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Two-source emission of relativistic alpha particles in ^{16}O-Em interactions at 3.7 A GeV*

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The emission of alpha projectile fragments has been studied in ^{16}O-emulsion interactions at 3.7 A GeV. The angular distributions of relativistic alphas cannot be explained by a clean-cut participant–spectator model. Therefore it is assumed that alphas originate from two distinct sources differing in their temperatures.

Keywords: relativistic heavy-ion collision, helium projectile fragments, angular distribution
PACC: 2570N, 2587, 2320E

1. Introduction

In the last 20 years the availability of relativistic heavy ion beams at CERN Super Proton Synchrotron (SPS), the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS) and Relativistic Heavy Ions Collider (RHIC) has given a great boost to the study of relativistic nucleus–nucleus interactions. Most of the studies have concentrated on particle production in highly excited nuclear matter with the goal of examining possible signals of quark gluon plasma in central collisions. The study of peripheral interactions has received less attention. A few emulsion experiments have been done on target and projectile fragmentation at the SPS, AGS, Bevalac and Dubna energies. The emission of multiply charged projectile fragments (PFs) is an interesting phenomenon and its study can help us understand the reaction mechanism and obtain the information about the fragmentation properties. The emission of helium projectile fragments (HPFs) has been studied in many experiments and these fragments are generally understood to be the projectile spectators in the context of a participant–spectator model.[1] Recent experiments with beams of increasing mass indicate that in the case of a heavier projectile alphas are emitted at large angles[2−11] compared with those of a relatively light beam.[12] This large-angle scattering implies the failure of the clean-cut participant–spectator model in explaining the experimental facts. To understand this large-angle scattering, the idea was introduced of a second source like a fireball,[13] which is formed when a projectile nucleus picks up a few nucleons from the target and moves at a velocity slightly less than that of the projectile nucleus, and attains a temperature higher than that expected from a participant–spectator model.

In earlier experiments[2,3,14] it was found that for heavy ion interactions at low energies ($\approx$ 300 A MeV to 2.1 A GeV) the spatial angle distributions of HPFs had long-tail relativistic Maxwell–Boltzmann distributions.[15] These distributions imply the existence of two distinct sources of HPFs. The dominant one of the two sources is the cold source with an average excitation energy of about 7–10MeV and the other is assumed to be a source of a fireball type at a high temperature of 40–70MeV. The cold source has a velocity, β, almost equal to the beam velocity while the hot source has a β value corresponding to $y = y_{\rm b} - 0.2$.[16] Aggarwal *et al*[2] observed that the $N_{\rm h} = 0$ events were consistent with those in a single(cold) source case, while the $N_{\rm h} > 0$ events required the presence of an additional hotter source.

This experiment is to study the angular distribution of HPFs using a Gaussian distribution. The re-

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sults may be confirmed using an alternative method.[6]

The detection of HPFs in nuclear research emulsion is quite definite because of their distinctive grain densities. The use of NIKFI BR-2 nuclear emulsion detectors in the present experiment allows an analysis of the exclusive type on an event by event basis. The emulsion detector is very suitable for the studies of nucleus–nucleus reactions because it registers all charged particles of an individual event in a 4π-geometry due to its high spatial resolution.

2. Experimental details

NIKFI BR-2 stacks of nuclear emulsions, 10cm$\times$ 10cm$\times$2cm in volume, were exposed horizontally to the 3.7 A GeV ^{16}O beam at the Synchrophasotron of the JINR, Dubna. The flux intensity was 10^3particles/cm^2. Emulsion plates, 600μm in thickness, were scanned by the along-the-track method using XSJ-1 and XSJ-2 microscopes under 100$\times$ oil objectives and 16$\times$ eyepieces. The tracks were picked up at a distance of 1cm from the edge of the pellicle and carefully followed until they either interacted with the nuclei of the emulsion or escaped from the pellicle. Details about scanning, measurements and track classification have been given elsewhere.[17–22] The total of 2960 interactions of oxygen with the nuclei of the emulsion was observed by following a primary track length of 35768.9cm, which led to a mean free path $\lambda = (12.08 \pm 0.22)$cm. Among these interactions, 152 events were found to be produced by electromagnetic interactions and 149 events were due to elastic interactions. Out of these 2960 interactions, 2196 interactions (2044 for inelastic events, 152 for electromagnetic dissociation (ED) of projectile) were picked up, without any bias, for the final analysis. Interactions which were within 30μm from the top or bottom surface of the emulsion were not taken into consideration for the final analysis.

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

(1) Near-central events: the events that 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: the events in which there exist projectile fragments (PFs) with the charges of $Z \geq 2$ emitted in a forward cone. These events show considerably less involvement of the projectile nucleus since they are formed at the relatively large values of b.

(3) Electromagnetic events: the events that are generated by the electromagnetic dissociation (ED) of the incident nucleus that are generated in collisions involving impact parameters large enough so that no nuclear interaction occurs and extremely strong electromagnetic fields from heavy target nuclei are produced in a very short time. Such events typically consist of PFs, which proceed in the direction of the projectile nucleus and are confined within an angle of 45mrad to the beam direction.

3. Experimental results

In 2044 inelastic interactions and 152 ED events, there are 938 and 63 events respectively having at least one helium projectile fragments (HPFs). The total of 1660 HPFs (1539 from inelastic interaction and 121 from ED) was investigated in the present work.

For the unbiased sample of 2044 inelastic nuclear events the average number of alpha particles emitted per interaction is $< N_\alpha >= 0.75 \pm 0.02$. If we exclude the $< N_\alpha >= 0$ events, the value of $< N_\alpha >$ comes out at 1.64 ± 0.03. The average numbers of $Z \geq 3$ and $Z \geq 2$ PFs, are $< N_{\rm F} >= 0.29 \pm 0.01$ and $< N_{\rm F} >= 1.04 \pm 0.02$, respectively. The average numbers of black and grey tracks per interaction are found to be $< N_{\rm b} >= 5.72 \pm 0.12$ and $< N_{\rm g} >= 5.25 \pm 0.15$, respectively.

3.1. Projected angular distribution of HPFs

The distribution of HPFs at a projected angle Θ (the angle between the projection of the fragment in the emulsion plane and the incident beam direction) has been systematically studied for the interactions produced by ^{12}C, ^{14}N and ^{16}O ions of 2.1 A GeV.[23–25] It is found that the momentum distributions in the projectile rest frame are typically Gaussian shaped. The spread of the angular distribution, $\sigma(\Theta)$, is related to the momentum distribution of the fragments through the relation[3]

$$\sin[\sigma(\Theta)] = \frac{\sigma(p)}{p_{\rm B} A_{\rm F}}, \qquad (1)$$

where $p_{\rm B}$ is the beam momentum per nucleon and $A_{\rm F}$ is the average atomic mass of the helium nucleus consisting of ^{3}He and ^{4}He isotopes. If we assume the abundance ratio ^{3}He:^{4}He=1:3, the value of $A_{\rm F} = 3.75$. $\sigma(p)$(p is the fragment momentum per nucleon in the

projectile rest frame) can be calculated by using the formulation of Lepore and Riddell.[26] They treated the fragmentation of high energy nuclei by using a quantum mechanical sudden approximation and thus deduced the following expression for $\sigma(p)$:

$$\sigma(p) = \left[\frac{W m_n A_{\rm F}(A_{\rm B} - A_{\rm F})}{2A_{\rm B}}\right]^{1/2} ({\rm MeV}/c), \qquad (2)$$

where $A_{\rm B}$ is the mass number of projectile nucleus, $m_{\rm n}$ is the nucleon mass and

$$W = 45A_{\rm B}^{-1/3} - 25A_{\rm B}^{-2/3}. \qquad (3)$$

According to Feshbach and Huang, the momentum distribution width, $\sigma(p)$, is related to the Fermi momentum, $p_{\rm F}$, of nucleons within the projectile.[27] Using the formulation of Goldhaber,[28] the relation between $\sigma(p)$ and $p_{\rm F}$ comes out in the form

$$\sigma^2(p) = \frac{p_{\rm F}^2}{5}\frac{A_{\rm F}(A_{\rm B} - A_{\rm F})}{A_{\rm B} - 1}. \qquad (4)$$

Assuming that, before disintegration, the excited projectile spectator comes to thermal equilibrium at a temperature T, and the value of $\sigma(p)$ is related to the equilibrium temperature T by the following relation:

$$E_0 = kT = \frac{\sigma^2(p)A_{\rm B}}{m_n A_{\rm F}(A_{\rm B} - A_{\rm F})}. \qquad (5)$$

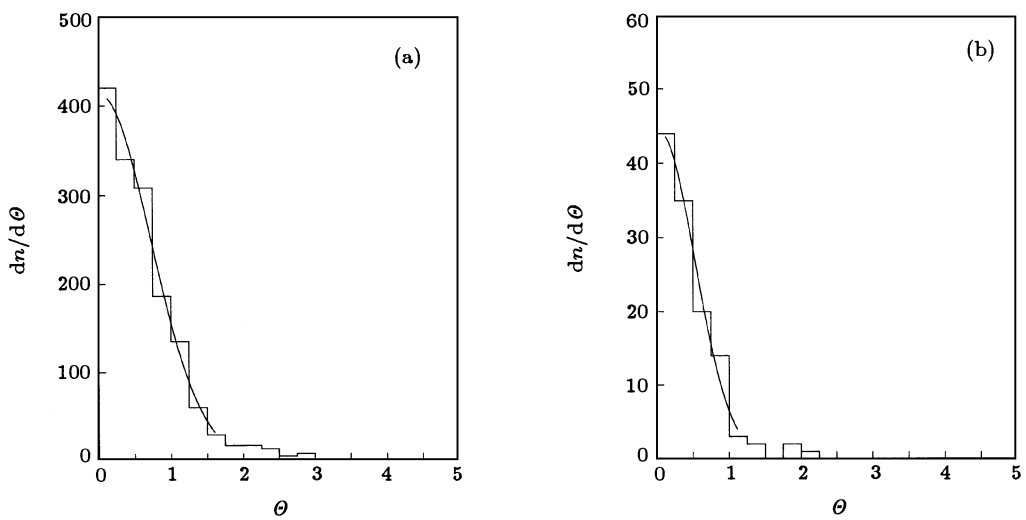


Fig.1. Projected angular distributions of HPFs respectively in (a) inelastic events and in (b) ED events.

The projected angular distribution for HPFs produced in the interactions of the inelastic type and that produced in ED events are shown respectively in Figs.1(a) and (b). One notices here that these angular distributions are both dominated by the narrow forward peaks having a characteristic width of $\approx 1°$. In the type of inelastic reactions there are some HPFs scattered at larger angles than those expected from the pure projectile fragmentation process. The projected angular distribution is fitted with the Gaussian distribution

$$\frac{{\rm d}n(\Theta)}{{\rm d}\Theta} = C{\rm exp}\left[\frac{-(\Theta - < \Theta >)^2}{2\sigma^2(\Theta)}\right]. \qquad (6)$$

The fitting parameters, the value of $\sigma(p)$ calculated from relation (1) and the average excitation energy calculated from Eq.(5) are given in Table 1. For ED events the best fitting parameters are $< \Theta >= 0.043 \pm 0.304$ and $\sigma(\Theta) = 0.489 \pm 0.144°$. The value of χ^2/DOF (where DOF means degree of freedom) for the fit is 0.66. Using the above value of $\sigma(\Theta)$ and relation (1) we obtain $\sigma(p) = 144 \pm 42{\rm MeV}/c$. Our value of $\sigma(p)$ when inserted in Eq.(5), yields a value of average excitation energy, $E_0 = kT = 7.7 \pm 4.5$MeV. This is of the order of the average binding energy per nucleon. This indicates that very few energy transfers take place between the target and the projectile during a fragmentation process for ED events. For inelastic interactions the best fitting parameters are $< \Theta >= 0.030 \pm 0.112$, $\sigma(\Theta) = 0.698 \pm 0.057°$. and the value of χ^2/DOF is 1.59. Using the same procedure we obtain the value of $E_0 = kT$ being 15.6 ± 2.6MeV, which is greater than the average binding energy per nucleon, indicating a few energy transfers take place between the target and the projectile during a fragmentation process.

Table 1. The fitting parameters of Fig.1, $\sigma(p)$ and kT for ^{16}O-Em interaction at 3.7 A GeV.

Type of reaction	C	$< \Theta >/(^\circ)$	$\sigma(\Theta)/(^\circ)$	$\sigma(p)/(\mathrm{MeV}/c)$	kT/MeV
ED events	44.24 ± 10.73	$.043 \pm .304$	$.489 \pm .144$	144 ± 42	7.7 ± 4.5
inelastic events	412.31 ± 27.48	$.030 \pm .112$	$.698 \pm .057$	205 ± 17	15.6 ± 2.6

Table 2 lists our results as well as those obtained by other investigations of various projectiles and beam energies. Also given in this table are the $\sigma(p)$ values calculated from Lepore and Riddell's theory (Eq.(2)) as well as those from Eq.(4) using the Fermi momentum values obtained from electron scattering experiment of Moniz *et al.*[29] It is seen that as a given emulsion target is bombarded by heavier and heavier projectiles the value $\sigma(p)$ increases. This trend is in disagreement with that obtained from the Lepore and Riddell's model which predicts a slow decrease of $\sigma(p)$ with the increase of projectile mass. On the other hand, the values of $\sigma(p)$ calculated from the Fermi momentum values in the electron scattering experiment show a similar trend as a function of the projectile mass.

Table 2. $\sigma(p)$ and kT values for various projectiles at different energies.

Beam	Energy /(A·GeV)	$\sigma(p)$ (MeV/c) Measured	Calculated using Eq.(2)	Calculated using relation (4)	kT /MeV	Ref.
^{12}C	1.05	125 ± 3	134	166	6.4 ± 0.3	[25]
^{12}C	2.1	129 ± 1	134	166	6.9 ± 0.1	[25]
^{16}O	2.1	131 ± 1	137	180	6.3 ± 0.1	[25]
^{16}O	3.7	144 ± 42	137	180	7.7 ± 4.5	this work
^{16}O	200	155 ± 8	137	180	8.9 ± 0.9	[30]
^{32}S	200	169 ± 9	135	203	9.1 ± 0.9	[8]
^{40}Ar	2.0	179.5 ± 6	133	210	9.5 ± 0.6	[3]
^{56}Fe	0.9	220 ± 12	129	220	13.8 ± 1.5	[3]

3.2. Spatial angular distribution of HPFs

The spatial angular distributions of HPFs for ^{16}O-Em inelastic events and those for ED interactions at 3.7 A. GeV, respectively, are shown in Figs.2(a) and 2(b). Very few alpha particles have angles greater than $\sim 2.5^\circ$ and thus we can define a ratio R_{tp} of the number of HPFs in a tail to that at the peak as

$$R_{\mathrm{tp}} = \frac{\Theta_{\mathrm{Lp}} < \Theta_{\mathrm{L}\alpha} \leq \Theta_{\mathrm{Lt}}}{\Theta_{\mathrm{L}\alpha} \leq \Theta_{\mathrm{Lp}}}, \qquad (7)$$

where Θ_{Lp} is the projectile fragmentation angle which is determined by Fermi momentum of nucleon. Here, we takes it as $\Theta_{\mathrm{Lp}} = 2.5^\circ$, and Θ_{Lt} is the maximum emission angle of HPFs where we takes it as 10°. In Table 3 we give a summary of the values of R_{tp} observed in different kinds of interactions for different beams and energies. For the same sample the value of R_{tp} decreases with the increase of beam energy per nucleon, but increases with the increase of projectile mass. From Fig.2 it can be seen that the two distributions have the same trend, the distribution cannot be fitted by one single Gaussian distribution. Therefore, the spatial angular distribution of HPFs can be fitted by two Gaussian distributions.

Table 3. The values of R_{tp} observed in different kinds of interactions.

Beam	Energy/(A·GeV)	Sample	R_{tp}	Ref.
^{56}Fe	0.9	$N_{\mathrm{h}} = 0$	0.22 ± 0.04	[3]
		$N_{\mathrm{h}} \geq 0$	0.39 ± 0.02	[3]
^{56}Fe	1.7	$N_{\mathrm{h}} = 0$	0.10 ± 0.02	[2]
		$N_{\mathrm{h}} \geq 0$	0.38 ± 0.02	[2]
^{40}Ar	2.0	$N_{\mathrm{h}} = 0$	0.14 ± 0.03	[3]
		$N_{\mathrm{h}} \geq 0$	0.27 ± 0.18	[3]
^{16}O	3.7	$N_{\mathrm{h}} = 0$(ED)	0.14 ± 0.05	Our work
		$N_{\mathrm{h}} \geq 0$	0.16 ± 0.02	Our work

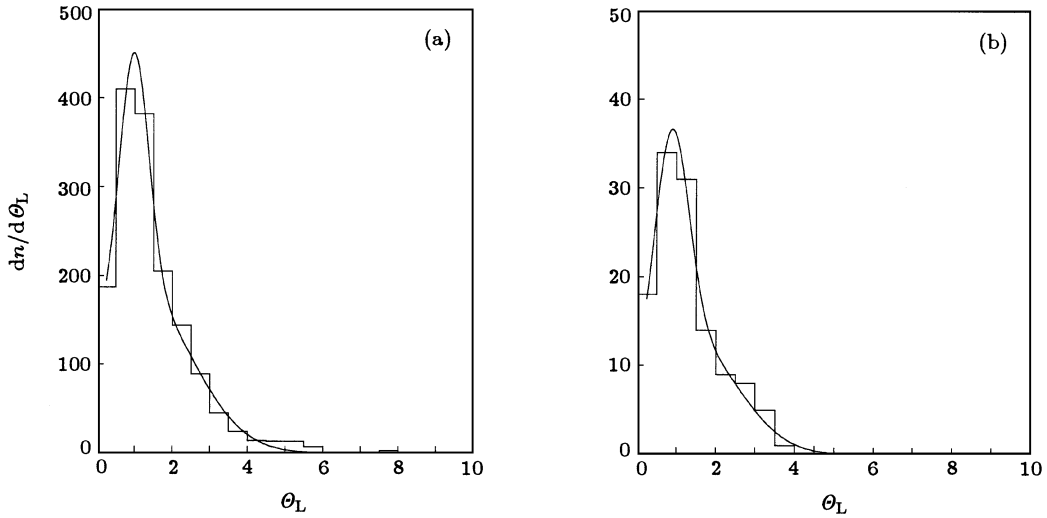


Fig.2. Spatial angular distributions of HPFs respectively in (a) inelastic events and in (b) ED events.

3.3. Transverse momentum distribution

Figure 3 shows the P_T distributions of HPFs, emerging from inelastic and ED events, respectively. It can be seen that both distributions can not be fitted by one single Gaussian distribution. Therefore, the P_T distribution of the HPFs can be fitted by two Gaussian distributions, which is in the form

$$\frac{dn}{dP_T} = C_1 \exp\left[\frac{-(P_T - < P_T >_1)^2}{2\sigma_1^2(P_T)}\right] + C_2 \exp\left[\frac{-(P_T - < P_T >_2)^2}{2\sigma_2^2(P_T)}\right]. \quad (8)$$

Table 4. Values of fitting parameters of P_T distribution using Eq.(8).

Event type	Parameters of two Gaussian distributions						
	C_1	$< P_T >_1$ /(A·GeV/c)	σ_1 /(A·GeV/c)	C_2	$< P_T >_2$ /(A·GeV/c)	σ_2 /(A·GeV/c)	χ^2/DOF
ED	14.0 ± 7.6	$.037 \pm .007$	$.020 \pm .013$	4.0 ± 10.8	$.017 \pm .216$	$.096 \pm .055$	0.88
inelastic	129.0 ± 14.2	$.037 \pm .002$	$.020 \pm .002$	51.8 ± 13.8	$.066 \pm .013$	$.047 \pm .006$	2.46

In Table 4 we present the values of fitting parameters of P_T distribution using the above formula. From this table it can be seen that the values of $< P_T >_1$ and σ_1 for the first Gaussian distribution are the same for both ED and inelastic events, but for the second Gaussian distribution the value of $< P_T >_2$ for ED events is less than that for the nuclear interactions. The first Gaussian distribution, dominating the whole distribution, is for HPFs from the cold source which is the same for both ED and inelastic interactions. The second Gaussian distribution is for HPFs emitted by the auxiliary high temperature source. For inelastic nuclear interactions, the fraction of HPFs emitted by the high temperature source is 29%.

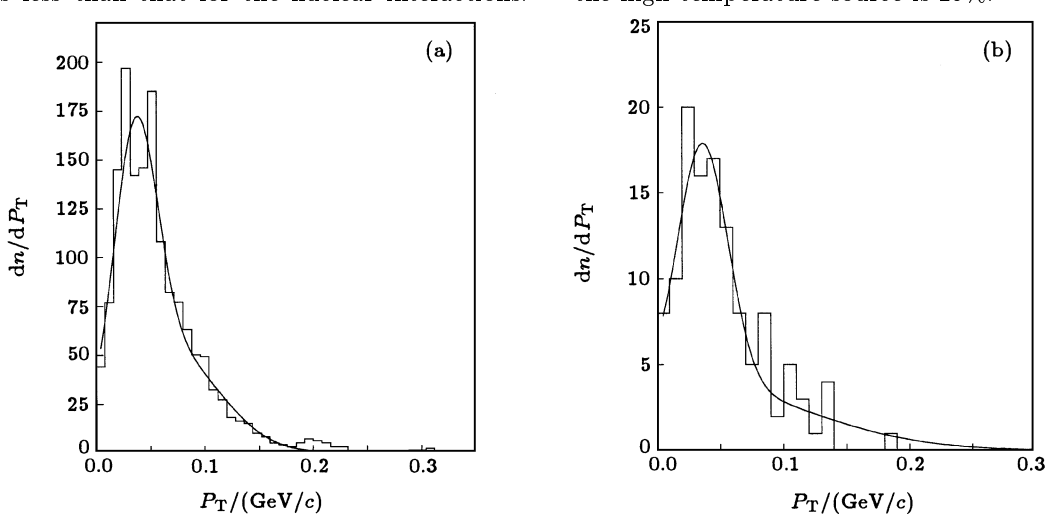


Fig.3. Transverse momentum distributions of HPFs respectively in (a) inelastic events and in (b) ED events.

In analysing the angular distribution of HPFs from ^{16}O-Em interactions within the framework of thermodynamic models a convenient representation is to plot the integral frequency distribution of the square of the transverse momentum per nucleon (q), i.e. $P_{\rm T}^2$ for ED and nuclear events respectively. Assuming the velocity of HPFs is the same as the beam velocity, we have

$$q = M_{\rm p}^2(\gamma^2 - 1)\sin^2\Theta_{\rm L}, \tag{9}$$

where γ is the Lorentz factor of the projectile, $M_{\rm p}$ is the mass of the proton, $\Theta_{\rm L}$ is the emission angle of HPF. If we assume that the emission of the fragment in the projectile frame is Maxwellian with a certain temperature T, then

$$\ln F(>P_{\rm T}^2) = -\frac{A}{2M_{\rm p}T}P_{\rm T}^2, \tag{10}$$

where A in this case is the mass number of alphas. The linearity of such a plot wound be strong evidence for a single temperature.

Figures 4(a) and 4(b) show the $P_{\rm T}^2$ distributions of HPFs produced in the two samples of ED and nuclear events respectively. For the nuclear interactions the figure cannot be fitted by a single Rayleigh distribution, but for the ED events the figure can be fitted by a single Rayleigh distribution of the form

$$F(P_{\rm T}^2) = C\exp\left(\frac{-P_{\rm T}^2}{2\sigma^2}\right), \quad \sigma = \sqrt{2/\pi} < P_{\rm T} > . \tag{11}$$

Therefore, the $P_{\rm T}^2$ distribution of HPFs produced in nuclear interactions can be fitted by two Rayleigh distributions having two different temperatures, $\sigma_{1,2}$, of two independent sources of HPFs production, which is in the form

$$F(P_{\rm T}^2) = C_1\exp\left(\frac{-P_{\rm T}^2}{2\sigma_1^2}\right) + C_2\exp\left(\frac{-P_{\rm T}^2}{2\sigma_2^2}\right),$$
$$\sigma_{1,2} = \sqrt{2/\pi} < P_{\rm T} >_{1,2}, \quad \sigma_2 > \sigma_1. \tag{12}$$

The best fitting parameters in Fig.4(a) using Eq.(12), and those in Fig.4(b) using Eqs.(11) and (12) are all listed in Table 5. For nuclear interactions, the distribution can be well explained by two Rayleigh distributions with different temperatures. Using Eq.(10) and the fitting parameter, we obtain a temperature of 7 MeV for the cold source, and 35 MeV for the hot source. For ED events, the distribution can be well explained by a single Rayleigh distribution. The temperature of source produced HPFs is 9.8 MeV.

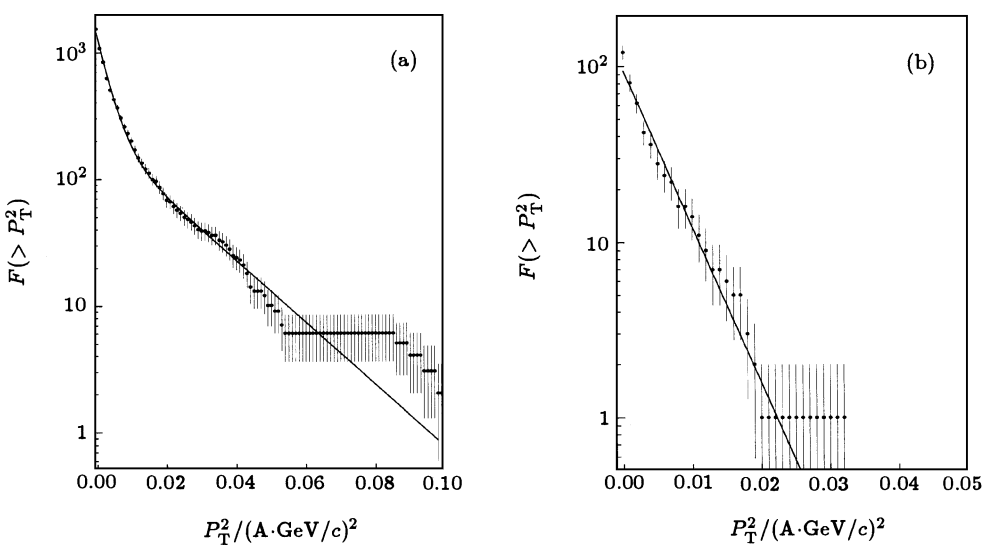


Fig.4. $P_{\rm T}^2$ distributions of HPFs respectively in (a) inelastic events and in (b) ED events.

Table 5. Values of fitting parameters of $P_{\rm T}^2$ distribution using Eqs.(11) and (12) for ED and nuclear events, respectively.

Event type	Parameters of two Rayleigh distributions				
	C_1	σ_1 /(A·GeV/c)	C_2	σ_2 /(A·GeV/c)	χ^2/DOF
ED	52.0 ± 15.7	0.024 ± 0.006	69.6 ± 12.5	.054 ± .024	0.21
	94.8 ± 6.4	0.049 ± 0.002			0.59
inelastic	1228.9 ± 30.1	0.041 ± 0.001	216.9 ± 19.9	.094 ± .002	1.01

4. Conclusions

It is quite interesting to study the projectile fragmentation of heavy ions such as ^{16}O, as some of the fragmentation characteristics change with the mass of the beam. The main conclusions of our experiment are as follows.

(1) The projected angular distribution of HPFs is broad for the nuclear interactions in comparison with that for the ED reactions.

(2) Our observations confirm that with the nuclear collisions induced by heavy ions taken into consideration, the relativistic HPFs must be ascribed to two emission sources. One of them is the projectile itself and the other is a fireball which is formed when nucleons are mutually swept away from the projectile and target. This can be confirmed by the angular distributions and the transverse momentum distributions of HPFs.

(3) For the ED events, the impact parameter is large enough so that no nuclear interaction occurs. The emission of HPFs can be ascribed to only projectile source, which can be confirmed by the projected angular distribution and P_{T}^2 distribution.

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