The anomalous behavior of the doubly charged projectile fragments produced from ^{16}O–Em interactions at 60 and 200 *A*-GeV

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(Submitted 7 July 1995; resubmitted 31 January 1996)
Zh. Éksp. Teor. Fiz. **110**, 17–25 (July 1996)

The anomalous behavior of the $Z=2$ projectile fragments (PFs) resulting from collisions between 60 and 200 *A*-GeV ^{16}O projectiles with nuclear emulsion was studied. The He PFs were classified according to the different multiplicities of these projectile fragments, as well as according to the values of the accompanying heavily ionizing target particles N_h, i.e., the corresponding impact parameter. It was found that the anomalous behavior is clearly apparent only in the case of ^{16}O dissociation into ^{4}He fragments. *© 1996 American Institute of Physics.* [S1063-7761(96)00207-7]

1. INTRODUCTION

The name *anomalons* has recently come to denote projectile fragments (PFs) of relativistic heavy nuclei possessing an anomalously short mean free path (MFP). It was shown by several authors[1-5] that when relativistic nuclei are incident on emulsion, some of the fragmentation products have anomalously large reaction cross sections (i.e., short MFPs) in the first few centimeters after their emission. Afterwards, these anomalons disappear at larger distances from the primary interactions; consequently, the values of the MFP approach the normal values observed for primary beams of corresponding charges.

Evidence for such anomalously short MFP has been reported in cosmic ray studies.[6-10] However, the results reported at the Seventh conference of High Energy Heavy Ion Study[11] showed that anomalons are not a general phenomenon observed under all experimental conditions. This is clearly shown by the negative results obtained with either light or heavy target nuclei using nuclear emulsion,[11,12] plastic track detector,[13-15] and plastic stack containing silver foils.[16]

Dealing with PFs having particular charges, Ismail *et al.*[17] found that the MFP for He PFs emitted from ^{40}Ar and ^{56}Fe at 2 *A*-GeV have the same value at all distances from their production point. The same result was also observed by Beri *et al.*[18] and by El-Nadi *et al.*[19] for PFs of $Z\geqslant 2$ originating from ^{40}Ar at about 1.8 *A*-GeV. Singh *et al.*[20] found that the interaction mean free paths of the He fragments produced by collisions of ^{28}Si projectiles at 14.5 *A*-GeV are independent of the He multiplicity and the target size. These findings corroborate their previous results on helium fragments produced at energies ranging from 1 to 2 *A*-GeV, with various incident heavy-ion projectiles (Ar, Fe and Kr).[21] On the other hand, a positive signal for anomalons was observed by Gasparian *et al.*[22] and El-Nadi *et al.*[23] for $Z=2$ PFs emitted from white stars resulting from 4.5 *A*-GeV/*c* ^{12}C nuclei. El-Nadi *et al.*[23] also detected the anomalon phenomenon when the multiplicity of He PFs is $\geqslant 3$ in the case of ^{22}Ne at 4.1 $A=$Gev/*c* and when alpha PFs[24] are emitted in the angular ranges $0.25° < \theta \leqslant 0.50°$ and $0.36° < \theta \leqslant 0.64°$ from ^{12}C and ^{22}N, respectively.

Evidence of anomalons in the first 3 cm from the interaction points for the $Z\geqslant 2$ PFs was observed by Killinger[25] and Klein[26] using ^{16}O and ^{56}Fe at about 2 *A*-GeV, ^{56}Fe at <1.6 *A*-GeV and ^{16}O and ^{56}Fe at about 1.8 *A*-GeV. Friedlander *et al.*[27] also found a positive signal for the He PFs emitted from ^{56}Fe at 1.88 *A*-GeV.

In high energy experiments, Sengupta *et al.*[28] and Singh *et al.*[29] observed that the values of the MFP for He PFs emitted from ^{16}O at 60 and 200 *A*-GeV, respectively, are the same at all distances from their production points. In these two references, the calculations were done for the combined He PFs multiplicities (i.e., for He PFs$\leqslant 4$).

In this paper, we are interested in investigating the effect of the multiplicity of the He PFs, emitted from interactions with nuclear emulsion of ^{16}O at both 60 and 200 *A*-GeV, on the values of their MFPs.

2. EXPERIMENTAL TECHNIQUE

In this work, two emulsion stacks were used. The first consisted of Fuji emulsion films coated on both sides of polystyrene films. The second stack was of the ILFORD-G5 type. The pellicle dimensions of the two stacks were 12 cm×4 cm×770 μm and 15 cm×6 cm×600 μm, respec-

TABLE I. Relative production rates, in percent, of $Z=2$ projectile fragments (with or without the emission of $Z\geqslant 3$ fragments) from the interactions of 2.1, 3.7, 60 and 200 A-GeV ^{16}O with nuclear emulsions.

Energy, A-GeV	^{1}He	^{2}He	^{3}He	^{4}He	Refs.
2.1	18.00±3*	10.00±2*	10.00±2*	≈1*	31
3.7	20.56±0.71	11.97±0.45	7.18±0.27	0.56±0.02	32
60	20.10±1.20	10.98±0.85	5.66±0.56	0.55±0.15	This work
200	20.60±1.39	12.00±0.98	4.96±0.57	0.62±0.18	This work

*This value is calculated from the results in Ref. 31.

tively. The two stacks were tangentially irradiated with 60 and 200 A-GeV ^{16}O ion beams at CERN SPS and developed at the CERN emulsion facility.

Each of the beam stacks was scanned along the tracks, rapidly in the forward direction and slowly in the backward one. The beam tracks were followed up to 8 cm potential path length from the beam entrance. These beams were also carefully examined by measuring the δ-ray density.

3. RESULTS AND DISCUSSION

Through a total length of 356.91 meters of beam tracks, 2722 inelastic interactions of 60 A-GeV ^{16}O with emulsion were picked up, for which the corresponding interaction mean free path λ_{int} was 13.11±0.25 cm. In 200 A-GeV ^{16}O interactions, the total scanned length, the total number of interactions, and the interaction MFP λ_{int} were 299.69 m, 2258 events, and 13.27±0.28 cm, respectively. Among these interactions there are 1015 and 862 interactions containing 1667 and 1399 doubly-charged projectile fragments emitted within an angle $\theta\leqslant 0.24°$ and $\theta\leqslant 0.072°$, in the forward cone, respectively. These PFs were carefully identified using both the grain density and the δ-ray counting methods.

In our previous work,[30] it was found that the percentage ratios for the multiplicities of all produced He PFs 1–4 which are emitted without being accompanied by any $Z\geqslant 3$ fragments are nearly constant within the stated errors as the energy increases from 2.1 to 200 A-GeV. In the present work, a study is carried out concerning the effect of the energy of the incident projectile on the relative production rates of different multiplicities of the He PFs 1–4 when they are emitted with or without the emission of $Z\geqslant 3$ fragments. Table I shows a comparison between the present results for ^{16}O at 60 and 200 A-GeV and the corresponding ones at 2.1 A-GeV[31] and 3.7 A-GeV.[32] From this table one can observe that

i) the relative production rates for the fragmentation of the ^{16}O projectiles into He PFs decreases as the multiplicity of these fragments increases;

ii) the relative production rates of ^{1}He, ^{2}He and ^{4}He PFs are, within the statistical errors, nearly independent of the energy of the ^{16}O projectile. In the case of the production of ^{3}He PFs, the relative rates are nearly constant for ^{16}O at the present two energies (60 and 200 A-GeV), while for the other lower energies (2.1 and 3.7 A-GeV)[30,31] the values of the corresponding rates are somewhat higher.

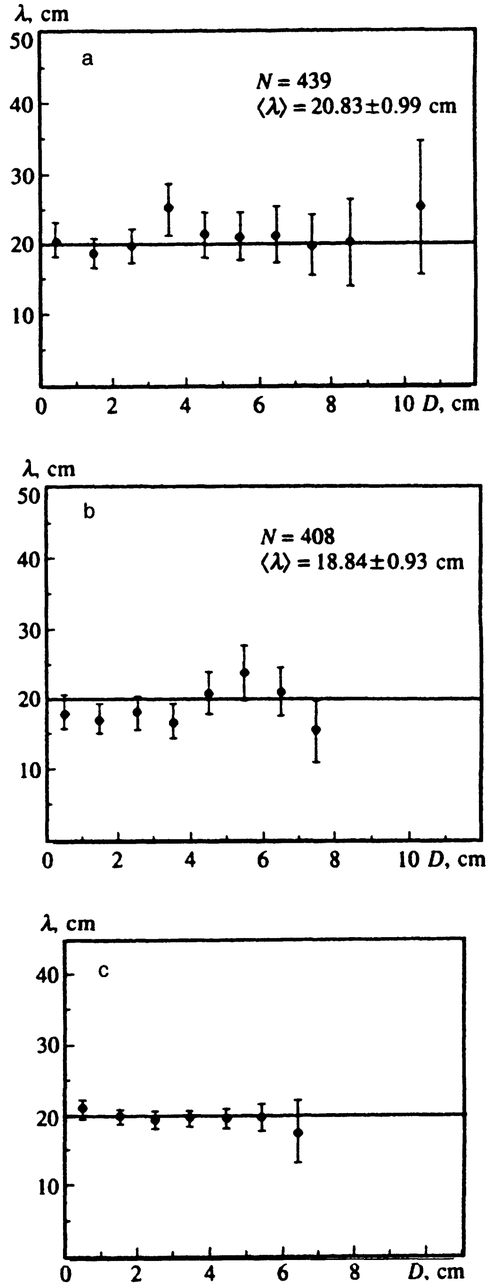

FIG. 1. Measured mean free path λ of: (a) $Z=2$ fragments from 60 A-GeV ^{16}O–Em interactions at different distances D from interaction vertex; (b) $Z=2$ fragments from 200 A-GeV ^{16}O–Em interactions at different distances D from interaction vertex; (c) 4.5 A-GeV/c primary alpha particles as a function of the distance D from the scan line (Ref. 23).

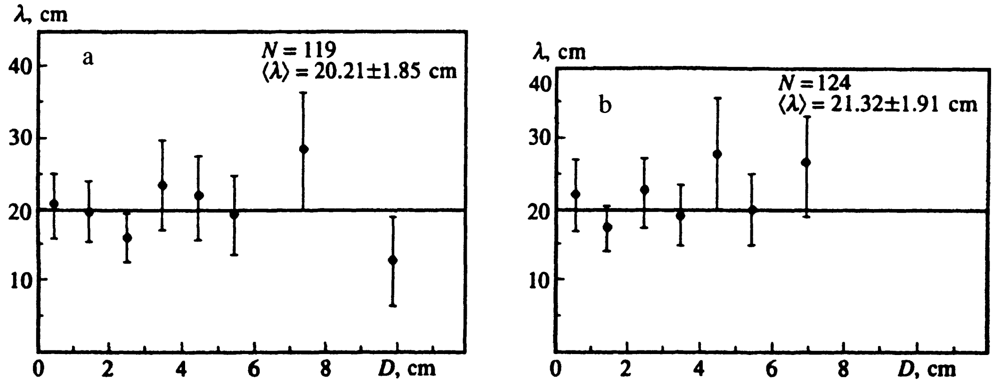

FIG. 2. Mean free path λ of $Z=2$ fragments from 60 A-GeV ^{16}O (a) and 200 A-GeV ^{16}O (b) at different distances D from the primary interaction in peripheral collisions, i.e., $N_h=0$.

Figures 1, 2 and 3 show the MFPs as a function of the distance D from the interaction vertex for $Z=2$ projectile-fragments emitted from the collisions with nuclear emulsion of ^{16}O at 60 and 200 A-GeV in the cases of

i) all types of ^{16}O interactions, i.e., all N_h values, where N_h is the number of accompanied heavily ionizing target particles. In other words, N_h refers to the sum of grey and black tracks. (In this case the same relationship for primary alpha particles at 4.5 A-GeV/c (Ref. 23) is also plotted for comparison);

ii) peripheral collisions, i.e., $N_h=0$ events;

iii) non-peripheral collisions, i.e., $N_h>0$ events.

In these figures (Figs. 1–3) the MFP λ_{int} was calculated by dividing the total track length in a certain path length interval by the number of interactions observed in that interval. Also, the MFPs for these $Z=2$ PFs emitted from 60 and 200 A-GeV ^{16}O–Em interactions having different ranges of slow target fragments, N_h, ($N_h\leq 2$, $2<N_h\leq 8$ and $N_h>8$), i.e., at different impact parameters, are presented in Fig. 4. From this figure it is clear that there is no anomalous behavior for He-PFs emitted from ^{16}O–Em interactions at different impact parameters. The present results indicate no statistically significant deviations between the values of the MFPs the He-PFs originating from ^{16}O–Em interactions at the energies used and that of the primary He (19.93±0.60 cm).[23] This suggests that the target has no effect on the MFP values for the He fragments.

We now study the dependence of the MFP of the He PFs produced by the interactions of ^{16}O at 60 and 200 A-GeV with emulsion on the multiplicity of these PFs. The results are presented in Fig. 5a, b and Table II. One may observe that there is no detectable anomalous behavior in the case of emission of ^{1}He, ^{2}He, and ^{3}He fragments,[1)] while an appreciable signal can be detected in the case of emission of ^{4}He PFs from the ^{16}O–Em interactions. Figure 6 represents the variation of MFP for these ^{4}He PFs (for the combined data from ^{16}O at 60 and 200 A-GeV) with distance D from the vertex of the primary interactions. The solid curve represents the best fit to the experimental points, which is obtained by applying a two-component model.[33] Taking $\lambda_{\text{anom}}=2.5$ cm,[23] the anomalon fraction a was found to be 15.9%, which is in agreement with the results obtained for He PFs from 4.5 A-GeV/c ^{12}C–Em interactions ($a=16\%$).[23]

Since in our study we are interested in anomalous behavior, the events showing such behavior were thoroughly investigated by measuring the range R of the black track particles to find the type of target nucleus with which the collision took place.[34] It was found that these events are characterized by the emission of, on the average, about two black target fragments having a range $R>65$ μm, i.e., these events are more likely due to heavy target nuclei (AgBr) than light ones (CNO). This might be explained by the calculations of Bayman *et al.*,[35] who found that the excitation energy of the fragment is much greater when the target nucleus is relatively heavy (such as Ag or Br) than when it is light (C or O).

Experimental MFPs of $Z=2$ projectile fragments emitted from ^{16}O–Em interactions. Combined data at two energies

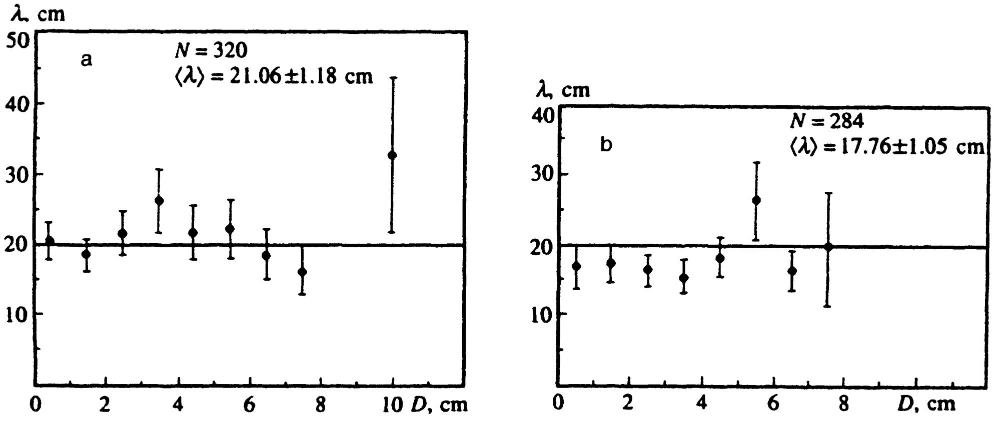

FIG. 3. Mean free path λ of $Z=2$ fragments from 60 A-GeV ^{16}O (a) and 200 A-GeV ^{16}O (b) at different distances D from the interaction point in non-peripheral collisions, i.e., $N_h>0$.

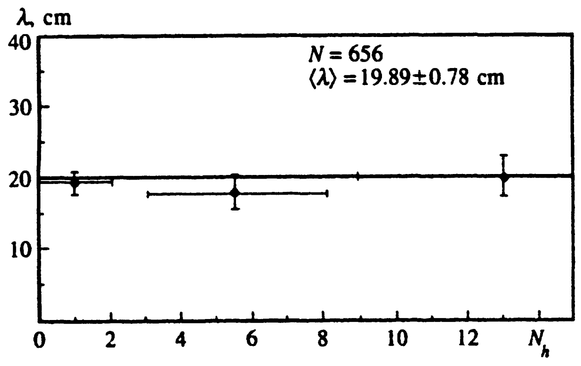

FIG. 4. Experimental mean free path λ of the fragments at different ranges of N_h of the primary stars for the combined data of ^{16}O at 60 and 200 *A*-GeV.

(60 and 200 *A*-GeV), at different distances from the interaction vertex [$D \leq 3$ cm, $D > 3$ cm and all distances (indicated as average)], and for different multiplicities of these PFs. The table also shows corresponding values of the standard deviation. (The observed number of interactions is indicated in parentheses.)

4. CONCLUSION

1. The interaction mean free path $\lambda_{\rm int}$ for ^{16}O interactions (13.11±0.25 cm at 60 *A*-GeV and 13.27±0.28 cm at 200 *A*-GeV) is independent of the energy of the projectile nucleus.

2. The relative rates for different He-PFs multiplicities are energy independent in the energy range between 2.1 and 200 *A*-GeV, which confirms the general concept of limiting fragmentation (omitting the relative rates of the ^{3}He-PFs at low energies).

3. The target multiplicity N_h, which is a measure of the impact parameter, has no effect on the MFP of He-PFs produced by the interaction of ^{16}O projectiles at the two present energies.

4. The dependence of the interaction mean free path for He-PFs-Em interactions at 60 and 200 *A*-GeV on the multiplicity of these PFs showed that there was no detectable signal for short MFP when there are at most three of these PFs.

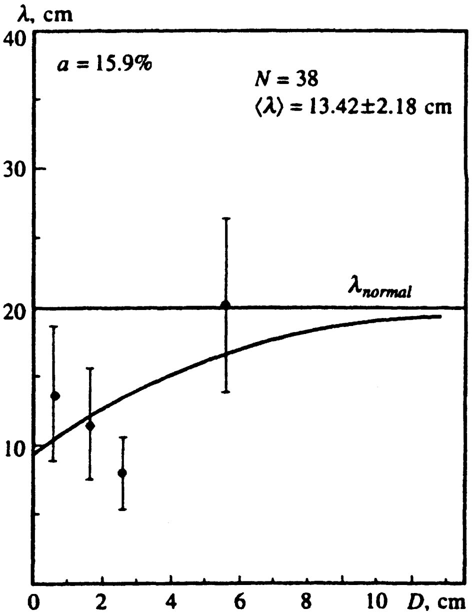

FIG. 6. Observed mean free path λ of He-fragments as a function of the distance *D* from the primary interactions producing four alphas for the combined data of ^{16}O at 60 and 200 *A*-GeV. The solid curve represents the best fit to the experimental points using the two-component model (Ref. 33).

5. A detectable signal was observed in the emission of ^{4}He PFs from the primary ^{16}O–Em interactions having very slow target fragments (about two black tracks on the average) of range $R > 65$ μm (i.e., primary ^{16}O–AgBr interactions). Therefore, the observed results indicate that the appearance of anomalous behavior depends on two factors—the size of the target nucleus with which the incident beam collides, and the multiplicity of the He fragments produced.

6. The present work reflects the importance of studying the anomalous behavior of the different He PFs multiplicities where the data manifest the presence of such behavior in the case of the emission of ^{4}He PFs which represents a small weight with respect to the other lower multiplicities.

5. ACKNOWLEDGMENTS

We are grateful to the late Prof. O. E. Badawy for his devotion to the high energy group in Cairo and for his help

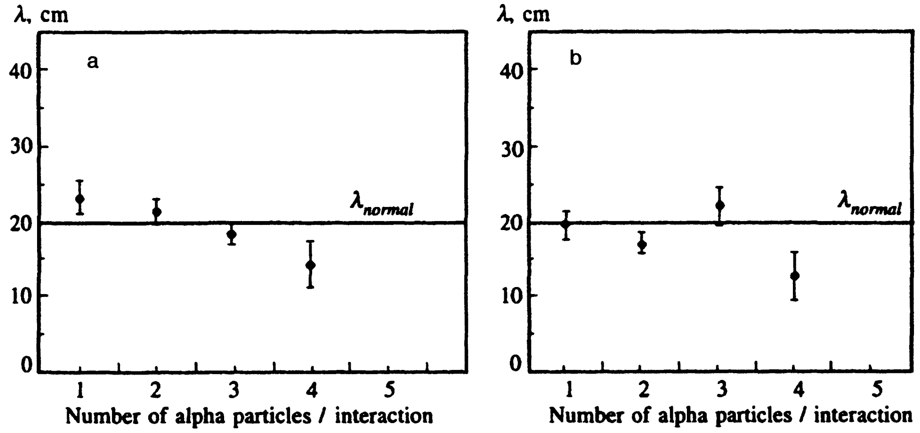

FIG. 5. Dependence of the mean free path of the $Z=2$ projectile fragments from ^{16}O at 60 *A*-GeV (a) and 200 *A*-GeV (b) on the number per interaction of these PFs.

TABLE II. Experimental MFPs of $Z=2$ projectile fragments emitted from ^{16}O–Em interactions. Combined data at two energies (60 and 200 A-GeV), at different distances from the interaction vertex [$D\leq3$ cm, $D>3$ cm and all distances (indicated as average)], and for different multiplicities of these PFs. The table also shows corresponding values of the standard deviation. (The observed number of interactions is indicated in parentheses.)

		$D\leq3$ cm		$D>3$ cm		Average values	
N_α	No. of tracks	λ	s.d.	λ	s.d.	λ	s.d.
1	1012	20.69±1.80 (131)	0.43	21.93±1.93 (129)	1.14	21.31±1.32 (260)	1.12
2	1140	17.12±1.28 (177)	1.88	21.72±1.80 (144)	1.08	19.19±1.07 (321)	0.67
3	798	20.97±2.05 (105)	0.53	18.77±1.69 (123)	0.65	19.78±1.31 (228)	0.11
4	116	10.92±2.06 (28)	2.39	20.43±6.46 (10)	0.08	13.42±2.18 (38)	2.01

in the exposure of the emulsion stack. Thanks go to Drs. N. Doble, M. Reinharz, and P. Grafstrom of CERN SPS for the excellent condition of the beam during irradiation. We also thank Dr. G. Romano, H. Sletten, K. Ratz, and M. Carchia for their help in emulsion handling and coordination of the irradiation. The authors would like to thank Prof. H. H. Heckman (LBL), Prof. I. Otterlund, and Dr. Soderstrom (Lund group) for the use of their exposure facility, and Prof. Y. Takahashi (ALOMBA and NASA) for emulsion supply and help in development.

*Deceased.

1)The average values of the black track particles observed in these events are, at 60 A-GeV, 6.89, 4.21, and 1.57, respectively, and at 200 A-GeV, 5.66, 3.52, and 2.35, respectively.

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