Search for Anomalous Fragments Produced in Collisions with Heavy Target Nuclei and in $\Delta Z = 1$ Peripheral Interactions

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We exposed a stack of CR39 track detectors containing Ag foils to a 1.7-GeV/nucleon ^{56}Fe beam and investigated the anomalous mean-free-path effect. Neither the whole set of 7517 nor a subset of 2542 interacting fragments produced probably in the Ag target show an effect. By combining the data of this and an earlier experiment we can also exclude an effect for 3219 interacting fragments produced in $\Delta Z = 1$ collisions.

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The state of mean-free-path (MFP) measurements for relativistic projectile fragments (PF's) under different experimental conditions is still not clear. The results of the early emulsion experiments[1-3] that showed an anomalously large interaction cross section of PF's within the first few centimeters from their point of emission are now contradicted by some other experiments which used different techniques such as Cherenkov detectors[4,5] and plastic nuclear track detectors,[6,7] and even by experiments which used nuclear emulsions.[8-10] But simultaneously new results were reported that support the existence of anomalous heavy-ion fragments for fragments with $Z > 2$.[11,12] In the present situation it seems that two special experimental conditions may be of particular importance for the observation of this effect. There are some indications that the effect is preferentially observed for fragments produced in collisions with heavy target nuclei and for fragments produced in extremely peripheral collisions.

A theoretical model[13] predicts that anomalons can be understood as quasimolecular states of nuclear matter. The probability for the creation of these states in nuclear collisions increases in heavy targets. In nuclear emulsion a large number of collisions occur with heavy target nuclei such as silver and bromine. For an Fe or Ar beam, these are about 50% of all collisions. This situation is quite different for the Cherenkov-detector experiments and for experiments using plastic nuclear track detectors where all collisions take place with targets not heavier than oxygen. If anomalons would be produced only in collisions with heavy targets, this would explain all of the negative results of the search for anomalons by Cherenkov-detector experiments[4,5] and by our experiments using CR39.[6,7] However, the discrepancies of emulsion experiments reporting no evidence for anomalous MFP's[8-10] and CR39 experiments reporting evidence, but having lower statistics,[14,15] would still remain.

Furthermore, some observations support the idea that anomalons are produced in extremely peripheral collisions. The most striking hint comes from a bubble-chamber experiment,[16] where collision products of a 3.7-GeV/nucleon ^{12}C beam were analyzed. No anomalous behavior was observed for any type of analyzed interaction products except ^{12}C projectiles that had undergone a collision, but did not loose charge. If we follow the hypothesis that anomalons are produced preferably in peripheral interactions, all experiments that have a low sensitivity for detection of these interactions should see a reduced or no effect of anomalous MFP's. An experiment of this type is our first plastic-track-detector experiment,[6] which did not include fragments produced in $\Delta Z = 0$ interactions and even most of the fragments produced in $\Delta Z = 1$ interactions. Also the negative result of the nuclear-emulsion experiment of Beri *et al.*[9] can be understood under this hypothesis because this experiment used rather insensitive emulsions, contrary to the early emulsion experiments,[1-3] and was not very efficient in the detection of $N_h = 0$ interactions, which are typically peripheral. A recent experiment[12] using a Kr beam has shown some spectacular fragmentation chains with successive fragmentation over short distances. For all of these events, the first-generation fragment has a small ΔZ compared to the beam, indicating that the fragment was produced in a peripheral collision. This picture of anomalons produced preferably in peripheral collisions is troubled by the results of a recent emulsion experiment[10] that reports no significance for anomalons, though it is sensitive to $N_h = 0$ interactions.

We performed a new experiment which meets the requirements of both heavy target and high efficiency for the detection of $\Delta Z = 1$ interactions. For this purpose, 200-μm-thick silver foils were stacked between the CR39 foils ($C_{12}H_{18}O_7$) of 600-μm thickness. A stack of 150 each of silver and plastic foils with a size

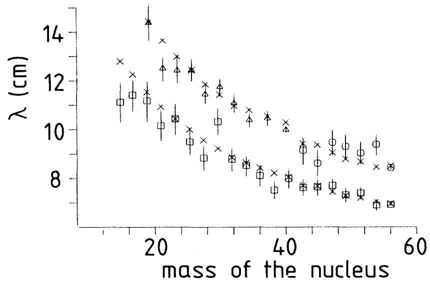

FIG. 1. Comparison of calculated and measured MFP's for different projectiles and targets as a function of the mean mass. This mean mass was determined with consideration of the relative yield of the different isotopes (Ref. 6). Measured values: ^{40}Ar beam and fragments in CR39 (triangles, Ref. 6); ^{56}Fe beam and fragments in CR39 (circles, Ref. 7) and in a stack composed of CR39 and Ag (squares). Calculated values for both types of target are shown by crosses.

of 10×8 cm^2 was exposed at the Bevalac to a 1.7-GeV/nucleon Fe beam with 10^3 particles/cm^2. The beam nuclei were slowed down in the stack to 0.8 GeV/nucleon. In this experiment we used CR39 without dioctylphthalate (DOP). Because of the high sensitivity of this material, tracks of fragments with charges $Z \geqslant 7$ were recorded.

After etching of the detectors, the tracks of all particles were measured with use of our automatic measuring system.[17] After a calibration, the particle charges were determined from the measured areas of the tracks. In the following analysis only tracks with a length >4 mm containing at least ten etch cones are included. The charge resolution for short tracks is about $\Delta Z = 0.2$ and improves for longer tracks. The reconstruction of particle trajectories through the stack was performed in a similar way as described earlier.[7,18] The uncertainty of the measured path lengths due to the experimental technique is half a foil thickness. Because of uncertainties in locating the points of interaction for $\Delta Z = 1$ collisions, in some cases an error in the order of one foil thickness has to be added. Since these uncertainties are small in comparison to the interaction MFP, they cause only a negligible systematic effect. By following the paths of the particles over all detector foils, charge-changing nuclear interactions were detected. By measuring the particle tracks on both sides of the detectors, it was in principle possible to separate the interactions that took place in the plastic from those that occurred in the silver foils. However, fluctuations of the size of the etch cones and the possibility that interactions may have occurred near the surface of the detector foils, which is etched away, make the separation more difficult, particularly for small charge changes. The measured ratio of the number of interactions in CR39 and in silver was compared with a calculated one. From this we conclude

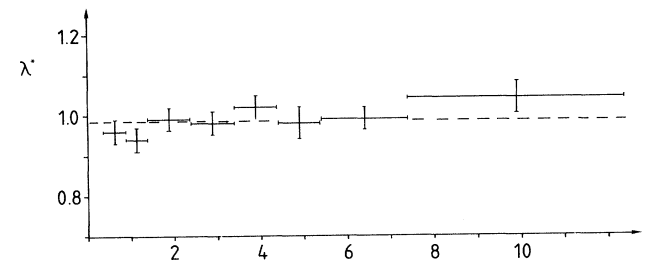

FIG. 2. Normalized interaction MFP as a function of distance x from the point of emission in the composed target CR39+Ag. The dashed line represents the mean value of 0.985 ± 0.012.

that the probability for a correct identification of the type of target for an individual interaction is nearly 0.75.

The interaction mean free paths $\lambda_Z(x)$ were determined for intervals of distance x from the point of emission of the fragments, as described earlier.[7] These $\lambda_Z(x)$ were normalized to a value λ_Z^c which was calculated with consideration of the relative yield of the different isotopes, as described in Ref. 6. Figure 1 shows calculated and measured average values of λ_Z^c and λ_Z for the target composition of Ag+CR39 of this experiment and for a stack of pure CR39. No statistically significant deviations between the measured interaction mean free paths and the calculated values can be observed. A χ^2 test gives $\chi^2 = 46.3$ for 37 degrees of freedom.

To improve the statistical significance, the normalized interaction mean free paths for all individual fragment charges were compiled into one data set, $\lambda^*(x)$, shown in Fig. 2. The horizontal bars indicate the intervals of distance from the interaction point. This result which is based on 7517 interactions of fragments with charges $7 \leqslant Z \leqslant 25$ shows no significant deviation from a constant mean free path.

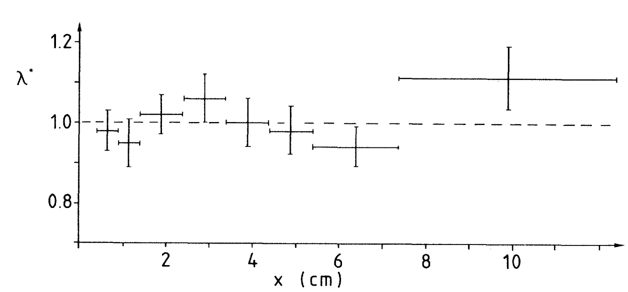

FIG. 3. Normalized interaction MFP of fragments produced in the Ag part of the target as a function of distance x from the point of emission. The mean value is 1.002 ± 0.020.

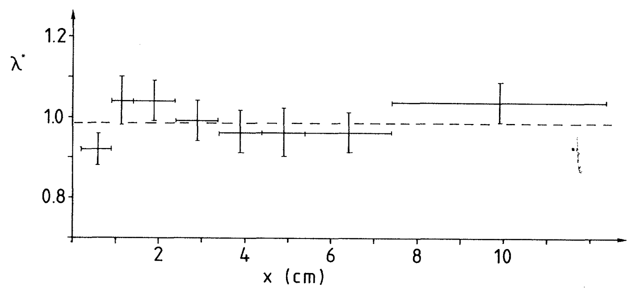

FIG. 4. Normalized interaction MFP of fragments produced in $\Delta Z = 1$ collisions as a function of distance x from the point of emission. The mean value is 0.986 ± 0.018.

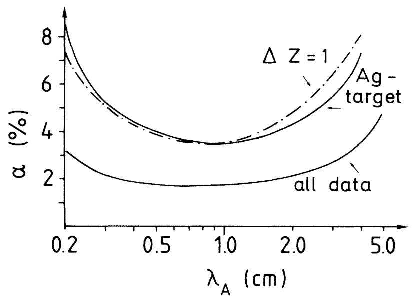

FIG. 5. Curves of confidence in the plane of the abundance of anomalons and their assumed MFP obtained from two subsets and a combination of all our data. The regions above the curves are ruled out at a 95% confidence level.

To investigate a dependence of the result on the mass of the target nucleus, we analyzed separately $\lambda^*(x)$ for those fragments produced in collisions with silver target nuclei. Because of the uncertainty of the separation, the data set contains only a part, of about 70%, of the fragments produced in silver, which, however, is greater than the equivalent part in experiments with nuclear emulsion. This result, shown in Fig. 3, which is based on 2542 interactions also gives no indication of a dependence of the mean free path on x.

As described above, the experimental data available until now indicate that anomalons may be produced more efficiently in peripheral collisions. Therefore, we analyzed separately the interactions of fragments produced in $\Delta Z = 1$ collisions for this experiment, including data of an earlier experiment exposed to an Ar beam for which the analysis was extended to $Z = 16$ and 17 fragments. From this stack, data of tracks longer than 2 mm are available. Our efficiency for the detection of a fragmentation with $\Delta Z = 1$ decreases from unity to about 84% when the length of the track decreases from twenty to ten foil layers. The efficiency was measured by an artificial shortening of long fragment trajectories contained in our data. Successively, track data were omitted until the algorithm for the detection of interactions failed. This reduced efficiency would diminish the number of short tracks, which means that an anomalous MFP effect could be hidden. We corrected our data on the basis of the measured efficiencies. Figure 4 shows the normalized $\lambda^*(x)$ of fragments produced in $\Delta Z = 1$ collisions of beam particles and fragments; 3219 interactions were observed. No anomalous MFP effect is seen beyond the first centimeter. A small effect for distances less than 1 cm cannot be excluded, but the significance is less than 2 standard deviations.

Figure 5 shows three curves of confidence in the plane of the parameters α and λ_A, where α is the admixture of the anomalons in the set of PF's and λ_A their MFP. Pairs of the parameters from the region above the curves can be rejected at a confidence level of 95%. One curve results from the fragments produced in $\Delta Z = 1$ collisions, and another from those produced in the heavy silver target. Additionally, we combined all of our data available until now from experiments described in this paper,[6,7] without any restriction. These experiments with Ar and Fe beams at 1.7 and 1.8 GeV/nucleon, fragments in the range from $Z = 7$ to 25, and CR39 or Ag targets have contributed altogether 16 847 interactions. The resulting curve is drawn in Fig. 5.

In summary, we have investigated two hypotheses about the anomalous MFP effect. In our high-statistics experiments using CR39 nuclear track detectors we found no evidence for the existence of anomalons. Neither the use of a heavy silver target nor the restriction to data obtained from fragments produced in $\Delta Z = 1$ collisions gives results consistent with the strong anomalous MFP effect reported earlier.[1-3] Because of the possibility of measurement of the MFP at small distances from the interaction point, our data provide a higher significance for the rejection of the anomalon hypothesis than earlier experiments[4] at interaction lengths below 0.5 cm.

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