Search for Anomalous Fragments of ^{56}Fe Using Plastic Nuclear Track Detectors

H. Drechsel, J. Dreute, C. Brechtmann, W. Heinrich, and W. Trakowski
Physics Department, University of Siegen, D-5900 Siegen, West Germany
(Received 24 September 1984)

We performed an experiment to investigate the anomalous mean-free-path phenomenon for projectile fragments of ^{56}Fe. 1846 charge-changing collisions of fragments with charges $Z=20$–25 were analyzed with plastic nuclear track detectors. We observed no evidence for anomalous fragments.

PACS numbers: 25.70.Np

The experimental results of mean-free-path (mfp) measurements for relativistic projectile fragments (PF's) are contradictory. Observations in cosmic-ray studies and in experiments with emulsions exposed at the Bevalac[1–3] showed an anomalously large interaction cross section of PF's within the first few centimeters from their point of emission. No dependence of this effect on charge or mass of the fragments was observable within the early data. Therefore this was believed to be a general phenomenon shown by all or most of the fragment types.

Confusion came up with the first experiments of Jain *et al.*[4] and Karant, Heckman, and Friedlander,[5] showing conflicting results for the fragments of charge $Z=2$ in nuclear emulsion. Further contradictory results for $Z=2$ fragments were reported by later investigations up to now.[6–8] For heavier fragments inconsistent observations were made when other experimental techniques were applied. Assemblies of thin Cherenkov detectors were used to analyze the anomalous mfp effect for ^{40}Ar and ^{56}Fe primary beams.[9,10] These experiments having high statistics showed no anomalous behavior of the fragments produced in Lucite.

For the Cherenkov experiments the experimental conditions in comparison to nuclear emulsion are different. It is not possible to detect nuclear interactions with $\Delta Z=0$. PF's with charges below ten were not measured. The Lucite target contains only constituents of light target nuclei. The accuracy in determination of the vertex position of an event is limited by the thickness of the single Cherenkov detectors which were 3.5 mm[9] and 3.17 mm,[10] respectively. Fragments emitted at large angles are not detected as a result of losses of Cherenkov light. Price[11] calculated that the loss of events by this effect starts already for angles as small as 2 deg. The controversial results observed by the Cherenkov detectors and emulsions may be due to these experimental differences.

In this situation investigations under experimental conditions which are closer to those of nuclear-emulsion experiments are important. These were performed in experiments with plastic nuclear track detectors. With stacks of these detectors like in the Cherenkov experiments only $\Delta Z \geqslant 1$ interactions can be analyzed. An advantage of this technique in comparison to the Cherenkov detectors is the smaller detector thickness, typically 0.6 mm, and the wider acceptance in production angle for the fragments. Disadvantages are the tedious track measurements which can be overcome by automated measuring techniques.[12,13]

In our first experiment[12] we observed no significant anomalous mfp effect. A conflicting result was reported by Tincknell, Price, and Perlmutter.[14] Both experiments used the same detector, PF's of almost the same charge range ($9 \leqslant Z \leqslant 17$), and the same beam particles (^{40}Ar). For ^{40}Ar projectiles also, no anomalous mfp was observed in a nuclear-emulsion experiment by the BCJJL collaboration.[8] The early experiment of Jain and Das[2] with ^{40}Ar projectiles showed an anomalous mfp effect in emulsion, but the results reported therein are combining data from a ^{56}Fe beam and a ^{40}Ar beam. Relying on the higher statistics of our experiment[12] in comparison to Tincknell, Price, and Perlmutter[14] one might conclude that fragments of the ^{40}Ar projectiles show no anomalous mfp effect for all types of experiments, emulsion, CR39, and Cherenkov detectors.

However, for projectiles heavier than ^{40}Ar an anomalous mfp effect was observed repeatedly in nuclear-emulsion experiments. Karant, Heckman, and Friedlander[5] confirmed their early observations.[1] Recently Jain, Aggarwal, and Gomber[15] found anomalous mfp's for fragments of charge $Z \geqslant 15$ produced in nuclear emulsion by the fragmentation of ^{86}Kr. However, no anomalous mfp effect was observed in a Cherenkov experiment[9] investigating fragments of a ^{56}Fe beam. In this situation experiments investigating the mfp effect for heavy beam particles with plastic track detectors are of particular interest.

We have extended our work to heavier beam nuclei and investigated fragments of ^{56}Fe. For this purpose a stack of 230 CR39 plastic foils, each of 0.6 mm thickness, was exposed at the Bevalac to ^{56}Fe ions with a beam energy of 1.7 GeV/nucleon and a density of 10^3 tracks/cm^2. In the part of the stack which was analyzed the beam nuclei were slowed down to 1.37 GeV/nucleon. That means all beam particles and their fragments had relativistic energies. In this experiment we used CR39 ($C_{12}H_{18}O_7$) containing 1% of dioctylphthalate (DOP) because the charge resolution for heavy fragments with $Z \geqslant 20$ is improved for this less-sensitive detector material. Additionally the surface quality is improved by the DOP.[16]

After etching of the plastic the particle tracks were measured on the front and rear sides of the detector foils with our automatic scanning system.[12] The particle charges were determined from the measured area of the tracks. As in our first experiment[11] we determined a local calibration of the detector foils based on the ratio of the measured areas of etch cones for fragment tracks and those for projectile tracks in the vicinity. For the CR39 used before, the size of the fragment tracks showed a linear dependence on the size of the beam tracks.[17] For the CR39 with DOP which we used in this experiment this dependence was not linear and, what was even more complicated, could not even be defined by a single function. All together the one batch of detectors ordered for this experiment[18] contained five types of material with different calibration curves. One type, which was rather insensitive, was not even usable for the experiment. Since these foils were placed in the downstream part of the stack a track reconstruction for fragments could not be performed in that part. The results reported here are from the first 180 detector foils of the upstream part of the stack. As a result of calibration problems the charge resolution for a single etch cone is poorer than optimally possible with CR39 track detectors. From our data we find that $\Delta Z = 0.45$ for $Z = 20$ fragments and $\Delta Z = 0.56$ for $Z = 25$ fragments.

The reconstruction of particle trajectories from the individual etch cones on the detector foils was performed in a similar way as described earlier.[12,17] But the analysis of this experiment was performed on a more powerful computer. Therefore it was possible to use more sophisticated methods considering geometric relations between neighboring tracks. As a result of this improvement problems with crossing over trajectories which we had in our first experiment did not arise. For very short tracks in some parts of the stack the charge measurement may have larger uncertainties as a result of the problems of charge calibration described above. Therefore, in the following analysis only tracks with a length > 4 mm are included. Interactions are defined by a change of the measured charge. The vertex of the interaction can be determined with a resolution of half a foil thickness (0.3 mm).

The interaction mean free paths λ^* were determined by $\lambda^* = \sum l_i/n$, where l_i is the path length measured for a fragment i either to the point of interaction or to the point were the particle left the detector, and n is the total number of detected interactions. As discussed by Pshenin and Voinov,[19] λ^* is a biased estimator of the mfp for small values of n. However, for the statistics of this experiment this bias is negligible.

Figure 1 shows the measured mfp $\lambda^*(d)$ for beam particles as a function of depth d in the stack. Trajectories of 14 077 beam nuclei with 8664 interactions were analyzed. The mean value over all data points of $\langle\lambda^*\rangle = 11.13 \pm 0.12$ g/cm^2 is shown as a dashed line. Deviations of the individual experimental points from $\langle\lambda^*\rangle$ are within the limits of statistical fluctuations (χ^2/d.o.f. = 4.52/5). That means that the detection efficiency for $\Delta Z \geqslant 1$ interactions is homogeneous throughout the stack.

This detection efficiency can be estimated by a comparison of the measured value of $\langle\lambda^*\rangle$ with a value calculated from the cross-section formula of Westfall *et al.*[20] If we assume for the beam particles which have the highest statistical significance that the calculated value of $\lambda = 10.43$ g/cm^2 is correct, then the difference in the interaction mfp indicates that our detection efficiency is below 1. By comparing the measured difference for $\lambda_{\Delta Z > 1} - \lambda_{\Delta Z \geqslant 1} = 1.26 \pm 0.18$ g/cm^2 with a value of 0.92 which was calculated as described by Heinrich *et al.*[12] we can estimate that the $\Delta Z = 1$ interactions have a reduced detection efficiency of 0.73. This limited detection efficiency for $\Delta Z = 1$ interactions explains nearly completely the difference of the calculated and measured value of $\langle\lambda^*\rangle$. The detection efficiency for the $\Delta Z > 1$ interactions is at least 0.97.

Figure 2 shows $\lambda^*(x)$ for fragments of charge $Z = 20$–25 as a function of distance x from the point of emission of the fragments. To enhance the statistical significance we pooled all the data for individual fragment charges. The interaction mean free paths of

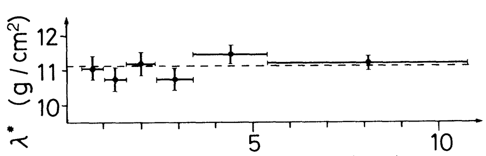

FIG. 1. Interaction mean free path of ^{56}Fe beam particles as a function of depth d in the stack. The dashed line gives the mean value.

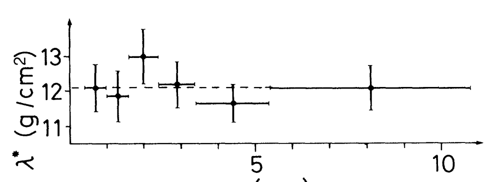

FIG. 2. Interaction mean free path as a function of distance x from the point of emission for fragments of $20 \leqslant Z \leqslant 25$. The dashed line gives the mean value.

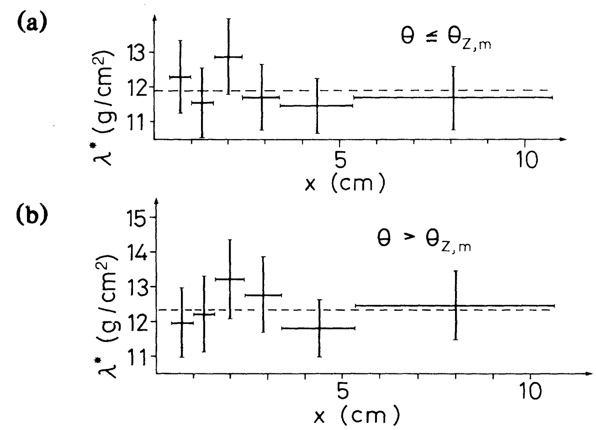

FIG. 3. Same as Fig. 2 but including only fragments with emission angles $\theta \leq \theta_{Z,m}$ in (a) and $\theta > \theta_{Z,m}$ in (b). $\theta_{Z,m}$ is the charge-specific median angle. For details see text.

the analyzed fragments differ only slightly. The maximum difference is about 13% for $Z=25$ and $Z=20$ fragments. For this reason we did not normalize the length of penetrated depth in the plastic to the calculated charge-specific interaction mfp as it was done in earlier experiments.[1–6, 12, 14, 15] We determined $\lambda^*(x)$ as described above for all analyzed fragment tracks ignoring the charge of the fragment. Deviations of the individual data points in Fig. 2 from the mean value which is shown as a dashed line are within the limits of statistical fluctuations ($\chi^2/\text{d.o.f.} = 2.05/5$). No indication of a reduced $\lambda^*(x)$ for small values of x can be observed.

The conflicting results of the emulsion and the Cherenkov experiments might be explained by the assumption that anomalous fragments are emitted at large angles and therefore not detected by the Cherenkov detectors.[11] From the complete analysis of the trajectories of the beam particles and the fragments we can determine the emission angle of the fragment for each interaction. Our trajectory reconstruction procedure limits this analysis to angles smaller than 8 deg. This value is above the maximum angle for tracks accepted in the emulsion experiments. Our measured distribution of the emission angles can be well understood in terms of the transverse-momentum distribution generally observed for relativistic PF's.[21] It drops to zero far below the value of 2 deg. From the charge-specific angular distributions we determined the median values $\theta_{Z,m}$ given in Table I which divide the data for the fragments of each charge into two subsamples with equal numbers of fragments. No statistically significant difference between these two subsamples for different angles of emission can be observed from the data plotted in Figs. 3(a) and 3(b).

TABLE I. Medians of the fragment emission angles.

Z	$\theta_{Z,m}$ (deg)
20	0.232
21	0.220
22	0.197
23	0.174
24	0.147
25	0.110

TABLE II. Confidence limits for the rejection of anomalon mean free path λ_a and abundance α of different experiments.

λ_a (cm)	α (%)	Confidence limit given by this exp. (%)	Ref.
2.5	6	99.0	1 and 5
1.0	3.6	97.5	13
1.55	3.3	92.0	22
1.0	3–5	93.5–99.9	15

In conclusion, we find no evidence for anomalons among ^{56}Fe secondaries of charge $Z = 20$–25 for distances of $x = 0.4$–10.8 cm from their point of emission. This observation is in agreement with the Cherenkov-detector experiment of Symons *et al.*[10] for ^{56}Fe projectiles. We can rule out at the confidence levels given in Table II parameters for the existence of anomalons reported by different experiments for fragments of iron and heavier projectiles. In comparison to the Cherenkov experiment our experimental conditions are closer to those of the nuclear-emulsion experiments[1,5] since we included $Z=25$ fragments and a large amount of $\Delta Z = 1$ interactions. Additionally our experiment had a high efficiency to detect also beam fragments emerging at larger angles, which might have been missed in the Cherenkov experiments.[11]

Our results are in contradiction to the two emulsion experiments investigating Fe secondaries[1,5] which show evidence for anomalons over distances of some centimeters from the point of emission. But we agree with recent results of an experiment by Baroni *et al.*[23] investigating mfp's of Fe secondaries in nuclear emulsion which is also in contradiction with Refs. 1 and 5.

This work was supported by the Bundesminster für Forschung und Technologie, No. 06SI159. We are grateful to the staff of the Bevalac for the exposure of the plastic stack.

[1]E. M. Friedlander, R. Gimpel, H. H. Heckman, Y. Karant, B. Judek, and E. Ganssauge, Phys. Rev. Lett. **45**,

1084 (1980), and references therein.
[2]P. L. Jain and G. Das, Phys. Rev. Lett. **48**, 305 (1982), and references therein.
[3]H. Barber, P. S. Freier, and C. J. Waddington, Phys. Rev. Lett. **48**, 856 (1982), and references therein.
[4]P. L. Jain, M. M. Aggarwal, G. Das, and K. B. Bhalla, Phys. Rev. C **25**, 3216 (1982).
[5]Y. J. Kurant, H. H. Heckman, and E. M. Friedlander, in Proceedings of the Second Workshop on Anomalons, Berkeley, Lawrence Berkeley Laboratory Report No. 16281, 1983 (unpublished), p. 23.
[6]A. Z. M. Ismail, M. S. El-Nagdy, K. L. Gomber, M. M. Aggarwal, and P. L. Jain, Phys. Rev. Lett. **52**, 1280 (1984).
[7]M. El-Nadi, O. E. Badawy, A. M. Moussa, E. I. Khalil, and A. A. El-Hamalawy, Phys. Rev. Lett. **52**, 1971 (1984).
[8]S. B. Beri *et al.*, unpublished.
[9]J. D. Stevenson, J. A. Musser, and S. W. Barwick, Phys. Rev. Lett. **52**, 515 (1984).
[10]T. J. M. Symons, M. Baumgartner, J. P. Dufour, J. Girard, D. E. Greiner, P. J. Lindstrom, D. L. Olson, and H. J. Crawford, Phys. Rev. Lett. **52**, 982 (1984).
[11]P. B. Price, CERN Report No. EP/84-85, 1984 (to be published).
[12]W. Heinrich, H. Drechsel, W. Trakowski, J. Beer, J. Dreute, and S. Sonntag, Phys. Rev. Lett. **52**, 1401 (1984).
[13]W. Trakowski, B. Schöfer, J. Dreute, S. Sonntag, C. Brechtmann, J. Beer, H. Drechsel, and W. Heinrich, Nucl. Instrum. Methods **225**, 92 (1984).
[14]M. L. Tincknell, P. B. Price, and S. Perlmutter, Phys. Rev. Lett. **51**, 1948 (1983).
[15]P. L. Jain, M. M. Aggarwal, and K. L. Gomber, Phys. Rev. Lett. **52**, 2213 (1984).
[16]G. Tarlé, S. P. Ahlen, and P. B. Price, Nature (London) **293**, 556 (1981).
[17]H. Drechsel, C. Brechtmann, J. Dreute, S. Sonntag, W. Trakowski, J. Beer, and W. Heinrich, to be published.
[18]We used CR39 produced by Pershore Mouldings, England.
[19]E. S. Pshenin and V. G. Voinov, Phys. Lett. **128B**, 133 (1983).
[20]G. D. Westfall, L. W. Wilson, P. J. Lindstrom, H. J. Crawford, D. E. Greiner, and H. H. Heckman, Phys. Rev. C **19**, 1309 (1979).
[21]D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cork, and F. S. Bieser, Phys. Rev. Lett. **35**, 152 (1975).
[22]M. L. Tincknell, in Proceeedings of the Seventh High Energy Heavy Ion Study, Gesellschaft für Schwerionenforschung, Darmstadt, October 1984 (unpublished).
[23]G. Baroni, A. M. Cecchetti, S. Di Liberto, A. Manfredini, F. Meddi, G. Raoman, and C. Sgarbi, in Proceedings of the Seventh High Energy Heavy Ion Study, Gesellschaft für Schwerionenforschung, October 1984 (unpublished).