Observation of Anomalously Short Mean Free Paths of Projectile Fragments of 1.85A-GeV ^{40}Ar in CR-39 Etched Track Detector

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When fragments of 1.85A-GeV ^{40}Ar projectiles are observed in a CR-39 etched track detector, anomalously short mean free paths of secondary nuclei with $11 \geq Z \geq 17$ are found within the first 2 cm after their production, at ~ 3 standard deviations. This confirms the previous reports of this "anomalon" effect in nuclear emulsion. The data can be fitted by the hypothesis that $\sim 3.6\%$ of the secondaries have a mean free path of ~ 1.0 cm and infinite lifetime.

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The anomalous mean-free-path (mfp) effect, in which the fragments from interactions of relativistic nuclear projectiles show an enhanced tendency to interact within a short distance after their formation, is still an unexplained enigma. The term "anomalons" has been adopted[1] to denote the unknown component of these secondary nuclei responsible for this effect. Virtually all published results on this phenomenon have used nuclear emulsion as both target and detector.[2-4] Thus, there is an urgent need to confirm this work with a new detector with different methodology and dissimilar potential systematic errors. The CR-39 plastic etched track detector provides this alternative.[5] It allows the sampling of a projectile's charge with high resolution at ~600-μm intervals along a nuclear track, and thus successive nuclear charge-changing interactions in short distances can be observed. We report here the observation of depressed secondary mfp's in the first 2 cm beyond the primary interactions in CR-39, in agreement with the previous emulsion work, and we give additonal data on anomalons.

In our experiment a beam of 1.85A-GeV ^{40}Ar ions from the Lawrence Berkely Laboratory Bevalac entered a stack of 640-μm-thick CR-39 sheets perpendicularly. After etching, the nuclear tracks appeared as conical pits on the top and bottom surfaces of each sheet. Because of the negligible ionizational slowing in our plastic stack, and because of the persistence of the beam velocity by projectile fragments, the nuclear charge was determined with charge resolution $\leq 0.25e$ for nuclei with charge $10 \leq Z \leq 18$, by the measurement of a single diameter.[6]

In contrast to nuclear emulsion, in CR-39 the particle's trajectory is discontinuously revealed by collinear etch pits on the sheet surfaces; in CR-39(DOP), i.e., doped with 1% dioctyl phthalate, only particles with $Z/\beta \geq 10$ record tracks; no useful information about target fragmentation is obtained; and only charge-changing interactions can be seen. Advantages of CR-39 over emulsion are that the nuclear charge can be quickly determined with high resolution so that interactions with $\Delta Z \geq 1$ are detected with ~100% efficiency.

In our measurement technique, an observer distinguishes each track being followed from neighbors, centers its video image on a screen, and ensures that the track diameter is not flawed. We use a computer-driven stage which indexes to prerecorded track positions, and an automatic system which finds the track diameter by detecting the edges of the track's video image. Our approach was to isolate tracks of secondary particles originating from primary interactions in short fiducial intervals near the front of the stack. We found the secondaries by superimposing and aligning two sheet surfaces which were five sheets apart (0.32 cm) in the original stack, focusing on the interface between the two sheets, and scanning for changes in diameter of the associated pairs of tracks. We followed these secondaries into the stack in 1-cm jumps, and located the interactions of the secondaries to within 0.25 cm by a binary search of successively smaller subintervals. New sheets to be measured were superimposed on previously measured upstream sheets so that ambiguities and interactions could be simply resolved by focusing through to the bottom sheet and matching the tracks. We scanned five consecutive five-sheet intervals and obtained 1530 secondaries with $11 \leq Z \leq 17$, and we found 612 interactions of these secondaries within ~6 cm downstream of their primary interactions.

Our technique of superimposing a new sheet on an already measured sheet enabled us to avoid confusing the track being followed with neighboring tracks. We also required observations of a track with the same charge value on two different surfaces to confirm its existence. This prevented erroneous interactions due to single spurious diameter values. Problem cases occurred quite infrequently, about 1 to 5 times for each 1000 diameters measured. A sample of 246 events was completely remeasured and only five disagreements were discovered for particles with charge $Z \geq 11$, three of which were uncertainties about interactions with $\Delta Z = 1$. Also, we have measured the interaction mfp's of primary Ne, Ar, and Fe in CR-39.[7] We obtained values which agree well with those calculated from the Bradt-Peters expression for geometrical cross sections[8]: $\sigma = \pi r_0^2(A_T^{1/3} + A_P^{1/3} - b)^2$, using parameters obtained by Westfall *et al.* for charge-changing interactions[9]: $r_0 = 1.35$ fm, $b = 0.83$.

The measured mfp for any charge species can be estimated over any distance interval either as $\lambda = (\sum_i l_i)/N$, where l_i is the path length of the ith particle in the distance bin, and N is the number of interactions in the bin, or by $\lambda = -D/\ln(1 - N/N_0)$, where D is the distance interval, and N_0 is the flux which either penetrates the bin or interacts within it. (Both methods give very similar results.) Several subtleties in applying this procedure to our data deserve mention. First, our method of initially finding secondaries demands that the newly created secondaries survive at least until the downstream sheet in the five-sheet interval.[10] Second, our insistence that we observe a secondary charge at least twice to confirm its existence inevitably removes some real

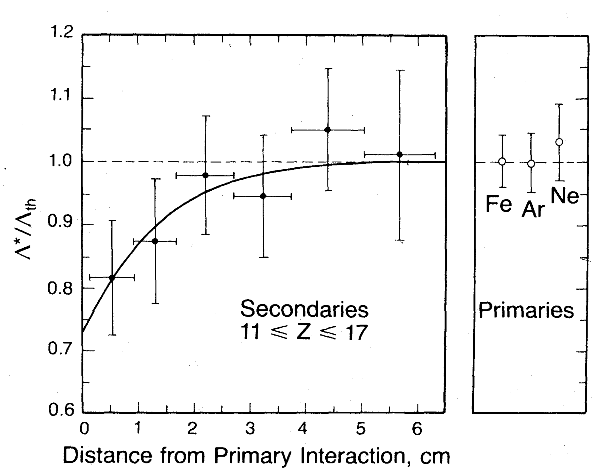

FIG. 1. Λ^* vs distance from primary interactions for secondaries with $11 \leq Z \leq 17$, and Λ^* for primary Ne, Ar, and Fe. Horizontal bars are bin widths and vertical bars are 1σ statistical error limits.

secondary interactions along with the spurious ones. To avoid these two distortions, we exclude the first 0.16-cm interval beyond the primary interactions from our data.

To increase statistical significance, we pooled the data for individual charges using two different methods.[1] First, we used a charge weighting derived from the empirical relation $\lambda = \Lambda Z^{-b}$ to define a parameter $\Lambda^* = (\sum_i l_i Z^{+b})/N$ for various distance bins beyond the primary interactions, as shown in Fig. 1. The normalization value $\Lambda_{th} = 52.25$ cm, and the exponent $b = 0.58$, were calculated from the Bradt-Peters geometrical cross sections with parameters from Westfall *et al.*, and an isotope-weighted spectrum of fragments of Ar interactions in CR-39 calculated with a program based on Silberberg and Tsao.[11] Figure 1 clearly demonstrates a depression of about 15% in Λ^* in the first 2 cm after the primary interactions, and recovery to normal quickly thereafter. To increase statistics we divided the data into two bins, from 0.16 to 2.14 cm, and from 2.14 to 6.30 cm, which have respectively 284 and 328 secondary interactions, and Λ^* values of 44.36 ± 3.1 and 52.93 ± 2.9, giving a 2.7-standard-deviation difference.

The second means of evaluating the data is to take the ratios of the measured mfp values in the upstream and downstream bins for each of the individual charges. These ratios are distributed like F (the ratio of chi-squared variates).[1] Since the same techniques were used to measure the mfp's in both bins, and only species of the same charge are being compared, some possible systematic errors will cancel. Also, there is no dependence on an assumed functional form for the mfp's, and no theoretically calculated values enter this analysis. None of the F probabilities p_i for the λ_1/λ_2 ratios for the secondaries with charges $11 \leq Z \leq 17$ exceeded 0.51, and the unweighted average of the F probabilities over these seven charges is 0.23, as compared with the expected value of 0.5 if there were no anomaly. The sum $g^2 = -2\sum \ln p_i$ over the seven different fragment charges is a chi-squared variate with $2 \times 7 = 14$ degrees of freedom,[1] and the probability of a statistical fluctuation giving a value $\geq g^2$ is 4.0×10^{-2}.

It is clear from these data that we do observe the anomalon effect in CR-39, with statistical significance comparable to that of the previous emulsion work. In Fig. 2 we have divided the data into even- and odd-charged secondaries and selected three distance bins. Both charge groups

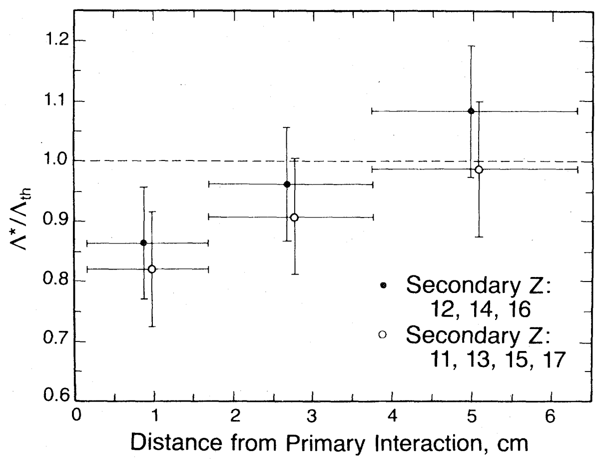

FIG. 2. Λ^* vs distance from primary interactions for even- and odd-charged secondaries. Bars are the same as in Fig. 1.

show anomalous behavior in the first bin and recover normal mfp's by the third bin. In another subdivision of the data, the Λ^* values were calculated for the partial mfp's of secondaries producing tertiaries with $10 \leq Z \leq 16$, and secondary interactions generating tertiaries with $Z < 10$, which are unobservable in CR-39(DOP). The group with $Z < 10$ is very low in the first bin, and rises sharply to normal, whereas the group with $10 \leq Z \leq 16$ is only slightly depressed in the first two bins, and is consistent with no anomaly.

Returning to the aggregate of all data for Λ^* versus distance from the primary interactions, we have fitted a curve (solid line in Fig. 1) to the data with the simple hypothesis that some fraction α of the fragments are anomalous with a single anomalous mfp λ_a and infinite lifetime. The least-squares best fit to the data gives $\alpha = 0.036(\pm 0.015)$, $\lambda_a = 1.0(+0.85, -0.50)$ cm. The fraction α is similar to that reported in nuclear emulsion, which indicates that anomalon production is not sensitively dependent on the target nuclei. The λ_a we infer is shorter than the ~2.5 cm usually quoted in emulsion, whereas the primary and asymptotic secondary mfp's are quite similar in CR-39 and emulsion when measured in centimeters. All three recent emulsion reports used data which contained ~50% secondaries with charge $Z \leq 10$ in their estimations of λ_a.[1,5] Our value of λ_a for secondaries of charge $11 \leq Z \leq 17$ may support Mac Gregor's conjecture that anomalous mfp's are a decreasing function of charge, similar in functional form to normal nuclear mfp's.[12]

If we combine data from nuclear emulsion with data from CR-39 plastic, a further analysis of the target-nucleus dependence of anomalous secondary interactions is possible. In particular, one may test the hypothesis that anomalons interact according to a simple "inflated nucleus" model, which states that anomalous cross sections follow an extrapolation of the Bradt-Peters formula: $\sigma_a = \pi(r_0 A_T^{1/3} + R_a)^2$, where R_a is the anomalon radius. To a reasonable approximation, the target nuclei may be grouped into three classes: H, CNO, and AgBr. Ilford G.5 nuclear emulsion may then be roughly modeled as 75% CR-39$(C_{12}H_{18}O_7)_n$ and 25% AgBr in compositon. Using the relation $\lambda_T = A(N\rho\sum_i n_i\sigma_i)^{-1}$, where λ_T is the total mfp, A is the average atomic number, N is Avogadro's number, ρ is the density, n_i is the atomic fraction of class i, and σ_i is the cross section for class i, we solve for the respective cross sections of anomalous interactions with a light group of nuclei, 0.5H + 0.5CNO, and a heavy group of AgBr:

$$\lambda(\text{CR-39}) \simeq A_{\text{CR}}\{(0.5\sigma_{\text{H}} + 0.5\sigma_{\text{CO}})N\rho_{\text{CR}}\}^{-1},$$

$$\lambda(\text{G.5}) \simeq A_{\text{G5}}\{[0.75(0.5\sigma_{\text{H}} + 0.5\sigma_{\text{CO}}) + 0.25\sigma_{\text{AgBr}}]N\rho_{\text{G5}}\}^{-1}.$$

Defining $\sigma_{\text{light}} \equiv 0.5\sigma_{\text{H}} + 0.5\sigma_{\text{CO}}$, we can solve for σ_{light} and σ_{AgBr} from the fits of λ_a in emulsion and plastic. In particular, the ratio of $\sigma_{\text{AgBr}}/\sigma_{\text{light}}$ could be expected to be ≤ 1.5 if anomalons are inflated nuclei with geometrical cross sections. We find $\sigma_{\text{AgBr}}/\sigma_{\text{light}} \simeq 5.4[\lambda(\text{CR-39})/\lambda(\text{G.5})] - 3$, and using Mac Gregor's λ_a in emulsion of 0.70 cm for the $9 \leq Z \leq 16$ charge group,[13] and our value of 1.0 cm in CR-39(DOP), we find $\sigma_{\text{AgBr}}/\sigma_{\text{light}} \simeq 4.7$, which seems to disagree with the inflated-nucleus model, although the errors in the fitted λ_a values are too large to test this model definitively.

The main conclusions of our work are as follows: Anomalons are observed at ~3.0 standard deviations in CR-39 for secondary projectile fragments of 1.85A-GeV ^{40}Ar with $11 \leq Z \leq 17$; secondaries with both even and odd charge show anomalous behavior; anomalons seem to interact with a larger loss of charge than do normal nuclei; the fitted fraction of anomalons is ~0.036, which is close to that reported in emulsion, and which indicates little target specificity for anomalon production; the fitted anomalon mfp of ~1 cm is shorter than the 2.5 cm value usually reported in nuclear emulsion, which may result from the different target composition of CR-39, or may support Mac Gregor's hypothesis that anomalous mfp's are a decreasing function of projectile charge.

These observations confirm the emulsion anomalon results with a very different technique and validate CR-39 as a useful detector for anomalon investigation. They cast doubt on theories of anomalons where just a few "magic number" charges may be anomalous, or which predict even-odd charge dependence. They also cast doubt on theories where anomalon production or anomalon interactions require heavy target nuclei.

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