EMISSION OF LIGHT CHARGED PARTICLES FROM REACTION OF ^{3}He IONS OF ENERGY OF 50.0 MeV WITH ^{59}Co NUCLEUS*

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This paper presents experimental double-differential and integral cross sections of reactions (^{3}He,xp), (^{3}He,xd) and (^{3}He,$x\alpha$) on the ^{59}Co nucleus. The experiment with ^{3}He ions, accelerated to the energy of 50.0 MeV, was performed at the isochronous cyclotron of the Institute of Nuclear Physics (Almaty, Kazakhstan). Theoretical analysis of the experimental results has been carried out in terms of a modified version of the exciton model. A satisfactory agreement between experimental and calculated values has been achieved.

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1. Introduction

The world is searching for alternative ways to develop nuclear energy, which would increase the level of security, reduce the amount of spent nuclear fuel and eliminate the uncontrolled proliferation of nuclear weapon components. One of the projects attempting to solve these problems is the creation of industrial prototypes of hybrid electric-nuclear systems (Accelerator Driven System, ADS), consisting of a deeply subcritical nuclear reactor and a high-energy proton accelerator [1].

New experimental data are required on the nuclear reactions with hydrogen and helium nuclides occurring in the target, fuel units, structural materials, which lead to formation of a cascade of subsequent secondary reaction products with a broad energy spectrum of p, d, t, ^{3}He, ^{4}He *etc.* [2, 3].

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Consequently, it is extremely important to obtain experimental cross sections of the reactions used as benchmarks in constructing and development of models of nuclear reaction mechanisms, and to improve their predictive power. It should be noted that mainly the integral characteristics of pre-equilibrium decay in reactions with nucleons are studied, while the experimental data related to the inclusive distributions of secondary light charged particles initiated by helium nuclides and particularly ^{3}He are limited [4, 5].

For this reason, we measured the double-differential cross sections of light particles (protons, deuterons, α-particles) emitted from ^{3}He-induced reactions on ^{59}Co at the incident energy of 50.0 MeV. The continuous spectra of light charged particles for ^{27}Al and ^{112}Sn at the same conditions were studied in Refs. [6, 7]. The ^{59}Co isotope was chosen as a candidate for a structural element of ADS [2]. The energy spectra of secondary (p, d, t, α) particles produced in the interaction of 34.8 MeV ^{3}He ions with this nucleus were measured in Ref. [8].

2. Experiment

The experiment was performed using a beam from the isochronous cyclotron U-150M of the Institute of Nuclear Physics (Almaty, Kazakhstan). The energy of the incident ^{3}He ions was 50.0 MeV. The measurements were made in the angular range of 30°–135° in the laboratory coordinate system with a step of 15°. The setup for transporting the beam from the cyclotron chamber to the reaction chamber located 25 m from the beam exit includes a quadrupole lens system, bending and correcting magnets and a collimator system. The maximum angular uncertainty of the collimator is ± 24 sec. This ensured the linear dimensions of the beam on the target to be 3 mm. To determine the number of particles incident on the target, a Faraday cup-current integrator system was used.

Foils of isotopically enriched ^{59}Co were prepared. The target thickness, equal to 2.3 mg/cm^{2}, was determined by measuring the energy loss of alpha particles from the ^{226}Ra isotope. To identify the reaction products in mass and energy, a (ΔE–E) technique based on a system of NIM and CAMAC modules was used. The counter telescope consisted of thin silicon ΔE detectors (200 μm thickness) and a CsI(Tl) E detector (25 mm thickness). The total systematic error did not exceed 10%. The statistical error depended on the type and energy of the detected particles and varied in the range of 1–15%.

For calibration, a target of CH_2 was used at the same experimental conditions in order to provide peaks corresponding to levels of residual nuclei and recoil protons. Subtracting the energy loss in the target and the ΔE detector from the kinetic energy of the detected particle, we found the reference calibration relating the energy absorbed by the E detector and the channel number. Based on this, taking into account the energy loss in the ΔE detector and in the target, we found the energy of the particle that left the nucleus.

Figures 1–3 show the integral cross sections of (^{3}He,xp), (^{3}He,xd), and (^{3}He,$x\alpha$) reactions on the ^{59}Co nucleus at 50.0 MeV ^{3}He energy, determined from the double-differential cross sections and averaged over the energy range of 0.5 MeV. Table I presents the experimental partial cross sections.

TABLE I

Experimental partial cross sections for the (^{3}He,xp), (^{3}He,xd) and (^{3}He,$x\alpha$) reactions on ^{59}Co nucleus for ^{3}He at the energy of 50.0 MeV.

Reaction	Energy range [MeV]	Partial cross section [mb]
^{59}Co(^{3}He,xp)	6.0–45.5	647.7 ± 0.1
^{59}Co(^{3}He,xd)	9.5–46.0	54.2 ± 0.2
^{59}Co(^{3}He,$x\alpha$)	23.0–53.0	6.72 ± 0.03

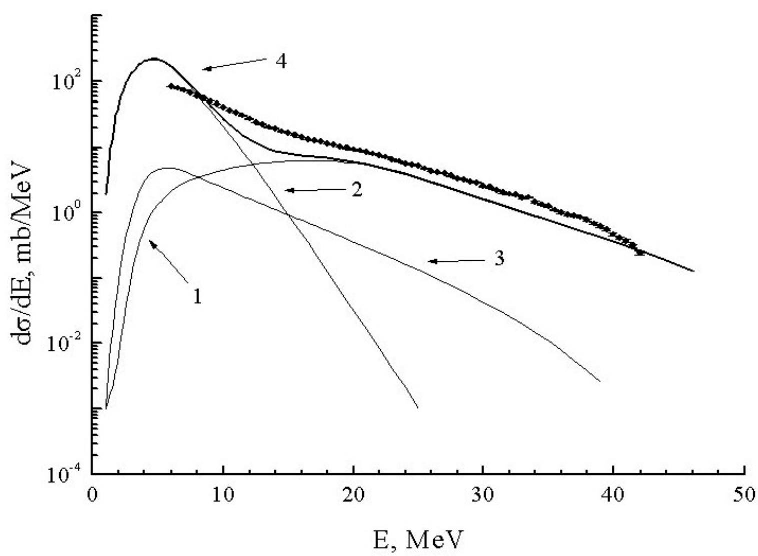

Fig. 1. Comparison of the experimental integrated cross sections for ^{59}Co(^{3}He,xp) reactions with calculations within the exciton model. Symbols, experiment: 1 — pre-equilibrium component, 2 — equilibrium emission, 3 — multiple pre-equilibrium emission, 4 — total.

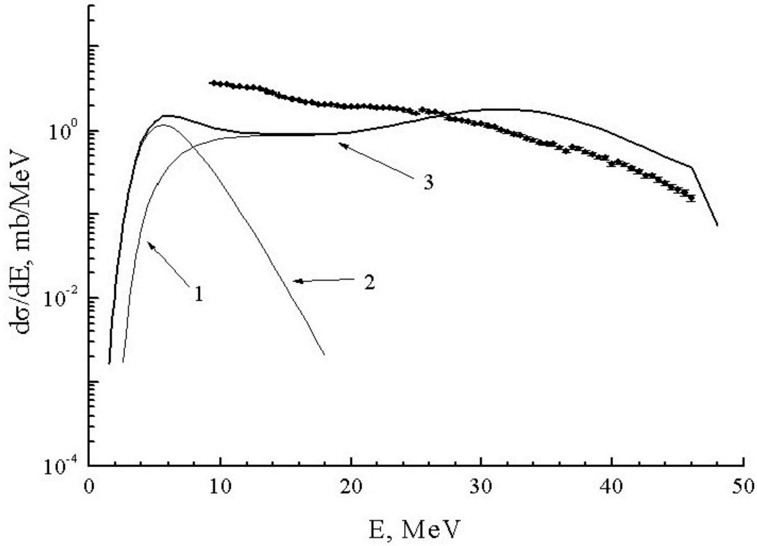

Fig. 2. Comparison of the experimental integrated cross sections for ^{59}Co(^{3}He,xd) reactions with calculations within the exciton model. Symbols, experiment: 1 — pre-equilibrium component, 2 — equilibrium emission, 3 — total.

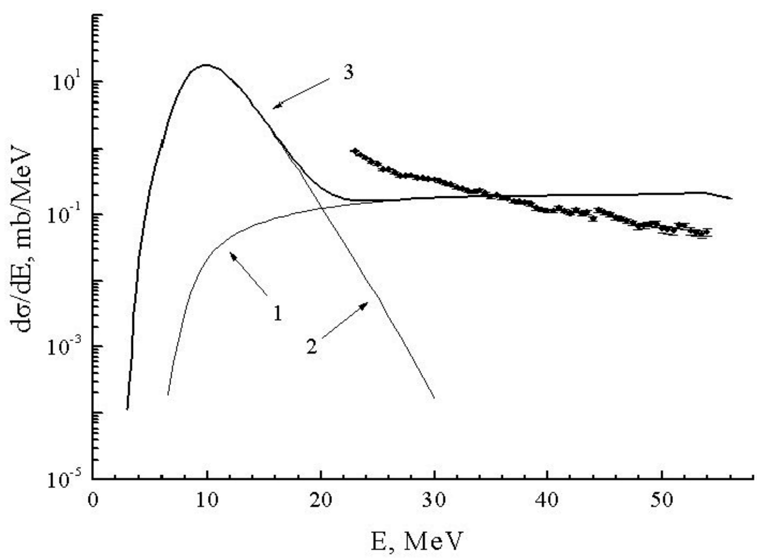

Fig. 3. Comparison of the experimental integrated cross sections for ^{59}Co(^{3}He,$x\alpha$) reactions with calculations within the exciton model. Symbols, experiment: 1 — pre-equilibrium component, 2 — equilibrium emission, 3 — total.

3. Analysis

The experimental results were analyzed using Griffin's model of exciton nuclear decay [9], which reflects the dynamics of the formation of an excited system and its transition to the equilibrium state. Despite all the ambiguities, the exciton model remains one of the most powerful tools for describing inclusive spectra. It is essentially a statistical model, where the excited states of a compound system are characterized by the number of excited particles (above the Fermi level) and holes (below the Fermi level). It is assumed that the system evolves through a sequence of more complicated configurations, and particle emission is possible at each phase of this evolution. In the two-component exciton model, the proton and neutron degrees of freedom are considered separately [10].

Theoretical calculations were carried out using the computer code TALYS [11]. To fully describe the emission of particles in nuclear reactions, in addition to calculations within the exciton model, the calculations were performed taking into account other mechanisms (compound decay, multiple Hauser–Feshbach emission, direct processes). The results of the calculations are given together with the experimental data in Figs. 1–3.

In Fig. 1, the calculated contributions of mechanisms forming inclusive cross sections for (^{3}He,xp) reactions on the ^{59}Co nucleus at an incident particle energy of 50.0 MeV are presented. It can be noted that the formation of protons up to 15 MeV occurs primarily through compound nucleus. From an energy above 15 MeV, the predominant process is the emission of pre-equilibrium protons.

Figure 2 shows the calculated contributions of the mechanisms that form the inclusive cross sections for the (^{3}He,xd) reaction. From a comparison of the experimental and theoretically calculated integral spectra, one can see that the low-energy part (up to 5 MeV) of the deuteron spectrum originates from the compound nucleus formation. More energetic deuterons are created due to the pre-equilibrium mechanism.

When considering the processes contributing to the integrated cross section of the (^{3}He,$x\alpha$) reactions shown in Fig. 3, one can observe that the equilibrium emission plays a crucial role in the formation of α particles with energy less than 20 MeV. Starting with an energy of 20 MeV, the pre-equilibrium mechanism predominates in the emission of alpha particles.

4. Conclusions

The experimental double-differential and integral cross sections of ^{59}Co(^{3}He,xp), ^{59}Co(^{3}He,xd) and ^{59}Co(^{3}He,$x\alpha$) reactions were obtained at the energy of incident ^{3}He ions equal to 50.0 MeV. The experimental partial cross sections of the investigated reactions were determined. Theoretical calculations of the experimental inclusive spectra of the reaction were performed within the framework of a modified two-component exciton model of the pre-equilibrium nuclear decay.

The obtained experimental results fill the gap in previously measured cross-section values and can be used in the development of new approaches in the nuclear reaction theory, as well as in the construction of safe and waste-free hybrid nuclear power plants.

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