FRAGMENT PRODUCTION BY 100-Mev PROTONS

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The production of multiply charged fragments by 100-Mev protons incident on photoemulsion nuclei was investigated. The cross section for the fragmentation was found to be (1.93 ± 0.64) mb for heavy emulsion nuclei and (1.16 ± 0.36) mb for light nuclei. Energy and angle characteristics of the process are presented. A number of arguments are given in favor of the hypothesis that the multiply charged fragments are produced at 100 Mev by quasielastic scattering on nucleon clusters in the nucleus.

1. INTRODUCTION

THE study of the process of emission of many-nucleon structures (nuclei of He, Li, Be, etc.) from nuclei under the influence of bombardment by high-energy particles has recently become of considerable interest.

A study of this phenomenon throws light on the subject of nuclear structure, and also provides us with a better understanding of the mechanism of nuclear reactions. The Brueckner[1] model of strongly correlated particles provides an additional stimulus for the study of the fragmentation process.

Despite the large number of papers devoted to the study of this phenomenon, there exists as yet no unified point of view as to the mechanism of production of many-nucleon structures, or fragments, in nuclear reactions.

In this paper we study the production of fragments in photoemulsion nuclei by 100-Mev protons. The choice of energy was dictated by two considerations. First, at this value of E_p the nuclear cascade is not yet very well developed, and secondly, fragmentation takes place at an energy below the meson production threshold. All these circumstances simplify the study of the fragmentation process.

2. EXPERIMENTAL METHOD

In this work we used fine-grain nuclear type P-9 (ch) photoplates, sensitive to protons with energies up to 100 Mev. The emulsion used made it possible to detect all charged products of nuclear disintegrations and to separate by visual means multiply charged particles with $Z > 2$ from α particles and protons.

The irradiation by 100-Mev protons was performed at the synchrocyclotron of the Joint Institute for Nuclear Research. A decrease in the energy of the accelerated protons was accomplished by slowing them down in a copper block. The geometry of the experiment excluded from the beam the admixture of higher energy protons and of background neutrons.

In the scanning process stars with dense cone-like tracks of fragments with $Z > 2$ were selected. The number of fragments with charge $Z = 3$ might have been somewhat underestimated, because the tracks of α particles and Li nuclei were separated from each other visually and some Li fragments may have been missed. The charge was determined only for those fragments whose tracks formed with the emulsion plane an inclination angle (prior to development) of less than 35° and whose range was longer than 18μ. The separation of fragments by their charge was accomplished by track thickness measurements.[2] Then a distribution of individual events was constructed as a function of the track width, utilizing the last 18μ of the range. The hammerlike tracks of Li^8 and Be^8 were used for calibration. As a result charges were determined for 86 fragments from among the 295 fragments found. These data include also events consisting of the emission of two α particles with approximately equal energies in a narrow cone (< 3°), which could be identified as the decay in flight of a Be^8 nucleus.

We discuss next the method used for separating stars formed from light (C, N, O) and heavy (Ag, Br) emulsion nuclei. To that end the Coulomb barrier criterion was used: stars containing α-particle tracks with a range less than 50μ ($E_\alpha \leq 9$ Mev) but more than 4μ (which corresponds to the maximum range of the recoil nucleus), as well as stars containing tracks of two protons with ranges less than 120μ ($E_p \leq 4$ Mev), were considered to be due to disintegrations of light nuclei. The validity of such a classification by "infra-barrier" particles, repeatedly verified for normal (without fragments) disintegrations of emulsion nuclei, was confirmed in the following manner. An analysis of the distribution in the number of prongs of stars with fragments produced from light nuclei showed, on one hand, good agreement with the corresponding distribution for normal stars also produced from light nuclei,[3,4] and, on the other hand, a difference from the distribution of stars with fragments produced in the disintegrations of heavy emulsion nuclei. As a final test the distribution in the number of prongs was analyzed for those stars with fragments which contained also a recoil nucleus and therefore must have been due to the disintegration of a heavy nucleus. It was found that the distributions of stars with fragments and stars with fragments and recoil nuclei were the same which testifies to the validity of the adopted criterion.

In this manner, 169 stars were classified as disintegrations of heavy nuclei and 126 stars as disintegrations of light nuclei. All these were subjected to a detailed analysis.

3. EXPERIMENTAL RESULTS

a) Cross section and character of the disintegrations. An estimate was obtained for the cross section for production of fragments from light and heavy emulsion nuclei. The proton flux was determined from the number of stars with prong number $n \geq 2$. The cross section for production of stars with $n \geq 2$ was taken to be equal to 139 mb.[5] In this manner the fragmentation cross section was found to be (1.93 ± 0.64) mb for Ag and Br nuclei and (1.16 ± 0.36) mb for C, N, and O nuclei.

A comparison with the data on fragment production cross sections by higher energy protons[6] is possible only for fragments with $Z \geq 4$ and with ranges $l > 15\mu$. In our case these cross sections are (0.81 ± 0.29) and (0.44 ± 0.16) mb respectively for heavy and light emulsion nuclei. Figure 1 shows data taken from reference 6 together with the results of this work. As can be seen, the fragment production cross section from heavy nuclei continues to fall with decreasing proton energy E_p. The light nuclei fragmentation cross section also falls with decreasing E_p, but considerably more slowly. However, the latter conclusion may be influenced by the inadequacy of the method used for identification of light and heavy nuclei in this work and in reference 6.

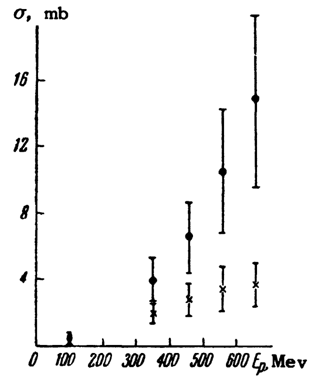

FIG. 1. Fragment production cross section σ as a function of the proton energy E_p: ● – from heavy nuclei, × – from light nuclei.

Disintegrations of heavy nuclei with fragment production are accompanied by a release of more energy than in normal disintegrations, as was also observed at other proton energies.[6] The average number of prongs in stars with fragments produced from heavy emulsion nuclei is equal to three, whereas in normal disintegrations it is equal to two (we use the average of the data of Hodgson[3] and Lees et al.[4]).

At the same time we obtained the relative probability for fragment emission from heavy nuclei as a function of the number of prongs in the star. The results of this analysis are given in Fig. 2 and show that the probability in question has a maximum.

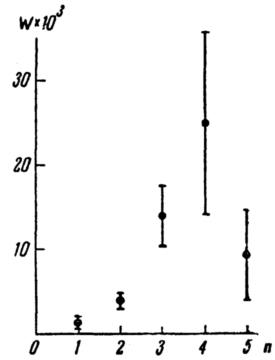

FIG. 2. Relative probability W of fragment emission as a function of the number n of prongs in the star (for heavy nuclei).

For stars due to light nuclei the large statistical errors make it impossible to draw any definite conclusions about the behavior of the corresponding probability.

b) Fragment distribution in charge, energy and range. Charges were determined for 49 fragments produced in disintegrations of Ag and Br nuclei, and for 37 fragments produced in disintegrations of C, N, and O nuclei. The results of the measurements are given in the table.

We note that the distribution in charge for fragments from Ag and Br nuclei is very similar to

Nuclei	Fragments		
	Li	Be	B
Ag, Br	30	14	5
C, N, O	20	12	5

the corresponding distribution obtained with 660 Mev protons.[6] Starting from the range-energy relations for multiply charged ions,[7] we constructed the energy spectrum for fragments with identified charges. The energy spectrum for Li and Be fragments is shown in Fig. 3 for light and heavy emulsion nuclei separately. Events corresponding to Be^8 are also included in the Be spectrum.

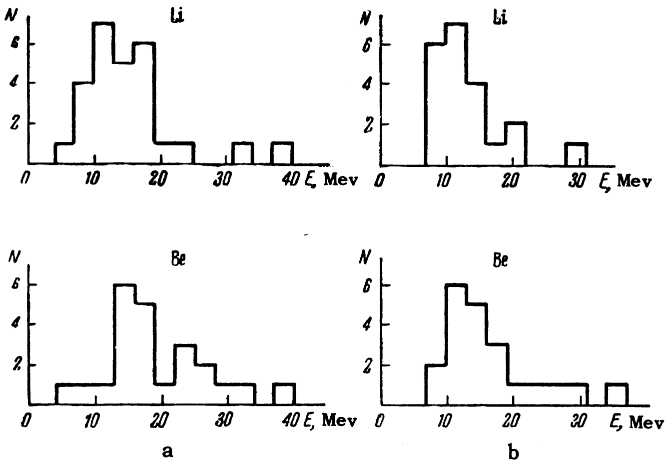

FIG. 3. Energy distribution of Li and Be fragments: a – for heavy nuclei, b – for light nuclei.

Poor statistics make it impossible to compare the fragment energy distributions with the corresponding distributions obtained with higher energy protons. However, the similarity of the distributions in charge permits a comparison of the distributions in ranges which is shown in Fig. 4. As can

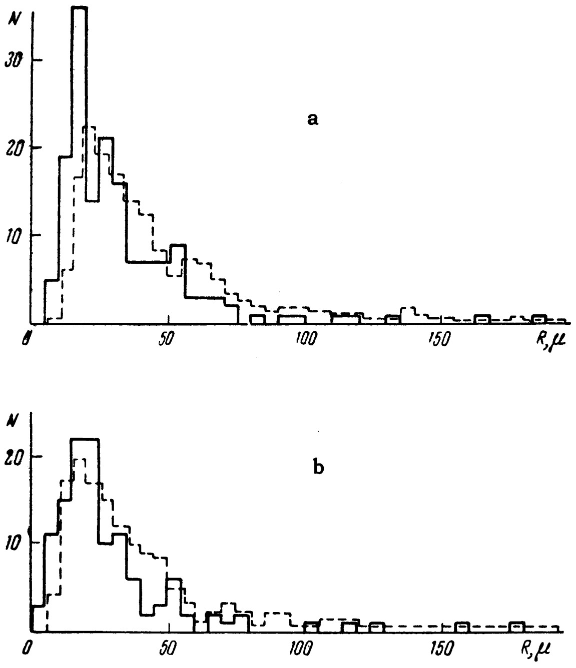

FIG. 4. The distribution of fragments in range R: a – for heavy nuclei, b – for light nuclei. The dashed line refers to the E_p = 660-Mev data.[6]

be seen the most probable range is approximately the same at different proton energies, despite the considerable difference in the distributions at large range values.

c) Angular distribution of the fragments. As can be seen from Fig. 5 a substantial asymmetry exists in the angular distribution of fragments obtained from the disintegrations of heavy and light

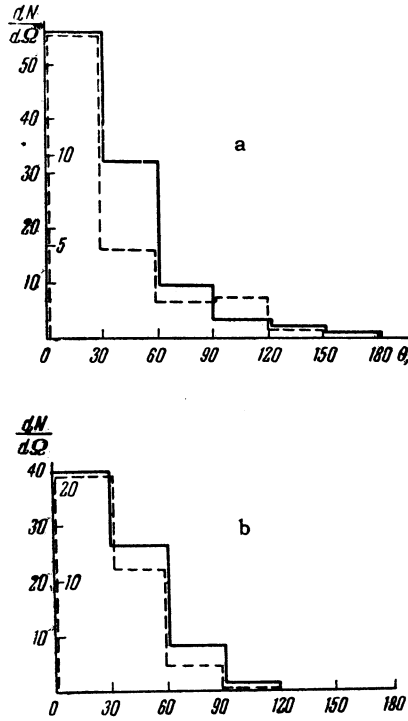

FIG. 5. Angular distribution of fragments produced on light (a) and heavy (b) emulsion nuclei. The solid line refers to all fragments, the dashed line refers to fragments with $l > 25\mu$ for light, and with $l > 40\mu$ for heavy, emulsion nuclei

emulsion nuclei. The ratio of the number of fragments in the forward hemisphere (with respect to the direction of the proton beam) to that in the backward hemisphere is equal to 9.0 ± 2.7 in the case of heavy emulsion nuclei. This is significantly larger than at higher proton energies (3.1 ± 0.5 at E_p = 350 Mev[6]). The asymmetry in the angular distribution of fragments from light nuclei is 24 : 1 and this value, too, is considerably larger than that obtained with 660-Mev protons. The previously obtained data[6,8] on the dependence on the incident proton energy of the asymmetry in the disintegrations of heavy emulsion nuclei are shown in Fig. 6. These data show quite unambiguously that as E_p increases the fragment distribution becomes more and more isotropic.

4. DISCUSSION OF RESULTS

We must first discuss the very fact that fragments are produced at energies below the meson

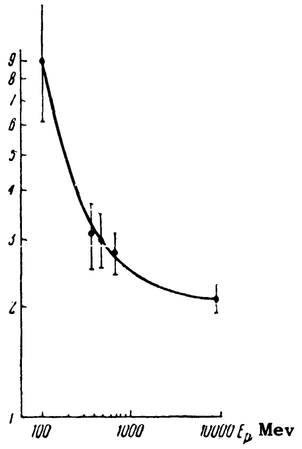

FIG. 6. The dependence of the asymmetry of fragment production in the disintegrations of heavy nuclei on the proton energy E_p. Along the ordinate is plotted the ratio of the number of fragments emitted in the forward and backward directions.

production threshold. In a number of radiochemical investigations (see, e.g., Friedlander et al.[9]) the production of fragments with masses $\sim 10-40$ was associated with intense meson production and absorption in the nucleus. It is, of course, not possible to put an equality sign between the reaction products studied by us and those obtained by Friedlander et al.,[9] but it does follow from our work that multiply-charged fragments can be produced also without meson participation. Consequently it is quite likely that at least some of the fragments produced in the bombardment of nuclei by high-energy ($\sim$ 1 Bev) protons are of the same origin as the fragments studied by us.

It is of interest to discuss the production of multiply-charged fragments by 100-Mev protons from the point of view of fission, evaporation, and nuclear cascade processes.

The possibility of fragment production as the result of asymmetric fission was studied in detail by Lozhkhin and Perfilov,[6] who showed that asymmetric fission fails to explain satisfactorily many of the experimental facts of fragmentation: for example, it is rather difficult to relate asymmetric fission and the appearance of fragments with energy in excess of the Coulomb repulsion.

It has been suggested by some authors (see, in particular, Hodgson[10] and Skjeggestad and Sorensen[11]) that fragments might be produced in the process of evaporation from a strongly excited nucleus. It appears to us that in this case, too, there are significant contradictions with experiment, of which the most important is the pronounced asymmetry in the fragment distribution. In the evaporation model the asymmetry is due to translational motion and is given by the ratio $(u+v)/(u-v)$, where u is the speed of the "evaporating" particle and v is the speed of the nucleus. This ratio is equal to 1.16, in disagreement with the experimental value of 9 for the asymmetry.

However, a certain fraction of the fragments might, apparently, be produced in the evaporation process. Indeed, of the 169 fragments found in the disintegrations of heavy nuclei, 17 were emitted into the backward hemisphere relative to the direction of the beam. Let us suppose that these fragments were produced in the evaporation process from the Ag and Br nuclei. Then, making use of the value of the asymmetry expected for the evaporation process (1.16), we come to the conclusion that only 37 fragments can be due to evaporation.

The probability for the emission of various particles relative to the probability for proton emission may be obtained from the evaporation theory developed by Hagedorn and Macke.[12] The calculation of the relative probability of evaporation of Be^9 fragments from Ru^{100} nuclei (Ru is between Ag and Br), using the values 2.58 Mev for the parameter T and 18.8 Mev for V, gives a result in good agreement with experiment if it is assumed that 37 fragments are due to evaporation.

Consequently it may be assumed that the evaporation process is responsible for the production of at most one fifth of all fragments.

The possibility that multiply charged fragments are produced by the nuclear cascade process is evident already from their anisotropic distribution. It may be supposed that the fragments are emitted from the nucleus as a result of quasielastic interactions of the incident nucleon with strongly bound nucleon clusters in the nucleus.[13] Indeed, there exist a number of reasons for the belief[14] that when a nucleus is traversed by a nucleon not only nucleon-nucleon interactions are possible, but also interactions between the nucleon and a cluster formed as a consequence of a shortlived nuclear matter fluctuation.[15] The experiments of Meshcheryakov et al.[14] showed that the existence of such clusters (type d) is possible; in all probability the cascade α particles detected in photoemulsion experiments[16] are also due to such shortlived clusters. The similarity of a majority of the characteristics of the knock-out processes of fast α particles and of heavier fragments should be noted. It is therefore plausible to assume that occasionally also larger structures of the light nuclei type can be formed in a nucleus and it is with these structures, as a whole, that the incident particle interacts. If fragment emission is due to quasielastic scattering of protons by nucleon clusters in the nucleus then there should exist a correlation between the directions of emission of the multiply charged fragments and the fast recoil proton. A search for such a correlation was carried out for all disintegrations with fragments. The number of disintegrations with two cascade protons did not exceed 4%. Consequently in almost all disintegrations we measured one spatial angle between the direction of emission of the fragment and of the proton with an energy in excess of 20 Mev. The angular distribution so obtained is shown in Fig. 7 for the disintegrations of heavy emulsion nuclei (the picture was analogous for fragments from light nuclei). As can be seen from the figure, a pronounced correlation exists between the directions of emission of the fragment and the fast proton. The dotted line in the figure refers to the calculated distribution in the angles between the fragments and cascade protons derived from the angular distributions of the fragments and the protons. Figure 7 shows that the discovered correlation is not accidental.

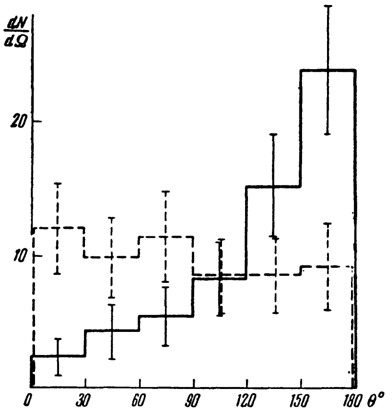

FIG. 7. Correlation between fragments and cascade protons (for heavy nuclei). The dashed line refers to calculated accidental correlation. Along the abscissa is plotted the angle between the directions of the fragment and the proton (E > 20 Mev).

Starting from the hypothesis of a collision mechanism for fragment production, we can discuss the dependence of the fragment energy on its emission angle according to the formulas for elastic collisions. Figure 8 shows curves calculated for the interaction of a 100-Mev proton with nuclei of mass 7 and 9, and also the experimental points. These experimental points are rather widely scattered and fall significantly below the calculated curve. This circumstance suggests that for 100-Mev protons the fragments are knocked out not by the primary, but by secondary, nucleons produced in the branching out process of the nuclear cascade and having a significantly lower energy. Indeed, if we construct curves for elastic collisions in such a manner that the deviations towards larger and smaller angles are approximately equal, we find that these curves correspond to protons with energies between 30 and 60 Mev, in agreement with

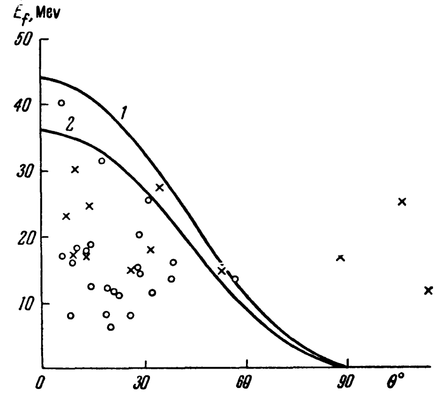

FIG. 8. The dependence of fragment energy E_f on the emission angle θ. The curves refer to calculations for elastic collisions: 1 – for fragments with mass M = 7 (Li); 2 – for M = 9 (Be). ● – experimental points for Li; × – for Be.

the results obtained for the knockout of cascade α particles.[17] The scatter of the points relative to the calculated curves might be explained by the momentum distribution of the fragments in the nucleus.

We conclude therefore that multiply-charged fragments are produced at E_p = 100 Mev mainly by quasielastic knock-out of nucleon clusters from the peripheral region of the nucleus by secondary nucleons, arising from a branched-out cascade.

The available data, unfortunately, do not allow a more precise determination of what part of the fragments under study is due to the nuclear cascade and what part is due to evaporation, although it seems to us that in such an approach to the fragmentation process the influence of the evaporation mechanism could have been only overemphasized, and that basically fragments are produced on heavy emulsion nuclei in the process of a branched-out nuclear cascade.

In the above discussion we have said little about fragmentation of light emulsion nuclei. The basic experimental results on fragment production are the same for light and heavy nuclei. The different energy dependence of the cross section and of the anisotropy are apparently related to a different degree of development of the cascade process. Indeed, calculations on the nuclear cascade process using the Monte Carlo method[18] show that for light nuclei the number of cascade nucleons changes slowly with proton energy, which explains the comparatively weak energy dependence of the cross section and anisotropy. In the fragmentation process of light nuclei the collision mechanism should operate almost exclusively, since the term "evaporation" is not applicable to light nuclei, and fragment production as residual nuclei is in contradiction with the angular distribution. Thus, in the case of nucleus pulverization the ratio of fragments emitted forward and backward should not exceed 1.5 and consequently no more than 10% of the fragments could be produced in this manner.

Thus the results of this work are evidence that at comparatively low incident proton energies (~ 100 Mev) fragments are produced by quasi-elastic scattering of secondary nucleons on moving nucleon clusters in the nucleus.

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