Optical model potential of deuteron with $1p$-shell nuclei

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Abstract

A set of global optical potential parameters, DA1p, for deuterons with the $1p$-shell nuclei is obtained by simultaneously fitting 67 sets of experimental data of deuteron elastic scattering from $^6$Li, $^9$Be, $^{10}$B, $^{11}$B, $^{12}$C, $^{13}$C, $^{14}$N, $^{16}$O and $^{18}$O with incident energies between 5.25 and 170 MeV. DA1p improves the description of the deuteron elastic scattering from the $1p$-shell nuclei with respect to the existing systematic deuteron potentials and can give satisfactory reproduction to the experimental data with radiative nuclei such as $^9$Li, $^{10}$Be, $^{14}$C and $^{14}$O.

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I. INTRODUCTION

Systematic optical model potentials (OMPs) are very useful in many fields of nuclear physics. They help to reduce the uncertainties of nuclear structure information extracted from direct nuclear reactions [1] and to make systematic analyses [2, 3]. They are also indispensable in reliable predictions of reaction rates of direct nuclear reactions which are not easy or impossible to be measured directly in laboratories. Over the past several decades, many systematic potentials have been proposed for nucleon \((A = 1)\) [4–7], deuteron \((A = 2)\) [8–12], \(^3\)H and \(^3\)He \((A = 3)\) [13–17], alpha-particles \((A = 4)\) [18–21], and heavy ions \((A \geq 6)\) [22–24]. They are widely used in studies of direct nuclear reactions.

In three-body models of the \((d, p)\) and \((p, d)\) reactions proton and neutron potentials are used instead of the deuteron-target potentials [25–27]. The deuteron-target OMPs are necessary in many other reactions, for instance, the \((^3\text{He}, d)\) reactions, for which the distorted wave Born approximation is usually still valid [28, 29]. Deuteron optical potentials are also needed in reactions induced by radiative nuclei with a deuterium target in inverse kinematics. In such reactions, one usually focuses on the weakly-bound nature of the radiative nuclei and will need the deuteron potential with the core nucleus in calculations with the continuum discretized coupled channel (CDCC) method [30].

Most of the existing systematic deuteron potentials are based on the analysis of angular distributions of elastic scattering cross sections of deuterons from heavy targets with atomic masses of, typically, \(A_T \gtrsim 30\) [8–10]. It is well-known that the systematics developed at such heavy mass region are different from that in the light mass region \((A_T \lesssim 20)\) [31, 32]. Phenomenological renormalization factors are found to be needed when systematic potentials developed in the heavy-mass region are applied to light targets [30, 33]. This is not convenient in theoretical calculations for reactions which have no corresponding elastic scattering data to constrain the OMP parameters. The database for the systematics of An Haixia et al. and Han YinLu et al. include \(^{12}\)C, \(^{14}\)N, and \(^{16}\)O targets [11, 12]. However, their systematics are not optimized for the light-target region. Many experimental data with other light-heavy targets are not included. It is thus very useful to establish a systematic deuteron potential for the \(1p\)-shell nuclei.

In this paper, we report a systematic deuteron potential with the \(1p\)-shell nuclei. It is designated as DA1p. The target nuclei include \(^6\)Li, \(^9\)Be, \(^{10}\)B, \(^{11}\)B, \(^{12}\)C, \(^{13}\)C, \(^{14}\)N, \(^{16}\)O, and \(^{18}\)O.
with deuteron incident energies between 5.25 and 170 MeV. The experimental data available for the $^6$Li and $^7$Li targets are mostly limited for deuteron energies below 14.7 MeV. Within such a low energy region, contributions from the compound processes are expected to be important in the elastic scattering of deuterons with these lightest 1p-shell nuclei. For this reason, these data are analyzed individually. The parameterization of DA1p is described in Section II A the resulting OMP parameters are reported in Section II B with comparisons between optical model calculations and experimental data. Examination of the application of DA1p to the total cross sections and elastic scattering from radiative nuclei are shown in Section III. Our conclusions are given in Section IV.

II. PARAMETERIZATION AND DETERMINATION OF THE SYSTEMATIC POTENTIAL PARAMETERS

A. Parameterization

The parameterization of the optical model potential in this work, $U(r)$, as a function of $r$ which is the distance between a projectile and target nuclei, is the same as that of HT1p [32]:

$$U(r) = -V_v f_{ws}(r, R_i, a_i) - iW_v f_{ws}(r, R_w, a_w)$$
$$- iW_s (-4a_w) \frac{d}{dr} f_{ws}(r, R_w, a_w)$$
$$+ V_C(r),$$

(1)

where $V_v$, $W_v$, and $W_s$ are the depths of the real, and the volume and surface imaginary potentials, respectively. $f_{ws}(r)$ is the Woods-Saxon form factor:

$$f_{ws}(r, R_i, a_i) = \frac{1}{1 + \exp \left[ (r - R_i)/a_i \right]}$$

(2)

with $i = v$ and $w$ for the real and imaginary potentials, respectively.

The diffuseness of these potentials are assumed to be independent on the target masses ($A_T$) and incident energies ($E$ in MeV). Such dependences, however, are parameterized in the radius parameters:

$$R_i = r_i A_T^{1/3} + r_i^{(0)} + r_{ie}(E - E_C),$$

(3)
where $E_C$ is the Coulomb correction to the incident energy $[^5, ^8, ^15]$:

$$E_C = \frac{6Z_P Z_T e^2}{5R_C},$$

in which $Z_T$ and $Z_P$ are the charge numbers of the target and the projectile nuclei, respectively, and $R_C = r_e A_T^{1/3}$ is the radius of the Coulomb potential:

$$V_C(r) = \begin{cases} 
\frac{Z_P Z_T e^2}{r}, & (r \geq R_C) \\
\frac{Z_P Z_T e^2}{2R_C} \left( 3 - \frac{r^2}{R_C^2} \right), & (r \leq R_C). 
\end{cases}$$

In this work $r_e$ is fixed to be 1.3 fm. The energy dependence of the radius parameters for both the real and the imaginary parts are found to be important to simultaneously describe the elastic scattering data in a wide energy range, as suggested in Ref. [^34].

The depth of the real potential in Eq. (1) is assumed to depend linearly on the incident energies:

$$V_r(E) = V_t + V_e(E - E_C),$$

The volume and surface terms of the imaginary potentials, $W_v$ and $W_s$, are defined as

$$W_v(E) = \frac{W_{v0}}{1 + \exp \left( \frac{W_{v0} - (E - E_C)}{W_{ve0}} \right)},$$

$$W_s(E) = \frac{W_{s0}}{1 + \exp \left( \frac{(E - E_C) - W_{se0}}{W_{sse0}} \right)}.$$ 

For $^6, ^7$Li at low energies, the imaginary potentials are assumed to depend linearly on the incident energies: $W_j = W_{j0} + W_{je}(E - E_C)$, with $j = v$ and $s$ for the volume and surface imaginary parts, respectively.

Spin-orbit potentials are not included in the parameterization of DA1p. We do this because of two practical reasons. Firstly, we expect DA1p to be used in CDCC calculations for reactions induced by weakly-bound radiative nuclei with the deuterium targets. Currently, in most CDCC calculations using, for example, computer code FRESCO [^35], spin-orbit couplings are not implemented. In such cases we need the OMP of deuteron to reproduce the elastic scattering data without a spin-orbit potential as well. Secondly, the experimental data analyzed in this work are all angular distributions of elastic scattering cross sections, which are not sensitive to the spin-orbit potentials, especially at forward angles, where the data are most well accounted for by the optical model. In total we have 16 free parameters for DA1p, which are listed in Table II.
B. Parameters of DA1p and comparisons with experimental data

89 sets of experimental data for deuteron elastic scattering from the 1p-shell nuclei are analyzed in this work, which consist of 65 sets for \( ^9\text{Be} \), \(^{10,11}\text{B} \), \(^{12,13}\text{C} \), \(^{14}\text{N} \), and \(^{16,18}\text{O} \) with incident energies below 171 MeV and 24 sets for \(^6,7\text{Li} \) from 4.5 MeV to 171 MeV. All the data sets are obtained from the EXFOR database \([36]\). Details of these data are shown in Table I.

In searching for the parameters of DA1p, 65 sets of data for the \(^9\text{Be} \), \(^{10,11}\text{B} \), \(^{12,13}\text{C} \), \(^{14}\text{N} \), and \(^{16,18}\text{O} \) targets together with the two sets of \(^6\text{Li} \) at 25 and 171 MeV are simultaneously fitted using the computer code MINOPT \([5]\). The OMP parameters are optimized with the usual minimization of \( \chi^2 \) method:

\[
\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{th}}}{\Delta \sigma_i} \right]^2,
\]

where \( \sigma_i^{\text{exp}} \), \( \sigma_i^{\text{th}} \), \( \Delta \sigma_i \) are the experimental and theoretical cross sections, and the experimental errors, respectively. Uniform uncertainty of the experimental data \( \Delta \sigma_i/\sigma_i^{\text{exp}} = 15\% \) is assumed in this work. Experimental data measured by different groups may have different systematic uncertainties. For this reason, normalization of the experimental data is allowed during the parameter searching with MINOPT \([5]\). Convergence of the searching is ensured by observing that the values of parameters came back to their optimized ones (within their uncertainties) in fittings with different initial values randomly set within 10\%.

The uncertainties of the parameters of DA1p are obtained with the bootstrap method \([37]\), which reduplicates the calculations 1000 times by random sampling with replacements of the datasets used in the original database. Details of applying the bootstrap method for the uncertainties of the systematic OMPs can be found in Refs. \([5, 15]\). The final parameters of DA1p and their uncertainties are given in Table II.

During this work, we found that the experimental data of \(^6\text{Li} \) and \(^7\text{Li} \) at low incident energies \((E < 15 \text{ MeV})\) are hard to be described together with the other datasets using a systematic potential. These data may have considerable contributions from compound processes, which can not be accounted for by the optical model implemented in MINOPT. We search for the deuteron potentials with \(^6\text{Li} \) and \(^7\text{Li} \) at low energies separately. The results are also given in Table III. As one can see, the parameters of these two targets differ very much from the systematics established by the other 1p-shell nuclei.
TABLE I: The database used in searching of the parameters of DA1p. \(\chi^2\) values with the systematics of DA1p, Daehnick \textit{et al}, and Haixia An \textit{et al}, are labeled as \(\chi^2_{DA1p}\), \(\chi^2_{Dae}\), and \(\chi^2_{An}\), respectively. The unit of \(E_d\) is MeV.

| target | \(E_d\) | \(\chi^2_{DA1p}\) | \(\chi^2_{Dae}\) | \(\chi^2_{An}\) | Ref | target | \(E_d\) | \(\chi^2_{DA1p}\) | \(\chi^2_{Dae}\) | \(\chi^2_{An}\) | Ref |
|--------|--------|-----------------|-----------------|-----------------|-----|--------|--------|-----------------|-----------------|-----------------|-----|
| \(^6\)Li | 4.5    | 0.46            | 39.09           | 16.47           | [38] | \(^9\)Be | 7      | 1.69            | 20.30           | 19.93           | [39] |
|        | 4.75   | 1.55            | 40.02           | 16.60           | [38] | \(^{12}\)C | 25.9   | 6.48            | 8.81            | 8.79            | [40] |
|        | 5      | 1.72            | 56.91           | 24.45           | [38] |        | 29.5   | 9.87            | 5.55            | 5.03            | [40] |
|        | 5.25   | 1.83            | 49.40           | 21.29           | [38] |        | 5.05   | 2.97            | 11.30           | 9.24            | [41] |
|        | 6      | 6.16            | 57.75           | 25.71           | [44] |        | 8      | 3.49            | 64.53           | 28.46           | [44] |
|        | 7      | 5.05            | 58.69           | 26.08           | [44] |        | 8      | 3.02            | 58.13           | 25.64           | [44] |
|        | 8      | 3.49            | 64.53           | 28.46           | [44] |        | 9      | 1.21            | 63.41           | 27.65           | [44] |
|        | 9      | 0.45            | 60.86           | 26.34           | [44] |        | 10     | 0.90            | 65.81           | 28.73           | [44] |
|        | 10     | 1.63            | 63.88           | 27.65           | [56] |        | 11.8   | 2.77            | 4.19            | 3.77            | [57] |
|        | 11.8   | 2.07            | 66.42           | 28.98           | [49] |        | 11     | 13.93           | 13.93           | 12.03           | [48] |
|        | 12     | 5.40            | 44.40           | 20.54           | [59] |        | 25     | 3.73            | 5.62            | 6.04            | [62] |
|        | 17     | 1.41            | 13.91           | 13.98           | [48] |        | 7      | 2.43            | 13.91           | 13.98           | [48] |
|        | 7      | 1.86            | 68.97           | 30.67           | [44] |        | 8      | 9.03            | 69.63           | 30.63           | [44] |
|        | 8      | 0.93            | 70.55           | 30.93           | [44] |        | 9      | 6.43            | 74.14           | 32.32           | [44] |
|        | 10     | 0.81            | 77.55           | 33.48           | [56] |        | 11.8   | 1.17            | 53.22           | 23.41           | [59] |
|        | 11.8   | 1.23            | 62.03           | 26.50           | [49] |        | 12.8   | 7.09            | 4.76            | [41] |
|        | 14.7   | 1.17            | 53.22           | 23.41           | [59] |        | 14.7   | 1.17            | 53.22           | 23.41           | [59] |
|        | 18     | 1.70            | 11.98           | 10.73           | [38] |        | 5.5    | 1.70            | 11.98           | 10.73           | [38] |
|        | 5.75   | 0.95            | 11.50           | 9.90            | [38] |        | 6      | 2.97            | 7.09            | 4.76            | [41] |
|        | 6      | 4.34            | 4.70            | 8.41            | [38] |        | 6.5    | 2.67            | 7.95            | 8.54            | [41] |
|        | 7      | 1.69            | 12.29           | 11.76           | [41] |        | 7      | 1.69            | 12.29           | 11.76           | [41] |

Comparisons with experimental data and optical model calculations of the DA1p parameters are given in Figs.1-4 together with the predictions using the systematics of Daehnick \textit{et al}. [10]. Clearly, DA1p improves the reproduction to the experimental data with respect to that of the latter, especially at low incident energies and at forward angles. At higher incident energies above around 30 MeV, both systematic potentials give satisfactory repro-
TABLE II: Values of parameters, $P$, and their uncertainties, $\Delta P$, of DA1p. $V_r$, $V_e$, $W_{v0}$, $W_{s0}$, $W_{se}$, $W_{ve0}$, $W_{vew}$, $W_{se0}$, and $W_{sew}$ are in MeV, and $r_r$, $r_r^{(0)}$, $r_{re}$, $a_r$, $r_w$, $r_w^{(0)}$, $r_{we}$, and $a_w$ are in femtometers.

| parameter | $^{1p}$-shell | $^{6}$Li | $^{7}$Li |
|-----------|---------------|--------|--------|
| $V_r$     | 98.9          | 47.9   | 26.1   |
| $V_e$     | -0.278        | 2.37   | 1.19   |
| $r_r$     | 1.11          | 1.62   | 1.45   |
| $r_r^{(0)}$ | -0.172      | -       | -       |
| $r_{re}$  | 0.00117       | 0.0122 | 0.097  |
| $a_r$     | 0.776         | 0.876  | 0.844  |
| $W_{v0}$  | 11.5          | 11.3   | 215.0  |
| $W_{s0}$  | 7.56          | 0.8    | 0.2    |
| $r_w$     | 0.561         | 2.83   | 2.12   |
| $r_w^{(0)}$ | 3.07        | -       | -       |
| $r_{we}$  | -0.00449      | -0.0911| 0.022  |
| $a_w$     | 0.744         | 0.27   | 0.261  |
| $W_{se}$  | -             | 3.44   | -16.1  |
| $W_{ve0}$ | 18.1          | 1.4    | -      |
| $W_{vew}$ | 5.97          | 1.33   | -      |
| $W_{se0}$ | 14.3          | 1.4    | -      |
| $W_{sew}$ | 4.55          | 0.86   | -      |

It is interesting to observe that the depth of the real part of DA1p, which has $V_r = 98.9$ MeV, is larger than those in the systematics established for heavy-targets, for example, the values of $V_r$ are 86, 91.85, and 82.18 MeV in the work of Daehnick et al. [10], Haixia An et al. [11] and Yinlu Han et al. [12], respectively. The same differences between systematic potentials in $1p$-shell nuclei and heavy-target nuclei are also found in systematic potentials of proton, $^3$H and $^3$He [31, 32]. Also, the radius parameter of the imaginary potential, $r_w^{(0)}$,
as shown in Table II shows stronger dependence on the target masses than the systematics established in the heavy-target region. This may be related to the fact that the 1p-shell nuclei distinguish with each other more strongly than those among the heavy targets in their structures.

![Graph](image)

FIG. 1: (Color online) Comparisons between the experimental data and optical model calculations with DA1p (solid curves) and Daehnick et al. (dashed curves) for deuteron impinging on $^9$Be. The deuteron incident energies are indicated along with the curves in MeV. The cross sections are offset by factors of $10^2$.

III. APPLICATION OF DA1P TO RADIATIVE NUCLEI AND TOTAL REACTION CROSS SECTIONS

Comparisons between optical model calculations using DA1p and the experimental data which are not included in our database, mostly with radiative nuclei, are given in Fig 6. Again, one sees that DA1p improves the reproduction to the experimental data with respect to the systematic potential of Daehnick et al.. A detailed comparison in $\chi^2$-values are given in Table III. This suggests that DA1p can give more reliable predictions to the elastic scattering cross sections of deuteron with nuclei that are away from the $\beta$-stability line.

Total reaction cross sections are not used to constrain the parameters of DA1p. Com-
Compared to optical model calculations and experimental data of total reaction cross sections, comparisons between optical model calculations and experimental data for $^9$Be, $^{12}$C, and $^{16}$O targets for deuteron incident energies of 37.9, 65.5, and 97.4 MeV [73]. Systematic potentials of DA1p, Haixia An et al. and Daehnick et al. are used here. These results seem to suggest that the systematics of Haixia An et al. and Daehnick et al. give better accounts of the total reaction cross sections of deuterons with light targets. However, we found that the discrepancies between results with DA1p and the experimental data might be reconciled when the breakup of deuteron is taken into account. We will discuss this problem in details in a following paper.

IV. CONCLUSIONS

In conclusion, we present in this paper a systematic phenomenological optical model potential, DA1p, of deuteron with the 1p-shell nuclei (except for $^6$Li and $^7$Li) for incident energies from around 5 to 170 MeV. Two sets of parameters are given for $^6$Li and $^7$Li targets for incident energies between around 5 and 15 MeV. Differences in the potential parameters are found between DA1p and the systematic potentials established for heavy-
FIG. 3: (Color online) The same as Fig. but for deuteron elastic scattering from (a) $^{16}$O (circles), (b) $^{10}$B (squares), $^{11}$B (X-marks), $^{18}$O (asterisks) and $^{6}$Li (triangles) at high energy.

FIG. 4: (Color online) The same as Fig. but for deuteron elastic scattering from $^{6}$Li (circles) and $^{7}$Li (triangles) at $E_d < 15$ MeV.

target region. DA1p is found to give satisfactory reproduction to the angular distributions of deuteron elastic scattering from both stable and radiative $1p$-shell nuclei. The experimental total reaction cross sections for $^{9}$Be, $^{12}$C and $^{16}$O targets are found to be overpredicted by
FIG. 5: (Color online) Comparisons with optical model calculations and experimental data for deuteron elastic scattering from $^{12}$C at 80 and 120 MeV. Separately plotted from Fig.2 to show in details of comparisons between results with DA1p and the Daehnick et al.

TABLE III: The same as Table I but for the experimental data shown in Fig.5

| target | $E_d$ | $\chi^2_{DA1p}$ | $\chi^2_{Dae}$ | $\chi^2_{An}$ | Ref |
|--------|-------|-----------------|----------------|----------------|-----|
| $^9$Li | 10    | 5.11            | 4.37           | 4.21           | [74]|
| $^{10}$Be | 12    | 20.61           | 262.11         | 163.01         | [75]|
|        | 15    | 9.22            | 94.86          | 65.02          | [75]|
|        | 18    | 3.55            | 31.73          | 25.65          | [75]|
|        | 21.4  | 10.40           | 146.73         | 126.63         | [75]|
| $^{11}$Be | 53.8  | 3.80            | 10.47          | 7.19           | [76]|
| $^{14}$C | 17.06 | 4.10            | 6.17           | 4.31           | [77]|
| $^{14}$O | 35.6  | 4.06            | 4.67           | 6.06           | [78]|
| $^{15}$N | 15    | 14.37           | 12.87          | 13.00          | [79]|

Theoretical calculations with systematic deuteron potentials, which was found to be due to the breakup cross sections of deuterons and will be further studied in a following paper.
FIG. 6: (Color online) The same as Fig.1 but for experimental data that are not included in our systematic analysis, mostly for radiative nuclei [74–79].

FIG. 7: (Color online) Optical model calculations of the total reaction cross sections with systematics of DA1p, Daehnick et al. and Haixia An et al. for targets $^9$Be (upper panel), $^{12}$C (middle panel) and $^{16}$O (bottom panel) and their comparisons with the experimental data [73].
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