# First order optical potentials and 25 to 40 MeV proton elastic scattering

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(Received 3 May 2000; published 26 July 2000)

The differential cross sections and analyzing powers from the elastic scattering of 25 and 40 MeV protons from many nuclei have been studied. Analyses have been made using a fully microscopic model of proton-nucleus scattering seeking to establish a means appropriate for use in analyses of radioactive beam scattering from hydrogen with ion energies 25*A* and 40*A* MeV.

PACS number(s): 25.40.Cm, 24.10.Ht

We present the results of analyses of elastic scattering of 25, 30, and 40 MeV protons from nuclei made using coordinate space optical potentials formed by folding complex energy dependent effective two-nucleon (*NN*) interactions with ground state density matrices given by shell model descriptions of the nuclei. The interest to find a credible prescription of the optical potentials at these energies lies with current and future analyses of data from the scattering of 25*A* and 40*A* MeV radioactive ions from hydrogen targets. Such experiments are being made at many facilities throughout the world [1]. These optical potentials are required not only for analyses of the elastic scattering cross sections but also to define the distorted waves and the transition operator for use in distorted wave approximation (DWA) analyses of the cross sections from the inelastic excitation of the radioactive ions. Measurements and subsequent analyses of such inelastic excitations are feasible and have been made recently [2] for the excitation of the $2^+$(1.8 MeV) state in $^6$He.

At the energies considered in the present work (25, 30, and 40 MeV), collective structures in the response function of a nucleus may contribute above any specific microscopic description based on an effective *NN* multiple scattering theory. For example, if the energy is consistent with excitation of a giant resonance, virtual excitation of that resonance could contribute to the scattering. Indeed past studies [3] indicated that such virtual excitation of the giant resonances gives energy-dependent signatures in cross sections. Those effects, however, are of the order of 1 mb/sr at most and so are evident basically only at large momentum transfers for elastic scattering. The usual (phenomenological) optical potential sufficed to give the bulk of the (elastic) scattering results in those studies [3]. Hence, one may expect that a first-order microscopic description of the optical potential, based on single-site *NN* scattering in medium, could still produce good agreement with data taken for energies in the range 25 to 40 MeV.

Still, at these energies, the specific character of the target response may be needed to specify appropriately the effective *NN* interaction one should use with a folding prescription to define the optical potential microscopically. If so, the standard prescription we have used to date to define the effective interactions may need some modification. Calculations at these energies using that standard prescription and comparison with data would calibrate any such modifications required. Of course, if the specific response function effects in the definition of the effective *NN* interaction are of sufficient import, their omission should be evident in the comparisons of current model results with data from light mass targets first, and at 25 MeV in particular, given the excitation energies of the giant resonances and their variation with target mass. Therefore we have analyzed proton elastic scattering data taken at both 25 and 40 MeV and from a number of nuclei in the mass range $A=6$ to 208. The coordinate space optical potentials we have used were obtained by folding effective *NN* interactions with one body density matrices (OBDME) obtained from reasonable models of nuclear structure and of single particle (SP) bound state wave functions of the targets. The method used was that with which successful analyses of cross section and spin-dependent data from 65 and 200 MeV proton scattering [4,5] have been made from many nuclei ranging in mass from $^3$He to $^{238}$U. As before, all details of the effective interactions and structure are preset and no *a posteriori* adjustment or simplifying approximation is made to the complex nonlocal optical potentials that result from this process which, hereafter, we term as *g* folding.

The effective *NN* interactions for 25 and 40 MeV incident protons are a mix of central, two-body spin-orbit, and tensor attributes each having a form factor that is a sum of Yukawa functions [6] and with complex, energy and density dependent strengths obtained by accurately mapping the (*NN*) *g* matrices of either the Paris *NN* interaction [7] or the Bonn-B potential [8]. Those *g* matrices, solutions of the Brueckner-Bethe-Goldstone equations, were generated [6] for diverse nuclear matter densities as linked to the Fermi momenta of infinite nuclear matter. Note that the energy and density dependences of the complex effective *NN* interactions so formed have been crucial in forming the optical potentials that yield good predictions at 65 and 200 MeV [4,5]. All details of the process and the resultant optical potentials are given in depth in a recent review [9].

The *g*-folding approach has been used herein with the same two effective *NN* interactions defined above as input. There are slight differences between the two sets of *g* matrices. To assess these effective interactions and the optical potentials formed with them, each has been folded with the same structures, OBDME and single nucleon bound state functions, that were used in the analyses of 65 and 200 MeV proton elastic scattering [5] from each nucleus considered. All the results shown were obtained from calculations made

 

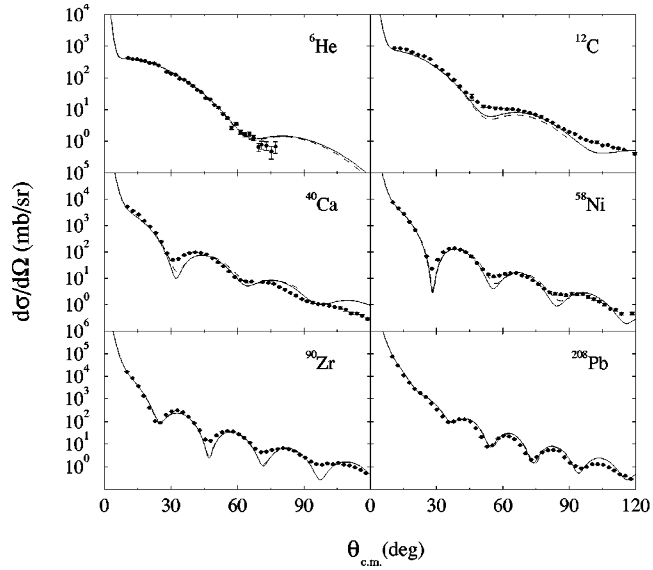


FIG. 1. The 40 MeV elastic proton scattering cross-section data [1,14] from a select set of nuclei compared with the optical model calculations.

using the code DWBA98 [10]. Thus the nonlocality aspects one finds with complete *g* folding (coordinate space) optical potentials have been evaluated and used without approximation.

Use of the optical potentials so generated for 40 MeV proton scattering gave the results shown in Figs. 1 and 2. Therein the result for the exotic nucleus $^6$He is also given as an example of use of the approach with radioactive ion-hydrogen scattering. For $^6$He, multi-$\hbar\omega$ space (no core) calculations provided the OBDME as well as the harmonic oscillator (HO) bound states to be used in the folding. The Zheng *G* matrix elements [11] were used in the $4\hbar\omega$ shell model calculations [12] and a set formed by Navrátil and Barrett were used for the $6\hbar\omega$ case [13]. For $^{12}$C, $(0+2)\hbar\omega$ shell model wave functions were used while for the heavier nuclei $0\hbar\omega$ or simple packed states were chosen. The optical potentials were fixed therefore and single runs of the scattering programs gave the results that are compared with data obtained from Ref. [14] for the stable nuclei and from Ref. [1] with a radioactive beam of 40*A* MeV $^6$He incident upon a hydrogen target.

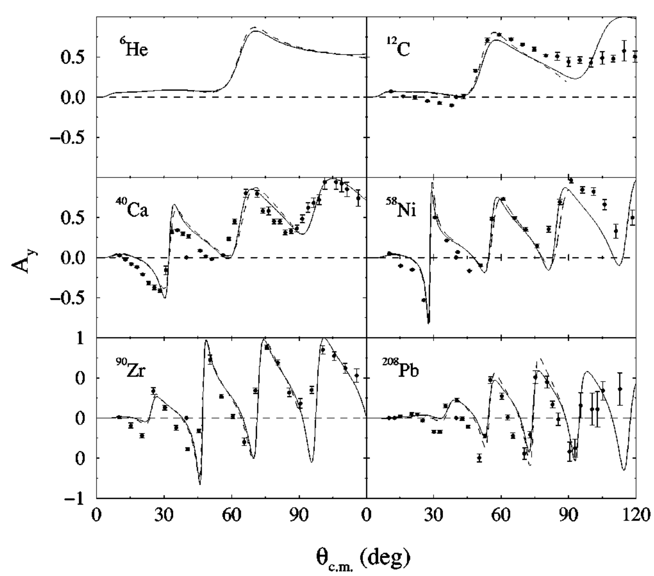


FIG. 2. The 40 MeV elastic proton scattering analyzing power data from a select set of nuclei compared with the optical model calculations.

In Fig. 1, the calculated cross sections for 40 MeV proton scattering are compared with data from a set of nuclei ranging in mass from $^6$He to $^{208}$Pb. The solid and long dashed curves in each segment identify the *g*-folding results obtained by using the effective interactions found from the Bonn-B and Paris potentials, respectively. The differences in these calculated cross sections are minor. These 40 MeV calculations agree with data almost as well as at the higher energies [5], although most have more sharply defined minima than is evident in the data. By and large though, the calculations are in good agreement with the shapes and magnitudes of the cross-section data and now to 120° scattering. For $^6$He, the results found with the $4\hbar\omega$ and $6\hbar\omega$ models are indistinguishable. Those structures, without adjustment to the SP wave functions, do not give such an extended neutron distribution in the ground state the ground state of $^6$He to classify $^6$He as a neutron halo nucleus. These elastic scattering data do not require any such property of the target but the elastic data have not been measured at momentum transfer values at which the nonhalo versus halo forms give noticeably different results. However, the inelastic scattering cross section with excitation of $^6$He to its first excited $2^+$ state does so [2]. The calculated cross sections for the elastic scattering from $^{12}$C, $^{58}$Ni, and $^{90}$Zr are quite reasonable in so far as the trend and magnitudes of the peaks are concerned, with only too sharp minima being predicted. The result found for $^{40}$Ca is the worst and that for $^{208}$Pb the best.

In Fig. 2, the analyzing powers associated with 40 MeV proton scattering from the same set of nuclei discussed above are compared with data. Again, the solid and long dashed curves portray the *g*-folding results found with the Bonn-B and Paris interactions as input. The two forces give very similar results, and ones that reflect the structure of the data quite reasonably. Reflecting the cross section predictions, that for $^{40}$Ca is the worst while that for $^{208}$Pb is the best.

While the degree of replication of these 40 MeV data (differential cross sections and analyzing powers) is not as good as found with the higher energy data analyses, nevertheless all results are satisfactory with no debilitating trend in quality of the fit with mass being evident. The study of 65 MeV scattering data revealed that medium effects of the *NN* interactions changed predictions by softening the predicted cross section minima, and so these 40 MeV results may indicate that an additional medium modification is needed in our generated interaction.

The results of calculations made for 25 MeV proton scattering from the nuclei $^6$Li, $^{12}$C, $^{28}$Si, $^{40}$Ca, and $^{152}$Sm, and of 30 MeV proton scattering from $^{208}$Pb, are compared with cross-section data in Fig. 3 and analyzing power data in Fig. 4. The differential cross section data shown were measured

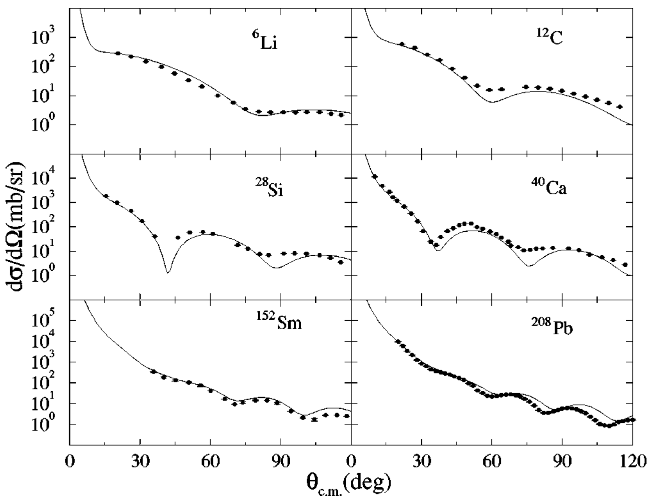


FIG. 3. The 25 MeV elastic proton scattering cross-section data (Refs. [15–20]) from a select set of nuclei compared with the optical model calculations.

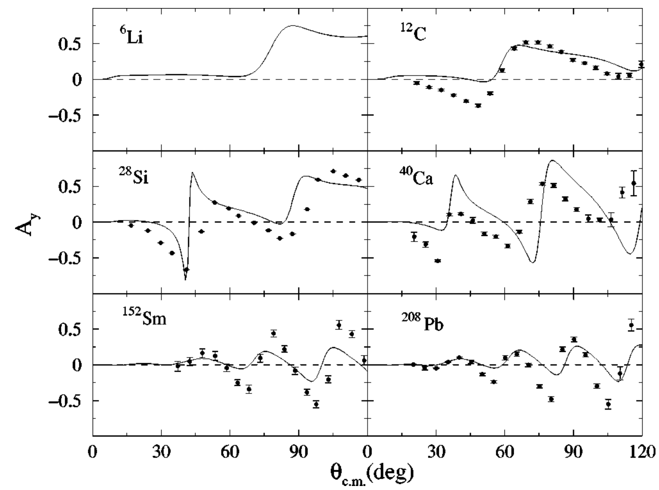


FIG. 4. The 25 MeV elastic proton scattering analyzing power data (Refs. [17,19,21,22]) from a select set of nuclei compared with the optical model calculations.

at 25.9 MeV [15] for $^{6}$Li, at 24.0 MeV [16] for $^{12}$C, at 25.0 MeV for $^{28}$Si [17] and $^{40}$Ca [18], at 24.5 MeV [19] for $^{152}$Sm, and at 30.3 MeV [20] for $^{208}$Pb. The analyzing powers were measured at 24.1 MeV [21] from $^{12}$C, at 25.0 MeV [17] from $^{28}$Si, at 29.0 MeV [22] from $^{40}$Ca, at 24.5 MeV [19] from $^{152}$Sm, and at 29.0 MeV [22] from $^{208}$Pb. The comparisons of our calculated values with the differential cross-section data are quite reasonable given that, at this energy, higher order processes involving virtual excitation of giant resonances [3] may be expected to influence results for $^{12}$C and $^{28}$Si in particular, and perhaps also for $^{40}$Ca. The result with$^{208}$Pb may be sensitive to the choice of structure and of the SP bound state functions in particular. A sensitivity to the surface distribution of nucleons in heavy nuclei has been noted at higher energies [9]. As might be expected, the predicted results of the analyzing powers are not in as good agreement with the data. Nevertheless, those calculated results follow the mass trend of the measured values well enough to give credibility to the basic attributes of our (first order) calculations and that our effective *NN* interactions at these energies are sensible.

The cross-section and analyzing power results obtained from the coordinate space nonlocal optical potentials formed by $g$ folding at 40 MeV are in quite reasonable agreement with the data obtained with targets of mass 6 to 208. In general the cross-section predictions give the magnitudes and trends of the peaks in the data but the minima are too sharply defined. The comparisons between the calculated results and the data for 25 MeV proton elastic scattering remain reasonable but the disparities are more pronounced than at higher energies. Nevertheless, the folded optical potentials remain a reasonable first approximation, sufficiently so that the results may still select between different structure inputs. Also the associated distorted wave functions and effective interactions still should be appropriate for use in distorted wave approximation analyses of inelastic scattering from stable nuclei [4], or of radioactive beam ions, as well as of other reaction calculations [23].

This work was partly supported by U.S. DOE Contract No. W-7405-ENG-36.


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