Microscopic reaction theory for many-body nuclear reactions

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Overview of this research

✓ Many-body nuclear direct reactions

✓ Microscopic reaction theory based on $NN$ effective interactions ($g$-matrix)

The effective interaction is constructed with a realistic nuclear force.

There is no *ad hoc* parameter!
Microscopic reaction theory has a predictive power.

Recently, we apply nuclear forces based on *chiral effective field theory* for many-body nuclear reactions.
We introduce our new approach to various reactions, mainly elastic scattering.
Elastic scattering

Elastic scattering is one of the most basic processes in nuclear reactions.

✓ Optical Model

Optical potential

\[ U(R) = V(R) + iW(R) \]

Real part Imaginary part

\( U(R) \) is phenomenologically determined to reproduce elastic scattering data.

✓ Theoretical foundation of optical model

• Feshbach theory
• Multiple scattering theory (microscopic point of view)

The basis of microscopic reaction theory
Multiple scattering theory

✓ Schrödinger equation based on a realistic nucleon-nucleon force

\[
\left[ K + h_P + h_T + \sum_{i \in P, j \in T} v_{ij} - E \right] \Psi = 0
\]

Multistep of \( v_{ij} \) between \( i \) th nucleon in projectile and \( j \) th nucleon in target

\[
\tau_{ij} = v_{ij} + v_{ij} \frac{P_P \ P_T}{E - K - h_P - h_T} \tau_{ij}^i \]

One-step Two-step Multistep

\[
\Rightarrow \left[ K + h_P + h_T + \sum_{i \in P, j \in T} \tau_{ij} - E \right] \hat{\Psi} = 0
\]

\( \tau_{ij} \) includes the medium effects.

**g-matrix interaction**

Effective interaction

\[ \tau_{ij} = v_{ij} + v_{ij} \frac{\mathcal{P}_P \mathcal{P}_T}{E - K - h_P - h_T} \tau_{ij} \]

In practice, the **g-matrix interaction** is used as an effective interaction within the local density approximation (LDA).

The g-matrix is a solution of the Brueckner-Bethe-Goldstone equation.

\[ g_{ij} = v_{ij} + v_{ij} \frac{Q}{E - K_i - U_i - K_j - U_j} g_{ij} \]

Medium effects

\[ \begin{cases} 
\text{Pauli operator } Q \\
\text{Single-particle potential } U \\
\end{cases} \]

→ Energy\((E)\)- and density\((\rho)\)-dependent complex interaction \(g(s, \rho, E)\)

Many types of g-matrix interactions were developed.
Historical developments of g-matrix interactions

**Realistic forces**
- 1935 Yukawa theory
- 1962 Hamada-Johnston
- 1968 Reid
- **OPEP/OBEP**
  - 1960
  - 1970
- **Meson exchange theory**
  - 1980 Paris
  - 1984 Argonne v14
  - 1987 Bonn
  - 1994 Nijmegen
  - 1995 Argonne v18
  - 1997 Urbana IX
  - 2001 CD-Bonn
  - 2006 ESC

**g-matrix interactions**
- 1955 Brueckner theory
- **Primitive g-matrices**
  - 1977 JLM (Reid)
  - Oxford (HJ/Reid)
  - M3Y (Reid)
  - 1983 CEG (HJ)
  - 1985 DDM3Y
- **More accurate interactions**
  - 1996 Full-folding (Paris)
  - 2000 Melbourne (Bonn)
  - 2007 Full-folding (AV18, CD-Bonn, …)
  - 2008 CEG07 (ESC+3NF eff.)
  - 2013 MP (ESC+MPP)
    - AMU (AV18+Urbana IX)
$g$-matrix folding model

✓ Schrödinger equation with a $g$-matrix interaction

$$\begin{bmatrix} K + h_P + h_T + \sum_{i \in P, j \in T} g_{ij} - E \end{bmatrix} \Psi = 0$$

$$\begin{bmatrix} K + U - E_{\text{in}} \end{bmatrix} \chi(R) = 0$$

Folding potential: $U = \left\langle \varphi_P \varphi_T \right| \sum_{i \in P, j \in T} g_{ij} \left| \varphi_P \varphi_T \right\rangle$

Frozen density approximation: $\rho = \rho_P + \rho_T$ for $g(s, \rho, E)$

Localization of the knockon-exchange term

Brieva-Rook localization

$F. A. Brieva et al., NPA297, 206 (1978)$.  

Validity of the localization


$U$ is nothing but the microscopic optical potential!
Success for nucleon elastic scattering

Our systematic calculations with the $g$-matrix folding model

- The Melbourne $g$-matrix interaction from the Bonn potential
  
  \[ K. \text{Amos, et al., ANP25, 275 (2000).} \]

- Spherical Hartree-Fock calculation for target densities

$p$-nucleus elastic scattering@65MeV

Energy dependence of $n$-$^{208}$Pb elastic scattering

Nucleon elastic scattering data are well reproduced with no adjustable parameter.
Scattering of neutron-rich nuclei


The red lines are our final results.

\[ ^6\text{He}-p@71\text{MeV/nucl.} \]

\[ p-^{22}\text{Ne}@35\text{MeV} \]

Great successes for description of nucleon scattering
We determined the ground state properties of neutron-rich Ne isotopes.
Failure cases

The Melbourne interaction succeeded to describe many scattering data. Can we reproduce all scattering observables? ...No!!

The Melbourne interaction fails to describe nucleus-nucleus scattering.

At large angles, the internal (nuclear overlapped) part of the potential is important.

At high density → Three-nucleon force (3NF) strongly affects.

The Melbourne interaction does not include 3NF effects explicitly.
Historical developments of $g$-matrix interactions

**Nuclear forces**
- 1935 Yukawa theory
- 1960
  - OPEP/OBEP
    - 1962 Hamada-Johnston
    - 1968 Reid
- 1962 Hamada-Johnston
- 1968 Reid
- 1970
- 1975 Brueckner theory
- 1980
  - Meson exchange theory
    - 1980 Paris
    - 1984 Argonne v14
    - 1987 Bonn
    - 1994 Nijmegen
    - 1995 Argonne v18
    - 1997 Urbana IX
    - 2001 CD-Bonn
    - 2006 ESC
- 1980 Paris
- 1984 Argonne v14
- 1987 Bonn
- 1994 Nijmegen
- 1995 Argonne v18
- 1997 Urbana IX
- 2001 CD-Bonn
- 2006 ESC
- 1990
- 1995 Argonne v18
- 1997 Urbana IX
- 2001 CD-Bonn
- 2006 ESC
- 2000
  - 2000 Melbourne (Bonn)
  - 2001 CD-Bonn
  - 2006 ESC
- 2000 Melbourne (Bonn)
- 2001 CD-Bonn
- 2006 ESC
- 2010
  - QCD-based
    - around 2000 Ch-EFT
    - 2NF + 3NF +…

**g-matrix interactions**
- 1955 Brueckner theory
- 1970
- 1977 JLM (Reid)
- 1980
- 1983 CEG (HJ)
- 1984 Argonne v14
- 1985 DDM3Y
- 1987 Bonn
- 1994 Nijmegen
- 1995 Argonne v18
- 1997 Urbana IX
- 2001 CD-Bonn
- 2006 ESC
- 2007 Full-folding (AV18, CD-Bonn, …)
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- 2013 MP (ESC+MPP)
- AMU (AV18+Urbana IX)
- AMU (AV18+Urbana IX)
- A new phase of MRT!
Studies of chiral interactions

✓ Nuclear forces based on chiral effective field theory (Ch-EFT)

E. Epelbaum et al., NPA747, 362 (2005); RMP81, 1773 (2009)
R. Machleidt et al., PR503, 1 (2011).

Two-, three-, and many-nucleon forces are treated systematically.
At this stage, these interactions are most reliable for treating 3NF effects.
(But, these cannot be applied to high energy region beyond the cutoff.)

✓ Application of the chiral interactions to many-body reactions

We construct a new g-matrix interaction with the chiral 2NF and 3NF.

\[
g_{12} = v_{12} + \frac{1}{3} v_{12(3)} + \left( v_{12} + \frac{1}{3} v_{12(3)} \right) \frac{Q}{\omega - H} g_{12}
\]

\[
\langle k_1' k_2' \mid v_{12(3)} \mid k_1 k_2 \rangle_A = \sum_{k_3} \langle k_1' k_2' k_3 \mid v_{123} \mid k_1 k_2 k_3 \rangle_A
\]

The 3NF effects are considered as the density-dependence of \( g_{12} \).
The chiral 3NF effect gives nice results.

KM et al., PRC90, 051601 (2014).
M. Toyokawa et al., JPG42, 025104 (2014).
Coupled-channels calculations of $^{16}$O-$^{16}$O scattering

The microscopic coupled-channels calculation including $0_1^+$, $3_1^-$, and $2_1^+$ states

Both elastic and inelastic cross sections are well described.

Coupled-channels calculations of $^{12}\text{C}-^{12}\text{C}$ scattering

The microscopic coupled-channels calculation including $0_{1}^{+}$, $2_{1}^{+}$, $0_{2}^{+}$, and $2_{2}^{+}$ states

$^{12}\text{C}-^{12}\text{C}@85\text{MeV/nucleon}$

Both elastic and inelastic cross sections are well described.

$^{12}\text{C}-^{12}\text{C}@30\text{MeV/nucleon}$

$\rightarrow$ Next step (knockout and breakup reactions)

Microscopic DWIA for knockout reactions

✓ Transition matrix based on distorted-wave impulse approximation (DWIA)

\[ T = \langle \chi_{1,k_1}^{(-)} \chi_{2,k_2}^{(-)} | g(\kappa', \kappa, \theta; E, \rho) | \chi_{0,k_0}^{(+)} \varphi_{nlj} \rangle \]

Microscopic framework

\( \chi_{0,k_0}^{(+)} \), \( \chi_{1,k_1}^{(-)} \), and \( \chi_{2,k_2}^{(-)} \):

- calculated with microscopic optical potentials

\( g(\kappa', \kappa, \theta; E, \rho) \): chiral g-matrix

\( \varphi_{nlj} \): calculated with some structure models

\(^{16}\text{O}(p,2p)@151\text{MeV} \)

with spectroscopic factor 2.25

Very Preliminary

\[ \text{triple differential cross section (mb/MeV/str)} \]

Kinetic energy of particle 1 (MeV)
Microscopic CDCC for breakup reactions

The Continuum Discretized Coupled-Channels method (CDCC)

*M. Yahiro et al., PTEP2012, 01A206 (2012).*

Eikonal Reaction Theory (ERT)

*M. Yahiro et al., PTP126, 167 (2011).*

- Two-neutron removal reaction of $^6$He

$$
\left[-\frac{\hbar^2}{2\mu} \nabla^2_R + U + h_P - E\right] \Psi = 0
$$

$$U = U^{\alpha_T} + U^{n_1T} + U^{n_2T}$$

Microscopic optical potentials

- Core
- Neutrons
- Nucl
- Coul
Summary

Our goal is to construct a microscopic reaction theory having a predictive power.

✓ Microscopic approach to many-body nuclear reactions

Multiple scattering theory is the basis of microscopic reaction theory.

The g-matrix folding model is useful to describe elastic scattering.

✓ A new phase of microscopic reaction theory

We constructed a new g-matrix interaction with chiral 2NF and 3NF.

The new interaction gives nice results for elastic and inelastic cross sections of nucleon-nucleus and nucleus-nucleus scattering.

We now obtain reliable microscopic optical potentials.

The microscopic framework will be applied for not only elastic scattering but also various reaction processes.
Thank you very much for your attention!