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Heavy Nuclear Fragments from Disintegration Produced by Fast Protons in Nuclear Emulsions*

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Fine-grain type P–9 nuclear emulsions have been used for the study of that interaction process of 350 to 660 mev protons with the nuclei of the emulsion which leads to the formation of multiple–charge particles with $Z \geq 4$. It has been observed that the production of multiple-charge particles of high energy (E_{kin} per nucleon > 3–4 mev) takes place on the light nuclei of the emulsion (*C*, *N*, *O*) as well as on the heavy ones (Ag, Br). The main characteristics of the nuclear fragment disintegration have been investigated. The analysis shows that—to explain the formation of fragments—one has to assume a series of specific properties of primary interactions of fast protons with nuclei

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1. INTRODUCTION

IT has been noted long ago[1–7] in the study of the stars produced by cosmic rays in nuclear emulsions that, in addition to hydrogen and helium isotopes, heavy nuclear fragments with $Z \geq 3$ are also emitted by the disintegration of the nucleus. Similar multiple–charge fragments have been observed[8–14] in the disintegration produced by fast protons, neutrons and α-particles with energy in the hundreds of mev. The study of their formation mechanism has indicated a series of peculiarities which have not been explained until now. The experimental data[15–17] show that the emission of the fragments cannot be explained by the usual model of evaporation of the highly excited nucleus or highly asymmetric fission. There is also a series of arguments against the assumption of a spallation mechanism of their formation.

A study of nuclear disintegration with emission of particles with $Z \geq 4$ has been carried out in our laboratory since 1955. We are reporting below the main results of our experiments.

2. EXPERIMENTAL METHOD

The experiment has been carried out on fine grain nuclear emulsions of type P–9, irradiated by protons with energy of 350, 460, 560 and 660 mev, from the synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Science.

The use of fine grain emulsions, sensitive to protons with energy of about 30 mev, permitted visual discrimination between particles with multiple charge and α-particles or protons. This is possible because of the good differentiating capacity of the fine grain emulsion, and because of the well known fact that the tracks of the particles with multiple charge have a characterisitc thin-down toward their end.

It has been shown, by means of photometric measurements on the track of multiple-charge particles of known nature, that a reliable visual identification of such particles is possible only for $Z \geq 4$. The latter may be seen in Fig. 1, which shows the darkening $(I_\varphi - I_C)/I_\varphi$ as a function of the residual path length for the ions N^{14}, B^8 and Li^8 in a P–9 emulsion. The darkening along the path can be appreciated visually in a reliable fashion only if it is not less than 15% for 25 μ of the path; a reliable visual discrimination between particles with multiple charge and α-particles is therefore possible only for $Z \geq 4$. The tracks of particles with $Z = 3$ can hardly be differentiated visually from the tracks of α-particles.

The experimental data described below correspond therefore to the events of radiation of particles with $Z \geq 4$ in nuclear fissions. Also included in the statistics are events of radiation of Li^8–nuclei (because of their reliable identification), and events of radiation of pairs of α-particles of approximately equal energies that are emitted in directions forming small angle (≈ 1 to 3°); these particles are apparently[15] the decay products of $Be_4{}^8$ nuclei.

Figure 2 shows some examples of nuclear disintegration where the emission of one or several particles with multiple charge has been observed. The microphotographs show well the main characteristics of the tracks of the particles with multiple charges: high grain density and presence of darkening which enables us to differentiate them from α-particles.

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*The main results of this work have been reported at the All Union Conference on High Energy Particles Physics (May, 1955), and at the International Conference on Nuclear Reactions at Amsterdam (June, 1956).

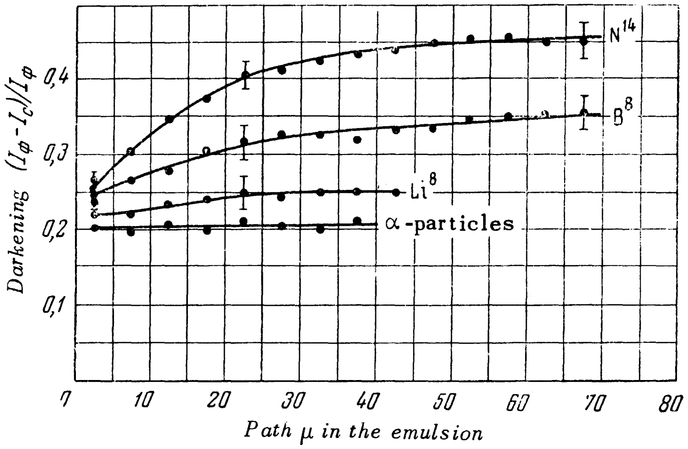

FIG. 1. Dependence of the darkening $(I_\varphi - I_c)/I_\varphi$ on residual path for ions N^{14}, B^8 and Li^8 in the P–9 emulsion.

The nuclear disintegrations which were observed to yield particles with multiple charge have been subjected to measurements with an ocular goniometer and an ocular scale. Furthermore, the multiple-charge fragments found in the plate irradiated by 660 mev protons have been investigated photometrically to determine their charge. The photometry has been performed with a "wide" slit the(width of the slit was larger than the width of the track) of dimensions $5 \times 0.8\ \mu^2$. The dependence of the total darkening on the residual path $(I_\varphi - I_C)/I_\varphi = P(R_{\text{resid}})$ was obtained. The charge was determined by a method described in Ref. 18, with the use of the slope of the curve $P(R_{\text{resid}})$ characterized by a certain average of the change $\overline{\Delta P}$ on the first 25 μ of the track from the end of the track, and a scaling curve which relates $\overline{\Delta P}$ to Z. The scaling curve was obtained from the experiment in the emulsion P–9 of the known particles N^{14}, B^8 and Li^8.

A few words should be said about the means of differentiating between the stars on light nuclei of the emulsion (C, N, O) and the stars on heavy ones (Ag, Br).

The following criteria were used: the presence or the absence of a recoil nucleus track and the total charge of the fission fragments which should not exceed 8 for a light nucleus. The accuracy of such a differentiation was checked by the amount of angular anisotropy for the fragments formed on the light nuclei, and by the results of the measurements of the fragments' charge: if the number of the tracks radiated from the star is ≤ 4, and there is no recoil nucleus track, the measurements do not give a value > 8 for the charge of the fragment.

3. EXPERIMENTAL RESULTS

In this section a description will be given of the experimental data for 660 mev protons; the characteristics of the fragments emission process are quite similar at other proton energies in the range which was studied.

1) *Yield of nuclear disintegrations with multiple charge particles*

The interaction of fast protons with the nuclei of the elements of the emulsion leading to the formation of stars with fragments is a very rare event for the proton energy range considered here. An important property of the process of fragments radiation is the fast rise of the yield when the proton energy is increased. Figure 3 shows the dependence on the energy of the inducing protons of the relative number of stars with fragments. The total number of such stars which was observed in the emulsion is 2500. The relative number of stars with fragments increases more than twice when the proton energy varies from 350 to 660 mev.

The relative yield of fragment disintegration of heavy nuclei has been determined with respect to the total number of stars with fragments at the proton energies of 350, 460 and 660 mev. A total of about 1000 stars with fragments has been analyzed at the proton energy of 660 mev, and about 250 stars with fragments have been analyzed for

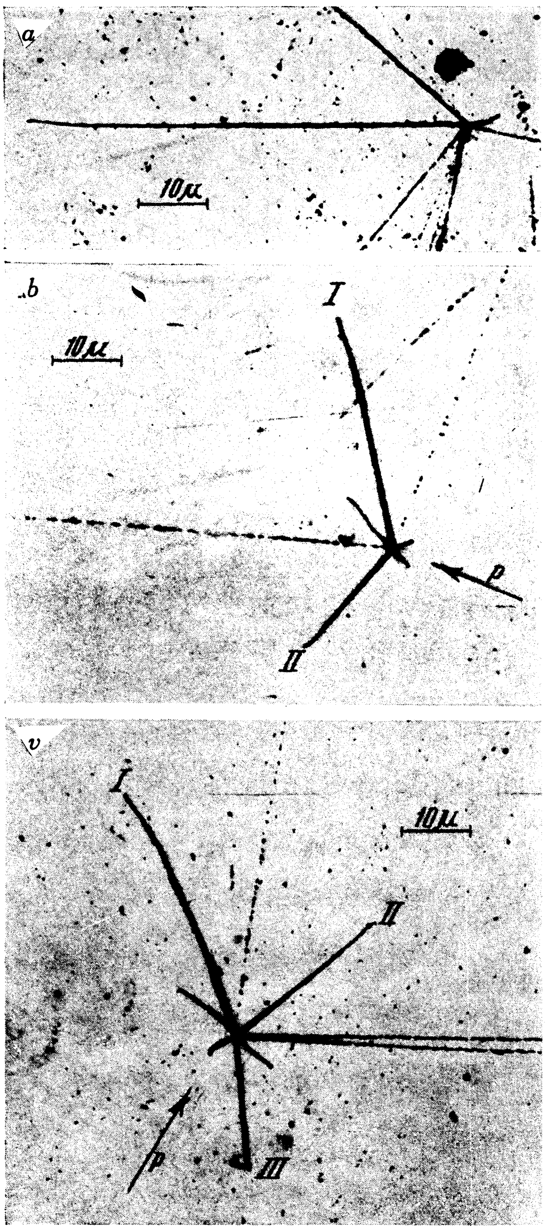

FIG. 2. Microphotographs of stars with fragments due to the disintegration of Ag and Br nuclei induced by 660 mev protons: *a*—disintegration with a single particle with multiple-charge ($Z = 7 \pm 1$), *b*—disintegration with two particles with mutliple charge ($Z_I = 7\pm1$. $Z_{II} = 8\pm1$), *v*—disintegration with three particles with multiple charge and with a recoil nucleus ($Z_I = 7\pm1.5$, $Z_{II} = 6\pm1$, $Z_{III} = 4\pm1$).

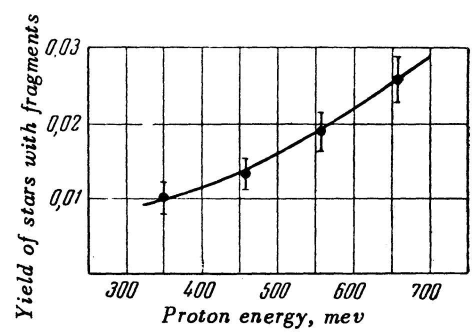

FIG. 3. Dependence of the relative yield of stars with fragments on the proton energy.

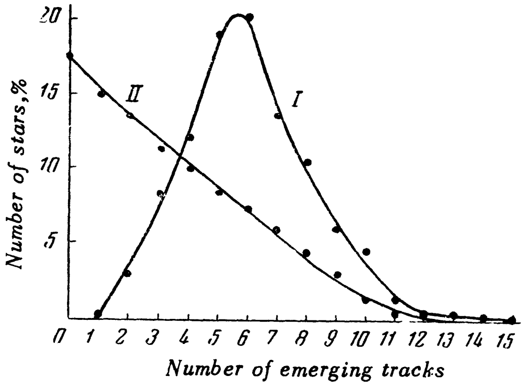

FIG. 4. Distribution of stars according to the number of rays: *I*—stars with fragments; *II*—stars without fragments, according to ref. 21.

each one of the 350 and 460 mev energies.

A lower limit to the number of fragment disintegrations produced on Ag and Br nuclei is about 80, 70 and 65% for the proton energies of 660, 460 and 350 mev respectively. From these data, and from the value of the total inelastic cross section of fast protons on Ag and Br nuclei, it is possible to estimate an approximate value of the absolute cross section of the interaction leading to disintegration with fragments. This cross section turns out to be of the order of 10^{-26} cm^2—which is appreciably larger than the value of the cross section obtained by the radiochemical method[14,17,19,20]. This discrepancy could be due to a relatively large contribution of the stable isotopes of the particles with multiple charge being considered.

The process of fragment formation on heavy nuclei of the emulsion has another important property. As one can see in Fig. 4 (which shows the distribution of the stars with fragments on Ag and Br nuclei according to the number of rays), the particles with multiple charge are mainly related to multiple-ray stars. From the comparison of the distribution of stars with fragments according to the number of rays with the analogous distribution of stars without fragments (obtained from the work of Ostroumov[21]), the following conclusion can be drawn: the probability offormation of stars with fragments rises with the increase of the number of the rays in the star. The mean number of α-particles and of protons in the stars with fragments produced on Ag and Br nuclei is close to 5 for a proton energy of 660 mev; the number of α-particles and protons is approximately 3.5 in the case of the usual disintegrations.

In addition to single-fragment stars, the interaction of fast protons with heavy nuclei can produce disintegration withtwo or more multiple-charge particles for which $Z \geq 4$. Examples of such disintegrations are shown on the microphotographs of Fig. 2. It should be noted that in these cases there is, in addition to the multiple-charge particle tracks, a recoil nucleus track. For a proton energy of 660 mev, the disintegrations with two particles having $Z \geq 4$ is approximately equal to 0.04 relative to the total number of single-fragment stars; the yield of stars with three multiple-charge particles is approximately 0.009 relative to the single-fragment stars. It should be emphasized that the cases of radiation of two multiple-charge particles in a single disintegration considered here are such that their characteristics do not allow their interpretation by the process of fission. The number of cases which can be interpreted as a fission of Ag or Br nuclei into fragments of comparable masses is about 3% of the total number of stars with fragments. In the further analysis such cases were not considered.

As far as the distribution of the stars with two fragments according to the number of rays is concerned, it should be noted that they have a somewhat larger mean value of α-particles and protons (5,6) than the stars with single fragments (5).

2) *Charge distribution of fragments due to disintegration of Ag and Br nuclei*

For the determination of the distribution mentioned, 142 fragments from the stars formed on Ag and Br nuclei were subjected to photometric measurements. The distribution ofthe quantity ΔP for the measured tracks is shown in Fig. 5; this gives a feeling of the degree of differentiability between particles of neighboring charges by the method described. Figure 6 shows the charge distribution of the fragments. In this case, events of emission of Be^8_4 forming pairs of α-particles have been added to the events of particles of charge 4. Two kinds of corrections should be made in this distribution: a) correction for the number of tracks for which the charge could not be measured, because ofthe short path in the emulsion ($< 20\ \mu$) and, b) correction for the number of fragments which left the emulsion (geometry correction). The following could be said about these two corrections: the mean path of the fragment is decreasing with the increase of the charge; therefore the geometry correction will be important for small Z, whereas the first correction is important only for large Z. If one assumes that all the fragments with a path $< 20\ \mu$ (approximately 10% of all the fragments) have a charge > 9, and if one takes into account the distribution of these fragments according to the path, then one can expect a charge distribution which will be approximately uniform up to $Z = 15-16$; for each charge there will be from one totwo fragments. The geometry correction does not play a substantial role for particles with smaller charge, because only such fragments which made an angle $< 14°$ withthe

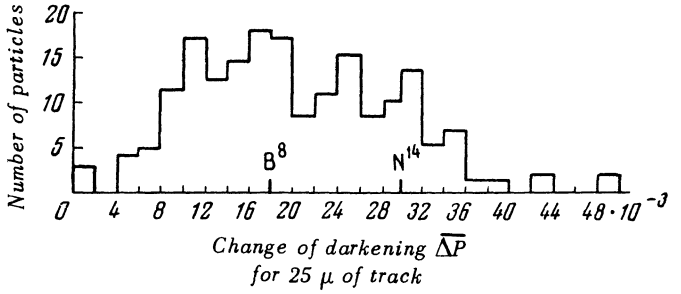

FIG. 5. Distribution of the measured quantities $\overline{\Delta P}$ for mutliple charge particles in disintegration($\overline{\Delta P}$ average change of darkening overthe first 25 μ of track, starting from the end ofthe track).

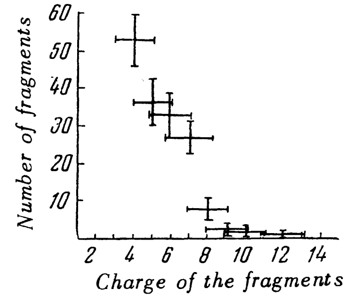

FIG. 6. Distribution of multiple-charge particles from Ag and Br nuclei, vs. charge.

plane of the emulsion were chosen for the photometric analysis.

The character of the charge distribution of the fragments as well as the absolute value of their yield, differs appreciably from what could be expected from the theory of evaporation of a highly excited nucleus. This can be illustrated by the data plotted in Fig. 7; Figure 7 shows, on one hand, the dependence of the probability of emission of multiple-charge particles on the charge of the particles as calculated by the evaporation theory,[22] and on the other hand, the experimental data. In both cases, the probability is given relative to the probability of proton emission. In the calculation by the evaporation theory, it was assumed that, for nuclei with $A = 80$, the mean excitation energy for fragment disintegration is equal to 150 mev.

3) *Angular distribution of charged particles in stars with fragments*

The angular distribution of the α-particles, of the protons and of the fragments (with respect to the proton beam) was investigated in the cases where a disintegration of Ag and Br nuclei (with emission of a fragment with $Z \geq 4$ produced by a proton bombarding energy of 660 mev) was found.

The amount of anisotropy in the angular distribution of the α-particles and of the protons turned out to be quite close to that which is observed for the usual disintegrations of Ag and Br nuclei by 660 mev protons. The ratio of the number of particles in the forward and backward hemispheres (with respect to the proton beam) is equal to 1.37 ± 0.17 and 1.26 ± 0.1 for the α-particles and the protons respectively. The angular distribution of the fragments, relative to the proton beam, shown in Fig. 8, is substantially anisotropic. The ratio of the number of particles in the forward and backward hemispheres is equal to 2.8 ± 0.3. For the 460 and 350 mev protons, the amount of anisotropy is about the same (3.0 and 3.1 respectively). If the center of mass motion is taken into account, these amounts change on the average by no more than 10 –15%.

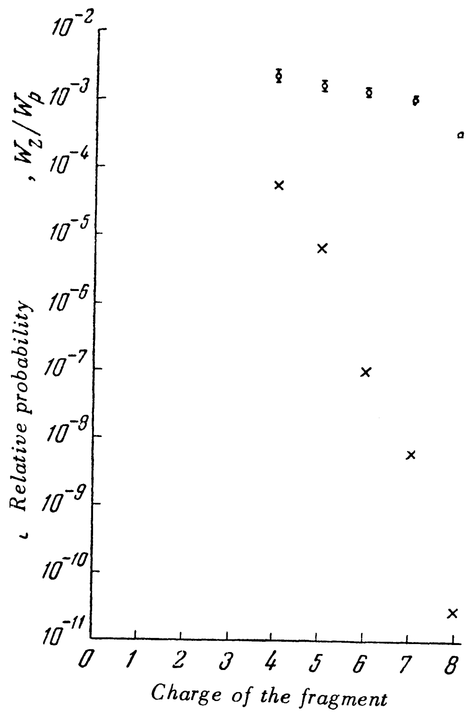

FIG. 7. Dependence of the relative probability (W_z/W_p) of the emission of a fragment on the charge. O—experimental data, × – theoretical calculation of W_z/W_p for the isotopes Be^{9}, B^{11}, C^{12}, N^{14}and O^{16}.

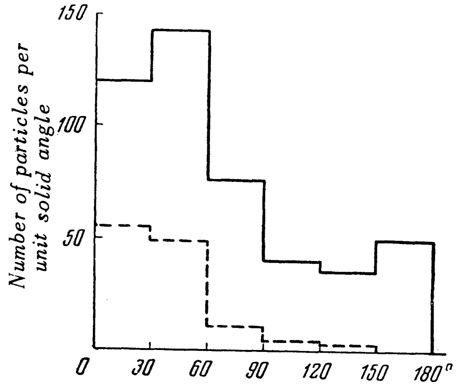

FIG. 8. Angular distribution for the fragments formed on heavy and light nuclei of the emulsion. ———— – fragments in stars on Ag and Br, – – – – – –fragments in stars on C, N and O.

The angular correlation between the fragments and the residual (recoil) nucleus is a problem which presents a substantial interest. It follows from the distributions shown on Fig. 9 that the direction of the recoil nucleus motion in most of the cases is determined by the direction of the fragment's motion; the fragment and the recoil nucleus separate preferentially in opposite directions. In the case of disintegration of Ag and Br nuclei accompanied by the emission of two multiple-charge particles, a definite correlation between the fragments is also observed: in most of the cases the angle between the fragments is close to 180°. Among 32 fissions with two fragments, there are only three cases where the angle between the fragments is somewhat smaller than 90°.

The multiple-charge particles from the interaction with the light nuclei of the emulsion are characterized by a strong forward peaking (cf. Fig. 8). The ratio of the number of particles in the forward and backward hemispheres is about 15 for proton energies of 660 mev. The amount of anisotropy is about the same for 460 and 350 mev proton energies.

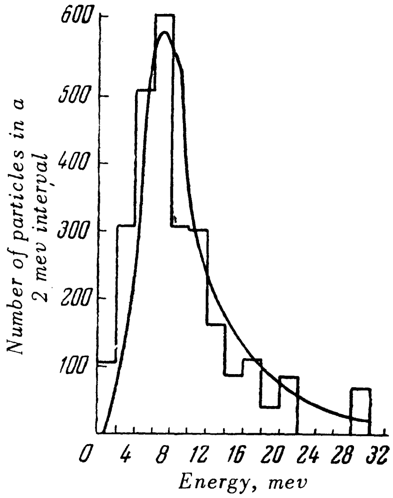

FIG. 10. Energy distribution of protons from fragment disintegration of Ag and Br. The energy of the inducing protons is 660 mev. The curve for stars without fragments was obtained from the data of Ref. 21.

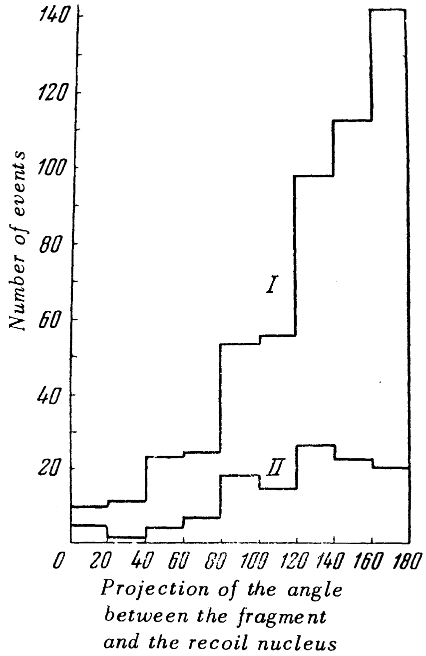

FIG. 9. Angular correlation of the fragment and of the recoil nucleus: I—all the stars, II—stars with a number of rays ≥ 8.

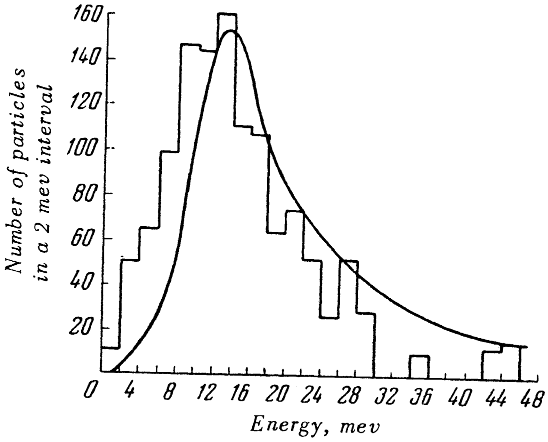

FIG. 11. Energy distribution of α-particles from fragment disintegration of Ag and Br. The energy of the inducing protons is 660 mev. The curve for stars without fragments was obtained from the data of Ref. 21.

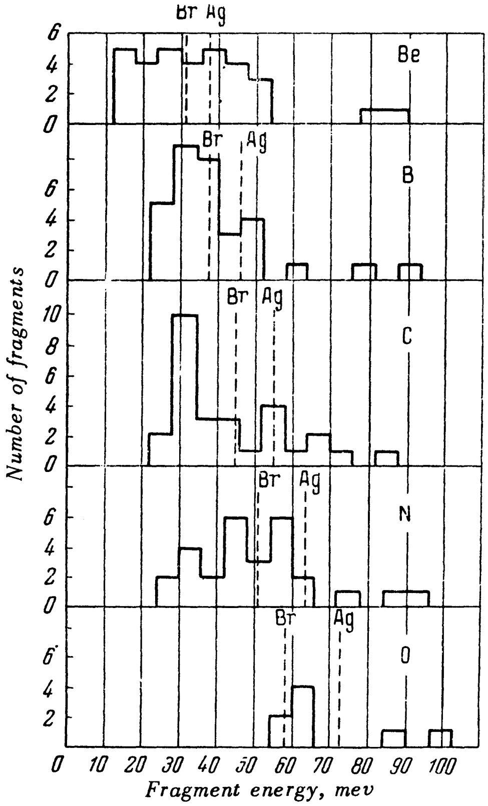

FIG. 12. Energy distribution of multiple-charge particles. The nominal value of the Coulomb repulsion energy for a given Z of the remaining nucleus is represented by a dotted line.

4) *Energy distribution of the α-particles, protons and fragments*

An interesting property of the fragment disintegration of Ag and Br nuclei is a certain difference between the energy spectra of the protons and of the α-particles, and the distribution obtained for the usual disintegrations of the same nuclei by 660 mev protons.[21] The spectra of the α-particles and protons obtained from the particles which have stopped inside the emulsion are shown in Figs. 10 and 11; they have been corrected for geometry. The data of Ostroumov[21] —spectra of α-particles and protons from the usual disintegration of Ag and Br nuclei—is also shown on the graphs. As it can be seen from the graphs, α-particles and protons dominate in the small-energy region of the spectra.

The energy distribution of multiple-charge particles could not be obtained with good statistics because of the small number of photometered tracks. Figure 12 shows the energy distribution of the fragments for $Z = 4, 5, 6, 7$ and 8. From the shape of the distribution, it can be said that, irrespective of the charge, the energy of the particles is in most cases close to the value determined by the Coulomb repulsion between the fragments and the recoil nucleus. The energy distribution for multiple-charge fragments from light nuclei was not investigated. Only the dependence of the mean path of the fragments on the energy of the inducing protons was obtained. As the energy of the protons is increased, the mean path of the fragments from light nuclei increases appreciably. It is approximately 76, 50 and 34 μ for energies of 660, 460 and 350 mev, respectively. The mean path of the fragments from Ag and Br nuclei remains constant for the different proton energies.

An important property of the energy distribution of the fragments radiated by Ag and Br nuclei is that the number of fragments with energies substantially higher than the Coulomb repulsion energy is small.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

The process of formation of fragments with $Z \geq 3$ in the interaction of high energy protons with the nuclei of the emulsion was observed to have the following characteristics.

1. The formation of multiple-charge particles with high energy (kinetic energy per nucleon > 3–4 mev) occurs in the interaction of high energy protons with heavy nuclei of the emulsion as well as in the interaction with the light ones.
2. The probability of fragment radiation rises rapidly with the increase in the energy transferred to the nucleus in the collision with the proton.
3. The particles with $Z \leq 8$ constitute the majority of the fragments observed in the fission of heavy nuclei. The remaining charge distribution is approximately uniform, up to $Z = 15–16$.
4. The angular distribution of the fragments is highly anisotropic; in the case of heavy nuclei (Ag, Br), this anisotropy barely changes when the energy of the inducing particles is increased from 350 to 660 mev (the "forward-to-backward" ratio is approximately 3 to 1). The angular anisotropy in the distribution of the fragments formed from light nuclei (C, N, O) is appreciably larger than for the stars on the heavy nuclei of the emulsion (the "forward-to-backward" ratio is 15 to 1 for 660 mev protons).
5. The energy distributions of particles with different charges have one common characteristic. The multiple-charge particles are distributed in energy principally around the value determined by the Coulomb charge repulsion. In a small number of cases, the energy of the multiple-charge particles exceeds the Coulomb repulsion energy by an appreciable amount.

6. There is a noticeable probability of radiation of two or more multiple-charge particles in a single disintegration of a heavy nucleus. In the case of the radiation of two multiple-charge particles, there is a definite angular correlation between them: in most of the observed cases the angle between the fragments is close to 180°.

7. The energy spectra of the α-particles and of the protons from the disintegration of the Ag and Br nuclei with multiple-charge particles differs somewhat from the spectra of the α-particles and of the protons from the usual fissions; namely they are enriched by particles of small energy.

8. There is a definite angular correlation between the fragment and the recoil nucleus: the fragment and the recoil nucleus separate preferentially in opposite directions.

The process of the interaction of a proton, with an energy of a few hundreds mev, with a heavy nucleus, is nowadays viewed as presenting two stages. In the first stage, the collision of the incoming particle with the nucleons in the nucleus produces a nuclear cascade process, as a result of which a certain number of protons, neutrons and possibly α-particles are knocked out from the nucleus; the remaining energy is statistically distributed among the nucleons of the nucleus . The phenomena which occur in the second stage of the process are described either by the evaporation model, or by a fission process which would be a result of the vibration of the nucleus (drops if the conditions are adequate). Each of these processes is characterized by a particular angular and energy distribution of the radiated particles.

The angular distribution of the nuclear fragments strongly disagrees with the assumption that a substantial part of these fragments could appear in the processes of usual evporation or fission of a highly excited nucleus. The high probability of fragment radiation, the shape of the charge distribution of the fragments and the formation of two or more fragments in a single fission are also facts which are hard to fit by the evaporation model. This does not exclude the possibility that a small part of the fragments could have an evaporation origin (mainly the fragments with small charge). The latter two situations disagree also with a fission mechanism for the formation of the fragments.** In addition, it is necessary to bear in mind that, in the considered process, we have to deal with fragments which are apparently stable isotopes in most of the cases. This deduction, which was made from comparison of the cross sections of the fragments (see above), is checked also by the investigation of the properties of the residual nucleus in the range of mass numbers which corresponds to the radiation of fragments.[17] . It can be expected, however, that the usual fission mechanism yields principally unstable particles with neutron excess.

Hence, the major part of the fragments observed in the fission of heavy nuclei can be explained neither by the evaporation, nor by the fission process, i.e., by the processes which take place after the energy released has been statistically distributed among the nucleons of the nucleus.

Let us now consider the possibility of the formation of the considered multiple-charge particles in the primary process of the interaction of a fast proton with heavy nuclei. The possibility of the formation of energetic particles with multiple-charge in the process of the collision of the primary proton with a group of nucleons in a heavy nucleus can be assumed, considering the fact that similar multiple-charge particles are formed in the interaction of protons with light nuclei of the emulsion. In the latter case, the observation of multiple -charge particles with high energy (energy per nucleon $\gtrsim 4$ mev) cannot be explained without the assumption of a direct transfer of the energy and momentum of the primary proton to the whole light nucleus or to one of its parts, but without the breaking of the nucleons' binding. The elastic scattering of fast protons by light nuclei at large angles could be such a process. If it is assumed that in the case of heavy nuclei (Ag, Br) the multiple-charge particles are also related to a similar process, then one has to make a series of assumptions to explain the observed characteristics of the fragment disintegration; for instance, 1) one has to assume a substantial, although maybe short lived, existence of strongly bound clusters of nucleons in the nucleus, 2) one has to assume a high probability for the scattering of a fast fragment inside the nucleus, to explain the cases of radiation of fragments on the backward hemisphere and, 3) one has to assume that in addition to the knocking out of the fragment, the residual nucleus is left with a high excitation energy.

In addition to the mentioned assumptions, each one of which can raise objections, there is a series of experimental data, which show the difficulties of the considered effect as a spallation process: for instance, the appearance of two or more multiple-charge particles in a single disintegration with the lack of the expected dependence of the fragment's energy on the energy of the primary particles and on the angle with respect to the direction of the primary particle. Indeed, the comparison of the

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**As discussed in Sec. 3, about 3% of all the stars with fragments can be interpreted by a fission process where Ag and Br nuclei split in fragments of comparable mass. Such cases are not considered here.

observed energy distribution of the fragments for a proton energy of 660 mev with the data from the work of Perkins[15] shows that the mean fragment energy changes only slightly when one switches to disintegration due to cosmic rays, whereas the energy of the primary particles changes drastically. If the spallation interaction is assumed, a substantial dependence of the secondary particles on the energy of the primary ones should be expected. There would also be no dependence of the fragment energy on the direction of the primary proton. This dependence of fragments formed in the disintegration of Ag and Br nuclei by 660 mev protons and whose $Z = 5$ and 6 is plotted on Fig. 13. The dependence calculated from the elastic scattering theory can also be found there.

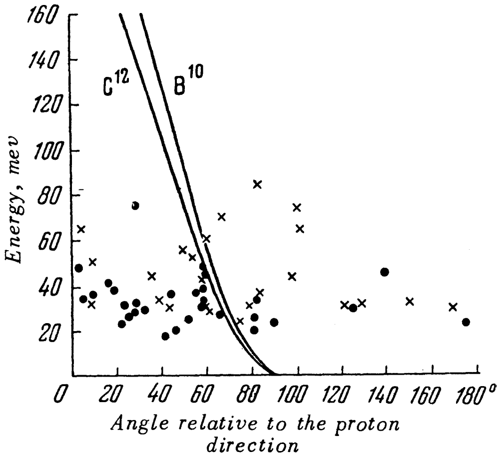

FIG. 13. Dependence of the energy of the fragment with $Z = 5$ and 6 on the angle with the direction of the proton beam: ●—fragments with $Z = 5$, ×—fragments with $Z = 6$. The curves are calculated from the formula for inelastic scattering for a proton energy of 660 mev.

To explain the fragment formation in the interaction of fast protons with heavy nuclei by a spallation process requires the assumption of very specific properties of the collision process. However, one could look for the reason for the multiple-charge particles formation in the primary interaction process of fast particles with nuclei, because it determines all the subsequent behavior of the nucleus.

A series of hypotheses has been made recently in the attempt to explain the effect of fragment formation in the disintegration induced by cosmic rays: the hypothesis of long range nuclear forces; the hypothesis that the fragment radiation is required to lower the high angular momentum of the excited nucleus;[15] the Heisenberg "turbulent effect" hypothesis; and the hypothesis that the fragment radiation is a result of pure surface oscillations.[24] The above hypotheses cannot explain all of the observed data for the disintegration induced by cosmic rays nor do they explain the observations made in the present work. For a more satisfactory explanation, further investigations are required.

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