RESULTS OF A STUDY OF THE DISINTEGRATION OF CARBON NUCLEI BY 660-Mev PROTONS

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The disintegration of the carbon nuclei in a suspension of diamond particles introduced into nuclear emulsion was investigated. The cross sections for the various reactions have been obtained. An analysis of the angular and energy distributions of the disintegration has been carried out under the assumption of a two-stage interaction between high-energy particles and light nuclei.

INTRODUCTION

THE last five years have brought a marked increase in the number of experiments devoted to the study of the interaction of high-energy particles with light nuclei, especially the nuclei of C, N, and O which are contained in nuclear photoemulsions. These investigations are of interest, on one hand, as an attempt at a better understanding of the mechanism of nuclear interactions and, on the other, because of the possibility of obtaining data valuable for the study of the influence of high-energy ionizing radiation on the cells of living tissues.

One of the main difficulties in the interpretation of the physical processes that occur in the emulsion is that it contains several elements. The interactions of different particles with the complex nuclei of the emulsion are divided into two main groups: interactions with the light nuclei (C, N, O) and interactions with the heavy ones (Ag, Br). The separation of these interactions is based on a potential-barrier criterion. By this criterion the stars containing a track with length smaller than $50\,\mu$ (this range corresponds to an α particle with energy of 9 Mev and to a proton of 2.3 Mev) are classified as disintegrations involving light nuclei. The emission of particles with such a range from heavy nuclei is considered as very improbable, because of a much higher Coulomb barrier than in light nuclei.

This selection criterion, correct for low excitation energies of the nucleus,[1,2] is under serious doubt for high excitation energies which arise in the interaction between a nucleus and an incident particle having an energy of several hundred Mev and more. When a heavy nucleus is strongly excited, the deformation of the nuclear surface can lead to a lowering of the potential barrier. On the other hand, an emission of unstable fragments, which disintegrate in a way similar to the disintegration of light nuclei, i.e., with the emission of low-energy α particles, is possible. Even if we assume that the potential-barrier criterion is correct, the correctness of experimental results obtained for light nuclei is in doubt. In fact, as was shown by McKeague[3] and by the authors, about half of the light nuclei disintegrate without emitting particles with ranges smaller than $50\,\mu$, and such disintegrations will evidently be more probable the larger the energy of the incident particle.

In view of the considerable difficulties in separating the interactions involving heavy and light nuclei of the emulsion in many experiments devoted to the study of interactions involving light nuclei, the methods of diluted emulsions[2] and "emulsion sandwiches"[4] were used.

The method of diluted emulsions is based on a comparison of the experimental data obtained on emulsions with various concentrations of gelatine. The drawback of this method is that it enables us to obtain only a limited amount of data with respect to the class of interactions studied. In addition, the lowering of the content of silver halides in diluted emulsions markedly increases the difficulty of finding and measuring the investigated stars.

In the emulsion-sandwich method, disintegrations of the light elements C, N, O, produced in a gelatine layer placed between two emulsion layers, are studied. This method makes it possible to pick out disintegrations of light elements with greater accuracy. However, admixtures from disintegrations of Ag and Br nuclei are present here, too, because of the diffusion of these nuclei into the gelatine layer during the production of the emulsion sandwiches, especially when thin gelatine layers are used. Increasing the thickness of the gelatine layer leads to considerable losses of tracks in the gelatine and makes it much more difficult to find the disintegration.

Apart from these drawbacks, there is an additional one, common to both types of experiments. Both methods provide only data averaged over several elements. For the study of light nuclei, this is clearly insufficient, since it is possible that each nucleus has its own individual features.

To study disintegrations involving the nuclei of a specific element, it has been proposed[5] to introduce this element into the emulsion in the form of a suspension. However, this method also is not free from drawbacks, the most important of which is the presence of "indeterminacy zones." These zones are due to the opacity of the introduced particles so that some of the disintegrations involving the emulsion nuclei near the particles can be regarded as disintegrations involving the investigated element itself. The admixture of such events, due to the "indeterminacy zones," in the case when light-element suspensions are used, is considerable and can completely distort the experimental results.

In the study of the interaction between protons and carbon nuclei, we used a suspension of diamond powder.[6] The diamond particles, $5-7\,\mu$ in diameter, are well transparent, which makes it possible to eliminate the "indeterminacy zones." Doubts that may be raised as to the nature of certain disintegrations in the lower parts of the introduced suspension particles are dispelled by scanning the disintegrations from the side of the glass of the plate, using a long-focus immersion objective 31×0.6.

EXPERIMENTAL METHOD

Sandwich emulsions were used in the experiment. The middle layer, $15-20\,\mu$ thick, contained the diamond particles. Two types of emulsions were used: emulsions recording protons with energies up to 16 — 20 Mev (type D), and relativistic emulsions (type S). Emulsions of the D type permit a good identification of α particles and protons in the study of the low-energy fraction of secondary particles for ranges up to $30\,\mu$, and also make it possible to increase considerably the yield of the studied reactions, owing to the increased time of emulsion irradiation. Emulsions of the S type contain a considerably smaller number of stars, but make it possible to observe the total picture of the investigated disintegrations on carbon.

The plates were irradiated by a 660-Mev proton beam of the proton synchrotron of the Joint Institute for Nuclear Research parallel to the emulsion plane. Tracks of α particles and protons in the D emulsion were identified independently by two persons, both visually and by grain counting. Practically identical results were obtained. The tracks in the S emulsion were identified by measuring the gaps in the particle tracks with a range greater than $50\,\mu$, using a special eyepiece for gap measurement.[7]

The nature of particles with a range insufficient for a good identification by the grain-counting method or by the measurement of the gaps, could, in the majority of cases, be established from the charge conservation in the disintegration. This condition, in any case, is the main criterion of checking the obtained nuclear decay scheme.

EXPERIMENTAL RESULTS

In scanning the plates, 540 disintegrations on carbon were found and measured, 190 of which were in the S emulsion and 350 in the D emulsion. The average number of secondary tracks per star in the disintegration of the C^{12} nucleus, found from the analysis of stars in the S emulsion, was found to be equal to three. This value was found taking into account the correction for the absorption of short tracks, mainly α particles, by the diamond particles with average radius $3\,\mu$. This correction was calculated according to the formula

$$N / N_t = (3l / 4\bar{R}^3)(\bar{R}^2 - \tfrac{1}{12} l^2), \qquad (1)$$

where N is the observed number of tracks with range l, N_t is the true number of tracks with range l $(0 \le l \le 2\bar{R})$, and $\bar{R}$ is the average radius of diamond particle. Taking the difference in the stopping powers of the diamond and the emulsion into account, the correction for the absorption of α particles amounted to 2% of the total number of α particles.

For disintegrations of carbon in the S emulsion the ratio of the number of α particles to the number of protons, n_α / n_p, equals 0.76. From a comparison of the mean number of tracks per disintegration of C_6^{12} in the S and D emulsions, it is found that, on the average, 0.84 protons per star were lost in the emulsion. A ratio $n_\alpha / n_p = 0.77$ was obtained by taking the proton losses for stars in the D emulsions into account. This value was obtained taking the admixture of Li among the α particles in the D emulsion into account. The number of Li tracks and their range distribution was obtained from the study of disintegrations of carbon in the S emulsion. The good agreement between the ratio n_α/n_p for two emulsions with different sensitivities served as a confirmation of the good identification of tracks.

1. Distribution of the disintegrations with respect to the number of prongs and the reaction type. The distributions were obtained from the results of the analysis of disintegrations in the S emulsion. The distribution of disintegrations of carbon with respect to the number of tracks is given in Table I. The track of the incident proton is included in the number of tracks given in the table.

TABLE I

Number of tracks	Percent of the total number of decays	Cross section, mb
1	13.0	31±2 *
2	12.0	28±2
3	9.2	17±4
4	15.0	34±5.5
5	34.0	78±8
6	14.0	32±5.5
7	2.2	5.5±2.2
8	0.6	1.5±1

*The cross section is taken from reference 8.

In view of the fact that only stars with $n \geq 2$ prongs were recorded, the cross section for the production of single-prong stars in the reactions $C_6^{12}(p, pn)C_6^{11}$ and $C_6^{12}(p, p2n)C_6^{10}$ for 648-Mev incident protons was taken from the work of Symonds, Warren, and Young.[8] The cross section for the production of two-prong stars in the reactions $C_6^{12}(p, 2pn)B_5^{10}$ and $C_6^{12}(p, 2p)B_5^{11}$ was also obtained in an indirect way, since omissions of stars with too fast protons were possible. Taking into account the fact that nuclei C_6^{11} and B_5^{11}, C_6^{10} and B_5^{10} are mirror nuclei, and also knowing the cross sections for p-p and p-n collisions, we obtained the cross section for the production of two-prong stars equal to 28 mb.

The distribution of stars according to the type of reaction and the cross sections for these reactions are given in Table II. The absorption cross section $\sigma_a = 227 \pm 12$ mb for carbon, for 650 Mev protons, was taken from the work of Moskalev and Gavrilovskiĭ.[9]

As can be seen from Table II, the most probable type of disintegration is the disintegration of C_6^{12} into two protons and two α particles. The explanation of this fact and a detailed discussion of the results of Table II will be given separately.

2. Particles with $Z \geq 3$. In addition to α particles and protons, we observed, in a number of cases, the emission of a particle with charge 3 or 4. The estimated cross sections of the fragmentation of Li and Be with ranges greater than 20 μ amounts to 6.5 ± 2.5 mb and 3 ± 1.5 mb respectively. These cross sections are in agreement, within the limits of errors, with the data of Ostroumov and Yakovlev,[10] obtained for the same proton energy.

The cross section for the production of Be given in Table II equals 15 ± 4 mb. The cross section for the production of Be_4^7 from carbon, obtained by Rowland and Wolfgang[11] for protons in the range 0.34 — 3 Bev, amounts to about 11 mb. Thus, the reaction $C_6^{12}(p, 3pxn)$ Be produces mainly the isotope Be_4^7. This result, strange at first glance, is clearly due to the strong dependence of the cross section on the energy of the first excited state of the decaying residual nucleus. For Be_4^9, this level is sufficiently low (2.43 Mev) so that, even for a small excitation energy, it decays into α particles and a neutron. The transition probability between this level and the ground state through an emission of a γ quantum is not greater than 0.01.[12] For Be_4^7, the level leading to the decay of the nucleus lies considerably higher (7.1 Mev),[13] which leads to a more pronounced yield of Be_4^7 as compared with Be_4^9.

It is interesting to calculate the fraction of decays in which the interaction of a 660-Mev proton with C^{12} leads to a total disintegration of the

TABLE II

Type of decay	Percent of the total number of decays	Cross section, mb	Type of decay	Percent of the total number of decays	Cross section, mb
$C_6^{12}\left(p, {pn \atop p2n}\right)C_6^{11,\,10}$	13.4	31±2	$p\alpha$Li	7.0	16±4
$C_6^{12}\left(p, {2p \atop 2pn}\right)B_5^{11,\,10}$	12.2	28±2	$2p$Be	6.5	15±4
			$6p$	2.35	6±2.5
$2p2\alpha$	32.6	74±8	$2p2\alpha\pi^+$	1.75	4±1.5
$4p\alpha$	12.2	28±5	$3p$Li	1.75	4±1.5
3α	7.0	16±4	$5p\alpha\pi^-$	0.56	1.3±0.8

nucleus into p, d, t, and α. From Table II, we find that this fraction amounts to 0.59 of the total number of disintegrations of light nuclei of the emulsion produced by 660-Mev and 1000-Mev protons. Serebrennikov[14] and Philbert[15] found the probability of a total disintegration of the nuclei into particles with $Z < 3$ to be 0.67 for $E_p = 660$ Mev and to 0.7 for $E_p = 1000$ Mev. The small discrepancy between the data of our experiments and those of references 14 and 15 is due partly to the unique features of the decay of C^{12}, and partly to the approximate character of the estimate of this probability in references 14 and 15.

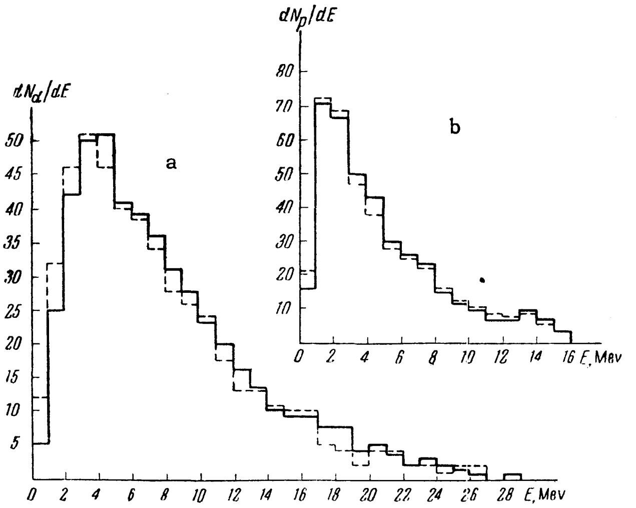

FIG. 1. Energy distribution; a – α particles; b – protons. Solid curve – in the laboratory system of coordinates; dashed – in the coordinate system affixed to the nucleus.

3. Energy and angular distribution of secondary particles. The energy distribution of α particles and protons in disintegrations recorded in the D emulsion is shown in Figs. 1a and b. The energy distribution of the protons is, at the high-energy end, limited by the sensitivity of the D emulsion. Such a limitation is absent for the energy distribution of α particles, and we can observe α particles from the decays of C^{12} up to 72 Mev. The energy distributions are corrected for the particles which escape into the air and into the glass of the plate, and the energy distribution for α particles is corrected for an admixture of tracks of Li, which has already been mentioned above.

Angular distributions of α particles and protons are given in Figs. 2a and b. The forward-backward ratios are 1.77 ± 0.2 and 1.55 ± 0.2 for α particles and protons respectively. The anisotropy in the angular distributions is due to two causes, if we assume a two-stage reaction mechanism: a) The particles knocked out of the nucleus in the first stage of the reaction in n-n collisions and in collisions between a nucleon and a group of nucleons of the nucleus (the knocked-out particles in light nuclei are, by an absolute majority, emitted into the forward hemisphere), and b) the excess of particles in the forward hemisphere due to the fact that the residual nucleus decaying in the second stage of the reaction is not at rest but moves with a certain average velocity v in the direction of the primary proton beam.

These two effects can be separated if the velocity v of the residual nucleus is known. We shall assume that, for any energy range of secondary particles, the anisotropy is due only to the motion of the nucleus. Then, knowing the velocity distribution of particles in the coordinate system affixed to the residual nucleus, which can easily be obtained from the velocity distribution in the laboratory system, one can calculate v from the expression that connects v with the fraction of particles emitted into the forward hemisphere.

In the calculation of v, we used the energy spectrum of the α particles. For α particle energies from 0 to 4 Mev in the system of coordinates of the moving nucleus, one can neglect the admixture of α particles knocked out of the

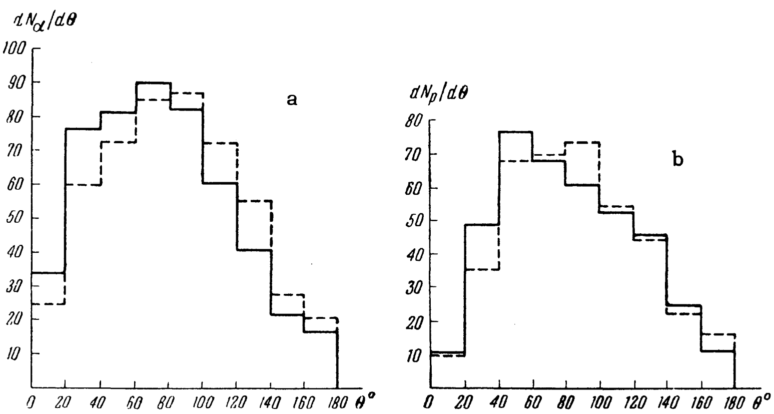

FIG. 2. Angular distribution: a – α particles; b – protons. Solid line – in the laboratory system of coordinates; dashed – in the system affixed to the moving nucleus. θ – space angle between the decay track and the proton beam from the accelerator.

nucleus, in view of the presence of a Coulomb barrier in the C^{12} nucleus. The value obtained is $v = (2.7 \pm 0.6) \times 10^8$ cm/sec.

Using the calculated value of v, we plotted the energy and angular distributions in the coordinate system affixed to the moving nucleus. These distributions are shown dotted in Figs. 1 and 2.

Assuming that all knocked-out particles are emitted into the forward hemisphere, one can determine, from the angular distributions, the number of α particles and protons knocked out from the nucleus. Calculation carried out by the Monte Carlo method confirms the correctness of the assumption with respect to the angles of emission of the knocked-out particles. According to the calculations, 94% of the protons knocked out of the nucleus move into the forward hemisphere. If we assume that all protons not recorded in the D emulsion, i.e., having an energy larger than 16 Mev, are also knocked-out protons, we obtain the result that 46% of the protons and 11% of the α particles are knocked out. This amounts to 0.97 protons and 0.18 α particles knocked out per star.

A calculation by the Monte Carlo method yields 0.75 knocked-out protons per star. The discrepancy between the experimental and calculated values is due, on one hand, to the fact that inelastic p-p, n-p, and nucleon-nucleon group collisions were neglected in the calculations, which leads to a decrease of the number of knocked-out protons. On the other hand, a small part of the protons with energies above 16 Mev are protons due to the decay of the residual nucleus, so that the obtained experimental value of the number of knocked-out protons is somewhat overestimated.

Results of the studies of the high-energy part of the decay products of carbon will be discussed elsewhere.

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