MICROSCOPIC OPTICAL POTENTIAL FROM NN CHIRAL POTENTIALS

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The OP provides a suitable framework to describe elastic nucleon-nucleus scattering. Its use can be extended to inelastic scattering and to calculate the cross section of a wide variety of nuclear reactions.

In our models for QE electron and neutrino-nucleus scattering, the OP describes FSI between the emitted nucleon and the residual nucleus.
PHENOMENOLOGICAL: assume a form and a dependence on a number of adjustable parameters for the real and imaginary parts that characterize the shape of the nuclear density distribution and that vary with the nuclear energy and the nucleus mass number.

Parameters obtained through a fit to pA elastic scattering data
PHENOMENOLOGICAL: assume a form and a dependence on a number of adjustable parameters for the real and imaginary parts that characterize the shape of the nuclear density distribution and that vary with the nuclear energy and the nucleus mass number.

Parameters obtained through a fit to pA elastic scattering data

Global OP: the adjustable parameters are fitted in a range of nuclei at many different energies with a dependence of the coefficients in terms of A and E

A independent OP: given for a single target nucleus
PHENOMENOLOGICAL: assume a form and a dependence on a number of adjustable parameters for the real and imaginary parts that characterize the shape of the nuclear density distribution and that vary with the nuclear energy and the nucleus mass number.

Parameters obtained through a fit to pA elastic scattering data

THEORETICAL: microscopic calculations require the solution of the full many-body nuclear problem. Some approximations are needed.

We do not expect better description of experimental data (at least for data in the database used to generate phen. OP) but greater predictive power when applied to situations where exp. data not available
OPTICAL POTENTIAL

- Complex
- E dependent
- Non local
M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)
Theoretical optical potential derived from nucleon-nucleon chiral potentials

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Optical potential derived from nucleon-nucleon chiral potentials at N^4LO
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Purpose: study the domain of applicability of microscopic two-body chiral potentials to the construction of an OP

Non relativistic optical potential
Comparison with elastic pA scattering data
M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)
Theoretical optical potential derived from nucleon-nucleon chiral potentials
Theoretical framework for pA elastic scattering

We start from the full \((A+1)\) body LS equation

\[ T = T + VG_0(E)VT \]

Separation into two coupled integral equations

\[ T = U + G_0(E)PT \]
\[ U = V + VG_0(E)QU \]

Free propagator

\[ G_0(E) = (E - H_0 + i\epsilon)^{-1} \]

Projection operators

\[ P + Q = 1 \]

Free Hamiltonian

\[ H_0 = h_0 + H_A \]

External interaction

\[ V = \sum_{i=1}^{A} v_{0i} \]
The spectator expansion

Consistent framework to calculate $U$ and $T$

\[
U = \sum_{i=1}^{A} T_i + \sum_{i,j \neq i}^{A} T_{ij} + \sum_{i,j \neq i,k \neq i,j}^{A} T_{ijk} + \ldots
\]
The spectator expansion

Consistent framework to calculate $U$ and $T$

\[ U = \sum_{i=1}^{A} \tau_i + \sum_{i,j \neq i} \tau_{ij} + \sum_{i,j \neq i,k \neq i,j} \tau_{ijk} + \ldots \]
The spectator expansion

Consistent framework to calculate $U$ and $T$

$$U = \sum_{i=1}^{A} T_i$$

$$T_i = \nu_{0i} + \nu_{0i} G_0(E) Q \tau_i$$
Impulse Approximation

\[ T_i \approx t_{0i} \]

The free $NN$ $t$ matrix

\[ t_{0i} = v_{0i} + v_{0i} g_i t_{0i} \]

The free two-body propagator

\[ g_i = \frac{1}{E - h_0 - h_i + i\epsilon} \]

\[ U = \sum_{i=1}^{A} t_{0i} \]
Impulse Approximation

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The free two-body propagator

\[ g_{i} = \frac{1}{E - h_{0} - h_{i} + i\varepsilon} \]

\[ U = \sum_{i=1}^{A} t_{0i} \]

We have to solve only 2-body equations
$$U(q, K; \omega) = \frac{A-1}{A} \eta(q, K) \sum_{N=n,p} t_{pN} \left[ q, \frac{A+1}{A} K; \omega \right] \rho_N(q)$$

$q = k' - k$

$K = \frac{1}{2} (k' + k)$
Optimum Factorization Approximation

\[ U(q, K; \omega) = \frac{A - 1}{A} \eta(q, K) \sum_{N=n,p} t_{pN} \left[ q, \frac{A + 1}{A} K; \omega \right] \rho_N(q) \]

Moeller factor imposes the Lorentz invariance of the flux when passing from the NA to the NN frame in which the t matrices are evaluated.
\[ U(q, K; \omega) = U^c(q, K; \omega) + \frac{i}{2} \sigma \cdot q \times K U^{ls}(q, K; \omega) \]

**central**

\[ U^c(q, K; \omega) = \frac{A - 1}{A} \eta(q, K) \sum_{N=n,p} t^c_{pN} \left[ q, \frac{A + 1}{A} K; \omega \right] \rho_N(q) \]

**spin-orbit**

\[ U^{ls}(q, K; \omega) = \frac{A - 1}{A} \eta(q, K) \frac{A + 1}{2A} \sum_{N=n,p} t^{ls}_{pN} \left[ q, \frac{A + 1}{A} K; \omega \right] \rho_N(q) \]
\[ U(q, K; \omega) = U^c(q, K; \omega) + \frac{i}{2} \sigma \cdot q \times K \ U^{ls}(q, K; \omega) \]

**central**

\[ U^c(q, K; \omega) = \frac{A - 1}{A} \eta(q, K) \sum_{N=n,p} t^c_{pN} \left[ q, \frac{A + 1}{A} K; \omega \right] \rho_N(q) \]

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**NN t-matrix**

**NN interaction**

**n, p densities**
Optimum Factorization Approximation

\[ U(q, K; \omega) = \frac{A-1}{A} \eta(q, K) \sum_{N=n,p} t_{pN} \left[ q, \frac{A+1}{A} K; \omega \right] \rho_N(q) \]

**Moeller factor**  
**NN t-matrix**  
**NN interaction**  
**n, p densities**

- **n,p densities** calculated within the RMF description of spherical nuclei using a DDME model
- **NN interaction** chiral potentials...
When the concept of EFT was applied to low-energy QCD, ChPT was developed.

Within ChPT it became possible to implement chiral symmetry consistently in a theory of pionic and nuclear interactions.

The theory is based on a perturbative expansion in powers of \((Q/\Lambda_\chi)^n\) where \(Q\) is the magnitude of the three-momentum of the external particles or the pion mass and \(\Lambda_\chi\) is the chiral symmetry breaking scale of the chiral EFT.

From the perturbative expansion only a finite number of terms contribute at a given order.
CHIRAL POTENTIAL

Graphs analyzed in terms of $(Q/\Lambda_{\chi})^n$ nuclear forces emerge as a hierarchy controlled by the power $n$. Nuclear forces dominated by NN int. many-body forces suppressed by powers of the expansion parameter $\Lambda_{\chi}$. 

<table>
<thead>
<tr>
<th>LO</th>
<th>2N Force</th>
<th>3N Force</th>
<th>4N Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(Q/\Lambda_{\chi})^0$</td>
<td>$\times\hbar$</td>
<td></td>
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</tr>
</tbody>
</table>

| NLO |         |          |          |
| $(Q/\Lambda_{\chi})^2$ |          |          |          |

| NNLO|         |          |          |
| $(Q/\Lambda_{\chi})^3$ |          |          |          |

| N$^3$LO |         |          |          |
| $(Q/\Lambda_{\chi})^4$ |          |          |          |
Graphs analyzed in terms of $(Q/\Lambda_{\chi})^n$ nuclear forces emerge as a hierarchy controlled by the power $n$. Nuclear forces dominated by NN int. many-body forces suppressed by powers of the expansion parameters.
CHIRAL POTENTIAL

3N forces start at 3\textsuperscript{rd} order, 4N forces start at 4\textsuperscript{th} order. 2 and many-body forces are created on an equal footing and emerge in increasing order going to higher order.
QCD symmetries are consistently respected order by order.

Order by order uncertainties can be evaluated of the order $(Q/\Lambda_{\chi})^n$. 
CHIRAL POTENTIAL

<table>
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<td>LO ((Q/\Lambda_{\chi})^0)</td>
<td>XH</td>
<td></td>
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<tr>
<td>NLO ((Q/\Lambda_{\chi})^2)</td>
<td></td>
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<tr>
<td>NNLO ((Q/\Lambda_{\chi})^3)</td>
<td></td>
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<tr>
<td>N^3LO ((Q/\Lambda_{\chi})^4)</td>
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CHIRAL POTENTIAL AT \(N^3\)LO ONLY 2N
Two different versions of chiral potentials at N$^3$LO
Entem and Machleidt (EM), Epelbaum et al. (EGM)

In general the integral in the LS eq. is divergent and needs to be regularized

Usual procedure:

\[ V(k', k) \quad \rightarrow \quad V(k', k) \ e^{-(k'/\Lambda)^{2n}} \ e^{-(k/\Lambda)^{2n}} \]

EM present results with $\Lambda = 450, 500, 600$ MeV
EGM present results with $\Lambda = 450, 550, 600$ MeV
and treat differently the short-range part of the 2PE contribution, that has an unphysically strong attraction.
EM dimensional regularization
EGM spectral function regularization introduces an additional cutoff $\tilde{\Lambda}$
and give cut-off combinations: $(\Lambda, \tilde{\Lambda}) = (450, 500), (450, 700), (550, 600), (600, 600), (600, 700)$
Two different versions of chiral potentials at $N^3$LO
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$$(\Lambda, \tilde{\Lambda}) = (450, 500), (450, 700), (550, 600), (600, 600), (600, 700)$$

sensitivity to the cutoff parameters order by order convergence
NN transition matrix

NN elastic scatt. amplitude related to the antisymmetrized NN-t matrix elements

\[ M(\kappa', \kappa, \omega) = \langle \kappa' | M(\omega) | \kappa \rangle = -4\pi^2 \mu \langle \kappa' | t(\omega) | \kappa \rangle \]

The most general form, consistent with invariance under rotation, time reversal, and parity

\[ M = a + c(\sigma_1 + \sigma_2) \cdot \hat{n} + m(\sigma_1 \cdot \hat{n})(\sigma_2 \cdot \hat{n}) \]
\[ + (g + h)(\sigma_1 \cdot \hat{l})(\sigma_2 \cdot \hat{l}) + (g - h)(\sigma_1 \cdot \hat{m})(\sigma_2 \cdot \hat{m}) \]

\[ \hat{l} = \frac{\kappa' + \kappa}{|\kappa' + \kappa|}, \quad \hat{m} = \frac{\kappa' - \kappa}{|\kappa' - \kappa|}, \quad \hat{n} = \frac{\kappa \times \kappa'}{|\kappa \times \kappa'|} \]

a, c, m, g, h complex functions of \( \omega, \kappa, \kappa' \)
NN transition matrix

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\]

\[
+ (g + h)(\sigma_1 \cdot \hat{l})(\sigma_2 \cdot \hat{l}) + (g - h)(\sigma_1 \cdot \hat{m})(\sigma_2 \cdot \hat{m})
\]

\[
\hat{l} = \frac{\kappa' + \kappa}{|\kappa' + \kappa|}, \quad \hat{m} = \frac{\kappa' - \kappa}{|\kappa' - \kappa|}, \quad \hat{n} = \frac{\kappa \times \kappa'}{|\kappa \times \kappa'|}
\]

\(a, c, m, g, h\) complex functions of \(\omega, \kappa, \kappa'\)

For even-even nuclei with \(J=0\) only \(a\) and \(c\) survive and they are connected to the central and spin-orbit part of the NN \(t\)-matrix.
THE NUCLEON-NUCLEON AMPLITUDES

NN AMPLITUDES 100 MeV

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)
OP and scattering observables

The most general form of the amplitude for elastic $p$ scattering from a spin 0 nucleus

$$M(k_0, \theta) = A(k_0, \theta) + \sigma \cdot \hat{N} C(k_0, \theta)$$

Scattering observables

$$\frac{d\sigma}{d\Omega}(\theta) = |A(\theta)|^2 + |C(\theta)|^2$$

unpolarized differential cross section

$$A_y(\theta) = \frac{2\text{Re}[A^*(\theta) C(\theta)]}{|A(\theta)|^2 + |C(\theta)|^2}$$

analyzing power

$$Q(\theta) = \frac{2\text{Im}[A(\theta) C^*(\theta)]}{|A(\theta)|^2 + |C(\theta)|^2}$$

spin rotation
ELASTIC P-A SCATTERING
ELASTIC P-A SCATTERING

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)
Theoretical optical potential derived from nucleon-nucleon chiral potentials

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2017)
Optical potential derived from nucleon-nucleon chiral potentials at N^4LO
# Chiral Potential at N^4LO

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<tbody>
<tr>
<td>LO (Q^0)</td>
<td>X H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLO (Q^2)</td>
<td>X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N^2LO (Q^3)</td>
<td></td>
<td>H H X</td>
<td></td>
</tr>
<tr>
<td>N^3LO (Q^4)</td>
<td></td>
<td></td>
<td>H H H X</td>
</tr>
<tr>
<td>N^4LO (Q^5)</td>
<td></td>
<td>H H H H X</td>
<td>H H H H X</td>
</tr>
</tbody>
</table>


D.R. Entem et al. PRC 91 014002 (2015), PRC 96 024004 (2017)  EMN
### CHIRAL POTENTIAL AT N⁴LO

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<tbody>
<tr>
<td>LO (Q⁰)</td>
<td>XH</td>
<td>—</td>
</tr>
<tr>
<td>NLO (Q²)</td>
<td>X X</td>
<td>—</td>
</tr>
<tr>
<td>N²LO (Q³)</td>
<td>D D</td>
<td>—</td>
</tr>
<tr>
<td>N³LO (Q⁴)</td>
<td>X X</td>
<td>—</td>
</tr>
<tr>
<td>N⁴LO (Q⁵)</td>
<td>X X</td>
<td>—</td>
</tr>
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D.R. Entem et al. PRC 91 014002 (2015), PRC 96 024004 (2017) EMN
Purpose: check the convergence and assess the theoretical errors associated with the truncation of the chiral expansion in the construction of an OP.
Regularization for EKM and EMN at N^4LO

**EKM**

Long-range part of the potential

\[ f \left( \frac{r}{R} \right) = \left( 1 - \exp \left( -\frac{r^2}{R^2} \right) \right)^n \]

n=6 \quad R=0.8, 0.9, 1., 1. 1, 1.2 fm

Short-range part

\[ f_\Lambda(k', k) = \exp \left( - \left( \frac{k'}{\Lambda} \right)^{2m} - \left( \frac{k}{\Lambda} \right)^{2m} \right) \]

\( \Lambda = 2R^{-1} \) and \( m=2 \)

**EMN**

SFR with \( \tilde{\Lambda} \sim 700 \text{ MeV} \) to regularize the loop contribution and a conventional regulator function with \( \Lambda = 450, 500, 550 \text{ MeV} \) and \( m = 2, 4 \) for multi-pion and single-pion exchange contribution
**Regularization for EKM and EMN at N^4LO**

**EKM**

Long-range part of the potential \( n=6 \quad R=0.8, 0.9, 1., 1.1, 1.2 \text{ fm} \)

\[
 f \left( \frac{r}{R} \right) = \left( 1 - \exp \left( -\frac{r^2}{R^2} \right) \right)^n
\]

Short-range part

conventional mom. space

\[
 f_\Lambda(k', k) = \exp \left( - \left( \frac{k'}{\Lambda} \right)^{2m} - \left( \frac{k}{\Lambda} \right)^{2m} \right)
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Regularization for EKM and EMN at N^4LO

**EKM**

Long-range part of the potential

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Short-range part

conventional mom. space

\[ \Lambda = 2R^{-1} \text{ and } m = 2 \]

**EMN**

SFR with \( \tilde{\Lambda} \sim 700 \text{ MeV} \) to regularize the loop contribution

and a conventional regulator function with \( \Lambda = 450, 500, 550 \text{ MeV} \) and \( m = 2, 4 \) for multi-pion and single-pion exchange contribution

all calculations performed with \( R = 0.9 \text{ fm for EKM and } \Lambda = 500 \text{ MeV for EMN} \)
Assess theoretical errors associated to the truncation of the chiral expansion: given an observable $O(p)$ the uncertainty at order $n$ is given by the size of neglected high-order terms. At $N^4$LO:

$$
\Delta O^{N^4\text{LO}}(p) = \max \left( Q^6 \times |O^{\text{LO}}(p)|, \right.
\times Q^4 \times |O^{\text{LO}}(p) - O^{\text{NLO}}(p)|, \\
\times Q^3 |O^{\text{NLO}}(p) - O^{\text{N^2LO}}(p)|, \\
\times Q^2 |O^{\text{N^2LO}}(p) - O^{\text{N^3LO}}(p)|, \\
\times Q |O^{\text{N^3LO}}(p) - O^{\text{N^4LO}}(p)| \right),
$$

$$Q = \max \left( \frac{p}{\Lambda_b}, \frac{M_\pi}{\Lambda_b} \right) \quad \Lambda_b = 600 \text{ MeV}.$$
NN AMPLITUDES 200 MeV

M. Vorabbi, P. Finelli, C. Giusti  PRC 96 044001  (2017)
$^{16}O$

200 MeV

EKM

M. Vorabbi, P. Finelli, C. Giusti  PRC 96 044001  (2017)
\( ^{16}\text{O} \quad 200 \text{ MeV} \quad ^{40}\text{Ca} \)
investigate and compare predictive power of our microscopic OP and of phenomenological OP in comparison with exp. data in a wider range of nuclei, including isotopic chains

**PHENOMENOLOGICAL OP**
parameters fitted to data, data very well described in particular situations. Investigate capability to describe data in different situations

**MICROSCOPIC OP**
obtained from a model and approximations may be less able to describe specific data should have a greater predictive power for situations for which data not yet available
Comparison phenomenological and microscopic NROP

**PHENOMENOLOGICAL OP**

GLOBAL given in a wide range of nuclei and energies

NROP up to ~200 MeV, for higher energies it is generally believed that the Schroedinger picture should be taken over by a Dirac approach. Global ROP available up to ~1 GeV

NROP Koning at al. NPA 713 231 (2003) (KON) for nuclei $24 \leq A \leq 209$ and energies from 1 keV to 200 MeV, recently extended to 1 GeV, to test at which energy the predictions of a phen. NROP fail

Calculations with TALYS (ECIS-06)

**MICROSCOPIC OP**

chiral potentials at N^4LO describe NN scattering data up to 300 MeV and our OP can be used up to ~300 MeV
Comparison phenomenological and microscopic NROP

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NROP Koning at al. NPA 713 231 (2003) (KON) for nuclei 24 - 64 and energies from 1 keV to 200 MeV, recently extended to ~1 GeV to test at which energy the predictions of a phenomenological NROP fail

Calculations with TALYS (ECIS-06)

MICROSCOPIC OP

chiral potentials at N^4LO describe NN scattering data up to 300 MeV and our OP can be used up to ~300 MeV

Results of the comparison in the energy range 150-330 MeV
Comparison phenomenological and microscopic NROP

**PHENOMENOLOGICAL OP**

- **GLOBAL** given in a wide range of nuclei and energies
- **NROP** up to ~200 MeV, for higher energies it is generally believed that the Schrödinger picture should be taken over by a Dirac approach. Global ROP available up to ~1 GeV
- **NROP** Koning et al. NPA 713 231 (2003) (KON) for nuclei 24 and energies from 1 keV to 200 MeV, recently extended to 1 GeV, to test at which energy the predictions of a phen. NROP fail
- Calculations with TALYS (ECIS-06)

**MICROSCOPIC OP**

- Chiral potentials at N^4LO describe NN scattering data up to 300 MeV and our OP can be used up to ~300 MeV
- Calculations with R=0.8, 0.9, 1.0 fm (EKM)
- $\Lambda=500,550$ MeV (EMN)
- The bands give the differences
Comparison with phenomenological OP
Comparison with phenomenological OP

![Graphs comparing phenomenological op with different isotopes and energies.](image-url)
Comparison with phenomenological OP
Comparison with phenomenological OP
Comparison with phenomenological OP

- $^{16}$O, 318 MeV
- $^{40}$Ca, 318 MeV
- $^{42}$Ca, 318 MeV
- $^{44}$Ca, 318 MeV
- $^{48}$Ca, 318 MeV
- $^{58}$Ni, 333 MeV

Ratio to Rutherford vs. $\theta$ [deg]
Comparison with phenomenological OP

**microscopic OP better description of data at higher energies**
model can be improved
Microscopic optical potentials derived from \textit{ab initio} translationally invariant nonlocal one-body densities

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TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada  
(Dated: December 11, 2017)

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TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

Background: The nuclear optical potential is a successful tool for the study of nucleon-nucleus elastic scattering and its use has been further extended to inelastic scattering and other nuclear reactions. The nuclear density of the target nucleus is a fundamental ingredient in the construction of the optical potential and thus plays an important role in the description of the scattering process.

Purpose: In this work we derive a microscopic optical potential for intermediate energies using \textit{ab initio} translationally invariant nonlocal one-body nuclear densities computed within the no-core shell model (NCSM) approach utilizing two- and three-nucleon chiral interactions as the only input.

Methods: The optical potential is derived at first-order within the spectator expansion of the non-relativistic multiple scattering theory by adopting the impulse approximation. Nonlocal nuclear densities are derived from the NCSM one-body densities calculated in the second quantization. The translational invariance is generated by exactly removing the spurious center-of-mass (COM) component from the NCSM eigenstates.

Results: The ground state local and nonlocal densities of $^4$He, $^6$He, $^{12}$C, and $^{16}$O are calculated and applied to optical potential construction. The differential cross sections and the analyzing powers for the elastic proton scattering off of these nuclei are then calculated for different values of the incident proton energy. The impact of nonlocality and the COM removal is discussed.

Conclusions: The use of nonlocal densities has a substantial impact on the differential cross sections and improves agreement with experiment in comparison to results generated with the local densities especially for light nuclei. For the halo nuclei $^6$He and $^8$He, the results for the differential cross section are in a reasonable agreement with the data although a more sophisticated model for the optical potential is required to properly describe the analyzing powers.

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PROSPECTS...

- the model can be improved
- folding integral
- 3N forces, medium effects
- application to nuclear reactions...? (e,e'p)