Vol 13 No 7, July 2004
1009-1963/2004/13(07)/1000-05

Chinese Physics

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Investigation of the mean free path of projectile fragments produced in ^{16}O–Em collision at 60 A GeV*

Zhang Dong-Hai(张东海)† and Gong Jin-Sheng(巩进生)

Institute of Modern Physics and Physics Department, Shanxi Teachers' University, Linfen 041004, *China*

(Received 1 April 2003; revised manuscript received 15 December 2003)

Results are presented for an investigation of the mean free path of projectile fragments with charge $3 \leq Z \leq 8$, produced by 60 A GeV ^{16}O in nuclear emulsion. No dependence of mean free path on the distance from the point of the fragment emission is observed and our result is consistent with the nonexistence of anomalons.

Keywords: relativistic heavy-ion collision, projectile fragments, mean free path
PACC: 2570N, 2587, 2940R

1. Introduction

It has been more than four decades since the first observation of the anomalous mean free paths (MFPs) of secondary projectile fragments (PFs) produced in the relativistic primary interactions from cosmic-ray studies.[1] However, up to now the obtained results are quite confusing, some supporting and others opposing the existence of anomalons.

Since the 1980s, due to the availability of relativistic heavy ion projectile from accelerator facilities such as the Bevalac at the Lawrence Berkeley Laboratory (LBL) and that at the JINR Dubna, numerous experiments have been done to study the MFP values of the secondary PFs with charge $Z \geq 3$ produced in heavy ion interactions within a few centimetres from the production points of the ion beams in the range ^{12}C to ^{84}Kr of energy 2–4 A GeV. Emulsions,[2−15] CR-39 plastics,[16−18] bubble chambers and Cherenkov-counter [19,20] were used as the detectors. About half of the experiments of the MFPs of PFs with charge $Z \geq 3$ in nuclear emulsion give positive evidence for the existence of anomalons,[9−15] while the others contradict them.[2−8] For other detector experiments, the results are also confused.

Despite the efforts by many groups, the evidence at the Bevalac and at Dubna for the creation of nuclear fragments with anomalously large cross sections for further fragmentation is weak, unconvincing, and unreproducible, and the entire case may be dismissed due to fluctuations or systematic error. However, the possibility cannot be completely ruled out that anomalous fragments might be produced only in certain types of collisions.

During the last decade, ultrarelativistic heavy ion beams (i.e. ^{16}O and ^{32}S beams at 200 A GeV from CERN SPS and ^{28}Si and ^{197}Au beams at 14.5 and 10.6 A GeV from Brookhaven National Laboratory (BNL) AGS) have become available. The MFPs of PFs with charge $Z \geq 3$ have been studied using as detectors not only emulsion but also CR-39 plastics. Jain and Singh [21] have studied the MFPs of PFs with charges $Z \geq 20$ produced by 10.6 A GeV ^{197}Au–Em interactions and found that for MFPs of PFs with charges $20 \leq Z \leq 30$, they are not anomalously short in the first few centimetres from production point, but for the MFPs of PFs with charges $Z > 30$ they are anomalously short within the first L=3.33mm from their production point. For CR-39 plastics the MFPs of PFs with charges $8 \leq Z \leq 14$ produced in collisions of 14.5 A GeV ^{28}Si with Pb and Cu target have been studied and it is found that there are no dependence on the distance from the point of origin.[22,23] So it is likely that both the energy and the structure of the projectile fragments as well as the mechanism of the primary interaction play an important role in the existence of

*Project supported by the National Natural Science Foundation of China (Grant No 10275042), the Natural Science Foundation of Shanxi Province, China (Grant No 20021007) and the Shanxi Provincial Foundation for Returnees Scholars, China.
†E-mail: zhangdh@dns.sxtu.edu.cn

this anomalous behaviour.

The observation of enhanced cross sections for anomalous PFs over some centimetres of the distance from their emission means that these particles have at least a lifetime $\tau \geq 10^{-10}$s. This long lifetime excludes explaining the effect through nuclear excitations with hadronic transitions ($\tau \sim 10^{-23}$s) or electromagnetic transitions ($\tau \sim 10^{-23}$s). To explain the possible existence of anomalons as a new state of hadronic matter, several speculative models have appeared in the literature. Some models are based on quark–gluon effects,[24–26] others on nuclear physics effects.[27,28] Even a more conventional but still exciting explanation based on quasi-molecular states of PFs was given.[29] To date, none of these models has supplied quantitative predictions that can be compared with the experimental data.

In this article, we discuss for the first time the MFPs of PFs with charges $3 \leq Z \leq 8$ from the ^{16}O–Em interactions at 60 A GeV.

2. Experimental details

NIKFI BR-2 stacks of nuclear emulsions, 10cm× 10cm×2cm in volume, were exposed horizontally to the 60 A GeV ^{16}O beam at CERN SPS. The flux intensity was 10^3particles/cm^2. Emulsion plates, 600μm in thickness, were scanned by the along-the-track method under 100× oil objectives. The details of scanning and the topologies of event classification can be found in our other papers.[30–33]

3. Experimental results

A total of 1842 events of ^{16}O nuclei were picked up by following 22094.9cm of the primary track length, giving rise to a MFP of ^{16}O nuclei in emulsion λ=12.00±0.28cm. Out of 1842 events, 1666 events were due to inelastic interactions, 25 events were elastic events, and the rest were due to electromagnetic dissociation. Among the 1666 inelastic events, 1138 events were found to be peripheral and semi-centric, which are always associated with noninteracting projectile spectator fragments of charge $Z \geq 2$ in the forward core relative to the beam direction. The charge of PFs were identified by counting the grain density/gap density and δ-ray methods.

A total of 746 PFs with charges $Z \geq 3$ (including the PFs produced by electromagnetic dissociation and elastic interaction) were selected for analysis in this paper. The charge distribution of PFs is presented in Fig.1. The MFP estimator of a nucleus with a given charge Z is calculated as follows:

$$\lambda^* = S/N, \tag{1}$$

where $S = \sum_i x_i$ is the total path length of both interacting and noninteracting tracks examined for that particular charge Z, with N observed interactions.

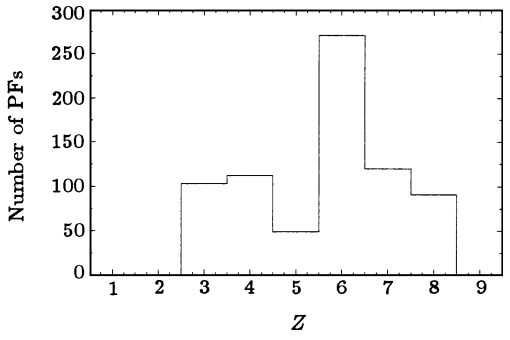


Fig.1. Charge distribution of PFs.

Table 1. Measured values of the MFP for PFs of different charges.

Charge of fragments	Length scanned/cm	Number of PFs	Number of interactions	MFP/cm
3	379.7	103	23	16.51 ± 3.44
4	388.2	112	32	12.13 ± 2.14
5	160.0	49	16	10.00 ± 2.50
6	1044.0	271	78	13.38 ± 1.52
7	415.1	120	36	11.53 ± 1.92
8	304.5	91	22	13.84 ± 2.95

Table 1 gives the total number, interacting number and the MFPs of various PFs produced in 60 A GeV ^{16}O–Em interactions. For a homogeneous beam of nucleus with charge Z the distribution of interaction distances x is exponential:

$$f(x) = \lambda^{-1}\exp(-x/\lambda). \tag{2}$$

Here λ is easily seen to be the MFP of the projectile

in nuclear emulsion. In this case λ^* defined in Eq.(1) is the unbiased estimate of MFP λ. This estimator is independent of the location of the track segment in which λ is measured. λ will depend on the nature of the projectile as well as on the target and principally also on the energy of the collision. For the relativistic projectile the dependence was found as a simple rule which just connects the charge of the projectile with two rather constant parameters in the way that the MFP

$$\lambda_Z = \Lambda Z^{-b}, \tag{3}$$

where the charge-independent parameters Λ and b comprise all the characteristics of the target which can be calculated by fitting the above equation to the experimental data. For our experiment the best-fit values, as shown in Fig.2, are $\Lambda = P_1 = 24.05 \pm 4.17$, and $b = -P_2 = 0.34 \pm 0.09$. This parametrization is consistent with the trend of MFP computed from cross sections based on the geometrical overlap model.[34] In Fig.2 the $n_{\rm df}$ means the number of degree of freedom. In Table 2, we summarize the constants Λ and b given by different experiments. From the table we can see that different experiments give different values of Λ and b. The main reason is that different PFs were used to fit the equation. Given Eq.(2), one is able to show that the quantity $2N\lambda_Z^*/\lambda_Z$ is distributed like χ^2 with $2N$ (where N is the number of interactions observed in the studied region) degrees of freedom. From the additivity of χ^2 variables, it follows that a maximum-likelihood estimate Λ^* for Λ, at fixed b, is provided by the expression

$$\Lambda^* = \sum_Z N_Z \lambda_Z^* Z^b / \sum_Z N_Z, \tag{4}$$

where $\lambda_Z^* = S_Z/N_Z$ is the estimator of MFP λ_Z, with S_Z being the total track length of fragments with charge Z, and N_Z the number of interactions of charge Z in a segment. This estimate is also independent of detector size. Combining the data from PFs of different charges in the same track segment we computed Λ^* for a number of independent segments after the point of emission of a PF and obtained the dependence of Λ^* on the distance L after emission, as presented in Fig.3. No dependence of the reduced MFP Λ^* on distance L is observed.

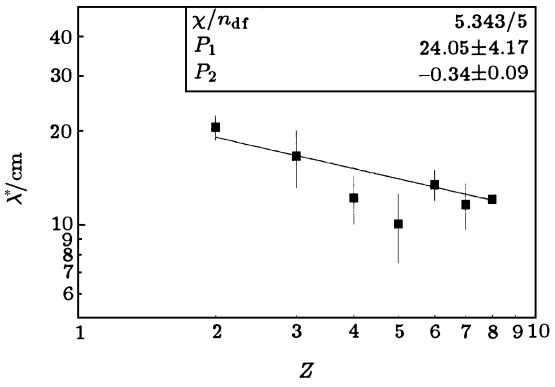


Fig.2. The MFP of PFs with charge $Z \geq 2$ as a function of Z.

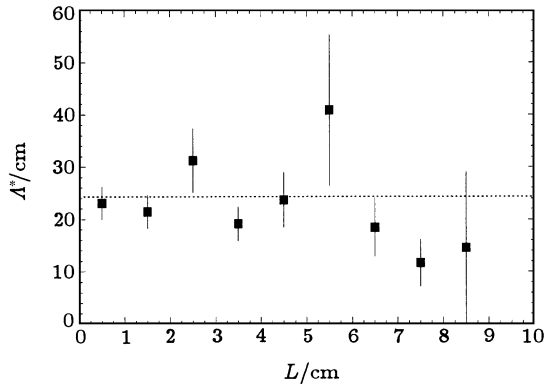


Fig.3. The MFP of PFs with charge $Z \geq 3$ as a function of L.

Table 2. Summary of the values of constants Λ and b.

Beam and energy	Charge of PFs	Λ/cm	b	Ref.
1.8 A GeV ^{40}Ar	$3 \leq Z \leq 18$	23.2	0.32	[4]
2 A GeV ^{16}O	$3 \leq Z \leq 8$	28.9 ± 2.5	0.43 ± 0.04	[10]
2 A GeV ^{56}Fe	$3 \leq Z \leq 26$	32.1 ± 2.1	0.44 ± 0.03	[10]
1.52 A GeV ^{84}Kr	$Z \geq 15$	33.6	0.45	[11]
2 A GeV ^{56}Fe, ^{40}Kr	$3 \leq Z \leq 26$	32.4 ± 1.7	0.42 ± 0.02	[14]
Cosmic-ray	$Z \geq 3$	25.1 ± 1.7	0.34 ± 0.03	[35]
1.8 A GeV ^{40}Ar	$3 \leq Z \leq 18$	24.1 ± 1.2	0.34 ± 0.03	[5]
1.9 A GeV ^{56}Fe	$3 \leq Z \leq 26$	23.3 ± 0.8	0.32 ± 0.01	[6]
60 A GeV ^{16}O	$2 \leq Z \leq 8$	24.3 ± 4.2	0.34 ± 0.09	This work

In order to test the dependence of reduced MFP of PFs on the distance from their emission point, we perform the F-test on the experimental data further.

Let λ_1 and λ_2 be the expectation values of λ_1^* and λ_2^* (the MFP estimate of PFs in the segment $L \leq 3$cm and $L > 3$cm from their production point), respectively. The null hypothesis to be tested is then

$$\lambda_1 = \lambda_2 = \lambda. \tag{5}$$

It turns out that a convenient test quantity for this null hypothesis is the ratio

$$F = \frac{\lambda_1^*}{\lambda_2^*}. \tag{6}$$

As long as Eq.(5) is true, F obeys a well-known distribution law, the so-called F, or variance ratio, irrespective of the concrete value of λ, with $2N_1$ and $2N_2$ degrees of freedom (N_1 and N_2 are the sizes of the samples from which λ_1^* and λ_2^* are derived). The ratio F can be rewritten as follows:

$$\begin{aligned} F =& \frac{\lambda_1^*}{\lambda_2^*} = \frac{S_1/N_1}{S_2/N_2} = \left[\left(\frac{2S_1}{\lambda}\right) \Big/ \left(\frac{2S_2}{\lambda}\right)\right]\frac{N_2}{N_1} \\ =& \left(\frac{h_1^2}{2N_1}\right) \Big/ \left(\frac{h_2^2}{2N_2}\right), \end{aligned} \tag{7}$$

where S_1 and S_2 are the total track lengths in the region of $L \leq 3$cm and $L > 3$cm, respectively, $h_1^2 = 2S_1/\lambda$ and $h_2^2 = 2S_2/\lambda$ are χ^2 distributed with $2N_1$ and $2N_2$ degrees of freedom. As is well known, the ratio of the two χ^2, each divided by their number of degrees of freedom ($v_1 = 2N_1$ and $v_2 = 2N_2$) obeys the so-called F distribution, commonly used in variance analysis. Its probability density is

$$\begin{aligned} P(F) =& \frac{v_1^{v_1/2} v_2^{v_2/2}}{B(v_1/2, v_2/2)} \\ & \times \Gamma^{(v_2-2)/2}(v_2 + v_1 F)^{-(v_2+v_1)/2}, \end{aligned} \tag{8}$$

where B is the beta function. Identifying the numbers of degrees of freedom v_1 and v_2 with $2N_1$ and $2N_2$, respectively, we obtain the integral probability of F as

$$\begin{aligned} P_F =& P(<F) = \frac{N_1^{N_1} N_2^{N_2}}{B(N_1, N_2)} \\ & \times \int_0^F t^{N_1-1}(N_2 + N_1 t)^{-(N_1+N_2)} \mathrm{d}t. \end{aligned} \tag{9}$$

If the null hypothesis is true, that is no dependence of the MFP of PFs on the distance from the emission point, the P_F is uniformly distributed between 0 and unity (or briefly, P_F is distributed $u(0,1)$). Hence, its expectation value is $1/2$ and its dispersion is $\sigma_{P_F} = (12v)^{-1/2}$, where v is the number of kinds of PFs.

Table 3. Detailed experimental information used in the F test for the comparison of estimated MFP at small and at large distances L from the origin of the PFs.

Charge	$L \leq 3$cm			$L > 3$cm			F-test	
of PFs	Tracks	Stars	λ^*	Tracks	Stars	λ^*	F	$P(<F)$
3	103	15	16.17 ± 4.18	52	8	17.14 ± 6.06	0.9434	0.4297
4	112	19	13.38 ± 3.07	60	13	10.31 ± 2.86	1.2978	0.7547
5	49	10	10.24 ± 3.24	25	6	9.60 ± 3.92	1.0667	0.5316
6	271	48	13.42 ± 1.94	164	30	13.33 ± 2.43	1.0068	0.5041
7	120	19	14.21 ± 3.26	66	17	8.54 ± 2.07	1.6639	0.9323
8	91	15	13.11 ± 3.39	45	7	15.40 ± 5.82	0.8513	0.3421

In Table 3, we summarize the results of the MFP of PFs with charges of $3 \leq Z \leq 8$ changing with the distance from their emission point and the F-test results. The average of the integral probability of P for all PFs is $\bar{P_F} = 0.58$, and the dispersion is $\sigma_{P_F} = 0.12$. Within the experimental errors, $\bar{P_F}$ is consistent with its expectation value of $< P_F >= 1/2$, which means that the MFP of PFs is independent of the distance from their production point.

Another method to observe the presence of anomalons suggested by Otterlund [36] is to compare the MFP of PFs of a given charge obtained over a distance $L < \lambda_a$ and $L > \lambda_a$ where λ_a is the conjectured MFP of the anomalons (≈ 2.5cm). It is clear that such a procedure would minimize the effects of scanning and other experimental biases. In the present experiment the MFP of PFs for $L \leq 3$cm (λ_1^*) is compared with the one for $L > 3$cm (λ_2^*). The results are presented in Fig.4. In this figure the diagonal $\lambda_1^* = \lambda_2^*$ curve is the result if no anomalon exists. Points below the diagonal can be reached if anomalons exist. The figure clearly shows that most of the experimental points are located above the diagonal. The experimental data do not show statistically significant deviations from the diagonal, which further confirm our above conclusion that no anomalon exists.

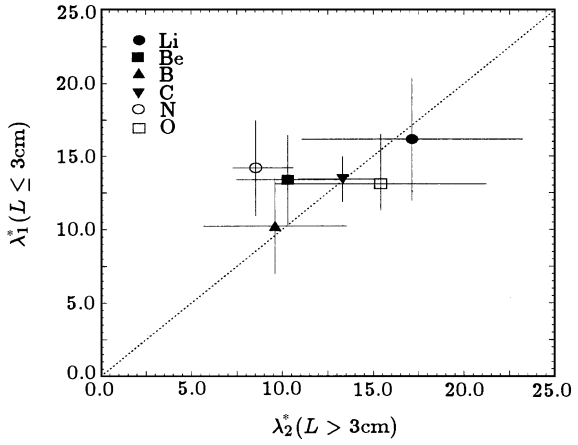


Fig.4. The MFP of PFs with charge $3 \leq Z \leq 8$ for $L \leq 3$cm vs the one for $L > 3$cm.

4. Concluding remarks

The results obtained from this study lead to the following conclusions: The mean free path of projectile fragments with charge $3 \leq Z \leq 8$, produced by interactions of ^{16}O–Em at 60 A GeV, does not show any dependence on the distance from their emission point, which is further confirmed by the F-test and Otterlund methods. Our results are consistent with the nonexistence of anomalons.

Acknowledgement

We are grateful to Professor I. Otterlund of the Lund University in Sweden for supplying the emulsion plates.

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