Anomalous behavior of singly charged relativistic secondary particles produced in collisions of ^{16}O ions with emulsion nuclei at $\sim 2A$ GeV

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Reaction mean free paths in emulsions, of the secondary particles from ^{16}O collisions, show normal behavior for the particles produced with $P\sin\theta < 200$ MeV/c (θ is the lab emission angle and P the incident momentum per nucleon). For $200 \le P\sin\theta < 400$ MeV/c, the particles exhibit shorter mean free paths for the first few cm from their origin than at larger distances. Conventional explanations of this result are rejected at 99.5% confidence level. The data are consistent with the presence of an $\sim 6\%$ anomalous component with a mean free path of 1.8 cm. Primary deuteron mean free path at 2.1A GeV, measured for comparison, is 20.7 ± 2.6 cm.

The observations of Friedlander *et al.*[1] of anomalously short reaction mean free paths (MFP's) of projectile fragments produced in relativistic nucleus-nucleus collisions have initiated a number of searches for similar effects. For fragments with charges $Z \ge 3$ controversial results have been reported with exposures to heavy ion beams at ~ 1–$2A$ GeV (Refs. 1 and 2) from the Berkeley Bevalac and at $\sim 3.5A$ GeV (Refs. 3–5) from the Dubna synchrophasotron. For the $Z=2$ fragments several groups[4–8] have observed short MFP's with incident momenta of $\sim 4A$ GeV/c. Recently, evidence for this effect was also obtained in a bubble chamber experiment[9] for the He nuclei from ^{4}He-p interactions.

The first evidence for the presence of components interacting with unusually high cross section among singly charged secondary particles was obtained in cosmic ray studies,[10] and more recently, similar observations were made using emulsions exposed to ^{16}O ions at 2.1A GeV.[11] On the other hand, bubble chamber measurements of the secondary particles from d-d collisions at 7.9 GeV/c (Ref. 12) and from π-p and p-p collisions at 360 GeV/c (Ref. 13) produced negative results.

The present paper reports on the continued observations[11] of the $Z=1$ fragments produced in collisions of the ^{16}O ions at $\sim 2A$ GeV in a large stack of Ilford G5 emulsions.[1] For comparison, measurements have also been performed on primary deuterons at 2.1A GeV. The deuteron MFP of 20.7 ± 2.6 cm has been observed, which is in statistical agreement with the value of 25.6 ± 1.1 cm reported by Vaisenberg *et al.*[14] at 9.4 GeV/c.

The ^{16}O stars were found by systematic scanning of the incoming tracks. In 838 events, the secondary particles produced with angles $\theta < 10°$ and grain densities corresponding to $\le 1.5 \times$ minimum ionization ($\beta \ge 0.7$) were followed through the emulsions. The emission angles of the particles were measured with an accuracy to $\sim 0.1°$. The ionization levels were determined by inspection and frequently checked by grain counting. An "interaction" was defined as an event in which at least two secondary prongs were produced.

In the analysis of the observations, comparisons are made of the behavior of particles produced at large and small angles to the primary direction. For grouping of the data the angles have been converted into units of $P\sin\theta$, where P is the primary momentum per nucleon corrected for the energy loss in the emulsion. For projectile fragments the $P\sin\theta$ parameter should correspond fairly closely to their transverse momentum per nucleon. The observed distributions[15] for light fragments with masses $A \le 3$ show a Gaussian shape, characteristic of the projectile "evaporation," up to about 200 MeV/c and an "exponential" tail at higher momenta, which is attributed to hadronic scattering processes. Thus it seems appropriate to split our data at $P\sin\theta = 200$ MeV/c. A cutoff at 400 MeV/c has also been applied.

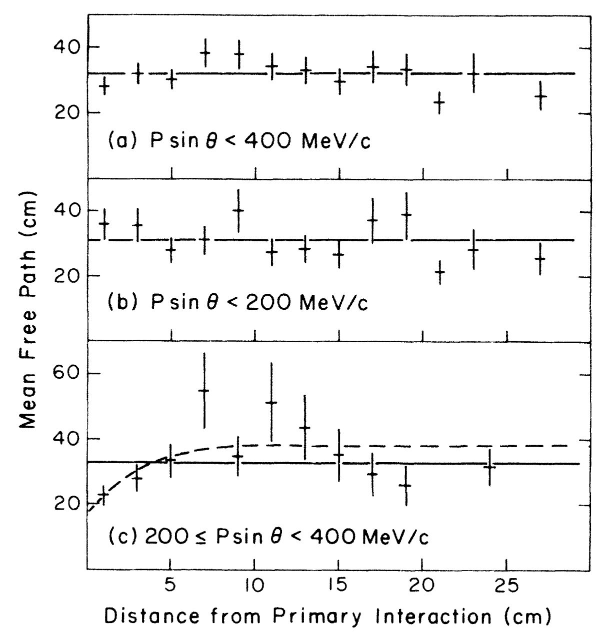

FIG. 1. Mean free paths versus distance for particles emitted in different $P\sin\theta$ intervals. The average values are shown by the solid lines. The dotted curve in (c) represents the best fit of the data.

TABLE I. Confidence levels, CL, from χ^2 tests performed on the data of Figs. 1(a)—(c), for different assumptions of particle compositions. (i) Single components interacting with average MFP's. (ii) Two components: protons and pions with an estimated MFP consistent with the observed values of 35.3 cm (Ref. 16) and 43.6 cm (Ref. 17), respectively, and deuterons and tritons using the deuteron MFP of this experiment. Their relative intensities, F, are adjusted for χ^2 minimization. (iii) A mixture of normal and anomalous components. In (a) and (c) both the MFP's and intensities are adjusted for best fit of the data. The numbers of degrees freedom are in parentheses.

	(a) $P\sin\theta<400$ MeV/c			(b) $P\sin\theta<200$ MeV/c			(c) $200\leq P\sin\theta<400$ MeV/c		
Components	MFP (cm)	F (%)	CL (%)	MFP (cm)	F (%)	CL (%)	MFP (cm)	F (%)	CL (%)
(i) single	31.7	100	25 (12)	31.1	100	17 (12)	32.7	100	0.25 (10)
(ii) protons, pions	36.0	84.6	22 (12)	35.3	79.9	13 (12)	38.0	78.2	0.35 (10)
deuterons, tritons	20.7	15.4		20.7	20.1		20.7	21.8	
(iii) normal	32.7	98.7	24 (10)	35.0	98.4	3 (12)	38.1	94.2	14.0 (8)
anomalous	1.5	1.3		5.0	1.6		1.8	5.8	
Total interactions		917			557			360	
Total tracks		1921			1054			867	

The MFP observations for the secondary particles produced in the different $P\sin\theta$ intervals are presented in Figs. 1(a)—(c) as a function of distance from the parent interactions. χ^2 tests have been performed to determine whether these data are consistent with the expected secondary particle compositions, i.e., a mixture of protons, deuterons, tritons, and pions as well as with the presence of anomalous projectile fragments (APF's), sometimes called "anomalons." The results are shown and explained in Table I.

The MFP's observed for the combined data set [Fig. 1(a)] and for small $P\sin\theta$ [Fig. 1(b)] are consistent with their average values, as well as the two-component models for a mixture of protons, pions, deuterons, and tritons.

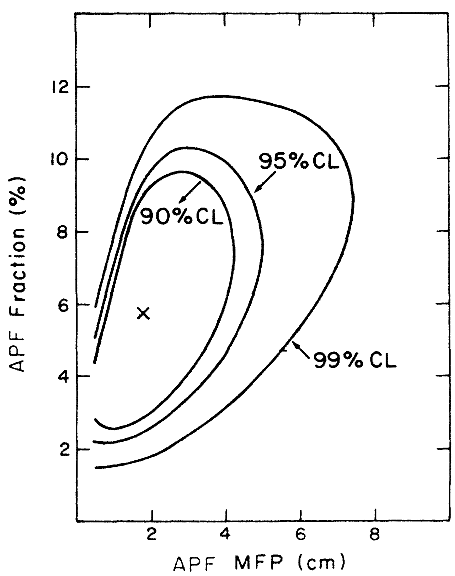

FIG. 2. Confidence level contours, CL, of APF MFP (>0.5 cm) vs APF fraction for the data in Fig. 1(c). $\times$ denotes the χ^2 minimum with $\chi^2=12.4$ and 8 degrees of freedom. The contours for 90%, 95%, and 99% CL have been calculated by incrementing the values of χ^2 to 17.0, 18.4, and 21.6, respectively (Ref. 18).

For $P\sin\theta<400$ MeV/c the data are also quite compatible with the presence of APF's with a MFP of 1.5 cm and a relative intensity of 1.3%.

A different behavior is observed for the secondary particles emitted in the $200\leq P\sin\theta<400$ MeV/c interval [Fig. 1(c)]. For the first few cm from the primary stars the MFP's are shorter than at larger distances (D). For $D\leq 2$ cm the observed MFP is 22.4 ± 2.6 cm, which is >3 standard deviations below the average value of 32.7 ± 1.7 cm. The interpretations of these data in terms of a single component and by a mixture of protons, deuterons, tritons, and pions is rejected at 99.5% confidence level (CL). The best representation is obtained with a MFP of 38.1 cm for the "normal" component, which is quite compatible with the expected composition, and a MFP of 1.8 cm and relative frequency of 5.8% for the anomalous component. χ^2-probability contours have also been calculated for the variation of the MFP and fraction of the anomalous component and are shown in Fig. 2. According to these calculations APF MFP's longer than 7.5 cm are rejected at 99% CL.

For the particles with $200\leq P\sin\theta<400$ MeV/c the

TABLE II. $P\beta$ distributions for the particles with $200\leq P\sin\theta<400$ MeV/c at different interaction distances based on multiple scattering measured with 500 and 1000 μm cells. Statistical errors for individual tracks are 15—33 % in (i) and 15% in (ii). The data were not corrected for noise and spurious scattering in order to avoid any additional uncertainties. At $p\beta>2000$ MeV/c, the spurious scattering becomes large in comparison with the true scattering.

$p\beta$	Interaction distance (cm)	
(MeV/c)	(i) 0.5—5.0	(ii) >5.0
<500	4%	3%
500—1000	15%	18%
1000—1500	37%	31%
1500—2000	23%	25%
>2000	21%	24%
Total particles	136	180

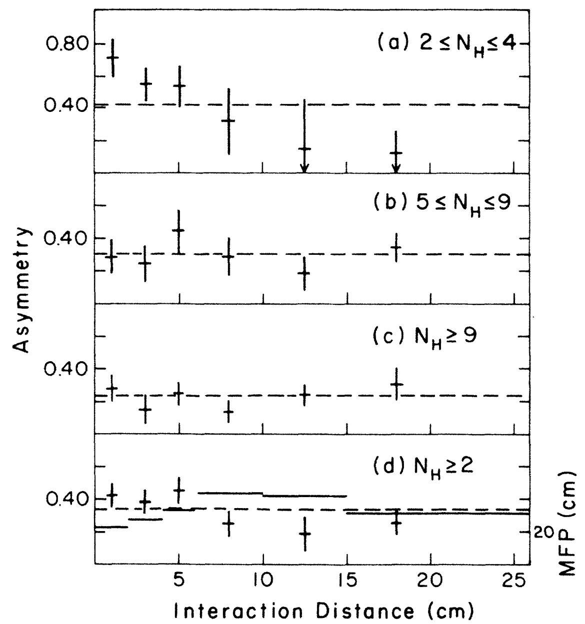

FIG. 3. Asymmetry versus interaction distance for secondary stars with different N_H, produced by particles with $200 \le P \sin\theta < 400$ MeV/c. The average values are shown by the dotted lines. For comparison, the observed MFP's are indicated by the solid lines in (d).

proportion of particles with momenta below 1 GeV/c has been estimated using multiple scattering measurements[19] to obtain lower limits of their "momenta" ($p\beta$). Table II compares the distributions obtained for all the particles interacting with $D \le 5$ cm and minimum length of 5 mm and for a sample of particles with longer interaction distances. There is no evidence of an excess of particles with lower momenta in the group interacting at the short distances. The two distributions look quite similar. About 80% of the particles have momenta above 1 GeV/c and only a few ($\sim$4%) below 0.5 GeV/c. If the estimated contribution of the particles with $p\beta \le 0.5$ GeV/c is removed from the data as well as the observations for $D \le 0.5$ cm, the MFP for $0.5 < D \le 2.0$ cm becomes $22.4 + 3.1$ cm, which is still ≥ 3 standard deviations below the average value of 33.3 ± 1.8 cm for $D > 0.5$ cm. Thus it is unlikely that the observed increase of the reaction cross section could be attributed to resonance effects, and in particular to the broad pion-nucleon resonance peak at ~ 300 MeV/c.

According to Table I [see parts labeled (c) and (iii)], we expect that $\ge 30\%$ of the secondary stars observed at distances $D \le 5$ cm and $< 3\%$ at $D > 5$ cm from the primary interactions should be produced by the short component. In the stars produced by the secondary particles with $200 \le P \sin\theta < 400$ MeV/c as well as by primary deuterons at $2.1A$ GeV, the angular distributions of the secondary prongs and grain densities of "minimum" tracks were measured. A comparison of some of the observed characteristic is shown in Table III. For the secondary particles, the $\overline{N}_S$ and $\overline{N}_H$ multiplicities are lower than for the primary deuterons, and are approximately equal in the two distance intervals. On the other hand, the forward/backward asymmetries of the secondary stars with $2 \le N_H \le 4$ are significantly higher at $D \le 5$ cm than at $D > 5$ cm and are comparable to the observations for the deuteron stars. The dependence of the asymmetries of the secondary stars on the interaction distance and also on the observed MFP's is illustrated in Figs. 3(a)—(d). These results seem to give a first indication of a difference between the "anomalous" and "normal" stars, suggesting that in the anomalous interactions a larger forward momentum may be transferred to the target fragments.

The "anomalous" MFP of 1.8 cm indicated by our experiment is of the same order as the lengths observed for fragments with $Z \ge 3$ in several emulsion investigations.[1,2] On the other hand, the negative results of the bubble chamber measurements[12,13] have been obtained with different projectile and target nuclei as well as incident energies at which we expect to have higher pion multiplicities.

The present results show a dependence of the mean free paths on the emission angles of the particles, which had been suggested by our early cosmic ray experiment.[10] Normal behavior is observed for the particles produced with $P \sin\theta < 200$ MeV/c, which should mainly consist of

TABLE III. Multiplicities of particles with $\le 1.5\times$min ionization, N_S, and of heavier prongs, N_H, and forward/backward asymmetries of heavy ionization prongs in stars produced by the secondary particles with $200 \le P \sin\theta < 400$ MeV/c at different interaction distances, D, and by primary deuterons at $2.1A$ GeV. The statistical errors are based on the spread of observations for each data point. The numbers of stars are in parentheses. Asymmetry $=(F-B)/(F+B)$, where F and B are the numbers of particles emitted in forward and backward hemispheres, respectively.

	Secondary particles $D \le 5$ cm	Secondary particles $D > 5$ cm	Deuterons at $2.1A$ GeV
$\overline{N}_S$	0.81±0.06 (157)	0.74±0.06 (158)	1.48±0.11 (67)
$\overline{N}_H$	4.8±0.3 (157)	5.4±0.4 (158)	6.7±0.7 (67)
Asymmetries:			
$2 \le N_H \le 4$	0.56±0.07 (54)	0.23±0.10 (40)	0.58±0.12 (20)
$5 \le N_H \le 8$	0.30±0.07 (47)	0.29±0.06 (41)	0.38±0.06 (17)
$N_H \ge 9$	0.23±0.06 (22)	0.23±0.04 (33)	0.28±0.07 (20)
$N_H \ge 2$	0.40±0.04 (123)	0.25±0.04 (114)	0.35±0.05 (57)

projectile fragments with transverse momenta in the Gaussian region of their distribution. The short MFP's are observed at larger angles at which we expect to have scattered protons, deuterons, and tritons as well as some pions. The MFP's normally observed for these particles at relativistic velocities are >20 cm, while the proportion of pions with momenta below 0.5 GeV/c, which might show an increase of the cross section due to resonances, is very small. Thus, it appears that the presence of APF's among the measured particles provides the best explanation for the results obtained in this experiment.

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