Charge-Changing Reactions of Secondary Fragments Produced in High-Energy Heavy-Ion Collisions

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Charge-changing cross sections have been measured for secondary fragments produced by the interactions of 1.88A-GeV ^{56}Fe and 1.82A-GeV ^{40}Ar nuclei in Lucite. The cross sections are found to vary by less than 1.5% between 6 and 120 mm from the primary interaction point and are consistent with values expected from the normal reaction cross sections of primary beams. No correlation between secondary and tertiary path lengths has been observed. The present results do not provide supporting evidence for the existence of anomalons.

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One of the most exciting recent developments in experimental nuclear physics has been the report that a substantial fraction of secondary fragments produced in high-energy heavy-ion collisions have reaction cross sections that are very much larger than normal. The particles responsible for this behavior have been named "anomalons." Although there has been controversy over the size of this effect, results have been presented by several groups using nuclear emulsions[1–4] and more recently CR-39 plastic track detectors.[5,6]

To investigate this phenomenon further, we have begun a program to measure charge-changing cross sections of projectile fragments using a quite different technique that is capable of much higher data acquisition rates. The principle of the experiment is simple. The primary beam impinges on a stack of fifty Lucite strips having an average thickness of 3.17 mm, emitting Cherenkov light as it passes through them.[7] Since at a given velocity the intensity of the light is proportional to Z^2, where Z is the charge of the particle, a fragmentation reaction in a particular strip will be registered as a drop in the light output from that and subsequent strips. We use total internal reflection to transport the light to photomultiplier tubes so that there is no wrapping between the strips. Since the energy threshold of the device is $\sim 1.1A$ GeV, low-energy target fragments will not contribute to the signal, a distinct advantage over similar schemes using energy loss to measure the fragment charge. The resolution of the individual strips is typically 0.58 charge units, full width at half maximum, allowing reactions to be well localized even for single-unit charge changes.

The principal disadvantage of this device compared to visual detectors such as nuclear emulsion, where individual fragments can be resolved, is that the signal is proportional to the sum of the squares of all the projectile fragments emitted in the reaction. The effect of this can be clearly seen by a simple example. Consider the fate of the projectile in the following two reaction sequences:

$$18 \rightarrow 13 + 5p \rightarrow 12 + 6p,$$

$$18 \rightarrow 12 + 5 + p \rightarrow 12 + 6p.$$

These two sequences are essentially indistinguishable in our detector since the light emitted by the intermediate system is the same in each case. However, the two-particle system mimicking the $Z = 13$ fragment will have an apparent mean free path at least 40% shorter since the cross section will be the sum of those for the $Z = 12$ and the $Z = 5$ fragments. This problem is minimized by studying heavy fragments and large charge changes.

In addition to the Cherenkov detectors, scintillators and Si(Li) detectors were used to measure precisely the position and charge of the incoming beam particle. We have taken data using two beams, ^{56}Fe and ^{40}Ar at 1.88A and 1.82A GeV, respectively, and two trigger modes, a free trigger to measure the reaction rate of the incoming beam and an inelastic trigger in which a reaction was required to occur in one of the first fourteen Cherenkov detectors. In the inelastic-trigger mode the instantaneous beam intensity was limited to 10^4 particles/sec to minimize pileup problems. Typically, 50 000 good interactions were recorded per hour and a total of 909 000 ^{56}Fe interactions and 460 000 ^{40}Ar interactions have been analyzed so far.

In the analysis which follows, we shall present the reaction rate in the form of the estimated mean free path λ_Z^*, for a particle of charge Z, deduced from the ratio of the total track length to the number of interactions in a given distance interval.[2] An important problem in the analysis has been to determine the efficiency of locating a secondary reaction as a function of its distance from the primary. We have investigated this by using Monte Carlo simulations of the detector response and by using a technique in which events are reanalyzed with successively less information available to the computer program from strips intermediate between the two reaction points. This latter technique is especially powerful since it automatically corrects for most irregularities in the detector. From these studies we conclude that at the 2% level, no corrections are needed for distances greater than 6 mm if we restrict ourselves to interactions with charge changes greater than 1. $\Delta Z = 1$ reactions require appreciable correction ($\sim$ 10%–20%) at distances < 1 cm and we choose to exclude these data rather than to make corrections which themselves have a large uncertainty. This choice is also reasonable since it reduces the multiple-fragment problem discussed above.

The secondary-charge spectrum produced by the ^{56}Fe beam is illustrated in Fig. 1. Individual charges are clearly resolved and broadening of the peaks due to multiple fragmentation can be seen for the lower charges. In Fig. 2, we show the mean free paths for the primary beams and for secondaries at distances greater than 3 cm from the primary interaction point. The primary-beam values are 8.14 ± 0.04 cm for ^{56}Fe and 9.8 ± 0.06 cm for ^{40}Ar. Agreement between the ^{56}Fe and ^{40}Ar secondaries at the same charge is generally good. We attribute the low mean free path for Fe secondaries of charges 11 and 12 to multiple fragmentation. It can be seen that this effect is greatly reduced for $\Delta Z > 1$ interactions. A reasonable parametrization of the $\Delta Z > 1$ interactions is $72.2Z^{-0.64}$.

Next we consider the variation of reaction rate with distance. For brevity, we follow here the procedure adopted by Friedlander *et al.* of accumulat-

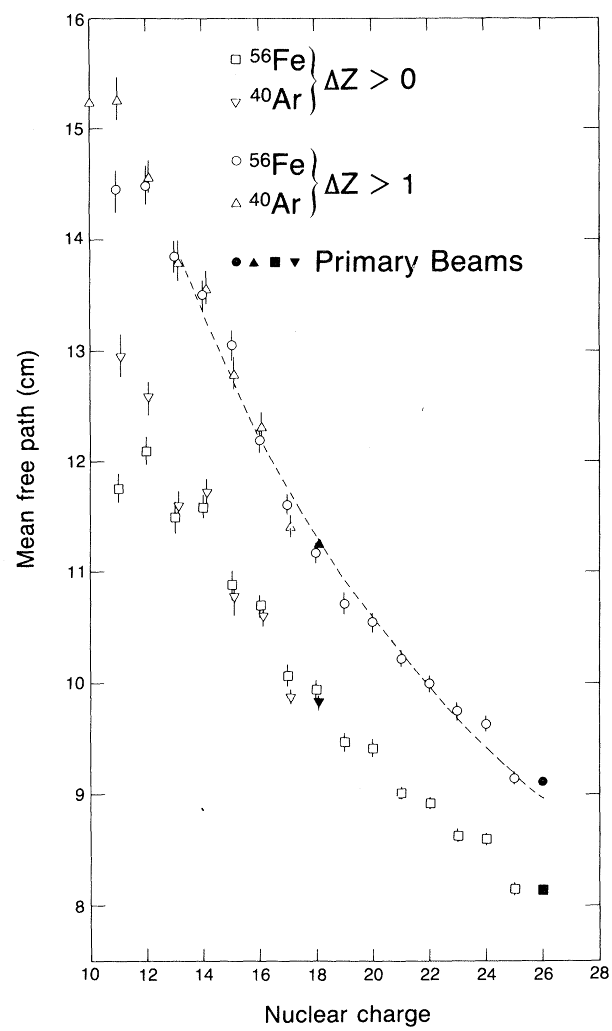

FIG. 2. Mean free paths of primary beams and secondary fragments for all interactions and for interactions with $\Delta Z > 1$. The dashed curve is the function $72.2Z^{-0.64}$ which represents our best fit to the $\Delta Z > 1$ data.

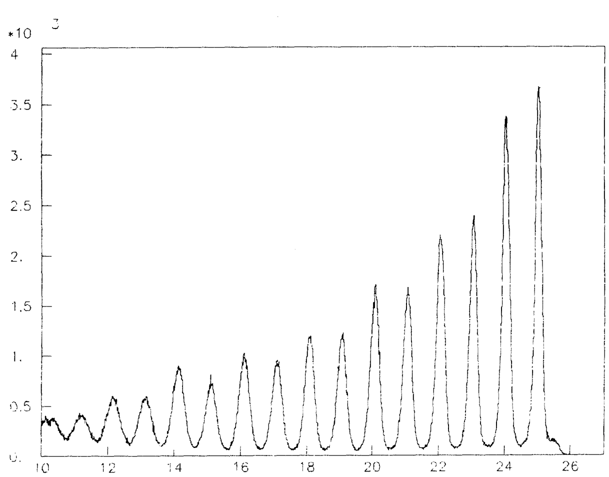

FIG. 1. Spectrum of secondary charges resulting from ^{56}Fe fragmentation at 1.88A GeV in Lucite.

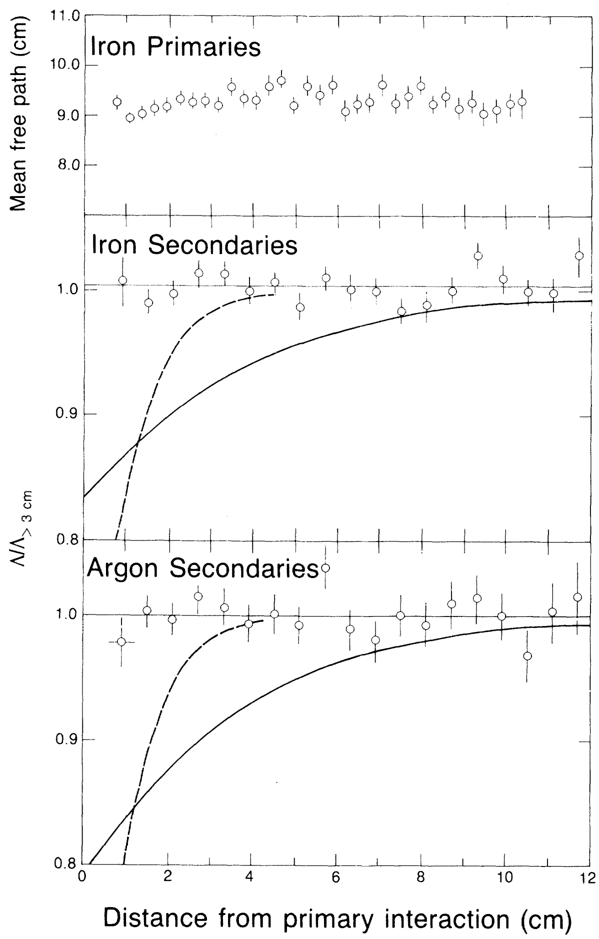

FIG. 3. Ratios of estimated to average mean free paths as a function of distance from the primary interaction point for ^{40}Ar and ^{56}Fe beams. For explanation of curves, see text.

ing different charges into a single data set. However, rather than using a parametric scaling law, we have scaled the individual charges by their values shown in Fig. 2, on the assumption that the anomalous effect will be small at distances greater than 3 cm. The results are shown in Fig. 3 where we have included charges 13–24 from ^{56}Fe and 11–16 from ^{40}Ar. For reference, we also show the estimates of the mean free path of ^{56}Fe as a function of depth in the stack. No corrections have been made to points on this plot. However, we have increased the errors on the first point to 2% and the next ten ^{56}Fe points to 1% to take into account our uncertainty concerning the shape of the efficiency curve. The fits for assuming a constant mean free path, the null hypothesis, are rather good, with χ^2 values of 22.4 and 16.5 for ^{56}Fe and ^{40}Ar with 18 degrees of freedom in each case. Also shown on the graph are the results of two experiments that have been performed using these beam nuclei. The solid curve is the prediction assuming a 6% admixture of fragments with a mean free path of 2.5 cm as originally proposed by Friedlander *et al.* and supported by their repeat experiment.[8] It must be emphasized, however, that these two experiments cover very different ranges of charge (3–26 for Friedlander *et al.*, 13–24 in our case). The dashed curve represents the 4.8%, 0.75-cm hypothesis suggested by Tincknell and Price, on the basis of ^{40}Ar fragmentation with a range of secondary charges similar to ours. Statistically, these two hypotheses have negligible probabilities. However, we emphasize more strongly the good agreement that we have with the null hypothesis. It is also very important to realize that combining charges can easily mask an effect that is present for some but not all charges. In our case all the individual charges are also consistent with a null hypothesis. These results will be presented and discussed in a longer paper.

Finally, we wish to discuss the observation of a correlation between reaction length in the second and third generations, the "memory effect."[2] As a preliminary search for an effect of this kind we have evaluated the mean free path of tertiary fragments with $Z > 15$ for short (3 cm) and long (3–5.4 cm) tracks. In this analysis we combined the charges using a scaling factor $72.2Z^{-0.64}$ which is our best fit for secondary charges in this same

TABLE I. Estimated tertiary mean free paths for different distances x between the primary and secondary interaction points and y between the secondary and tertiary interaction points. Also shown are the ratios F and their errors.

	$0.6 < y < 3$ (cm)	$3 < y < 5.4$ (cm)	F
$0.6 < x < 3$	67.76 ± 0.98	68.29 ± 1.16	1.008 ± 0.022
$3 < x < 5.4$	66.78 ± 1.07	66.17 ± 1.24	0.991 ± 0.024

charge range. The results are shown in matrix form in Table I together with the ratio, F, of values for short- and long-distance tertiaries. We find no significant variation. Furthermore, the absolute values are in reasonable agreement with those of the secondary fragments.

In conclusion, we find no evidence for the existence of a short mean-free-path component in Fe or Ar secondaries with $Z = 13-24$ and $Z = 11-16$, respectively. Nor do we observe any correlation between secondary and tertiary mean free paths. It is, of course, possible that the effect is limited to cases that we have not tested, namely $Z < 11$, distances less than 6 mm, as suggested by Barber *et al.*,[9] reactions with heavy target nuclei, or reactions in which the charge does not change. Nevertheless, lack of any positive evidence at the levels predicted by the visual-detector experiments is surprising. The analysis of this experiment is by no means complete and we shall continue to search for evidence for contributions of an anomalous component in our data. We are also planning further experiments which will increase our sensitivity for lower charges and at shorter distances.

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