Conference Paper

ENERGY DEPENDENCE OF TOTAL CROSS SECTIONS FOR REACTIONS WITH ^{4,6}He, ^{6,7,9}Li NUCLEI

Yu. Penionzhkevich[1,2], Yu. Sobolev[1], V. Samarin[1,3], and M. Naumenko[1]

[1]Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
[2]Department of Experimental Methods in Nuclear Physics, National Research Nuclear University MEPhI, Moscow, Moscow Region, Russia
[3]Department of Nuclear Physics, Dubna State University, Dubna, Moscow Region, Russia

Abstract

The paper presents the results of measurement of the total cross sections for reactions ^{4,6}He + Si and ^{6,7,9}Li + Si in the beam energy range 5–50 *A*·MeV. The enhancements of the total cross sections for reaction ^{6}He + Si compared with reaction ^{4}He + Si, and ^{9}Li + Si compared with reactions ^{6,7}Li + Si have been observed. The performed microscopic analysis of total cross sections for reactions ^{6}He + Si and ^{9}Li + Si based on numerical solution of the time-dependent Schrödinger equation for external neutrons of projectile nuclei ^{6}He and ^{9}Li yielded good agreement with experimental data.

Keywords: nuclear reactions, neutron rearrangement, time-dependent Schrödinger equation.

Corresponding Author:
M. Naumenko
anaumenko@jinr.ru

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1. Introduction

It is well known that neutron rearrangement may play an important role in nuclear reactions. The aim of this work is the investigation of the reactions with light nuclei having different external neutron shells. The experiments on measurements of total cross sections were performed for reactions ^{4,6}He + Si and ^{6,7,9}Li + Si. The interesting results are the unusual wide enhancement of total cross section for ^{9}Li + Si reaction as compared with ^{6,7}Li + Si reactions. The similar weaker behavior was found for ^{6}He + Si reaction as compared with ^{4}He + Si reaction. The time-dependent quantum approach combined with the optical model was used for explanation of these effects. Based on this approach the observed local enhancements of total reaction cross sections for the studied reactions were explained by rearrangement of external weakly bound neutrons of projectile nuclei during the collision.

2. Experiment

The experimental setup for the implementation of the transmission method using a multilayer telescope [1] is shown in Fig. 1. A system of silicon detectors ΔE_i-E, (i = 0–4) (Si-telescope) was surrounded by the CsI(Tl) γ-spectrometer of complete geometry for registration of γ-rays and neutrons. The thin detectors ΔE_0, ΔE_1 were used to identify the beam particles and determine the particle flux incident on the target. The position-sensitive detector ΔE_2 was used as a so-called active collimator [2] which determined the particle flux incident on the central region of the target ΔE_3. The detectors ΔE_4, E were used to analyze the products of reactions occurring in the material of the target ΔE_3.

The experiment was performed on the accelerator U400M of the Flerov Laboratory of Nuclear Reactions (FLNR), Joint Institute for Nuclear Research (JINR). To obtain the secondary beam the fragmentation reaction of ^{11}B beam with the energy E_{lab} = 32 A·MeV on the target ^{9}Be was used. The secondary beam consisting of a mixture of particles ^{6}He and ^{9}Li was formed and purified by the magnetic system of the achromatic fragment separator ACCULINNA [3]. The beam energy was varied by a fragment separator magnetic system, the choice of the thickness of the hydrogen-containing plates of CH_2 absorbers in the range E ~5–50 A·MeV without significant loss of intensity of the beam of particles. Identification was carried out by energy losses of particles in ΔE_0, ΔE_1 detectors of the telescope and the time of flight. In order to reduce the energy uncertainty, detectors of different thickness (100, 380, or 500 microns) were used in the experiment depending on the beam energy. Detectors of γ-spectrometer recorded γ-quanta and neutrons in coincidence with the start signal from the detector ΔE_1. The number of events of the reaction was determined from the analysis of energy losses in natural Si-target as well as the analysis of gamma and neutron radiation detected by the spectrometer.

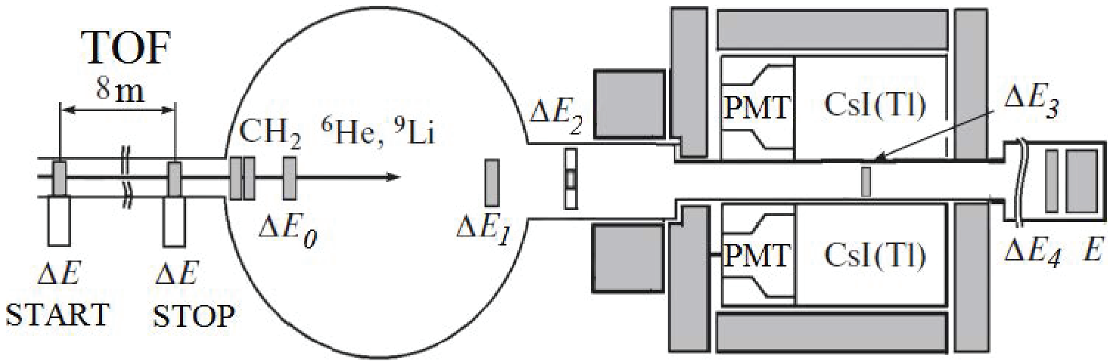

Figure 1: Schematic representation of the experimental setup for measuring the reaction cross sections by the method of the 4π scintillation γ-spectrometer.

The results of measurements of total cross sections for reactions ^{6,7,9}Li + Si and ^{4,6}He + Si are presented in Fig. 2.

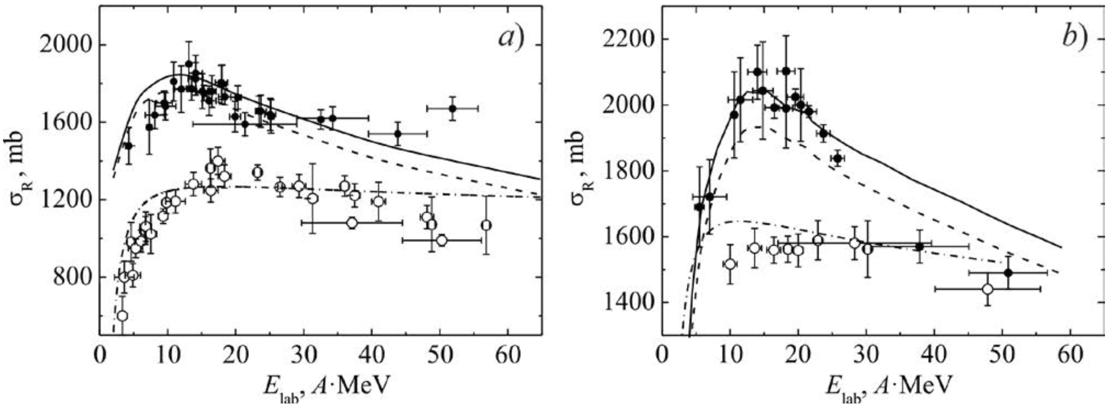

Figure 2: The total cross sections for reactions ^{4,6}He + ^{28}Si (*a*) and ^{7,9}Li + ^{28}Si (*b*), symbols are the experimental data from Refs. [1, 4–9]: ^{6}He + ^{28}Si and ^{9}Li + ^{28}Si (filled circles), ^{4}He + ^{28}Si and ^{7}Li + ^{28}Si (empty circles), curves are the results of calculation within the optical model with the potentials (3), (7): (*a*) for $R_a = 5.0$ fm (solid line) and $R_a = 4.8$ fm (dashed line), (*b*) for $R_a = 5.8$ fm (solid line) and $R_a = 5.6$ fm (dashed line); dash-dotted lines are the results of calculations with the potentials (9), (10) for the reactions ^{4}He + ^{28}Si (*a*) and ^{7}Li + ^{28}Si (*b*).

The cross section for the reaction for the ^{6}He nucleus exceeds the cross section with the ^{4}He nucleus in the entire energy range, which may be explained by the large size of the ^{6}He nucleus. The measurements showed that the dependence on energy of the total cross section for the reaction ^{9}Li + Si has a broad maximum. Enhancement of the cross section for ^{9}Li nuclei compared to ^{7}Li is observed in the energy range 10–30 $A \cdot$MeV.

The analysis of these effects using the microscopic complex folding potential in Ref. [10] as well as within the optical model in Ref. [11] did not provide satisfactory explanation of the observed features in the behavior of the energy dependence of the total cross section. In this study, the potentials of the optical model were modified to take into account the dynamic rearrangement of two external neutrons of projectile nuclei^{6}He and ^{9}Li. The obtained results are in good agreement with the experimental data (Fig. 2).

3. Theory

For theoretical description of neutron rearrangement during collisions of atomic nuclei we used the time-dependent Schrödinger equation (TDSE) approach [12–14] for the external neutrons combined with the classical equations of motion of atomic nuclei. The evolution of the components ψ_1, ψ_2 of the spinor wave function $\Psi(\vec{r}, t)$ for the neutron with the mass *m* during the collision of nuclei is determined by Eq. (1) with the operator of the spin-orbit interaction $\hat{V}_{LS}(\vec{r},t)$

$$i\hbar\frac{\partial}{\partial t}\Psi(\vec{r},t)=\left\{-\frac{\hbar^2}{2m}\Delta+W(\vec{r},t)+\hat{V}_{LS}(\vec{r},t)\right\}\Psi(\vec{r},t). \quad (1)$$

The centers of nuclei $\vec{r}_1(t)$, $\vec{r}_2(t)$ with the masses m_1, m_2 move along classical trajectories. We may assume that before contact of the surfaces of spherical nuclei with the radii R_1, R_2 the potential energy of a neutron $W(\vec{r},t)$ is equal to the sum of its interaction energies with both nuclei. The initial conditions for the wave functions were obtained based on the shell model calculations with the parameters providing neutron separation energies close to the experimental values.

Examples of the evolution of the probability density of the external neutrons of ^{9}Li nucleus when colliding with the nucleus ^{28}Si at different energies were given in Ref. [9]. During a slow (adiabatic) relative motion of the colliding nuclei the external neutrons (dineutron cluster) of ^{9}Li nucleus are penetrating the ^{28}Si nucleus and populating the slowly changing two-center ("molecular") states, the probability density for which fills a large part of the volume of the target nucleus. During the rapid (diabatic) relative motion the probability density of neutrons does not have time to fill all the target nucleus and its change is more local. After the separation of the nuclei the wave packet in the surface region of the target nucleus remains spreading and rotating with large angular momentum. At intermediate velocities there is a transition from the adiabatic regime to the diabatic one.

The qualitative character of the rearrangement of external neutrons during the approach of nuclei depends on the ratio of the average velocity $\langle v\rangle$ of the external neutron and the relative velocity v_{rel} of the nuclei in the process of collision. The average kinetic energy $\langle\varepsilon\rangle$ of weakly bound neutrons in the nuclei ^{6}He and ^{9}Li may be approximately calculated within the shell model. Using estimation $v_{rel}\sim v_1=\sqrt{2E_{lab}/m_1}$, where E_{lab} is the energy of the projectile nucleus with the mass $m_1=Am_0$, m_0 is the atomic mass unit, we obtain the ratio of velocities

$$\frac{v_1}{\langle v\rangle}\approx\gamma\equiv\left(\frac{E_{lab}}{\langle\varepsilon\rangle A}\right)^{1/2}. \quad (2)$$

At low energies, when $\langle v\rangle >> v_1$, $\gamma << 1$, during the flight of the projectile nucleus close to the target nucleus the weakly bound neutrons may, relatively speaking, make many turns around the cores of both nuclei. In the extremely diabatic case (at intermediate energies), when $\langle v\rangle << v_1$, $\gamma >> 1$, the neutron may not be able to move to the target nucleus during the time of flight. The value of the parameter γ may be used to estimate the degree of adiabaticity of the collision.

The real part of the potential $\bar{V}(R)$ for nuclei with "frozen" neutrons was supplemented with the diabatic correction arising from an increase in neutron density between the surfaces of the nuclei as they approach

$$V_d(R, E_{lab}) = \bar{V}(R) + \eta(E_{lab})\delta V_d(R, E_{lab}) \tag{3}$$

with the function $\delta V_d\left(R(t), E_{lab}\right)$

$$\delta V_d\left(R(t), E_{lab}\right) = \int_{\Omega} d^3 r_3 \delta\rho_1(r_3, t) U_T\left(\left|\vec{r}_3 - \vec{r}_2(t)\right|\right), \tag{4}$$

where $U_T(r)$ is the mean field for neutrons in the target nucleus, $\delta\rho_1(r_1, t) = \rho_1(r_1, t) - \rho_1^{(0)}(r_1)$, $\rho_1(r_1, t)$ is the probability density of the external neutrons of the projectile nucleus, $\rho_1^{(0)}(r_1)$ is the same density calculated in the absence of interaction of these neutrons with the target nucleus, Ω is the region between the surfaces of the nuclei,

$$\eta(E_{lab}) = \frac{1}{1 + \exp\left[\frac{1}{\alpha}\left(\langle\varepsilon\rangle - \left(\frac{E_{lab}}{A}\right)\right)\right]} \tag{5}$$

with the variable parameters $\langle\varepsilon\rangle$ ≈10 MeV determining the position $\bar{E}_{lab} = \langle\varepsilon\rangle A$ of the transition region and $\alpha \approx$ 2 MeV determining its width. The diabatic correction $\delta V_d\left(R, E_{lab}\right)$ reduces the height $B\left(E_{lab}\right)$ and shifts to the right the position $R_B\left(E_{lab}\right)$ of the Coulomb barrier

$$R_B(E) = R_{B,0} + \delta R_B(E). \tag{6}$$

For the imaginary part of the potential we used the approximation with the exponential dependence

$$W(r) = \begin{cases} -W_1, r < R_b \\ W_1 \exp\left(-\frac{r - R_b}{b}\right), r \geq R_b \end{cases} \tag{7}$$

and the radius R_b, increasing according to the shift of the barrier position

$$R_b(E) = R_a + k\delta R_B(E), \tag{8}$$

where b = 1 fm, k = 2, R_a = 5.8 fm for the reaction ^{9}Li + ^{28}Si. In the case of reactions with nuclei ^{4}He, ^{7}Li for the real and the imaginary parts of the nuclear potential the Woods–Saxon form was used

$$Re\left\{V_N(R)\right\} \equiv V(R) = -V_0\left[1 + \exp\left((R - R_V)/a_V\right)\right]^{-1}, \tag{9}$$

$$Im\left\{V_N(R)\right\} \equiv W(R) = -W_0\left[1 + \exp\left((R - R_W)/a_W\right)\right]^{-1}. \tag{10}$$

For collisions ^{6,7}Li + ^{28}Si the parameters of the real part of the potential V_0, R_V, a_V were obtained by fitting the angular distributions of the elastic scattering. The results of calculation of the total cross sections for reactions ^{6,7}Li + ^{28}Si thus obtained (Fig. 2) are also in good agreement with the experimental data [1, 6, 8].

4. Conclusions

In this paper we presented experimental results of a direct measurement of the total cross sections for the reactions ^{4,6}He + Si and ^{6,7,9}Li + Si in the beam energy range 5–50 *A*·MeV. The enhancements of the total cross sections for reactions ^{6}He + Si and ^{9}Li + Si have been observed. The theoretical analysis of the possible causes of these effects in the collisions of nuclei ^{6}He and ^{9}Li with Si nuclei was performed including the influence of external neutrons of weakly bound projectile nuclei. The time-dependent model proposed in the paper shows that the rearrangement of external weakly bound neutrons of nuclei ^{6}He and ^{9}Li during the collision changes the real and the imaginary parts of the interaction potential, which may cause a local enhancement in the total reaction cross section. This enhancement is most noticeable in the range of energies where the relative velocity of the nuclei is close in magnitude to the average velocity of external neutrons of the studied light weakly bound nuclei.

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