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#理研RIBFミニワークショップ「理論と実験で拓く中性子過剰核の核分裂」
(理化学研究所・和光キャンパス・RIBF棟大会議室)

rプロセス計算へ向けた核分裂の評価

Theoretical study of nuclear fission by dynamical model
toward r-process calculation

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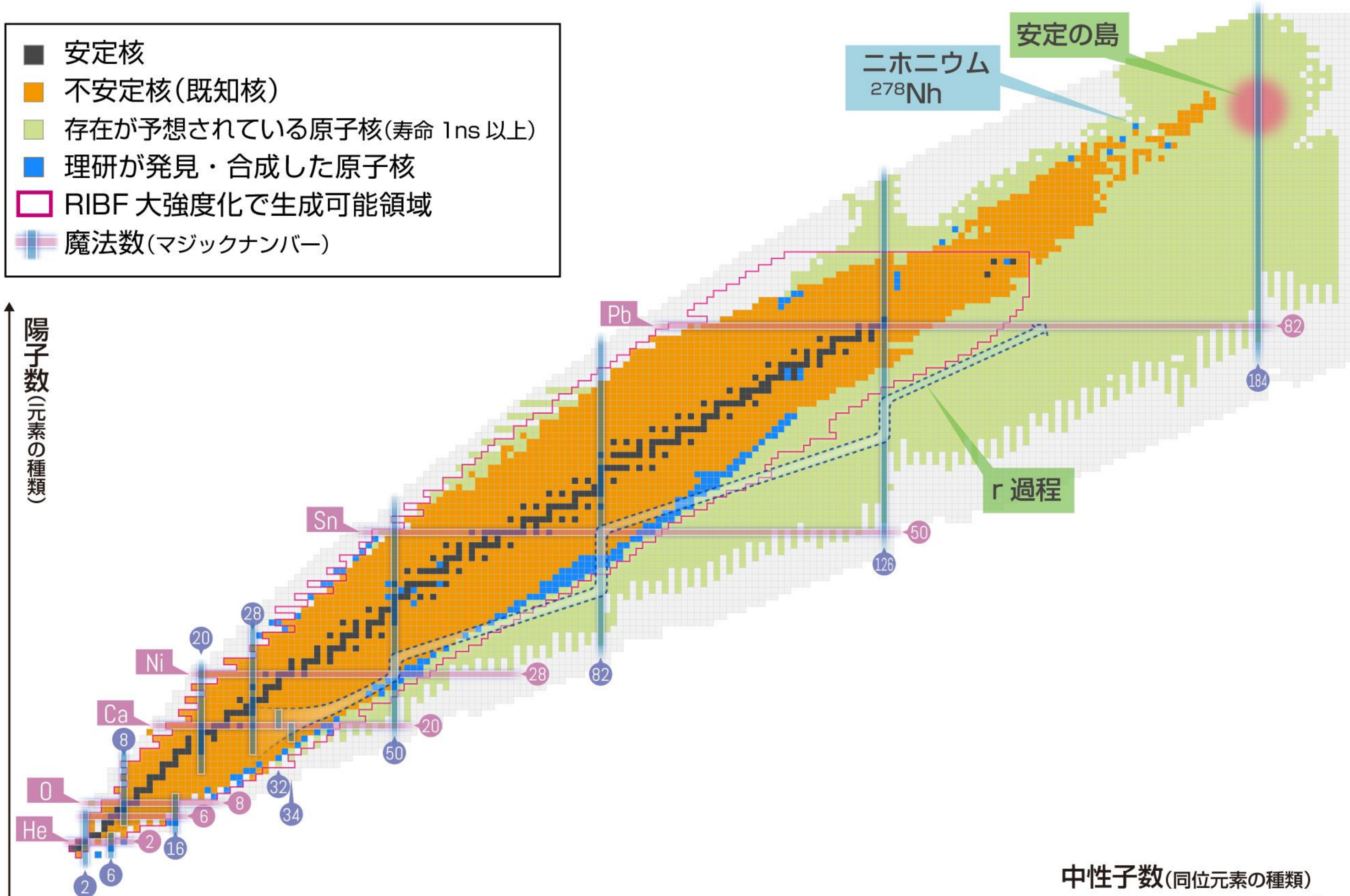
1. 研究背景

r プロセス元素合成

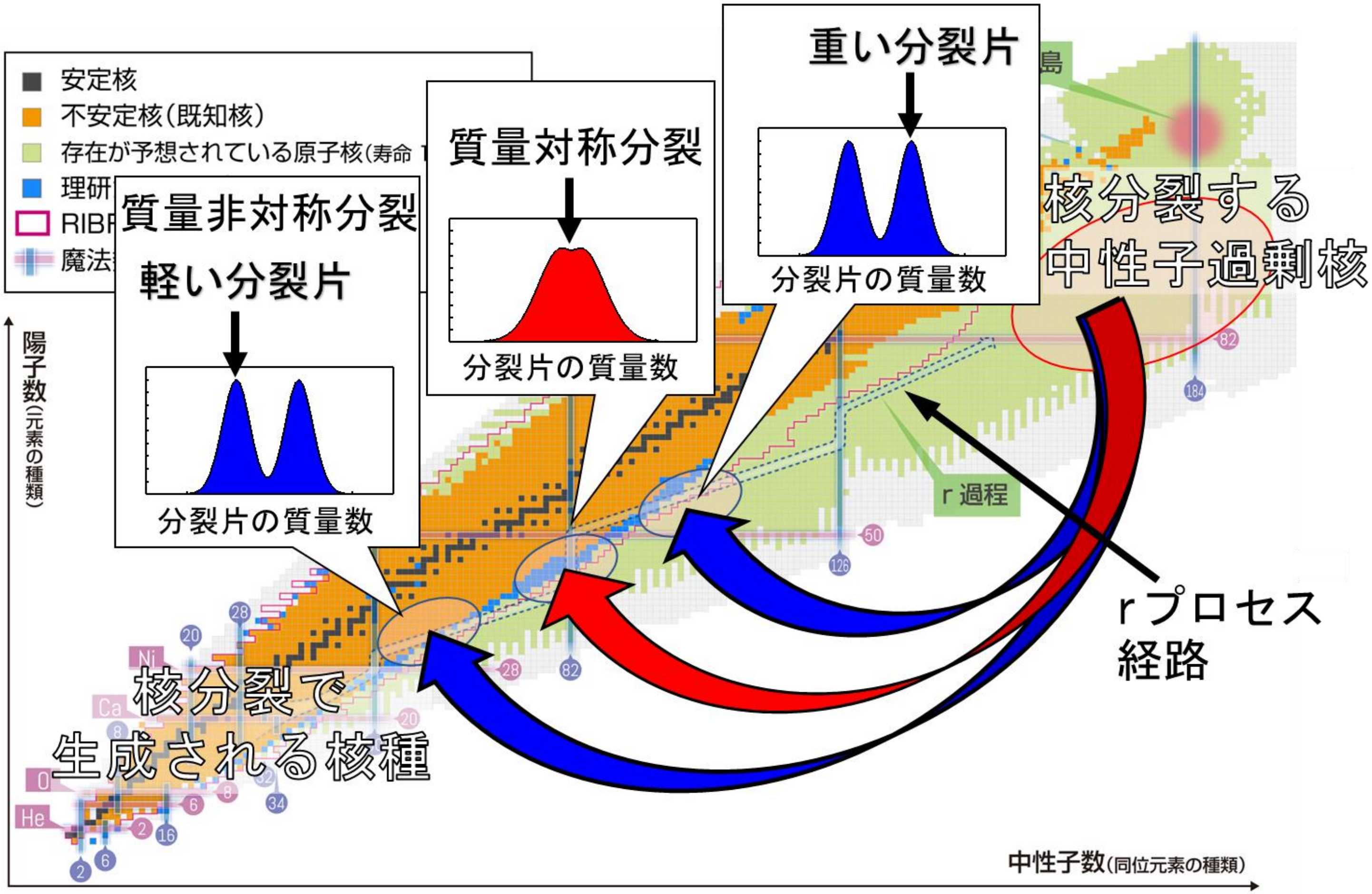
- r プロセスは鉄より重い金や白金、ウランなどを合成する主要な起源である。
- 元素合成の経路が安定核から大きく外れた中性子過剰領域に存在する。
- 中性子捕獲とベータ崩壊の連続によって進むが超ウラン元素付近に到達すると核分裂も重要になる。



https://www.nishina.riken.jp/researcher/archive/illust.html

r プロセスにおける核分裂の役割

核分裂はr プロセスの終端を決め、核分裂リサイクルによって分裂後の核分布（質量数100から150 付近）が最終的な元素組成へ影響を与え、その崩壊熱はキロノヴァの主要な熱源の一つであるなど、元素合成にて重要な役割を果たす。



質量対称か非対称に分裂するかが重要となる。

太陽系の元素組成への影響

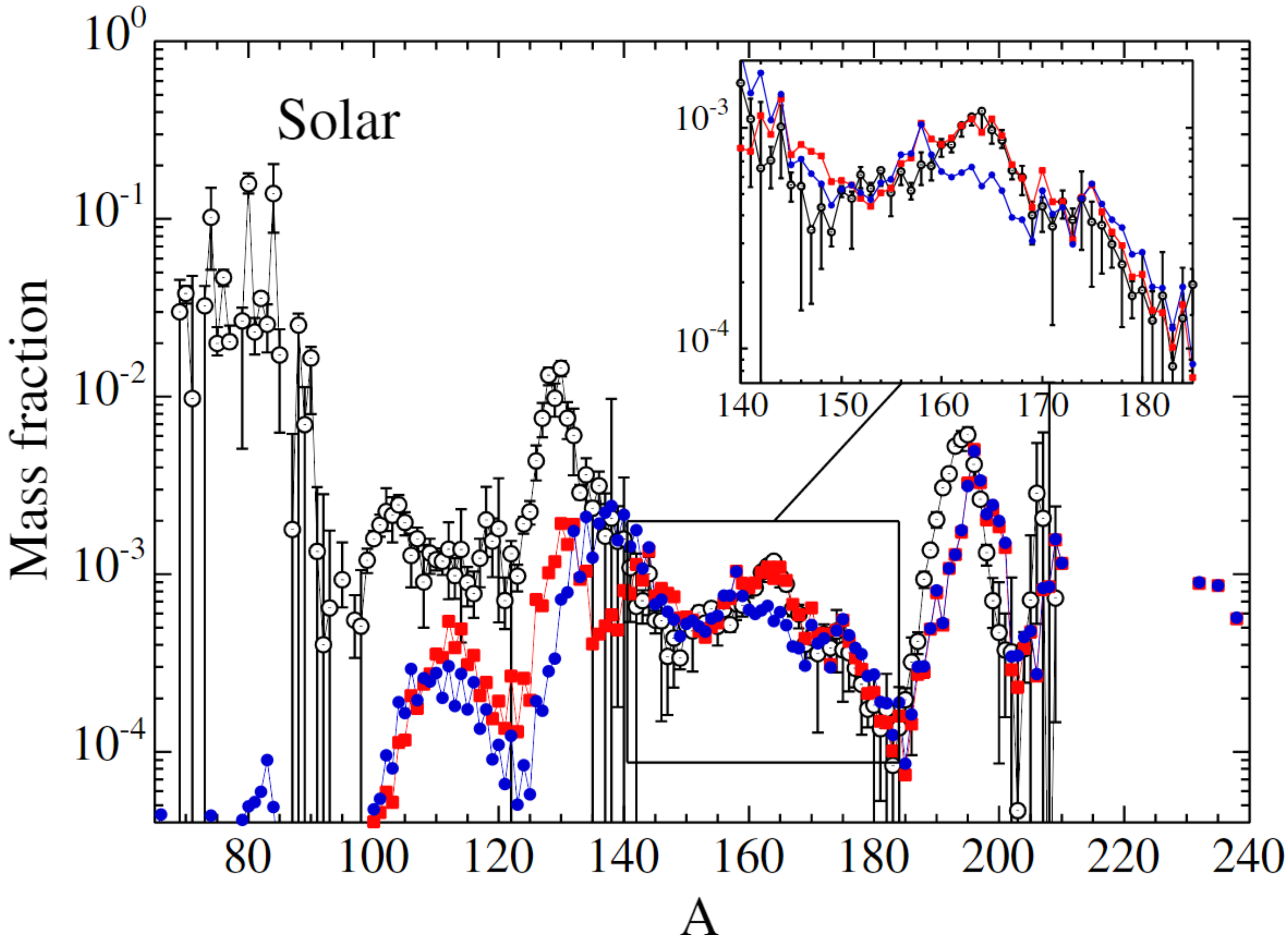


FIG. 4 (color online). Final abundance distribution vs atomic mass for ejecta from 1.35–1.35 $M_\odot$ NS mergers. The red squares are for the newly derived SPY predictions of the FFDs and the blue circles for essentially symmetric distributions based on the 2013 GEF model [52]. The abundances are compared with the solar ones [56] (dotted circles). The insert zooms on the rare-earth elements.

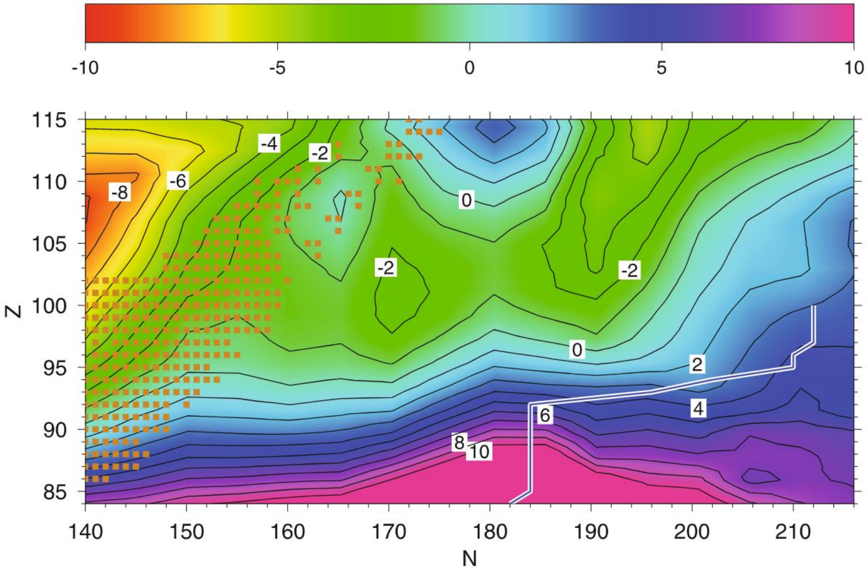
- SPY (質量非対称分裂を含む)
- GEF (基本的に質量対称分裂)

S. Goriely et al., Phys. Rev. Lett. **111**, 242502 (2013).

想定する核分裂

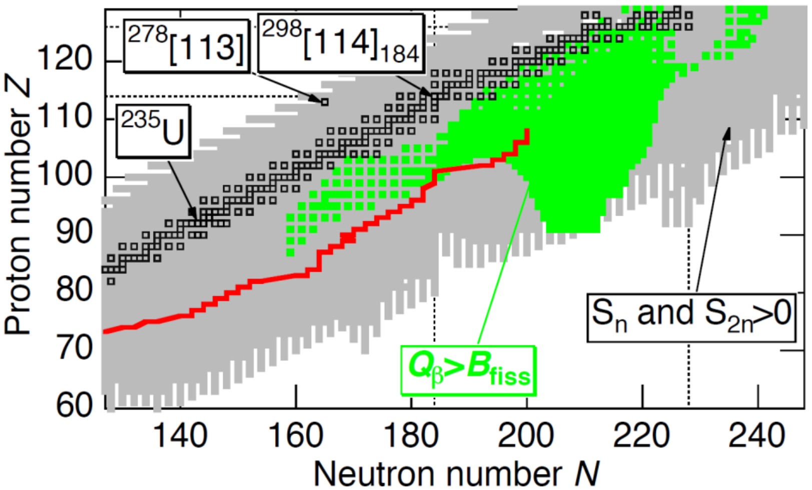
- 中性子入射核分裂 (Neutron-induced fission)
- 自発核分裂 (Spontaneous fission)
- β遅延核分裂 (β-delayed fission)

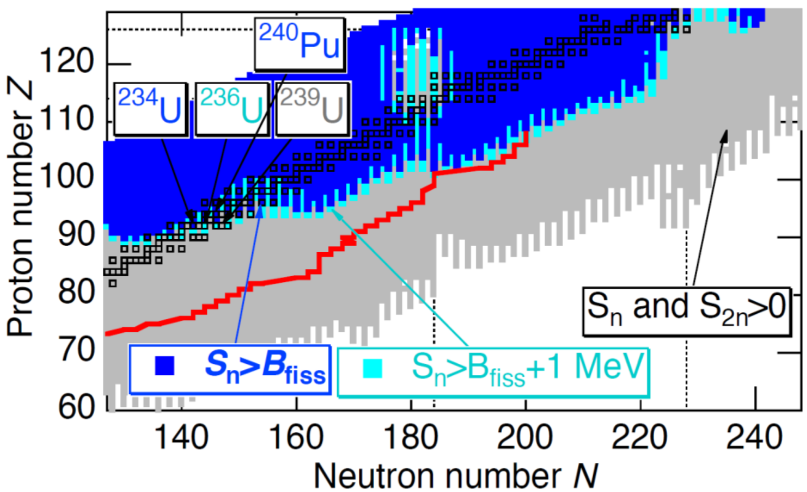
FRDM masses ＋ Thomas-Fermi fission barrier
で評価した$B_\mathrm{f} - S_\mathrm{n}$[MeV]の値。



値が負の領域で中性子入射核分裂が起きやすい。

I. V. Panov et al., Astron. Astrophys. 513, A**61** (2010).

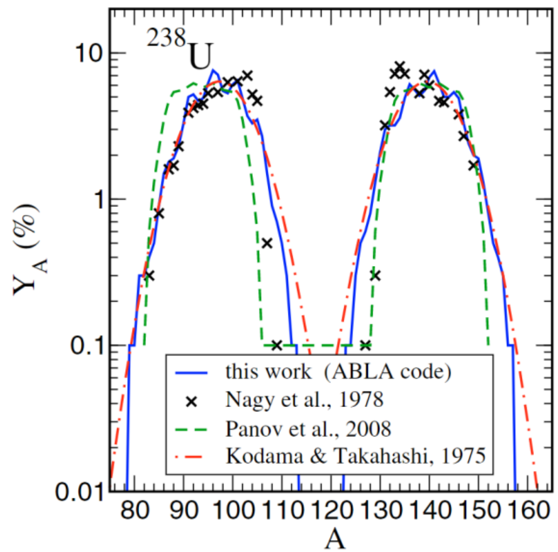




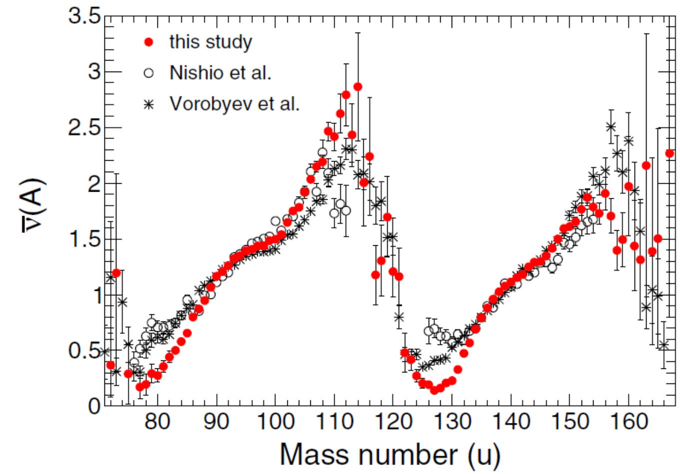
calculated by H. Koura (2016).

どういう物理量が必要か

- 核分裂片独立収率
- 中性子放出多重度
- 崩壊熱
- 崩壊半減期
- 核分裂障壁



I. V. Panov et al., Astron. Astrophys. 513, A**61** (2010).



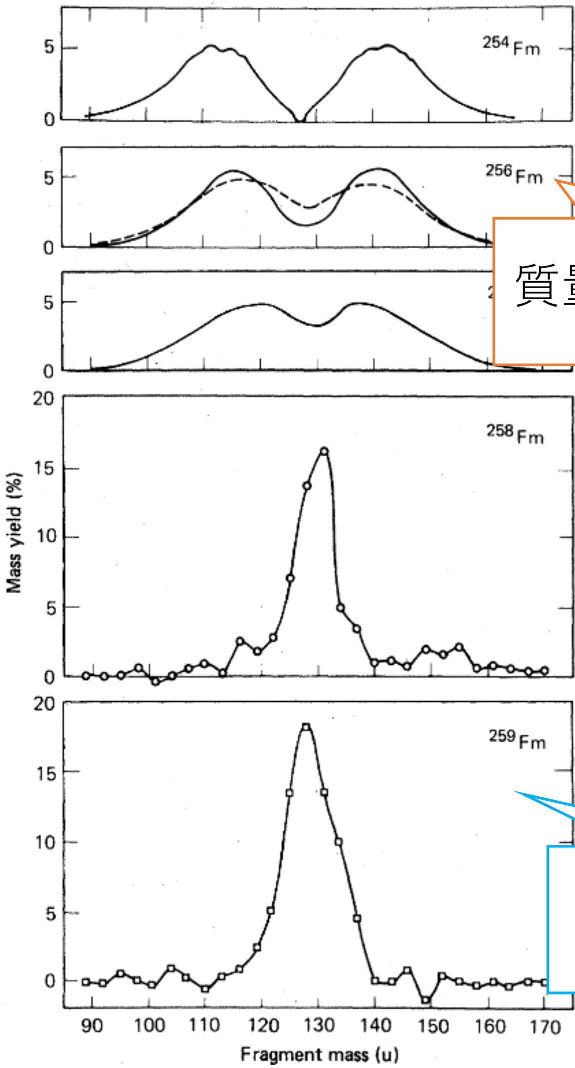
Alf Göök, Franz-Josef Hambsch, Stephan Oberstedt, and Marzio Vidali, Phys. Rev. C **98**, 044615 (2018).

$$^{235}_{92}U + n \rightarrow {}^{137}_{56}Ba + {}^{97}_{36}Kr + 2n + Q$$

O. Hahn and F. Straßmann, Naturwissenschaften **27**, 11 (1939).
L. Meitner and O. R. Frisch, Nature (London) **143**, 239 (1939).

Fm原子核における核分裂モードの変化

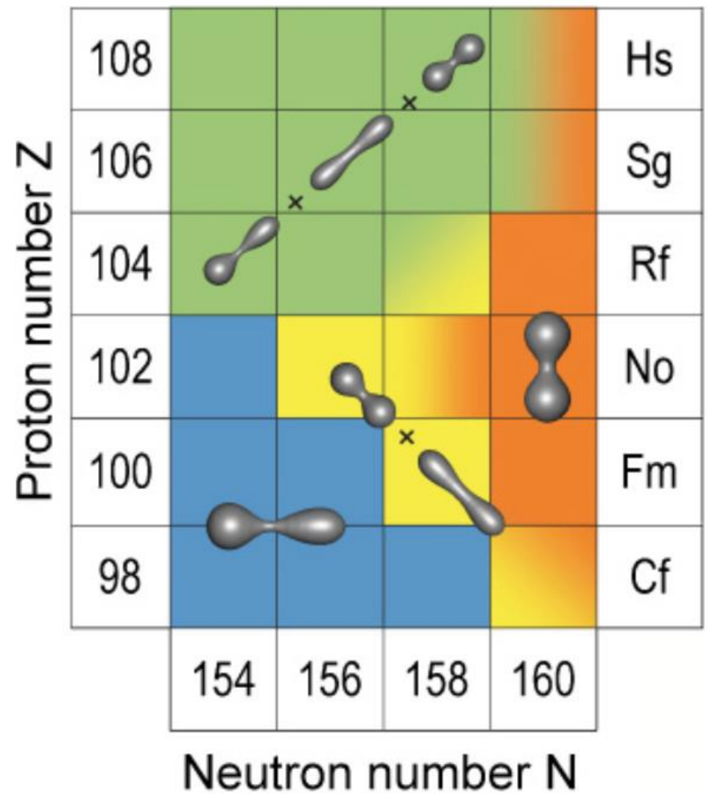
核分裂モードが急激に変化することが実験的に観測されている。
これはSn-132の二重魔法核に起因する変化であると考えられている。



質量非対称分裂が優勢

質量対称分裂が優勢

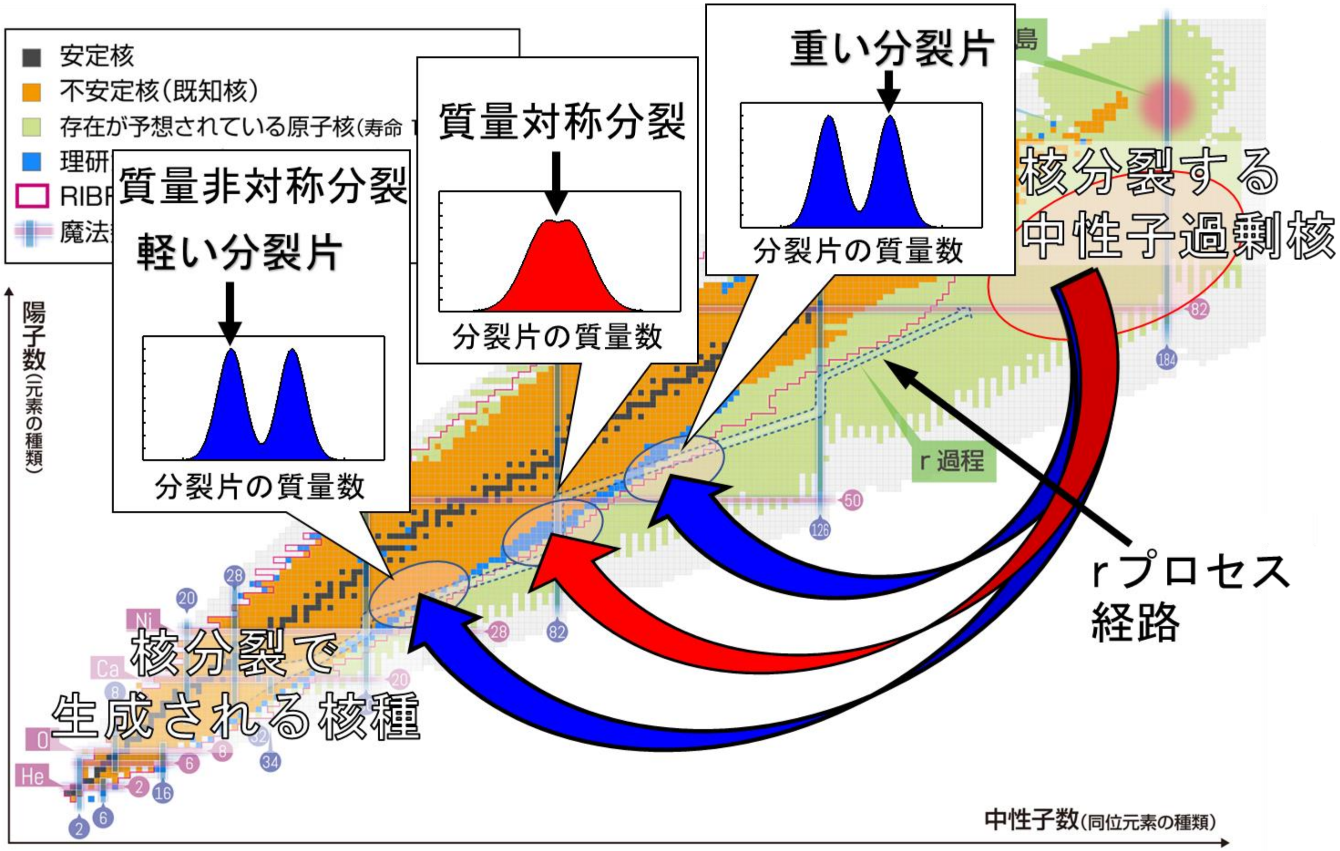
D. C. Hoffman, J. B. Wilhelmy, J. Weber, W. R. Daniels, E. K. Hulet, R. W. Lougheed, J. H. Landrum, J. F. Wild, and R. J. Dupzyk, Phys. Rev. C **21**, 972 (1980).



A. Staszczak et al., Phys. Rev. C **80**, 014309 (2009).

研究目的

ｒプロセスで直接生成される原子核の核分裂は興味深いものの、現在の実験技術ではここまで中性子の過剰な原子核に到達することは不可能である。



本研究では、動力学模型計算を用いて中性子過剰核の分裂メカニズムを調べるとともに、rプロセス計算に必要な新たな核分裂データベースの構築を目指す。

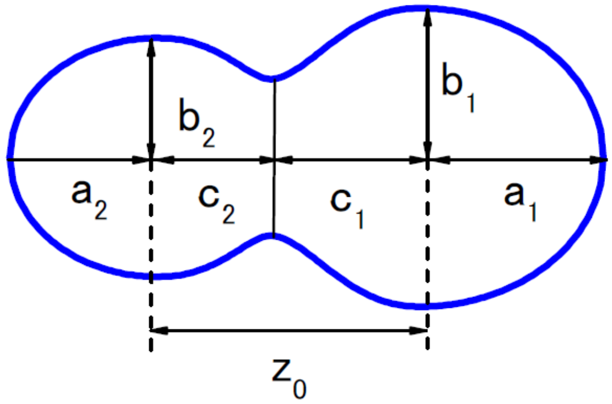
2. 理論模型

Nuclear shape

■ Two-center parametrization

two-center parametrization $q\{z, \delta, \alpha\}$

J. Maruhn and W. Greiner, Z. Phys. **251**, 431-457 (1972).



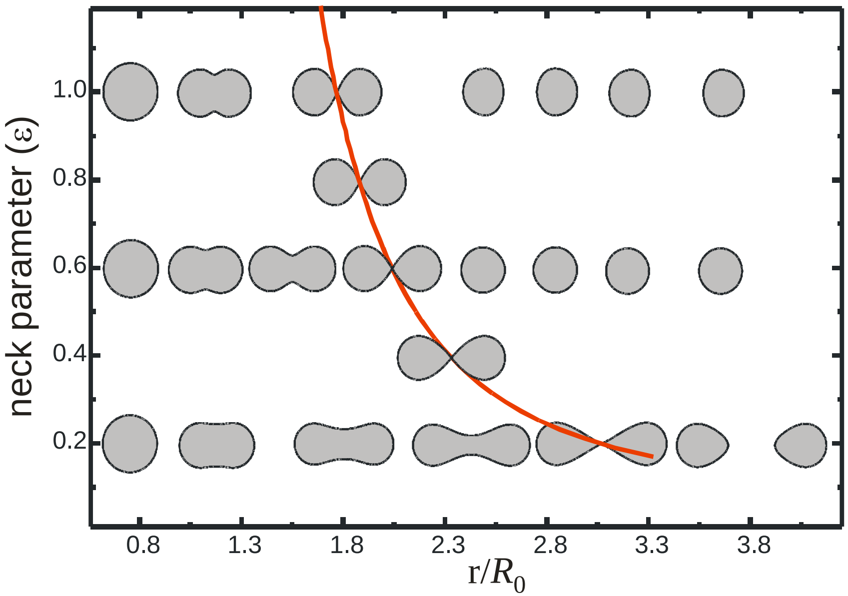
$$z = \frac{z_0}{BR}$$

$$B = \frac{3+\delta}{3-2\delta}$$

R: Radius of the spherical compound nucleus

$$\delta = \frac{3(a-b)}{2a+b} \; (\delta_1 = \delta_2)$$

$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$



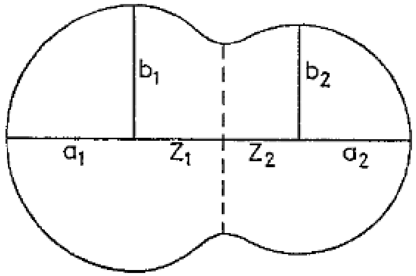
z: Center of Mass Distance

δ: Deformation

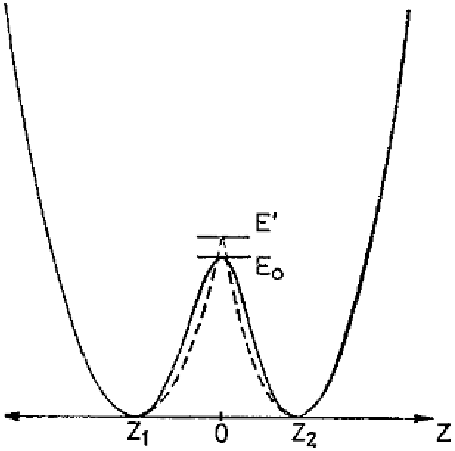
α: Mass Asymmetry

Two Center Shell Model

$$H = -\frac{\hbar^2\nabla^2}{2m_0} + V(\rho, z) + V_{LS}(\boldsymbol{r}, \boldsymbol{p}, \boldsymbol{s}) + V_{L^2}(\boldsymbol{r}, \boldsymbol{l})$$



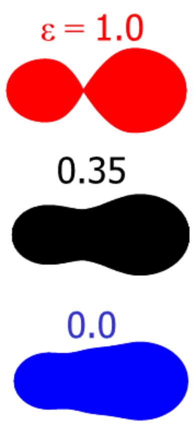
$$V(\rho, z) = \begin{cases} \frac{1}{2}m_0\omega_{z1}^2 z'^2 + \frac{1}{2}m_0\omega_{\rho 1}^2\rho^2, z < z_1 \\ \frac{f_0}{2}m_0\omega_{z1}^2 z'^2(1 + c_1 z' + d_1 z'^2) + \frac{1}{2}m_0\omega_{\rho 1}^2(1 + g_1 z'^2)\rho^2, z_1 < z < 0 \\ \frac{f_0}{2}m_0\omega_{z2}^2 z'^2(1 + c_2 z' + d_2 z'^2) + \frac{1}{2}m_0\omega_{\rho 1}^2(1 + g_2 z'^2)\rho^2, 0 < z < z_2 \\ \frac{1}{2}m_0\omega_{z2}^2 z'^2 + \frac{1}{2}m_0\omega_{\rho 2}^2\rho^2, z > z_2 \end{cases}$$



$$z' = \begin{cases} z - z_1, z < 0 \\ z - z_2, z > 0 \end{cases} \qquad c = \frac{2 - 4\varepsilon/f_0}{z_0}, \quad d = \frac{1 - 3\varepsilon/f_0}{z_0},$$

$$\varepsilon = \frac{E_0}{E'}$$

The neck parameter is the ratio of smoothed potential height to the original one where two harmonic oscillator potentials cross each other.



$$E' = \frac{1}{2}m_0\omega^2 z_0^2 = \frac{1}{2}m_0\omega_{z1}^2 z_1^2 = \frac{1}{2}m_0\omega_{z2}^2 z_2^2$$

J. Maruhn and W. Greiner, Z. Phys. **251**, 431-457 (1972).

Potential Energy

$$V(q,l,T) = V_{LD}(q) + V_{SH}(q,T)$$

$$V_{LDM}(q) = E_S(q) + E_C(q)$$

$$V_{SH}(q,T) = E^0_{shell}(q)\Phi(T)$$

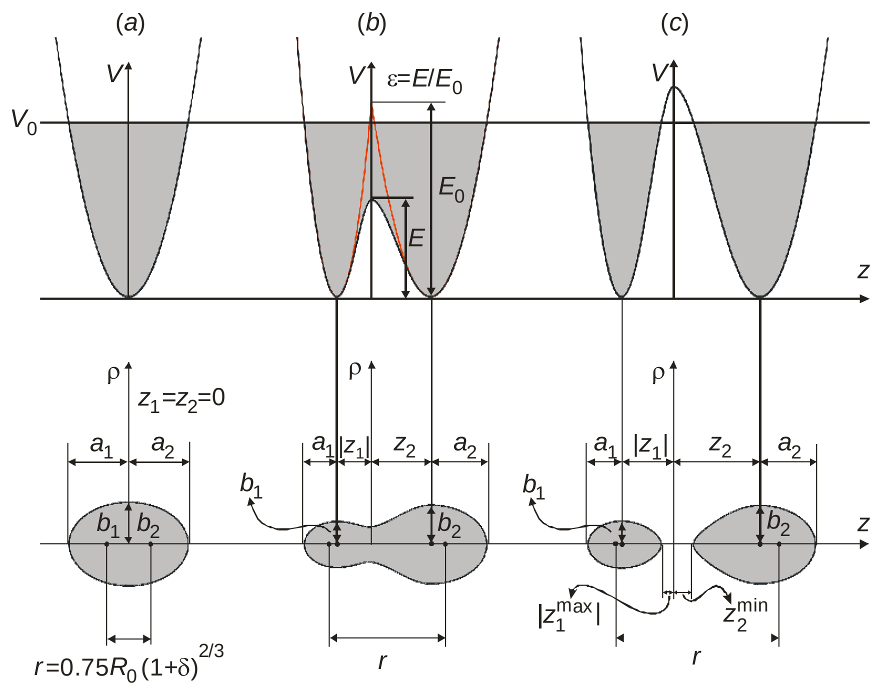
$$\Phi(T) = exp\left(-\frac{aT^2}{E_d}\right)$$

$$E_d = 20\ MeV$$

T : nuclear temperature

$E^* = aT^2$ a : level density parameter

Toke and Swiatecki



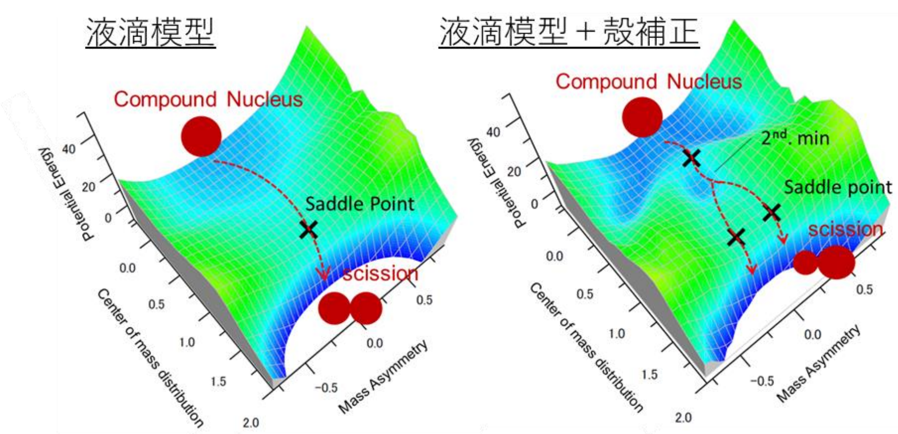
E_S : Generalized surface energy (finite range effect)

E_C : Coulomb repulsion for diffused surface

$E^0{}_{shell}$: Shell correction energy at T=0

I : Moment of inertia for rigid body

$\Phi(T)$: Temperature-dependent factor



Multi-dimensional Langevin Equation

$$\frac{dq_i}{dt} = (m^{-1})_{ij} p_j$$

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk} p_j p_k - \gamma_{ij}(m^{-1})_{jk} p_k + g_{ij} R_j(t)$$

Friction — Dissipation

Random Force — Fluctuation

$\langle R_i(t) \rangle = 0, \langle R_i(t_1) R_j(t_2) \rangle = 2\delta_{ij}\delta(t_1 - t_2)$: white noise (Markovian process)

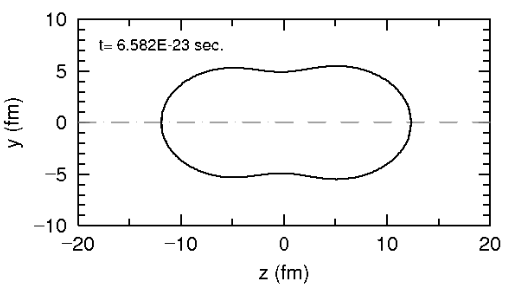
$\sum_k g_{ik} g_{jk} = T\gamma_{ij}$: Einstein relation

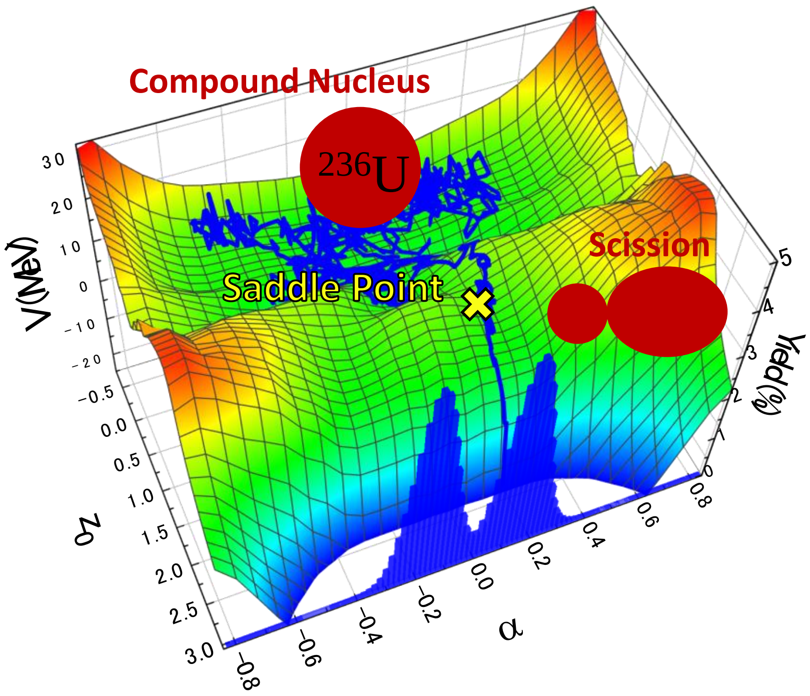
q_i : Deformation coordinate (nuclear shape)
two-center parametrization

p_i : Momentum

m_{ij} : Hydrodynamical mass (inertia mass)

γ_{ij}: Wall and Window (one-body) dissipation (friction)

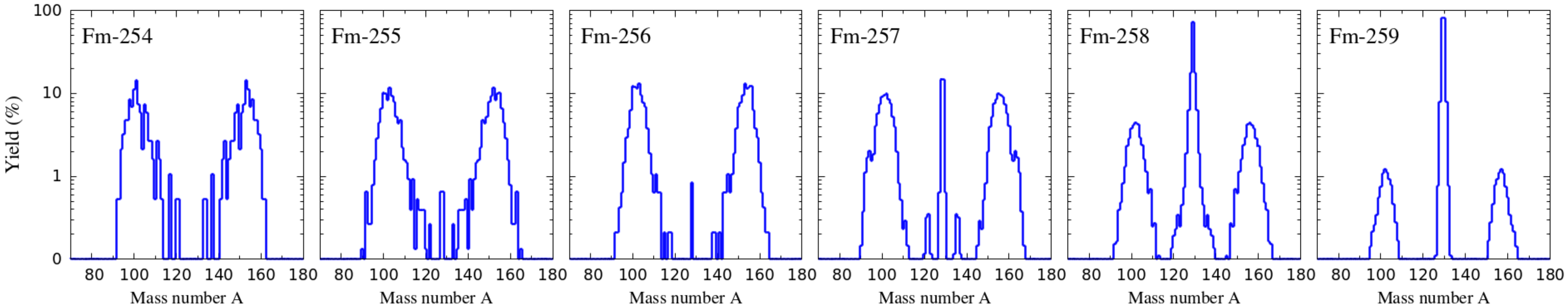


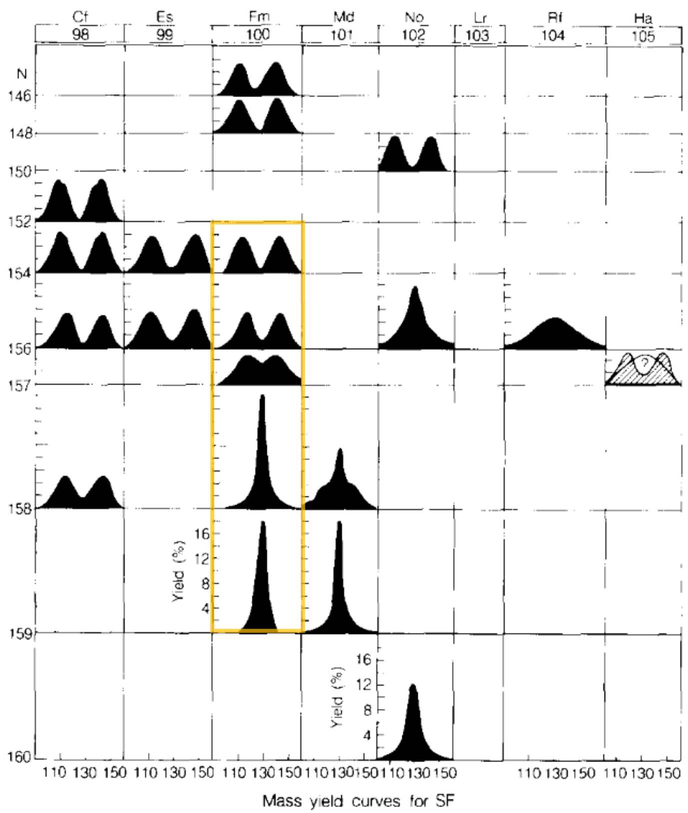


3. 計算結果

Fm分裂モード変化の評価

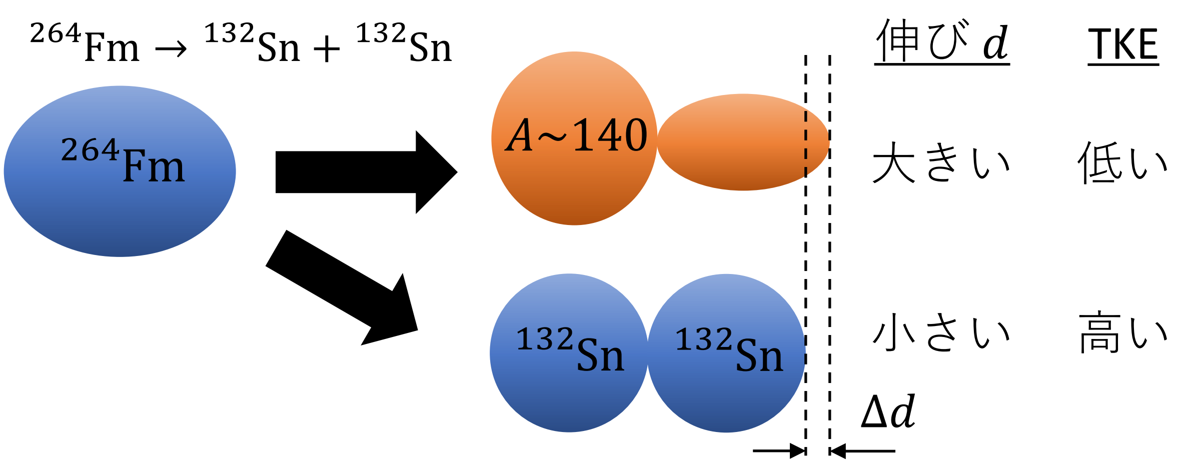
■ $^{254\text{-}259}$Fmにおける核分裂片質量分布 (Fission fragment mass distribution)





通常のアクチノイド領域と同様の質量非対称分裂へ向かう分裂経路

$^{264}\mathrm{Fm} \rightarrow {}^{132}\mathrm{Sn} + {}^{132}\mathrm{Sn}$

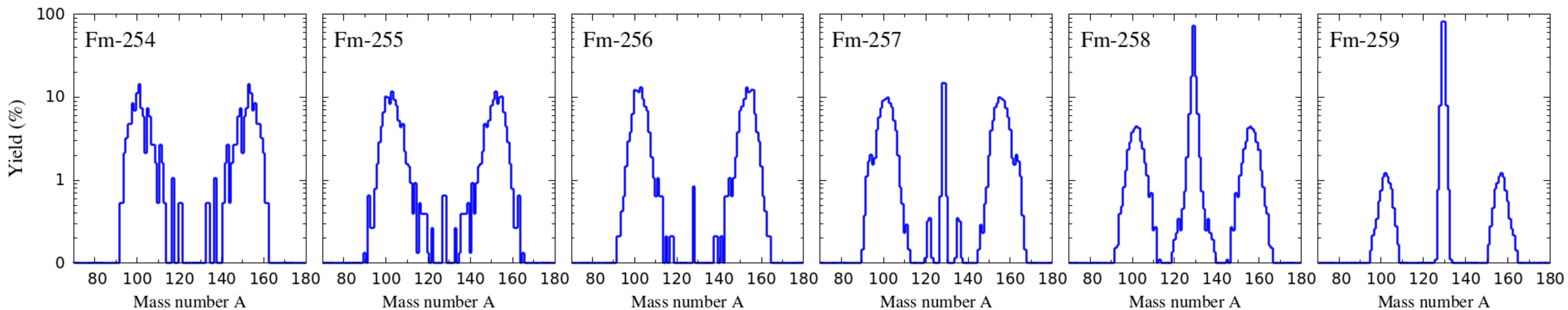


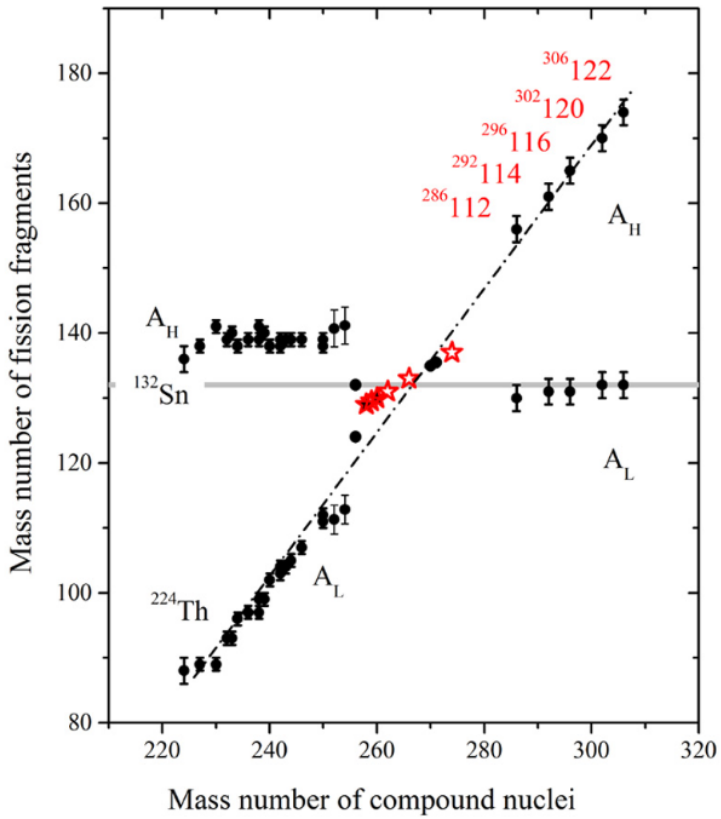
非常にコンパクトな質量対称の分裂経路が現れる

D. C. Hoffman et al., Nuclear Physics A**502** (1989).

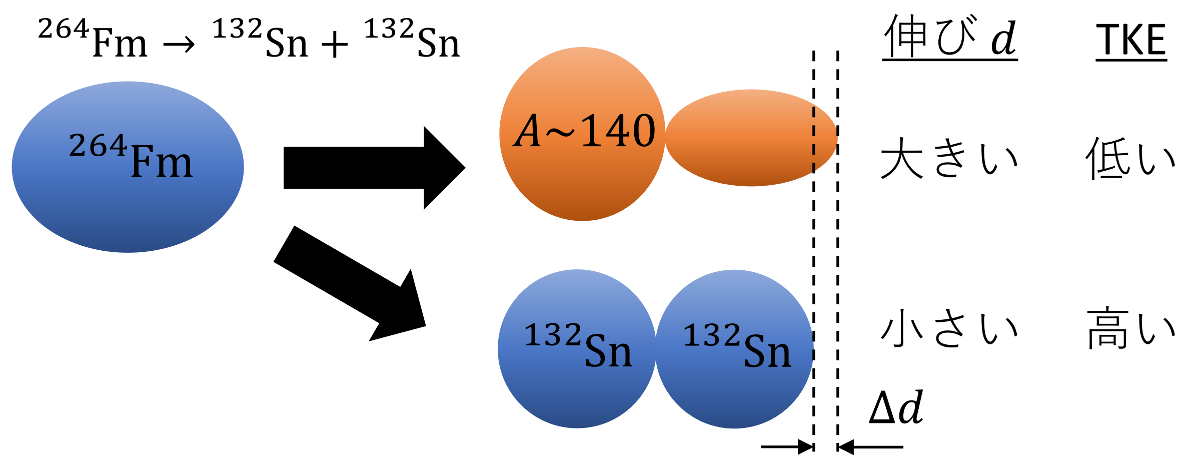
Fm分裂モード変化の評価

■ $^{254\text{-}259}$Fmにおける核分裂片質量分布 (Fission fragment mass distribution)





通常のアクチノイド領域と同様の質量非対称分裂へ向かう分裂経路

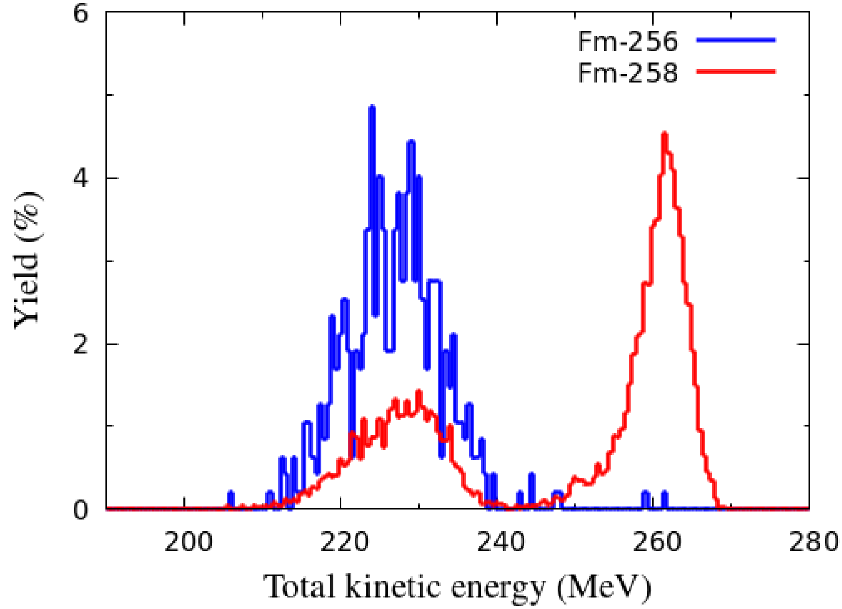


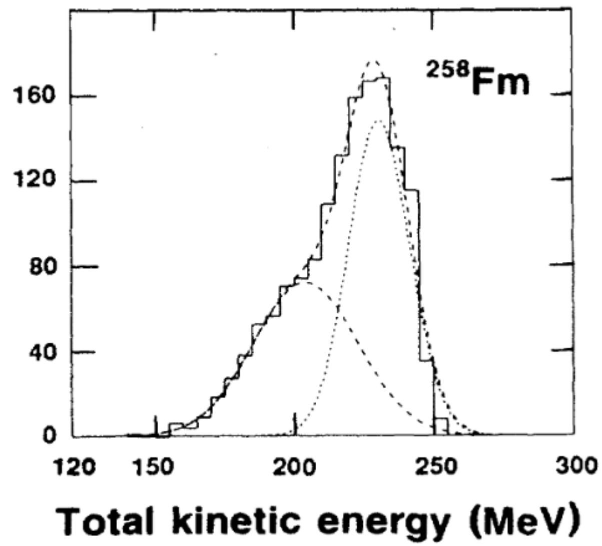
非常にコンパクトな質量対称の分裂経路が現れる

M.G. Itkis et al., Nucl. Phys. A**944**, 204-237 (2015)

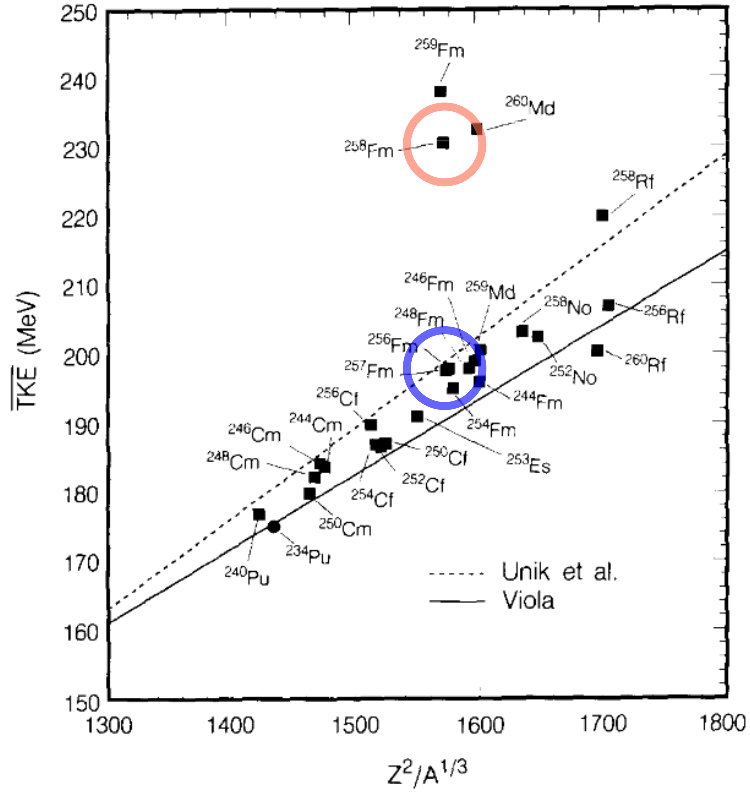
全運動エネルギー分布

■ ^{256,257}Fmにおける計算結果





E. K. Hulet et al., Phys. Rev. C**40**, 770 (1989).



D. C. Hoffman et al., Nuclear Physics A**502** (1989).

$$E_{TKE} \propto {}^{1}/_{d}$$

定性的に分裂モードの変化が結果に表れているが、実験データと比べてエネルギーのピークが異なる。

ポテンシャルエネルギー上における原子核変形経路の違い

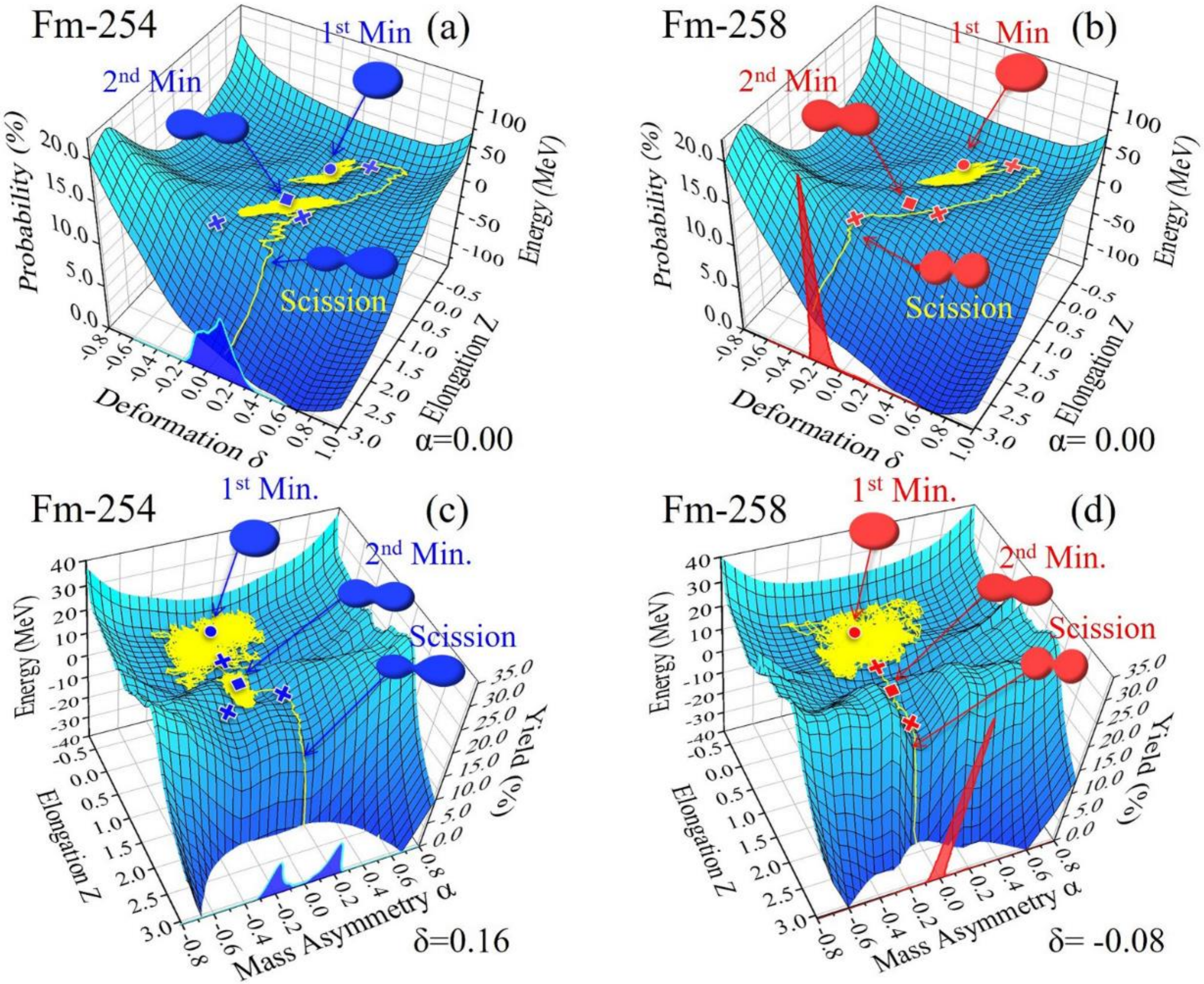
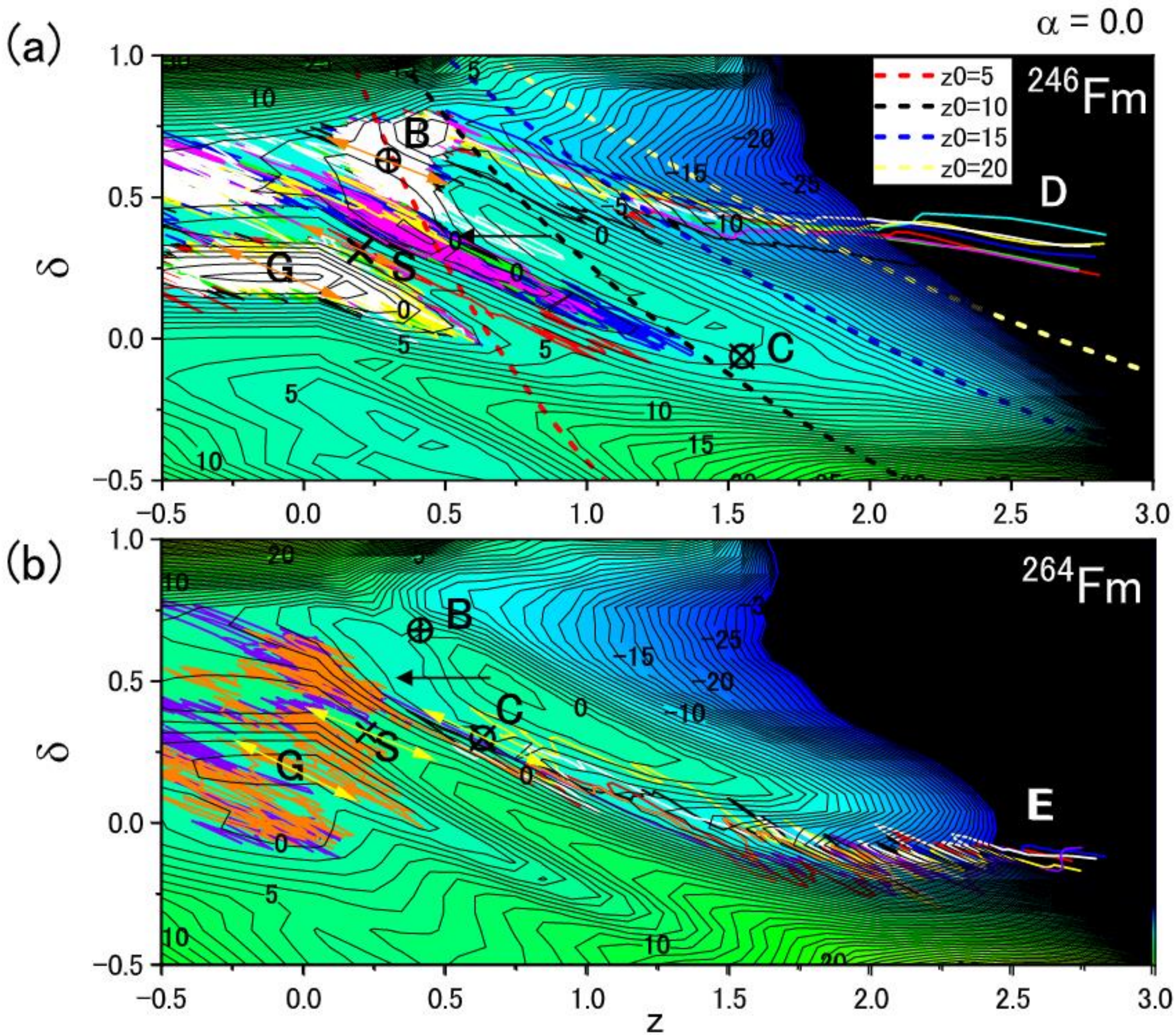


Fig. Potential energy on the z-δ plane for (a) ^{254}Fm and (b) ^{258}Fm, obtained at a fixed mass asymmetry α = 0. A sample shape trajectory is shown for each nucleus. The trajectories are also shown on the z-α plane for (c) ^{254}Fm and (d) ^{258}Fm as well as the potential energy at a fixed δ value, 0.16 for ^{254}Fm and −0.08 for ^{258}Fm, respectively.

Y. Miyamoto, Y. Aritomo, S. Tanaka, K. Hirose, and K. Nishio, Phys. Rev. C **99**, 051601(R) (2019).

ポテンシャルエネルギー上における原子核変形経路の違い



Y. Aritomo, A. Iwamoto, K. Nishio, and M. Ohta, Phys. Rev. C **105**, 034604 (2022).

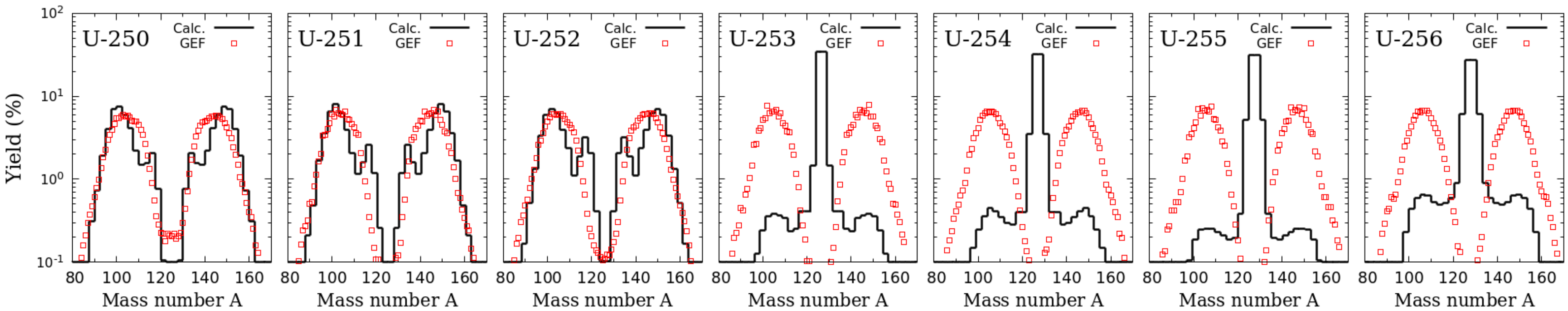
TABLE I. Elements of the friction tensor in the (z, δ) space and their eigenvalues for the ^{246}Fm and ^{264}Fm cases. The region of the deformation space where the friction tensors analyzed are indicated in the first column; g.s., first, and second saddles. They imply the region around the ground state, the first saddle, and the second saddle point, respectively. As the friction tensor is symmetric, one of the off-diagonal elements is listed. The large differences between the two eigenvalues λ_1 and λ_2 are observed as noted in the text. The rotation angles θ derived from the transformation matrix [by Eqs. (27) and (28)] and the slope angles of the directional oscillation of the trajectories in Fig. 2, $\theta_{measure}$, are presented in the last two columns. The consistency can be observed in these two angles.

position	γ_{zz} $[/\hbar]$	$\gamma_{\delta\delta}$ $[/\hbar]$	$\gamma_{z\delta}$ $[/\hbar]$	λ_1	λ_2	λ_2/λ_1	θ [deg]	$\theta_{measure}$ [deg]
^{246}Fm								
g.s.	0.172×10^3	0.686×10^3	0.327×10^3	0.128×10^2	0.845×10^3	0.657×10^2	−25.93	−23.0
First	0.242×10^3	0.120×10^4	0.512×10^3	0.194×10^2	0.142×10^4	0.732×10^2	−23.46	−21.0
Second	0.123×10^3	0.474×10^3	0.231×10^3	0.863×10	0.588×10^3	0.682×10^2	−26.38	−24.0
^{264}Fm								
g.s.	0.189×10^3	0.754×10^3	0.360×10^3	0.141×10^2	0.930×10^3	0.657×10^2	−25.94	−24.0
First	0.352×10^3	0.165×10^4	0.707×10^3	0.424×10^2	0.196×10^4	0.463×10^2	−23.69	−22.0
Second	0.276×10^3	0.103×10^4	0.503×10^3	0.238×10^2	0.128×10^4	0.537×10^2	−26.65	−27.0

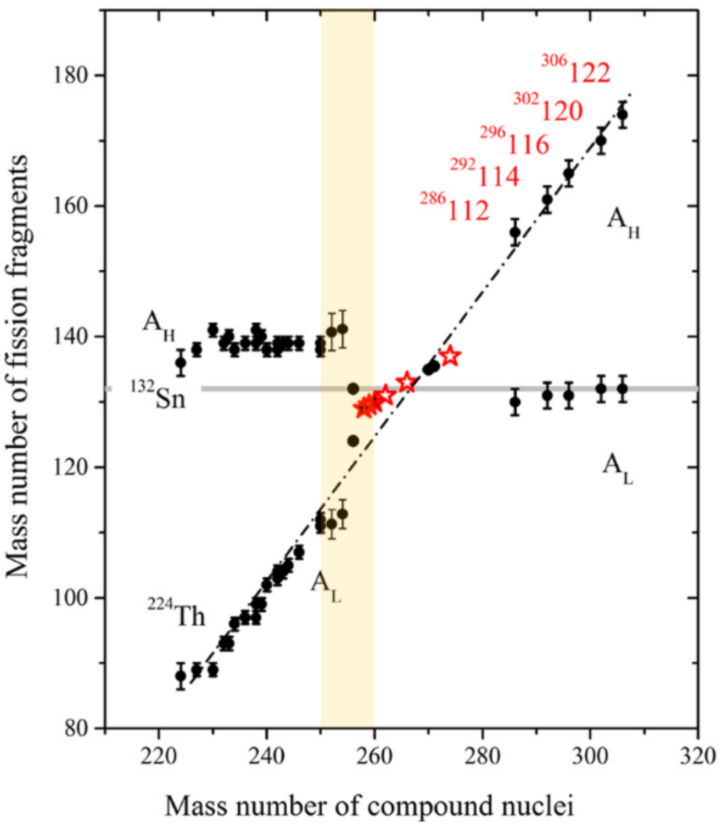
Y. Aritomo, A. Iwamoto, K. Nishio, and M. Ohta, Phys. Rev. C **105**, 034604 (2022).

中性子過剰領域におけるウラン同位体の核分裂

■ $^{250\text{-}256}$Uの核分裂片質量分布の計算結果およびGEFモデルとの比較 (E*=7 MeV)。



GEF code [K.-H. Schmidt et al., Nucl. Data Sheets **131**, 107 (2016)].



ウラン同位体でもFmと同様に中性子数が増えると質量非対称分裂から質量対称分裂へと変化する傾向がみられる。
比較として載せているGEFコードによる計算結果では分裂モードの変化は見られなかった。

M.G. Itkis et al., Nucl. Phys. A**944**, 204-237 (2015)

分裂片の電荷分布

We determined charge distributions with UCD (Unchanged Charge Distribution) assumption and Gaussian fitting.

◆UCD assumption

a simple assumption
, which the charge asymmetry equals the mass asymmetry

mass asymmetry α_A
from Langevin calculation

$$\alpha_A = \frac{A_1 - A_2}{A_{CN}}$$

$$\alpha_Z = \alpha_A \quad \text{(UCD)}$$

◆Results：Z distributions

■ Exp.(JENDL-4.0)
— Langevin Cal. （E*=15MeV）

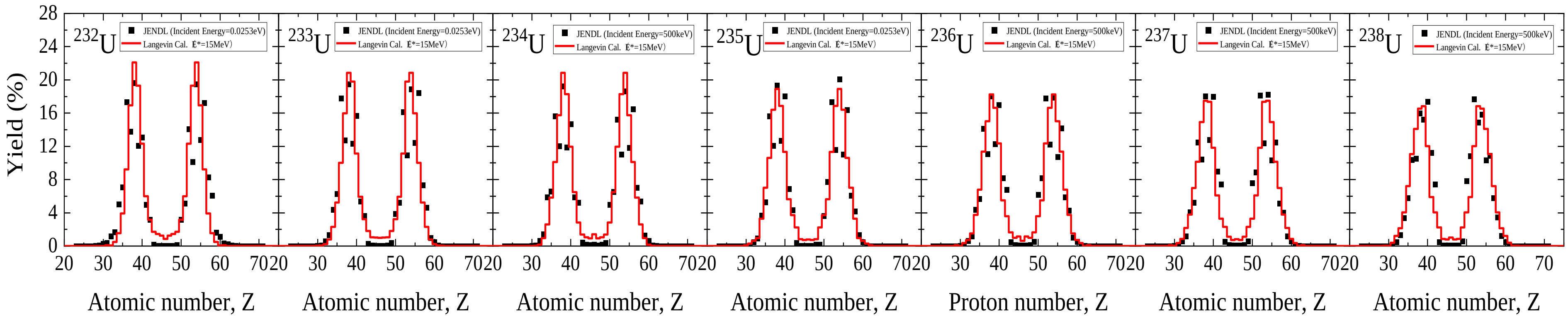
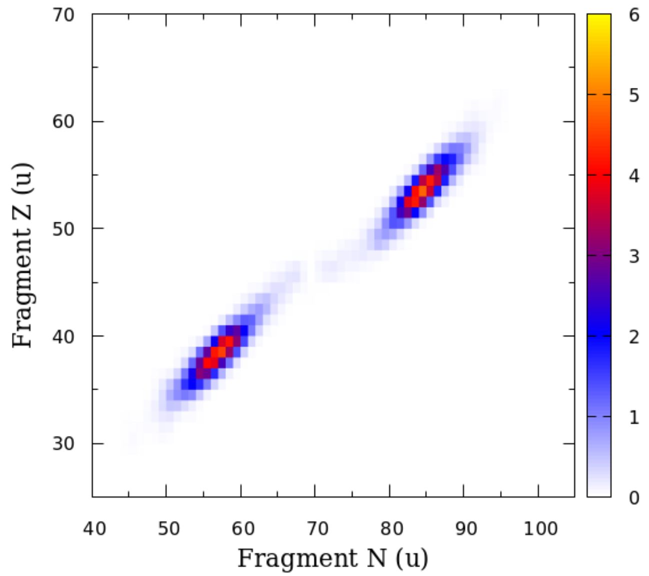


Fig. The calculation results of Z distributions for ^{232}U to ^{238}U with the excitation energy of E*=15 MeV. The present work (red line) is compared with the data from JENDL-4.0 [K. Shibata, O. Iwamoto, et al.: "JENDL-4.0: A New Library for Nuclear Science and Engineering," J. Nucl. Sci. Technol. 48(1), 1-30 (2011)].

分裂片のN-Z分布

(a) Calculation result
N-Z distribution of ^{236}U



(b) Experimental data
N-Z distribution of ^{236}U

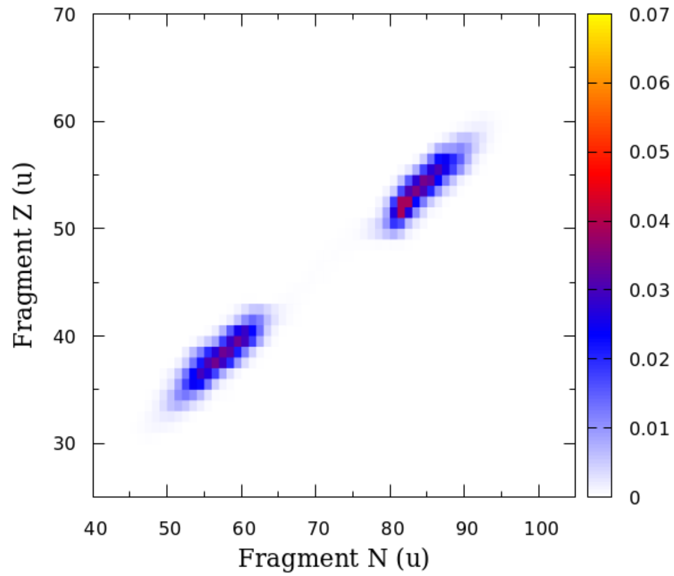
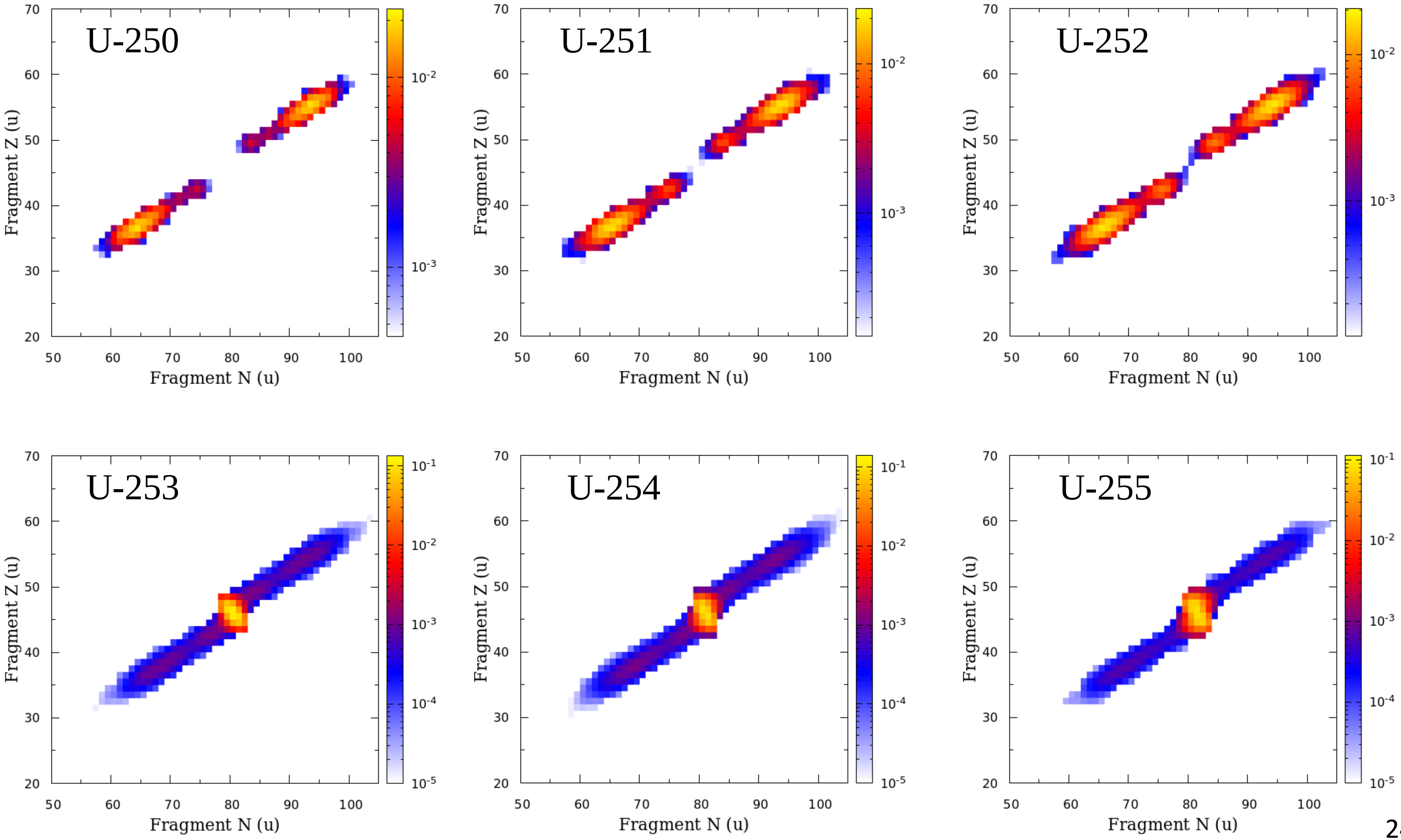


Fig. (a) The calculation result of fission fragment distribution on the N-Z plane for U-236 (E*=10 MeV) is plotted. The calculation result is compared with the experimental data of U-235 neutron-induced fission (Ek=500 KeV) from JENDL-4.0.

実験データにおける$Z_{\mathrm{CN}}/A_{\mathrm{CN}}$からのずれを再現するために、幅を持たせているガウス分布の平均値μを^{132}Snに寄るように補正している。

$^{250\text{-}255}$Uにおける分裂片の電荷分布

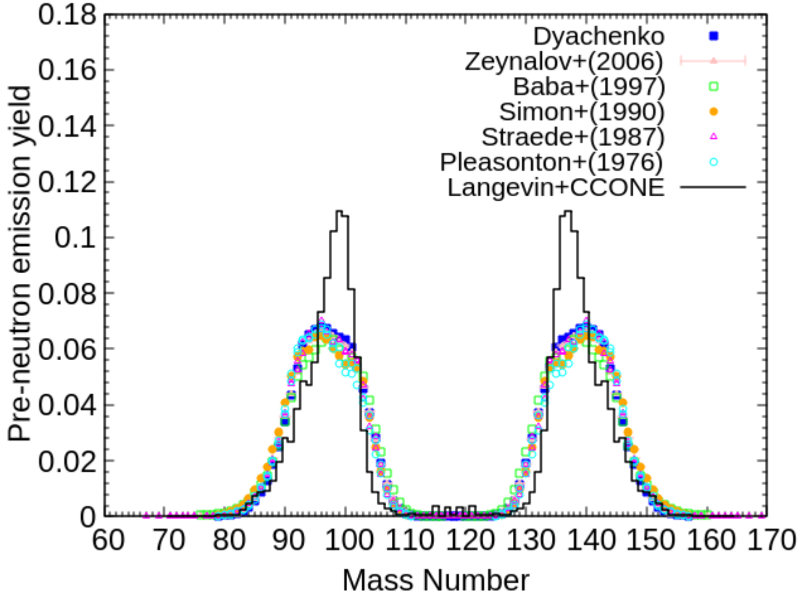
The calculation results of fission fragment distribution on the N-Z plane for uranium isotopes (E*=7 MeV) are plotted.



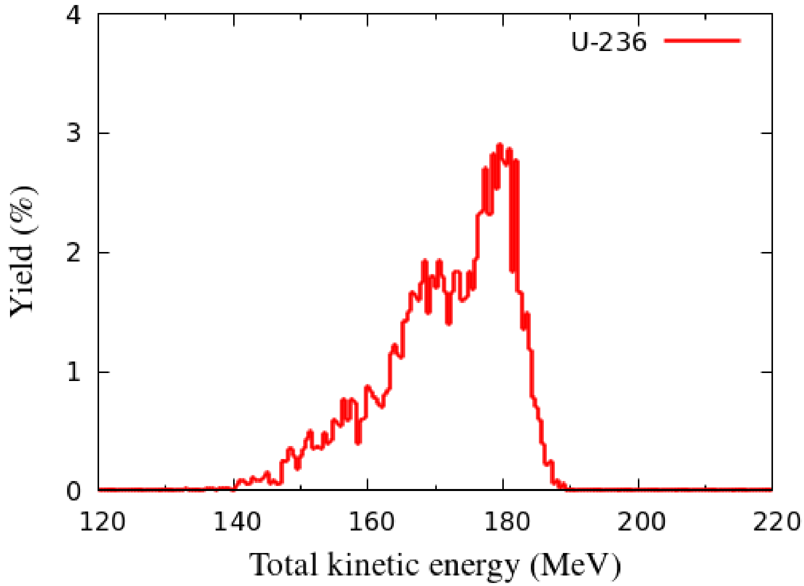
CCONEによる即発中性子放出計算

■ ^{235}Uの中性子入射核分裂

(a) 核分裂片質量分布



(b) 分裂片の全運動エネルギー分布



By combining Langevin calculations with a statistical model implemented in the CCONE [O. Iwamoto, N. Iwamoto, S. Kunieda, F. Minato, K. Shibata, Nuclear Data Sheets, Volume **131**, pp. 159-288 (2016)], we calculated independent yields and prompt neutron emissions.
Excitation energy partitions for two fragments are determined by the anisothermal model.

$$TXE(Z_l, A_l, Z_h, A_h) = E_{inc} + B_n + [M_n(Z_{CN}, A_{CN}) - M_n(Z_l, A_l) \\ - M_n(Z_{CN}, A_h)]\, c^2 - TKE(Z_l, A_l, Z_h, A_h)$$

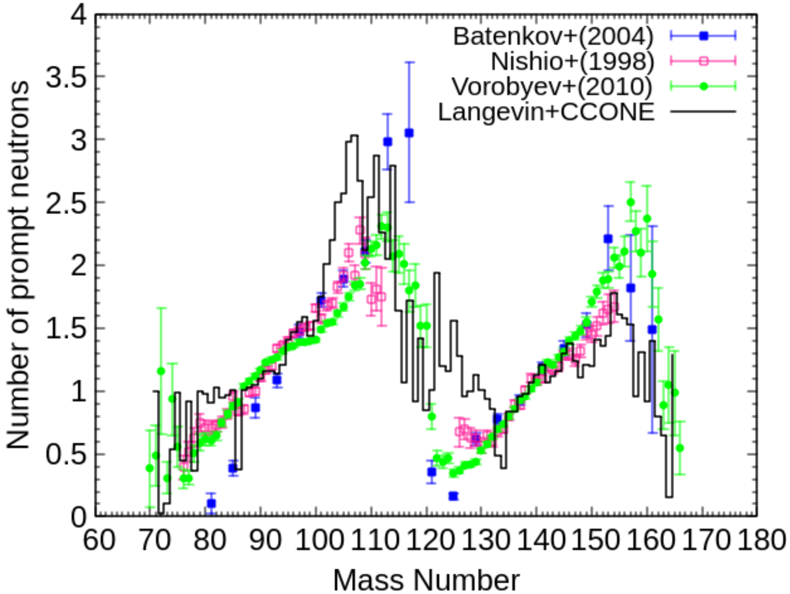
$$R_T = \frac{T_l}{T_h} = \sqrt{\frac{U_l}{U_h}\frac{a_h(U_h)}{a_l(U_l)}}$$

T. Kawano, P. Talou, I. Stetcu, M. B. Chadwick, Nucl. Phys. A **913**, 51 (2013)

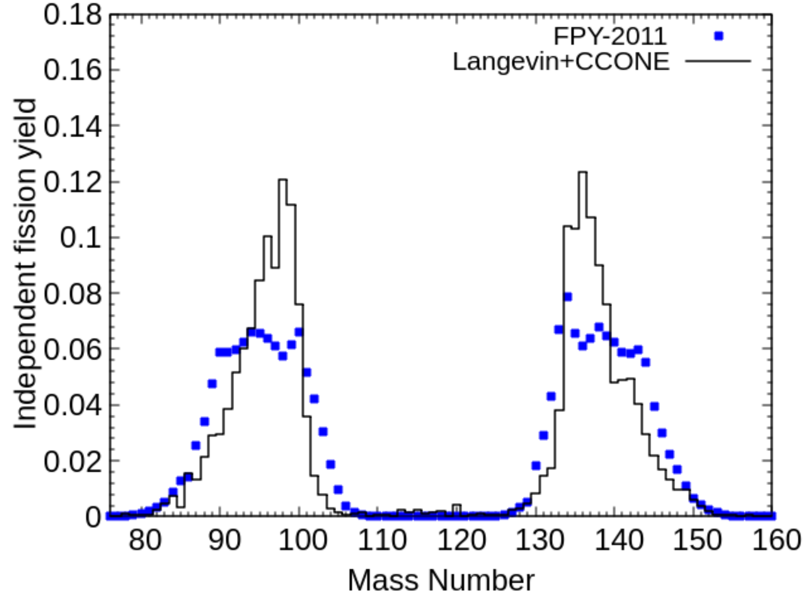
中性子放出の計算結果

- ^{235}Uの中性子入射核分裂

(c) 即発中性子放出多重度



(d) 即発中性子放出後の核分裂収率



平均中性子放出数：$\langle \nu_n \rangle = 2.517$

The prompt neutron emission multiplicity was calculated using the CCONE code with the results of the Langevin calculation as input data. The result reasonably reproduces the sawtooth structure of experiment data. The calculated average number of the prompt neutron was 2.517, which is in good agreement with the experimental value of 2.43 [K. Nishio, Y. Nakagome, H. Yamamoto, I. Kimura, Nucl. Phys. A 632, 540 (1998)].

独立収率の計算結果

赤点：計算結果
黒点：実験データ[Rudstam G, Aagaard P, Ekström B, et al., Radiochimica Acta. 1990;49(4):155–192.]

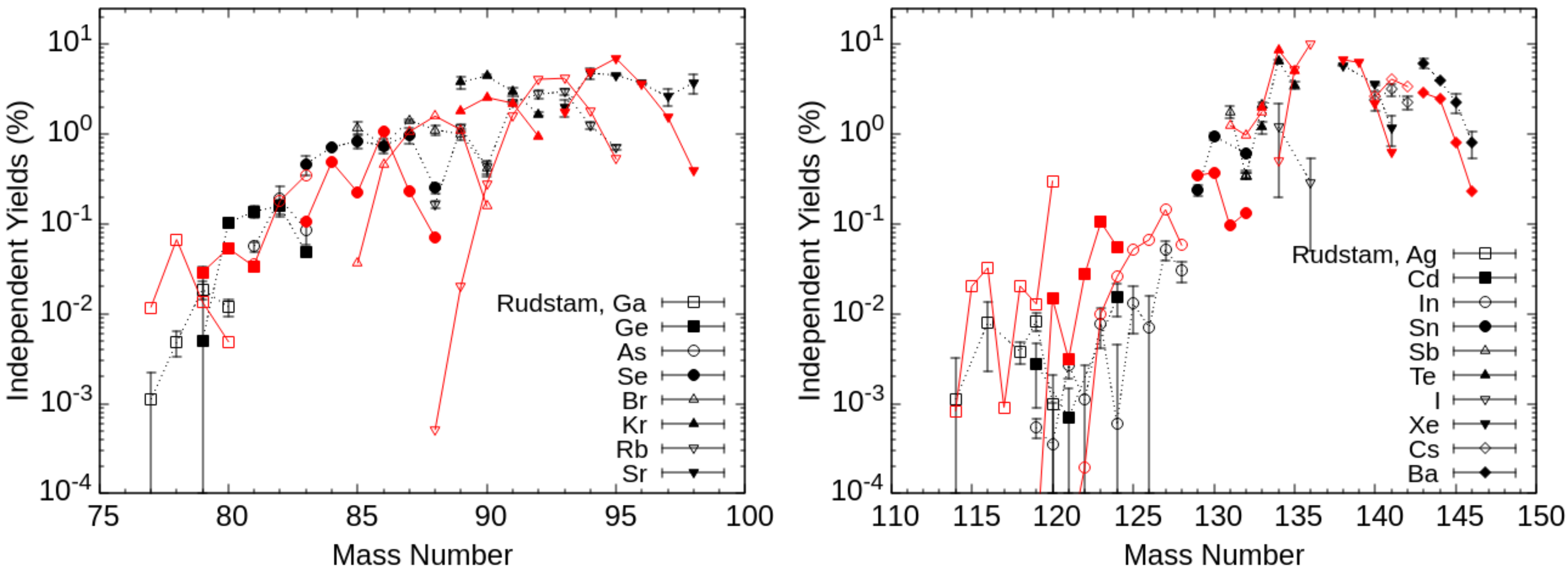


Fig. Comparison of the calculated independent yield Y_I(Z, A) with the experimental data.

核分裂によってどのような核種が生成されたかを評価することに成功した。

まとめ

- ｒプロセス元素合成において核分裂は重要な役割を果たす。
- 本研究では動力学模型を用いてFmの分裂モード変化およびUの中性子過剰核の核分裂を評価し、ウラン同位体においても中性子数が増えた場合、分裂モードが変化することが確認された。
- UCD仮定を用いて分裂片の核種を決定した。
- CCONEと組み合わせることで即発中性子放出を評価することに成功した。

<u>Future works</u>

◆ 分裂片の運動エネルギー分布や寿命などを評価する。

◆ 他モデルによる電荷分布評価を行う。

◆ 現存する実験データの評価や他モデルとの比較によるベンチマークを行い、計算範囲を広げr-プロセス計算へ応用可能なデータを揃える。

◆ 中性子過剰核のにおける核分裂の定性的な理解を目指す。

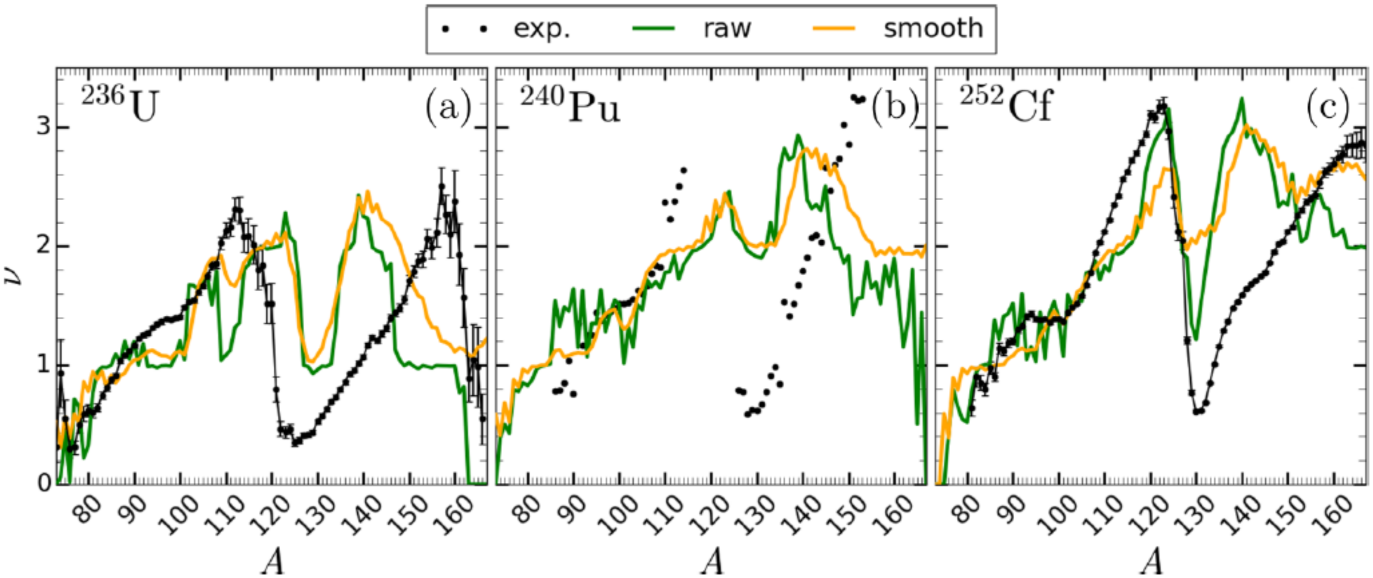


FIG. 3. Evaporated neutron distributions as a function of the fragment mass number. The black dotted lines represent experimental evaporated neutron distribution of (a) ^{236}U ($Q = 6.5$ MeV) [77], (b) ^{240}Pu ($Q = 6.5$ MeV) [78], and (c) ^{252}Cf ($Q = 0$ MeV) [79]. The orange (green) lines [labeled by "smooth" ("raw")] are SPY evaporated neutron distribution using smooth (raw) preneutron yields.

J.-F. Lemaître, S. Goriely, A. Bauswein, and H.-T. Janka, Phys. Rev. C **103**, 025806 (2021).

Z分布のペアリングについて

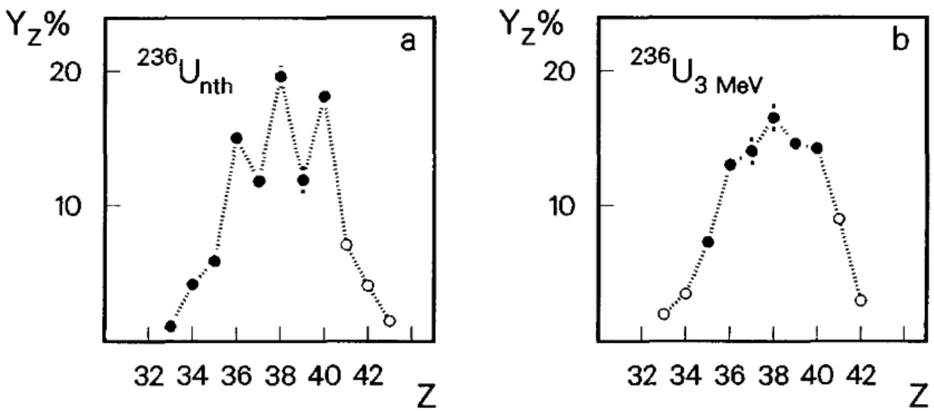


Figure 8 The element yields, obtained by radiochemical methods for: a) thermal neutron fission of uranium, b) 3MeV neutrons induced fission.

J.P. Bocquet, R. Brissot, Nucl. Phys. A **502**, 213 (1989).

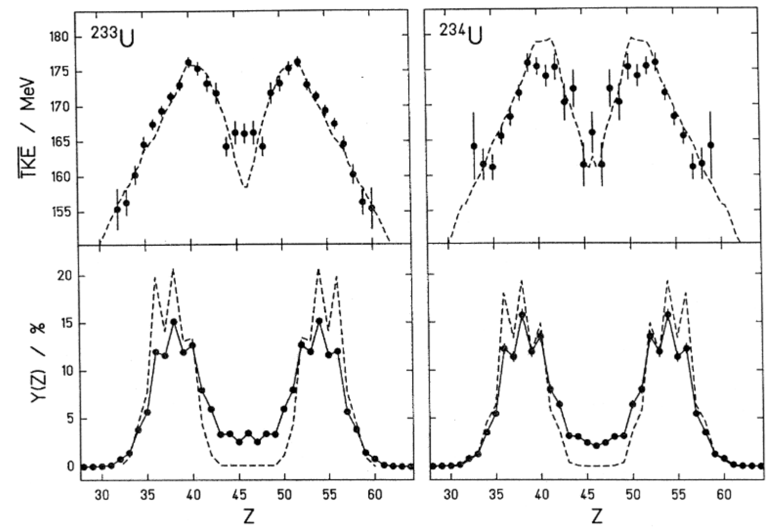


Fig. 18. Comparison of electromagnetic-induced with thermal-neutron-induced fission. Upper parts: Mean total kinetic energies as a function of the fission-fragment charge for electromagnetic-induced fission of ^{233}U (left) and ^{234}U (right) in a lead target (data points) compared to data from Ref. [89] (dashed lines) for TKE as a function of fragment mass for ^{232}U (n_{th}, f) and ^{233}U (n_{th},f). The mass scale of the data from thermal-neutron-induced fission is adapted to the charge range. Lower parts: Nuclear-charge yields for electromagnetic-induced fission of ^{233}U (left) and ^{234}U (right) in a lead target (data points) and from Refs. [90] and [54] (dashed lines) for ^{232}U (n_{th},f) and ^{233}U (n_{th},f), respectively. For the present data, only the statistical errors are shown. The TKE values of the present work are subject to an additional systematic uncertainty of 2%.

K.-H. Schmidt et al., Nucl. Phys. A **665**, 3 (2000).

■ <u>核分裂片の電荷分布評価モデル</u>

MPE：minimum of potential energy 仮定
ECD：equal charge displacement postulate 仮定
Particle number projection method

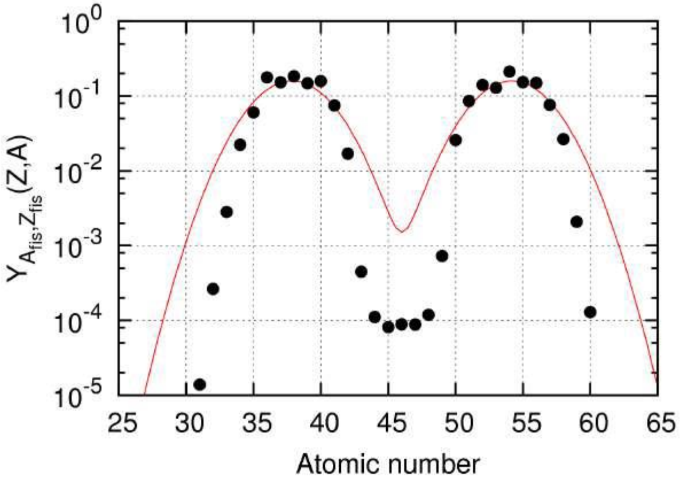
Marc Verriere, Nicolas Schunck, and Toshihiko Kawano, Phys. Rev. C **100**, 024612 (2019).

R. D. Present, Phys. Rev. **72**, 7 (1947).
P. P. Benjamin, D. A. Marsden, N. T. Porile, and L. Yaffe, Canadian Journal of Chemistry **47**,2 (1969).

Takahashi & Kodama

ある元素$(Z_{\mathrm{fis}}, A_{\mathrm{fis}})$ が核分裂を起こしたときに生成する核分裂生成物(Z, A) の分布 (fission yield) を、Takahashi & Kodama (1975)の経験式で表す。

$$Y_{Z_{fis},A_{fis}}(Z,A) = exp\left\{-\frac{(Z-Z_A)^2}{c_Z}\right\}\frac{1}{\sqrt{\pi c_Z c_A}}\left[exp\left\{-\frac{(A-A_L)^2}{c_A}\right\} + exp\left\{-\frac{(A-A_H)^2}{c_A}\right\}\right]$$



$$A_L = 0.85A_{fis} - 104.98$$
$$A_H = 0.15A_{fis} - 103.87$$
$$Z_A = (A+0.6)\frac{Z_{fis}}{A_{fis}}$$
$$c_Z = 0.8$$
$$c_A = 78$$

また、ある元素i$(Z_{\mathrm{fis}}, A_{\mathrm{fis}})$ が核分裂を起こし元素j$(Z_{\mathrm{j}}, A_{\mathrm{j}})$を生成するとき、

$$\frac{dY_j}{dt} = -\frac{dY_i}{dt} \times Y_{Z_{fis},A_{fis}}(Z_j, A_j)$$

という関係を満たす。

T. Kodama and K. Takahashi, Nucl. Phys. **239**, 489 (1975).

Konan Model

$$f(A) = \frac{1}{\sqrt{2\pi}\sigma}(1 - w_s)\left(e^{-(A_H - A)^2/2\sigma^2} + e^{-(A_L - A)^2/2\sigma^2}\right) + 2w_s \frac{1}{\sqrt{2\pi}\sigma} e^{-((A - N_{loss})/2 - A)^2/2\sigma^2}$$

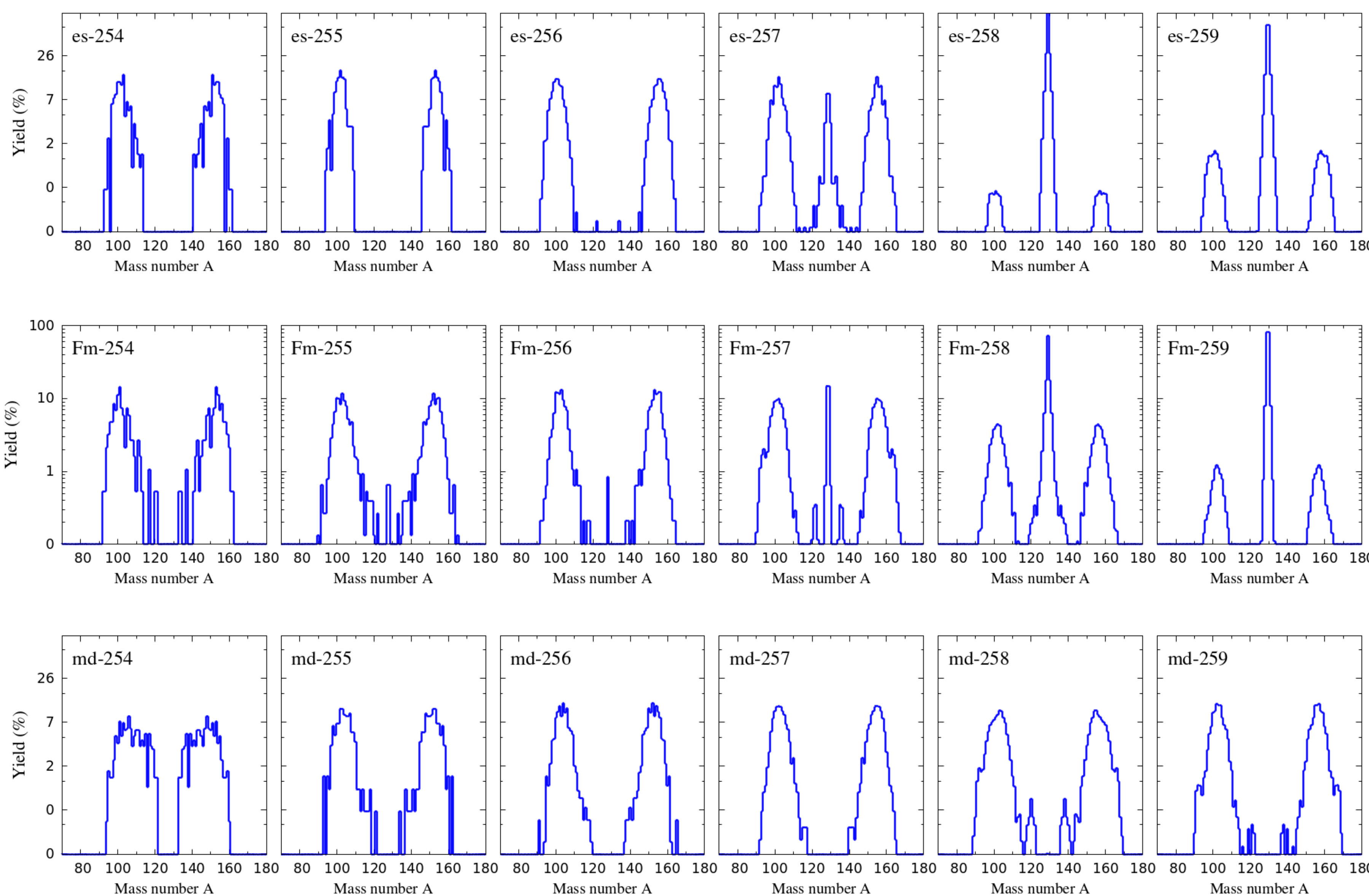
$$\sigma = 0.7$$
$$A_H = (1 + \alpha)(A - N_{loss})/2$$
$$A_H = (1 - \alpha)(A - N_{loss})/2$$
$$Z/N = Z_H/\left(N_H + (N_{loss}/2)\right) = Z_L/\left(N_L + (N_{loss}/2)\right)$$

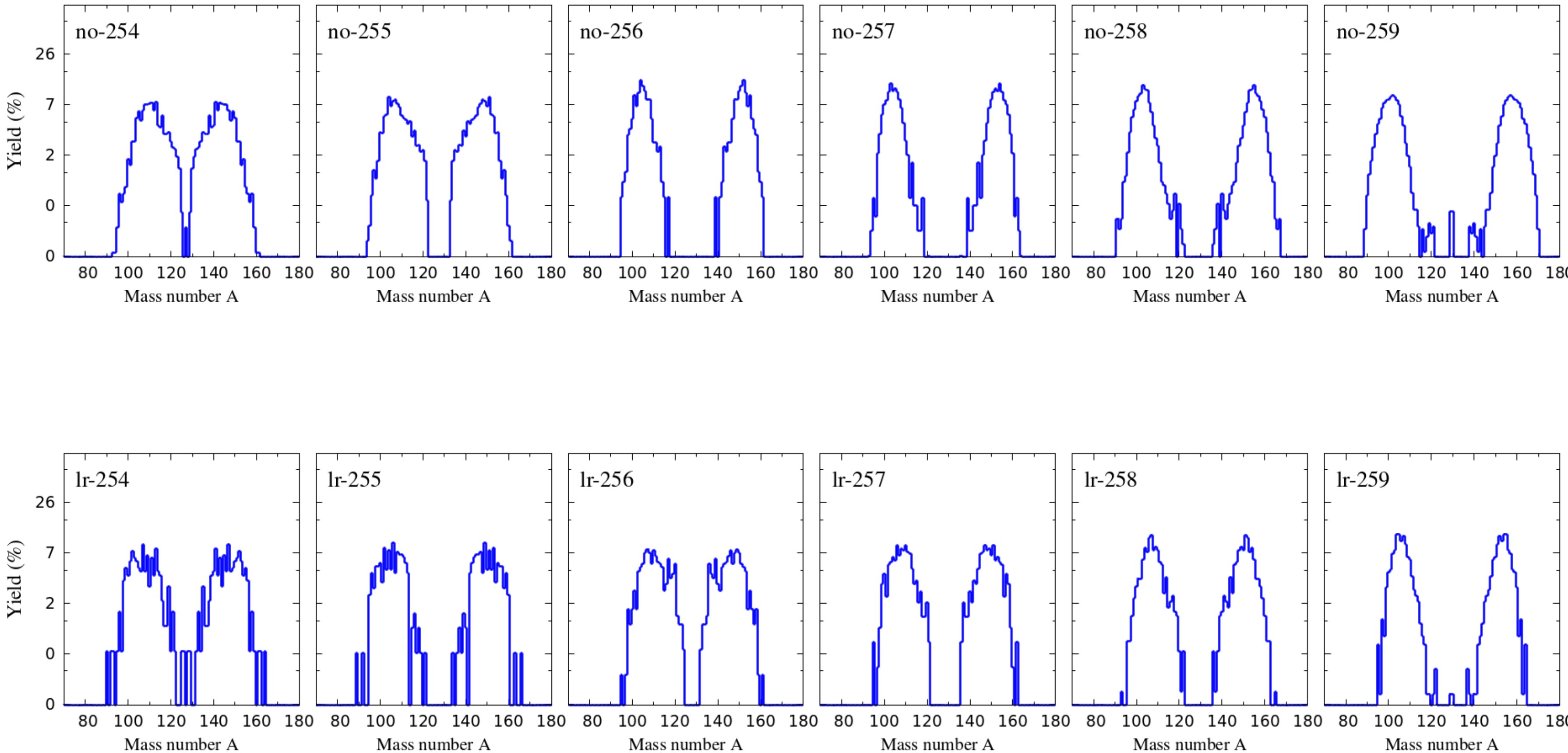
International Conference on Nuclear Data for Science and Technology 2007
DOI: 10.1051/ndata:07302

Systematic study for the mass distribution of fission fragments in the neutron rich region

M. Ohta[1,a], S. Tatsuda[1], T. Hashizume[2], K. Yamamoto[1], T. Wada[1,b], K. Sumiyoshi[3], K. Otsuki[4], T. Kajino[5], H. Koura[6], S. Chiba[6], and T. Tachibana[7]

[1] Department of Physics, Konan University Kobe 658-8501, Japan
[2] Allid Engineering Corporation, Tokyo, Japan
[3] Numazu College of Technology, Ooka 3600, Numazu 410-8501, Japan
[4] Department of Astronomy and Astrophysics, University of Chicago, USA
[5] National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[6] Advanced Science Research Center, JAEA Tokai, Naka, Ibaraki 319-1195, Japan
[7] Senior High School of Waseda University, 3-31-1 Kamishakujii, Nerima-ku, Tokyo 177-0044, Japan


es-254
es-255
es-256
es-257
es-258
es-259
Fm-254
Fm-255
Fm-256
Fm-257
Fm-258
Fm-259
md-254
md-255
md-256
md-257
md-258
md-259
Yield (%)
26
7
2
0
0
100
10
1
0
80 100 120 140 160 180
Mass number A


no-254
no-255
no-256
no-257
no-258
no-259
lr-254
lr-255
lr-256
lr-257
lr-258
lr-259
Yield (%)
26
7
2
0
0
80
100
120
140
160
180
Mass number A

PRL **111,** 242502 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

New Fission Fragment Distributions and *r*-Process Origin of the Rare-Earth Elements

S. Goriely,[1] J.-L. Sida,[2] J.-F. Lemaître,[2] S. Panebianco,[2] N. Dubray,[3] S. Hilaire,[3] A. Bauswein,[4,5] and H.-T. Janka[5]

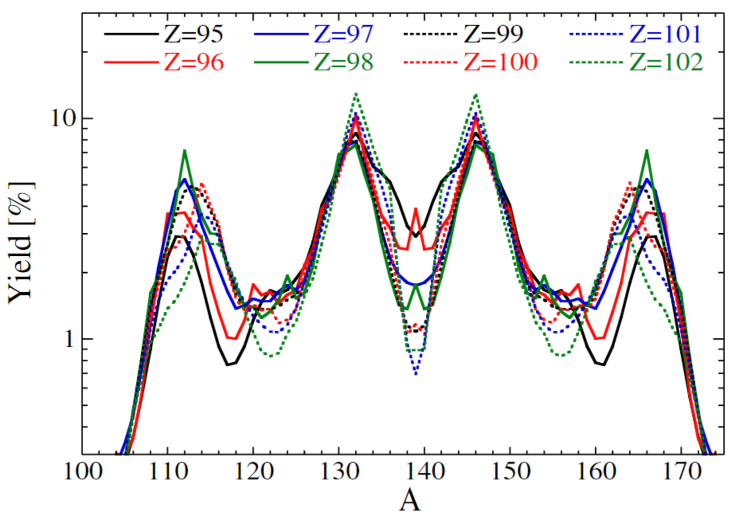


FIG. 2 (color online). FFDs from the SPY model for eight $A = 278$ isobars.

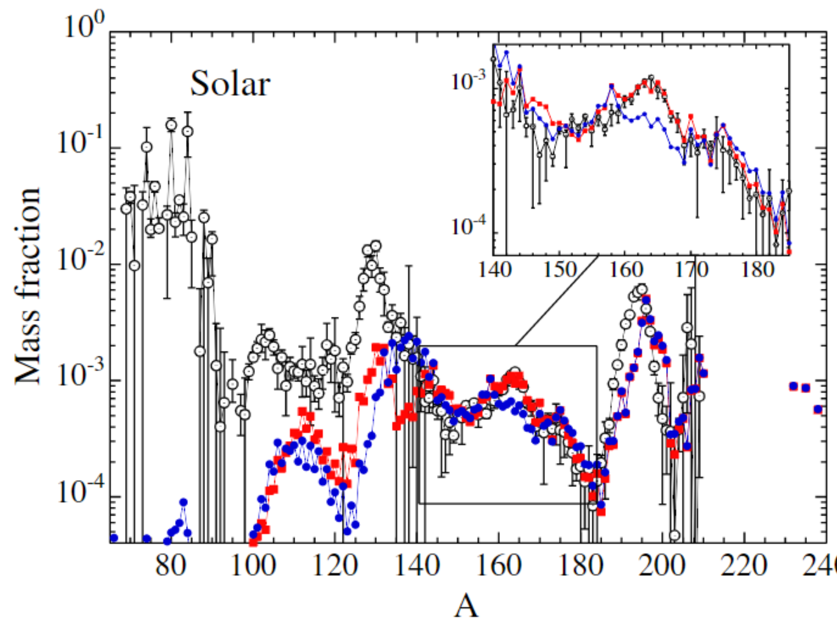
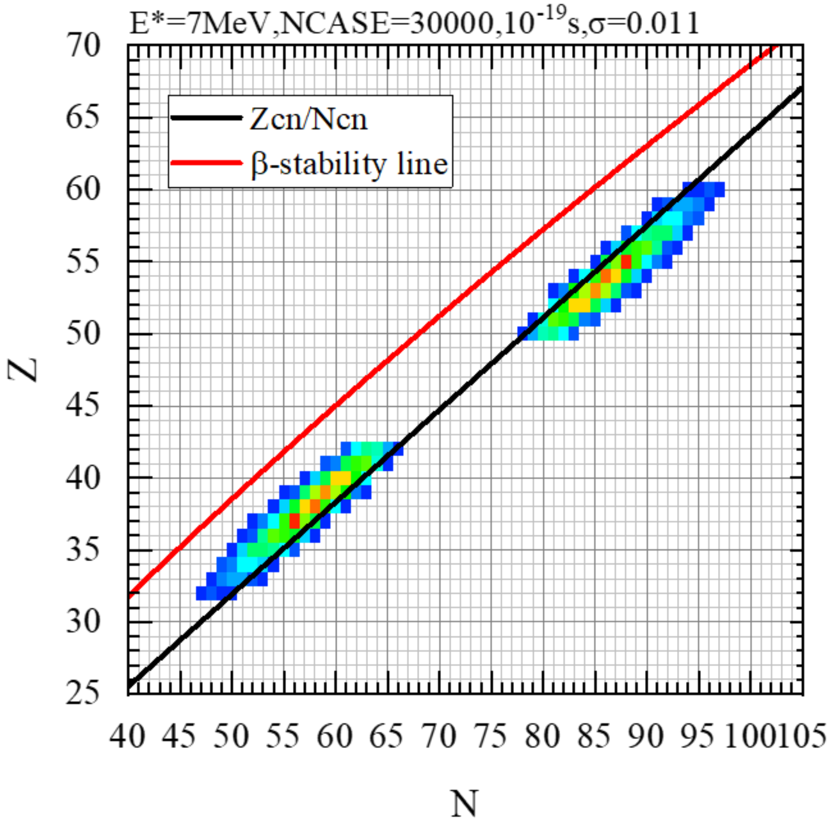
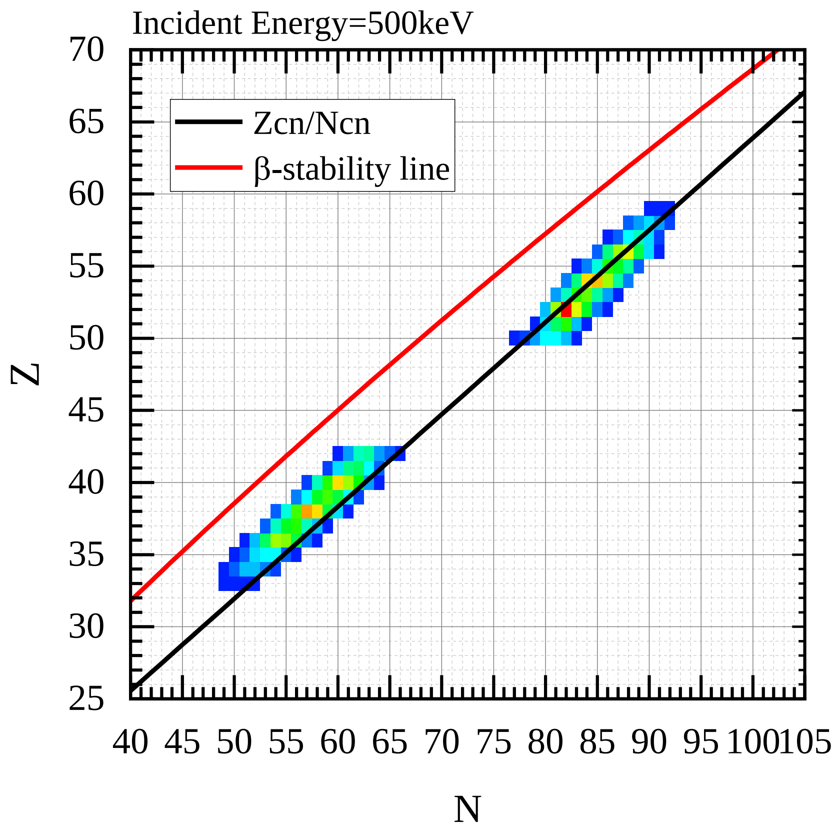


FIG. 4 (color online). Final abundance distribution vs atomic mass for ejecta from 1.35–1.35 $M_\odot$ NS mergers. The red squares are for the newly derived SPY predictions of the FFDs and the blue circles for essentially symmetric distributions based on the 2013 GEF model [52]. The abundances are compared with the solar ones [56] (dotted circles). The insert zooms on the rare-earth elements.

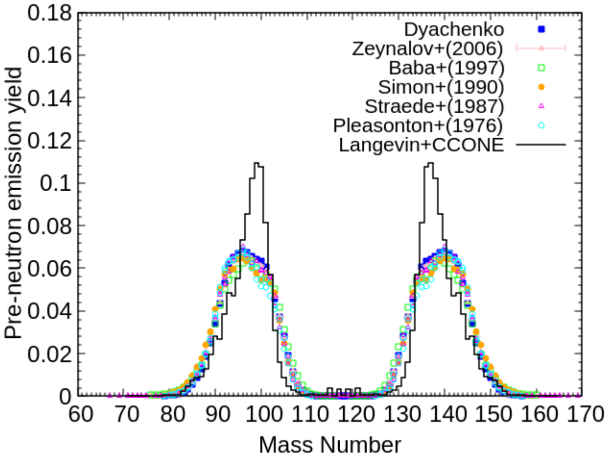
Cal.

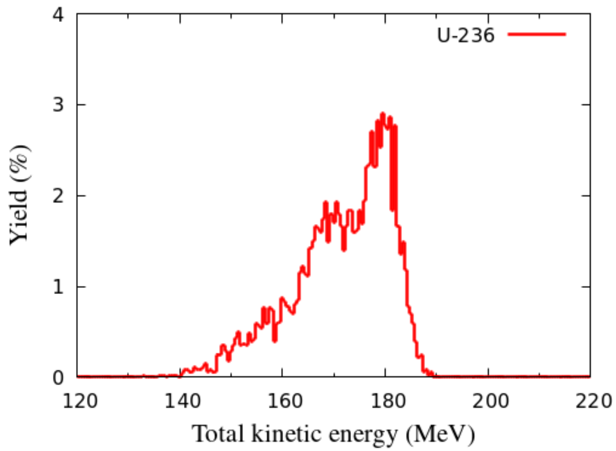


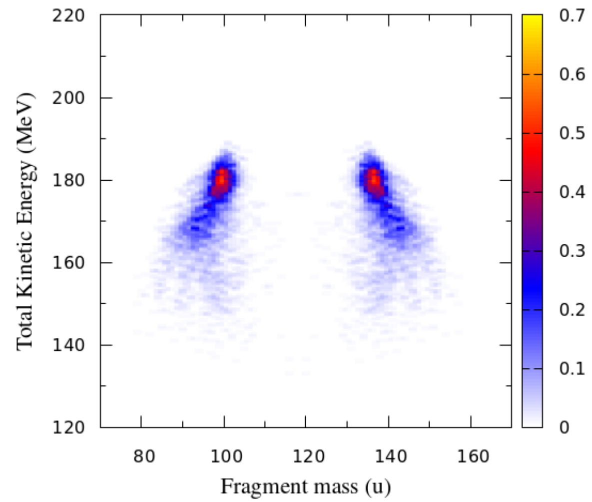
Exp.



$$\mu = \frac{\frac{Z_{cn}}{A_{cn}} + \frac{50}{82}}{2}$$

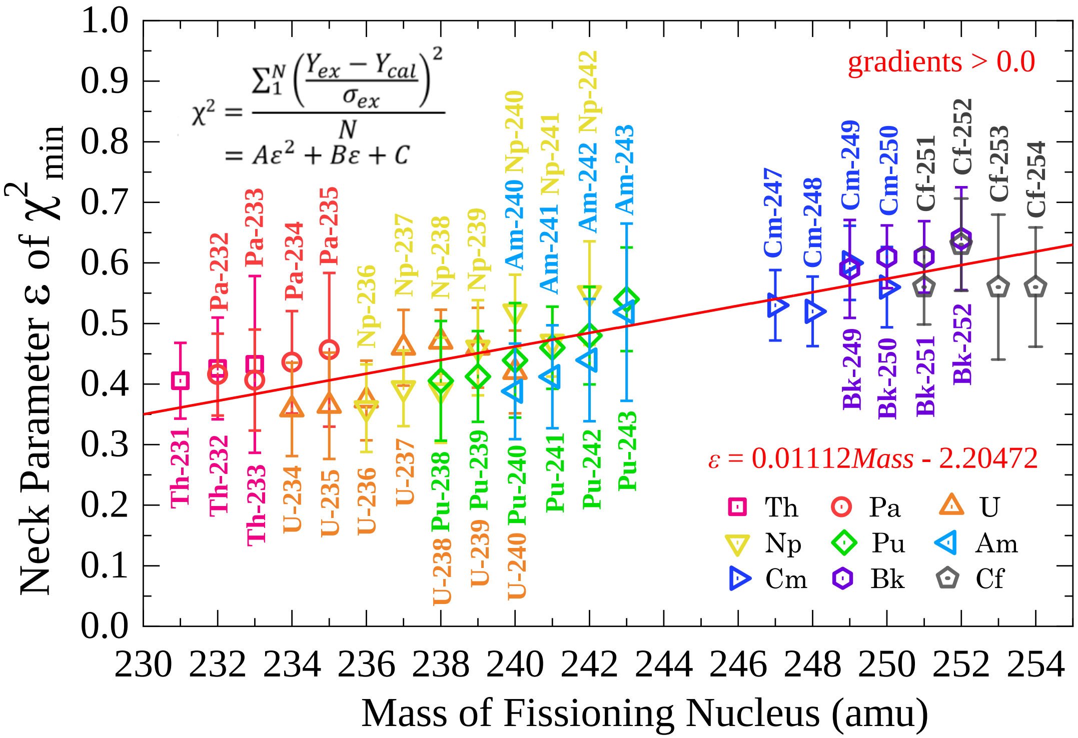

Dyachenko
Zeynalov+(2006)
Baba+(1997)
Simon+(1990)
Straede+(1987)
Pleasonton+(1976)
Langevin+CCONE
Pre-neutron emission yield
Mass Number
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18
60 70 80 90 100 110 120 130 140 150 160 170


U-236
Yield (%)
Total kinetic energy (MeV)
0 1 2 3 4
120 140 160 180 200 220


Total Kinetic Energy (MeV)
Fragment mass (u)
120 140 160 180 200 220
80 100 120 140 160
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

Neck parameter

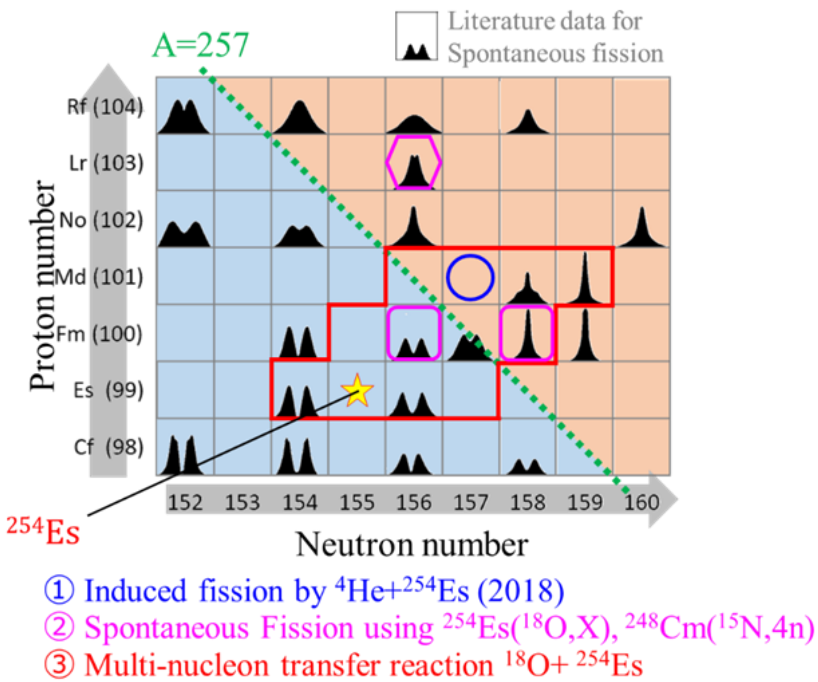
$$\varepsilon = 0.01112M - 2.20472$$

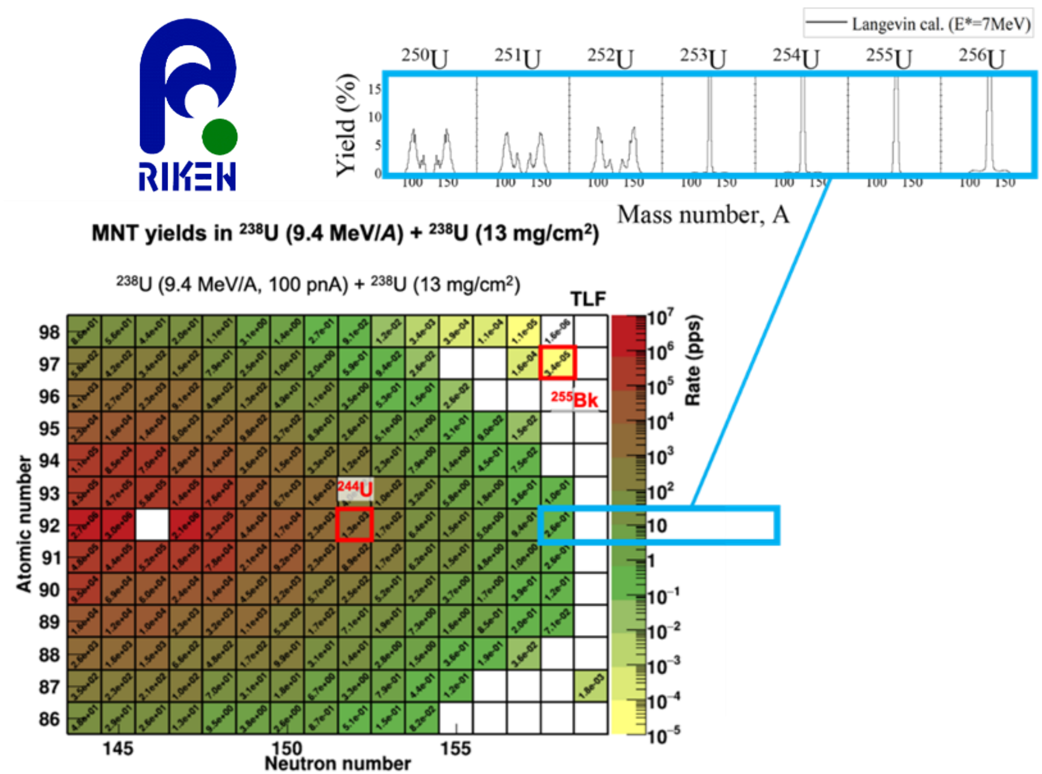


実験によるアプローチ

◆ Es標的と代理反応法による測定

◆ ^{238}U標的と代理反応法による測定





Calc. by Y.X. Watanabe (KEK)

■ 日本原子力研究開発機構（JAEA）や理化学研究所による実験の可能性

■ 理論計算が検証されることが期待される

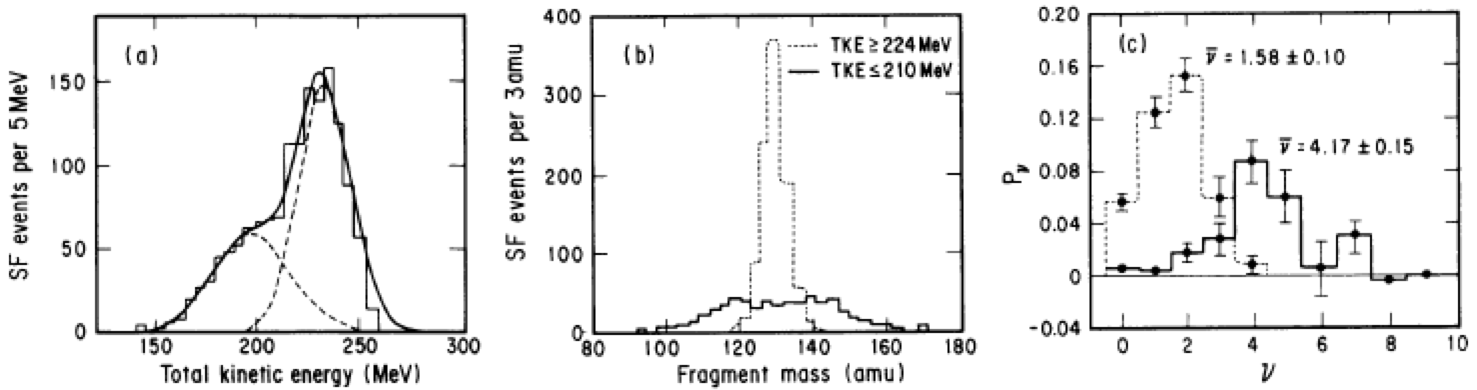
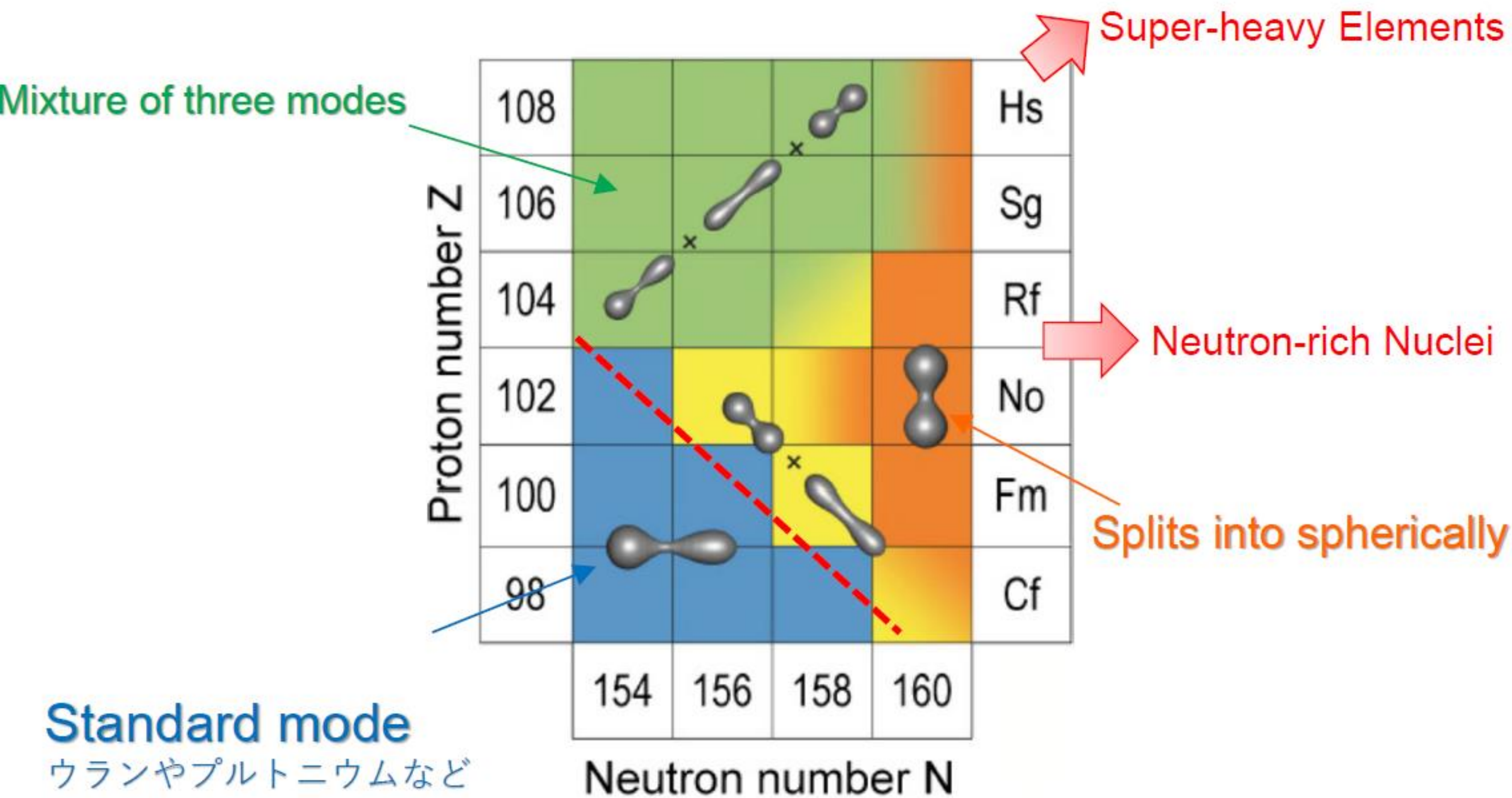


図 1　^{260}Md の自発核分裂で得られた (a) 分裂片の運動エネルギー（TKE）分布，(b) TKE≧224 MeV（点線）成分と TKE≦210 MeV（実線）成分からの質量収率分布，(c) TKE≧224 MeV（点線）成分と TKE≦210 MeV（実線）成分での分裂片からの放出中性子数の確率分布[3)]

1)　たとえば Hoffman, D. C.：*Nucl. Phys.*, **A502**, 21c–40c（1989）
2)　Hulet, E. K., Wild, J. F. et al.：*Phys. Rev. Lett.*, **56**, 313–316（1986）
3)　Wild, J. F., Aarle, J. van, et al.：*Phys. Rev. C*, **41**, 640–646（1990）
4)　Kudo, H., Muramatsu, H. et al.：*ibid.*, **25**, 3011（1982）
5)　Ohtsuki, T., Nagame, Y. et al.：*Phys. Rev. Lett.*, **66**, 17–20（1991）
6)　Ohtsuki, T., Ikezoe, H. et al.: Proc. Int. Workshop on Dynamical Aspects of Nuclear Fission, pp. 186–191（1991）
7)　Möller, P. and Nix, J. R.：*J. Phys. G*, **20**, 1681–1747（1994）
8)　Brosa, U., Grossmann, S. et al.：*Phys. Rep.*, **197**, 167–262（1990）

（日本原子力研究所東海研究所）

核分裂モードの混在



A. Staszczak *et al.*, Phys. Rev. C **80**, 014309 (2009).

35 Systematical calculation of probabilities of beta-delayed neutron emission and fission in the entire region of nuclear chart

Hiroyuki KOURA

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Shirakata 2-4, Tokai-mura, Ibaraki 319-1195, Japan

Fumitaka Endo

Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

e-mail: koura.hiroyuki@jaea.go.jp

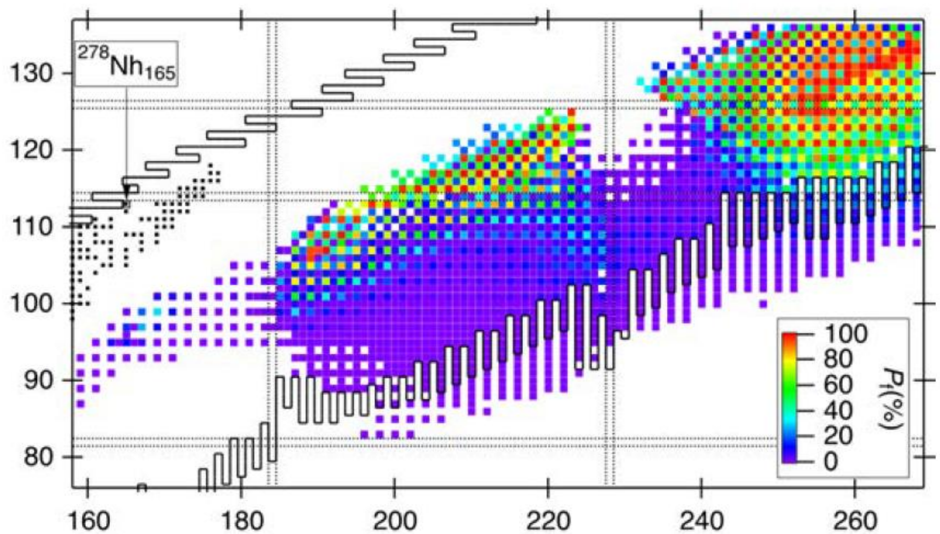
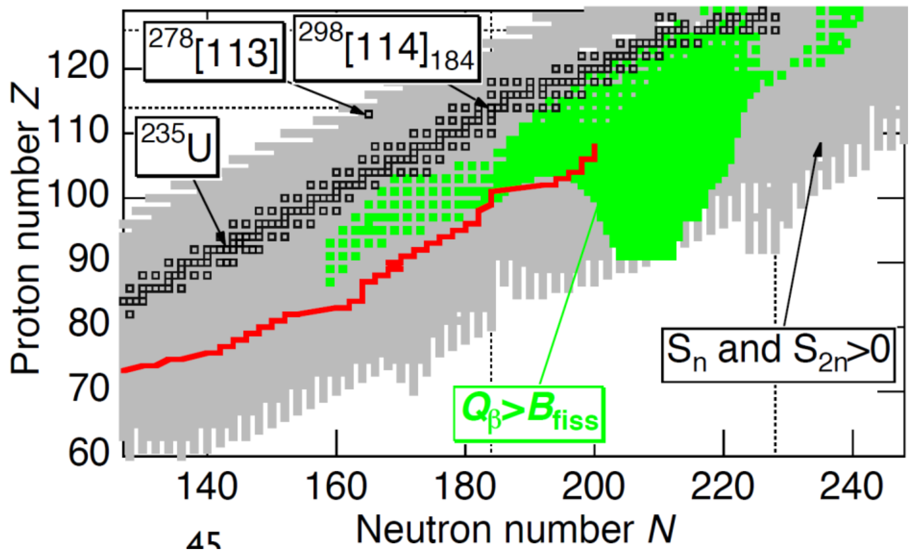
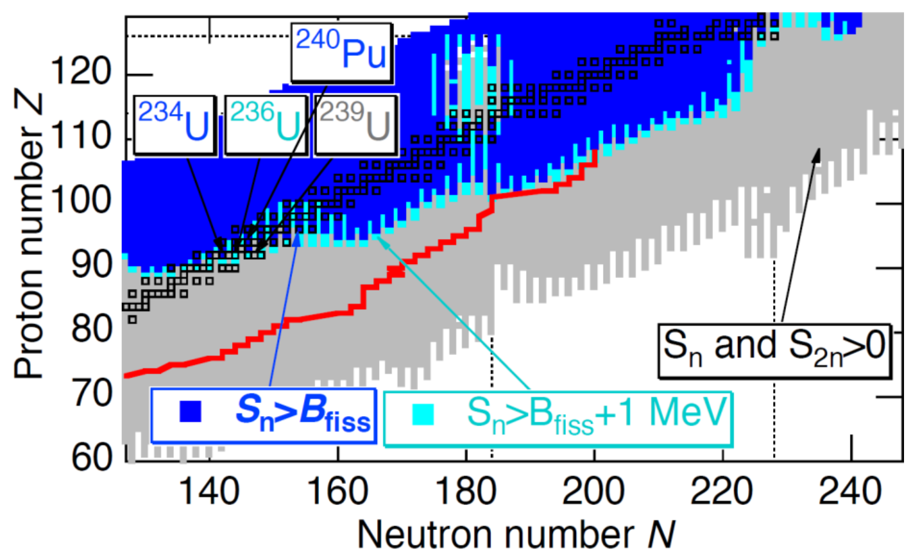


Figure 4: Beta-delayed fission probabilities. The black points indicate experimentally-identified nuclides until 2018, from the chart of the JAEA nuclides 2018 [13].





calculated by H. Koura (2016).

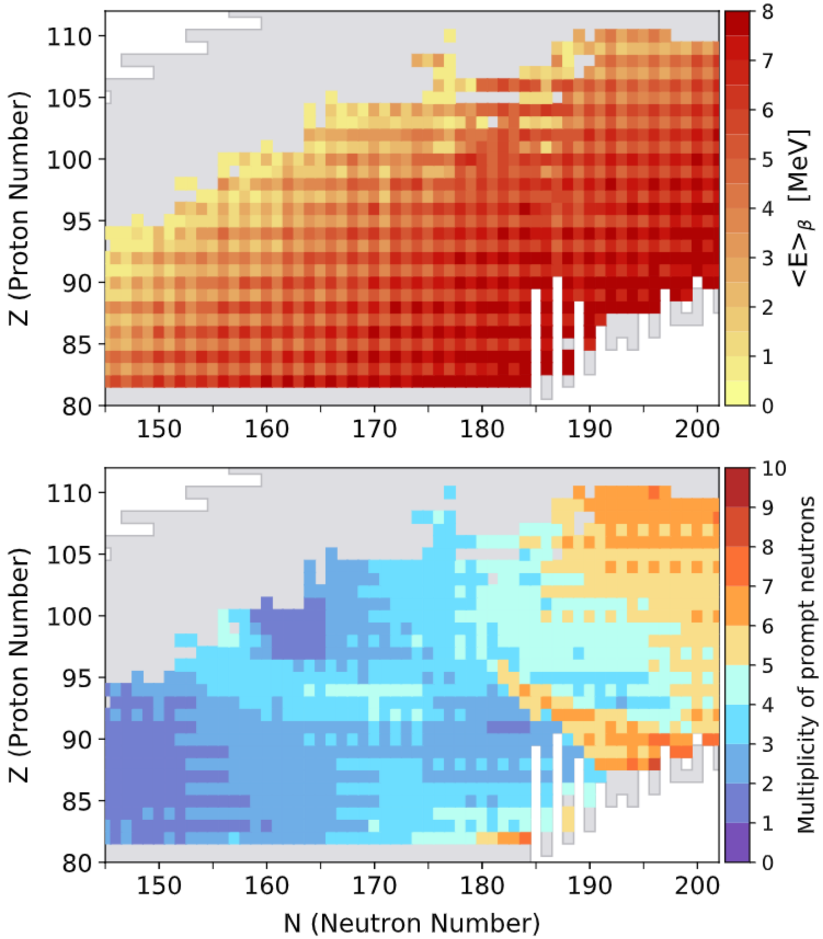
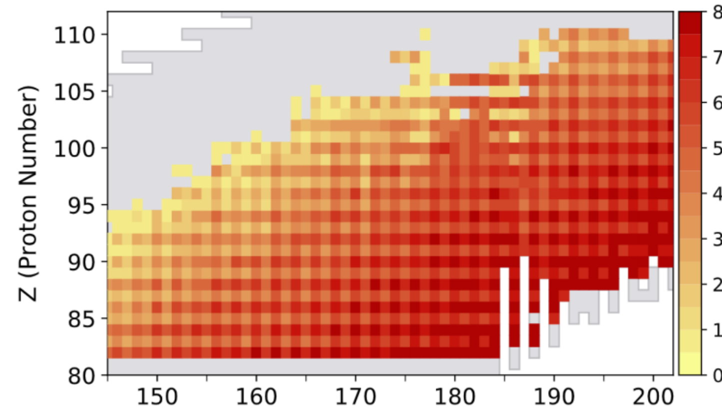


FIG. 4. (Color online) The average excitation energy for the daughter nucleus populated by β-decay [37] (upper panel) and the corresponding average prompt neutron emission as predicted by GEF when this excited daughter fissions (lower panel).



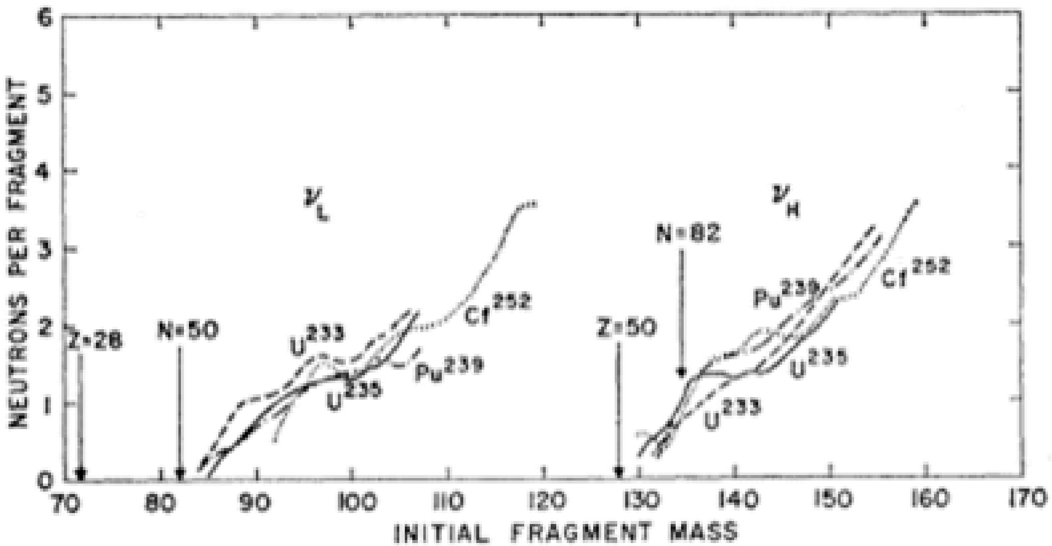
N Vassh et al., J. Phys. G: Nucl. Part. Phys. **46** 065202 (2

即発中性子放出数（Prompt neutron multiplicity）

■ Terrellらによる経験式

$$\nu_l = 0.08(A_l - 82)$$
$$\nu_h = 0.10(A_h - 126)$$

A_l, A_h：即発中性子放出前の質量数



J. Terrell, Phys. Rev. **127**, 880 (1962)