Anomalous Mean Free Path of $Z = 2$ Fragments from $4.5A$-GeV/c ^{12}C Projectiles in Emulsion

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An anomalously short mean free path of 10.93 ± 2.00 cm is found for secondary $Z = 2$ fragments of $4.5A$-GeV/c ^{12}C projectiles at distances $D \leqslant 2.5$ cm from their production in nuclear emulsions. The largest contribution to this anomalous short–mean-free-path component comes from $N_h = 0$ interactions of ^{12}C in emulsion.

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The anomalous short mean free path (mfp) of projectile fragments (pf) at small distances from their emission vertex has been detected for fragments of $Z \geqslant 3$ from different projectiles at energies up to $\sim 2.0A$ GeV (Friedlander *et al.*[1] and references therein). For $Z = 2$ fragments no clear cut conclusion could be made (Jain *et al.*[2] and Ganssauge *et al.*[3]).

Here we report on some measurements of the mfp of $Z = 2$ ^{12}C pf at $4.5A$ GeV/c (the highest available momentum now). Two NIKFI-BR-2 nuclear emulsion stacks (pellicle dimensions 10 cm$\times$20 cm$\times$600 μm) were tangentially irradiated with $4.5A$-GeV/c ^{12}C ions and α particles at the synchrophasatron of the Joint Insitute of Nuclear Research, Dubna, U.S.S.R. A total of 509 $Z = 2$ pf's emitted within a 3° cone were collected by along-the-track scanning for the primary ^{12}C interactions. These pf's were classified according to the number N_h (number of heavily ionizing secondary particle tracks) of the primary ^{12}C interaction events. Each pf was followed until it interacted or left the stack. The maximum path length detected for these pf's was ~ 15.0 cm; 223 secondary interactions were observed.

In Fig. 1 values of the mfp λ for the primary α-particle beam in nuclear emulsions at $4.5A$ GeV/c are shown for different segments D, the distances from the entry point (scan line) in the emulsion stack. From this figure we conclude that no detectable deviation from the average value $\lambda = 19.9 \pm 0.6$ cm is observed.

The absorption curve for the $Z = 2$ secondary pf emitted in $N_h = 0$ interactions of the $4.5A$-GeV/c ^{12}C in nuclear emulsions is shown in Fig. 2. This absorption curve can be resolved into two exponential curves. Starting from the large distance tail of the attenuation curve, the dashed straight line represents the absorption with a mfp $\lambda = \lambda_{\text{beam}} = 19.9$ cm. The difference between the observed absorption curve and that expected for $\lambda_{\text{beam}} = 19.9$ cm (normalized to the data at $D = 9.0$ cm) yields evidence for a short-mfp component among $Z = 2$ pf's, curve B, Fig. 2. The slope of the latter line gives a value of $\lambda_{\text{an}} \simeq 2.5$ cm. From these curves the fraction of the anomalous component from $N_h = 0$ parent stars is found to be $\simeq 16\%$.

Table I shows the dependence of the average mfp of the secondary $Z = 2$ ^{12}C pf on N_h observed at the primary vertex (the ^{12}C primary star size with emulsion nuclei). It is clear that the interactions corresponding to pure ^{12}C fragmentations on H, CNO, and on AgBr emulsion nuclei (i.e., $N_h = 0$ events) produce $Z = 2$ fragments with the lowest average mean free path, $\lambda = 11.77 \pm 1.39$ cm. This value of mfp λ is shorter, by about $\simeq 4$ standard deviations,[4] than that of normal, i.e., $Z = 2$ beam, nuclei. This type of interaction ($N_h = 0$) corresponds to the most peripheral collisions of ^{12}C with emulsion nuclei.

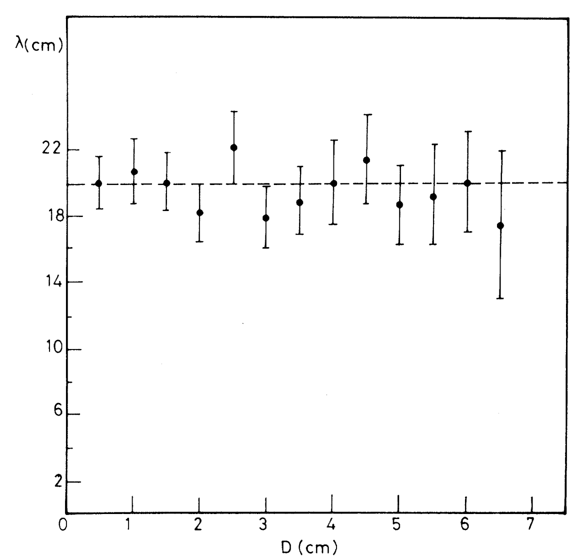

FIG. 1. Measured values of mean free path of $4.5A$-GeV/c primary alpha particles (λ_{beam}) as a function of the path length D from the scan line.

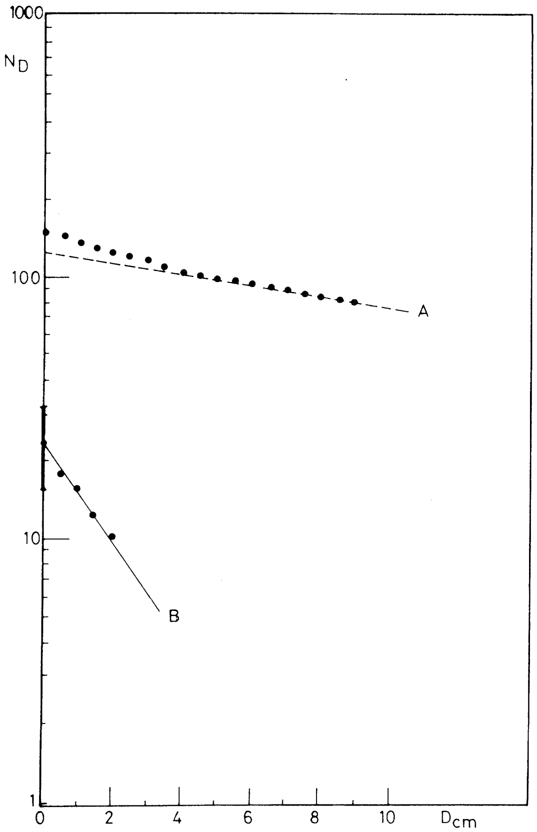

FIG. 2. Curve A, dependence of the number of noninteracting $Z=2$ projectile fragments (produced in pure ^{12}C fragmentations, i.e., $N_h=0$ events) on the distance D from the primary vertex. The data can be resolved into two exponentials, one corresponding to λ_{beam} (dashed line) and the other having $\lambda_{an} \simeq 2.5$ cm, curve B.

In Fig. 3 we present the values of the mfp for $Z=2$ ^{12}C secondary fragments as a function of the distance D from the primary vertex for $N_h=0$, $N_h \geqslant 1$, and for all events. The data points indicate a lower mfp (λ_{an}) at small distance D up to about $D=3$ cm where the fragments seem to approach the normal behavior. The solid curves in Fig. 3 are calculated on the following basis[1]: The $Z=2$ fragments consist of a fraction α with an anomalously short mfp λ_{an} in addition to a primarylike component with mfp λ_{beam}. Considering $\lambda_{an}=2.5$ cm as discussed before and applying a χ^2 fit, we obtained the following values for the fraction α for best fit: $\alpha=20.27\%$ and 5.27% for $N_h=0$ and all N_h curves, respectively. The group with $N_h \geqslant 1$ shows no signal for short mean free path. The value of $\alpha=5.27\%$ for the all-N_h group is near to that estimated before for fragments of $Z \geqslant 3$ emitted from ^{16}O, ^{56}Fe ($\alpha=6\%$)[1] and from ^{40}Ar, ^{56}Fe ($\alpha=4\%$)[5] at energies $\simeq 2A$ GeV. In all these experiments no investigation about the N_h dependence of the fraction α was carried out.

The present results show a larger production cross section for anomalous $Z=2$ pf in the case of ^{12}C interactions with $N_h=0$, i.e., for peripheral collisions. It is to be mentioned that the anomalous behavior of $Z=2$ He fragments emitted from 2.1A-GeV ^{16}O ions was observed by Judek[6] and from $\sim 2A$-GeV ^{16}O and ^{56}Fe beams by Friedlander, Heckman, Karant, and Judek[7] and Ganssauge.[3] In Judek's[6] work, a mfp as low as $\lambda=14.1 \pm 1.4$ cm was observed, while a preliminary value of $\lambda/\lambda_{beam}=0.89 \pm 0.04$ cm was estimated at distance $D \leqslant 3$ cm in Friedlander *et al.*'s experiment with $\alpha=6\%$.

From the data given in Table I one observes that the mfp for $Z=2$ pf produced in peripheral collisions of carbon ($N_h=0$) is 11.77 ± 1.39 cm while in the rest of carbon interactions its value is 18.77 ± 1.53 cm. The corresponding value of the F parameter,[1,4] that is the ratio of the two values, is $F=0.627$ with 144 and 302 degrees of freedom for

TABLE I. Detailed experimental information used for the comparison of estimated mean-free path at $D \leqslant 2.5$ and $D > 2.5$ cm from the origin of the projectile fragment for different values of N_h (interaction size of ^{12}C with emulsion). The values of $P(<\chi^2)$ are based on $\lambda_{beam}=19.9$ cm.

N_h of ^{12}C primary stars	$D \leqslant 2.5$ cm Number of $Z=2$ pf	stars	λ (cm)	$P(<\chi^2)$	$D > 2.5$ cm Number of $Z=2$ pf	stars	λ (cm)	Average values Number of $Z=2$ pf	stars	λ (cm)
0	150	30	10.93 ± 2.00	1.63 $\times 10^{-3}$	120	42	12.37 ± 1.91	150	72	11.77 ± 1.39
$\geqslant 1$	359	39	21.40 ± 3.43	6.83 $\times 10^{-1}$	320	112	17.85 ± 1.69	359	151	18.77 ± 1.53
All	509	69	16.85 ± 2.03	9.00 $\times 10^{-2}$	440	154	16.36 ± 1.32	509	223	16.51 ± 1.11

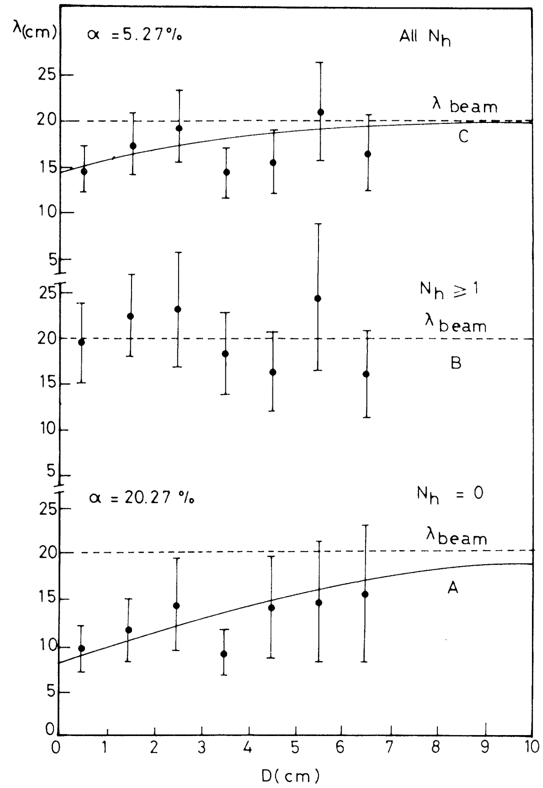

FIG. 3. Values of the mean free path λ of $Z=2$ fragments from $4.5A$-GeV/c ^{12}C (of different star size, i.e., ranges of N_h defined below) at different distances D from the origin of projectile fragments: (a) $N_h=0$; (b) $N_h \geq 1$; (c) all N_h. The continuous, fitted lines reflect the determination of the percentage α of anomalons.

the two subsets, respectively. This shows a discrepancy at the level of 3.14 standard deviations with a probability $P(<F)=8.5\times10^{-1}$, pointing to a shorter mfp for $Z=2$ fragments originating in $N_h=0$ stars.

To see whether there is a difference between the interaction characteristics of $Z=2$ pf originating in $N_h=0$ carbon interactions and those produced in the rest of the events, we present Table II which is a Fisher 2×2 table for the events with $N_h=0$ and $N_h \neq 0$ at either the production or the interaction vertex. The probabilities for the production of $N_h=0$ interaction events for $Z=2$ fragments produced in peripheral ($N_h=0$) collisions of $4.5A$ GeV/c carbon and in the rest ($N_h \neq 0$) of the collisions are 0.278 ± 0.053 and 0.099 ± 0.027, respectively. According to the 2×2 Fisher test,[4] the difference is equivalent to 3.42 standard deviations with a probability 3.10×10^{-4}.

TABLE II. Number of events with $N_h=0$ and $N_h\neq0$ at either the production or the interaction vertex of $Z=2$ projectile fragments of ^{12}C.

N_h at interaction \ N_h at production	0	$\neq 0$
0	20	15
$\neq 0$	52	136

To conclude, the present work may be summarized in the following:

(1) Production of $Z=2$ pf having a much enlarged interaction cross section (about ten times the normal value) with a fraction of 20% in ^{12}C ($N_h=0$) interactions in nuclear emulsions at $4.5A$-GeV/c incident momentum is observed. The mfp of these fragments is ~4 standard deviations lower than that of a normal beam.

(2) A significant correlation between N_h at production and at interaction of $Z=2$ carbon fragments is rigorously established.

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[1]E. M. Friedlander, R. W. Gimpel, H. H. Heckman, Y. L. Karant, B. Judek, and E. Ganssauge, Phys. Rev. C **27**, 1489 (1983).

[2]P. L. Jain, M. M. Aggrawal, G. Das, and K. B. Bhalla, Phys. Rev. C **25**, 3216 (1982).

[3]E. Ganssauge *et al.*, Gesellschaft für Schwerionenforschung, Darmstadt, Report No. GSI-82-ISSn 0174-081 (unpublished).

[4]M. Abramovitz and J. A. Stegun, *Handbook of Mathematical Functions* (Dover, New York, 1972), p. 940. Thanks are due to Professor E. M. Friedlander for the use of his computer programs for statistical calculations.

[5]P. L. Jain and G. Das, Phys. Rev. Lett. **48**, 5, 305 (1982).

[6]B. Judek, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975*, edited by Klaus Pinkau (Max-Planck-Institute für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 7, p. 2349.

[7]Y. J. Karant *et al.*, in *Proceedings of the Sixth High Energy Heavy Ion Study and Second Workshop on Anomalons, University of California, Berkeley, California, 1983*, Lawrence Berkeley Laboratory Report No. 16281 (Lawrence Berkeley Laboratory, Berkeley, California), p. 23.