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Scaling of the multiplicity distribution of evaporated fragments in oxygen-emulsion collisions at 3.7*A* GeV

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The multiplicity distributions of projectile light fragments and target black fragments produced in oxygen-emulsion collisions at 3.7*A* GeV have been analyzed. The Koba-Nielsen-Olesen scaling presentation of $\psi(z) = 4z\exp(-2z)$ can describe well the multiplicity distributions of nuclear fragments.

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Recently [1], the investigation of nuclear fragments produced in high-energy nucleus-nucleus collisions has shown that the multiplicity distributions of projectile light fragments and target black fragments (with a residual range of $\leqslant 3$ mm in nuclear emulsion and a velocity of $\leqslant 0.2$ c) [2–5] can be described by a scaling law, Koba-Nielsen-Olesen (KNO) scaling [6], with a mass-independent universal function of the following form:

$$\psi(z) = 4z\exp(-2z), \tag{1}$$

where $z = n/\langle n\rangle$, $\psi(z) = \langle n\rangle P(n)$, and n, $\langle n\rangle$, and $P(n)$ are the multiplicity, mean multiplicity, and normalized multiplicity distribution of light fragments, respectively. Meanwhile, the experiential formula

$$\psi(z) = az\exp(-bz), \tag{2}$$

where $a = 4.65 \pm 0.09$ and $b = 2.10 \pm 0.04$, is used in Refs. [3,5,7] to describe the multiplicity distribution of projectile helium fragments produced in nucleus-nucleus collisions at high energy.

Describing multiplicity distribution of nuclear fragments, Eqs. (1) and (2) are similar. Our recent work shows that the two equations are in good agreement with the experimental data at energies of 160*A* and 200*A* GeV [1]. This energy range is much higher than the Dubna energy (a few *A* GeV). What is the multiplicity distribution of projectile light fragments and target black fragments produced in nucleus-nucleus collisions at the Dubna energy? Does the multiplicity distribution obey the KNO scaling? We answer these questions in this paper.

The experimental data [8] analyzed in this paper have been measured in NIKFI-BR2 nuclear emulsion. The pellicle size is 10 cm$\times$10 cm$\times$600 μm. The beam is 3.7*A* GeV ^{16}O nuclei at the Dubna Synchrophasotron. Each interaction was scanned using the ''along-the-track'' method with the help of a Russian microscope of the Mbu9 type. We have excluded the events occurring within a 20 μm thickness from the top or bottom surface of the pellicle. Great care has been taken in the identification of different tracks. The data studied in the present work consist of 266 random events.

In nuclear emulsion, the charges of projectile fragments can be measured by the grain density and δ-ray counting methods [9], as well as the technique of lacunarity measurement [10]. Let I_0 denote the experimental minimum value of the track grain density of relativistic singly charged particle. According to the grain density method, the track grain densities of projectile hydrogen (H) and helium fragments are I_0 and $4I_0$, respectively. In order to distinguish the projectile hydrogen fragments from other singly charge particles, we have scanned the tracks in the forward cone (the cone angle $\theta_0 = 54$ mrad) for a long distance (2 cm). The charge pions and kaons do not appear in the forward cone at the long distance due to their multiscattering in nuclear emulsion. By this method, we have distinguished maximally the projectile hydrogen fragments from other singly charged particles. For projectile fragments with charge $Z > 2$, we have used the δ-ray counting method due to a very large track grain density. Let n_{O} and n_Z denote the experimental track δ-ray densities of projectile ^{16}O and projectile fragment with charge Z. According to the δ-ray counting method, $Z = 8\sqrt{n_Z/n_{\mathrm{O}}}$, where 8 is the charge of ^{16}O. In nuclear emulsion, we can measure the charge of projectile fragments one by one. Then, the multiplicity distribution of projectile fragments with different charges can be obtained.

The track grain density of target fragments in nuclear emulsion is greater than $1.4I_0$ [11,12], and the residual range of target black fragments is less than or equal to 3 mm. As for a proton, the kinetic energy is smaller than or equal to 26 MeV [11]. We can measure the track grain density and residual range of target fragments one by one. Then, the multiplicity distribution of target black fragments can be obtained in 3.7*A* GeV ^{16}O-emulsion collisions.

The projectile fragments excluding the heaviest one and target black fragments can be regarded as a result of the evaporation process. We call both of them the evaporated fragments. The multiplicity distributions of projectile H (hydrogen) fragments, all fragments excluding the heaviest one and target black fragments produced in ^{16}O-emulsion collisions at 3.7*A* GeV have been investigated. According to the normalized distributions of these multiplicities of evaporated

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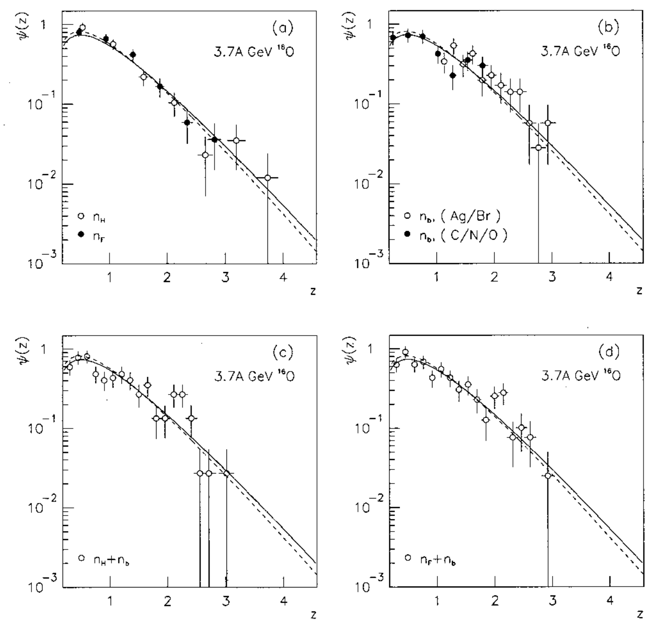

FIG. 1. Multiplicity distribution of $\psi(z)=\langle n\rangle P(n)$ as a function of the scaled variable $z=n/\langle n\rangle$ for projectile light fragments and target black fragments produced in ^{16}O-emulsion collisions at 3.7*A* GeV. The solid and dashed curves are the results of Eqs. (1) and (2), respectively. (a) For projectile H and *F* fragments, where *F* denotes all the projectile fragments excluding the heaviest one; (b) for target black fragments; (c) for compound projectile H fragments and target black fragments; (d) for compound projectile *F* fragments and target black fragments.

fragments [8], we redraw the data in the form of KNO scaling.

Figure 1(a) presents the KNO scaling distributions of multiplicity n_H of projectile H fragments and multiplicity n_F of all projectile fragments excluding the heaviest one. The circles and black points are the experimental data of 3.7*A* GeV ^{16}O-emulsion collisions corresponding to the results of n_H and n_F, respectively, and the error bars are statistical errors. The solid and dashed curves are the results of Eqs. (1) and (2), respectively. One can note that the multiplicity distributions of projectile H fragments and all fragments excluding the heaviest one produced in nucleus-nucleus collisions at the Dubna energy are well described by Eqs. (1) and (2). The values of χ^2/degrees of freedom (DOF) for Eqs. (1) and (2) are 0.302 and 0.260, respectively.

Figure 1(b) presents the KNO scaling distribution of multiplicity n_b of target black fragments produced in ^{16}O-emulsion collisions at 3.7*A* GeV. The circles and black points are the experimental data corresponding to the results of Ag/Br and C/N/O targets, respectively, and the error bars are statistical errors. The solid and dashed curves are of the same meaning as in Fig. 1(a). We know that the two main components, C/N/O and Ag/Br, consist of emulsion, and we have to consider them, accordingly. Generally speaking, the maximum values of n_b for the C, N, and O targets are 6, 7, and 8, respectively. The mean maximum value of n_b for the C/N/O target is 7. Then, the distribution region of n_b for the C/N/O target is in the range from 1 to 7. The distribution region of n_b for the Ag/Br target is mainly in the range from 8 to maximum. In peripheral collisions, i.e., in collisions with a very low multiplicity of target fragments, the value of n_b for the Ag/Br target will be smaller than 8. In redrawing the data, we neglect the contribution of peripheral ^{16}O-Ag/Br collisions and regard all the events with $n_b\leqslant 7$ as a contribution of the C/N/O target. The first circle and the last black point are the same data with $n_b=7$ in the normalized multiplicity distribution of target black fragments. If we do not distinguish the Ag/Br and C/N/O targets, only the values of $\psi(z)$ in the region of low *z* have a little difference from Fig. 1(b). The multiplicity of target black fragments in nucleus-nucleus collisions at the Dubna energy is found to obey the KNO scaling presentation of Eqs. (1) and (2). The values of χ^2/DOF for Eqs. (1) and (2) are 0.404 and 0.480, respectively.

In order to study the multiplicity distribution of compound evaporated fragments, in Fig. 1(c) the KNO scaling of the n_H+n_b distribution in ^{16}O-emulsion collisions at 3.7*A* GeV is plotted. The circles are the experimental data and the error bars are statistical errors. The Ag/Br and C/N/O targets are not distinguished. The solid and dashed curves are the same as in Fig. 1(a). We see that the n_H+n_b distribution can be presented by Eqs. (1) and (2). The values of χ^2/DOF for Eqs. (1) and (2) are 0.616 and 0.685, respectively.

The KNO scaling of the n_F+n_b distribution in ^{16}O-emulsion collisions at 3.7*A* GeV is given in Fig. 1(d). The circles are the experimental data and the error bars are statistical errors. The Ag/Br and C/N/O targets are not distinguished. The solid and dashed curves are of the same meaning as in Fig. 1(a). One can note again that the multiplicity distributions at the Dubna energy obeys the KNO scaling presentation of Eqs. (1) and (2). The values of χ^2/DOF for Eqs. (1) and (2) are 0.372 and 0.450, respectively.

In conclusion, we can point out that the multiplicity distribution of nuclear evaporated fragments produced in nucleus-nucleus collisions at the Dubna energy obeys the KNO scaling presentation of $\psi(z)=4z\exp(-2z)$. Excluding the heaviest projectile fragment, the multiplicity distributions of relativistic H and other light fragments are well described by the KNO scaling presentation, and the multiplicity distributions of target black fragments can be described by the KNO scaling presentation. Meanwhile, the multiplicity distributions of compound evaporated fragments obey the KNO scaling presentation. One can say that the KNO scaling applies as energies of 3.7*A* GeV for an oxygen beam, as well as at higher energies, at which the KNO scaling has been known for some time. To the extent that such scaling indicates that limiting fragmentation applies, then, for oxygen, limiting fragmentation must set in at or below 3.7*A* GeV.

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