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# *FRAGMENTATION OF* Ag *AND* Br *NUCLEI BY 9-Bev PROTONS*

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Formation of multiply-charged particles with $Z \geq 4$, due to interaction of 9-Bev protons with Ag and Br nuclei in photographic emulsions, was investigated. The fragment-production cross section, and the angular, energy, and charge distribution of the fragments were determined. The peculiarities of nuclear disintegrations involving the formation of fragments are examined.

## 1. INTRODUCTION

THE fragmentation process, formation of multiply-charged particles with $Z \geq 3$ in nuclear disintegrations, a process which plays a rather small role at comparatively low energies of bombarding particles (on the order of several hundreds Mev), assumes great significance at energies greater than 1 Bev. The cross section of the fragmentation process reaches in this energy range, for silver and bromine, values on the order of 10% of the total cross section of inelastic interaction. This circumstance results in a substantial change in the mass curve of nuclear disintegration products in the region near several Bev. Failure to account for fragmentation in the "cascade-evaporation" model of interaction between high-energy particles and nuclei leads thus to a substantial distortion of the actual picture of nuclear disintegration. In addition, fragmentation is in itself an interesting object of study, for it can yield information on the structural features of nuclei and on the interaction between fast particles and nucleon clusters in the nuclei.

We report here the first results of an investigation of fragmentation at proton energies near 10 Bev.

## 2. EXPERIMENTAL PROCEDURE

Small emulsion chambers containing ten layers of P-R 200-$\mu$ emulsions were bombarded by 9-Bev protons in the proton synchrotron of the Joint Institute for Nuclear Research. The individual layers of the chambers were marked by the method described by Sidorov and Trukhin.[1] The thickness of the emulsion chambers made it possible to obtain complete range distributions of multiply-charged particles produced in the nuclear disintegrations, and the sensitivity of the emulsion to relativistic particles made it possible to observe all the charged particles emitted from the nuclei.

In scanning the emulsion we analyzed nuclear disintegrations containing tracks of particles with $Z \geq 4$, which could be reliably distinguished from tracks of singly and doubly charged particles. In the analysis of the nuclear disintegrations, the tracks were classified as "black," "gray," and "thin" ("black" — proton energy less than 30 Mev; "gray" — proton energy $\leq 1$ Bev; "thin" — proton energy $> 1$ Bev). The number of particles, their angles with the direction of the incident proton, and different characteristics of the fragments were determined.

The fragment charge was determined by measuring the integral track width over a fixed length from the end of the range (see reference 2). The widths were measured with an ocular micrometer on seven sections of the track, spaced every $3\,\mu$ from the end of the range.

## 3. EXPERIMENTAL RESULTS

In scanning the nuclear emulsions irradiated by 9-Bev protons, a total of 1028 disintegrations with more than four prongs were investigated. This number of ordinary disintegrations included 188 disintegrations containing fragments with $Z \geq 4$. An additional 709 disintegrations with fragments were obtained for the investigation of the fragmentation process. Thus, a total of 997 disintegrations with fragments having $Z \geq 4$ were registered.

a) Characteristics of nuclear disintegrations with fragments. One of the essential features of nuclear disintegrations with fragments produced by 9-Bev protons is, as in the case of lower proton energies, the considerably greater average number of par-

| Character of disintegrations | Average number of prongs | | | |
|---|---|---|---|---|
| | "black" | "gray" | "thin" | Total |
| Disintegration without fragments | 8.3 | | | |
| Disintegration with one fragment of $Z \geqslant 4$ | 10.2 | 4.8 | 1.44 | 16.5 |
| Disintegration with two and more fragments of $Z \geqslant 4$ | 11.0 | 5.8 | 1.5 | 18.3 |
| Disintegration with fast fragments | $11.4 \pm 1.5$ | $5.2 \pm 0.8$ | $1.8 \pm 0.3$ | 18.4 |

ticles in the disintegration than in ordinary disintegration, this difference being due, essentially, to relatively slow particles.

The table lists data on the average number of particles in disintegrations with fragments and in ordinary stars.[3] In disintegrations with fragments, the fragments themselves are not included in the number of "black" prongs.

The average number of particles in disintegrations with fragments is considerably greater than in ordinary disintegrations. This number is even greater in disintegrations containing several fragments, and in disintegrations with fast fragments at energies greater than the Coulomb barrier (with ranges greater than $100\mu$).

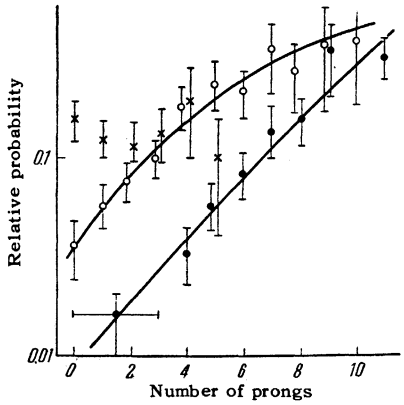


FIG. 1. Dependence of the probability of disintegrations with fragments on the number of prongs: ● – "black," o – "gray," and × – "thin."

This increase in the average number of particles in stars with fragments is due to the considerable increase in the probability of fragment emission with increasing number of particles in the disintegration. Figure 1 shows the dependence of the probability of the production of disintegration with fragments on the number of "black," "gray," and "thin" prongs. A strong dependence of the probability of fragment production on the number of "black" and "gray" prongs in the disintegration is observed. The dependence for the production of fast fragments is analogous.

b) Cross section of production of stars with fragments. The cross section of production of fragments was found starting with the proton current, determined from the number of tracks in the emulsion, the number of nuclei per unit volume of the emulsion, and the observed number of disintegrations with fragments. In addition, the fragmentation cross section can be determined from the known cross section of inelastic interaction of 9-Bev protons with photoemulsion nuclei and the distribution of disintegrations by number of prongs,[3] knowing the relative fraction of stars with fragments among all the disintegrations induced by protons.

The results obtained by both methods were in agreement. The cross section for the production of disintegrations with fragments of $Z \geq 4$ was found to be $100 \pm 30$ mb in Ag and Br nuclei. Thus, the cross section for production of disintegrations with fragments with $Z \geq 4$, for 9-Bev incident protons, was ~ 10% of the total cross section of inelastic interaction. For the sake of comparison with results obtained at lower proton energies, it is useful to determine the cross section of production of $Li_3^8$ and $B_5^8$ nuclei. This cross section amounts to approximately 3 mb for 9-Bev protons.

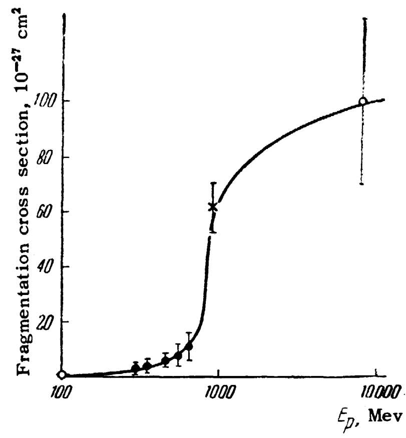


FIG. 2. Dependence of the cross section of production of fragments with $Z \geqslant 4$ in the disintegration of Ag and Br nuclei on the energy of the incident protons, $E_p$: ● – data of reference 4, × – data of reference 5, o – present data.

Figure 2 shows the dependence of the cross section for the production of fragments of $Z \geq 4$ in the disintegration of Ag and Br nuclei on the energy of the incident protons, plotted from data available at the present time. The sharp increase in the cross section at energies near 1 Bev is clearly pronounced.

c) Multiplicity of fragment production. As the the energy of the incident proton increases, the relative fraction of stars containing two or more tracks of multiply-charged particles increases. In the investigation of disintegrations due to 9-Bev protons, it was found that out of 838 disintegrations with one fragment of $Z \geq 4$, there are 144 disintegrations with two, 13 with three, and 2 disintegrations with four such fragments. Thus, the average number of fragments with $Z \geq 4$ in disintegrations with fragments is approximately 1.2. The relative fraction of disintegrations with $\geq 2$ fragments amounts to 0.2 at 9-Bev proton energy, whereas for 660-Mev protons this value is approximately 0.05.[6]

d) Nature of the fragments. To measure the charge, we used tracks of fragments with depth angle not greater than 7° in the developed emulsion and with lengths not less than $15\,\mu$. The emulsion was calibrated with the tracks of $Li_3^8$ and $B_5^8$. A total of 120 tracks of particles of $Z \geq 4$ were measured. The analysis of the resultant distribution of tracks by integral widths has led to the charge dependence of the fragment yield shown in Fig. 3. The same figure shows the distribution of fragments by charge at proton energies of 6.2 Bev.[7]

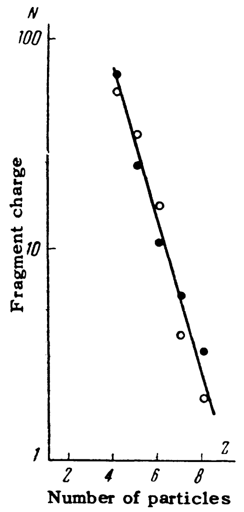


FIG. 3. Distribution of fragments by charge. ● – energy of incident protons 6.2 Bev,[7] ○ – energy of incident protons 9 Bev.

A comparison shows a close agreement between the charge distributions of the fragments at these proton energies. Comparison with the data of references 5 and 6 leads, in addition, to the conclusion that the fragment distribution by charge depends little on the energy of the incident protons.

During the course of the work we investigated the possible $\beta$ activity of the fragments for the purpose of obtaining certain information on their mass distribution. For this purpose we estimated the effectiveness of registration of decay electrons by stopping a $\beta$-active particle in the emulsion; this could be done by observing the decay electrons due to muons and $Li_3^8$ and $B_5^8$ ions stopped in the emulsion. This effectiveness was found to be approximately 70%.

From anong the 175 fragments of charge $Z \geq 4$, investigated for this purpose, we could observe tracks of fast electrons at the end of the fragment range in only nine cases. Of these nine fragments, two are $B_5^8$ ions. Thus, if fragments with $Z \geq 4$ are considered, allowing for the probability of observing the decay electron, we find that not more than 10% of the fragments can be $\beta$-active.

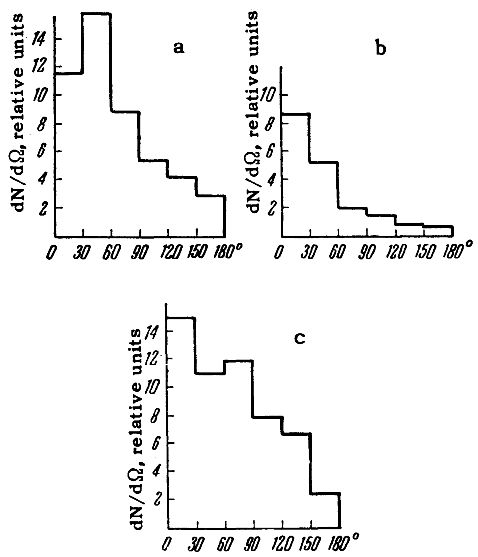


FIG. 4. Angular distribution of fragments with $Z \geqslant 4$ relative to the direction of incident protons: a – disintegrations with one fragment; b – disintegrations with fast fragments, c – disintegrations with two and more fragments.

e) Angular and energy distributions of the fragments. The angular distribution of the fragments with $Z \geq 4$ in space, relative to the direction of incident protons, was found by recalculating the angular distribution found in projection on the emulsion plane, by the method described by Ostroumov and Filov.[8]

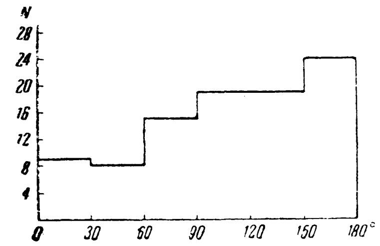


FIG. 5. Distribution of the number of disintegrations with several fragments with respect to the angle between fragment tracks (projected on the emulsion plane).

Figure 4 shows the angular distributions obtained for the fragments, and Fig. 5 shows the distribution of the number of stars with two fragments relative to the angle between these fragments, measured in projection on the emulsion plane. An analogous correlation with the direction of emission of two multiply-charged particles was noted earlier at 660 Mev.[9]

As the fragment energy increases, the angular distribution becomes more anisotropic: for fragments with $R > 100\,\mu$, the forward/backward ratio is $3.6 \pm 1.1$, while for all other fragments the ratio is $2.1 \pm 0.2$.

Along with investigating the dependence of the probability of disintegrations with fragments on the number of thin prongs, a study was also made of the angular correlation between the fragments and fast particles (thin prongs). It was found that for the most part small angles (< 90°) between fragments and thin prongs are observed. A comparison of this correlation with that calculated on the basis of the experimental angular distributions of fragments and thin prongs shows that the observed angular correlation can be attributed to a random distribution of the angles.

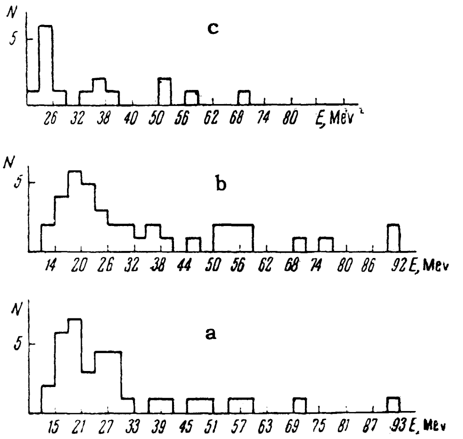


FIG. 6. Energy distribution of fragments with following charges: a – 4, b – 5, c – 6.

The energy distribution (Fig. 6) was plotted for those fragments, the charge of which was determined.

Owing to the identical charge distribution of the fragments at different proton energies, a comparison can be made between the range distribution of the fragments, observed at different energies. Figure 7 shows distributions of fragments with $Z \geq 4$ by ranges at proton energies of 660 Mev (reference 9) and 9 Bev. The difference between the two distributions is due to the different fraction of fragments with ranges greater than $100\,\mu$.

A comparison of these distributions, and also the energy distribution of particles with charges 4, 5, and 6 (Fig. 6) shows that the energy spectrum of the fragments has a weak dependence on the energy of the incident particles. The only important factor is the increase in the relative fraction of fast fragments.

f) Formation of hyperfragments. In a total of 997 investigated fragments with $Z \geq 4$, three cases were found of hyperfragment production, one of which had a charge 6, and the other two had a charge 2 or 3. It must be indicated that the procedure of scanning in our experiment admitted of the possibility of losing sight of a considerable portion of the long-range light hyperfragments (H or He nuclei).

## 4. CONCLUSION

A comparison of the experimental data, obtained in the present investigation for disintegrations of Ag and Br nuclei, with the data available for lower energies of bombarding protons, leads to the following conclusion:

1. If the energy of bombarding protons is approximately 9 Bev, the fragmentation cross section continues to increase, but apparently more slowly.

2. Disintegrations with fragments, at 9-Bev proton energies, are due to the greater average transfer in energy, than in ordinary disintegrations. The probability of a disintegration with a fragment increases with increasing number of both black and gray prongs and is independent of the number of thin prongs.

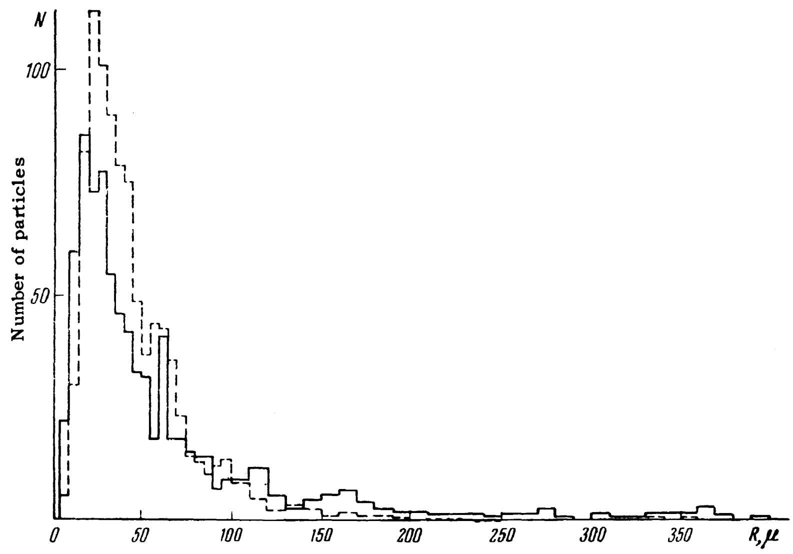


FIG. 7. Distribution of fragments by ranges R at proton energies of 660 Mev (reference 9) (dotted line) and 9 Bev (solid line).

3. The charge distribution differs little from the distributions obtained at lower energies of the bombarding particles.

4. The angular distribution of the fragments at a proton energy of 9 Bev has a lower anisotropy relative to the direction of the incident protons than at energies less than 1 Bev.

5. The fragments produced are for the most part stable isotopes of light nuclei.

6. The energy distribution of the fragments differs little from the distributions obtained at different incoming-particle energies.

In conclusion, the authors take this occasion to thank the High-energy Laboratory staff of the Joint Institute for Nuclear Research for aid in irradiating the emulsion chambers.

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