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Study of compound particle production in ^{84}Kr-emulsion interactions at 1.7 *A* GeV*

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Abstract: The characteristics of compound particle multiplicity distribution and multiplicity correlations between the compound particle and the grey particle, black particle, shower particle and heavily ionized track particle are investigated in this paper. It is found that the average multiplicities of the grey particle, black particle, shower particle and heavily ionized track particle increase with an increase in the number of compound particles, which can be explained by the impact geometrical model. The compound multiplicity distribution is observed to obey a Koba-Nielson-Olesen (KNO) type of scaling law.

Key words: relativistic heavy-ion collision, compound particle, nuclear emulsion

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1 Introduction

In the last few years, the characteristics of shower particle production in hadron-nucleus and nucleus-nucleus collisions at relativistic energy have been studied extensively [1–10]. Production of the grey particles in such collisions has also attracted more and more attention recently [8–15]. It is believed that grey particles are the medium energy (30–400 MeV) knocked-out target protons, and they are emitted during, or shortly after, the passage of a leading particle. Hence, they are supposed to carry some information about the interaction dynamics, because the time scale of emission of these particles is of the same order ($\approx 10^{-22}$ s) as that of the produced particles (shower particles). Furthermore, the grey particle may also be taken as a good measure of the number of encounters made by the impinging hadron inside the struck nucleons [16–20]. In order to refine the models for multiparticle production in hadron-nucleus and nucleus-nucleus collisions at high energy, a new variable termed compound multiplicity, $N_c(=N_g+N_s)$, was introduced by Jurak and Linscheid [21], and some interesting characteristics of grey and shower particles, taken together per interactions, have been investigated by several workers [22–34].

On the basis of the participant-and-spectator model, the characteristic features of relativistic nucleus-nucleus interactions depend, from the geometrical point of view, on the impact parameter. The type of interaction is determined by the value of impact parameter $b=R_p+R_t$ for peripheral interactions and $0\leqslant b<(R_p+R_t)$ for semi-central and central interactions, where R_p and R_t are the radium of projectile and target nucleus, respectively. In the overlapped region, called the "participant" region, violent nucleon-nucleon collisions would be expected, so that the local density will suddenly increase and energy will be distributed among them. This process is called the thermal equilibrization. Therefore, when the nuclear collision starts, both density and temperature would sharply increase. After the collision, the system would then expand and be cooled down, and the relativistic particles (shower particles) would be produced. The remaining parts are called spectators, which are left in an excited state and subsequently decay into fragments. A projectile spectator is fragmentized or multi-fragmentized into projectile fragments, which are emitted within a narrow cone around the beam direction, while the target spectator is evapora-

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ted into fragments that are nearly isotropically distributed in the laboratory frame.

In relativistic heavy ion induced nuclear emulsion target reactions, the produced particles are classified into four categories [35]. (a) Black particles. These are target fragments with ionization greater than or equal to $9I_0$, I_0 being the minimum ionization of a single charged particle. Their ranges are less than 3 mm, their velocities less than $0.3c$ and their energies less than 26 MeV. The multiplicity of black particles is denoted as N_{b}. (b) Grey particles. These are mostly recoil protons in the kinetic energy range $26 \leqslant E \leqslant 375$ MeV, a few kaons of kinetic energies $20 \leqslant E \leqslant 198$ MeV and pions with kinetic energies $12 \leqslant E \leqslant 56$ MeV. They have ionizations of $1.4I_0 \leqslant I \leqslant 9I_0$. Their ranges in emulsion are greater than 3 mm and they have velocities in the range of $0.3c \leqslant v \leqslant 0.7c$. The multiplicity of the grey particle is denoted as N_{g}. The grey and black particles together are called heavy ionizing particles. The multiplicity of the heavy ionizing particle is denoted as $N_{\mathrm{h}}(=N_{\mathrm{g}}+N_{\mathrm{b}})$. (c) Shower particles. These are produced as single-charged relativistic particles having a velocity greater than or equal to $0.7c$. Most of them belong to pions contaminated with small proportions of fast protons and K mesons. The multiplicity of the shower particle is denoted as N_{s}. The grey and shower particles together are called compound particles. The multiplicity of the compound particle is denoted as $N_{\mathrm{c}}(=N_{\mathrm{g}}+N_{\mathrm{s}})$. (d) The projectile fragments are a different class of tracks with constant ionization, long range, and a small emission angle (less than the projectile fragmentation angle, which is about 5° for the present study).

Multiplicity correlations of the type $\langle N_i(N_j)\rangle$, where N_i and N_j are the multiplicities of the black particle (N_{b}), grey particle (N_{g}), shower particle (N_{s}), and heavy ionizing particle (N_{h}), and $i \neq j$, have been studied in hadron-nucleus and nucleus-nucleus collisions over a wide range of energies using different projectiles. But no serious investigation has been made on the correlations between N_{b}, N_{g}, N_{s}, N_{h} and N_{c}. Therefore it is necessary to investigate the compound multiplicity correlations using different emulsion data. This can help us to understand the dynamics of hadronization of final-state secondaries produced in relativistic heavy ion collisions. Because of the different types of interactions, the participant region and the spectator regions are different, and the pionizaion and recoiled proton production from the participant region and target evaporated fragments from the target spectator region are different.

The present investigation is devoted mainly to a discussion of the compound multiplicity distribution and its dispersion in ^{84}Kr-emulsion collisions at 1.7 A GeV. Furthermore, the correlations of various final-state charged particles are also carried out in great detail.

2 Experimental details

Stacks of Ilford G-5 nuclear emulsion plates were horizontally exposed to a ^{84}Kr beam at 1.7 A GeV at Bevalac Berkeley. XSJ-1 and XSJ-2 microscopes with a 100× oil immersion objective and 16× ocular lenses were used to scan the plates. The tracks were picked up at a distance of 5 mm from the edge of the plates and were carefully followed until they either interacted with emulsion nuclei or escaped from the plates. Interactions that are within 30 μm from the top or bottom surface of the emulsion plates are not considered in the final analysis. All of the primary tracks are followed back to ensure that the events chosen do not include the interactions from the secondary tracks of other interactions. When they are observed to do so, the corresponding events are removed from the sample. In each interaction, all of the produced particles were identified, and their emission angles were measured.

3 Experimental results

There are 558 unbiased inelastic ^{84}Kr-emulsion events that were used in the present investigation. Based on the number of heavy ionizing particles N_{h}, the events are classified into three categories. Events with $N_{\mathrm{h}} \leqslant 1$ are mainly ^{84}Kr-H interactions (interactions with free and quasi-free nucleons) and peripheral interactions with other targets (interactions with only one bound nucleon in CNO or AgBr nuclei). Events with $1 < N_{\mathrm{h}} < 8$ are mostly interactions with CNO targets and with some admixture of peripheral ^{84}Kr-AgBr interactions. Events with $N_{\mathrm{h}} \geqslant 8$ are only ^{84}Kr-AgBr interactions. According to the above criteria, we obtained 93 events with $N_{\mathrm{h}} \leqslant 1$, 233 events with $1 < N_{\mathrm{h}} < 8$, and 232 events with $N_{\mathrm{h}} \geqslant 8$, respectively. Table 1 presents the percentage of events with $N_{\mathrm{h}} \leqslant 1$, $1 < N_{\mathrm{h}} < 8$, and $N_{\mathrm{h}} \geqslant 8$. Comparing the corresponding results from 2.1 A GeV ^{14}N [38], 2.0 A GeV ^{16}O [39, 40], 1.8 A GeV ^{40}Ar [37], 1.0 A GeV ^{56}Fe [36, 41], and 1.0 A GeV ^{84}Kr [42] induced different groups of emulsion target we find that the percentage of occurrence of events with $N_{\mathrm{h}} \leqslant 1$ increases with the increase in projectile mass, whereas the percentage of occurrence of events with $N_\mathrm{h} \geqslant 8$ decreases with increasing mass of the beam.

The average multiplicities of grey, black and shower particles in different ensembles of ^{84}Kr-emulsion interactions are presented in Table 1. For comparison, the corresponding results from ^{56}Fe-emulsion collisions at the same energy [43] are also listed in Table 1. It should be stressed that the emulsion plates in our experiment are not fully developed, so some shower particles are missed. In the data of ^{56}Fe-emulsion interactions [43], the authors stated that the grey particles contain not only single charged recoil protons from the target nucleus but also the low-energy pions ($10 < E_\mathrm{k} < 70$ MeV) and some participating protons from the projectile. From the results of the table we can see that the average multiplicity of grey, black and shower particles increases with the increase in the average target mass (because events with different ranges of N_h have different average target masses) for both ^{84}Kr-emulsion and ^{56}Fe-emulsion interactions. The average multiplicity of the black particle is almost the same for ^{84}Kr-emulsion and ^{56}Fe-emulsion interactions within experimental errors. In our data sets, the participating protons from the projectile are not included in the grey particles, and the spectating protons from the projectile are not included in the shower particles, so the average multiplicity of the grey and shower particle becomes lower.

Table 1. Percentage occurrence and average multiplicities of charged particles in different groups of ^{84}Kr- and ^{56}Fe-emulsion interactions at 1.7 A GeV.

beam	type of event	percentage	$\langle N_\mathrm{b}\rangle$	$\langle N_\mathrm{g}\rangle$	$\langle N_\mathrm{s}\rangle$	Ref.
^{56}Fe	$N_h \leqslant 1$	14.33 ± 1.24	0.15 ± 0.03	0.32 ± 0.05	2.77 ± 0.20	[43]
^{56}Fe	$1<N_h<8$	34.12 ± 1.91	1.84 ± 0.07	2.91 ± 0.13	8.03 ± 0.43	[43]
^{56}Fe	$N_h \geqslant 8$	51.55 ± 2.35	7.38 ± 0.18	14.90 ± 0.50	19.60 ± 0.60	[43]
^{56}Fe	$N_h \geqslant 0$	100	4.45 ± 0.14	8.71 ± 0.34	13.30 ± 0.40	[43]
^{84}Kr	$N_h \leqslant 1$	16.67 ± 1.73	0.075 ± 0.028	0.194 ± 0.041	4.677 ± 0.786	present work
^{84}Kr	$1<N_h<8$	41.76 ± 2.74	2.172 ± 0.105	1.970 ± 0.095	7.082 ± 0.479	present work
^{84}Kr	$N_h \geqslant 8$	41.58 ± 2.73	10.223 ± 0.288	9.909 ± 0.440	14.685 ± 0.773	present work
^{84}Kr	$N_h \geqslant 0$	100	5.174 ± 0.223	4.975 ± 0.258	9.842 ± 0.437	present work

The compound particle multiplicity distribution of ^{84}Kr induced different targets of emulsion interactions at 1.7 A GeV is shown in Fig. 1. It can be seen that the multiplicity distribution becomes broader, and the peak of the distribution shifts towards a higher value of N_c with increasing target size. The average value of the compound multiplicities $\langle N_\mathrm{c}\rangle$, its dispersions $D(N_\mathrm{c})$ $(=\sqrt{\langle N_\mathrm{c}^2\rangle-\langle N_\mathrm{c}\rangle^2})$, and the ratio $\langle N_\mathrm{c}\rangle/D(N_\mathrm{c})$ are presented in Table 2.

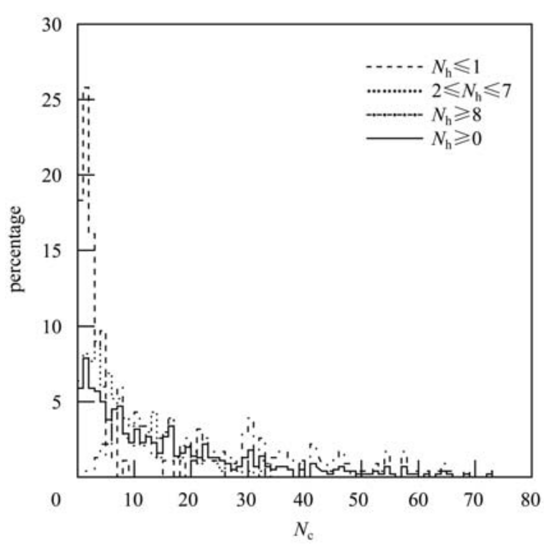

Fig. 1. Compound particle multiplicity distributions for different groups of N_h in ^{84}Kr-nucleus interactions at 1.7 A GeV.

Table 2. Values of $\langle N_\mathrm{c}\rangle$, $D(N_\mathrm{c})$ and $\langle N_\mathrm{c}\rangle/D(N_\mathrm{c})$ for different groups of ^{84}Kr-emulsion interactions at 1.7 A GeV.

type of event	$\langle N_\mathrm{c}\rangle$	$D(N_\mathrm{c})$	$\langle N_\mathrm{c}\rangle/D(N_\mathrm{c})$
$N_\mathrm{h} \leqslant 1$	4.871 ± 0.812	7.786 ± 1.031	0.626 ± 0.021
$1<N_\mathrm{h}<8$	9.052 ± 0.526	8.008 ± 0.417	1.130 ± 0.007
$N_\mathrm{h} \geqslant 8$	24.595 ± 1.081	16.428 ± 0.468	1.497 ± 0.023
$N_\mathrm{h} \geqslant 0$	14.817 ± 0.627	14.806 ± 0.500	1.001 ± 0.009

Figure 2 presents the dependence of $\langle N_\mathrm{c}\rangle$ on the target mass A_T in ^{84}Kr-emulsion collisions at 1.7 A GeV. It is found that the value of $\langle N_\mathrm{c}\rangle$ increases with the increase in target mass. The experimental data are fitted by a relation of the form

$$\langle N_\mathrm{c}\rangle = aA_\mathrm{T}^b, \qquad (1)$$

where A_T means the average target mass for different groups of N_h in ^{84}Kr-emulsion interactions. The best fitting parameters are $a=2.64\pm0.66$, $b=0.47\pm0.07$, and the minimum fitting χ^2/DOF=7.157, where DOF means the degree of freedom of simulation. Comparing the corresponding fitting parameters from ^{12}C ($a=3.25\pm0.12$, $b=0.40\pm0.36$) [29], ^{24}Mg ($a=2.61\pm0.14$, $b=0.49\pm0.01$) [31], and ^{28}Si ($a=2.77\pm0.18$, $b=0.48\pm0.01$), it is found that our result is consistent with the results from ^{12}C, ^{24}Mg, and ^{28}Si-emulsion interactions at 3.7 A GeV.

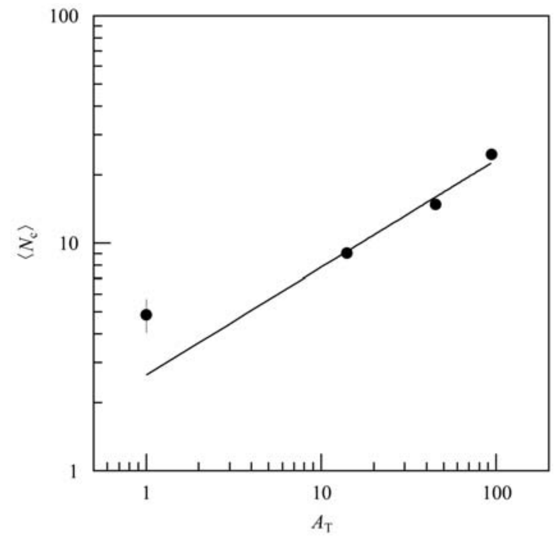

Fig. 2. Dependence of $\langle N_c \rangle$ on the target mass in ^{84}Kr-nucleus collisions at 1.7 A GeV.

According to the participant-and-spectator model, the shower particles come from the excited energy and grey particles come from the target nucleons of the participant volume, and the excited energy and the target nucleons in the participant volume increase as the value of the cylinder cut in the target by the projectile increases. This volume increases with the increase in the mass of the target and consequently the average number of compound particles increases.

Koba-Nielsen-Olesen (KNO) scaling is a well established empirical law for multiparticle production in pp collisions [44], and it can be compared with the experimental data on the multiplicity distribution of relativistic particles, to see whether it favors the universal scaling law. Ghosh et al. [45] studied the compound multiplicity distributions in hadron-nucleus collisions at different energies and found that they obey a KNO type scaling. Since then, the KNO type scaling of compound multiplicity distributions has been studied in nucleus-emulsion collisions at 3.7 A GeV by several groups [22, 23, 30, 31, 33, 34]. The KNO type of scaling behavior of compound multiplicity distributions is observed in the above emulsion data.

In Fig. 3, we plot $\langle N_c\rangle(\sigma_n/\sigma_{inel})$ versus $N_c/\langle N_c\rangle$ for ^{84}Kr-emulsion interactions at 1.7 A GeV, where σ_n denotes the partial cross section for producing n charged compound particles, σ_{inel} denotes the total inelastic cross section, and $z=N_c/\langle N_c\rangle$, respectively. It should be noted that data with $N_c/\langle N_c\rangle=0$ are not included in the figure, and the value of $\langle N_c\rangle$ in the figure does not include the contribution of events with $N_c=0$. From this figure, it can be seen that the experimental data lie on a universal curve, which can be fitted by a KNO scaling function with the form

$$\Psi(z)=(Az+Bz^3+Cz^5+Dz^7)e^{Ez}, \qquad (2)$$

which is the same as the formula used in nucleus-emulsion collisions at 3.7 A GeV [22, 23, 30, 31, 33, 34]. The best fitting parameters are $A=8.443\pm1.765$, $B=-(1.666\pm2.660)$, $C=4.118\pm3.323$, $D=1.236\pm0.701$, and $E=-(3.835\pm0.583)$. The minimum fitting χ^2/DOF is 0.931, which means that the experimental data can be well explained by the KNO scaling law.

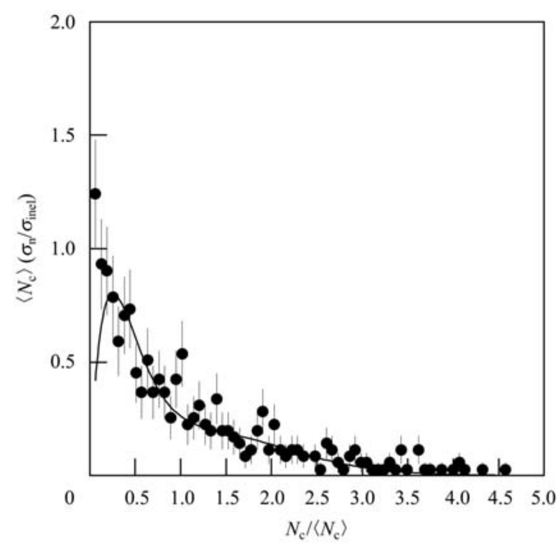

Fig. 3. Plot between $\langle N_c\rangle(\sigma_n/\sigma_{inel})$ and $N_c/\langle N_c\rangle$ for ^{84}Kr-emulsion interactions at 1.7 A GeV.

Figure 4 presents the correlations between $\langle N_b\rangle$, $\langle N_g\rangle$, $\langle N_s\rangle$, $\langle N_h\rangle$ and N_c. From the figure, it can be concluded that the values of $\langle N_g\rangle$, $\langle N_s\rangle$, $\langle N_h\rangle$ increase with increasing N_c, and $\langle N_b\rangle$ increases first and then becomes saturated with the increase in N_c. The experimental data can be nicely fitted by a linear relation of the form

$$\langle N_b\rangle=(0.255\pm0.026)N_c+(1.752\pm0.194), \qquad (3)$$

$$\langle N_g\rangle=(0.376\pm0.007)N_c-(0.050\pm0.060), \qquad (4)$$

$$\langle N_s\rangle=(0.620\pm0.007)N_c+(0.062\pm0.061), \qquad (5)$$

$$\langle N_h\rangle=(0.544\pm0.014)N_c+(2.027\pm0.195), \qquad (6)$$

and the minimum fitting χ^2/DOF of the above linear relations are 1.792, 4.508, 4.417, and 2.461, respectively. The fitting range of formula (3) is $N_c \leqslant 30$.

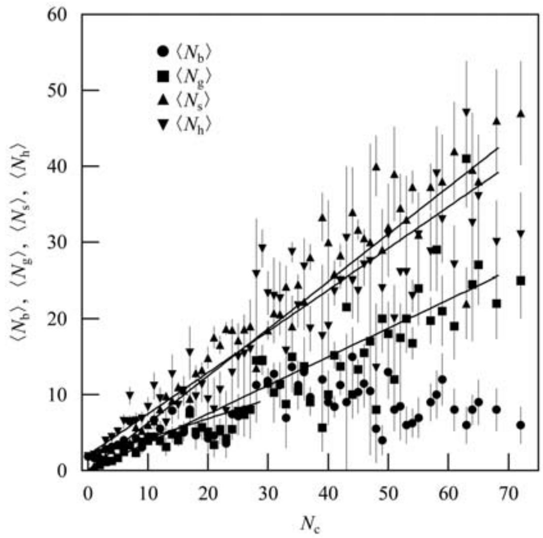

Fig. 4. Variation in $\langle N_b\rangle$, $\langle N_g\rangle$, $\langle N_s\rangle$ and $\langle N_h\rangle$ with N_c in ^{84}Kr-emulsion interactions at 1.7 A GeV.

Figure 5 shows the correlations between $\langle N_c\rangle$ and N_b, N_g, N_s, N_h for ^{84}Kr-emulsion collisions at 1.7 A GeV. These correlations are nicely fitted by a linear relation of the form

$$\langle N_c\rangle = (1.241\pm0.045)N_b + (8.032\pm0.578), \quad (7)$$

$$\langle N_c\rangle = (2.057\pm0.052)N_g + (3.905\pm0.318), \quad (8)$$

$$\langle N_c\rangle = (1.351\pm0.020)N_s + (1.223\pm0.169), \quad (9)$$

$$\langle N_c\rangle = (0.866\pm0.024)N_h + (3.087\pm0.371), \quad (10)$$

and the minimum fitting χ^2/DOF are 2.295, 3.469, 1.118, and 5.641, respectively.

These correlation properties can be explained by using a participant-and-spectator model based on impact geometry. According to the participant-and-spectator model, the shower particles come from the excited energy and grey particles come from the target nucleons of the participant volume. With the decrease in impact parameter, the participant volume or the number of compound particle increases, the exciting energy and target nucleon from the participant volume increase, so the average number of shower and grey particles increases. With the increase of the number of compound particles, the exciting energy of target spectator increases, the average number of black particles increases, but this increase is limited by the size of target spectator, so $\langle N_b\rangle$ increases firstly and then becomes saturated. Finally with the increase of the number of compound particles, the average number of the sum of grey and black particles increases.

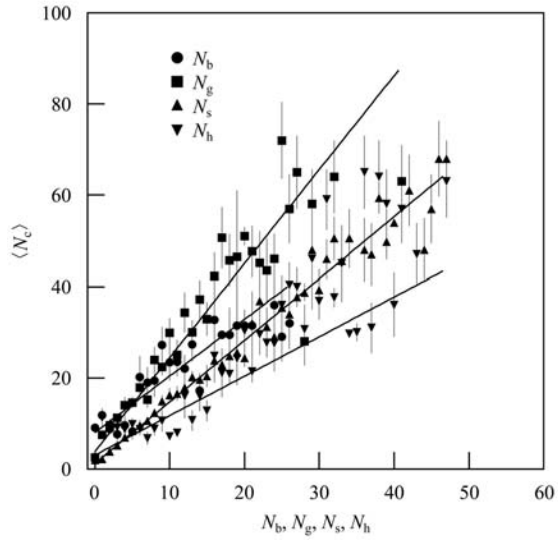

Fig. 5. Variation in $\langle N_c\rangle$ with N_b, N_g, N_s and N_h in 1.7 A GeV ^{84}Kr-emulsion collisions.

4 Conclusions

From the present study of the 1.7 A GeV ^{84}Kr-emulsion interactions, it may be concluded that (1) the compound particle multiplicity distribution becomes broader with the increase in target size; (2) the average compound particle multiplicity increases with the increase in target mass with the form of $\langle N_c\rangle = (2.64\pm0.66)A_T^{0.47\pm0.07}$; (3) multiplicity correlations between N_b, N_g, N_s, N_h and N_c can be nicely fitted by a linear function; and (4) the compound multiplicity distribution is observed to obey a KNO type of scaling law, which is independent of the mass and the energy of the projectile.

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