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TRANSVERSE MOMENTUM SPECTRUM OF ULTRA-RELATIVISTIC Li PROJECTILE FRAGMENTS ($Z = 3$) IN 60 A GeV/c OXYGEN-EMULSION INTERACTION

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A measurement of charge of ultra-relativistic projectile fragments ($1 \leq Z \leq 3$) obtained in ^{16}O-emulsion interaction at 60 A GeV/c has been made. Li-projectile fragments were identified from the charge distribution of the projectile fragments. The transverse momentum distribution of the Li projectile fragments ($Z = 3$) was studied. The data were compared with Maxwell-Boltzmann distribution and they revealed the existence of a single temperature. The results are compared with other data on ultra-relativistic nuclear collisions.

1. Introduction

A number of experiments with nuclear emulsion have been done to study the transverse momentum distribution of nucleons and α-particle projectile fragments (PFs). The experiments with Li PFs ($Z = 3$) are much more difficult because their multiplicity is low. Another problem is their detection in emulsion experiments. Measurement of charge of PFs in heavy-ion interactions has been improved very much in the quark search experiments. Plastic detector technique [1], Čerenkov-radiation detector technique [2] and a search within stable matter [3] were devoted to the search for fractional charges. Bloomer et al. [4] adopted the well-developed nuclear-emulsion technique and raised the selectivity to make the detection of fractional charges possible. They obtained negative results in the search for a free quark. Their method [4] is very efficient in measuring charges of ultra-relativistic PFs of $1 \leq Z \leq 3$ by determination of the lacunarity, i.e. of the fractional transparency or fractional opacity in the linear track structure of ionization as observed in a developed emulsion. This method yields an estimate of charges for relativistic PFs having $1 \leq Z \leq 3$ with a standard deviation of less that 0.03 for the measured charges of each track. Therefore, one can identify charged of PFs with high reliability. Bhalla et al. [5], Baumgardt et al. [6], Aggarwal et al. [7] and Ghosh et al. [8] reported transverse momentum distribution of two α-particle PFs in nuclear emulsion studies and indicated the evidence of two different nuclear temperatures. Their results are supported by Raha's argument [9] and seemed to be an experimental signature of the quark-gluon plasma (QGP). The analysis was based on the participant-spectator concept [10] and simple fireball model [11]. It is assumed that the targets and the projectile are spheres and make cylindrical cut through each other, leaving target and projectile spectators. Raha et al. [9], proposed that although the spectators may be considered separated from the participants, some interaction between them does exist and the spectators are also excited. They suggested that the shear viscosity of the nuclear fluid causes friction over the region of contact and work done against friction shows up as heat in the cut surface. The energy available to spectators produces particle emission in the fragmentation regions. If QGP is formed in the participant region, the coefficient of shear viscosity would be much reduced in comparison to the situation where no QGP is formed. Hence, the existence of two different types of events and two different temperatures in the case of relativistic α-particle PFs. Ghosh et al. [12] reported a study of transverse momentum (p_T) distribution of relativistic proton PFs emerging from interactions of ^{12}C with nuclear emulsion at 4.5 A GeV/c. When compared with the Maxwell-Boltzmann distribution, the p_T-distribution reveals the existence of a single temperature. The energy momenta of the projectiles used in these experiments did not exceed 4.5 A GeV/c. Therefore, further study on PFs produced by other heavy ion beams of higher enegy is needed. The study would be important for a better understanding of the dynamics of heavy ion collisions. With this aim, we measured charges of ultra-relativistic PFs obtained in 60 A GeV/c ^{16}O-emulsion interaction, by the measurement of lacunarity (L) or opacity (ϕ) of the track structure in the nuclear emulsion track detector. We identified different PFs for $1 \leq Z \leq 3$ from their charge distribution and studied transverse momentum distribution of Li PFs.

2. *Experimental details*

We have used a stack of ILFORD K2 plates exposed to the ^{16}O beam with the average momentum 60 *A* GeV/*c*, obtained at CERN, Geneva. Leitz–Metalloplan microscope with oil immersion objective having a magnification 100× and occular lens 20× along with an image processor is used for scanning. The data is taken with ASM 68K semi-automatic measuring system. A SUSY system disk and a suitably developed programme is used to measure lacunarity (L) and/or opacity (ϕ) of the track structure. We followed the method of Bloomer et al. [4] to identify relativistic PFs having charges $1 \leq Z \leq 3$. This technique is a precise one and gives the fast-particle charges to a precision of better than 0.03 *e*. The details of the theory were presented in our previous work [13].

We used a random sub-sample of 557 events from a bigger collection of events. Average multiplicity was found to be 3.5 *e* considering all charged PFs. Multiplicity of Li PFs is only 0.4. The lacunarity (L) and/or opacity (ϕ) were determined on 1000 μm of the linear track structure for each track. It is seen that the lacunarity (L) obtained directly or calculated from the opacity (ϕ) belongs to three distinct groups that have been identified to belong to particles with $Z = 1,2$ and 3. 217 Li PFs ($Z = 3$) were identified by this method. Particles lying beyond the emission angle of 2° with respect to the incident beam direction were rejected. Thus, the observed PFs possess velocity very close to that of the beam. Each event was scanned by two independent observers and the scanning efficiency is estimated at 98%.

3. Analysis

The analysis was done within the framework of the fireball model [11,14] for the relativistic heavy-ion collision. It was assumed that when the projectile and target nuclei collide, a localisation of interaction of the two overlapping parts of the projectile and target nuclei take place and form participants. The rest of the two nuclei remain relatively undisturbed forming spectators. The available energy in the centre of mass heats the swept out nucleons leading to a quasi-equilibrium fireball. It was assumed that the fireball is formed by the nucleons in the swept out region only. The large number of swept out nucleons combined with an anticipated fairly large number of interactions per particle is presumably responsible for the quasi-equilibrated system, i.e. the fireball which can then be described in terms of mean values and statistical (Maxwell-Boltzmann) distribution. The transverse momentum of a projectile fragment is given by,

$$p_T = Am_0(\gamma^2 - 1)^{1/2} sin\theta, \tag{1}$$

where A is the mass number of the fragment, m_0 the nucleon rest mass and γ the Lorentz factor of the projectile. The decrease in kinetic energy of the oxygen projectiles on their way through the emulsion has been taken into account using the Bethe-Bloch formula, Assuming that the momentum of the Li PFs is distributed according to the Maxwell-Boltzmann in the projectile rest frame with some temperature T, the integral frequency distribution of transverse momentum per nucleon squared $Q = p_T^2/A^2$ is given by

$$\ln F(> Q) = -\frac{A}{2m_0 T} Q. \tag{2}$$

If the plot is linear, then from the slope of the line we obtain a single characteristic temperature of the distribution.

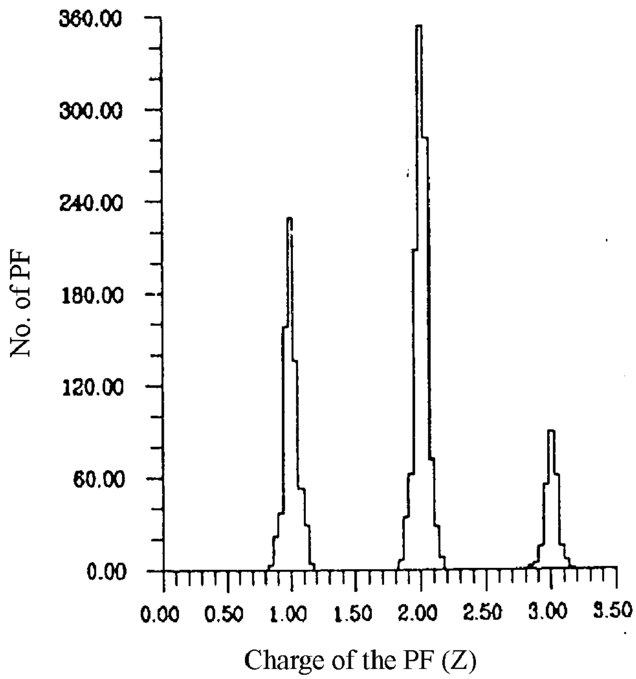

Fig. 1. Distribution of charges $1 \leq Z \leq 3$ *of projectile fragments emitted in* ^{16}O- *emulsion interaction at 60 A* GeV/*c.*

TABLE 1. Results of measurements of projectile-fragment charges for $1 \leq Z \leq 3$. $K_0 = Z/\overline{\rho}$, *where* $\overline{\rho} = \sqrt{-\ln L}$ *and L is the lacunarity of the track structure. The fifth column shows the number of measured charges of projectile fragments in a peak for a value of* $Z = 1, 2,$ *or 3,* δN, *beyond the limits* $Z \pm 3D_Z$.

Z	No. of tracks	K_0	Dispersion	δN
1	645	2.974	0.071	0
2	997	2.979	0.075	0
3	217	2.975	0.073	0

Figure 1 shows the charge distribution of the PFs. It is obvious from the figure that the charges are distributed sharply around the integer values of Z, where $Z = 1, 2$ and 3. Table 1 shows that all PFs lie within three times the dispersion (D_z) around the integer charges. Figure 2 shows the transverse momentum (p_T) distribution of Li PFs ($Z = 3$) observed in all 557 events. The distribution shows a prominent peak at 0.25 GeV/c. Figure 3 shows a cumulative plot of $\ln F(> Q)$ as gives a good linear fit with $\chi^2/d.o.f. = 0.08$. An error bar is given in the figure to account for the typical statistical error. In this case of a single Maxwell-Boltzmann distribution, we get a temperature of 246 MeV for the Table 2 represents the results of some previous experiments and shows the values of temperatures obtained from the transverse momentum distributions of different PFs from different projectiles at several energies.

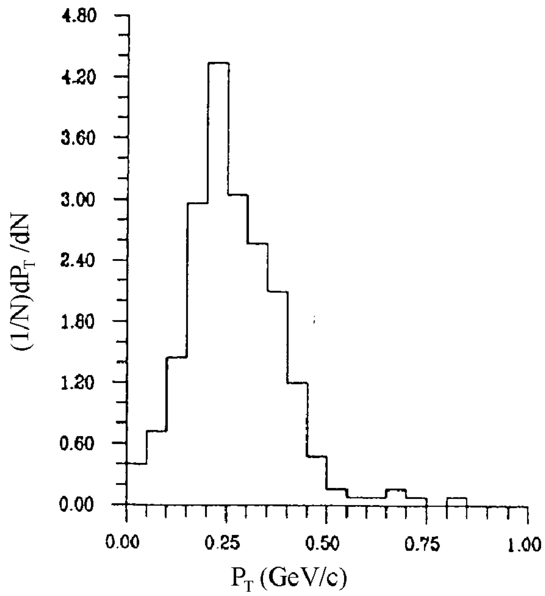

Fig. 2. Transverse momentum distribution of the identified relativistic Li *projectile fragments ($Z = 3$) produced in oxygen-emulsion interaction at 60 A* GeV/c. *N is the total number of* Li *projectile fragments.*

TABLE 2. Values of temperatures of the fragmentation region from the transverse momentum distributions of different projectile fragments obtained in heavy-ion interactions at several energies. Abbreviation n. a. means not available.

Interaction	Energy or momentum	No. of Events	Projectile fragment	Temperature (MeV)	Ref.
^{56}Fe+emulsion	1.7 A GeV	423	α	12 and 52	[5]
^{56}Fe+emulsion	1.9 A GeV	368	α	10 and 43	[6]
^{56}Fe+emulsion	0.9 A GeV	900	α	8 and 40	[7]
^{40}Ar+emulsion	2.0 A GeV	975	α	9 and 68	[7]
^{12}C+emulsion	4.5 A GeV/c	1200	α	10 and 40	[8]
^{12}C+emulsion	4.5 A GeV/c	1200	p	8	[12]
^{28}Si+^{27}Al	14.6 A GeV/c	n. a.	p	7 and 170	[15]
^{28}Si+^{197}Au	14.6 A GeV/c	n. a.	p	200 to 220	[17]
^{16}O+emulsion	60 A GeV/c	557	Li	246	Present work

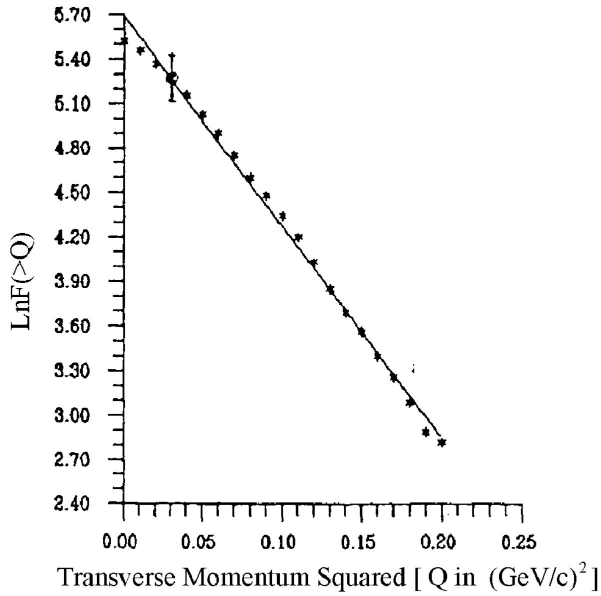

Fig. 3. Cumulative plot of $\ln F(>Q)$ *as a function of* Q *. Here* Q *is the transverse momentum per unit mass squared* (p_T^2/A^2) *in* $(\mathrm{GeV}/c)^2$.

It is very interesting to note that all the heavy-ion data at relatively lower energies of the projectiles with α-particle PFs speak in favour of the existence of two types of events, the so-called cold and hot events. This observation was interpreted, following Raha et al. [9] as a possible signature for the production of QGP. However, for proton PFs, we observed a single temperature [12], and our present data also favour the existence of a single temperature, which is several times larger than for the previous data [12]. The momentum of the projectiles used in the present work is several times larger than the previous value, suggesting that the temperature of the fragmentation region increases with the projectile-momentum. Thus, the Raha's argument fails to explain such behaviour. One may comment that the physical processes involved for this behaviour of Li PFs at 60 A GeV/c must be different from the one we depicted from Raha's hypothesis.

J. Barrette et al. [15], in the E814 collaboration experiments at the Brookhaven AGS, indicated the existence of two distinct domains, one of the beam rapidity spectator nucleons, and the second of the participant nucleons, as a result of nuclear transparency. For the ^{28}Si + ^{27}Al interaction at 14.6 A GeV/c, a temperature of 170 MeV for the interacting-nucleons from an analysis of the transverse momentum spectrum was observed. T. Abbott et al. [16], in the E802 collaboration experiments used ^{28}Si projectiles from AGS at 14.6 A GeV/c. In the ^{28}Si + ^{197}Au interaction, they observed normal momentum distribution of identified protons with a temperature of (215 ± 5) MeV for the exponential and (187 ± 5) MeV for the Boltzmann distribution. They observed from similar experiments [17], temperatures in the range of 200 to 220 MeV for identified kaons and protons. Therefore, our data are in accord with the values from 150 to 250 MeV, as obtained by other heavy-ion experiments.

4. Conclusion

Our latest data on the transverse momentum distribution of Li PFs ($Z = 3$) in the ^{16}O-emulsion interaction at 60 A GeV/c indicate a single temperature in the fragmentation region. Previous data [12] on the p_T distribution of proton PFs of ^{12}C-emulsion interaction at 4.5 A GeV/c support the present work, but a different temperature of the fragmentation region is obtained. The order of the temperature is consistent with the values obtained by other heavy-ion experiments.

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SPEKTAR POPREČNIH IMPULSA ULTRA-RELATIVISTIČKIH FRAGMENATA Li ($Z = 3$) U SUDARIMA KISIK–EMULZIJA PRI 60 A GeV/c

Načinili smo mjerenja naboja fragmenata sudara ($1 \leq Z \leq 3$) iz sudara ^{16}O u nuklearnoj emulziji pri 60 GeV/c. Prepoznavanje litijevih jezgri među fragmentima zasniva se na određivanju naboja fragmenata. Proučavala se raspodjela poprečnih impulsa Li fragmenata. Podaci se uspoređuju s Maxwell-Boltzmannovom raspodjelom i oni ukazuju na jednu temperaturu u području sudara. Rezultati se uspoređuju s drugim podacima za ultra-relativističke sudare.