Complex analysis of scattering 1p-shell nuclei in the framework of coupled channel method

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Abstract. The scattering process on 1p-shell nuclei, having the cluster structure, can be seen in the anomaly increasing of cross sections for large angles. Most often, this increasing of cross sections is connected with mechanism of transfer of clusters or nucleons. The study of the α-cluster transfer mechanism in the elastic scattering of ²⁰Ne ions on ¹⁶O nuclei is important for investigation burning process in evolution of the Universe immediately after the Big-Bang. Therefore new experiment on the heavy ion accelerator (Warsaw University) was carried out with a significant expansion of the range of angles up to 170° in center mass system at E_{lab}=50.0 MeV. Data analysis of angular distribution was performed in framework of the optical model and coupled channel method. The optimal parameters of the optical potential were obtained and the spectroscopic factor was obtained 1 for ²⁰Ne as α + ¹⁶O.

1. Introduction
Better knowledge about spectroscopic factor could provide us useful information about nuclear structure of nuclei and reaction mechanism. It is well known that, the spectroscopic factor is related to the preformation probability of the cluster configuration in a nucleus. Usually, there are different methods to extract the value of the spectroscopic factors from the experimental measurements. The spectroscopic factors play significant role especially in elastic transfer reactions which result in increasing the differential cross sections at backward angles and consequently coupled channel calculations are required to describe this process. Transfer reactions usually take place at low energies. The growth of the cross sections at backward angles was observed which is typical for α-cluster structured nuclei [1]. This increase could be interpreted to be due to the contribution of mechanism of α-cluster transfer [2]. The interaction of these nuclei has been represented by Stock et al. [3]. In the present work reanalysis of differential cross section for ²⁰Ne + ¹⁶O system was performed at E_{lab}=50 MeV.
2. Experiment

The measurements were carried out at the extracted beam $^{20}\text{Ne}$ from the $K = 160$ cyclotron of the Heavy Ion Laboratory, University of Warsaw. The beam energy was 2.5 MeV/n. The charged particles were detected and identified by four $\Delta E$-$E$ counter telescopes installed in the ICARE experimental chamber. The overall energy resolution was about 700 keV. Self-supporting targets of aluminum-oxide with a thickness of 150 $\mu$g/cm$^2$ were mounted in the chamber. In order to determine thicknesses of targets there was used the scattering chamber, installed in the protons ion wire of the accelerator “UKP-2-1”, were measured energy losses of the protons beam during the passage through target. For this purpose the reaction $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ was used with narrow resonance with $E_R=992$ keV and with detection of gamma-quanta with $E_\gamma=1779$ keV. The thicknesses of the fine films (see figure 1) were determined by analyzing the shift of the resonance $E_R=992$ keV in the reaction $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ which takes place at the expense of protons energy losses in the thickness of target, using table values of brake quantities “$S(E_p)$ (MeV$^\ast$cm$^2$/g), there were determined thicknesses of fine films (see figure 1). Such method allows to determine thicknesses of films in the interval of $(10\div100)$ $\mu$g/cm$^2$ with the accuracy not worse than 5%.

![Figure 1](image)

Figure 1. The shift of the 992 keV resonance in reaction $^{27}\text{Al} (p, \gamma)^{28}\text{Si}$ due to the loss of energy of protons in the film thickness of $^9\text{Be}$. The thickness of the target for $^9\text{Be}$ is 10.75 g / cm$^2$ with an accuracy of 5%.

The $\Delta E$-$E$ spectrum of the $^{20}\text{Ne} (^{16}\text{O}, ^{16}\text{O})^{20}\text{Ne}$ reaction products was obtained via ROOT (see figure 2). Our experimental measurements showed scattering pattern at forward hemisphere while, a significant increase in differential cross section at backward hemisphere is observed as shown in figure 3.
Figure 2. $\Delta E$-E spectrum of the $^{20}\text{Ne} (^{16}\text{O},^{16}\text{O})^{20}\text{Ne}$ reaction products.

Figure 3. Angular distribution of the elastic scattering of $^{20}\text{Ne}$ on $^{16}\text{O}$ at the 50 MeV energy. Circles are experimental data; the blue line is the optical model prediction, and the red line represents the coupled reaction channels calculation by code FRESCO with taking into account the exchange mechanism of the $\alpha$-cluster transfer.
3. Data analysis

Experimental data of elastic scattering at forward hemisphere were analyzed within the framework of optical model (OM). For all calculations on OM, the Woods-Saxon form factor was used for both the real and imaginary potential

\[ U = V + iW \]  

\[ V = V_o \left[ 1 + \exp \left( \frac{r - R_r}{a_r} \right) \right]^{-1} \]  

\[ W = W_o \left[ 1 + \exp \left( \frac{r - R_i}{a_i} \right) \right]^{-1} \]  

\( V_o \), \( W_o \), \( a_r \), \( R_r \), \( a_i \), and \( R_i \) being the depth, diffuseness and radii of the real and imaginary potentials, respectively. The radii are expressed in terms of the mass numbers \( A_1 \) and \( A_2 \) of the nuclei involved given by

\[ R = r_o \left( A_1^{1/3} + A_2^{1/3} \right) \]  

Parameters of optical potential (OP) were selected to achieve the best agreement between theoretical and the experimental angular distributions (see table). The description of experimental data is shown in figure 3 (represented by the blue line). It can be seen that OM fails to describe the differential cross section of elastic scattering in backward hemisphere.

| E (MeV) | \( V_0 \) (MeV) | \( R_r \) (fm) | \( a_r \) (fm) | \( W_0 \) (MeV) | \( R_i \) (fm) | \( a_i \) (fm) | SF |
|--------|----------------|-------------|-------------|----------------|-------------|-------------|-----|
| 50.0   | 100.0          | 1.20        | 0.49        | 35.0           | 1.31        | 0.49        | 1   |

Proposed nuclear system has been analyzed earlier by Stock et al. [3] and it shows an oscillatory structure at the intermediate angles and a dramatic rise of the cross section at backward hemisphere. The optical model description could not give a reasonable explanation of cross section behavior at intermediate and large angles. In a recent work, Yang and Li [4] have studied the same nuclear system in the energy range of \( E_{c.m.} \) = 24.5 to 35.5 MeV in framework of folding model which assumes \( ^{16}\text{O} \) nucleus consist of four-\( \alpha \)-particle and \( \alpha+^{16}\text{O} \) the configuration for the \( ^{20}\text{Ne} \). They have obtained a sufficient description of the experimental data for these energies. Our first attempt to describe the \( ^{20}\text{Ne}+^{16}\text{O} \) system in framework of optical and coupled channel models was done in [5]. The key of that work we used a mixed combination of the potentials (deep real potential with a sum of Woods-Saxon typed surface and volume imaginary potentials). Such calculation also was made in other work for different nuclear system [6]. In that paper, the significant rise of the scattering cross section of \( \alpha \) particles on \( ^{9}\text{Be} \) nuclei can be reproduced with using a set of optical potential with deep real part that not taking into account the possible contribution of elastic and inelastic transfer of \( \alpha \)-cluster. Therefore, the relevant description of data in backward hemisphere needs to be taken into account the \( \alpha \)-transfer mechanism for the system

\[ A + (A' + x) \rightarrow A' + (A + x) \]  

at \( A = A' \) allows reproducing the cross sections rise at large angles (see figure 4).
Figure 4. Schematic representation for the transfer reaction.

The contribution of the $\alpha$-transfer mechanism was calculated within the framework of the coupled channel method via code FRESCO [7] using the optical model potential parameters from the table. Result of the calculation is shown in the figure 3 by the red line. The spectroscopic factor $S = 1$ for $^{20}$Ne $\rightarrow ^{16}$O + $\alpha$ was extracted from agreement of experimental data with the coupled channel calculations. The better fitting between the experimental data and coupled channel method calculations was given for the oscillations at the intermediate angles comparing to Stock et al. [3]. In addition, our experimental data were obtained in a wide angular range, up to $170^0$.

4. Summary
This work was devoted to the interaction of $\alpha$-cluster structure type nuclei such as $^{20}$Ne+$^{16}$O system at $E_{lab}=50.0$ MeV. The experimental elastic $^{20}$Ne+$^{16}$O scattering data have been obtained with a significant expansion of the range of angles up to $170^0$ in c.m. Were obtained the optimal parameters of the optical potential. The $\alpha$-cluster transfer mechanism calculated in framework of the coupled channel method can only give a reasonable description in whole range of angles including the intermediate region which responses for the oscillation structure. The extracted spectroscopic factor is 1 for $^{20}$Ne as $\alpha$+$^{16}$O.

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