Perspectives of research and education in nuclear data after Fukushima

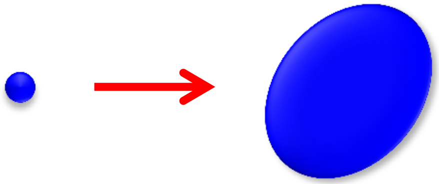
Satoshi Chiba
Tokyo Institute of Technology
chiba.satoshi@nr.titech.ac.jp

Contents

Background

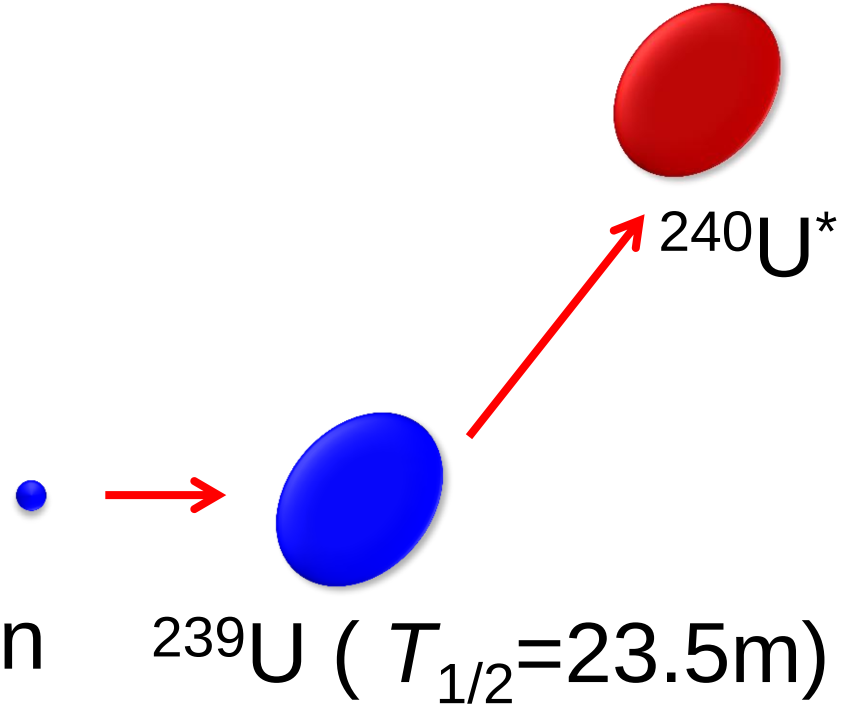
- All the nuclear power stations have been shut down in Japan after Fukushima accident
- Future of nuclear energy became unclear in Japan --> only strongly-motivated students enter to school of nuclear engineering
- Nuclear data field serves to absorb those who are interested in basic phenomena: in general they are one of the best students
- We must provide attractive subjects to those motivated young students : are we scientific enough?
- Some of our current studies (on fission-related subjects) are presented, and scope for future directions will be given

S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U

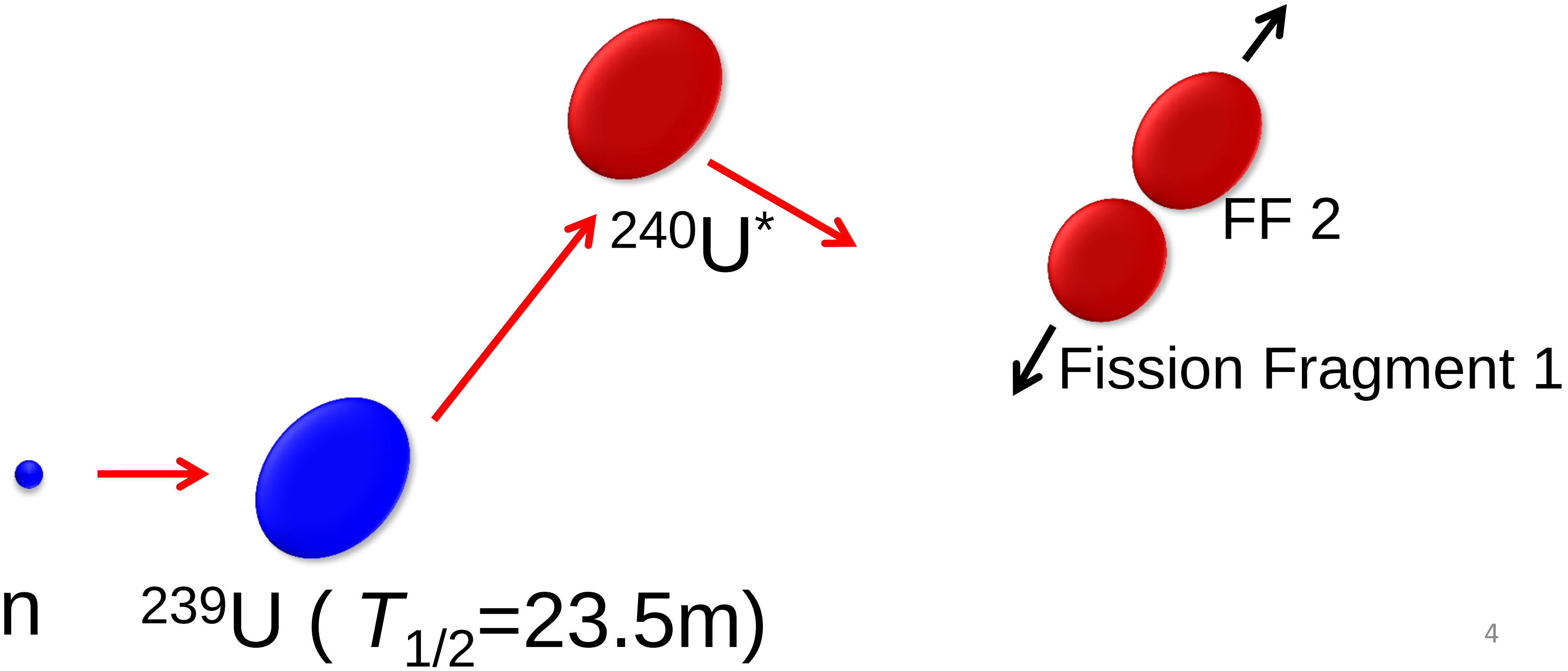


n ^{239}U ($T_{1/2}$=23.5m)

S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U



S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U



^{240}U*

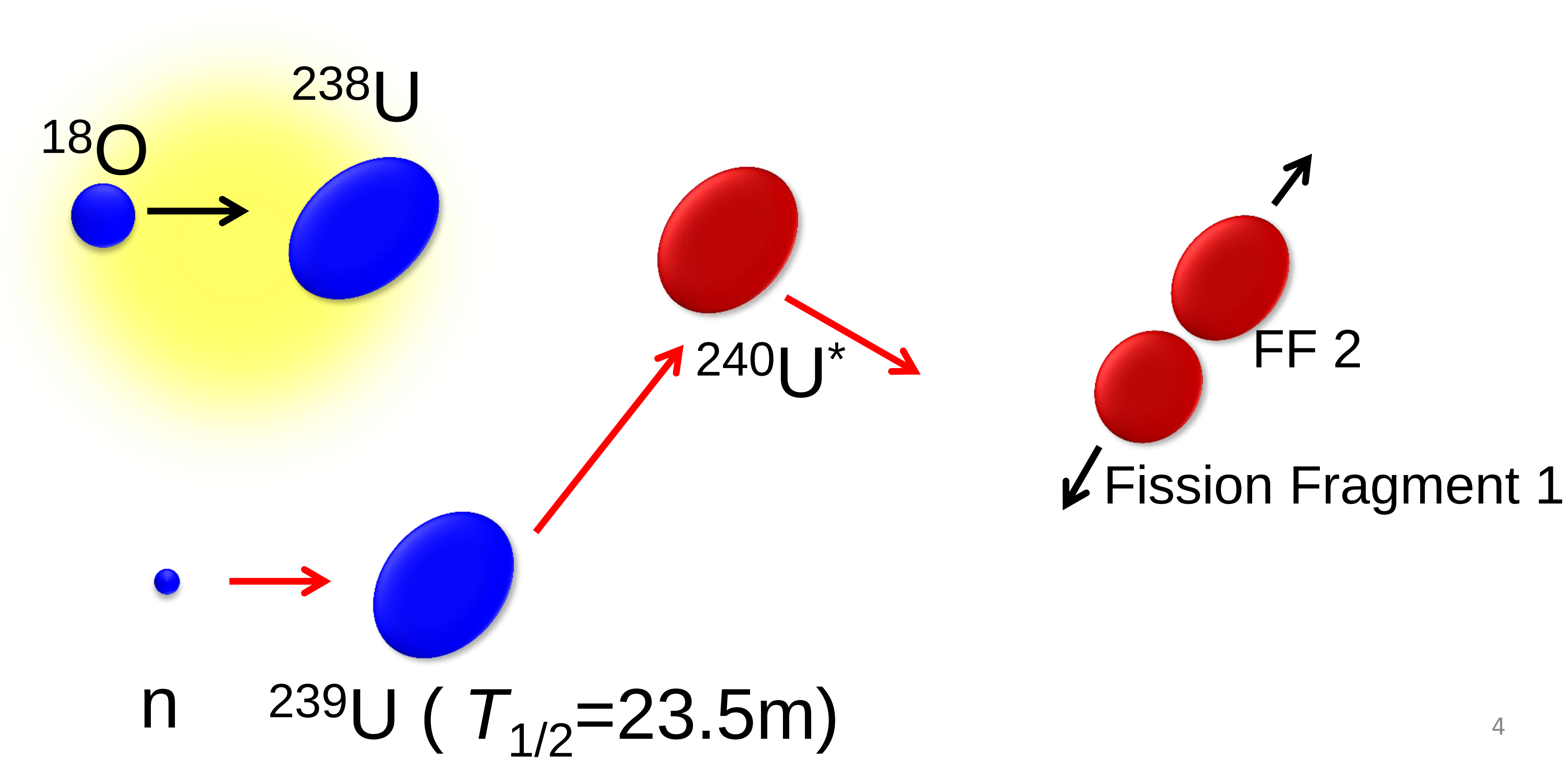
FF 2

Fission Fragment 1

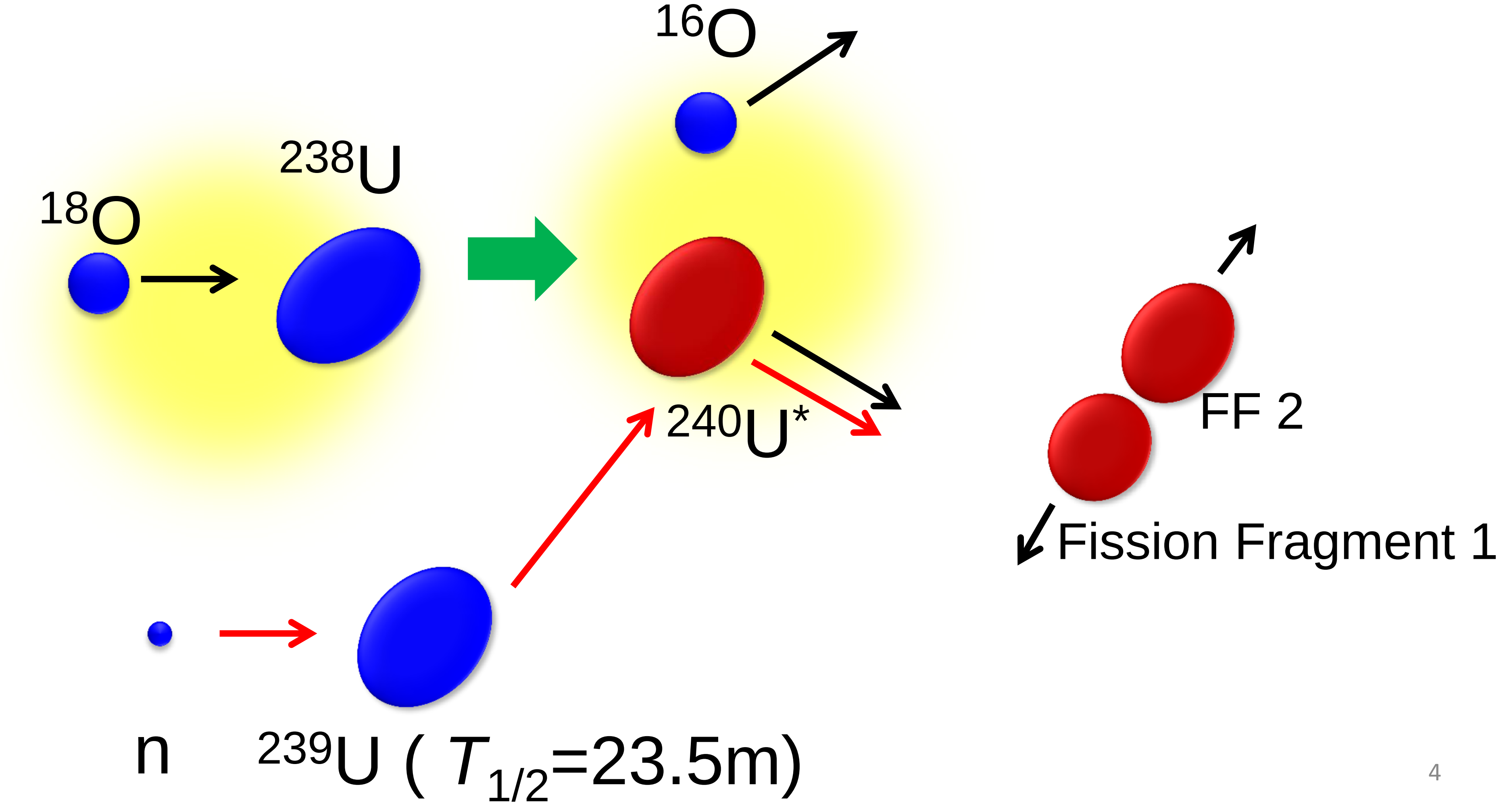
n

^{239}U ($T_{1/2}$=23.5m)

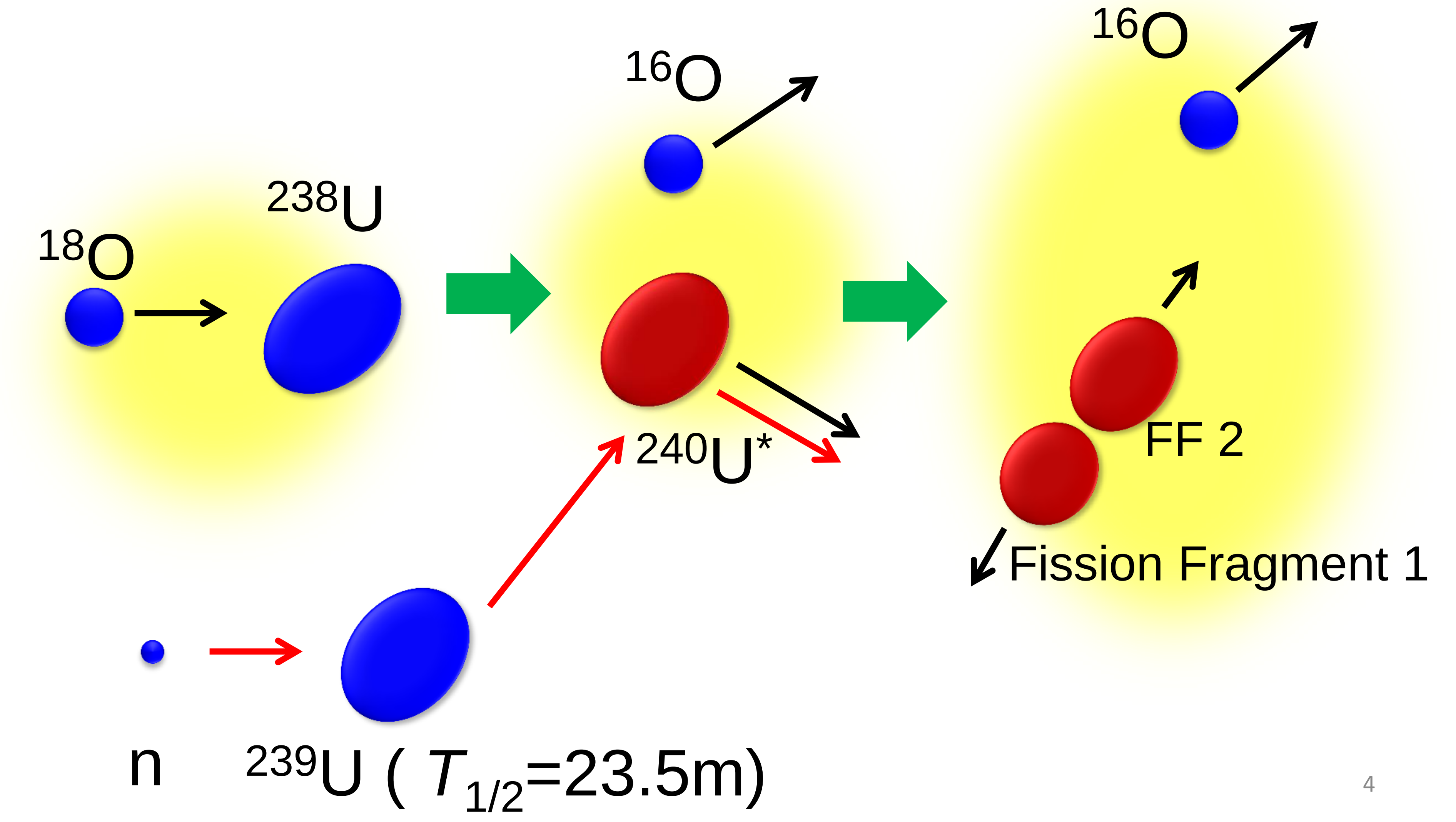
S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U



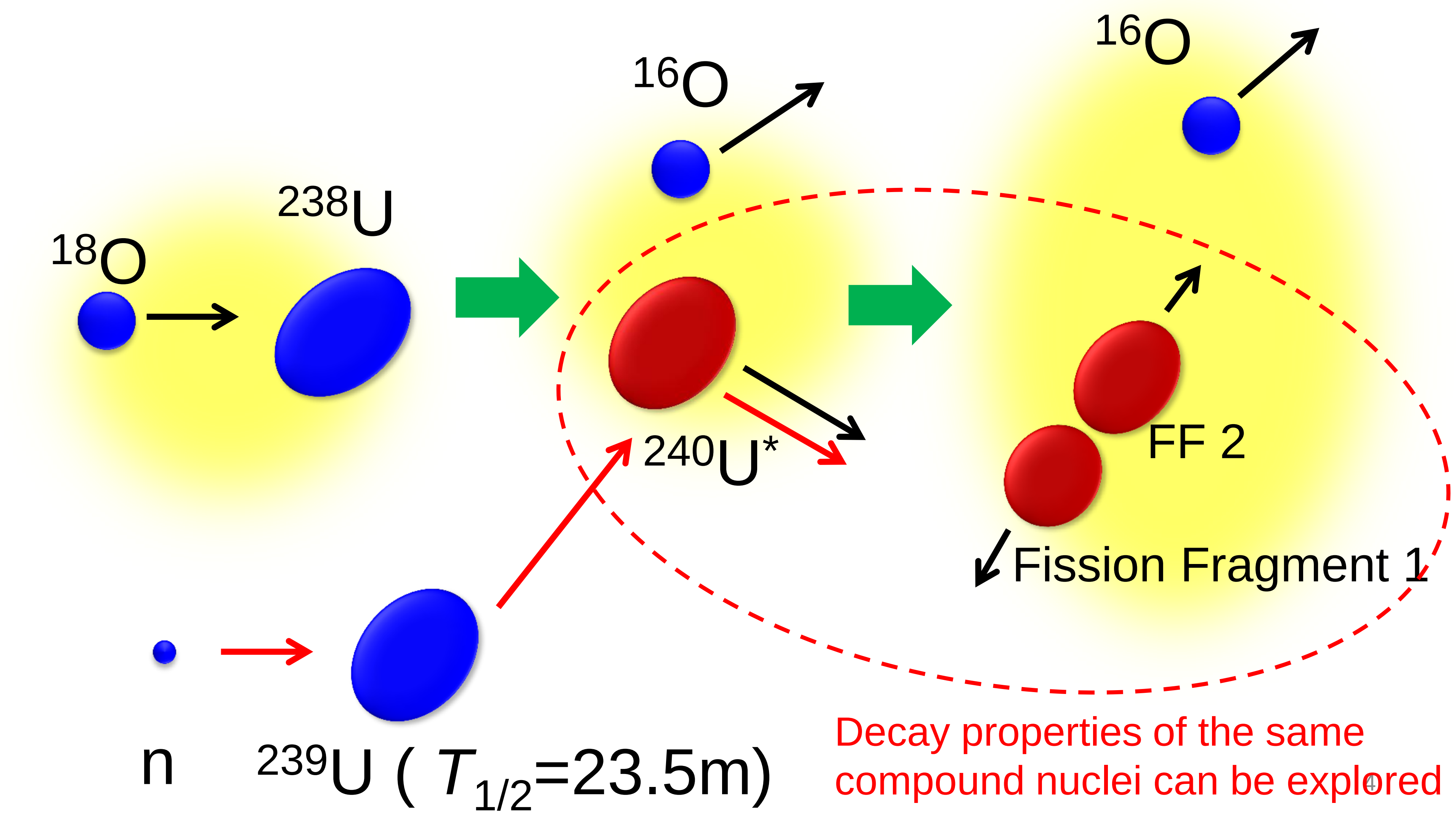
S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U



S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U

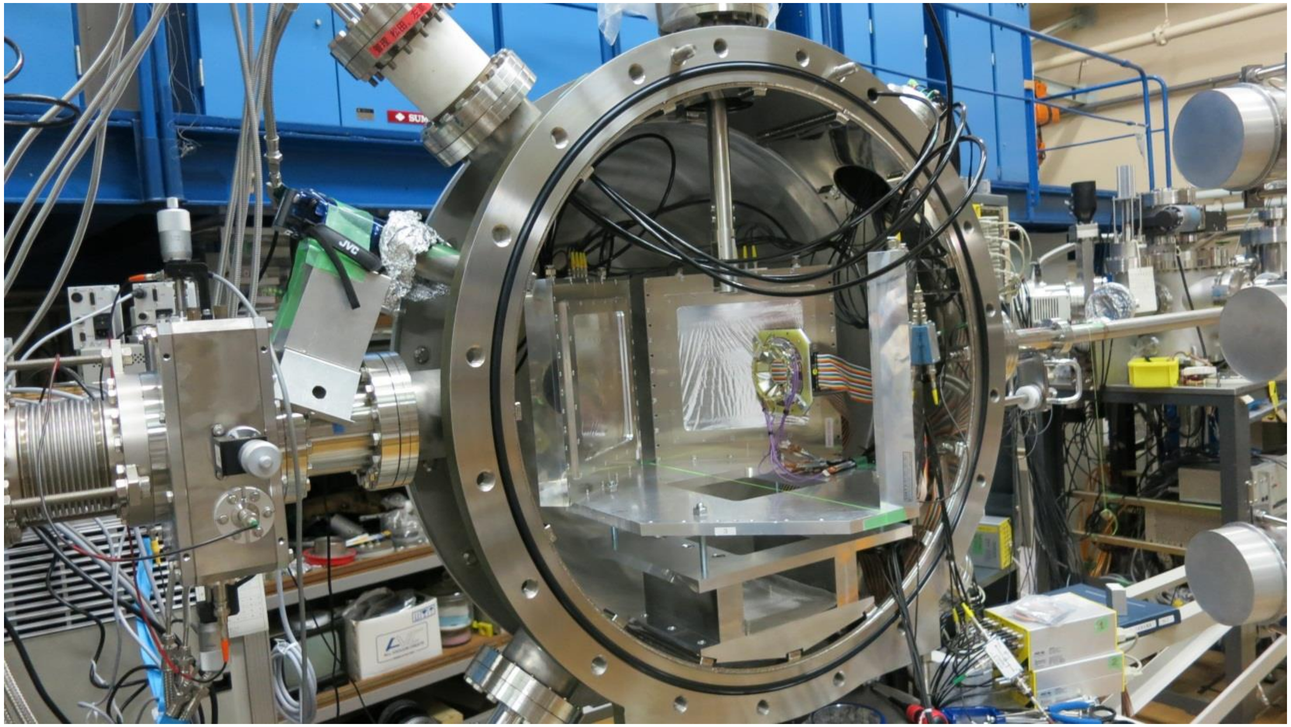


S.M. with heavy projectile : Desired neutron reaction (ex. n + ^{239}U) and its surrogate reaction ^{238}U(^{18}O,^{16}O)^{240}U

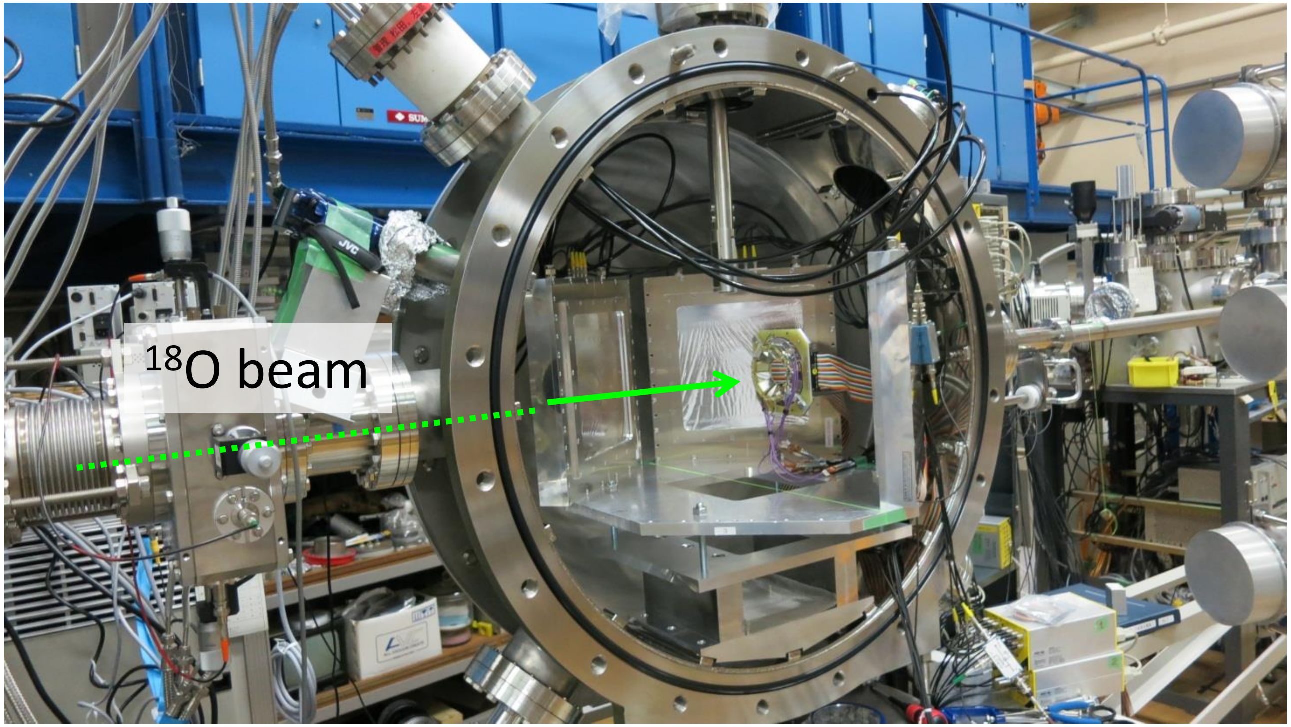


Decay properties of the same compound nuclei can be explored

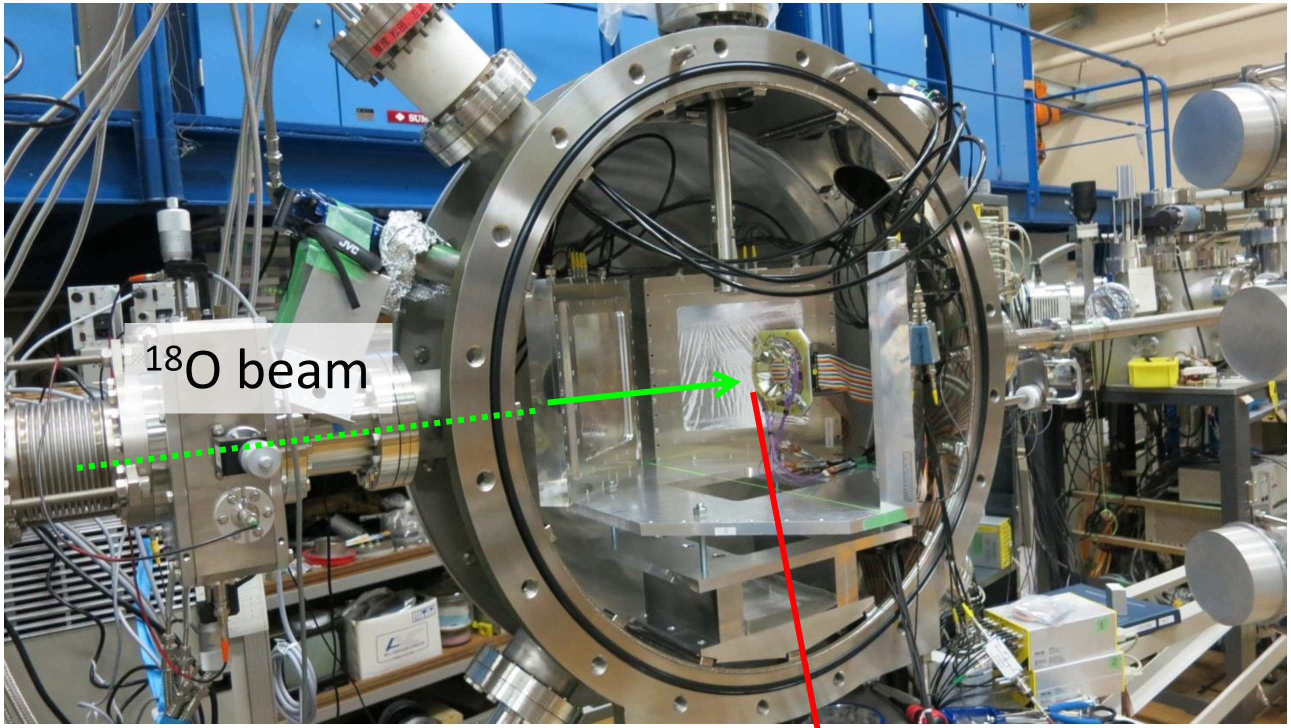
Fission Setup

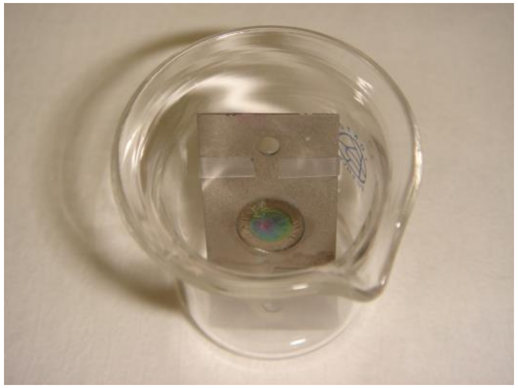


Fission Setup



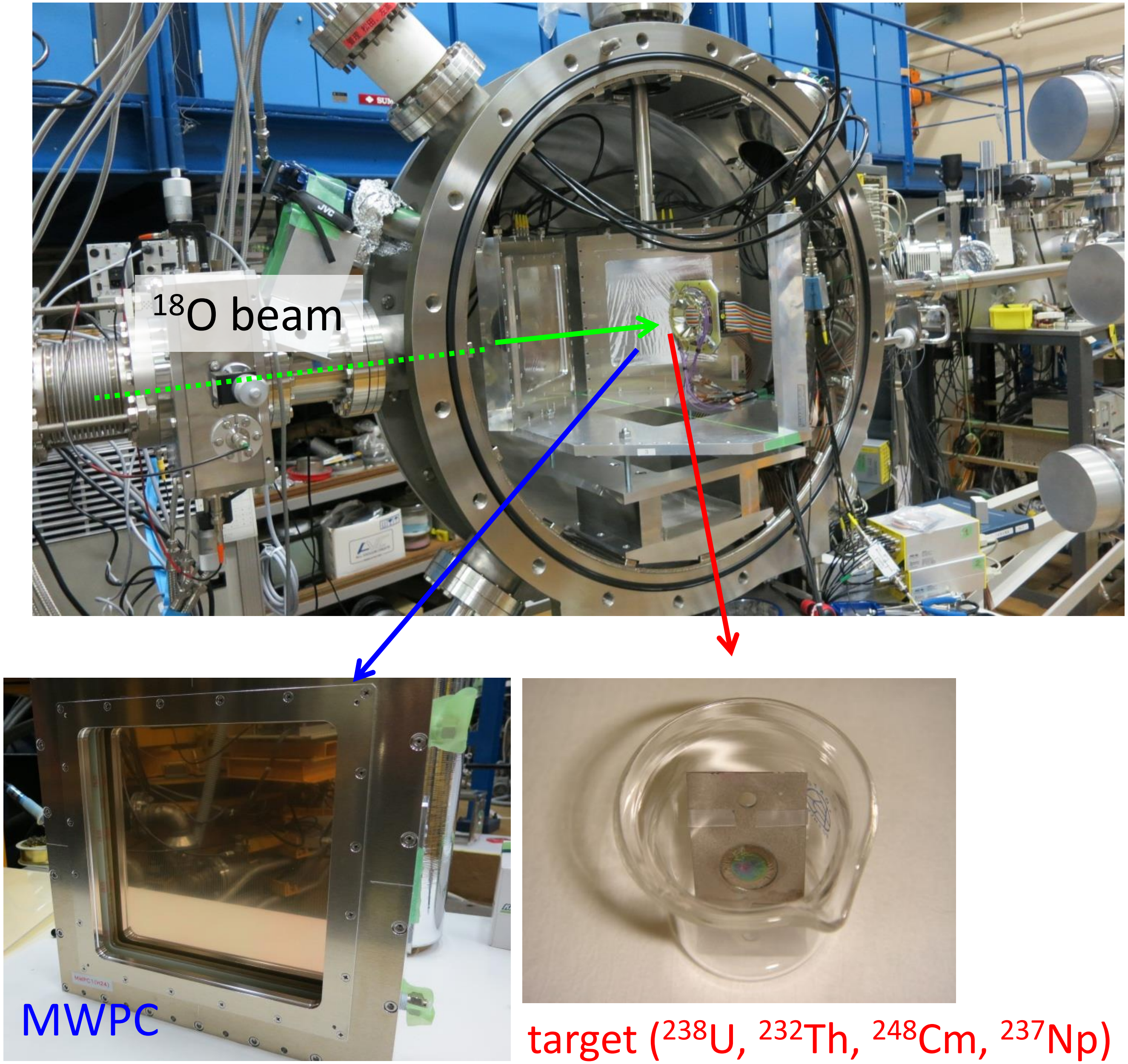
Fission Setup





target (^{238}U, ^{232}Th, ^{248}Cm, ^{237}Np)

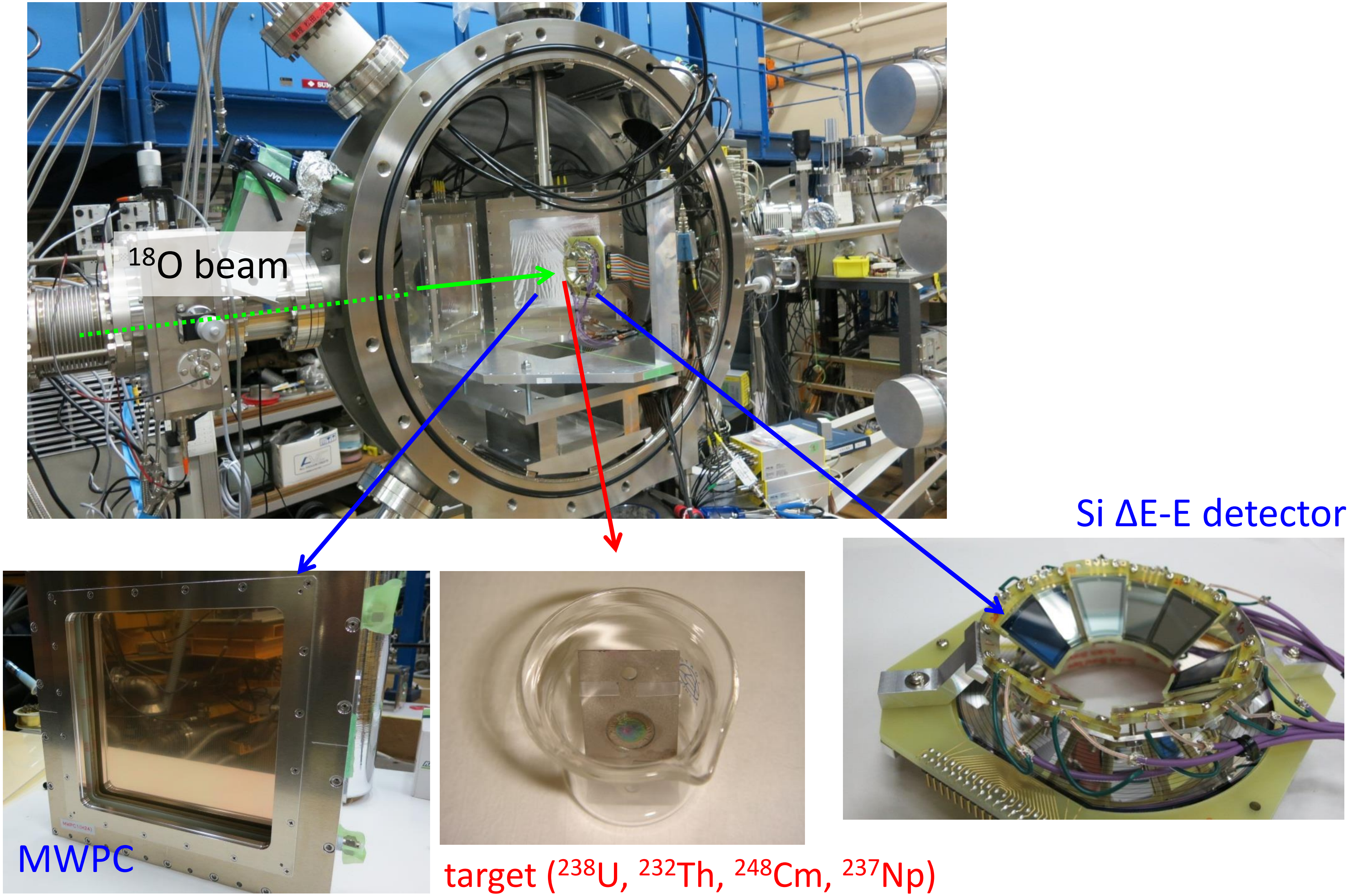
Fission Setup



MWPC

target (^{238}U, ^{232}Th, ^{248}Cm, ^{237}Np)

Fission Setup



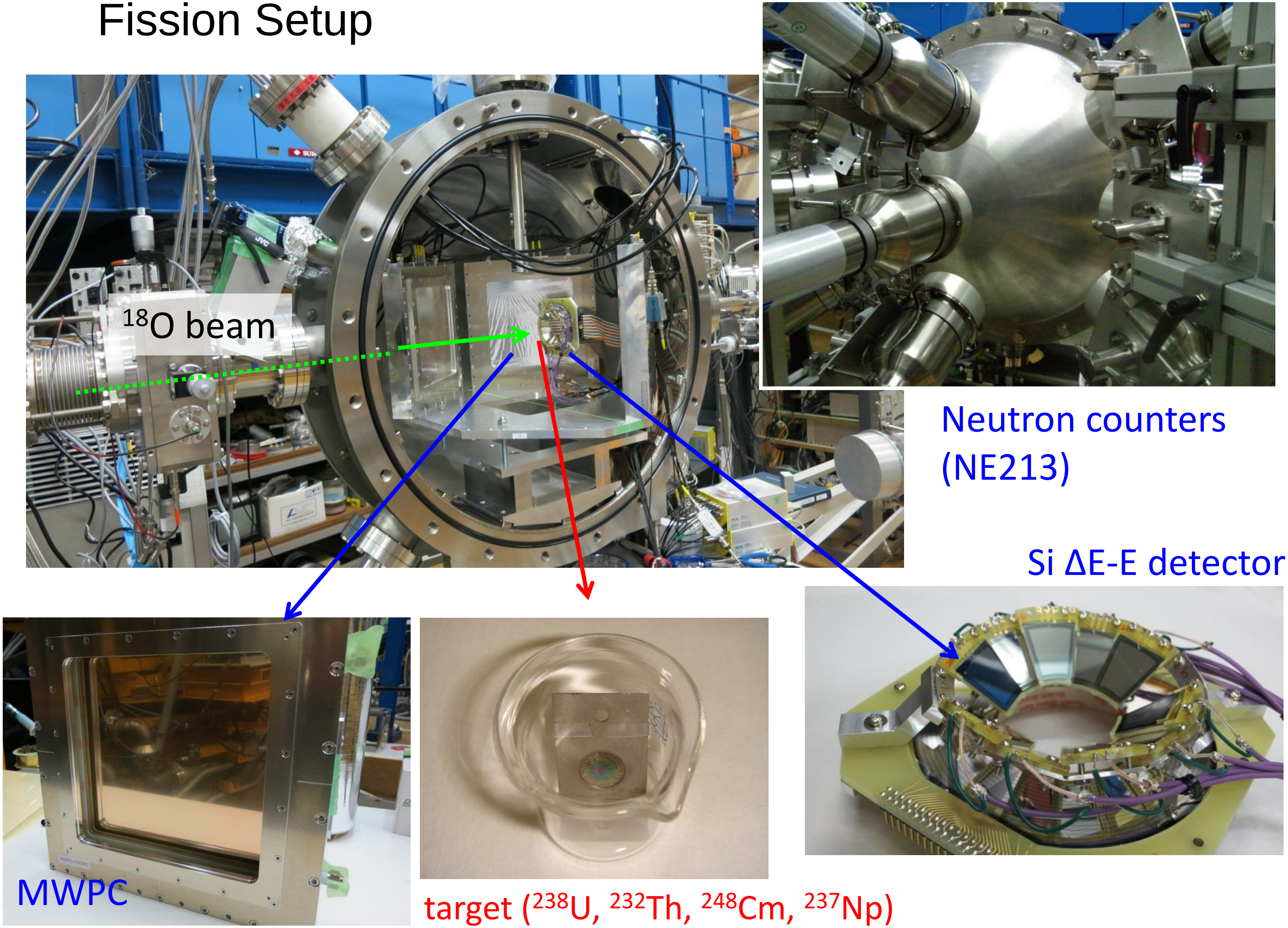
^{18}O beam

Si ΔE-E detector

MWPC

target (^{238}U, ^{232}Th, ^{248}Cm, ^{237}Np)

Fission Setup



^{18}O beam

Neutron counters (NE213)

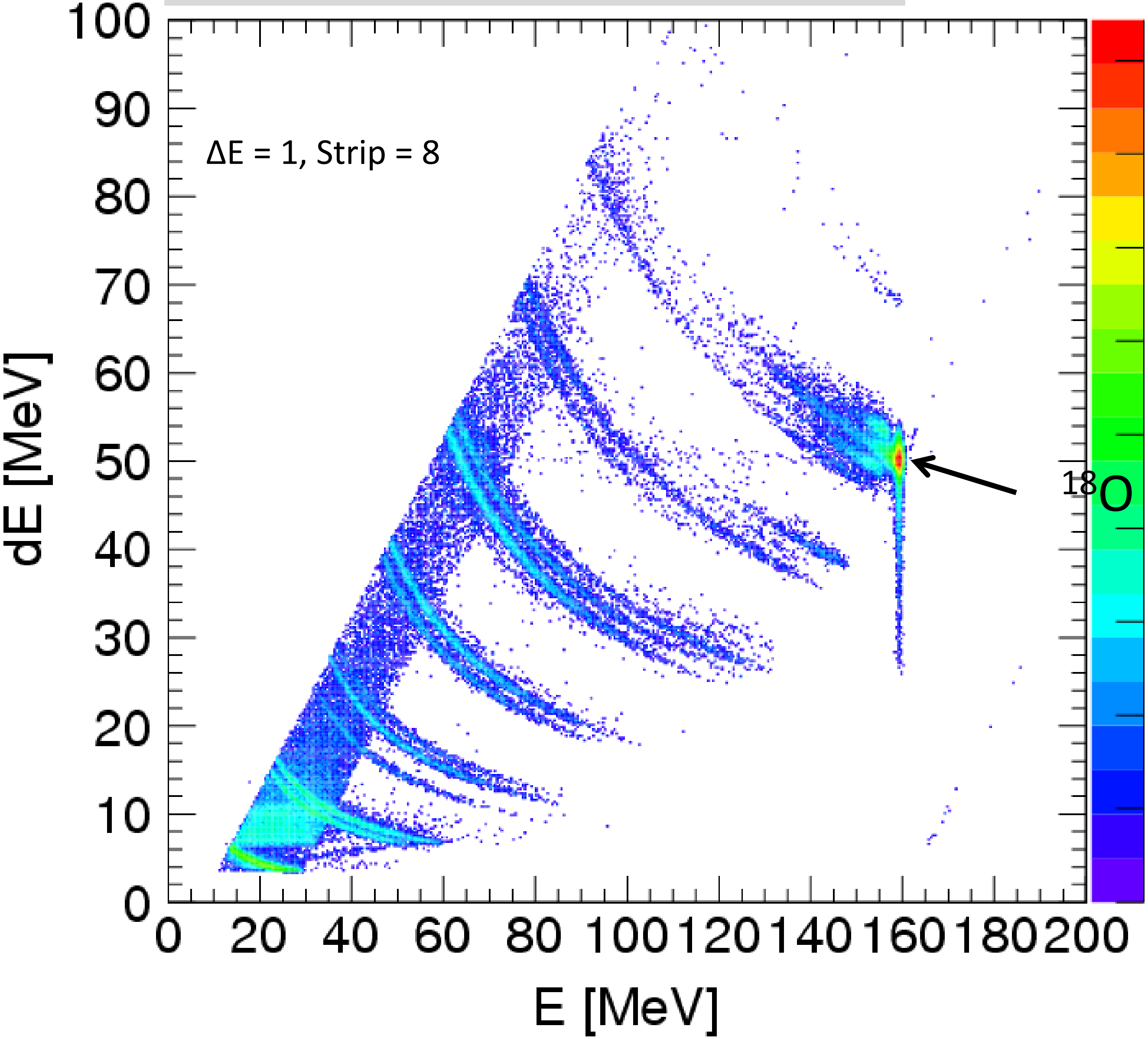
Si ΔE-E detector

MWPC

target (^{238}U, ^{232}Th, ^{248}Cm, ^{237}Np)

Spectra of projectile-like ejectiles measured by the ΔE-E detector

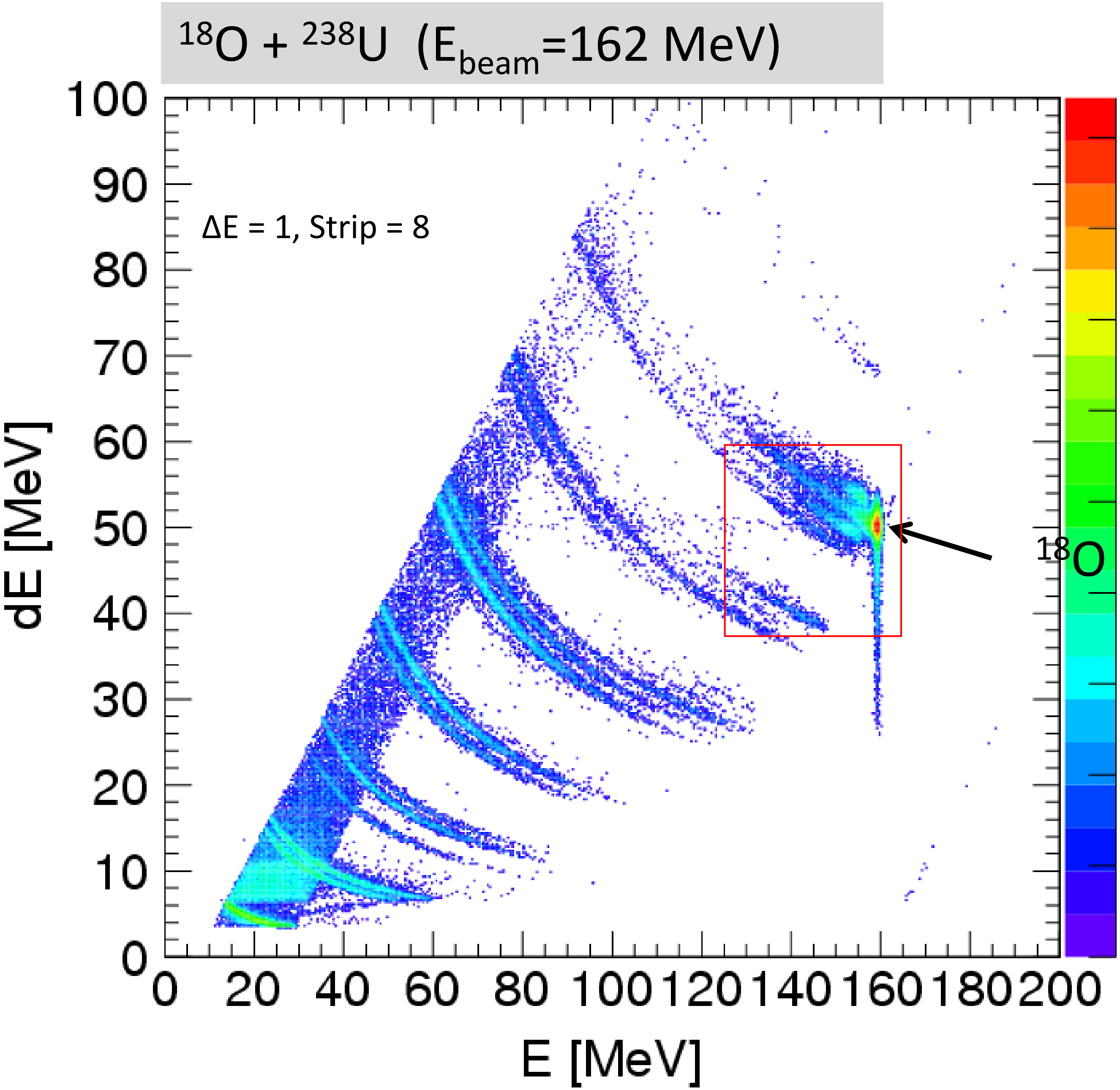
$^{18}O + ^{238}U$ (E_{beam}=162 MeV)



900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

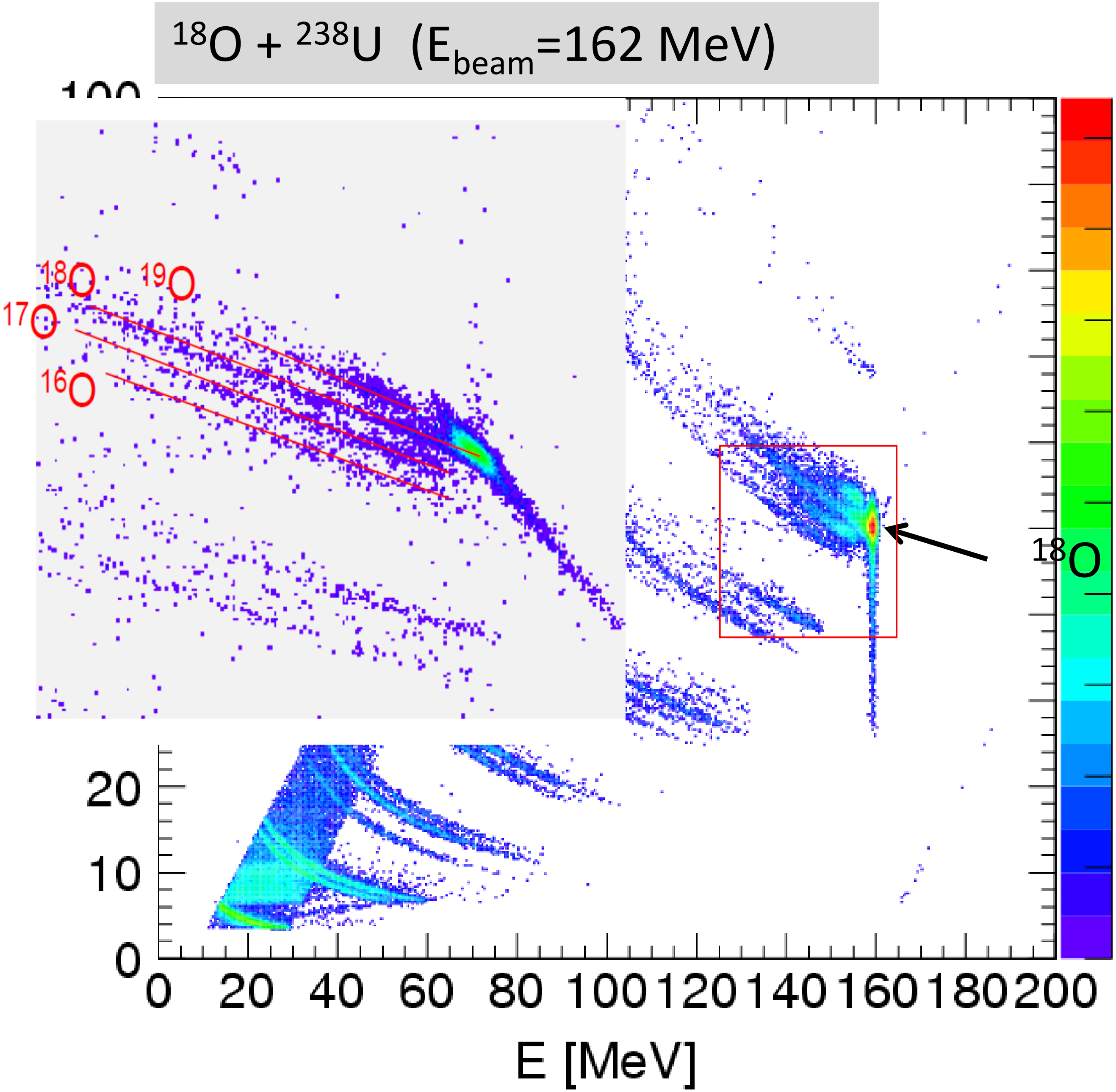
Spectra of projectile-like ejectiles measured by the ΔE-E detector



900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

Spectra of projectile-like ejectiles measured by the ΔE-E detector

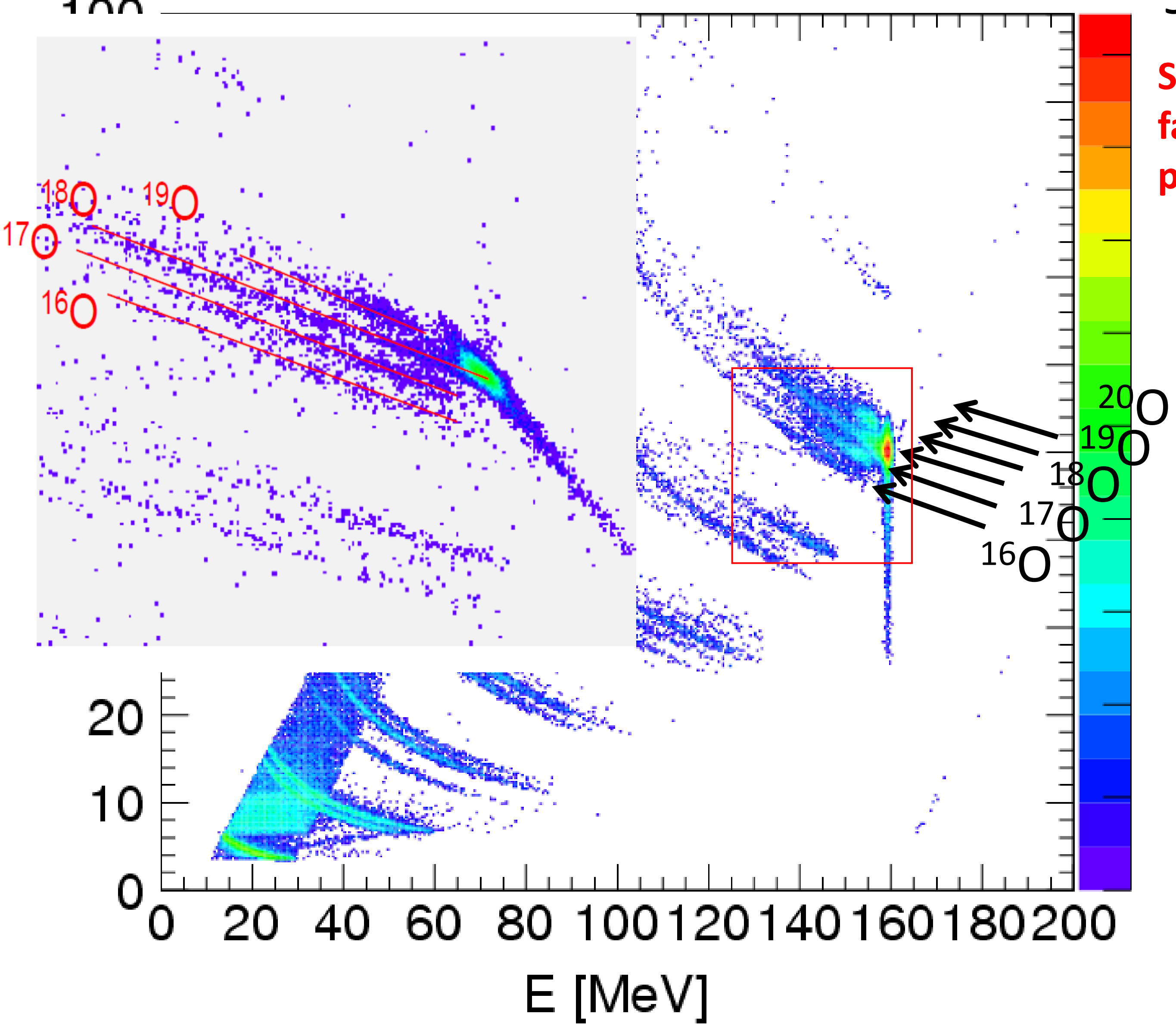


900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

Spectra of projectile-like ejectiles measured by the ΔE-E detector

$^{18}O + ^{238}U$ (E_{beam}=162 MeV)



900 keV (FWHM)

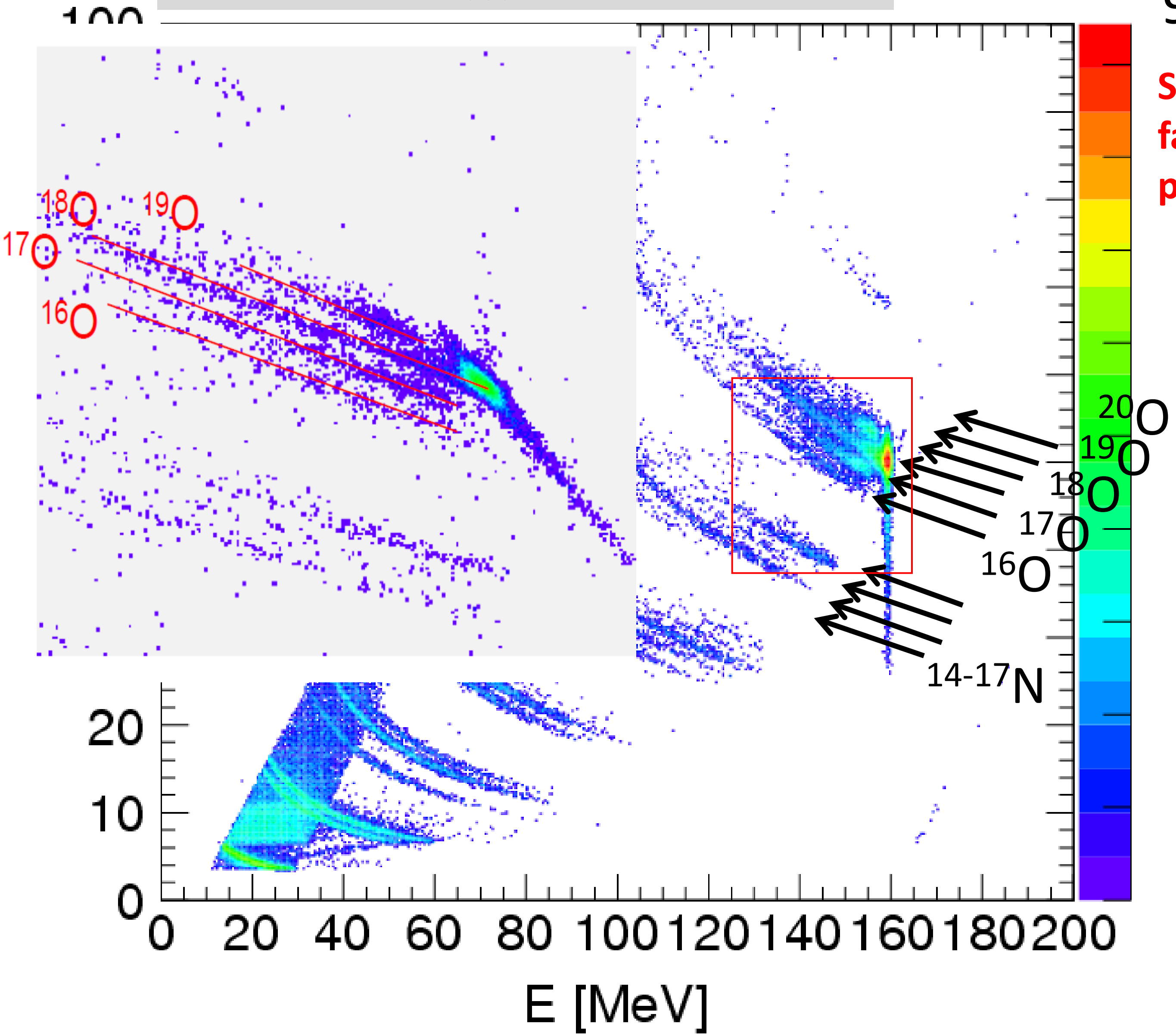
Stripping reactions are favored significantly than pick-up reactions!!

Spectra of projectile-like ejectiles measured by the ΔE-E detector

$^{18}O + ^{238}U$ (E_{beam}=162 MeV)

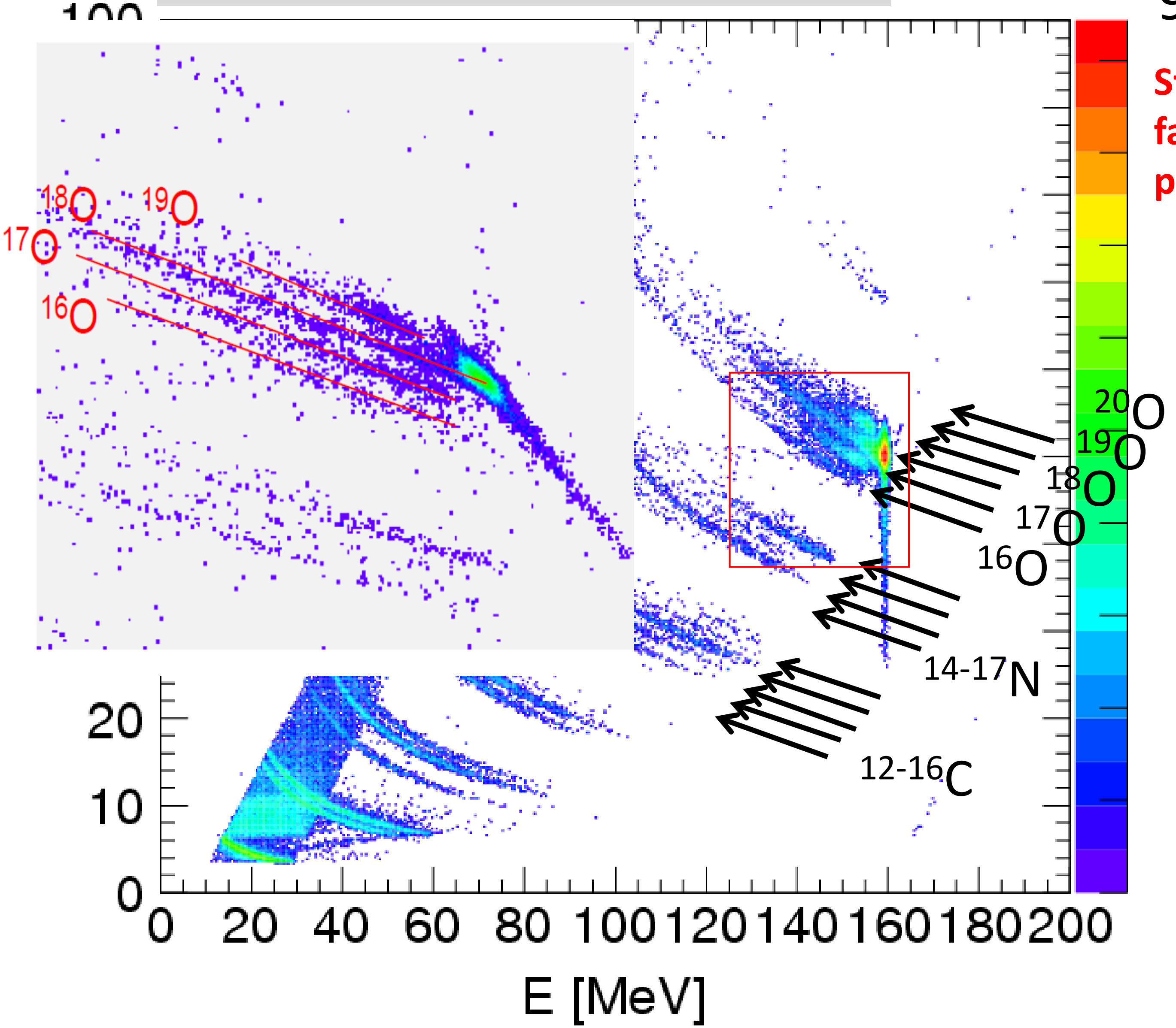
900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!



Spectra of projectile-like ejectiles measured by the ΔE-E detector

$^{18}O + ^{238}U$ (E_{beam}=162 MeV)

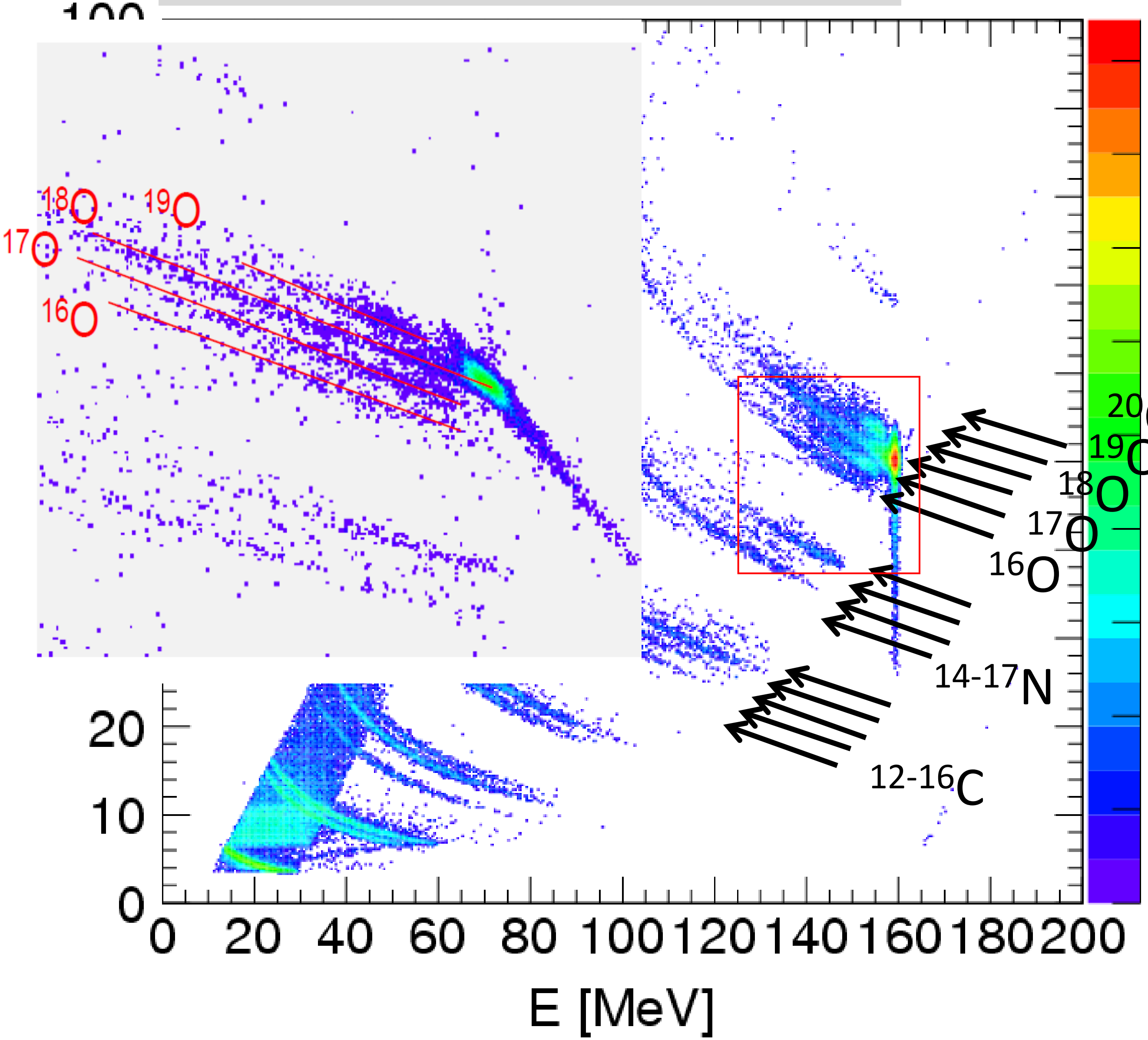


900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

Spectra of projectile-like ejectiles measured by the ΔE-E detector

^{18}O + ^{238}U (E$_{beam}$=162 MeV)



900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

^{240,239,238,237}U*

n + ^{239}U (23.5 min)
n + ^{237}U (6.8 day)

^{242,241,240,239}Np*

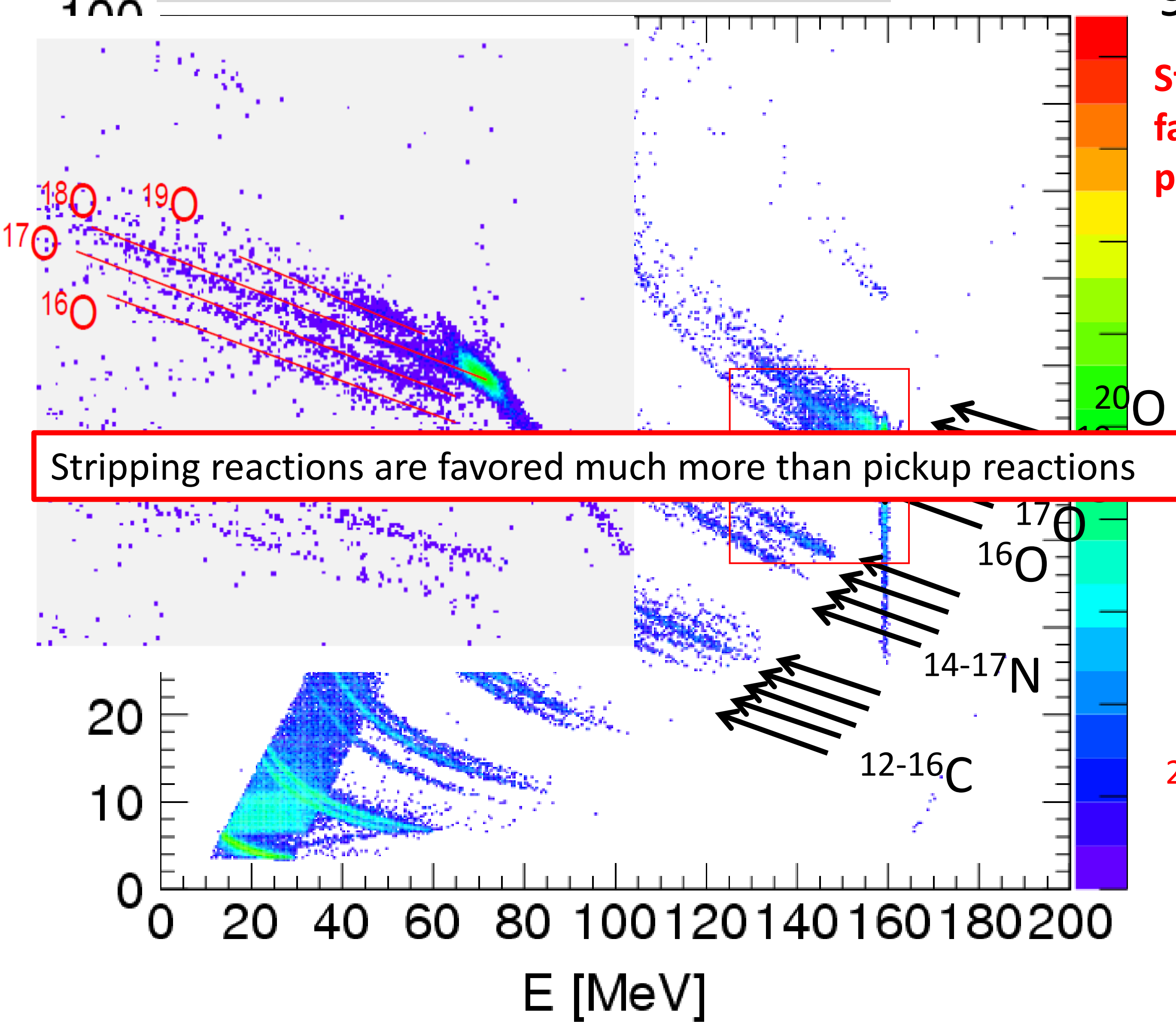
n + ^{241}Np (13.9 min)
n + ^{240}Np (65 min)
n + ^{239}Np (2.4 day)
n + ^{238}Np (2.1 day)

^{244,243,242,241,240}Pu*

n + ^{243}Pu (4.9 hr)
n + ^{241}Pu (14 yr)

Spectra of projectile-like ejectiles measured by the ΔE-E detector

$^{18}O + ^{238}U$ (E_{beam}=162 MeV)



Stripping reactions are favored much more than pickup reactions

900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!

$^{240,239,238,237}U^*$

n + ^{239}U (23.5 min)
n + ^{237}U (6.8 day)

$^{242,241,240,239}Np^*$

n + ^{241}Np (13.9 min)
n + ^{240}Np (65 min)
n + ^{239}Np (2.4 day)
n + ^{238}Np (2.1 day)

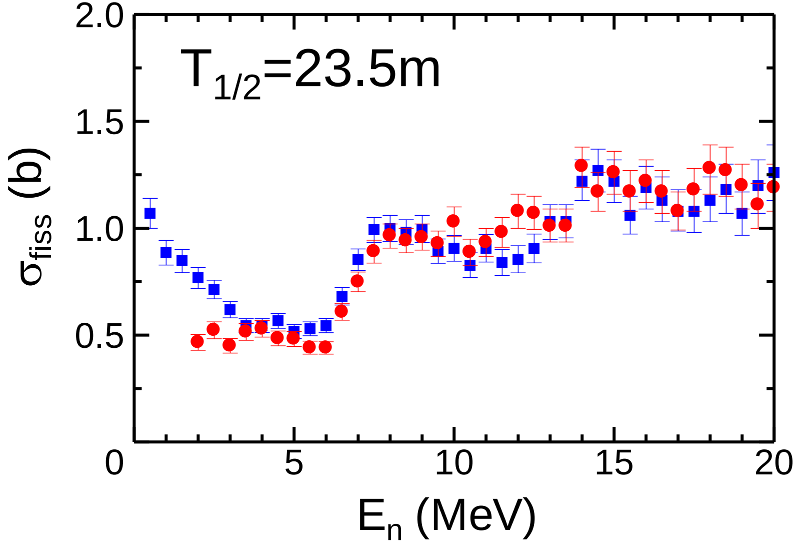
$^{244,243,242,241,240}Pu^*$

n + ^{243}Pu (4.9 hr)
n + ^{241}Pu (14 yr)

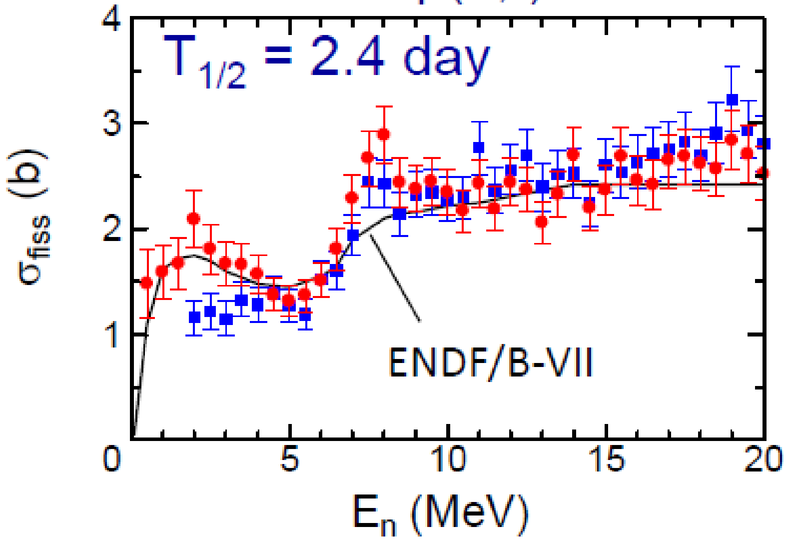
Some preliminary results on (n,f) reactions

ND2013

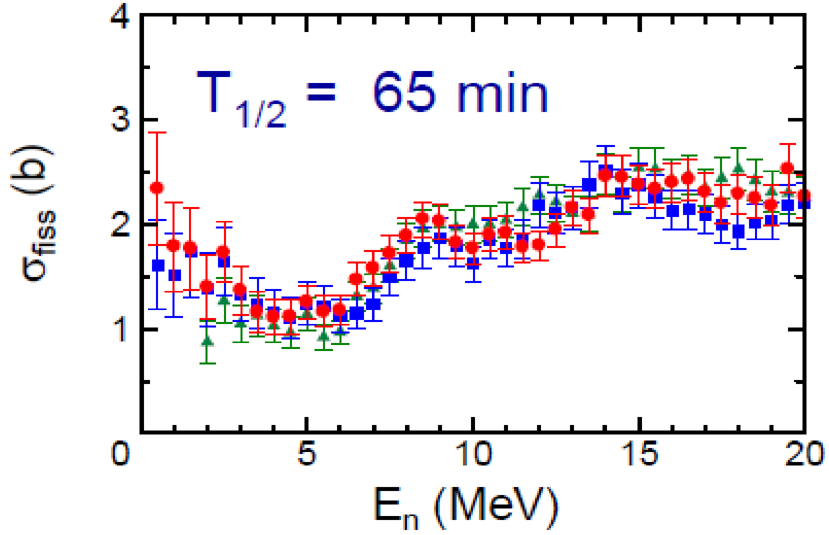
^{239}U(n,f)



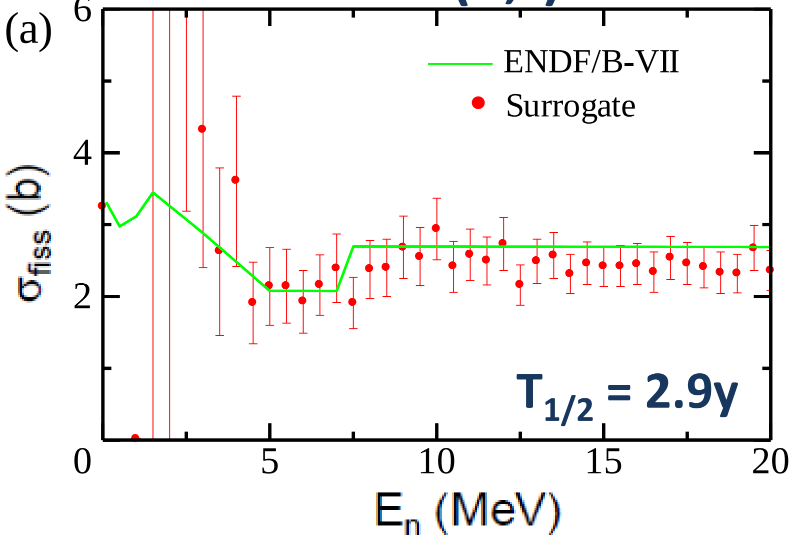
^{239}Np(n,f)



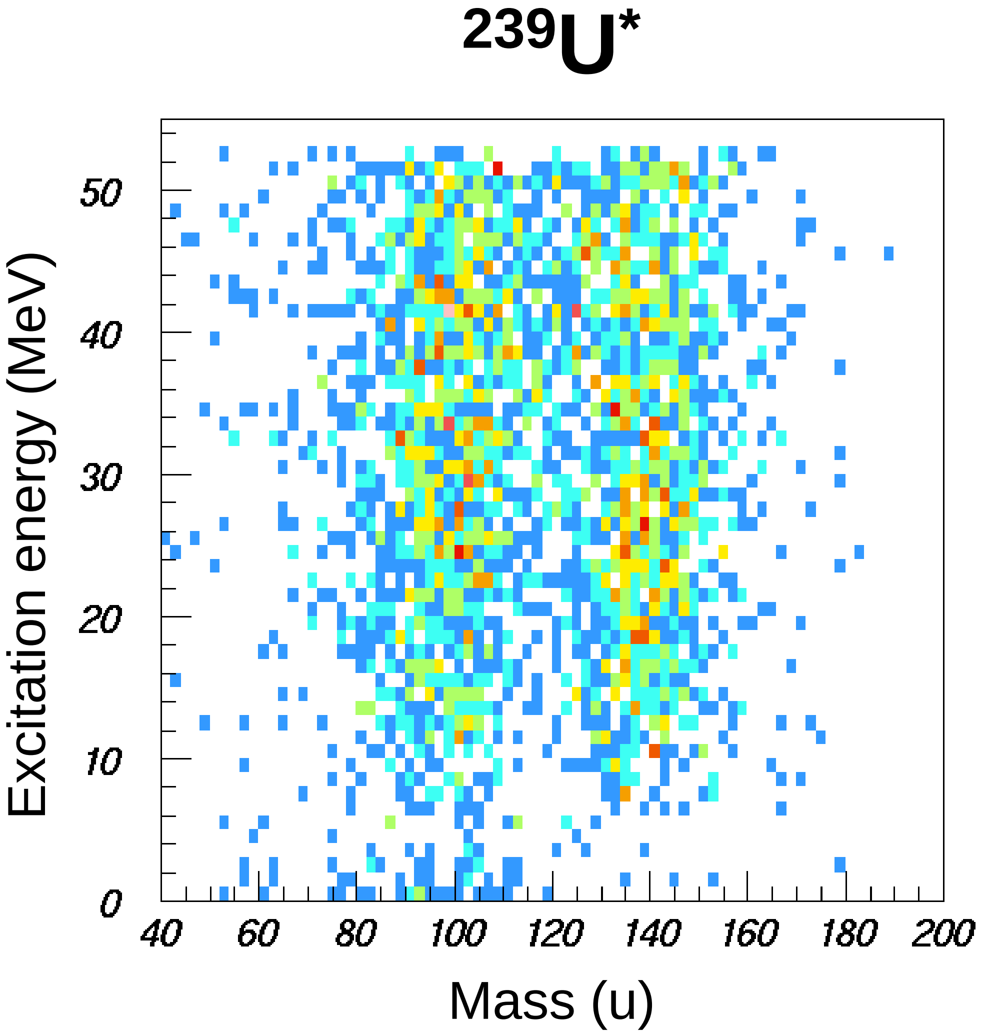
^{240}Np(n,f)



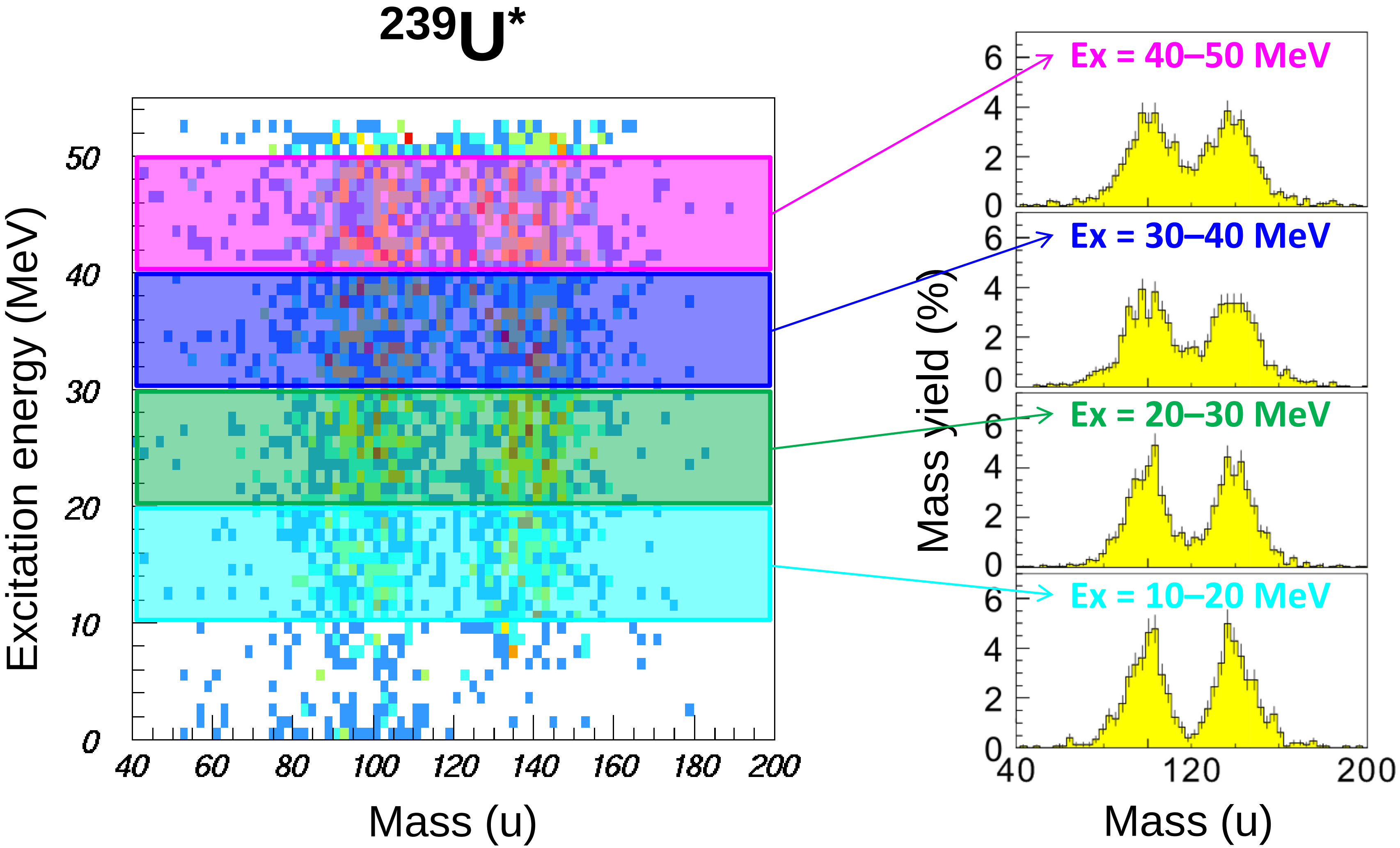
^{236}Pu(n,f)



Mass distribution of fission fragments: its dependence on excitation energy and comparison with neutron data

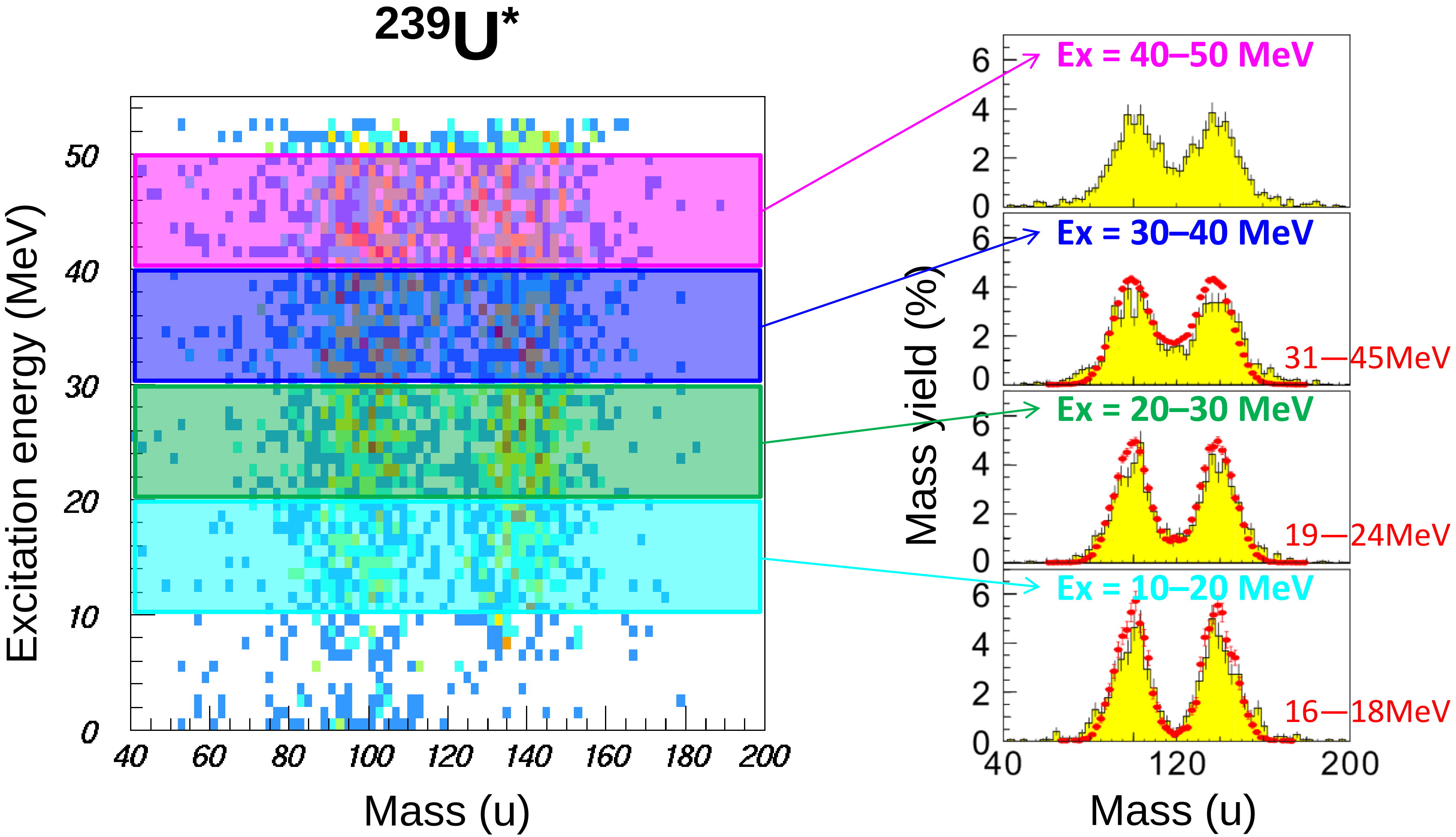


Mass distribution of fission fragments: its dependence on excitation energy and comparison with neutron data

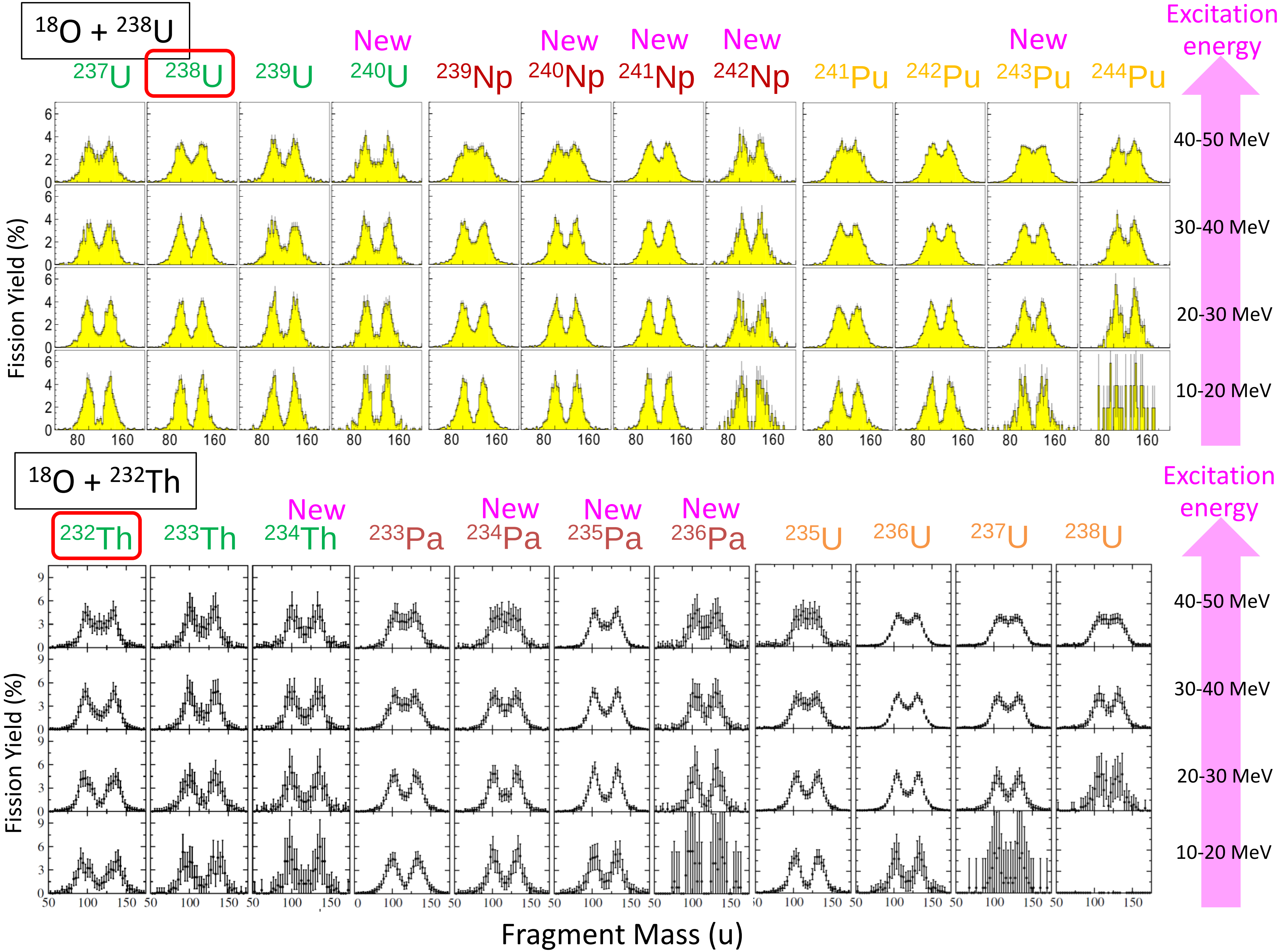


^{239}U*

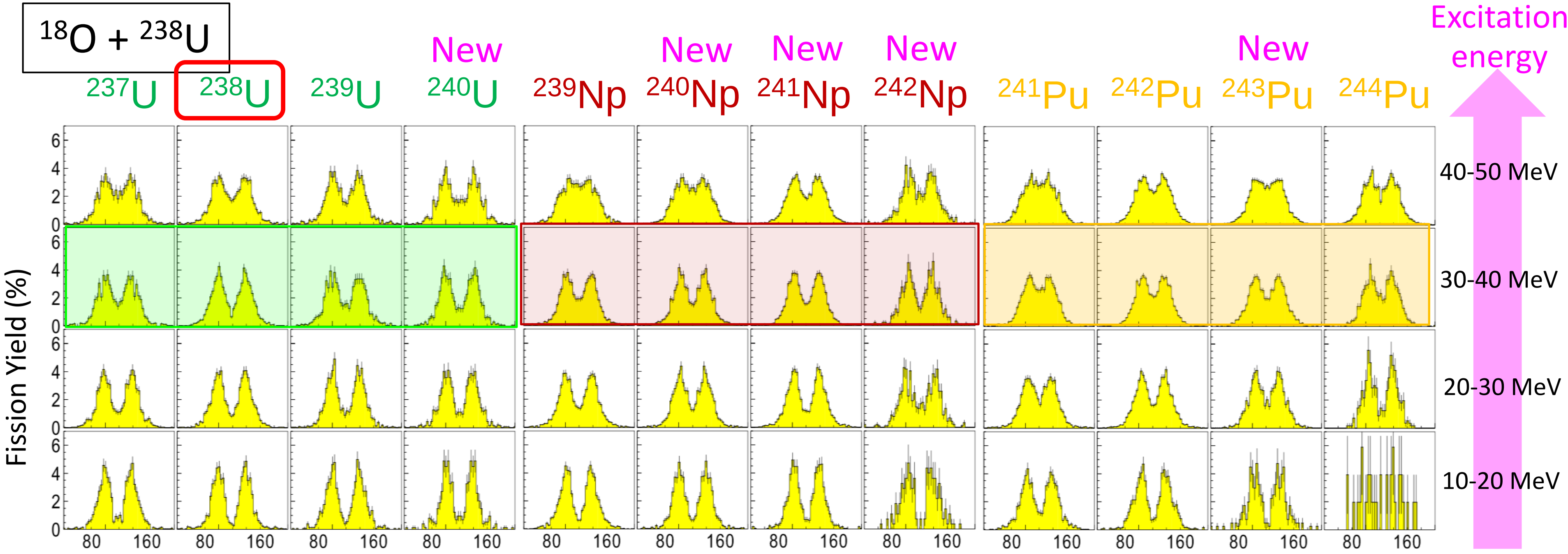
Mass distribution of fission fragments: its dependence on excitation energy and comparison with neutron data



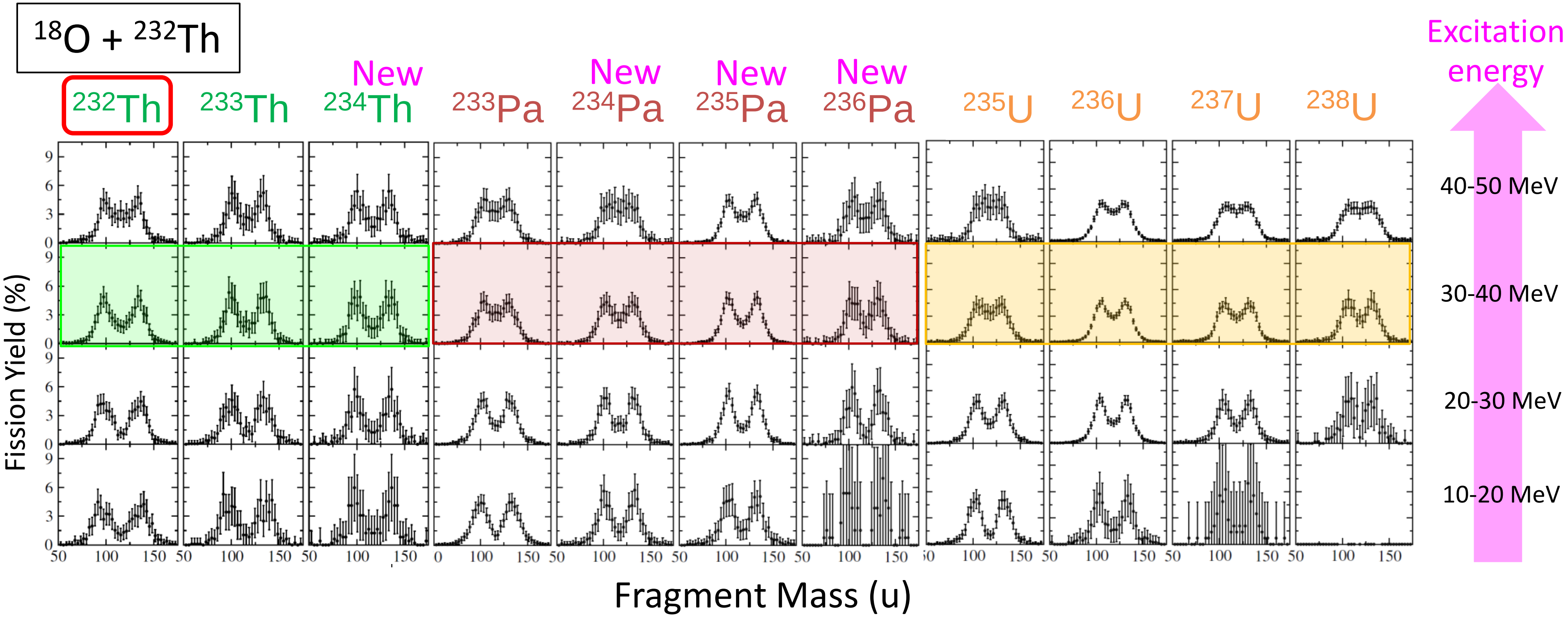
V.D.Simutkin et al.
Nuclear Data Sheets 119(2014)331


$^{18}O + ^{238}U$
^{237}U
^{238}U
^{239}U
New ^{240}U
^{239}Np
New ^{240}Np
New ^{241}Np
New ^{242}Np
^{241}Pu
^{242}Pu
New ^{243}Pu
^{244}Pu
Excitation energy
40-50 MeV
30-40 MeV
20-30 MeV
10-20 MeV
Fission Yield (%)
0
2
4
6
80
160
$^{18}O + ^{232}Th$
^{232}Th
^{233}Th
New ^{234}Th
^{233}Pa
New ^{234}Pa
New ^{235}Pa
New ^{236}Pa
^{235}U
^{236}U
^{237}U
^{238}U
Excitation energy
40-50 MeV
30-40 MeV
20-30 MeV
10-20 MeV
Fission Yield (%)
0
3
6
9
50
100
150
Fragment Mass (u)

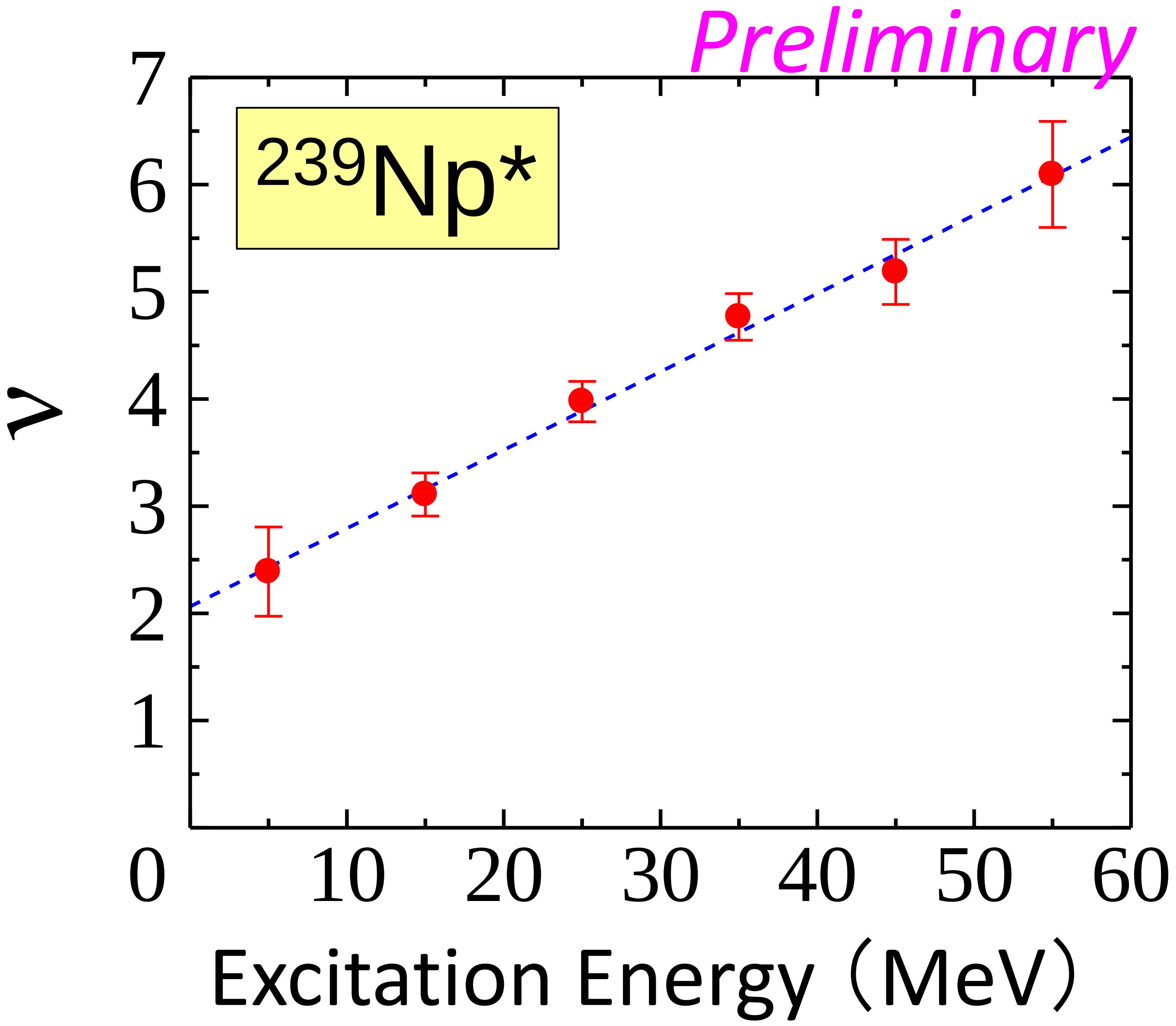
$^{18}O + ^{238}U$



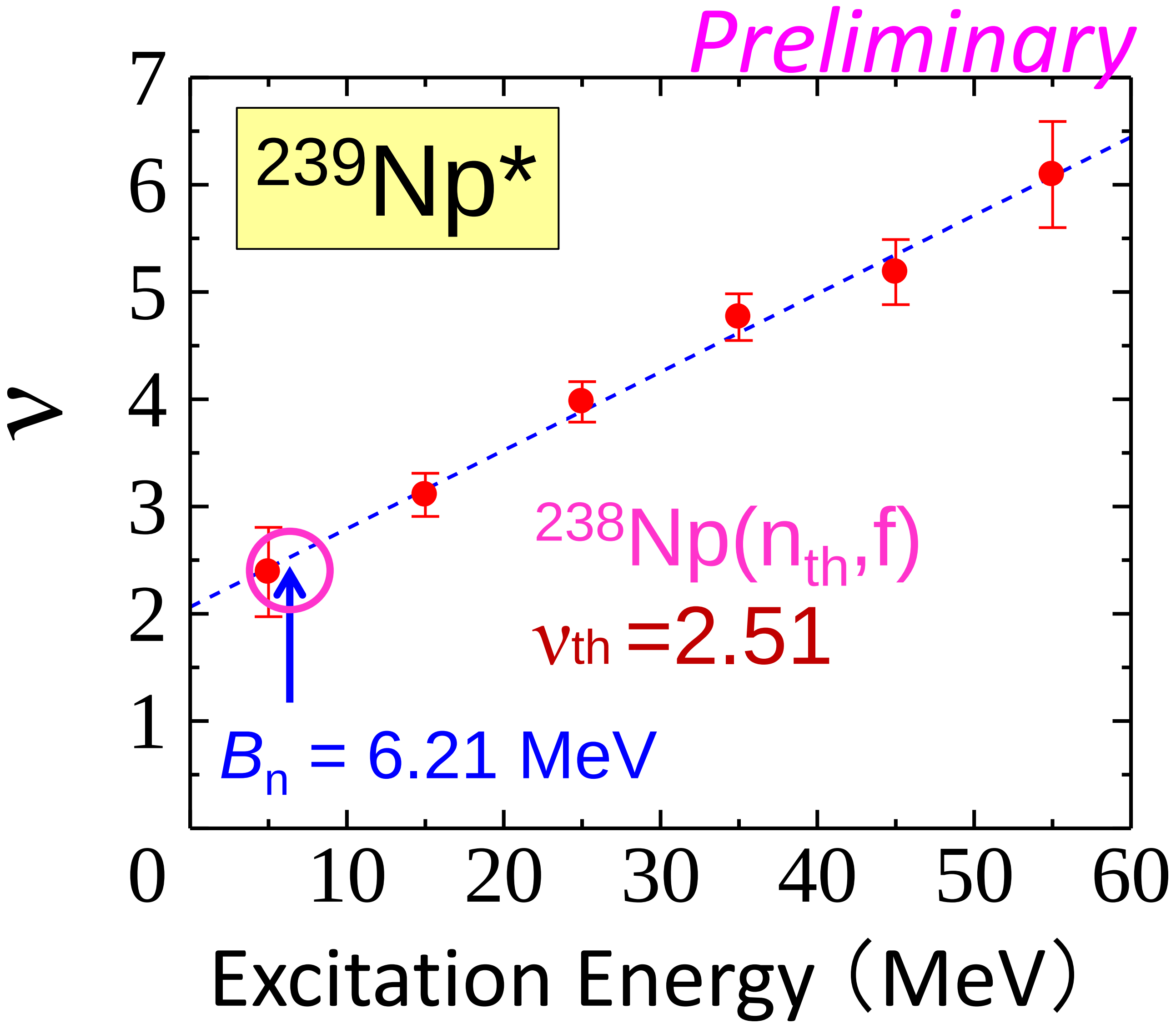
$^{18}O + ^{232}Th$



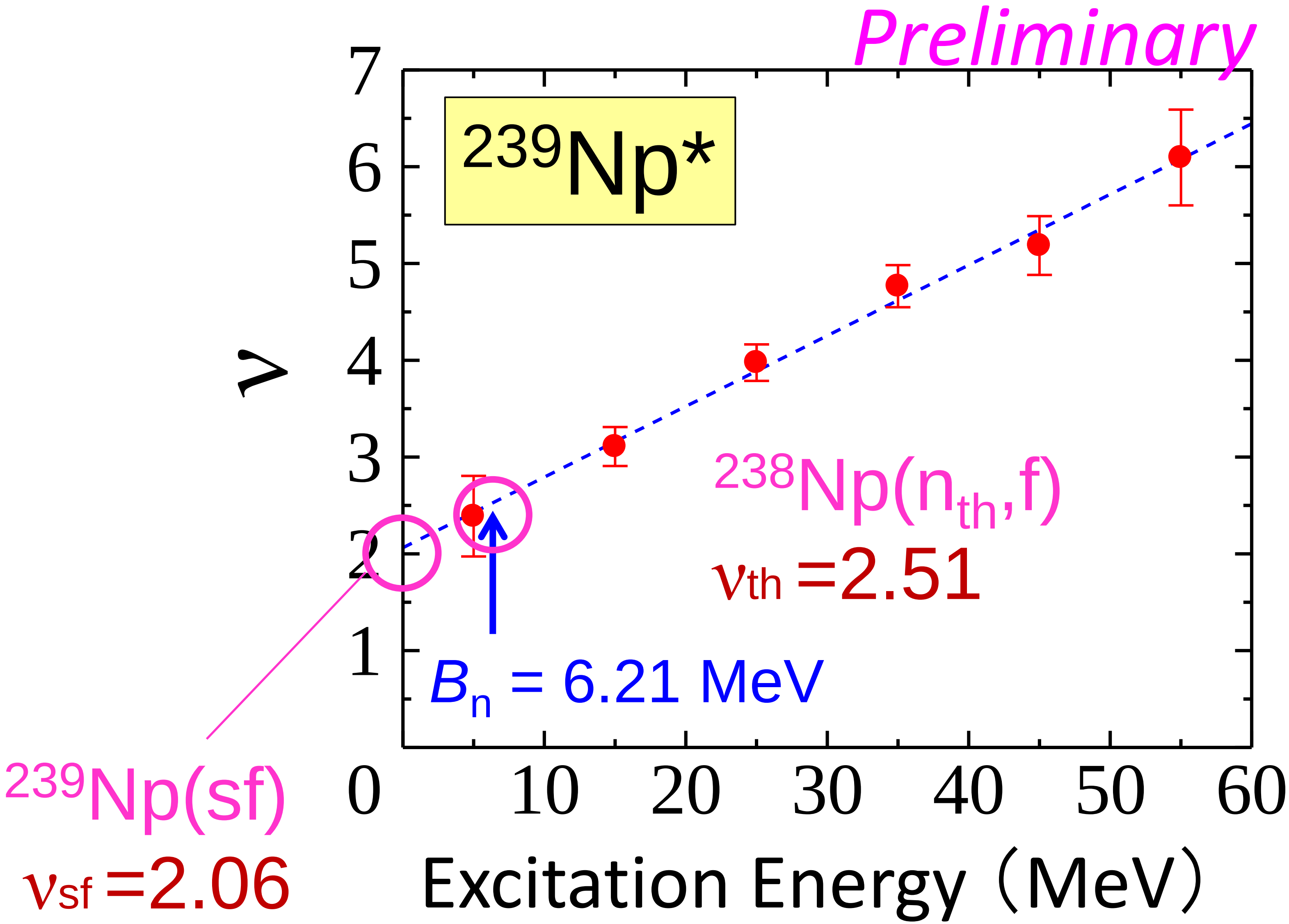
Number of prompt fission neutrons from ^{239}Np*



Number of prompt fission neutrons from $^{239}Np^*$



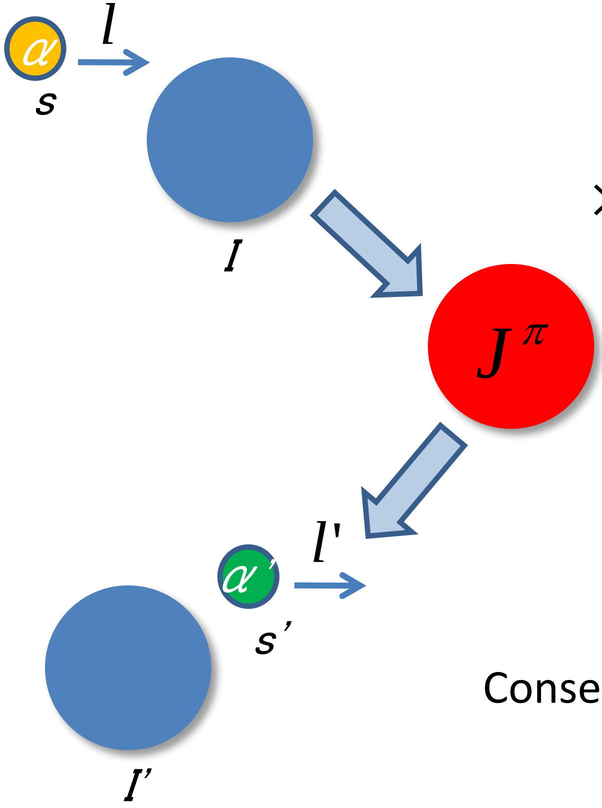
Number of prompt fission neutrons from ^{239}Np*



Hauser-Feshbach formula and surrogate method

$$\sigma_{\alpha\alpha'}(E_x) = \sum_{J=\mathrm{mod}(I+s,1)}^{l_{\max}+I+s} \sum_{\pi=-1}^{1} \sum_{j=|J-I|}^{J+I} \sum_{l=|j-s|}^{j+s} \sum_{j'=|J-I'|}^{J+I'} \sum_{l'=|j'-s'|}^{j'+s'} \delta_{\pi^{\alpha}} \delta_{\pi^{\alpha'}} D \frac{\pi}{k_{\alpha}^{2}} \frac{2J+1}{(2I+1)2s+1} T_{\alpha l j}^{J}(E_{\alpha})$$

$\sigma_R(J^\pi)$ Formation cross section of a fixed J^π state



$$\times \frac{\int_{E_x-\Delta E}^{E_x+\Delta E} \rho(E_{x'}, J^{\pi}) T_{\alpha' l' j'}^{J}(E_{\alpha'}) dE_{x'}}{\sum_{\alpha'' l'' j''} \delta_{\pi^{\alpha''}} \int_{0}^{E_{x\max}} \rho(E_{x''}, J^{\pi}) T_{\alpha'' l'' j''}^{J}(E_{\alpha''}) dE_{x''}}$$

Decay branching ratio $R_f^{\alpha}(\varepsilon_{\alpha}, J, \pi)$

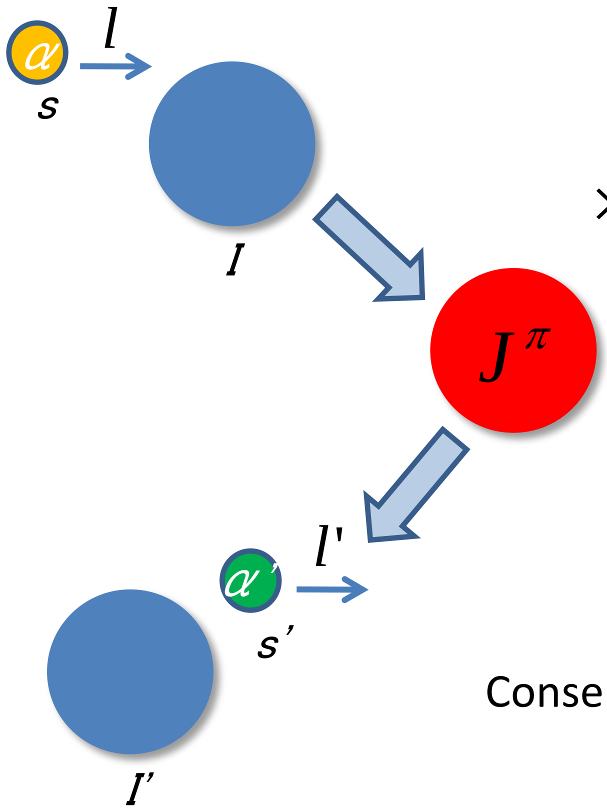
Conservation laws

$$\begin{cases} E_{\alpha} + S_{\alpha} = E_{\alpha'} + E_x + S_{\alpha} \\ s + I + l = s' + I' + l' = J \\ \pi_{\alpha}\pi_{i}(-)^{l} = \pi_{\alpha'}\pi_{f}(-)^{l'} = \pi \end{cases}$$

Hauser-Feshbach formula and surrogate method

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

$\sigma_R(J^\pi)$ Formation cross section of a fixed J^π state
(can be different for n- and surrogate reactions)



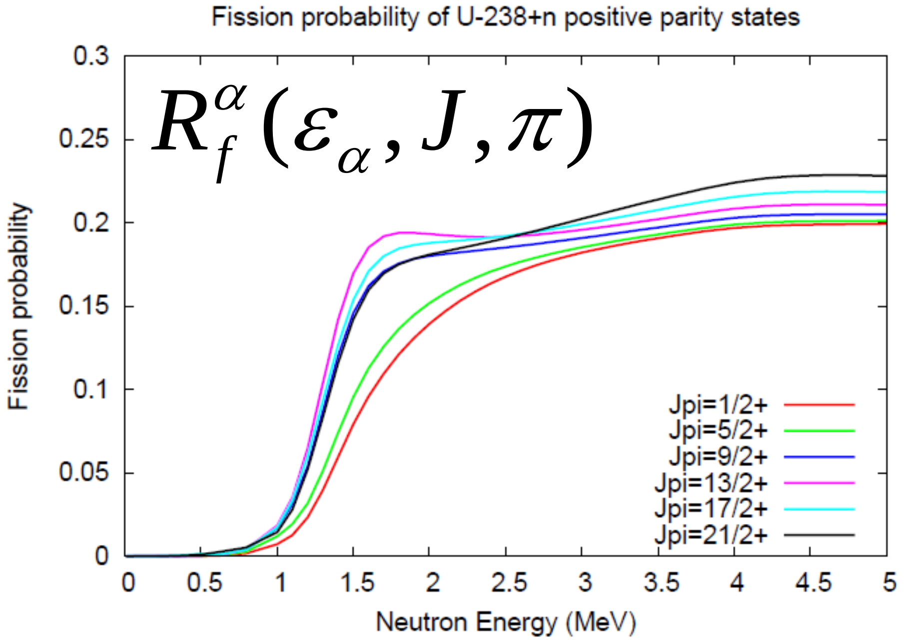
$$\times \frac{\int_{E_x-\Delta E}^{E_x+\Delta E} \rho(E_{x'}, J^\pi) T^J_{\alpha' l' j'}(E_{\alpha'}) dE_{x'}}{\sum_{\alpha'' l'' j''} \delta_{\pi\alpha''} \int_0^{E_{x\max}} \rho(E_{x''}, J^\pi) T^J_{\alpha'' l'' j''}(E_{\alpha''}) dE_{x''}}$$

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

Conservation laws

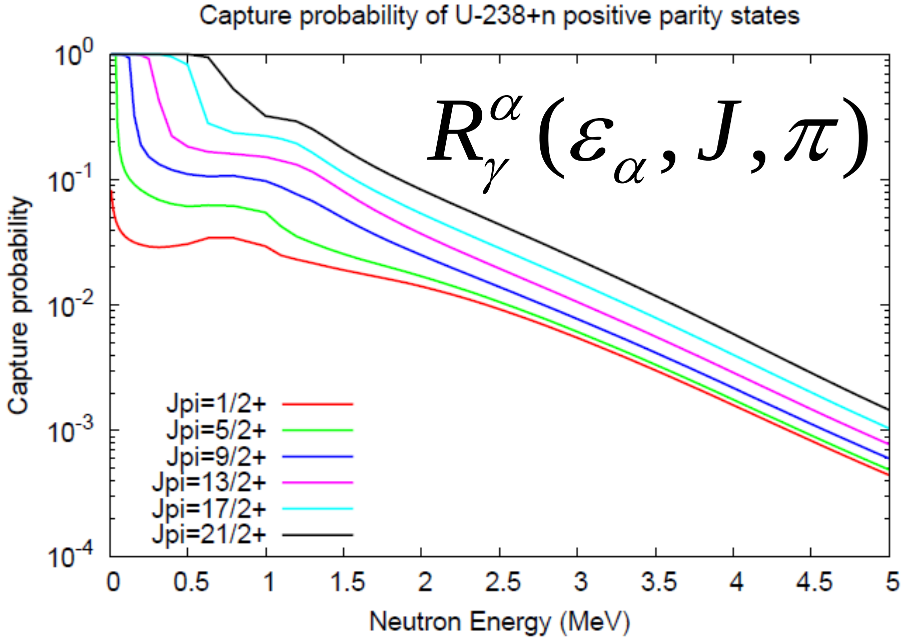
$$\begin{cases} E_\alpha + S_\alpha = E_{\alpha'} + E_x + S_\alpha \\ s + I + l = s' + I' + l' = J \\ \pi_\alpha \pi_i (-)^l = \pi_{\alpha'} \pi_f (-)^{l'} = \pi \end{cases}$$

Justification of s.r.m. :Branching ratio of $^{239}U^*$



Fission probability of U-238+n positive parity states

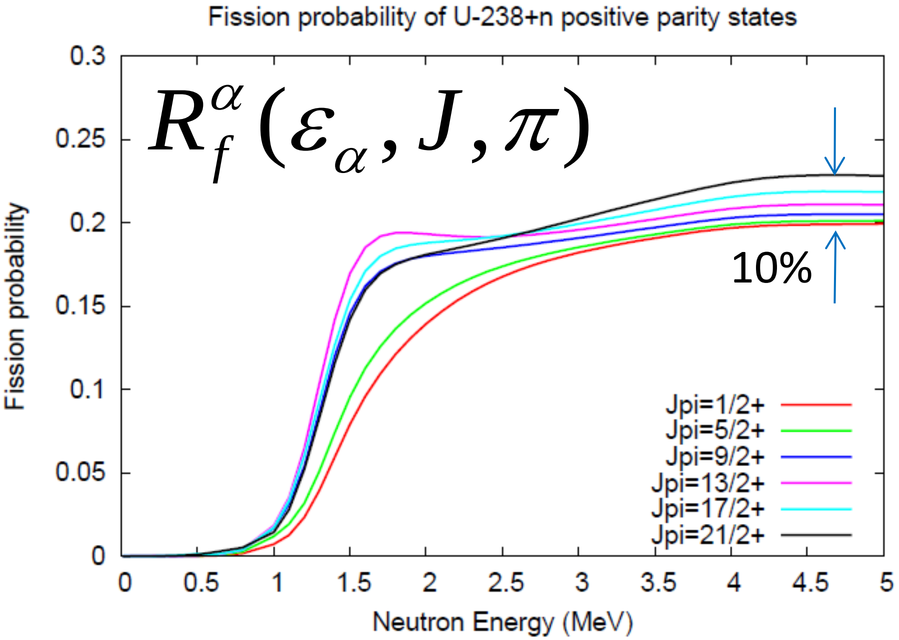
$$R_f^{\alpha}(\varepsilon_\alpha, J, \pi)$$



Capture probability of U-238+n positive parity states

$$R_\gamma^{\alpha}(\varepsilon_\alpha, J, \pi)$$

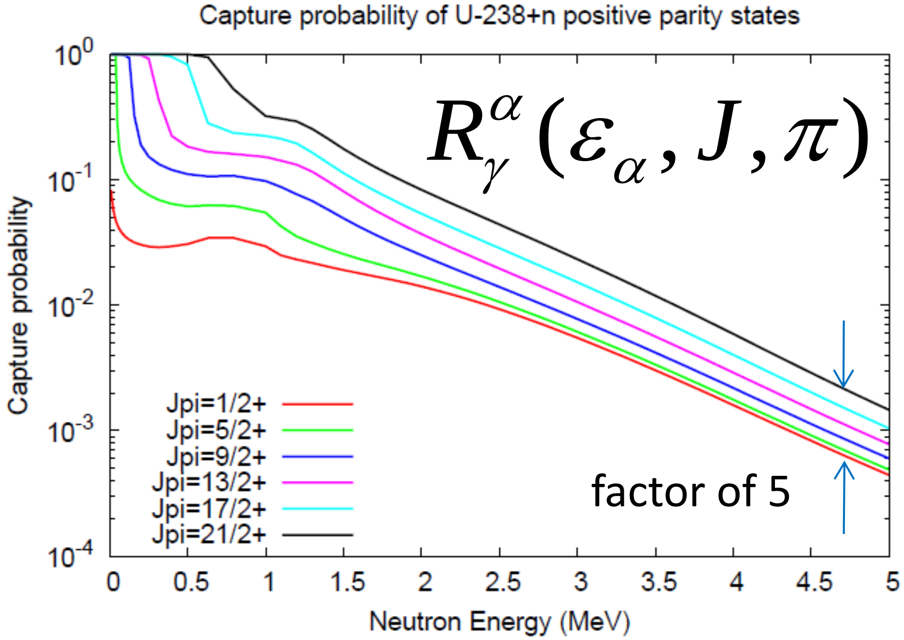
Justification of s.r.m. :Branching ratio of $^{239}U^*$



Fission probability of U-238+n positive parity states

$R_f^\alpha(\varepsilon_\alpha, J, \pi)$

10%

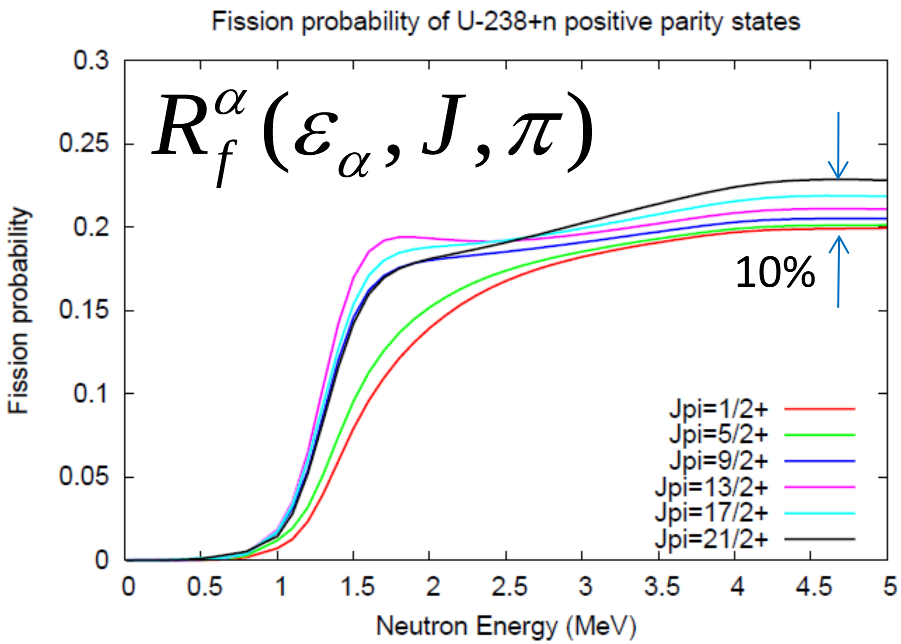


Capture probability of U-238+n positive parity states

$R_\gamma^\alpha(\varepsilon_\alpha, J, \pi)$

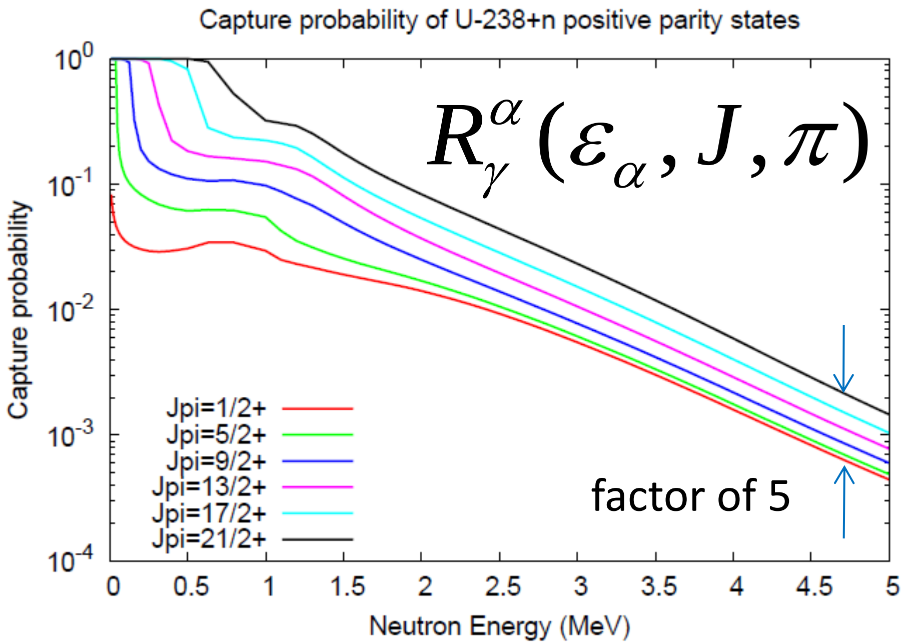
factor of 5

Justification of s.r.m. :Branching ratio of ^{239}U*



$R_f^\alpha(\varepsilon_\alpha, J, \pi)$

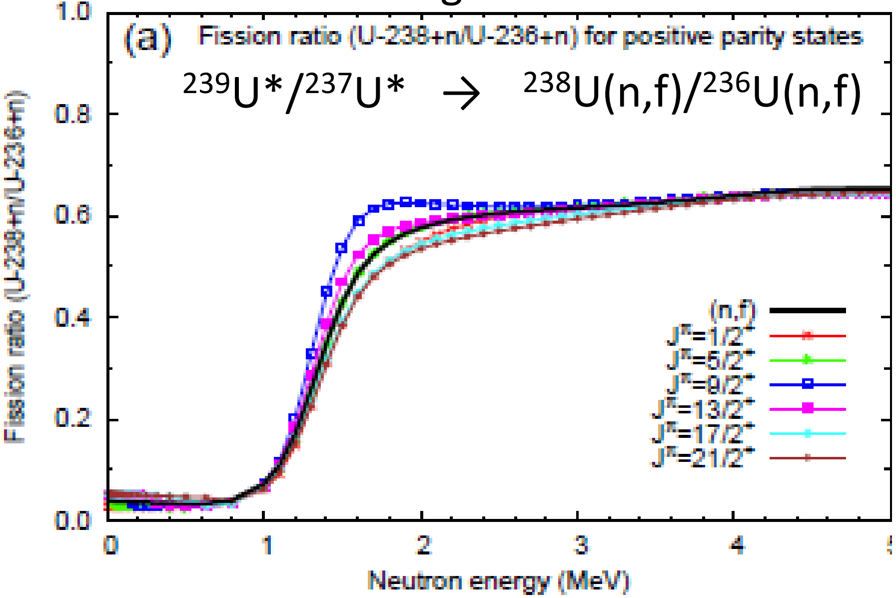
10%



$R_\gamma^\alpha(\varepsilon_\alpha, J, \pi)$

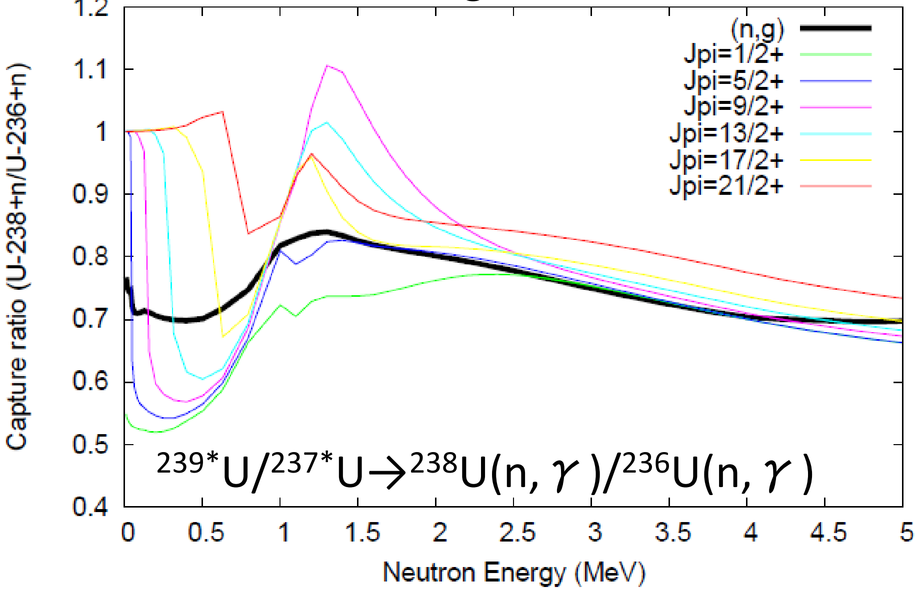
factor of 5

Ratio of branching ratios to fission



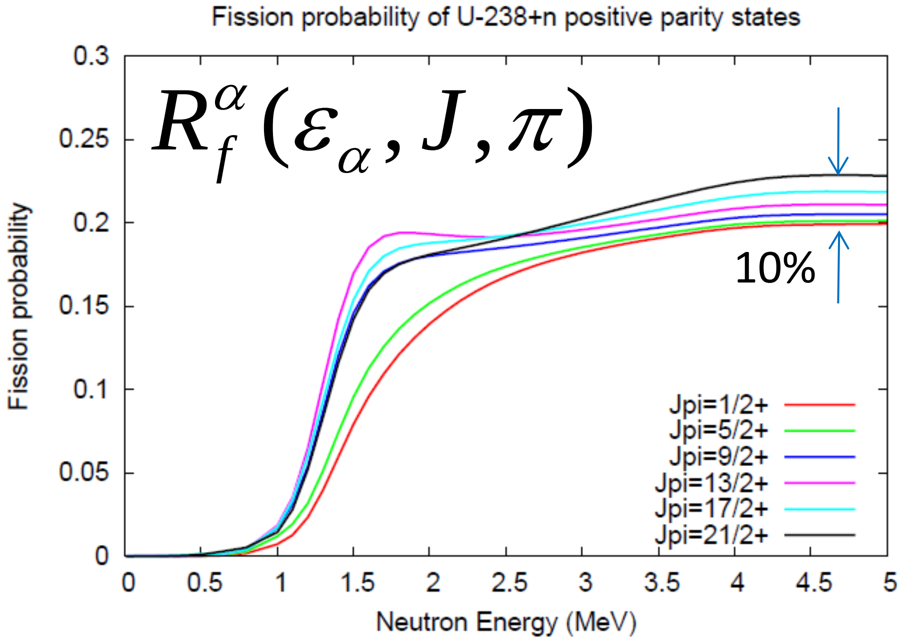
^{239}U*/^{237}U* → ^{238}U(n,f)/^{236}U(n,f)

Ratio of branching ratios to capture



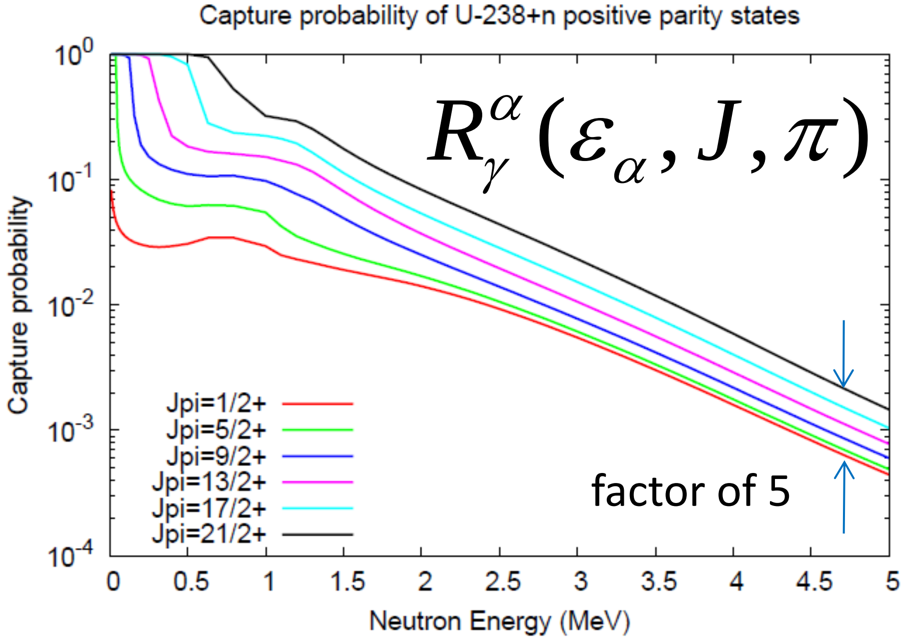
^{239*}U/^{237*}U→^{238}U(n, γ)/^{236}U(n, γ)

Justification of s.r.m. :Branching ratio of $^{239}U^{*}$



$R_f^{\alpha}(\varepsilon_{\alpha}, J, \pi)$

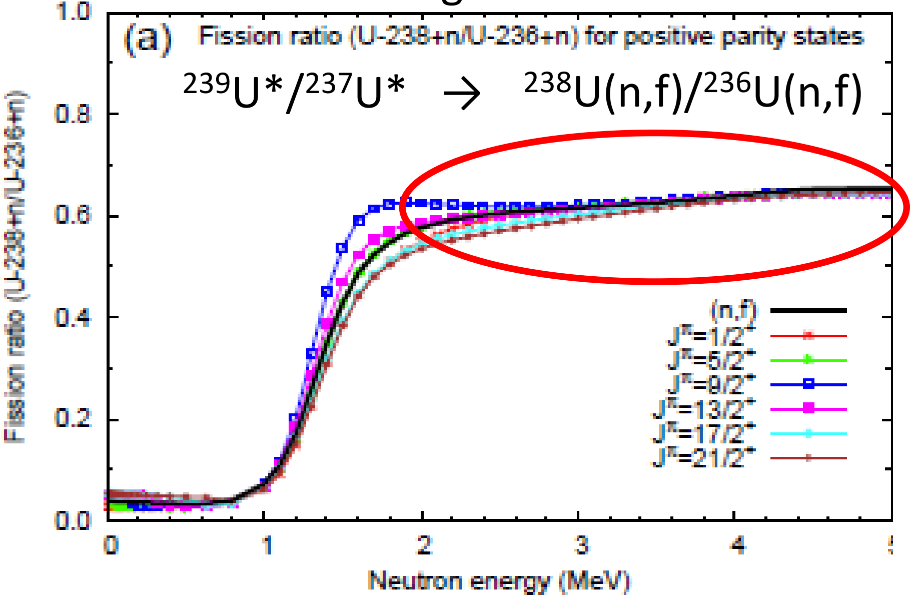
10%



$R_{\gamma}^{\alpha}(\varepsilon_{\alpha}, J, \pi)$

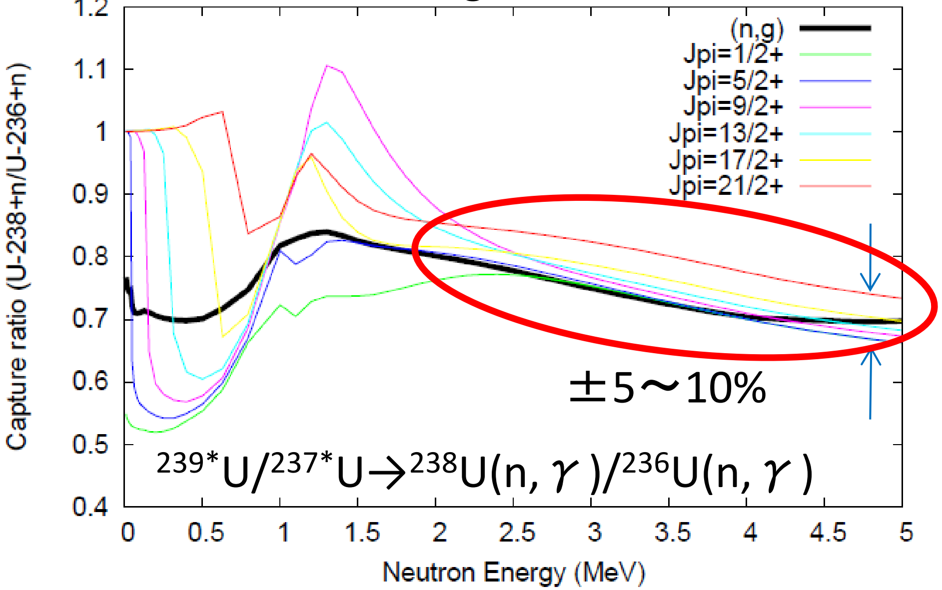
factor of 5

Ratio of branching ratios to fission



$^{239}U^{*}/^{237}U^{*} \rightarrow {}^{238}U(n,f)/^{236}U(n,f)$

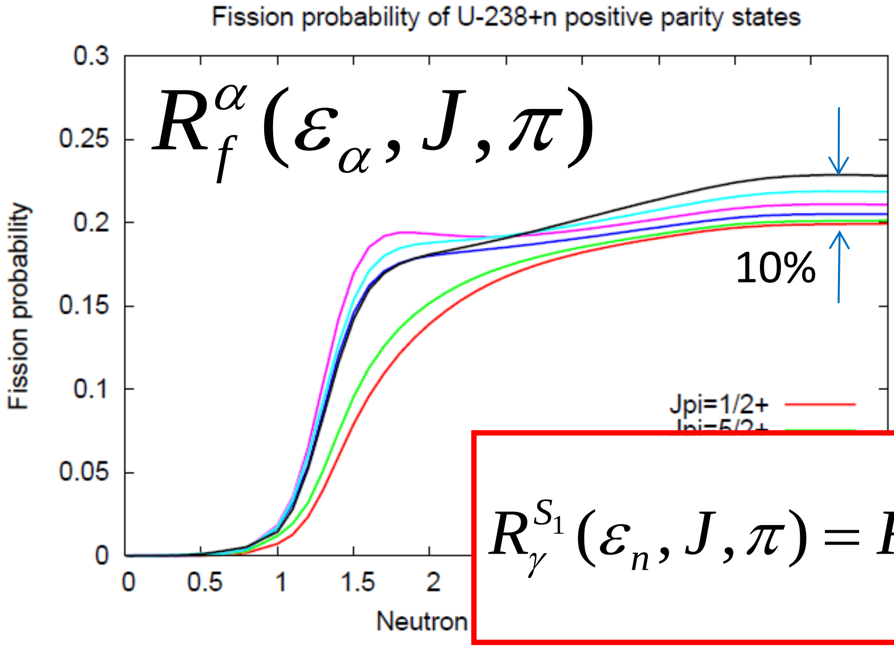
Ratio of branching ratios to capture



±5～10%

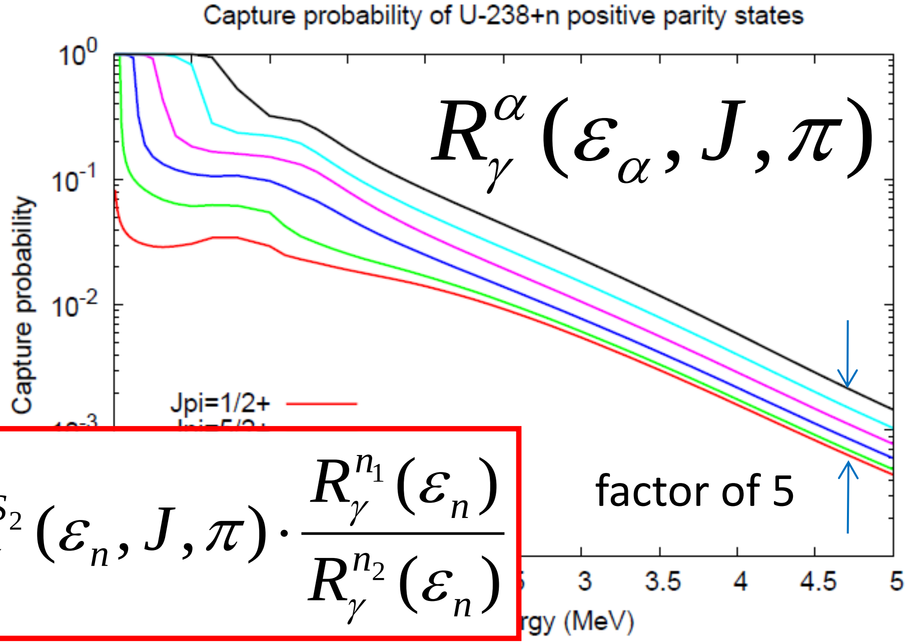
$^{239*}U/^{237*}U \rightarrow {}^{238}U(n,\gamma)/^{236}U(n,\gamma)$

Justification of s.r.m. :Branching ratio of $^{239}U^*$



$R_f^{\alpha}(\varepsilon_\alpha, J, \pi)$

10%

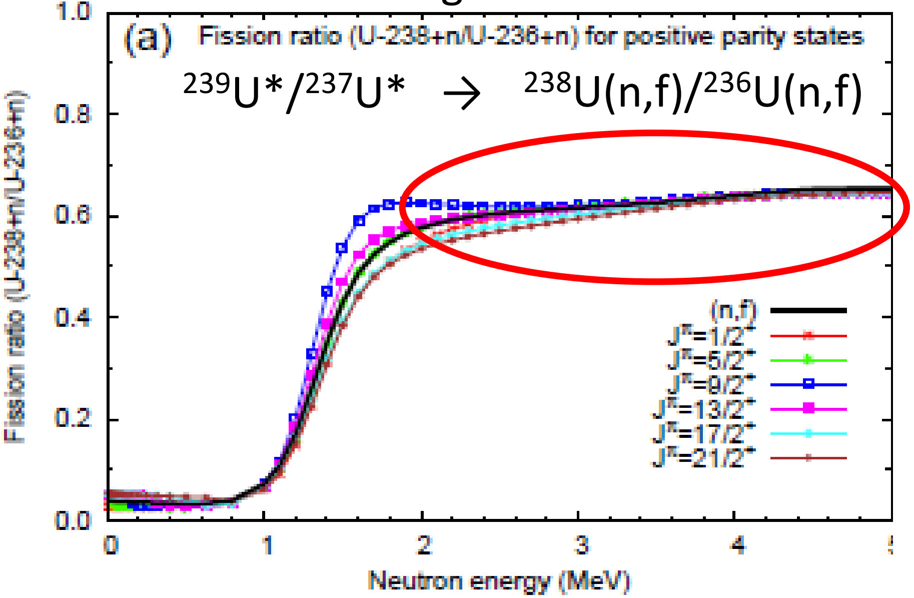


$R_\gamma^{\alpha}(\varepsilon_\alpha, J, \pi)$

factor of 5

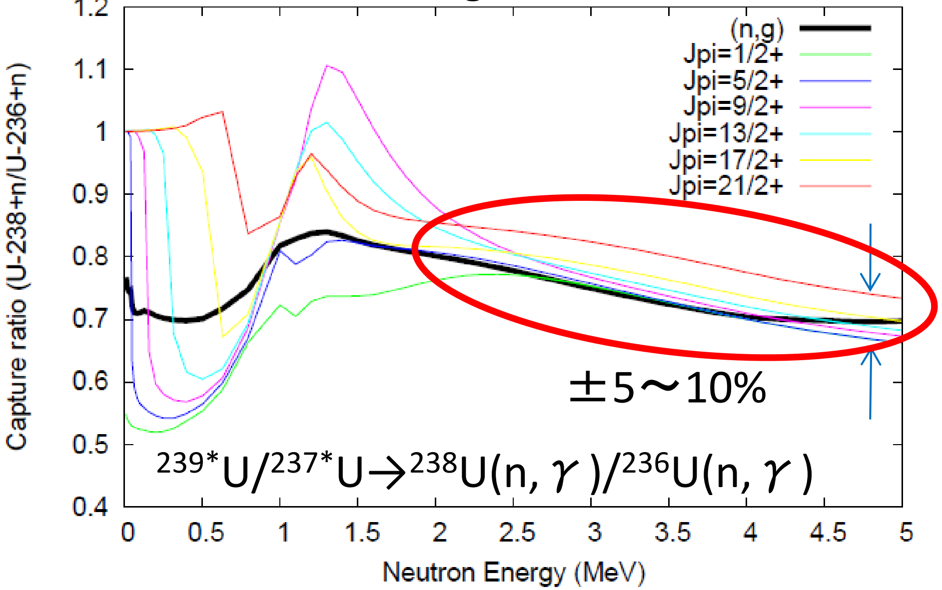
$$R_\gamma^{S_1}(\varepsilon_n, J, \pi) = R_\gamma^{S_2}(\varepsilon_n, J, \pi) \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)}$$

Ratio of branching ratios to fission



$^{239}U^*/^{237}U^* \rightarrow {}^{238}U(n,f)/^{236}U(n,f)$

Ratio of branching ratios to capture



±5～10%

$^{239*}U/^{237*}U \rightarrow {}^{238}U(n,\gamma)/^{236}U(n,\gamma)$

Justification of the Surrogate ratio method

SC, Iwamoto, PRC 81, 044604(2010)

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

: Weak Weisskopf-Ewing condition

$$R_\gamma^{S_1} = \frac{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi) \cdot R_\gamma^{S_1}(\varepsilon_n, J, \pi)}{\sum_{J^\pi} \sigma_{dir}^{s_1}(\varepsilon_n, J, \pi)} = \frac{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi) \cdot R_\gamma^{S_2}(\varepsilon_n, J, \pi) \cdot \frac{R_\gamma^{n1}(\varepsilon_n)}{R_\gamma^{n2}(\varepsilon_n)}}{\sum_{J^\pi} \sigma_{dir}^{S_1}(\varepsilon_n, J, \pi)}$$

$$= \frac{\sum_{J^\pi} \sigma_{dir}^{S_2}(\varepsilon_n, J, \pi) \cdot R_\gamma^{S_2}(\varepsilon_n)}{\sum_{J^\pi} \sigma_{dir}^{s_2}(\varepsilon_n, J, \pi)} \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)} = R_\gamma^{S_2}(\varepsilon_n) \cdot \frac{R_\gamma^{n_1}(\varepsilon_n)}{R_\gamma^{n_2}(\varepsilon_n)}$$

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

If the J^π distribution in the 2 reactions employed in the SRM are equivalent (σ^s1 (J^π) and σ^s2 (J^π) are proportional), it gives the correct answer (under weak Weiskopf-Ewing condition)

Neutron capture cross sections (preliminary)

ND2013

$$\mathbf{R^s} = \frac{B^{S(Gd\text{-}157)}{}_{\gamma}(E_n)}{B^{S(Gd\text{-}159)}{}_{\gamma}(E_n)}$$

Ratio R^s of branching ratios to γ emission from ^{157}Gd and ^{159}Gd obtained by the surrogate reaction (^{18}O,^{16}O) on 155 and 157Gd

Neutron capture cross sections (preliminary)

ND2013

$$\mathbf{R^s} = \frac{B^{S(\text{Gd-157})}{}_{\gamma}(E_n)}{B^{S(\text{Gd-159})}{}_{\gamma}(E_n)}$$

Ratio R^s of branching ratios to γ emission from ^{157}Gd and ^{159}Gd obtained by the surrogate reaction (^{18}O,^{16}O) on 155 and 157Gd

$\mathbf{R^s}$ × [^{158}Gd(n,γ)^{159}Gd cross section]
=^{156}Gd(n,γ)^{157}Gd cross section

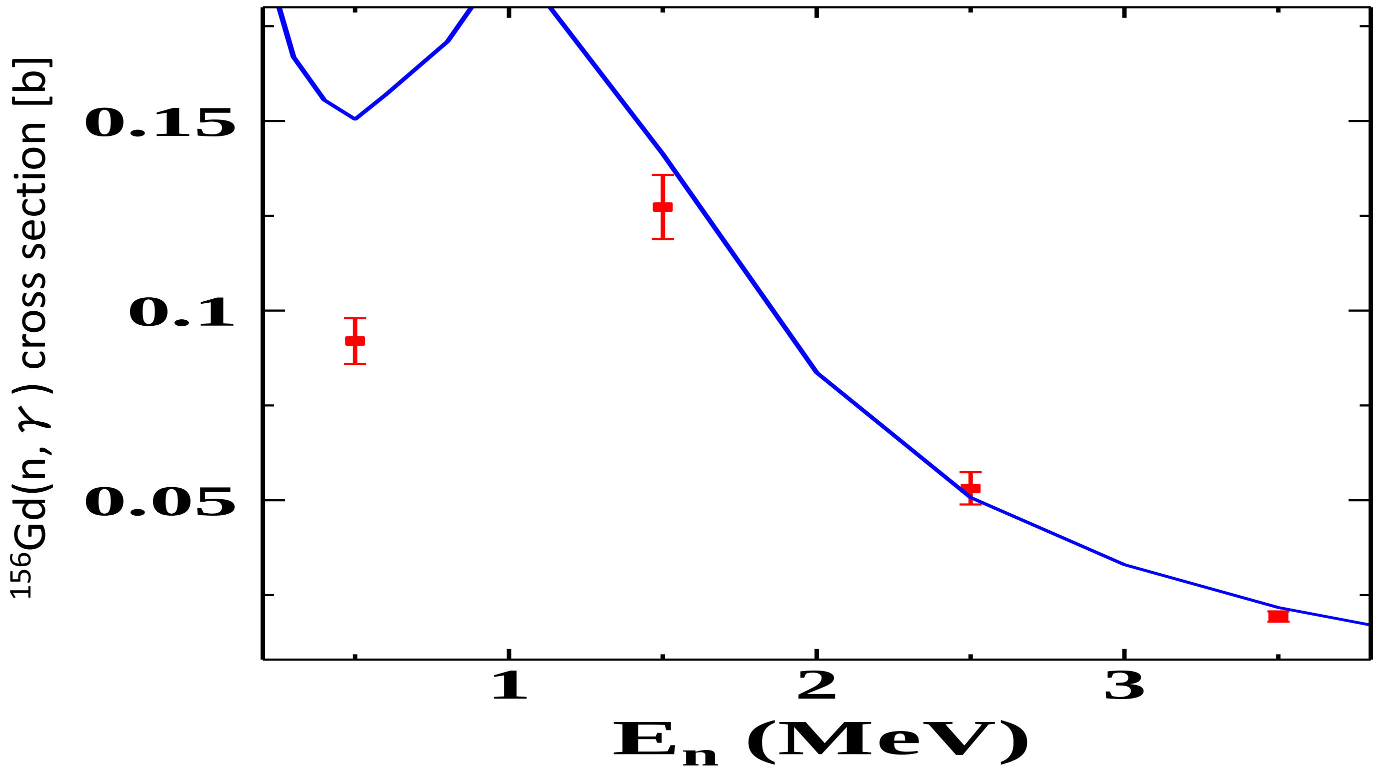
Neutron capture cross sections (preliminary)

ND2013

$$\mathbf{R^s} = \frac{B^{S(Gd\text{-}157)}{}_{\gamma}(E_n)}{B^{S(Gd\text{-}159)}{}_{\gamma}(E_n)}$$

Ratio R^s of branching ratios to γ emission from ^{157}Gd and ^{159}Gd obtained by the surrogate reaction (^{18}O,^{16}O) on 155 and 157Gd

$\mathbf{R^s}$ × [^{158}Gd(n,γ)^{159}Gd cross section]
=^{156}Gd(n,γ)^{157}Gd cross section



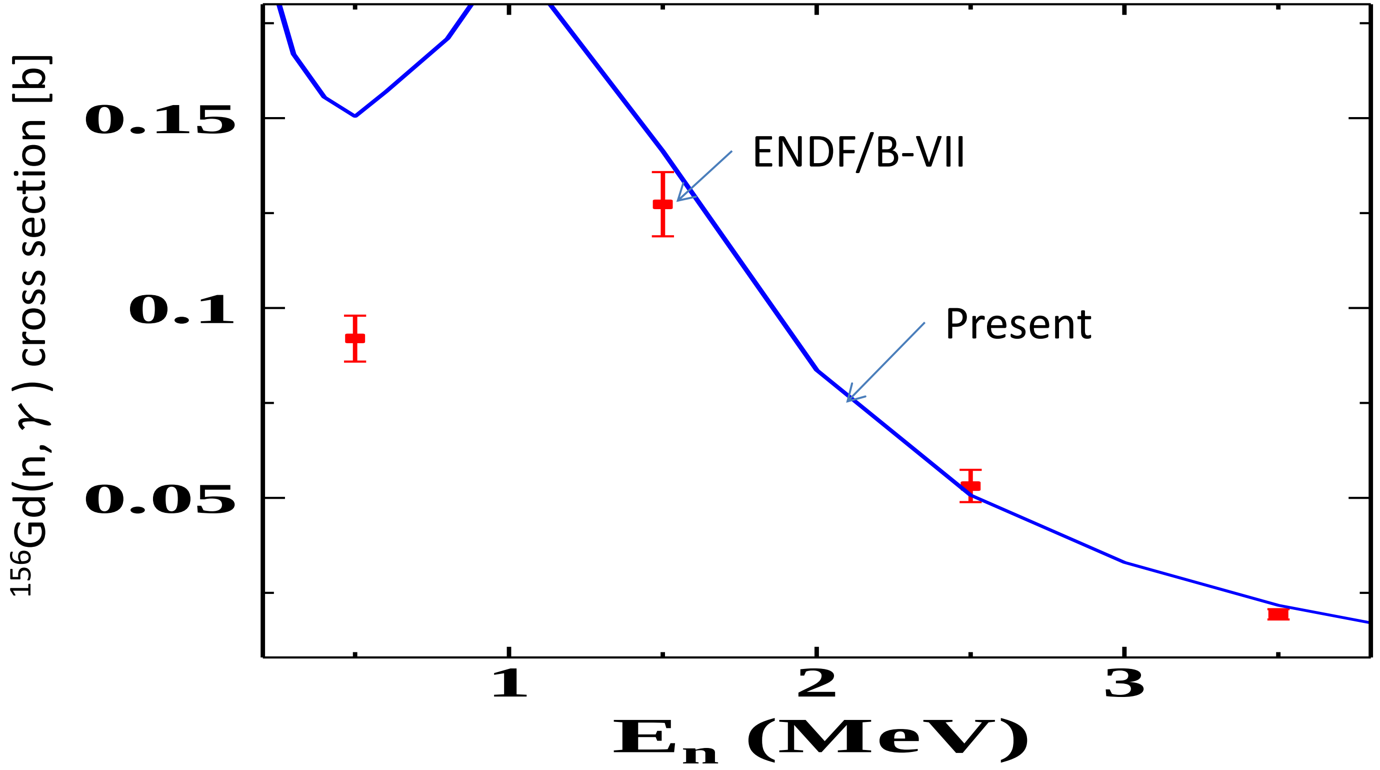
Neutron capture cross sections (preliminary)

ND2013

$$\mathbf{R^s} = \frac{B^{S(Gd\text{-}157)}{}_{\gamma}(E_n)}{B^{S(Gd\text{-}159)}{}_{\gamma}(E_n)}$$

Ratio R^s of branching ratios to γ emission from ^{157}Gd and ^{159}Gd obtained by the surrogate reaction (^{18}O,^{16}O) on 155 and 157Gd

$\mathbf{R^s}$ × [^{158}Gd(n,γ)^{159}Gd cross section]
=^{156}Gd(n,γ)^{157}Gd cross section



Cases when pre-equilibrium particle emission and breakup contamination coexist

S.C and O. Iwamoto, PRC 81, 044604(2010)

- Let *Q* be a probability that surrogate reaction leads to population of compound nuclei, and *P* a probability that particles are emitted by preequilibrium :（*P*+*Q*=1)
- The probability that reaction f (e.g., fission) to occur in the surrogate reaction (left hand side) is smaller than when there is only Q process.

$$R_f^{S_1}(P+Q) = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)} \le R_f^{S_1}(U) = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)}$$

Cases when pre-equilibrium particle emission and breakup contamination coexist

S.C and O. Iwamoto, PRC 81, 044604(2010)

- Let *Q* be a probability that surrogate reaction leads to population of compound nuclei, and *P* a probability that particles are emitted by preequilibrium :（*P*+*Q*=1)
- The probability that reaction f (e.g., fission) to occur in the surrogate reaction (left hand side) is smaller than when there is only Q process.

$$\boxed{R_f^{S_1}(P+Q)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)} \le \boxed{R_f^{S_1}(U)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)}$$

Observable in s.r.

quantity to be determined

Cases when pre-equilibrium particle emission and breakup contamination coexist

S.C and O. Iwamoto, PRC 81, 044604(2010)

- Let *Q* be a probability that surrogate reaction leads to population of compound nuclei, and *P* a probability that particles are emitted by preequilibrium :（*P*+*Q*=1)
- The probability that reaction f (e.g., fission) to occur in the surrogate reaction (left hand side) is smaller than when there is only Q process.

$$\boxed{R_f^{S_1}(P+Q)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)} \leq \boxed{R_f^{S_1}(U)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)}$$

Observable in s.r.

quantity to be determined

- If weak Weisskopf-Ewing condition is satisfied : $B_f^{S_1}(U,J^\pi) = B_f^{S_2}(U,J^\pi)\cdot\frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}$

and if $\sigma^{s1}(J^\pi)$ and $\sigma^{s2}(J^\pi)$ are proportional to each other, the following is valid even if there is a contamination by the pre-equilibrium and breakup reactions

Cases when pre-equilibrium particle emission and breakup contamination coexist

S.C and O. Iwamoto, PRC 81, 044604(2010)

- Let Q be a probability that surrogate reaction leads to population of compound nuclei, and P a probability that particles are emitted by preequilibrium :（$P+Q=1$)
- The probability that reaction f (e.g., fission) to occur in the surrogate reaction (left hand side) is smaller than when there is only Q process.

$$\underset{\text{Observable in s.r.}}{\boxed{R_f^{S_1}(P+Q)}} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)} \le \underset{\text{quantity to be determined}}{\boxed{R_f^{S_1}(U)}} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)}$$

- If weak Weisskopf-Ewing condition is satisfied : $B_f^{S_1}(U,J^\pi) = B_f^{S_2}(U,J^\pi)\cdot\frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}$

  and if σ^{s1}（J^π) and σ^{s2}（J^π) are proportional to each other, the following is valid even if there is a contamination by the pre-equilibrium and breakup reactions

$$\frac{R_f^{S_1}(P+Q)}{R_f^{S_2}(P+Q)} = \frac{\dfrac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)}}{\dfrac{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_2}(U,J^\pi)}} = \frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}\cdot\frac{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)} = \frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}$$

Cases when pre-equilibrium particle emission and breakup contamination coexist

S.C and O. Iwamoto, PRC 81, 044604(2010)

- Let *Q* be a probability that surrogate reaction leads to population of compound nuclei, and *P* a probability that particles are emitted by preequilibrium :（*P*+*Q*=1)
- The probability that reaction f (e.g., fission) to occur in the surrogate reaction (left hand side) is smaller than when there is only Q process.

$$\boxed{R_f^{S_1}(P+Q)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)} \le \boxed{R_f^{S_1}(U)} = \frac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)}$$

Observable in s.r.

quantity to be determined

- If weak Weisskopf-Ewing condition is satisfied : $B_f^{S_1}(U,J^\pi) = B_f^{S_2}(U,J^\pi)\cdot\frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}$

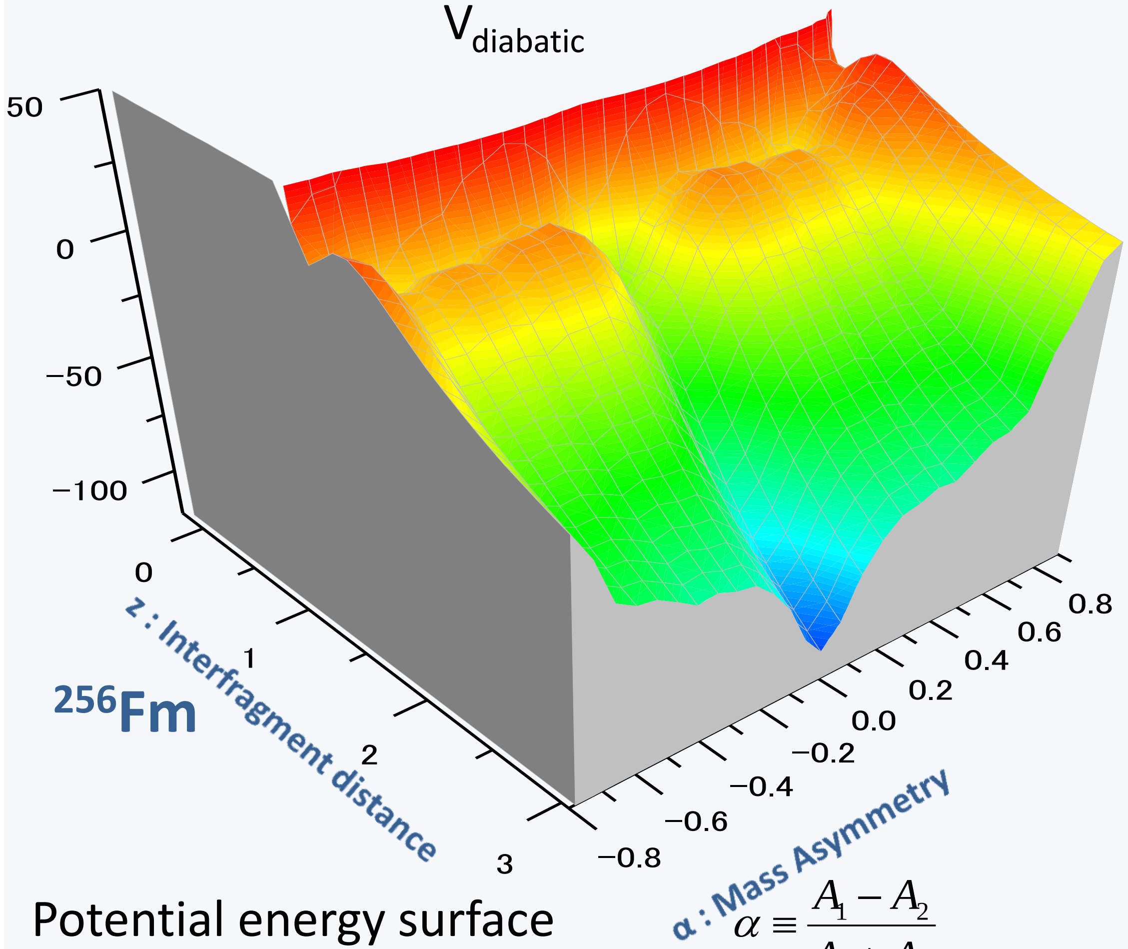
and if σ^{s1}（J^π）and σ^{s2}（J^π）are proportional to each other, the following is valid even if there is a contamination by the pre-equilibrium and breakup reactions

$$\boxed{\frac{R_f^{S_1}(P+Q)}{R_f^{S_2}(P+Q)}} = \frac{\dfrac{\sum_{J^\pi} Q\sigma^{S_1}(U,J^\pi)\cdot B_f^{S_1}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_1}(U,J^\pi)}}{\dfrac{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)}{\sum_{J^\pi}(P+Q)\sigma^{S_2}(U,J^\pi)}} = \frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}\cdot\frac{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)}{\sum_{J^\pi} Q\sigma^{S_2}(U,J^\pi)\cdot B_f^{S_2}(U,J^\pi)} = \boxed{\frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}}$$

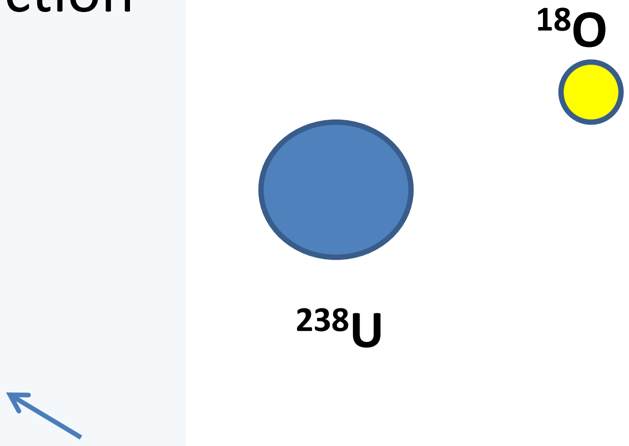
Observables in surrogate method

quantity to be determined

Unified-model description of the surrogate reaction



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



Potential energy surface
→Two-center shell model

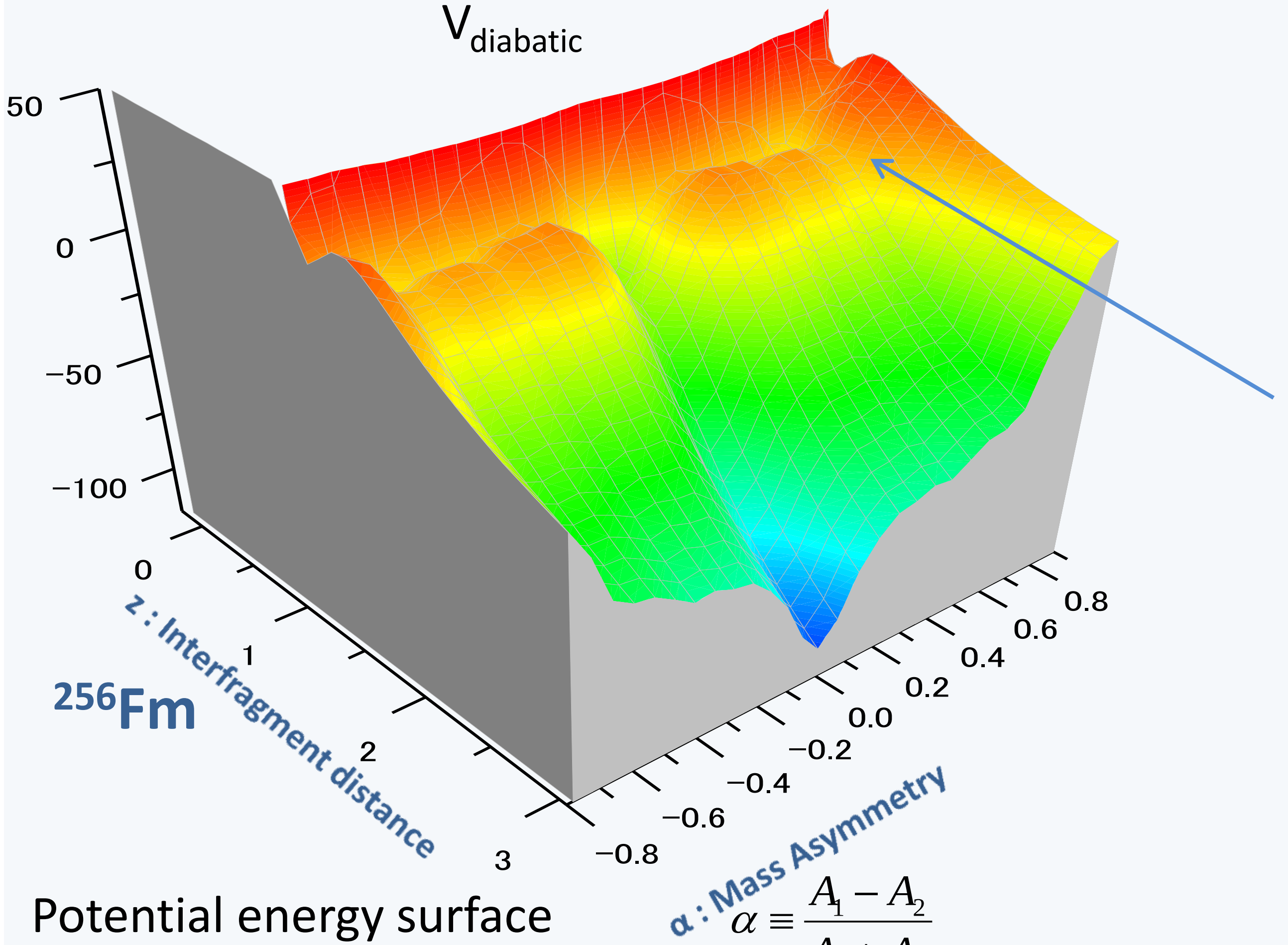
Dynamical effects
→multi-dimensional Langevin calculation

^{18}O + ^{238}U → ^{16}O + ^{240}U

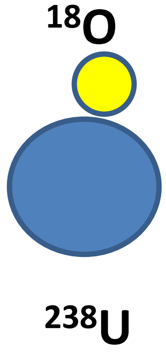
FF mass and angular dist.
Neutron emission

Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

Unified-model description of the surrogate reaction



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



Potential energy surface
→Two-center shell model

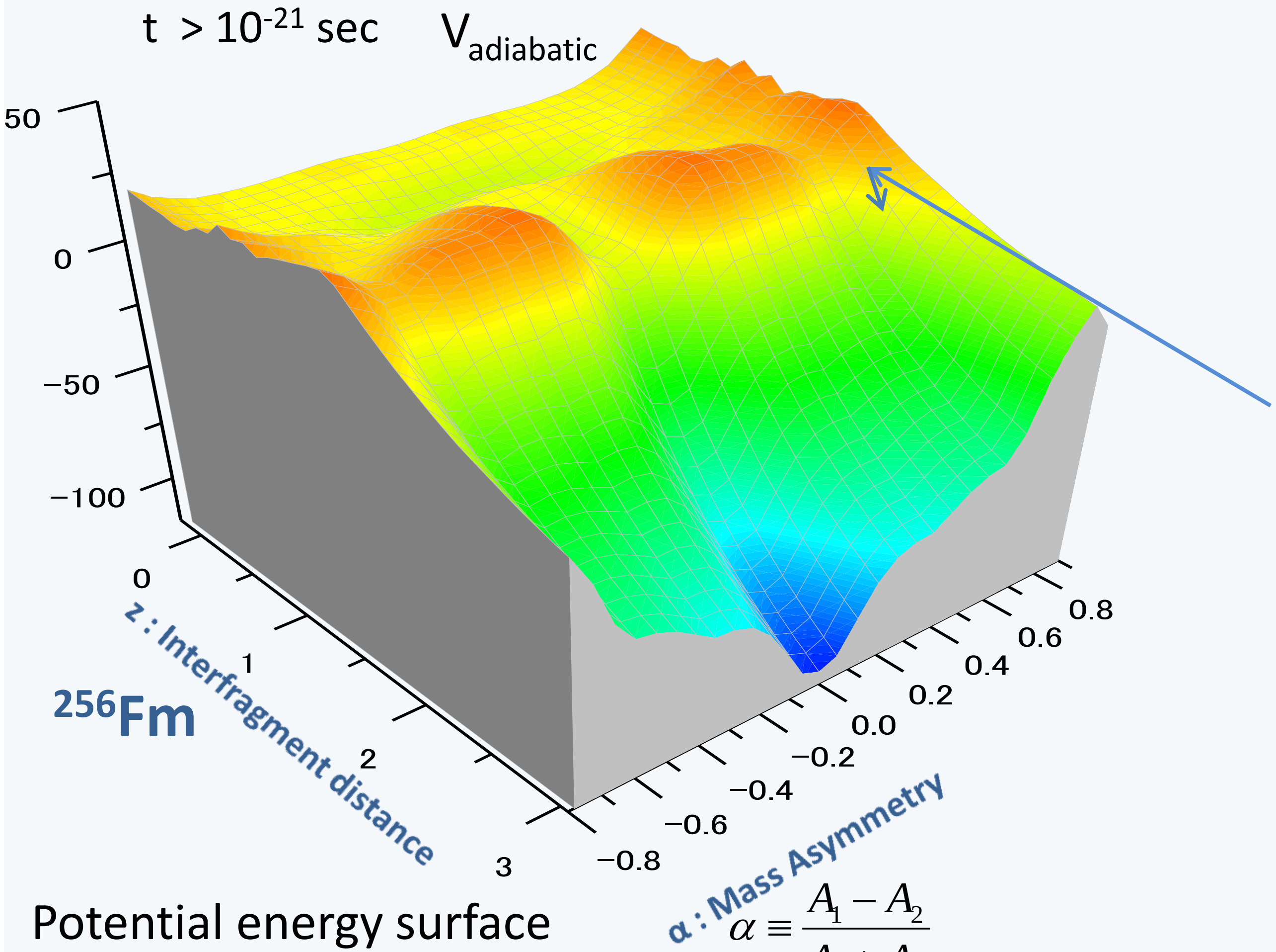
Dynamical effects
→multi-dimensional Langevin calculation

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

FF mass and angular dist.
Neutron emission

Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

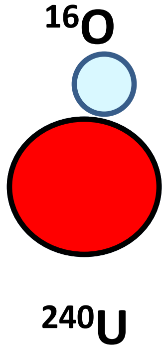
Unified-model description of the surrogate reaction



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

Potential energy surface
→Two-center shell model

Dynamical effects
→multi-dimensional Langevin calculation

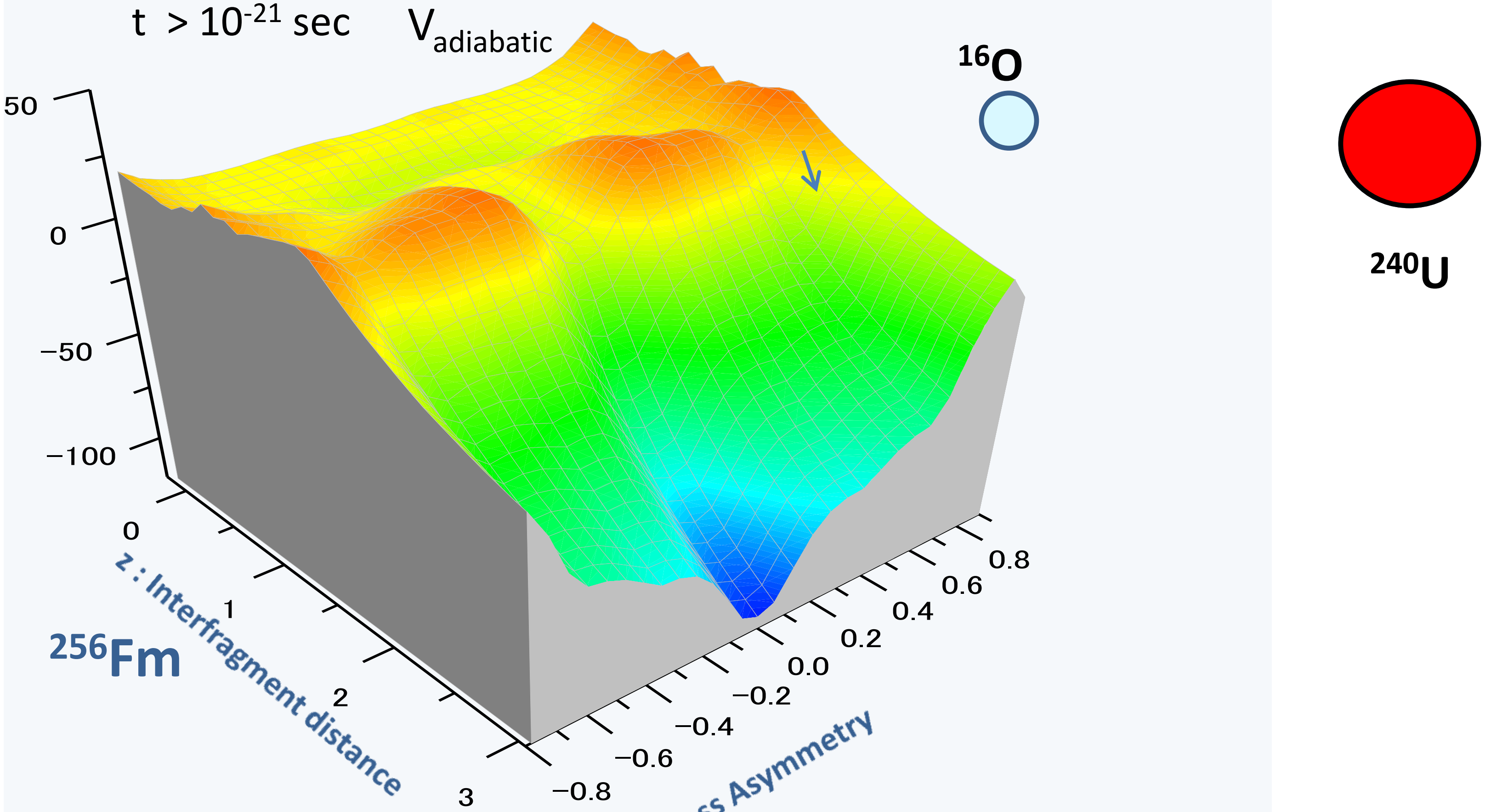


^{18}O + ^{238}U → ^{16}O + ^{240}U

FF mass and angular dist.
Neutron emission

Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

Unified-model description of the surrogate reaction



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

Potential energy surface
→Two-center shell model

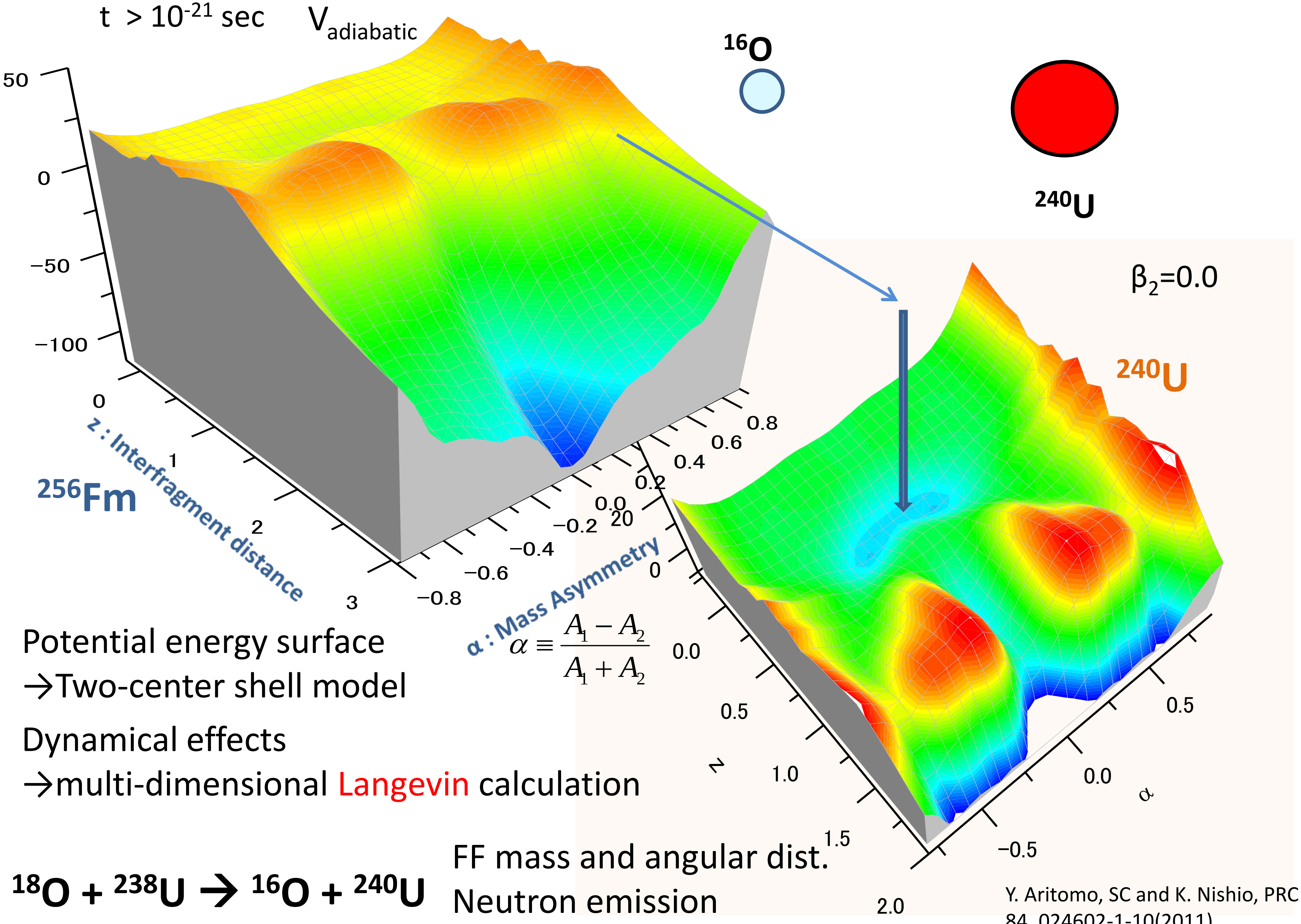
Dynamical effects
→multi-dimensional Langevin calculation

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

FF mass and angular dist.
Neutron emission

Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

Unified-model description of the surrogate reaction



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

Potential energy surface
→Two-center shell model

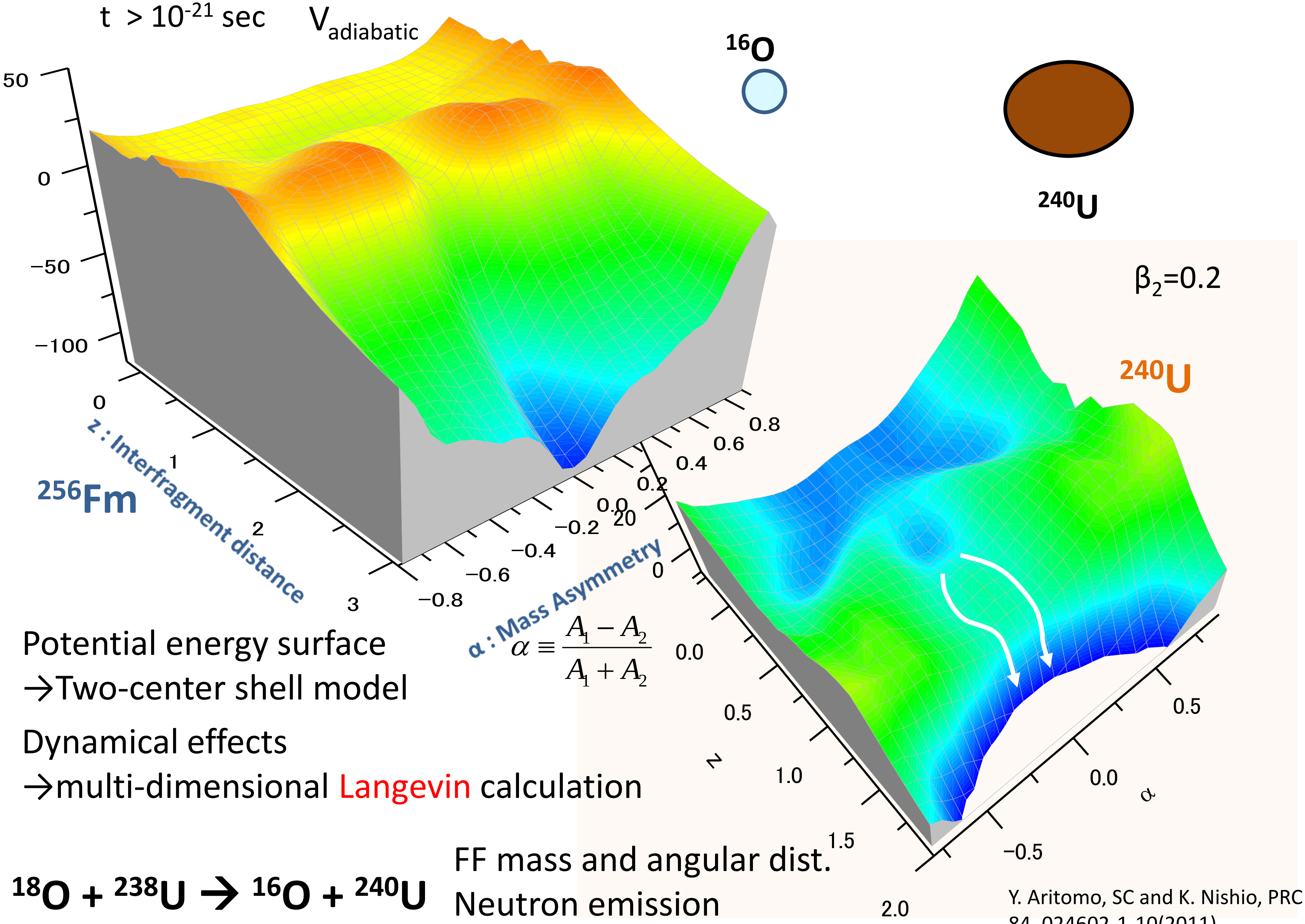
Dynamical effects
→multi-dimensional Langevin calculation

FF mass and angular dist.
Neutron emission

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

Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

Unified-model description 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 calculation

FF mass and angular dist.

Neutron emission

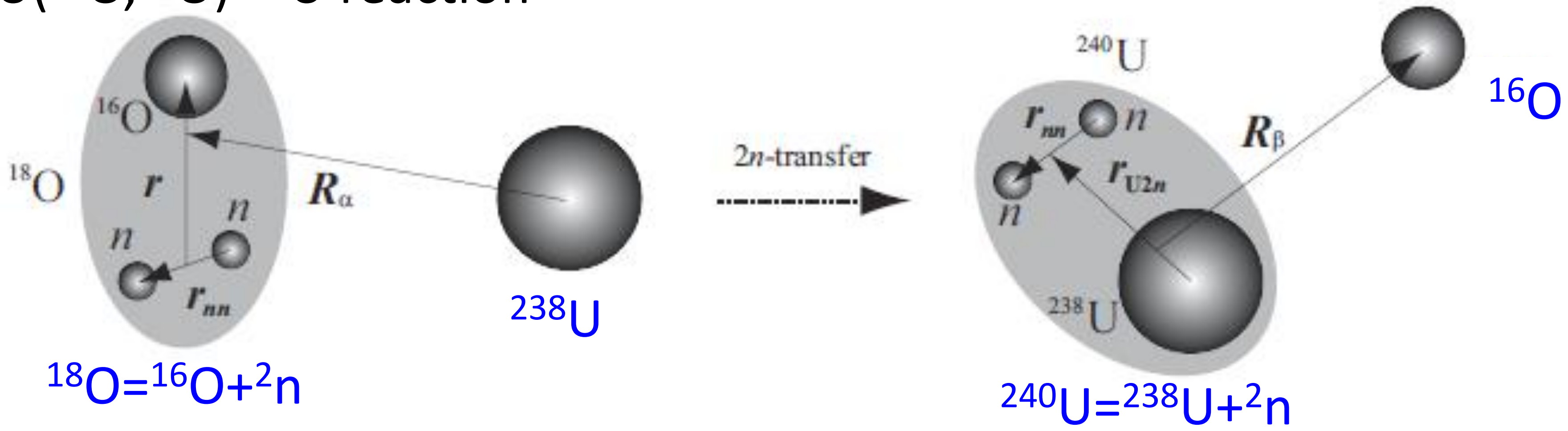
^{18}O + ^{238}U → ^{16}O + ^{240}U

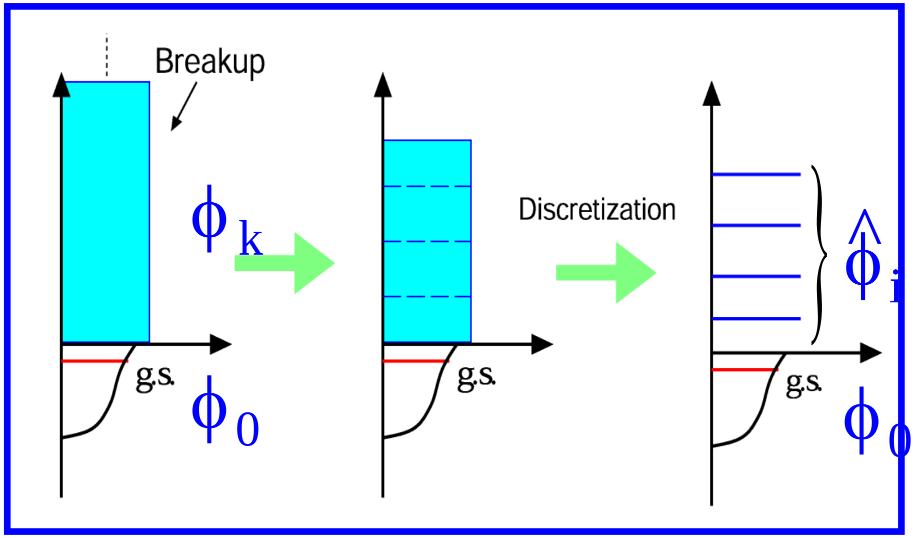
Y. Aritomo, SC and K. Nishio, PRC 84, 024602-1-10(2011).

Quantum mechanical calculation of 2 neutron transfer reactions by CDCC-BA

K. Ogata, S. Hashimoto and S.Chiba, J. Nucl. Sci. Technol. 48, 1337-1342(2011)

^{238}U(^{18}O,^{16}O)^{240}U reaction

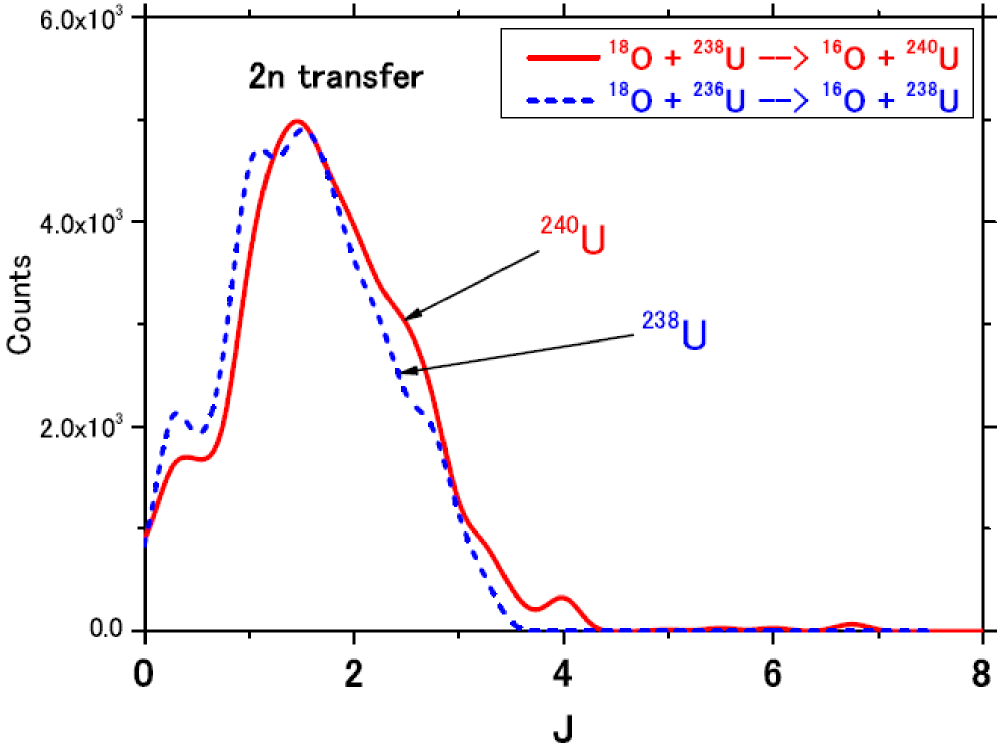




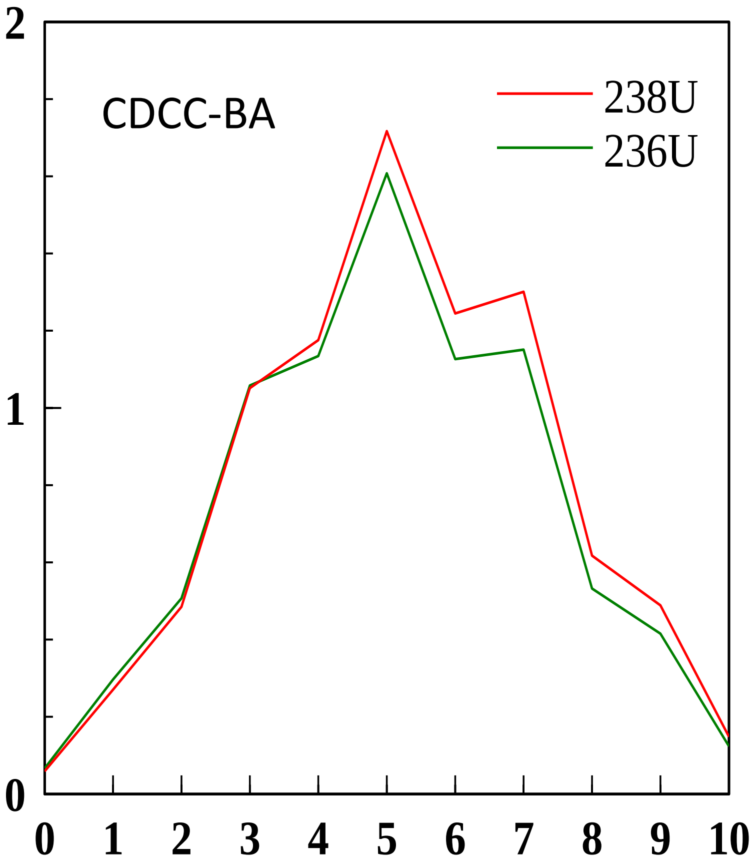
Breakup process of ^{18}O to ^{16}O + 2n was considered by the CDCC

J-distributions from (^{18}O,^{16}O) on ^{236}U, ^{238}U

Langevin



Y. Aritomo, S.Chiba and K. Nishio, Phys. Rev. C 84, 024602-1-10(2011).

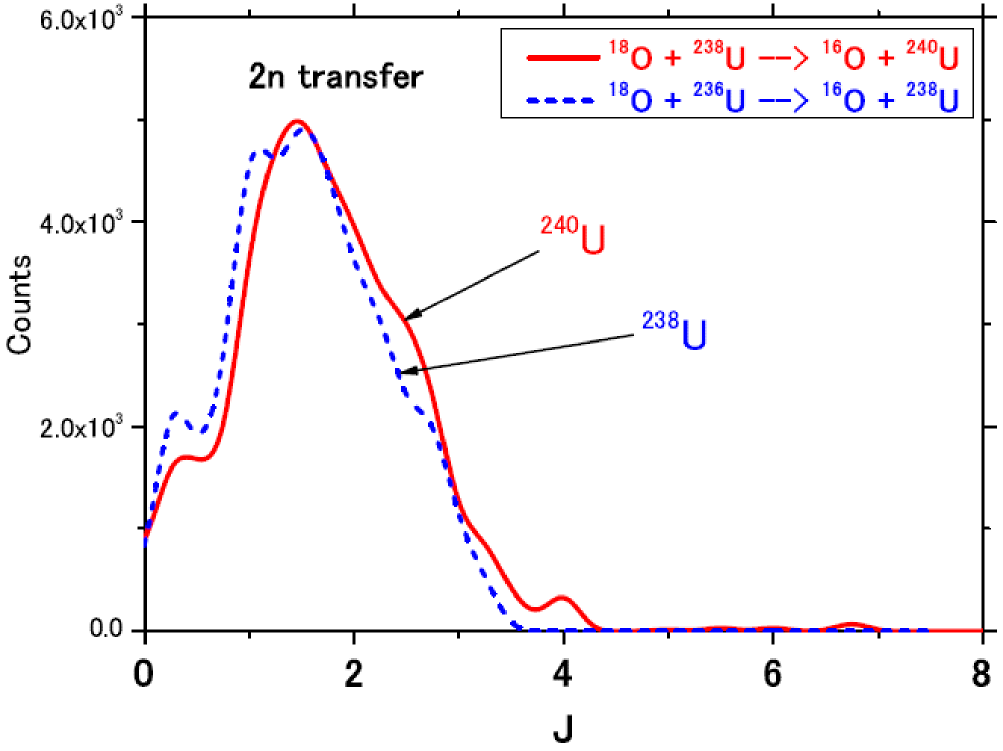


K. Ogata, S. Hashimoto and S.Chiba, JNST. 48, 1337-1342(2011).

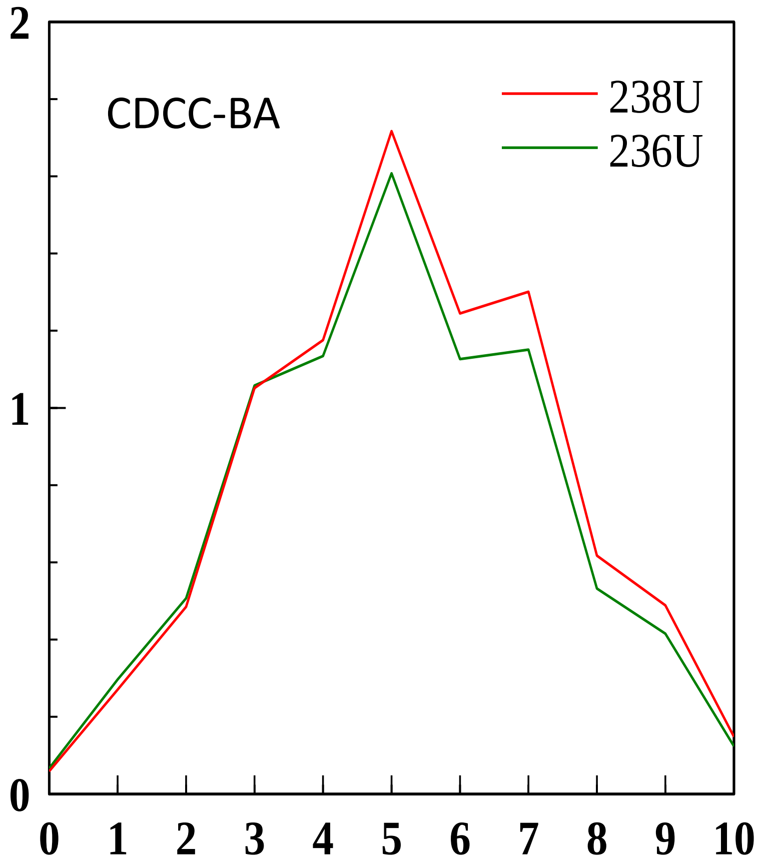
J-distributions from (^{18}O,^{16}O) on ^{236}U, ^{238}U

The assumption that $\sigma^{s1}(J^{\pi})$ and $\sigma^{s2}(J^{\pi})$ are proportional to each other seems to be quite reasonable even though these 2 theories predict different shape of the J-distribution

Langevin



Y. Aritomo, S.Chiba and K. Nishio, Phys. Rev. C 84, 024602-1-10(2011).



K. Ogata, S. Hashimoto and S.Chiba, JNST. 48, 1337-1342(2011).

Multi-dimensional Langevin Equation for nuclear fission

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

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

Friction dissipation

Newton equation

q_i: deformation coordinate (nuclear shape)

two-center parametrization (z,δ,α) (Maruhn and Greiner, Z. Phys. 251(1972) 431)

p_i: momentum conjugate to q_i

m_{ij} : Hydrodynamical mass (inertia mass)

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

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

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

Einstein relation Fluctuation-dissipation theorem

$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q) = aT^2$$

E_{int} : intrinsic energy, E^* : excitation energy

Neutron emission competition is taken into account

Multi-dimensional Langevin Equation for nuclear fission

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

Friction
dissipation

Random force
fluctuation

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

q_i: deformation coordinate (nuclear shape)

two-center parametrization (z, δ, α) (Maruhn and Greiner, Z. Phys. 251(1972) 431)

p_i: momentum conjugate to q_i

m_{ij} : Hydrodynamical mass (inertia mass)

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

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

$\sum_k g_{ik} g_{jk} = T\gamma_{ij}$ Einstein relation Fluctuation-dissipation theorem

$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q) = aT^2$$

E_{int} : intrinsic energy, E^* : excitation energy

Neutron emission competition is taken into account

Multi-dimensional Langevin Equation for nuclear fission

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

Friction dissipation

Random force fluctuation

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

q_i: deformation coordinate (nuclear shape)

two-center parametrization (z, δ, α) (Maruhn and Greiner, Z. Phys. 251(1972) 431)

p_i: momentum conjugate to q_i

m_{ij} : Hydrodynamical mass (inertia mass)

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

Needs for microscopic treatment of transport coefficients

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

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

Einstein relation

Fluctuation-dissipation theorem

$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q) = aT^2$$

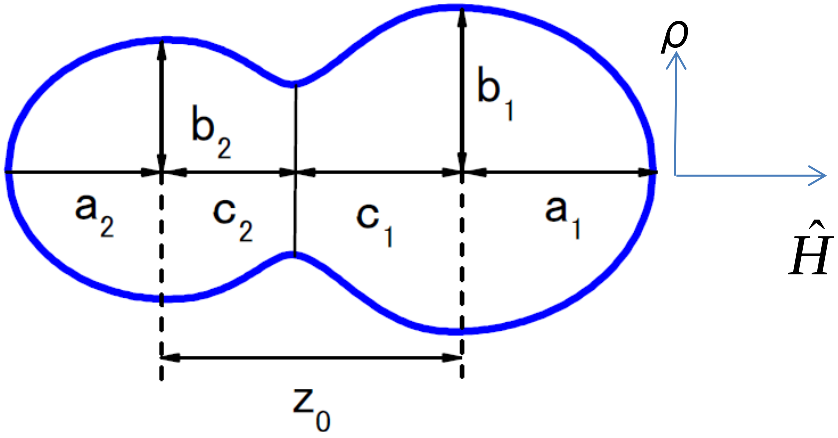
E_{int} : intrinsic energy, E^* : excitation energy

Neutron emission competition is taken into account

Shape parametrization and potential V : 2-center shell model

Shape parametrization

J. Maruhn and W. Greiner, Z. Phys, 1972



$$\hat{H} = -\frac{\hbar^2}{2m_0}\nabla^2 + V(\mathbf{r}) + V_{\mathrm{LS}}(\mathbf{r},\mathbf{p},\mathbf{s}) + V_{\mathrm{L}^2}(\mathbf{r},\mathbf{p}).$$

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

Normalized inter-fragment distance

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

$R :$ Radium of compound nucleus

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

Deformation of each fragment

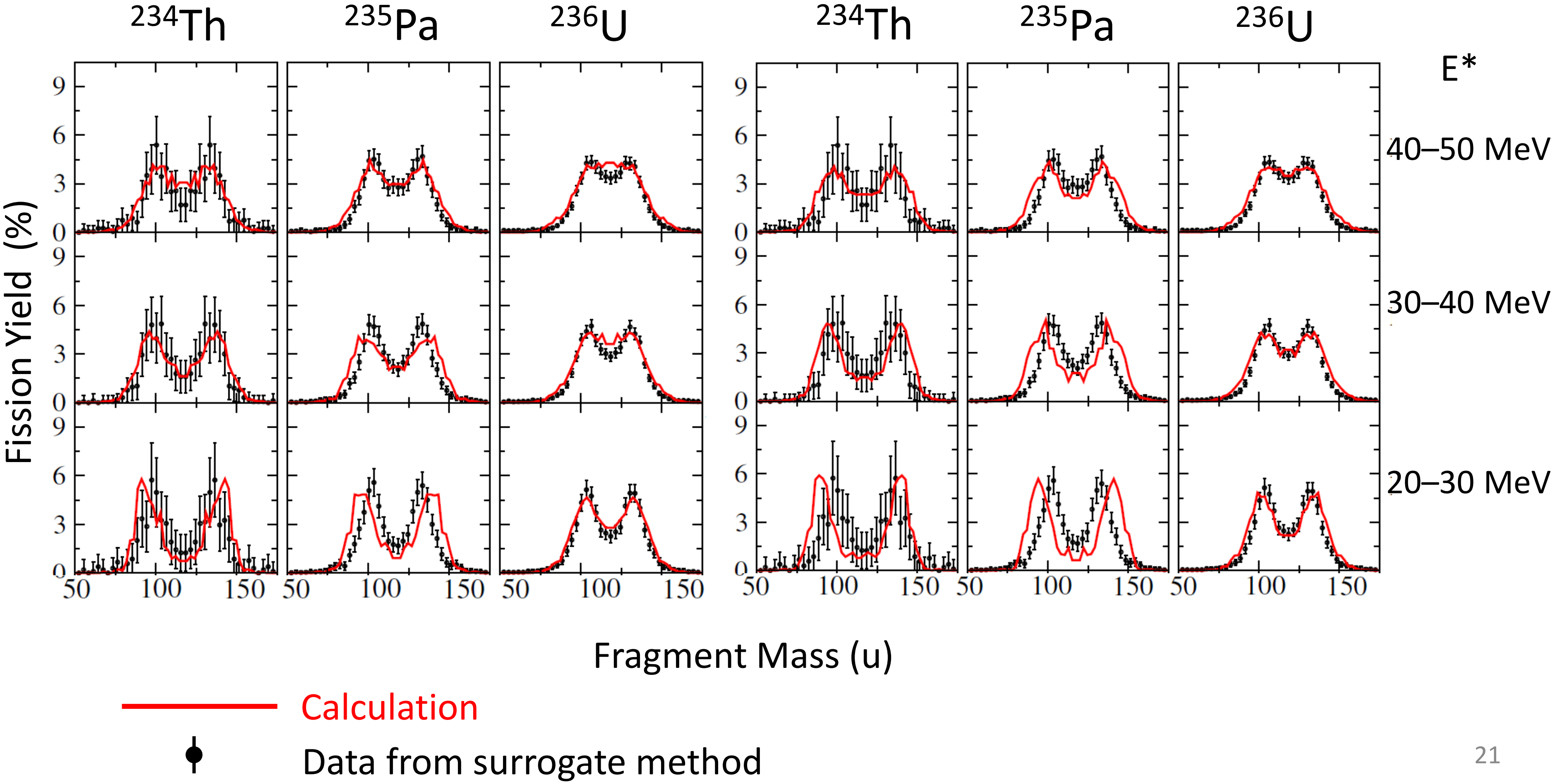
$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$

Mass asymmetry

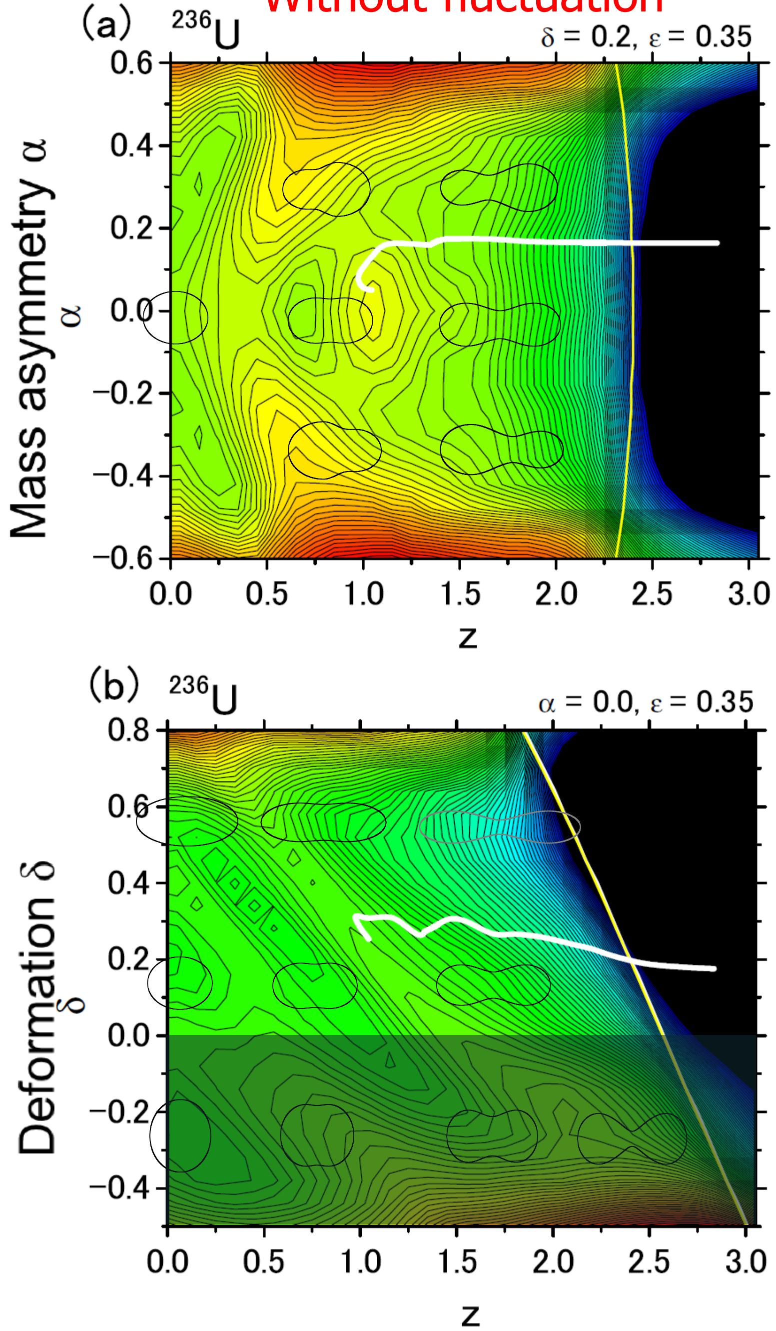
$$V(\rho,z) = \frac{1}{2}m_0 \begin{cases} \omega_{z1}^2 z'^2 + \omega_{\rho 1}^2 \rho^2, \quad z < z_1 \\ \omega_{z1}^2 z'^2 \left(1 + c_1 z' + d_1 z'^2\right) + \omega_{\rho 1}^2 \left(1 + g_1 z'^2\right)\rho^2, \\ \quad z_1 < z < 0 \\ \omega_{z2}^2 z'^2 \left(1 + c_2 z' + d_2 z'^2\right) + \omega_{\rho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

$$z' = \begin{cases} z - z_1 & z < 0 \\ z - z_2 & z > 0 \end{cases}$$

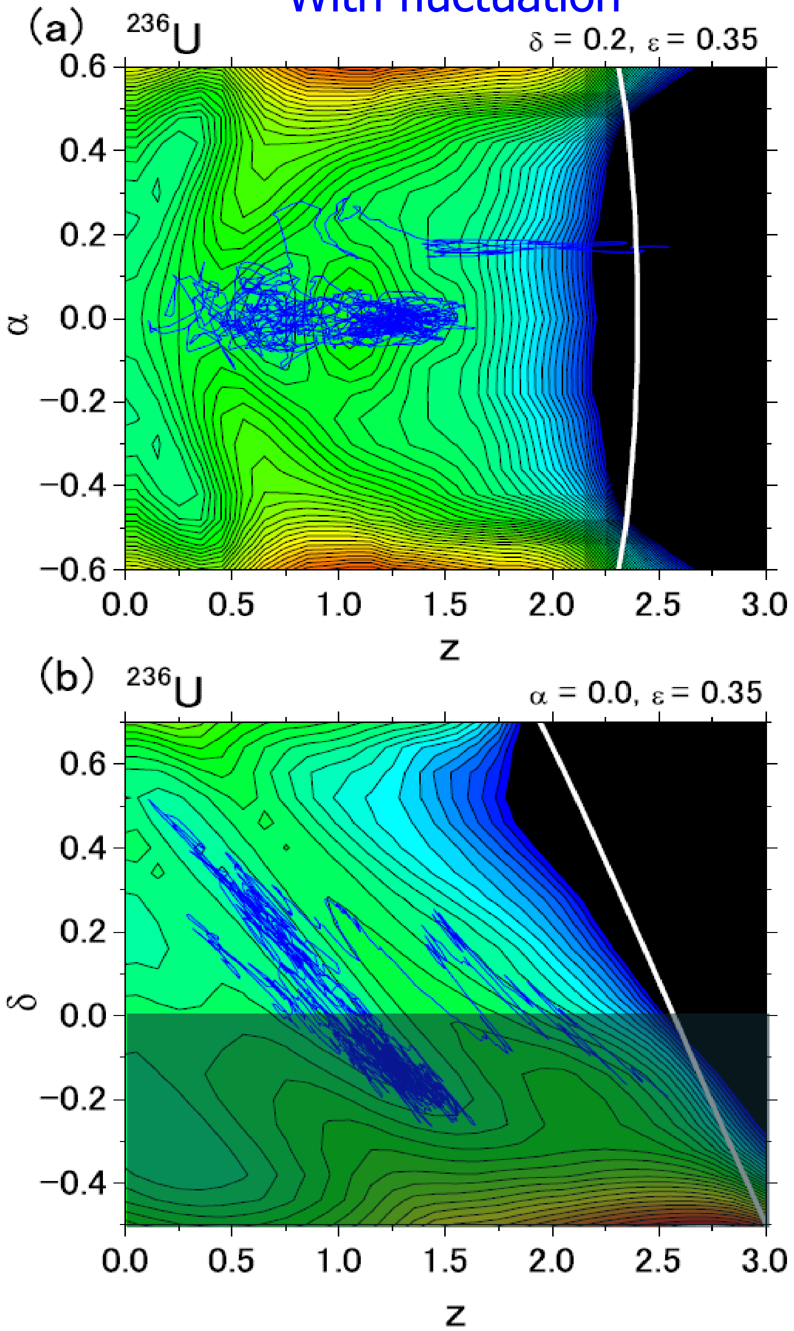
Comparison of measured (by surrogate method) and Langevin calculation



Without fluctuation



With fluctuation

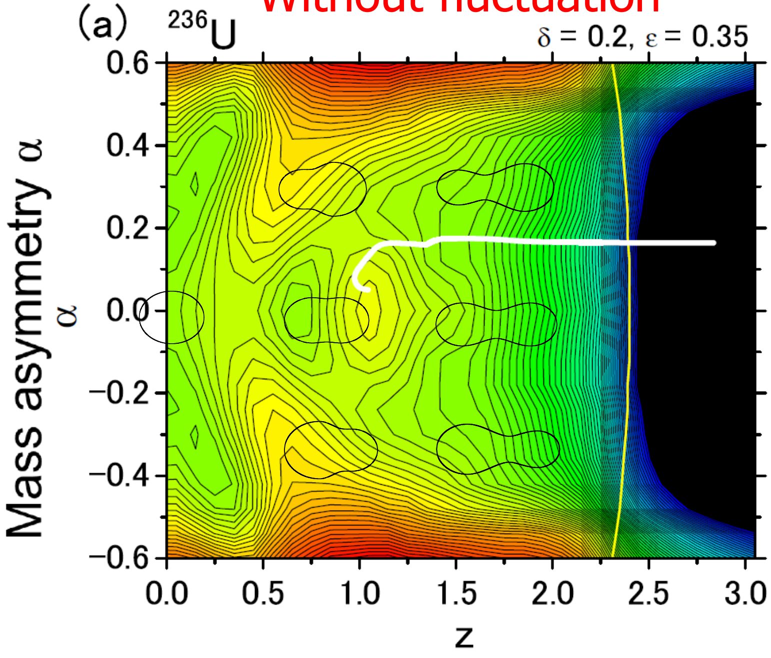


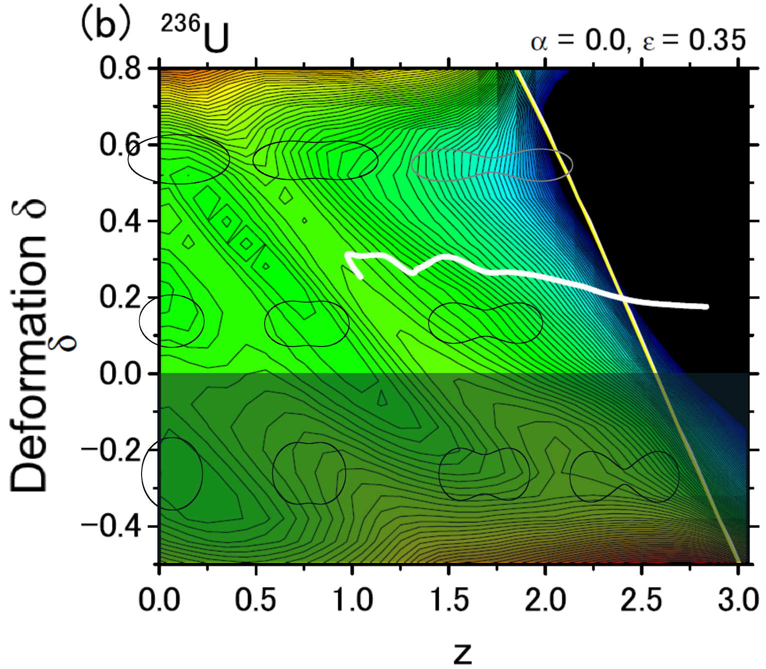
Projection on two-dim. plan

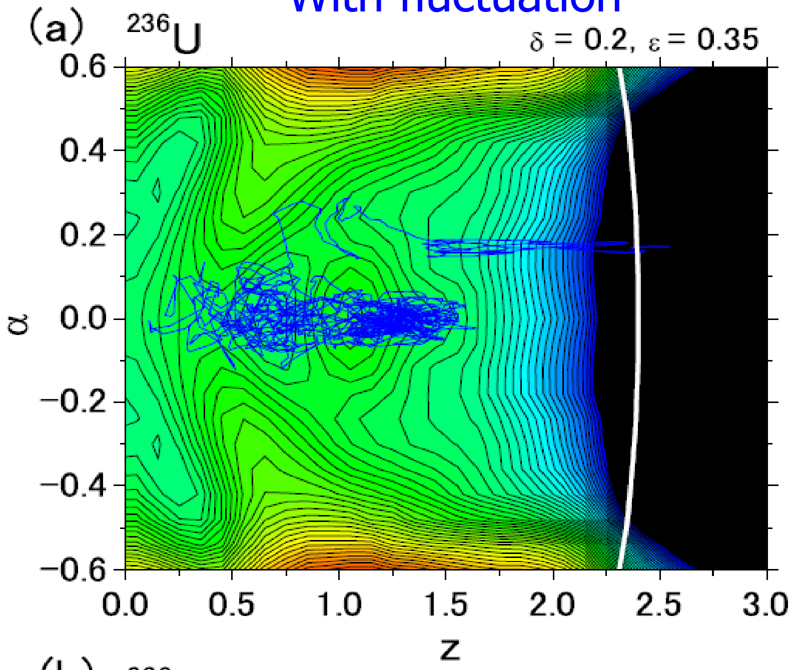
Without fluctuation

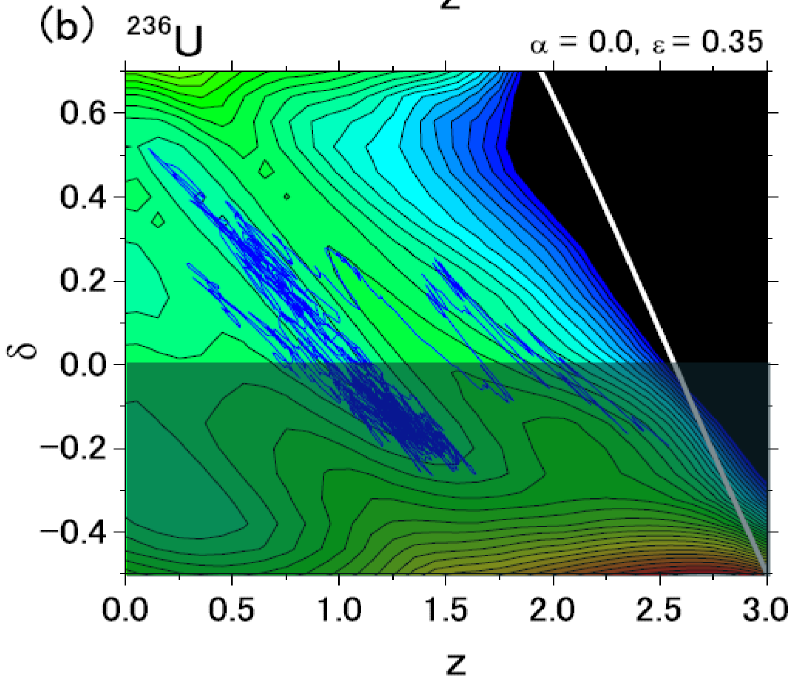
With fluctuation

Projection on two-dim. plan



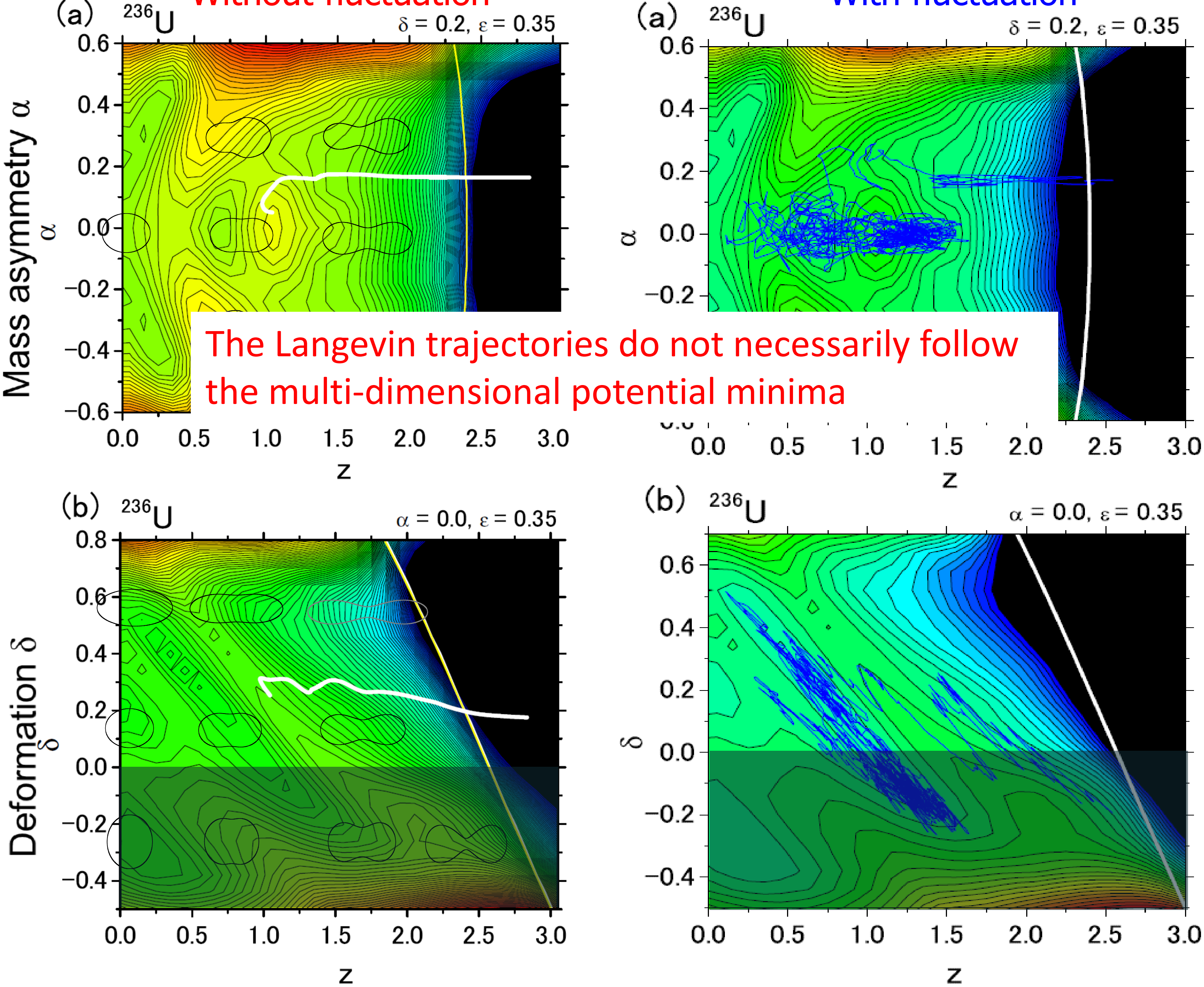






Without fluctuation

With fluctuation



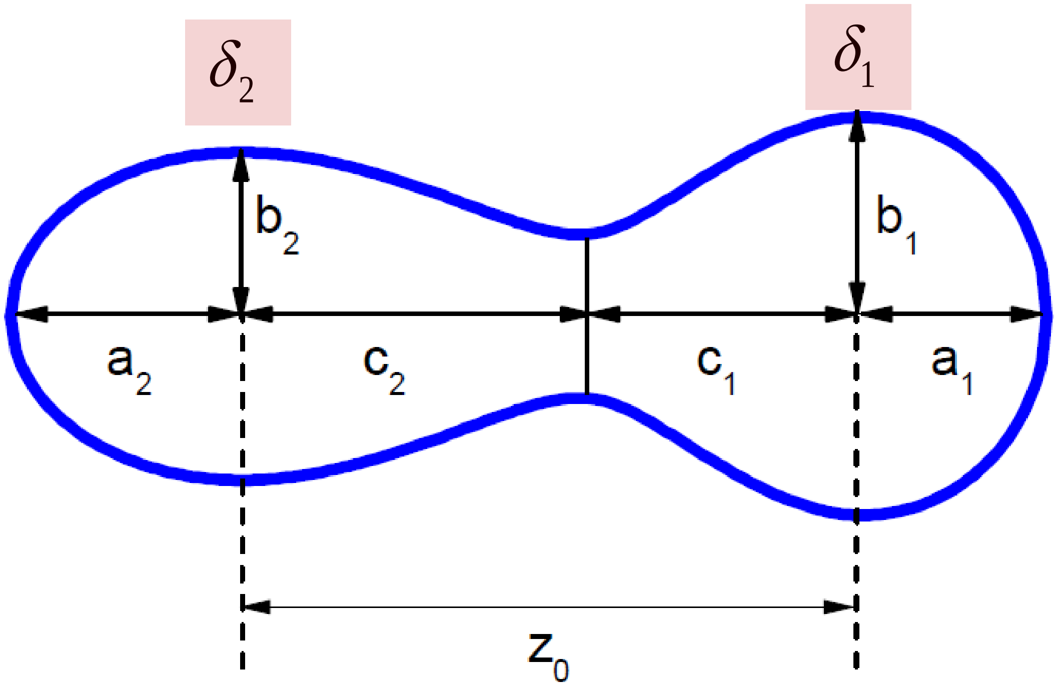
The Langevin trajectories do not necessarily follow the multi-dimensional potential minima

Projection on two-dim. plan

4-dimensional calculation

2 center shell model
(Maruhn and Greiner,
Z. Phys. 251(1972) 431)

$$q(z,\delta_1,\delta_2,\alpha)$$



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

$$B = \sqrt{B_1 B_2}$$

$$B_1 = \frac{3+\delta_1}{3-2\delta_1}, \quad B_2 = \frac{3+\delta_2}{3-2\delta_2}$$

R Radius of compound nucleus

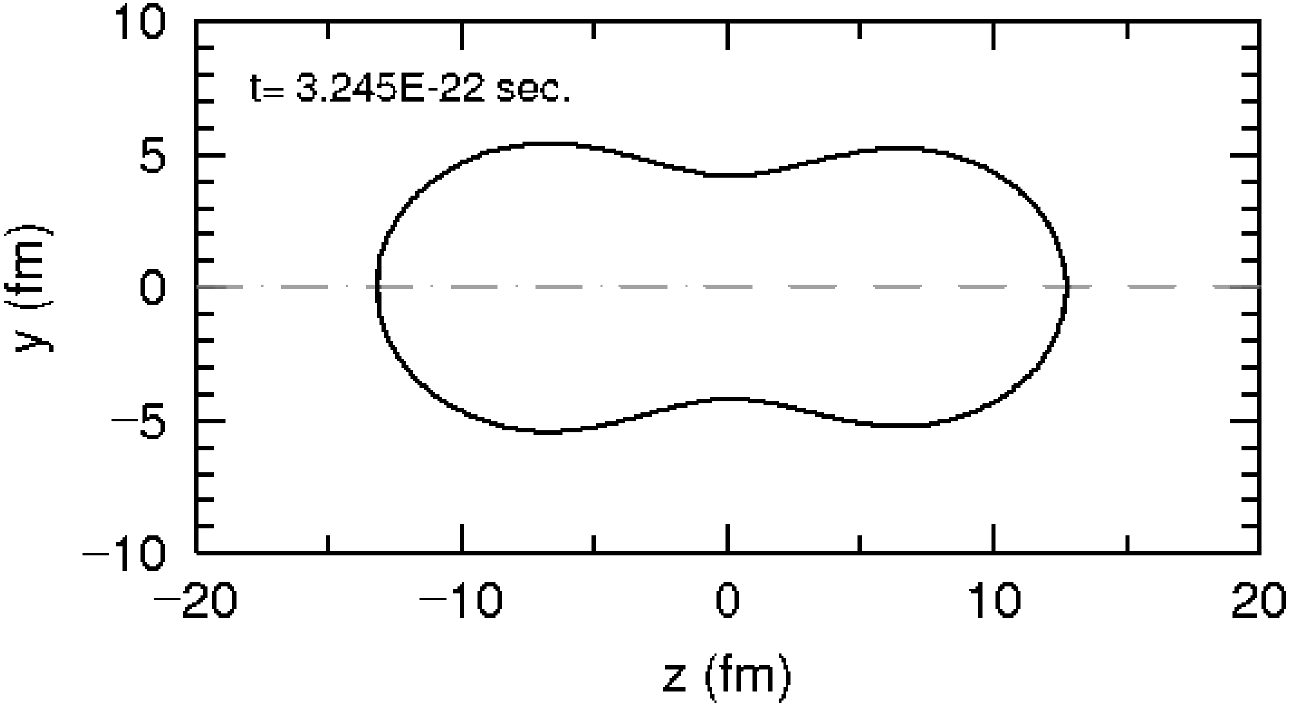
$$\delta 1 = \frac{3(a_1-b_1)}{2a_1+b_1}, \quad \delta 2 = \frac{3(a_2-b_2)}{2a_2+b_2}$$

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

$$V(q,\ell,T) = V_{DM}(q) + \frac{\hbar^2 \ell(\ell+1)}{2I(q)} + V_{SH}(q,T)$$

Time evolution by 4-dimensional Langevin calculation

^{236}U E^{*}=20 MeV



Fission dynamics by TDDFT

with Y. Iwata (CNS, Univ. Tokyo)

- Functional form of TDDFT (TDHF)

  = time-dependent density functional theory

  _ it covers light to heavy-mass nuclei

  ~ no fitting parameter w.r.t. dynamics

  _ shell effect is included (2,8,20,28, ...)

  ~ spin-orbit force is included

  _ it has never been succeeded to reproduce fission dynamics in the framework of TDDFT

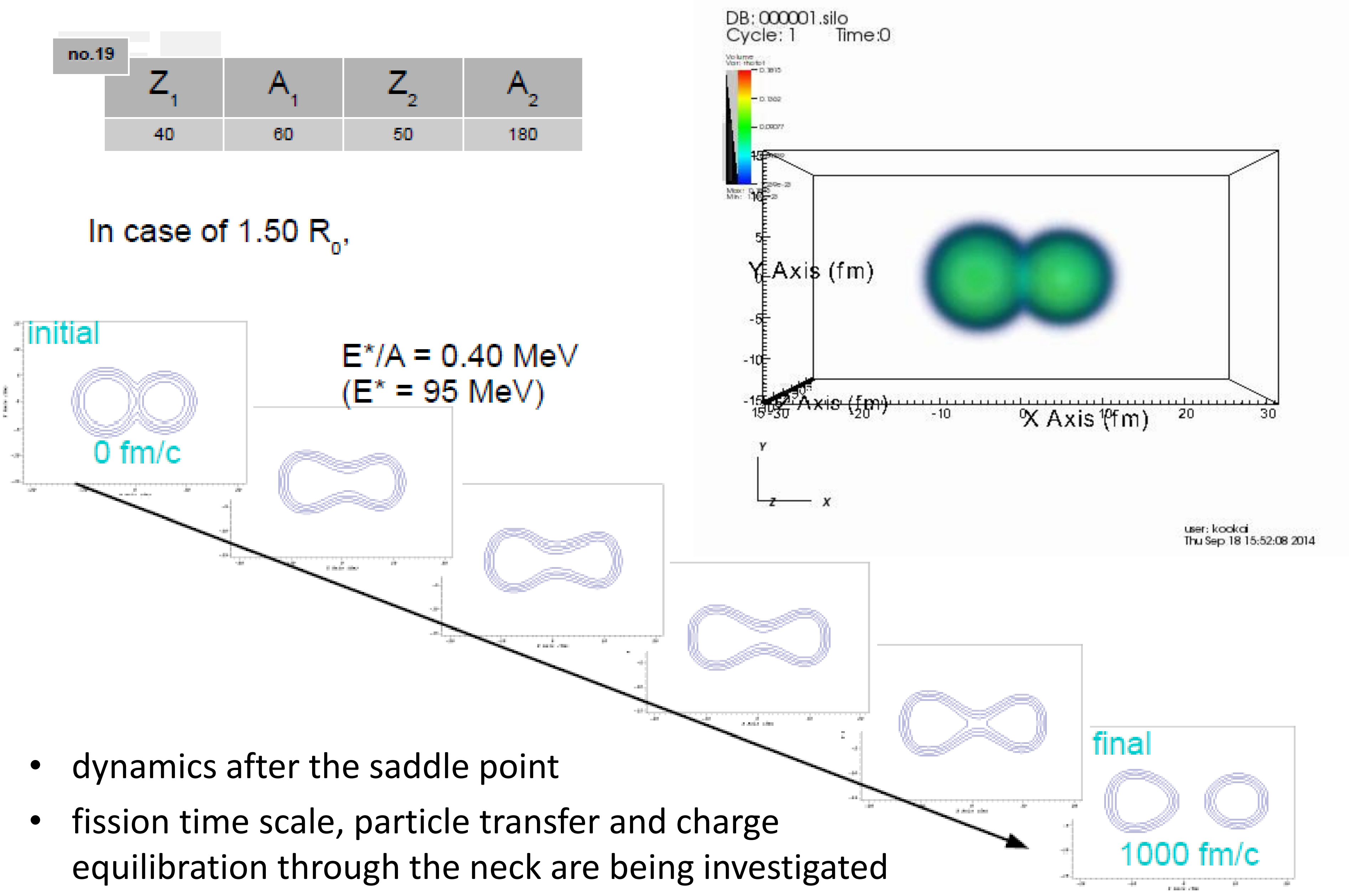
Abinitio-like reaction theory
accounting for nucleon degrees of freedom

TDDFT with SV-bas interaction

no.19

Z_1	A_1	Z_2	A_2
40	60	50	180

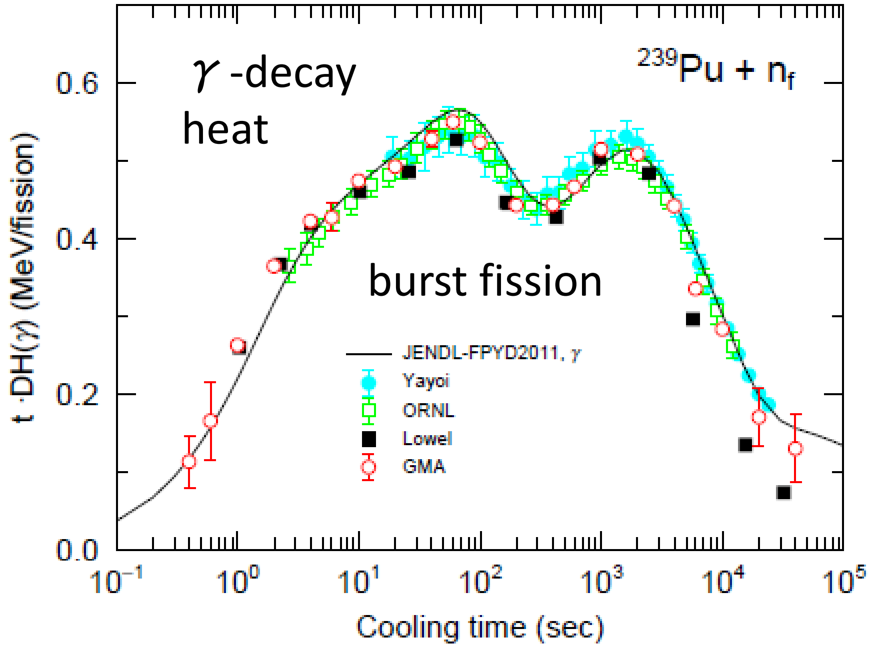
In case of 1.50 R_0,

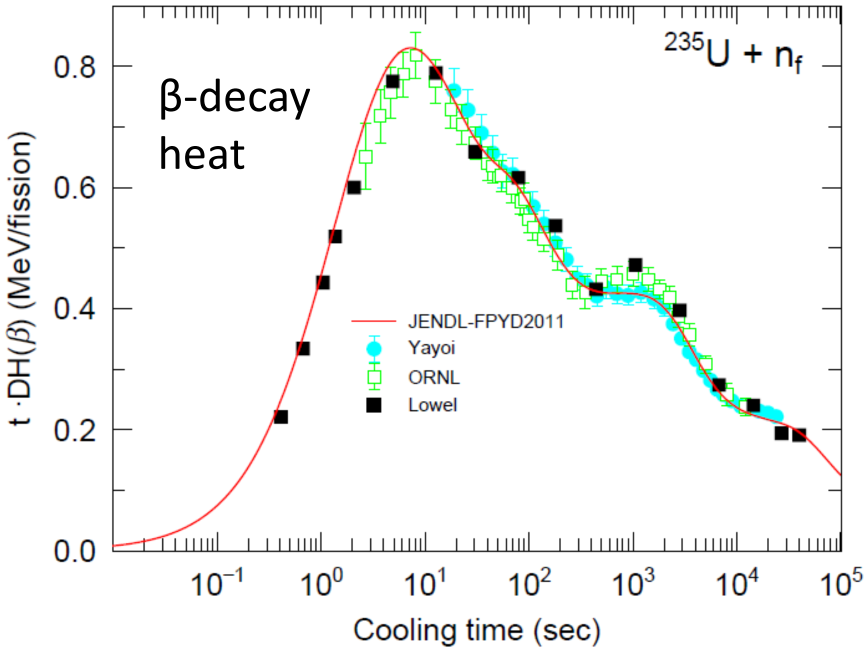


$E^*/A = 0.40$ MeV
($E^* = 95$ MeV)

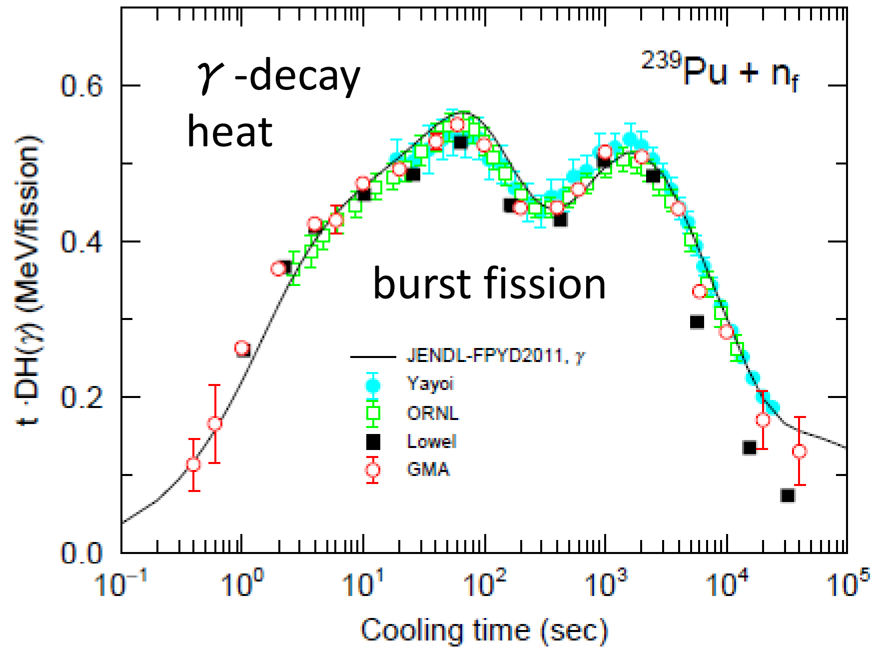
- dynamics after the saddle point
- fission time scale, particle transfer and charge equilibration through the neck are being investigated

Summation calculation of decay heat and emission of delayed neutron

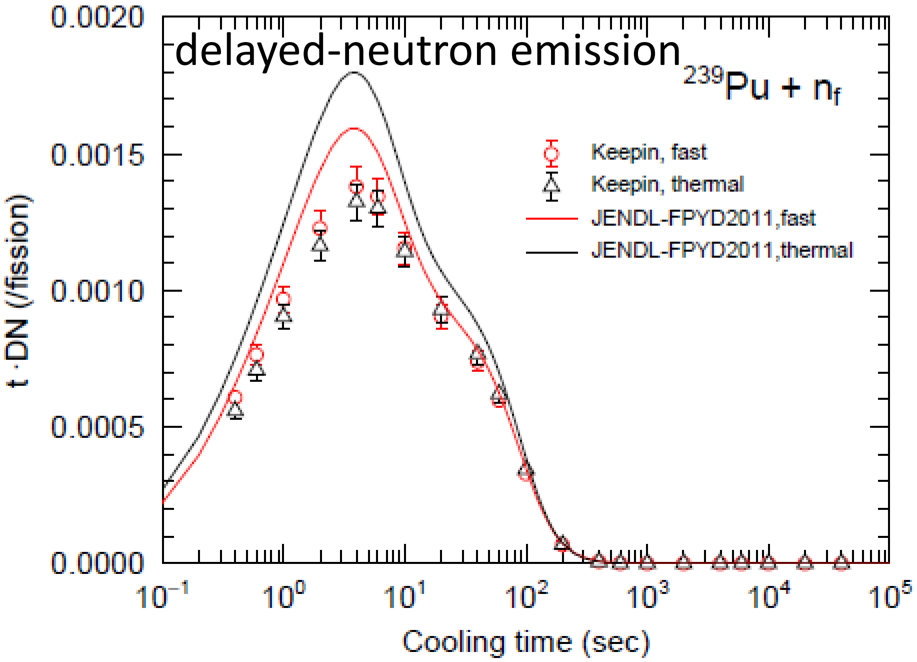


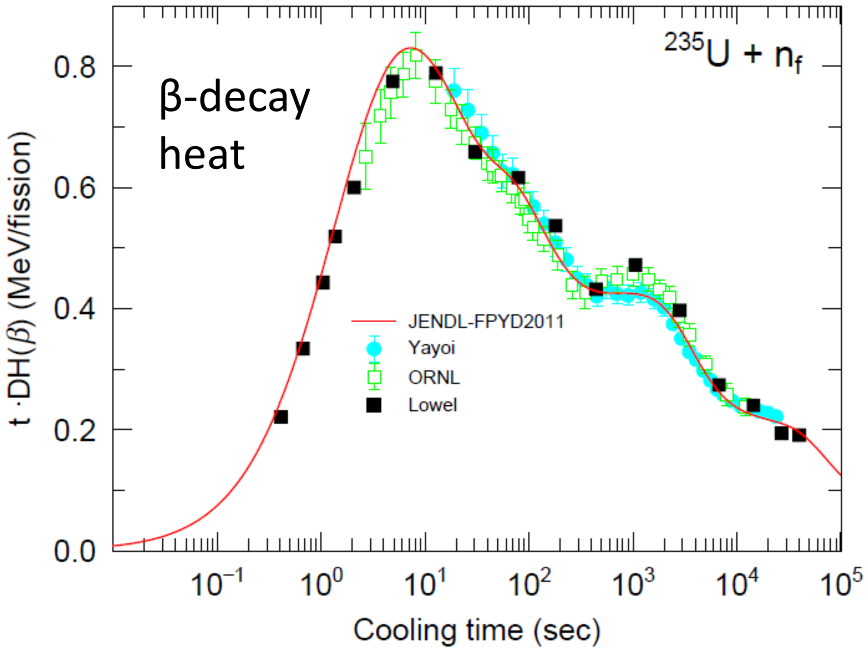


Summation calculation of decay heat and emission of delayed neutron

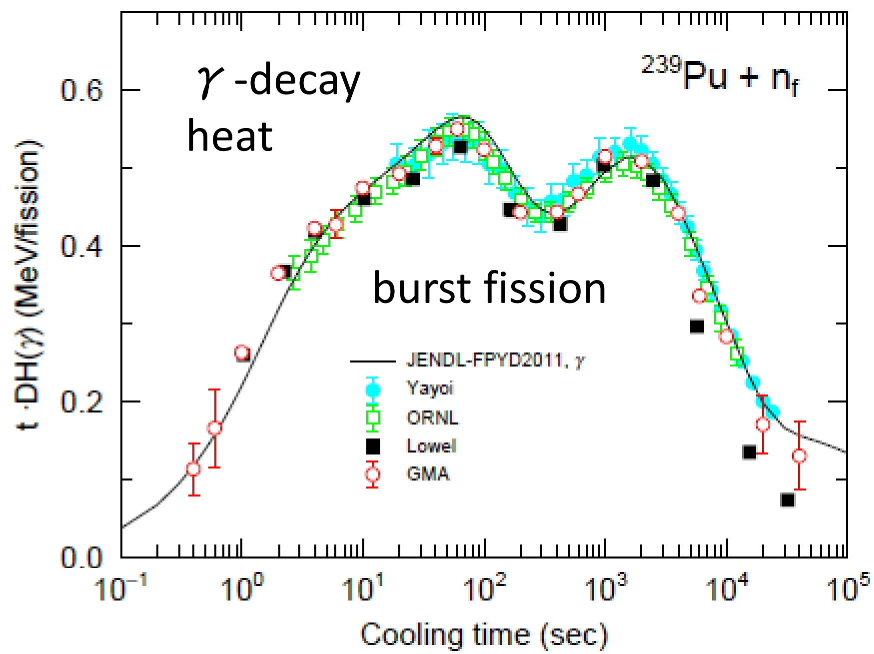

γ -decay heat

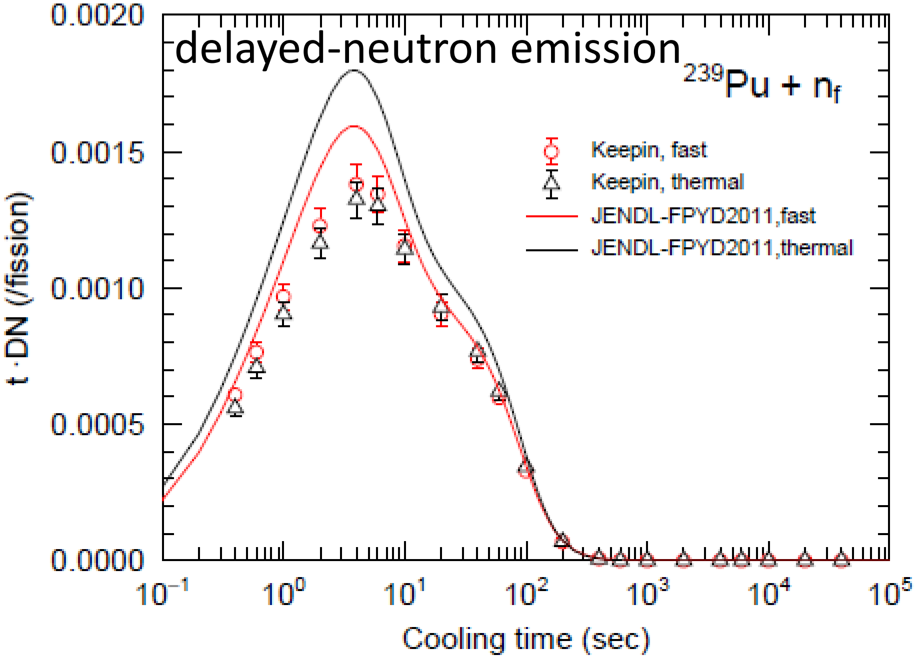
burst fission

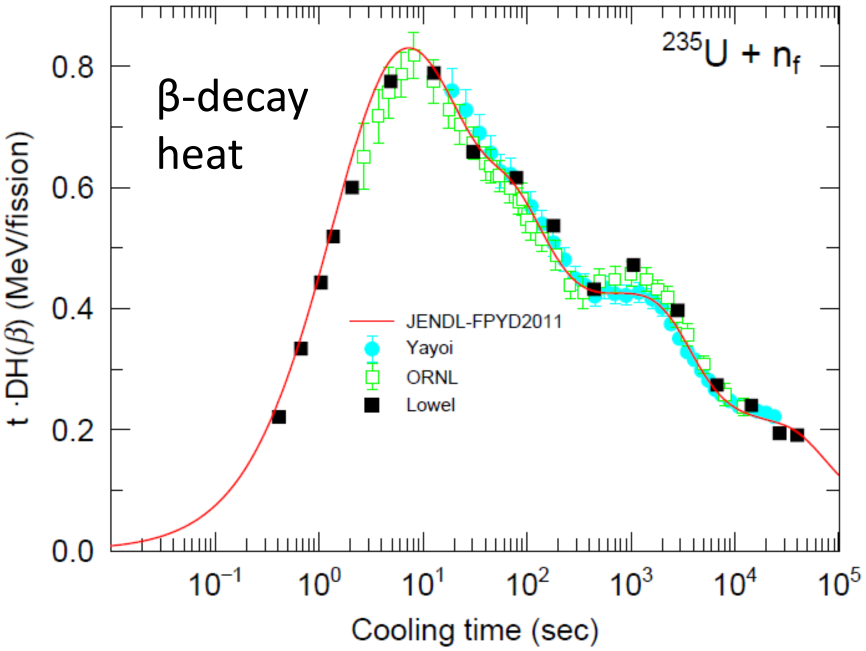

delayed-neutron emission

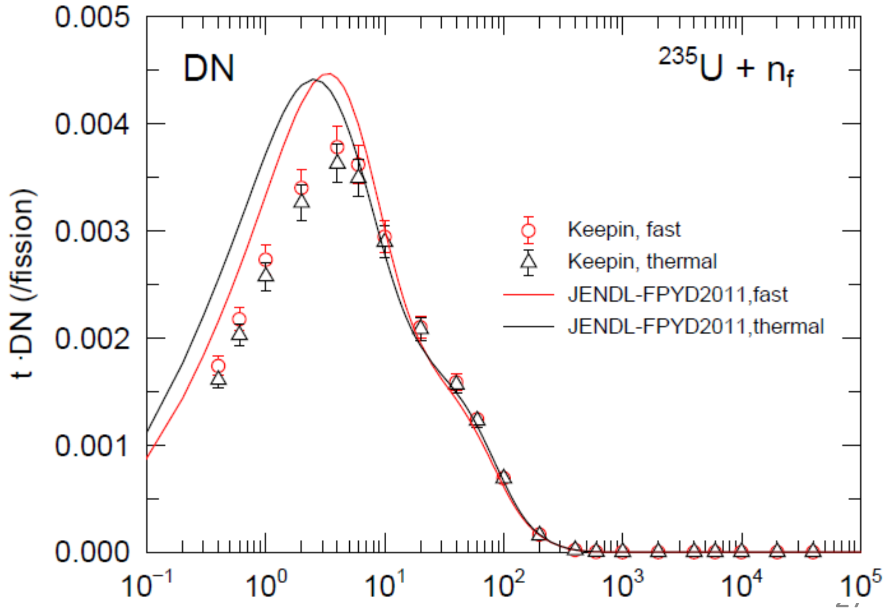

β-decay heat

Summation calculation of decay heat and emission of delayed neutron

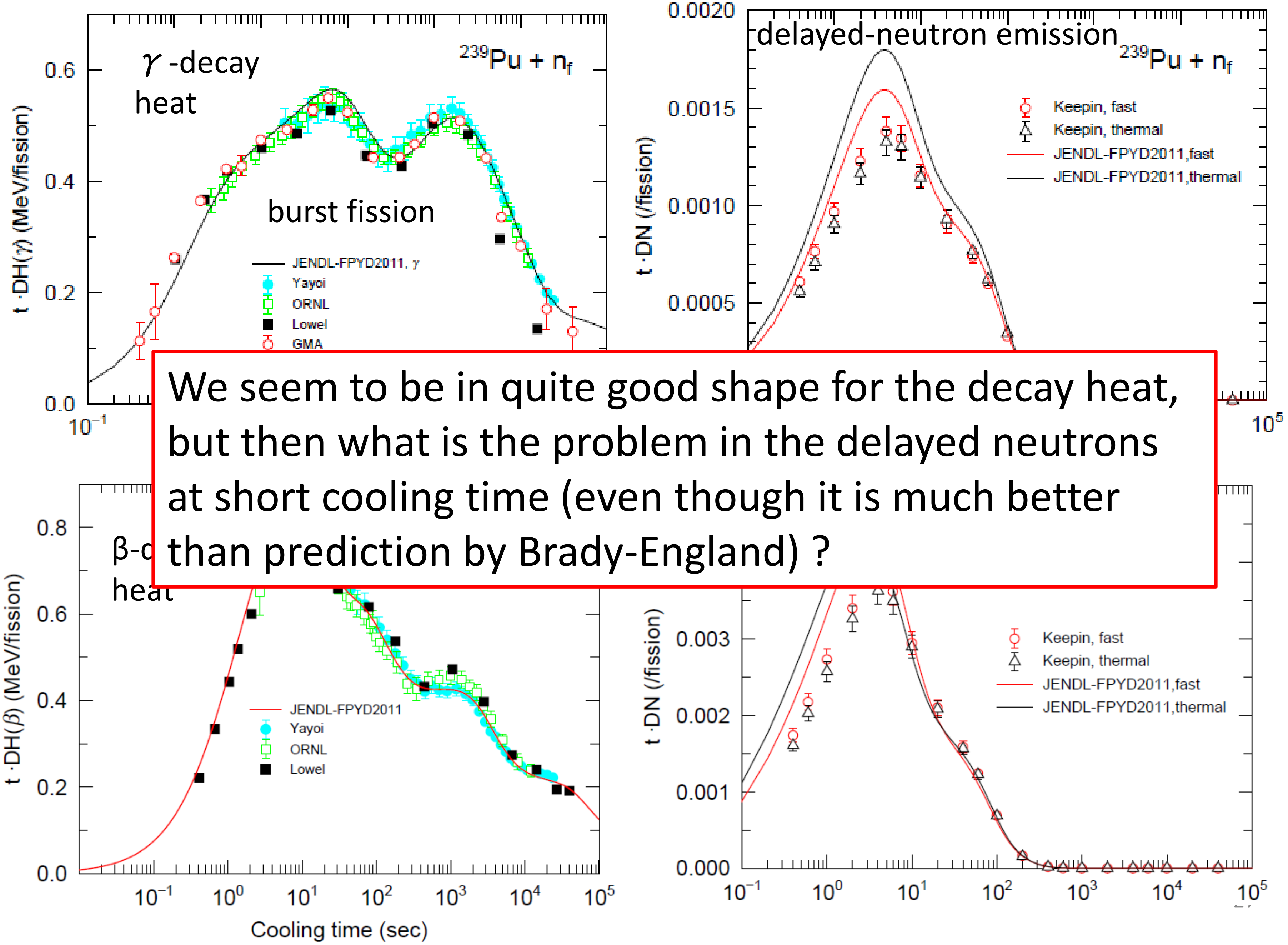








Summation calculation of decay heat and emission of delayed neutron



We seem to be in quite good shape for the decay heat, but then what is the problem in the delayed neutrons at short cooling time (even though it is much better than prediction by Brady-England) ?

Summary

- Foundation of the surrogate method must be given more firmly : better understanding of multi-nucleon transfer reactions is necessary
- Microscopic methods such as TDDFT, which have less assumptions w.r.t. dynamics, will be of great help for future work even though phenomenological methods such as Langevin equation will still be important tools for realistic calculation of fission
- Properties of fission related quantities : fission fragment yields, emission of prompt and delayed neutrons, β-ray and antineutrinos must be quantified better especially for the region of most neutron-rich fission fragments