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Scattering of ^{13}C ions by ^{12}C nuclei at energies close to the Coulomb barrier

Abstract: Angular distributions of the elastic and inelastic scattering of ^{13}C ions on ^{12}C nuclei were measured on the heavy-ion Warsaw Cyclotron at the energy of 32.5 MeV in the laboratory system. Elastic scattering in the forward hemisphere is well described by the standard optical model, while at the same time the possible rise of the cross section in the backward direction can be only reproduced with taking into account the contribution of the neutron transfer mechanism. The experimental data on elastic and inelastic scattering have been analyzed within the framework of the optical model and the Coupled Reaction Channels method via code FRESCO.
Key words: elastic scattering, optical model, potential parameters, differential cross sections, neutron transfer mechanism.

Introduction

Study of elastic scattering in the collision of light heavy ion nuclei at energies near the Coulomb barrier is of interest both in terms of establishing reliable values of the parameters of interaction potentials at low energies and determining the role of the cluster exchange mechanism in the scattering. Some of the key reactions for the carbon and oxygen burning stages are ^{12}C+^{12}C [1], ^{12}C+^{16}O [2, 3] and ^{16}O+^{20}Ne [4] leading to a synthesis of more heavy nuclei.

For the ^{12}C + ^{13}C system the neutron transfer mechanism ^{12}C (^{13}C, ^{12}C)^{13} C can manifest at backward angles. In this context, study of the cross sections in this area is of great interest for astrophysics since it allows us to estimate cross sections of the possible radiative capture ^{12}C(n, γ) ^{13}C reaction and its role in the evolution of the Universe immediately after the Big-Bang. It is expected that the neutron transfer reaction will be peripheral because of the Coulomb repulsion.

Previously elastic scattering ^{12}C + ^{13}C at an energy close to our was investigated in limited range of angles up to 60^0 [5]. Scattering in this system has been also investigated by Chua et al. [6, 7] in the energy range from E_{lab}=20 to 35.5 MeV. They got a reasonable agreement with the experimental data for these energies in the optical model. But their calculations do not predict the cross section rise at larger angles where the neutron exchange mechanism can be dominant.

In present work the differential cross sections of elastic and inelastic scattering for ^{12}C + ^{13}C system were measured at E_{lab} = 32.5MeV in the substantially extended angular range (up 120^0 in the center mass system) and the obtained experimental data were analyzed by coupled reaction channels method (CRC) taking into account coupling the elastic, inelastic as well as the neutron transfer mechanism.

Experimental Setup:

Angular distributions of elastic and inelastic scattering of ^{13}C ions by ^{12}C nuclei were measured using beam with the energy of 2.5 MeV/nucleon extracted from the Heavy Ion Laboratory Cyclotron (K = 160) of the Warsaw University.

The charged particles were detected and identified by four ΔE-E counter telescopes installed in the ICARE scattering chamber. The overall energy resolution was about 700 keV. The telescopes consisted of the ionization chamber as ΔE detector and the semiconductor silicon detector (E). The carbon foils with a thickness of about 150μg/cm^2 were used as a target. Their thicknesses were determined at the proton beam of the UKP-2 accelerator (Almaty, Kazakhstan) by measuring yield of γ-rays (E_γ = 1779 keV) depending on the protons energy loss during the passage through the target. For this purpose the narrow resonance with E_R = 992 keV in the reaction $^{27}Al(p, \gamma)^{28}Si$ was used. In this case the target was a fine film of aluminum oxide (Al_2O_3). An example of film thickness measurement is shown in the Fig. 1. Such method allows determining thicknesses of films in the interval of (10÷100) μg/cm^2 with the accuracy not worse than 5%.

A two-dimensional (*ΔE-E*) and single energy spectra of carbon produced in the $^{12}C+^{13}C$ collision are shown in Fig. 2 and 3 respectively.

The measured angular distributions for the elastic and inelastic scattering are shown in Fig. 4 by the red and black circles respectively.

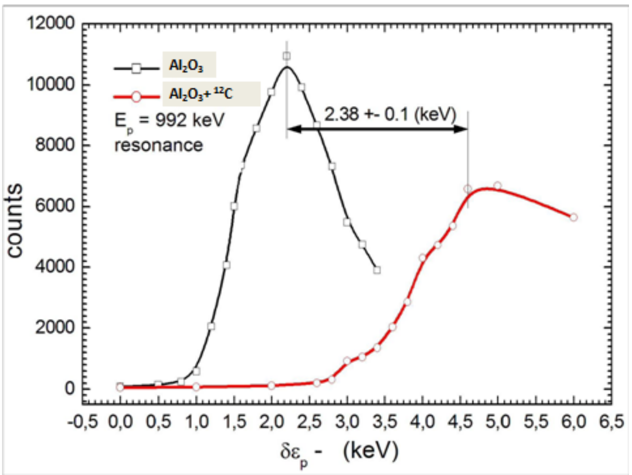

Figure 1 – The shift of the 992 keV resonance in reaction $^{27}Al\ (p, \gamma)\ ^{28}Si$ due to the energy loss of of protons in the carbon film.

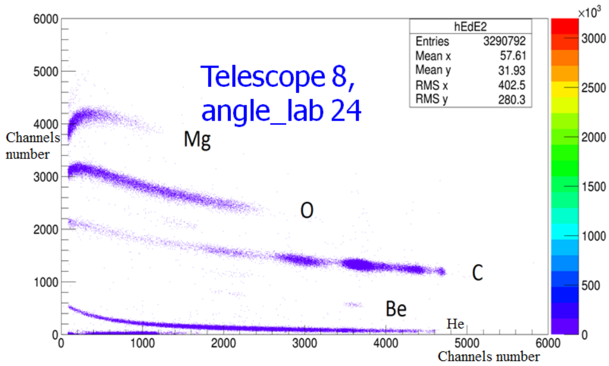

Figure 2 – The two-dimensional (ΔE-E) spectrum of charged nuclei produced from the collision of $^{12}C+^{13}C$. The spectrum was measured at the angle of 24^0 in the laboratory system.

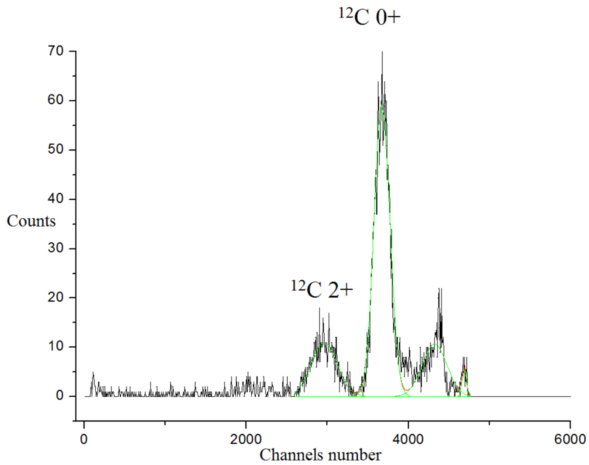

Figure 3 – The energy spectrum of carbon from the $^{12}C(^{13}C,^{13}C)^{12}C$ reaction.

Data Analysis

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

$$U = V + iW, \quad (1)$$

$$V = V_o\,[1+\exp\,(r-R_r)/a_r]^{-1} \quad (2)$$

$$W = W_o\,[1+\exp\,(r-R_i)/a_i]^{-1} \quad (3)$$

V_o and W_o, a_r and a_i, R_r 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

$$R = r_o\,(A_1^{1/3} + A_2^{1/3}) \quad (4)$$

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 Fig. 4 by the blue line. It can be seen that OM well describes the differential cross section of elastic scattering in forward hemisphere. However, this model does not reproduce the smooth behavior of the experimental cross sections at the angles 50-90° and does not predict the rise cross sections at backward direction.

Table – Potential parameters

E (MeV)	V_0 (MeV)	r_V (fm)	a_V (fm)	W_0 (MeV)	r_W (fm)	a_W (fm)
32.5	73.1	1.03	0.699	35.22	1.19	0.211

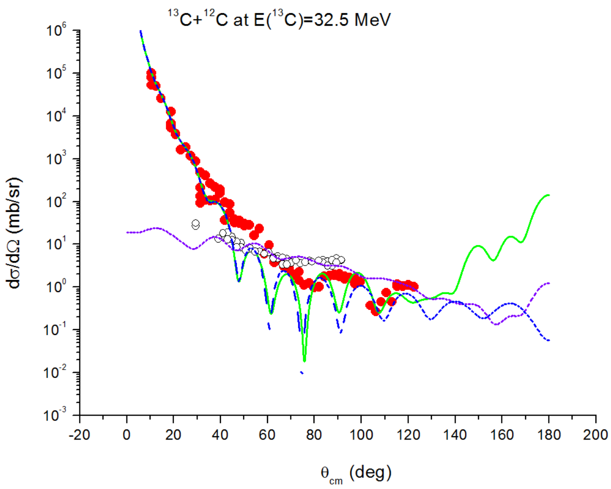

Figure 4 – The angular distributions of elastic and inelasic scattering of ^{13}C on ^{12}C measured at the 32.5 MeV. The red and white circles are experimental data for elastic and inelastic scattering respectively. Curves: the blue dash line is the optical model prediction; the green solid line represents the coupled reaction channels calculation of elastic scattering by code FRESCO with taking into account the neutron transfer mechanism; the violet dot line represents FRESCO calculation of inelastic scattering.

The experimental angular distributions show weak oscillations up to the angles of 100-120°. For the reaction ^{12}C (^{13}C, ^{12}C) ^{13}C, an important process affecting the scattering at large angles is the mechanism of one neutron transfer between the ^{13}C projectile nucleus and the ^{12}C target nucleus. To describe this mechanism we used the Coupled Reaction Channels method realized in the code FRESCO [8].

The theory of collisions that take into account the coupling of different reaction channels, called a multichannel theory. A variant of this theory, which without any approximation strictly takes into account the coupling between a limited numbers of channels and the influence of all other channels is discarded, called the coupled channels method. The method allows for coupling to rearrangement channels by including basis vectors classified according to different mass partitions.

Therefore, the relevant description of data in backward hemisphere needs to be taken into account the n-transfer mechanism for the system

$$A + (A' + x) \rightarrow A' + (A + x) \quad (5)$$

at allows reproducing the cross sections rise at large angles (see Fig. 5).

The angular distribution of inelastic scattering has been analyzed within the code FRESCO which took into account the coupling between the elastic and inelastic scattering as well as the neutron transfer. We assume that the rotation is the dominant mechanism for transition to the 2^+ level at the excitation energy of 4.43 MeV of the ^{12}C nucleus. The transition to this level was calculated using the form-factor:

$$V_\lambda(r) = -\frac{\delta_\lambda}{\sqrt{4\pi}}\frac{dU(r)}{dr}, \qquad (6)$$

where δ_λ is the length of the multipole (λ) deformation. In our case $\lambda = 2$ for the quadrupole transitions. The value of deformation length $\delta_2 = 2.59$ fm was extracted from the analysis of experimental data of inelastic scattering. This value corresponds to the deformation parameter $\beta_2 = 1.1$ ($\beta_2 = \delta_2/R_V$).

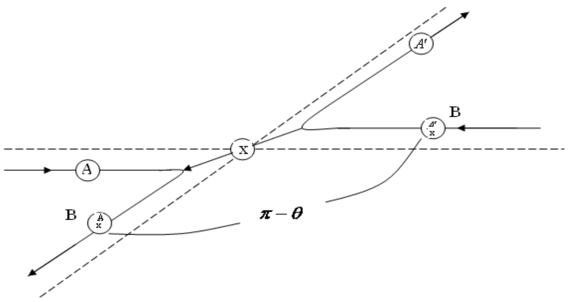

Figure 5 – Schematic representation for the transfer reaction

Conclusion

The experimental data on elastic and inelastic scattering have been analyzed within the framework of the optical model and the Coupled Reaction Channels method with code FRESCO taking into account the neutron transfer mechanism. As it seen from Fig. 4, OM does not provide cross sections enhancement in backward direction. Only taking into account the neutron transfer mechanism gives rise to cross sections at large angles. So, it is important to extend the measurements for angles greater than 120°. The value of deformation length δ_2 =2.59 fm was extracted from the analysis of experimental data of inelastic scattering by CRC.

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