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Features of the total disintegration events of heavy emulsion targets caused by 4.5 A GeV/c ^{16}O*

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Total disintegration events produced by 4.5 A GeV/c ^{16}O–AgBr interactions are analysed to investigate the characteristics of secondary charged particles produced in such collisions. The multiplicity distributions of grey, black, and relativistic charged particles can be well represented by Gaussian distribution. The average multiplicity of grey particles is found to increase with the mass of projectile increasing, while that of black particles is found to decrease with the mass of projectile increasing. This result is in good agreement with the prediction of fireball model. Finally, the linear dependence between grey and black particles is observed, but there is no distinct dependence between the production of relativistic charged particles and the target excitation.

Keywords: relativistic heavy-ion collision, total disintegration, nuclear emulsion

PACC: 2570N, 2940R

1. Introduction

The study of heavy-ion interactions at high energies is an important up-to-date field of particle and nuclear physics. The study of such interactions is attracting a significant and steadily increasing interest in the search of quark–qluon plasma (quark matter) predicted by various theories originating from nuclear reactions at high energies. However, the intermediate goal is to study the characteristics of secondary charged particles produced in relativistic heavy-ion reactions.

Many current theoretical and experimental activities[1−9] are for analysing the data of high energy collisions in terms of selected central events. In the study of the inelastic interactions of relativistic heavy ions with AgBr nuclei using the nuclear emulsion as target and detector, the investigators are attracted by events with complete destructions (i.e. without an appreciable residual nucleus existing) because during such collisions, nuclear matter might be compressed several times in density and consequently several interesting phenomena are expected to occur. The study of central collisions of relativistic nuclei can throw light on the possibility of investigating the effects of multi-nucleon interactions, collective properties of nuclear matter, production of shock waves in nuclear matter and its possible transitions to the quark matter. Furthermore, some characteristics of central collisions are more critical to the choice of collision model. Thus, experimental data on central collisions may also be used to improve the existing models for explaining the dynamics of multiparticle production in heavy ion interactions at high energies.

Nowadays, there are a large number of data concerning the study of this phenomenon. Different beam nuclei at various energies have been used in the experiments. There are two main approaches to the interpretation of the experimental results of total disintegration. One is to consider such events as a tail in the multiplicity distribution, which can be accounted for by the cascade evaporation process inside the target nucleus, and the other is a one step-like process that occurs because of the collective effect of the target nucleons together.

In this work, the criterion $n_{\rm h} \geq 28$ is used to select events for the total disintegration (TD) of AgBr nuclei in nuclear emulsion. It is found that this condition corresponds to the destruction of target nucleus into nearly individual nucleons without a measurable

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residual nucleus existing. Since then, this criterion is used to select the TD events of AgBr.

In this paper, the TD events caused by 4.5 A GeV/c ^{16}O ions with heaviest nuclei, AgBr, presented in nuclear emulsion are systematically selected and analysed to study the general characteristics of secondary particles. We try to shed light on the preferred mechanism of the TD phenomenon by studying the probability of occurrence, the multiplicity distribution, and their correlations with the characteristics of interaction nuclei.

2. Experimental details

NIKFI BR-2 stacks of nuclear emulsions, 10 cm × 10 cm × 2 cm in volume, were exposed horizontally to the 4.5 A GeV/c ^{16}O beam at synchrophasotron of the JINR, Dubna. The flux intensity was 10^3 particles/cm^2. Emulsion plates, 600 μm in thickness, were scanned by the along-the-track method using XSJ-1 and XSJ-2 microscopes under 100 × oil objectives and 16 × eyepieces. A total of 2960 interactions of oxygen with the nuclei of the emulsion were observed by following a primary track length of 35768.9 cm, which led to a mean free path $\lambda = (12.08 \pm 0.22)$ cm. Among these interactions, 152 events were found to be produced by electromagnetic interactions and 149 events were due to elastic interactions. Out of these 2960 interactions, 2044 inelastic interactions were picked up, without any bias, for the final analysis. Interactions which were within 30 μm from the top or bottom surface of the emulsion were not taken into consideration for the final analysis. The general characteristics of these events have already been presented in our early publications.[10−14]

Secondary particles are generally divided into four categories, namely singly charged shower ($\beta > 0.7$), grey ($0.3 \leq \beta \leq 0.7$), black ($\beta < 0.3$), and projectile fragments particles, their numbers in an interaction are denoted by $n_{\rm s}$, $n_{\rm g}$, $b_{\rm b}$, and $n_{\rm F}$, respectively. The shower tracks correspond to relativistic charged particles, whereas grey and black tracks are produced by relatively slow particles emitted from the target nuclei. Grey tracks are mostly recoil protons with $40 < E < 400$ MeV, and range $R > 3$ mm in emulsion, with less than a few percent admixture of low energy pions. Black tracks are due to slow particles and evaporated target fragments with $E < 40$ A MeV, and range $R \leq 3$ mm. The sum of grey and black tracks in an interaction is represented by $n_{\rm h}$ $(= n_{\rm g} + n_{\rm b})$, and these tracks are thought to originate from heavily ionizing charged particles. Projectile fragments have momentum per nucleon almost equal to that of the parent nucleus, so they are essentially emitted inside a narrow forward angular cone centred around the direction of incident beam.

3. Experimental results

By using the criterion $n_{\rm h} \geq 28$ for selecting the TD of AgBr nuclei of emulsion, 216 events induced by 4.5 A GeV/c ^{16}O are selected for final analysis. The average multiplicities of different secondary particles emitted from the TD events are given in Table 1. For a comparison, the results from other TD events induced by relativistic heavy ions at the same energy are also presented in Table 1.

Table 1. Experimental values of the mean multiplicities for TD events in 4.5 A GeV/c nucleus–nucleus collisions.

Projectile	$< n_{\rm g} >$	$< n_{\rm b} >$	$< n_{\rm s} >$	Reference
^{2}H	16.4 ± 0.4	16.2 ± 0.2	2.9 ± 0.2	[15]
^{4}He	19.1 ± 0.4	14.4 ± 0.3	6.6 ± 0.2	[15]
^{12}C	26.1 ± 1.7	14.4 ± 0.9	15.3 ± 1.0	[16]
	19.7 ± 0.7	13.2 ± 0.5	13.8 ± 0.5	[7]
^{16}O	26.2 ± 1.1	11.0 ± 0.5	25.1 ± 1.1	[17]
	20.1 ± 0.5	15.2 ± 0.3	22.1 ± 0.6	This work
^{24}Mg	23.2 ± 0.7	14.8 ± 0.4	28.9 ± 0.9	[18]
	25.0 ± 0.5	12.9 ± 0.3	28.5 ± 0.6	[19]
^{28}Si	26.1 ± 0.5	14.4 ± 0.4	29.9 ± 0.9	[20]
	24.3 ± 0.5	12.4 ± 0.4	32.3 ± 0.9	[15]
^{32}S	27.5 ± 1.3	13.5 ± 0.6	30.0 ± 1.0	[19]

It can be seen that $< n_s >$ increases with the increase of projectile mass. This result is in agreement with that in Ref.[17] in which it has been found that the ratio between $< n_s >$ and the number of the projectile nucleons participating directly in the interaction is approximately equal to the average multiplicity of the hadron–nucleon interaction. Moreover, $< n_g >$, which is a measure of both the number of the interacting projectile nucleons and the corresponding number of intranuclear collisions, increases with the mass of the projectile increasing. It is also of interest to note that the average number of black particles, $< n_b >$, decreases with the mass of the projectile increasing. These observations may be explained based on the fireball model.[21] According to this model, the grey particles come from the participant volume and the number of participant nucleons increases with the increase of the volume of the cylinder cut in the target nucleus by the projectile. This cylinder volume increases with the increase of the projectile mass, and consequently the value of $< n_g >$ increases. Since the size of the target is limited, the average number of black particles, $< n_b >$, decreases as the number of grey particles increases.

An important characteristic of the TD of AgBr nuclei induced by very fast projectiles is the probability, W_{TD}, which is the ratio of number of events having $n_h \geq 28$ and total number of disintegrations involving AgBr nuclei, i.e. $W_{TD} = N_{TD}/N_{AgBr}$. The probabilities of the TD of AgBr nuclei in heavy ion interactions at 4.5 A GeV/c are listed in Table 2.

Table 2. Probabilities of TD of AgBr nuclei in 4.5 A GeV/c nucleus–nucleus collisions.

Projectile	Probability/%	Reference
^{1}H	0.5 ± 0.2	[22]
^{2}H	2.6 ± 0.5	[15,22]
^{4}He	6.8 ± 0.9	[15,22]
^{12}C	11.7 ± 0.9	[16]
	11.9 ± 1.3	[7]
	18.5 ± 2.3	[22]
^{16}O	21.5 ± 2.1	This work
^{22}Ne	20.0 ± 0.9	[22]
^{24}Mg	22.0 ± 1.3	[18]
	23.0 ± 1.5	[19]
^{28}Si	29.9 ± 1.6	[20]
	23.8 ± 1.9	[22]
^{32}S	36.8 ± 1.8	[19]

It can be seen from the Table 2 that the probability of the TD of heavy emulsion nuclei increases with the increase of the mass of the projectile. This fact is also reflected in Fig.1.

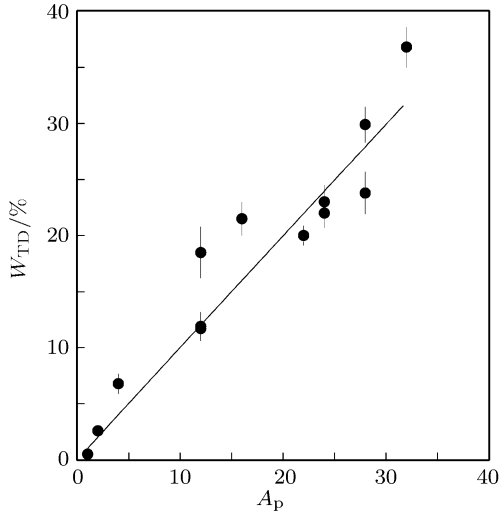


Fig.1. Variation in the probability of TD of AgBr nuclei with the mass of projectile.

It should be pointed out that the continuous line shown in Fig.1 can be represented by the following relation:

$$W_{TD} = \alpha A_p^{\beta}, \tag{1}$$

where A_p denotes the number of projectile mass. The best fitting values of parameters are found to be $\alpha = 1.01 \pm 0.32$ and $\beta = 0.99 \pm 0.10$, with $\chi^2 = 5.46$ and degree of freedom $N_{fit} = 13$.

The multiplicity distributions of shower, black, and grey particles produced in the totally disintegrated ^{16}O–AgBr interactions at 4.5 A GeV/c are shown in Figs.2–4.

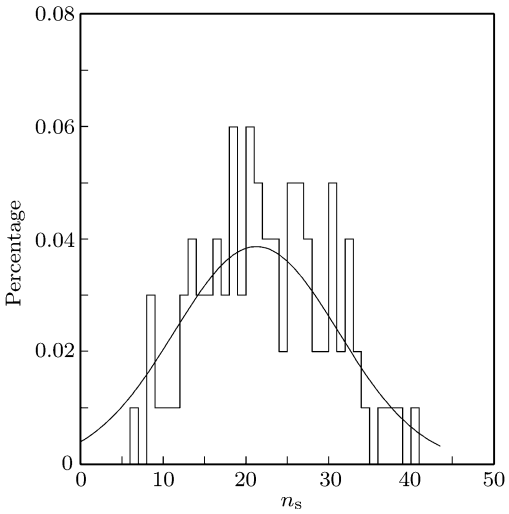


Fig.2. Multiplicity distribution of shower particles in TD events of ^{16}O–AgBr at 4.5 A GeV/c.

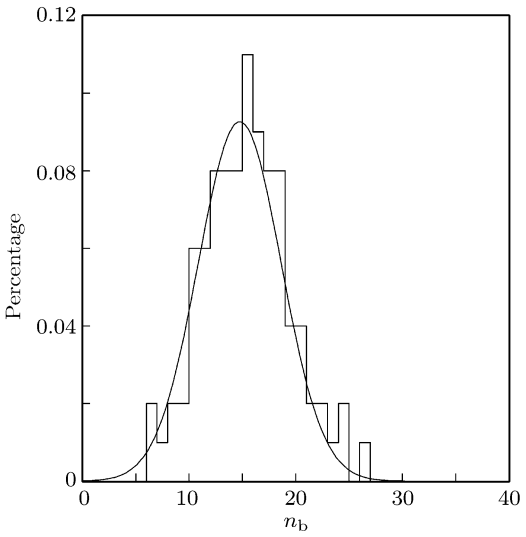


Fig.3. Multiplicity distribution of black particles produced in central ^{16}O–AgBr collisions at 4.5 A GeV/c.

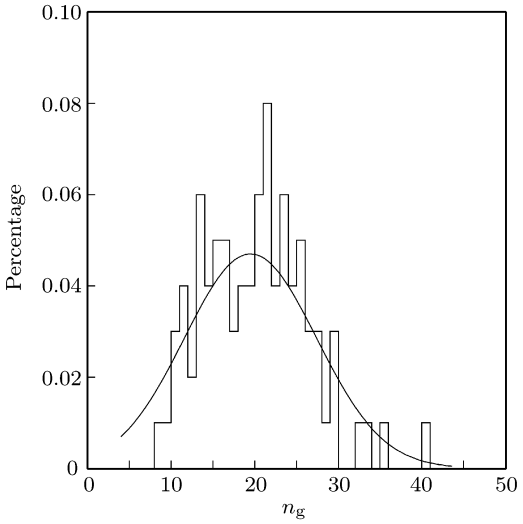


Fig.4. Multiplicity distribution of grey particles produced in central ^{16}O–AgBr collisions at 4.5 A GeV/c.

It is shown that all of the distributions can be described by a Gaussian curve in the form

$$p(n_i) = A\exp((n_i - < n_i >)^2/2\sigma^2). \qquad (2)$$

where i means the s, b, and g-particles, respectively. For shower particles, the distribution has a peak at multiplicity $n_s \approx 21$ with a rapid fall on both sides, which is the same as the results from Refs.[5,19,23] but the position of the peak shifts towards the right with the increase of projectile mass at the same incident energy.

Another important characteristic of nucleus–nucleus collisions is the quantity $Q = \Sigma n_i Z_i$ (n_i is the number of projectile fragments with charge Z_i), i.e. the total charge of the spectator of the projectile nucleus. The quantity Q is a convenient experimental parameter to classify nucleus–nucleus interactions and the degree of their peripherality: interactions with small Q are naturally considered to be central collisions having a low impact parameter, and events with large Q to be peripheral collisions having a large impact parameter. In Fig.5 we show the Q distributions for different values of impact parameter (i.e. different values of n_h).

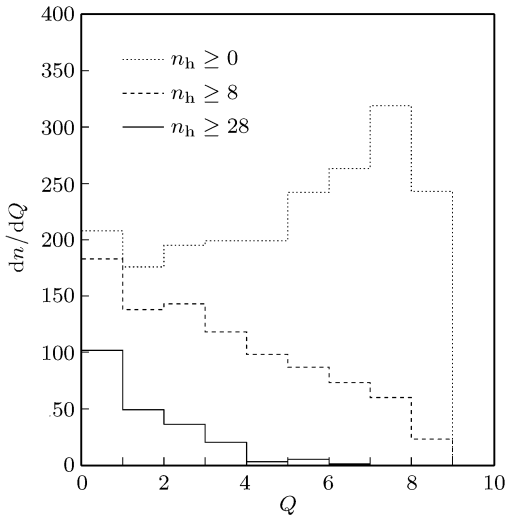


Fig.5. Q distributions for events with $n_h \geq 8$, $n_h \geq 28$ and total sample for ^{16}O–Em collisions at 4.5 A GeV/c

From Fig.5, we see that the large value of Q is typical of collisions with light emulsion nuclei (H, CNO) and peripheral interactions with AgBr nuclei ($n_h < 8$). We note that the TD of AgBr nuclei can be realized even in interactions that are quite peripheral (Q reaches 5). On the other hand, such disintegrations do not always occur even for practically complete overlap of the projectile nucleus ($Q = 0{,}1$) and target nucleus. Figure 5 also indicates that for $n_h \geq 8$ events, the major contribution is toward the small values of Q characterizing the violent processes in these central and near central events. On the other hand, for quasinucleon events ($n_h = 0, 1$), the major contribution is toward the large values of Q characterizing the gentle processes.[24]

We now consider the specific multiplicities of those particles $< n_i > /\nu$ (i = s, b, g), i.e. the average number of particles per nucleon that has interacted, where $\nu = A_p - (A_p/n_p)Q$, and n_p is the number of protons of the incident nucleus. Specific multiplicity of the produced particles is an important parameter of nucleus–nucleus collisions and indicates how effective an incoming nucleon is in producing particles in subsequent collisions.[19]

In Figs.6–8, we show the dependences of the specific multiplicities of shower, grey, and black particles on ν.

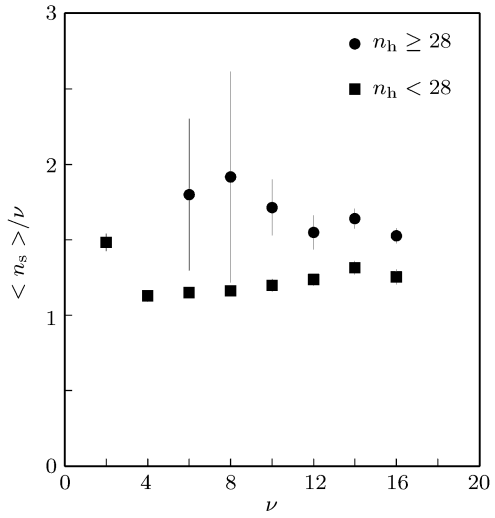


Fig.6. Dependences of the specific multiplicity of shower particles $< n_s > /\nu$ on ν.

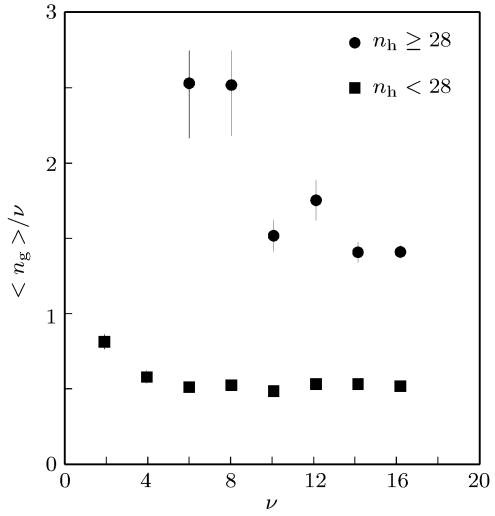


Fig.7. Dependences of the specific multiplicity of grey particles on ν.

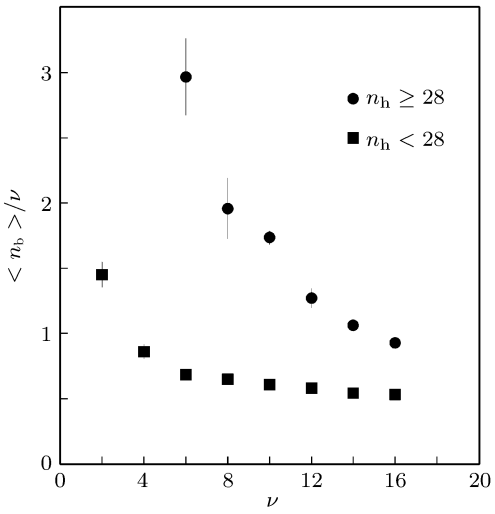


Fig.8. Dependences of $< n_b > /\nu$ on ν.

From these figures we see that the values of $< n_s > /\nu$ are independent of ν for TD events and for events with $n_h < 28$ generated by ^{16}O nuclei. The value of this quantity is systematically higher for TD events than for events with $n_h < 28$, and it coincides with the mean value of shower particles in p–Em interactions. The differences in dependence of $< n_g > /\nu$ and $< n_b > /\nu$ on ν between the two groups of events (the curve lies considerably higher for TD events) are noticeable. We recall that for p–Em interactions, ($< n_g >= 2.8 \pm 0.1$ and $< n_b >= 3.8 \pm 0.1$), i.e. the two values are considerably larger than those for nucleus–nucleus interactions studied.

From Figs.6–8, one can see that $< n_i > /\nu$ (i = g, b), in the case of TD events, increases with the decrease of the value of ν. The ratio $< n_s > /\nu \approx$ constant, which shows the evidence for the validity of the approximation in assuming that nucleus–nucleus collisions at an energy equal to a few GeV per nucleon can be considered as an incoherent superposition of nucleon–nucleon collisions. It is evident that the specific multiplicities of all types of charged particles depend substantially on the impact parameter of the nucleus–nucleus collisions.

The multiplicity correlations among various charged secondaries produced in nucleus–nucleus collisions have been studied exclusively. However, little attention has been paid to studying the multiplicity correlations of these secondary charged particles in the TD of AgBr nuclei caused by the projectile. Thus, in the present work, we have studied some multiplicity correlations of the type $< n_i(n_j) >$, where i and j mean s, g, and b-particle, and $i \neq j$ for the TD events produced in ^{16}O–AgBr interactions at 4.5 A GeV/c. These results are presented in Figs.9 – 11.

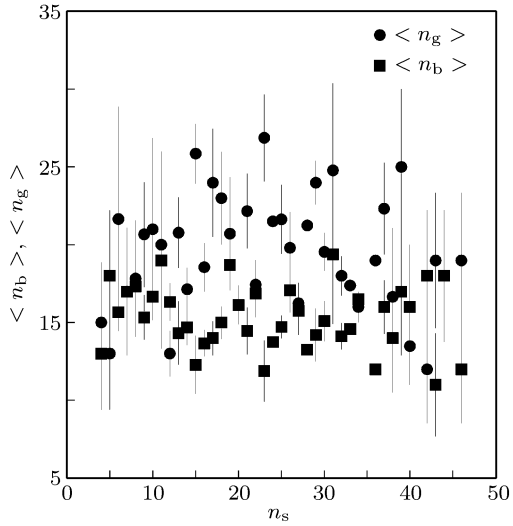


Fig.9. Variations of $< n_g >$ and $< n_b >$ as a function of n_s.

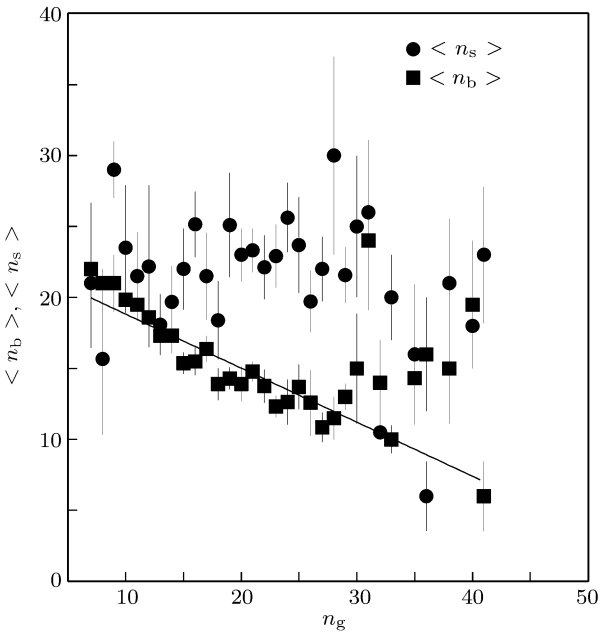


Fig.10. Dependences of $< n_s >$ and $< n_b >$ on n_g.

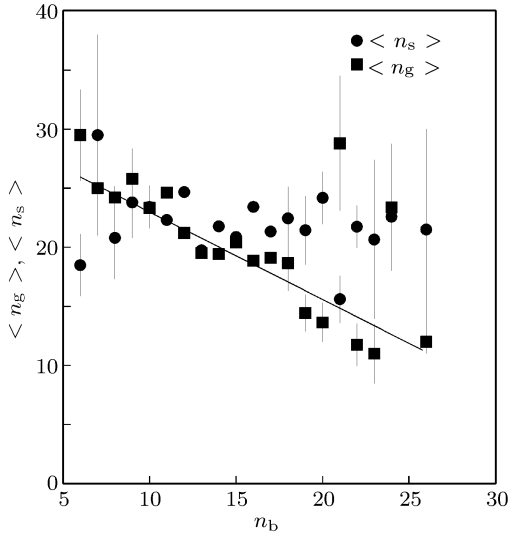


Fig.11. Dependences of $< n_s >$ and $< n_g >$ on n_b.

From Fig.9 we can see that there are practically no dependences of $< n_g >$ and $< n_b >$ on n_s for the TD events of ^{16}O–AgBr collisions, signifying that the target excitation is independent of the production of relativistic particles in the TD events, which means that the target excitation reaches its maximum in the TD events. From Figs.10 and 11 we can also see that there are no dependences of $< n_s >$ on n_g and n_b, signifying that the number of relativistic particles produced in TD events is independent of the target excitation. The dependence of $< n_b >$ on n_g is plotted in Fig.10. It is clear from this figure that the value of $< n_b >$ decreases with the value of n_g increasing, and vice versa, the value of $< n_g >$ decreases with the increase of n_b (see Fig.11). These observations further support our conclusion above and can be explained by the fireball model.[22] The correlation of $< n_b >$ with n_g can be fitted by a linear relation in the form $< n_b >= a + bn_g$ with best fitting parameters being $a = 22.64 \pm 0.52$, and $b = -0.38 \pm 0.03$. For the linear relation of $< n_g >$ to n_b, the best fitting parameters are $a = 30.40 \pm 0.96$, and $b = -0.74 \pm 0.06$. It is interesting to note that all correlation coefficients of inclination in the TD events of ^{16}O–AgBr collisions are negative, which are the same as the results from p–emulsion and central ^{12} C–AgBr reactions at the same energy.[7]

4. Conclusions

On the basis of the present investigation the following conclusions can be drawn.

(i) The probability of the TD of AgBr nuclei increases with the mass of the projectile. This result may be explained by the fact that at high energies the inelastic cross section increases with the projectile mass.

(ii) The multiplicity distributions of grey, black, and relativistic charged particles agree with the Gaussian distribution.

(iii) The average multiplicities $< n_s >$ and $< n_g >$ increase rapidly, while $< n_b >$ decreases with the mass of projectile increasing. This result is in good agreement with the prediction of the fireball model.

(iv) The specific multiplicities of all charged particles depend substantially on the impact parameter of nucleus–nucleus collisions, a qualitative measure of which is Q or ν.

(v) The ratio $< n_s > /\nu \approx$ constant, which indicates that the production of shower particles in nucleus–nucleus collisions can be considered as an incoherent superposition of nucleon–nucleon collisions.

(vi) There is no distinct correlation between the shower particle production and the target excitation, but the average value of grey particles decreases with the increase of the number of black particles, and vice versa. This correlation can also be explained by the fireball model.

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