SOME FEATURES OF MULTIPLE FRAGMENT PRODUCTION BY 9-Bev PROTONS

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Submitted to JETP editor February 21, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 327-333 (August, 1961)

The disintegration of Ag and Br nuclei induced by 9-Bev protons and accompanied by the emission of two or more multicharged particles ($Z = 3 - 9$) is investigated. Various characteristics of the multiple emission of fragments, such as the probability of disintegration with the emission of N_f fragments, the charge and energy distributions of the fragments, and their angular correlations, are analyzed. It is concluded that multiply produced fragments are emitted independently.

1. INTRODUCTION

AN interesting phenomenon connected with the production of fragments with $Z \geq 3$ in the disintegration of complex nuclei by fast particles is the emission of two or more fragments in one disintegration. This multiple fragment production becomes rather conspicuous at proton energies greater than 1 Bev. If, for 660-Mev protons, the cross section for disintegration with a production of two or more fragments with $Z \geq 4$ amounts to ~ 0.5 mb[1] (roughly 4% of the total cross section for fragment production), then, for 9-Bev protons, this cross section is equal to ~ 16 mb[2] (this amounts to $\sim 16\%$ of the total fragment-production cross section). In the 1 — 3 Bev energy range, one should expect that the multiple production constitutes a still greater fraction of the total fragment production cross section, judging from the available preliminary data.[3,4]

In addition to the above, rather scanty, information on the energy dependence of the fragment production multiplicity, very little is known about other features of this phenomenon. Thus, it was mentioned by Perkins[5] that, in disintegrations involving two or more fragments, the fragment with the greater charge has a greater velocity. Lozhkin[6] indicates a strong angular correlation of two fragments in the disintegration, and confirms the tendency mentioned by Perkins.[5]

At the same time, it is absolutely clear that the study of the multiplicity can provide relevant information on the mechanism of the fragmentation process. The question whether some of the fragmentation process characteristics, such as the multiplicity, can be calculated[7] makes it even more necessary to carry out an experimental study of this feature of the fragmentation process. Results of a study of multiple fragment production at 9-Bev proton energy are presented in this article.

The nuclear emulsion method used has great advantages, since it permits us to study many features of the multiplicity at the same time.

In order to determine the fragment charge, the width of the fragment tracks was measured on fine-grain emulsion of the P-9ch type. The measurements were carried out using a special photometer whose optical system enables us, while observing the measured track through a binocular attachment, to scan a certain portion of the track by a narrow slit placed in front of a photomultiplier tube. The pulse from the photomultiplier, representing the transverse profile of a given section of the particle track, was fed to an electronic circuit (Fig. 1). This circuit produced a number of pulses proportional to the half-width of the photomultiplier pulse. The instrument had a dispersion of $\sim 1\%$ for a multiple measurement of one object. The length of the measured track portion could be varied. To exclude the necessity of introducing corrections, only the tracks of particles having an angle of dip less than 12° with the emulsion surface (in the developed emulsion) were selected.

2. EXPERIMENTAL RESULTS

1. Statistics of the disintegrations. From the scanning of nuclear emulsions irradiated by 9-Bev protons, 405 disintegrations with two or more fragments ($N_f \geq 2$) were found. This number of disintegrations corresponds to about 2000 disintegrations involving one fragment. The determination

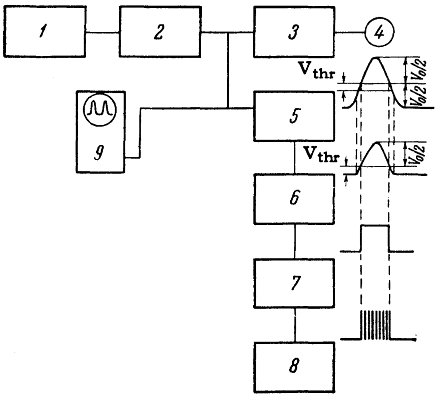

FIG. 1. Block diagram of the apparatus: 1 – photomultiplier with preamplifier, 2 – main amplifier, 3 – memory device, 4 – milliammeter, 5 – limiting circuit, 6 – Schmitt trigger circuit, 7 – blocking generator, 8 – scaler, 9 – oscilloscope. The shape of pulses at various points is indicated at the right-hand side of the figure.

of the fragment charge revealed that the majority of the fragments had charge between 4 and 9. Fragments with charge 3 were almost completely rejected in the selection of the disintegrations because of the small difference between them and the He nuclei. An exception was the isotope $_3Li^8$, which produces a characteristic T-shaped track.

The classification of the found disintegrations involving several fragments is shown in the table.

2. Disintegrations involving two fragments. In order to determine the charge distribution of the fragments in multiple emission and to compare it with the usual charge distribution, 193 tracks were selected from disintegrations with $N_f \geq 2$, and 209 tracks from disintegrations with $N_f = 1$. The distributions of the tracks with respect to the integral width, which was measured on the $38\,\mu$ of the residual range, were constructed for both groups. In the distributions, the tracks which did not end in the emulsion were not taken into account. As has been shown by the study of the geometrical conditions of tracks which were suitable for the width measurement, the corrections due to this effect are small, and, what is more important, are the same for both types of selected disintegrations.

Characteristics of the disintegrations	N_f			
	1	2	3	4
Only with fragments with Z = 4–9	~2000	289	35	5
Only with $_3Li^8$ fragments	153	4	1	0
One of fragments $_3Li^8$, the rest with Z = 4–9	–	54	9	2
One of fragments $_5B^8$, the rest with Z = 4–9	14	4	3	2

In view of the small range of the fragments studied, the track distribution with respect to the integral width does not give a sharp differentiation with respect to the fragment charge. Therefore, in order to compare the distributions, we did not pass from the measured track-width distribution to the charge distribution, but analyzed the data obtained directly. To compare the obtained distribution, the χ^2 test was used.

The obtained statistics make it possible to apply the test only in the range of charges $Z = 4-6$ (in this range, the width distribution was divided into 8 intervals). As a result, the probability $P(\chi^2)$ that purely statistical reasons will not make the difference between the distributions smaller than the actually observed value of χ^2, was found to equal 0.8. The value $P = 0.8$ shows that the compared distributions can be considered as identical.

After having established the above fact, we can, in addition, compare both distributions with respect to the average values of the track width. We can then take into account fragments with $Z > 6$, which could not be used in comparing the distribution according to the χ^2 test. It has been found that the mean values of the track width in both distributions are fully identical (the difference is less than 2%).

Thus, the results lead to the conclusion that the distribution of the tracks with respect to the width, and consequently the charge distribution of multicharged particles in multiple and single emission events, are identical within the limits of experimental error.

The charge distribution of fragments obtained from the total distribution of the track width of 402 fragments [in disintegrations with $N_f = 1$ and $N_f \geq 2$, after calibrating the latter using particles with $Z = 3$ ($_3Li^8$) and with $Z = 5$ ($_5B^8$)] is shown in Fig. 2. The relative frequency of charge pairs Z_n, Z_m in single disintegrations as a function of the sum $Z_n + Z_m$, and the frequency of observation of two fragments with different charges as a function of the fragment charge, are also shown in the figure, based on the study of 36 disintegrations in which the charges of both fragments could be measured.

The distribution of space angles between the two fragments shown in Fig. 3 was obtained from the angle measurements in 303 disintegrations. A marked angular correlation of the fragments in this disintegration is visible: the fragments are emitted predominantly at angles > 120° to each other. No variation of the mean angle between the

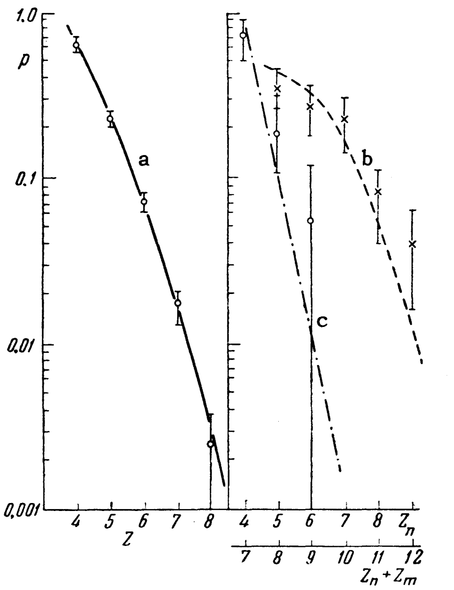

FIG. 2. a – charge distribution of fragments in the disintegration of Ag and Br nuclei; b – probability of the emission per disintegration of fragments with charge Z_n and Z_m as a function of the sum $Z_n + Z_m$: the points represent experimental values, and the curve is calculated; c – probability of emission of two fragments with different charge Z_n as a function of Z_n: points – experimental values, curve – calculated.

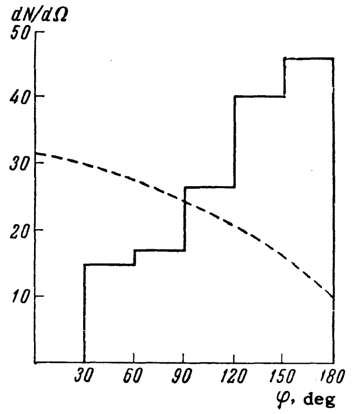

FIG. 3. Distribution of spatial angles between fragments. Histogram – experimental values, curve – calculation for the case of independent fragment emission.

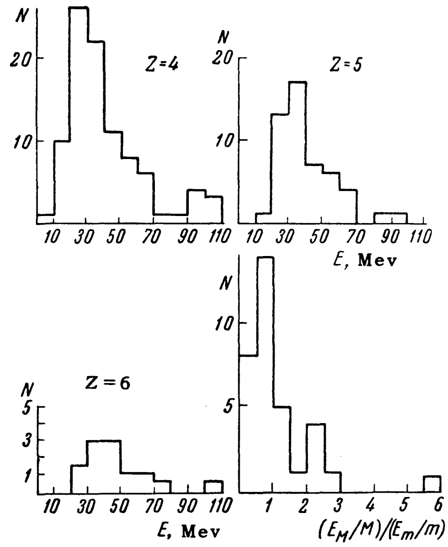

FIG. 4. Energy spectra of fragments in disintegrations with two fragments for Z = 4–6, and the ratios of energy per nucleon in heavy and light fragments $(E_M/M)/(E_m/m)$.

fragments from the sum of their charges has been established; for a variation of the fragment charges from 6 to 10, the mean angle between the fragments remains about 110°.

The energy spectra of fragments in disintegrations with $N_f = 2$ for Z equal to 4, 5, and 6 are shown in Fig. 4. In the same figure, the distribution of the ratio of the energy per nucleon in heavy and light fragments emitted in the same disintegration is also shown. The energy spectra of the fragments are similar to those observed in disintegrations involving one fragment[2] and the most probable ratio of the energy per nucleon in heavy and light fragments is close to unity.

3. Disintegrations involving three fragments. Because of the small statistics of disintegrations involving three fragments (44 cases), it was impossible to carry out a sufficiently complete study of the characteristics of such disintegrations. The most reliable information is obtained for the angular distribution of the fragments in these disintegrations. The distribution of the projected angles between adjacent fragments in disintegrations with three fragments is shown in Fig. 5, which clearly shows the predominance of large angles between fragments.

The measurement of the fragment charges in the disintegrations gave the following charge distribution of fragments for $Z \geq 4$; the number of fragments corresponding to charge 4, 5, 6, and 7 is equal to 18, 9, 2, and 1 respectively. The comparison of these numbers with the total charge dis-

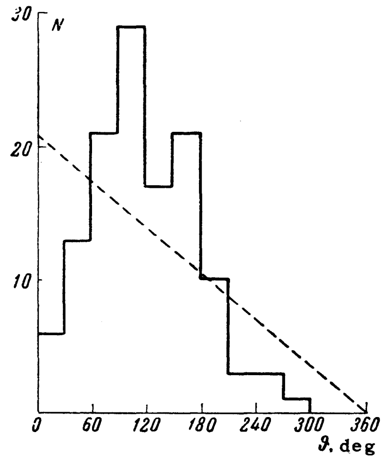

FIG. 5. Distribution of projected angles (ϑ) between fragments in disintegrations involving three fragments. Histogram – experimental results, dotted line – calculation carried out assuming independent fragment emission.

tribution for disintegrations with $N_f = 1$ and $N_f = 2$ (Fig. 2) shows that they agree, within the limits of statistical error.

3. ANALYSIS OF EXPERIMENTAL RESULTS AND CONCLUSIONS

The experimental results presented above were analyzed assuming independent fragment production in disintegrations involving several fragments. This problem can be considered independently of the actual mechanism of the fragment production. The idea of independent fragment production already follows from the study of the charge distribution of the fragments in disintegrations with different numbers of fragments. Identical charge distributions in disintegrations with one and two fragments will be obtained if the probability p_{nm} of observing a pair of charges Z_n and Z_m is equal to the product of the probabilities for the production of each charge: $p_{nm} = p_n p_m$. Thus, if

$$\sum_n p_n = 1, \qquad \sum_m p_m = 1,$$

then the probability of observing fragments with a charge Z_n in disintegrations involving two fragments will be given by

$$P_n = \sum_m p_{mn} = p_n \sum_m p_m = p_n,$$

i.e., is found to equal the probability of observing a charge Z_n in a disintegration with one fragment.

Figure 2 shows the calculated probabilities p_{nn} as a function of the sum of charges $Z_n + Z_m$, and the probability of observing identical charges P_{nm} as a function of charge Z_n. It can be seen that the experimental functions p_{nm} and p_{nn} are close to the theoretical ones.

The relative probabilities of observing a different number of fragments in a single disintegration, assuming their independent production, will follow, to a first approximation, a geometrical series with the common ratio determined by the probability of the production of one fragment in a disintegration. If we denote the probability of emission of $_3Li^8$ in a disintegration by p_1, and the probability of emission of fragments with $Z \geq 4$ by p_2, we can expect the following relation between the numbers of disintegrations with different numbers of fragments:

$$N(2_{fr})/N(1_{fr}) = N(3_{fr})/N(2_{fr}) = N(4_{fr})/N(3_{fr}) = p_2 \tag{1}$$

$$N(2Li_3^8)/N(1Li_3^8) = N(3Li_3^8)/N(2Li_3^8) = p_1, \tag{2}$$

$$N(1_{fr} + Li_3^8)/N(1_{fr}) = N(2_{fr} + Li_3^8)/N(2_{fr}) = N(3_{fr} + Li_3^8)/N(3_{fr}) = p_1, \tag{3}$$

$$N(2_{fr} + Li_3^8)/N(1_{fr} + Li_3^8) = N(3_{fr} + Li_3^8)/N(2_{fr} + Li_3^8) = p_2. \tag{4}$$

The probabilities p_1 and p_2 are calculated as a ratio of corresponding cross sections to the total cross section for the inelastic interaction of 9-Bev protons with Ag and Br nuclei.

We shall analyze the number of disintegrations with a different number of fragments, substituting the data from the table into Eqs. (1) to (4).

For row (1), we have the experimental values 0.14, 0.12, and 0.06. Within the limits of statistical error of the experiment these coincide with the value of $p_2 = 0.09$. Because of the small statistics available, this value cannot be considered as contradicting the values 0.17 and 0.22 of row (4).

For row (2), the values are 0.026 and 0.25, while for row (3) we have 0.030, 0.032, and 0.057, which are somewhat greater than the value $p_1 = 0.01$ but are in good agreement with each other with the exception of the ratio $N(3\,{}_3Li^8)/N(2\,{}_3Li^8)$, but this ratio is statistically inaccurate.

Thus, the study of separate probabilities of observation of different numbers of fragments in each disintegration also does not contradict the assumption of the independent emission of fragments in disintegrations involving several fragments.

The energy spectra of fragments in disintegrations involving two fragments, and the ratio of the energy per nucleon in light and heavy fragments (Fig. 4), also do not contradict the hypothesis of an independent emission of fragments.

At the same time, the angular correlation of fragments in disintegrations involving two and three fragments (Figs. 3 and 5) are very unusual for such a picture of an independent emission. In Fig. 3, the dotted line shows the distribution of spatial angles between the two fragments for an independent emission from the nucleus. This distribution was calculated by the Monte Carlo method, and the angular distribution of fragments was taken from [2]. In contrast to the experimentally observed distribution, the expected distribution falls off monotonously from 0 to 180°, while in the interval 0 to 30° there is not a single event in the experimental distribution.

For distributions with three fragments, the expected distribution of the projected angles between two adjoining fragments can be constructed according to the formula given in [8] (dotted line in Fig. 5). The experimental distribution is substantially different from that expected for an independent fragment emission.

Thus, while the relative emission probabilities of different numbers of fragments and the correlations of their energies and charges are in agreement with the hypothesis of their independent production, the angular correlation of fragments contradicts it. The situation is not changed if we take into account the fact that the fragments emitted from the nucleus may interact with each other through their Coulomb field. Because of the fact that the interaction with the residual nucleus is much stronger than that of the fragments with each other, we cannot expect a shift of the angular distribution between fragments to the region around 180°. The effect of the Coulomb interaction can only deplete the range of small angles between the fragments. In addition, the Coulomb interaction between the fragments should depend substantially on the fragment charge. No dependence of the mean angle of the sum of the fragment charges for the given distribution was observed in the experiment.

However, we cannot at present discard the hypothesis of an independent production of fragments only because of the angular correlation, but, on the contrary, should try to understand it assuming an independent fragment emission. Moreover, in contrast to other features of the independent emission of several fragments, it is necessary to have recourse to models in the study of angular correlation.

There are, in principle, two possible explanations. Since, in the picture in which the fragments are produced in a cascade process in a nucleus (both assuming quasi-elastic collisions of cascade nucleons with groups of nucleons in the nucleus[2,3] or assuming ruptured bonds during the passage in the nucleus[7]), the existence of an angular correlation of produced fragments demands the assumption of a spatial non-uniformity in the distribution of nucleons in the nucleus, it is not very probable for two large nucleon groups to occupy nearby locations in the nucleus. Thus, the emission of fragments will occur from regions of the nucleus far from each other, and the requirement that the emitted fragments have small orbital momenta will lead to large angles of emission between them.

The other possibility of explaining the angular correlation of fragments lies in assuming that the fragments may be produced as a result of a so-called direct nuclear decay, whose characteristics are determined by the statistical distribution of the energy and momentum between the products of disintegration before their emission from the interaction volume. In such a case, the angular correlations of fragments follows from conservation laws.

It is difficult at present to draw final conclusions supporting this or the other model. It is necessary to develop the methods of calculating the processes under question, and further increase the accuracy of the experimental data.

In conclusion, the authors would like to thank the workers of the Joint Institute for Nuclear Research I. V. Chuvilo, V. A. Sviridov, and É. N. Tsyganov for help in irradiating the emulsions, and the workers of the Radium Institute V. F. Darovskikh, N. P. Kocherov, and M. M. Makarov for discussion of the results.

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Translated by H. Kasha
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