Search for Anomalons in Projectile Fragments of ^{40}Ar Using Plastic Nuclear Track Detectors

W. Heinrich, H. Drechsel, W. Trakowski, J. Beer, C. Brechtmann, J. Dreute, and S. Sonntag
Physics Department, University of Siegen, 5900 Siegen, West Germany
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We performed an experiment using plastic nuclear track detectors to investigate the phenomenon of enlarged cross sections for projectile fragments of relativistic ^{40}Ar nuclei. This effect had been observed within the first few centimeters after fragment emission in Bevalac and cosmic-ray experiments with nuclear emulsion. On the basis of 6444 charge-changing nuclear collisions we conclude that under our experimental conditions no statistically significant anomalous mean free path effect can be observed.

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The property that identifies anomalons is the considerable smaller mean free path (mfp) of fragments of relativistic heavy ions within the first few centimeters after their production. Beyond this distance the mfp approaches the value observed for the beam nuclei. The first observations of Friedlander *et al.*[1] were consistent with an admixture of $\alpha = 6\%$ of anomalous projectile fragments having a mfp of $\lambda_a = 2.5$ cm in nuclear emulsion. The existence of an anomalous mfp effect has been confirmed by two experiments using nuclear emulsion.[2,3] The aim of our experiment was to investigate the anomalous mfp effect by use of a different experimental method and to improve the underlying statistics.

A stack of 300 foils of CR39 ($C_{12}H_{18}O_7$) plastic nuclear track detector each 0.6 mm thick was exposed at the Bevalac to ^{40}Ar ions incident vertically to the surface of the foils. The beam particles had an energy of 1.8 GeV/nucleon and a total energy loss of 400 MeV/nucleon in the stack. Thus all beam particles and their fragments had relativistic energies. By means of etching, the particle tracks were developed to cones. Altogether 1.5×10^7 etch cones were measured on the front and rear sides of the foils with an automatic measuring system.[4] The coordinates of the etch cones and their areas were recorded by this system. We determined the charge of a fragment from the ratio of the area of its etch cone to the mean cone size of projectile tracks in the vicinity. As a result of this local calibration of the detector foils, a charge resolution for a single etch cone of $\Delta Z = 0.2$ for charge-8 fragments and of about $\Delta Z = 0.7$ for charge-17 fragments was achieved.

From the positions of the etch cones on every foil the trajectories for individual projectile fragments were reconstructed. The charge resolution determined from the average of a large number of etch cones is better than $\Delta Z = 0.1$. In the following analysis only fragment trajectories with a length > 2 mm are included. For these trajectories interactions are defined by a change in the measured charge. The position of an interaction can be determined with a resolution of half a foil thickness (300 μm). Relativistic nuclei with charges below 8 were not detectable because of the threshold of energy loss for track formation in the CR39 and fragments of charge 16 and 17 were excluded from the analysis.

A possible source of systematic error in our experiment arises from occasionally crossing over trajectories for which the reconstruction fails. In these cases short trajectories that are artifacts are reconstructed. Therefore we reinspected visually all fragment trajectories shorter than 1.2 cm and eliminated these artifacts. Additionally a subsample of 960 tracks having lengths 2.2 cm $x < 3.2$ cm and 6.2 cm $< x < 8.2$ cm was reinspected. This analysis showed that systematic effects only influence the measurements of the mfp for tracks shorter than 1 cm. Since all these short tracks were reinspected we conclude that the results given in Figs. 1 to 3 are free of systematic errors.

A detailed description of our experimental method to investigate nuclear collisions of heavy ions will be given elsewhere.[5]

For each fragment i with charge Z the path length l_i^Z in a detector interval was measured either to the point of interaction or to the point where the particle left the interval. The interaction mfp λ_Z can be determined by dividing the sum of all l_i^Z by the number n_Z of interactions detected.

Figure 1 shows the measured mfp $\lambda_{18}(d)$ for the beam particles as a function of depth d in the stack. Only a part of the beam nuclei, 5795 particles with 3968 interactions, were analyzed to determine λ_{18}. The mean value over all data points shown as a line

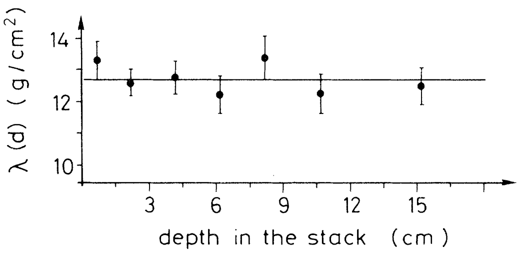

FIG. 1. Interaction mean free path of ^{40}Ar beam particles as a function of depth d in the stack. The solid line gives the mean value.

in Fig. 1 is 12.64 ± 0.27 g cm^{-2}. No systematic deviations from this mean value can be observed. That means that the sensitivity to detect interactions is homogeneous throughout the plastic stack.

For individual fragment charges the statistics are limited. Therefore the information from the different fragment charges was pooled by normalizing the λ_Z for each charge to a calculated interaction mfp λ^c_Z. On the basis of this normalization we determined

$$\lambda^* = \textstyle\sum_Z \sum_i (l_i^Z/\lambda_Z^c)/\sum_Z n_Z.$$

This normalized interaction mfp is shown in Fig. 2 for different intervals of depth in the plastic stack. Data from fragments 9 to 15 and all fragment generations are included. We excluded fragments of charge 16 and 17 from the analysis because the poorer resolution for these charges complicates the detection of $\Delta Z = 1$ fragmentations. The line shows the mean value of $\lambda^* = 0.96 \pm 0.01$ which is below the normalization value of 1. This figure also shows that the sensitivity for the detection of interactions is homogeneous with depth in the plastic stack.

To investigate the anomalous mfp effect, $\lambda^*(x)$ was determined for intervals of distance x from the point of emission of the fragments. In Fig. 3 the result for 14185 fragments of charge $9 \leq Z \leq 15$ including 6444 charge-changing interactions is presented. These data show an interaction mfp which is reduced in comparison to the normalization value within distances $x < 1.2$ cm and surprisingly also above $x > 4.2$ cm.

The normalization value of the interaction mfp, λ^c_Z, was calculated with use of the empirical formula of Letaw, Silberberg, and Tsao[6] for total interaction cross sections of nuclear collisions with hydrogen in the plastic. For collisions with carbon and oxygen the empirical overlap formula of Lindstrom *et al.*[7] was used. A correction for non-charge-changing interactions was included. This was derived from the

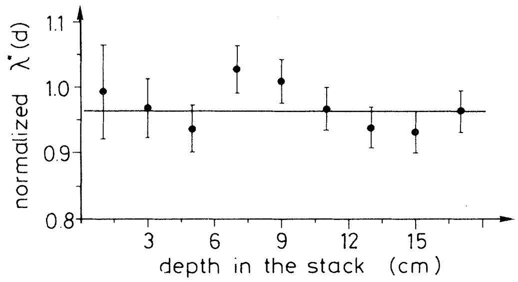

FIG. 2. Normalized interaction mean free path as a function of depth d in the stack for fragments of $9 \leq Z \leq 15$. The solid line gives the mean value.

semiempirical formula for partial fragmentation cross sections of Silberberg and Tsao[8] and with the assumption of a factorization of the cross sections for heavier targets. The interaction mfp was calculated for the different isotopes of each fragment charge. Then the weighted mean of λ^c_Z for the different isotope masses was determined based on calculated mass yields.[8]

The cross-section formula for collisions with hydrogen is accurate within $\sigma = 1.0\%$.[6] For the heavier targets the overlap formula[7] fits experimental data within $\sigma = 7\%$. The partial fragmentation cross sections[8] have a standard deviation of $\sigma = 20\%$. On the basis of these uncertainties a limit for the normalization of $\pm 4\%$ was determined. This uncertainty which is shown as dashed lines in Fig. 3 is dominated by the total interaction cross sections for collisions with C and O nuclei in the plastic.

An interpretation of the result for $\lambda^*(x)$ shown in Fig. 3 depends on the validity of the normalization of the measured mfp's. We discuss two extreme points of view. The one favoring the existence of anomalons is to assume that the normali-

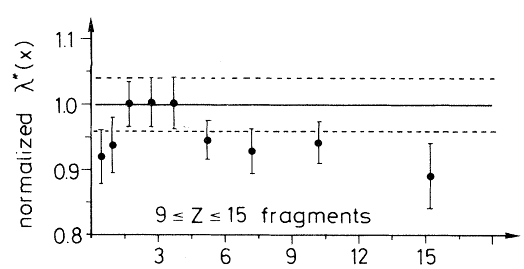

FIG. 3. Normalized interaction mean free path as a function of distance x from the point of emission. The solid and the dashed lines give the normalization and the uncertainty of the normalization.

zation is correct and to compare the data points of Fig. 3 with the solid line for $\lambda^* = 1$. Within the first 1.2 cm λ^* is 2.8 standard deviations away from the normalization value of 1. The contribution of anomalons can be derived from the data points for $x < 4.2$ cm ignoring the results for larger x. A parametrization of our data based on the model of Friedlander *et al.*[1] shows that an admixture of $\alpha = 1.2\%$ fragments having an interaction mfp of $\lambda_a = 0.65$ cm can explain these observations. A restriction of the mfp effect observed in our experiment to small values of x and a smaller magnitude was already indicated in a preliminary analysis for $Z = 14$ fragments.[9]

We compare parameter sets different from those giving a best fit of our data by the ratio of the likelihood functions. This normalized likelihood for the parameters $\alpha = 6\%$ and $\lambda_a = 2.5$ cm^1 is 2×10^{-6}. With the assumption that anomalous fragments are stable and disappear only because of a large collision cross section, we must consider the density of target nuclei for a comparison of different materials. It is greater by a factor of 1.37 for CR39 than for emulsion. The parameters $\alpha = 6\%$ and $\lambda_a = 2.5/1.37$ cm yield a normalized likelihood of 4×10^{-9}. If we compare our data with the recent results of Tincknell, Price, and Perlmutter[10] who found parameters of $\alpha = 3.6\%$ and $\lambda_a = 1$ cm in CR39 we get a normalized likelihood of 1.8×10^{-4}. That means that even for an interpretation of our results in a way favoring the anomalons we are in clear contradiction to the parameters of Ref. 1 and also of Ref. 10. On the other hand we cannot reject the hypothesis that all fragments have geometric cross sections ($\alpha = 0$) which has a normalized likelihood of 0.02.

The other extreme interpretation, discarding the existence of anomalons, is to assume that the interaction cross sections in CR39 are underestimated. This may be indicated by the data compared in Table I. The calculated values of λ_Z^c fit the measured mean values if we reduce them by 4%. This is within the limits of uncertainty of the normalization indicated by the dashed lines in Fig. 3. The χ^2 value of 8.75 for eight degrees of freedom indicates that the decrease of $\lambda^*(x)$ for small and large values of x can be understood as a statistical fluctuation. This interpretation of the variation of $\lambda^*(x)$, however, ignores the smoothness of the variation of λ^* with x.

A presentation of the data which is free of the normalization can be given by comparison of λ_1 $(< l_1)$ and λ_2 $(> l_2)$ as proposed by Otterlund.[12] These data for $l_1 = l_2 = 1.2$ cm are plotted in Fig. 4 for individual fragment charges. The diagonal divides the diagram into two triangles. The upper triangle is forbidden; the lower triangle is only allowed if beam fragments contain anomalons. The data presented in Fig. 4 indicate a somewhat higher population in the lower triangle. This can be expressed quantitatively by the F ratios λ_1/λ_2 for the individual fragments and by calculation of the integral probabilities $P(<F)$. These $P(<F)$ determined for each Z are expected to be uniformly distributed between 0 and 1 for normal fragments. The mean value $\bar{P}$ has an expectation value of 0.5 if no anomalons are present, whereas for fragments containing anomalons this value is below 0.5. From the data of Fig. 4 we obtain a mean value of $\bar{P} = 0.40 \pm 0.10$. It is only one standard deviation below the expectation value of 0.5. On the basis of this and on the discussions above we conclude that we observe no statistically significant anomalous mfp effect, although the statistics of our experi-

TABLE I. Comparison of measured and calculated mean free paths $\lambda_{\Delta Z \geq 1}$ (g/cm^2) for beam particles in CR39.

Beam	This experiment	Price[a]	Calculated
^{20}Ne	$\cdots$	18.72 ± 1.16	18.11
^{40}Ar	12.64 ± 0.27	12.61 ± 0.61	13.36
^{56}Fe		10.44 ± 0.44	11.12

[a]Ref. 11.

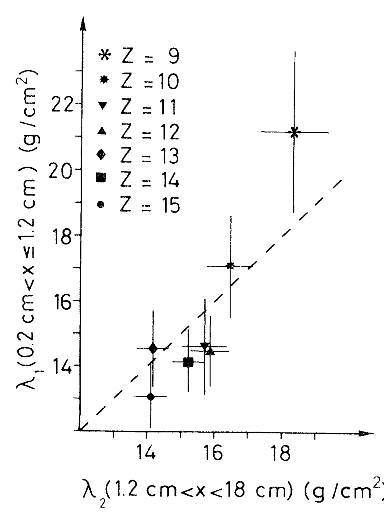

FIG. 4. λ_1 (0.2 cm $< x <$ 1.2 cm) vs λ_2 (1.2 cm $< x$ $<$ 18 cm) for individual fragment charges.

ment has been increased significantly in comparison to earlier experiments. A comparable result was recently reported by Holynski[13] for fragments of charge $3 \leq Z \leq 9$ from $4.1A$-GeV/c ^{22}Ne projectiles in nuclear emulsion.

In a CR39 target all nuclear collisions take place with light target nuclei. For about 30% of the collisions hydrogen is the target. This is different from an experiment using nuclear emulsion. On the basis of the contradiction between our results and those of Refs. 1–3 it seems likely that the anomalous mfp effect depends on experimental parameters like mass of the projectile, target, and fragment. Following this idea we will presently analyze stacks that were exposed to ^{56}Fe beam nuclei and contained heavy target foils between the plastic detectors.

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