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SHORT RANGE PRODUCTS FROM NUCLEAR DISINTEGRATIONS INDUCED BY PROTONS WITH ENERGIES BETWEEN 2 AND 9 GeV

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An analysis is presented of the heavy emulsion nucleus disintegrations, in which two short range particles are emitted mainly in opposite directions. It is shown that disintegrations of this type should not be classified as fission of the Ag or Br nuclei, but as disintegrations in which a short-range fragment and a recoil nucleus are formed. The upper limit of the cross section for fission of Ag and Br nuclei induced by 2–9 BeV protons is ~ 1 mb.

INTRODUCTION

If fission accompanies the interaction between high-energy particles and nuclei such as silver, the mass distribution obtained for the product-nuclei by the radiochemical method does not make it possible to separate the products formed during the fission. The reason is the large contribution made by disintegration and fragmentation processes in the region of products with $A \approx \frac{1}{2} A_{\text{target}}$, where the presence of the fission products has maximum probability. Therefore a study of the mass distributions of the product nuclei gives only a very crude estimate of the fission cross section. More reliable information can be obtained by methods which make possible, along with a determination of the fragment mass, measurement of the energy and angular distributions of the product nuclei. In this case the separation of the fission of medium nuclei can be based on definite criteria, which are established in analogy with the fission of heavy nuclei.

Figure 1 shows all the known estimates of the silver fission cross section at different incident-proton energies[1-9]. What is striking in the figure is the exceeding contradictoriness of the different estimates of the fission cross section, due to the indicated difficulties in separating similar events and aggravated by the small value of the measured cross sections. Whereas for incident-particle energies < 1 GeV there is still a crude correspondence between the data of different workers and it can be concluded that the fission cross section increases in the energy region 100–660 MeV, for incident-proton energies ≥ 1 GeV there is evidently a strong disparity between the results obtained by Baker and Katcoff[1] and of the data obtained in our laboratory, although the same nuclear photoemulsion method was used in both cases. Whereas in [1] the silver and bromine fission cross section is given as 110 mb for $E_p = 3$ GeV, according to unpublished data available to us the fission cross section for $E_p = 9$ GeV should be estimated at not more than 1 mb.

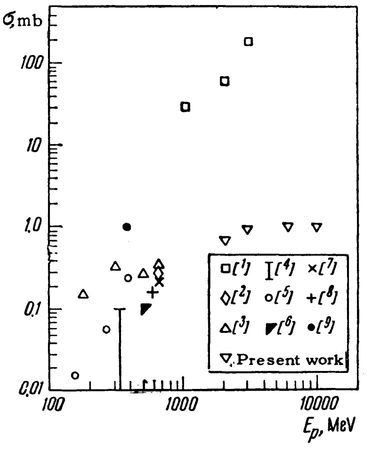

FIG. 1. Dependence of the cross section for the fission of Ag nuclei on the incident-proton energy.

In order to explain so large a discrepancy between the results, we have decided to carry out a thorough analysis of the disintegrations of heavy emulsion nuclei, accompanied by the production of two short-range particles, in the energy region 2–9 GeV. We present here the results of this analysis.

EXPERIMENTAL RESULTS

A stack of nuclear emulsions was irradiated in the internal beam of the Joint Institute proton synchrotron with 2, 3, 6, and 9 GeV protons. The emulsion could register protons up to ~ 150 MeV. From an examination of the kinematic characteristics of the fission of nuclei of the Ag type, it follows that the average range of the fission fragments with $A \approx \frac{1}{2} A_{\text{target}}$ in the emulsion is ~ 8 microns. Therefore, in order to investigate the contribution of the fission process to the nuclear disintegrations, we have decided to study the disintegration accompanied by the emission of particles of arbitrary charge with range $< 15\,\mu$. We thus take full account of all the possible fission products. We set aside for the time being the question of the nature of the indicated short-range products, and consider the features of their production in nuclear disintegrations at incident-proton energy of 3 GeV.

Table I lists the distributions of the disintegrations of Ag and Br by the number N_s of the short-range products with range $R < 15\,\mu$ in one disintegration. N_f is the number of fragments with $Z = 4$–9 and $R \geq 15\,\mu$ in the same disintegrations.

Table I

N_f	N_s			
	1	2	3	4–5
0	~1200	129	27	5
1	208	44	13	2
2	38	8	2	—
3–4	4	—	—	—
σ, mb		20.4	4.7	0.78

The table shows clearly the relatively high probability of production of disintegrations with three and four short-range products. The range distribution of these products is shown in Fig. 2 for ordinary disintegrations and for disintegrations containing one fragment with $Z \geq 4$.

In an examination of Fig. 2 we can note one interesting circumstance. Whereas the range distribution of the single short-range products has a clear-cut maximum and can be well explained by assuming that the bulk of these products comprises residual nuclei from the disintegration process, the range distributions in stars with $N_s \geq 2$ are "smeared" over the entire region of the indicated ranges and have no distinct maximum. In connection with the fission of medium nuclei, which we are considering here, disintegrations with two short-range products ($N_s = 2$) are of particular interest. It is precisely among these disintegrations that we can attempt to find events of the fission type. At first glance the angular correlation (Fig. 3) observed in these disintegrations confirms this point of view: the angles between two short-range particles lie essentially in the interval 140—180°.

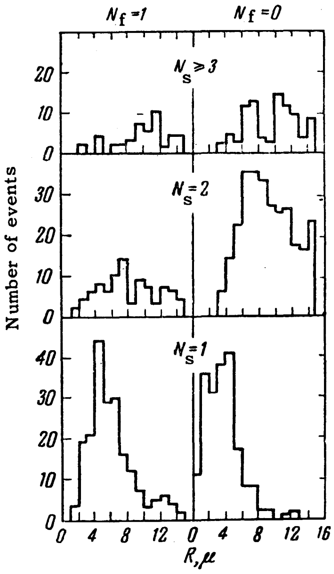

FIG. 2. Range distribution of short-range particles in different disintegrations. N_f – number of fragments with $Z \geq 4$ and range $R_f \geq 15\mu$ in one disintegration; N_s – number of short-range products with range $R < 15\mu$ in one disintegration (data for $N_f = 0$ and $N_s = 1$ are taken from [1]).

Figure 4 shows the distribution of the ratios of the ranges of two tracks with $R < 15\,\mu$ in one disintegration. It is seen from the figure that the short-range particles are produced as a rule with different ranges, and the distribution maximum lies at 1.2.

Finally, it must be noted that disintegrations with two (or more) short-range products belong by their nature to the class of multi-prong disintegrations, similar to those in which fragments with $Z \geq 4$ are observed (Fig. 5): the average number of accompanying charged particles is ~12.

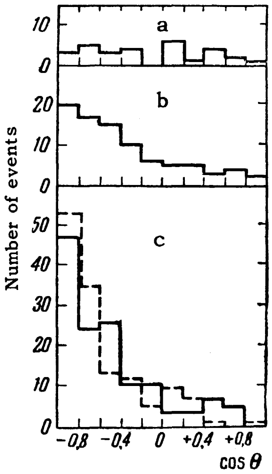

FIG. 3. Distribution with respect to the cosines of the angles (angular correlation) between: a – fragment with $Z \geq 4$ and $R_f \geq 100\mu$ and the recoil nucleus; b – fragment with $Z \geq 4$ and $35\mu \leq R_f < 100\,\mu$ and the recoil nucleus; c – fragment with $Z \geq 4$ and $15\mu \leq R_f < 35\mu$ and the recoil nucleus (solid line) and two short-range products ($R < 15\mu$) in one disintegration (dashed line).

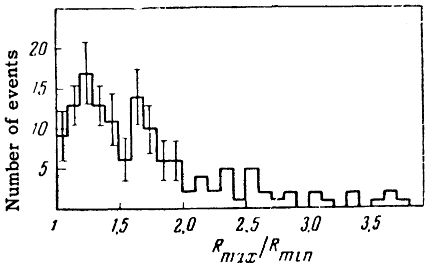

FIG. 4. Distribution of the ratio of the ranges of two short-range products in one disintegration.

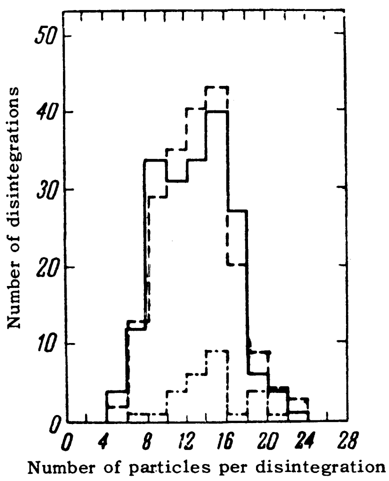

FIG. 5. Prong number distribution for stars containing one fragment and a recoil nucleus (dashed line), two short-range particles (continuous line), and three or more short-range particles in one disintegration (dash-dot line).

DISCUSSION OF RESULTS

If we compare our experimental results (Figs. 2—5) with those obtained by Baker and Katcoff[1], it turns out that all the main characteristics of disintegrations with two short-range particles coincide with the characteristics of that disintegration group, which is assigned in [1] to the fission of the nuclei Ag and Br. This agreement is observed in spite of the fact that in our investigations we studied all the disintegrations in which there are two short-range particles of arbitrary charge, whereas in [1] the investigations concerned disintegrations with two short-range particles with $Z > 7$, emitted approximately in opposite directions. A discrepancy is observed only in the cross sections of these processes. In our case $\sigma(N_S = 2) = (20.4 \pm 1.6)$ mb, and in [1] it is approximately 110 mb at proton energy 3 GeV. The formula which we used to calculate the cross section is given in Appendix 1.

This comparison leads to the following two conclusions.

First, the disintegrations classified by Baker and Katcoff[1] as fissions of Ag and Br include disintegrations with short-range products containing an admixture of particles with $Z < 7$, possibly extending to $Z = 3$. This is connected essentially with the fact that reliable discrimination of particles with $Z > 7$ from the lighter charged particles is very difficult at such small ranges ($\sim 10\,\mu$). In fact, the specific losses of the nuclei N_7^{14} and Li_3^8 at a residual range of $10\,\mu$ amount to 1.5 and 0.87 MeV/μ, so that this difference does not exceed a factor of 2, while the difference in the density of the developed grains will be much smaller.

Second, the estimate of the cross section given in [1] is patently exaggerated. The reason for this, in our opinion, may be the underestimate in [1] of the contribution made to the total inelastic cross section by those disintegrations which are not registered in the low-sensitivity emulsion. The correction for this contribution for the emulsion used by Baker and Katcoff, which registered alpha particles only up to 50 MeV, was approximately 10%, whereas for our more sensitive emulsion, for which we introduced a correction only for stars with 0—2 prongs, it amounted to 34%.

Ionization measurements of short-range tracks in our emulsion have shown that reliable discrimination between fragments with $Z = 4$—9 and the possible fission fragments of Ag and Br ($Z \sim 20$) does not exist[10]. Therefore, to clarify the nature of the disintegrations with two short-range tracks, and the possible presence among them of events of the fission type, a thorough analysis is necessary of all other properties of these particles. In this analysis account must be taken of the following factors:

1. The maximum of range distribution for fragments with $Z \geq 4$ at incident-proton energies of several GeV is located at ~ 20—25[11]. This distribution contains a subbarrier part, extending to ranges $\sim 5\mu$, that is, the existence of a considerable number of fragments with range $< 15\,\mu$ is possible (see Appendix 2).
2. Fission of nuclei of medium weight at high energies has apparently a symmetrical character [12]. Therefore the maximum in the distribution of the range ratios of two fission fragments should lie close to unity.
3. The fraction of triple and quadruple fissions of nuclei is small compared with the number of double fissions. For uranium, however, it amounts to $\sim 0.1\%$ for a proton energy of 660 MeV[13].

If we turn to an examination of Table I and Fig. 4, we see that the latter two conditions do not satisfy the disintegrations considered by us. From this we can conclude only that the main fraction of these disintegrations is not the fission of Ag and Br. It is most probable that these disintegrations can be regarded as disintegrations containing one or more short-range fragments and a recoil nucleus. Evidence in favor of this statement is apparently the fact, noted in [1], that the energy spectra of the alpha particles coincide in the distributions accompanied by short-range particles and in the ordinary distributions, which are more sensibly treated not as an indication of an emission fission mechanism, which has low probability in this case, but as an indication of a small difference between the mechanisms whereby both types of disintegrations are produced. This agrees also with the fact that the amount of energy released in disintegrations with $N_S \geq 2$ does not differ from the energy released by star production with ordinary fragments ($R \geq 15\,\mu$) and a recoil nucleus. Figure 5 demonstrates this premise clearly.

If we regard one of the short-range particles in disintegrations with $N_S = 2$ as a recoil nucleus, and the other as a short-range fragment, then it is natural to classify the particle with the shorter range as the recoil nucleus and that with the larger range as the fragment. Separating the particles in this manner, we can compare their angular and range characteristics with the same characteristics that are obtained for ordinary recoil nuclei and fragments with $R \geq 15\,\mu$ from disintegrations, in which the latter appear together. Such a comparison is given in Figs. 6 and 7. It is seen from Fig. 6 that the short-range particles from stars with $N_S = 2$ have a range distribution similar to the distribution of the recoil nuclei. but shifted somewhat towards the larger ranges. The shift amounts to $\sim 2\,\mu$. At the same time, the distribution of particles with larger ranges has no maximum whatever, and increases monotonically with increasing range. The character of this distribution offers evidence that we are dealing apparently simply with a subbarrier tail of the range distribution of the fragments.

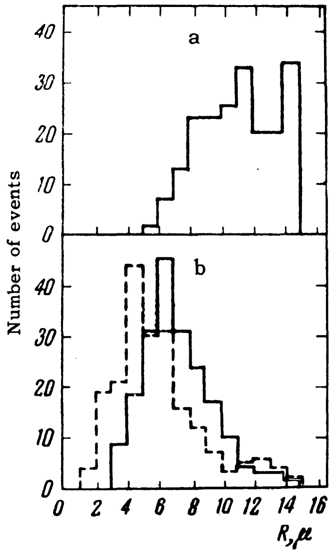

FIG. 6. Range distribution of short-range particles: a – for the product with the largest range in one disintegration; b – for the product with the smallest range (continuous line), and also for the recoil nuclei of disintegrations containing one fragment with $Z \geq 4$ and $R_f \geq 15\,\mu$ (dashed line).

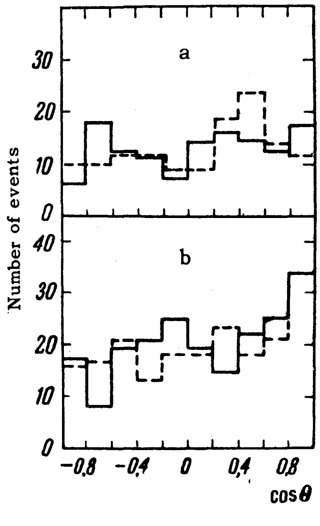

FIG. 7. Angular distributions of different products: a – for the product with the largest range from among two short-range products in a single disintegration (solid line) and for the fragment with $Z \geq 4$ and range $15\,\mu \leq R_f < 35\,\mu$ from stars containing one fragment and a recoil nucleus (dashed line), b – from the product with the smallest range among two short-range products in a single disintegration (solid line) and for the recoil nucleus of disintegrations containing a fragment with $Z \geq 4$ and $15\,\mu \leq R_f < 35\,\mu$ (dashed line).

A comparison of the angular distributions of the products with smaller and larger ranges with the distribution of the recoil nuclei and fragments with ranges $15\,\mu \leq R_f < 35\,\mu$ shows no difference whatever between them within the limits of statistical errors (Fig. 7).

Thus, the idea that stars with $N_S = 2$ contain a recoil nucleus and a short-range fragment does not contradict the description of ordinary stars, which contain simultaneously a fragment with $R_f \geq 15\,\mu$ and a recoil nucleus. This is also confirmed by the excitation function for disintegrations with $N_S = 2$, which is similar in character to the excitation function for the fragmentation process.

Let us consider, in addition, the dependence of the angular correlation between the ordinary fragment and the recoil nucleus on the range of the fragment (Fig. 3). From Fig. 3 it is seen that it varies monotonically with the fragment range. The long-range fragments ($R_f \geq 100\,\mu$) do not correlate at all with the recoil nucleus. For fragments with ranges $R_f < 100\,\mu$, the smaller the range of the fragment, the stronger angular correlation at larger angles. Such a variation of the angular correlation with variation of the fragment range can be readily understood by recalling the range—energy dependence for different fragments. At a given energy, the smaller the fragment mass and charge the larger its range. Therefore smaller ranges in fragment range spectrum correspond to heavier fragments; the subbarrier range region contains, with maximum probability, the heaviest fragments.

For fragments with range $15\,\mu \leq R_f < 35\,\mu$, the character of the angular correlation is shown in conjunction with the angular correlation of two short-range particles. We see that the degree of correlation is even smaller than in the latter, but it is not so small as for fragments with larger ranges. As already mentioned, a subbarrier "tail" is expected in the distribution of the fragment ranges, so that the angular correlation between the subbarrier fragments and the recoil nuclei should be even more sharply pronounced than for fragments with $15\,\mu \leq R_f < 35\,\mu$, that is, it should have approximately the same character as observed for two short-range particles. It follows therefore that the presence of the angular correlation of two disintegration products is still insufficient to classify the disintegration itself as fission.

From all the foregoing we must conclude that the bulk of the disintegrations accompanied by production of two short-range particles cannot be fission of Ag and Br nuclei. Most characteristics of these disintegrations do not contradict the assumption that they are ordinary disintegrations containing a short-range fragment along with the recoil nucleus. The short-range fragment, which correlates with the recoil nucleus and whose ionization density does not differ greatly from that of the possible fission fragments, produces in the nuclear emulsion a picture similar to that expected for fission processes.

What is the true fraction of the fission of Ag and Br nuclei at such high energies? Inasmuch as the ionization measurements do not make it possible to answer this question exactly, we can estimate it indirectly by starting with the premise that the fission of these nuclei has a predominantly symmetrical character. Using the distribution of the range ratios (Fig. 5) and selecting sufficiently dense particle tracks, we estimate that the upper limit of the fission cross section in this region of energy is not larger than 1 mb.

APPENDIX 1

The cross section was estimated in the following manner. The cross section σ_f of any process of interest to us on heavy emulsion nuclei of Ag and Br is connected with the concentration of these nuclei N_h and the flux of incident particles N_p by the simple relation $\sigma_f = N_f / N_p N_h$, where N_f is the obtained number of necessary events. In turn, $N_p = N_t / \Sigma_i N_i \sigma_{t_i}$, where N_i is the concentration of the i-th component of the nuclear emulsion, σ_{t_i} is the total inelastic cross section by the nuclei of this component, and N_t is the total number of inelastic interactions. Hence

$$\sigma_f = \frac{\Sigma_i N_i \sigma_{t_i}}{N_h} \, \frac{N_f}{N_t}.$$

Knowing the concentrations of the different nuclei in the emulsion and the total inelastic cross sections for them, we can calculate the first factor of the above formula for the employed emulsion. For our emulsion we got $\sigma_f = 1375\, N_f / N_t$, where N_f and N_t are taken in the same volume of the emulsion. Since the registration of inelastic disintegrations was carried out by us for stars with $N_h \geq 3$ black and gray tracks, in order to find N_t we must add to the observed number of stars with $N_h \geq 3$ the unobserved number of stars with $N_h = 0$, 1, and 2. An estimate of this number was made on the basis of several investigations[14]. For energies 2, 3, 6, and 9 GeV it amounts to 36, 34, 32, and 31 per cent, respectively.

APPENDIX 2

The presence of strong subbarrier fragments can be clearly illustrated with Li_3^8 as an example.

In Table II are gathered all the cases registered by us in which Li_3^8 fragments with $R_f \leq 15\,\mu$ appeared, corresponding to energies ≤ 7.3 MeV. The most probable energy in the Li_3^8 spectrum is near 15 MeV, and therefore the appearance of an appreciable number of strongly subbarrier fragments (on the order of 5 per cent of the total yield of Li_3^8) calls for an explanation.

From an examination of Table II we can draw the following conclusions:

1. The disintegrations in which the product contains a low-energy Li^8 fragment are accompanied by very large transfer of energy from the incident particle to the initial nucleus. The average num-

Table II

Maximum energy of protons registered by the emulsion, MeV	Energy of incident protons, GeV	Range of Li_3^8, μ	Energy of Li_3^8, MeV	Angle with the incident proton, deg	Type of reaction	Total no. of particles in the disintegration	Total charge of all visible particles
30	9	14	7	126	$Li^8 + 5\alpha + 11p$ + recoil nucleus	18	>24
30	9	12	6	80	$Li^8 + Be + Be^8 + 3\alpha + 21p$	27	38
30	9	6	3	63	$Li^8 + Li + 3\alpha + 15p$	20	27
30	9	7	3.7	141	$Li^8 + Be + 3\alpha + 9p$	14	22
30	9	10.5	5.5	113	$Li^8 + Be + 5\alpha + 10p$	17	23
30	9	6	3	122	$Li^8 + B + 2Li + 3\alpha + 12p$	19	32
150	9	2	~ 1	177	$Li^8 + Be + \alpha + 12p$	15	21
150	3	15	7.3	160	$Li^8 + \alpha + 16p$ + short track	19	≥ 21
150	3	15	7.3	125	$Li^8 + 3\alpha + 10p$ + recoil nucleus	15	≥ 19
150	3	6	3	133	$Li^8 + Be + 2\alpha + 13p$ + short track	18	≥ 24
150	3	10	5	95	$Li^8 + Li + 4\alpha + 9p$ + short track	16	≥ 23

ber of all the particles produced in the disintegration is 18, whereas even in stars with two fragments it amounts to 14. As a rule, in such disintegrations there is in addition to the Li_3^8 another fragment with charge $Z \geq 4$. The average total charge carried away by the particles with charges $Z = 1-6$ is equal to 25, and the maximum registered value is 38.

2. Another interesting feature of these disintegrations is that the low-energy Li_3^8 fragment moves almost always in a direction opposite that of the incident particle. Only two Li_3^8 fragments out of 11 were emitted in the forward hemisphere.

On the basis of these facts we can state that the production of such Li_3^8 fragments is connected either with the complete disintegration of the target nucleus, or else with a partial disintegration but one which is exceedingly large. The Li_3^8 is either the residual nucleus, or a fragment resulting from the decay of a strongly-excited nucleus which has, however, a smaller mass and is in turn the result of disintegration of the initial nucleus. In this case the "subbarrier" nature of the low-energy fragments will not be so strongly pronounced. Since a target-nucleus receives in the case of large energy transfer from the incident proton a considerable translational momentum, which is essentially in the forward direction, the emission of Li_3^8 in the opposite direction in the c.m.s. of the decaying nucleus will lead, in turn, to a decrease in the Li_3^8 energy in the laboratory frame. This agrees with the fact that the observed low-energy Li_3^8 fragments move opposite to the incident proton.

In conclusion, the authors take the opportunity to express gratitude to the administration of the High-energy Laboratory of the Joint Institute for Nuclear Research for making available the proton synchroton of the Institute, and to the nuclear-emulsion reduction group of the High-energy Laboratory, headed by S. I. Lyubomilov and V. I. Baranov, for scanning the emulsions used in the work. The authors are particularly grateful to S. I. Lyubomilov for help and direct participation in the irradiation of the pellicle stacks. The authors are grateful to Yu. P. Yakovlev of the Radium Institute for a discussion of some of the problems touched upon here.

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