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FIRST AND SECOND ORDER CORRECTIONS TO THE EIKONAL PHASE SHIFTS FOR THE INTERACTIONS OF α-PARTICLE WITH ^{12}C AND Ca ISOTOPES

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The high-energy double-folding optical potential approximation to the exact nucleus-nucleus multiple scattering series derived by Wilson has been used to calculate the optical potential and the elastic scattering differential cross-section for the interactions of α-particle with $^{12}\mathrm{C}$ and Ca isotopes at energy 1370 MeV. The Pauli correlation effect has been considered. The first- and second-order corrections to the optical potential and to the eikonal phase shifts have been calculated for our reactions. Also, the transparency function has been calculated.

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1 Introduction

Investigation of the scattering of alpha particles is a very active and important field of research. It is realized [1] that entrance channel alpha-particle measurements give information about the interaction near the nuclear surface, and the qualitative fact that the alpha particle absorption in the nuclear interior must be strong. There is a similarity between alpha particle and heavy ion scattering [1]. The elastic scattering of alpha particle from heavy ion target has been studied in the framework of the local density dependence of the effective nucleon-nucleon interaction [2]. The effective interaction is based on, what is termed, a low-energy approach where the interacting nucleons have been considered as being bound close to the Fermi surface. The interactions of α-particle with $^{12}\mathrm{C}$ and $^{40}\mathrm{Ca}$ nuclei have been studied at low energy using the density-dependent interactions [3,4] and realistic interactions. It is shown [5] that when the absorption is increased a smooth exponential-like falloff associated with diffractive scattering is obtained. For higher energies the angular distribution has been studied for the interactions of α-particle with $^{12}\mathrm{C}$ [6] and Ca isotopes [7] at energy 1370 MeV. The optical potential has been studied in the energy range from 200 MeV to 700 MeV both phenomenologically and in the folding approach [8]. This study suggests that the real potential should change from attractive to repulsive at about 1 GeV. It is found [9] that the optical potential must be weakly attractive to reproduce the minima observed in the elastic angular distributions for α + $^{12}\mathrm{C}$ and the Ca isotopes at 1370 MeV.

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Studying the optical potential for the interactions of alpha particle with $^{12}\mathrm{C}$ nucleus and $^{40}\mathrm{Ca}$ nucleus at energy 1370 MeV shows that no evidence is found for deviations of the real part from the usual Woods-Saxon shape [10]. Study angular distribution of the interactions of alpha particle with $^{12}\mathrm{C}$ and $^{40}\mathrm{Ca}$ nuclei in terms of a phenomenological optical potential shows that the angular distribution is not sensitive to details of the potential shape [10,11]. And the best fit potential has a "Mexican-hat" shape which is characterized by a long-ranged and weak attractive part in the surface region and a repulsion in the central region [12]. A further increase in nuclear transparency is found compared to 700 MeV. The theory of composite particle scattering at high energy has been examined for the interactions of alpha particle with Ca isotopes [13]. The agreement with experiment is extremely good. These two interactions have been studied by expanding the S-matrix for elastic nucleus-nucleus collisions within the framework of Glauber multiple scattering theory [14]. The first term of the expansion series corresponds to the well known optical limit. The other terms depend respectively on two-three and other many body densities of the two colliding nuclei. Including the two-body density term in $^{40}\mathrm{Ca}$ leads to a considerable improvement in the theoretical situation. The disagreement present at large momentum transferee is due to neglecting higher order terms which are expected to be important in higher momentum transferee regions. The situation for $^{12}\mathrm{C}$ is not so good. There is a sizable discrepancy in the region of the first minimum. Glauber calculation [15,16] based on the "rigid projectile" [15] assumption and using empirical nucleon-nucleon amplitude and experimental one-body form factors as an input represents rather well the interactions of alpha particle with $^{40}\mathrm{Ca}$ nucleus. This model fails to describe the scattering of alpha particle from $^{12}\mathrm{C}$ nucleus. Long-range correlations which are reflected in the presence of strong low-lying collective states in $^{12}\mathrm{C}$ may play an important role in $^{4}\mathrm{He}$–$^{12}\mathrm{C}$ scattering. Using Glauber theory, collactive excitations to one phonon level have been treated using the Tassie model [17]. The effect of the coupling between the elastic and inelastic channels has been considered. The elastic scattering differential cross-section has been calculated for the interactions of $^{4}\mathrm{He}$ + $^{12}\mathrm{C}$ at 1370 MeV on the basis of multiple diffraction scattering theory and α-cluster model with dispersion [18]. According to this model the carbon nucleus is considered as made up of three α-clusters arranged at the vertices of equilateral triangle. This approach does not give satisfactory agreement with the experimental data.

The eikonal phase shifts and its higher order corrections have been used to calculate the interaction of α-particle with heavy ion nuclei at low energies [19,20]. The transparency function has been calculated for these reactions [20]. It is found that above 100 MeV nuclei are more transparent for α-particle, which can probe the interior of the nuclei.

In this work the high energy double-folding optical potential approximation to the exact nucleus-nucleus multiple scattering series derived by Wilson has been used in the context of the eikonal approximation to calculate the elastic scattering differential cross-section for the interactions of α-particle with $^{12}\mathrm{C}$ and Ca isotopes at energy 1370 MeV. The optical potential has been calculated for these interactions. The first and second order corrections to the eikonal phase shifts have been included in our calculations. The $^{12}\mathrm{C}$ nucleus is considered to have a static quadrupole deformation. The transparency function has been calculated for our reactions taking into consideration the second order correction to the eikonal phase shifts. Section 2 presents the formalism, section 3 is devoted to the results and discussion and the conclusions are given in section 4.

2 The Formalism

The elastic scattering amplitude considering the Coulomb effect is given by

$$f(\theta) = f_{\mathrm{c}}(\theta) + (2\mathrm{i}k)^{-1} \sum_{l} (2l+1) \exp(2\mathrm{i}\eta_l)(S_l - 1) P_l(\cos\theta)\,, \tag{1}$$

$f_{\mathrm{c}}(\theta)$ is the usual point charge Coulomb amplitude, η_l is the point charge Coulomb scattering phase shift, and S_l is given by

$$S_l = \exp(2\mathrm{i}\delta_l)\,, \tag{2}$$

where δ_l is the complex nuclear phase shift, which is obtained from [21]

$$\delta_l = \frac{1}{2}\chi(b)\,. \tag{3}$$

According to Wallace [22], the expansion of the phase shift function $\chi(b)$, as a power series in the strength of potential scattering is given by

$$\begin{aligned} \chi_j(b) &= \sum_{n=0}^{j} \chi^{(n)}(b)\,, \\ \chi^{(n)}(b) &= -\frac{\mu^{n+1}}{k(n+1)!}\left(\frac{b}{k^2}\frac{\partial}{\partial b} - \frac{\partial}{\partial k}\frac{1}{k}\right)^n \int_{-\infty}^{\infty} V^{n+1}(r)\mathrm{d}z\,, \end{aligned} \tag{4}$$

where

$$\overline{r} = \overline{b} + \hat{k}z\,,$$

V is the optical potential, b is the impact parameter, μ is the reduced mass, and k is the momentum in the c.m. system $(\hbar = c = 1)$. The zero order term in equation (4) gives the eikonal phase shift

$$\chi^{(0)}(b) = -\frac{\mu}{k}\int_{-\infty}^{\infty} V(r)\mathrm{d}z\,. \tag{5}$$

For local potential the first and second order corrections are given, respectively, by [23]

$$\chi^{(1)}(b) = -\frac{\mu^2}{2k^3}\left(1 + b\frac{\partial}{\partial b}\right)\int_{-\infty}^{\infty} V^2(r)\mathrm{d}z\,, \tag{6}$$

$$\chi^{(2)}(b) = -\frac{\mu^3}{6k^5}\left(3 + 5b\frac{\partial}{\partial b} + b^2\frac{\partial^2}{\partial b^2}\right)\int_{-\infty}^{\infty} V^3(r)\mathrm{d}z\,. \tag{7}$$

The phase shift function $\chi_j(b)$ is given by [19]

$$\chi_j(b) = -\frac{\mu}{k}\int_{-\infty}^{\infty} U_j(r)\mathrm{d}z \tag{8}$$

with

$$U_j(r) = \sum_{n=0}^{j} U^{(n)}(r)\,,$$

$$U^{(n)}(r) = \frac{\mu^n}{(n+1)!}\left[\frac{1}{k^2}\left(1 + r\frac{\partial}{\partial r}\right) - \frac{\partial}{\partial k}\frac{1}{k}\right]^n V^{n+1}(r)\,. \tag{9}$$

$U_j(r)$ is an effective potential of the j-th order. The first and second order corrections to the effective potential are given by

$$U^{(1)}(r) = \frac{\mu}{2k^2}\left(2 + r\frac{\partial}{\partial r}\right)V^2(r)\,, \tag{10}$$

$$U^{(2)}(r) = \frac{\mu}{6k^4}\left(8 + 7\,r\frac{\partial}{\partial r} + r^2\frac{\partial^2}{\partial r^2}\right)V^3(r)\,. \tag{11}$$

In our calculations $V(r)$ is the optical potential. The nucleus-nucleus optical potential as derived by Wilson takes the form [24],

$$V(r) = A_{\mathrm{p}}A_{\mathrm{T}}\int \mathrm{d}^3r_{\mathrm{T}}\rho_{\mathrm{T}}(r_{\mathrm{T}})\int \mathrm{d}^3y\rho_{\mathrm{p}}(r + y + r_{\mathrm{T}})t(e,y)[1 - C(y)]\,, \tag{12}$$

where A_{i} $(i = \mathrm{p},\mathrm{T})$ are the mass numbers of the projectile and the target, ρ_{i} are the ground state single particle nuclear densities for the colliding nuclei; $t(e,y)$ is the energy dependent constituent-averaged two-nucleon transition amplitude obtained from scattering experiments, e is the NN kinetic energy in the c.m. frame, y is the NN relative separation and $C(y)$ is the Pauli correlation function, given by

$$C(y) \approx \frac{1}{4}\exp(-k_{\mathrm{F}}^2y^2/10) \qquad \text{and} \quad k_{\mathrm{F}} = 1.36\,\mathrm{fm}^{-1}\,. \tag{13}$$

This six dimensional integral (12) is calculated using the momentum space method as derived by Walter Greiner [25]. If the Fourier transform of a function $f(\overline{x})$ is denoted by $\tilde{f}(\overline{k})$, the folded potential is given by

$$V(r) = (2\pi)^{-3}\int \mathrm{d}^3k\,\exp(-\mathrm{i}\overline{k}\overline{r})\tilde{\rho}_{\mathrm{P}}(+\overline{k})\tilde{\rho}_{\mathrm{T}}(-k)\tilde{t}'(e,\overline{k})\,, \tag{14}$$

where

$$t'(e,Y) = t(e,Y)[1 - C(y)]\,,$$

i. e., the Fourier transformed integrand reduces to a product of the Fourier transforms of the two densities and the transition nucleon-nucleon scattering amplitude. If the target nucleus is considered to have a static quadrupole deformation, following the same steps and notations as in ref. [25], we obtain

$$V(r) = \frac{2}{\pi}\int_0^\infty \mathrm{d}k\, k^2 j_0(kr)\tilde{t}'(e,k)A_{00}^{'(1)}(k) + A_{00}^{'(2)}(k) + + \frac{2\sqrt{5}}{\pi}\int_0^\infty \mathrm{d}k\, k^2 j_2(kr)\tilde{t}'(e,k)A_{00}^{'(1)}(k)A_{20}^{'(2)}(k)P_2(\cos\beta_2)\,, \tag{15}$$

where

$$A'_{ln} = \delta_{n0}\int_0^\infty \mathrm{d}r' r'^2 \rho_{l0}(r') j_l(kr')$$

and β_2 is the Euler angle.

2.1 The density parameters

In our work we used nuclear single particle matter densities which are extracted from the charge density.

A harmonic oscillator matter density for ^{12}C.
The harmonic well charge density has the form [26]

$$\rho_c(r) = \rho_0[1 + \nu(r/a)^2]\exp(-r^2/a^2)\,. \tag{16}$$

The constants a and ν are fitting parameters to electron scattering data [26] and ρ_0 is determined by the normalization condition

$$\int \rho(r)\mathrm{d}r = 1\,. \tag{17}$$

The matter density is extracted from the charge density by the method discussed in ref. [27], which gives for the harmonic well matter density

$$\rho_m(r) = \frac{\rho_0 a^3}{8s^3}\left(1 + \frac{3\nu}{2} - \frac{3\nu a^2}{8s^2} + \frac{\nu a^2 r^2}{16s^4}\right)\exp(-r^2/4s^2)\,, \tag{18}$$

with

$$s^2 = \frac{a^2}{4} - \frac{r_\mathrm{p}^2}{6}\,,$$

where r_p is the proton rms radius and is equal to 0.87 fm.

A one term Gaussian density for α-particle.
The Gaussian density has the form

$$\rho_c(r) = \rho_0\exp(-r^2/a^2)\,, \tag{19}$$

where

$$\rho_0 = 1/(a\sqrt{\pi})^3 \tag{20}$$

and

$$a = \langle r^2\rangle^{1/2}(1.5)^{-1/2}\,. \tag{21}$$

The corresponding matter density is

$$\rho_m(r) = \frac{\rho_0 a^3}{8s^3} \exp(-r^2/4s^2)\,, \tag{22}$$

with

$$s^2 = \frac{a^2}{4} - \frac{r_{\mathrm{p}}^2}{6}\,.$$

The density for Ca isotopes.
The nuclear density distribution is of the form [28]

$$\rho(r) = \rho(0)\mathrm{e}^{-(\mathrm{r/a})^2}\,. \tag{23}$$

The parameters $\rho(0)$ and a are given by

$$a^2 = \frac{4ct + t^2}{k} \tag{24}$$

and

$$\rho(0) = \frac{1}{2}\rho_0 \exp(c/a)^2\,, \tag{25}$$

where

$$\rho_0 = \frac{3A}{4\pi c^3[1 + (\pi^2 t^2/19.36c^2)]} \tag{26}$$

and

$$k = 4(\ln 5) = 6.43775\,.$$

The parameters c and t are given by $1.07A^{1/3}$ and 2.4 fm respectively. The corresponding matter density is

$$\rho_m(r) = \frac{\rho(0)a^3}{8s^3} \exp(-r^2/4s^2) \tag{27}$$

with

$$s^2 = \frac{a^2}{4} - \frac{r_{\mathrm{p}}^2}{6}$$

The nucleus deformation.
The density of a nucleus with an axially symmetric deformation, may be written as [29]

$$\rho(r) = \rho_{00}(r) - r\frac{\mathrm{d}\rho_{00}(r)}{\mathrm{d}r} \sum_l B_{l0} Y_{l0}(\theta, \phi)\,, \tag{28}$$

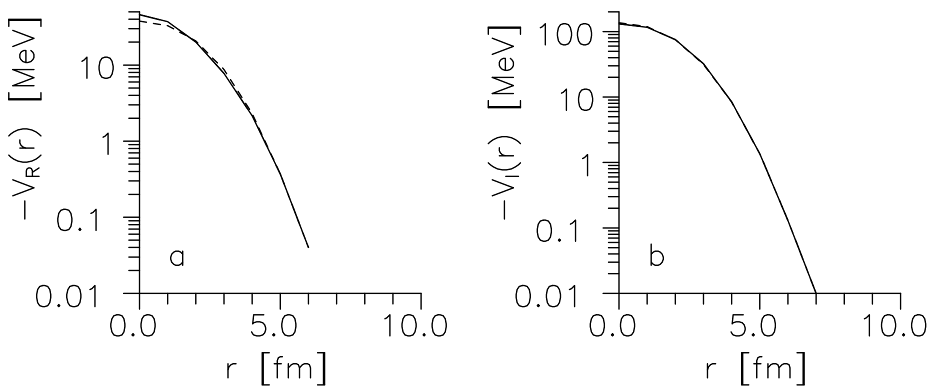

Fig. 1. The real (a) and the imaginary (b) parts of the optical potential for the interactions of α – ^{12}C. The short dashed curves represent the zero order calculations for the optical potential. The long dashed and the solid curves represent the first and the second order corrections for the optical potential.

where $\rho_{00}(r)$ parametrized the spherical part of the nucleus and B_{l0} is the deformation parameter of the nucleus matter distribution. To calculate the deformation parameter B_{20}, let us consider the transition density

$$\rho_{\rm tr}(r) = B_{l0} r^{l-1} \frac{{\rm d}\rho_{00}(r)}{{\rm d}r} \,. \tag{29}$$

The normalization constant B_{20} is determined by assuming that the proton transition density is (Z/A) times the mass transition density and choosing B_{20} to give the measured value of $B(E2)$ for the given nucleus [30], i.e.,

$$\int A\rho_{\rm tr}(r) r^{l+2} {\rm d}r = (A/Ze)(B(El))^{1/2} \,, \tag{30}$$

where A and Z are the mass number and the charge number. The deformed nucleus considered in this work is ^{12}C. The measured value of $B(E2)$ for this nucleus is [31] $B(E2) = 42e^2$ fm^4.

3 Results and Discussion

3.1 The optical potential

The optical potential has been calculated for the interactions of α-particle with ^{12}C nucleus and Ca isotopes. The ^{12}C nucleus is considered as a deformed nucleus and the orientation angle is considered to be 60° [32]. Fig. 1.a,b shows the real and the imaginary parts of the optical potential calculated for α – ^{12}C reactions. The first and second order corrections to the optical potential have been considered in our calculations. The short dashed curves represent the zero-order calculations, the long dashed curves and the solid curves represent the first and the second order corrections to the optical potential. We can see from Fig. 1 that the first and the second-order corrections to the optical potential coincide completely with each other. Fig. 1.a shows that the real potential becomes deeper on introducing the first and the second order corrections to the optical potential. The imaginary potential does not affect by including the first

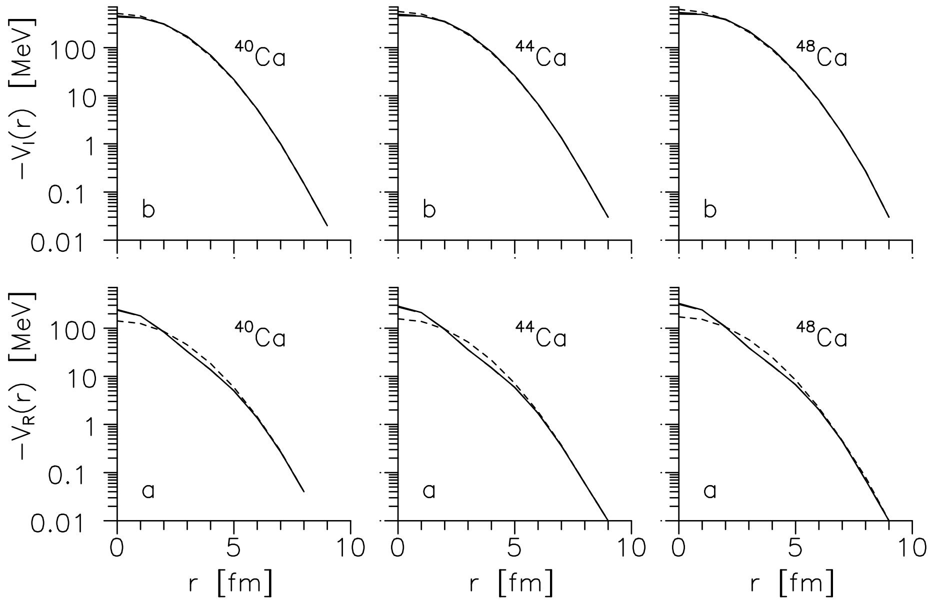

Fig. 2. The same as Fig. 1 but for the interactions of α-particle with Ca isotopes.

and the second order corrections to the optical potential as can be seen from Fig. 1.b. It is also seen from Fig. 1.a,b that the imaginary potential is deeper than the real potential.

The optical potential has been calculated for the interactions of α-particle with Ca isotopes. The first and the second order corrections to the optical potential have been considered in our calculations. Fig. 2.a,b shows the real and the imaginary parts of the optical potential for the interactions of α-particle with Ca isotopes. Fig. 2.a,b shows that the second order calculations overlap the first order calculations and the imaginary potential is deeper than the real potential. Fig. 2.a shows that the real potential does not have substantial change when increasing the mass number of the target. Including the first and the second order corrections to the optical potential increases the depth of the real potential. Fig. 2.b shows that the imaginary potential becomes shallower when including the first and the second order corrections to the optical potential. The imaginary potential becomes deeper for heavier nuclei.

3.2 The elastic scattering differential cross-section

The elastic scattering differential cross-section has been calculated for the interactions of α-particle with ^{12}C and Ca isotopes. In our calculations we consider ^{12}C nucleus to be deformed nucleus and the orientation angle is considered to be $60°$. Fig. 3 shows the elastic scattering differential cross-section for α – ^{12}C reactions compared with the experimental data [6]. Fig. 3 shows that the first maximum is well reproduced. The positions of the second and third maxima are shifted to the right of the experimental data. Also Fig. 3 shows that even considering the ^{12}C nucleus as a deformed nucleus, the agreement between the theoretical calculations and the experimental data is not so good at large scattering angle $\theta > 11°$. The elastic scattering differential

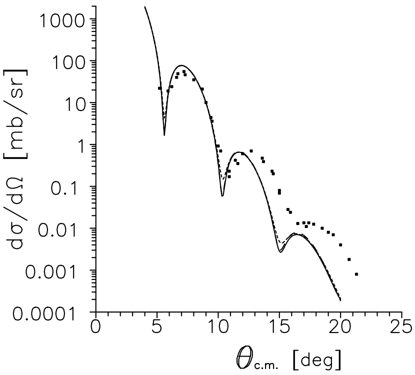

Fig. 3. The elastic scattering differential cross-sections for the reactions of α – ^{12}C. The short-dashed curve represents the zero-order correction to the eikonal phase shifts. The long dashed and the solid curves represent the calculations for the first and the second-order corrections to the eikonal phase shifts.

cross-section has been calculated including the first order correction to the eikonal phase shifts (long dashed curve) and the second order correction to the eikonal phase shifts (solid curve). The short dashed curve is the result for the zero-order eikonal phase shifts. As seen from Fig. 3, the differences between the short-dashed, long dashed and the solid curves are not substantial when compared to the experimental results. These differences give some variations in the depths of the minima. The differences between the results from the first and second-order corrections are too small so that the long-dashed curve overlap with the solid curve. As a whole we can find from Fig. 3 that the first and the second-order corrections do not improve the agreement between the theoretical calculations and the experimental data.

The elastic scattering differential cross-section has been calculated for the interactions of α-particle with Ca isotopes. Fig. 4 shows the elastic scattering differential cross-section for the in-

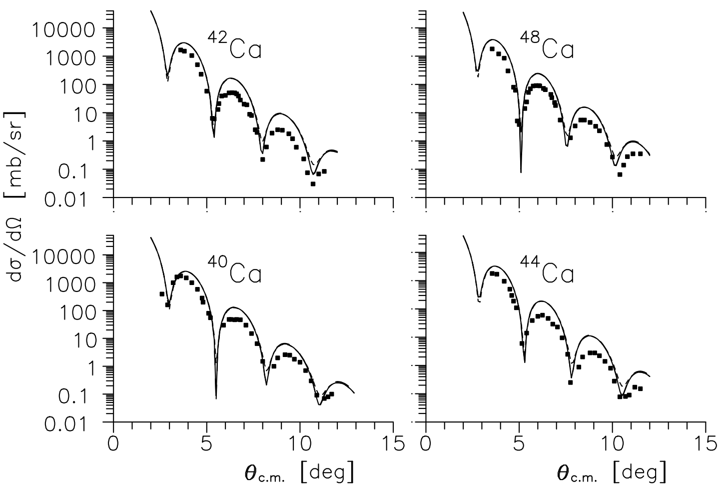

Fig. 4. The same as Fig. 3 but for the interactions of α-particle with Ca isotopes.

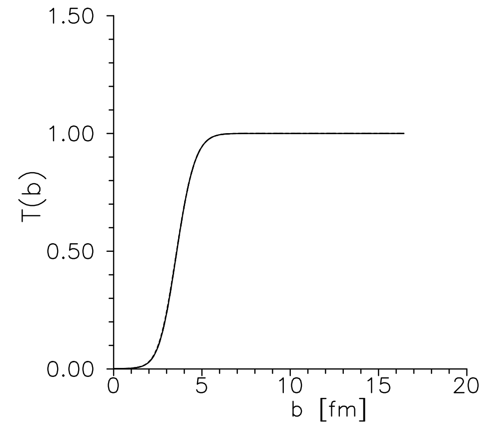

Fig. 5. The transparency function for the reactions of $\alpha - {}^{12}$C including the second order corrections to the eikonal phase shifts.

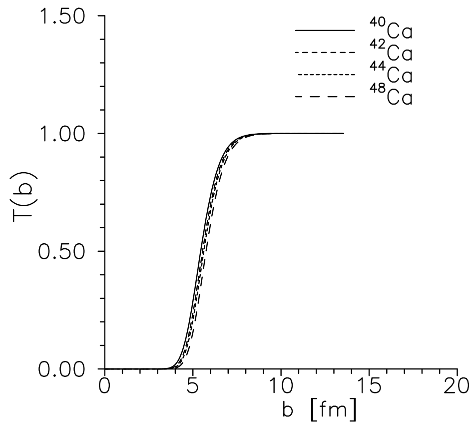

Fig. 6. The same as Fig. 5 but for the interactions of α-particle with Ca isotopes.

teractions of α-particle with Ca isotopes compared with the experimental data [7]. The short dashed curves represent the results for the zero-order eikonal phase shifts. The elastic scattering differential cross-section including the first (long dashed curves) and the second (solid curves) order corrections to the eikonal phase shifts is shown in Fig. 4. Fig. 4 shows that our calculation agree well with the experimental data for the four reactions. The positions of the maxima and the minima are the same as those of the experimental data. However the values of the calculated cross-sections at the maxima are larger than the values of the experimental data. Including the first and the second order corrections to the eikonal phase shifts gives some variations in the depth of the minima. The differences between the results from the first and the second order-corrections to the eikonal phase shifts are too small so that the long dashed curves overlap the solid curves. We can find from Fig. 4 that including the first and the second order corrections to the eikonal phase shifts does not improve the agreement between the experimental data and the theoretical calculations.

The transparency function has been calculated for our reactions. The transparency function is given from the total reaction cross-section which is given by

$$\sigma_R = 2\pi \int [1 - \exp(-2\chi_{\rm I}(b))] b \, {\rm d}b = 2\pi \int [1 - T(b)] b \, {\rm d}b \,, \tag{31}$$

where $\chi_{\rm I}(b)$ is the imaginary part of the phase shift function and $T(b)$ is the transparency function at an impact parameter b. The transparency function is calculated using the second order correction to the eikonal phase shifts. Fig. 5 shows the transparency function for the interactions of $\alpha - {}^{12}$C system at energy 1370 MeV. Fig. 6 shows the transparency function for the interactions of α-particle with Ca isotopes. We can see from Figs. 5 and 6 that the absorption increases with increasing the mass number of the target.

4 Conclusion

The optical potential and the elastic scattering differential cross-section have been calculated for the interactions of α-particle with $^{12}\mathrm{C}$ and Ca isotopes at energy 1370 MeV. The $^{12}\mathrm{C}$ nucleus is considered to be a deformed nucleus. The first and the second-order corrections to the optical potential and the eikonal phase shifts have been considered in our calculations. We can see from our calculations that the optical potential becomes deeper on increasing the mass number of the target nucleus. Introducing the first and the second-order corrections to the optical potential increases the depth of the real potential and decreases the depth of the imaginary potential. The elastic scattering calculated by our model does not satisfy the experimental data for α – $^{12}\mathrm{C}$ reactions at large scattering angle even when considering the $^{12}\mathrm{C}$ nucleus as a deformed nucleus. However our calculations for the elastic scattering satisfy well the experimental data for the interactions of α-particle with Ca isotopes. To improve our calculations, may be it is important to include the 3 state of $^{12}\mathrm{C}$ nucleus. Also, if we consider more sophisticated density form for Ca isotopes, we can obtain a better agreement between the theoretical calculations and the experimental data for the interactions of α-particle with Ca isotopes.

Including the first and the second order corrections to the eikonal phase shifts does not improve much the agreement between the theoretical calculations and the experimental data in this case. Calculating the transparency function shows that the absorption increases with increasing the mass, number of the target.

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