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GREY PARTICLE DISTRIBUTIONS IN HIGH ENERGY NUCLEUS-NUCLEUS COLLISIONS

M.K.Hegab*, M.M.Sherif*, S.A.Krasnov, S.Vokál

We propose a simple analytic model for the description of grey particle production (mostly recoil target protons in the energy range of 26<E<<400 MeV) in high energy nucleus-nucleus collisions. The model is parameter-free and its input information is the distribution of grey particles produced in proton-induced reactions. We obtained good agreement with experimental multiplicity distributions and mean values of grey particles produced in heavy ion Dubna emulsion experiments.

The investigation has been performed at the Laboratory of High Energies, JINR.

Распределения серых частиц в высокоэнергетических ядро-ядерных столкновениях

М.К.Хегаб и др.

Предложена простая аналитическая модель для описания испускания g-частиц (в основном протонов, выбитых из мишени с энергиями 26<E<400 МэВ) в высокоэнергетических ядро-ядерных соударениях. Это беспараметрическая модель, а в качестве исходной информации используется распределение g-частиц, возникающих в реакциях, вызванных протонами. Мы получили хорошее согласие с экспериментальными распределениями по множественности и средними множественностями g-частиц, возникающих в эмульсионных экспериментах с тяжелыми ионами, проведенных в Дубне.

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1. Introduction

A lot of experimental results on high-energy heavy-ion (AA) reactions have been recently accumulated. The main emphasis has been put on multiparticle production mechanisms, i.e. only the multiplicities n_s and rapidities of shower particles are considered. To achieve complete

*Physical Department, Faculty of Science, Cairo Univ., Giza, Egypt.

understanding of reaction mechanisms in AA collisions, the target fragmentation region should also be investigated. Target associated particles are usually classified, in emulsion experiments, into two categories:

i) Grey or g-particles (N_g), which are singly charged particles with velocity in the range $0.23 \le \beta = V/c < 0.71$. They are mostly recoil target protons with energy in the range of $26 < E < 400$ MeV.

ii) Black or b-particles (N_b). These are charged particles with $\beta < 0.23$. They are mainly evaporation products from the target remnant.

Both g- and b-particles are called heavily ionizing particles and their combined multiplicity is denoted by $N_h = N_g + N_b$.

The study of g-particle production in hadron-induced (hA) reactions proved to be of utmost importance [1]. The importance lies in that the number of g-particles N_g on a given event is strongly correlated to the number of unobserved collisions ν that occurred in the event. This number of collisions ν is a crucial parameter in all theoretical models on multiparticle production in hA interactions [2,3]. These studies on g-particles have revealed that N_g is a more precise measure on ν than the over-all average number

$$\langle\nu\rangle = A\sigma_{hN}/\sigma_{hA},$$

where A is the target mass number and σ_{hA} or σ_{hN} are the inelastic hadron-nucleus and hadron-nucleon cross sections, respectively. In addition, g-particles have extended the range of measurement of ν up to $\sim 2\langle\nu\rangle$ instead of the maximum value $\langle\nu\rangle \sim 4$ which is only achieved in p-Pb interactions.

Proceeding to a higher level of complication, we consider high-energy AA collisions. Experimental results in these interactions have shown that nuclear geometry is the dominant ingredient in the production mechanism [4]. In other words, the number of participants is the decisive parameter in the shower particle production. But the number of these participants fluctuates in a wide range. Guided by the successful achievements in hA interactions, it is worth knowing whether g-particles measurement in AA collisions could narrow these fluctuations or not, i.e. is the number N_g, in a given event, a precise measure of the number of participants in that event?

Very recently, the EMU01 collaboration has studied the target associated particles in the framework of two Monte Carlo simulation codes, namely, the multichain model by Ranft and the Lund model FRITIOF [5-7]. The two models were essentially constructed for, and are indeed successful, describing the general trends of multiparticle production in both high-energy hA and AA interactions. In the FRITIOF-code the target cascade is totally neglected and the only contribution to the target particles comes from the low-energetic particles emerging from the fragmenting strings. In the Ranft-code the cascade is partly accounted for via a free parameter which is related to the formation time. The FRITIOF-code fails to reproduce both the N_g- and N_b-distributions whereas Ranft-code, with a suitable choice of its free parameter, could reproduce only the N_g-distribution. Even for this choice of parameter the N_g-distribution in pA interactions is not reproduced. They concluded that, although the cascade plays an important role in the target break-up, it is less developed in nuclear collisions as compared to pA collisions.

In the present work we propose a simple analytic model for the description of the g-particle production in high-energy AA collisions. The cascade is accounted for in the model via its input information which is the g-particle distribution from pA interactions. The latter is either calculated from any one the well-known models on g-particles [8], or directly taken from pA experiments. In the following section the model is described. Results of calculations are presented in section 3. Concluding remarks are given in section 4.

2. Model Description and Formulation

It has recently been shown that, at least for inclusive nuclear collisions, the distributions for shower particles can be well reproduced when AA collisions are viewed as a superposition of independent NA collisions. On the average

$$\langle n_s \rangle_{AA} \sim \langle N_p \rangle \langle n_s \rangle_{NA} , \qquad (1)$$

where $\langle n_s \rangle_{AA}$ ($\langle n_s \rangle_{NA}$) is the mean shower particles multiplicities in AA(NA) interactions at a given incident energy per nucleon and $\langle N_p \rangle$ is the mean number of participating projectile nucleons. If that is the case in g-particle production, then one should obtain

$$\langle N_g \rangle_{AA} \sim \langle N_p \rangle \langle N_g \rangle_{NA} . \qquad (2)$$

Considering for example the case of ^{12}C-CNO interactions in emulsion, we have $\langle N_g \rangle_{pCNO} \sim 1.37$ [9] and $\langle N_p \rangle_{C,CNO} \sim 4.2$ [10], so that (2) gives $\langle N_g \rangle_{C,CNO} \sim 6$. This is equal to the maximum number of target fragments ($N_h = 6$) that is expected from the interaction with the light component (CNO) of the emulsion. Thus (2) overestimates, to a large extent, the number of g-particles produced in AA collisions so that no other target particles will be left to account for other phenomenon, e.g. evaporated particles N_b. The reason for this overestimation comes from the fact that the dominant contribution to g-particle production in pA interaction results from the intranuclear cascade and not only from the participants (i.e. ν) as in the case of shower particle production.

Hence, if we want to preserve the picture of independent NA collisions, then we should expect that not every participating projectile nucleon will produce, independently, the same g-particle distribution as in pA collisions. In other words, $\langle N_p \rangle$ in (2) should be modified to account correctly for $\langle N_g \rangle_{AA}$.

In the present model we assume that the projectile participants incident with the same impact parameter, i.e., those lying in one row, will produce only one g-particle distribution as in pA interactions (Fig.1a). This assumption, though plausible, can only be tested by comparison with experiment. Denoting the number of rows by M, then the mean number of interacting projectile rows, at a given impact parameter $\vec{b}$, will be given by

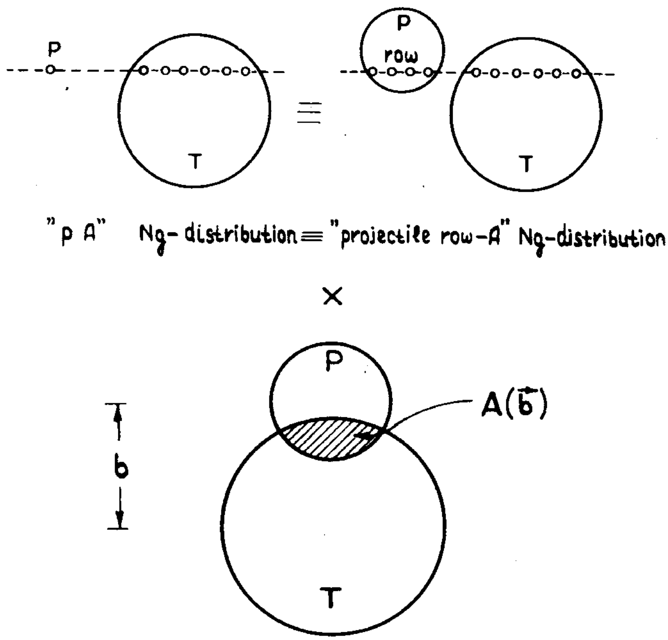

Fig.1. a) Main assumption of model; b) Intersection area in impact parameter plane.

$$\bar{M}(\vec{b}) = \frac{A(\vec{b})}{\sigma_{NN}}, \tag{3}$$

where $A(\vec{b})$ is the overlap (interaction) area, in the impact parameter plane, between the interacting nuclei (Fig.1b) and σ_{NN} is the total NN cross section. The maximum number of interacting projectile rows, which is achieved in central collisions, is thus

$$M_0 = \frac{\pi R^2_{min}}{\sigma_{NN}}, \tag{4}$$

where R_{min} is the smaller of the target (R_T) and projectile (R_P) nuclear radii. Of course, M_0 is approximated to the nearest integer.

The distribution of the number of interacting projectile rows, at a given impact parameter $\vec{b}$, is simply given by the binomial distribution

$$W(M, \vec{b}) = \binom{M_0}{M} [p(\vec{b})]^M [1 - p(\vec{b})]^{M_0 - M}, \tag{5}$$

where

$$p(\vec{b}) = \frac{\bar{M}(\vec{b})}{M_0} = \frac{A(\vec{b})}{\pi R^2_{min}} \tag{6}$$

is the probability for the interaction of one row at this value of $\vec{b}$. The distribution (5) is then averaged over all impact parameter to give

$$W(M) = \frac{1}{\sigma_{AA}} \int d^2\vec{b}\, W(M, \vec{b}), \tag{7}$$

where σ_{AA} is the total inelastic AA cross section.

Assuming the projectile rows to interact independently with the target, the g-particle multiplicity distribution in AA collisions will be folded according to

$$P_{AA}(N_g) = \sum_M W(M)\, P(M, N_g), \tag{8}$$

where $P(M,N_g)$ is the multiplicity distribution of g-particles resulting from the interaction of exactly M projectile rows. According to our assumption, each interacting projectile row will produce an N_g-distribution equivalent to that obtained in pA interactions. Thus, $P(M,N_g)$ can, in turn, be calculated by folding M of the pA N_g-distributions

$$P(M, N_g) = \sum_{\{N_i\}}^{M} \prod_{i=1}^{M} P_{pA}(N_i)\, \delta(N_g - \sum_{i=1}^{M} N_i)\,. \qquad (9)$$

The N_g-distribution in pA collisions, $P_{pA}(N_i)$, can be either calculated from one of the pA models for g-particles or directly taken from pA experiments.

The mean g-particle multiplicity in AA collisions is readily calculated from (8) to give

$$\langle N_g \rangle_{AA} = \langle M \rangle \langle N_g \rangle_{pA}\,. \qquad (10)$$

This differs considerably from (2) in that it contains the factor $\langle M \rangle$, which is the mean number of interacting projectile rows, in place of the mean number $\langle N_p \rangle$ of interacting projectile nucleons.

3. Results and Discussion

We now proceed to test the model by experiment. The experimental data used here for comparison are taken from Dubna emulsion experiments with α, C, Ne and Si nuclei as projectiles incident at an energy of 3.7 A GeV. The emulsion, which is a heterogeneous target, is considered to be mainly composed of these components: hydrogen H, the light (CNO) component and the heavy (AgBr) component. The reaction percentage of each component depends on its abundance in emulsion as well as its reaction cross section with the respective projectile. These percentages (cf. Table 1) can be easily calculated or directly taken from Ref. /11/.

Two parameters enter in the calculation of the distribution W(M), namely

1) The nuclear radii, which are simply taken to be $R = 1.2\, A^{1/3}$ fm,

Table 1. The reaction percentages α_{AA_1} [%]

Projectile / Target	p	α	C	Ne	Si
H	3	6	10	13	14
CNO	25	29	32	33	33
AgBr	72	65	58	54	53

2) The total NN cross section which is $\sigma_{NN} = 42.7$ mb at this incident energy.

It is left to calculate the distributions $P(M,N_g)$. The required input information for these distributions is the N_g-distribution $P_{pA}(N_g)$ in pA interactions. For the latter distribution we applied each one of the following choices:

i) $P_{pA}(N_g)$ calculated from the Lund model [1].

ii) $P_{pA}(N_g)$ calculated from the intranuclear cascade model by Hegab and Hüfner [2].

iii) Experimental N_g-distribution from pEm interactions [9].

The final N_g-distribution for A-Em interactions is added up in the following way

$$P_{AEm}(N_g) = \sum_i \alpha_{AA_i} P_{AA_i}(N_g), \tag{11}$$

where A stands for the projectile nucleus, $A_1 \equiv H$, $A_2 \equiv CNO$, $A_3 \equiv AgBr$ and α_{AA_i} are the respective reaction pecentages listed in Table 1.

Figures (2a-d) show a comparison between experimental and calculated N_g-distributions. The above-mentioned three choices for $P_{pA}(N_g)$ give nearly coinciding distributions and therefore we present them only in Figure (1b). The third choice, (iii), differs only at $N_g = 0$. This is attributed to the experimental difficulty in disintangling the N_g-distributions for the three emulsion components in p-Em interactions and to the experimental difficulty in observing these events. It is noticed also from the figures that the experimental values at high N_g values posses large error bars due to the low statistics at these high multiplicities. This can, in general, be remedied by combining these events into larger intervals of N_g. Nevertheless we wanted to make the comparison with the rest form of the data.

Table 2 summarizes all the results of the present work. The values for the hydrogen component are not included in the table since they are obviously known to be $\langle M \rangle = 1$ and $\langle N_g \rangle \simeq 0.5$. From the table we see that the calculated $\langle N_g \rangle_{AA}$ values are in good agreement with the experimental values. There are still, however, some differences, e.g., in the case of Si interactions. The sources of these differences may be one of the following:

1) The assumption of clean-cut geometry which is used in the calculation of W(M), i.e., the interacting nuclei are considered uniform and not diffused spheres.

2) The division of the emulsion into only three main groups of nuclei and not taking the interactions with each of the exact constituents of the emulsion.

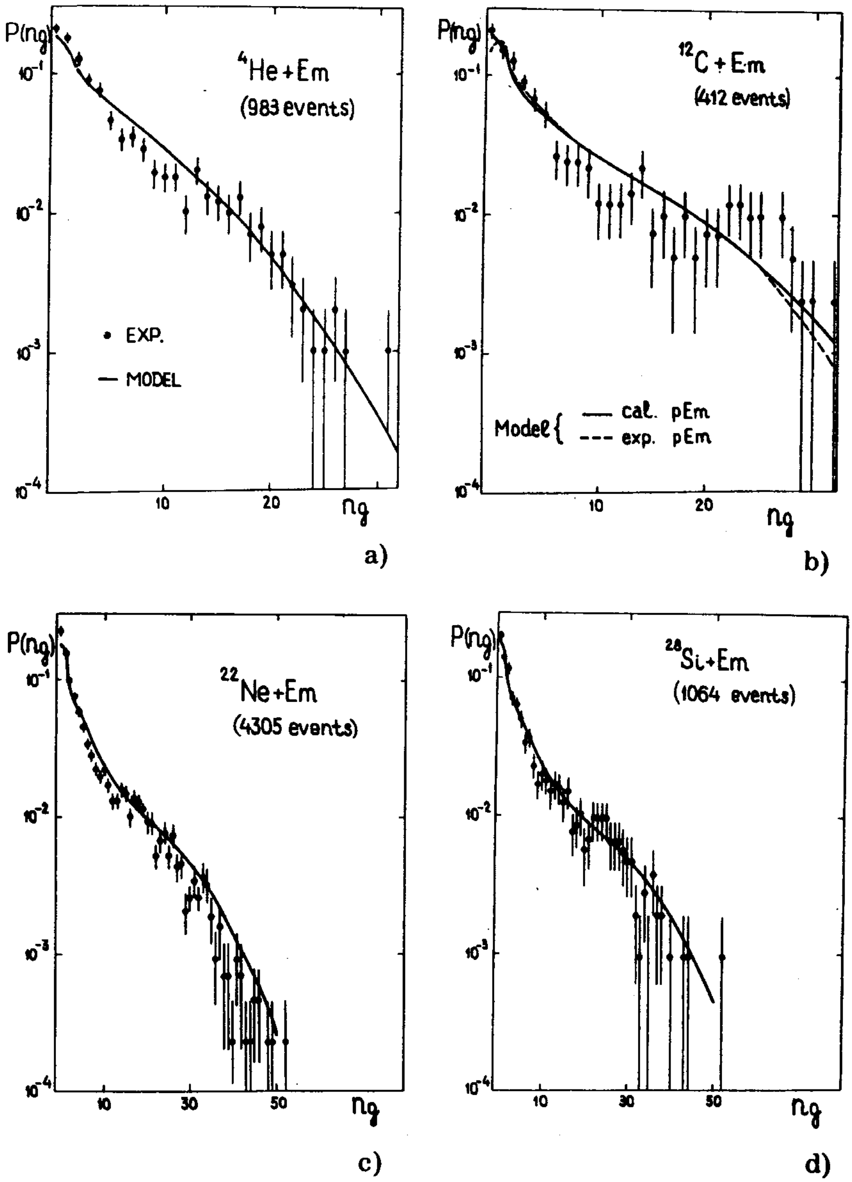

Fig.2(a — d). The experimental (full circles) and calculated (solid line) N_g-distributions.

Nevertheless, we see that the model, in this simple form, reproduced fairly well both the experimental distributions and mean values of g-particles.

Table 2. The mean number of interacting projectile rows $\langle M \rangle$ and the mean number of g-particles $\langle N_g \rangle$

		CNO	AgBr	Em	Exp.
p	$\langle M \rangle$	1	1	1	
	$\langle N_g \rangle$	1.37	3.40	2.81	2.81±0.06
α	$\langle M \rangle$	1.09	1.65	1.45	
	$\langle N_g \rangle$	1.50	5.63	4.13	4.38± 0.20
C	$\langle M \rangle$	1.58	2.65	2.14	
	$\langle N_g \rangle$	2.16	9.01	5.96	5.90± 0.30
Ne	$\langle M \rangle$	2.09	3.06	2.47	
	$\langle N_g \rangle$	2.86	10.40	6.62	6.32±0.04
Si	$\langle M \rangle$	2.35	3.59	2.82	
	$\langle N_g \rangle$	3.22	12.21	7.60	6.60± 0.30

4. Conclusions

From the above discussion of the results of the proposed model, we arrive to the following conclusions:

1) The nuclear geometry is still the dominant ingredient in high energy nuclear collisions.

2) The interacting projectile rows, and not the interacting projectile nucleons, are responsible for g-particle production in AA collisions.

3) Exclusive or semi-inclusive events could be selected according to certain values of N_g. For instance, in central collisions, where we have total overlap of the two nuclei, i.e., $0 \leq b \leq |R_T - R_B|$, the N_g values produced will be only those decided by the distribution $P(M_0, N_g)$ and its dispersion. This is an investigation to be done in the near future.

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