Perspectives of research and education in nuclear data after Fukushima

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• Background
• Some topics on the surrogate method
• Dynamical treatment of fission by Langevin equation and TDDFT
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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. $n + ^{239}\text{U}$) and its surrogate reaction $^{238}\text{U}(^{18}\text{O},^{16}\text{O})^{240}\text{U}$

$n$ $^{239}\text{U}$ ($T_{1/2}=23.5$ m)
S.M. with heavy projectile: Desired neutron reaction (ex. $n + ^{239}\text{U}$) and its surrogate reaction $^{238}\text{U}(^{18}\text{O},^{16}\text{O})^{240}\text{U}$

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

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

$\text{n }^{239}\text{U } (T_{1/2}=23.5\text{m})$
S.M. with heavy projectile: Desired neutron reaction (ex. $n + ^{239}\text{U}$) and its surrogate reaction $^{238}\text{U}(^{18}\text{O},^{16}\text{O})^{240}\text{U}$
S.M. with heavy projectile: Desired neutron reaction (ex. $n + ^{239}U$) and its surrogate reaction $^{238}U(^{18}O, ^{16}O)^{240}U$

$^{238}U$ \rightarrow $^{18}O$ \rightarrow $^{239}U$ ( $T_{1/2} = 23.5$ m)
S.M. with heavy projectile: Desired neutron reaction (ex. n + $^{239}\text{U}$) and its surrogate reaction $^{238}\text{U}(^{18}\text{O},^{16}\text{O})^{240}\text{U}$

$^{18}\text{O} \rightarrow ^{238}\text{U}$

$^{238}\text{U} \rightarrow ^{16}\text{O}$

$^{16}\text{O} \rightarrow ^{240}\text{U}^*$

$^{240}\text{U}^* \rightarrow \text{Fission Fragment 1, FF 2}$

n $^{239}\text{U}$ ($T_{1/2}=23.5\text{m}$)
S.M. with heavy projectile: Desired neutron reaction (ex. n + $^{239}$U) and its surrogate reaction $^{238}$U($^{18}$O, $^{16}$O)$^{240}$U.

$^{238}$U

$^{18}$O

$^{16}$O

Decay properties of the same compound nuclei can be explored.
Fission Setup
Fission Setup

$^{18}$O beam
Fission Setup

$^{18}\text{O}$ beam

target ($^{238}\text{U}$, $^{232}\text{Th}$, $^{248}\text{Cm}$, $^{237}\text{Np}$)
Fission Setup

$^{18}\text{O}$ beam

MWPC

target ($^{238}\text{U}$, $^{232}\text{Th}$, $^{248}\text{Cm}$, $^{237}\text{Np}$)
Fission Setup

$^{18}$O beam

Si ΔE-E detector

MWPC

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

- $^{18}$O beam
- MWPC
- Neutron counters (NE213)
- Si $\Delta E$-$E$ detector
- Target ($^{238}$U, $^{232}$Th, $^{248}$Cm, $^{237}$Np)
Spectra of projectile-like ejectiles measured by the $\Delta$E-E detector

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

$\Delta E = 1$, Strip = 8

900 keV (FWHM)

Stripping reactions are favored significantly than pick-up reactions!!
Spectra of projectile-like ejectiles measured by the ΔE-E detector

\[^{18}\text{O} + ^{238}\text{U} \ (E_{\text{beam}}=162 \text{ MeV})\]

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Spectra of projectile-like ejectiles measured by the $\Delta E$-$E$ detector

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Stripping reactions are favored significantly than pick-up reactions!!
Spectra of projectile-like ejectiles measured by the $\Delta E$-E detector

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

$900$ keV (FWHM)

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

$^{240,239,238,237}\text{U}^*$
- $n + ^{239}\text{U}$ (23.5 min)
- $n + ^{237}\text{U}$ (6.8 day)

$^{242,241,240,239}\text{Np}^*$
- $n + ^{241}\text{Np}$ (13.9 min)
- $n + ^{240}\text{Np}$ (65 min)
- $n + ^{239}\text{Np}$ (2.4 day)
- $n + ^{238}\text{Np}$ (2.1 day)

$^{244,243,242,241,240}\text{Pu}^*$
- $n + ^{243}\text{Pu}$ (4.9 hr)
- $n + ^{241}\text{Pu}$ (14 yr)
Spectra of projectile-like ejectiles measured by the $\Delta E$-$E$ detector

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

900 keV (FWHM)

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

$^{240,239,238,237}\text{U}^*$
- $n + ^{239}\text{U}$ (23.5 min)
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- $n + ^{241}\text{Np}$ (13.9 min)
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$^{244,243,242,241,240}\text{Pu}^*$
- $n + ^{243}\text{Pu}$ (4.9 hr)
- $n + ^{241}\text{Pu}$ (14 yr)
Some preliminary results on (n,f) reactions

$^{239}\text{U}(n,f)$

$T_{1/2} = 23.5\text{m}$

$^{240}\text{Np}(n,f)$

$T_{1/2} = 65\text{min}$

$^{236}\text{Pu}(n,f)$

$T_{1/2} = 2.9\text{y}$

$^{239}\text{Np}(n,f)$

$T_{1/2} = 2.4\text{day}$

$T_{1/2} = 23.5\text{m}$

$T_{1/2} = 65\text{min}$

$T_{1/2} = 2.9\text{y}$

$T_{1/2} = 2.4\text{day}$
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

Mass yield (%)

Mass (u)

Excitation energy (MeV)

239\textsuperscript{U}\textsuperscript{*}

Ex = 10–20 MeV

Ex = 20–30 MeV

Ex = 30–40 MeV

Ex = 40–50 MeV

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

239U*

Mass (u)

Excitation energy (MeV)

Ex = 10–20 MeV

Ex = 20–30 MeV

Ex = 30–40 MeV

Ex = 40–50 MeV

V.D. Simutkin et al.
Nuclear Data Sheets 119(2014)331
Number of prompt fission neutrons from $^{239}\text{Np}^*$

![Graph showing the number of prompt fission neutrons from $^{239}\text{Np}^*$ as a function of excitation energy. The graph includes data points and a trend line labeled "Preliminary."
Number of prompt fission neutrons from $^{239}\text{Np}^*$

$B_n = 6.21$ MeV

$\nu_{th} = 2.51$

$^{238}\text{Np}(n_{th,f})$
Number of prompt fission neutrons from $^{239}\text{Np}^*$

$^{239}\text{Np}^* (sf) \ \nu_{sf} = 2.06$

$^{238}\text{Np} (n_{th,f}) \ \nu_{th} = 2.51$

$B_n = 6.21$ MeV

Preliminary
Hauser-Feshbach formula and surrogate method

\[ \sigma_{\alpha \alpha'}(E_x) = \sum_{J = \text{mod}(I+s,1)} \sum_{J+I} \sum_{j+s} \sum_{J+I'} \sum_{j'+s'} \delta_\pi \delta_{\pi'} D \frac{\pi}{k_\alpha^2} \frac{2J+1}{(2I+1)2s+1} T_{alg}^J(E_\alpha) \]

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

\[ \int_{E_x + \Delta E}^{E_x} \rho(E_{x'}, J^\pi) T_{\alpha' l' j'}^J(E_{\alpha'}) dE_{x'} \]

\[ \times \]

\[ \sum_{\alpha'' l'' j''} \int_{E_x}^{E_{x\text{max}}} \rho(E_{x''}, J^\pi) T_{\alpha'' l'' j''}^J(E_{\alpha''}) dE_{x''} \]

Decay branching ratio

\[ R_f^\alpha(\varepsilon_\alpha, J, \pi) \]

Conservation laws

\[ E_\alpha + S_\alpha = E_{\alpha'} + E_x + S_\alpha \]

\[ s + I + l = s' + I' + l' = J \]

\[ \pi_\alpha \pi_i(-)^l = \pi_\alpha \pi_f(-)^{l'} = \pi \]
Hauser-Feshbach formula and surrogate method

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

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

\[
\int_{E_x - \Delta E}^{E_x + \Delta E} \rho(E_{x'}, J^\pi) T^J_{\alpha' \alpha} (E_{x'}) dE_{x'}
\]

\[
\sum \delta_{\pi'' \pi'''} \int_{E_{x''} - \Delta E}^{E_{x''} + \Delta E} \rho(E_{x''}, J^\pi) T^J_{\alpha'' \alpha'} (E_{x''}) dE_{x''}
\]

Decay branching ratio

\[
R_f(\varepsilon, J, \pi)
\]

Conservation laws

\[
E_{\alpha} + S_{\alpha} = E_{\alpha'} + E_{x} + S_{\alpha}
\]

\[
s + I + l = s' + I' + l' = J
\]

\[
\pi_{\alpha \pi_i} (-)^l = \pi_{\alpha' \pi_f} (-)^{l'} = \pi
\]
Justification of s.r.m.: Branching ratio of $^{239}\text{U}^*$
Justification of s.r.m.: Branching ratio of $^{239}\text{U}^*$

Fission probability of U-238+n positive parity states

$R^\alpha_f(\varepsilon_\alpha, J, \pi)$

Capture probability of U-238+n positive parity states

$R^\alpha_\gamma(\varepsilon_\alpha, J, \pi)$

factor of 5
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

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

10%

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

$^{239}$U*/$^{237}$U* $\rightarrow$ $^{238}$U(n,γ)/$^{236}$U(n,γ)
Justification of s.r.m.: Branching ratio of $^{239}\text{U}^*$

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

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

Ratio of branching ratios to fission

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

Ratio of branching ratios to capture

$$\frac{^{239}\text{U}/^{237}\text{U} \rightarrow ^{238}\text{U}(n,\gamma)/^{236}\text{U}(n,\gamma)}$$
Justification of s.r.m.: Branching ratio of $^{239}\text{U}^*$

Fission probability of U-238+n positive parity states

Capture probability of U-238+n positive parity states

\[ R_f^\alpha (\varepsilon_\alpha, J, \pi) \]

\[ R_\gamma^\alpha (\varepsilon_\alpha, J, \pi) \]

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

Ratio of branching ratios to fission

\[ \frac{^{239}\text{U}^*/^{237}\text{U}^*}{^{238}\text{U}(n,f)/^{236}\text{U}(n,f)} \]

Ratio of branching ratios to capture

\[ \frac{^{239}\text{U}^*/^{237}\text{U}^*}{^{238}\text{U}(n,\gamma)/^{236}\text{U}(n,\gamma)} \]

±5~10%
Justification of the Surrogate ratio method

SC, Iwamoto, PRC 81, 044604(2010)

\[ R^{S_1}_{\gamma} (\epsilon_n, J, \pi) = R^{S_2}_{\gamma} (\epsilon_n, J, \pi) \cdot \frac{R^{n_1}_{\gamma} (\epsilon_n)}{R^{n_2}_{\gamma} (\epsilon_n)} \]

: Weak Weisskopf-Ewing condition

\[ R^{S_1}_{\gamma} = \frac{\sum_{J^\pi} \sigma^{S_1}_{dir} (\epsilon_n, J, \pi) \cdot R^{S_1}_{\gamma} (\epsilon_n, J, \pi)}{\sum_{J^\pi} \sigma^{S_1}_{dir} (\epsilon_n, J, \pi)} = \frac{\sum_{J^\pi} \sigma^{S_1}_{dir} (\epsilon_n, J, \pi) \cdot R^{S_2}_{\gamma} (\epsilon_n, J, \pi) \cdot \frac{R^{n_1}_{\gamma} (\epsilon_n)}{R^{n_2}_{\gamma} (\epsilon_n)}}{\sum_{J^\pi} \sigma^{S_1}_{dir} (\epsilon_n, J, \pi)} \]

\[ = \frac{\sum_{J^\pi} \sigma^{S_2}_{dir} (\epsilon_n, J, \pi) \cdot R^{S_2}_{\gamma} (\epsilon_n)}{\sum_{J^\pi} \sigma^{S_2}_{dir} (\epsilon_n, J, \pi)} \cdot \frac{R^{n_1}_{\gamma} (\epsilon_n)}{R^{n_2}_{\gamma} (\epsilon_n)} = R^{S_2}_{\gamma} (\epsilon_n) \cdot \frac{R^{n_1}_{\gamma} (\epsilon_n)}{R^{n_2}_{\gamma} (\epsilon_n)} \]

\[ \Rightarrow R^{n_1}_{\gamma} (U) = \frac{R^{S_1}_{\gamma} (U)}{R^{S_2}_{\gamma} (U)} R^{n_2}_{\gamma} \]

If the J^\pi distribution in the 2 reactions employed in the SRM are equivalent (\(\sigma^{s_1}(J^\pi)\) and \(\sigma^{s_2}(J^\pi)\) are proportional), it gives the correct answer (under weak Weiskopf-Ewing condition)
Neutron capture cross sections (preliminary)  

\[ R_s = \frac{B^{S(Gd-157)}_{\gamma(E_n)}}{B^{S(Gd-159)}_{\gamma(E_n)}} \]

Ratio \( R_s \) of branching ratios to \( \gamma \) emission from \(^{157}\text{Gd}\) and \(^{159}\text{Gd}\) obtained by the surrogate reaction \(^{18}\text{O},^{16}\text{O}\) on 155 and 157Gd
Neutron capture cross sections (preliminary)

$$R_s = \frac{B^{S(Gd-157)}_\gamma(E_n)}{B^{S(Gd-159)}_\gamma(E_n)}$$

Ratio $R_s$ of branching ratios to $\gamma$ emission from $^{157}\text{Gd}$ and $^{159}\text{Gd}$ obtained by the surrogate reaction $(^{18}\text{O},^{16}\text{O})$ on $^{155}$ and $^{157}\text{Gd}$

$$R_s \times [^{158}\text{Gd}(n,\gamma)^{159}\text{Gd cross section}] =^{156}\text{Gd}(n,\gamma)^{157}\text{Gd cross section}$$
Neutron capture cross sections (preliminary)

\[ R^s = \frac{B^{S(Gd-157)}_{\gamma}(E_n)}{B^{S(Gd-159)}_{\gamma}(E_n)} \]

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

\[ R^s \times [^{158}\text{Gd}(n,\gamma)^{159}\text{Gd} \text{ cross section}] = ^{156}\text{Gd}(n,\gamma)^{157}\text{Gd} \text{ cross section} \]
Neutron capture cross sections (preliminary)

The ratio $R^s$ of branching ratios to $\gamma$ emission from $^{157}\text{Gd}$ and $^{159}\text{Gd}$ obtained by the surrogate reaction $(^{18}\text{O},^{16}\text{O})$ on $^{155}$ and $^{157}\text{Gd}$ is given by:

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

This can be expressed as:

$$R^s \times [^{158}\text{Gd}(n,\gamma)^{159}\text{Gd cross section}] = ^{156}\text{Gd}(n,\gamma)^{157}\text{Gd cross section}$$

The diagram shows the neutron cross section $^{156}\text{Gd}(n,\gamma)^{157}\text{Gd}$ as a function of $E_n$ (MeV). The data points represent measurements from ENDF/B-VII and the present work.
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.

\[
R_f^{S_1}(P + Q) = \frac{\sum Q \sigma^{S_1}(U, J^\pi) \cdot B_f^{S_1}(U, J^\pi)}{\sum (P + Q) \sigma^{S_1}(U, J^\pi)} \leq R_f^{S_1}(U) = \frac{\sum Q \sigma^{S_1}(U, J^\pi) \cdot B_f^{S_1}(U, J^\pi)}{\sum Q \sigma^{S_1}(U, J^\pi)}
\]
Cases when pre-equilibrium particle emission and breakup contamination coexist

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$$R_{f}^{S_1}(P+Q) = \frac{\sum_{J^\pi} Q\sigma_{S_1}^{S_1}(U, J^\pi) \cdot B_{f}^{S_1}(U, J^\pi)}{\sum_{J^\pi} (P+Q)\sigma_{S_1}^{S_1}(U, J^\pi)} \leq R_{f}^{S_1}(U) = \frac{\sum_{J^\pi} Q\sigma_{S_1}^{S_1}(U, J^\pi) \cdot B_{f}^{S_1}(U, J^\pi)}{\sum_{J^\pi} Q\sigma_{S_1}^{S_1}(U, J^\pi)}$$

Observable in s.r. quantity to be determined

$P$ is the probability that particles are emitted by preequilibrium.
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.

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

Observable in s.r.

• 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 $\sigma^{S_1} (J^\pi)$ and $\sigma^{S_2} (J^\pi)$ 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.

\[
R_f^{S_1}(P+Q) = \frac{\sum_{J^π} Q\sigma^{S_1}(U, J^π) \cdot B_f^{S_1}(U, J^π)}{\sum_{J^π} (P+Q)\sigma^{S_1}(U, J^π)} \leq R_f^{S_1}(U) = \frac{\sum_{J^π} Q\sigma^{S_1}(U, J^π) \cdot B_f^{S_1}(U, J^π)}{\sum_{J^π} Q\sigma^{S_1}(U, J^π)}
\]

Observable in s.r. quantity to be determined

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

and if \( \sigma^{S_1}(J^π) \) and \( \sigma^{S_2}(J^π) \) are proportional to each other, the following is valid even if there is a contamination by the pre-equilibrium and breakup reactions

\[
R_f^{S_1}(P+Q) = \frac{\sum_{J^π} (P+Q)\sigma^{S_1}(U, J^π)}{\sum_{J^π} (P+Q)\sigma^{S_2}(U, J^π)} = \frac{\sum_{J^π} Q\sigma^{S_1}(U, J^π) \cdot B_f^{S_1}(U, J^π)}{\sum_{J^π} Q\sigma^{S_1}(U, J^π) \cdot B_f^{S_2}(U, J^π)} = \frac{R_f^{n_1}(U)}{R_f^{n_2}(U)}
\]
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.

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

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 $\sigma^{S_1}(J^\pi)$ and $\sigma^{S_2}(J^\pi)$ are proportional to each other, the following is valid even if there is a contamination by the pre-equilibrium and breakup reactions

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

Observables in surrogate method quantity to be determined
Unified-model description of the surrogate reaction

$V_{\text{diabatic}}$

Potential energy surface
→ Two-center shell model
Dynamical effects
→ multi-dimensional Langevin calculation

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

Unified-model description of the surrogate reaction

$V_{\text{diabatic}}$

Potential energy surface

→ Two-center shell model

Dynamical effects

→ multi-dimensional Langevin calculation

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

Neutron emission

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

Unified-model description of the surrogate reaction

$$t > 10^{-21} \text{ sec} \quad V_{\text{adiabatic}}$$

Potential energy surface
→ Two-center shell model
Dynamical effects
→ multi-dimensional Langevin calculation

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

Neutron emission

Unified-model description of the surrogate reaction

\[ t > 10^{-21} \text{ sec} \quad V_{\text{adiabatic}} \]

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

Unified-model description of the surrogate reaction

t > 10^{-21} \text{ sec} \quad V_{\text{adiabatic}}

Potential energy surface
→ Two-center shell model
Dynamical effects
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Neutron emission

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


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

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

$^{18}\text{O} = ^{16}\text{O} + 2n$

$^{240}\text{U} = ^{238}\text{U} + 2n$
J-distributions from $(^{18}\text{O},^{16}\text{O})$ on $^{236}\text{U}$, $^{238}\text{U}$


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

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


Multi-dimensional Langevin Equation for nuclear fission

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

Friction dissipation

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

Newton equation

\( q_i \): deformation coordinate (nuclear shape)

\( p_i \): momentum conjugate to \( q_i \)

\( m_{ij} \): Hydrodynamical mass (inertia mass)

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

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

\[ \sum_k g_{ik} g_{jk} = T \gamma_{ij} \]  

Einstein relation

Fluctuation–dissipation theorem

\[ E_{\text{int}} = E^* - \frac{1}{2} (m^{-1})_{ij} p_i p_j - V(q) = a T^2 \]

\( E_{\text{int}} \): intrinsic energy, \( E^* \): excitation energy

Neutron emission competition is taken into account
Multi-dimensional Langevin Equation for nuclear fission

\[
\begin{align*}
\frac{dq_i}{dt} & = (m^{-1})_{ij} p_j \\
\frac{dp_i}{dt} & = -\frac{\partial V}{\partial q_i} - \frac{1}{2} \frac{\partial}{\partial q_i} \left( m^{-1} \right)_{jk} p_j p_k - \gamma_{ij} \left( m^{-1} \right)_{jk} p_k + g_{ij} R_j(t)
\end{align*}
\]

\(q_i\): deformation coordinate (nuclear shape)

\(p_i\): momentum conjugate to \(q_i\)

\(m_{ij}\): Hydrodynamical mass (inertia mass)

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

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\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)  
\( p_i \): momentum conjugate to \( q_i \)  
\( m_{ij} \): Hydrodynamical mass  
\( \gamma_{ij} \): Wall and Window (one-body) dissipation

Friction dissipation  
Random force fluctuation

Needs for microscopic treatment of transport coefficients

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

\[
\sum_k g_{ik} g_{jk} = T \gamma_{ij}
\]

Einstein relation

Fluctuation–dissipation theorem

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

\( E_{\text{int}} \): 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

![Diagram of a nucleus with parameters](image)

- **Normalized inter-fragment distance**  
\[ z = \frac{z_0}{BR} \]

- **Radium of compound nucleus**  
\[ B = \frac{3 + \delta}{3 - 2\delta} \]

- **Deformation of each fragment**  
\[ \delta = \frac{3(a - b)}{2a + b} \]

- **Mass asymmetry**  
\[ \alpha = \frac{A_1 - A_2}{A_{CN}} \]

\[ \hat{H} = -\frac{\hbar^2}{2m_0} \nabla^2 + V(\mathbf{r}) + V_{LS}(\mathbf{r}, \mathbf{p}, \mathbf{s}) + V_L^2(\mathbf{r}, \mathbf{p}) \]

\[ V(\rho, z) = \frac{1}{2} m_0 \left\{ \begin{array}{ll} \omega_{z_1}^2 z' + \omega_{\rho_1}^2 \rho^2, & z < z_1 \\ \omega_{z_1}^2 z'_2 \left(1 + c_1 z' + d_1 z'^2 \right) + \omega_{\rho_1}^2 \left(1 + g_1 z'^2 \right) \rho^2, & z_1 < z < 0 \\ \omega_{z_2}^2 z'_2 \left(1 + c_2 z' + d_2 z'^2 \right) + \omega_{\rho_2}^2 \left(1 + g_2 z'^2 \right) \rho^2, & 0 < z < z_2 \\ \omega_{z_2}^2 z'^2 + \omega_{\rho_2}^2 \rho^2, & z > z_2 \end{array} \right. \]

\[ z' = \begin{cases} z - z_1, & z < 0 \\ z - z_2, & z > 0 \end{cases} \]
Comparison of measured (by surrogate method) and Langevin calculation

Fission Yield (%) vs. Fragment Mass (u) for 
- \(^{234}\)Th
- \(^{235}\)Pa
- \(^{236}\)U

Data from surrogate method and Calculation
Without fluctuation

\[ ^{236}\text{U} \]

\[ \alpha = 0.0, \varepsilon = 0.35 \]

Mass asymmetry \( \alpha \)

Deformation \( \delta \)

With fluctuation

\[ ^{236}\text{U} \]

\[ \delta = 0.2, \varepsilon = 0.35 \]

Projection on two-dim. plan

Potenaial \( V \) and fission process of

\[ ^{236}\text{U} \]

by Langevin equation (\( E^* = 20 \text{ MeV} \))
Without fluctuation

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

Potential $V$ and fission process of $^{236}\text{U}$ by Langevin equation ($E^* = 20 \text{ MeV}$)
The Langevin trajectories do not necessarily follow the multi-dimensional potential minima.
4-dimensional calculation

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

\[ q(z, \delta_1, \delta_2, \alpha) \]

\[ z = \frac{z_0}{BR} \]
\[ B = \sqrt{B_1B_2} \]
\[ B_1 = \frac{3+\delta_1}{3-2\delta_1}, \quad B_2 = \frac{3+\delta_2}{3-2\delta_2} \]

\( R \)  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

$^{236}\text{U} \quad E^*=20 \text{ MeV}$
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

In case of 1.50 $R_0$,

- 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

$\gamma$-decay heat

$\beta$-decay heat

$^{239}\text{Pu} + n_f$

$^{235}\text{U} + n_f$
Summation calculation of decay heat and emission of delayed neutron

\[ ^{239}\text{Pu} + n_f \]

\( \gamma \)-decay

\( \beta \)-decay

Heat

\( ^{235}\text{U} + n_f \)

Delayed-neutron emission

Burst fission

Cooling time (sec)

Cooling time (sec)

Cooling time (sec)

Cooling time (sec)
Summation calculation of decay heat and emission of delayed neutron

$\gamma$-decay heat

$\beta$-decay heat

delayed-neutron emission

$\gamma$-decay heat

burst fission

$\beta$-decay heat

DN
Summation calculation of decay heat and emission of delayed neutron

\[ ^{239}\text{Pu} + n_f \]

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, $\beta$-ray and antineutrinos must be quantified better especially for the region of most neutron-rich fission fragments.