ELASTIC SCATTERING OF ^{4}He BY ^{12}C AT 96.6 MeV

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Differential cross section for the ^{4}He-^{12}C elastic scattering at 96.6 MeV is reported. The data taken as well as existing data at 104 and 139 MeV are found to be well described by using the scattering-matrix formalism with a model-free determination of the real part of the nuclear phase-shift. The variation of the rainbow angle with energy is discussed.

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1. Introduction

Angular distributions for elastic scattering of ^{3}He and ^{4}He particles from atomic nuclei at $E \geqslant 25$ MeV/nucleon [1–5] exhibit distinct diffraction patterns of Fraunhofer type only in the range of small scattering angles. At larger angles strong damping of the diffraction oscillations occurs. Then beyond a certain angle the differential cross section is characterized by an exponential-like decrease.

Theoretical analyses of ^{3}He and ^{4}He elastic scattering data were performed within the framework of the optical model, for example, in the works of Hyakutake et al. [1], Goldberg et al. [2, 3] and the effect of oscillation damping was interpreted as arising due to strong refraction of scattered waves by the real part of the optical potential. The differential cross sections for the elastic scattering of ^{3}He and ^{4}He nuclei in the energy range under consideration were also analysed by using the scattering-matrix formalism [6–9]. The oscillation damping effect was attributed to strong nuclear refraction and small transmissivity of the target nucleus for partial waves with small angular momenta (Refs. [7, 9]).

The behaviour of the light-ion scattering differential cross sections we have mentioned above is referred to as the manifestation of the rainbow scattering accompanied by strong absorption. In quasi-classical terms at angles on the 'bright' side of the rainbow ($\theta < \theta_r$, where θ_r denote the nuclear rainbow angle that correspond to the minimum of the deflection function) the elastic scattering cross section is an oscillating function of the scattering angle and at $\theta > \theta_r$ ('dark' side of the rainbow) it falls off rapidly and smoothly with increasing θ [10]. The rainbow angle increases with mass number of the target nucleus and decreases with projectile energy [1, 3, 11].

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The present paper deals with elastic ^{4}He-scattering by ^{12}C at 96.6 MeV. The angular distribution for α-particles has been measured in the range 10–70°C (c.m. system). The data were analyzed in quasi-classical approximation, using the scattering-matrix formalism with a model-free determination of the real part of the nuclear phase-shift. Similar analyses as for the 96.6 MeV incident energy were performed for the elastic scattering at 104 and 139 MeV.

2. Experimental techniques

Data were collected at 96.6 MeV incident ^{4}He energy, using U-240 isochronous cyclotron from the Kiev Institute for Nuclear Research. The carbon target was 5 mg/cm^2 thick. The extracted beam with an average intensity of 10 nA was collimated and focused to a 3-mm-diam spot on the target. Particle identification for ^{4}He was provided from three ΔE-E telescopes used in conjunction with a multiplier circuit and conventional electronics [12]. ΔE-E telescopes were located in the reaction plane outside the scattering chamber at a distance of 340 mm from the target. Each ΔE-E telescope with the energy resolution of 2–2.5% consisted of 100-mcm silicon surface-barrier ΔE detector and 16×16 mm^2 NaI(Tl) E detector. Two scintillation detectors outside the reaction plane surved as an extra beam monitors in addition to a Faraday cup system with a current integrator. A SM-3 computer was used as an accumulator of a two-dimensional spectra. Besides, a one-dimensional energy spectrum was controlled by an ICA-70 analyser.

3. Experimental results and theoretical analyses

The results of our measurements and the calculated differential cross section are presented in Fig. 1. Calculations were made by making use of an approach proposed by Berezhnoy and Pilipenko [8, 9].

The elastic scattering amplitude $f(\theta)$ can be written as

$$f(\theta) = f_C(\theta) + \frac{i}{k}\sqrt{\frac{\theta}{\sin\theta}}\int_0^\infty \exp[2i\sigma(\sigma)]\,(1-\eta(L)\exp[2i\delta(L)]) \times J_0(L\theta)L\,dL, \tag{1}$$

where $f_C(\theta)$ is the Coulomb scattering amplitude, k is a wave number, $\sigma(L)$ denote the Rutherford phase-shift function in the angular momentum space, $J_0(L\theta)$ is the Bessel function.

The modulus of the scattering matrix $\eta(L)$ in the presence of strong absorption is assumed to have the form

$$\eta(L) = 1-(1-\varepsilon)g(L, L_0, \Delta_0) = 1-(1-\varepsilon)\left[1+\exp\left(\frac{L-L_0}{\Delta_0}\right)\right]^{+1} \tag{2}$$

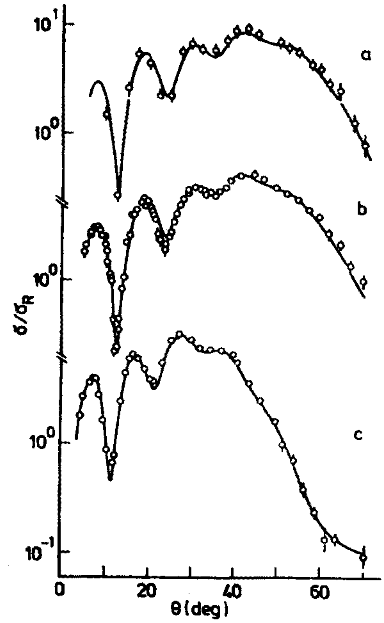

Fig. 1. The ratio of the differential cross section to the Rutherford one for the ^4He-^{12}C elastic scattering at 96.6 MeV (a), 104 MeV (b) and 139 MeV (c) incident energy. The solid curves are calculated with parameters given in Table I. Experimental data at 104 MeV and 139 MeV are taken from Refs [6, 14]

characterized by a boundary angular momentum L_0, a diffuseness parameter Δ_0 and a nuclear transparency parameter ε.

The nuclear phase-shift function $\delta(L)$ in the model-free representation is determined by an infinite sum

$$2\delta(L) = \sum_{n=0}^{\infty} a_n \Delta_1^n \frac{d^n}{dL^n} g(L, L_1, \Delta_1). \tag{3}$$

Equation (3) defines an expansion of $2\delta(L)$ through a complete set of functions [13].

With these expressions the differential cross section for elastic scattering is calculated from (1) as $\sigma(\theta) = |f(\theta)|^2$. The coefficients a_n are adjusted to fit experimental data. By an appropriate choice of the parameters L_1 and Δ_1 a series in (3) can be done quickly convergent. This allows to bring the calculated cross section into agreement with the experimental one when some of the first terms in (3) are retained [9]. The parameter values for elastic ^4He-scattering at 96.6 MeV are listed in Table I. The experimental cross section is well reproduced by using eight termes in expansion (3).

The quantum deflection function $\Theta(L)$ is connected with the nuclear phase-shift function by the relation

$$\Theta(L) = \frac{d}{dL}[2\delta(L)+2\sigma(L)]. \tag{4}$$

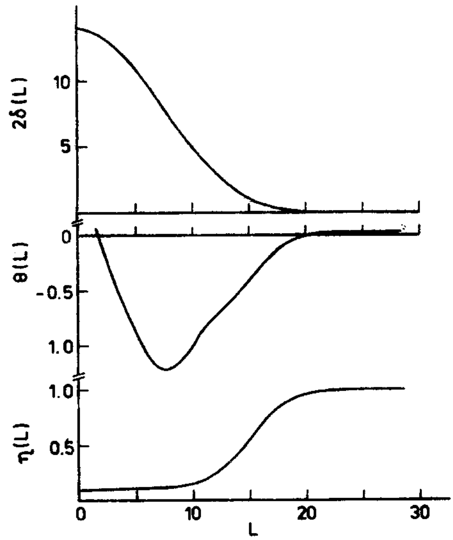

Fig. 2. The nuclear phase-shift function $2\delta(L)$, the deflection function $\Theta(L)$ and the scattering-matrix modulus $\eta(L)$ for the elastic scattering of ^{4}He by ^{12}C at 96.6 MeV

TABLE I

Parameters from analysis of ^{4}He-^{12}C elastic scattering data

E (MeV)	L_0	L_1	Δ_0	Δ_1	ε	a_0	a_1
96.6	14.99	10.75	1.77	3.05	0.093	15.05	14.00
104.0	15.02	10.92	1.78	3.24	0.094	15.08	14.77
139.0	17.15	11.94	2.00	3.47	0.100	12.66	11.49

E (MeV)	a_2	a_3	a_4	a_5	a_6	a_7
96.6	2.37	0.92	−2.41	−0.38	−0.06	−0.03
104.0	2.21	0.73	−2.40	−0.50	−0.09	0.03
139.0	2.30	1.35	−2.08	−0.55	−0.25	0.02

In Fig. 2 we have drawn the nuclear phase-shift function $2\delta(L)$, the deflection function $\Theta(L)$ and the scattering matrix modulus $\eta(L)$ calculated from (2)–(4) with parameters of Table I for the case under consideration. One sees that the function $2\delta(L)$ reaches large values for small angular momenta and decreases smoothly with increasing L. Thus, the behaviour of $2\delta(L)$ indicates the presence of strong nuclear refraction. The quantum deflection function $\Theta(L)$ has a negative minimum, leading to the angle $\theta_r = 69.9°$.

Similar analyses as described above have been carried out for the ^{4}He–^{12}C elastic scattering data at 104 and 139 MeV. The calculated differential cross sections are shown in Fig. 1 and the parameter sets are given in Table I. The functions $2\delta(L)$, $\Theta(L)$ and $\eta(L)$ for the cases under discussion are similar to those presented in Fig. 2. Our calculations yield the rainbow angles 65.8° and 47.0° for the 104 and 139 MeV incident energy respectively. The result for θ_r at $E = 139$ MeV is close to that obtained by Smith et al. [14] from the optical model fit to the analysed cross section. To verify the value of θ_r it is desirable to have more detailed data, extending over a wider angular range.

By comparing the values of θ_r for the analysed set of data one may conclude that in the energy range under consideration the angle θ_r decreases while the energy increases. We find that the variation of θ_r with energy can be expressed as $\theta_r \cdot E = \text{const}$ [15] with an accuracy of 5%. Since $\theta_r \cdot E \sim V$, where V is the depth of the real potential, the latter should have week energy dependence in the range 96.6–139 MeV. This conclusion is consistent with the results of Smith et al. [14] for the energy range 104–139 MeV close to that of the present analyses.

According to the calculations performed the differential cross sections for the elastic scattering of ^{4}He by ^{12}C at incident energies close to 100 MeV seem to be sensitive to the inner partial waves that probe the interior of the potential down to a rather small radius $r \cong 2.0$ fm (see also Refs. [6, 16]), i.e. several fm inside the strong absorption radius, which is greater than 4 fm. With increasing energy the potential can be determined to slightly smaller distances [17, 18].

Using the parameters given in Table I for $E = 96.6$, 104 and 139 MeV the total reaction cross section σ_r was found to be 836, 780 and 756 mb respectively. It is seen that σ_r decreases with increasing energy. The calculated value of σ_r at $E = 96.6$ MeV is consistent with the experimentally measured total reaction cross section $\sigma_r^e = 748 \pm 64$ mb at $E = 100$ MeV [19] and predictions of De Vries et al. [20, 21]. The result for σ_r at $E = 104$ MeV turnes out to be in better agreement with σ_r^e than the values of σ_r obtained from the optical potential [6], the scattering-matrix parametrization [6] and the microscopic model calculations [21]. At $E = 139$ MeV the calculated total reaction cross section is close to the data of De Vries et al. [20, 21].

4. *Conclusions*

Measurements of the differential cross section for the elastic scattering of α-particles by ^{12}C nuclei have been made at 96.6 MeV. It has turned out that the pronounced rainbow structure of the measured cross section can be well described by making use of the scattering-matrix formalism with a model free choice of the real part of the nuclear phase-shift which accounts for the nuclear refraction. This approach also provides a good description of the experimental differential cross sections for the elastic scattering of 104 and 139 MeV α-particles by ^{12}C. The rainbow angle for the cases under discussion has been shown to decrease with increasing energy, so that, approximately, $\theta_r \cdot E = \text{const}$. This behaviour corresponds to a real potential rather independent of the incident energy in the range $E = 96.6$–139 MeV.

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