# Particle multiplicity distributions in silicon-emulsion collisions at 4.5*A* GeV/*c*

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The experimental results of particle multiplicity distributions in silicon-emulsion collisions at 4.5*A* GeV/*c* (the Dubna synchrophasotron momentum) are reported. The correlations between the multiplicities of target fragments are given. The saturation effect of target black fragment multiplicity in the collisions is observed.

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According to the "participant-spectator model" [1], the nuclear interacting system in high energy 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. There are relations between the participant and the spectator. It is expected that a quark-gluon plasma (quark matter) [2] will be formed in the participant at very high incident energies, and a liquid-gas phase transition [3] will occur in the spectator. Both the participant and the spectator are relevant for studying the nuclear reaction mechanism.

The Dubna energy (a few *A* GeV) is a special energy, at which the nuclear limiting fragmentation applies initially. For silicon, the limiting fragmentation may set in at or below the Dubna energy. To study nuclear reaction, e.g., silicon induced nuclear reaction at the Dubna energy, is of great importance.

The aim of the present work is to perform an investigation of particle multiplicities in silicon-emulsion collisions at 4.5*A* GeV/*c*. The multiplicity distributions of the target black and gray fragments and shower particles, as well as the correlations between the target fragment multiplicities are obtained. The saturation effect of the target black fragment multiplicity is observed in the collisions.

The nuclear emulsion stacks measured in the experiment were exposed by the silicon beams at the synchrophasotron of the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The beam momentum is 4.5*A* GeV/*c*. The emulsion type is Russian NIKFI-BR2 and the pellicle size is 20 cm×10 cm×600 $\mu$m. Each interaction was scanned using the "along-the-track" method with the help of a microscope. We have excluded the events occurring within a 20 $\mu$m thickness from the top or bottom surface of the pellicle. Great care has been taken in the identification of different tracks [4]. The data studied in the present work consist of 250 minimum bias nuclear reaction events.

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The number of final state target fragments in an event is called the multiplicity of target fragments and is denoted by $N_h$. The track grain density of target fragments in a nuclear emulsion is greater than $1.4I_0$ [4,5], where $I_0$ denotes the experimental minimum value of the track grain density of a relativistic singly charged particle. We can divide target fragments into two parts: target black fragments and target gray fragments. The multiplicities of black and gray fragments are denoted by $N_b$ and $N_g$, respectively. The residual range $R$ of black fragments is less than or equal to 3 mm, and that of gray fragments is greater than 3 mm. For a proton, the kinetic energy corresponding to a residual range of 3 mm is 26 MeV [5]. We can measure the track grain densities and residual ranges of all the target fragments. Then, the multiplicity distribution of each kind of target fragment can be obtained.

The number of final state relativistic singly charged particles in an event is called the multiplicity of shower particles and is denoted by $N_s$. The track grain density of shower particles in a nuclear emulsion is less than or equal to $1.4I_0$. We can measure the track grain densities and obtain the multiplicity distribution of shower particles.

According to the values of $N_h$ and $R$, we can select approximately the interactions with AgBr and CNO groups in a nuclear emulsion [6]. AgBr events have $N_h \geqslant 9$ or $N_h < 8$ and at least one track with $R \leqslant 10$ $\mu$m and no track with $10 < R \leqslant 50$ $\mu$m. CNO events with $2 \leqslant N_h < 8$ have no track with $R \leqslant 10$ $\mu$m and for $N_h = N_b = 1$ the secondary has not the range $R \leqslant 10$ $\mu$m and is going into the backward direction.

Figure 1 presents the multiplicity distributions of target black fragments (a), target gray fragments (b), and shower particles (c) produced in silicon-emulsion collisions at 4.5*A* GeV/*c* (solid histograms). The mean multiplicities $\langle N_b \rangle$, $\langle N_g \rangle$, and $\langle N_s \rangle$ are 5.69±0.35, 7.28±0.55, and 11.98 ±0.67, respectively. In order to give a comparison, the multiplicity distributions of target black and gray fragments produced in oxygen-emulsion collisions at 3.7*A* GeV (the Dubna energy) and 200*A* GeV (the maximum SPS energy) and the multiplicity distribution of shower particles produced in oxygen-emulsion collisions at 3.7*A* GeV [7] are given in the figure.

From Fig. 1 we see that the target fragment multiplicity distribution from the 200*A* GeV oxygen-emulsion collisions is clearly higher at $N_b, N_g = 0$, and the other multiplicity distributions of target fragments are approximately similar

 

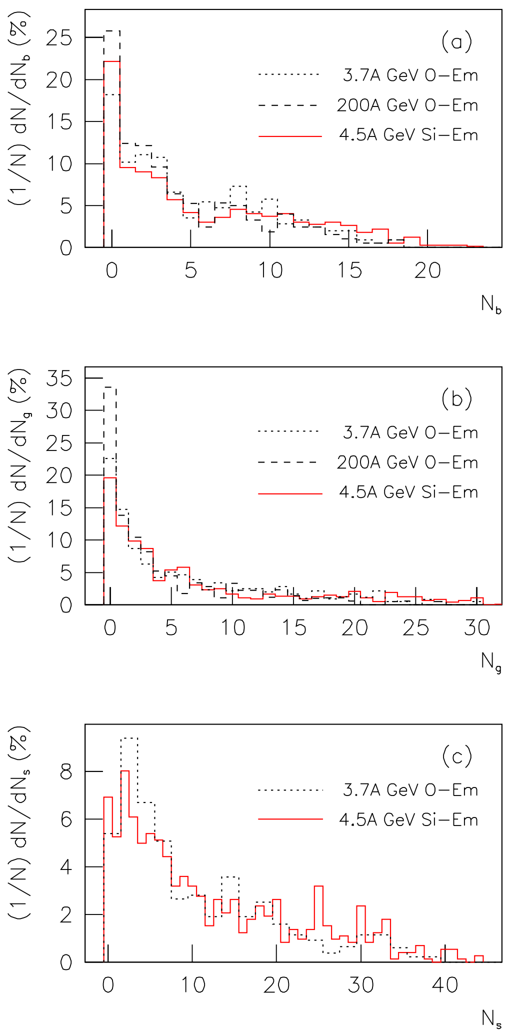


FIG. 1. Multiplicity distributions of target black fragments (a), target gray fragments (b), and shower particles (c) produced in heavy ion induced interactions in nuclear emulsion at high energies.

for the three kinds of interactions. The shower particle multiplicity distributions for the two kinds of interactions in the Dubna energy range are approximately similar, too. It is well known that the shower particle multiplicity at the maximum SPS energy is very large (a few hundreds [8]). The distributions of shower particles at the Dubna and SPS energies are different. We can explain qualitatively the similarities in the target fragment multiplicity distributions and the differences in the shower particle multiplicity distributions at the Dubna and SPS energies. At the two energies, the incident nuclei are similar and the target nuclei are the same. At the present accelerator energy region, the production of a target fragment is mainly determined by the nuclear geometry and the production of a shower particle is mainly determined by both the nuclear geometry and incident energy.

Figure 2 presents the multiplicity distributions of target black fragments (a), target gray fragments (b), and shower particles (c) produced in Si-CNO (dotted histograms) and Si-AgBr (solid histograms) collisions at 4.5$A$ GeV/$c$. The distributions for the CNO and AgBr events are normalized separately. The labels on the ordinate read $1/N$ in Fig. 2 for

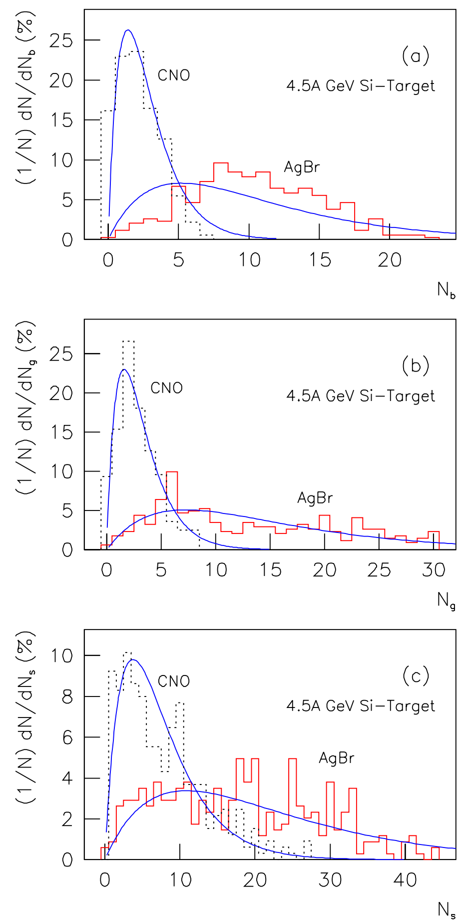


FIG. 2. Multiplicity distributions of target black fragments (a), target gray fragments (b), and shower particles (c) produced in Si-CNO and Si-AgBr interactions in nuclear emulsion at 4.5$A$ GeV/$c$.

the CNO and AgBr events, respectively, while those in Fig. 1 for the minimum bias emulsion events. The curves in Fig. 2 are the results calculated by [9,10]

$$f(N_i)=\frac{4N_i}{\langle N_i\rangle^2}\exp\left(-\frac{2N_i}{\langle N_i\rangle}\right), \tag{1}$$

where $i=b$, $g$, or $s$. $N_i$ and $\langle N_i\rangle$ are the multiplicity and the mean multiplicity, respectively.

From Fig. 2 we see that the target black fragment and shower particle multiplicity distribution shapes in Si-AgBr collisions at 4.5$A$ GeV/$c$ cannot be described by Eq. (1). The other four distribution shapes are approximately in agreement with the result calculated by Eq. (1). In the calculation, the mean multiplicities for Si-CNO collisions are $\langle N_b\rangle=2.8$, $\langle N_g\rangle=3.2$, and $\langle N_s\rangle=7.5$. The mean multiplicities for Si-AgBr collisions are $\langle N_b\rangle=10.4$, $\langle N_g\rangle=14.5$, and $\langle N_s\rangle=21.8$.

The correlations between $\langle N_b\rangle$ and $N_h$ (a), as well as $\langle N_g\rangle$ and $N_h$ (b), for silicon-emulsion collisions at 4.5$A$ GeV/$c$ (closed circles) are given in Fig. 3. In order to give a comparison, the corresponding results for oxygen-emulsion collisions at 3.7$A$ GeV (open circles) and 200$A$ GeV (open squares) are given in the figure, too. From

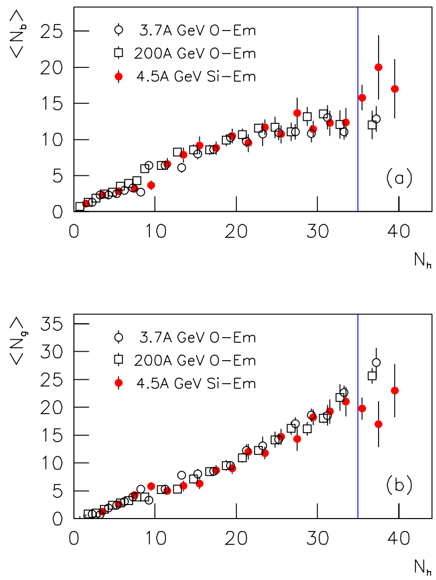


FIG. 3. Correlations between $\langle N_b \rangle$ and $N_h$ (a), as well as $\langle N_g \rangle$ and $N_h$ (b), in heavy ion induced interactions in nuclear emulsion at high energies.

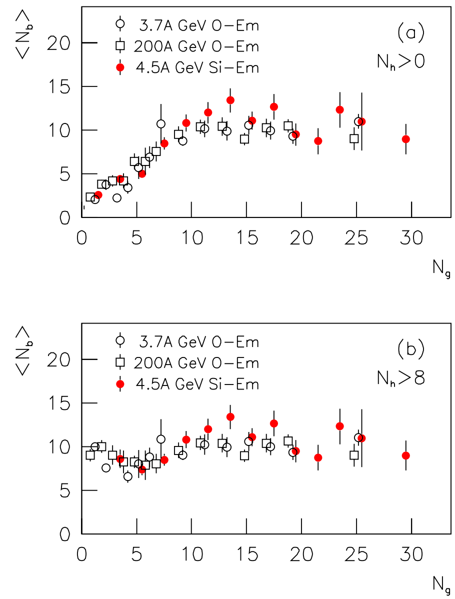


FIG. 4. Correlations between $\langle N_b \rangle$ and $N_g$ for events with $N_h > 0$ (a) and $N_h > 8$ (b) in heavy ion induced interactions in nuclear emulsion at high energies.

Fig. 3 we can see that the values of $\langle N_b \rangle$ and $\langle N_g \rangle$ increase with increasing $N_h$. In the region of $N_h < 35$, the correlations for the three interactions are almost the same. In the region of $N_h > 35$, we cannot draw a solid statement due to the rather large statistic errors in the silicon-emulsion data.

Figure 4(a) presents the dependence of $\langle N_b \rangle$ on $N_g$ for silicon-emulsion collisions at 4.5*A* GeV/*c* (closed circles). The corresponding results for oxygen-emulsion collisions at 3.7*A* GeV (open circles) and 200*A* GeV (open squares) are given in the figure, too. One can see that the value of $\langle N_b \rangle$ increases with increasing $N_g$ in the region of $N_g < 8$, and the saturation effect appears in the region of $N_g > 8$. The saturation effect was previously observed in proton-emulsion collisions at high energy [11]. Recently, in oxygen-emulsion collisions at the Dubna and SPS energies, the saturation effect was also observed [7]. The present work shows that the saturation effect is observed in silicon-emulsion collisions at the Dubna energy. In order to study the saturation effect in detail, Fig. 4(b) presents the correlations between $\langle N_b \rangle$ and $N_g$ for the events with $N_h > 8$. The meanings of the symbols in Fig. 4(b) are the same as those in Fig. 4(a). One can see that the experimental data are the same as those in Fig. 4(a) for the events with $N_g > 8$. This renders that the saturation effect is a characteristic of heavy target fragmentation in nonperipheral collisions.

The target black fragments have the saturation effect, and the gray fragments do not have. The reason is that the black fragments are the results of the target spectator's evaporation, and the gray fragments are the results of cascading collisions in the target spectator and participant.

To conclude, the target fragment multiplicity (except for the zero multiplicity) distribution in heavy ion induced interactions in nuclear emulsion approximately does not depend on the incident energy in the Dubna energy and the SPS energy regions. The similarities in the target fragment multiplicities at the above two energy regions can be explained by the nuclear geometry characteristic. There is a saturation effect in the target black fragment multiplicity. This saturation effect is a characteristic of heavy target fragmentation in nonperipheral collisions.

In our opinion, in the study of nuclear fragmentation, the Dubna energy region is more important than the SPS energy region because the nuclear limiting fragmentation may set in at the Dubna energy. Although the Dubna energy may be the initial energy of the nuclear limiting fragmentation, we do not assume the SPS energy to be the endmost energy of the nuclear limiting fragmentation. We hope to compare the present results with the experimental data of nuclear fragmentation at the Relativistic Heavy Ion Collider (RHIC) energies soon.

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