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DISINTEGRATION OF EMULSION NUCLEI BY 930-Mev PROTONS

O. V. LOZHKIN, N. A. PERFILOV, A. A. RIMSKIĬ-KORSAKOV and J. FREMLIN*

Radium Institute, Academy of Sciences, U.S.S.R.

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The interaction of 930-Mev protons with emulsion nuclei has been investigated, special attention being directed to interactions involving the emission of multiply charged particles with Z ≥ 3 from the nuclei. The relative yields of isotopes of hydrogen, helium, lithium, and nuclei with Z ≥ 4 were determined for disintegrations of light and heavy nuclei with three or more prongs. The cross section for the production of lithium isotopes in the disintegration of Ag and Br nuclei was found to be (135 ± 13) mb; for fragments with Z ≥ 4 the cross section was (62 ± 11) mb. The angular and energy distributions of the fragments, multiplicity of fragment production, dependence of the fragment-production probability on the number of α particles and protons in one disintegration, and other characteristics of the fragmentation process were studied. The fragmentation mechanism is discussed.

1. INTRODUCTION

INVESTIGATION of the phenomenon of the emission of multiply charged particles (fragments) in nuclear disintegrations, for various energies of the incident particles and various atomic numbers of the target nuclei, indicates a number of interesting characteristics of this phenomenon: a sharp increase in the cross section for fragment production and an increase in the number of fragments per disintegration with increasing energy of the incident protons, a considerable angular anisotropy of the produced fragments relative to the direction of the incident protons, a connection between the probability of fragment emission and the total energy transferred to the nucleus during the collision, and others. Interest in the phenomenon of fragment production in nuclear disintegrations produced by high-energy particles has considerably increased recently in connection with the question of the existence of correlated clusters of nucleons in nuclei and the presence of collective interactions between the high-energy particles and these clusters.

The data describing the properties of the emitted fragments is at present far from complete, and sometimes contradictory, which leads to great differences in the basic points of view on the nature of the fragmentation process. Some of the known facts prove to be difficult to explain within the framework of generally accepted ideas on various interactions of high-energy particles with nuclei (nuclear cascade, evaporation, fission). However, another basic point of view which envisages the production of fragments by a quite distinct mechanism of nuclear disintegration[1-3] has not yet been supported by sufficiently weighty evidence.

The possibility of direct investigation of many characteristics of the fragments emitted in disintegrations by means of the nuclear emulsion method makes this method very valuable for a study of the fragmentation process.

In this article we present experimental material on the interaction of 930-Mev protons with emulsion nuclei, particular attention being directed to disintegrations accompanied by the emission of fragments with Z $\geq$ 3.

2. EXPERIMENTAL METHOD

Especially fine-grained type P-R emulsions, used in the experiment and prepared in N. A. Perfilov's laboratory without additional sensitization in triethanolamine, were irradiated in the 930-Mev proton beam of the Birmingham (England) proton synchrotron. Figure 1 shows the sensitometric characteristic of the emulsion for charged particles. As can be seen from the figure, although the emulsion was also sensitive to relativistic electrons, the grain density of relativistic particle tracks was insufficient for a reliable visibility on the random grain back-

*Professor at the University of Birmingham (England).

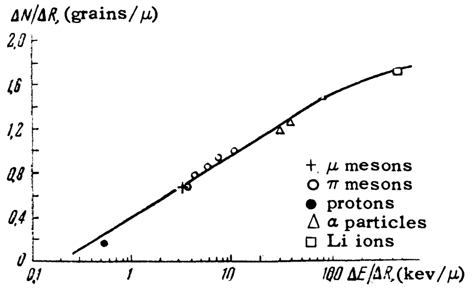


FIG. 1. Sensitometric characteristic of P-R emulsion not sensitized with triethanolamine.

ground, and therefore only protons of energy ≤ 500 Mev were reliably recorded. But the low contrast of the emulsion (i.e., the weak variation of dN/dR with dE/dR) leads to the formation of a great number of gaps between grains at the end of the range of tracks produced by particles of charge Z = 3, which permits use of the "scale" method[4] for identifying particles of charge Z = 1, 2, and 3. The tracks of particles with Z ≥ 4 had almost no gaps close to the end of the range and, furthermore, were marked by a very noticeable thinning down; therefore they could be reliably distinguished from particles of smaller charge. The charge of particles in the region Z ≥ 4 was measured by the method[5] of integral track-width measurement* at a given distance from the end of the range.

The "scale method" used in this work to identify particles with Z = 1, 2, and 3 was first used by Serebrennikov[6] and later developed by Rimskiĭ-Korsakov.[4] This method is based on studying the track by means of an eyepiece scale with uniform divisions of a given length. When the scale is superimposed over the track image, the grains of the track overlap part of the scale divisions. Each track is characterized by some number G of overlapped scale divisions completely filled by grains of the track at a given distance from the end of the range. This number is a nonlinear function of the grain density dN/dR. The choice of the size of the scale division is determined by the region of values of dN/dR in which the estimate given by the scale most strongly depends on dN/dR, and in this way one can obtain the best separation of the particles in the grain density region of interest to us. For the emulsion used by us, a scale division length of 1.25μ in the plane of the object gave the best separation of particles in the region of 120 — 180 grains per 100μ, which corresponded to particles of charge one to three at the end of the range.

In the analysis of nuclear disintegrations the scale was used for the analysis only of tracks of particles stopping in the emulsion with ranges ≥ 60μ and dip angles ≤ 30° to the plane of the emulsion. For particles with Z ≥ 4, only tracks of length > 15μ were taken; multiply charged particles of smaller length were regarded as recoil nuclei. The following criteria were used for separating the disintegrations into disintegrations of heavy and light nuclei of the emulsion: 1) total charge of the particles in the disintegration (for ΣZ > 8 the disintegration was regarded as that of a heavy nucleus); 2) the presence or absence of a recoil nuclei (when there was a recoil nucleus, the disintegration was regarded as that of a heavy nucleus); 3) the presence or absence of short-range α particles or protons of range < 50μ and < 100μ, respectively (in the case of short-range particles the disintegration was regarded as that of a light particle). Disintegrations which could not be classified by all three criteria, i.e. disintegrations with ΣZ ≤ 8 without a recoil nucleus and not having any short-range particles, were regarded as disintegrations of light nuclei, although some of them may, of course, have been due to disintegrations of heavy nuclei. Since, however, the relative amount of disintegrations not satisfying the above criteria is small, the uncertainty introduced by our separation is also correspondingly small. Indeed, since only disintegrations having three or more prongs (i.e. ΣZ ≥ 3) were studied, the doubtful disintegrations could be only those containing no recoil nuclei and with total particle charge 3 ≤ ΣZ ≤ 8, which constituted only 14% of all disintegrations. The use of the third characteristic (α-particle and proton energy) reduced this value still further.

3. EXPERIMENTAL RESULTS

To determine the nature of particles in the region of Z between 1 and 3, a total of 1054 stars with three or more prongs was analyzed. Of these, 905 stars were classed as disintegrations of heavy nuclei and 149 as disintegrations of light nuclei. The estimate of the fragment yield was obtained from the fact that out of 1430 stars with three or more prongs it was found that the number of stars with fragments of Z ≥ 4 were 103 and 30 for the heavy and light

*The method involves the measurement of the particle's track width on successive segments from the end of its range, and the summation of all the values obtained on the preceding segments.

nuclei, respectively. In order to study the production process for such fragments, an additional 147 stars with fragments of $Z \geq 4$ were found.

Among the disintegrations with fragments of $Z \geq 4$, the major part consisted of disintegrations in which one or several fragments of $Z < 12$ were emitted. Sometimes, however, disintegrations were observed with two multiply charged fragments having approximately the same range of the order 8μ and emitted in opposite directions; according to Shamov,[7] such stars should be considered to be cases of the fission of the silver nucleus. Eleven such events were observed, which constituted about 5% of the total number of disintegrations with fragments of $Z \geq 4$.

In Fig. 2 is shown the distribution of the G values, obtained with the aid of the scale,

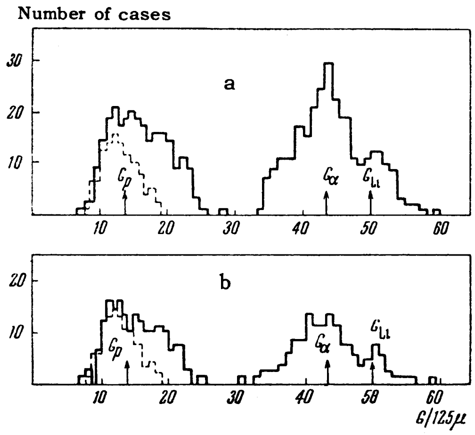


FIG. 2. Distribution of evaluation of G (over 125μ range) obtained by means of the scale method for particles stopped in the emulsion. a) Disintegration products of heavy nuclei of the emulsion; b) light nuclei. The dotted lines indicate the G-value distribution for protons.

for tracks of particles emitted in the disintegration of light and heavy nuclei. It is seen from the figure that the tracks of singly and doubly charged particles with ranges $\geq 62.5\mu$ are clearly separated; for tracks of Li nuclei and of doubly charged particles of the same range, the separation is much poorer. In the same figure are shown the distributions of the evaluation of G for tracks of known protons in emulsion of the same type; also shown are the mean values of G for tracks of protons, α particles, and Li nuclei. The mean values of G for Li ions were obtained by measuring the tracks of Li^8, which give a characteristic T shape in the emulsion; and for the analysis of the α-particle tracks we used α particles from the decay of Be^8 nuclei.

The obtained distribution of G values for the nuclear disintegration products clearly shows the presence of some isotopes of hydrogen (heavier than H^1) and, possibly, helium. Knowledge of the shape of the G-value distribution curves for H^1 and He^4 isotopes would permit an analysis of the obtained G-distribution curve and allow one to find the ratio of the isotope yields of singly and doubly charged particles. In the present work, however, it was possible to do this only for the hydrogen isotopes, since we did not have an α-particle source of sufficient energy to calibrate the emulsions.

The table gives the characteristics of nuclear disintegrations with three or more prongs analyzed in this work. As seen from the table, a high yield of H^2 and H^3 isotopes was observed in comparison with H^1. The relative number of Li^8 isotopes is extremely small in

Characteristics of nuclear disintegrations with three or more prongs

Characteristics of stars		Ag, Br	C, N, O
Mean number of particles	H isotopes	3.7±0.8	2.6±0.7
	He isotopes	0.8±0.1	1.7±0.3
	Li isotopes	0.18±0.04	0.10±0.04
	Fragments with $Z \geqslant 4$	0.10±0.01	0.09±0.03
Cross section, mb	Li isotopes	135±31	20±8
	Fragments with $Z \geqslant 4$	62±11	18±5
Relative yields	$\frac{He^3+He^4}{H^1+H^2+H^3}$	0.22±0.07	0.66±0.12
	$\frac{H^2+H^3}{H^1+H^2+H^3}$	0.18±0.8	—
	$\frac{Li^8}{Li^6+Li^7+Li^8}$	0.012±0.009	0.03±0.04

comparison with the lighter isotopes of lithium.

Figure 3 shows the distribution of 46 measured tracks of particles with $Z \geq 4$ produced

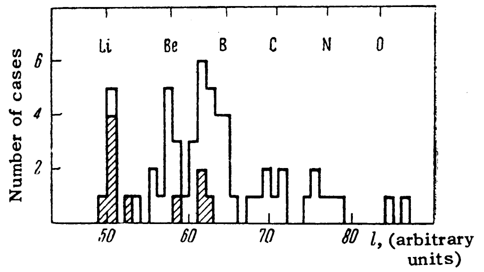


FIG. 3. Distribution of tracks of particles with $Z \geqslant 4$ as a function of the integral width l. The shaded area corresponds to T-shaped tracks of Li^8 and B^8.

in the disintegration of Ag and Br nuclei as a function of their integral width. In the case of tracks with dip angles $\leq 30°$ (in unprocessed emulsion), 7 segments were measured through 3.5μ. For the calibration we used the T-shaped tracks, part of which proved to be Li^8 and part B^8. Shown in the figure are the values of the integral width for particle tracks of various charge relative to the width of the Li^8 tracks for an assumed dependence on Z of the integral width of the form $\sqrt{Z}$. The analysis of the distribution shown in Fig. 3 indicates that the ratio of the number of fragments Be : B : C : N : O corresponds approximately to the ratio 15 : 16 : 7 : 6 : 2. It should be noted that the number of recorded Be fragments is considerably reduced, owing to the decay of the Be^8 isotope into two α particles immediately after emission from the nucleus.

The production cross sections for the individual products of nuclear disintegration were evaluated from their frequency in the observed number of disintegrations of emulsion nuclei with three or more prongs on the basis of the production cross section of the latter, which was (859 ± 57) mb (according to the data of Philbert[8]). The cross sections calculated in this way are also shown in the table.

It should be noted that the cross section for the production of Li^8 fragments is ~2 mb, in close agreement with the value (1.1 ± 0.3) mb found by Munir[9] for the disintegration of Ag and Br nuclei at the same incident particle energy, but turns out to be considerably larger than that for particles of lower energy. Simultaneously with the increase in the cross section for the production of multiply charged particles, the multiplicity of the fragment production process also increases with the energy of the incident particles. Thus, for 71 disintegrations with one fragment of $Z \geq 4$, there were observed 24 disintegrations with two fragments and 8 disintegrations with three fragments, while for a proton energy $E_0 = 660$ Mev the number of disintegrations with two and three fragments were 4 and 0.8%, respectively, of the number of disintegrations with one fragment.[10]

For disintegrations with fragments of $Z \geq 4$* an additional analysis was made of the various characteristics of nuclear disintegration in order to explain the nature of the fragmentation process. The angular distribution of the fragments with $Z \geq 4$ in the disintegration of Ag and Br nuclei are characterized by a considerable anisotropy with respect to the direction of the incident particles. The forward–backward ratio in the laboratory system turned out in this case to be 2.3 ± 0.7.

The mean number of singly and doubly charged particles in disintegrations with fragments was 8, which is considerably greater than the mean number of particles in ordinary disintegrations.

In Figs. 4 and 5 are shown the relative probability of the emission of fragments with $Z \geq 4$ in stars with various numbers of particles for proton energies $E_p < 30$, ≥ 30, and ≥ 100 Mev, relative to the total number of disintegrations with a given number of particles. While the relative probability of the emission of fragments sharply increases with the number of slow particles ($E_p < 30$ Mev) and with the number of particles of cascade origin ($E_p \geq 30$ Mev), the probability of emission of a fragment decreases with an increase in the number of fast "cascade" particles ($E_p \geq 100$ Mev).

Also investigated were the energy and angular distributions of the disintegration products

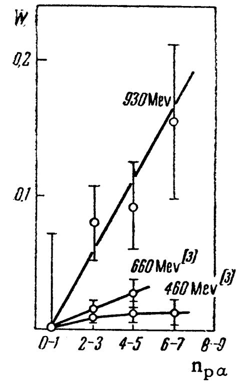


FIG. 4. Dependence of probability W of fragment emission with $Z \geqslant 4$ in disintegrations of Ag and Br nuclei on number of particles $n_{p\alpha}$ in one disintegration with $E_p < 30$ Mev at three energies of incident particles. The data for $E_0 = 460$ and 660 Mev are taken from the work of Lozhkin.[3]

*Fragments with $Z = 3$ were not considered, since they could be separated from α particles only statistically.

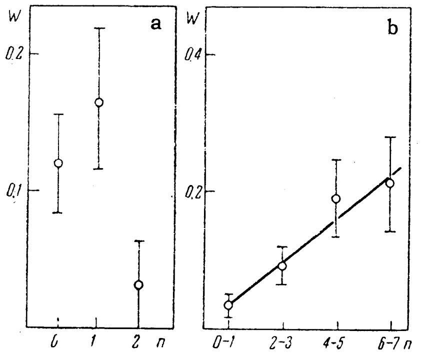


FIG. 5. Dependence of probability W of fragment emission with $Z \geqslant 4$ in disintegrations of Ag and Br nuclei on the number of particles $n_{p\alpha}$ in one disintegration: a) with energy $E_p \geqslant 100$ Mev; b) with energy $E_p \geqslant 30$ Mev.

of the Ag and Br nuclei. For singly and doubly charged particles the results of the present work are in good agreement with the results of Lock et al.[11] for the same incident-proton energy E_0.

The energy distribution of Li fragments shown in Fig. 6 was obtained by subtracting the range distribution for helium from the total distribution for helium and lithium; it is in satisfactory agreement with the energy distribution of Li^8 reported by Munir,[9] and also with the energy distribution of Li in the disintegration of Ag and Br nuclei by 6.2 Bev protons.[12]

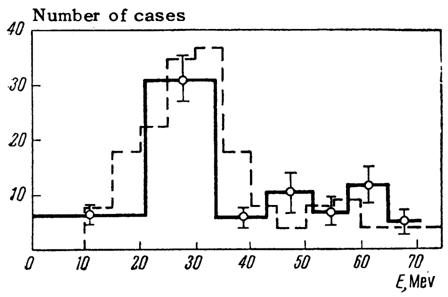
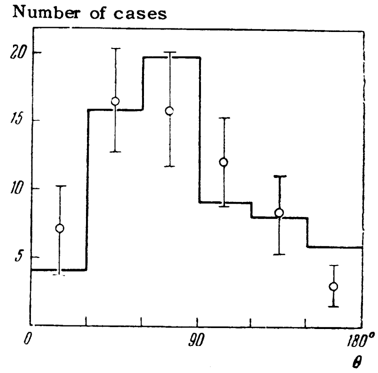


FIG. 6. Energy distribution of Li fragments in disintegrations of Ag and Br nuclei by protons of energy: $E_0 = 930$ Mev (solid line), $E_0 = 6.2$ Bev[12] (dotted line).

A study of the angular correlation between multiply charged particles and fast "cascade" particles led to the dependence portrayed in Fig. 7, which shows a considerable predominance of angles of emission of fragments in the region 30 — 90° with respect to the cascade particle. However, owing to the anisotropy of the distribution of the fragments and of the cascade particles with respect to the direction of the incident particles, such a distribution turns out to be entirely natural. In the same figure is shown the distribution of the angles between the fragments and the cascade particles calculated on the basis of the experimentally found angular distributions of fragments and fast "cascade" particles. Therefore the observed angular correlation between fragments and fast "cascade" nucleons still leads to no conclusions on the existence of genetic ties between these and other particles.

FIG. 7. Distribution of space angle θ between fragments and fast cascade particles ($E_p \geqslant 100$ Mev). Histogram — experimental distribution; the points represent the calculated results.



4. DISCUSSION OF RESULTS

A. Cross Sections for the Production of Various Fragments. The use of the scale method for analyzing particles with Z = 1, 2, 3 allowed us to obtain information on the relative yield of hydrogen, helium, and lithium isotopes among the nuclear disintegration products. Moreover, it proved to be possible to estimate the relative number of heavy isotopes among all the isotopes of hydrogen. The comparatively small track length ($\sim 60\mu$) at which the separation of particles of different nature by means of the scale method becomes sufficiently good permits the analysis of practically all particles involved in the disintegration of heavy nuclei and of the greater part of the particles involved in the disintegration of light nuclei. The obtained yield ratio of different isotopes of hydrogen is based on the shape of the G-value distribution curve for protons, which is found experimentally, and on the adopted manner of normalizing the G-value distribution. The accuracy of the results obtained is, moreover, determined by the statistics of the measurements.

The yield ratio of doubly to singly charged particles found in this work, 0.22 ± 0.07, is quite reliable, owing to the complete separation of hydrogen and helium by the scale method. The obtained value of the He/H ratio is somewhat smaller than the ratio $\alpha/p = 0.36$ reported by Lock et al.[11] for the same incident-proton energy. The relative amount of tritium and deuterium among the isotopes of hydrogen, obtained from the analysis of the N(G) curve for singly charged particles, is in agreement with the data published in reference 13 for disintegrations produced by cosmic rays. They give a value of 0.21 — 0.43 for the relative abundance of deuterium and tritium in stars of various numbers of prongs.

The investigation of the lithium isotopes shows that the emission of Li^8 makes up a very small part of the total production cross section for lithium, only ~1%, which is characteristic for other incident-particle energies as well.

The charge distribution of fragments with $Z \geq 4$ given above proves to be close to the distribution observed at other energies of the incident particles. In the incident-particle energy range from several hundred Mev to several Bev, as seen from Fig. 8, the distribution of fragments over Z may be described approximately by the exponential expression $P(Z) = \exp(-Z^n)$. For fragments with $Z \geq 4$ the exponent n is very close to unity.

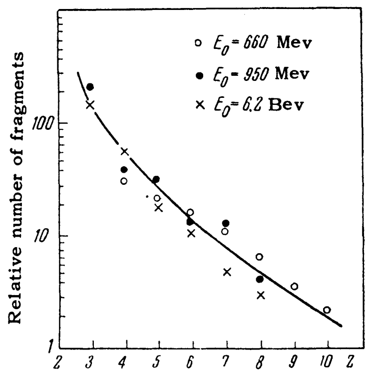


FIG. 8. Charge distribution of fragments for various incident proton energies E_0.

The existing differences in the distributions for different incident-particle energies do not exceed the limits of statistical error of the experiments.

B. Characteristics of the Fragmentation Process. We shall consider the experimental data obtained in this experiment for multiply charged particles with $Z \geq 4$. The production cross section for fragments with $Z \geq 4$ in the disintegration of Ag and Br nuclei by 930-Mev protons proves to be much higher than at 660 Mev[14] (Fig. 9). The strongest dependence of the fragmentation process on the incident-particle energy is in the incident-proton energy region close to 1 Bev. This conclusion is in agreement with the data of Caretto, Hudis, and Friedlander[15] on the measurement of the variation of the cross section for the production of

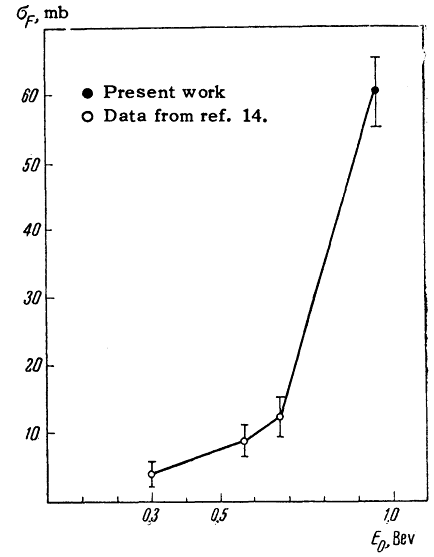


FIG. 9. Dependence of cross section σ_F for production of fragments with $Z \geq 4$ on proton energy E_0.

F^{18} and Na^{24}, with different incident-proton energies E_0.

Together with the increase in the total cross section for fragment production in nuclear disintegrations with an increase in the energy of the incident protons, the relative number of disintegrations with several fragments also increases. Figure 10 shows the dependence of the relative number of disintegrations with fragments on the number of fragments in one disintegration for various incident proton energies, prepared from the available data in the literature.[3, 16] At proton energies above 2 Bev, the disintegrations with more than two fragments ($Z \geq 3$) begin to predominate.

Just like low-energy protons, 930-Mev protons produce fragments primarily in multiprong disintegrations, where the probability of fragment emission increases with the total number of particles in the disintegration. As shown

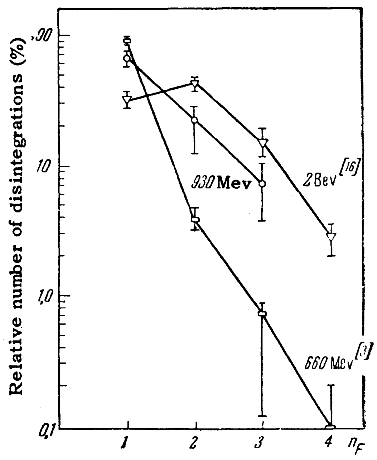


FIG. 10. Dependence of yield of disintegrations with fragments on number of fragments in a disintegration (n_F) for various incident proton energies E_0.

in Figs. 4 and 5, the probability of the production of fragments in one disintegration is a function of both the number of "cascade" particles with $E_p > 30$ Mev and the number of comparatively slow particles with $E_p < 30$ Mev. The character of this dependence is, in general, in agreement with that obtained at other proton energies.[3,17]

In order to explain the dependence of the probability of fragment emission on the number $n_{\alpha p}$ of slow particles ($E_p < 30$ Mev), Fig. 4 also shows the variation of the fragment production probability with the number of particles $n_{\alpha p}$ for lower proton energies, taken from the work of Lozhkin.[3] From an examination of Fig. 4 it is seen that the relative probability of disintegrations with fragments for an incident proton energy of $E_0 = 930$ Mev and a given number $n_{\alpha p}$ is greater than for 660 and 420 Mev. As is known,[18] the relative number of "cascade" particles among all particles with $E_p < 30$ Mev increases with the energy of the incident particles. Thus, the more rapid increase in the fragment production probability with an increase in the total number of particles in a disintegration produced by high-energy incident protons can be related to the change in the total number of "cascade" particles, while the excitation energy of the residual nucleus even decreases (for a given value of $n_{\alpha p}$) with the increase in the energy of the incident particles.

Another interesting feature of the fragmentation process is the dependence of the anisotropy of the angular distribution of the fragments (with respect to the direction of the incident particles) on their energy. As is known, the angular distribution of fragments in the laboratory system is essentially anisotropic with respect to the forward—backward direction, where the size of this anisotropy can by no means be explained by the velocity transferred from the target nucleus. Figure 11 shows the data describing the change in the anisotropy of the angular distribution with a change in the incident proton energy. The decrease in the angular anisotropy determined from the ratio of the number of fragments emitted in the forward and backward hemispheres with respect to the incident particles is quite clearly seen. Since we know that with an increase in the energy of the incident particles the relative number of "cascade" particles among all particles in the disintegration increases, and, together with this, the angular distribution "spreads

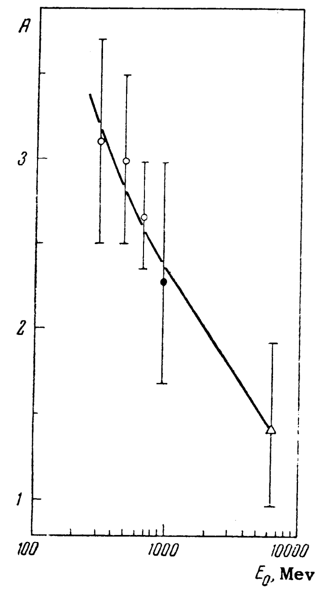


FIG. 11. The anistropy of the angular distribution of fragments as a function of the incident-proton energy. A – the ratio of the number of fragments emitted in the forward and backward hemispheres (relative to the direction of the incident protons); ● – data from the present work, ○ – reference 3, Δ – reference 12.

out" with respect to the direction of the incident particles, the decrease in the angular anisotropy with increasing energy of the incident protons and the dependence of the fragment yield on $n_{\alpha p}$ can be explained by the interconnection between the cascade-particle and fragment production processes. If the fragments are due to "evaporation," the fragment angular distribution should be all the more anisotropic with an increase in the energy of the incident particles, owing to the increase in the momentum transferred to the nucleus.

The poor statistics of recorded fragments did not allow us to obtain the energy distribution of fragments with $Z \geq 4$. From the results obtained and from comparison with published data[10,17] it can be concluded only that the most probable energy of such fragments almost does not differ from the most probable energy at both lower and higher energies of the incident protons E_0. This conclusion can also be made from a comparison of the energy spectra of lithium for various energies of incident protons (see Fig. 6).

C. Remarks on the Mechanism of the Fragmentation Process. Examination of the experimental data on the emission of multiply charged particles in disintegrations obtained in this work and their comparison with data at other incident-particle energies allows us to draw several conclusions on the basic aspects of the fragmentation process. A number of characteristics of the production process for multiply charged particles prove to be functions of the energy of the incident particles E_0. With an increase in E_0, the cross section for fragment production, the multiplicity of fragment production in one disintegration, the mean number of protons and α particles in disintegrations with fragments, and the probability of fragment emission for a given number of α particles and protons in the disintegration all increase, while the anisotropy of the angular distribution of the fragments with respect to the direction of the incident particles decreases. Moreover, it is known that with increasing incident-proton energy the very shape of the curve of the fragment production cross section vs. atomic weight of the target nucleus changes. At proton energies $E_0 = 300 - 400$ Mev the production cross section for the Li^8, Be^7, C^{11}, and F^{18} isotopes decreases by almost three orders of magnitude as one goes[19,20] from Al to Pb, while at an energy of $E_0 > 3$ Bev the opposite is observed for the Be^7 and F^{18} isotopes, i.e. a certain increase in the cross section with an increase in the atomic weight of the target nucleus.[15]

Along with this, several characteristics of the process of fragment production apparently are either not functions of the energy of the incident particles, or very weakly depend on it. These are, first, the charge distribution of the fragments, which remains constant over a large range of energy of the incident particles, and, second, the energy distribution of the fragments. Although with an increase in the energy of the incident particles the relative number of fragments with energies exceeding the repulsive Coulomb barrier increases, the most probable fragment energy remains almost unchanged and close to the value of the Coulomb barrier of the nucleus.

The above-mentioned features of the fragment production process in nuclear disintegrations, and also all the other features mentioned in this article and known at present from other work, should be explained by some single mechanism of their formation in the nuclear disintegrations. Such a mechanism should also explain the production, in part, of lighter nuclei such as helium or the heavy isotopes of hydrogen, since, in principle, there should be no sharp difference between small and large clusters of nucleons. The results of experiments in which the characteristics of the process of fast α-particle production in the disintegration of Ag and Br nuclei were investigated[21,22] serve as a basis for this.

At the present time the ''cascade-evaporation'' model is generally accepted for the interaction of high-energy particles with nuclei. The occurrence of fragments in the cooling-down process of an excited nucleus has been considered by a large number of authors.[3,9,10,17,23-26] At present it may be considered that the bulk of the experimental data on the production of Li and Be fragments is in sufficiently satisfactory agreement with the calculations based on the theory of evaporation, both as regards the probability of their emission (as compared to protons) and the dependence of this probability on the excitation energy of the residual nucleus and the energy of the incident particles, and as regards the shape of the fragment energy spectrum. When it comes to fragments with $Z \geq 4$, the agreement with the theory of evaporation as to the production probability is far worse. The probability of the production of fragments with $Z \geq 4$ turns out to be higher than that which can be expected from evaporation theory.[3,10] Furthermore, the hypothesis of the production of fragments in some equilibrium process of the evaporation type disagrees with such characteristics of the fragmentation process as the independence of the fragment charge distribution of the incident-particle energy, the increase in the fragment production cross section with increasing atomic number of the target nucleus, the large anisotropy in the angular distributions of the fragments, and the fact that several fragments are emitted in one disintegration.

Therefore, the analysis of the evaporation mechanism does not offer much promise for the further development of views on the fragmentation process. One can also find many contradictions between the known characteristics of the fragmentation phenomenon and the suggestion that fragments are caused by fission of the nuclei. They concern the energy and angular distributions of the fragments produced, as well as the cross sections for both processes, and the mass and excitation energy distributions.[3]

Thus the fission mechanism apparently cannot give results that explain the fragmentation process.

Far more promising is the suggested connection between the fragment-production process and the cascade process in the nucleus. There are direct experimental data indicating the existence of such a connection. These are the dependence of the fragment-production probability on the number of "cascade" particles, the angular anisotropy of the fragments with respect to the direction of the incident particles, and the dependence of the fragment-production probability on the energy of the incident particles for a given number of particles in the disintegration. One can explain from this standpoint such characteristics of the fragmentation process as the fact that the Z distribution of the fragments remains constant for various incident-proton energies E_0, the decrease in the anisotropy of the angular distribution of the fragments with increasing energy of the protons, and some others.

To verify the given picture of the occurrence of fragments in nuclear disintegrations, apart from the further accumulation of experimental data, it would be desirable to carry out the corresponding calculations of the nuclear cascade process type by the Monte-Carlo method.[27] In so doing, it would be useful to assume the existence in the nuclei of definite clusters of nucleons with some momentum distribution, and the possibility of quasi-elastic scattering of the cascade nucleons and clusters of nucleons by other nucleons in the nucleus and by their clusters. All this complicates greatly the concepts which serve at the present as the basis of calculations of the nuclear cascade process by the Monte-Carlo method. The difficulty involved in such calculations results from the insufficient knowledge of the differential cross sections for the scattering of fast nucleons on light nuclei, and especially their scattering on one another.

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