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5次元Cassiniパラメータを用いた核分裂の動力学的研究

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研究背景

5次元Cassiniパラメータを用いた核分裂のLangevin計算

・超重核領域における変形核形状の描写

・多次元Langevin方程式への適用

Cassiniパラメータの特徴

・多様な変形が表せる: 伸びαとLegendre展開係数α_n

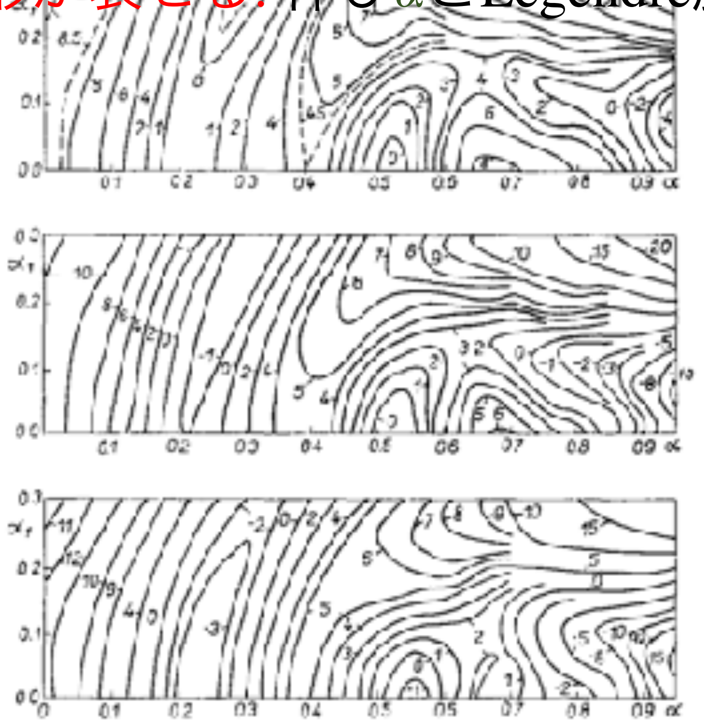
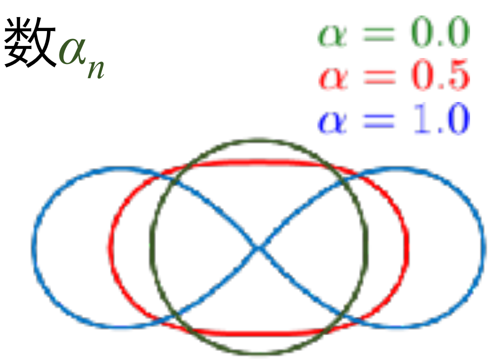


Fig. 8. The same as in fig. 7 for ^{236}U at the top, ^{240}Pu in the middle and ^{252}Cf at the bottom.



Cassini楕円(R = 一定)

$$R(x) = 1 + \sum_{n=1}^{\infty} \alpha_n P_n(x)$$

V. V. Pashkevich, Nucl. Phys. A 477, 1(1971)

研究背景

Cassini shape parameterization

Static approach (not Langevin)

・pre-scission shape

・potential energy of deformation

α=0.985

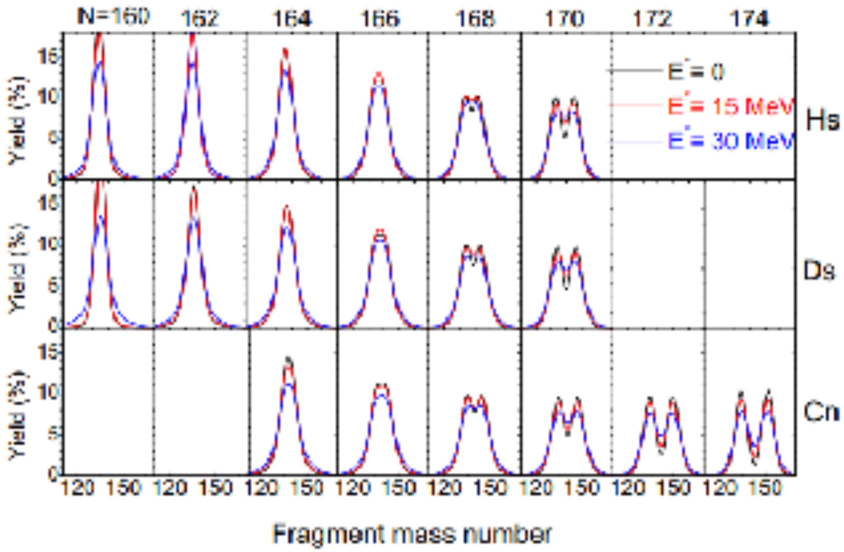


FIG. 3. The calculated fragment mass distributions for isotopes of Hs, Ds, and Cn for which spontaneous fission has been detected. Three values of the excitation energy E^* have been considered. T_{coll} = 2 MeV, E_d = 40 MeV.

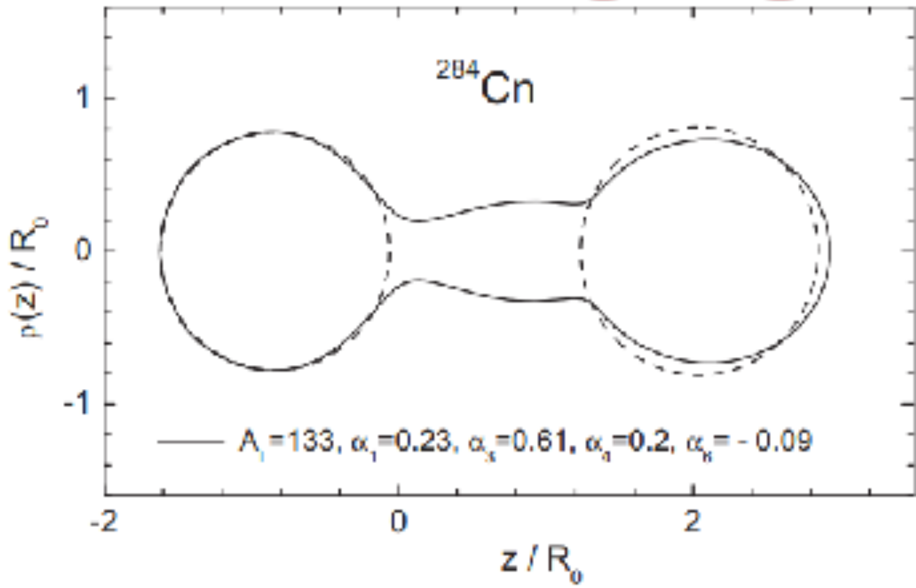


FIG. 2. The just-before-scission shape of ^{284}Cn for A_L = 133 (solid) and the fit of left and right part of nucleus by spheroids (dash).

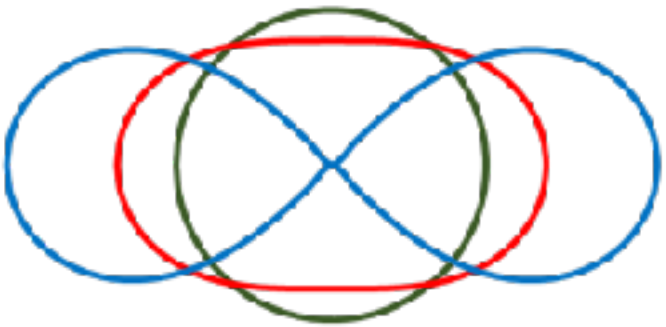
N. Carjan, F. A. Ivanyuk, Yu. Ts. Oganessian, Phys. Rev. C **999**, 064606 (2019).

α_1, α_3, α_4, α_6が重要 (超重核)

5次元{α, α_1, α_3, α_4, α_6}Langevin方程式

系統的な核分裂計算

Cassini Shape Parameterization



$\alpha = 0.0$
$\alpha = 0.5$
$\alpha = 1.0$

Cassini ovals (R = const.)

$$\alpha = \frac{z_R^2 + z_L^2 - 2\rho_{\text{neck}}^2}{z_R^2 + z_L^2 + 2\rho_{\text{neck}}^2}$$

α : elongation

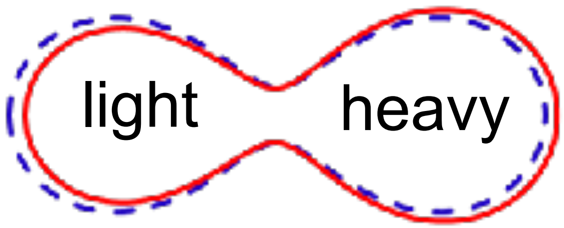
Pashkevich, Nucl. Phys. A **169** (1971) 275.

$$R(x) = 1 + \sum_{n=1}^{\infty} \alpha_n P_n(x)$$

Legendre expansion of R for additional parameters

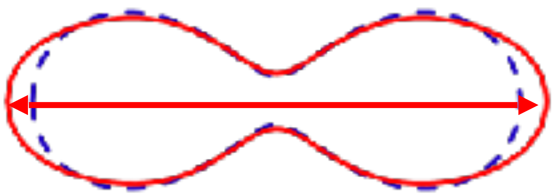
n
- odd: asymmetric deformation α_1 α_3
- even: symmetric deformation ~~α_2~~ α_4 α_6

Cassini Shape Parameterization



α_1 mass asymmetry

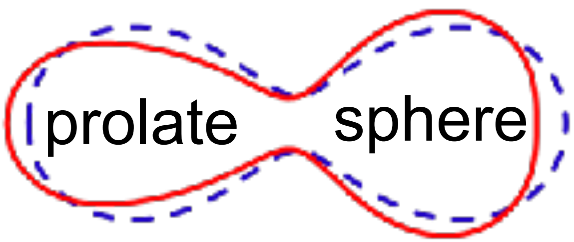
FMN



α_4 quadrupole deformation of fragments

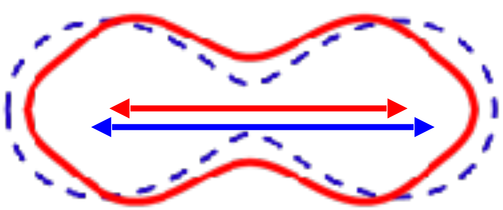
GS, 1stB, 2ndM

necessary parameters



α_3 shape asymmetry

double magic ^{132}Sn



α_6 octupole deformation of fragments

super-long (short) shape

additional parameters

Langevin方程式

$$\{q_i\} = \{\alpha,\ \alpha_n\}$$

$$< R_j(t) > = 0$$
$$< R_i(t) R_j(t') > = 2\delta(t - t')$$
$$T^* \gamma_{ij} = g_{ik} g_{kj}$$

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

$$V(\boldsymbol{q}, T) = V_{\mathrm{LDM}}(\boldsymbol{q}) + V_{\mathrm{micro}}(\boldsymbol{q}) \exp(-aT^2/E_D) \qquad E_D = 25\,\mathrm{MeV}$$

変形ポテンシャル　macroscopic-microscopic approach

V. M. Strutinsky, Nucl. Phys. A **95** (1967) 420

$m_{ij}(\boldsymbol{q})$　慣性テンソル　Werner-Wheeler method　K. T. R. Davies et al., Phys. Rev. C 13, 2385 (1976)

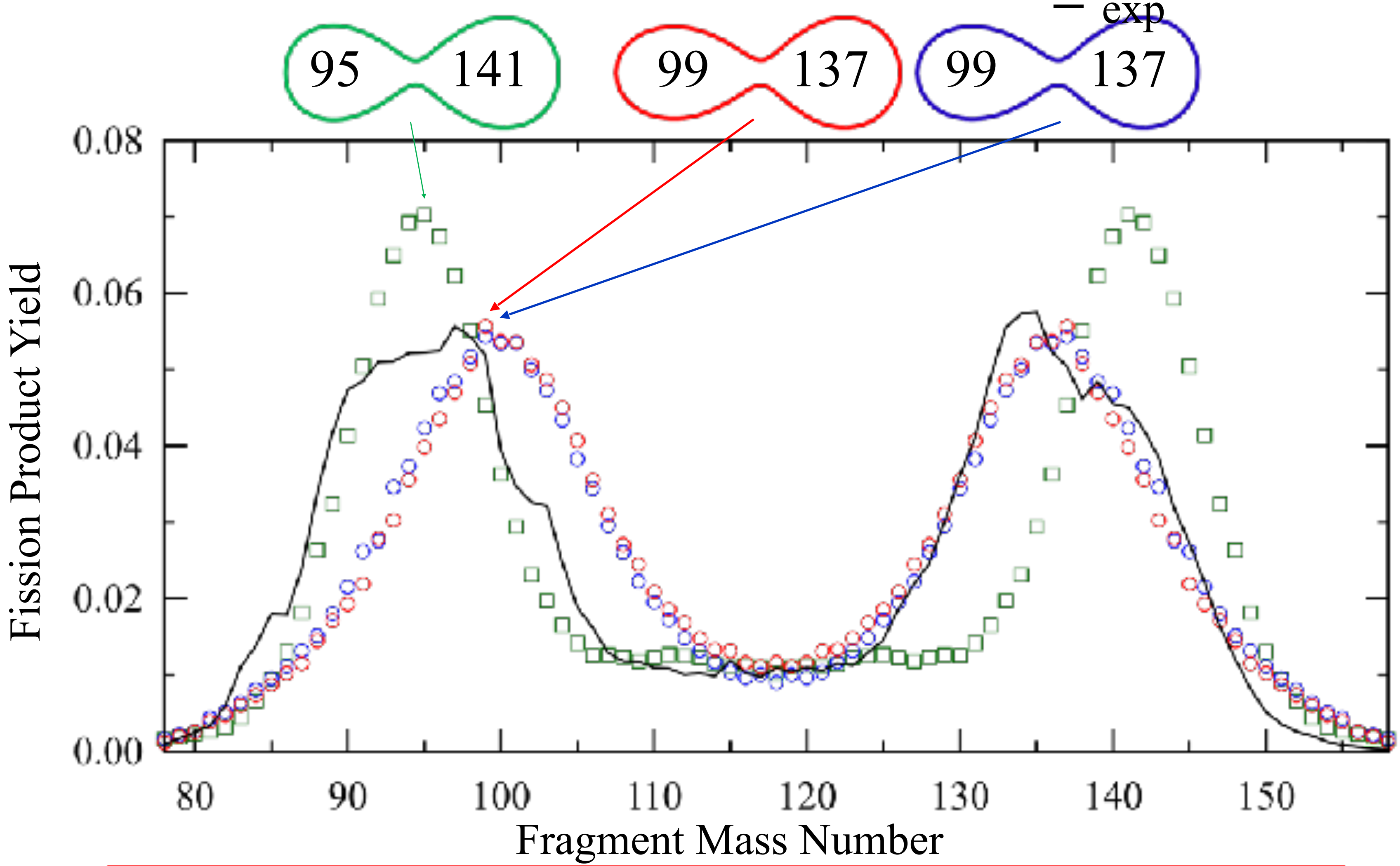
$\gamma_{ij}(\boldsymbol{q})$　摩擦テンソル　Completed wall-and-window formula

J. Randrup and W. J. Swiatecki, Nucl. Phys. A 429, 105 (1984)

3D $\{\alpha,\ \alpha_1,\ \alpha_4\}$ ・ 4D $\{\alpha,\ \alpha_1,\ \alpha_3,\ \alpha_4\}$ $\{\alpha,\ \alpha_1,\ \alpha_4,\ \alpha_6\}$ ・ 5D $\{\alpha,\ \alpha_1,\ \alpha_3,\ \alpha_4,\ \alpha_6\}$ での比較

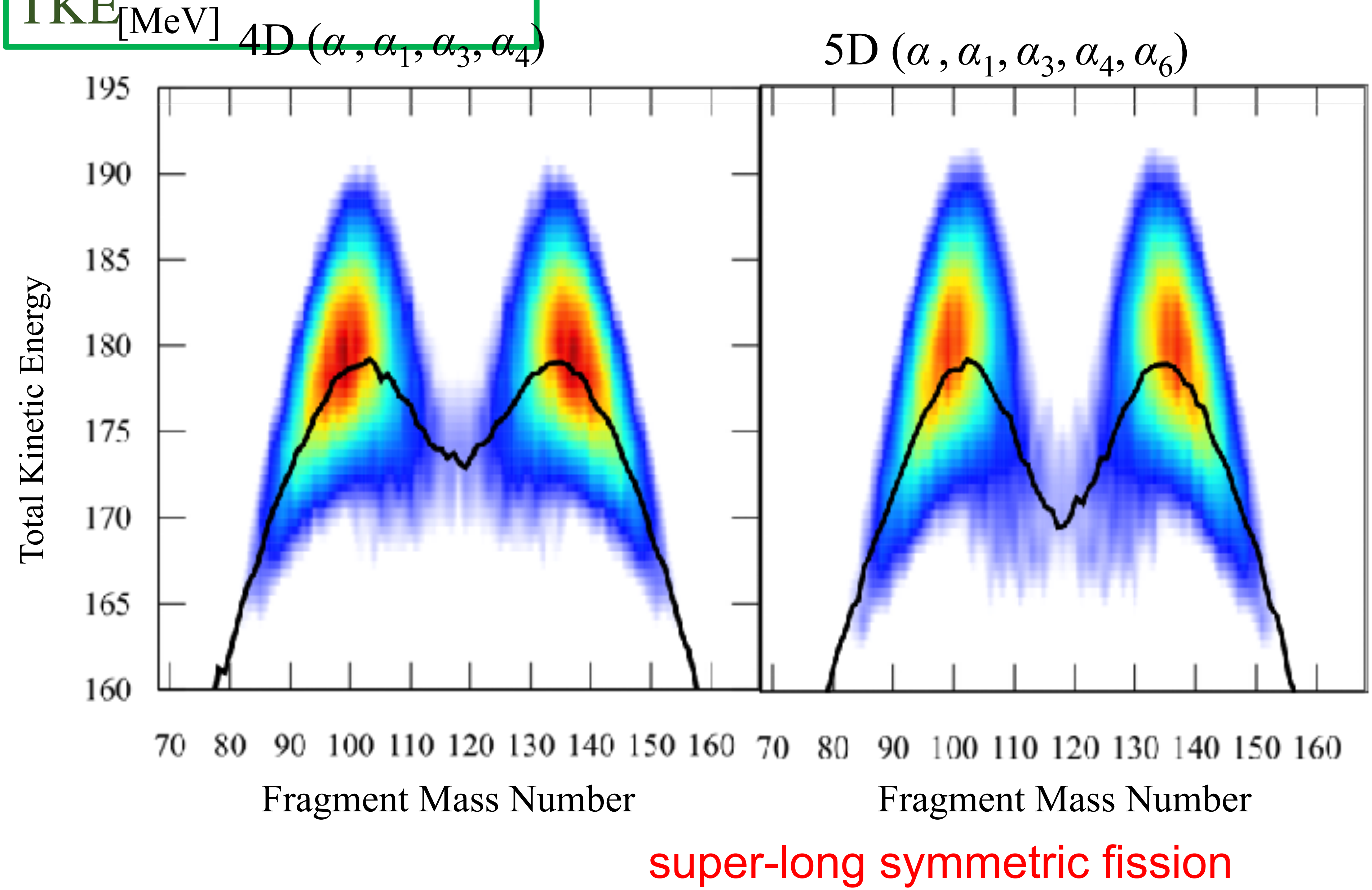
Result: ^{236}U Fragment Mass Distributions

14 MeV n + ^{235}U



3D → 4D (3D + α_3), 5D (4D + α_6): prolate + sphere

Result: ^{236}U FMN-TKE



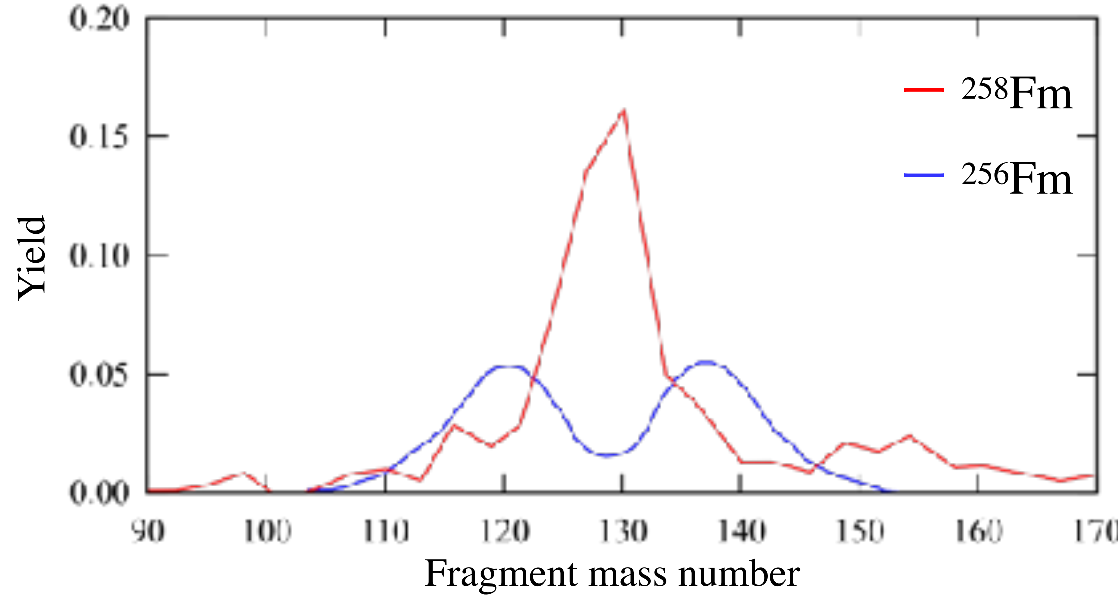
Fm同位体の分裂片質量分布

・質量分布が変化

非対称分裂(^{256}Fm)

↓

対称分裂(^{258}Fm~)



Fm分裂片質量分布 (実験値)

D. C. Hoffman et al., Phys. Rev. C 21, 972–981, (1980).

・対称分裂を描写できる自由度

$\alpha,\ \alpha_1,\ \alpha_4\ +\alpha_6$

・Cassiniパラメータの追加

→

$\alpha,\ \alpha_1,\ \alpha_4,\ \alpha_6\ +\alpha_3$

・非対称分裂の考慮

Result: ^{258}Fm Fragment Mass Distributions

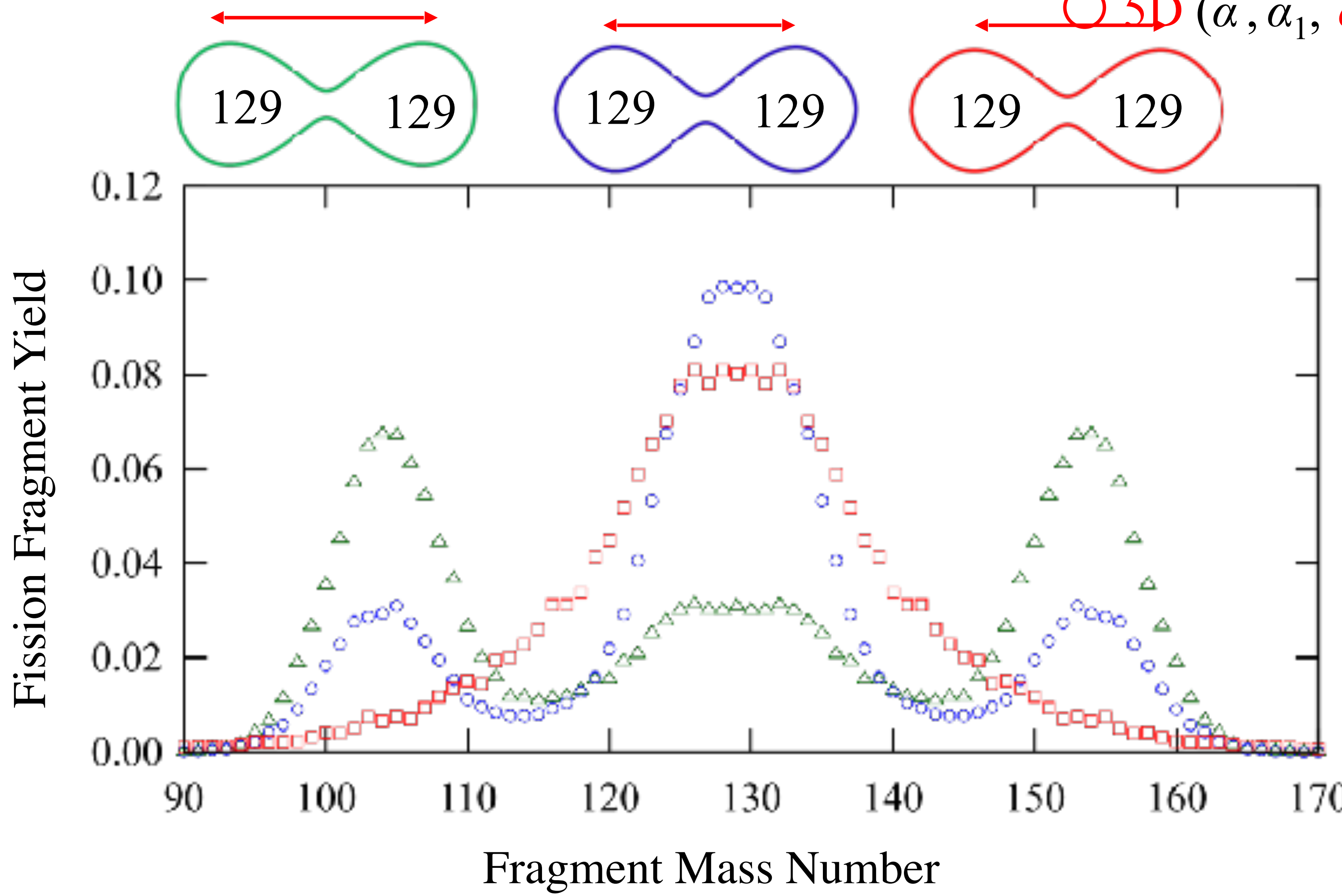
△ 3D (α , α_1, α_4)

↓

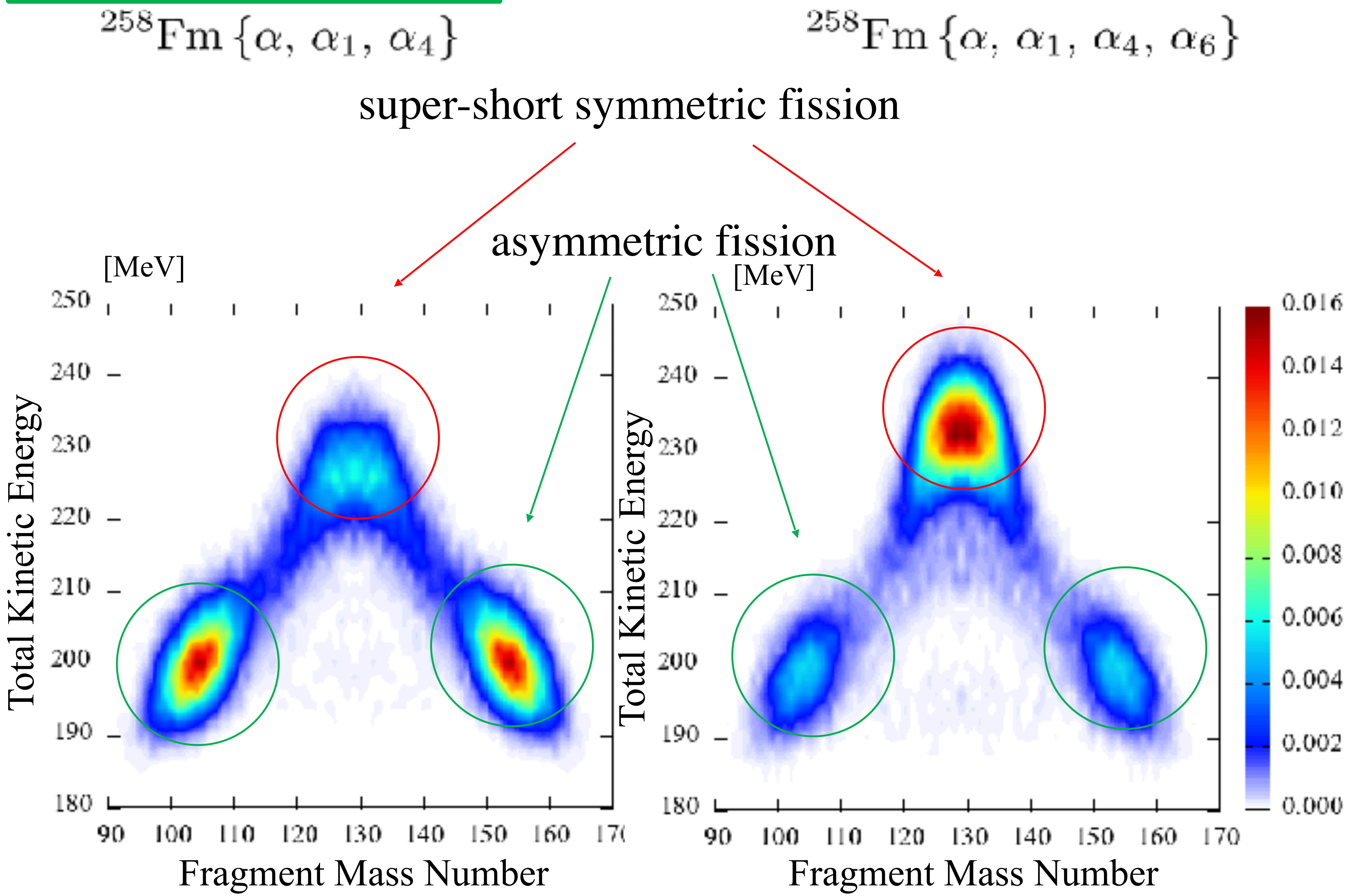
□ 4D (α , α_1, α_4, α_6)

↓

○ 5D (α , α_1, α_3, α_4, α_6)



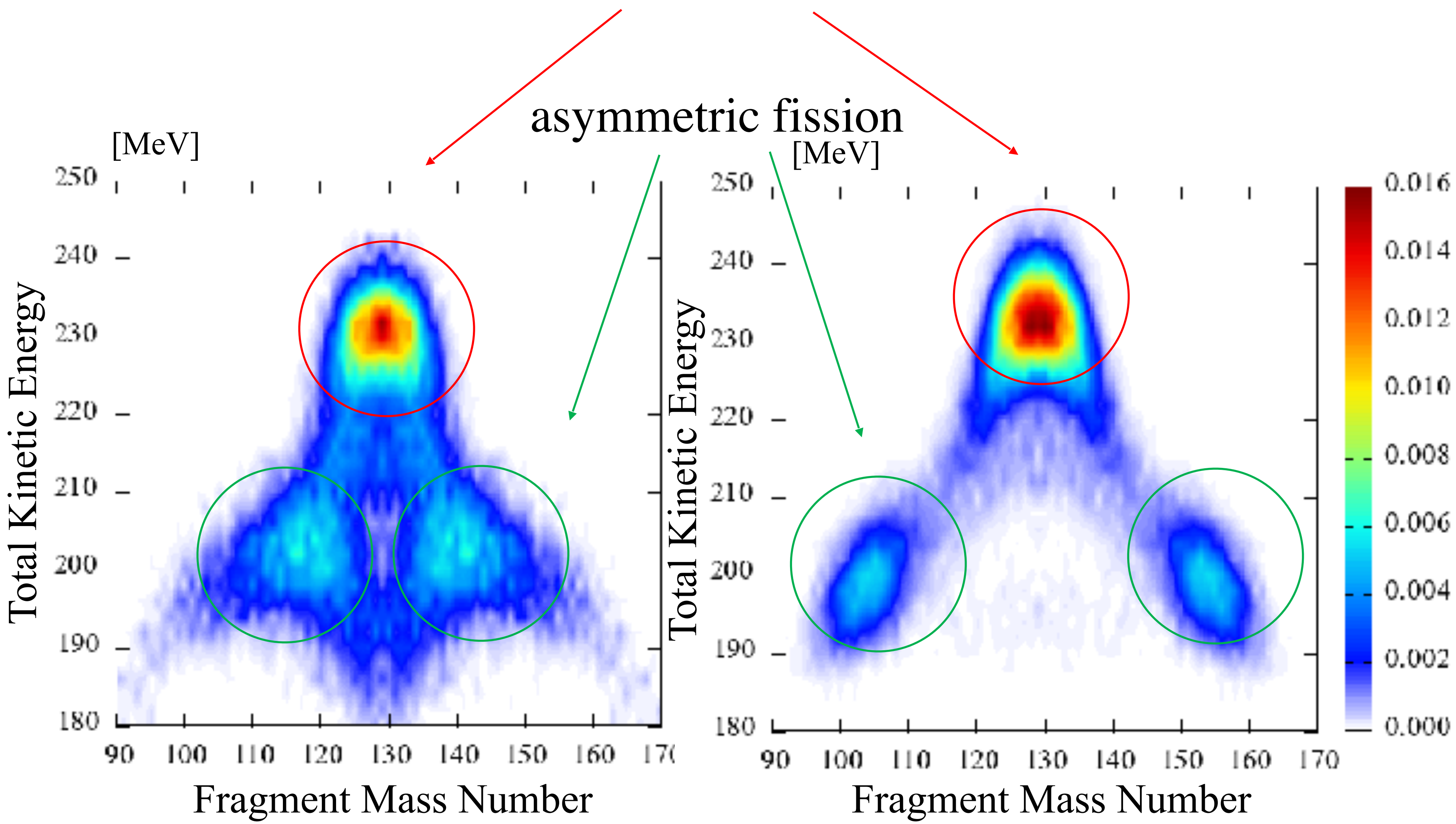
Result: ^{258}Fm TKE-FMN



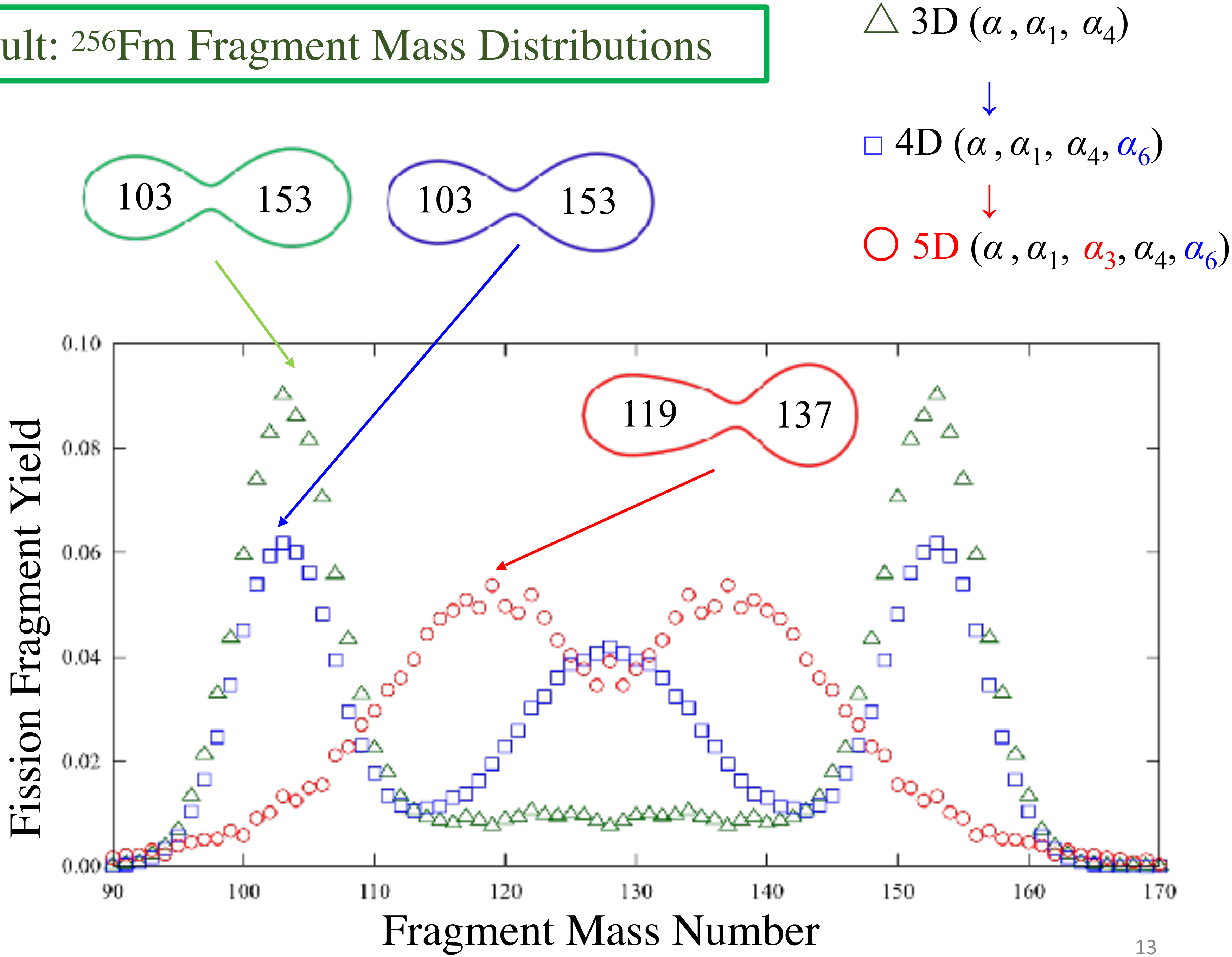
Result: ^{258}Fm TKE-FMN

$^{258}\mathrm{Fm}\,\{\alpha,\,\alpha_1,\,\alpha_3,\,\alpha_4,\,\alpha_6\}$ $\quad$ $^{258}\mathrm{Fm}\,\{\alpha,\,\alpha_1,\,\alpha_4,\,\alpha_6\}$

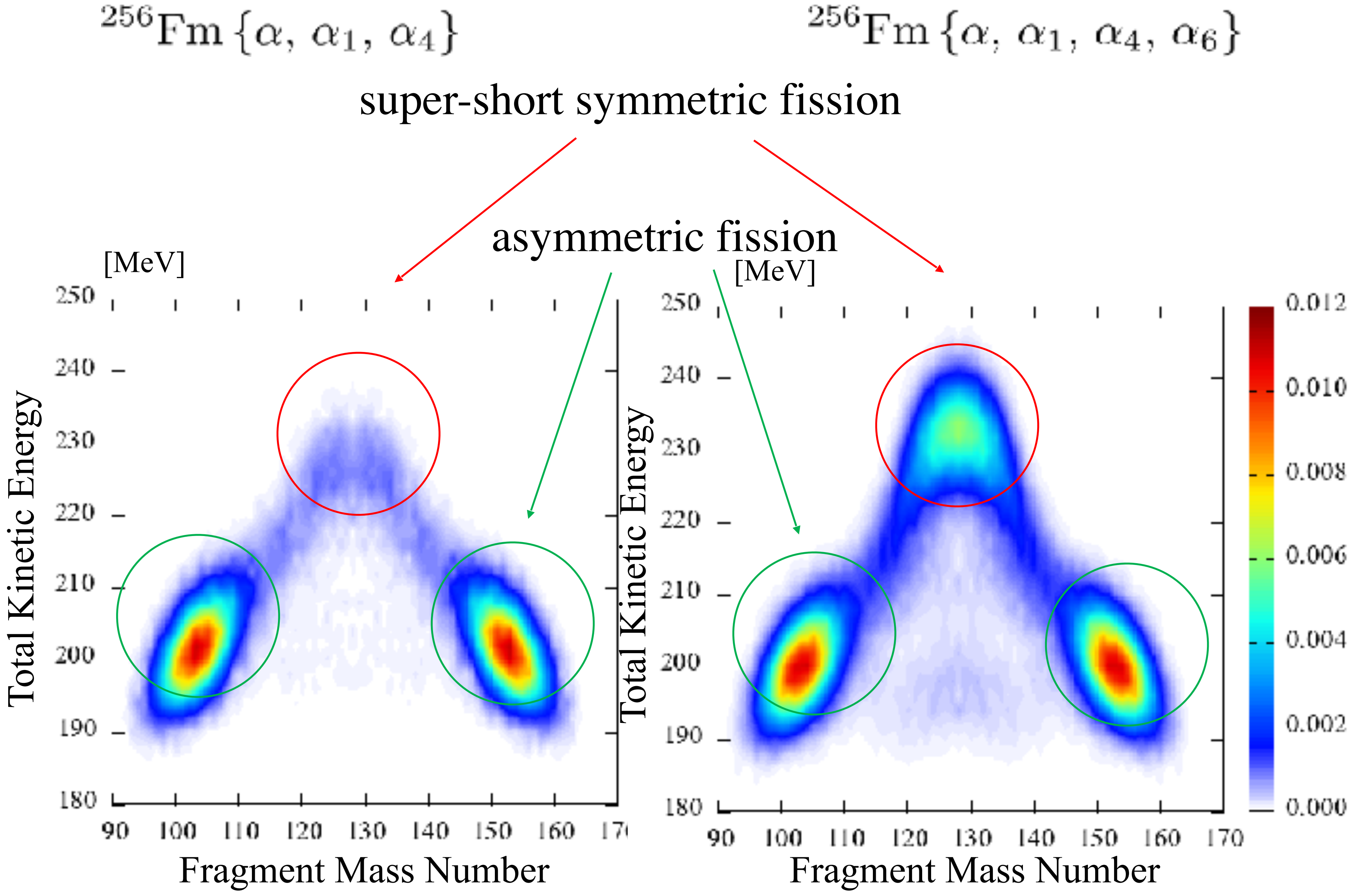
super-short symmetric fission



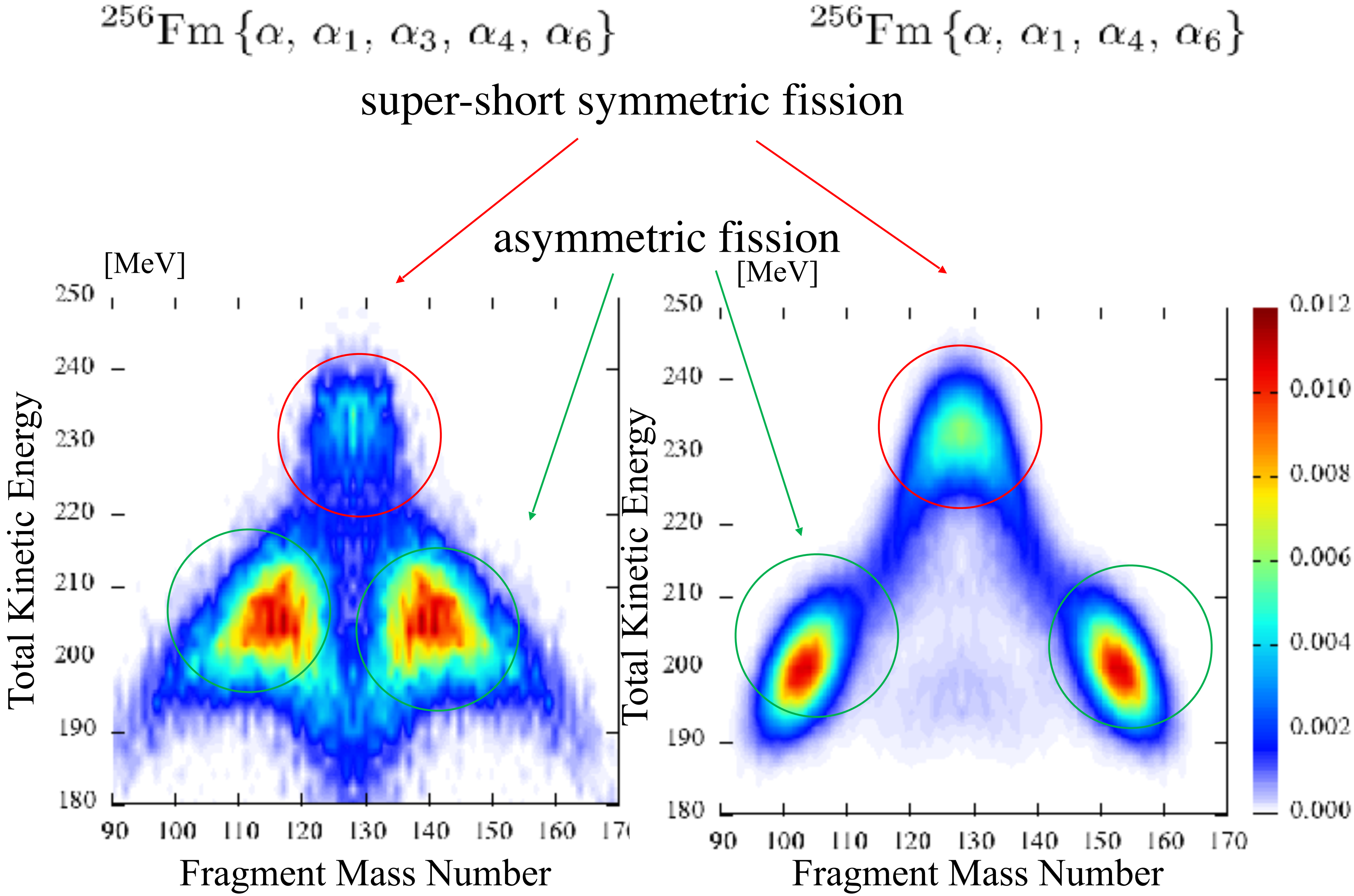
Result: ^{256}Fm Fragment Mass Distributions



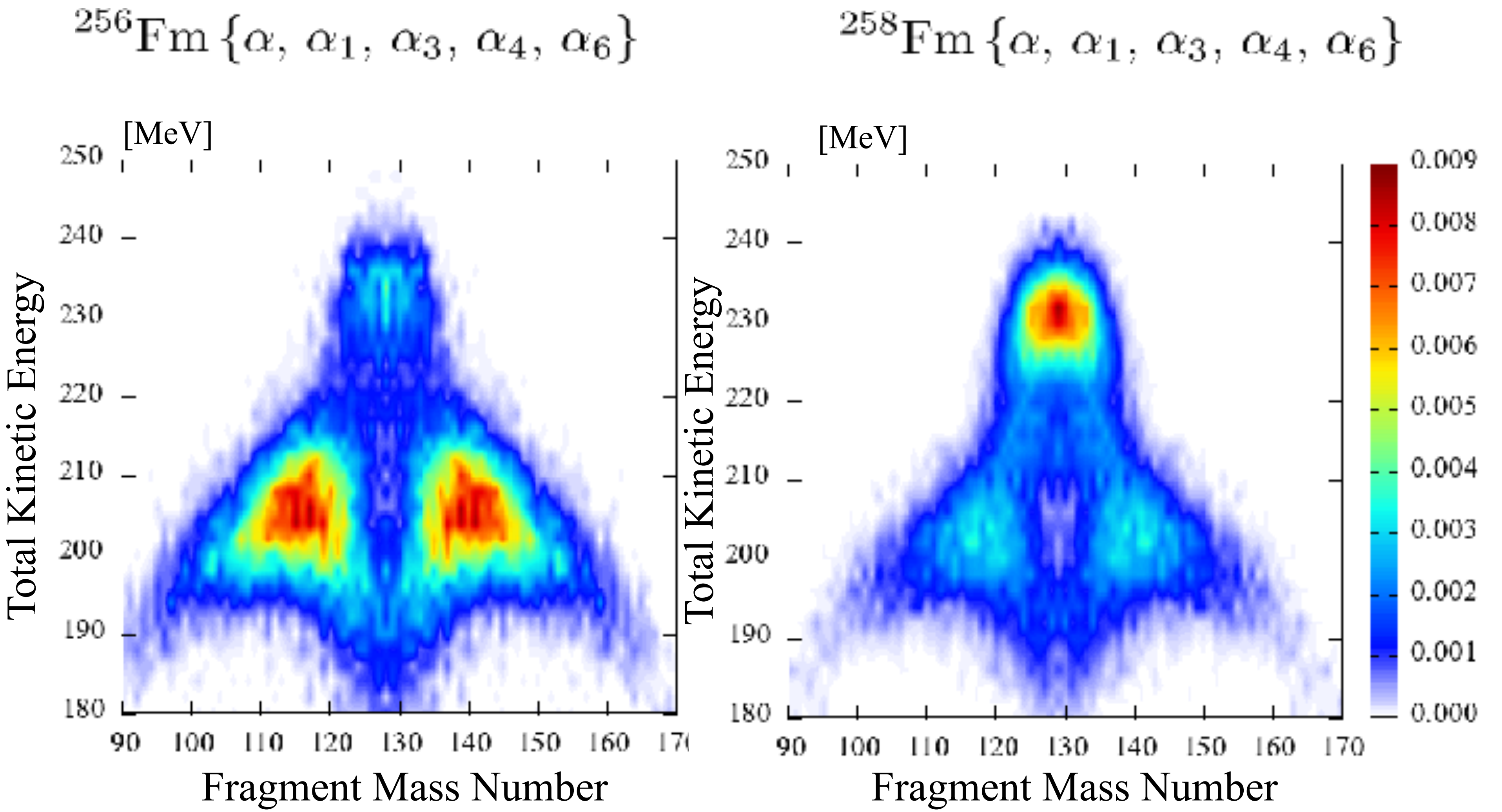
Result: ^{256}Fm TKE-FMN



Result: ^{256}Fm TKE-FMN



Result: TKE-FMN

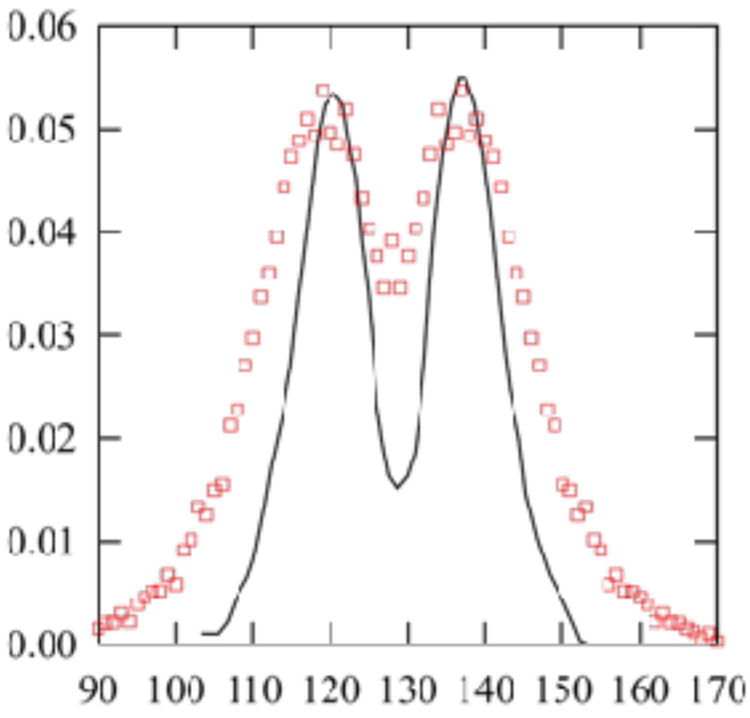


Result: Fm Fragment Mass Distributions

○ 5D (α, α_1, α_3, α_4, α_6)

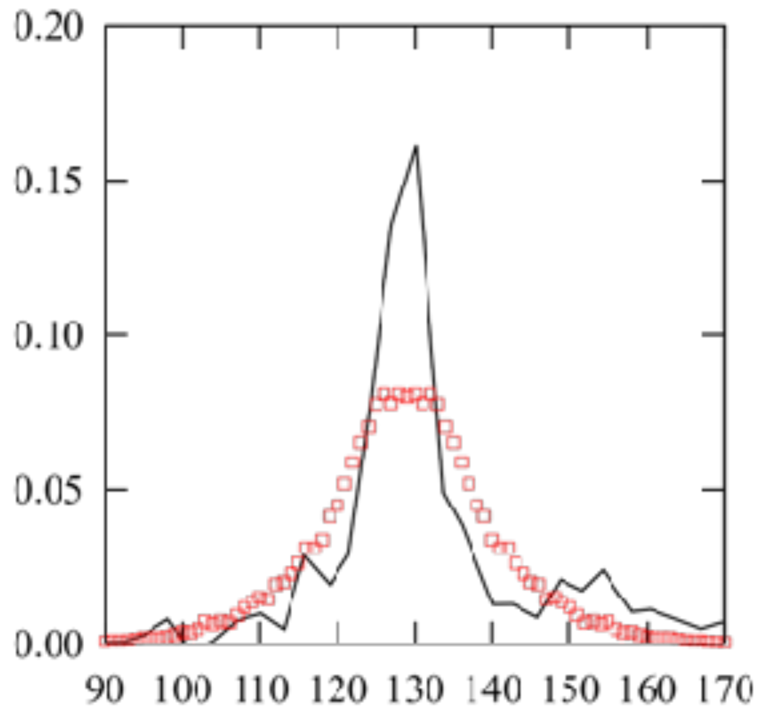
— exp

D. C. Hoffman et al., Phys. Rev. C 21, 972–981, (1980).



Fragment Mass Number

^{256}Fm



Fragment Mass Number

^{258}Fm

まとめ

・Cassiniパラメータを用いた核分裂Langevin計算の5次元化

非対称分裂に特化 $\{\alpha, \alpha_1, \alpha_3, \alpha_4\}$

対称分裂に特化 $\{\alpha, \alpha_1, \alpha_4, \alpha_6\}$

⇩

$\{\alpha, \alpha_1, \alpha_3, \alpha_4, \alpha_6\}$

系の分裂様相に関わらず

採用すべきパラメータセット

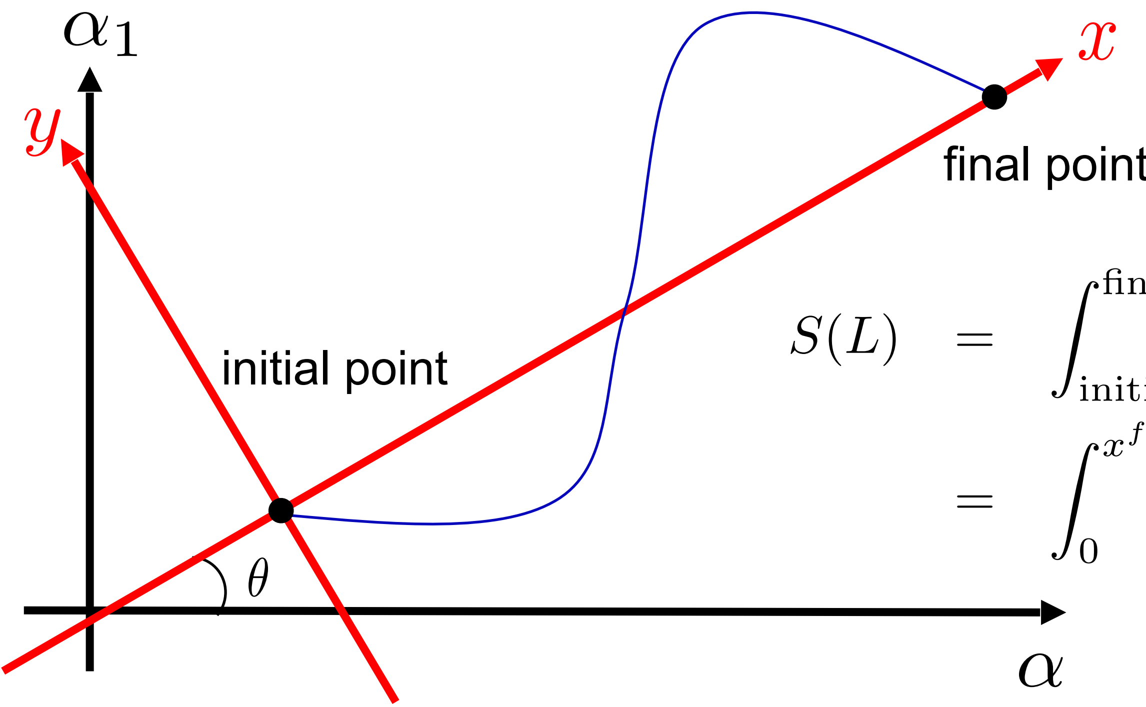
展望

今後: アクチノイド領域での検討

Langevin計算の改良 (particle emission, linear response)

5次元ポテンシャル上fission pathの解析 (次スライド)

Future Work (1): Action Integral



Action integral

$$S(L) = \int_{\text{initial}}^{\text{final}} \sqrt{M(s)(V(s)-E)}ds$$
$$= \int_0^{x^f} \sqrt{M(x,\, y(x))(V(x,\, y(x)-E)}dx$$

initial point: $(\alpha,\, \alpha_1) = (\alpha^0,\, \alpha_1^0)$

$(x,\, y) = (0,\, 0)$

final point: $(\alpha,\, \alpha_1) = (\alpha^f,\, \alpha_1^f)$

$(x,\, y) = (x^f,\, 0)$

- Formulation of Ritz method

$$y(x) = \sum_k a_k \sin \frac{k\pi x}{x^f}$$

A. Baran, Phys. Lett. 76B (1978) 8

Future Work (1): Action Integral

2D → 多次元化

・Multi-dimensional Ritz method

$$\overline{\alpha_i}(\bar{\alpha}) = \sum_{k=1}^{N_i} b_k^i \sin\frac{k\pi\bar{\alpha}}{\bar{\alpha}^f}$$

Action integral

$$\begin{aligned} S(L) &= \int_{\mathrm{initial}}^{\mathrm{final}} \sqrt{M(s)(V(s)-E)}ds \\ &= \int_0^{x^f} \sqrt{M(x,\,y(x))(V(x,\,y(x))-E)}dx \end{aligned}$$

Werner-Wheeler mass
or
Cranking mass

deformation
energy

^{256}Fm, ^{258}Fm 自発核分裂へのアプローチ

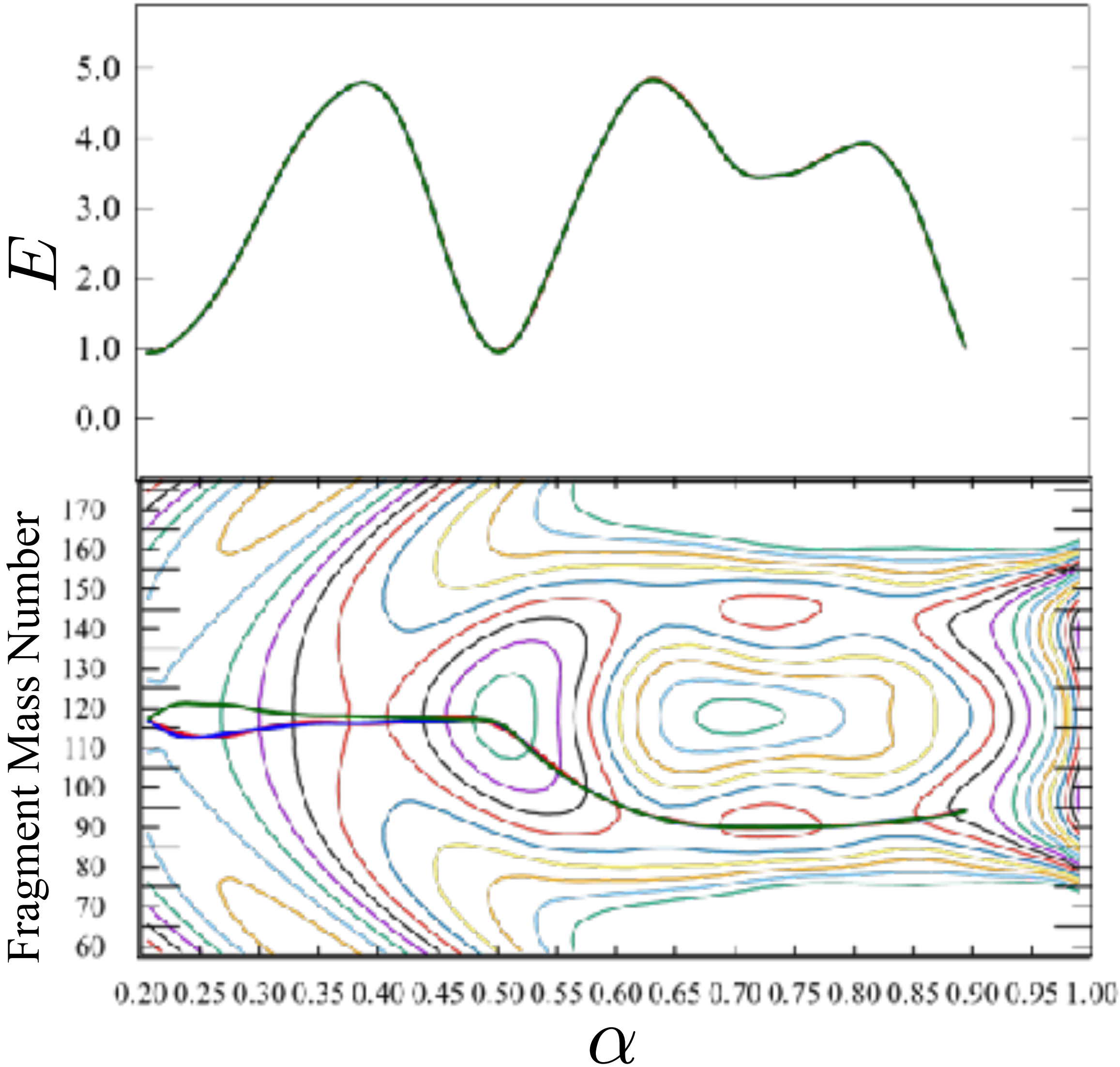
5次元ポテンシャルの解析

Future Work (1): Action Integral

2D $\{\alpha,\ \alpha_1\}$

$^{236}\mathrm{U}$

red: N_i=10
blue: N_i=20
green: N_i=30

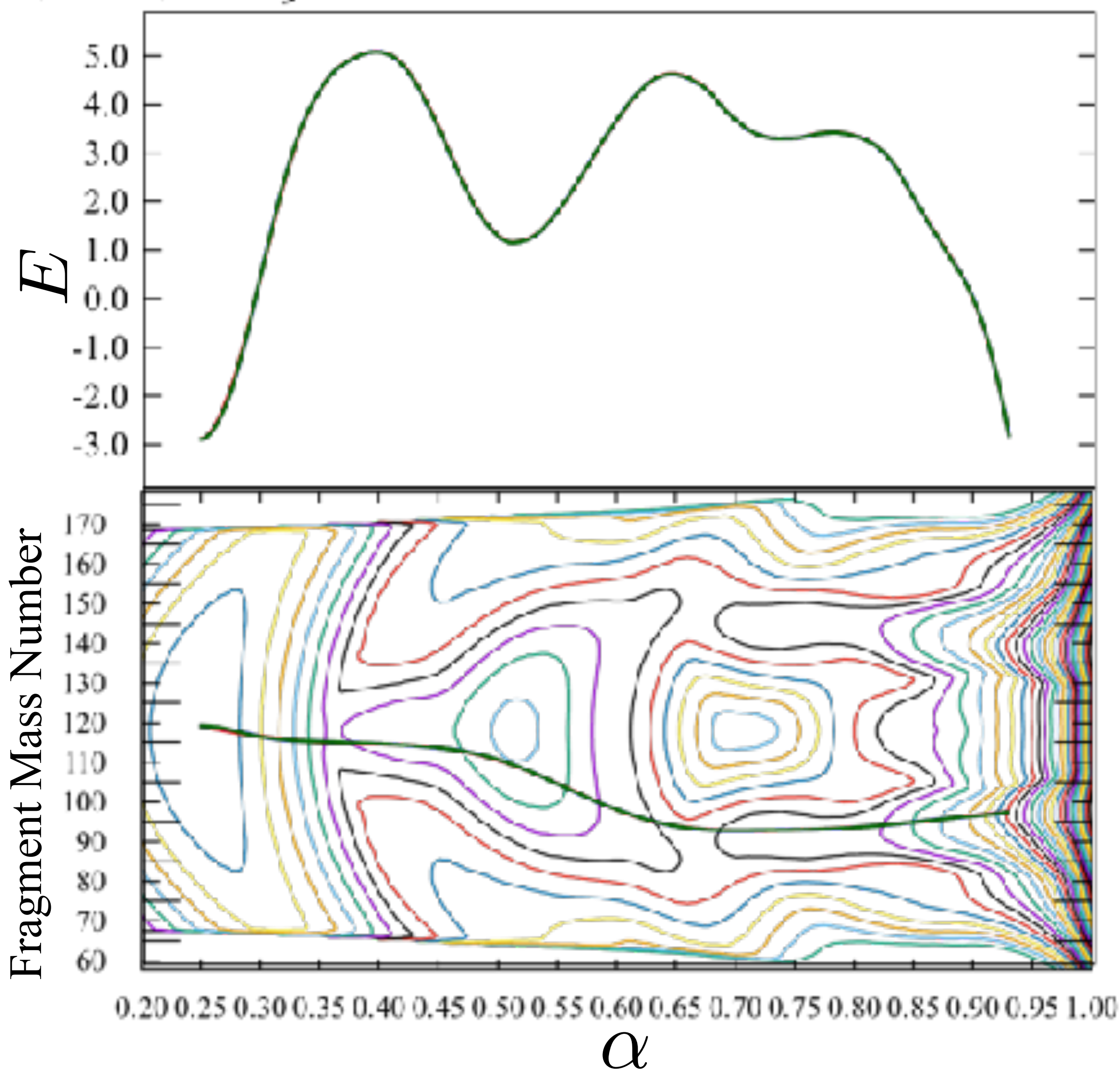


Future Work (1): Action Integral

3D $\{\alpha,\ \alpha_1,\ \alpha_4\}$

red: N_i=10
blue: N_i=20
green: N_i=30

^{236}U

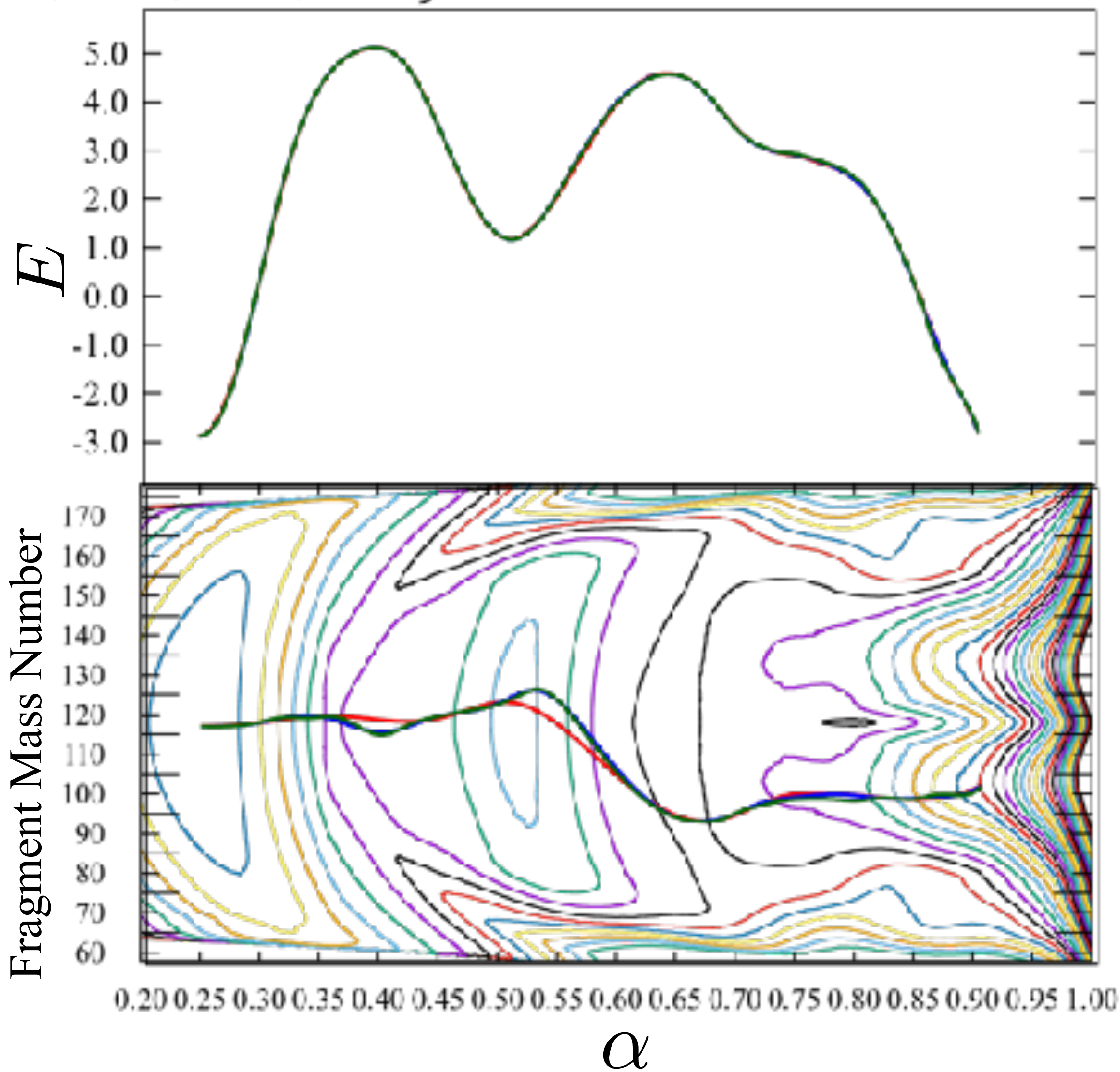


Future Work (1): Action Integral

4D $\{\alpha,\ \alpha_1,\ \alpha_3,\ \alpha_4\}$

red: N_i=10
blue: N_i=20
green: N_i=30

^{236}U



展望

5次元Cassiniパラメータを用いた核分裂研究

$$\{\alpha,\ \alpha_1,\ \alpha_3,\ \alpha_4,\ \alpha_6\}$$

fission pathの解明

・Langevin計算から得られる軌跡を解析

・Minimum action integral計算

⇒ 中性子数変化に対する劇的な分裂様相の変化にアプローチ

Thank you for your kind attention!