Development of Microscopic Effective Reaction Theory for Nuclear Transmutation Studies

ImPACT International Symposium on “New Horizons of Partitioning and Transmutation Technologies with Accelerator System”
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Plan of this talk

I. Brief summary of our activities / achievements

II. Microscopic description of nucleon-nucleus scattering

III. Microscopic effective reaction theory for deuteron scattering

IV. Toward a more realistic description of one-nucleon knockout processes
    S. Weili, Y. Watanabe, M. Kohno, KO, and M. Kawai, PRC 60, 064605 (1999).
    KO, arXiv:1801.09994.

V. Summary
Role Assignment in PJ3

RIST
Event generation with PHITS

JAEA
Data evaluation

Nuclear theory Gr.

Tsukuba
Nuclear structure

Osaka
Nuclear reactions

Cross sections

Hokkaido
Database

Existing data

New data measurement

PJ2
Publications (peer reviewed journal papers)


+ 3 peer-reviewed conference proceedings and 18 oral presentations (including a lecture at high school)
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V. Summary
Phenomenology to Microscopic Theory

TABLE I. Optical-Model Parameters

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Success of microscopic optical potential

$p$ scattering at 65 MeV

\[ \frac{d\sigma}{d\Omega} \] vs. \( \theta_{\text{c.m.}} \) [deg]

- Experiment
- w/ 3NF
- w/o 3NF

\( ^{40}\text{Ca} \times 10^4 \)
\( ^{58}\text{Ni} \times 10^2 \)
\( ^{208}\text{Pb} \)

\( A_y \)

\( \theta_{\text{c.m.}} \) [deg]

\( 0 \ 30 \ 60 \ 90 \ 120 \ 150 \ 180 \)

\( \omega \)

\( \exp. \)

\( \text{w/ 3NF} \)

\( \text{w/o 3NF} \)

\( ^{40}\text{Ca} (+4) \)
\( ^{58}\text{Ni} (+2) \)
\( ^{208}\text{Pb} \)

\( \alpha \) scattering at 72 A MeV

\[ \frac{d\sigma}{d\Omega} \] vs. \( \theta_{\text{c.m.}} \) [deg]

- Experiment
- w/ 3NF
- w/o 3NF

\( ^{58}\text{Ni} \times 10^3 \)

\( ^{208}\text{Pb} \)

No free parameter ("prediction")

M. Toyokawa, M. Yahiro, T. Matsumoto, K. Minomo, KO, and M. Kohno,
Success of microscopic optical potential (ctnd.)

$n$ scattering at 65 MeV

No free parameter ("prediction")
We have validated nucleon-nucleus cross sections implemented in PHITS.
Success of microscopic optical potential (ctnd.)

We can microscopically describe the nucleon elastic scattering and the total reaction cross section (not shown).

- We cannot describe all the reaction processes of the nucleon-nucleus system.
- Thus, our framework is not ab-initio but an effective microscopic theory

**NOTE**

- “Predictability” and wide applicability

No free parameter (“prediction”)
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V. Summary
Microscopic description of deuteron scattering

$p$-$n$ breakup treated explicitly

Microscopic Pot.

Microscopic Effective Reaction Theory (MERT)

1. Degrees of freedom selected (= setting model space)
2. Distorting (“Mean-field”) potential generated microscopically
3. Reaction process due to residual interaction calculated with 1. and 2.
The Continuum-Discretized Coupled-Channels method: CDCC

\[ \psi = \phi_0 \chi_0 + \int_0^\infty \phi_k \chi_k \, dk \quad \rightarrow \quad \psi^{\text{CDCC}} = \sum_{i=1}^{i_{\text{max}}} \phi_i \hat{\chi}_i \]

Description of deuteron breakup process by CDCC

\[ E_i + \varepsilon_i = E \]
(Energy Cons.)
MERT (M-CDCC) for deuteron-induced reactions


Elastic scattering on $^{58}$Ni

Total reaction cross section at 56 MeV
CDCC is implemented in DEURACS to evaluate elastic breakup cross sections of deuteron.

FIG. 7. Calculated and experimental TTNYs at several angles for (a) the $^9\text{Be}(d,xn)$ reactions and (b) the $^{12}\text{C}(d,xn)$ reactions. The solid curves represent the TTNYs derived from the DEURACS calculation. The dashed lines are results of the Monte Carlo simulation codes PHITS.
MERT evaluation for deuteron reaction cross sections


MERT vs Exp. / PHITS

Transmutation energy for $^{135}$Cs

- 50% increase

58Ni

208Pb

12Sn

12C
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   KO, arXiv:1801.09994.

V. Summary
Spallation cross section taken at RIBF

$^{93}$Zr at 100 MeV/nucleon

S. Kawase et al., PTEP 2017, 093D03 (2017).
Problem on –1N process

$^{137}\text{Cs} 185\text{MeV on proton}$

$E_{\text{ex}} = E_F - E_{\text{kin}}$

kinetic energy of a nucleon inside a nucleus

Outline of the model

✓ SemiClassical Distorted Wave model (SCDW) [QM-INC] is adopted.

\[ \frac{d^2 \sigma}{dE_f d\Omega_f} = C \int dk_\beta dk_\alpha \, \delta (K_f + k_\beta - K_i - k_\alpha) \, \delta (E_f + \varepsilon_\beta - E_i - \varepsilon_\alpha) \]

\[ \times \int dR \left| \tilde{\chi}_{f, K_f}^\text{(-)} (R) \right|^2 \left[ 2 - f_h^{(\beta)} (k_\beta, R) \right] f_h^{(\alpha)} (k_\alpha, R) \left| \tilde{t}_{NN} (\kappa', \kappa) \right|^2 \left| \tilde{\chi}_{i, K_i}^{(+)} (R) \right|^2 \]

DDX for \((p, p' x)\)

Incoherent sum of contributions from collision points

Wigner Transform of nucleon in a nucleus ("Pauli principle")

S. Weili, Y. Watanabe, M. Kohno, KO, and M. Kawai, PRC 60, 064605 (1999).
Schematic illustration of SCDW

Y. L. Luo and M. Kawai, PRC 43, 2367 (1991); M. Kawai and H. A. Weidenmüller, PRC 45, 1856 (1992);
Y. Watanabe et al., PRC 59, 2136 (1999); S. Weili et al., PRC 60, 064605 (1999); K. Ogata et al., NPA 703, 152 (2002);
KO et al., Proc. Kyudai-RCNP Int. Mini Symp. on Nuclear Many-body and Medium Effects in Nuclear Interaction and
DDX for $^{40}$Ca(p,p'x) at 392 MeV

KO, Y. Watanabe, W. Sun, M. Kohno, and M. Kawai, Proc. of MEDIUM02, p.231 (2003).

Exp. data: A.A. Cowley et al., PRC62, 044604 (2000).
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DDX for \((p,p'\times)\)

\[
\frac{d^2\sigma}{dE_d d\Omega_f} = C \int dk_\beta dk_\alpha \delta (K_f + k_\beta - K_i - k_\alpha) \delta (E_f + \varepsilon_\beta - E_i - \varepsilon_\alpha) \times \int dR |\tilde{\chi}_{f,K_f}(R)|^2 \left[ 2 - f_h^{(\beta)}(k_\beta, R) \right] f_h^{(\alpha)}(k_\alpha, R) \mid t_{NN}(\kappa', \kappa)|^2 \mid \tilde{\chi}_{i,K_i}(R) |^2
\]

Incoherent sum of contributions from collision points

Wigner Transform of nucleon in a nucleus ("Pauli principle")

\(\omega\): energy transfer

Note: \(R\) and \(k_\alpha\) determine nucleon s.p. energy, hence the excitation energy of the residual nucleus

\[
\frac{d^4\sigma}{dE_d d\Omega_f dk_\alpha dR} = \frac{d^3\sigma}{d\omega dk_\alpha dR} = \frac{d^2\sigma}{d\varepsilon_\beta d\varepsilon_{ex}} = \frac{d\sigma}{d\omega} \equiv \frac{d\sigma}{d\varepsilon_{ex}}
\]

\(\varepsilon_\beta > \text{Coulomb barrier and } \varepsilon_{ex}^{(A-1)} > \varepsilon_0:\)

[Pre-Fragment = \(A-1\)]

Otherwise

[Pre-Fragment = \(A\)]
Excitation energy distribution

for $^{137}$Cs, $-1n$ and $-1p$

KO, arXiv:1801.09994.
Incident energy dependence

KO, arXiv:1801.09994.
1N cross sections by neutron

KO, arXiv:1801.09994.
The microscopic description of nucleon-nucleus elastic scattering and total reaction cross sections at energies higher than about 30 MeV is now feasible.

We have proposed a framework of the microscopic effective reaction theory (MERT) for describing various direct reaction processes.

- Essential degrees of freedom for the process of interest are taken into account explicitly.
- Microscopic optical potentials between the constituents of the reaction system are used.
- It is not ab-initio but has a wide applicability.

As an example of MERT, we use a microscopic CDCC for describing deuteron scattering.

- We have improved significantly the deuteron reaction cross sections used by PHITS.
- This reduces the energy cost for transmutation with deuteron.

We proposed a new model for describing one-nucleon knockout reactions.

- It seems that this model needs further validation/improvement by looking carefully all the data taken in this program (PJ2).