Microscopic optical model potentials for $p$-nucleus scattering at intermediate energies

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A comparative study of the microscopic optical potentials viz., semimicroscopic with extended Jeukenne-Lejeune-Mahaux interaction and microscopically Brueckner theory using Hamada-Johnston as well as Urbana V14 soft-core internucleon interactions, has been carried out. These microscopic optical potentials are compared with that of Dirac phenomenology (DP) for the polarized proton-40Ca elastic scattering at 35 MeV and 200 MeV. These potentials have different shapes for 200 MeV below 4 fm. In particular, for the real part of the central potential, only the Dirac phenomenology and the microscopic optical potential calculated with the Hamada-Johnston interaction exhibit the well known wine-bottle-bottom shape. It is found that the calculated observables (cross section, analyzing power and spin rotation function) using these potentials having different shapes, compare well with the experiment.

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It is known that the conventional optical model with phenomenological potential of Woods-Saxon shape fails to account for the spin observables (like analyzing power $A_y$ and spin rotation function $Q$) in the polarised proton-nucleus scattering at intermediate energies. On the other hand, Dirac phenomenology (DP) [1,2] is found to be remarkably successful in describing these observables. The most crucial point emerged from this analysis is that the real part of the central potential changes its shape and sign, for example, becoming wine-bottle-bottom (WBB) shape at intermediate energies and then turns repulsive with the further increase in projectile energy. There are other models like the relativistic impulse approximation that are well known to work successfully in the medium- and high-energy regions [3]. It has been shown that the nonrelativistic optical model with microscopically derived potentials can qualitatively reproduce the cross sections and spin observables. For example, Bauge et al. [4] have calculated the nucleon optical potential employing the extended Jeukenne, Lejeune, and Mahaux (JLM) interaction while similar calculations by Haider et al. [5] (Saliem et al. [6]) have been carried out within the framework of the first order Brueckner theory using Hamada-Johnston (HJ) [7] (Urbana V14 soft-core [8]) internucleon interaction. It is seen that both these calculations ([4] and [8]) yield very mild WBB shape for the real central optical potential at a radial distance close to root-mean-square radius of the target nucleus while the corresponding DP and HJ potentials have a prominent WBB shape.

In this short communication as an illustration, we examine the scattering of polarized proton on 40Ca. We analyze the results obtained from semimicroscopic approach using extended JLM interaction (MOM) [4] valid up to 200 MeV projectile energy and microscopically Brueckner theory with Hamada-Johnston [7] as well as Urbana V14 [8] inter-nucleon potentials (denoted by HJ and V14, respectively) and compare with those of the Dirac phenomenology (DP).

The physical quantities of interest are the elastic scattering angular distributions and the spin observables. In the elastic scattering of spin $\frac{1}{2}$ projectiles, the differential cross section ($\sigma(\theta)$), the analyzing power ($A_y$) and the spin rotation function ($Q$) are given by the standard well known expressions [9].

A brief description of different models for generating the nucleon-nucleus optical potential used in the present analysis now follows.

The semimicroscopic optical model (MOM) [4] is a Lane-consistent, optical model potential which is built by folding radial matter densities with an effective interaction in nuclear matter that is based on the extension of the original approach proposed by JLM. This interaction is a hybrid in which the energy- and density-dependent, spin-independent interaction in nuclear matter comes from the original work of JLM, with a new parametrization defined in [10]. In MOM, the imaginary part of the effective interaction is multiplied by an effective mass. The JLM interaction, established for nuclear matter, has been applied to finite nuclei by using the improved local density approximation (LDA) and is also extended to deformed nuclei. To calculate the complex spin-orbit potential, Scheerbaum’s prescription coupled with the phenomenological complex potential depths was used as shown in Ref. [10]. This yields through the standard code MOM [4], both real and imaginary central and spin-orbit parts of the optical potential. This optical potential is then used to get the elastic scattering differential cross section, analyzing power and spin rotation function. Such an analysis of the scattering and the reaction data has been successfully employed in the past [4,11–15].

Here we use this approach for the analysis of the elastic proton scattering on 40Ca. All the required parameters along with the energy-dependent normalisation factors for the various terms of the optical potential given in Ref. [4] are...
The calculation of nucleon optical potential in the first order Brueckner theory of infinite matter, starting from realistic internucleon interaction, mainly involves two steps [5,6]. First one evaluates the radial dependence of the complex effective NN interaction (g-matrices) after obtaining self-consistency [5,6] at several nuclear matter densities for the nuclear matter optical potential using realistic internucleon potentials. In the second step, these effective interactions are folded over the point nucleon densities in the ground state of the target nucleus to obtain the nucleon-nucleus optical potential. Since the effective interactions are complex, this approach consistently predicts both the real and imaginary parts of the optical potentials. The effective interactions in this approach are energy- and density-dependent.

We have calculated the nucleon optical potential in first order Brueckner theory for $^{40}$Ca at 35 MeV and 200 MeV, using Hamada-Johnston [7] and Urbana V14 [8] internucleon potentials following the procedure described in detail in [5,6]. For the target $^{40}$Ca, we have used the nucleon densities from Ray [17]. Further, for incident protons, correction to the incident energy due to Coulomb repulsion for calculating the effective interaction has also been taken into account [5]. The potentials thus calculated are denoted by HJ and V14, respectively, in this work. Using these optical potentials, we have calculated the elastic scattering differential cross section, analyzing power and spin rotation function.

The DP approach starts with the Dirac equation having Lorentz scalar, $S$, and Lorentz vector, $V$, type potential terms. The nonrelativistic reduction of the Dirac equation leads to a Schrödinger-equivalent equation which has effective central and spin-orbit potentials. The effective potentials have explicit energy dependence and a nonlocal Darwin term. The complex $S$ and $V$ potentials can be introduced phenomenologically (e.g., Woods-Saxon type). It turns out that in general, the real vector potential is large and repulsive whereas the real scalar potential is somewhat larger and attractive. The imaginary vector potential is attractive, and the imaginary scalar is repulsive. The details are given in [1,2]. Using algebraic expressions for $S$ and $V$ potentials, a global DP have been reported [18]. The Dirac equation so structured is suitable for calculations of nucleon-nucleus scattering data for incident energies up to several GeV [1,2]. This approach has been found to be successful in reproducing both the differential cross sections and the spin observables [1,2,18–20].

The normalization constants for the real and the imaginary central ($\lambda_V$ and $\lambda_W$) and the spin-orbit ($\lambda_{Vso}$ and $\lambda_{Wso}$) potentials are obtained through the best fit to the observed data. The best fit values for these normalisation constants for MOM, V14 and HJ along with the chi-squared values for the differential cross section ($\chi^2_\sigma$), analyzing power ($\chi^2_\chi$), spin rotation function ($\chi^2_Q$) are listed in Table I. It is observed that at 35 MeV proton energy, $\chi^2_\sigma$ and $\chi^2_\chi$ values are similar for all the potentials. However for the case of 200 MeV proton, V14 yields the lowest $\chi^2_\sigma$ and $\chi^2_\chi$ while MOM has the smallest value of $\chi^2_Q$.

The final potentials are then obtained by multiplying the respective nucleon-nucleus optical potentials by the corresponding normalization constants listed in Table I. The

![Diagram](image-url) FIG. 1. (Color online) MOM, HJ, V14, and DP potentials for $p-^{40}$Ca scattering evaluated at 35 MeV and 200 MeV (a) Real part of the central potential (b) Imaginary part of the central potential (c) Real part of the spin-orbit potential (d) Imaginary part of the spin-orbit potential.

<table>
<thead>
<tr>
<th>Potential</th>
<th>35 MeV</th>
<th>200 MeV</th>
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<tbody>
<tr>
<td>$\lambda_V$</td>
<td>0.894</td>
<td>0.845</td>
</tr>
<tr>
<td>$\lambda_W$</td>
<td>0.681</td>
<td>0.563</td>
</tr>
<tr>
<td>$\lambda_{Vso}$</td>
<td>0.702</td>
<td>0.912</td>
</tr>
<tr>
<td>$\lambda_{Wso}$</td>
<td>1.028</td>
<td>0.688</td>
</tr>
<tr>
<td>$\chi^2_\sigma$</td>
<td>43.59</td>
<td>35.99</td>
</tr>
<tr>
<td>$\chi^2_\chi$</td>
<td>27.61</td>
<td>29.15</td>
</tr>
<tr>
<td>$\chi^2_Q$</td>
<td>0.771</td>
<td>0.937</td>
</tr>
</tbody>
</table>

TABLE I. The best fit normalization constants for the real and imaginary central ($\lambda_V$ and $\lambda_W$) and the spin-orbit ($\lambda_{Vso}$ and $\lambda_{Wso}$) potentials and the resulting $\chi^2_\sigma$, $\chi^2_\chi$, and $\chi^2_Q$ values for $\sigma$, $A_1$, and $Q$, respectively.
resulting real ($V$) and the imaginary ($W$) parts of the central potential both for 35 MeV and 200 MeV protons on $^{40}$Ca are shown in Figs. 1(a) and 1(b), respectively. Figures 1(c) and 1(d) depicts the corresponding real and the imaginary parts of the spin-orbit potential. All DP results (potentials and scattering observables) for 35 MeV and 200 MeV $p$-$^{40}$Ca scattering are taken from [20] and [21], respectively, for comparison and discussion.

Figure 1(a) reveals that in the case of 200 MeV, these potentials (MOM, HJ, V14, and DP [21]) differ from each other considerably in the interior while in the surface region beyond 4 fm all the potentials overlap. It is clear from the figure that HJ and DP yield the desired WBB shape around 4 fm. On the other hand both MOM and V14 have a mild WBB shape at around 4 fm. In the case for 35 MeV, the shape of $V$ is similar in all the cases. However, V14 is slightly deeper in the interior while HJ is relatively less attractive as compared to MOM and DP [20].

All the approaches yield very similar results for the imaginary part of the central potential for $p$-$^{40}$Ca at 200 MeV shown in Fig. 1(b). However, these do differ somewhat among themselves in the interior region and beyond 4 fm they merge. The imaginary V14 for 200 MeV is slightly more attractive. For 35 MeV, the imaginary part of the central potential is small in magnitude. Further, imaginary central DP potential is slightly repulsive in the interior then becomes attractive and remains constant for a while till 6 fm, finally merges with that of the microscopic potentials. All the potentials have different shapes in the interior with microscopic potentials to be relatively more attractive than DP.

The corresponding analyzing powers are shown in Figs. 2(b) and 3(b), respectively. All the calculations (MOM, HJ, V14, and DP) are in agreement with the experimental data at smaller angles. However, at 35 MeV deviations appear at higher angles ($>60^\circ$), in particular the maxima appear a little
earlier except for DP. For angles above 120°, considerable differences are noticed both in magnitude and position of maxima and minima.

The spin rotation function is shown in Fig. 3(c) for p-40Ca elastic scattering at 200 MeV projectile energy. All the calculations agree well with the experimental data. The experimental Q for p-40Ca elastic scattering at 35 MeV is not yet available. The various calculations for the spin rotation function Q agree among themselves and reveal similar systematics as observed in the case of analyzing power.

In summary, we have compared the microscopic potentials viz., semimicroscopic analysis using extended Jeukenne, Lejeune, and Mahaux interaction and microscopic Brueckner theory using Hamada-Johnston as well as Urbana V14 soft-core inter-nucleon interactions with that of the Dirac phenomenology for the polarized proton-40Ca elastic scattering at 35 MeV and 200 MeV. It is observed that the calculated (MOM, HJ, V14, and DP) real part of the central potential have different shapes in the interior with HJ and DP having a wine-bottle-bottom shape. It is interesting to note that the observables (cross section, analyzing power, and spin rotation function) calculated using these potentials though having different shapes compare well with the experiment. This indicates, contrary to the present belief, that the prominent WBB shape as predicted by DP, may not be essential for the reproduction of the experimental observables at intermediate incident nucleon energies.

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