算**

$$\mathrm{Log}_{10}(T_{\mathrm{SF}}) = \mathrm{Log}_{10}\left(1 + \exp\left[\frac{2}{\hbar}K\right]\right) + \mathrm{Log}_{10}(N_{\mathrm{Coll}}) - 0.159 + \boldsymbol{h}\delta_{\mathrm{odd}\,Z} + \boldsymbol{h}\delta_{\mathrm{odd}\,N} - \Delta_{\mathrm{oo}}\delta_{\mathrm{odd}\,Z}\delta_{\mathrm{odd}\,N}$$

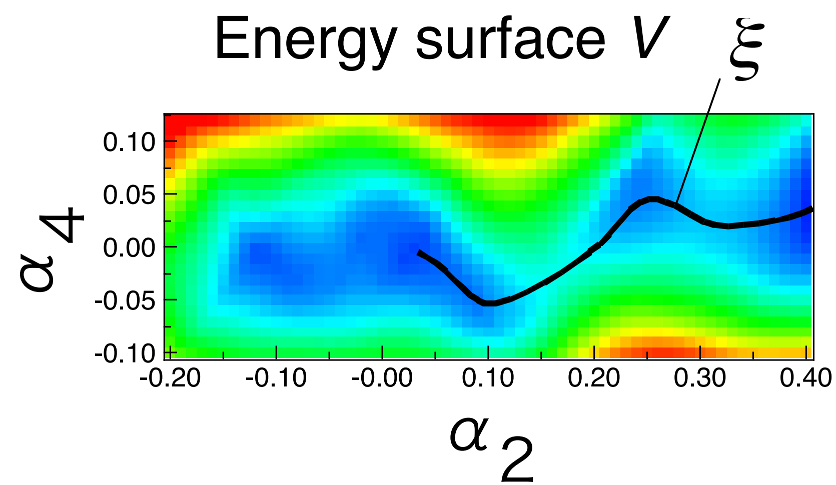
$$K = \int \sqrt{2M(V(\xi) - E_{\mathrm{gs}})}\, d\xi$$

$M = \boldsymbol{k}\mu$, μ:reduced mass

$$d\xi = r_0 A^{1/3} d\alpha$$

$r_0 = 1.2\mathrm{fm}$, $\mathrm{Log}_{10}(N_{\mathrm{Coll}}) = 20.38$

$$\delta_{\mathrm{odd}\,Z} = \begin{cases} 0 & \text{for even}-Z \\ 1 & \text{for odd}-Z, \end{cases} \quad \delta_{\mathrm{odd}\,N} = \begin{cases} 0 & \text{for even}-N \\ 1 & \text{for odd}-N, \end{cases}$$

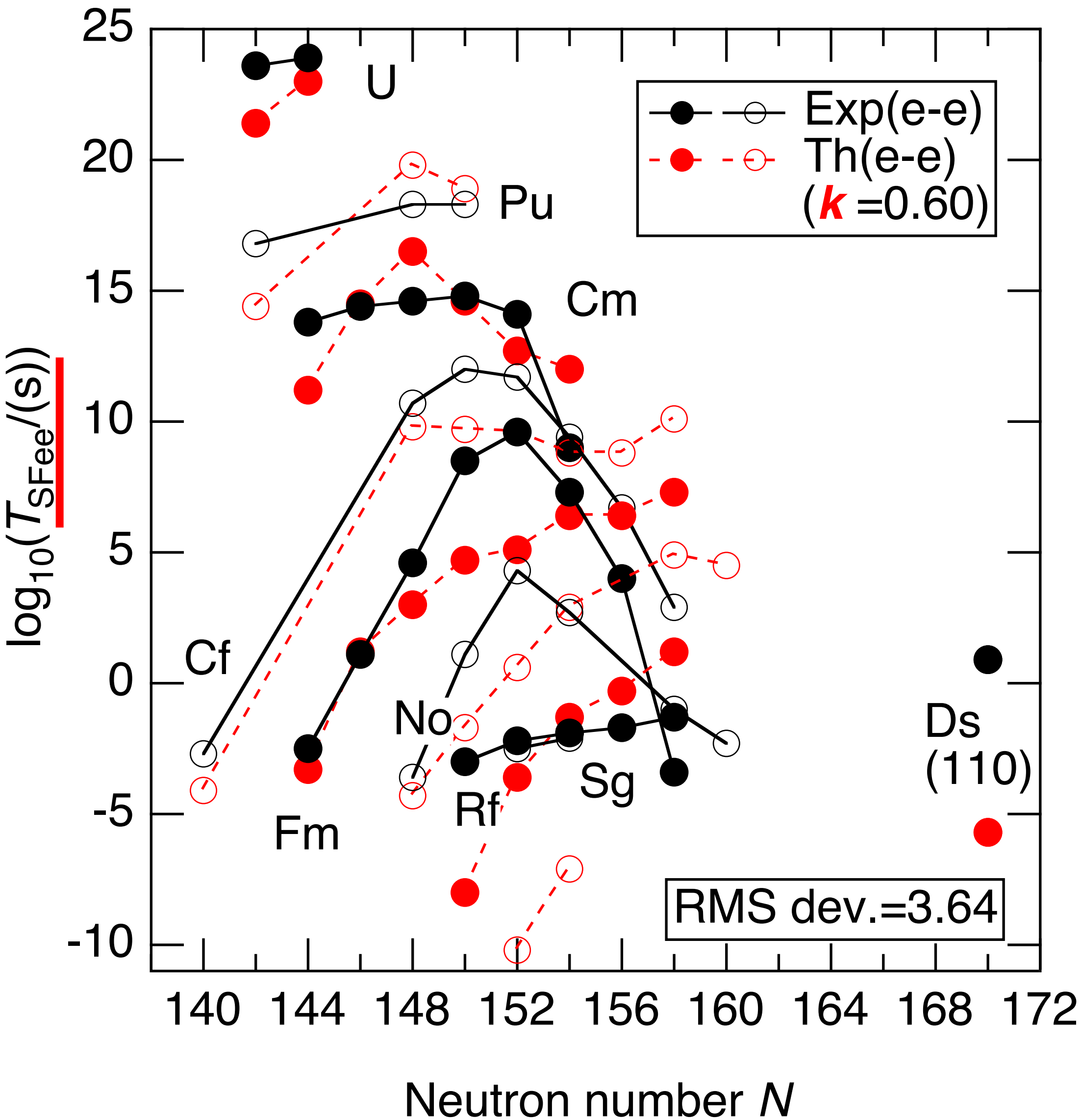


Adjustable parameter

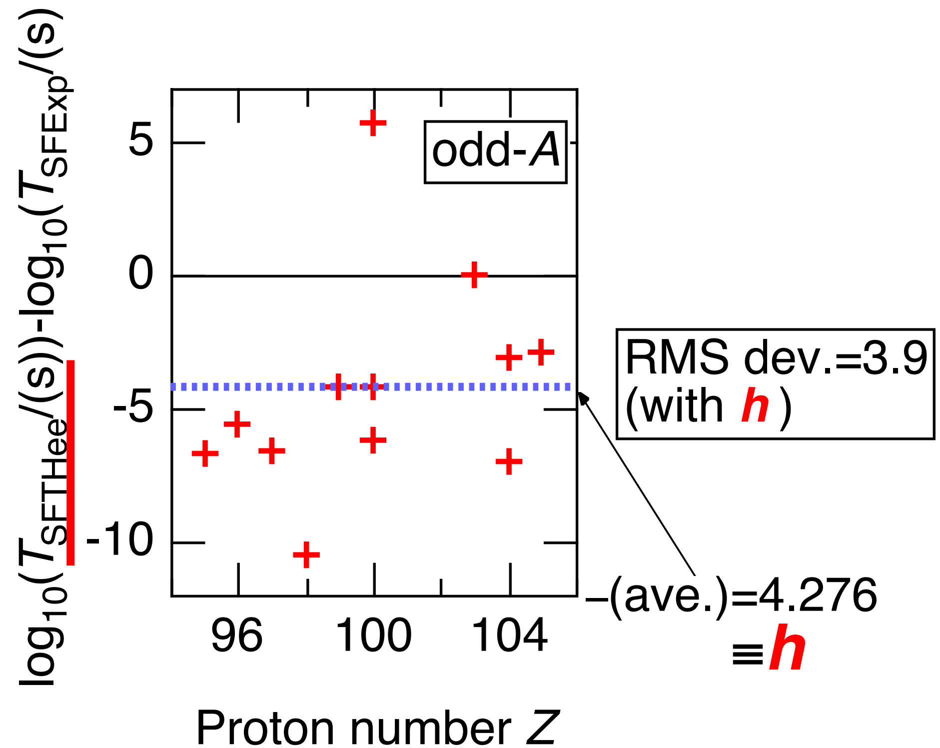
$\boldsymbol{k}$	for e-e nuclei
$\boldsymbol{h}$, Δ_{oo}	for odd-A, o-o nuclei

T_{sf}(s) の実験値と計算値との比較

Even-even nuclei



odd-A nuclei

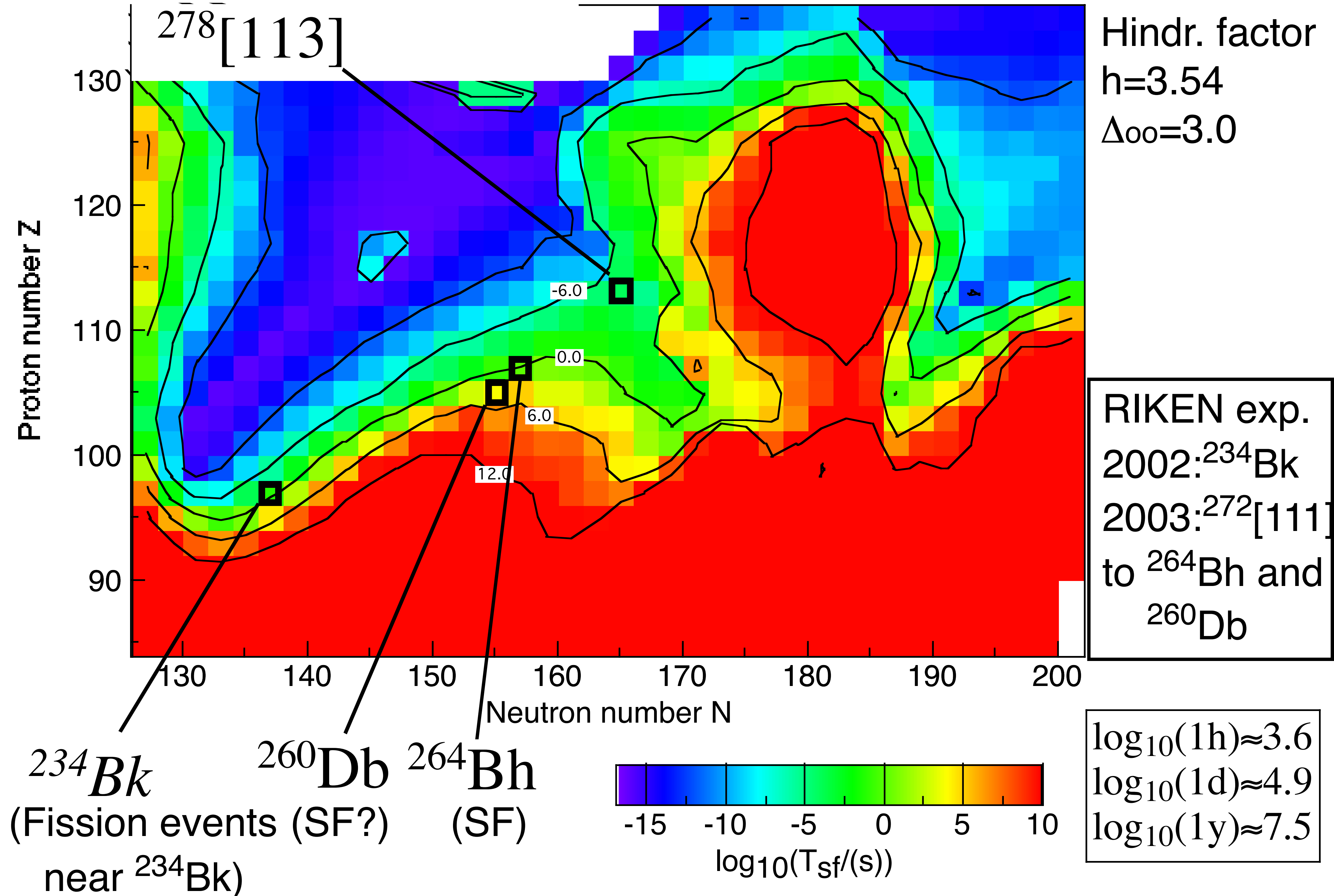


odd-odd nuclei:

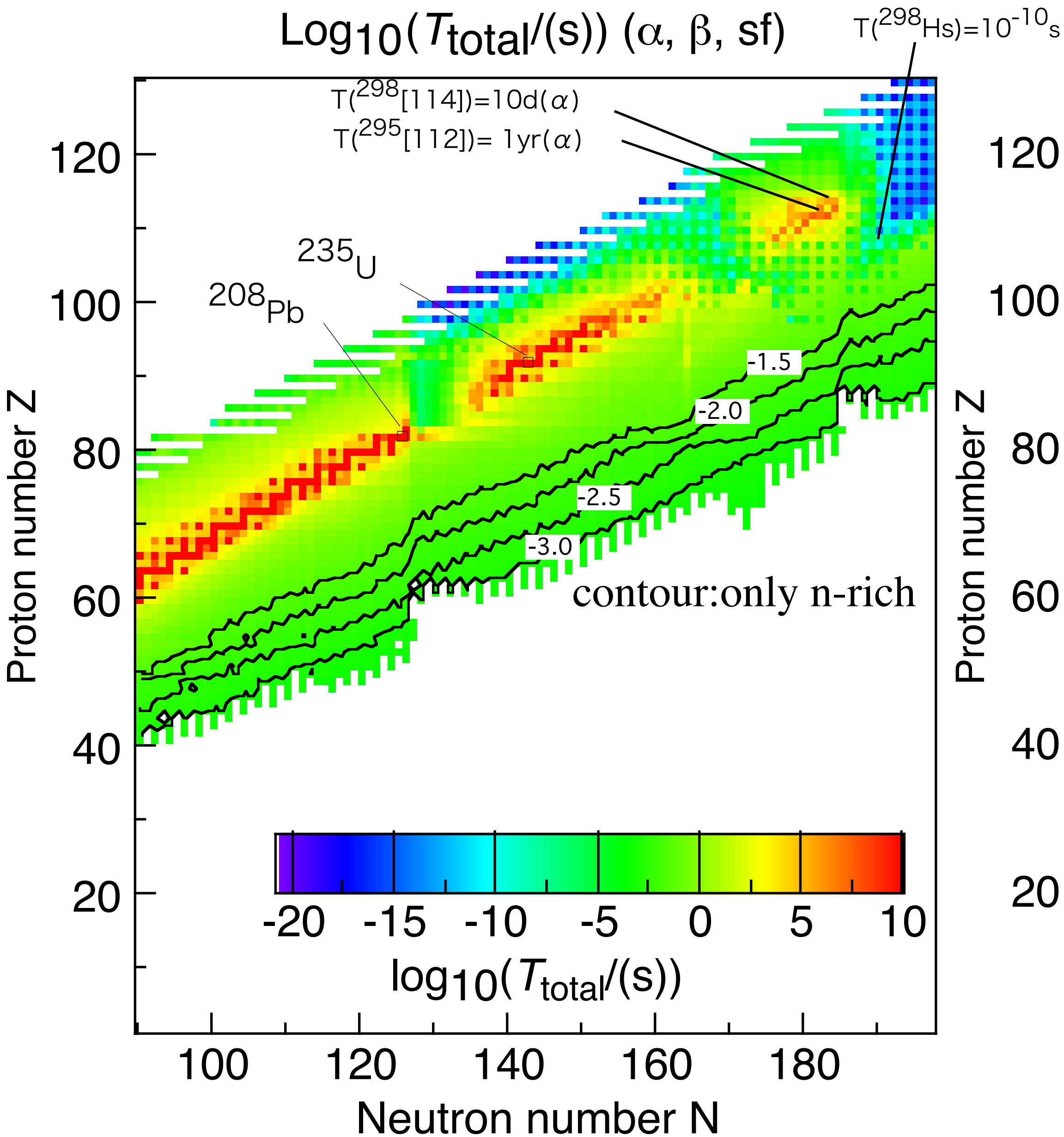
o-o correction $-\Delta_{oo}$=-2.83

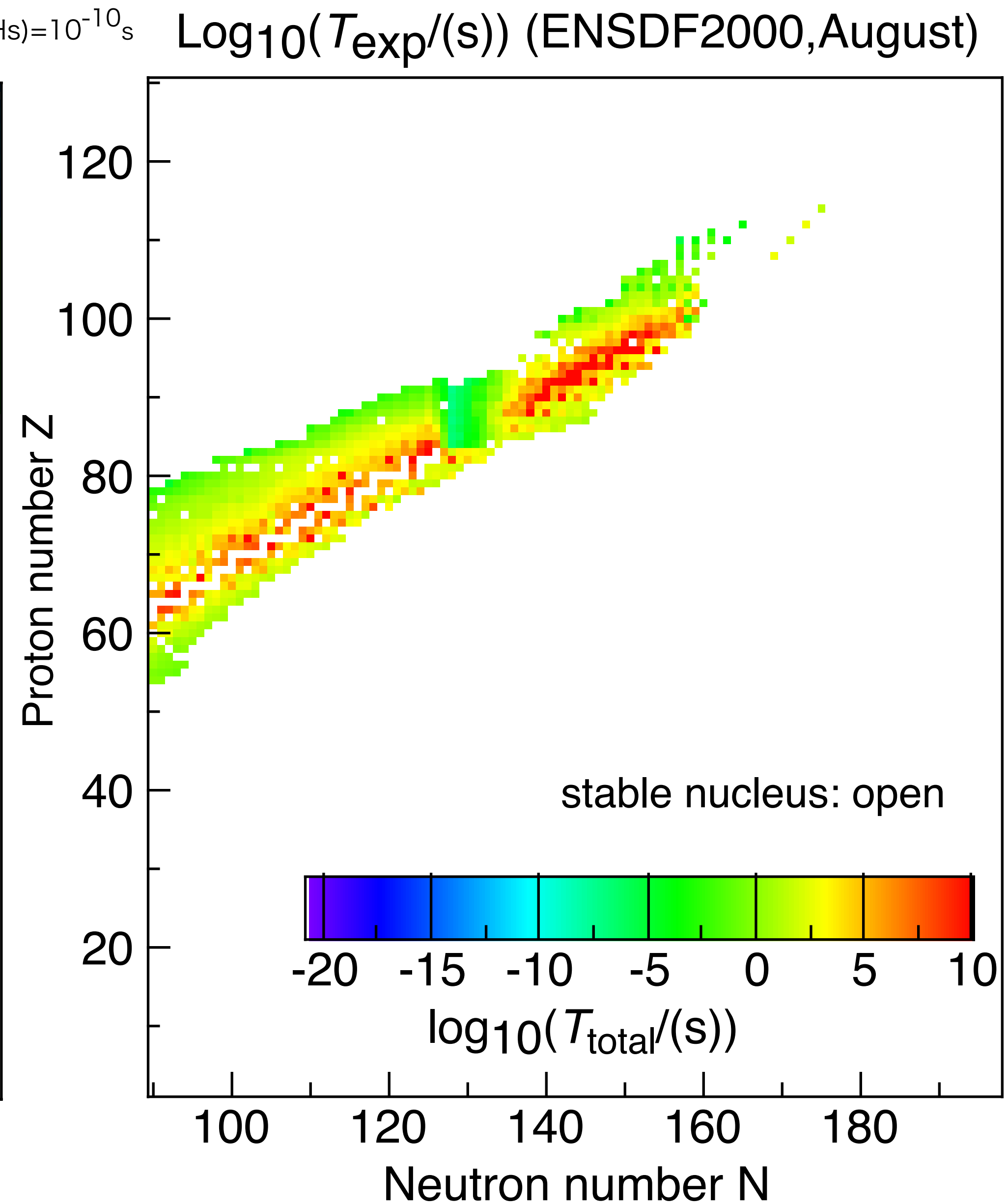
is added

Calculated log10(Tsf/(s)) for odd-odd nuclei



Total half lives(N≤200)

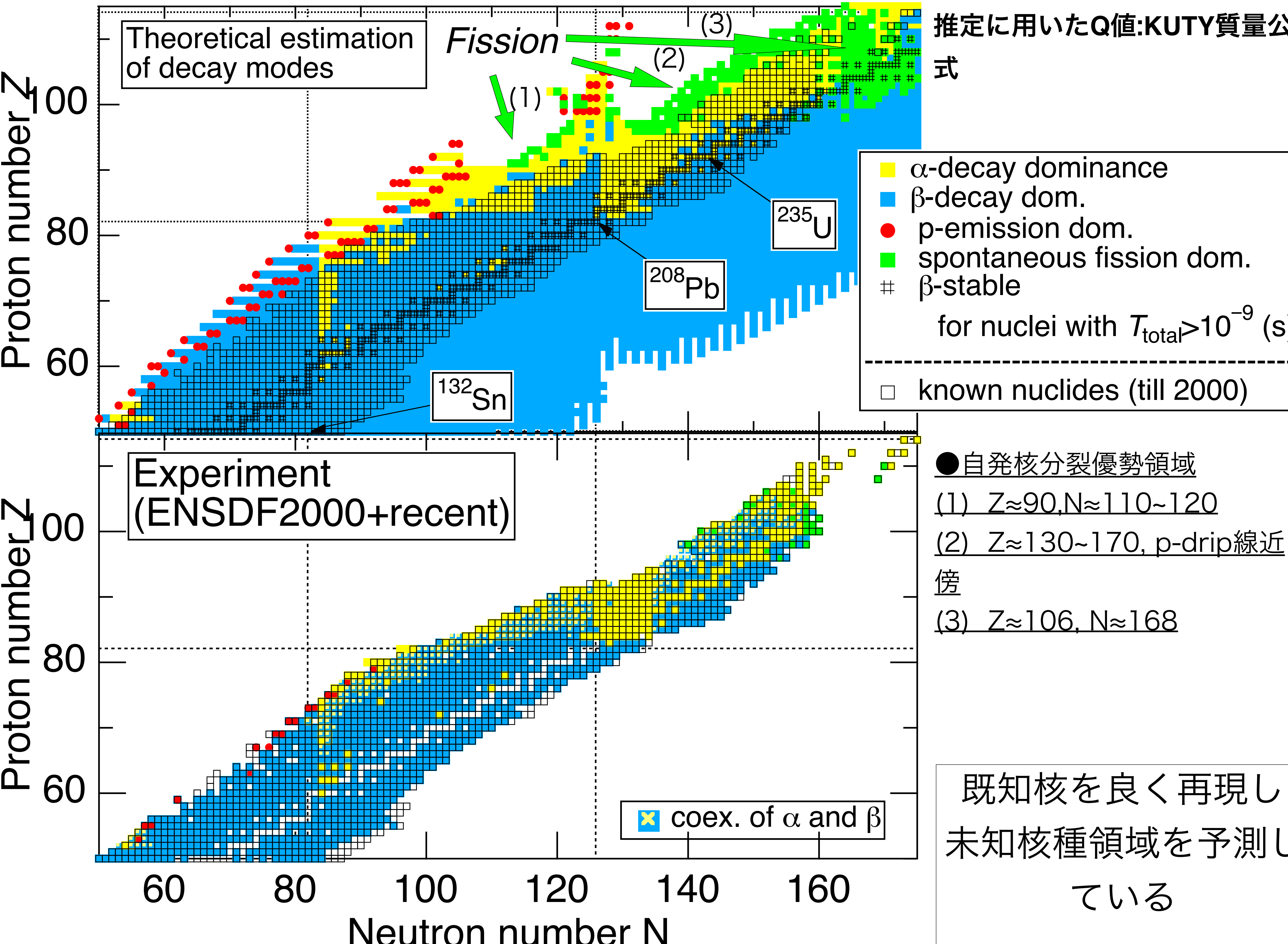




$$\frac{1}{T_{\rm total}} = \frac{1}{T_\alpha} + \frac{1}{T_\beta} + \frac{1}{T_{\rm sf}}$$

既知核を良く再現し未知核種領域を予測している

推定に用いたQ値:KUTY質量公式



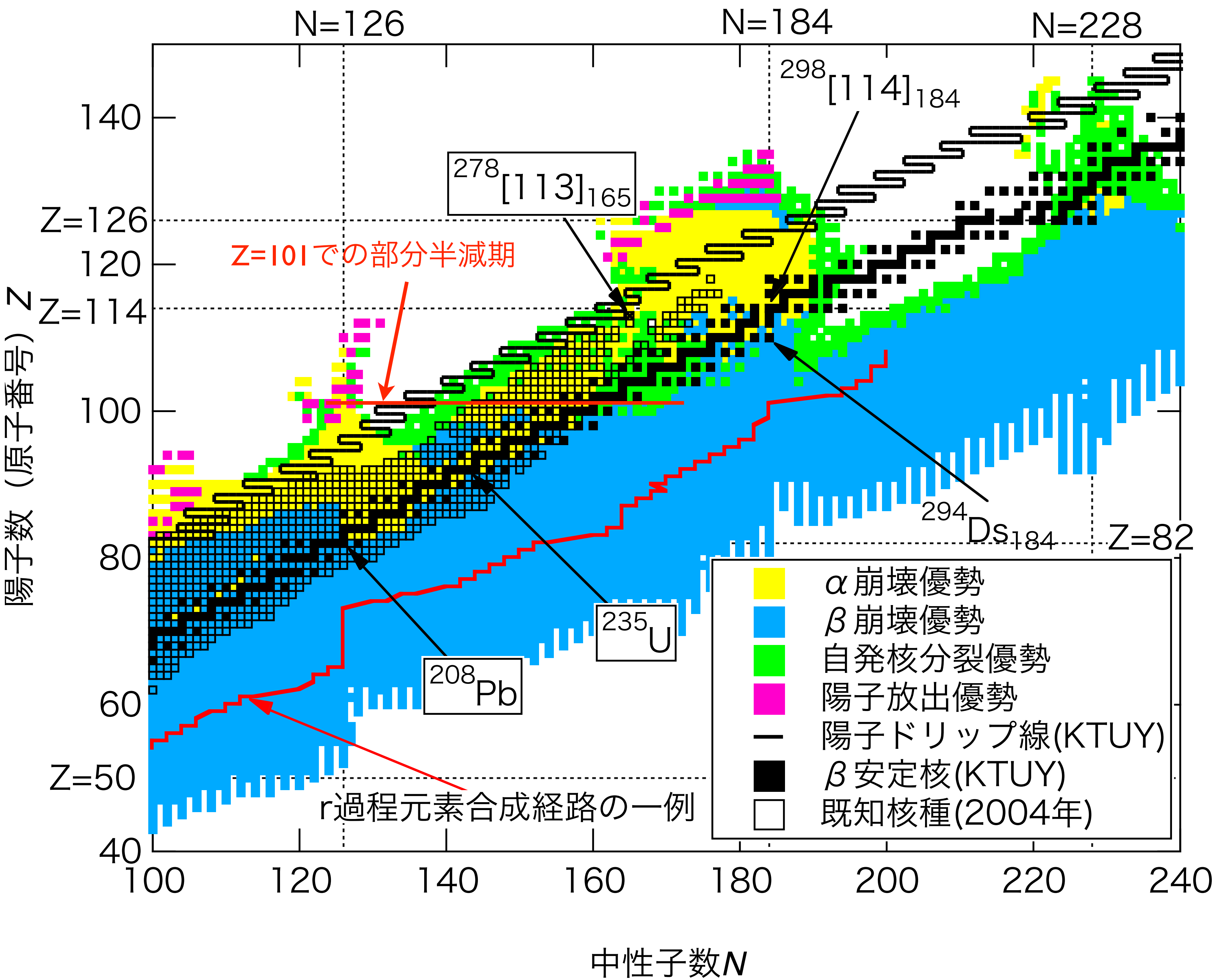
●<u>自発核分裂優勢領域</u>

<u>(1)　Z≈90,N≈110~120</u>

<u>(2)　Z≈130~170, p-drip線近傍</u>

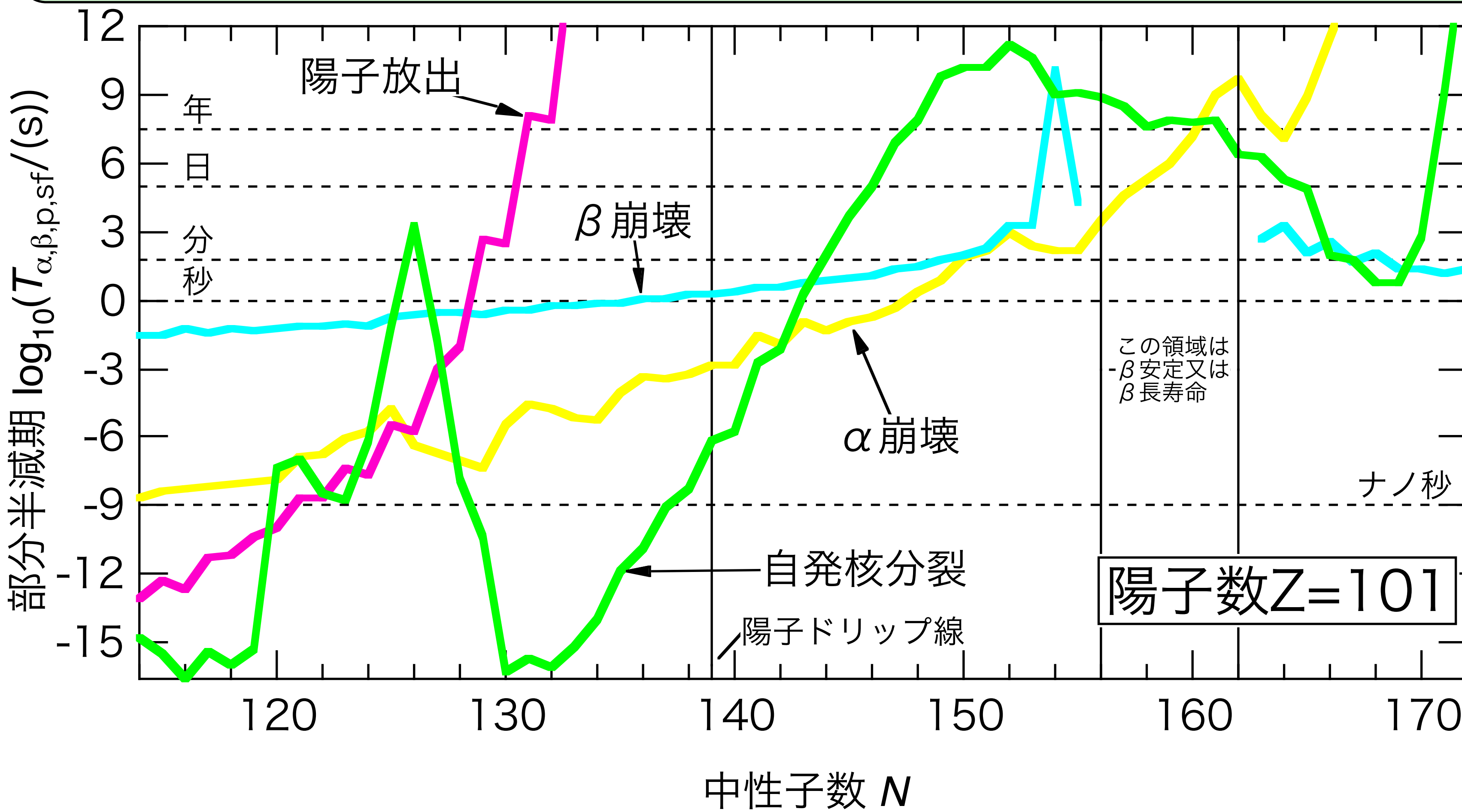
<u>(3)　Z≈106, N≈168</u>

既知核を良く再現し未知核種領域を予測している



N=126
N=184
N=228
298[114]184
278[113]165
Z=126
Z=101での部分半減期
Z=114
294Ds184
Z=82
235U
208Pb
Z=50
r過程元素合成経路の一例
α崩壊優勢
β崩壊優勢
自発核分裂優勢
陽子放出優勢
陽子ドリップ線(KTUY)
β安定核(KTUY)
既知核種(2004年)
陽子数（原子番号）Z
中性子数N

各崩壊の部分半減期



陽子放出: 陽子ドリップ線の(かなり)外から有意な寿命. かなり急変化.

α崩壊:

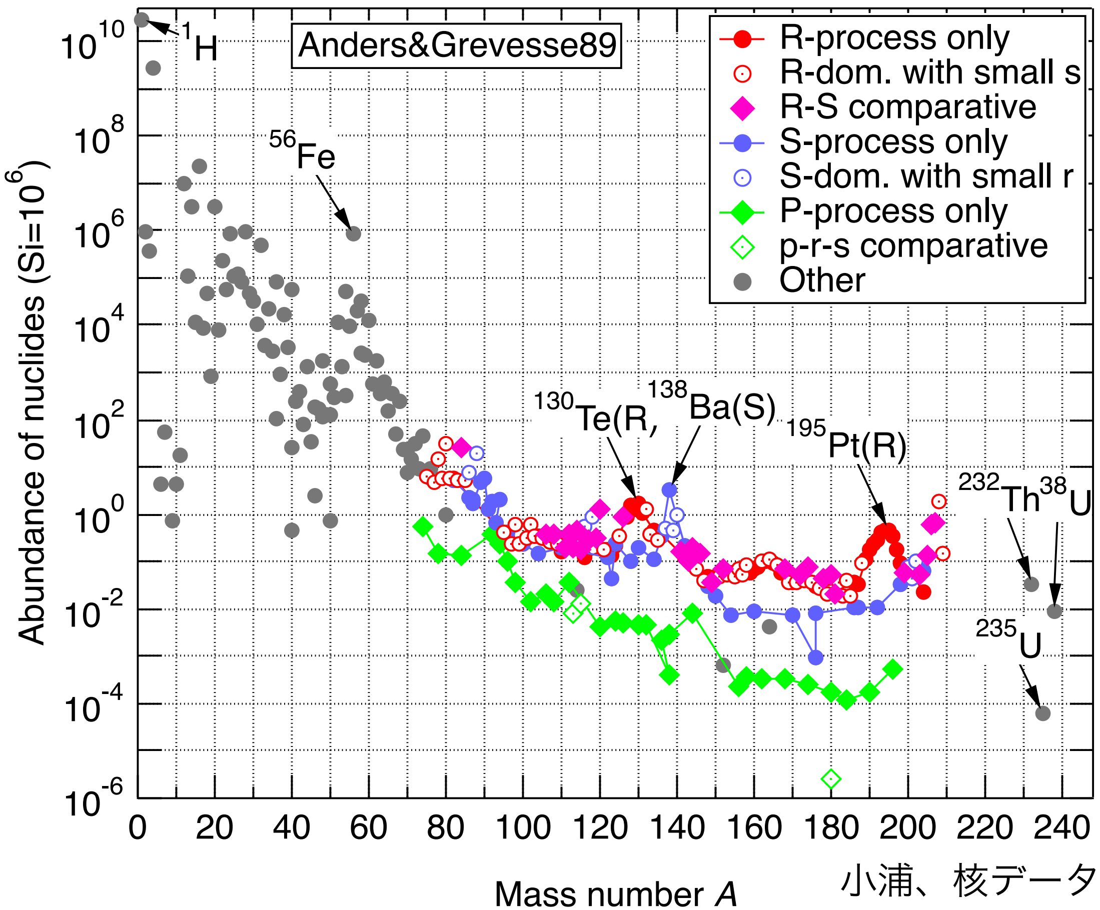
β崩壊: 1ms程度以上をなだらかに推移. N=154-162付近で長寿命orβ安定.

自発核分裂: 核子数依存性が大きい (閉殻およびその中間領域が長寿命)

自発核分裂、陽子放出＞＞α崩壊＞ベータ崩壊

r-process nucleosynthesis

原子核の起源の理論的探求：星の元素合成



小浦、核データニュース**101**, (2012)

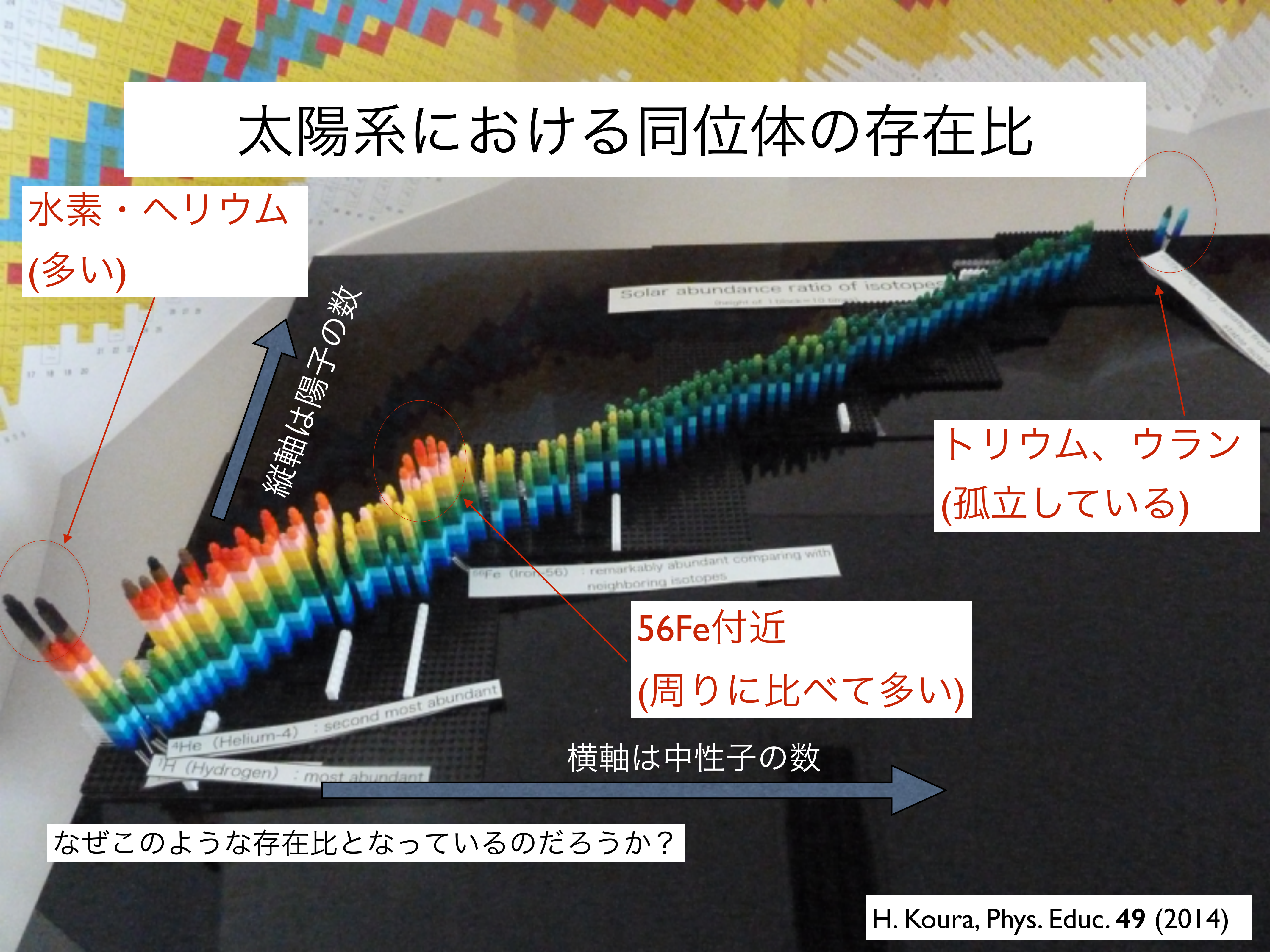
- **S-process:**遅中性子捕獲過程。赤色巨星などで数千年程度かけて中性子捕獲反応が進む。
- **R-process:**速中性子捕獲過程。超新星爆発などで数秒で中性子捕獲反応が進む。

太陽系における同位体の存在比（観測値）

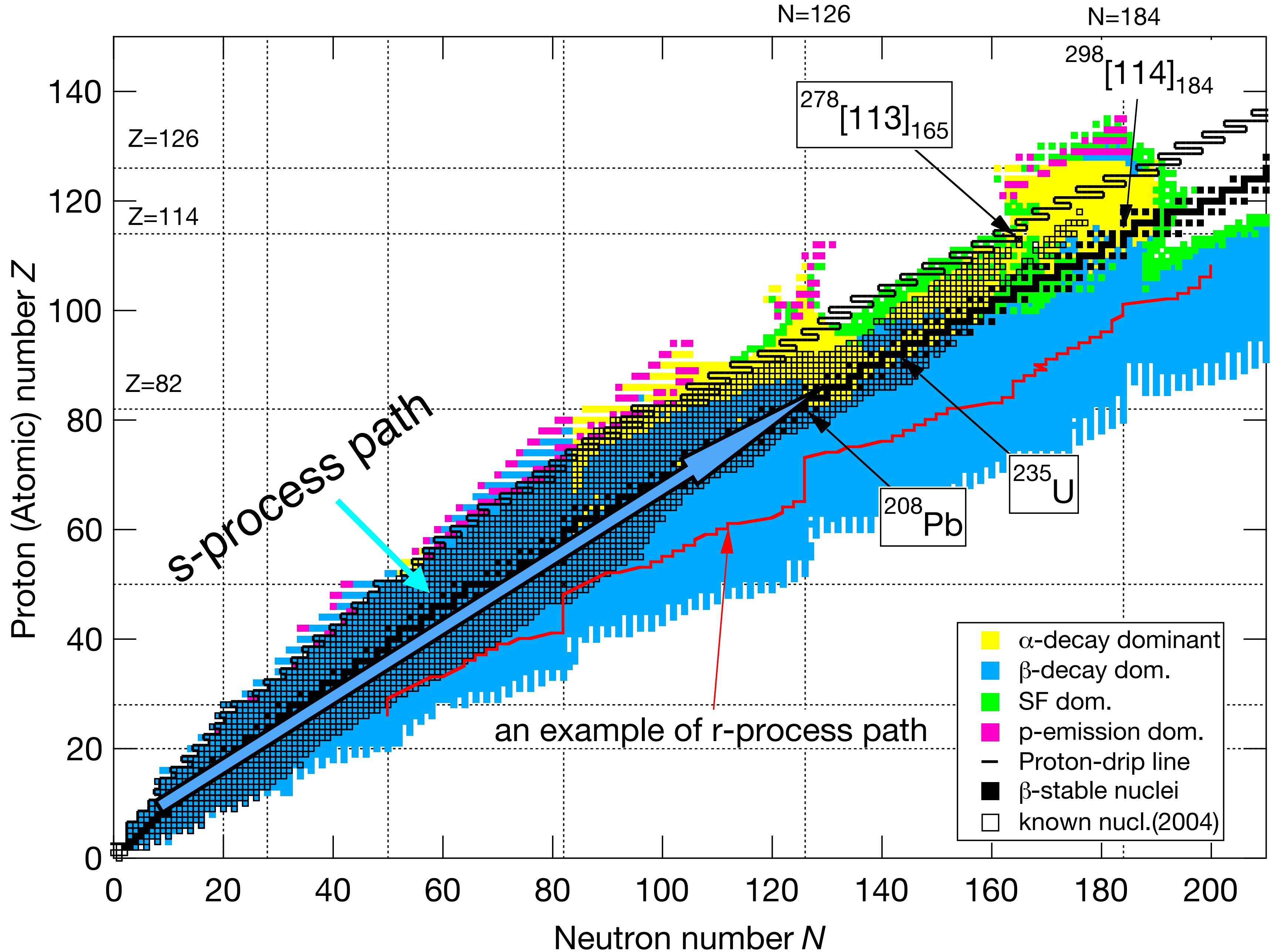
鉄(Fe)より重い原子核の現在の理解

- Fe-Bi：赤色巨星によって作られた(s過程(slow process)
- **Fe-U：超新星爆発によって作られた(r過程(rapid process))**

太陽系における同位体の存在比

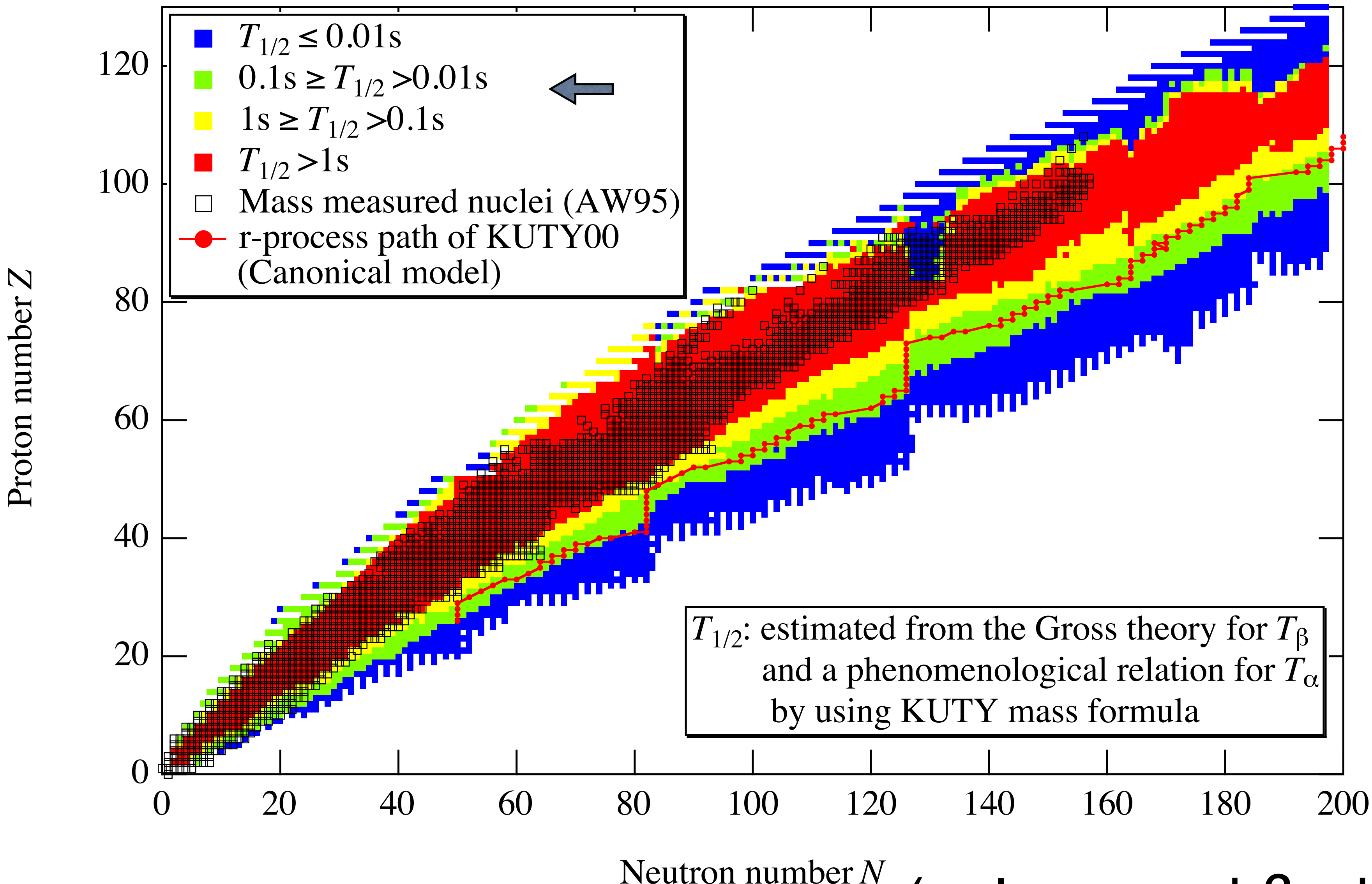


s- and r-process path



Calculated by the KTUY formula

α崩壊とβ崩壊を考慮した半減期計算値



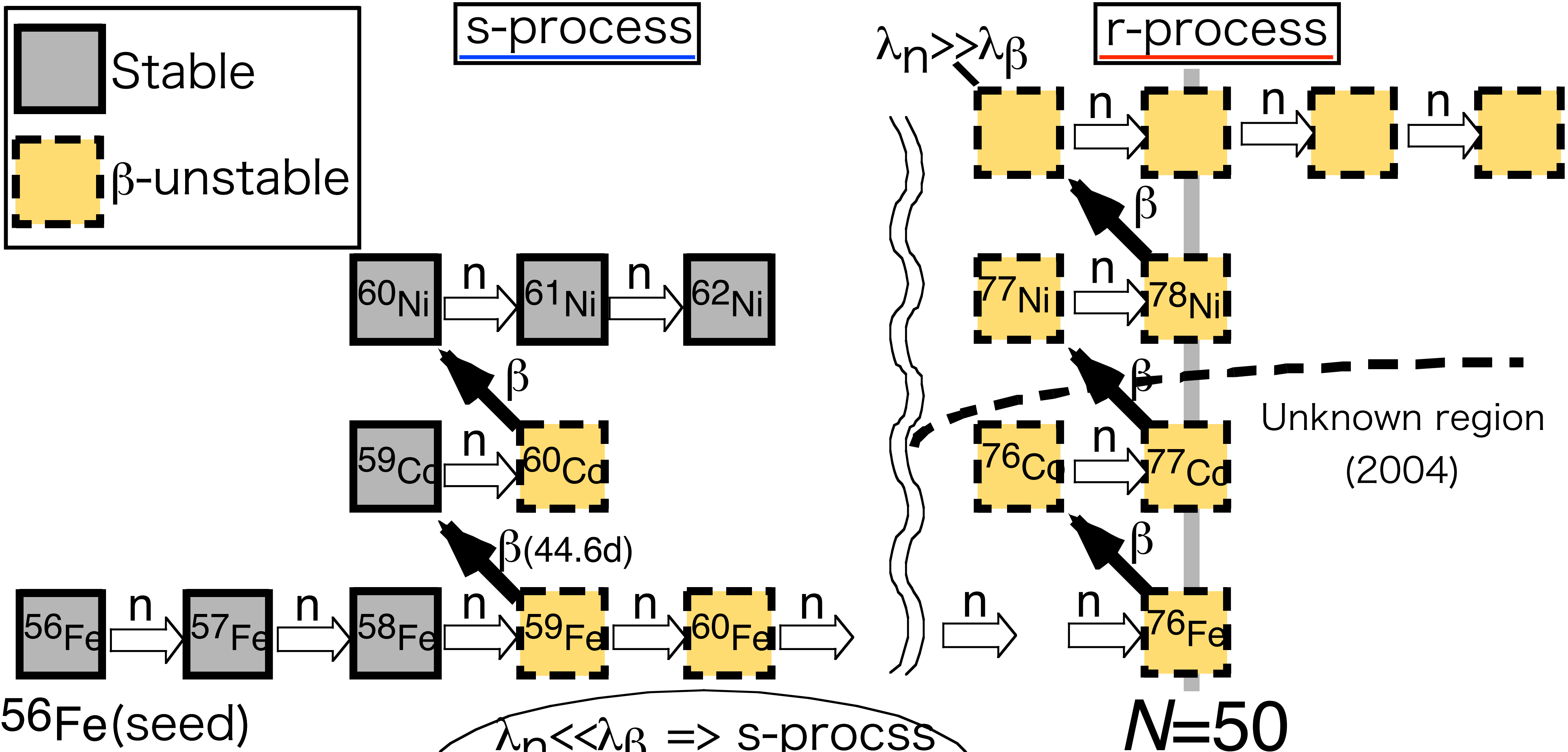
(only α- and β- decay)

r過程経路核：0.1-0.01s

r過程後β崩壊核：0.1s-

$$\frac{1}{T_{1/2}} = \frac{1}{T_\alpha} + \frac{1}{T_\beta}$$

S- and R-process path from ^{56}Fe regarded as a seed nucleus



$\lambda_n \ll \lambda_\beta$ => s-procss

$\lambda_n \gg \lambda_\beta$ => r-procss

(Magic number, λ_n is small)

K. Takahashi

$\lambda_\beta = \ln 2 / T_{\beta 1/2}$

$\lambda_n = N_n v_T \langle\sigma\rangle$

number density

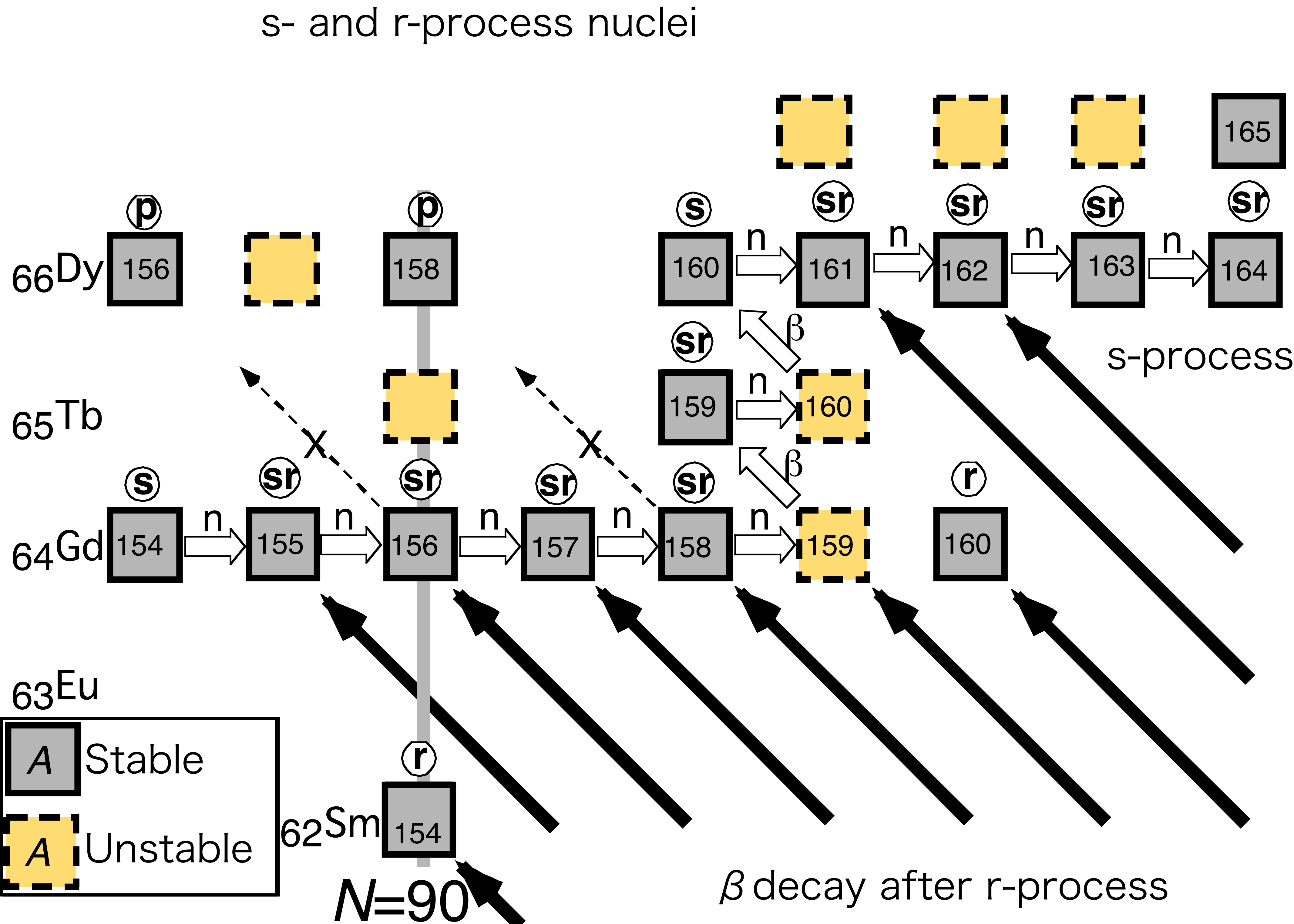
thermal velocity at T

Maxwell-averaged cross section

ex. ^{59}Fe $(v_T\langle\sigma\rangle(^{59}Fe) = 3\times10^{-18} cm^3/s)$

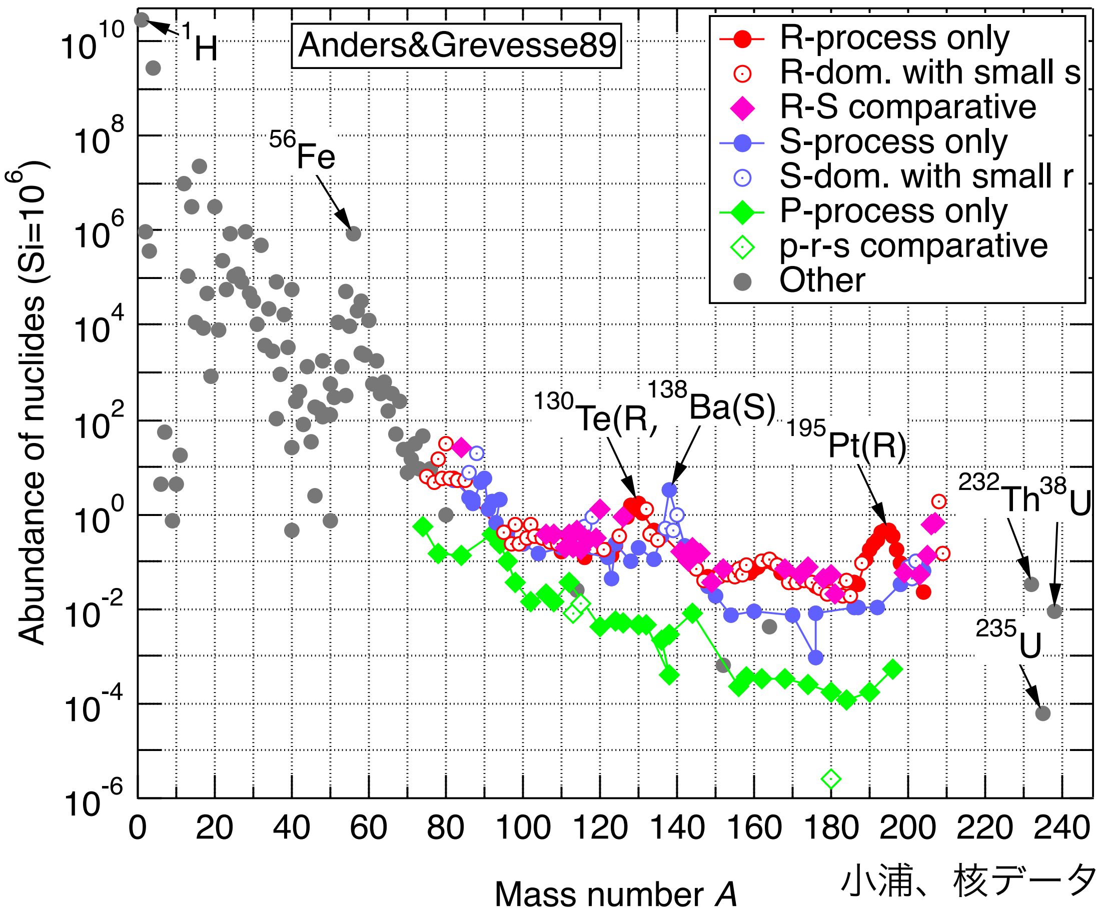
$N_n = 10^6 cm^{-3}$ => $\lambda_n = 3\times10^{-12} s^{-1} \ll \lambda_\beta$ => s-process

$N_n = 10^{20} cm^{-3}$ => $\lambda_n = 3\times10^{2} s^{-1} \gg \lambda_\beta$ => r-process



s- and r-process nuclei
66Dy
65Tb
64Gd
63Eu
62Sm
p
156
158
p
s
160
n
sr
161
n
sr
162
n
sr
163
n
sr
164
165
β
sr
159
n
160
β
s
154
n
sr
155
n
sr
156
n
sr
157
n
sr
158
n
159
r
160
X
X
s-process
r
154
A Stable
A Unstable
N=90
β decay after r-process

目的：原子核の起源の理論的探求　ー星の元素合成ー



小浦、核データニュース101, (2012)

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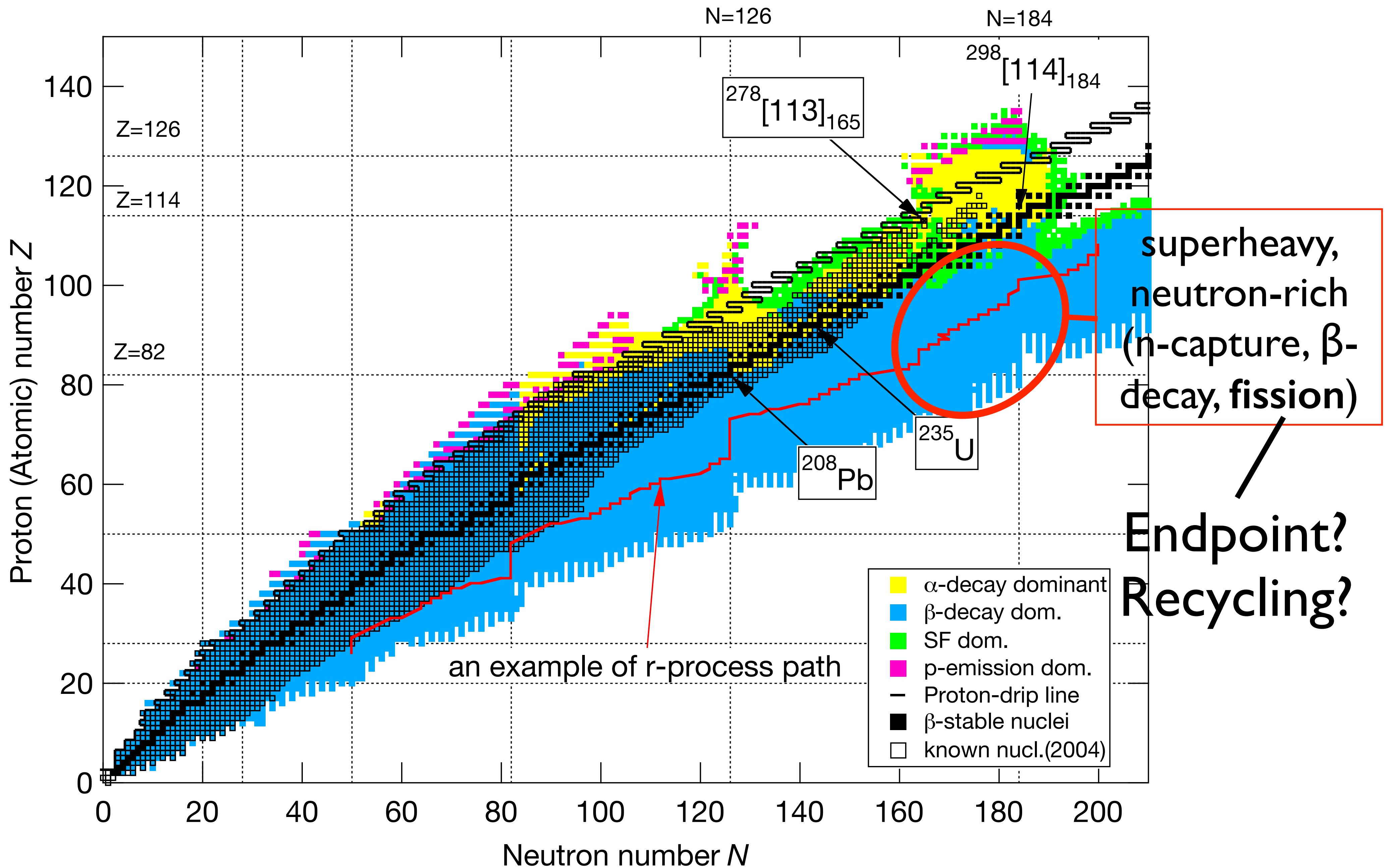
r-process region



Calculated by the KTUY formula

r-process nucleosynthesis and nuclear fission

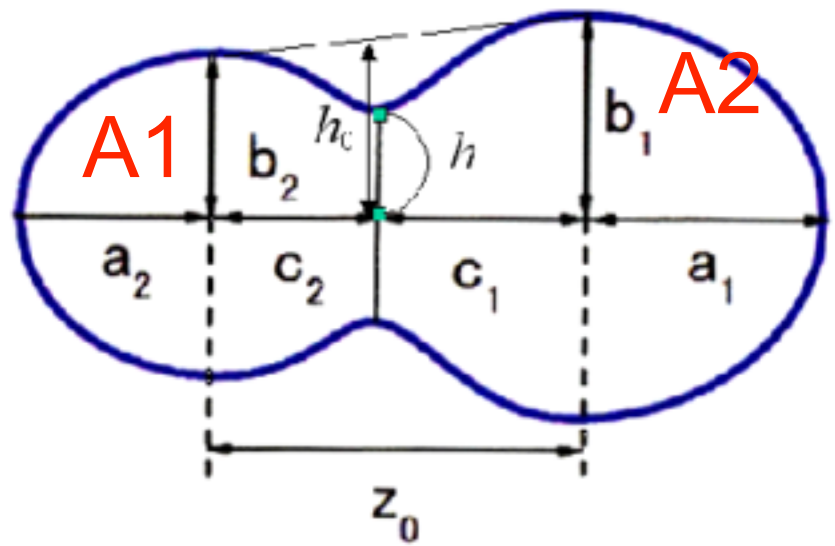
Potential Energy Surface (PES)

Liquid−drop model + Two-center shell model

Code:Yamaji-Iwamoto (70)

PES: 3-dim. deformation parameter space

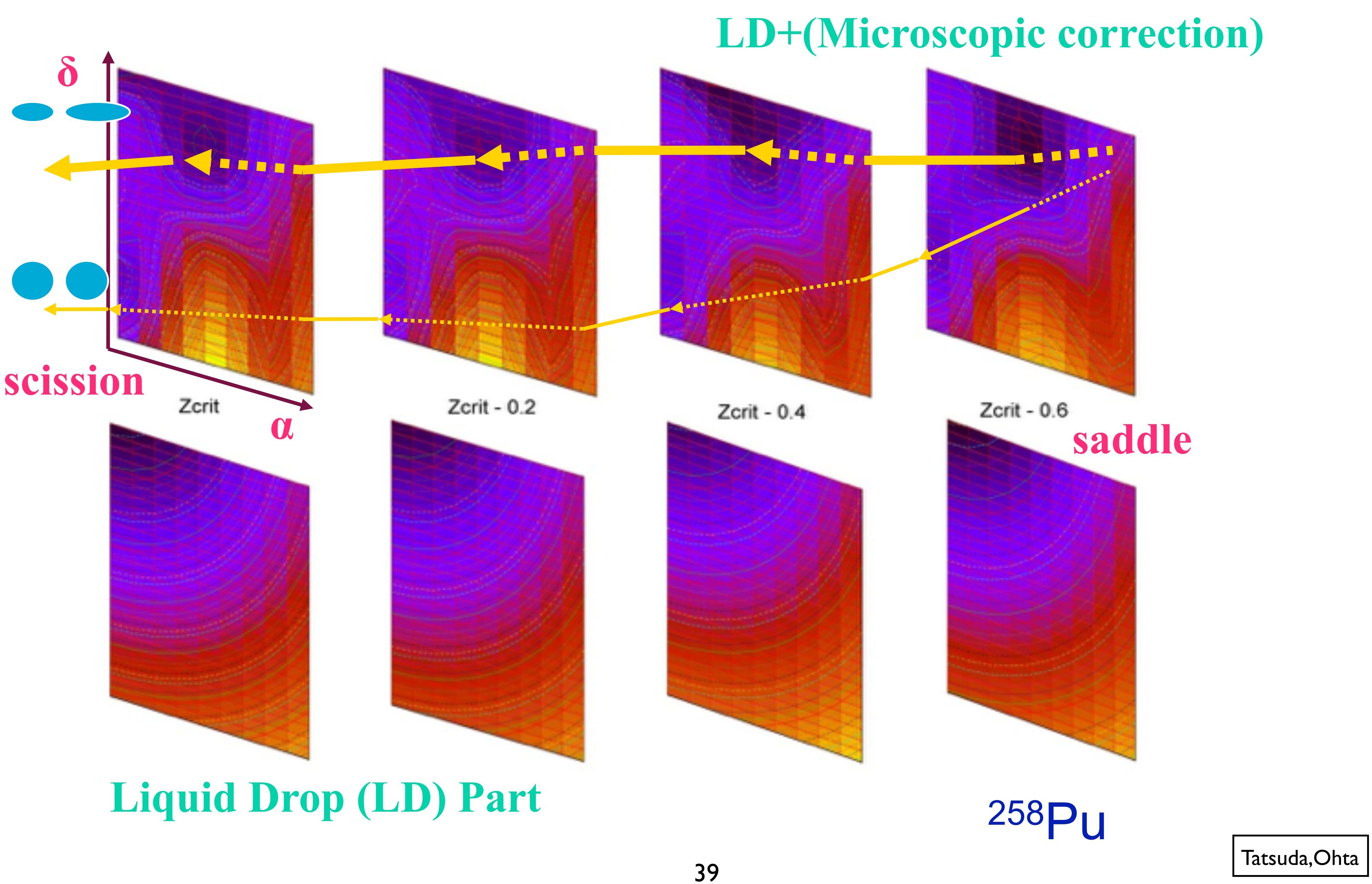
- Center-of-mass distance: $Z = \dfrac{Z_0}{BR}$
- Deformation of fragment: $\delta = \dfrac{3(a-b)}{2a+b}$
- Mass asymmetry: $\alpha = \dfrac{A_1 - A_2}{A_1 + A_2}$



$\left(B = \dfrac{3+\delta}{3-2\delta} \right.$, R : Radius of the spherical compound nucleus $\left. \right)$

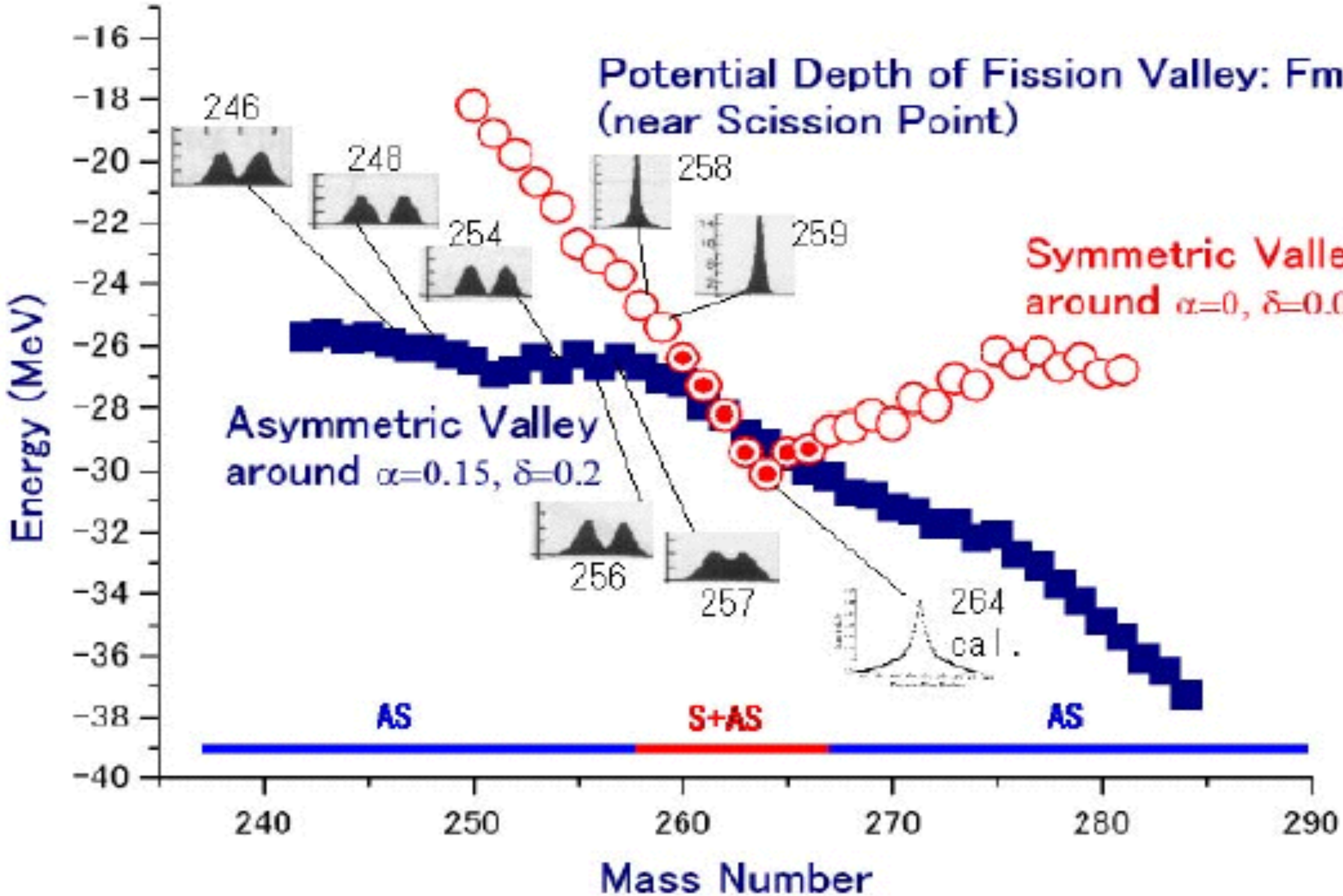
Tatsuda,Ohta

Path of fragments in the 3-dim. deformation space



Region of Symmetric/Asymmetric fission

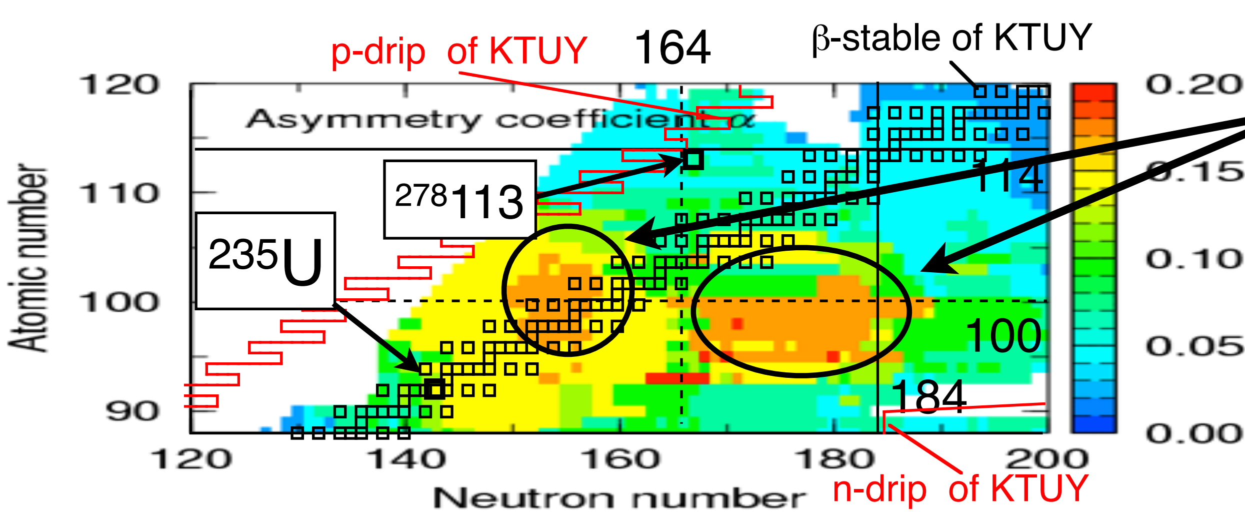
Analysis of PES near Scission Point for Fm isotopes



Tatsuda,Ohta

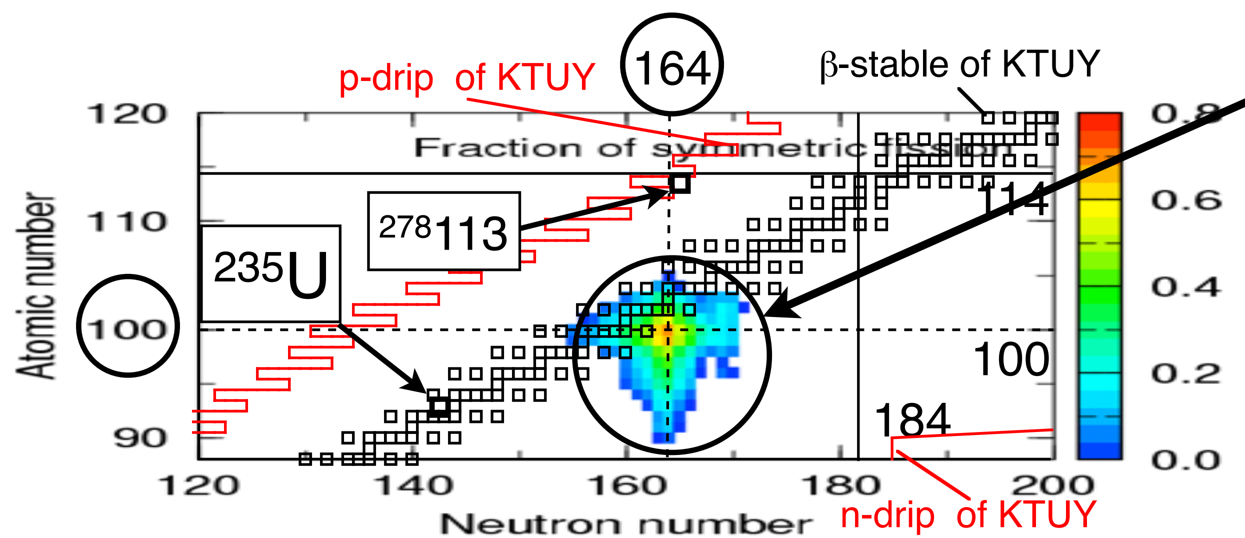
Result - Asymmetric parameter

Asymmetric coefficient α



Well-asymmetric region:
Located around ^{254}Fm (Z=100, N=154) and ^{264}Cf (Z=98, N=176)

Fraction of Symmetric fission



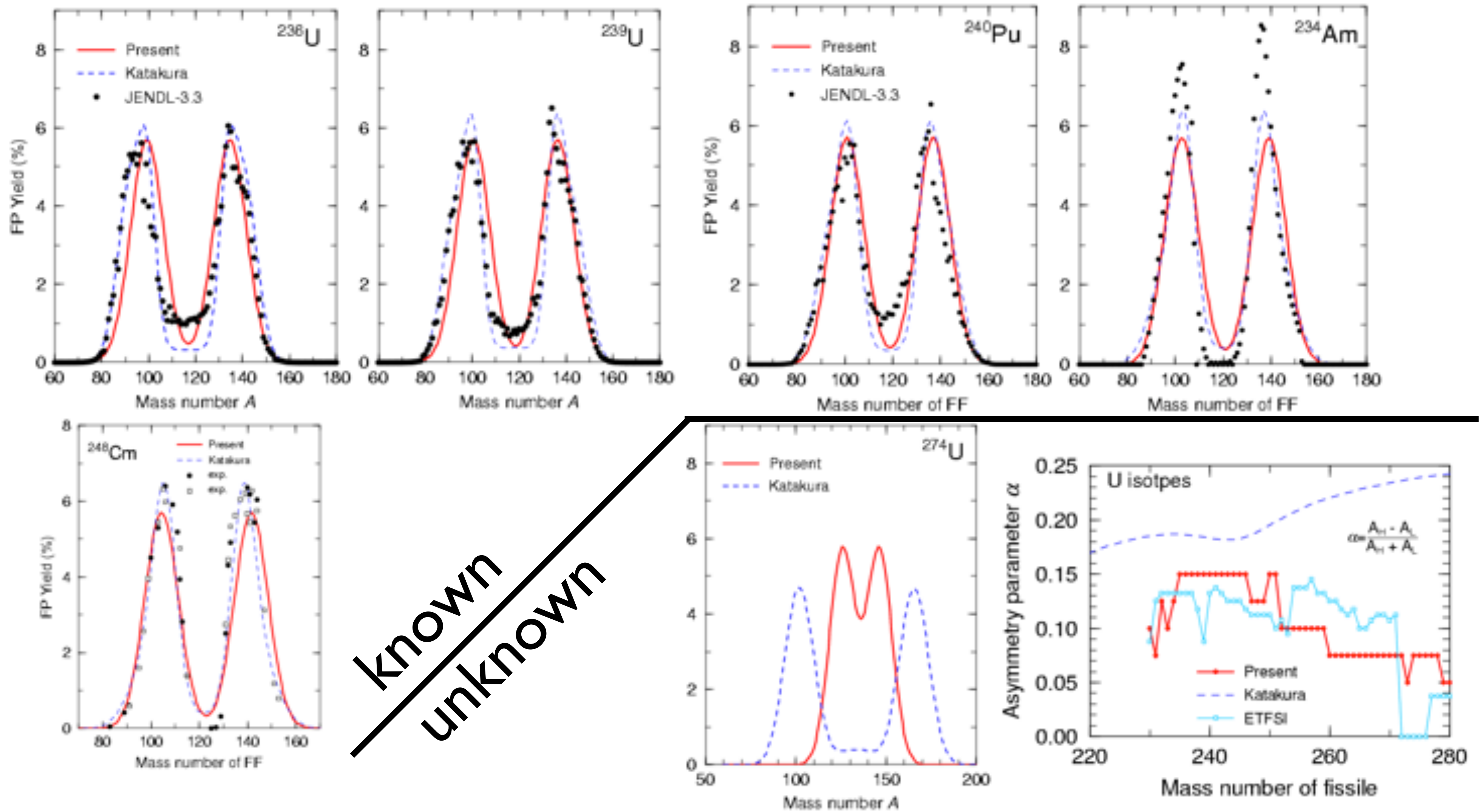
Symmetric-fissioning region:
Located around ^{264}Fm(Z=100, N=164)

Double of ^{132}Sn(Z=50, N=82)

Tatsuda,Ohta

Results - ^{236}U, ^{239}U, ^{240}Pu, ^{234}Am, ^{248}Cm, ^{236}U

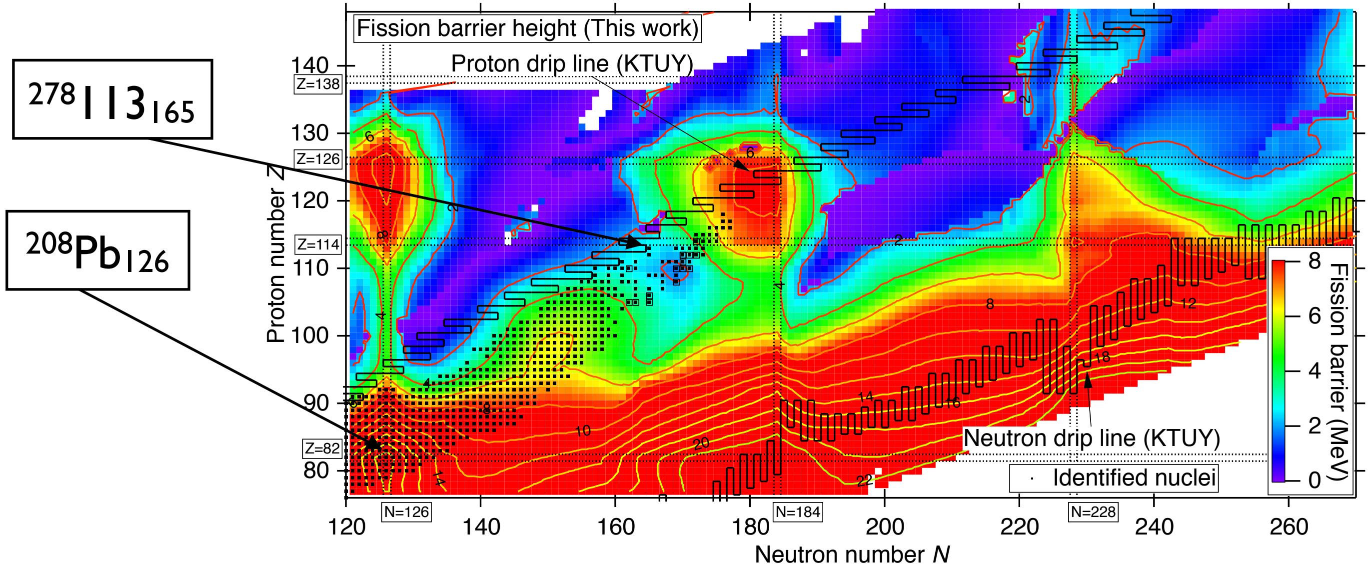
Distribution width:Sum of 3 gauss. on analysis of multi-dim. Langevin eq.



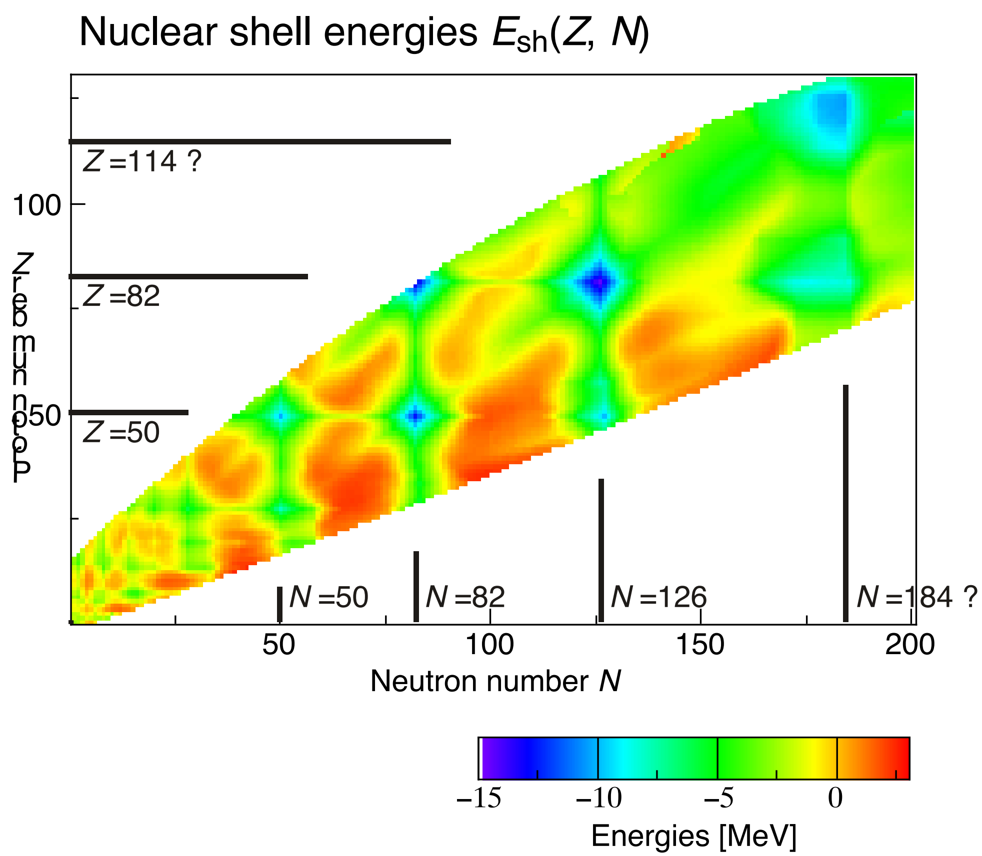
JENDL: Evaluated experimental data
Katakura: Empirical FFMD formula (function of A)

Tatsuda,Ohta

Nuclear mass and fission barrier height



Fission barrier height

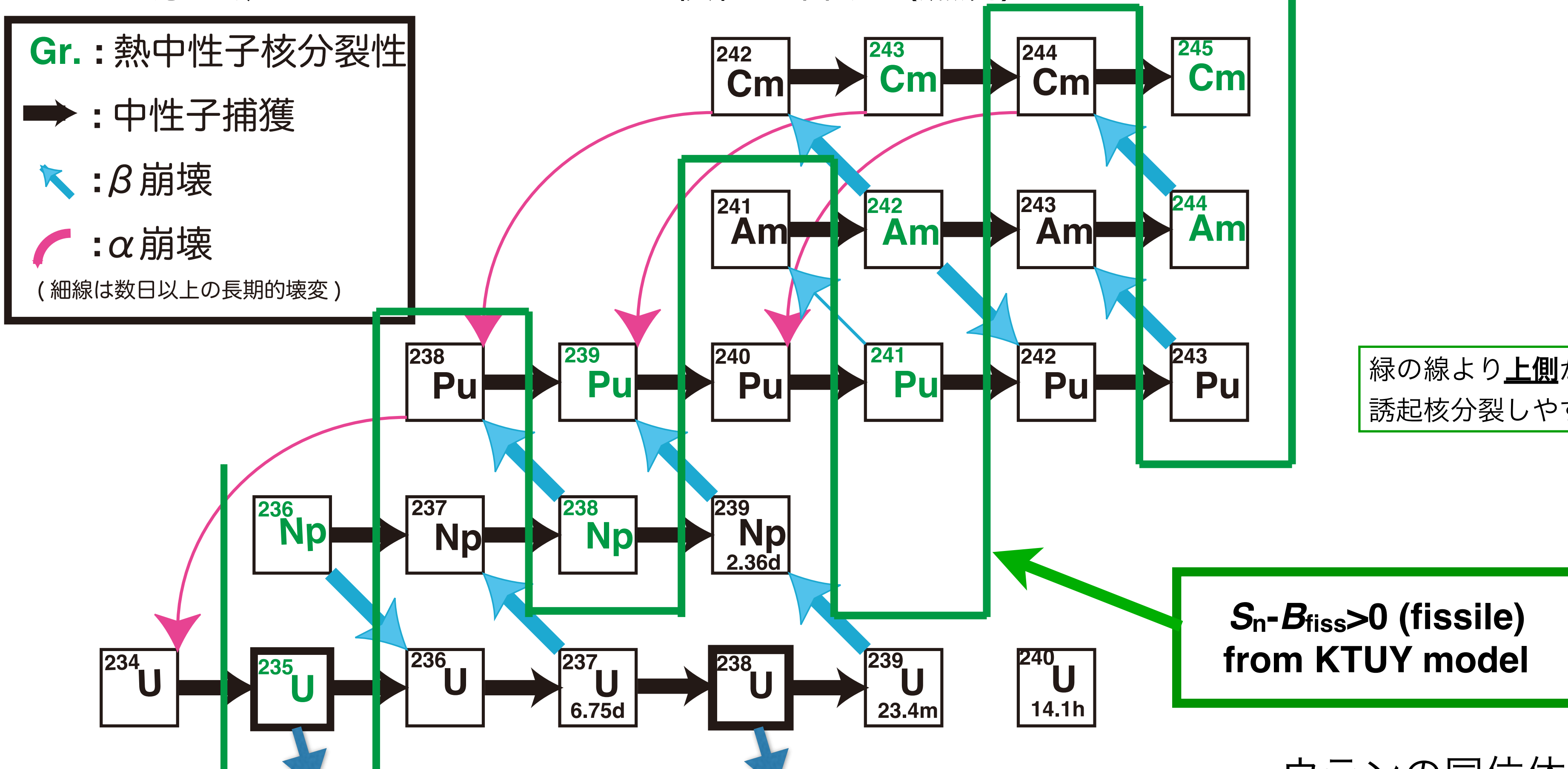


Nuclear shell energy

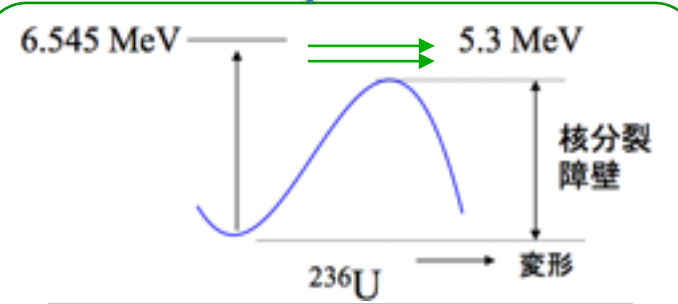
Koura

ウランと中性子の核反応

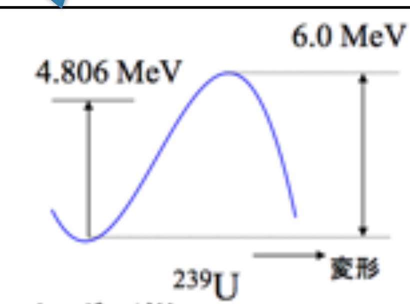
原子炉におけるアクチノイド核種の合成（燃焼）プロセス



緑の線より**上側**が中性子誘起核分裂しやすい



●^{235}Uは核分裂性



●^{238}Uは非核分裂性

ウランの同位体比(天然)

^{235}U : ^{238}U =
0.7 : 99.7

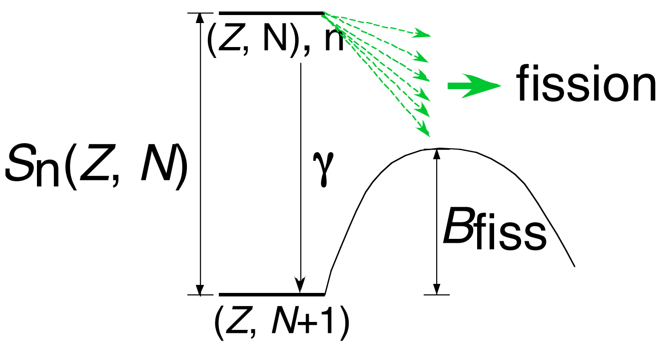
これを利用

2. β-delayed fission (β-df) probability

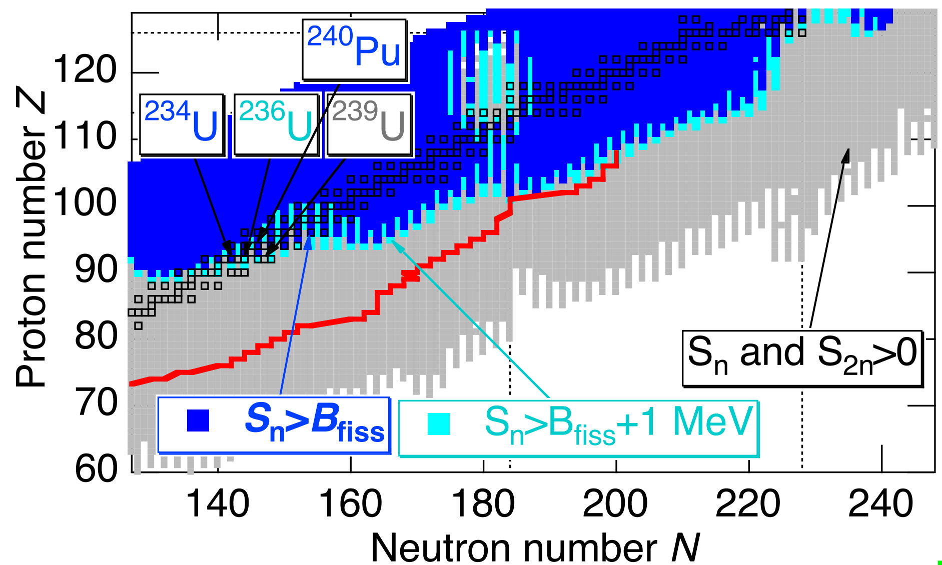
Region of β-delayed and n-induced fission

Nuclear masses and fission barrier:
KTUY (Koura-Tachibana-Uno-Yamada) mass formula

- n-induced fission

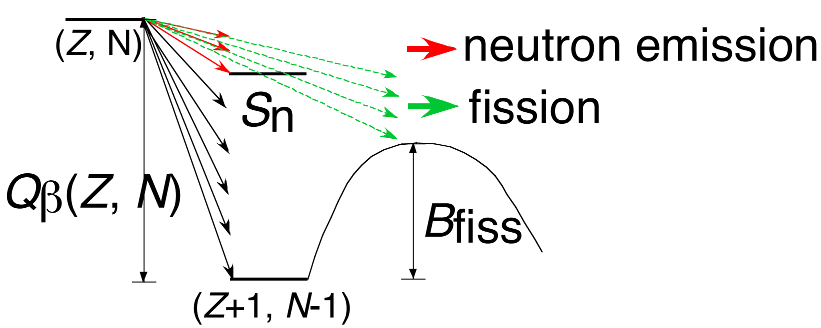


neutron-induced fission

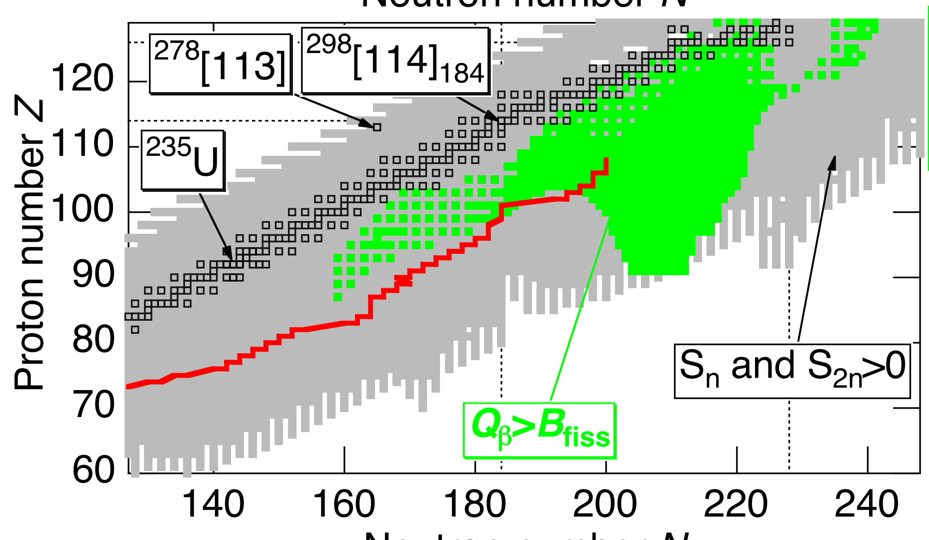


$S_n > B_{fiss}$

- β-delayed fission



β-delayed neutron emission and β-delayed fission



$Q_\beta > B_{fiss}$

Koura

β-delayed fission probability P_f

β-delayed fission or neutron probability

$$P_k = \frac{C}{\lambda}\int_{-Q_\beta}^{0} S_\beta(E) f(-E) \frac{\Gamma_k}{\Gamma_n + \Gamma_\gamma + \Gamma_f} dE$$

$k = \mathrm{f}$: delayed fission

$k = \mathrm{n}$: delayed neutron

Gross Theory of β-decay

(Tachibana, Yamada)

$S_\beta(E)$: β-strength function

λ: decay const. of β-decay

$f(-E)$: Fermi function

KTUY mass formula

Q_β : β-decay Q-value

S_n: neutron sep. energy

B_f: fission barrier height

δW: shell energy

Decay width Γ_n and Γ_f

$$\Gamma_n(E) = \frac{1}{2\pi}\frac{1}{\rho(E)}\frac{2MR^2}{\hbar^2} g \int_0^{E-S_n} \rho^*(E-S-\epsilon)\epsilon d\epsilon$$

$$\Gamma_f(E) = \frac{1}{2\pi}\frac{1}{\rho(E)}\int_{-\infty}^{E-B_f} \frac{\rho^*(E-S-\epsilon)}{1+exp(-2\pi E/\hbar\omega)} d\epsilon$$

Phenom. formula

(Kawano, Chiba, HK, JNST 43 (2006))

$$E_x = U + A$$

$$\sigma = C^{1/2} A^{5/6} (U/A)^{1/4}$$

$$a = a^* \left\{1 + \frac{\delta W}{U}\left(1 - e^{-\gamma U}\right)\right\}$$

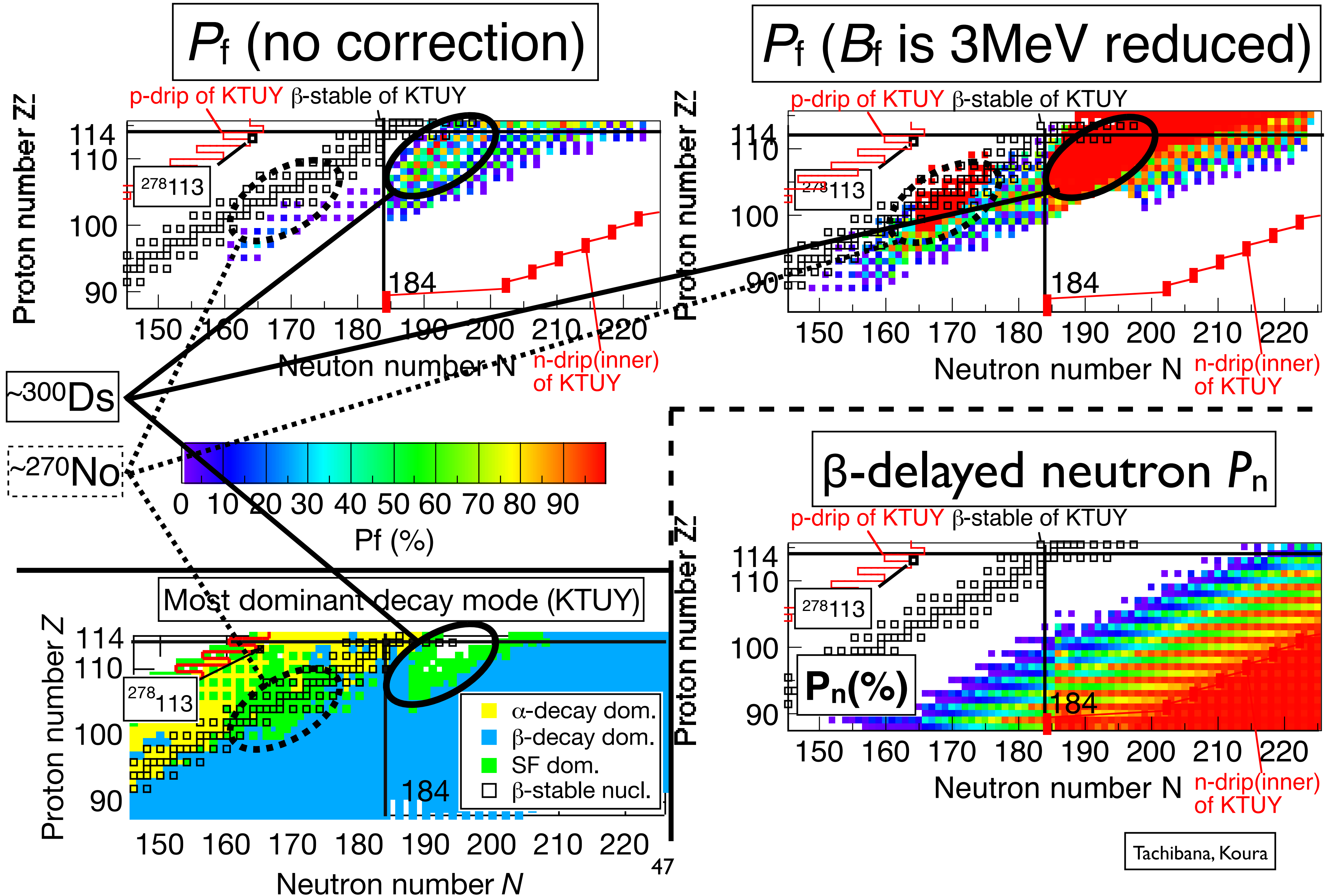
Level density formula (Gilbert-Cameron type)

$$\rho_{GC}(E_x, J) = \frac{1}{12\sigma\sqrt{2}} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} \frac{2J+1}{2\sigma^2} \exp\left(-\frac{(J+1/2)^2}{2\sigma^2}\right)$$

$$\rightarrow \rho_{GC}(E_x) = \frac{1}{12\sigma\sqrt{2}} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} \ (\mathrm{MeV}^{-1})$$

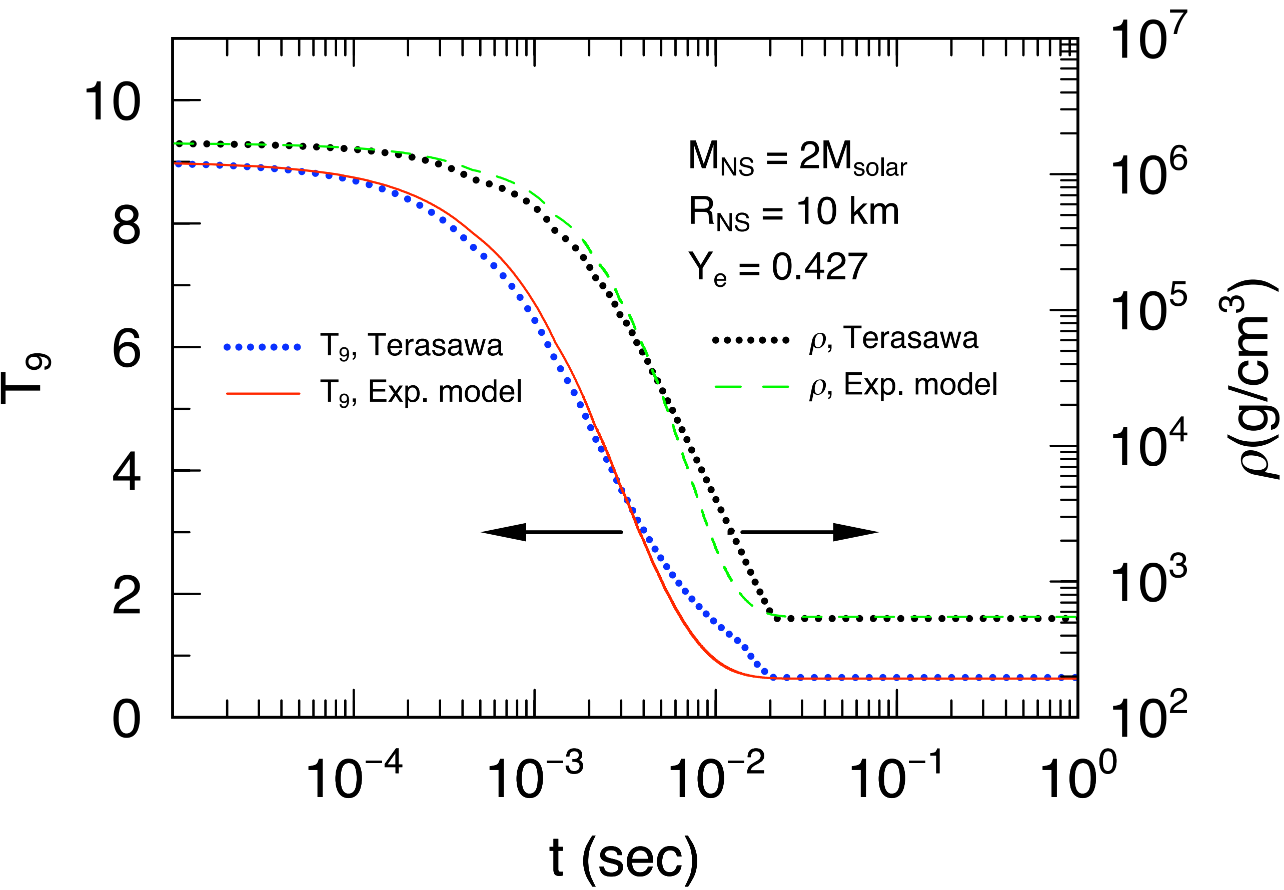
Tachibana

Results -β-delayed fission probability P_f



R-process network calculation

Trajectory of supernova matter



exponential model

$$T_9 = T_{9_0} \exp(-t/T_{\rm ex}) + 0.7$$

$$\rho(t) = \frac{3.33 \times 10^5 T_9(t)^3}{S}$$

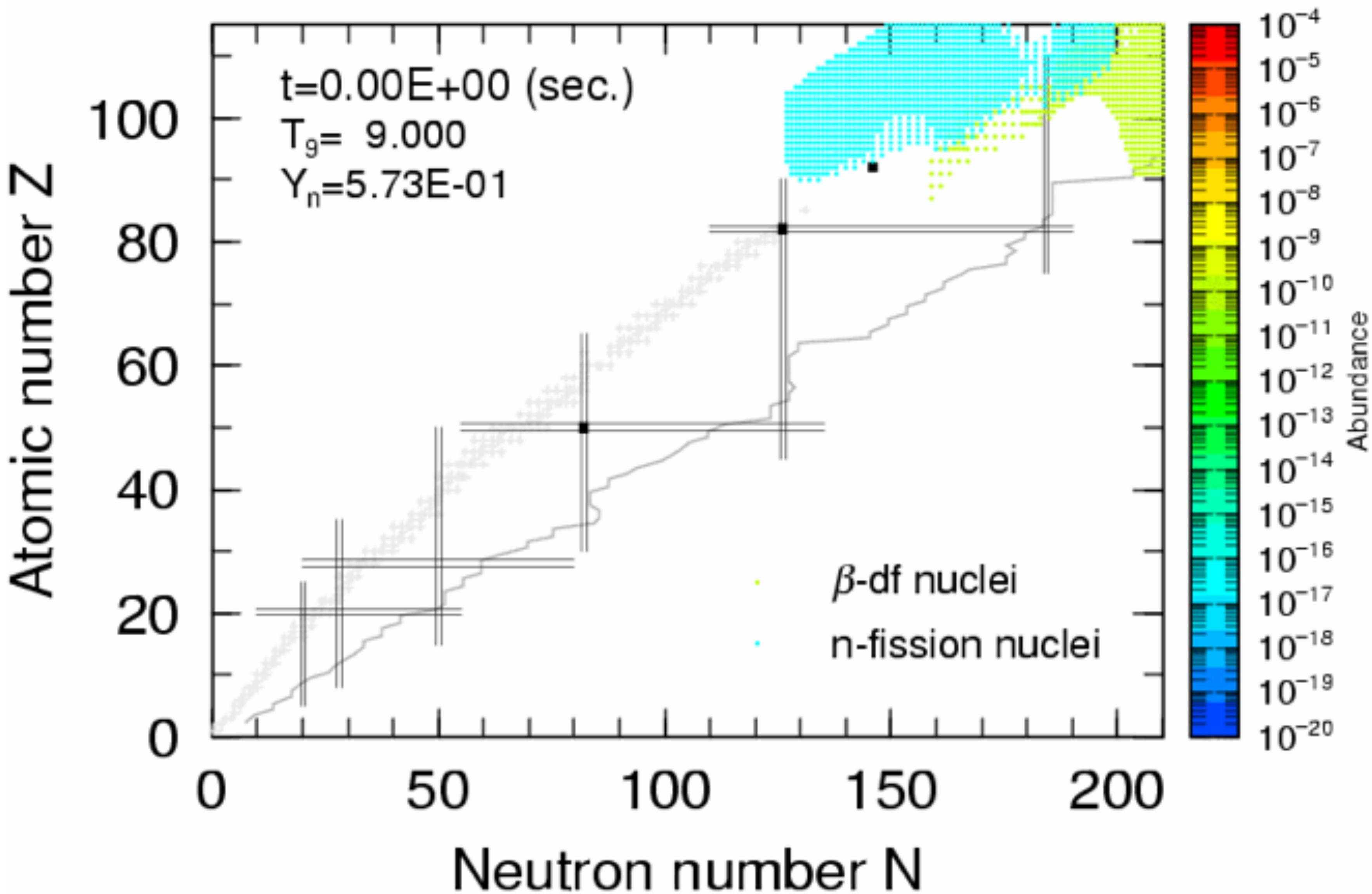
$$T_9(t=0) = 9$$

Considered fission:only β-delayed fission

Sumiyoshi, Chiba, Otsuki, Kajino

Time evolution of the r- process

S=200, B_f -> B_{fKTUY}−3MeV



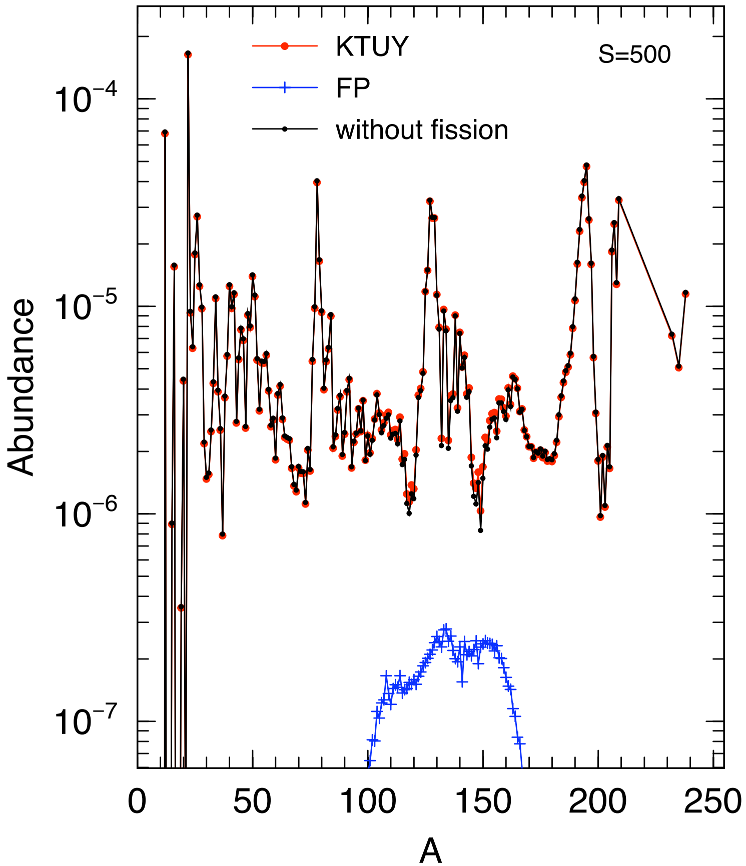
25 sec in actual time

Chiba

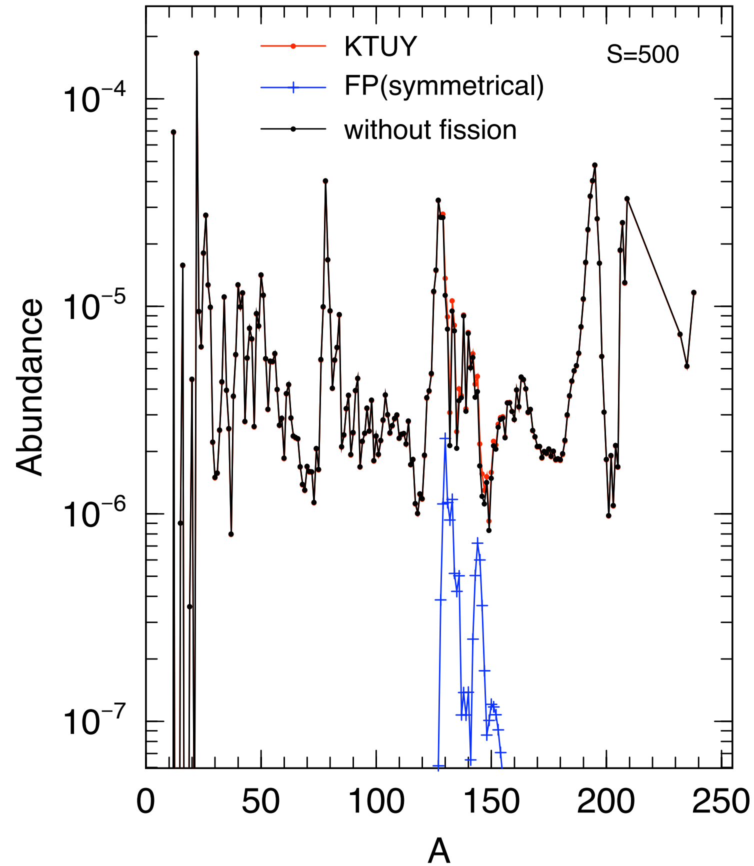
Results -r-process abundances (fission effect)

S=200, B_f -> B_{fKTUY}

FFMD: 2-center shell.



FFMD: Symmetric



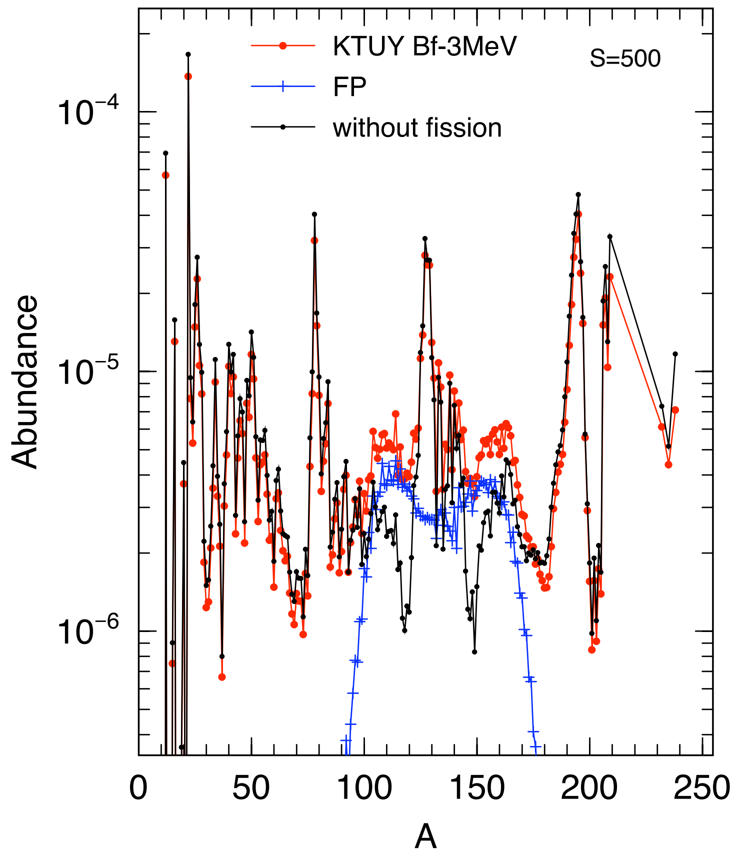
Little contribution to r process
-> To check the effect of fission, we reduce fission barrier by 3MeV.

Chiba

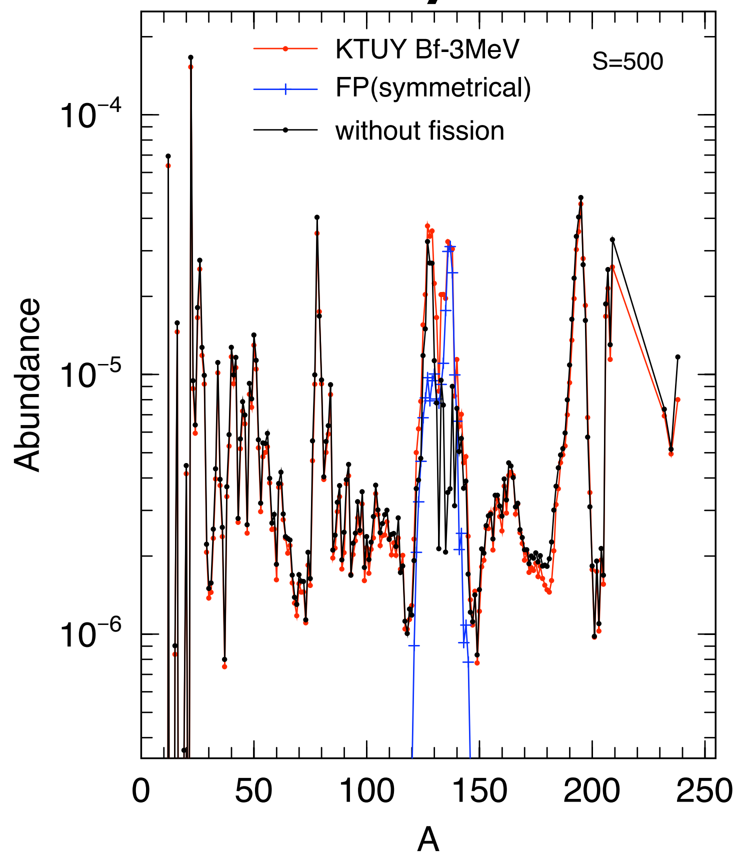
Results -r-process abundances (fission effect)

S=200, B_f -> B_{fKTUY}−3MeV

FFMD: 2-center shell.



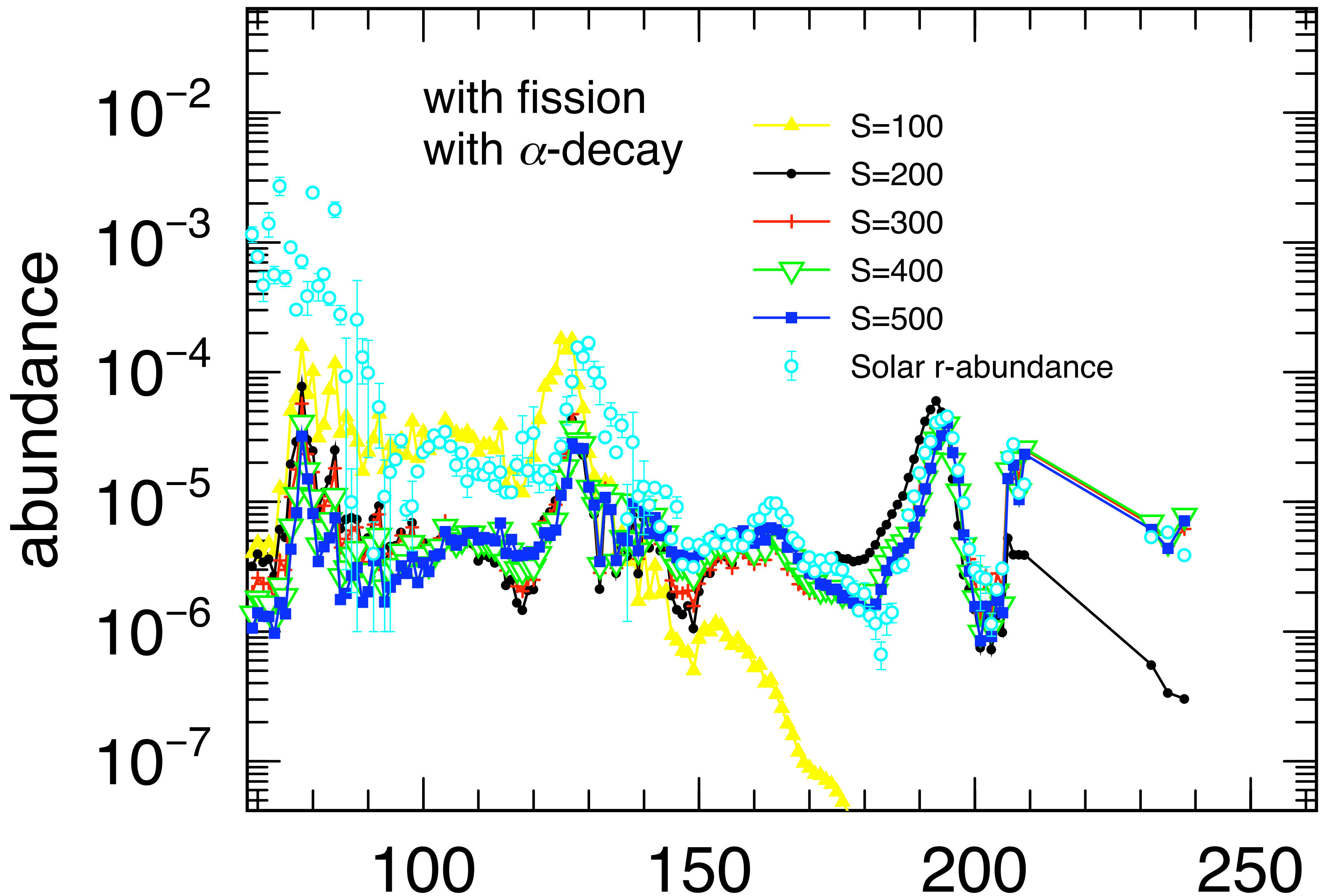
FFMD: Symmetric



Accumulated fission mass fragments could compensate A~110, 150 region.
(depends on predicted fission barrier heights)

Chiba

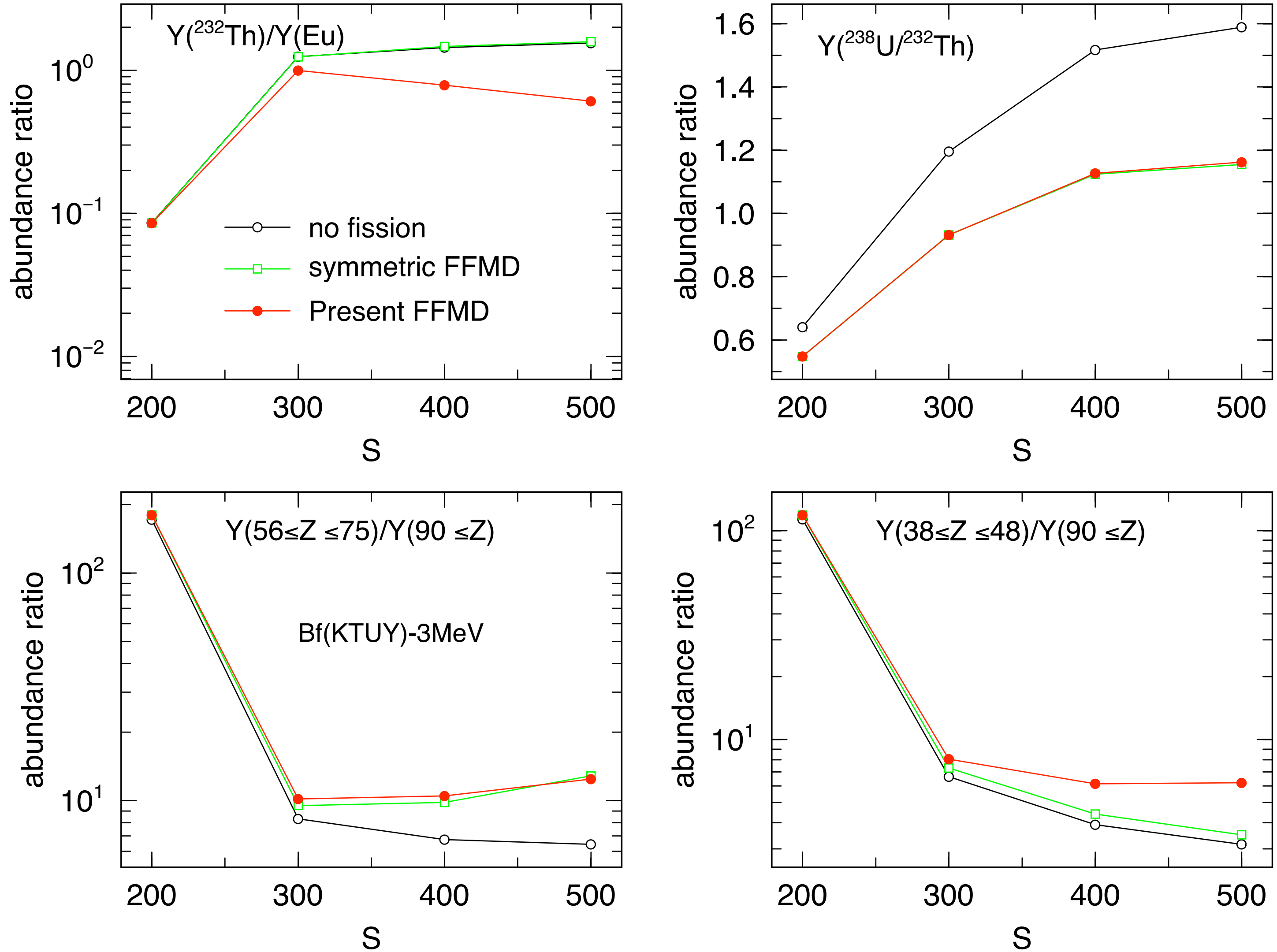
Results -r-process abundances (S-dependency)



Chiba

Results - S-dependency of isotope ratio

$B_f \rightarrow B_{fKTUY} - 3\mathrm{MeV}$



Summary

Bulk properties of nuclei

- **Current status of experimental nuclei**

- Recent dat are reviewed by using the JAEA Chart of the Nuclides 2014

- **KTUY mass model (Spherical-basis method)**

-Calculation of masses and fission barrier is reviewed

R-process and fission

From Nuclear Physics of superheavy nuclei:

- **Fission mass fragment calculation from a two-center shell model**
  - **-**Symmetric fission region is rather localized around ^{264}Fm(100,164).
- **Beta-delayed fission probability from the KTUY mass model**
  - -Region with large P_f is rather localized around ^{300}Ds (110,190).

From the r-process study:

- **Reaction Network calculation**
  - -Fission fragment tends to compensate a discrepancy near A=110 and 140 region (without adopting an N=82 quenching) *Qualitatively!*
  - -S has to be larger than 2-300 or more? (by considering in our model. More analysis is required.)