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SOVIET PHYSICS JETP VOLUME 6 (33), NUMBER 6 JUNE, 1958

DISSOCIATION OF C^{12} INTO THREE ALPHA PARTICLES INDUCED BY FAST NEUTRONS

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Submitted to JETP editor June 21, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 1321-1324 (December, 1957)

The energy dependence of the effective cross-section for the neutron-induced disintegration of C^{12} into three α particles was investigated for neutron energies between threshold and 19 Mev. Information about the mechanism by which this reaction goes (in the indicated energy range) was obtained from calculations of the excitation energy of intermediate nuclei formed during the decay, and also from the distributions of the reaction products in space and energy.

MANY authors have studied the disintegration of C^{12} into three α particles as induced by fast neutrons. The most detailed examination of this reaction was carried out by Frye, Rosen, and Stewart,[1] whose work extends the data given by earlier workers (Ref. 2, and others). However, several points remained unclear, in particular the energy dependence of the effective cross section near the threshold and the maximum, how the mechanism of the reaction depended on the energy of the incident neutrons, and the question of whether direct interaction processes occurred at neutron energies of 18 to 20 Mev.

In this paper we investigate the energy dependence of the effective cross section for the decay of C^{12} into three α particles from threshold ($Q = -7.28$ Mev) to 19 Mev, and try to see how the mechanism of the decay depends on the energy of the incident neutrons.

Decay stars were observed both in NIKFI-Ia-2 emulsions and also in specially prepared layered emulsions loaded with a powder of spectroscopically pure carbon, the grain size being about 1 μ. The carbon powder enabled us to distinguish between three-pronged stars corresponding to the decay $C^{12} \rightarrow 3\alpha$ and three-pronged stars due to the reaction $N^{14}(n, 2\alpha)Li^7$, and also enabled us to take into account decays which looked like two-pronged stars because the third α particle had too little energy to make a track in the emulsion, thus giving a better value for the effective cross section.

The plates were exposed to neutrons from a thick lithium target bombarded by deuterons accelerated to 4 Mev in a cyclotron. Before hitting the emulsion, which was inclined at an angle of 6° to the incident current, the neutrons passed through a system of collimators. The cassettes containing the emulsions were shielded from scattered neutrons.

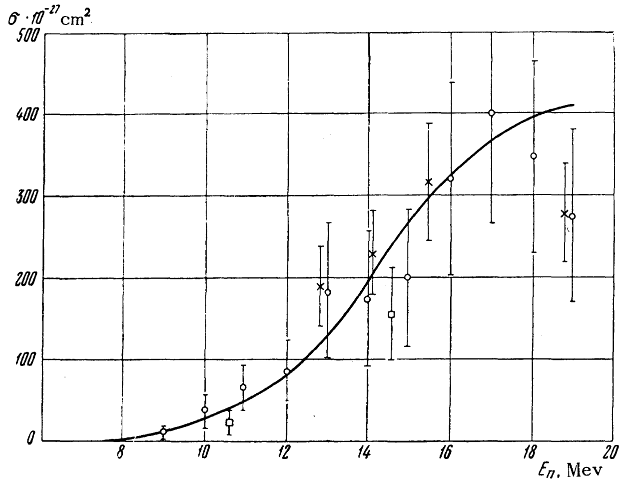

FIG. 1. The effective cross section for the decay of C^{12} into three α particles when bombarded by fast neutrons. ○ — data of the work reported in this paper, × — data from Ref. 1, □ — data from Ref. 2. Solid curve — the cross section according to Sachs' semi-empirical formula,[4] with R = 0.88, a = 1.06.

More than 500 stars, corresponding to the disintegration of C^{12} into three α particles, were observed. Taking the direction of the incident neutron to be known, the laws of energy and momentum conservation were used (see Ref. 2) to calculate, for each star, the energy of the incident neutron, the energy of the inelastically scattered neutron, and the direction in which the inelastically scattered neutron flew away. The neutron current was obtained from the recoil protons in the same plate used to observe the decay stars.

The wide energy range over which the lithium neutrons were distributed allows us to obtain the energy dependence of the cross section near threshold, and also to get a better value for the position of the maximum (Fig. 1). As one can see, our cross section agrees with the data of Refs. 1 and 2 within experimental error. Changes in the form of the cross section can be explained by the presence of various mechanisms for the decay, the probability associated with each mode depending on the energy of the incident neutrons.

The two fundamental reactions involved in the disintegration of C^{12} into three α particles are (n, n′) and (n, α); each can go through various intermediate nuclei in varying states of excitation. The reaction C^{12} (n, n′) can go in the following ways: (a) simultaneous disintegration into a neutron and three α particles, $C^{12}(n, n'3\alpha)$; (b) the neutron is inelastically scattered from C^{12}, and the excited carbon nucleus then breaks up, all at once, into three particles, $C^{12}(n, n')C^{12*}3\alpha$; (c) the excited C^{12} nucleus can emit an α particle, and the residual Be^8 nucleus in its ground state or an excited one then breaks up into two α particles. The reaction (n, α) on the nucleus C^{12} can go in two ways: in the first way, the excited Be^9 nucleus emits a neutron, leaving Be^8 in either its ground state or an excited one, with subsequent decay into two α particles; in the second way, the Be^9 nucleus emits an α particle, leaving the unstable He^5 nucleus which then breaks up into an α particle and a neutron.

In order to clarify the mechanism by which the reaction goes at various energies of the primary neutrons, we calculated the excitation energies of the intermediate nuclei C^{12}, Be^9, and Be^8 for the observed stars. The excitation energies so calculated corresponded, more or less, to the known energy levels of these nuclei. This indicates that in a given energy range there is a definite probability for decay through a given intermediate nucleus; as the energy of the primary neutrons increases, higher and higher energy levels appear in the intermediate nuclei, while the relative probabilities for decay through these levels tend to decrease. The table shows, for each energy of the primary neutrons, the fraction of the total number of decays which go through various levels of the intermediate nuclei. From an examination of the table it appears that a considerable fraction of the disintegrations occur without the formation of the intermediate Be^8 nucleus, and even without the formation of the intermediate C^{12} and Be^9 nuclei in the (n, n′) and (n, α) reactions respectively — i.e., some of the disintegrations are a direct breakup of the intermediate nuclei C^{12} or Be^9, or of the system C^{13}. This is confirmed by a comparison of the observed energy distribution of the reaction products (α particles and an inelastically scattered neutron)

Energy of the incident neutron	Fraction, in %, of the total number of disintegrations at a given energy which go through various levels of the intermediate nuclei.					
	Excitation energy of C^{12} (Mev)	%	Excitation energy of Be^9 (Mev)	%	Excitation energy of Be^8 (Mev)	%
9—11	<9.6	10			Ground state	40
11—14	level at 9.6	20	<11.6	12		
	>9.6	25			level at 2.9	10
14—17	level at 9.6	13				
	from 9.6 to 14	16	<11.6	4	Ground state	13
	>14.0	10			level at 2.9	8
17—19	level at 9.6	5				
	from 9.6 to 14	23	~11.6 level	4	Ground state	15
	from 14 to 15	5			level at 2.9	10
	>15	3				

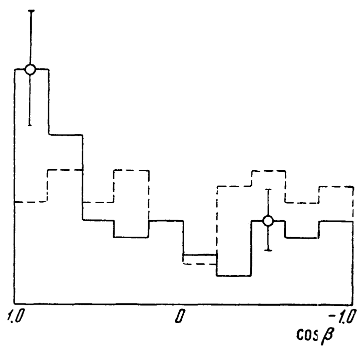

FIG. 2. The angular distribution of the inelastically scattered neutron in the center-of-mass system. Solid curve — E_n = 18 — 19 Mev, dashed curve — E_n = 13 — 14 Mev.

in the center-of-mass system with a theoretical energy distribution calculated for the corresponding process by the statistical theory.[3] The comparison has shown that the fraction of direct break-ups increases with increasing energy of the primary neutrons.

A theoretical curve for the effective cross section has been calculated by Sachs,[4] who assumed that the system $n + C^{12}$ broke up into a neutron and three α particles after statistical equilibrium had been reached within the interaction radius of $n + C^{12}$. This theoretical curve agrees well with the experimental one, which confirms the existence of direct break-ups. The agreement between the experimental and theoretical curves is particularly good in the first half of the energy range, the empirical coefficients characterizing the interaction volume being $R = 0.88$, $a = 1.06$ (Fig. 1).

As the energy of the primary neutrons increases, the effective cross section for the process $C^{12} \rightarrow 3\alpha$ decreases. This can be partially explained by the presence of direct interaction processes, which occur without the formation of a compound nucleus. It is well known that a direct interaction is characterized by an anisotropic angular distribution for the inelastically scattered neutron (in the center-of-mass system), and the presence of reaction products with an anomalously high energy. For neutron energies E_n larger than 18 Mev, the center of mass angular distribution of the inelastically scattered neutron does have a peak in the forward direction (Fig. 2). In this same energy range, the energies of the inelastically scattered neutrons were anomalously high. This confirms the existence of a direct interaction for $E_n \geq 18$ Mev. These processes must, of course, decrease the effective cross section since the energy of the emitted neutron is, in many cases, too large for disintegration to take place.

For $E_n \geq 18$ Mev, there are also anisotropies in the angular distributions of the α particles. About 70% of the α particles from the disintegration fly out forward, which suggests that the incident neutron might just knock the α particle out of the C^{12} nucleus.

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