Multiplicity Distribution of Relativistic Charged Particles in Oxygen-Emulsion Collisions at 3.7A GeV

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(Received November 11, 2002)

The multiplicity distributions of relativistic charged particles produced in oxygen-emulsion collisions at 3.7A GeV are reported. The KNO scaling form can describe the multiplicity distributions of projectile He and H fragments. There is a positive correlation between the shower particle multiplicity and the target fragment multiplicity, and a negative correlation between the shower particle multiplicity and the bound system charge of the projectile spectator. The nuclear geometry plays an important role in nucleus-nucleus collisions at the Dubna energy.

PACS numbers: 25.75.-q

According to the “participant-spectator model” [1], the interacting system in relativistic nucleus-nucleus collisions can be divided into three parts: a target spectator, a participant, and a projectile spectator. The overlapping part of the two colliding nuclei is called the participant and the other parts are called the target spectator and the projectile spectator, respectively. The violent collisions happen in the participant, and the weak excitations and cascade collisions happen in the spectator. Relativistic charged particles, including produced mesons, projectile hydrogen (H), and helium (He) fragments are produced in the participant and the projectile spectator, respectively.

The Dubna energy (a few A GeV) is a special energy, at which the nuclear limiting fragmentation applies initially. For oxygen, the limiting fragmentation may set in at or below the Dubna energy. To study nuclear fragmentation at the Dubna energy is of great importance. In recent work [2], we studied target fragmentation in oxygen-emulsion collisions at 3.7A GeV (the Dubna energy)

As a continuation, in this paper we will give a systematic analysis of the multiplicity distributions of relativistic charged particles in oxygen-emulsion collisions at 3.7A GeV. In the analysis, the relativistic H and He fragments produced in the projectile spectator are also included in the relativistic charged particles.

The nuclear emulsion stacks measured in the experiment were exposed to oxygen beams at the Synchrophasotron of the Joint Institute for Nuclear Research (JINR), Dubna,
Russia. The beam energy was 3.7 A GeV. The emulsion type was Russian NIKFI-BR2 and the pellicle size was 10 cm × 10 cm × 600 μm. Each interaction was scanned using the “along-the-track” method, with the help of a Russian Mbu9 type microscope. We excluded the events occurring within 20 μm of the top or bottom surface of the pellicle. Great care was taken in the identification of different tracks [3].

Three interaction types were found in the experiment. They were elastic collisions, electromagnetic dissociations, and nuclear reactions. An elastic collision is an interaction occurring between the projectile oxygen and the target hydrogen in the emulsion. The final state products are only the projectile oxygen and the target hydrogen. An electromagnetic dissociation is an interaction occurring between the projectile and the target due to electromagnetic interactions. The final state products contain the projectile fragments and/or the target fragments. A nuclear reaction is an interaction occurring between the two colliding nuclei due to nuclear interactions. The final state products contain the projectile fragments, the target fragments, the relativistic produced particles, and a few slow mesons. We focus our attention on the nuclear reaction in the present work. The data studied in the present work consist of 266 random nuclear reaction events [2].

The numbers of projectile He and H fragments in an event final state are called the multiplicities and are denoted by $n_{He}$ and $n_{H}$, respectively. The track grain densities of projectile He and H fragments in a nuclear emulsion are about $4I_{0}$ and $I_{0}$ [3,4], respectively, where $I_{0}$ denotes the experimental minimum value of the track grain density of a relativistic singly charged particle. Let $I_{PF}$ and $I_{P}$ be the densities of the $\delta$-rays of a projectile fragment track and a projectile track; the charge $Z_{PF}$ of the projectile fragment is $Z_{PF} = Z_{P}I_{PF}/I_{P}$, where $Z_{P}$ is the charge of the projectile. The residual range of the projectile fragments is greater than 2 cm and the emission angle is less than $\theta_{0} = 0.2/P_{\text{beam}} \approx 0.2/3.7 \approx 0.054$ rad, where $P_{\text{beam}}$ is the beam momentum in A GeV/c [3,4]. We can measure the track grain densities and residual ranges of all the projectile fragments in the forward cone ($\theta_{0} = 0.054$ rad). The multiplicity distribution of each kind of projectile fragment can then be obtained. Going a step further, we define $Q = \Sigma Z_{PF}(\geq 2)$ to be the bound system charge of the projectile spectator.

The number of relativistic single final state charged particles in an event is called the multiplicity of the shower particles and is denoted by $N_{s}$. The track grain density of shower particles in a nuclear emulsion is less than $1.4I_{0}$. The velocity of shower particles is greater than 0.7c, where c is the velocity of light in vacuum. According to the definition of the track grain density of the shower particles, the projectile H fragments are also shower particles. Because the projectile H fragments are not produced by the participant but by the projectile spectator, a careful distinction of the shower particles with or without the inclusion of projectile H fragments is necessary; we thus define $n_{s} = N_{s} - n_{H}$. Now we know that $N_{s}$ and $n_{s}$ denote the multiplicities of shower particles including and excluding of projectile H fragments, respectively.

The number of final state target fragments in an event is called the multiplicity of the target fragments and is denoted by $N_{t}$. The track grain density of the target fragments in a nuclear emulsion is greater than $1.4I_{0}$ [3,4]. We can divide target fragments into two types: target black fragments and target grey fragments. The multiplicities of the black
and grey fragments are denoted by $N_b$ and $N_g$, respectively. The residual range of the black fragments is less than or equal to 3 mm, and that of grey fragments is greater than 3 mm. For a proton, the kinetic energy corresponding to a residual range of 3 mm is 26 MeV [4]. We can measure the track grain densities and the residual ranges of all the target fragments. Then the multiplicity distribution of each kind of target fragment can be obtained [2].

Figure 1(a) presents the multiplicity distribution, $P(n_{He})$, of projectile He fragments produced in oxygen-emulsion collisions at 3.7 $A$ GeV. In order to give a comparison, the experimental results of the oxygen-emulsion collisions at 200 $A$ GeV are presented in the same plot [5]. The points, circles, and squares correspond to the 3.7 $A$ GeV oxygen-emulsion (O-Em), 200 $A$ GeV oxygen-emulsion stack (O-ES), and 200 $A$ GeV oxygen-emulsion chamber (O-EC) collisions results, respectively. One can see that the three sets of experimental results are similar. The value of $P(n_{He})$ decreases with the increase of $n_{He}$. The mean values of $n_{He}$, i.e. $\langle n_{He} \rangle$, for the three kinds of collisions are 0.80 ± 0.06, 0.68 ± 0.05, and 0.66 ± 0.05, respectively. Figure 1(b) presents the multiplicity distributions in Koba-Nielsen-Olesen (KNO) scaling form [6]. We use $n_{He}/\langle n_{He} \rangle$ and $\langle n_{He} \rangle P(n_{He})$ in Fig. 1(b), instead of $n_{He}$ and $P(n_{He})$ as in Fig. 1(a). The meanings of the symbols in Fig. 1(b) are the same as those in Fig. 1(a), but the number of data points in Fig. 1(b) is less than that in Fig. 1(a). Generally speaking, in studying KNO scaling, events with zero-multiplicity should be excluded [6-8]. Data with $n_{He}/\langle n_{He} \rangle = 0$ are not included in Fig. 1(b), and the value of $\langle n_{He} \rangle$ in Fig. 1(b) does not include the contribution of events with $n_{He} = 0$. The curve in Fig. 1(b) follows the distribution [7,8]

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

where

$$z = n_{He}/\langle n_{He} \rangle$$  \hspace{1cm} (2)

and

$$\psi(z) = \langle n_{He} \rangle P(n_{He})$$  \hspace{1cm} (3)
are the KNO scaling [6]. The values of $\chi^2$/Degree Of Freedom (DOF) for the O-Em, O-ES, and O-EC collisions, are 0.472, 0.359, and 0.105, respectively. One can see that the multiplicity distributions of the projectile He fragments produced in oxygen-emulsion collisions at 3.7$A$ and 200$A$ GeV obey KNO scaling in the form of Eq. (1) [7,8].

Excluding events with projectile fragments greater than helium, we obtain 187 subsample events. The multiplicity distribution, $P(n_{He})$, of the projectile He fragments produced in the 187 events is given in Fig. 2(a) by points. The corresponding experimental results for the 60$A$ and 200$A$ GeV oxygen-emulsion collisions [5] are also given in Fig. 2(a) by circles and squares, respectively. One can see that the three kinds of experimental results are similar. The value of $P(n_{He})$ decreases with the increase of $n_{He}$. Figure 2(b) gives the multiplicity distributions in the KNO scaling form [6]. The points are the experimental data; the contribution of events with $n_{He} = 0$ is not included. The curve is the distribution of Eq. (1). The values of $\chi^2$/DOF for the three kinds of collisions are 0.658, 0.522, and 0.481, respectively. One can see that the multiplicity distributions of the projectile He fragments produced in the subsample events obey KNO scaling in the form of Eq. (1) [7,8].

Figures 1 and 2 show that the multiplicity distribution of projectile He fragments produced in oxygen-emulsion collisions does not depend on the incident energy in the concerned energy region. This means that the production of projectile fragments is mainly determined by the nuclear geometry. For oxygen the limiting fragmentation may set in at or below the Dubna energy.

The multiplicity distribution, $P(n_H)$, of projectile H fragments produced in oxygen-emulsion collisions at 3.7$A$ GeV is presented in Fig. 3(a). One can see that the value of $P(n_H)$ decreases with the increase of $n_H$. The mean value of $n_H$ is 1.15 $\pm$ 0.08. Generally speaking, for collisions between oxygen and emulsion, the incident nucleus is smaller than the target nucleus. From the point of view of impact parameters, the distribution of $n_H$ does not reflect peripheral and central collisions, but only a mean effect. In peripheral collisions, the multiplicity of projectile H fragments is not high, due to the low degree of excitation of the projectile spectator. In the central collisions, the multiplicity of projectile H fragments is also low, due to the almost zero projectile spectator. The middle-$n_H$ events...
are mainly the results of semi-central collisions. The high-$n_H$ events are mainly the collision results of oxygen nuclei with hydrogen nuclei in the emulsion. Figure 3(b) presents the KNO form of the projectile H fragment multiplicity distribution for 3.7A GeV oxygen-emulsion collisions. The points are our experimental data; the contribution of events with $n_H = 0$ is not included. The curve is the distribution of Eq. (1). The value of $\chi^2$/DOF is 0.328. One can see that the multiplicity distribution of projectile H fragments produced in the 3.7A GeV oxygen-emulsion collisions obeys KNO scaling in the form of Eq. (1) \[7,8\].

In order to study the multiplicity distribution of projectile H fragments in detail, Figure 4 gives the $P(n_H)$ vs $n_H$ for the events with different $N_h$ groups. From the upper to lower, the figures in the left panel are the $n_H$ distributions for the events with $N_h = 0 - 1$, $N_h = 2 - 8$, and $N_h > 8$, respectively. The mean values of $n_H$ for the three kinds of events are $1.31 \pm 0.21$, $1.26 \pm 0.13$, and $0.99 \pm 0.11$, respectively. These results show that the value of $n_H$ is high in the collisions of oxygen nuclei with light target fragment multiplicities in the emulsion. The value of $n_H$ is low for collisions of oxygen nuclei with heavy fragment multiplicities in the emulsion. The reason is that the projectile spectator is large in the collisions of oxygen with a light target, while the projectile spectator is small in the collisions of oxygen with a heavy target. We can say that the multiplicity of projectile H fragments is mainly determined by the nuclear geometry. The corresponding KNO scaling distributions are given in the right panel of Fig. 4. The data points do not include the contribution of events with $n_H = 0$. The curves are the result of Eq. (1). The values of $\chi^2$/DOF for the three kinds of events are $0.360$, $0.277$, and $0.590$, respectively. One can see that the multiplicity distributions of projectile H fragments produced in the different event groups selected by $N_h$ in oxygen-emulsion collisions at 3.7A GeV obey KNO scaling in the form of Eq. (1) \[7,8\].

$P(n_H)$ vs $n_H$ for the events with different $Q$ groups are given in Fig. 5. From the upper to lower, the figures in the left panel are the $n_H$ distribution for events with $Q = 0$, $Q = 2 - 4$, and $Q = 5 - 8$, respectively. The mean values of $n_H$ for the three kinds of events are $1.24 \pm 0.18$, $1.57 \pm 0.14$, and $0.70 \pm 0.08$. These results show that the $n_H$ values for the central and peripheral collisions are smaller than those for the semi-central
collisions. The reasons are that the projectile spectator is small for the central collisions and the excitation degree of the projectile spectator is low for the peripheral collisions. In the semi-central collisions, the projectile spectator is not too small and the excitation degree of the projectile spectator is not too low. We can say that the multiplicity of projectile H fragments is mainly determined by the nuclear geometry. The corresponding KNO scaling distributions are given in the right panel of Fig. 5. The points are our experimental data in which the contribution of events with \( n_H = 0 \) is not included. The curves are the result of Eq. (1). The values of \( \chi^2/\text{DOF} \) for the three kinds of collisions are 1.053, 0.172, and 0.355, respectively. One can see that the multiplicity distributions of projectile H fragments...
FIG. 5: As for Fig. 4, but for the events with different $Q$ values.

produced in different event groups selected by $Q$ in oxygen-emulsion collisions at 3.7A GeV obey KNO scaling in the form of Eq. (1) [7,8].

The multiplicity distributions, $P(N_s)$ and $P(n_s)$, of shower particles, including and excluding the projectile H fragments in oxygen-emulsion collisions at 3.7A GeV, are given in Figs. 6(a) and 6(c), respectively. The mean values are $\langle N_s \rangle = 11.4 \pm 0.6$ and $\langle n_s \rangle = 10.2 \pm 0.6$, respectively. One can see that the values of $P(N_s)$ and $P(n_s)$ decrease as the multiplicity of the shower particles increases. Figures 6(b) and 6(d) present the KNO form of shower particle multiplicity distributions for 3.7A GeV oxygen-emulsion collisions. The points are our experimental data. The curves are the distribution of Eq. (1). The values of $\chi^2$/DOF for Figs. 6(b) and 6(d) are 1.599 and 1.713, respectively. If the last five data points are not
included, the values of $\chi^2$/DOF will be 0.867 and 0.549 respectively. One can see that KNO scaling in the form of Eq. (1) seems to qualitatively describe the trend of the multiplicity distributions of shower particles produced in oxygen-emulsion collisions at 3.7$A$ GeV. If we do not consider events with a multiplicity greater than 30, a good agreement between the experimental data and the calculated results can be obtained. Because the statistical significance of the experimental data is not high, to draw a conclusion is impracticable.

The correlations between $h_{N_s}$ (or $h_{n_s}$) and $N_b$, $N_g$, $N_h$, as well as $Q$, in oxygen-emulsion collisions at 3.7$A$ GeV, are given in Figs. 7(a)–7(d), respectively. One can see that the values of $\langle N_s \rangle$ and $\langle n_s \rangle$ increase with the increase of $N_b$, $N_g$, and $N_h$, and decrease with the increase of $Q$. These situations are mainly determined by the nuclear geometry. The large values of $N_s$, $n_s$, $N_b$, $N_g$, and $N_h$, and the small value of $Q$ correspond to small values of the impact parameter. While the small values of $N_s$, $n_s$, $N_b$, $N_g$, and $N_h$, and the large value of $Q$ correspond to large impact parameters.

Figure 8 presents the multiplicity distributions of shower particles produced in different event groups selected by $N_h$ and $Q$ in oxygen-emulsion collisions at 3.7$A$ GeV. From the upper to lower, the figures in the left panel are the distributions for events with $N_h = 0–1$, $N_h = 2–8$, and $N_h > 8$, respectively. The figures in the right panel are the distributions for the events with $Q = 0$, $Q = 2–4$, and $Q = 5–8$, respectively. The mean values of $N_s$ and $n_s$ for different event groups are given in Table I. From Fig. 8 one can see that
The emission of relativistic charged particles, produced in oxygen-emulsion collisions at 3.7A GeV, is presented and discussed. The multiplicity distribution of the projectile He fragments does not depend on the incident energy, in the energy range from 3.7A to 200A GeV. The multiplicity distributions of projectile He and H fragments obey KNO scaling in the form of Eq. (1). There is a positive correlation between the
FIG. 8: Multiplicity distributions of shower particles for the events with different $N_h$ values (the left panel) and different $Q$ values (the right panel) in oxygen-emulsion collisions at 3.7$A$ GeV.

The experimental data presented in this paper shows that the nuclear geometry plays an important role in nucleus-nucleus collisions at the Dubna energy.
Acknowledgments

The author would like to thank Profs. H. Sun and P. Zheng for supplying the emulsion sample. This work was partly finished at the Laboratory of High Energies, Joint Institute for Nuclear Research, Dubna, Russia, and the Cyclotron Institute, Texas A&M University, College Station, USA. This work was supported by the National Natural Science Foundation of China, the China Scholarship Council, the Shanxi Scholarship Council of China, the Shanxi Provincial Foundation for Returned Overseas Scholars, the Shanxi Provincial Foundation for Natural Sciences, and the Shanxi Provincial Foundation for Key Subjects.

References

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