# PHYSICS

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## Abstract

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## INVESTIGATION OF THE $(n,\alpha)$ AND $(n,t)$ REACTIONS ON $\mathrm{Be}^9$

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The reactions $\mathrm{Be}^9(n,\alpha)\mathrm{He}^6$ and $\mathrm{Be}^9(n,t)\mathrm{Li}^7$, under the action of fast neutrons with energies from 1 to 19 MeV, were observed in specially prepared layered nuclear photographic emulsions with a filler in the form of a fine powder of spectrally pure beryllium (1). The neutron source was a lithium target irradiated with deuterons accelerated to 4 MeV in the 72-cm cyclotron of the Research Institute of Nuclear Physics.

After passing through a collimator made of paraffin, cadmium, and iron, the neutrons entered photographic plates positioned at an angle of 6° to the direction of the neutron beam. The need for good collimation of the neutron flux was due to the fact that, for the subsequent calculation of the stars of the reactions under study, formed in the emulsion by neutrons of indeterminate energy, it was necessary to know the direction of the neutron that produced each individual star.

The irradiated and developed photographic plates were examined under a microscope in order to find two-prong stars with their center in a particle of the beryllium filler. These stars could be formed as a result of the $(n,\alpha)$, $(n,t)$, and $(n,2n)$ reactions on $\mathrm{Be}^9$ nuclei. From the total number of these stars, most of which belonged to the $(n,2n)$ reaction, the cases of interest to us, namely the reactions $\mathrm{Be}^9(n,\alpha)\mathrm{He}^6$ and $\mathrm{Be}^9(n,t)\mathrm{Li}^7$, were selected according to the following criteria. The tracks of the $\alpha$-particle and the $\mathrm{He}^6$ nucleus, and the tracks of the triton and the $\mathrm{Li}^7$ nucleus, forming two-prong stars in the case of the $(n,\alpha)$ and $(n,t)$ reactions, lay in the plane containing the direction of the incident neutron, which is unlikely for the tracks of $\alpha$-particles formed in the decay of the $\mathrm{Be}^8$ nucleus in the case of the $(n,2n)$ reaction.

Furthermore, if the direction of the incident neutron is taken as the $OX$ axis, then the projections of the momentum vectors onto the $OY$ axis in the plane of the emulsion of $\alpha$-particles and $\mathrm{He}^6$ nuclei, and of tritons and $\mathrm{Li}^7$ nuclei, respectively, are equal and opposite in sign.

The difference between stars belonging to the reaction $\mathrm{Be}^9(n,\alpha)\mathrm{He}^6$ and stars belonging to the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ is manifested in the fact that the ranges of $\alpha$-particles and $\mathrm{He}^6$ nuclei in the photographic emulsion are approximately

Fig. 1. Effective cross section of the reaction Be9(n, $\alpha$)He6. a—values obtained in the present work; b—in work (10); c—in work (11); the dashed curve shows the cross section determined in work (5). The arrows indicate the positions of known levels of the Be10 nucleus

Figure 1: Fig. 1. Effective cross section of the reaction Be9(n, $\alpha$)He6. a—values obtained in the present work; b—in work (10); c—in work (11); the dashed curve shows the cross section determined in work (5). The arrows indicate the positions of known levels of the Be10 nucleus

the same, whereas the range of the triton is several times greater than the range of the $\mathrm{Li}^7$ nucleus.

Special attention was devoted to identifying stars of the $(n, t)$ reaction, since, as far as we know, no data on this reaction had been reported in the literature.

As a result of measurements of selected cases of the reactions $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$ and $\mathrm{Be}^9(n, t)\mathrm{Li}^7$, calculations were carried out, based on the laws of conservation of energy and momentum, to determine the energy of the primary neutron that produced the given star, and to verify that the case under consideration was correctly assigned to the reaction being studied.

In the calculations, the range-energy relations in NIKFI-Ya2 and Ilford-C2 photographic emulsions for protons, $\alpha$-particles, and $\mathrm{Li}^7$ nuclei, given in works ([2], [3]), were used. The range-energy relations for tritons

and the $\mathrm{He}^6$ nuclei were calculated from the known dependences for protons and $\alpha$-particles.

The energy of the primary neutron $E_n$ in the case of the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$ was calculated from the formula

$$E_n = \left[(m_1 E_1)^{1/2} \cos\varphi_1 + (m_2 E_2)^{1/2} \cos\varphi_2\right]^2, \tag{1}$$

where $m_1$, $E_1$, and $\varphi_1$ are the mass number, energy, and emission angle in the laboratory coordinate system of the $\alpha$-particle relative to the direction of the incident neutron;

**Fig. 1.** Effective cross section of the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$. *a*—values obtained in the present work; *b*—in work ([10]); *c*—in work ([11]); the dashed curve shows the cross section determined in work ([5]). The arrows indicate the positions of known levels of the $\mathrm{Be}^{10}$ nucleus.

$m_2$, $E_2$, and $\varphi_2$ are the mass number, energy, and emission angle of the $\mathrm{He}^6$ nucleus. The accuracy in determining $E_n$ is ±0.5 MeV.

For each star of the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$, the value of the reaction energy $Q'$ was determined from the relation

Fig. 2. Angular distribution of $\alpha$-particles in the center-of-mass system in the case of the reaction Be9(n, $\alpha$)He6 for neutron energies from 2 to 5 MeV. The abscissa gives the angles between the directions of the emitted $\alpha$-particles and the incident neutrons

Figure 2: Fig. 2. Angular distribution of $\alpha$-particles in the center-of-mass system in the case of the reaction Be9(n, $\alpha$)He6 for neutron energies from 2 to 5 MeV. The abscissa gives the angles between the directions of the emitted $\alpha$-particles and the incident neutrons

$$Q' = E_n - E_1 - E_2. \tag{2}$$

Using formulas (1) and (2), the same calculation was performed for stars of the reaction $\mathrm{Be}^9(n, t)\mathrm{Li}^7$.

The flux intensity for each group of incident-neutron energies, necessary for calculating the effective cross sections, was determined from recoil protons ($^4$) in NIKFI-Ya2 photographic plates with an emulsion thickness of $200\,\mu$, exposed simultaneously with the photographic plates in which the reactions under study were observed.

For finding the values of the effective cross sections, such stars of the $(n, \alpha)$ and $(n, t)$ reactions were selected for which the difference between the known value of the reaction energy $Q$ and the calculated value $Q'$ did not exceed 1.5 MeV (for the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$, $Q = -0.64$ MeV; for the reaction $\mathrm{Be}^9(n, t)\mathrm{Li}^7$, $Q = -10.3$ MeV in the case of formation of $\mathrm{He}^6$ and $\mathrm{Li}^7$ nuclei in their ground states).

For the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$, the dependence of the effective cross section on the energy of the incident neutrons was constructed (Fig. 1). The values of the effective cross section obtained by us agree well with the cross section given in the work

**Fig. 2.** Angular distribution of $\alpha$-particles in the center-of-mass system in the case of the reaction $\mathrm{Be}^9(n, \alpha)\mathrm{He}^6$ for neutron energies from 2 to 5 MeV. On the abscissa are plotted the angles between the directions of the emitted $\alpha$-particles and the incident neutrons.

[5] for incident-neutron energies from threshold to 4.4 MeV. As is seen from the figure, the cross section has a well-pronounced maximum in the region of $E_n$ from 2 to 4 MeV. This maximum can to some extent be explained by the fact that the $(n, \alpha)$ reaction proceeds through the compound nucleus $\mathrm{Be}^{10}$, which in this energy region has a group of closely spaced levels: 9.27 and 9.4 MeV. In addition, the decrease in the cross section for incident-neutron energies above 4 MeV is explained by the growth of the effective cross section of the reaction $\mathrm{Be}^9(n, 2n)$ in this energy region [1,6].

Fig. 3. Angular distribution of tritons in the center-of-mass system in the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ for neutron energies from 13 to 18 MeV. The abscissa axis gives the angles between the directions of the emitted tritons and the incident neutrons.

Figure 3: Fig. 3. Angular distribution of tritons in the center-of-mass system in the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ for neutron energies from 13 to 18 MeV. The abscissa axis gives the angles between the directions of the emitted tritons and the incident neutrons.

Figure 2 presents the angular distribution of $\alpha$-particles in the center-of-mass system for $E_n$ from 2 to 5 MeV. It turned out that the angular distribution does not depend on the energy of the incident neutrons and is symmetric with respect to 90°. These data confirm the assumption that the reaction $\mathrm{Be}^9(n,\alpha)\mathrm{He}^6$ proceeds through a compound nucleus.

For several groups of incident-neutron energies, values of the effective cross section of the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ were obtained:

$$\text{for } E_n = 14.0 \pm 0.5 \text{ MeV} \quad \sigma(n,t) = 110 \pm 50 \text{ mb};$$

$$\text{for } E_n = 15.0 \pm 0.5 \text{ MeV} \quad \sigma(n,t) = 120 \pm 60 \text{ mb};$$

$$\text{for } E_n = 16.0 \pm 0.5 \text{ MeV} \quad \sigma(n,t) = 130 \pm 60 \text{ mb}.$$

In this range of primary-neutron energies the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ may proceed either through a compound nucleus or by direct interaction, for example of the "pickup" type. The possibility of "pickup" in the case of $(n,t)$ and $(p,t)$ reactions, by analogy with $(n,d)$ and $(p,d)$ reactions, is shown in [7]. In a direct interaction of the "pickup" type, the momentum vector of the emitted particle is the sum of the large forward-directed momentum vector of the incident particle and the comparatively small momentum vector of the "picked-up" particle; therefore the angular distribution of the emitted particles is, generally speaking, characterized by a maximum at small angles. As is seen from Fig. 3, the angular distribution of tritons in the case of the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ for incident-neutron energies from 13 to 18 MeV has no peak at 0°, but a strongly pronounced asymmetry with respect to 90° is observed, with a maximum at 40° in the center-of-mass system.

**Fig. 3.** Angular distribution of tritons in the center-of-mass system in the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ for neutron energies from 13 to 18 MeV. Along the abscissa axis are plotted the angles between the directions of the emitted tritons and the incident neutrons.

Deviation from symmetry with respect to 90° in the angular distribution means either that the assumption of formation of a compound nucleus is invalid, i.e., that direct interactions are present, or (if the assumption of formation of a compound nucleus is retained) that the condition of statisticality of the compound-nucleus decay process is not fulfilled. In the latter case, with a small change in the energy of the incident neutrons, the character of the angular distribution may change significantly [12]. Since the angular distribution shown in Fig. 3 was constructed as a result of averaging over a wide interval of incident-neutron energies, it is difficult to explain its asymmetry by a violation of the condition of statisticality. This circumstance suggests that the reaction $\mathrm{Be}^9(n,t)\mathrm{Li}^7$ proceeds by the "pickup" mechanism, while the absence of a peak at 0° in the angular distribution can be explained on the basis of the law of conservation of angular momenta in direct-interaction reactions [8].

The "pickup" mechanism in the $(n,t)$ reaction on $\mathrm{Be}^9$ is difficult to consider from the point of view of the model developed in works [9], according to which the $\mathrm{Be}^9$ nucleus is represented as a system $(n,\mathrm{Be}^8)$ or $(n,\alpha,\alpha)$ with an unpaired neutron in a $P$-state in the outer part of the nucleus. It is probable that in the outer region of the $\mathrm{Be}^9$ nucleus there may temporarily exist a quasdeuteron, formed during dissociation of an $\alpha$-particle or by some other means, which is "picked up" by the incident neutron.

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*Note: Figure translations are in progress. See original paper for figures.*