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# Microscopic study on proton elastic scattering of helium and lithium isotopes at energy range up to 160 MeV/nucleon.

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**Abstract.** The proton elastic scattering data on $^{4,6,8}$He and $^{6,7,9,11}$Li nuclei at energies below 160 MeV/nucleon are analyzed using the optical model. The optical potential (OP) is taken microscopically, with few and limited fitting parameters, using the single folding model for the real part and high-energy approximation (HEA) for the imaginary one. Clear dependencies of the volume integrals on energy and rms radii are obtained from the results. The calculated differential and the reaction cross sections are in good agreement with the available experimental data. In general, this OP with few and limited fitting parameters, which have a systematic behavior with incident energy and matter radii, successfully describes the proton elastic scattering data with stable and exotic light nuclei at energies up to 160 MeV/nucleon.

## 1 Introduction

The cross sections' data of the proton elastic scattering of light nuclei are studied by the optical model potential that has been developed in phenomenological and microscopic approaches. The phenomenological OP, which their parameters are adjusted by fitting to scattering experimental data, is successful in a wide region of incident energy. However, it gives a generalized description and does not include the nuclear structure information. In addition, it cannot give unique values of these parameters [1]. The ambiguity of the OP is arises from in particular the existence of a large number of optical potentials describing equally well a given set of elastic scattering data [2]. The microscopic OP based on the folding model is useful to decrease this ambiguity.

A large amount of experimental data at energies below 160 MeV/nucleon are existed for the proton elastic scattering of the stable and exotic light nuclei. Most of these experimental data, and their references can be obtained from EXFOR database [3].

In the present work, a microscopic analysis of the available proton elastic scattering data of these light nuclei, $^{4,6,8}$He and $^{6,7,9,11}$Li in the energy range below 160 MeV/nucleon is considered. The theoretical calculation is given in section 2, while the results of calculations are presented in section 3. The conclusions are given in section 4.

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## 2 Theoretical calculation

The famous Woods-Saxon phenomenological OP can be replaced by a microscopic potential as shown in our work [4, 5]. The our microscopic optical potential can be rewritten as:

$$U_{opt}(r) = N_R V_F(r) + i[N_I W_H(r) - N_{IS} r \frac{d}{dr} W_H(r)] - 2\lambda_\pi^2 N_{SO} \frac{1}{r} \frac{d}{dr} V_F(r) \mathbf{L}.\mathbf{S}. \tag{1}$$

where $V_F$ is the real OP using the single folding model and $W_H$ is the volume imaginary potential using high-energy approximation model. The nucleon-nucleus potential using the single folding approach is given as [6]

$$V_F(r) = \int \rho(\acute{\mathbf{r}}) v_{nn}(s) d\acute{\mathbf{r}}, \tag{2}$$

where $s = |\mathbf{r} - \acute{\mathbf{r}}|$, is the distance between the two nucleons, $\rho(\acute{\mathbf{r}})$ is the density of the nucleus at $\acute{\mathbf{r}}$, and $v_{nn}(s)$ is the effective $NN$ interaction between two nucleons. The density-independent M3Y effective $NN$ interaction is used. It is given in the form [6]

$$v_{nn}(s) = 7999 \frac{\exp(-4s)}{4s} - 2134 \frac{\exp(-2.5s)}{2.5s} - 276(1 - 0.005 \frac{E}{A}), \tag{3}$$

where $E$ is the incident energy and $A$ is the mass number of the projectile.

On the other hand, the imaginary part of the OP is calculated within the high-energy approximation (HEA) was derived in Ref. [7] on the basis of the eikonal phase inherent in the optical limit of the Glauber theory. It is expressed as [5, 7]:

$$W_H(r) = -\frac{\hbar v}{(2\pi)^2} \bar{\sigma}_{NN} \int_0^\infty dq q^2 j_0(qr) \rho(q) f_{NN}(q), \tag{4}$$

where $v$ is the velocity of the nucleon-nucleus relative motion, $\rho(q)$ is the form factors corresponding to the point-like nucleon density distribution of the nucleus, and $f_{NN}(q)$ is the amplitude of the $NN$ scattering which depends on the transfer momentum $q$ and can be specified in the form of a Gaussian function [7, 8]. The quantities $\bar{\sigma}_{NN}$ is the averaged over the isospins total $NN$ cross section. It has been parameterized in Refs. [5, 8] as functions of energies.

The Green function Monte Carlo (GFMC) density [9, 10] is used for the stable nuclei, $^4$He and $^{6,7}$Li and the large-scale shell model (LSSM) density [11] is used for $^{6,8}$He and $^{9,11}$Li exotic nuclei The volume integrals of the real and imaginary parts of the OP ($J_R$ and $J_I$), respectively, are expressed as [5]

$$J_R = -\frac{4\pi}{A} \int [N_R V_F(r)] r^2 dr, \tag{5}$$

$$J_I = -\frac{4\pi}{A} \int [N_I W_H(r) - N_{IS} r \frac{d}{dr} W_H(r)] r^2 dr. \tag{6}$$

## 3 Results and discussion

The elastic angular distribution data for the proton elastic scattering of helium and lithium isotopes at different energies are calculated using the optical potential [Eq.(1)] and shown in Fig. 1. The renormalization factors and $\sigma_R$ obtained by fitting the experimental cross sections' data are listed in Tables I and III in our recently paper [5]. Clearly, the obtained results for $p$+$^{4,6,8}$He and $p$+$^{6,7,9,11}$Li elastic scattering are in good agreement with the data. However, at forward angles ($\theta > 120°$) elastic

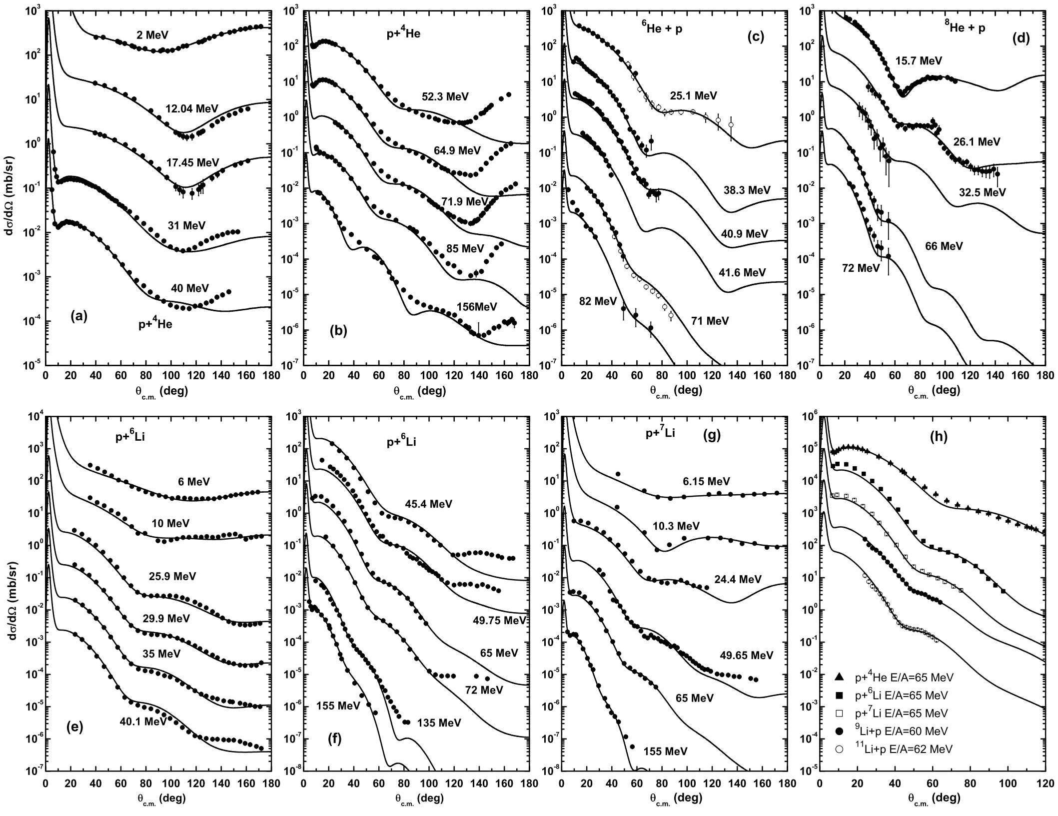

**Figure 1.** Differential cross sections of proton elastic scattering of helium and lithium isotopes at different energies (in MeV/nucleon). The data and their calculations also presented in our work [5].

scattering, the result give disagreement with the experimental data as seen in the results of $p$+$^4$He reaction.

Figure 2(a) presents the obtained reaction cross sections for proton elastic scattering of helium and lithium isotopes in comparison with the available experimental data [12]. In general, the results for $\sigma_R$ for the considered reactions are in agreement with the the experimental data. The $\sigma_R$ for the different reactions decrease with increasing projectile incident energy for the same reaction.

Figures 2(b) and (c) present the energy dependence of the volume integrals for the proton elastic scattering with helium and lithium isotopes using the OP ($U_{opt}$ [Eq. 1]). Figure 2 (b) presents the real and imaginary volume integrals for $^{4,6,8}$He+$p$ elastic scattering. Clearly, $J_R$ for $p$+$^4$He is greater than the two halo nuclei scattering $^{6,8}$He+$p$. Furthermore, the $J_R$ values obtained for $^8$He+$p$ elastic scattering are found to be greater than that values for $^6$He+$p$ elastic scattering. On the other hand, the $J_I$ values obtained for $^6$He+$p$ is the greatest whereas the $J_I$ values for $p$+$^4$He scattering is the smallest. The $J_R$ values for $^{6,7,9,11}$Li+$p$ lie approximately in the same range values as shown in Fig. 2(c). However, the $J_I$ of $p$+$^6$Li is slightly less than that of $p$+$^7$Li scattering. Whereas the $J_I$ for $^{11}$Li+$p$ scattering has the greatest value. Clearly, the halo nuclei have imaginary volume integrals larger than their stable isotopes. Then, the behavior of $J_I$ is related to the rms radius of the scattered nuclei. In general, the volume integrals of the different OPs have similar behavior for all the considered

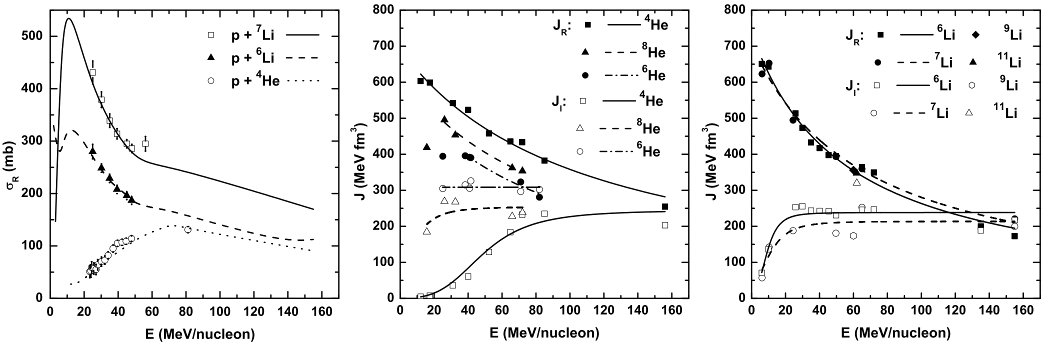

**Figure 2.** Energy dependence of the $\sigma_R$ and the volume integrals for the proton elastic scattering of helium and lithium isotopes. These results also given in our work [5].

reactions. With energy increasing, it is found that $J_R$ decreases exponentially with a slow rate. On the other hand, $J_I$ starts off small at low energies, and then increases rapidly up to a specific energy. Thereafter, $J_I$ values are saturated and approximately seem to be constant.

## 4 Summary

The results showed that the microscopic OP that used in this work, which has only few and limited fitting parameters, successes to reproduce most of the considered reaction and differential cross sections data. The volume integrals of the OPs have systematic behaviors with energy for the considered reactions in this work. With increasing the incident energy, $J_R$ values decrease slowly and exponentially. On the other hand, $J_I$ values increase rapidly up to a specific value of energy. Then, $J_I$ values are saturated. In addition, $J_I$ have larger values for the halo nuclei than their isotopes. Hence, the volume integrals can be considered as constraints for the choice of the OP parameters through the fitting procedure.

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