INVESTIGATION OF DEUTRON ENERGY SPECTRA FROM THE (d, xd) REACTION ON ^{nat}Cu NUCLEUS AT A DEUTRON ENERGY OF 14.5 MeV*

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The paper presents new experimental data on the double-differential and integral (d, xd) reaction cross sections from the interaction of deuterons of 14.5 MeV energy with copper. The experiment was performed at the isochronous cyclotron of the Institute of Nuclear Physics, Kazakhstan. The experimental data were analysed within the framework of the TALYS-1.9 calculation code. It is established that the obtained cross section is mainly formed by mechanisms of pre-equilibrium decay.

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1. Introduction

Experimental data on the continuous energy spectra of secondary particles formed as a result of the interaction of nuclei with nuclei make it possible to trace the dynamics of the formation and evolution of an excited system to an equilibrium state, which remains an urgent task of the theory of nuclear reactions [1]. At the same time, it is worth noting that such data are necessary for the correct modelling of processes occurring in the structural materials of existing and projected nuclear installations, in particular, ADS [2].

Reactions with light complex particles (deuterons, tritons, ^{3}He, and α-particles) are more difficult to describe since they involve other reaction mechanisms, such as direct transfer and knocking out of nucleons, including cluster degrees of freedom and the break up of the bombarding particle.

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Investigation of such reactions induced by light-charged particles, in particular deuterons, is poorly studied [3, 4]. This problem directly depends on the availability of new experimental data. Most studies of deuteron-induced reactions, up to energies of 100 MeV, were carried out in the late seventies and eighties, and focused mainly on understanding the measured angular distributions of elastic and inelastic deuterons and scattering into discrete states over a wide range of nuclei [5–7]. However, in order to fully understand the dominant mechanisms in reactions induced by light hydrogen ions, it is necessary to measure all energy spectra, extending from several MeV to the maximum permissible kinematic energy of the emitted particles. The goal of this paper was the investigation of (d, xd) reactions at 14.5 MeV deuteron energy on natural copper. The work is a continuation of research carried out at the Institute of Nuclear Physics, Kazakhstan to determine the double-differential and integral reaction cross sections in a number of structural elements of the nuclear power system [8–10].

2. Experiment

Experimental data on the (d, xd) reaction on the $^{\mathrm{nat}}$Cu nucleus at an energy of 14.5 MeV were obtained on the deuteron beam of the isochronous cyclotron U-150M of the Institute of Nuclear Physics. The cross sections of the nuclear reaction were measured using a scattering chamber equipped with a rotating charged particle spectrometer, a collimation system, and a Faraday cup to measure the number of particles passing through the target. To register deuterons, a telescope consisting of two silicon detectors with thicknesses of 50 microns and 2 mm was used. The use of such a detectors configuration makes it possible to reliably sort the products of nuclear reactions by the types of secondary particles emitted.

A self-supporting foil with a thickness of 3.5 microns made of natural copper was used as a target. The thickness was determined by the change in the energy losses of α-particles from the radioactive source ^{226}Ra (whose spectrum contains five α-lines with energies of 4.782, 5.305, 5.490, 6.002, and 7.687 MeV) when passing through the target.

The double-differential and integral cross sections of the (d, xd) reaction on the $^{\mathrm{nat}}$Cu nucleus were measured in 30°–135° (with a step of 15°) range of angles in a laboratory system. The total error of the measured double differential cross sections did not exceed 20% for all angles.

After integration by the angle of the double-differential cross sections, the integral cross sections of the $^{\mathrm{nat}}\mathrm{Cu}(d, xd)$ reactions averaged in the energy range of 0.2 MeV are determined. The value of the experimental partial cross section of the reaction (d, xd) was 827.1 ± 2.7 mb. The obtained experimental data are presented in Figs. 1 and 2. The spectrum of outgoing deuterons is characterized by a broad peak corresponding to the compound process located in the low-energy distribution region, a smooth medium-energy component, and a bump corresponding to elastic and quasi-elastic processes in its rigid part.

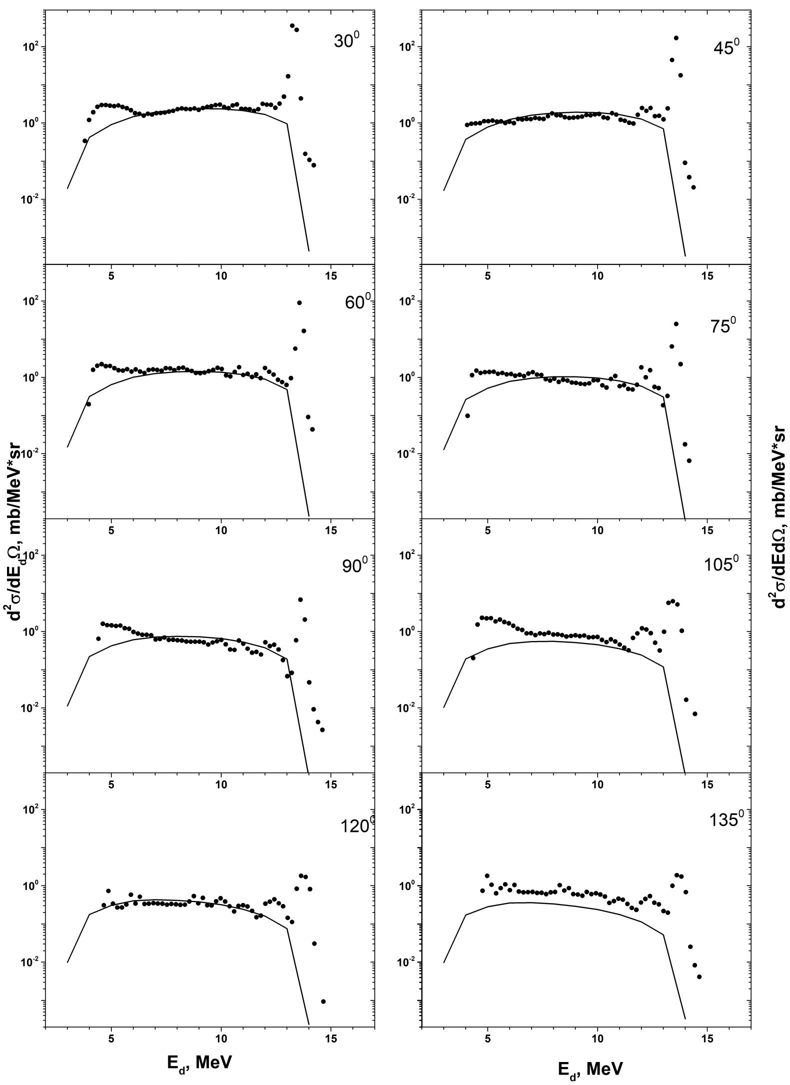

Fig. 1. Double differential cross sections of the (d, xd) reaction at deuteron energy of 14.5 MeV on the $^{\mathrm{nat}}$Cu nucleus. Symbols — experiment, lines — theoretical calculations.

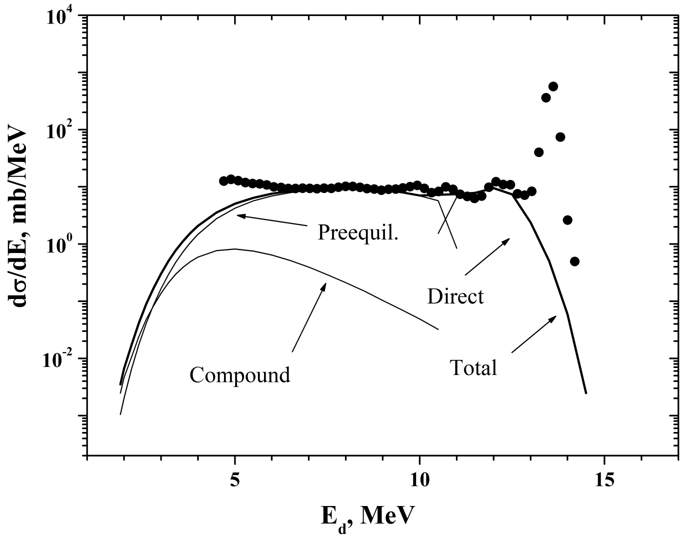

Fig. 2. Comparison of experimental integral cross sections of the $^{\rm nat}$Cu(d, xd) reactions with calculations within the exciton model. Symbols — experiment, lines — theoretical calculations.

3. Analysis

The experimental data were analysed within the framework of the phenomenological exciton model of pre-equilibrium decay within the framework of the calculation code TALYS-1.9 [11]. The developed fast methods for solving kinetic equations have opened up the possibility of studying multiparticle emissions. The exciton model simultaneously describes the energy spectra of not only nucleons but also complex particles.

In the case of complex bombarding particles, a greater variety of pre-equilibrium mechanisms can contribute to the emission of a certain type of particles than in the case of nucleon particles. Separating the contributions of these different mechanisms is often an ambiguous process. In addition, the parameters of the exciton model also require adjustments for such nuclei [3].

Within the framework of the two-component exciton model, it is assumed that the nucleus is characterized by the parameters p_π, h_π, p_ν, and h_ν, where p and h denote partial and hole, and π and ν are the proton and neutron degrees of freedom, respectively. Calculations based on the exciton model begin with the configuration $(p_\pi,\ h_\pi,\ p_\nu,\ h_\nu) = (Z_a, 0, N_a, 0)$, which looks like a particle will decay, but this is done only in order to obtain the correct ratio between p_p, p_n, and n_n interactions when creating the first pair. First, the emission of particles from states formed in the interaction of $(Z_a + 1,\ 1,\ N_a,\ 0)$ and $(Z_a,\ 0,\ N_a + 1,\ 1)$ configurations is allowed.

In addition to calculations within the exciton model, calculations were carried out within the framework of other mechanisms of nuclear reactions: direct processes (transfer — knocking out of nucleons, inelastic scattering) and equilibrium cross section using the Hauser–Feshbach composite core decay formalism. Figures 1 and 2 show a comparison of theoretical and experimental data on the double-differential and integral reaction cross sections (d, xd) on the ^{nat}Cu nucleus. It is established that the main contribution to the formation of the integral cross section of the (d, xd) reactions in the energy range up to 12 MeV, corresponding to elastic and inelastic scattering, is provided by the pre-equilibrium mechanism. In the medium-energy part of the spectrum, in addition to the pre-equilibrium, there is a significant contribution of direct processes. The contribution of the compound mechanism is insignificant.

4. Conclusion

The double-differential and integral cross sections of the (d, xd) reaction on the ^{nat}Cu nucleus were measured in a wide range of angles. The experimental integral and partial cross sections of the studied reaction are determined. The value of the experimental partial cross section of the studied reaction was 827.1 ± 2.7 mb. The experimental data were analysed within the framework of the phenomenological exciton model of the pre-equilibrium decay within the framework of the calculation code TALYS-1.9. It has been established that the main contribution to the formation of the integral cross section of the (d, xd) reaction in the energy range up to 12 MeV, corresponding to elastic and inelastic scattering, is provided by the pre-equilibrium mechanism. In the rigid energy part of the spectrum, in addition to the pre-equilibrium, there is a significant contribution of direct processes.

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