Commun. Theor. Phys. **58** (2012) 135–140 Vol. 58, No. 1, July 15, 2012

An Investigation of ^{4}He+^{12}C and ^{4}He+^{16}O Reactions Using the Cluster Model

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(Received December 2, 2011; revised manuscript received March 30, 2012)

Abstract *The α-target semimicroscopic single folding potentials have been derived by folding a composite (repulsive and attractive) effective α-α interaction with the α-cluster distribution density in the target nuclei. The obtained potentials are considered as the real part of the nuclear optical model potentials, while the imaginary parts are phenomenologicaly expressed using the Woods–Saxon form. Nine sets of measured experimental data of the ^{4}He+^{12}C and ^{4}He+^{16}O elastic rainbow scattering over the energy range 80–240 MeV are analyzed using the obtained potentials. The data are successfully reproduced using the extracted potentials. The resulted reaction cross sections are also investigated and compared with the available corresponding data.*

PACS numbers: 25.70.Bc, 24.10.Ht, 27.20.+n, 21.60.Gx
Key words: optical model, elastic scattering, folding potential, cluster model

1 Introduction

Determining the shape of the nuclear potential between two nuclei is a long-standing problem. Phenomenological optical potentials (POP's) are often successfully used to describe the heavy ions (HI) elastic scattering data. The use of folding model (FM), however, is appealing because it allows one to predict the potentials of systems for which scattering data are not available. Furthermore, the folding potentials make it possible to eliminate ambiguities, which appear with the phenomenological ones.[1]

On the other side, at lower energies ($<$ 100 MeV), α-scattering shows an anomalous large angle scattering (ALAS)[2−3] where angular distribution becomes more sensitive to detailed shape of the real part of the optical potential at a small radius ($<$ 2 fm). Such details cannot be reproduced with a standard Woods–Saxon (WS) potential and discrete ambiguities of the potential were observed.[4] At higher energies ($>$ 100 MeV), the α-particle seems to be reasonably transparent and refractive rainbow scattering is observed.[5−7] Precise determination of optical potential which fits ALAS at low energies and rainbow scattering at high energies[8] allows more investigations of internuclear interactions at short distances.[9] In order to analyze the α-nucleus scattering, Kobos *et al.*,[10−11] Chaudhuri[12] and Khoa *et al.*[13] have evaluated the real central part of the α-nucleus optical potential. They used the M3Y effective nucleon-nucleon (NN) interaction[14] modified by a density-dependent factor. The exchange part turned out to be both density- and energy-dependent.

In the same context, following the folding procedure, the α-cluster model has been successfully employed to calculate the folding optical model potential for composite projectiles through the single and double folding cluster model.[15−24] Through the last decade, El-Azab Farid and his collaborators[20−23] have adopted the α-cluster structure of light nuclei to generate the α-nucleus single folding cluster (SFC) and nucleus-nucleus double folding cluster (DFC) potentials, based upon an α-α interaction folded with the α-cluster distributions in the colliding nuclei.

In the present work, we investigate α+^{12}C and α+^{16}O elastic scattering at the rainbow energies using the SFC potential. Our calculations are performed to analyze the elastic scattering cross sections over a wide range of energies (80–240 MeV). The folding formalism is based upon repulsive and attractive terms of the effective α-α interaction. The paper is organized as follows, in the next section the theoretical formalism is introduced while results of the analysis and discussion are presented in Sec. 3. Section 4 summarizes the conclusions extracted from the present study.

2 Formalism

2.1 *Nuclear Densities of ^{12}C and ^{16}O*

Consider a nucleus of mass number A composed of an integral number n of α-particles, i.e., $A = 4n$, $n = 3$ (4) for ^{12}C (^{16}O). Consider $\rho_c(r)$ as the α-cluster distribution function inside the nucleus. Then, the nuclear matter distribution of the nucleus, $\rho_m(r)$, can be related to that of

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the α-particle nucleus, $\rho_\alpha(r)$, as

$$\rho_m(r) = \int \rho_c(r')\rho_\alpha(|r-r'|)\,\mathrm{d}\vec{r}'\,. \tag{1}$$

In our calculations we use a modified Gaussian form for the target density $\rho_m(r)$ and a Gaussian form for the alpha-particle density $\rho_\alpha(r)$, as follows:

$$\rho_m(r) = \rho_{0m}(1+\omega r^2)\exp(-\beta r^2)\,, \tag{2}$$

$$\rho_\alpha(r) = \rho_{0\alpha}\exp(-\lambda r^2)\,, \tag{3}$$

where ω, β, and λ parameters are listed in Table 1.[20] The extracted root mean square (rms) radii from Eqs. (2) and (3) are also shown in Table 1. The table includes also $\rho_{0\alpha}$ and ρ_{0m} which are determined from the normalization condition

$$\int \rho(r)\,\mathrm{d}\vec{r} = A\,. \tag{4}$$

Table 1 Parameters of the nuclear matter densities of ^{4}He, ^{12}C and ^{16}O.[20]

Nucleus	$\rho_{0m}/(\mathrm{fm}^{-3})$	$\omega/(\mathrm{fm}^{-2})$	$\beta(\lambda)/(\mathrm{fm}^{-2})$	$\langle r^2\rangle^{1/2}/\mathrm{fm}$
^{4}He	0.4229	0.0	0.7024	1.46
^{12}C	0.1644	0.4988	0.3741	2.407
^{16}O	0.1317	0.6457	0.3228	2.64

To calculate the alpha cluster distribution function $\rho_c(r')$ from expression (1) we use Fourier transform techniques.[1] Then using Eqs. (2) and (3), one can get

$$\rho_c(r') = \rho_{0c}(1+\mu r^2)\exp(-\zeta r^2)\,, \tag{5}$$

where

$$\mu = \frac{-\delta}{4\gamma^2+6\gamma\delta}\,,\quad \zeta = \frac{1}{4\gamma}\,,\quad \gamma = \frac{1}{4\beta}-\frac{1}{4\lambda}\,,$$

$$\delta = \frac{-\omega}{4\beta^2+6\beta\omega}\,,\quad \rho_{0c} = \frac{n}{(4\pi\gamma)^{3/2}}\Big(1+\frac{3\delta}{2\gamma}\Big)\,.$$

2.2 *Folding Model*

We recall that the nucleus-nucleus interaction may be written as

$$U(R) = V(R) + \mathrm{i}W(R) + V_C(R)\,, \tag{6}$$

where $V(R)$ and $W(R)$ are the central real and imaginary nuclear parts of the optical potential, respectively, and $V_C(R)$ is the repulsive Coulomb interaction. We consider the target as a uniformly charged sphere of radius $R_C = 1.3A_T^{1/3}$where A_T is the target mass number. Then, the Coulomb potential, $V_C(R)$, is given as

$$V_C(R) = \Big[\frac{Z_T e^2}{R_C}\Big]\Big[3-\frac{R^2}{R_C^2}\Big] \quad \text{for} \quad R \le R_C\,,$$

$$V_C(R) = \frac{2Z_T e^2}{R} \qquad\qquad \text{for} \quad R \ge R_C\,, \tag{7}$$

where Z_T is the target atomic number.

In the framework of the SF model,[1] the microscopic real part of nucleon-nucleus optical potential can be obtained by folding the effective NN interaction with the nucleon density in the target nucleus. In the same context, we formulate the semimicroscopic SFC real part of the α-nucleus optical model potential by folding the α-α interaction with α-cluster density distribution in the target nucleus as

$$V(R) = \int \rho_c(r)V_{\alpha\alpha}(\vec{R}-\vec{r})\,\mathrm{d}\vec{r}\,. \tag{8}$$

Considering the α-cluster structure of ^{12}C (^{16}O) nucleus defined by Eq. (5) and the effective α-α interaction defined in the Gaussian form as[23,25–27]

$$V_{\alpha\alpha}(s) = V_{01}\,\mathrm{e}^{-\mu_1 s^2} - V_{02}\,\mathrm{e}^{-\mu_2 s^2}\,, \tag{9}$$

one can get

$$V(R) = \sum_{i=1}^{2} V_{0i}\rho_{0c}\Big(\frac{\pi}{\zeta+\mu_i}\Big)^{3/2} \times\Big[1+\frac{3\mu_i}{2(\zeta+\mu_i)}+\frac{\mu_i^2}{(\zeta+\mu_i)^2}R^2\Big]\exp[-X_iR^2]\,, \tag{10}$$

where $X_i = \zeta\mu_i/(\zeta+\mu_i)$, V_{01} and V_{02} are, respectively, the attractive and repulsive depths and μ_1 and μ_2 are the corresponding range parameters. We consider $V_{01} = 122.62$ MeV, $\mu_1 = 0.22$ fm^{-2}, and $\mu_2 = 0.25$ fm^{-2}, while the depth V_{02} is kept free in the calculations.

The imaginary part is considered in the phenomenological Woods–Saxon form as

$$W(R) = \frac{W_0}{1+\exp((R-R_I)/a_I)}\,,$$

$$R_I = r_I(A_P^{1/3}+A_T^{1/3})\,, \tag{11}$$

where W_0, r_I, and a_I are the depth, radius and diffuseness parameters, respectively. The computer code HIOPTM-94.2[28] is used to carry out elastic scattering calculations. Best fits are obtained by minimizing χ^2, where

$$\chi^2 = \frac{1}{N}\sum_{k=1}^{N}\Big[\frac{\sigma_{\mathrm{th}}(\theta_k)-\sigma_{\exp}(\theta_k)}{\Delta\sigma_{\exp}(\theta_k)}\Big]^2\,, \tag{12}$$

σ_{th} ($\sigma_{\exp}$) is the theoretical (experimental) cross section at angle θ_k in the center-of-mass system, $\Delta\sigma_{\exp}$ is the experimental error and N is the number of data points. An average value of 10% is used for the experimental errors of all considered data. In order to obtain best fits to the observed angular distributions of the elastic scattering cross section, the search has been carried on the three imaginary phenomenological WS potential parameters, W_0, r_I, and a_I. However, the choice of V_{02} is manually judged in order to find best fits to the data.

3 Results and Discussion

The real part of the nucleus–nucleus interactions are obtained analytically by the SFC potential using the expression (10) for the α+^{12}C and α+^{16}O reactions. The results are checked by recalculating this potential numerically using the modified momentum space folding DFPOT computer code.[29] Both methods yielded identical results.

The resulted $\alpha-{}^{12}$C and $\alpha-{}^{16}$O SFC potentials derived using $V_{02} = 0$, are shown in Fig. 1. The

present potentials are consistent with those obtained either by Friedrich and Langanke[30] or by Buck, Merchant, and Perez[31] considering the α-cluster structure of ^{16}O. Furthermore, the obtained energy dependence of the calculated potentials is similar to that found by Yamaguchi, Yabana, and Hariuchi.[32] However, their folded potentials[30−31] extracted at the considered energies are substantially shallower than those plotted in Fig. 1 due to inserting the repulsive part in the α-α interaction (9). One can also notice that the nuclear potential for ^{16}O nucleus is deeper than that for ^{12}C nucleus all over the radial range $r = 0$–7 fm.

The calculated potentials are used to analyze the observed data at nine energies of the following reactions: α+^{12}C at energies of 104, 120, 139, 166, 172.5, and 240 MeV and α+^{16}O at energies of 80.7, 104, and 146 MeV. The best fit parameters extracted from the search are listed in Table 2.

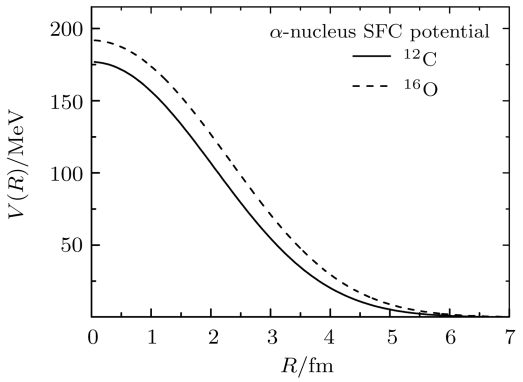

Fig. 1 The α-nucleus semimicroscopic SFC potentials based upon the α-cluster structure of the considered nuclei using expression (10).

The obtained angular distributions of the elastic scattering differential cross section of α+^{12}C and α+^{16}O reactions are demonstrated in Figs. 2 and 3, respectively, in comparison with the corresponding experimental data. It is evident that the derived folded potentials successfully reproduce the observed rainbow scattering for both reactions all over the measured angular range at the nine considered energies. The present results seem to be quite equivalent to those achieved using more complicated calculations in the framework of the double folding procedure based upon different versions of the density dependent effective NN interactions such as the DDM3Y[2,8,13] and JLM[33] ones.

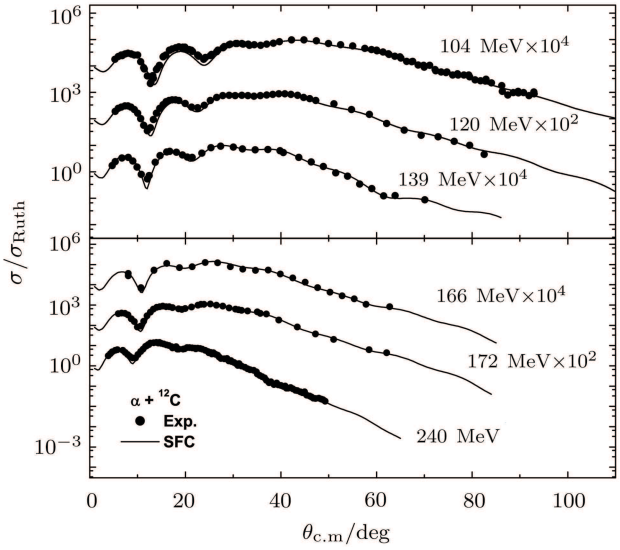

Fig. 2 Angular distributions for α+^{12}C elastic scattering obtained by SFC potentials in comparison with experimental data[34] at energies 104,[35] 120,[36] 139,[37] 166, 172,[38] and 240[39] MeV.

From Table 2, for α+^{12}C reaction, it is obvious that the repulsive depth in the α-α interaction, V_{02}, has a constant value at lower energies (41 MeV) then slightly increases with increasing energy at higher energies. However, the situation is not the same for α+^{16}O reaction where a strongly energy-dependence is noticed for the values obtained for the three considered energies, see Fig. 4.

Table 2 Parameters of the real and imaginary potentials obtained from best fits analysis of α+^{12}C and α+^{16}O elastic scattering at different energies.

E/MeV	V_{02}/MeV	W_0/MeV	r_I/fm	a_I/fm	J_R/(MeV·fm^3)	J_I/(MeV·fm^3)	χ^2	σ_R/mb
			α+^{12}C					
104	41.0	11.18	1.127	0.689	299.4	101.4	8.8	821
120	41.0	12.60	1.127	0.525	299.4	104.8	6.8	785
139	41.0	22.43	0.877	0.732	299.4	112.2	3.2	768
166	45.0	13.68	1.072	0.531	288.2	99.6	3.7	698
172.5	48.0	14.11	1.071	0.572	279.9	108.5	2.6	720
240	52.0	16.41	1.036	0. 623	268.8	114.7	1.8	699
			α+^{16}O					
80.7	36.5	19.99	0.845	0.873	311.8	89.1	2.7	1000
104	46.5	23.28	0.789	0.874	284.0	89.2	5.4	922
146	67.0	6.218	1.492	0.533	226.9	100.6	2.0	1105

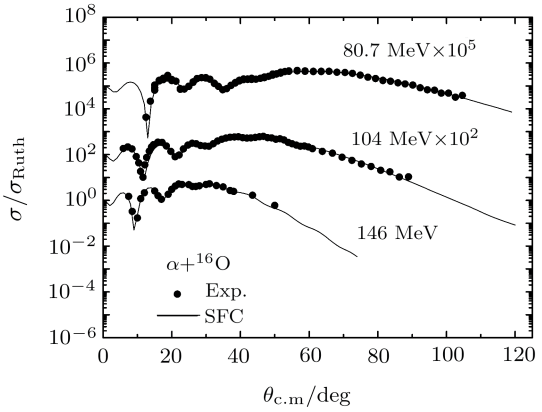

Fig. 3 The Same as Fig. 2 but for ^{16}O target at energies 80,[8] 104,[35] and 146 MeV.[8]

Malik and his collaborators[27] analyzed the same scattering reactions considering a substantial unclustered nucleonic configuration besides the α-cluster structure in the target nucleus. They found [27] that the repulsive potential α+^{12}C reaction has an intelligible energy-dependence. Their V_{02}values, however, are clearly larger than our corresponding values. For α+^{16}O reaction, contrary to our results, they used almost constant repulsive depth ($\sim$ 30 MeV) in order to deduce successful description of the data at the same three considered energies. This depth is clearly smaller than those used in the present work. From Fig. 4, one may deduce that the energy dependence of V_{02} to be represented by the linear relation $V_{02} = 30.5[1 + 0.003E]$ MeV, for α+^{12}C reaction. A stronger dependence is obtained for the α+^{16}O reaction represented as $V_{02} = -1.76[1 - 0.266E]$ MeV.

Table 2 shows also the real volume integral per interacting nucleon pair, J_R, extracted from the calculated potentials. We recall that, according to the α-α interaction (9), the behavior of J_R with energy is correlated to that of the repulsive depth, V_{02}, where the real volume integral is given by the linear relation

$$J_R = 413.5 - 2.784V_{02}\ \text{MeV}\cdot\text{fm}^3\,. \qquad (13)$$

On the other hand, it is interesting to mention that, for α+^{12}C, the present J_R values are quite consistent with those obtained in by Malik group.[27] However, they deduced larger values for α+^{16}O reaction.

Figure 5 displays the behavior of the volume integral of imaginary potentials, J_I, with energy. It is evident that J_I increases with increasing energy. The figure shows also that for the α+^{16}O reaction the energy dependence is substantially stronger than that for α+^{12}C one. This behavior can be represented by the linear relations $J_I = 95[1 + 0.0008E]$ MeV·fm^3 and $64[1 + 0.0044E]$ MeV·fm^3 for α+^{12}C and α+^{16}O reactions, respectively. This result is qualitatively and quantitatively consistent with that extracted in Ref. [27]. On the other hand, from Figs. 5 and 6, one may notice that, for both considered reactions, there is a coherency between the repulsive depth V_{02} and the imaginary volume integral J_I where both reveal almost similar energy dependence.

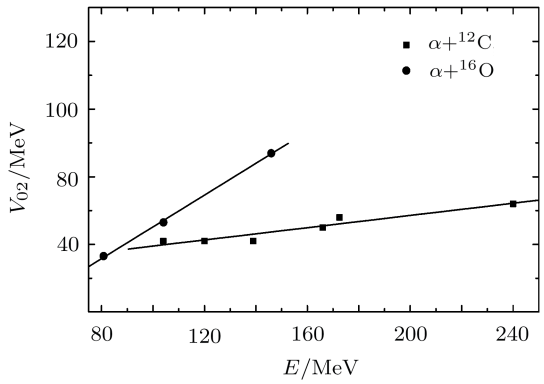

Fig. 4 The energy dependence of the repulsive part in the α-α interaction (9). Filled squares and circles represent the extracted values and straight lines are the linear fits.

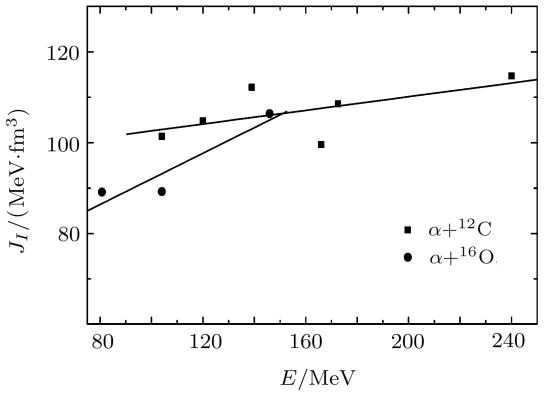

Fig. 5 The energy dependence of the volume integral of imaginary potentials, J_I, obtained for α+^{12}C and α+^{16}O reactions. Straight lines are the linear fits.

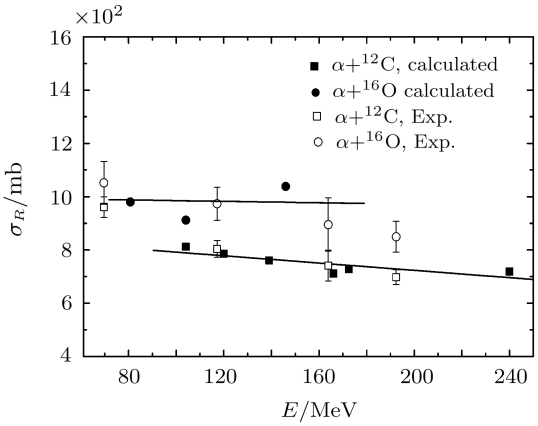

Fig. 6 The derived reaction cross section, σ_R, in comparison with the measured data[40] for α+^{12}C and α+^{16}O reactions. Straight lines are the linear fits to the calculated values.

Another quantity, which is frequently investigated as an additional guide to test the validity of the considered nuclear potential, is the total reaction (absorption) cross section, σ_R. Hence, it would be interesting to investigate

whether one could generate a reasonable determination of σ_R using the derived potentials. Therefore, we demonstrate in Fig. 6 the energy dependence of σ_R obtained from the present analysis of α+^{12}C and α+^{16}O reactions. For comparison, four values of the measured reaction cross section for each reaction are also introduced in the Fig. 6 as follows: for α+^{12}C (^{16}O) at energies of 69.6, 117.2, 163.9, and 192.4 MeV are 961 (1052) ±39 (80), 804 (973) ±31 (62), 741 (895) ±58 (100), and 698 (850) ±28 (58) mb respectively.[40]

As clearly noticed from Fig. 6, both reactions reveal almost similar behaviors with energy, where σ_R slightly decreases with increasing energy. Good agreement between the calculated and measured values is evident for α+^{12}C reaction, particularly at the higher energy range. For the α+^{16}O reaction, unfortunately, there are no calculated values at energies higher than 146 MeV. That is because of the lack of measured elastic scattering cross section upon which we deduce the corresponding reaction cross sections. Nevertheless, regarding the common range of energy between the calculated and measured values, one may notice that the measured values are reasonably expected by the SFC potential. Furthermore, it is interesting to mention that present results show good consistency with those extracted by Khallaf *et al.*[33] from analysis using microscopic DF potentials based upon the JLM effective NN interaction. So, the obtained compatibility between the theoretical and observed values of reaction cross section may present an additional confirmation of the validity of the SFC potential to successfully describe the α+^{12}C and α+^{16}O reactions through the considered energy range.

4 Conclusions

In the present work we have analyzed the elastic scattering data of ^{4}He projectiles from ^{12}C and ^{16}O targets at different energies in the rainbow scattering region in terms of the single folding cluster (SFC) optical model potential. The SFC real potential has been generated by folding a composite (repulsive and attractive) effective $\alpha t\alpha$ interaction over the α-cluster density distribution of the target nucleus. Full α-clustering (3α and 4α) of nucleons inside ^{12}C and ^{16}O nuclei, respectively, is considered. The imaginary potential is represented by the conventional volume Woods–Saxon phenomenological form.

The derived potentials are successfully employed to describe nine sets of the elastic scattering data using an energy-dependent repulsive part of the effective α-α interaction which linearly increases with increasing energy. The obtained results emphasize the necessity of the repulsive part in order to avoid the compulsion to renormalize the folded potentials, particularly at higher energies. Furthermore, the deduced reaction cross sections at the nine investigated energies agree well with those experimentally determined as well as with those theoretically estimated using microscopic double folding potentials.

Finally, it is worthwhile to point out that the present analysis shows an additional confirmation of the ability of the SFC potential to successfully reproduce the measured elastic scattering and reaction cross sections.

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