INTERACTION OF 14.1-Mev NEUTRONS WITH Be^9

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The interaction between 14.1-Mev neutrons and Be^9 was investigated by the nuclear emulsion method. Energy and angular distributions of neutrons and alpha particles produced in the (n, 2n) reaction were measured. The data obtained indicate that the reaction generally involves the formation of a 2.9-Mev excited state in the Be^8 nucleus (cross section 0.19 ± 0.06 b) and the 2.43 Mev excited level of the Be^9 nucleus. The cross section for excitation of the Be^9 (2.43 Mev) nucleus and for formation of the ground state in the Be^8 nucleus is 0.2 ± 0.1 b. Direct interactions also yield an appreciable contribution to the (n, 2n) reaction. The total cross section for the reaction is 0.54 ± 0.07 b.

INTRODUCTION

THE interaction of neutrons with Be^9 nuclei has been examined in a number of works,[1] but the mechanism of the reaction is at present still imperfectly known. There exist several possible methods of bringing about the (n, 2n) reaction on Be^9, involving both the formation of a compound nucleus and direct interactions.

1) Production of the compound nucleus Be^{10} and its decay according to the schemes

a) $Be^{10} \to n + Be^{9*}$, $\quad Be^{9*} \to n + Be^8 \to n + 2\alpha$;

b) $Be^{10} \to n + Be^{9*}$, $\quad Be^{9*} \to \alpha + He^5 \to n + 2\alpha$.

2) Formation of excited states of the Be^9 nucleus in the process of a direct interaction between neutrons and Be^9, and subsequent decay by scheme a) or b).

3) Breakup into three or four particles both with and without the formation of a compound nucleus:

$$Be^9 + n \to 2n + Be^8, \qquad Be^9 + n \to 2n + 2\alpha.$$

The interaction of neutrons with Be^9 has been most fully studied for the case of low-energy neutrons.[2] Experimental research with 14-Mev neutrons[3] has been devoted principally to determining the total cross section for the interaction between neutrons and Be^9. The formation of excited states of the Be^8 nucleus in the (n, 2n) reaction on Be^9 has only been examined in two works.[4,5] The results obtained in these works do not agree with one another. Thus, according to one of them,[4] the (n, 2n) reaction on Be^9 proceeds primarily with the formation of only one 2.9-Mev level of the Be^8 nucleus; results from the other work[5] indicate the significant role of ~5- and ~8-Mev levels in Be^8 formed during the (n, 2n) reaction on Be^9. The excitation of Be^8 levels has been investigated in many other reactions,[6] but this matter is not yet completely clarified.

In the present work an attempt has been made to evaluate the role of individual levels in the Be^8 nucleus which can be excited during the (n, 2n) reaction on Be^9. To get a more complete idea of the mechanism of the (n, 2n) reaction, the angular and energy distributions of alpha particles and neutrons produced in this reaction were investigated, for whatever the course of the (n, 2n) reaction on Be^9, the final reaction products are always alpha particles and neutrons.

EXPERIMENTAL METHODS AND RESULTS

The reaction $T(d, n)He^4$ served as the source of 14.1-Mev neutrons in all the experiments performed. The neutron flux on the radiator amounted to $\sim 1 \times 10^9$ neutrons/cm^2. In the first experiment NIKFI T-3 photoplates doped with metallic Be^9 powder were irradiated by neutrons. The beryllium powder was introduced between emulsion layers 100 μ thick. The amount of beryllium used is equivalent to uniform (by volume) doping with ~ 20 mg of beryllium compound solution per cm^3 of emulsion. The average grain diameter of the beryllium powder was $2 - 3\ \mu$. The metallic powder was prepared by the spark discharge method.[7]

The irradiation was made parallel to the surface of the emulsion. In order to select events due to the (n, 2n) reaction on Be^9, all two-prong alpha stars with vertices located in the metallic beryl-

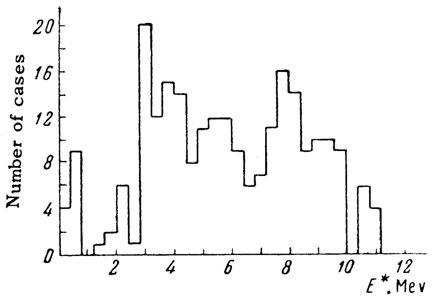

FIG. 1. Alpha-star distribution as dependent on excitation energy of Be^8 nucleus.

lium grains were chosen when scanning the developed plates. To estimate background events, an undoped layer of emulsion on these same plates was also scanned, choosing all two-prong alpha stars and also three-prong stars if one of the prongs was $\leq 3\ \mu$ in length. The background was evaluated under the assumption that it is possible to distinguish between background stars and true alpha stars arising in beryllium grains except when they are formed in the 1-μ emulsion layer directly adjoining the beryllium grains. The background constituted 5 — 7%.

About 250 cases could be related to the (n, 2n) reaction on Be^9. Among the alpha stars found, 22 cases of the reaction $Be^9(n, \alpha)He^6$ were also discovered, which served as a control for the reliability of this experiment. When processing the alpha stars it was assumed that alpha stars corresponding to the (n, 2n) reaction on Be^9 were formed following the decay of excited Be^8 nuclei, and for each such star the energy of the corresponding Be^8 nuclear level was determined. The spectrum of excited states in the Be^8 nucleus constructed in such a manner with the background taken into account is presented in Fig. 1.

Two principal peaks stand out in the spectrum: the first peak corresponds to the 2.9-Mev excited level of the Be^8 nucleus, the second to the ~ 8-Mev level. When calculating the number of events related to decay from the 2.9-Mev level, we made use of data of reference 8 on the shape of the resonance line. The cross section for formation of the 2.9-Mev excited state in the Be^8 nucleus equals 0.19 ± 0.06 b. The cross section for alpha stars which could have been formed following the decay of a Be^8 nucleus in the ~ 8-Mev excited state is 0.14 ± 0.04 b. The data obtained are in good agreement with the results of Sakisaka.[5]

It is possible to distinguish on the spectrum another group of alpha stars, which corresponds to the ~ 5 Mev level of Be^8; the cross section for this group is 0.04 ± 0.02 b. However, as shown below, it is more probable that this group of alpha stars owes its origin to a process which occurs without the formation of the Be^8 nucleus.

In evaluating the cross sections presented above, corrections were made for the omission during scanning of alpha stars due to short-range alpha particles and for the loss of events lying in a plane perpendicular to the surface of the emulsion. The cross section for alpha stars corresponding to decay of a Be^8 nucleus in the ground state or of a Be^9 nucleus in the 2.43-Mev excited state (events which are energetically indistinguishable in this experiment) was not determined, since the correction for the omission of such events exceeds the number counted by several times. The large probability for omitting such alpha stars can be explained by the fact that the alpha particles forming them are of low energy. The cross section for the $Be^9(n, \alpha)He^6$ reaction determined in this experiment is 11 ± 4 mb.

In the second experiment we examined the energy spectrum of alpha particles produced in the (n, 2n) reaction on Be^9 at various angles relative to the incident-neutron direction. A layer of metallic beryllium ($\sim 4\ \mu$) deposited on a tantalum backing (a disc 5 cm in diameter) was used as the target. The incident neutron beam passed through a collimator constructed along the lines of Rosen's collimator.[9] NIKFI T-2 ($100\,\mu$) plates served as alpha-particle detectors. The irradiation was carried out in a vacuum chamber with continuous evacuation (0.1 mm mercury).

The experiment was set up in two geometries. In the first case a single-plate camera was used, which permitted the recording of alpha particles making an angle of 0° and small angles with respect to the direction of the incident neutron beam.

In the second experiment a multiplate camera was used, in which the photoplates were arranged in a circle around the targets at 20, 45, 65, 90, 105 and 120° to the incident neutron beam. The targets were placed in the center of the camera and turned with their coated surface towards the photoplates. To evaluate the background, an irradiation was made with an uncoated tantalum disk. The total number of alpha particles recorded in this experiment was ~ 2,500. Figure 2 presents energy spectra (to be more accurate, range distributions) for alpha particles emitted from the target at 0, 20, 65, 90 and 105° to the incoming neutron beam. The largest number of low-energy alpha particles is observed at the small angles. As the angle increases, the maximum is displaced toward the higher energy alpha particles. The total cross section for the (n, 2n) reaction on

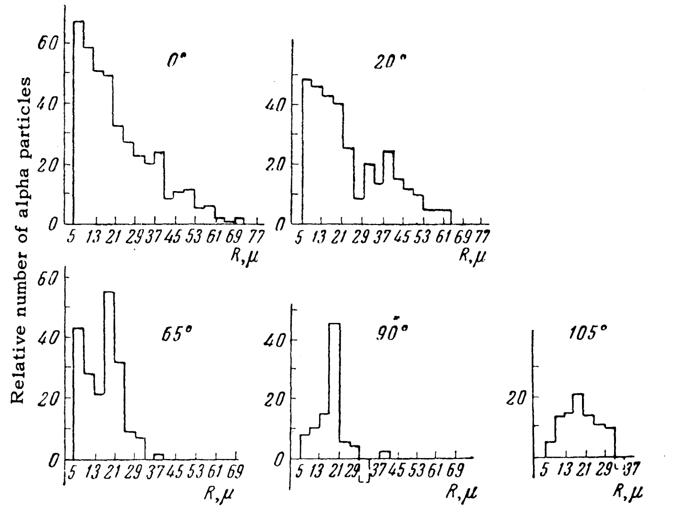

FIG. 2. Energy distribution of alpha particles (R is the range in microns).

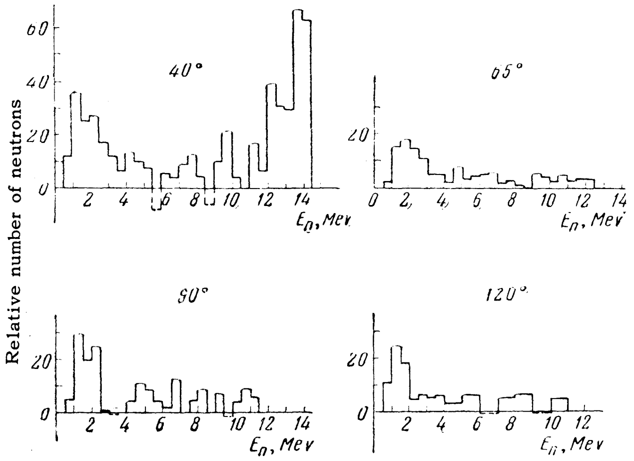

FIG. 3. Energy distribution of neutrons.

Be^9, as calculated from the given angular distribution of alpha particles, is 0.48 ± 0.09 b [taking into account a correction for the loss of short-range ($< 5\ \mu$) alpha particles]. The cross section for the reaction $Be^9(n, t)Li^7$ was roughly estimated from this experiment and the experiment with alpha stars: the average was ~ 20 mb.

In the third experiment the energy and angular distributions of neutrons produced in the (n, 2n) reaction on Be^9 were investigated. Spectrum measurements were made for the scattering of collimated neutrons by a thin-walled glass sphere filled with metallic beryllium powder. Total weight of the powder was 125 g. Background was determined by measurements with an empty sphere. NIKFI Ya-2 (200 μ) photoplates served as neutron detectors. The irradiation was carried out in a special airtight box with controlled humidity. The plates were positioned around the beryllium sphere at 20, 40, 65, 90 and 120° to the incident neutron beam. About 5,000 tracks of recoil protons were recorded. The background amounted to $\sim 40\%$ of the effect. The data obtained were processed according to the method applied in Rosen's work.[10] The minimum energy at which recoil protons were recorded was 0.5 Mev.

The energy distributions of the neutrons emitted at angles of 40, 65, 90 and 120° are presented in Fig. 3. The angular distribution of neutrons with energies from 0.5 to 4 Mev and from 4 Mev to limiting energy values, which correspond to inelastic scattering of neutrons at the given angle, are presented in Fig. 4. The distribution of neutrons with energies greater than 4 Mev is strongly anisotropic. The total cross section for the reaction (n, 2n) on Be^9 was determined from the angular distribution of inelastically scattered neutrons to be $\sigma = 0.6 \pm 0.1$ b. When calculating the cross section, the loss of tracks of recoil protons with energies below 0.5 Mev was taken into consideration, and a correction was also applied for multiple scattering of neutrons in the beryllium sphere.

DISCUSSION OF MEASUREMENT RESULTS

According to the results of our measurements with alpha particles and neutrons produced in the (n, 2n) reaction on Be^9, the total cross section for the reaction is 0.54 ± 0.07 b; this is in good agreement with the results of other authors.[3] Effective cross sections for the (n, 2n) reaction on Be^9 leading to the ground state in the Be^8 nucleus and the 2.43-Mev excited state in Be^9 can be estimated rather reliably. The stars formed in these cases consist of low-energy alpha particles; owing to the insufficient reliability in recording these events, their number was not determined in the experiment with alpha stars. The effective

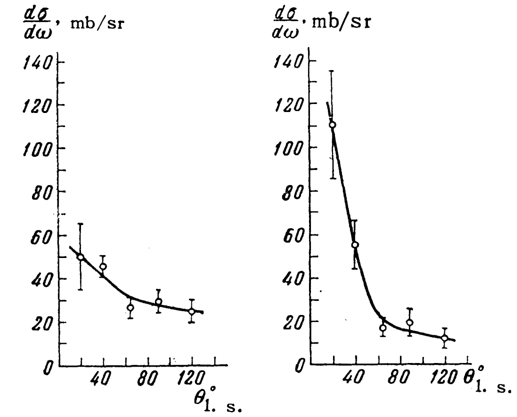

FIG. 4. Angular dependence of differential cross section for inelastic scattering of neutrons on Be^9.

cross section of interest to us can be computed, therefore, as the difference between the total effective cross section for the (n, 2n) reaction presented above and the effective cross section determined in the experiment with alpha stars. This difference amounts to 0.2 ± 0.1 b.

According to Anderson's data,[11] the cross section for the (n, n′) reaction on Be^9, leading to the formation of the 2.43-Mev excited state of the Be^9 nucleus, is 0.17 ± 0.03 b. Comparing these two values, we arrive at the conclusion that the formation of low-energy alpha stars occurs primarily upon the decay of the excited Be^9 nucleus from the 2.43-Mev level. In the experiment with alpha stars it was discovered that, along with stars due to decay of the Be^8 nucleus from the 2.9-Mev level, alpha stars are formed which may correspond to higher excited states of the Be^8 nucleus. The production of high-energy alpha particles in the (n, 2n) reaction on Be^9 is also confirmed by the shape of the alpha-particle energy spectrum, especially the spectrum of alpha particles emitted at large angles (for example 90°). From kinematic relations, alpha particles corresponding to the decay of highly excited nuclear states of Be^8 and Be^9 (decay of Be^9 into an alpha particle and a He^5 nucleus) become noticeable in the spectrum at large angles.

For reasons which we are about to state, it is most probable that the group of alpha stars associated with the ~ 5-Mev level of the Be^8 nucleus in reality owe their origin to a process which proceeds primarily without the formation of the Be^8 nucleus. This process may be explained either as the decay of a Be^9 nucleus into an alpha particle and a He^5 nucleus or as the four-particle decay of Be^{10}. At the same time, the group of alpha stars corresponding to the ~ 8 Mev level of the Be^8 nucleus is probably formed upon the decay of the Be^8 nucleus (possibly when the Be^8 nucleus decays from the broad, 11.7-Mev level with width $\Gamma = 6.7$ Mev[12]).

In reference 4, where beryllium was introduced into an emulsion in the form of a soluble compound, in order to reduce the background only those alpha stars were selected in which the alpha particles had equal ranges. Such a selection method favors the choice of cases corresponding to the decay of the Be^8 nucleus over other possible ways of forming two alpha particles. Here, it turned out that at energies up to ~ 7 Mev only alpha stars associated with the 2.9 Mev level of the Be^8 nucleus were observed; furthermore, the curve of the alpha star distribution falls off rather sharply on the high energy side. If we trace out a similar curve on our spectrum (Fig. 1), a considerable number of alpha stars remain in the ~ 5 Mev region beyond the curve; it is rather difficult to explain their origin as being due to the decay of the Be^8 nuclei in an excited state at 2.9 Mev. Moreover, applying an analogous selection process to our data, we discovered that only two groups of alpha stars, corresponding to the 2.9- and ~ 8-Mev excited states of the Be^8 nucleus, remain in the spectrum, which is also evidence for the above assertion. This conclusion is also confirmed by other works in which excited states of the Be^8 nucleus have been observed.[13] The shape of the spectra of alpha particles and neutrons is not inconsistent with these conclusions.

Therefore, the formation of a Be^8 nucleus in the 2.9-Mev excited state and the excitation of the 2.43-Mev level in the Be^9 nucleus seem to be basic channels for the (n, 2n) reaction on Be^9. It is possible that higher nuclear levels of Be^8 or Be^9 nuclei are also excited in the (n, 2n) reaction (the Be^9 levels of 6.8, 7.9 and 9.1 Mev; the 11.7-Mev level of Be^8). However, we cannot pursue in more detail the formation of excited states in the Be^8 and Be^9 nuclei. The scantiness of statistics does not allow us to distinguish with sufficient reliability groups of neutrons in the neutron spectra which could be due to transitions between various excited states of beryllium nuclei. Besides, the individual groups of neutrons will be extremely diffuse in energy because of the three-particle nature of the decay. A similar situation holds for the energy spectrum of alpha particles.

The absence of symmetry with respect to 90° in the angular distribution of neutrons with energies above 4 Mev (Fig. 4) indicates the marked contribution of direct processes to the Be^9(n, 2n) reaction for 14-Mev neutrons. Our experimental results are inadequate for a qualitative determination of the role, and even less the specific mechanism, of direct interactions in the investigated reaction.

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