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Application of a microscopic optical potential of chiral effective field theory in (p, d) transfer reactions

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Abstract

The microscopic global nucleon–nucleus optical model potential (OMP) proposed by Whitehead, Lim, and Holt, the WLH potential 1 , which was constructed in the framework of many-body perturbation theory with state-of-the-art nuclear interactions from chiral effective field theory (EFT), was tested with (p, d) transfer re#2;actions calculated using adiabatic wave approximation. The target nuclei included both stable and unstable nuclei and the incident energies reached 200 MeV. The results were compared with experimental data and pre#2;dictions using the phenomenological global optical potential of A. J. Koning and J. P. Delaroche, the KD02 potential. Overall, we found that the microscopic WLH potential described the (p, d) reaction angular distri#2;butions similarly to the phenomenological KD02 potential; however, the former was slightly better than the latter for radioactive targets. On average, the obtained spectroscopic factors (SFs) using both microscopic and phenomenological potentials were similar when the incident energies were below approximately 120 MeV. However, their difference tended to increase at higher incident energies, which was particularly apparent for the doubly magic target nucleus 40Ca.

Full Text

Preamble

Application of a microscopic optical potential from chiral effective field theory in (p, d) transfer reactions∗

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The microscopic global nucleon–nucleus optical model potential (OMP) proposed by Whitehead, Lim, and Holt—the WLH potential [1]—which was constructed within the framework of many-body perturbation theory using state-of-the-art nuclear interactions from chiral effective field theory (EFT), has been tested through (p, d) transfer reaction calculations employing the adiabatic wave approximation. The target nuclei encompassed both stable and unstable isotopes, with incident energies extending up to 200 MeV. The results were compared with experimental data and with predictions using the phenomenological global optical potential of A. J. Koning and J. P. Delaroche, known as the KD02 potential. Overall, we found that the microscopic WLH potential described the (p, d) reaction angular distributions comparably to the phenomenological KD02 potential; however, the former performed slightly better for radioactive targets. On average, the spectroscopic factors (SFs) obtained using both microscopic and phenomenological potentials were similar when the incident energies were below approximately 120 MeV. However, their differences tended to increase at higher incident energies, a trend that was particularly evident for the doubly magic target nucleus ^{40}Ca.

Keywords: microscopic optical model potential, (p, d) transfer reactions, spectroscopic factors

Introduction

Single-nucleon transfer reactions such as (d, p) and (p, d) are valuable tools for investigating the single-particle structure of atomic nuclei. In recent years, numerous studies employing radioactive beams have significantly advanced our understanding of nuclear structure evolution and nuclear astrophysics (see, for instance, the review papers in Refs. [2–4]). Nuclear reaction theories serve as essential intermediaries between nuclear structure information and measured reaction data.

In nearly all theoretical frameworks for transfer reactions—including the distorted wave Born approximation (DWBA) [5, 6], adiabatic wave approximation (ADWA) [7, 8], continuum discretized coupled-channel method (CDCC) [9–11], and Faddeev equation-based models [12–14]—optical model potentials (OMPs) constitute indispensable inputs. These OMPs influence theoretical cross sections and consequently affect the nuclear structure information extracted from experimental data [15]. Therefore, reliable OMPs are crucial for nuclear reaction calculations.

Phenomenological global OMPs such as CH89 [16], the more recent KD02 [17], Becchetti–Greenlees [18], and WP [19] for nucleons, along with those cited in Refs. [20–25] for deuterons and other nuclei, are derived by fitting elastic scattering data for a given particle across wide ranges of incident energies and target masses. Such phenomenological global OMPs are widely used in nuclear reaction calculations [26–34]. However, most experimental data concern stable nuclei, necessitating caution when applying these potentials to reactions involv-

ing exotic isotopes. Microscopic optical potentials, which are based on more fundamental principles of nuclear many-body interactions, may be more appropriate for simultaneously describing elastic scattering and transfer reactions for unstable nuclei. Microscopic OMPs for nucleons, such as the Bruyères–Jeukenne–Lejeune–Mahaux model (the JLMB potential) [35] and the global potential based on the Dirac–Brueckner–Hartree–Fock approach developed by R. R. Xu et al. (CTOM [36, 37]), as well as those for deuterons [38], tritons [39], α particles [40], and heavy ions [41], are increasingly employed in direct nuclear reaction studies. Moreover, microscopic OMPs have been found to be more reliable for extracting nuclear structure information from transfer reaction data [42]. Nevertheless, many microscopic OMPs remain strictly semi-microscopic because some parameters are still constrained by nucleon scattering data.

It has been established that nucleon elastic scattering and transfer reactions are sensitive to different regions of the OMPs [42]. Consequently, phenomenological OMPs constrained solely by elastic scattering data (and thus only well-constrained within certain radial ranges) may not be optimal for transfer reaction calculations. Recently, Whitehead, Lim, and Holt constructed a microscopic global nucleon–nucleus optical potential based on an analysis of 1800 isotopes within many-body perturbation theory using state-of-the-art nuclear interactions from chiral effective field theory (EFT) [1]. An attractive feature of the WLH potential is that none of its parameters are fitted to nucleon–nucleus scattering data. One might expect that a fully microscopic derivation would render the WLH potential more suitable for probing nuclear structure information via transfer reactions. Therefore, testing the WLH potential with (p, d) transfer reactions and comparing the results with experimental data and with calculations using phenomenological global nucleon–nucleus potentials is necessary.

In this study, tests were conducted using 28 sets of (p, d) reaction angular distributions on 15 nuclei, including both stable and unstable isotopes, for incident energies below 200 MeV/nucleon. The global phenomenological nucleon–nucleus potential of Koning and Delaroche (KD02 potential) [17] was used for comparison. The Johnson–Soper adiabatic wave approximation (ADWA) was employed for the (p, d) and (d, p) reaction calculations. The ADWA, which is essentially a three-body nuclear reaction model, accounts for deuteron breakup effects simply yet effectively [7] and is widely used in analyzing (p, d) and (d, p) reactions (see Refs. [43, 44]). Importantly, it does not require deuteron-target OMPs; instead, it treats the deuteron as a p+n system and calculates the distorted waves for the (p+n)+target three-body system using proton- and neutron-target OMPs. Thus, only nucleon-target OMPs are needed in the ADWA model, which suits our purpose of evaluating the microscopic WLH potential with (p, d) and (d, p) reactions.

The remainder of this paper is organized as follows: In Sec. II, we briefly introduce the theoretical model and data analysis procedures. An analysis of the transfer reactions is presented in Sec. III A. Results for incident energies above 150 MeV are presented in Sec. III B, and those for unstable nuclei are

given in Sec. III C. A discussion of the spectroscopic factors (SFs) appears in Sec. III D. Finally, we summarize our conclusions in Sec. IV.

II. Methodology

To investigate the effects of the microscopic WLH potential on transfer reaction cross sections, we studied (p, d) transfer reactions on 15 target nuclei: ^{28}Si, ^{34},^{46}Ar, ^{40}Ca, ^{54}Fe, ^{56},^{58},^{60}Ni, ^{90}Zr, ^{120}Sn, ^{102}Ru, ^{140}Ce, ^{142},^{144}Nd, and ^{208}Pb. The incident energies ranged from 18 to 200 MeV/nucleon. The ranges of target nuclei and incident energies were primarily limited by the upper bounds of the WLH and KD02 potentials, the lower bound of the target mass for KD02, and the availability of experimental data. All experimental data were obtained from the nuclear reaction database EXFOR/CSISRS [45] or digitized from original papers, as shown in Tables 1 and 2.

We adopted the three-body model reaction methodology (TBMRM) proposed by Lee et al. for analyzing (p, d) reactions [43, 44, 72]. This methodology uses the Johnson–Soper ADWA model for (p, d) and (d, p) reactions [7], where the amplitude of the A(p, d)B reaction is given by [73]

Spectroscopic factors (SFs) obtained with the WLH and KD02 potentials for stable isotopes at different energies. The reference to the experimental data set used in the extraction is also listed.

Target ^{102}Ru ^{120}Sn ^{140}Ce ^{142}Nd ^{144}Nd ^{208}Pb
Ep/MeV SFWLH SFKD02

SFs obtained with the WLH and KD02 potentials for unstable isotopes at different energies. The reference to the experimental dataset used in the extraction is also listed.

Target Ep/MeV SFWLH SFKD02

np. Using the ADWA model, exit-channel distorted waves are generated with the following effective "deuteron" (as a subsystem composed of neutrons and protons) potential [7, 73]:

Tpd = SF$^1/^2$nlj (−)dB np|Vnp| (+)pA nlj ,

UdB(R) = np|Vnp (UnB(R + r/2) + UpB(R − r/2))| np

where SFnlj is the spectroscopic factor with n, l, and j being the node number, angular momentum, and total angular momentum, respectively, of the single neutron wave function nlj in the nucleus A (A = B + n); pA and dB are the entrance- and exit-channel distorted waves, respectively; and Vnp is the neutron–proton interaction that supports the bound state of the n–p pair np (the deuteron wave function).

In this work, Vnp is the Gaussian potential with a depth of 72.15 MeV and a radius of 1.484 fm, taken from Ref. [74]. With this potential, only the s-wave was considered in where UnB and UpB are the neutron and proton OMPs on the

target nucleus B evaluated at half of the deuteron incident energies (the "Ed/2 rule"). In the zero-range version of ADWA, the effective deuteron potential becomes UdB(R) = UnB(R) + UpB(R).

Clearly, with the three-body ADWA model, only the neutron and proton OMPs are required. This allows the calculation of (p, d) and (d, p) reactions using only one set of systematic OMPs. Zero-range ADWA has been found satisfactory for describing deuteron pickup and stripping reactions [43, 44]. Therefore, although the finite-range version of the ADWA model and more sophisticated yet complicated continuum-discretized coupled channel models are available for analyzing (d, p) reactions [8, 73], we adopted the zero-range ADWA model in this study. To examine the microscopic WLH potential and compare its results with the phenomenological KD02 potential, zero-range ADWA should be sufficient.

The single-particle wave functions were calculated using the separation energy prescription with Woods–Saxon form single-particle potentials. The depths of these potentials were adjusted to reproduce the neutron separation energies in the ground states of the target nuclei. The radius and diffuseness parameters of these potentials, r_0 and a_0, are also important for nuclear transfer reactions. Their empirical values were $r_0 = 1.25$ fm and $a_0 = 0.65$ fm.

However, these empirical values do not represent the specific structure of individual nuclei. A better approach is to constrain the r_0 and a_0 values using reliable nuclear structure theory. The TBMRM constrains the r_0 and a_0 values using modern Hartree–Fock (HF) calculations [43, 72, 75–83]. Using this procedure, the diffuseness parameter was fixed at $a_0 = 0.7$ fm. The radius parameter r_0 was determined by requiring the root mean square (rms) radius of the single neutron wave function, $\sqrt{r^2}$, to be related to the rms radius of the corresponding single-particle orbital from HF calculations, $\sqrt{r^2}$ HF, by $r^2 = [A/(A-1)]\, r^2$ HF. The factor $[A/(A-1)]$ was used to correct for the fixed potential center assumption employed in the HF calculations, where A is the mass number of the composite nucleus. All HF calculations performed in this work were based on the SkX interaction [84]. We adopted the same procedure as in our previous studies [42, 81]. All transfer differential cross sections were calculated using the TWOFNR code [85].

III. Results and Discussions

A. Transfer Reactions on Stable Nuclei at Low Energies

The reliability of the WLH potential for (p, d) transfer reactions was first verified using stable nuclei at incident energies Ep $\leq$ 150 MeV, which fall within the validated range of the WLH potential. The target nuclei included ^{28}Si, ^{40}Ca, ^{54}Fe, ^{58,60}Ni, ^{90}Zr, ^{120}Sn, ^{102}Ru, ^{140}Ce, ^{142,144}Nd, and ^{208}Pb. The results are shown in Figs. 1–3 together with experimental data. For comparison, results calculated using the global phenomenological KD02 potential are also presented. All calculated results were normalized to the experimental data at the first peaks of the angular distributions or at the angles where the maximum

measured differential cross sections occurred. Neutron SFs were extracted using this procedure. All experimental data correspond to neutron transfer from the ground states of the target nuclei to the ground states of the residual nuclei; thus, the results obtained in this work represent single-neutron SFs in the ground states of the target nuclei.

As shown in Figs. 1–3, the experimental data can generally be satisfactorily reproduced by the WLH potential at forward angles, as well as by the KD02 potential. The WLH potential even outperformed the KD02 potential in some cases, such as ^{120}Sn_g.s.(p, d)^{119}Sn_g.s. at 18 MeV. In certain individual cases, the experimental angular distributions were not satisfactorily reproduced by either OMP, for example, ^{120}Sn_g.s.(p, d)^{119}Sn_g.s. at 26.3 MeV. Problems other than the OMP may exist in these cases.

[Figure 1: see original paper]

B. Extrapolation to Higher Energies

The WLH potential is expected to be valid for incident energies below 150 MeV. Above this range, theoretical uncertainties may become uncontrolled. However, it is interesting to examine its behavior when extrapolated to higher energies. When incident energies exceed approximately 150 MeV, the randomly generated WLH potential may produce unphysical positive potentials. In these cases, we set the number of random pulls to 1500, which allowed us to obtain at least 1000 negative-valued potentials from which we could derive reasonable averaged potentials.

In Fig. 4, we show results for (p, d) reactions on ^{28}Si and ^{40}Ca targets at incident energies between 150 and 200 MeV. Again, it can be observed that the WLH potential reasonably reproduces these higher-energy data and yields results very close to those of the KD02 potential at forward angles.

[Figure 2: see original paper]

C. Transfer Reactions on Unstable Nuclei

There is a pressing need for high-quality optical potentials for nuclei far from stability, which represent a frontier in nuclear physics [86–88]. Phenomenological potentials are most suitable for reactions where target masses fall within the range of the experimental database used to constrain the potential parameters. Since most elastic scattering data used to obtain phenomenological OMPs were measured on stable targets, the resulting OMP parameters may be biased by the limited range of target masses in the database. Therefore, caution is always advised when extrapolating these potentials to unstable nuclei, particularly when they are far from the β-stability line. Meanwhile, microscopic OMPs, which are derived from effective nucleon–nucleon interactions with reliable nuclear structure models, are expected to be more sophisticated when applied to reactions with unstable nuclei. It is interesting to examine how the microscopic

WLH potential performs for unstable nuclei and how it compares with the phenomenological KD02 potential.

The results are presented in Fig. 5 for (p, d) reactions on unstable targets ^{34},^{46}Ar and ^{56}Ni. As can be observed, the WLH potential again reproduces the experimental data reasonably well. In the ^{56}Ni case, the WLH potential performed even slightly better than the KD02 potential. Unfortunately, experimental data for (p, d) reactions on unstable nuclei are limited. More measurements of (p, d) reaction data on targets further from the β-stability line are required to thoroughly examine the applicability of the WLH potential.

[Figure 3: see original paper]

D. Spectroscopic Factors

OMPs affect not only the angular distributions but also the magnitudes of (p, d) reactions. Both aspects are important in nuclear reaction studies. Comparisons between theoretical and experimental angular distributions determine whether the assumed reaction mechanism and parameters in the theoretical model are appropriate, whereas the magnitudes of (p, d) reactions determine the SFs that provide crucial information about nuclear single-particle structure. As noted above, SFs are extracted experimentally by matching theoretical and experimental angular distributions at the maximum cross sections, where uncertainties in both the experimental data and extracted SFs are minimized [70] (see Figs. 1–5). The SFs from all reactions analyzed in this study are presented in Tables 1 and 2.

Comparisons between SFs obtained using the microscopic WLH potential and the phenomenological KD02 potential are shown in Fig. 6 as ratios SFWLH/SFKD02 at different incident energies. The target nuclei include the doubly magic isotopes ^{40}Ca and ^{208}Pb, stable nuclei ^{28}Si, ^{58},^{60}Ni, ^{90}Zr, ^{120}Sn, ^{102}Ru, ^{140}Ce, and ^{142},^{144}Nd, and unstable nuclei ^{34},^{46}Ar and ^{56}Ni. Interestingly, when the incident energy was below approximately 120 MeV, the two systematic potentials yielded, on average, very similar SFs for all types of nuclei. However, when the incident energy range increased to approximately 200 MeV, the ratios showed an increasing trend. This was especially apparent for the doubly magic nucleus ^{40}Ca (there is a lack of experimental data for ^{208}Pb above 100 MeV). When examining the results in the tables, it can be observed that the changes in SFs for ^{40}Ca with the KD02 potential are much smaller over the range of incident energies than those with the WLH potential.

It is well known that OMPs for doubly magic nuclei do not follow the systematics established for other nuclei because of their relatively larger excitation energies for the first few excited states [16, 22, 94]. The increased disagreement between the SFs from the WLH and KD02 potentials at higher energies may indicate deficiencies in these potentials. Therefore, we compared their descriptions of proton elastic scattering from ^{40}Ca at higher energies. The results are presented in Fig. 7 for the ^{40}Ca target. It can be observed that at lower energies,

the two potentials describe the experimental data similarly. However, at higher energies, the phenomenological KD02 potential appears to perform better than the microscopic WLH potential. Nevertheless, neither potential reproduced the higher-energy data well, nor even the low-energy data perfectly. Since all other parameters are identical in the transfer reaction calculations, this could be the reason for the differences between the SFs obtained with the two potentials. Note that these incident energies are outside the range of validity for WLH, which is for Ep $<$ 150 MeV. This suggests that caution is needed when extrapolating the WLH potential to higher incident energies. Meanwhile, improving the systematic potential for lighter targets and/or higher-energy regions would be valuable, especially for doubly magic nuclei.

[Figure 4: see original paper]

[Figure 5: see original paper]

[Figure 6: see original paper]

[Figure 7: see original paper]

IV. Summary

We have verified the performance of the new microscopic optical WLH potential based on EFT in (p, d) reactions. In the present study, we performed zero-range adiabatic calculations for 15 nuclei, covering a wide energy range of 18–200 MeV/nucleon. The phenomenological KD02 potential parameters were used for comparison. This purely microscopic optical potential effectively reproduced the angular distributions for both stable and unstable nuclei as well as the phenomenological KD02 potential. Our results suggest that the microscopic WLH potential can serve as an advanced approach for predicting transfer reactions on unstable nuclei and for extracting nuclear structure information for exotic nuclei.

Furthermore, we studied the magnitudes of the transfer cross sections with the WLH potential. The SFs extracted using the WLH potential were close to those obtained using the KD02 potential for all types of nuclei below approximately 120 MeV. However, when the incident energy range increased to approximately 200 MeV, the ratios showed a significant increasing trend with incident energy, particularly for the doubly magic nucleus ^{40}Ca. Comparisons between the WLH and KD02 potentials in describing proton elastic scattering from ^{40}Ca were performed up to 200 MeV. The results revealed some imperfections at higher energies for both potentials. Improvement of the WLH potential at higher incident energies for doubly magic nuclei is desirable. Nevertheless, in general, the successful application of the WLH potential in (p, d) transfer reactions is encouraging.

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