JAEAにおける代理反応研究
Research in Surrogate Reactions at JAEA

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Present study is the result of "Development of a Novel Technique for Measurement of Nuclear Data Influencing the Design of Advanced Fast Reactors" entrusted to Japan Atomic Energy Agency (JAEA) by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

Collaborators

- Theory
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  - K. Ogata,（RCNP）、K. Hagino（Tohoku）
  - （A. Ono（Tohoku））
- Experiment
  - S. Mitsuoka, K. Nishio, I. Nishinaka, H. Makii, Y. Wakabayashi, S. Ota, T. Nagayama（JAEA）
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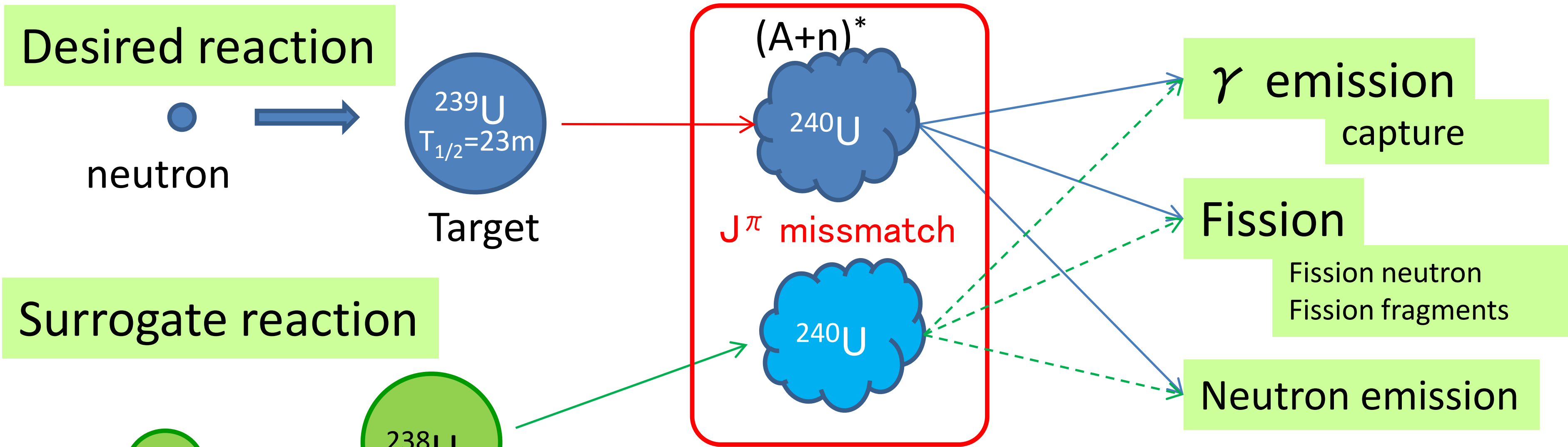
  - Aga. Chezmska(UCBerkeley)

Surrogate Method

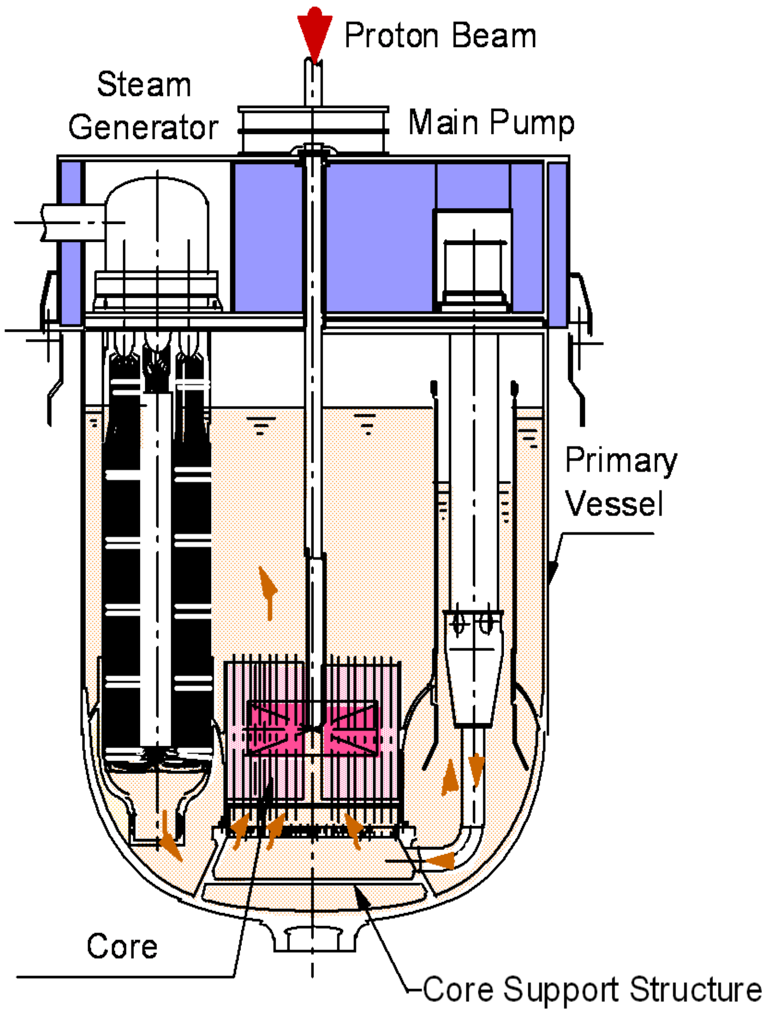
- Reaction properties of unstable (radioactive) nuclei
  - Nuclear Technologies
  - Origin of elements (Neutron capture nucleosynthesis)
- Need to develop and establish physical foundation of "**Surrogate Method**"



Decay probability of compound nucleus depends only on the excitation energy and spin-parity

→ Determination of the branching ratio

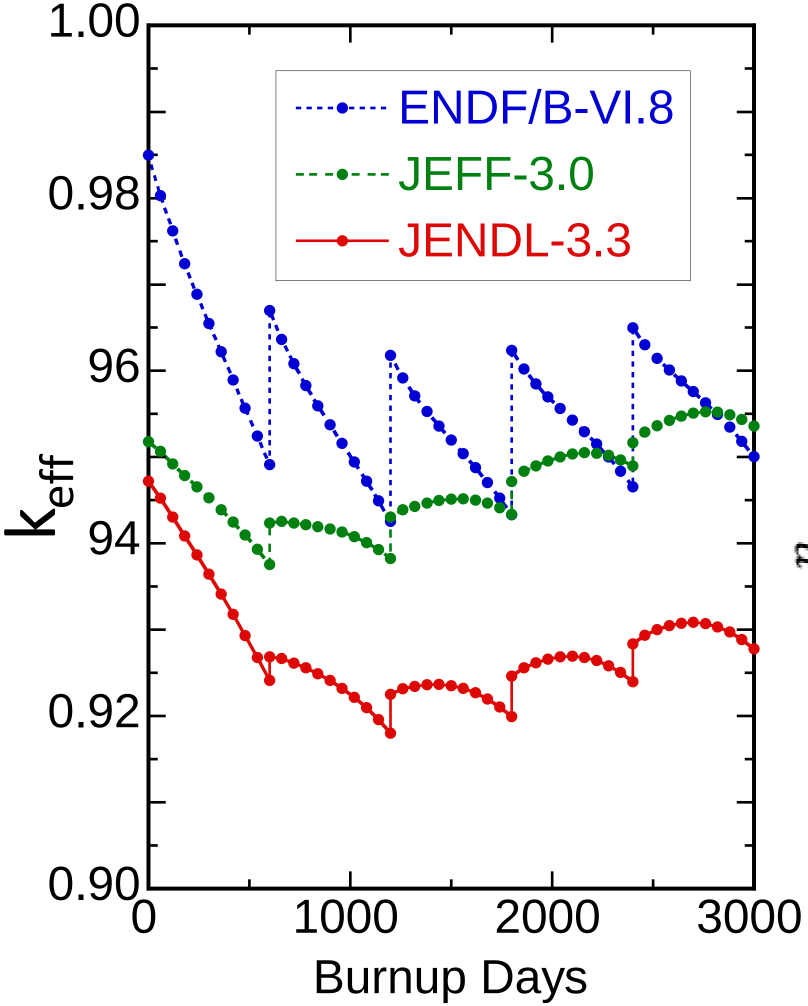
Pb-Bi cooled ADS



Pb-Bi cooled ADS

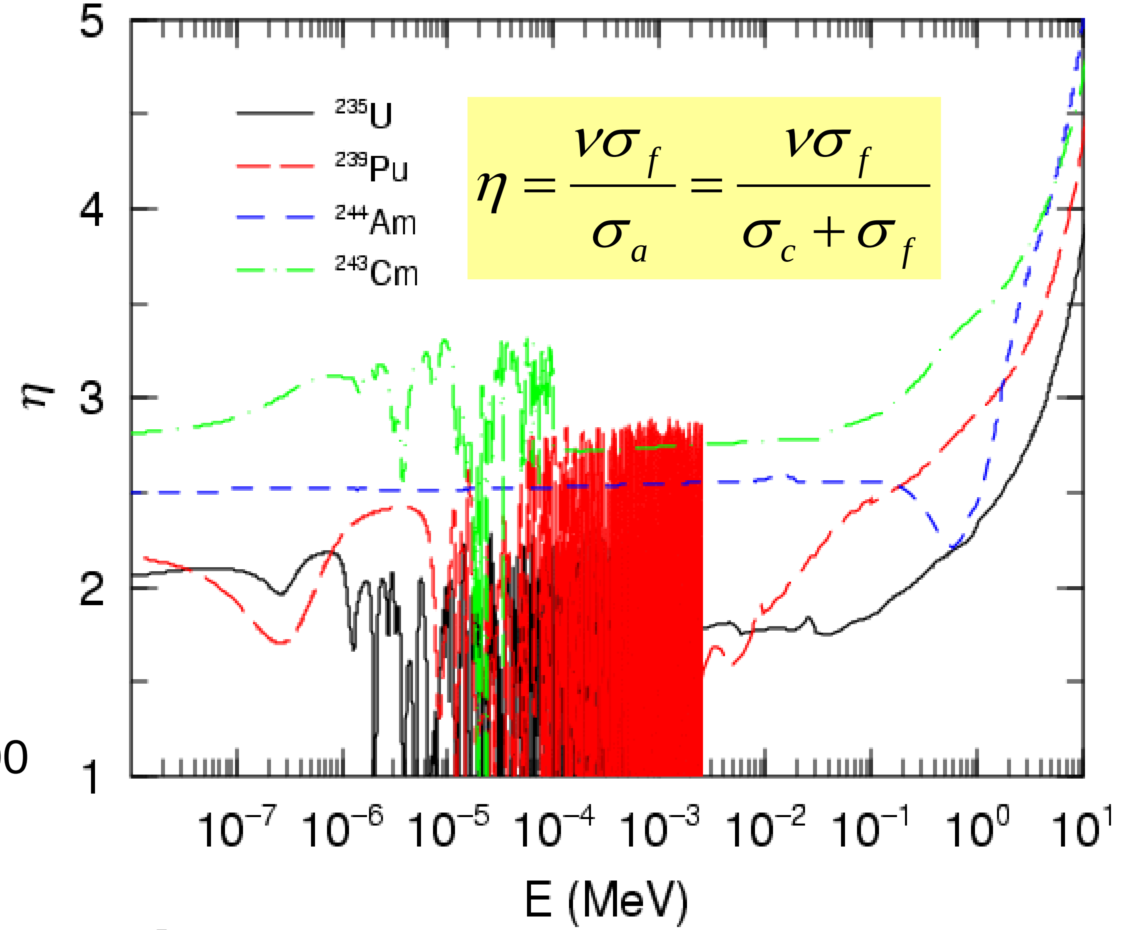
Reactor	
Thermal power	800 MWth
Initial k-eff	0.95
Core height	1000 mm
Core diameter	2440 mm
Accelerator	
Accelerator type	Proton linac
Beam energy	1.5 GeV
Fuel	
Fuel type	Mono-nitride
Pu / MA	40%Pu + 60 %MA
Ma loading	2500 kg
MA transmutation	250 kg / year

Nuclear Data of MA（Minor Actinide）: Large impacts to fast systems including ADS

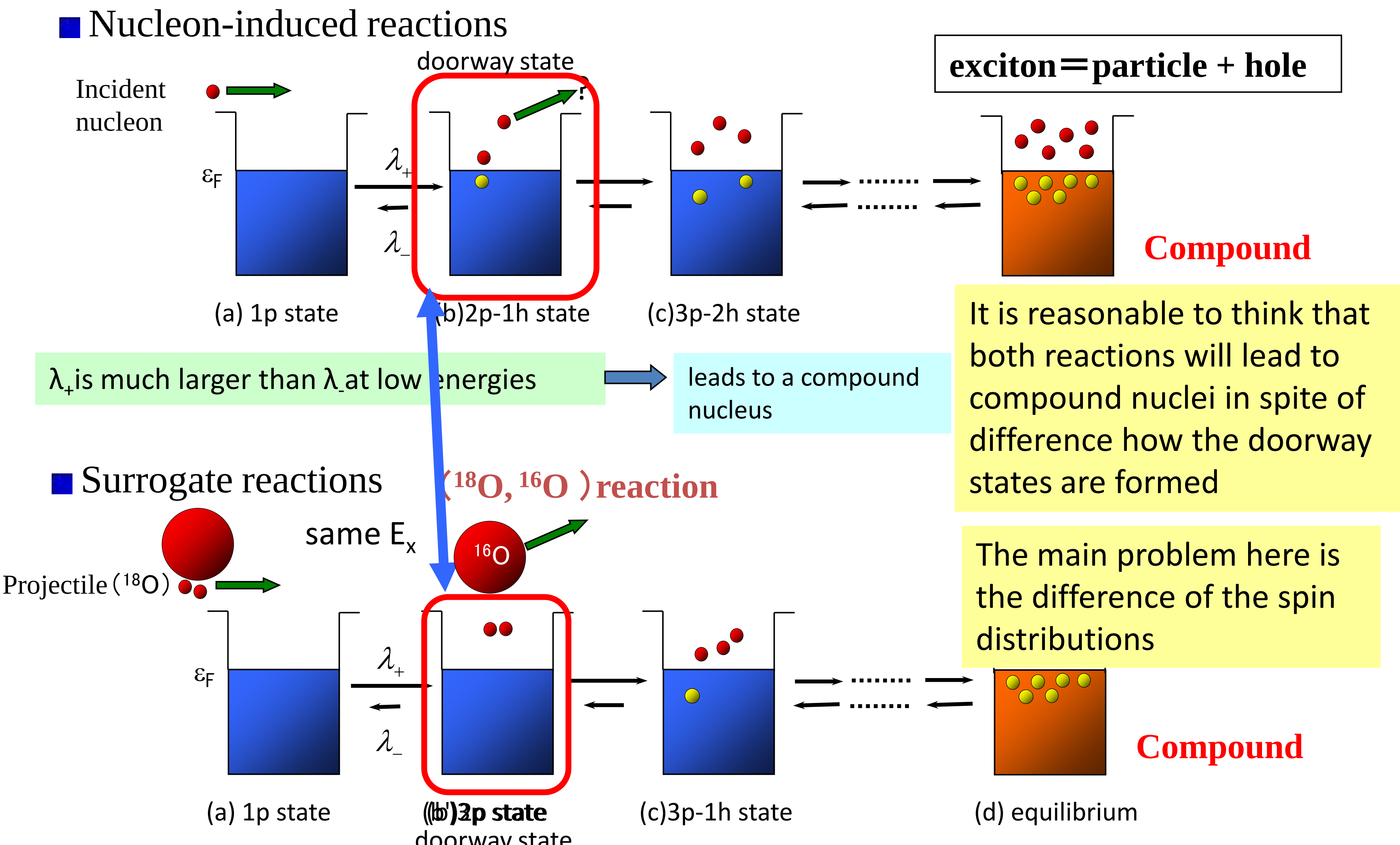


Burn−up dependence of k_{eff} for ADS(40%Pu+60%MA)

η values of MAs

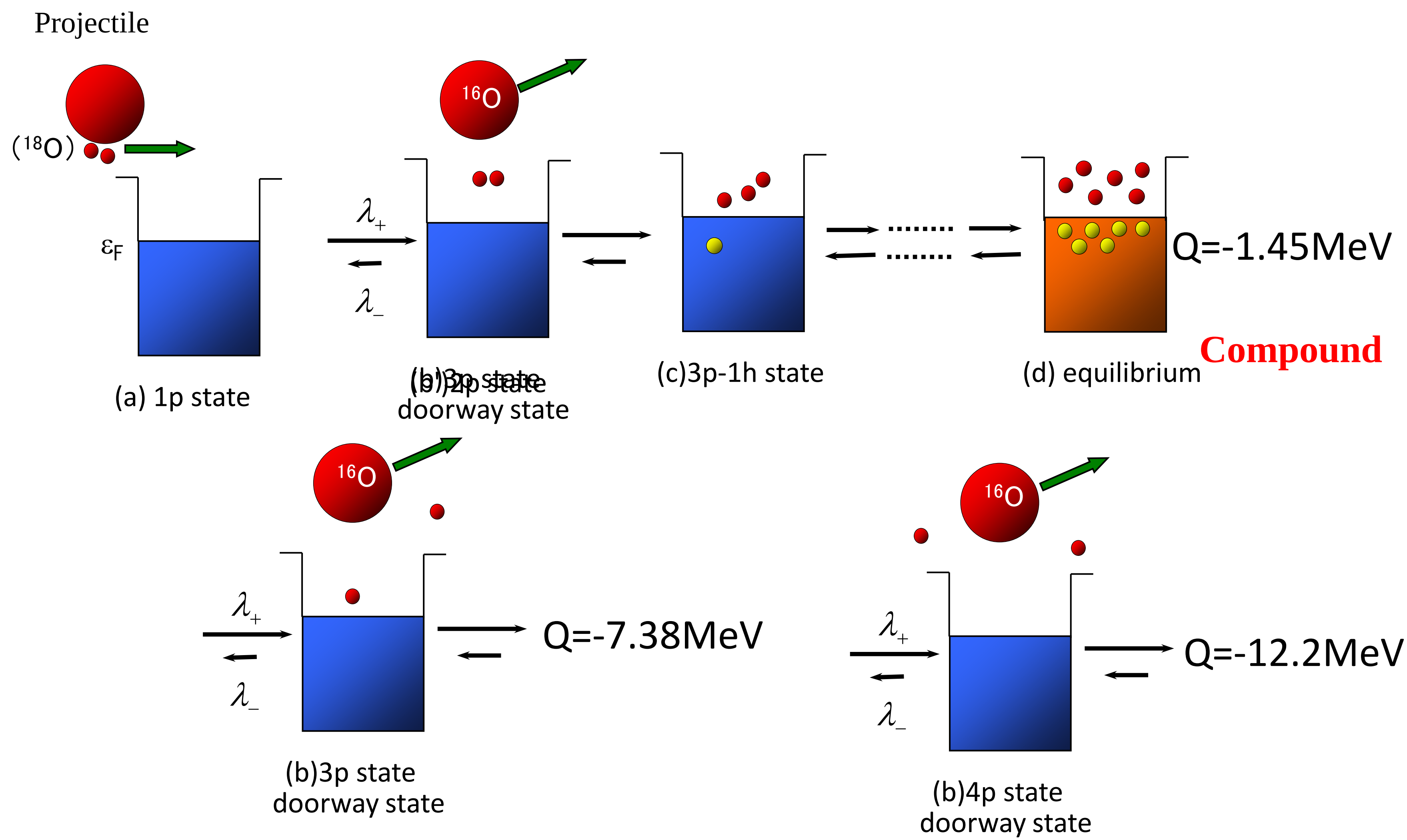


Population of compound nuclei by nucleon-induced and surrogate reactions : excition model

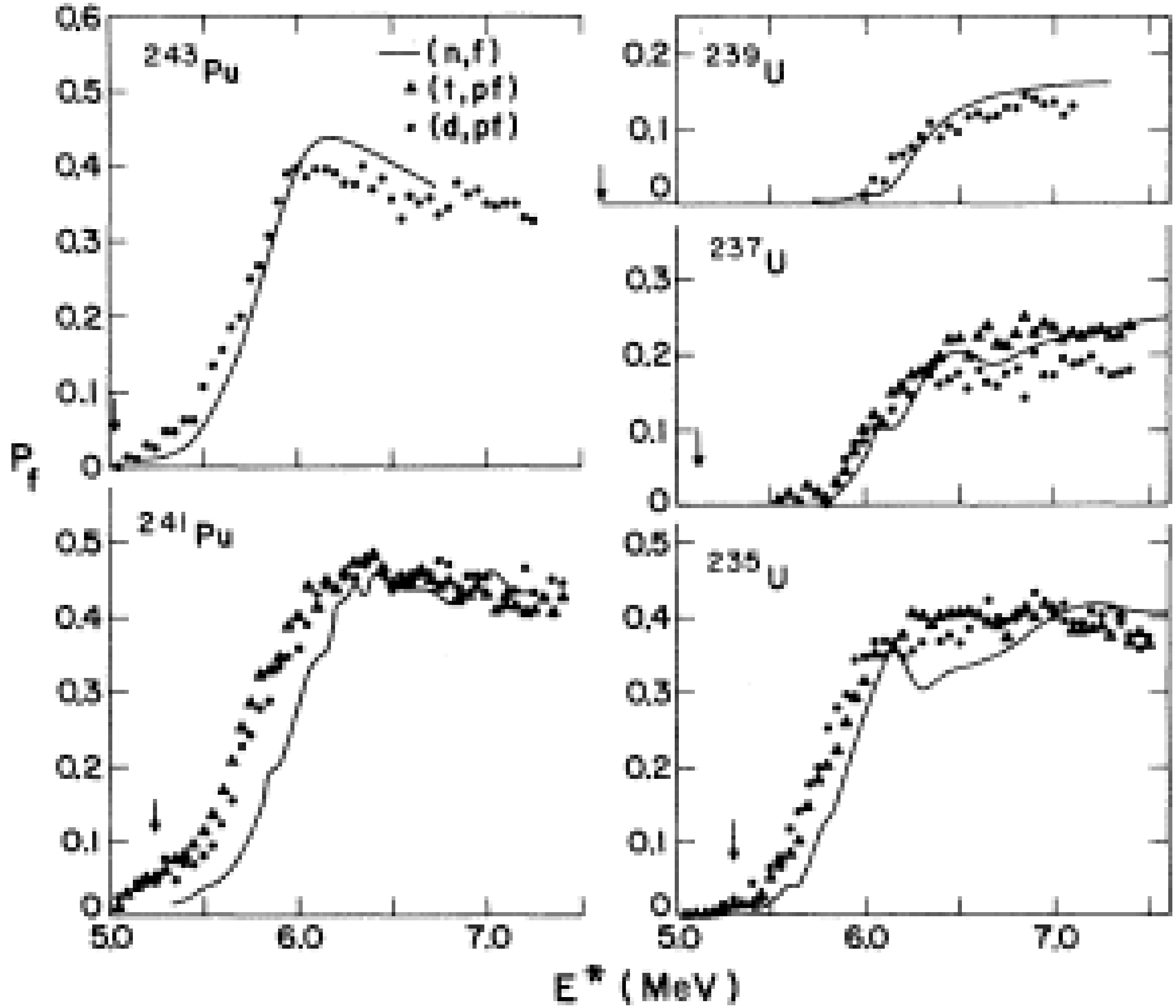


Population of compound nuclei by surrogate reactions : excition model picture

■ Surrogate reactions $^{238}U(^{18}O, ^{16}O)$ reaction



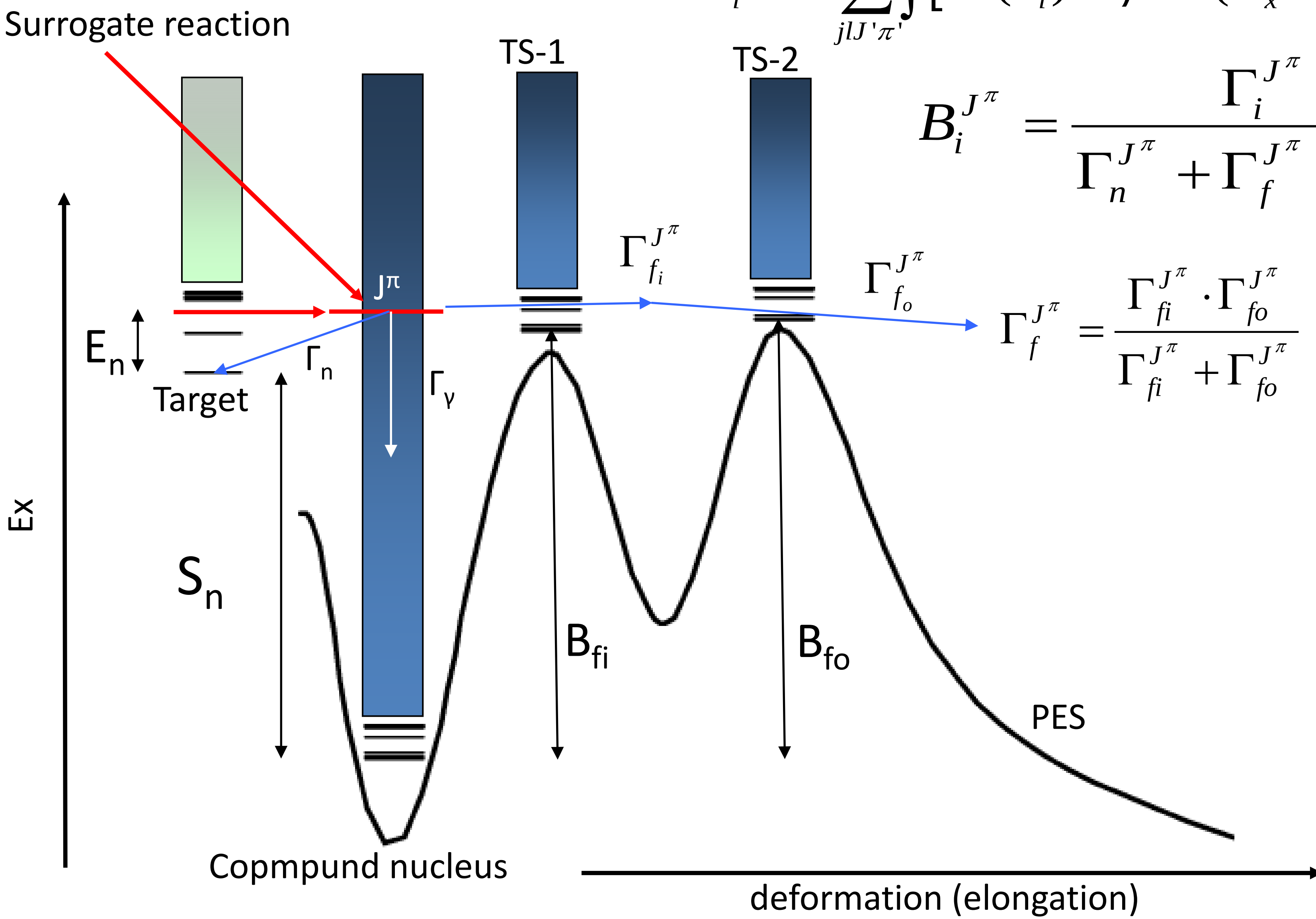
Britt and Cramer, PRC 2, 1758(1970)



n-induced and surrogate reactions

$$\Gamma_i^{J^\pi} = \sum_{jlJ'\pi'} \int \left[T^{lj}(\varepsilon_i) \otimes \rho^{J'\pi'}(E_x - \varepsilon_i) \right]^{J^\pi} d\varepsilon_i$$

$$B_i^{J^\pi} = \frac{\Gamma_i^{J^\pi}}{\Gamma_n^{J^\pi} + \Gamma_f^{J^\pi} + \Gamma_\gamma^{J^\pi}}$$



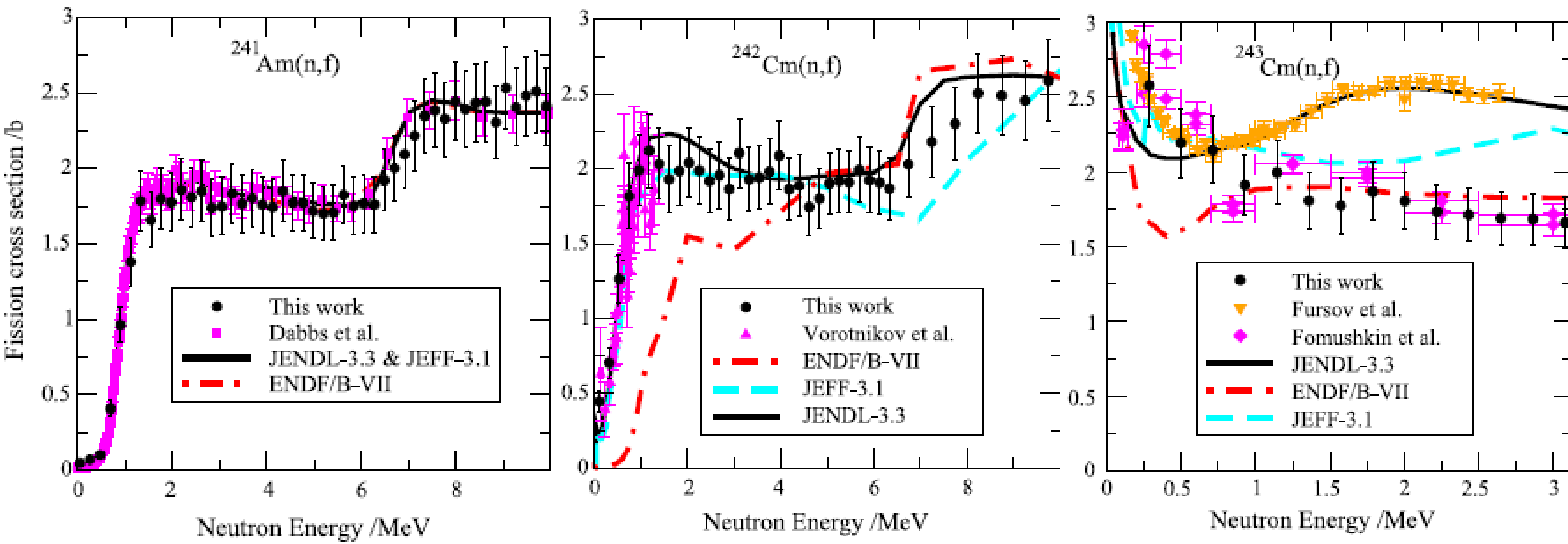
$$\Gamma_f^{J^\pi} = \frac{\Gamma_{fi}^{J^\pi} \cdot \Gamma_{fo}^{J^\pi}}{\Gamma_{fi}^{J^\pi} + \Gamma_{fo}^{J^\pi}}$$

Kessedjian et al.(PLB 692, 297(2010)

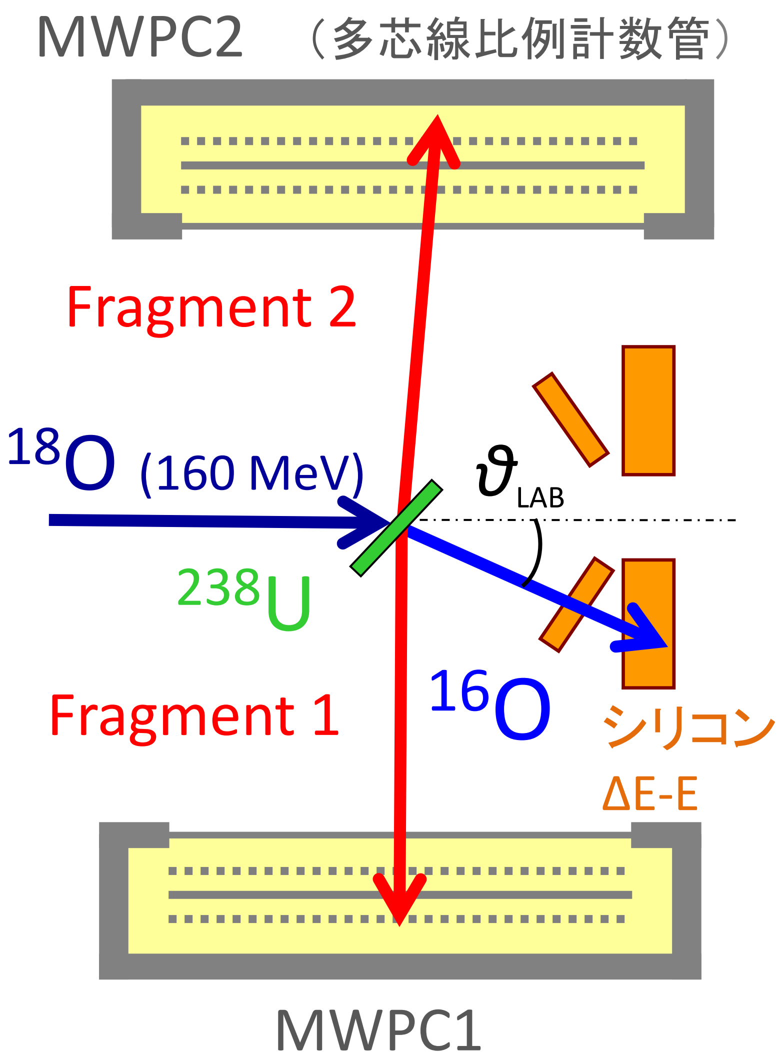
Transfer channels investigated in the reaction $^{3}He + ^{243}Am$ and the corresponding neutron-induced fission reactions.

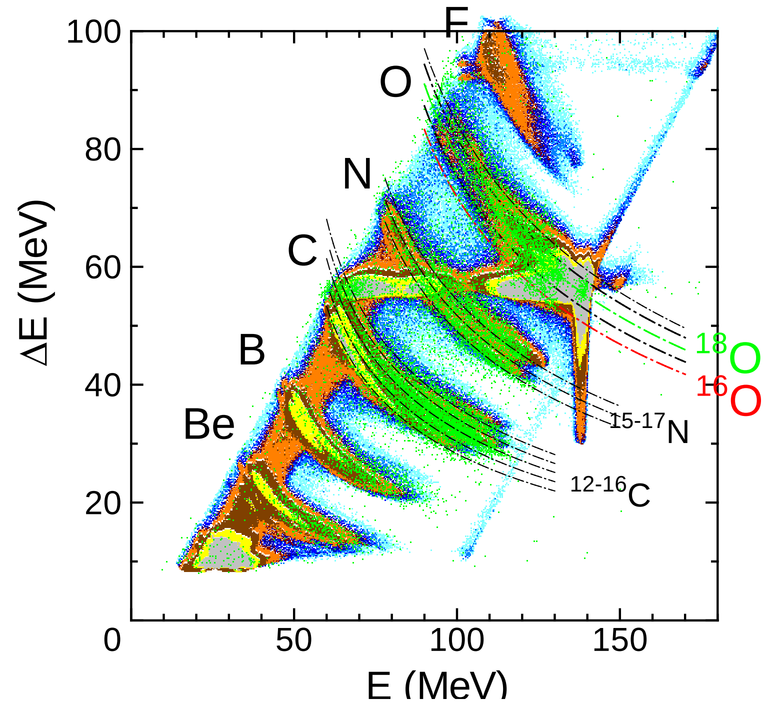
Transfer channel	Neutron-induced reaction
$^{243}Am(^{3}He, d)\ ^{244}Cm$	$^{243}Cm(n, f)$
$^{243}Am(^{3}He, t)\ ^{243}Cm$	$^{242}Cm(n, f)$
$^{243}Am(^{3}He, \alpha)\ ^{242}Am$	$^{241}Am(n, f)$

- Surrogate method seems to work for fission
- Production of compound nuclei is verified



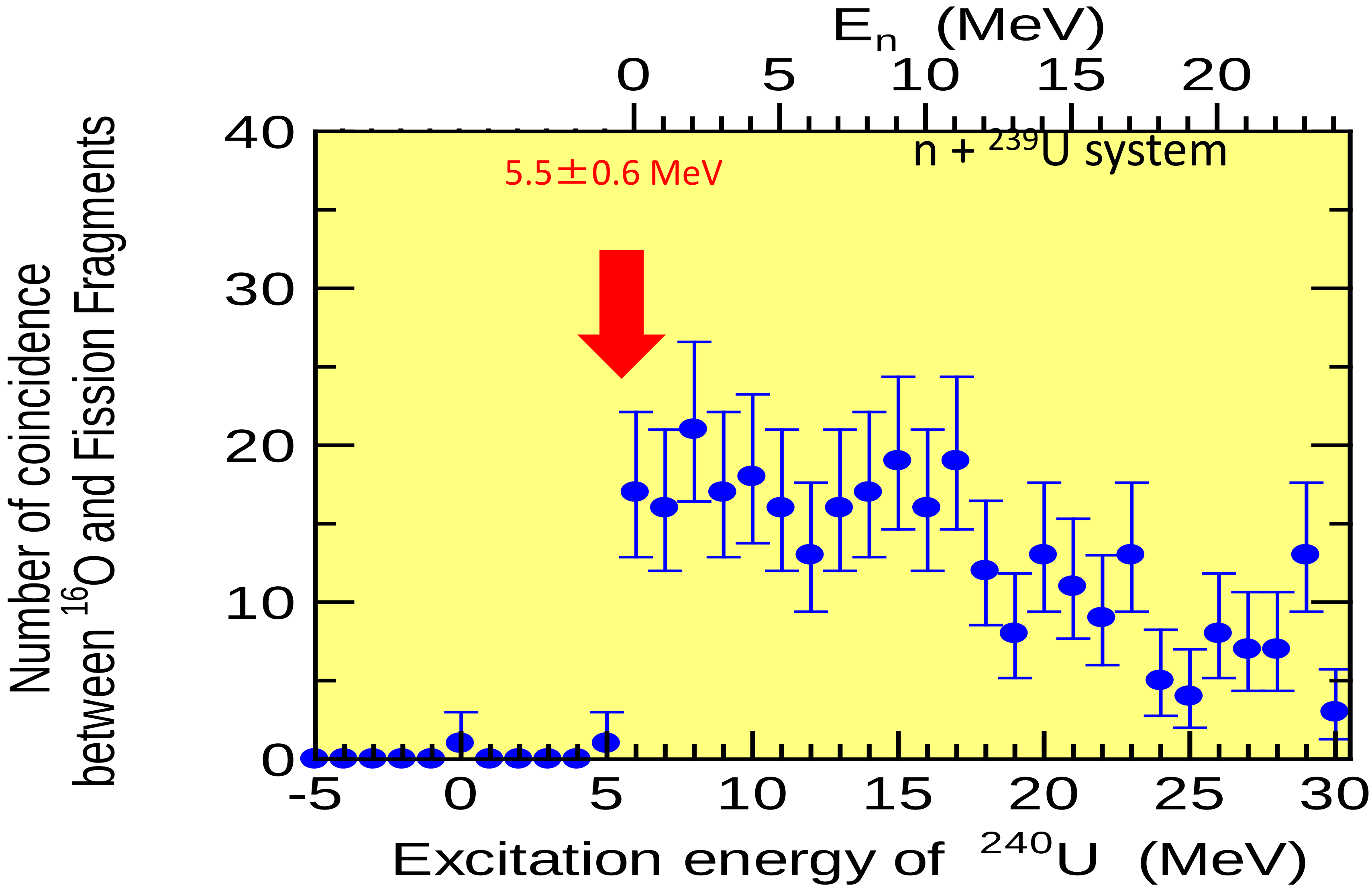
Test experiment for a surrogate reaction : ^{18}O + ^{238}U system



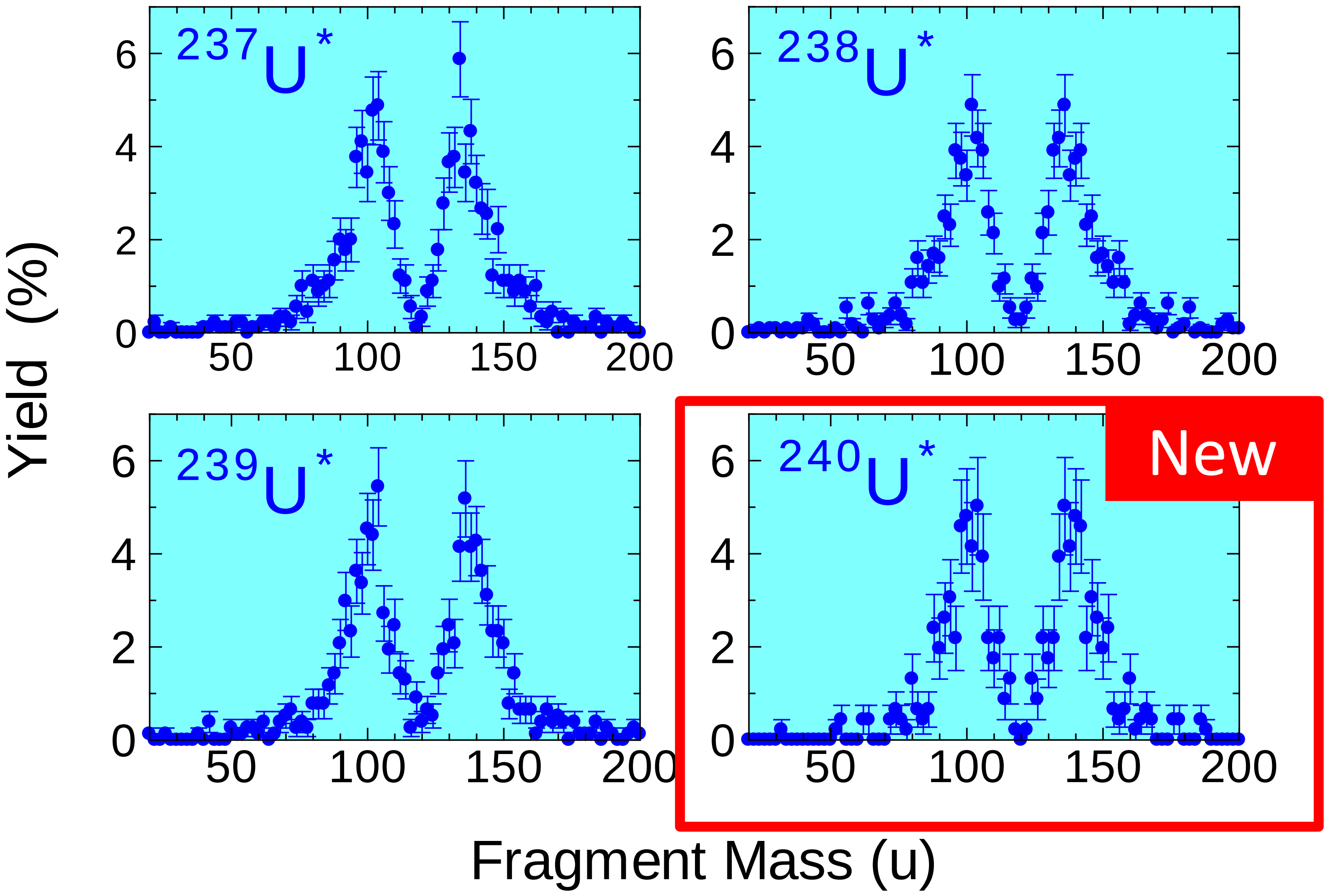


^{238}U (^{18}O,^{16}O) ^{240}U*	n + ^{239}U (23.5 min)
^{238}U (^{18}O,^{18}O) ^{238}U*	n + ^{237}U (6.8 day)
^{238}U (^{18}O,^{15}N) ^{241}Np*	n + ^{240}Np (65 min)
^{238}U (^{18}O,^{16}N) ^{240}Np*	n + ^{239}Np (2.4 day)
^{238}U (^{18}O,^{12}C) ^{244}Pu*	n + ^{243}Pu (4.9 hr)
^{238}U (^{18}O,^{14}C) ^{242}Pu*	n + ^{241}Pu (14 yr)
^{238}U (^{18}O, B) Am*	
^{238}U (^{18}O, Be) Cm*	

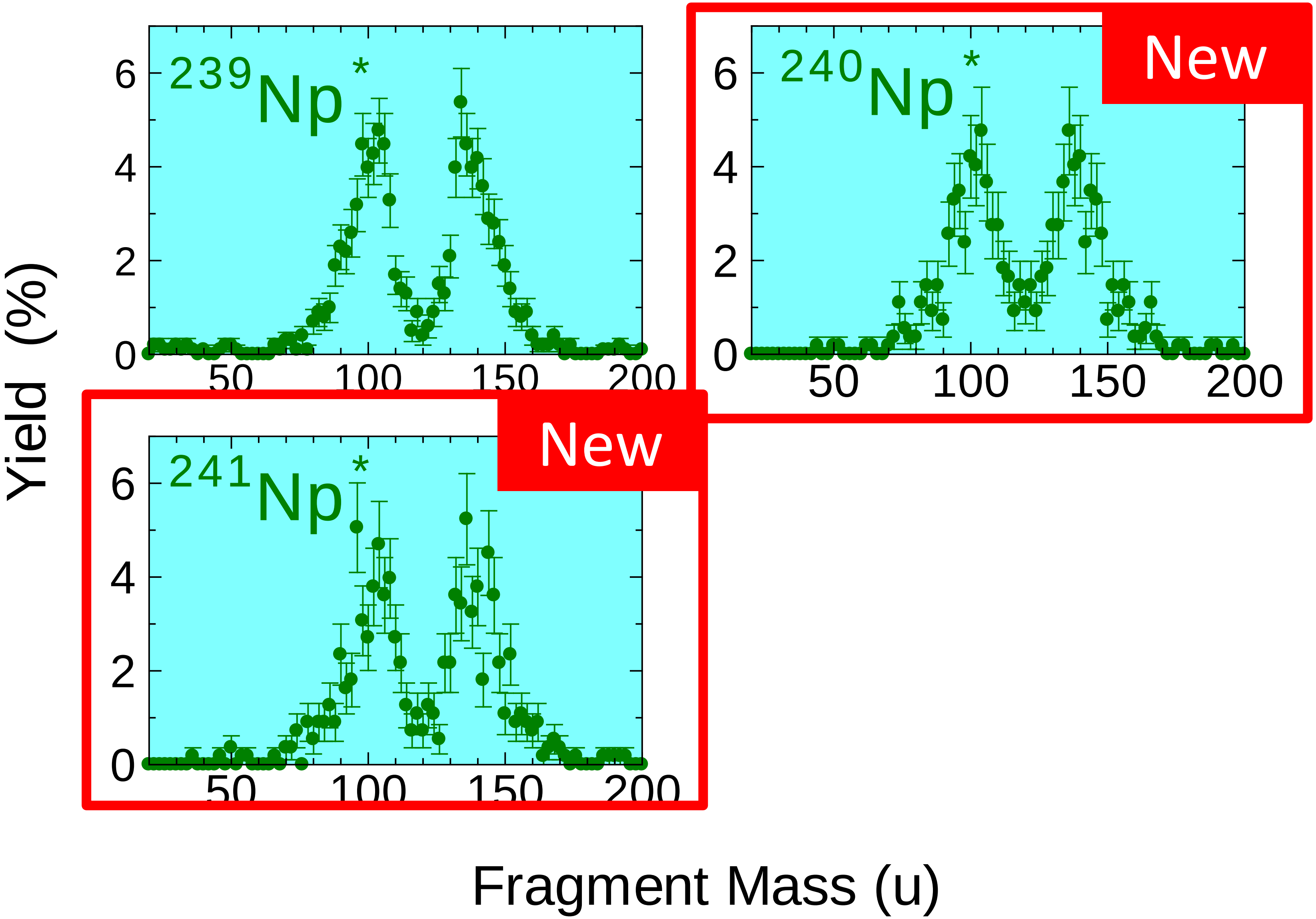
Excitation fuction of $^{238}U(^{18}O,^{16}O)^{240}U$ (f) reaction



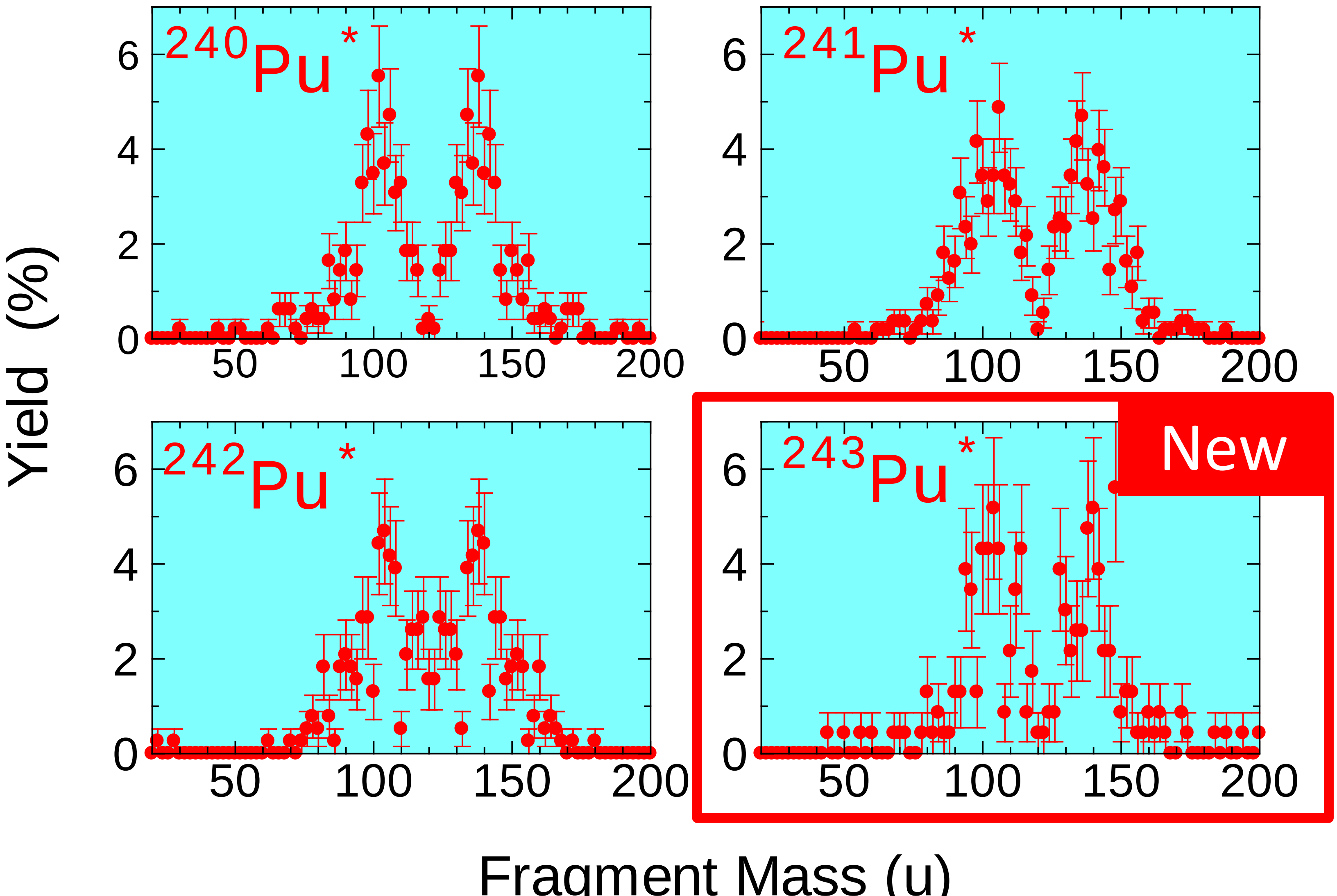
Fission Fragment Mass Distribution (FFMD) of U   E* < 20 MeV



FFMD of Np isotopes   E* < 20 MeV



FFMD of Pu isotopes   E* < 20 MeV

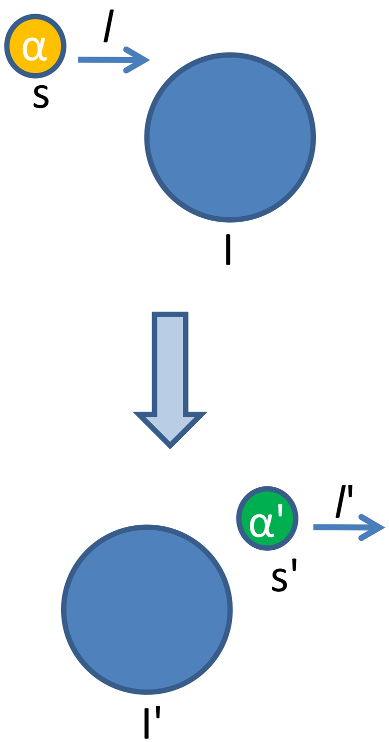


Hauser-Feshbach Formula

$$\sigma_{\alpha\alpha'}(E_x) = \sum_{J=\mathrm{mod}(I+s,1)}^{l_{\max}+I+s} \sum_{\pi=-1}^{1} \sum_{J=\mathrm{mod}(I+s,1)}^{l_{\max}+I+s} \sum_{\pi=-1}^{1} \sum_{j=|J-I|}^{J+I} \sum_{l=|j-s|}^{j+s} \sum_{j'=|J-I'|}^{J+I'} \sum_{l'=|j'-s'|}^{j'+s'} C^2 S^{I'} B^{J^\pi}_{\alpha'\alpha} \langle \phi_{\alpha'} | T | \phi_\alpha \rangle'$$

Formation cross section

(can be different for n- and surrogate reactions)



$$\times \frac{\int_{E_x-\Delta E}^{E_x+\Delta E} \rho(E_{x'}, J^\pi) T^J_{\alpha' l' j'}(E_{\alpha'}) dE_{x'}}{\sum_{\alpha'' l'' j''} \delta_{\pi^{\alpha''}} \int_0^{E_{x\max}} \rho(E_{x''}, J^\pi) T^J_{\alpha'' l'' j''}(E_{\alpha''}) dE_{x''}}$$

Decay branching ratio $B_f^\alpha(\varepsilon_\alpha, J, \pi)$

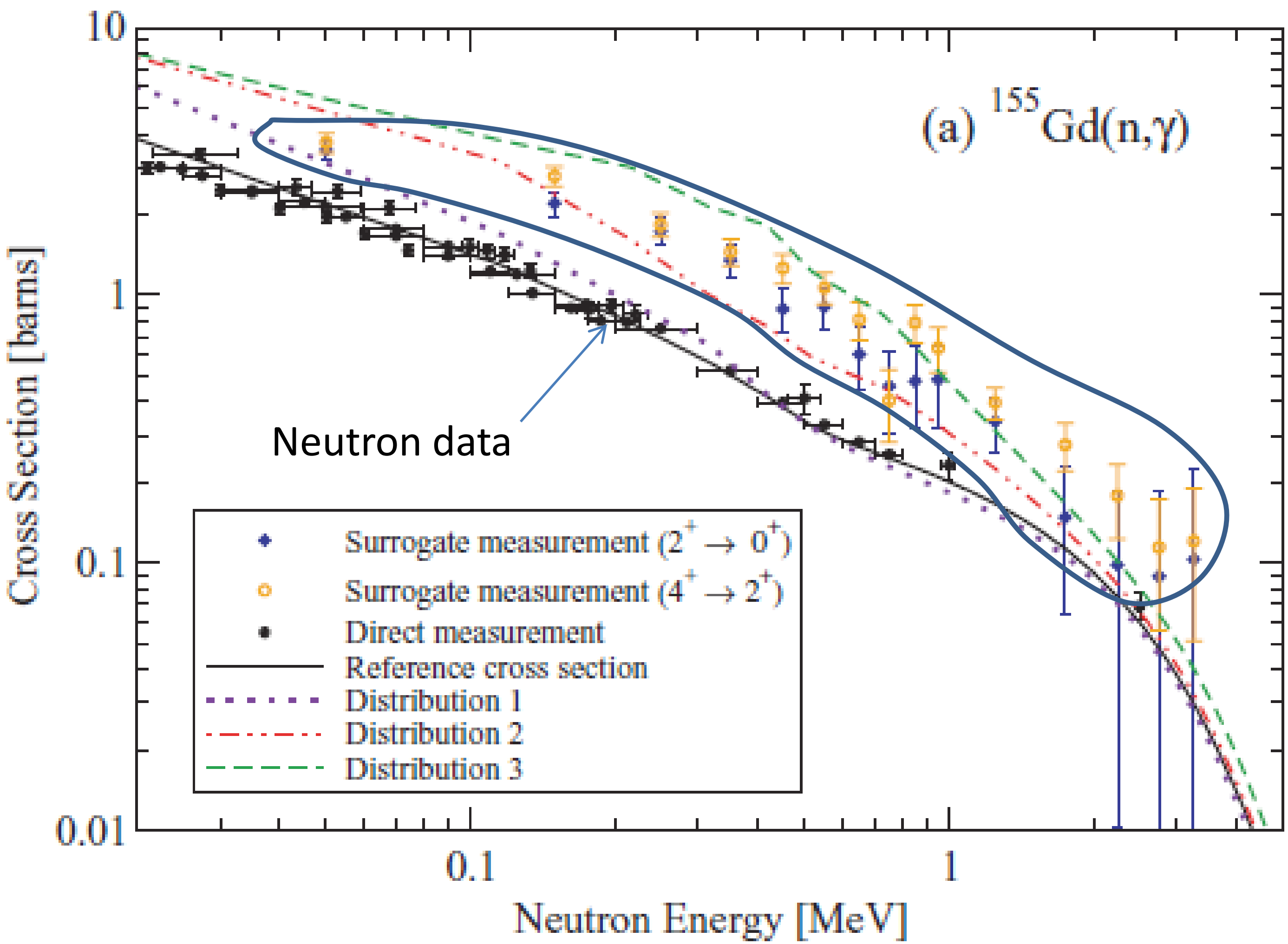
Conservation laws

$$E_\alpha + S_\alpha = E_{\alpha'} + E_x + S_\alpha$$
$$s + I + l = s' + I' + l' = J$$
$$\pi_\alpha \pi_i (-)^l = \pi_{\alpha'} \pi_f (-)^{l'} = \pi$$

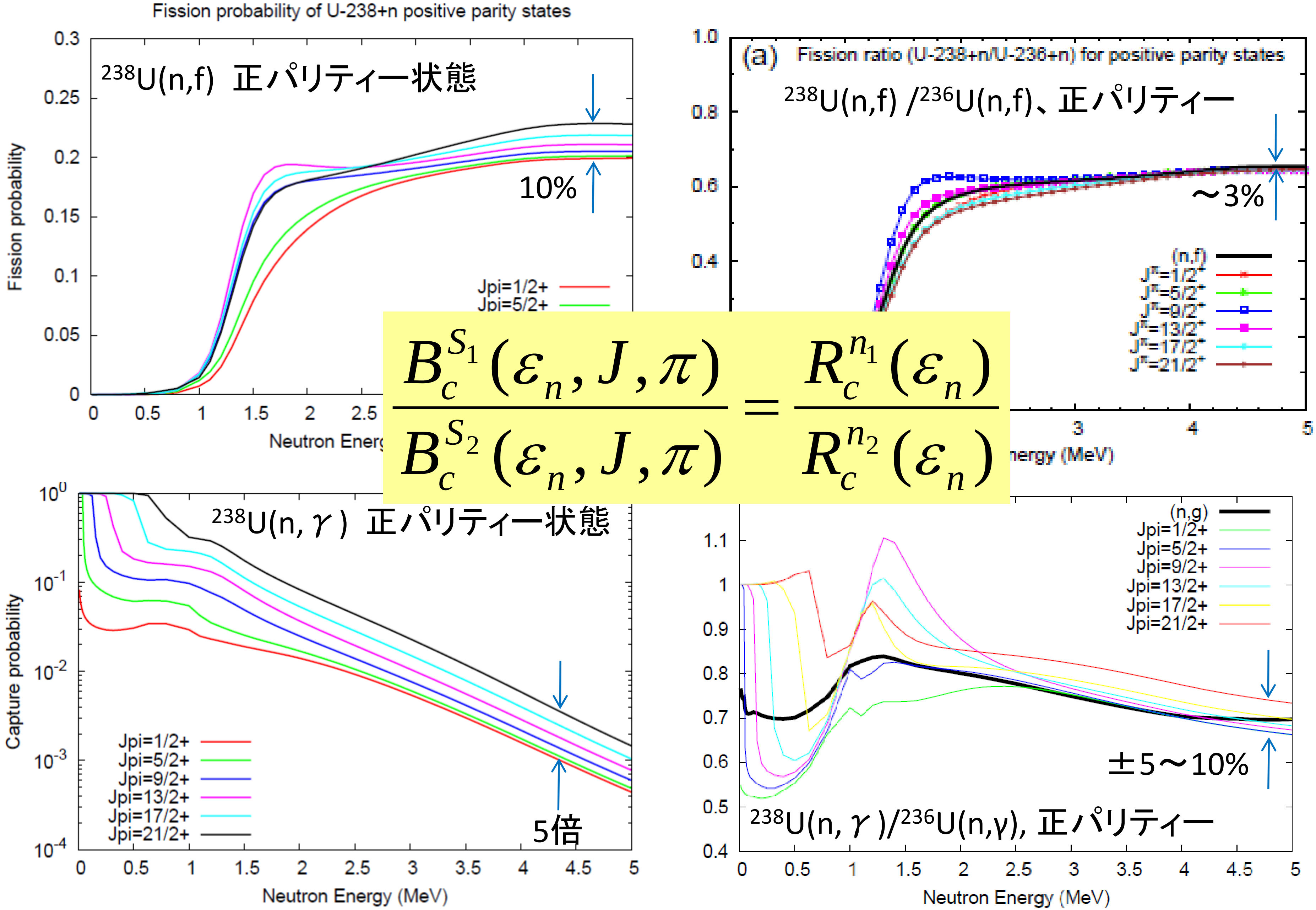
•Scielzo et al., PRC 81, 034608(2010)

•Surrogate method does not work for capture reaction?

•In which condition does it work?



Convergence of J$^{\pi}$-dependent branching ratios



$$\frac{B_c^{S_1}(\varepsilon_n, J, \pi)}{B_c^{S_2}(\varepsilon_n, J, \pi)} = \frac{R_c^{n_1}(\varepsilon_n)}{R_c^{n_2}(\varepsilon_n)}$$

Verification of the Surrogate ratio method

SC, Iwamoto, PRC 81, 044604(2010)

$$\frac{B_\gamma^{S_1}(\varepsilon_n, J, \pi)}{B_\gamma^{S_2}(\varepsilon_n, J, \pi)} = \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)}$$

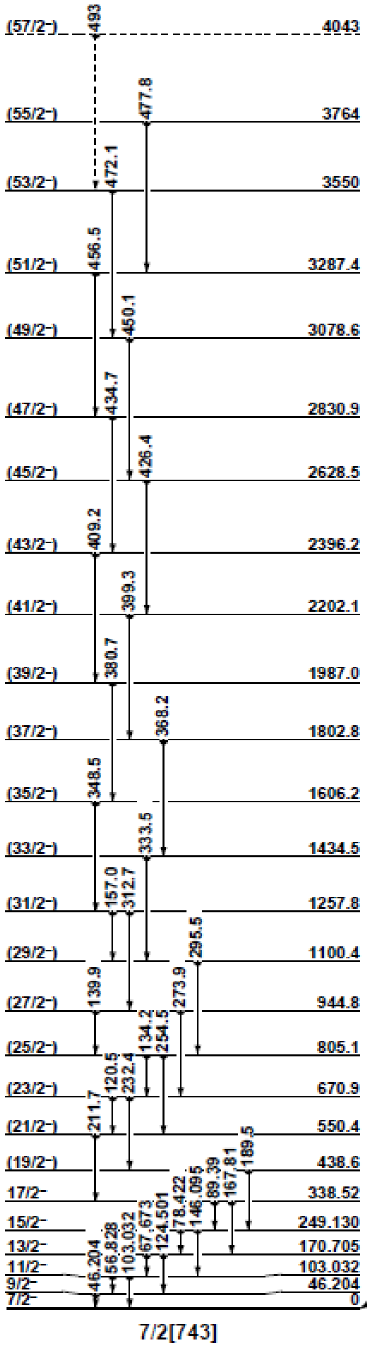
Weak Weisskopf-Ewing condition

$$R_\gamma^{S_1} = \frac{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi) \cdot B_\gamma^{S_1}(\varepsilon_n, J, \pi)}{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi)} = \frac{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi) \cdot B_\gamma^{S_2}(\varepsilon_n, J, \pi) \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)}}{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi)}$$

$$= \frac{\sum_{J^\pi} \sigma_{dir}^{S_2}(\varepsilon_n, J, \pi) \cdot B_\gamma^{S_2}(\varepsilon_n)}{\sum_{J^\pi} \sigma_{dir}^{S_2}(\varepsilon_n, J, \pi)} \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)} = R_\gamma^{S_2}(\varepsilon_n) \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)}$$

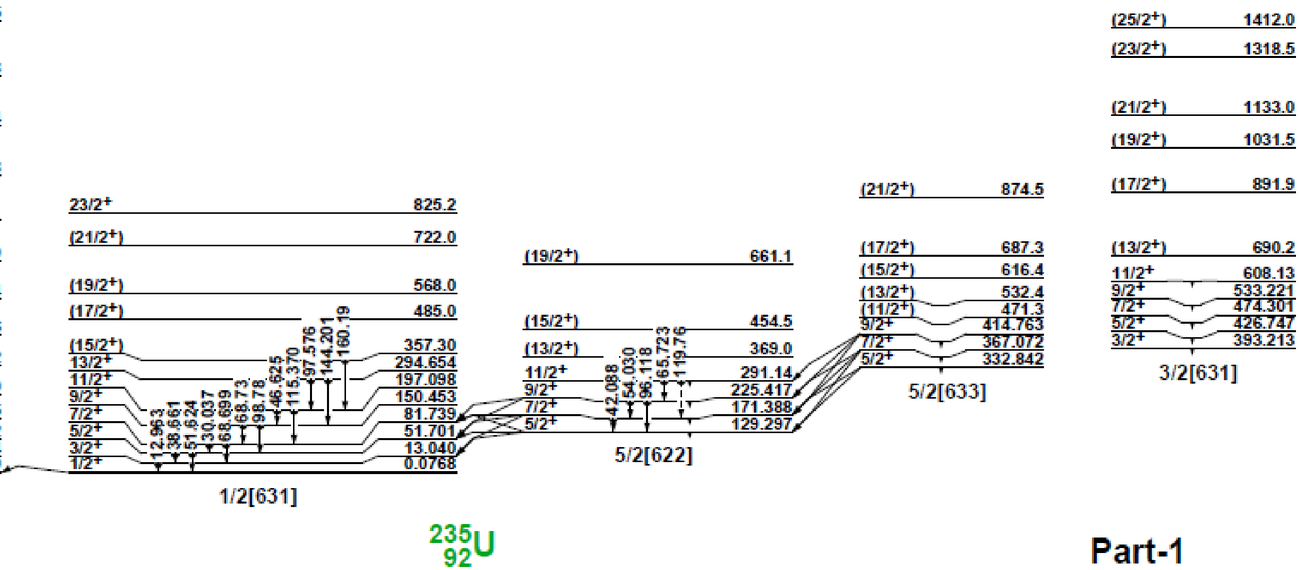
$$\Rightarrow R_\gamma^{n_1}(U) = \frac{R_\gamma^{S_1}(U)}{R_\gamma^{S_2}(U)} R_\gamma^{n_2}$$

If the J^π distribution in the 2 surrogate reactions employed in the SRM are equivalent, it gives the correct answer

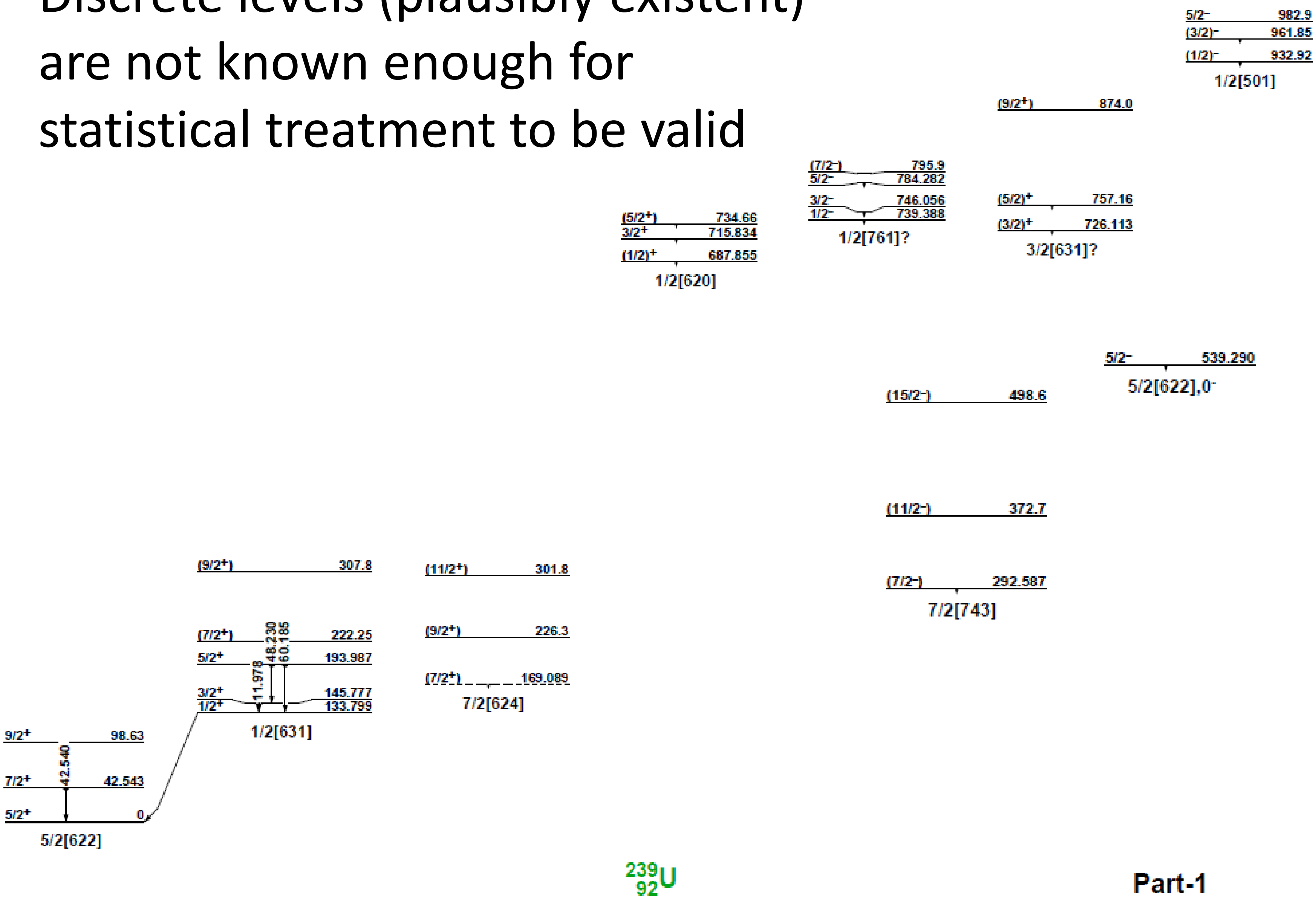


Discrete level information is known enough for statistical treatment

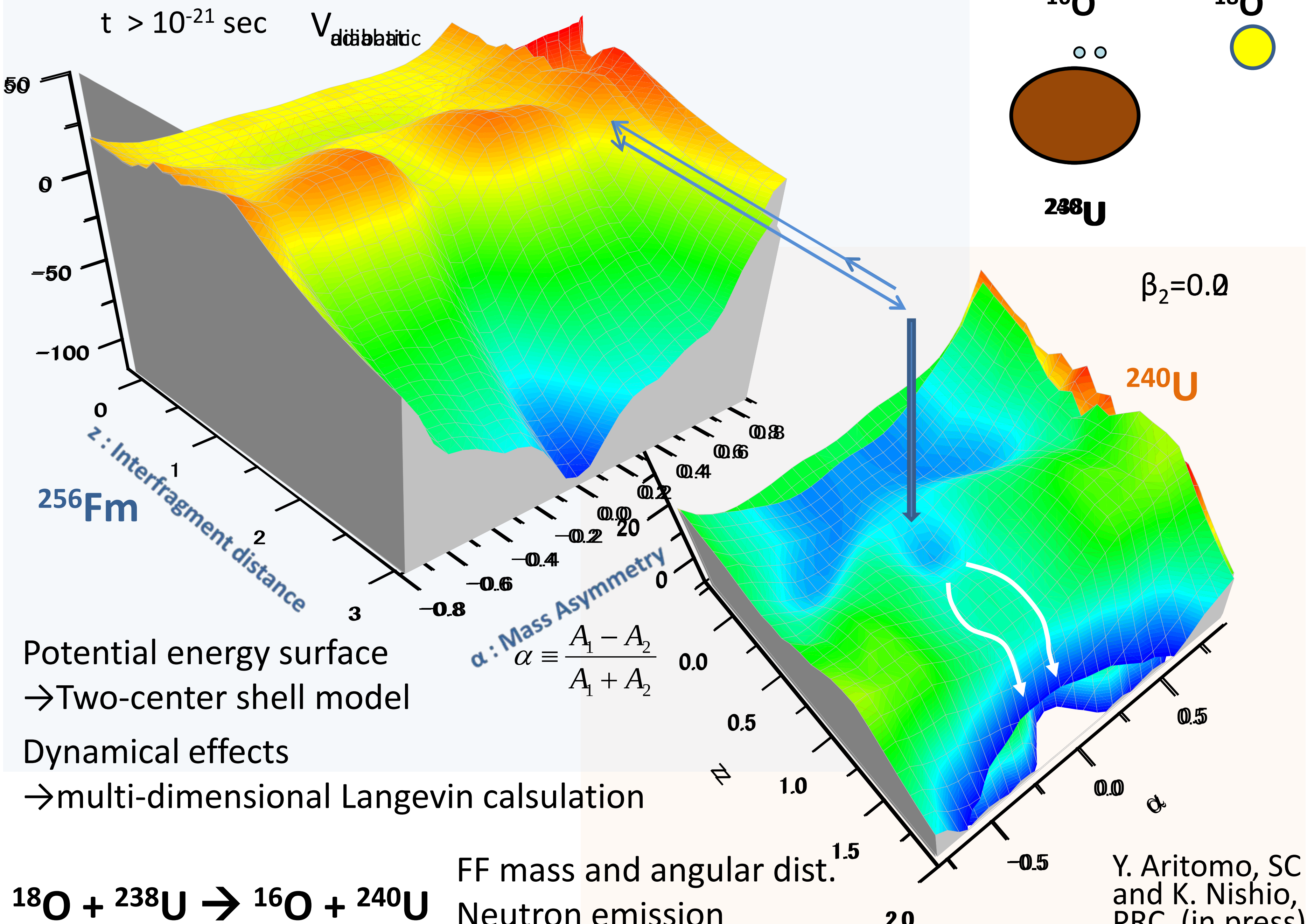
Hopefully, more information on the side-bands is known



Discrete levels (plausibly existent) are not known enough for statistical treatment to be valid



Semi-classical picture of the surrogate reaction



$\alpha \equiv \frac{A_1 - A_2}{A_1 + A_2}$

Potential energy surface
→Two-center shell model

Dynamical effects
→multi-dimensional Langevin calsulation

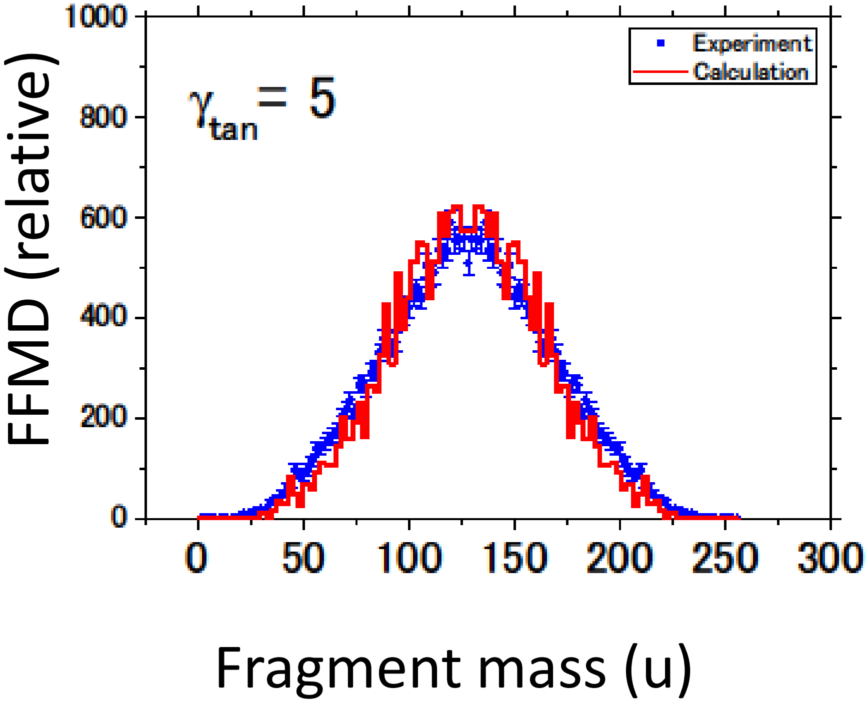
$^{18}O + ^{238}U \rightarrow ^{16}O + ^{240}U$

FF mass and angular dist.
Neutron emission

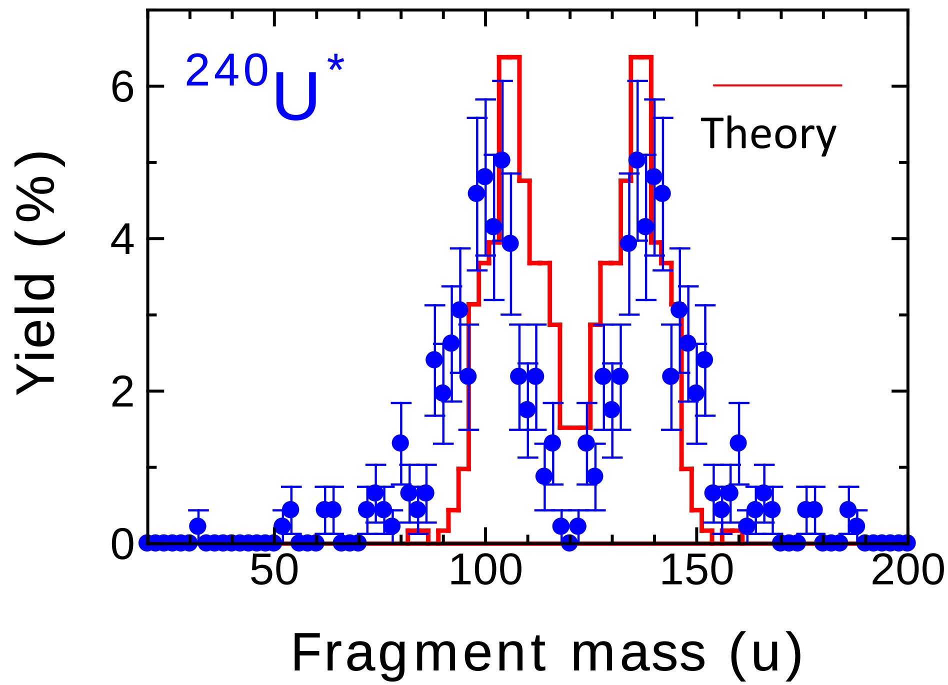
Y. Aritomo, SC and K. Nishio, PRC (in press)

FFMD for $^{18}O + ^{238}U$ system

^{256}Fm



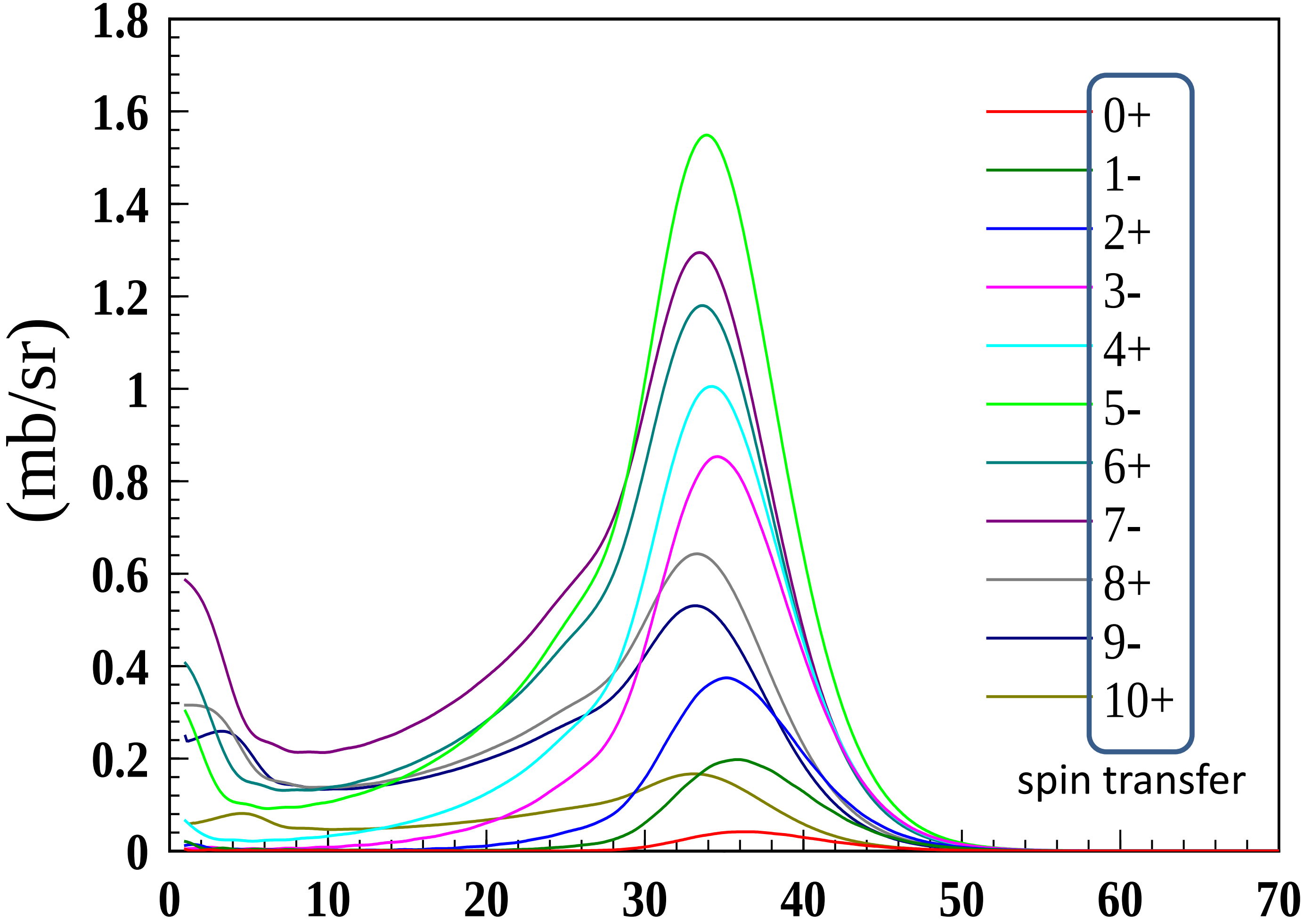
^{240}U, $E^* < 20$ MeV



FFMD for both of the fusion-fission (left) and transfer fission (right) processes can be described by a unified dynamical framework based on 2-center shell model + Langevin calculation

Angular distribution (CDCC-BA, Ogata)

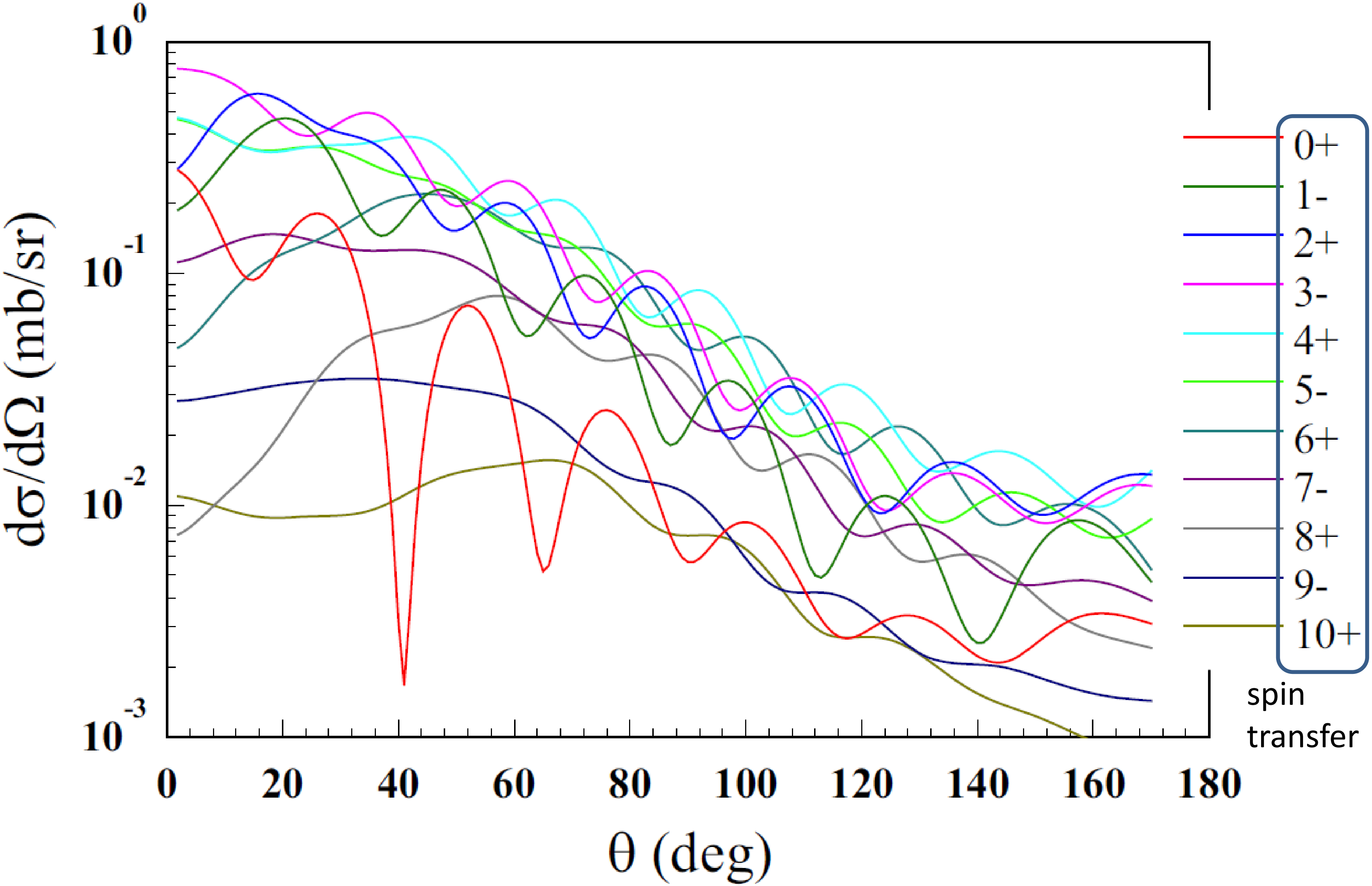
$^{238}U(^{18}O,^{16}O)^{240}U$ reaction at 180 MeV



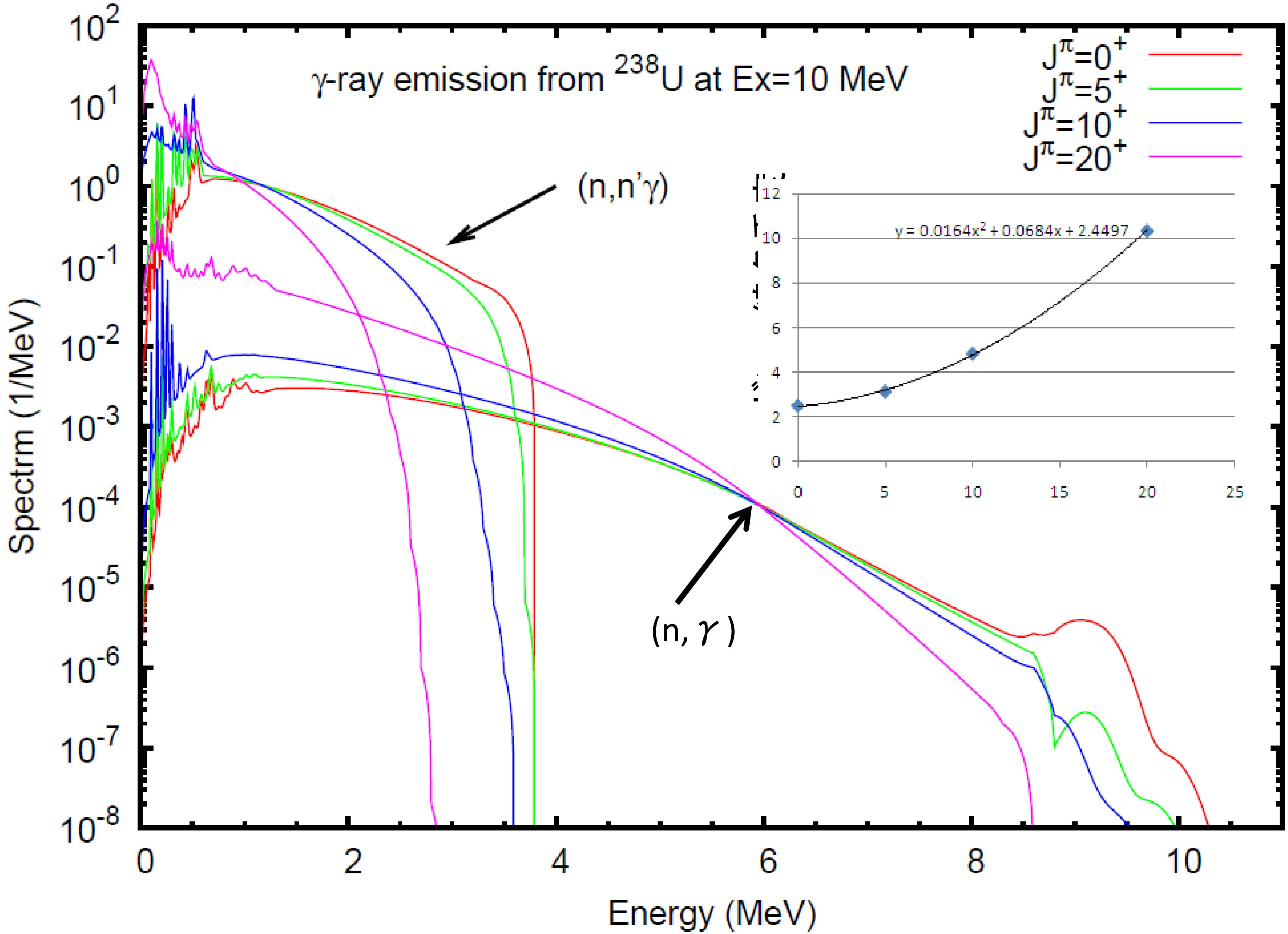
Emission Angle of ^{16}O

K.Ogata, S. Hashimoto and SC, JNST(in press)

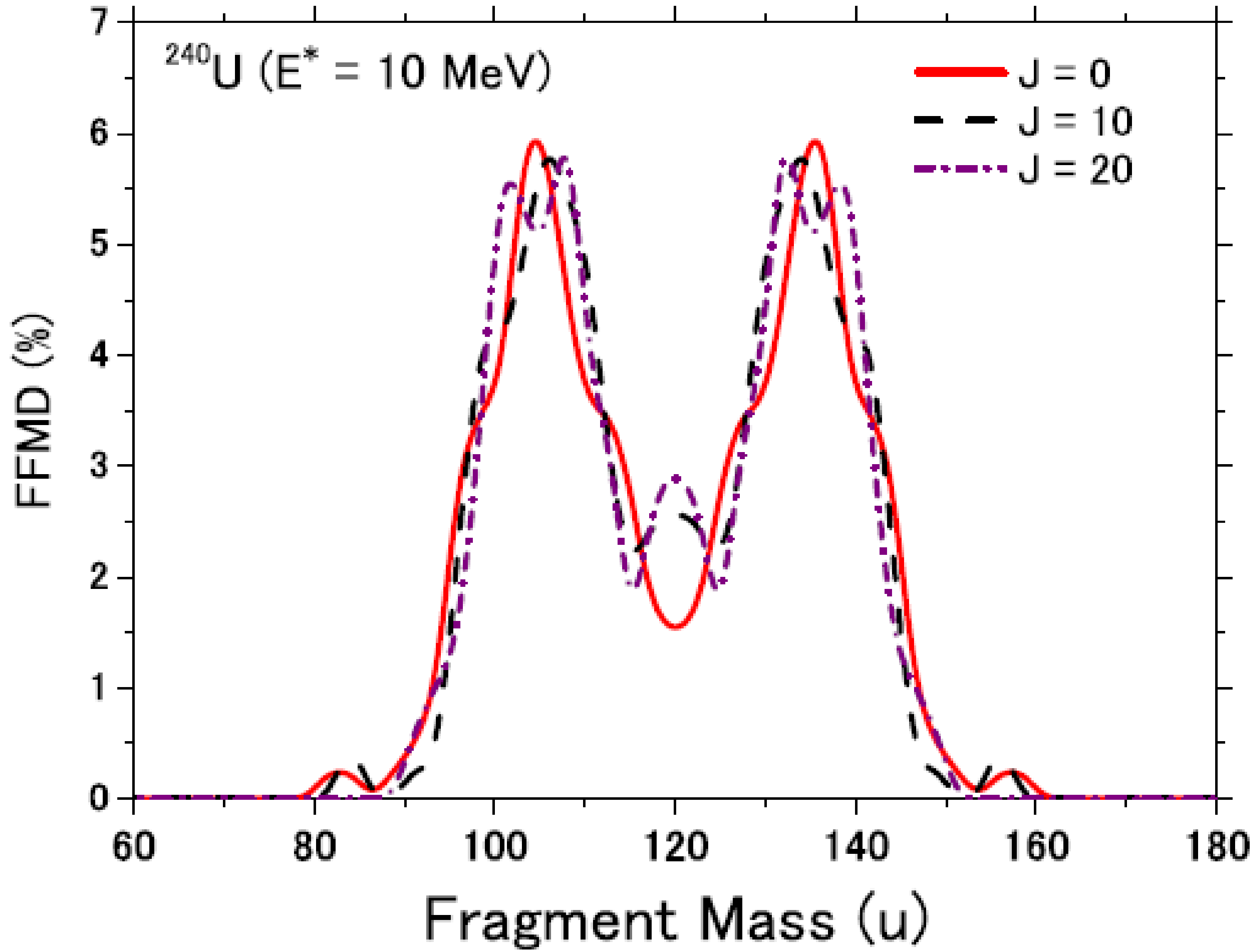
$^{238}U(^{3}He,p)^{240}Np$ at 30 MeV



Spin-dependent observables



Spin-dependence of FFMD

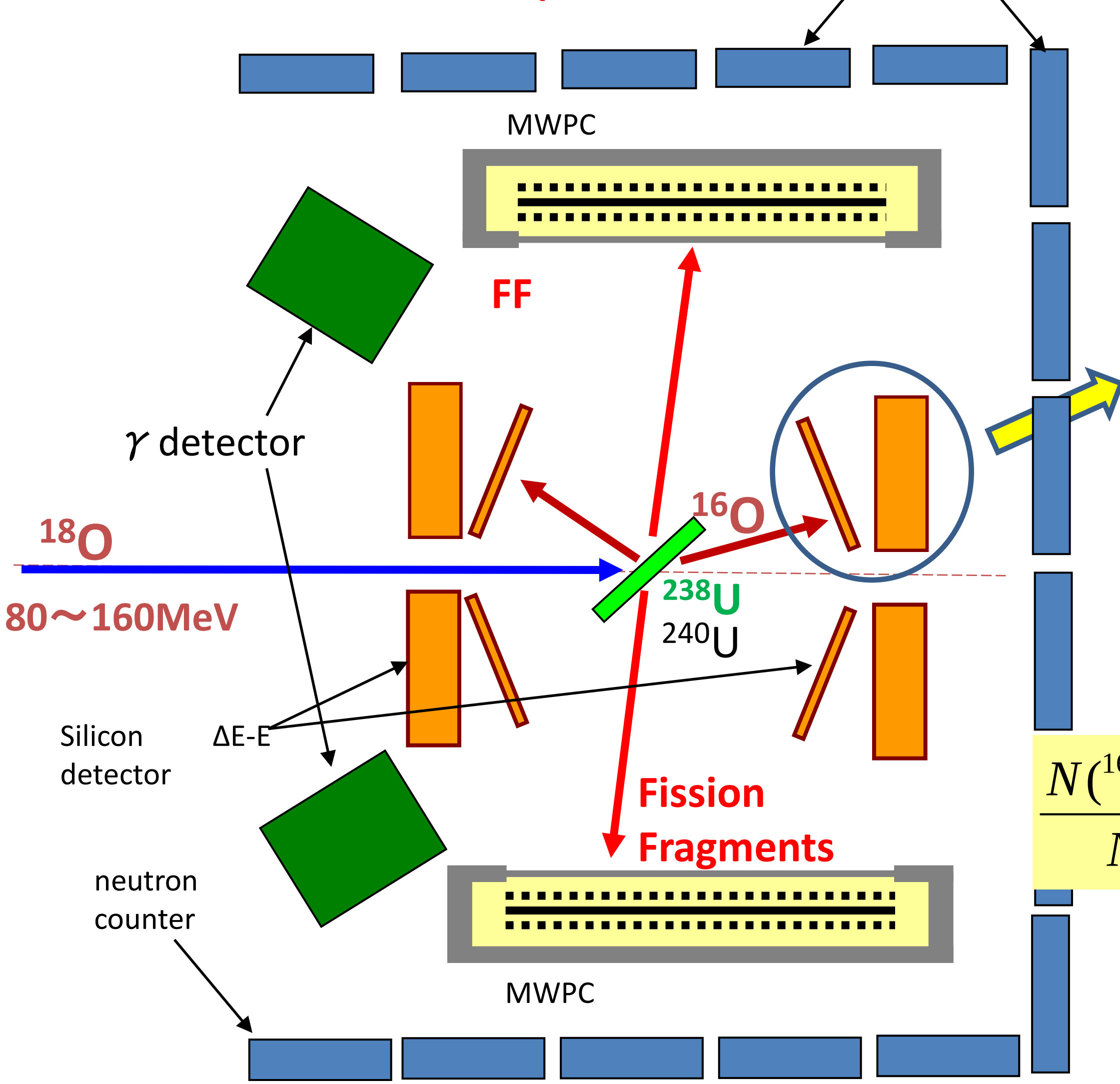


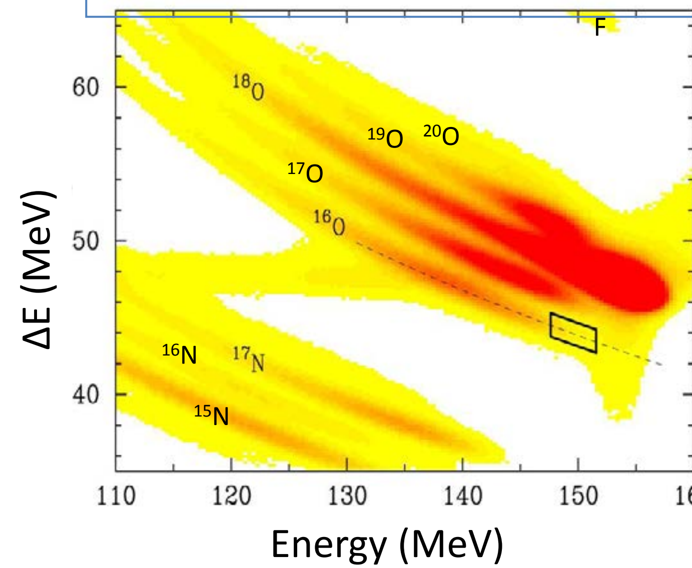
Schematic experimental layout

Neutron c.s. of $^{239}U(T_{1/2}=23.5\text{min})$

$n+^{239}U \rightarrow ^{240}U$ (Compound)

- Fission c.s.
- Capture c.s.
- Number of fission neutrons
  - $E_n = 0.5 \sim 5$ MeV
  - 10～15% precision





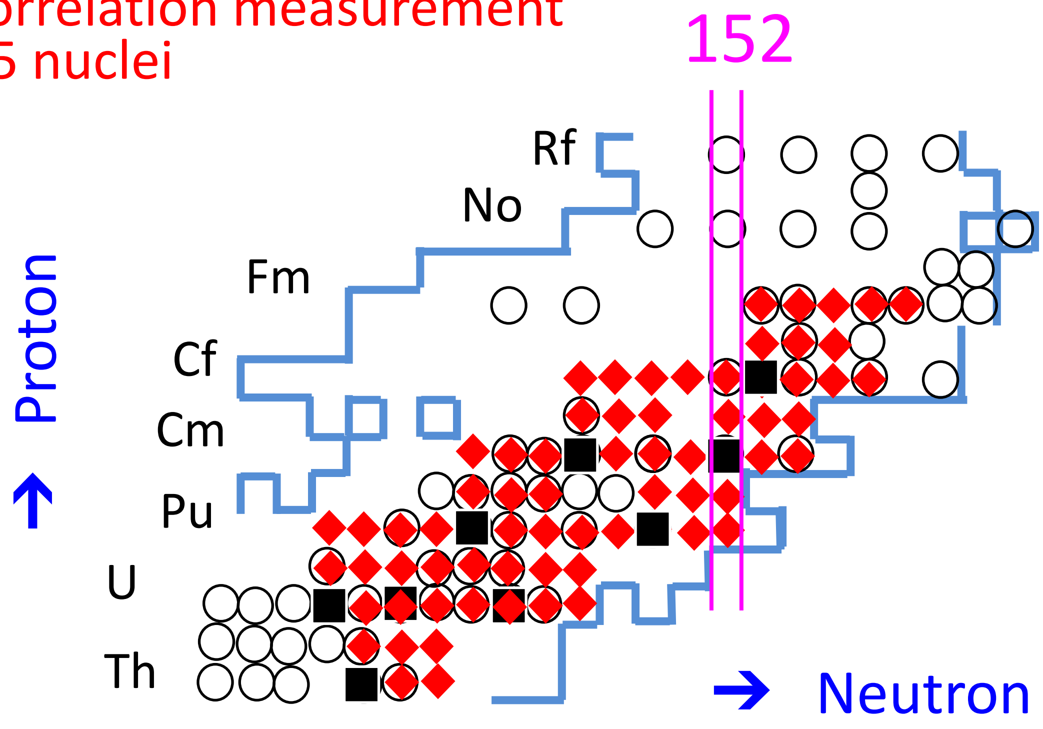
$$\frac{N(^{16}O \otimes FF)}{N(^{16}O)} \longleftrightarrow \frac{\sigma_f^n(^{239}U)}{\sigma_R^n(^{239}U)} \equiv R_f^S(^{240}U)$$

σ_R:Total reaction c.s.

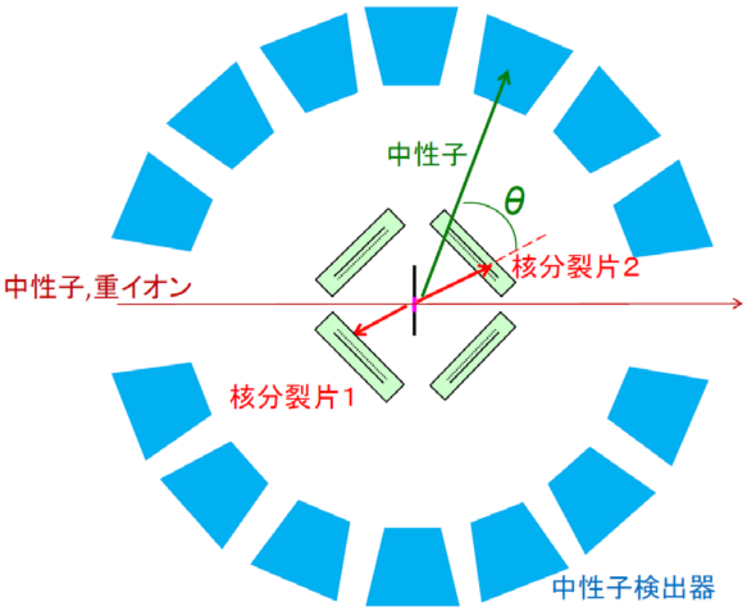
Neutron-induced Fission c.s. of ^{239}U

Future plans : transfer-induced fission

New data for fragment-neutron correlation measurement
35 nuclei

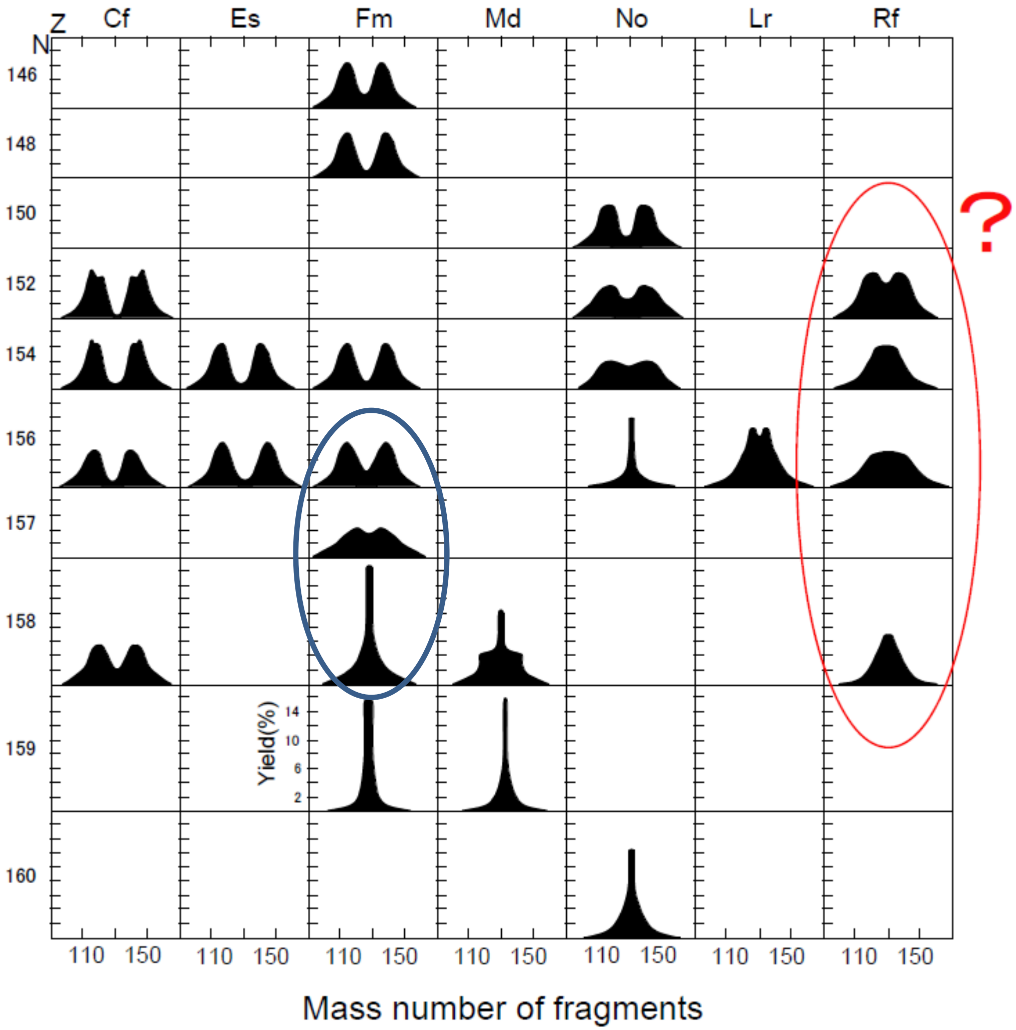


【target】^{232}Th, ^{233,235,238}U, ^{240,244}Pu, ^{244,248}Cm, ^{251}Cf



Fission detectors + Neutron detectors

重・超アクチノイド核の自発核分裂特性



$^{248}Cm(^{15}N, 4n)^{259}Lr$ (6.3 s)
$^{248}Cm(^{18}O, 4n)^{262}Rf$ (2.1 s)
$^{248}Cm(^{16}O, 5n)^{259}Rf$ (3.0 s)
$^{248}Cm(^{19}F, 4n)^{263}Db$ (27 s)
$^{248}Cm(^{19}F, 5n)^{262}Db$ (34 s)

Transfer reactions can populate various excitation energies

M. R. Lane *et al.*, Phys. Rev. C **53**, 2893 (1996).

JAEA Tandem Accelerator at Tokai

- つくばのタンデム崩壊後、国内唯一の大型静電加速器
- 第一種管理区域、ISOLがあり、非密封RI、核燃料物質、アクチノイドをはじめとするα放射体を使える数少ない加速器施設（核医学用At製造も計画）
- H24概算：一時ゼロ査定（シャットダウンを前提）
- 年間予算1.7億→0.3億への減額でどうにか運転継続可能に

Summary

- Surrogate reaction project is being carried out at JAEA
- Multi-nucleon transfer reactions induced by various projectiles (^{3}He, ^{18}O, ...) are employed
- Fast neutron cross sections relevant to FBR, ADS and neutron-capture nucleosynthesis studies
  - fission cross sections
  - number of prompt fission neutrons and their energy spectra
  - neutron capture cross sections
  - fission fragment mass distributions
- Understanding of reaction mechanisms is highly desired
  - Nuclear reaction physics is important
- Discrete level information is also important