Interactions of 1.0-, 2.0-, and 3-GeV Protons with Ag and Br in Nuclear Emulsion. II*

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Cross sections for star production and for emission of α particles, light fragments ($3\leqslant Z\leqslant 6$), and Li^8 nuclei are reported for interaction of high-energy protons with the heavy elements in Ilford K.0 nuclear emulsion. These cross sections increase rapidly between 1.0 and 2.0 GeV, and then they level off between 2 and 3 GeV. Those stars which are characterized by two dense tracks in approximately opposite directions have cross sections of 7 ± 2, 30 ± 7, and 50 ± 10 mb at 1.0, 2.0, and 3 GeV, respectively. Arguments are presented which strongly support the idea that the two fragments are of roughly comparable mass and are both mainly in the region $A\approx15$–35 with $Z\approx7$–17. This view is compared with that of Gorichev, Lozhkin, and Perfilov according to which the two fragments are very different in mass, the lighter one being a fragment of $Z=4$–9 and the heavier one a nuclear recoil.

INTRODUCTION

In a previous paper,[1] data were presented on the various types of nuclear interactions of 1–3-GeV protons with the Ag and Br in low-sensitivity nuclear emulsions. Because the proton beam intensities could not be monitored in the earlier experiments, only relative yields of the different processes were reported. Comparisons of yields at different incident energies were somewhat uncertain.

In this paper the results of a series of absolute cross-section measurements are reported. These involved determinations of beam intensities from the activities of 20.4-min C^{11} induced in plastic scintillators. The relative yields reported previously[1] can be transformed to absolute cross sections, and it now becomes possible to make more valid comparisons with similar work reported from other laboratories.[2–4]

EXPERIMENTAL

Each target consisted of a stack of four Ilford 1 in.×3 in. plates, coated with 200-μ K.0 emulsion, and backed by Pilot *B* plastic scintillator $\frac{3}{8}$ in. thick. The scintillator was divided into three parts; only the central $1\frac{1}{2}$ in.×1 in. piece was used for measurement of the induced C^{11} activity. These targets were irradiated at the Cosmotron with external proton beams incident perpendicular to the surface of the emulsion. In each run the beam was defocused somewhat in order to distribute it more uniformly over the 10 cm^2 area of the target. The intensity at the edges was about $\frac{2}{3}$ of the peak intensity. Irradiation times varied from 1.3 min to 4.0 min.

After each irradiation the central piece of scintillator was mounted on a photomultiplier tube and the 20.4-min C^{11} activity was measured.[5,6] The efficiency was estimated[5–8] as $(96\pm1)\%$. From the earlier measurements of this kind,[6–8] it is estimated that corrections for production of C^{11} by secondary particles originating in the target stack (scintillator downstream) are 4%, 8%, and 10%, respectively, at 1.0, 2.0, and 3 GeV. The average beam intensity was determined in each irradiation from the corrected C^{11} activity, the known number of carbon atoms per cm^2 in the plastic scintillator, and the known cross sections[9] for production of C^{11}. These are shown in Table I.

The K.0 emulsions were processed in the same way as in the previously reported work,[1,10,11] and the plates showed grain densities in the same range as before. The total number of stars within the area of interest in each plate was determined by scanning ~900 fields (260-μ diam) distributed uniformly over this 10 cm^2 area in each of two plates at each of the three energies. Criteria for identification of the interactions with Ag and Br were identical with those used in the earlier work.[1,10,11] The effect of secondary particles on star production was considered negligible because the emulsions were upstream in the stack and the scanning criteria excluded events of low excitation. Nearly all of the plates were scanned twice by the two scanners who observed the stars in the earlier work.[1,10,11] The mean results are given in Table I.

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TABLE I. Irradiation data, results of C^{11} counting, and stars observed in Ilford K.0 emulsion.

Beam energy	1.0 GeV	2.0 GeV	3 GeV
Pilot B, thickness (cm)	0.950	0.912	0.912
Pilot B [(C atoms)/cm²]	4.49×10^{22}	4.31×10^{22}	4.31×10^{22}
Time of irradiation (min)	4.0	1.3	3.0
C^{11} at end of irrad. (counts/min)	12,700	6900	3300
Beam intensity (protons/cm²min)	8.07×10^{6}	13.5×10^{6}	2.83×10^{6}
Emulsion area scanned (cm²)	0.994	0.774	0.966
Stars observed (number)	2147	2498	1644

RESULTS AND DISCUSSION

The cross sections for star formation in Ilford K.0 nuclear emulsion (Table II) were calculated from the data given in Table I. The listed uncertainties include an estimate of scanning errors. It should be noted that these are stars in Ag and Br which can be classified into three groups: type I, in which only α particles and a recoil were observed; type II, in which light fragments ($3\leqslant Z\leqslant 6$) were observed in addition to the alphas and recoil; and type III, in which two short, very heavily ionizing tracks are seen rather than one recoil. The cross sections (Table II) for each of these types at the three energies were derived by combining the total star cross sections with the fractional yields reported in the earlier paper.[1] Interactions which did not produce stars characteristic of the above three groups either were not visible at all or were indistinguishable from interactions with the light elements of the emulsion.

Since the mean total reaction cross section for Ag and Br at these incident proton energies is $\sim$1000 mb, the fractions of the inelastic interactions recorded and identified in the K.0 emulsion are 0.14, 0.40, and 0.41, at 1.0, 2.0, and 3 GeV, respectively. In the earlier paper[1] these fractions were estimated to be considerably higher: 0.6, 0.8, and 0.9. The general trend of all the cross sections with incident beam energy is a large increase between 1.0 and 2.0 GeV with a leveling off between 2.0 and 3 GeV.

Type III stars were referred to earlier[1,11] as "fission events" because of the similarity in appearance with well known uranium fission in nuclear emulsion: two heavily ionizing particles producing dense tracks in roughly opposite directions. Perhaps it would have been more appropriate to call these events "fissionlike" rather than fission. Use of either term does not imply that the mechanism involved is necessarily the same as in low-energy fission. However, analysis of the emulsion data[11] strongly indicated that the two short range fragments, in most cases, do not differ widely in mass. A subsequent radiochemical study[12] of the range distributions of several specific products from the interaction of 2.9-GeV protons with silver indicated that the most abundant "two-body breakup" products have $A=20$–30.

TABLE II. High-energy proton cross sections in Ilford K.0 nuclear emulsion for production in AgBr of stars, alpha particles, light fragments, and Li^8 hammer tracks. The results are expressed in millibarns.

Beam energy	1.0 GeV	2.0 GeV	3 GeV
All stars observed in Ag+Br	138±20	397±50	410±50
Type-I stars	94±16	220±40	220±40
Type-II stars	37±8	147±25	140±25
Type-III stars	7±2	30±7	50±10
Alpha particles	250[a]±40	800[b]±100	960[b]±100
Light fragments	52±8	240±40	270±40
Li^8 production[c]	0.6±0.2	6±1	4±1

[a] To obtain the total α-particle cross section, this value should be increased by $\sim$35% to correct for certain small stars excluded by the scanning criteria.
[b] For total α-particle cross sections these should be increased by $\sim$20% for reason given in footnote a.
[c] Numbers of Li^8 tracks observed: 10 in 2950 stars at 1.0 GeV, 36 in 3132 stars at 2.0 GeV, and 13 in 2158 stars at 3 GeV.

Gorichev, Lozhkin, and Perfilov[3] have discussed in considerable detail the kind of stars which are classified here as type III. Their observations are similar to those from this laboratory, but their interpretation is somewhat different. They report a cross section of 26 mb, at 3-GeV incident proton energy, for disintegrations in which two (or more) short-range ($<15\,\mu$) products are emitted. This result is in fair agreement with the value of 50±10 mb given in Table II, considering the differences in emulsion sensitivities and scanning criteria. Observations are also similar on distribution of range ratios and on the angular correlation of the two fragments. Gorichev *et al.* maintain, however, that this type of disintegration should not be classified as fission but rather as a breakup into a subbarrier short-range fragment ($4\leqslant Z\leqslant 9$) and a recoil nucleus. In their analysis they attempt to show that these events can be considered as a limiting case of ordinary fragment emission (range$>15\,\mu$). They reserve the use of the term "fission" for a split into two roughly equal fragments, each with about $\frac{1}{2}$ the mass of the target nucleus, i.e., $A\approx45$ for AgBr targets. For this kind of event, Gorichev *et al.*[3] report an upper limit of $\sim$1 mb at incident proton energies in the range 1–9 GeV.

New radiochemical and mass spectrometric data[13] further support the idea that both short-range products in type III events are usually in the mass region 15–35. It was found[13] that the isobaric cross sections of products from 2.9-GeV proton irradiation of silver are 4–7 mb per mass number in this region, and the total cross section is 100±15 mb for products with $A=15$–35. This value may be compared with the cross sections found here for type III events: 30±7 mb at 2.0 GeV and 50±10 mb at 3 GeV. Of course, these values should be doubled to give the total cross sections of both fragments. Thus, these data are compatible with identification of most of the type III fragments with the mass region 15–35, corresponding to $Z\approx7$–17.

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The strongest evidence for this view comes from the observations[3,4,11] that the fragments are emitted in roughly opposite directions to each other and that they have a most probable range ratio near unity. Considerations of momentum conservation and range-energy relations[11,12] show that the two fragments are most often of roughly comparable mass. Since the measured ranges of these fragments correspond approximately with the measured range distribution[12] of Na^{24} produced by 2.9-GeV proton irradiation of Ag, it is likely that most of the fragment masses lie in the region $A=15$–35. It appears that type III interactions involve very high nuclear excitation with emission of many nucleons, deuterons, alpha particles, perhaps one or two light fragments ($6\leqslant A\leqslant 14$), and in addition a pair of heavier fragments ($15\leqslant A\leqslant 35$).

It should be noted that the assignment of $Z\approx 7$–17 to most of these fragments overlaps Gorichev's assignment of $Z=4$–9 to the lighter of the two partners. When considering the interaction of GeV particles with complex nuclei, it is very difficult to clearly distinguish one type of process from another. As the energy of the projectile increases, the differences become blurred, the regions of overlap become larger, and the magnitudes of different processes tend to become more nearly comparable. Therefore it is not surprising that experiments in this field sometimes lead to apparently discrepant results and interpretations. Further work on the interaction of high-energy protons with silver is proceeding in this laboratory by two techniques: mica track detectors[14] and scattering chamber experiments utilizing Si counters and time-of-flight measurement.[15] Hopefully, these new experiments should further clarify this complex problem.

The observed α-particle cross sections shown in Table II should be increased somewhat because the scanning criteria excluded small stars in which no recoil track was evident. It is estimated that these losses amount to $\sim$35% at 1.0 GeV and 20% at 2.0 and 3 GeV. Thus the corrected α-particle cross sections are 340 ± 60 mb at 1.0 GeV, 960 ± 130 mb at 2.0 GeV, and 1160 ± 130 mb at 3 GeV. These values may be compared with some recent mass spectrometric measurements[16] of combined He^4+He^3 cross sections: Ag irradiated with 0.6-GeV protons, 370 mb; Cu with 0.6-, 2.2-, and 25-GeV protons, 630 mb, 700 mb, and 910 mb, respectively. The agreement is not very good, even considering the differences in targets and bombarding energies. The most disturbing dissimilarity is in the change of cross section between 0.6 and 2 GeV. The emulsion work shows an almost threefold increase for Ag+Br (1.0 to 2.0 GeV) while the mass spectrometry experiments show only a 10% increase for Cu (0.6 GeV to 2.2 GeV).

The light fragment cross sections listed in Table II are for Li, Be, B, and C combined. Since the problem of identification is severe, especially with the shorter tracks, the uncertainty in the values is substantially larger than the statistical errors which are given in the Table. In fact, the errors are more likely to lead to high results because of the difficulty in resolving Li tracks from the more numerous alpha tracks. From the papers of Gorichev *et al.*,[3,4] a value of 33 mb is deduced for the combined cross section for production of the fragments Be through F at 3 GeV incident proton energy. Assuming that the errors of identification are not excessive in both experiments, this comparison implies that Li isotopes account for most of the light-fragment cross sections listed in Table II.

The Li^8 cross sections reported here can be compared in an approximate way with earlier work. Munir[17] gives a value of 1.1 ± 0.3 mb for the Ag+Br in Ilford G.5 emulsion irradiated with 950-MeV protons. W. Gajewski *et al.*[18] found a value of 16 ± 2 mb for a similar irradiation with 9-GeV protons. These results are based on the assumption that each inelastic collision of an incident proton with a Ag or Br nucleus leads to an observable star in G.5 emulsion. A different kind of experiment,[19] in which fragments were emitted from a thin external silver target irradiated with 2.0-GeV protons, yielded a Li^8 cross section of 2.8 ± 1.0 mb. All of these results are roughly consistent with each other.

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