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INTERACTION MEAN FREE PATH OF He PROJECTILE FRAGMENTS FROM ^{16}O-EM COLLISION AT 60 A GeV*

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The interaction mean free path of He projectile fragments, produced by the collisions of ^{16}O at 60 A GeV in a nuclear emulsion, has been investigated. In the present analysis, 1555 He projectile fragments, giving rise to 320 secondary interactions, have been used. At a level of 3% a very weak signal of anomalons is observed, which comes mainly from the 3×He channel.

Keywords: mean free path, projectile fragments, anomalon
PACC: 2575, 2940

I. INTRODUCTION

Heavy-ion collisions at high energies have been attracting more and more interest in recent years due to the development of the accelerator facilities at the CERN Super Proton Synchrotron (SPS), the LBL Berkeley Bevalac and the Joint Institute for Nuclear Research (JINR) Dubna Synchrophasotron. The main objective of heavy-ion collisions is to observe the signatures of unusual forms of nuclear matter, such as the quark–gluon plasma, which may be produced in collisions at relativistic energies. However, other interesting domains of physics can also be studied, such as the mean free path (MFP) values of the secondary projectile fragments (PFs).

With the availability of relativistic heavy-ion projectiles from accelerator facilities, numerous experiments have been carried out to study the MFP values of the secondary He PFs produced in heavy-ion interactions within a few centimetres from the production points.[1−12] On the MFPs of He fragments in a nuclear emulsion, four experiments have yielded positive evidence for the existence of anomalons,[9−12] while the others contradicted them[1−8]. To explain the possible existence of anomalons, various theoretical models have been proposed in the literature.[13]

At the JINR Dubna Synchrophasotron, the MFP of secondary He PFs produced in heavy-ion interactions within a few centimetres from the production points has been studied by many groups, two[9−12] of which have found that the interaction MFP of He PFs produced in a ^{12}C emulsion interaction at 4.5 A GeV/c is anomalously short for a few centimetres after emission and has significant dependence on the distance from emission points, the target size and the type of collisions. But Khan *et al.*[4] and Nadi *et al.*[8] have obtained contradicting results based on good statistics with the same projectile at the same energy/nucleon.

At CERN SPS, the MFP of secondary He PFs produced in relativistic heavy-ion collisions within the first few centimetres from the production points has also been studied in recent years;[1−3] there are no anomalously short MFPs for 60 and 200 A GeV ^{16}O and 200 A GeV ^{32}S induced interactions in a nuclear emulsion. Recently, Jain and Singh[14] have studied the MFP of PFs with charges $Z > 30$ from 10.6 A GeV ^{197}Au–Em interactions. They observed an increase of more than 51% in secondary interactions within a distance of $L = 3.33$mm from their production point. So, further studies and more data of the relativistic heavy-ion interactions are needed. The purpose of this paper is to study the MFP of He fragments produced in ^{16}O-induced interactions at 60 A GeV on the basis of He multiplicity and the heavily ionizing track multiplicity $N_{\rm h}$. We are also interested in studying the variation in the MFPs of the emitted He fragments in electromagnetic dissociated events (EDs) as a function of the distance from their production points.

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Ⅱ. EXPERIMENTAL DETAILS

A NIKFI BR-2 stack of nuclear emulsions, 10cm×10cm×2cm in volume, was exposed horizontally to the 60 A GeV ^{16}O beam at CERN SPS. The beam flux was 10^3 particles/cm^2. Emulsion plates, 600μm thick, were scanned by the along-the-track method under 100×oil objectives. The primary tracks were selected visually for the scanning. Any doubtful primary track was not followed. The beam tracks were followed leaving 1cm from the edge of the plate until they either interacted with nucleus in the stack or left the pellicle. In each event, the number of black tracks N_b (the evaporated fragments from the excited target remnant in a later stage of the collision and mostly protons of kinetic energies ≤26MeV), grey tracks N_g (mainly recoil protons knocked out of the target nucleus in the later stages of the collision in the kinetic energy range of 26–375MeV, kaons between 20 and 198MeV and pions between 12 and 56MeV), shower tracks n_s (minimum ionizing tracks, mostly pions with a velocity greater than 0.7c) and the number of projectile fragments with a charge of $Z \geq 2$ n_f, if any, were recorded. The charges of all the projectile fragments ($Z \geq 2$) were determined by measurements of grain density, gap density, and by δ-ray counting.[6]

Each event was carefully examined and qualitatively classified into three principal categories, depending upon the following visual characteristics.

1. Near-central events: events which exhibit no visible forward cone fragments of charge $Z \geq 2$ from the projectile. Such events are thought to be created by violent destruction of the projectile and target nuclei at small values of the impact parameter (b) of the collision.

2. Semi-central or peripheral events: events with PFs of charge $Z \geq 2$ emitted in a forward core. These events show considerably less involvement of the projectile nucleus since they are formed at relatively large values of b.

3. Electromagnetic events: events due to electromagnetic dissociation (ED) of the incident nucleus are generated in collisions involving impact parameters large enough that no nuclear interaction occurs and extremely strong electromagnetic fields from heavy target nuclei are produced for a very short time. Such events typically consist of PFs which proceed in the direction of the projectile nucleus and are confined within 3.3mrad to the beam direction.

Ⅲ. 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 an 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 ED. Among 1666 inelastic events, 1138 events were found to be peripheral and semicentric, which were always associated with noninteracting spectator fragments of charge $Z \geq 2$ emitted in the very forward core. The alpha projectile fragments were identified by the method of counting the grain/gap density.

A total of 1403 He tracks were selected in 789 inelastic peripheral and semicentric events. The He tracks were followed with the utmost care, under 100×oil objectives, from pellicle to pellicle, until they either interacted with the nucleus in the stack or escaped from the stack. By following 5573.1cm of the He track length, 281 secondary inelastic interactions were recorded.

To calculate the interaction MFP of He PFs as a function of distance L from the interaction points, the tracks were divided into successive intervals. All the track segments lying within the same interval were added together and then divided by the total number of interactions observed in that interval. For a homogeneous beam of nuclei of a charge Z, the MFP λ is defined via the distribution of interaction distance x as $f(x)\mathrm{d}x = \exp(-x/\lambda)\mathrm{d}x/\lambda$. A maximum-likelihood

Table 1. Topologies of primary inelastic interactions of ^{16}O having different He multiplicity and the MFP of the He fragments produced in these events.

Information of primary events		Information of the secondary events			
He PFs multiplicity	No. of events	Total track length followed/cm	No. of events	λ/cm $L \leq 3$cm	λ/cm $L > 3$cm
1	423	2015.4	105	20.35±2.58	17.52±2.67
2	256	2124.9	103	19.69±2.48	22.11±3.50
3	105	1358.0	69	15.95±2.30	28.21±6.16
3,4	110	1432.8	73	15.85±2.22	28.38±6.05
all	789	5573.1	281	18.81±1.42	21.54±2.10

estimate is obtained from $\lambda = \Sigma S_i/N_i$, where ΣS_i is the total length of both interacting and noninteracting tracks followed in the ith interval, and N_i is the total number of interactions observed in the ith interval.

In Table 1, we present the characteristics of the primary inelastic events along with the MFP of the secondary He PFs on the basis of different He multiplicity. In Table 2, we give the overall features of the primary and secondary inelastic events used in this paper. The errors quoted in Tables 1 and 2 are of statistical origin.

Table 2. Topologies of primary inelastic interactions of ^{16}O with different types in emulsion, having at least one He fragment and the MFPs of the He fragments produced.

Information of primary events		Information of the secondary events			
Types of interactions	No. of events	No. of He tracks followed	Total track length/cm	No. of events	λ/cm
Emulsion	789	1403	5573.1	281	19.83±1.18
Peripheral	244	485	1946.3	92	21.16±2.21
Semi-central	545	918	3626.8	189	19.19±1.40
ED	75	152	622.3	39	15.96±2.56

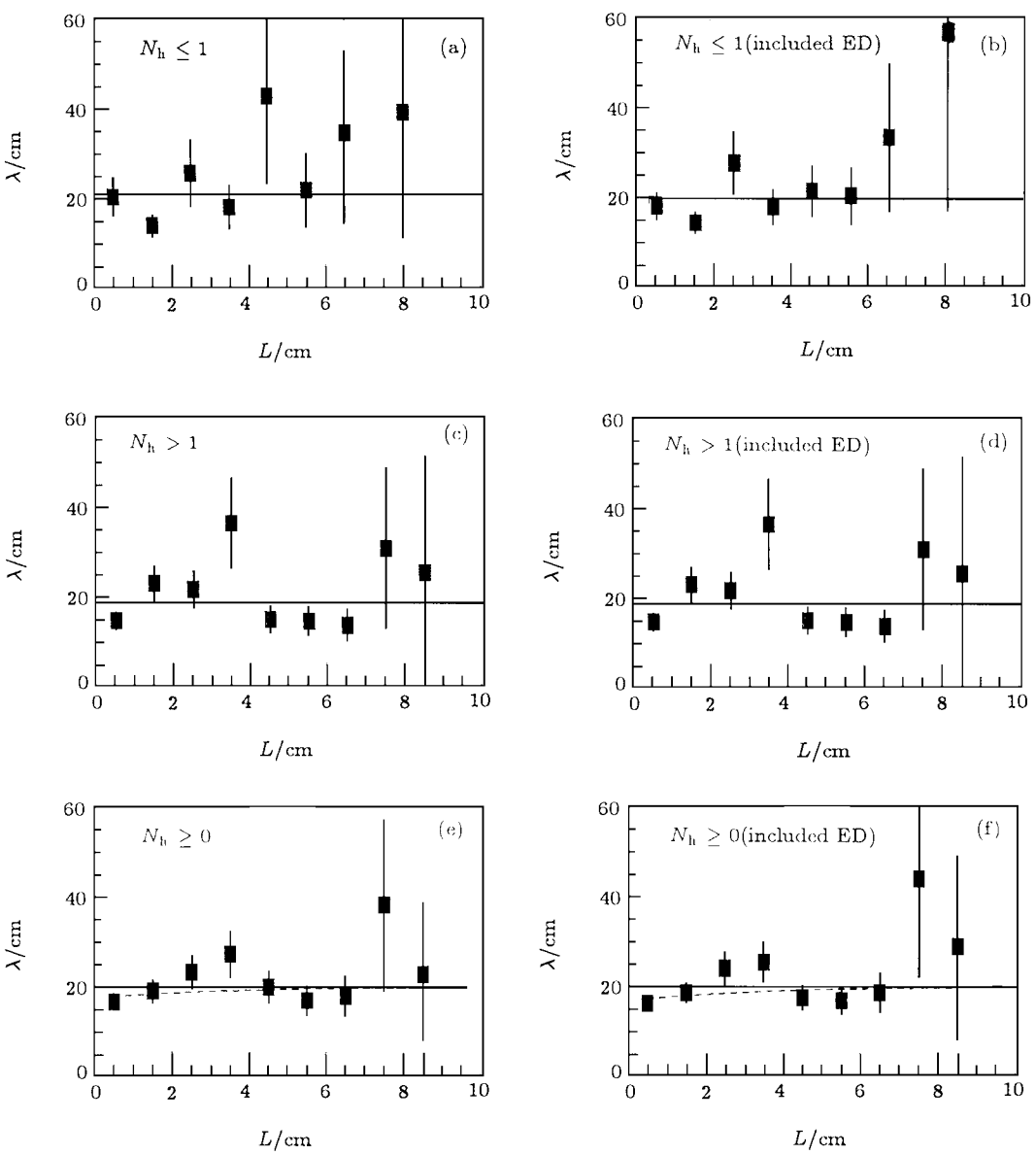


Fig.1. The MFP of He PFs produced in ^{16}O–Em interactions versus path length (L) for $N_h \leq 1$, $N_h > 1$ and $N_h \geq 0$ (left part, inelastic events; right part, inelastic events and EDs).

In Fig.1, we present the values of the MFP for He PFs as a function of the distance L from the production points for $N_h \leq 1$, $N_h > 1$ and $N_h \geq 0$. The dotted curves in Fig.1 for $N_h \geq 0$ are calculated on the following basis: the He fragments consist of a fraction α with an anomalously short MFP λ_{an} in addition to a primary-like component with an MFP λ_{beam}. Considering λ_{an}=2.5cm, λ_{beam}=20cm and applying a χ^2 fit, we obtained the following values for the fraction α for the best fit: α=2.19% and 2.88% (included EDs) for $N_h \geq 0$. From the above best fit, it is concluded that anomalous He PFs come mainly from EDs if anomalon exists. For our experiment, the He PFs produced by EDs contribute to about 31.4% of all the anomalous PFs, although there is 9.8% of all the He PFs.

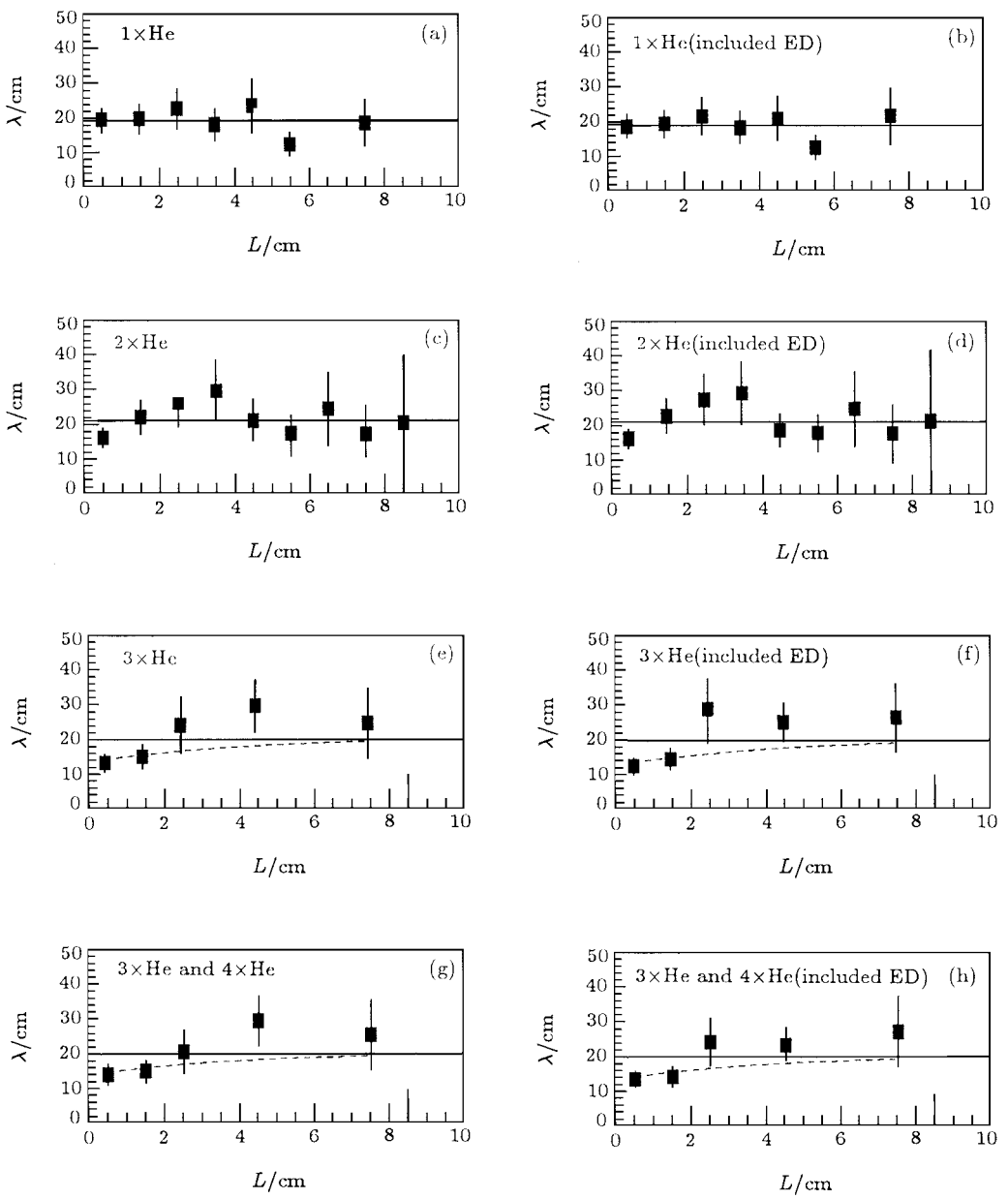


Fig.2. The MFP of He PFs produced in ^{16}O–Em interactions versus path length (L) for different He channels (left part, inelastic events; right part, inelastic events and EDs).

To study the He multiplicity dependence, the MFP of He PFs, as a function of the distance L from the production point, is plotted in Fig.2 for 1×He, 2×He, 3×He and 3×He+4×He multiplicity events. Within their statistical errors, the observed MFPs do not seem to change with the distance L from

the production point for the 1×He and 2×He channels, but for the 3×He and 3×He+4×He channels, the data points indicate a lower MFP at a small distance L up to about L=3cm, where the fragments seem to approach the normal behaviour. Using the same programme as the above χ^2 fit, we have obtained the following values: α=6.58% and 7.46% (included EDs) for the 3×He channel; α=5.80% and 6.45% (included EDs) for the 3×He+4×He channel. From the above χ^2 fit, we conclude that anomalous He fragments come mainly from the 3×He channel because the 3×He+4×He channel has the same contribution as the 3×He channel to anomalous fragments.

Another method of observing the presence of anomalons, suggested by Otterlund,[15] is to compare the MFP of PFs of a given charge obtained over a distance $L < \lambda_{\rm an}$ and $L > \lambda_{\rm an}$, where $\lambda_{\rm an}$ is the conjectured MFP of the anomalons (≈2.5cm). It is clear that such a programme would minimize the effects of scanning and other experimental biases. In the present experiment, the MFP of He PFs for $L \leq$3cm(λ_1) is compared with the MFP for $L >$3cm(λ_2). The results are presented in Figs.3(a) and 3(b) for the dependence of the impact parameter and He multiplicities, respectively. In the figures, the diagonal $\lambda_1 = \lambda_2$ curve is the result if no anomalons exist. Points below the diagonal can be reached if anomalons exist. The upper triangle of Fig.3(a) has only one point for He PFs coming from $N_{\rm h} >1$ events. All other points lie in the lower triangle, showing the presence of anomalous PFs among the He PFs coming from the $N_{\rm h} \leq 1$ events and $N_{\rm h} \geq 0$ events. In Fig.3(b), it is shown that the points coming from the 1×He and 2×He channels lie in the upper triangle and the points coming from the 3×He and 3×He+4×He channels are in the lower triangle, which further confirms the above conclusion about the presence of anomalons.

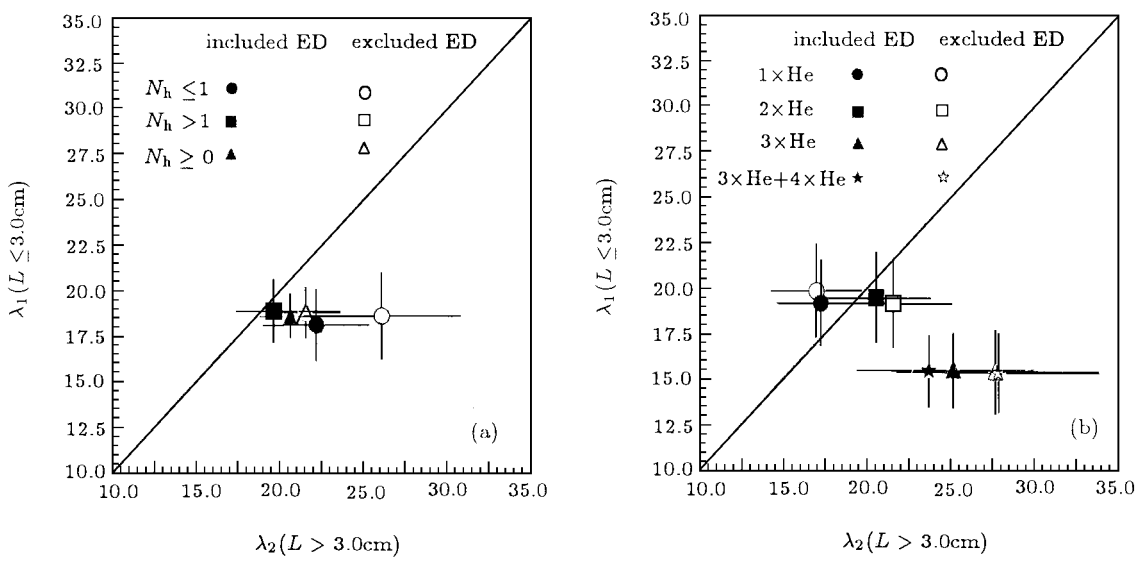


Fig.3. The MFP of He PFs $\lambda_1(L \leq$3cm) versus $\lambda_2(L >$3cm) for dependence of the impact parameter (a) and He multiplicities (b).

IV. CONCLUSIONS

In our final data sample, consisting of 320 He secondary interactions, we have observed a fragile signal of anomalons at the 3% level. From the dependence of the MFP on distance L from the production points for different impact parameters (different $N_{\rm h}$ groups), it is very difficult to give a sound signal of anomalons. But, for different He multiplicities, a clear signal of anomalons is observed in the 3×He channel at the 7.5% level and in the 3×He+4×He channel at the 6.5% level, although with decreased statistics. From the best χ^2 fit, we can conclude that about 70% of all anomalous PFs come from the 3×He channel. By applying the $\lambda_1(L \leq$3cm) versus λ_2 ($L >$3cm) correlation, the signal of anomalons can be confirmed further.

According to relativistic mean-field theory (RMFT)[16−19] predictions, if multistrange nuclei are produced in some relativistic heavy-ion interactions, they will exhibit an enhanced interaction radius as the size of the hypernuclei increases with the increasing number of Λ's, although the baryon number is kept

constant. Thus, these enhanced interaction radii offer a possibility of observing multi-Λ hypernuclei and they would behave just like anomalons.[20−23] These exotic multi-Λ hypernuclei would have lifetimes of $\approx 10^{-10}$s and exhibit unusually large interaction cross sections, compared with normal nuclei with the same Z. This also means that their interactions with target nuclei would result in no change in the PF charge and such interactions could not be observed in electronic detectors. When 60 A GeV ^{16}O peripherally interact with emulsion nuclei, the projectile spectators obtain small exotic energy and then break into He fragments. In this process, Λ hypernuclei may be produced if the neutron in He PF obtains a π^0-meson. Occurrence of the process $n + \pi^0 \rightarrow \Lambda$ in the projectile spectator fragmentation needs a proper energy. This would explain why anomalons can only be observed in some fragmentation channel.

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