# Microscopic description of proton scattering at 295 MeV from Pb isotopes

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Microscopic analysis of the recently reported 295-MeV-proton scattering data from Pb isotopes and $^{58}$Ni is presented within the framework of the Brueckner-Hartree-Fock theory. The effective interaction (g matrix) has been calculated using three Hamiltonians with Urbana v-14, Argonne v-18, and Ried93 internucleon potentials. The microscopic optical potential is calculated by folding the effective interactions over nucleon density distributions obtained in the relativistic mean field framework. The Argonne v-18 and Ried93 interactions have been used for the first time to calculate the nucleon-nucleus optical potential. The calculations reproduce the experiment well thus revalidating the use of microscopic optical potential in such analyses.

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Nucleon density in nuclei is a property of fundamental importance in nuclear physics. Experimentally, the charge (and hence proton) density can be measured to a high degree of accuracy through electron scattering [1,2]. A number of such measurements have been carried out in the past, and the corresponding model independent charge densities have been reported. On the other hand, for the neutron density distributions, one needs to rely on indirect methods, and hence the extracted neutron densities are model dependent. Hadron scattering in the intermediate energy region has proved to be an important tool in studying the neutron density distributions in nuclei [3–5]. However, the extracted neutron densities are not as accurate as compared to the corresponding proton density distributions.

Heavy nuclei are expected to have neutron skin which is strongly correlated with the nuclear symmetry energy of the equation of state. Further, a precise knowledge of neutron skin in $^{208}$Pb would be helpful in understanding the cooling mechanism and properties of neutron stars [6]. In view of the above Terashima *et al.* [7] and Zenihiro *et al.* [8] have measured and analyzed the 295-MeV-proton scattering data to extract neutron densities in Sn and Pb isotopes, respectively. The method of analysis used in Refs. [7,8] is based on the relativistic impulse approximation (RIA) using the Love-Franey interaction as proposed by Murdock and Horowitz [9]. A medium modification of the nearest neighbor (NN) interaction has been included in a phenomenological manner by introducing density dependence in the coupling constants and masses of $\sigma$ and $\omega$ mesons and calibrated to fit the proton scattering data from $^{58}$Ni. The proton and neutron density distributions are assumed to have the same shape in $^{58}$Ni. Using this medium modified interaction Zenihiro *et al.* [8] have parametrized the neutron densities as a sum of twelve Gaussians with eleven independent parameters for each isotope of Pb ($^{204,206,208}$Pb). The parameters of the Gaussians for each isotope have been determined by minimizing $\chi^2$ per degree of freedom to reproduce the experimental data. Using these as free parameters for each isotope, they have been able to obtain neutron densities and a reasonably good agreement with both the differential cross-section and analyzing-power data for the scattering of 295-MeV protons from $^{204,206,208}$Pb.

Alternatively, one may attempt an inverse problem, with the aim to extract the nucleon density distributions from the scattering data. This can be achieved by assuming certain forms for the neutron and proton density distributions, with a few free parameters. Starting with a given nucleon-nucleon interaction, these free parameters can be fitted by $\chi^2$ minimization to reproduce the scattering data. The density distributions thus obtained would yield the skin thickness compatible with the scattering data. However, one should note that such an estimate of skin thickness may be model dependent.

The nonrelativistic Brueckner theory has been used extensively [10–14] in the past for analyzing the proton scattering data in the low and intermediate energy region. It is well known that the use of a two body interaction alone in nonrelativistic Brueckner-Hartree-Fock (BHF) theory fails to reproduce the saturation property of the symmetric nuclear matter. This can be rectified by the inclusion of three-body forces or by using the relativistic BHF approach. In the nonrelativistic regime the major effect of three-body forces is increased repulsion (see Fig. 1 of Ref. [15]) in the nuclear matter potential at high densities. This reduction of the real central part of the optical potential substantially improves the agreement of analyzing power at forward angles [15]. A detailed analysis incorporating the three-body effects is in progress.

Most of the analyses [10–14] for the nucleon scattering data have used g matrices calculated from two-body NN interactions only. In the present work, we use the nonrelativistic Brueckner-Hartree-Fock approach in analyzing the above mentioned scattering data since it provides a transparent way of including the medium modification and Pauli correction of the NN interaction in the medium. We have calculated the effective interaction in the BHF approach using the Urbana v-14 [16], Argonne v-18 [17], and Reid93 [18] internucleon potentials. The v-18 and Reid93 NN interactions have been used for the first time.

Besides NN interaction the other important inputs required to calculate the nucleon-nucleus optical potential are the

 

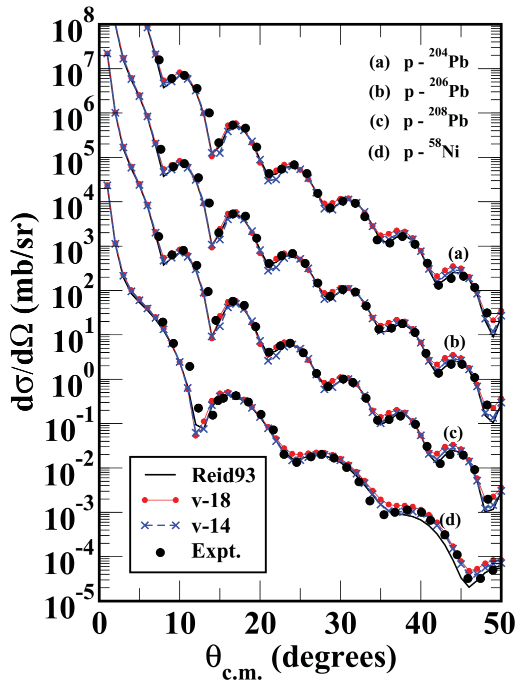


FIG. 1. (Color online) Calculated (best fit) and the corresponding experimental values of differential cross sections for scattering of protons from $^{58}$Ni and Pb isotopes using Reid93, Argonne v-18, and Urbana v-14 internucleon potentials in the BHF framework.

proton and neutron density distributions in the target nuclei. The densities employed here have been calculated using the relativistic mean field (RMF) theory [19–21] along with the NL3 Lagrangian parameter set [22]. The RMF equations are solved in a spherical oscillator basis, using 20 oscillator shells both in the Fermionic and the Bosonic sectors. The pairing correlations, important for the open shell nuclei, have been incorporated using the constant gap approximation. The required pairing gaps have been determined so as to reproduce the pairing correlation energy [$= \mathrm{Tr}(\kappa\Delta)$, $\kappa$ being the anomalous density and $\Delta$, the pairing field] calculated

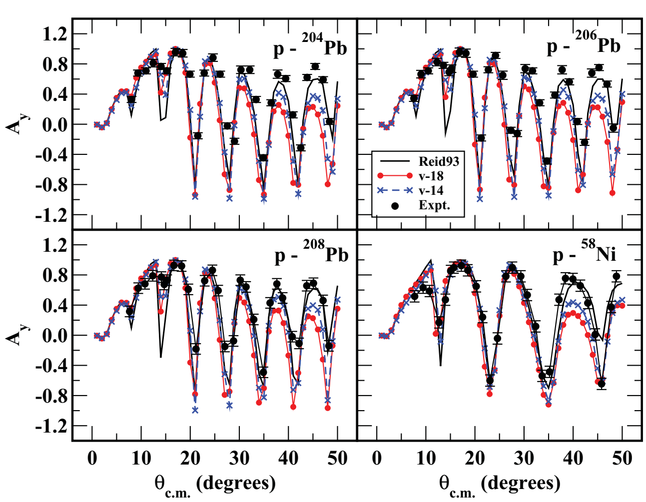


FIG. 2. (Color online) Same as for Fig. 1 but for the proton analyzing-power data at 295 MeV.

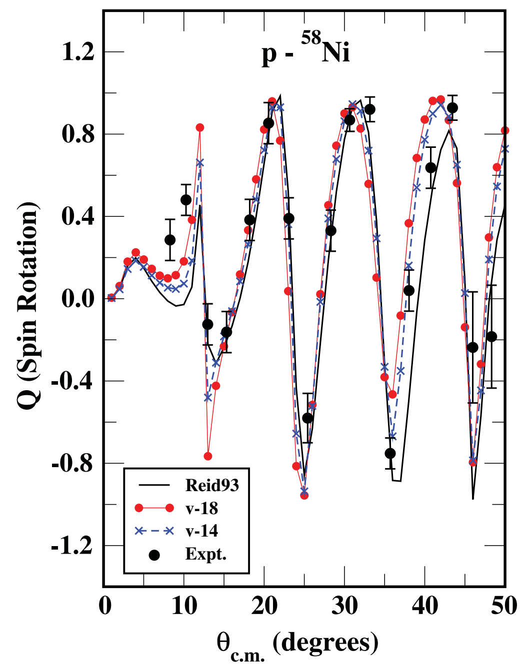


FIG. 3. (Color online) Same as for Fig. 1 but for proton $p$-58Ni spin-rotation parameter.

by using the finite range Gogny D1S interaction [23,24] in the relativistic Hartree-Bogoliubov [19–21] framework. The RMF calculations reproduce the experimental ground state properties (binding energies, radii, deformation parameters, etc.) quite well [19–21,25] as expected.

Following the usual practice, the calculated central [real $V(E,r)$ and imaginary $W(E,r)$] and spin-orbit parts [real $V_{\mathrm{so}}(E,r)$ and imaginary $W_{\mathrm{so}}(E,r)$] of the optical potential are multiplied [10] by normalization constants ($\lambda$'s), which are adjusted to minimize $\chi^2$ per degree of freedom to reproduce the scattering data. Thus the optical potential used to calculate the desired observables is

$$U(E,r) = \lambda_R V(E,r) + i\lambda_I W(E,r) + \lambda_R^{\mathrm{so}} V_{\mathrm{so}}(E,r) + i\lambda_I^{\mathrm{so}} W_{\mathrm{so}}(E,r). \quad (1)$$

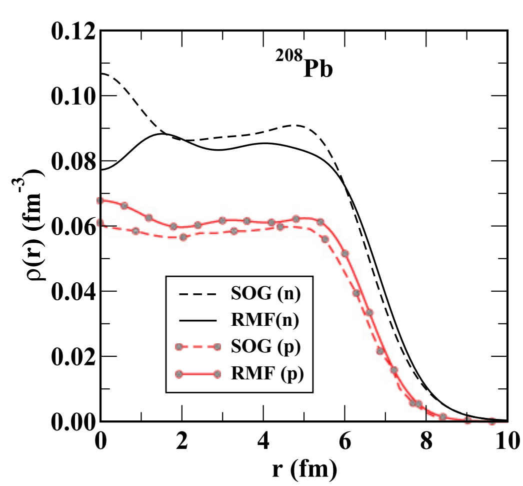


FIG. 4. (Color online) Proton and neutron densities in $^{208}$Pb from RMF calculations and SOG [8].

TABLE I. Normalization constants that give best fit to the 295-MeV-proton scattering data from $^{204,206,208}$Pb and $^{58}$Ni for three Hamiltonians in BHF.

| Target | Reid93 | | | Argonne v-18 | | | Urbana v-14 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\lambda_V$ | $\lambda_W$ | $\lambda_R^{so}$ | $\lambda_V$ | $\lambda_W$ | $\lambda_R^{so}$ | $\lambda_V$ | $\lambda_W$ | $\lambda_R^{so}$ |
| $^{204,206,208}$Pb | 0.85 | 0.76 | 0.72 | 0.70 | 0.83 | 0.70 | 0.70 | 0.75 | 0.72 |
| $^{58}$Ni | 0.70 | 0.88 | 0.70 | 0.70 | 1.00 | 0.70 | 0.70 | 0.97 | 0.70 |

Equation (1) shows that there are four free parameters ($\lambda$'s) to obtain the best fit to the data. However, we have kept $\lambda_I^{so} = 1$ in all the cases due to its insensitivity to data at 295 MeV. The results for the differential cross sections, analyzing power, and spin-rotation parameter (only for $^{58}$Ni) for the scattering of protons from $^{204,206,208}$Pb and $^{58}$Ni are presented in Figs. 1–3, respectively. The figures clearly reveal satisfactory agreement with the scattering data for all the nuclei considered here with only three parameters for each Hamiltonian. The values of the scaling parameters ($\lambda$'s) are given in Table I. It is observed that there are only minor differences between the scaling parameters ($\lambda$'s) for the three Hamiltonians considered here. Further, the scaling parameters are less than unity for all three internucleon potentials used. This in turn implies that the calculated potential is larger than that required by the data. This is consistent with the findings of the recent calculation [15], indicating that the inclusion of three-body forces in BHF leads to a reduction in the strength of the central potential at high densities. Hence the inclusion of three-body forces is expected to bring the normalization parameters close to unity.

The RMF densities calculated with the NL3 parameter set used here yield slightly larger neutron skin ($\Delta r_{np}$) for the Pb isotopes as compared to those obtained from other sources employing semiempirical and theoretical methods (e.g., proton elastic scattering [26], antiprotonic atoms [27], DD-ME2 [28], FSUGold [29], SkM* [30], SkP [31], Sly4 [32], and Ref. [8]) as shown in Fig. 8 of Ref. [8]. The same figure reveals that there are still substantial uncertainties in the neutron skin. Further, the error bars corresponding to the semiempirical values of the neutron skin [8] show that our results are close to the upper limit of $\Delta r_{np}$ [8]. It is important to experimentally measure the large angle cross-section, analyzing-power and spin-rotation data as it may help in reducing the uncertainties in the neutron skin. The parity violating elastic electron scattering experiment proposed at the Jefferson Laboratory is expected to provide a more precise value of the neutron skin in Pb.

The calculated (RMF) proton and neutron density distributions for $^{208}$Pb along with the corresponding SOG distributions [8] are presented in Fig. 4. As there are considerable differences in the neutron density distributions, we have calculated for the case of the Reid93 internucleon potential, the differential cross sections, and analyzing power for $^{208}$Pb using the same (RMF) proton density and both the RMF and SOG neutron density distributions. The results are presented in Fig. 5. Clearly, both neutron density distributions yield qualitatively similar results. However, there are minor differences at larger angles (center of mass angles $> 20^o$), and the results with the RMF densities are slightly in better agreement with the experiment.

In order to test the predictions of the present microscopic optical potential further, the reaction cross section for $p$-$^{208}$Pb scattering has been calculated for the case of the v-18 Hamiltonian in the energy region $20 < E < 500$ MeV and is compared in Fig. 6 with the corresponding experimental data [33–35]. The results for other Hamiltonians used in the

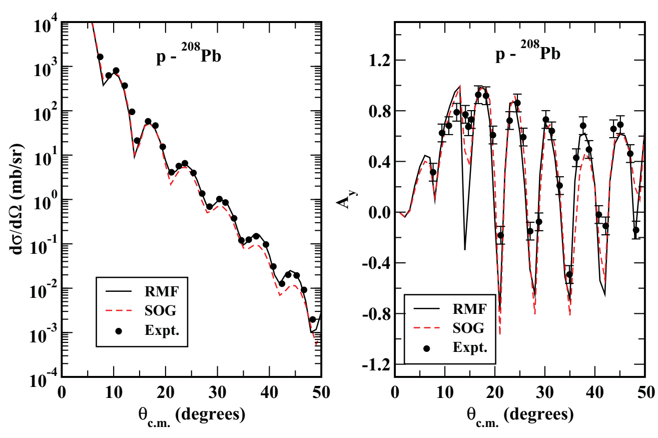


FIG. 5. (Color online) Differential cross section and analysing power for $p$-$^{208}$Pb obtained using our RMF densities and the sum of Gaussian (SOG) neutron density [8] for the Reid93 potential in BHF.

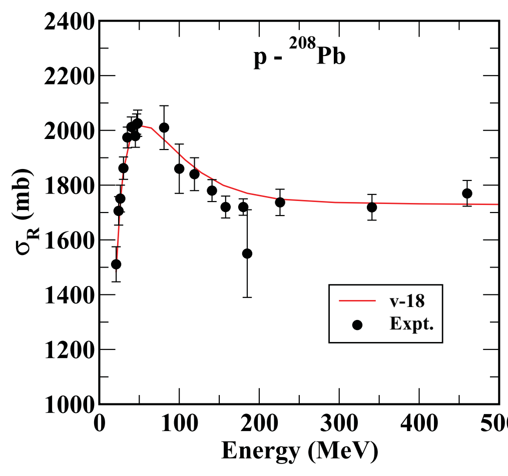


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FIG. 6. (Color online) Calculated reaction cross section for $p$-$^{208}$Pb using the Argonne v-18 interaction in BHF. Solid line shows our result whereas solid circles are experimental data taken from Refs. [33–35]

present work are similar. We note that although the reaction cross-section data has not been included in $\chi^2$ minimization, the agreement with the data over the entire energy region is quite satisfactory.

In summary we have been able to obtain a satisfactory agreement with the proton scattering from Pb isotopes at 295 MeV in the BHF approach using RMF densities and the three (Reid93, Argonne v-18, and Urbana v-14) internucleon interactions. The Reid93 and Argonne v-18 have been used to calculate nucleon-nucleus optical potential. It is important to examine the effect of three-body forces, which are required to obtain the saturation properties, on the proton-nucleus scattering process.

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