Characteristics of Projectile Fragments Produced from Heavy-Ion Collisions at 2*A* GeV

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The interaction mean free paths in nuclear emulsion of relativistic projectile fragments, $3 \leq Z \leq 26$, emitted from heavy-ion beams of ^{40}Ar and ^{56}Fe at an energy of ~2 GeV/nucleon have been measured, and they gave evidence for anomalously shorter mean free paths in the first 2–3 cm after their production than at larger distances. Some characteristics of the primary and the secondary interactions connected with the anomaly are presented.

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Before the time of the operation of high-energy accelerators at CERN, Chicago, and Dubna, and the heavy-ion accelerator at Berkeley, California, most of the basic knowledge about the interaction of fundamental particles came from the studies of cosmic-ray physics. In some studies of heavy-ion interactions in emulsions exposed to cosmic rays, the reaction mean free path (mfp) of the projectile fragments (PF's) was observed to be small in the first few centimeters.[1] In cosmic-ray studies, the statistics have always been small, with the result that the above-stated fact was not taken seriously. Now heavy-ion beams are available at the Bevalac and shorter mean free paths of secondary fragments have been reported[2] and we have followed the methods of Ref. 2 with the following new results.

To investigate the short reaction mean free path of heavy secondary particles, we have used ^{56}Fe and ^{40}Ar beams at ~2*A* GeV from the Bevalac at Berkeley, California. In their interactions in nuclear emulsions, we observe an unusual number of secondary interactions of PF's near the point of the primary interactions which lead to anomalously short mean free paths for these fragments. In the present experiment, we used two stacks of Ilford G-5 emulsion pellicles 600 μm thick of dimension 12×8 and 10×10 cm^2 exposed to ^{56}Fe and ^{40}Ar beams at ~2 GeV/nucleon, respectively, parallel to the pellicle surfaces. Each pellicle was scanned by the along-the-track method,[3] under high magnification. We thus found about 5000 primary interactions out of which 2100 relativistic tracks of $Z \geq 3$ emitted from the primary interactions within 0.1 rad forward cone were followed until they either interacted (865 PF's) or left the stack. At such energies, each of the PF's is produced at the rapidity of its parent projectile. In heavy-ion interactions, about 10% of the primary interactions in emulsion are "pure" projectile fragmentation events known as "white stars" with $N_h = 0$, where N_h is the number of nonrelativistic particles emitted from the interactions with $\beta \leq 0.7$. We used these standard events for the calibration of charge of the secondary particles[4] by δ-ray and gap-density measurements for light elements and by track-width measurements for heavier elements on the assumption of charge balance, i.e., $\sum Z_{\rm PF} = Z_{\rm beam}$ for "charge calibration" tracks. For each PF we measured its charge Z to a precision of one charge unit and the charge spectrum of all the PF's followed is shown in Fig. 1. The mfp of interactions in nuclear emulsion of a homogeneous beam of nuclei of charge Z is given by $\lambda = D/N$, where D is the

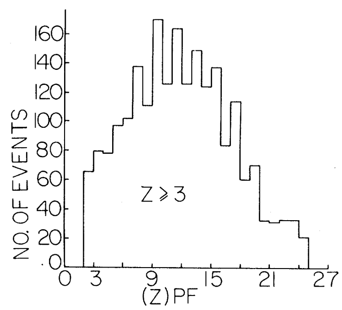

FIG. 1. Charge spectrum of secondary projectile fragments with $Z \geq 3$.

TABLE I. Mean free paths (λ^*) at different distances L from the origins of PF's for grouped charges.

Z	λ_1^* ($L \leq 2.5$ cm)	λ_2^* ($L > 2.5$ cm)
4–8	11.06 ± 1.10	14.85 ± 1.37
9–14	9.39 ± 0.69	12.71 ± 1.02
15–20	8.50 ± 0.84	10.65 ± 0.91

total path length of both interacting and noninteracting tracks followed for charge Z with N observed interactions. In order to avoid approximately geometrical dependence of mfp on the projectile mass, we used the charge (Z) dependence mean free path λ_z in terms of constants λ_0 and b of the form[2]

$$\lambda_z = \lambda_0 Z^{-b}, \qquad (1)$$

where[5] $\lambda_0 = \lambda_{\text{beam}} = 32.4 \pm 1.7$ cm and $b = 0.42 \pm 0.024$. In following the PF's of charge $Z \geq 3$ the majority of the fragments found are below charge twenty and their mfp's are displayed in Table I for $L \leq$ and > 2.5 cm. Here λ in a particular group is calculated simply by dividing the total track length by the number of interactions and no parameter is involved to bias the result. The mfp's of the anomalous components are shorter by at least 2.5 standard deviations than the normal mean free path. These anomalous components, after their production, interact in shorter distances, and they constitute a drastic departure from the geometric cross section.[6]

For N_z secondary events of charge Z and mfp λ_z, we get, using Eq. (1) at fixed b, the value of charge-independent mean-free-path parameter λ_0^* for each interval of path length as

$$\lambda_0^* = \sum_z N_z \lambda_z^* Z^b / \sum_z N_z . \qquad (2)$$

For all the PF's with charges $Z \geq 3$, we show in Fig. 2(a) the observed dependence of λ_0^* on path length L, as calculated from Eq. (2) for a number of independent segments. The dashed line is the prediction from λ_{beam}. Data points beyond 8.4 cm are not shown here. We may note the low values of λ_0^* in the first few centimeters; beyond $L = 3$ cm, the estimate of λ_0^* is comparable with λ_{beam}. These results of secondary beams are further compared with the primary beam. In Fig. 2(b) are shown the results of the primary ^{56}Fe beam for the same intervals of path length as in the secondary beams. No statistically significant deviations from the average are apparent for the primary-beam data with the same value of constants as in Eq. (1).

In order to check the abnormality[2] of mfp as a function of distance, independent of the validity of Eq. (1), we find the ratio of mfp's of secondaries in the first 2.5 cm (say λ_1^*), to those beyond 2.5 cm (say λ_2^*) for various charges as $F = \lambda_1^*/\lambda_2^*$. We calculate for each pair a number P_L which is the integral probability of the ratio $F = \lambda_1^*/\lambda_2^*$ and is uniformly distributed for normal events between 0 and 1. In Fig. 3(a) is

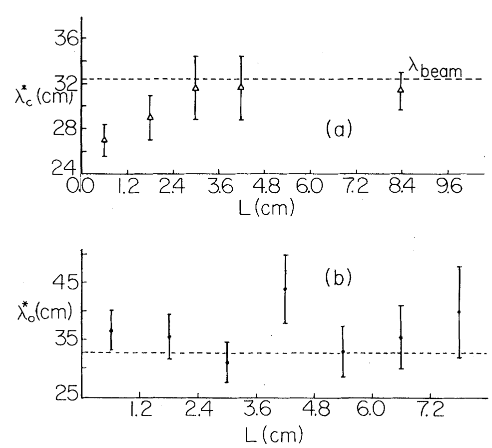

FIG. 2. (a) Experimental estimation of λ_0 from Eq. (2) at different distances L from the origins of projectile fragments. (b) Mean-free-path parameter λ_0 as a function of path length for primary ^{56}Fe beams. Dashed line is the prediction for λ_{beam}.

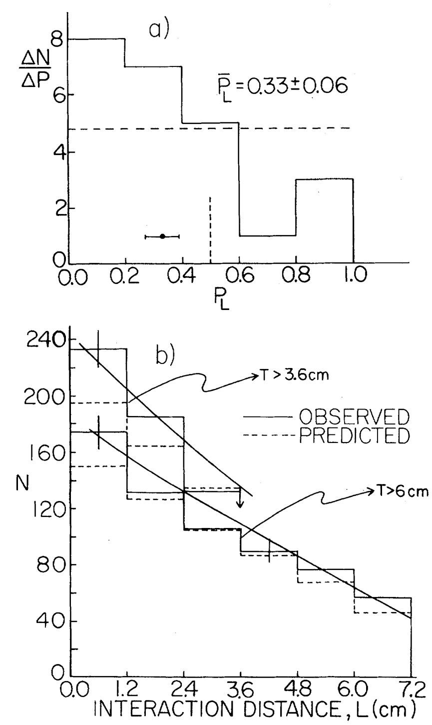

FIG. 3. (a) Experimental frequency distribution of P_L ($< F_L$); the dashed line is the expected uniform distribution; the point with error bars means $\bar{P}_L = 0.33 \pm 0.06$, to be compared with expectation ($\langle P_L \rangle = \frac{1}{2}$). (b) Distributions of interaction distances L for events with potential path $T \geq T_1$. Solid straight line, prediction under the assumption of a 4% admixture of PF's with $\lambda_s = 2.6$ cm.

shown the experimental frequency distribution of P_L for 24 PF's with $\overline{P}_L = 0.33 \pm 0.06$ which is about 2.8 standard deviations away from the expected value of 0.5. The dashed line is the expected uniform distribution. The result is independent of Eq. (1), and shows with better than 99% confidence that the reaction mfp is significantly less within the first few centimeters after PF emission than at larger distances. This effect is present in all charges of PF's as shown in Table I.

In Fig. 3(b) we present two distributions of interaction distance L for events with potential paths $T \geq T_1 = 3.6$ and 6.0 cm, respectively. For small distance $L \leq 2.4$ cm, the experimental observation for $T_1 = 3.6$ cm (solid-line histogram) shows an excess of events over the number predicted (dotted line) from the expression $N_{\text{exp}} = \sum_{Z=3}^{26}(D_z/\lambda_z)$, where λ_z is given by Eq. (1) and D_z is the total track length of particular charge in a given segment; it amounts to about 2.7 standard deviations. In order to estimate the excess of events in the first few centimeters, we assume that in addition to normal nuclei, there is a fraction "s" of the PF's which interacts with a constant short mfp $\lambda_s \ll \lambda$ leaving a fraction $(1-s)$ of PF's which interact normally obeying Eq. (1). By a least-squares fit, we get the best estimates from our data for $s \simeq 4\%$ and $\lambda_s \simeq 2.6$ cm which, however, depends on the parameters λ_0 and b. The solid curves in Fig. 3(b) are drawn with 4% mixture of anomalous PF's which interact with a mfp of $\lambda_s = 2.6$ cm and fit the experimental data quite well.

As yet no efforts have been made to identify the nature of the anomalous interactions and thus any experimental clues to the nature of the cause of this anomalous mfp effect would be very important. In order to understand the result of this experiment, we looked at the characteristics of the primary (parent) interactions from which the PF's originate, and also the secondary (normal and abnormal) interactions. In general their characteristics are similar. In particular we observe the following facts: (a) We divide the distribution of mfp's of PF's further into two types of primary events from which they are produced: one, with lighter elements (i.e., C, N, O with $N_h \leq 7$), and the other, with heavier elements (i.e., Ag, Br with $N_h > 7$). We find that for a group of charges (4–14) with $N_h \leq 7$ the values of mfp's λ_1 ($L \leq 2.5$ cm) and λ_2 ($L > 2.5$ cm) are 9.8 ± 0.78 and 13.48 ± 1.21, respectively, and for $N_h > 7$, the values for λ_1 and λ_2 are 10.61 ± 0.99 and 11.89 ± 1.14, respectively. The overall values of λ^* for $N_h < 7$ and ≥ 7 are 11.45 ± 0.68 and 11.29 ± 0.75, respectively. We observe that a large portion of anomalous interactions appear in events with $N_h \leq 7$ (light targets). The mfp of the anomalous components (λ_1) produced with lighter elements is shorter by about 2.5 standard deviations while the mfp's, λ_1 and λ_2, for events with $N_h > 7$ are approximately the same within the statistical errors. (b) Multiplicity (n_s) distributions of all the secondary interactions are quite similar for $L \leq 2.5$ cm and > 2.5 cm as shown in Fig. 4(a), but peaks slightly at lower value for $L \leq 2.5$ cm than for $L > 2.5$ cm. (c) In order to see if there is any preference of charges carried by the anomalous tracks, we show in Fig. 4(b) the charge spectrum of PF's with mfp's λ_1 and λ_2 produced from lighter targets ($N_h \leq 7$). It looks as if there is a small preference for low charges of PF present in events with λ_1 (≤ 2.5 cm) over that in λ_2 (> 2.5 cm). (d) We further observe the effect of the target in the production of abnormal nuclei which produce a secondary interaction as a white star (i.e., $N_h = 0$). The percentage of the production of secondary interaction as a white star ($N_h = 0$) is about 3.5% more for primary events in their interactions with lighter targets ($N_h \leq 7$) than with heavier

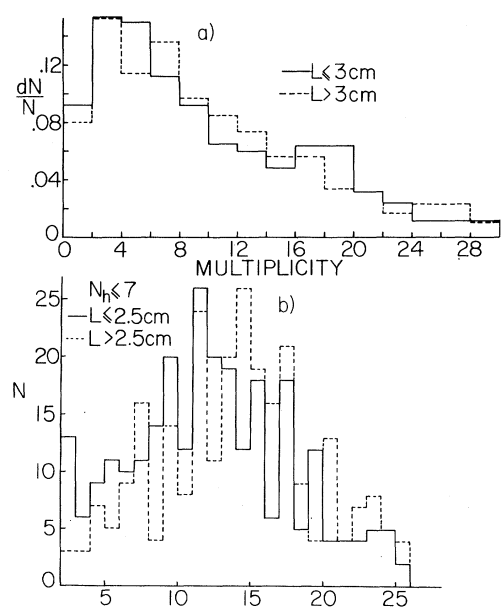

FIG. 4. (a) Multiplicity (n_s) distribution of secondary interactions by PF's produced in the primary collisions. (b) Charge spectrum of projectile fragments interacting with lighter elements.

targets ($N_h > 7$). (e) Multiplicity (n_s) distributions of all the white stars with $L \leq 2.5$ cm peak at a lower n_s value than for white stars with $L > 2.5$ cm.

In conclusion, our data indicate a diminution in the measured mfp of secondary fragments in the first few centimeters (or $\sim 10^{-11}$ sec) of their path length after their production. The energy of the primary beam plays an important part in the production of anomalous nuclei, as we did not observe any anomalous effect[7] with a ^{56}Fe beam of about 1 GeV/nucleon. In our present investigation, we did not include the PF's of charge 2, i.e., α particles, from the Fe and Ar primary beams which are under investigation for the observation of the anomalous effect. The analysis of the primary stars (interactions) seem to indicate that lighter targets favor the production of abnormal nuclei and these nuclei produce more white stars (interactions) than the regular nuclei. We are continuing our present investigations about the primary and secondary interactions connected with these fragments to understand the origin of the anomalous effect.

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Bremsstrahlung from ^{12}C + p near the 461-keV Resonance

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The spectrum of bremsstrahlung radiation emitted by the scattering of protons by ^{12}C near the 461-keV resonance has been studied at bombarding energies 130, 235, and 335 keV above the resonance. The measured spectra were analyzed and compared with the theoretical predictions calculated from the soft-photon approximation and the Feshbach-Yennie approximation.

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In an earlier paper[1] we reported good agreement between theory (the Feshbach-Yennie approximation[2]) and experiment for the bremsstrahlung cross sections measured near the 1.7-MeV resonance in the proton-carbon (p-^{12}C) scattering. In this Letter we wish to report our new measurements of the bremsstrahlung cross sections near the 461-keV resonance in the p-^{12}C scattering and to point out some disagreements between the Feshbach-Yennie approximation and the experimental data.

The bremsstrahlung process has attracted much attention during the past two decades not only because it is the ideal process for the study of the off-shell effects[3] but also because it can be used to study the electromagnetic properties of resonant states[4] and nuclear reactions.[5-7] The idea of using bremsstrahlung emission as a tool for investigating nuclear reactions was first proposed by Eisberg, Yennie, and Wilkinson,[5] whose clas-