Nuclear data measurement by surrogate reactions using ion beam

Katsuhisa Nishio （西尾 勝久）

Advanced Science Research Center

Japan Atomic Energy Agency

Tokai, Japan

2023年核データ研究会（東海）

Contents

- ☑ Tandem accelerator facility
- ☑ Surrogate method for fission cross sections
- ☑ Competition between fission and neutron evaporation ; multichance fission
- ☑ Planned measurement of probability for each neutron-emission channel
  (γ-ray detection technique and direct recoiled-nucleus technique)
- ☑ Future facility
- ☑ Summary

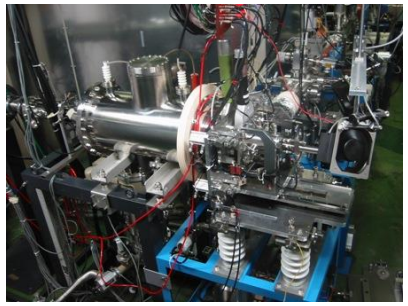
JAEA Tandem facility

Many radioactive target materials can be used;

^{226}Ra, ^{232}Th, $^{233,235,238}U$, ^{237}Np, $^{239,242,244}Pu$, $^{241,243}Am$, ^{248}Cm, ^{249}Bk, $^{249,250,251,252}Cf$, ^{254}Es

Experimental setups.

e.g. ISOL, Recoil Mass Separator, Fission setups..

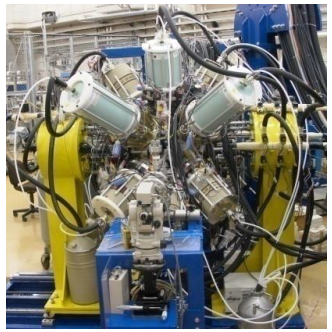


Isotope Separator On-Line

Recoil Mass Separator

Magnetic Spectrograph

Prompt Fission Setup

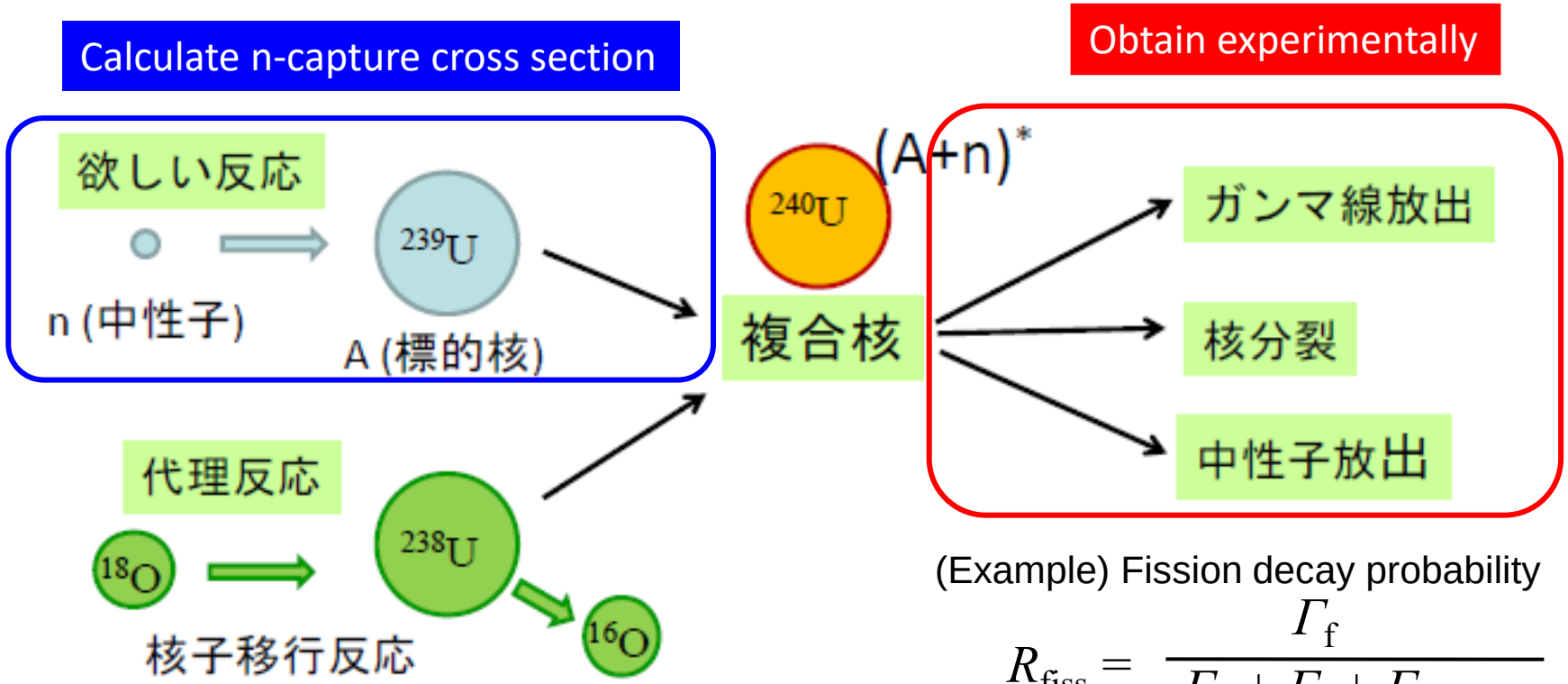


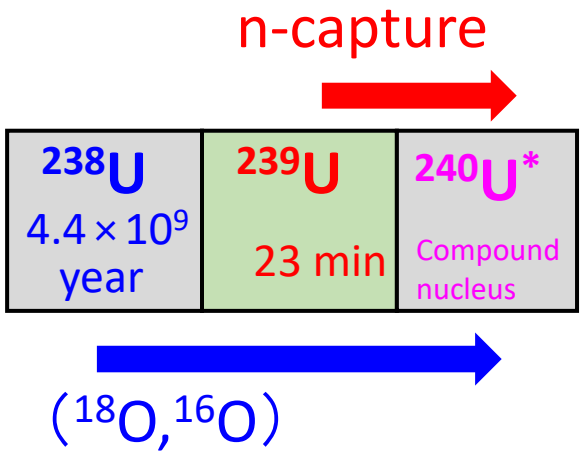
Ge-detector array

Surrogate reaction
- Fission cross section -

Calculate n-capture cross section

Obtain experimentally



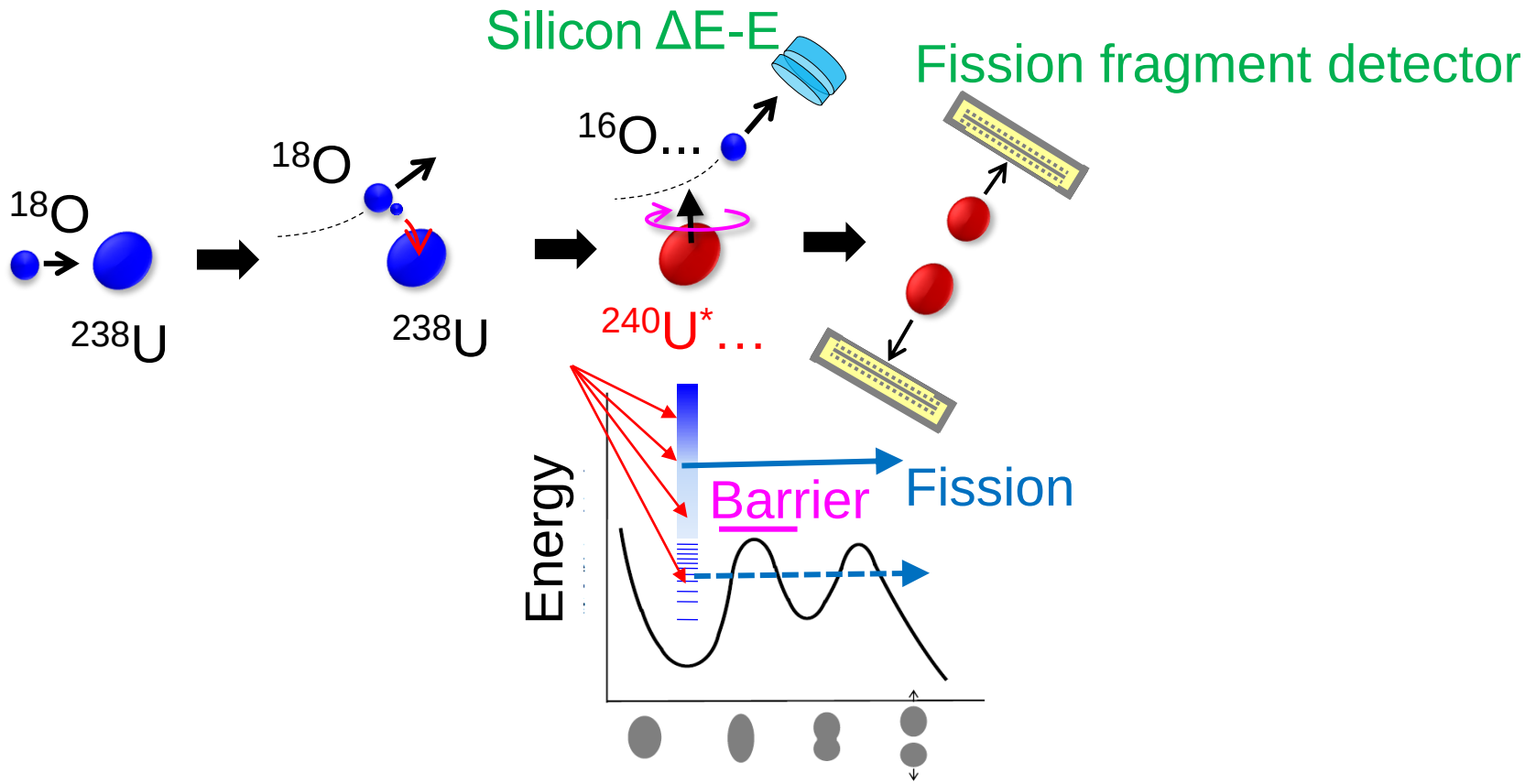


(Example) Fission decay probability

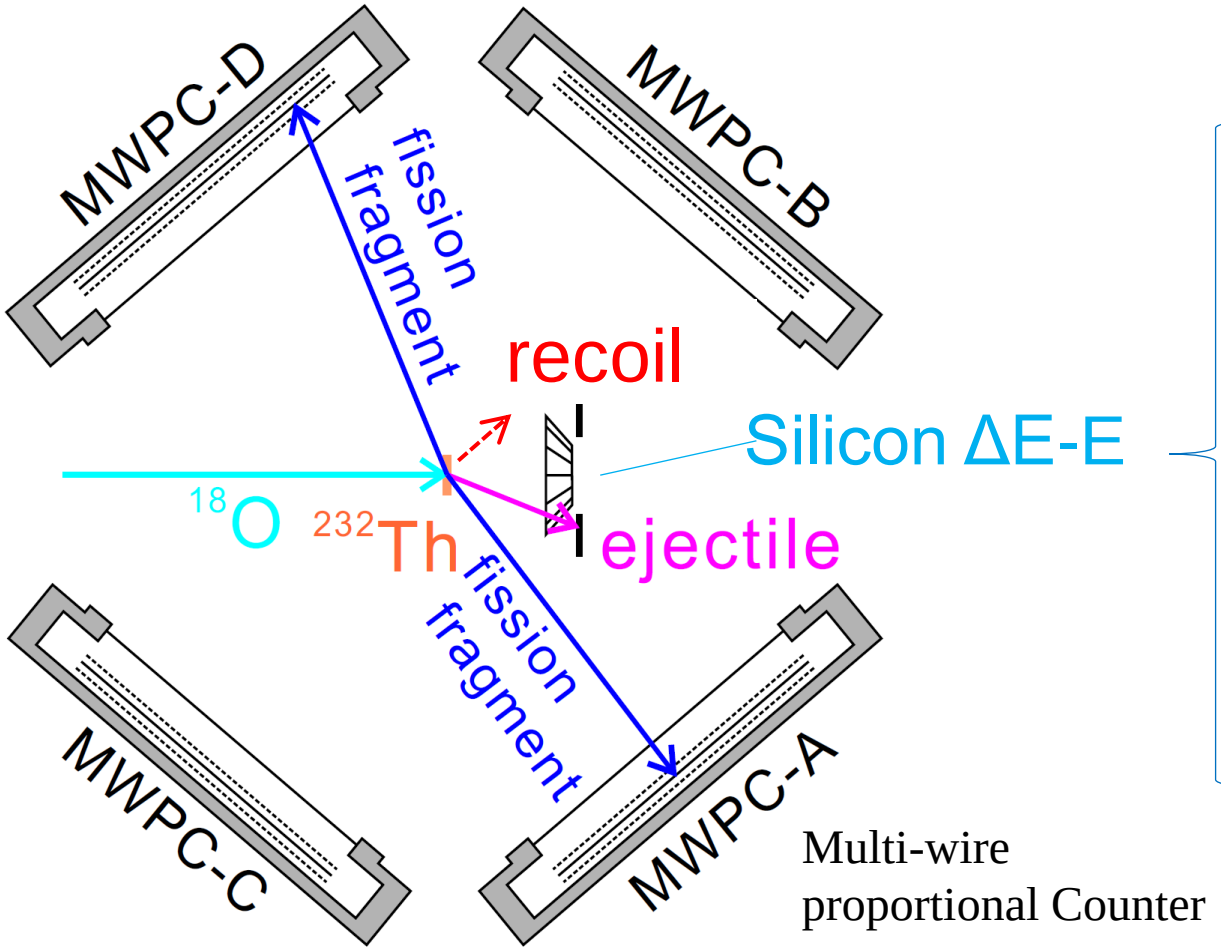
$$R_{\mathrm{fiss}} = \frac{\Gamma_{\mathrm{f}}}{\Gamma_{\mathrm{n}} + \Gamma_{\mathrm{f}} + \Gamma_{\gamma}}$$

Fission cross section ⟸ n + A (標的核) Cross section to form compound nucleus × Fission decay probability

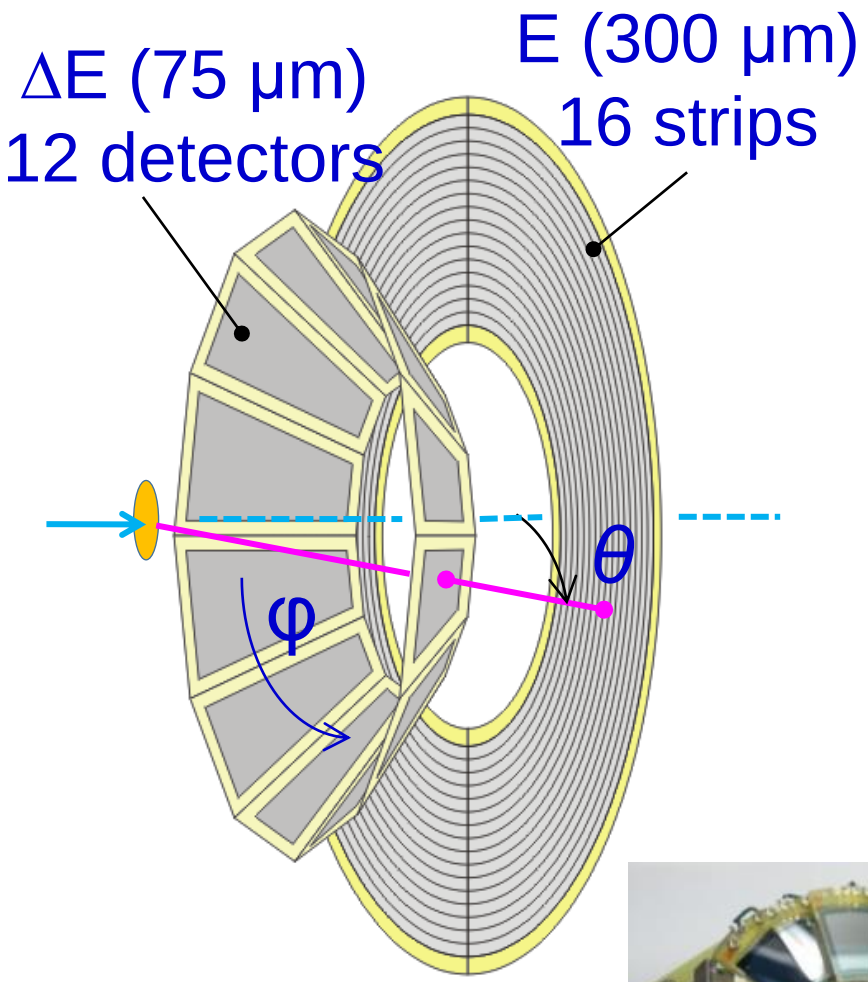
Fission measurement for surrogate reaction
- transfer/multinucleon transfer reaction -

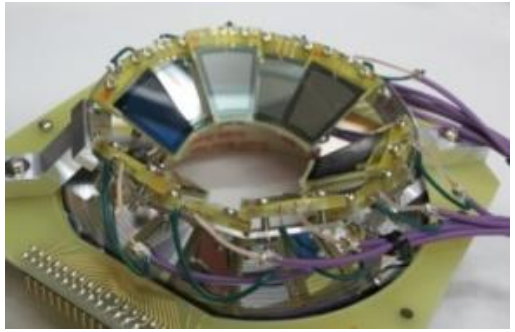


Experimental setup for surrogate fission data



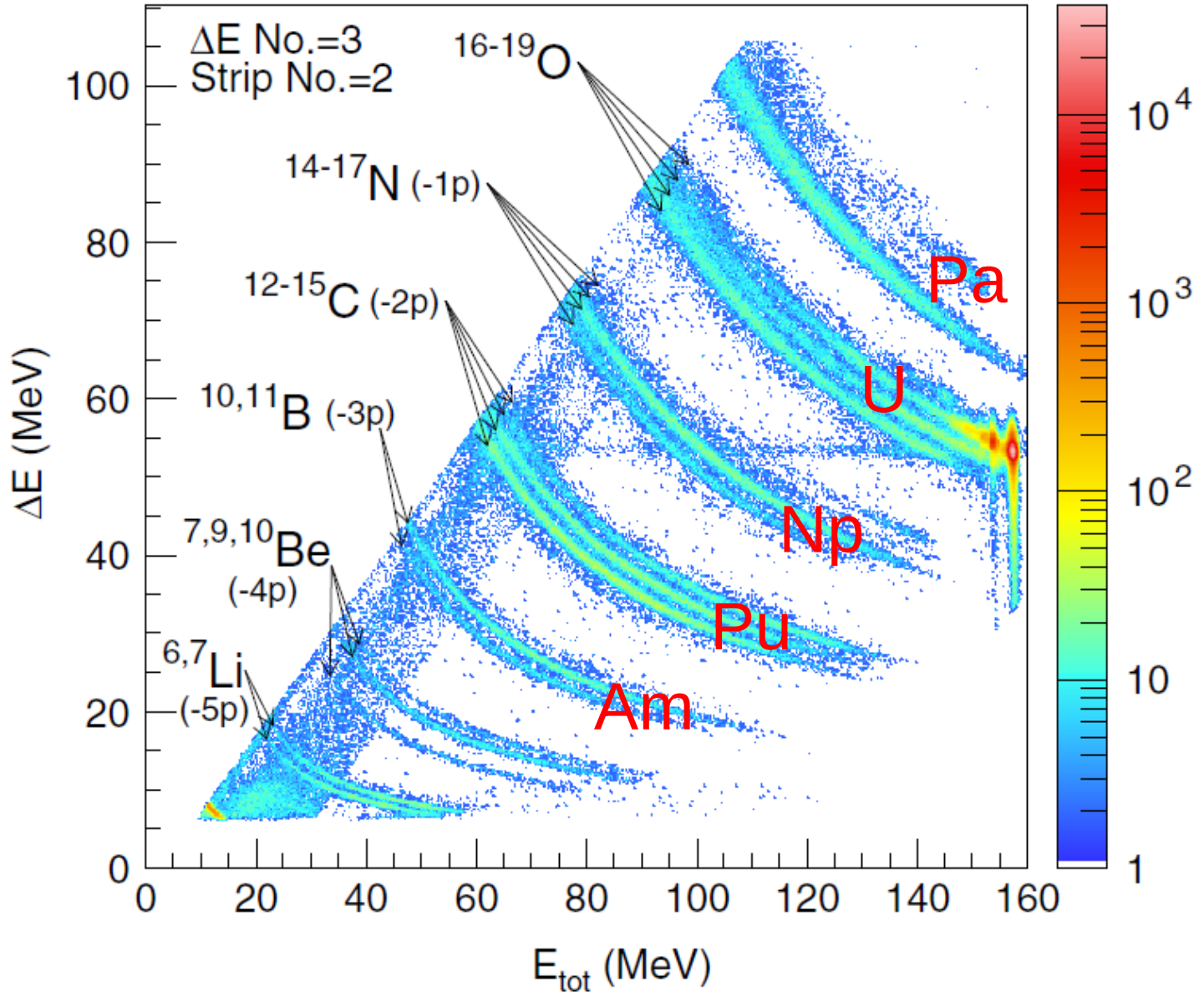
Multi-wire proportional Counter





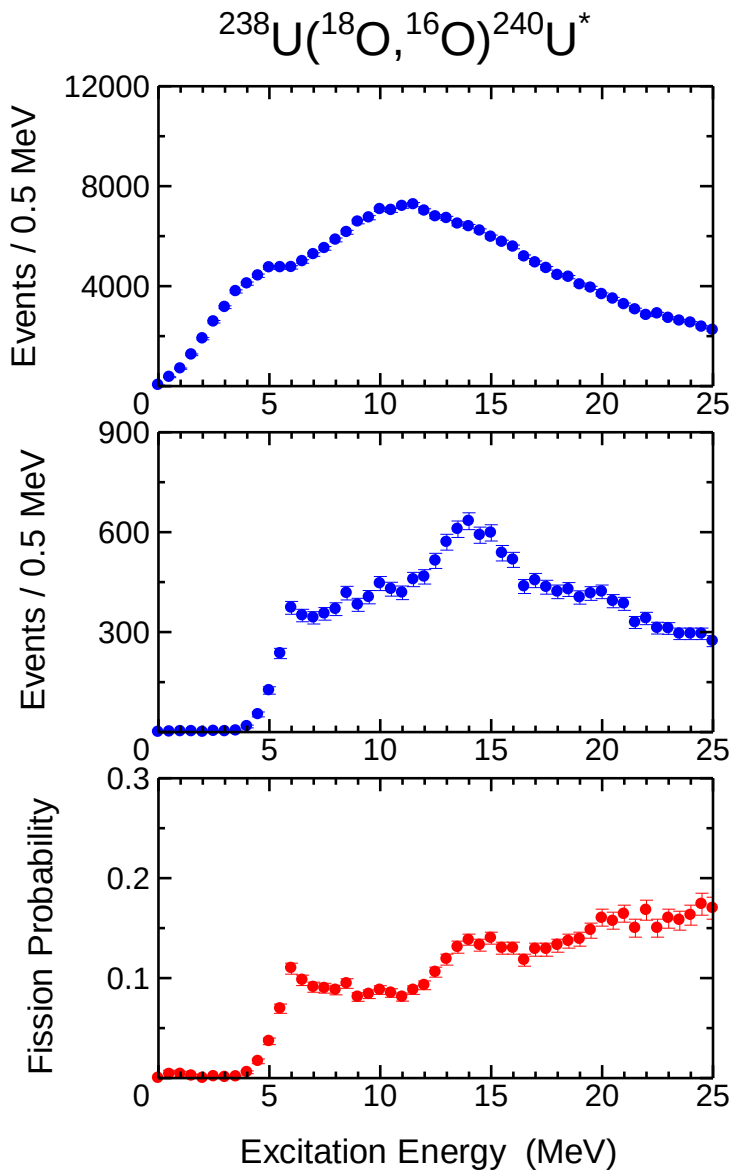
R. Léguillon *et al.*, Phys. Lett. B **761**, 125 (2016).

Particle identification in the ^{18}O + ^{238}U reaction



E_{beam} = 157.5 MeV

Determination of Fission Probability

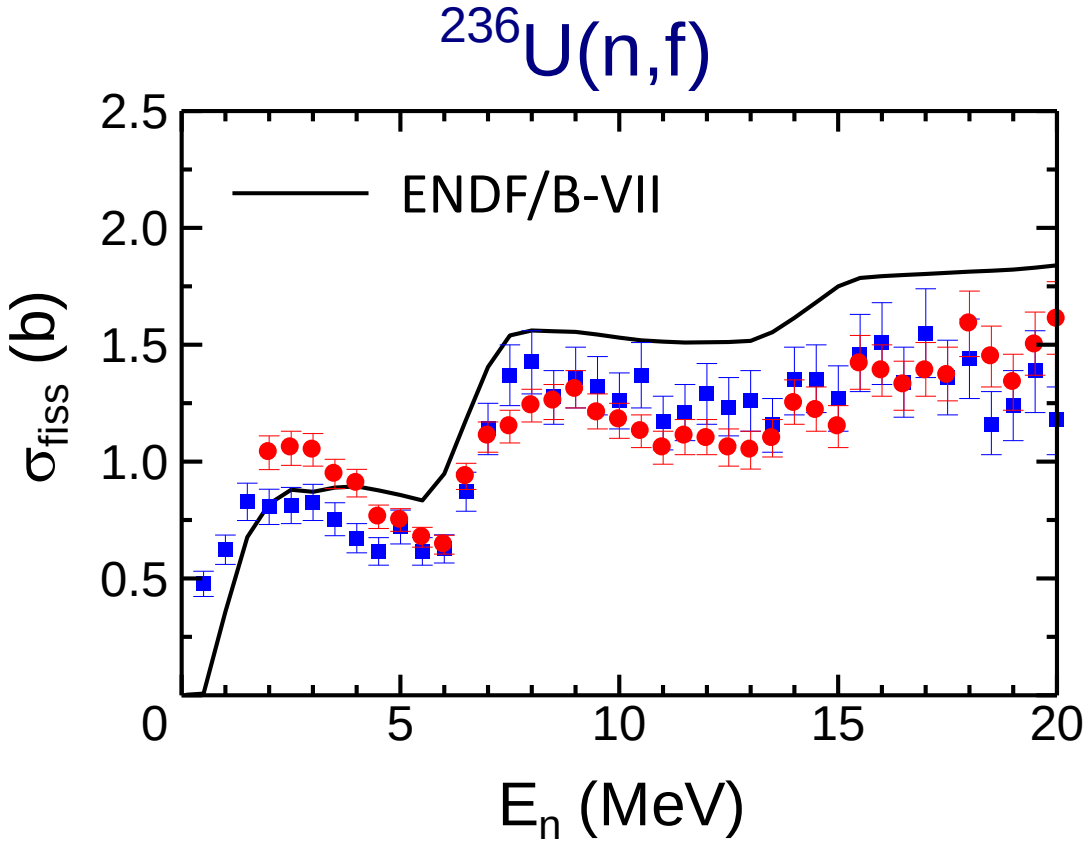


^{16}O single spectrum

^{16}O coincidence with fission fragment

Fission probability

Fission cross section of ^{236}U(n,f) from surrogate ratio method



$^{235}\mathrm{U}(^{18}\mathrm{O},^{16}\mathrm{O})^{237}\mathrm{U}$

ENDF/B-VII

$$\sigma_{^{238}\mathrm{U}(n,f)} \frac{P_f(^{237}\mathrm{U}^*)}{P_f(^{239}\mathrm{U}^*)}$$

$^{238}\mathrm{U}(^{18}\mathrm{O},^{17}\mathrm{O})^{239}\mathrm{U}$

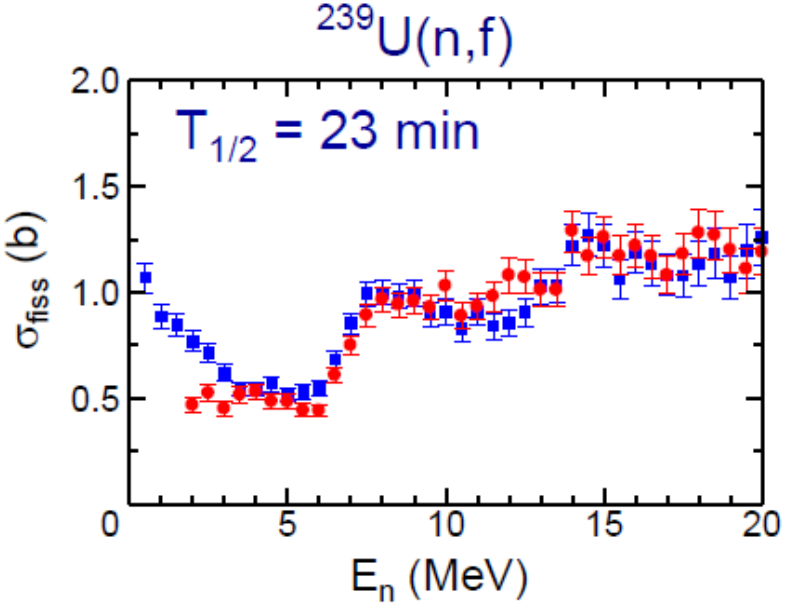
ENDF/B-VII

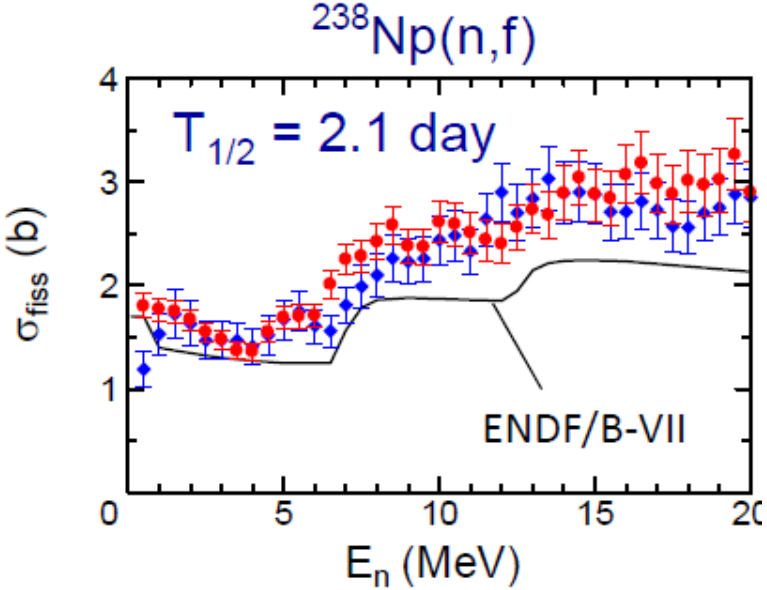
$$\sigma_{^{235}\mathrm{U}(n,f)} \frac{P_f(^{237}\mathrm{U}^*)}{P_f(^{236}\mathrm{U}^*)}$$

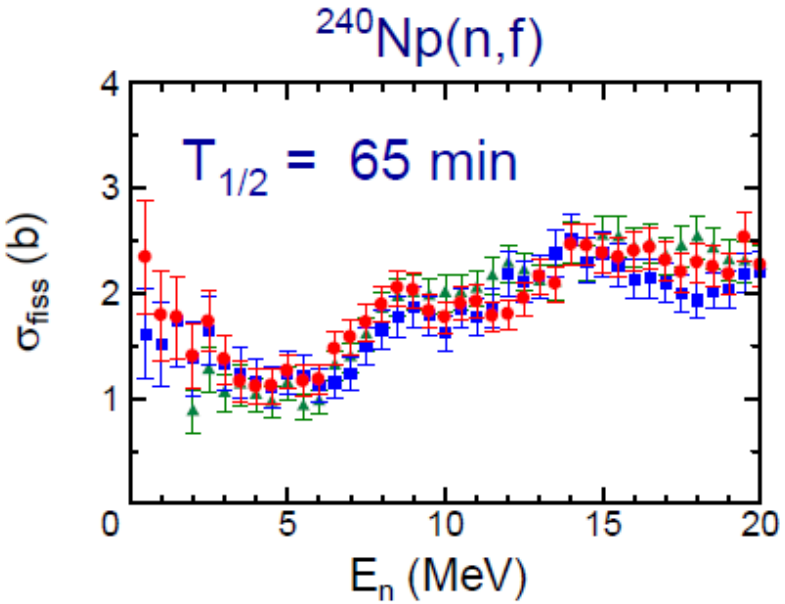
$^{235}\mathrm{U}(^{18}\mathrm{O},^{17}\mathrm{O})^{236}\mathrm{U}$

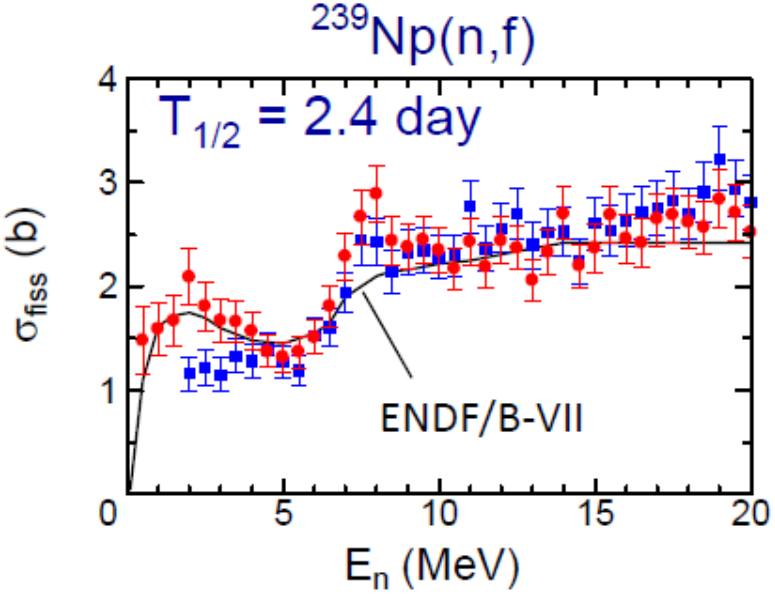
原子力システム研究開発事業 革新技術創出型研究開発（革新的原子炉技術）平成21年度～23年度事業
「高速系革新炉の成立性に影響する核データの新規測定技術開発」

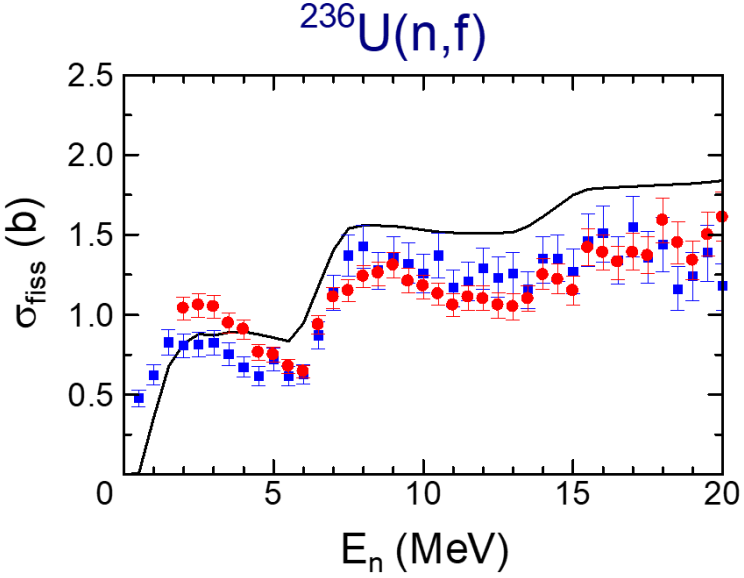
Fission cross section by surrogate ratio method





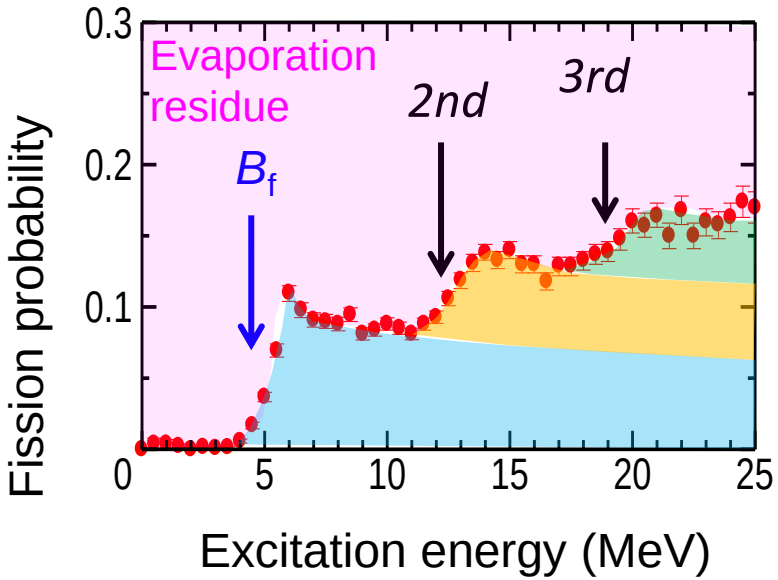


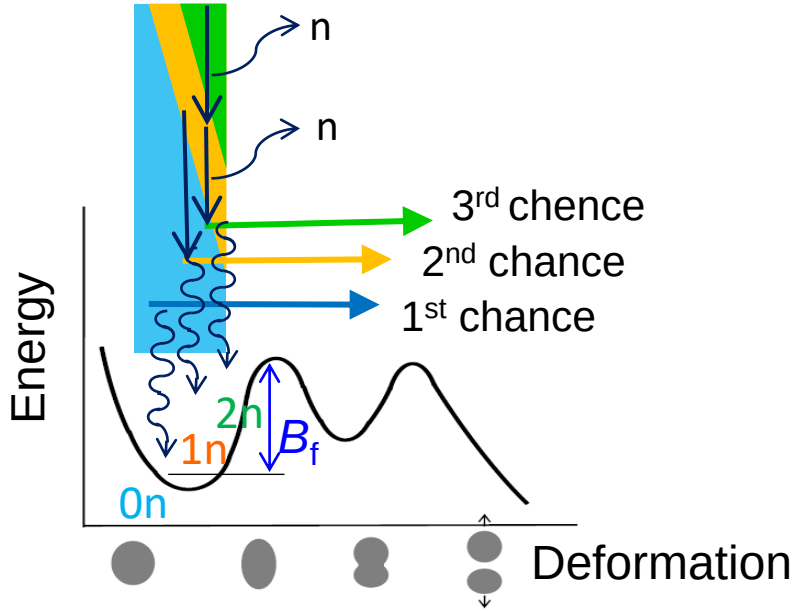




Fission barrier and multichance fission
- competition between fission and neutron emission -

$^{18}O + {}^{238}U \rightarrow {}^{16}O + {}^{240}U^*$ → fission / fission

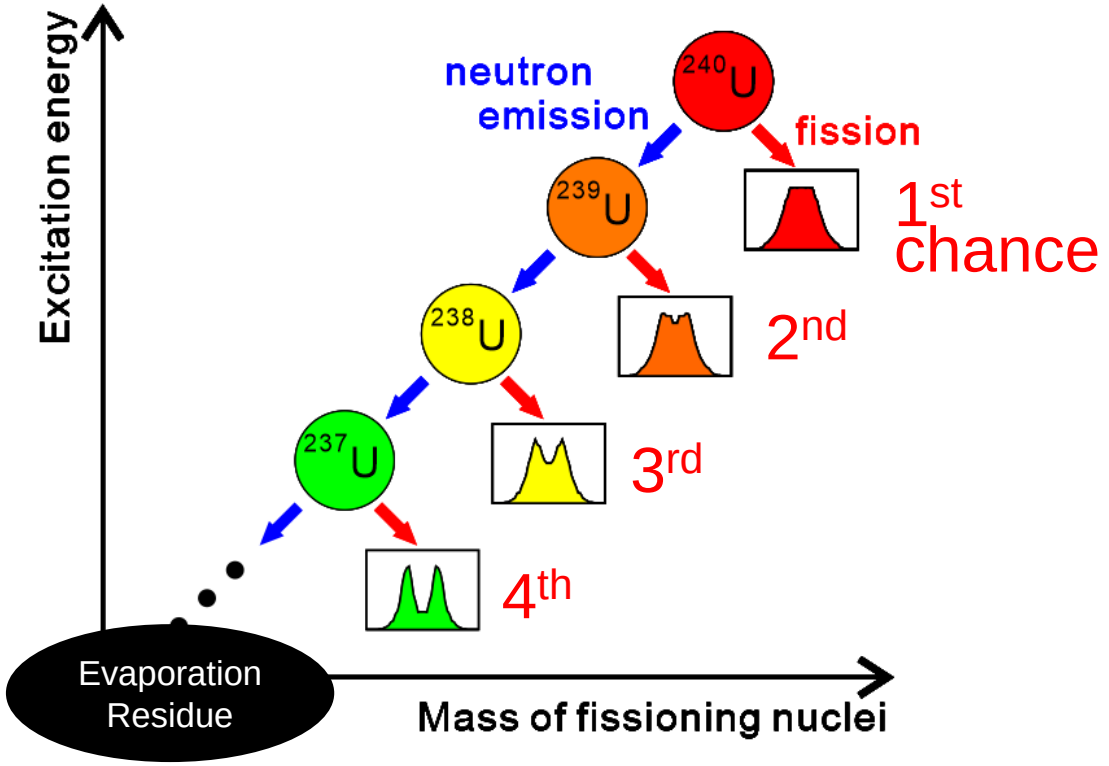


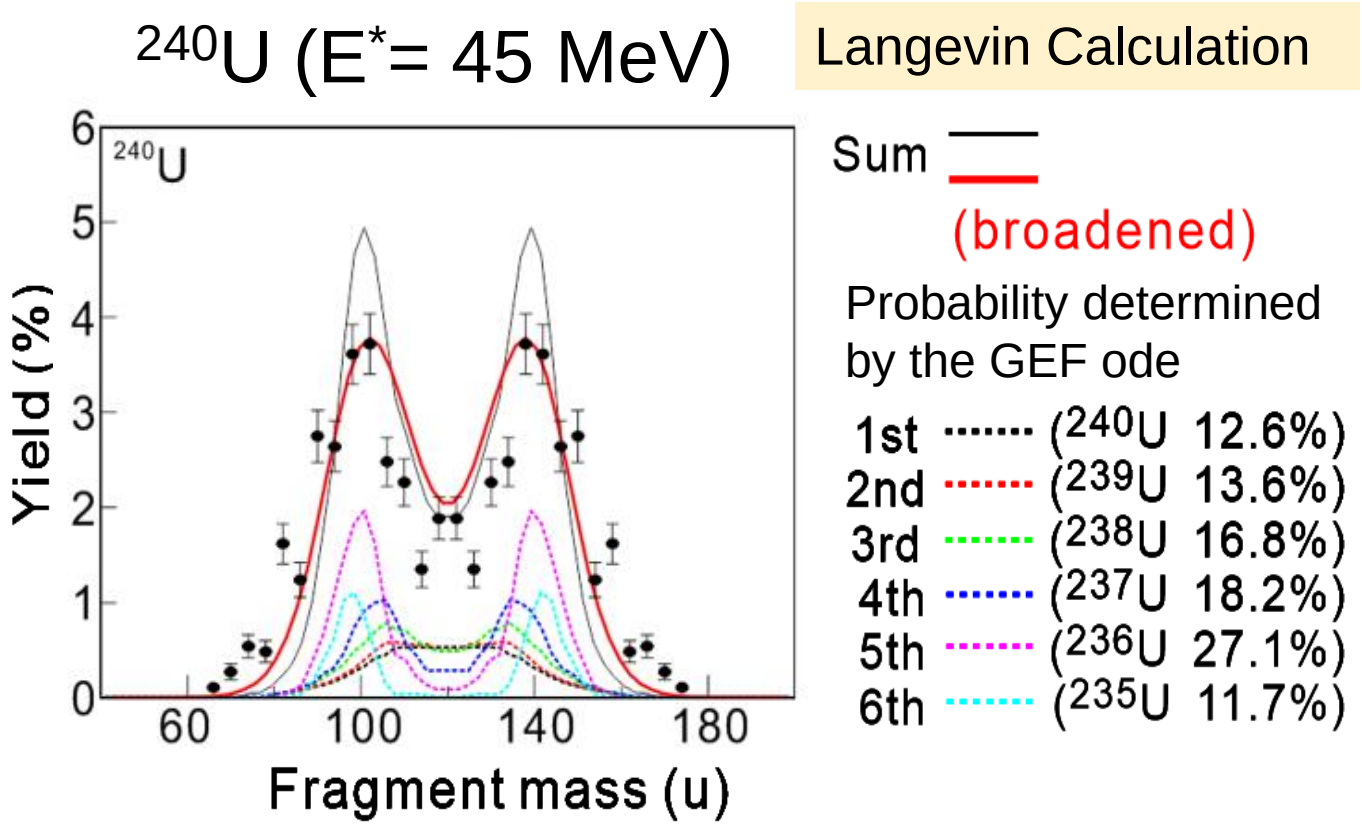


B_f（Fission barrier）= 5.5 MeV

K.R. Kean *et al*., Phys. Rev. C, **100**, 014611 (2019).

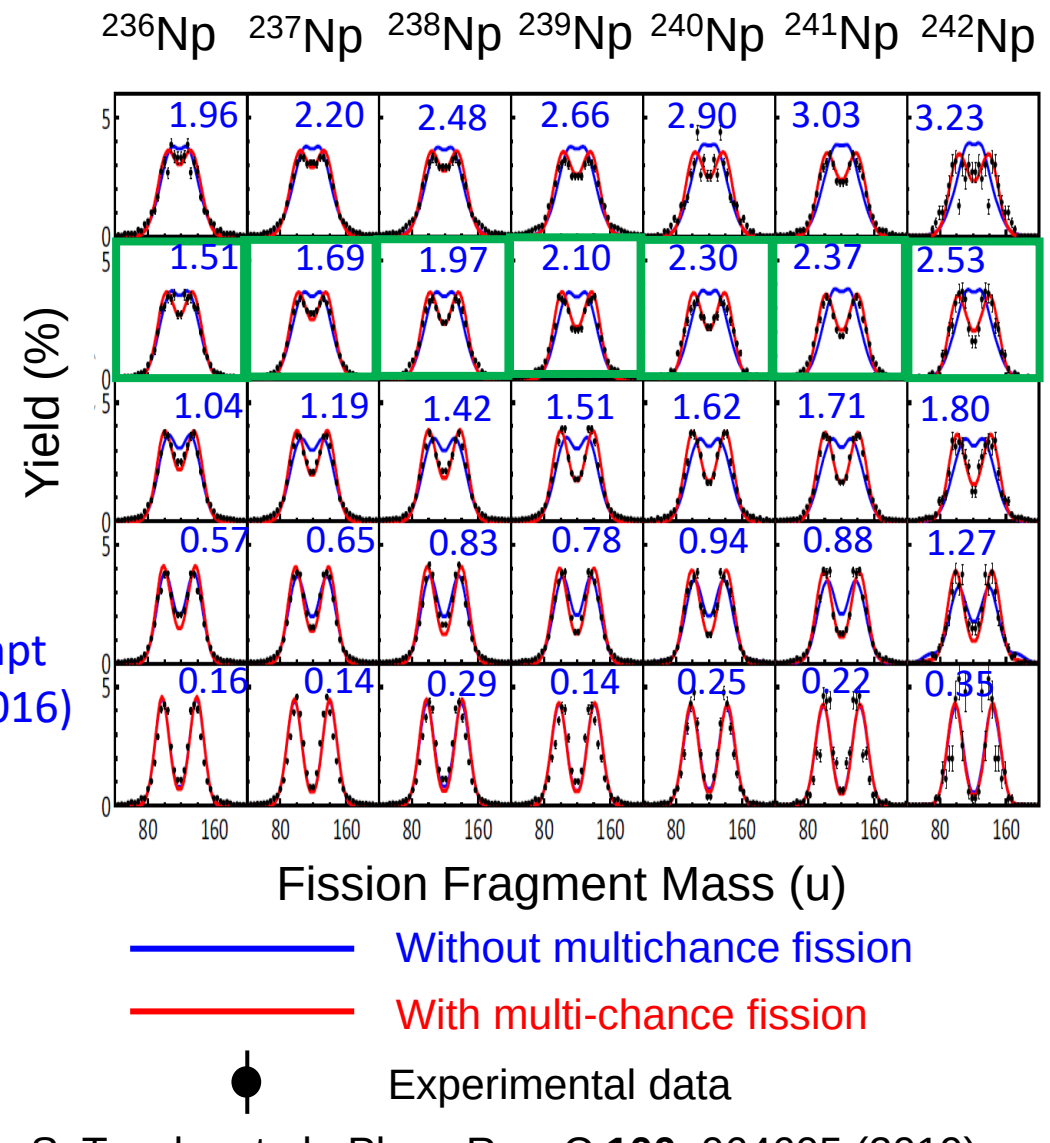
Effects of “Multi-chance Fission” on Fission Fragment Mass Distributions

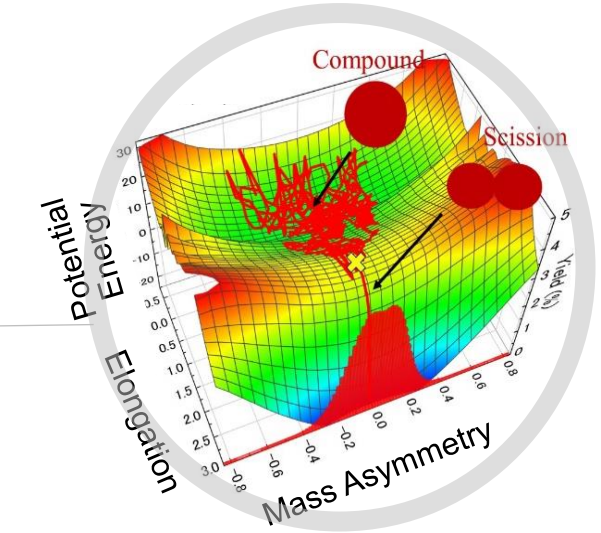


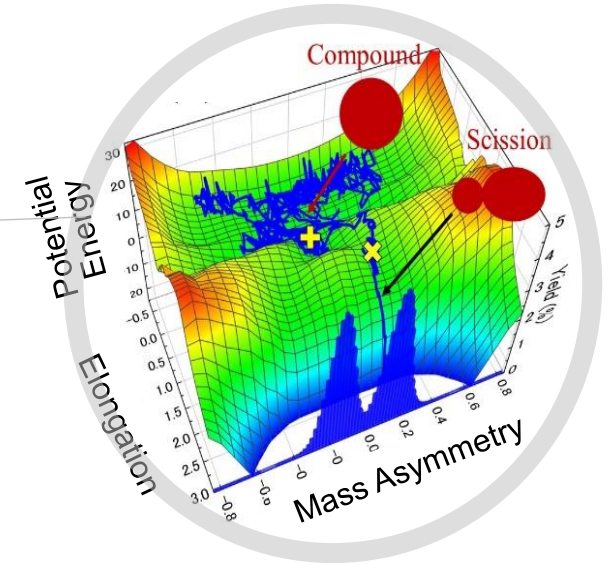


K. Hirose *et al*., Phys. Rev. Lett., **119**, 222502 (2017).

Neutron evaporation before fission

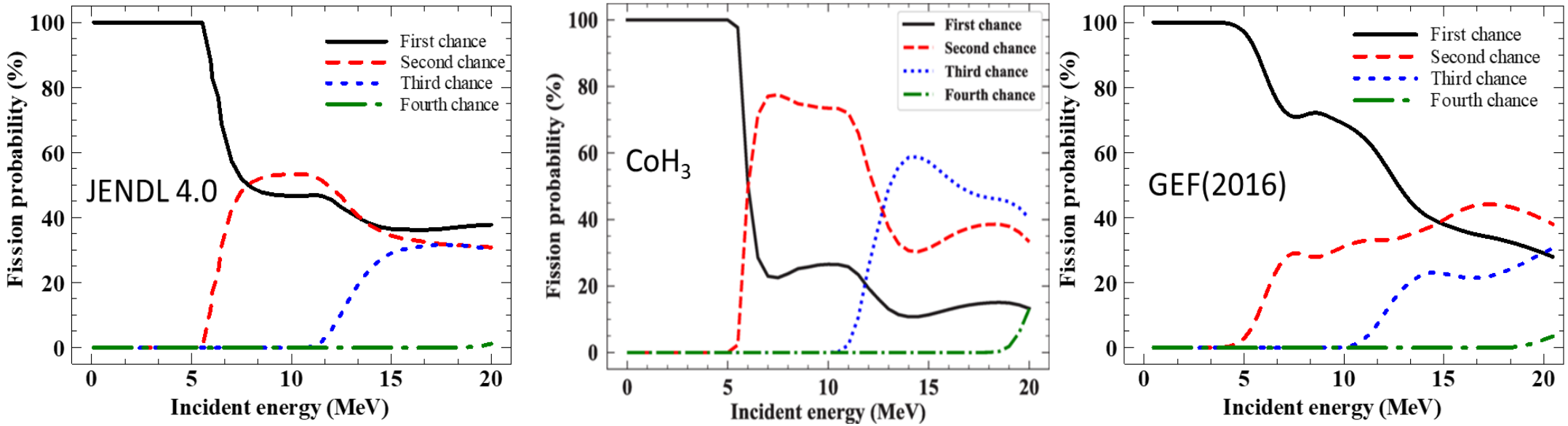






S. Tanaka et al., Phys. Rev. C **100**, 064605 (2019).

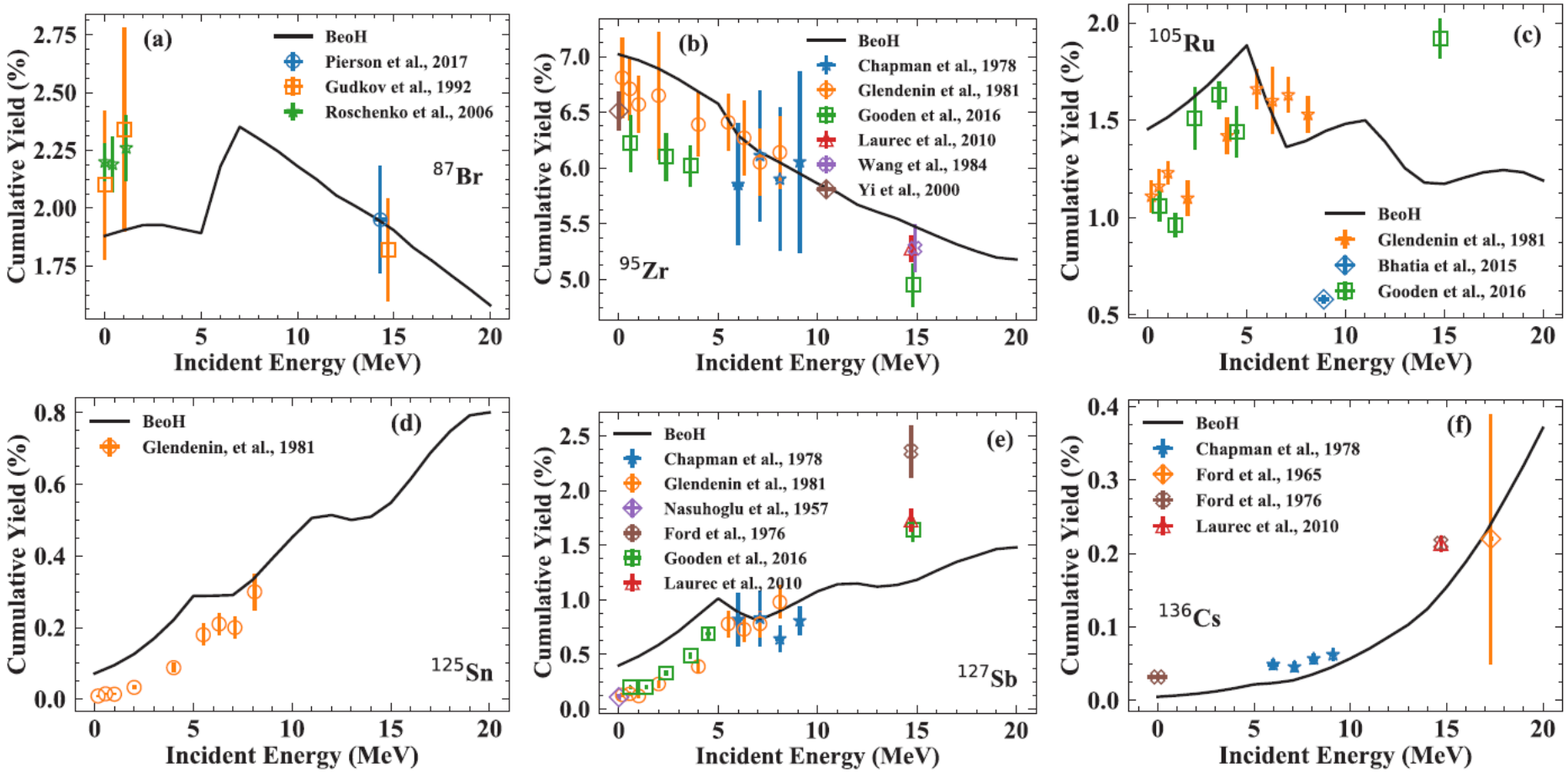
Chance fission probability in neutron-induced fission of ^{235}U



Even neutron-induced fission of ^{235}U, competition between fission and neutron evaporation are differently evaluated.

Yields of fission products evaluated using multichance fission

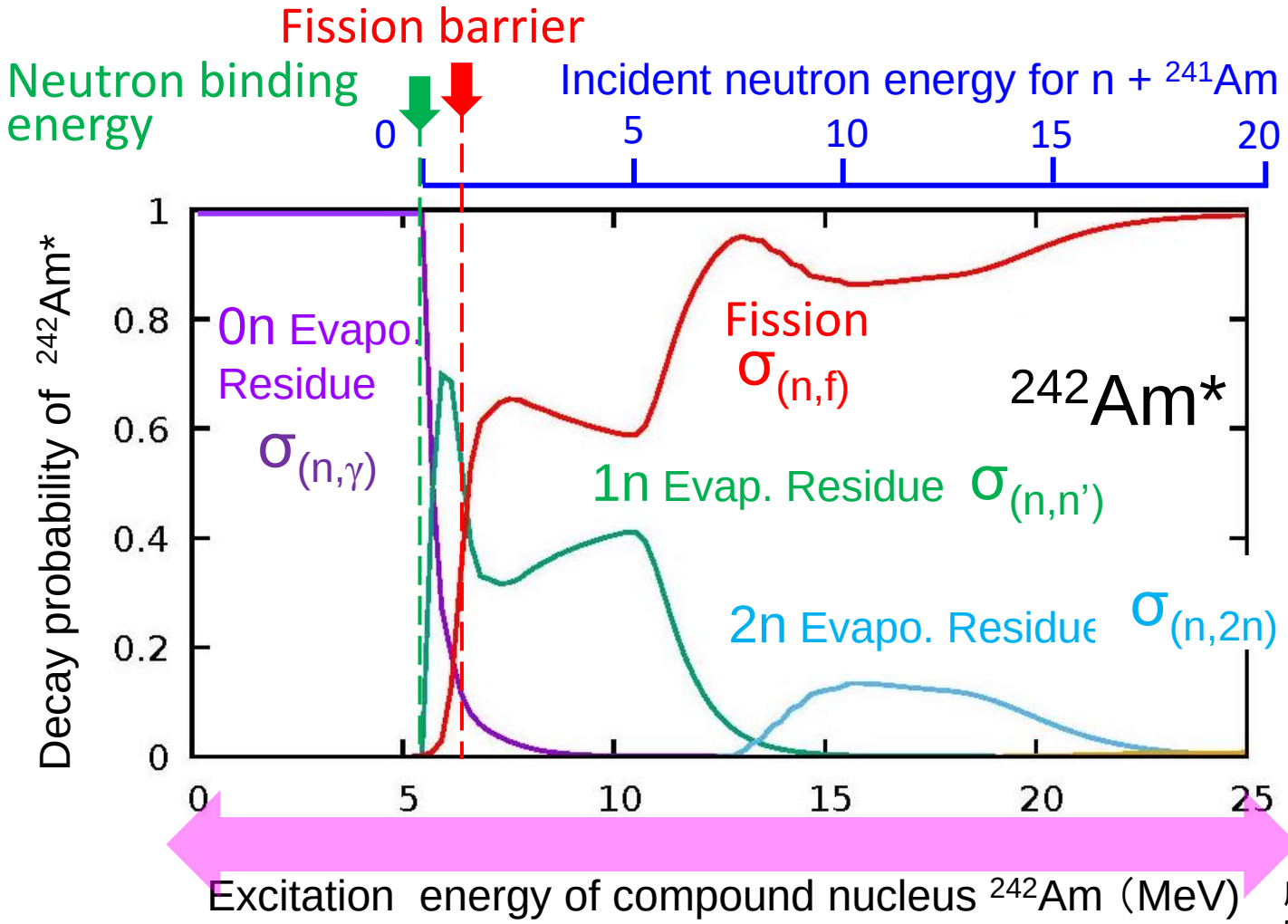
Fission product yields are largely changed by introducing multichance fission,



A.E. Lovell et al., Phys. Rev. C **103**, 014615 (2021).

Decay of compound nucleus

To determine chance fission probabilities, we will measure probabilities to produce evaporation residues for each neutron emission channel



$$P_f(E^*)+P_{0n}(E^*)+P_{1n}(E^*)+P_{2n}(E^*)=1$$

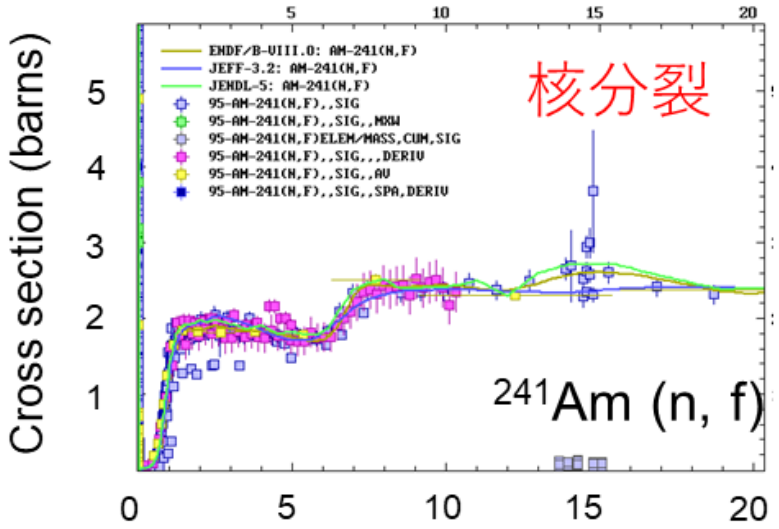
Calculation using CCONE code
(calculated by O. Iwamoto)

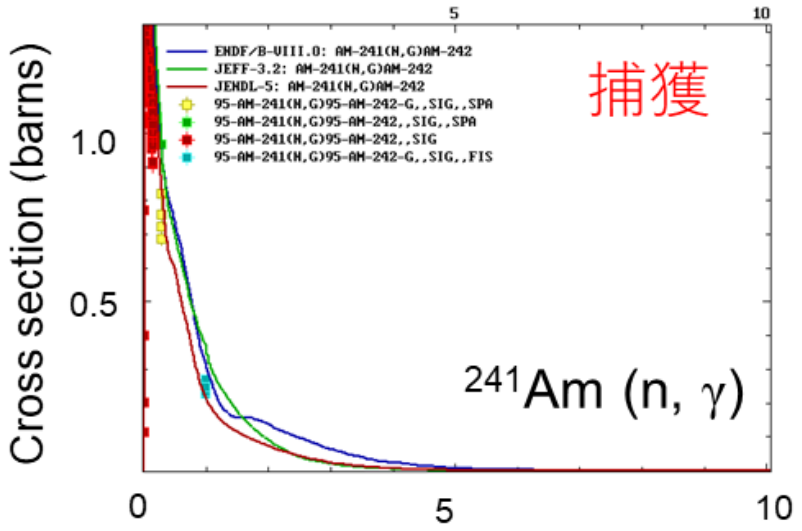
Transfer reactions
^{243}Am(^{3}He,^{4}He)^{242}Am*

原子力システム研究開発事業R5-R7
R5-R7 高エネルギー中性子核データ高度化のための複合核崩壊過程の研究

Simultaneous measurement of neutron induced cross sections

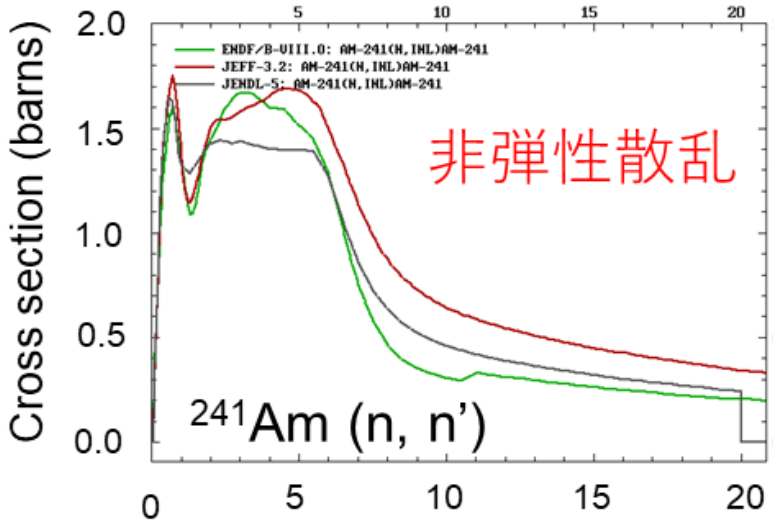
$P_f(E^*)$

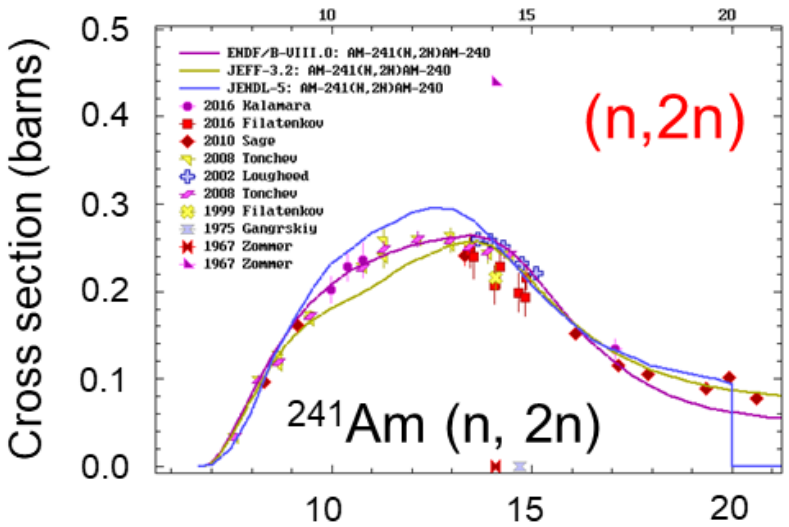




$P_{0n}(E^*)$

$P_{1n}(E^*)$



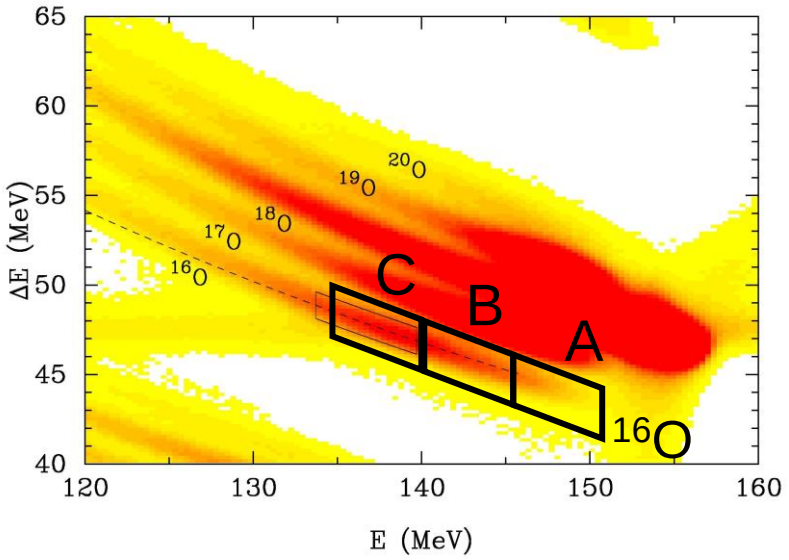


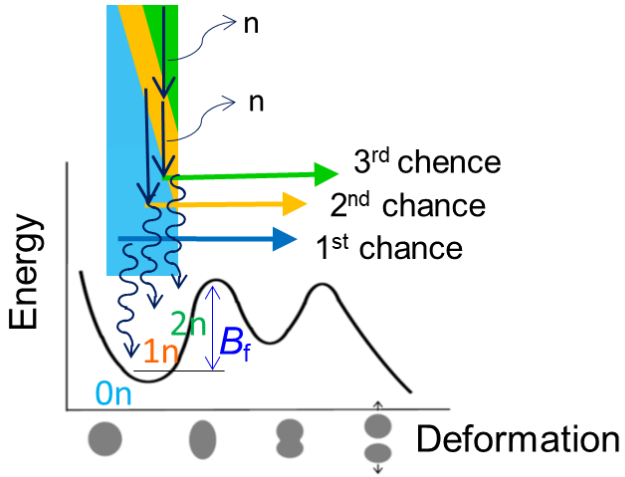
$P_{2n}(E^*)$

Neutron energy (MeV)

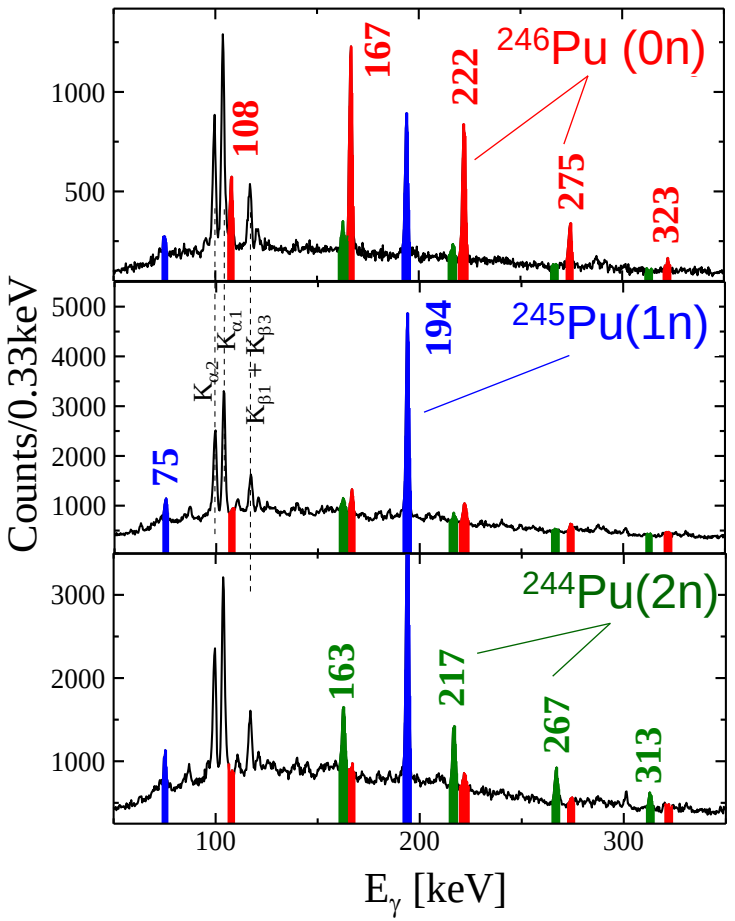
Identification of evaporation residues in γ–ray measurement

$^{18}O + {}^{244}Pu \rightarrow {}^{16}O + {}^{246}Pu^*$





γ-ray spectrum



Excitation energy of $^{246}Pu^*$

0 - 6 MeV

A

6 - 12 MeV

B

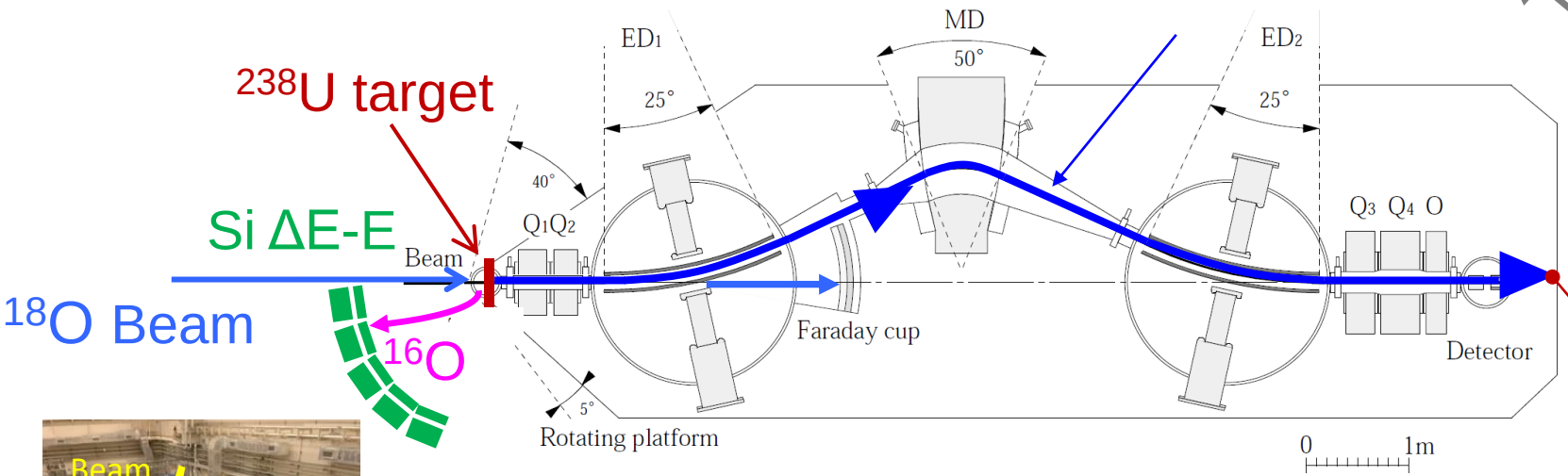
12 - 18 MeV

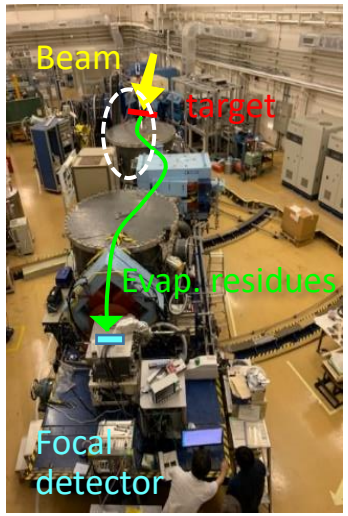
C

H. Makii et al., Phys. Rev. C **76**, 061301(R) (2007).

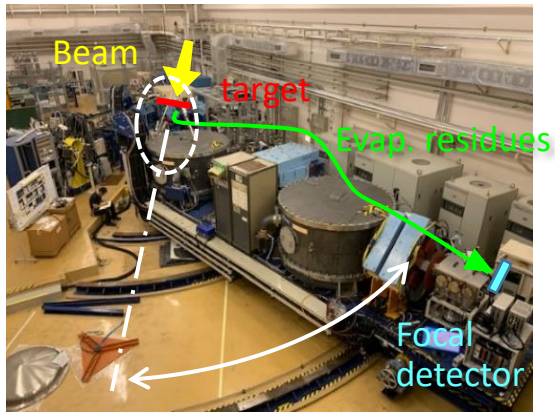
Detection of evaporation residues produced in MNT reactions using JAEA Recoil Mass Separator (RMS)

$^{18}O + {}^{238}U \rightarrow {}^{16}O + {}^{240}U^* \rightarrow$ Evaporation residues $^{240}U(0n), {}^{239}U(1n), {}^{238}U(2n)$





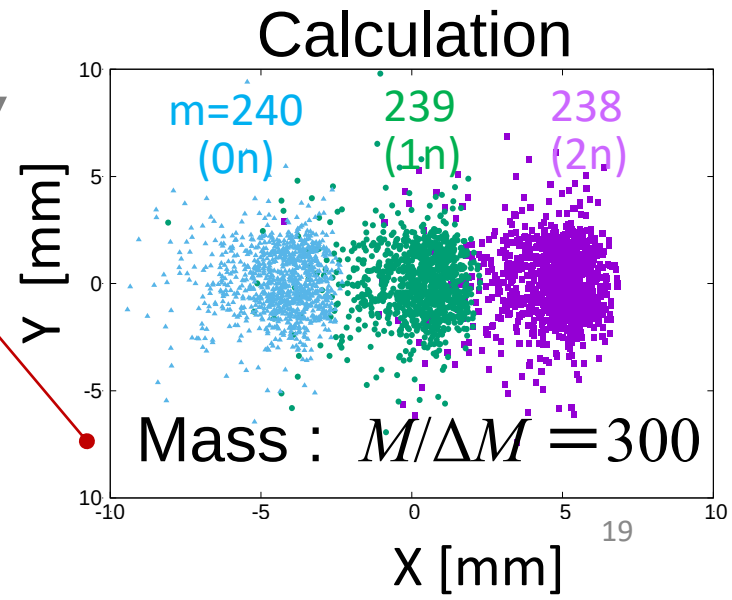
$\Theta = 0^\circ$



$\Theta = 40^\circ$

RMS Rotation angle

$\Theta_{max} = 40^\circ$

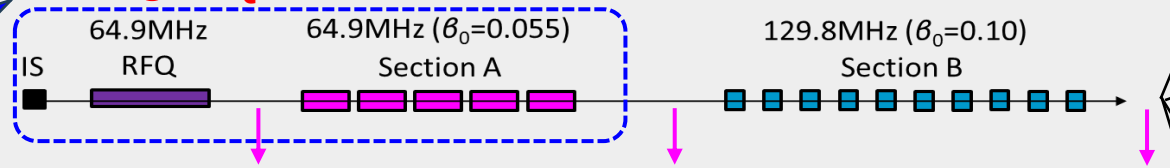


Plan of Post-Tandem Accelerator

文科省ロードマップ2023
「大強度重イオンビームが先導する量子科学フロンティア」

タンデムを
置き換える

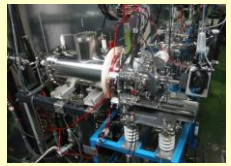
① イオン源
② RFQ
③ 超伝導空洞
④ ブースター加速器



新規開発　　既存

開発済の分離装置


反跳生成核分離装置


オンライン同位体分離装置


磁気スペクトロメータ

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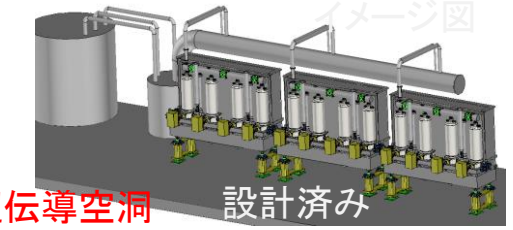
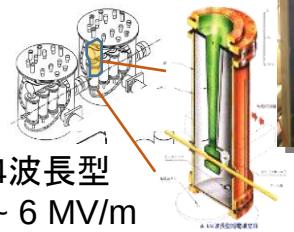
① イオン源

② RFQ

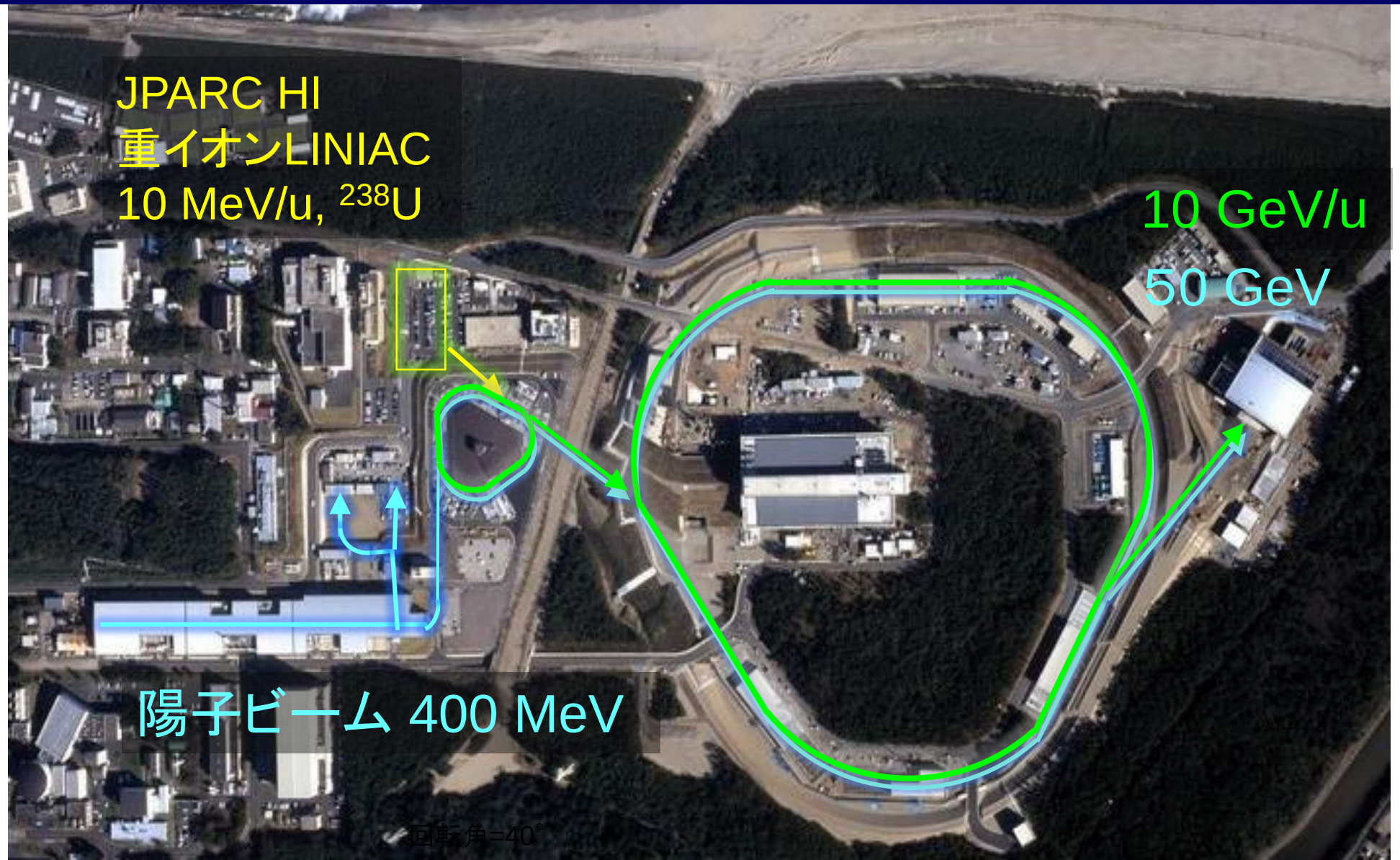


③ 超伝導空洞



1/4波長型
5 ~ 6 MV/m
日本初の超伝導線形加速器（1995年）

J-PARC HI
- Heavy-ion acceleration using J-PARC -



Summary

☑ Surrogate ratio method for fission cross sections

☑ Concept of multichance fission is well known, but the probabilities have not been precisely determined so far.

☑ Probability for each neutron-emission channel will be determined by γ-ray detection technique and direct recoiled-nucleus technique.

☑ Post tandem accelerator facility

Thak you