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Features of the Compound Multiplicity of the Interactions of ^{24}Mg and ^{28}Si Ions with Emulsion Nuclei at 4.5A GeV/c

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Abstract

The present paper deals with the interactions of ^{24}Mg and ^{28}Si nuclei at 4.5A GeV/c with emulsion. Some characteristics of the compound multiplicity given by the numerical sum of grey and shower particles have been investigated. The obtained results indicate that the compound multiplicity distribution is consistent with KNO-Scaling and its width increases with the size of the projectile nucleus. The dependence of the average compound multiplicity on the numbers of black and the grey particles and the sum of them is obvious and the values of the slope has been found to be independent of the projectile nucleus.

1. Introduction

The study of the relativistic nucleus-nucleus interactions in nuclear physics has become a subject of interest among the physicists [1]. In the last few years, most of the experiments on high energy hadron-nucleus and nucleus-nucleus collisions were performed in order to study the characteristics of the shower particles and of the grey particles produced in such collisions [2-9]. The importance of investigating the grey particles is due to the fact that they are emitted during, or shortly after, the passage of a leading particle. Hence, they are expected to keep some memory of the reaction history. Furthermore, the grey particles may also be taken as a good measure for the number of encounters made by the impining hadron inside the struck nucleus [3,10 -13]. The grey particles are generally produced by the mean knocked out protons in the energy range 30 - 400 MeV, slow pions having energy ≈(30 - 60) MeV, and an admixture of the deuterons and tritons. Although the process responsible for the production of these particles is not yet clearly known, it is generally believed that these are the low-energy part of the internuclear cascade which leave the target nucleus on the same time scale as the secondaries of the interaction. Moreover, the properties of the relativistic shower and grey particles summed together per interaction have been studied [14]. Also, some interesting characteristics of the compound multiplicity have been investigated by several authors [15-22]. The main motivation for studying the compound multiplicity in heavy-ion reactions is that the data on the nucleus-nucleus collisions may help in refining the models for the multiparticle production. The present work is devoted mainly to the discussion of the experimental data on the compound multiplicity distributions and their dispersions in the inelastic collisions of ^{24}Mg and ^{28}Si nuclei with the nuclei of the nuclear emulsion at 4.5A GeV/c.

2. Experimental Technique

Nuclear emulsions of the type Br-2 were exposed to 4.5A GeV/c ^{24}Mg and ^{28}Si beams at the Dubna Synchrophasotron. The pellicles of emulsion have the dimensions 20 cm $\times$ 10 cm $\times 600\ \mu$m (undeveloped). The intensity of the beam was $\approx 10^4$ particles/cm^2 and the beam diameter was approximately 1 cm. Along the track, a double scanning has been carried out fast in the forward direction and slow in the backward one.

The scanned beam tracks have been further examined by measuring the delta-electron density [23] on each of them to exclude any track having a charge less than the beam particle charge Z_b. The scanning has been performed giving 1000 and 1300 events for ^{24}Mg and ^{28}Si, respectively.

In the measured interactions, all the charged secondary particles have been classified into the following groups[24]:

(1) Shower tracks producing particles called "s-particles". Tracks having emission angle $\theta \leq 3^o$ have been further subjected to multiple scattering measurements for momentum determination [25] in order to separate the produced pions from the singly charged projectile fragments.

(2) Grey tracks producing "g-particles".

(3) Black tracks producing "b-particles".

(4) The "b" and "g" tracks are both called heavily ionizing tracks producing "h-particles".

(5) The "s" and "g" tracks are both called compound tracks producing called "c-particles".

Determination of the momentum of the s-particles emitted within $\theta \leq 3^o$ enables the separation of the produced pions from the non-interacting singly-charged projectile fragments (protons, deuterons and tritons) [26]. The g-particles emitted within $\theta \leq 3^o$ and having $L > 2$ cm are considered as projectile fragments having $Z = 2$. The b-particles having $\theta \leq 3^o$ and $L > 1$ cm are due to heavy projectile fragments $Z \geq 3$. The number of delta-electrons has been measured for each of these particles in order to determine the corresponding charge $Z = 3, ...Z_b$.

3. Compound Multiplicity

As already stated, the grey particles are emitted shortly after the passage of the leading hadron. Therefore, one may expect that it is worthy to use the compound multiplicity for the grey and shower particles. Let us define the variable n_c which equals the sum n_s plus n_g. This variable is used to study the particle production mechanism.

Figure 1 presents the compound multiplicity distributions for 4.5A GeV/c ^{28}Si and ^{24}Mg interactions with emulsion and shows that the n_c-distributions for these two reactions are consistent with each other and it can be seen that the peak of the distribution shifts towards a higher value of n_c with increasing projectile mass. Also, it may further be seen that the compound multiplicity distribution becomes broader with increasing projectile mass. A similar result has been observed in refs. [27,28]. Table 1 presents the values of the average compound multiplicity $< n_c >$, the dispersion $D = [(< {n_c}^2 > - < n_c >^2)^{1/2}]$ and the ratio $< n_c > /D(n_c)$. From Table 1, one can see that the average value of the compound multiplicity increases with the increase of the projectile mass and that the ratio $< n_c > /D(n_c)$ does not depend on the projectile mass.

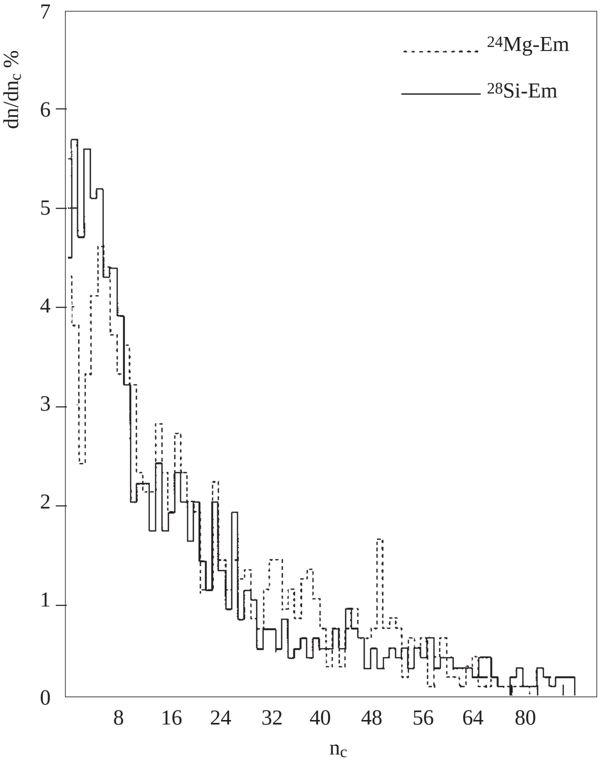

Figure 1. Compound multiplicity distribution for 4.5A GeV/c, ^{24}Mg and ^{28}Si interactions with emulsion.

Table 1. Values of different parameters in nucleus-nucleus collisions at 4.5A GeV/c.

Projectile	$< n_c >$	$D(n_c)$	$< n_c > /D(n_c)$	Ref.
^{1}H	4.44 ±0.66			18
^{2}H	5.42 ±0.09			19
^{4}He	8.60 ±0.22			20
^{12}C	12.08 ±0.24	7.50 ±0.24	1.61 ±0.24	16
^{12}C	13.60 ±0.42			6
^{12}C	16.17 ±0.18	10.51 ±0.34	1.54 ±0.05	28
^{16}O	18.10 ±0.85			21
^{24}Mg	23.63 ±0.48	15.34 ±0.48	1.61 ±0.22	16
^{24}Mg	19.50 ±0.50	16.80 ±1.50	1.21 ±0.05	32
^{24}Mg	19.50 ±0.50	19.23 ±0.22	1.01 ±0.05	Present work
^{28}Si	19.85 ±0.45			6
^{28}Si	18.20 ±0.40	18.80 ±0.80	1.00 ±0.10	32
^{28}Si	21.85 ±0.70	14.09 ±0.70	1.55 ±0.09	17
^{28}Si	20.60 ±0.63			22
^{28}Si	19.04 ±0.50	18.80 ±0.80	0.97 ±0.03	Present work

4. Variation of the dispersion with the average compound multiplicity

To investigate the dependence of the dispersion $D(n_c)$ in the nucleus-nucleus collisions at a given projectile energy, the experimental data given in Table 1 were used. A plot of $D(n_c)$ as a function of average compound multiplicity $< n_c >$, is shown in Figure 2. From this figure one can see that the $D(n_c)$ increases linearly with $< n_c >$. By the least squares method, the following relation has been obtained and is found to fit the experimental data points quite satisfactorily:

$$D(n_c) = (0.67 \pm 0.02) < n_c > +(-0.41 \pm 0.20).$$

In the high energy nucleus-nucleus collisions, the relation between the dispersion and the average value of the shower particles has been studied. Morever, the relation between the dispersion and the average multiplicity of the sum of the grey and shower particles, taken together per interaction have been investigated by several physicists [14-21].

Figure 3 is a plot of D as a function of the average number of the shower multiplicities and the compound multiplicities for the cases of ^{24}Mg and ^{28}Si interactions with emulsion. A linear dependence of D upon the average number is obtained irrespective of any specific form of the distribution of multiplicity. From the figure, one can see that D is linearly related to $< n_s >$ and $< n_c >$ and this means that the grey particles are of special interest due to the fact that they are emitted during, or shortly after, the passage of the leading particle.

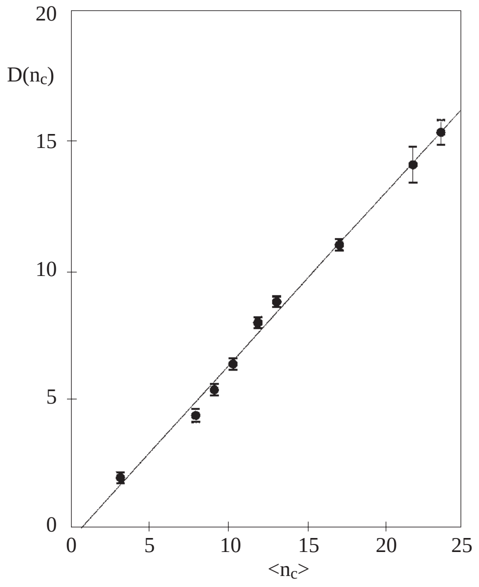

Figure 2. Dependence of the dispersion $D(n_c)$ on the average of the compound multiplicity.

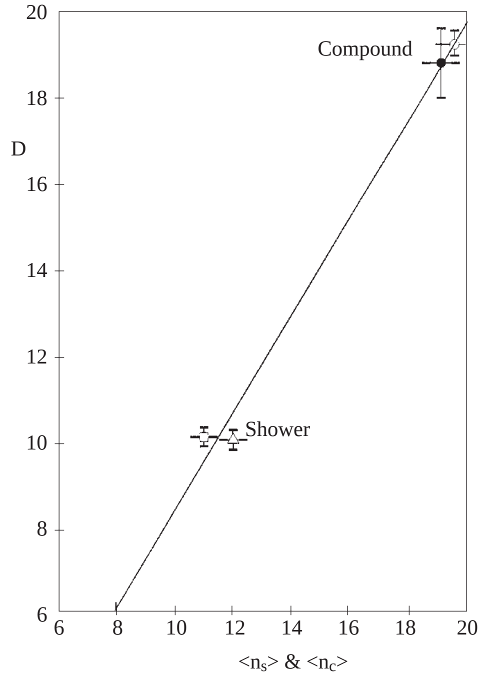

Figure 3. Variation of the dispersion D with the average shower and compound multiplicity for ^{24}Mg and ^{28}Si with emulsion at 4.5A GeV/c [□ ^{24}Mg, △ ^{28}Si] for shower multiplicity, [○ ^{24}Mg, ● ^{28}Si] for compound multiplicity.

In Figure 4, we have plotted $< n_c > (\sigma_{\rm n}/\sigma_{\rm in})$ versus $n_c/ < n_c >$ where $< n_c >$ is the average compound multiplicity, σ_n is the particle cross-section for producing n_c compound multiplicity and σ_{in} is the total inelastic cross-section. The histograms were obtained from the experimental data for ^{24}Mg and ^{28}Si interactions with emulsion at 4.5A GeV/c. It can be seen that the experimental data obtained from these two different types of nucleus-nucleus interactions at the same incident momentum per nucleon can be fitted to a single universal Koba-Nelson-Olesen [29] scaling function (KNO) using the following equation:

$$\psi(z) =< n_c > (\sigma_n/\sigma_{in}) = (2.52Z + 3.09Z^3 - 3.29Z^5 + 1.04Z^7)e^{-4.08Z}, \qquad (1)$$

where $Z = n_c/ < n_c >$. From this figure one may see that the experimental data agree fairly well with the universal curve which may be fitted by KNO scaling given in eq. (1).

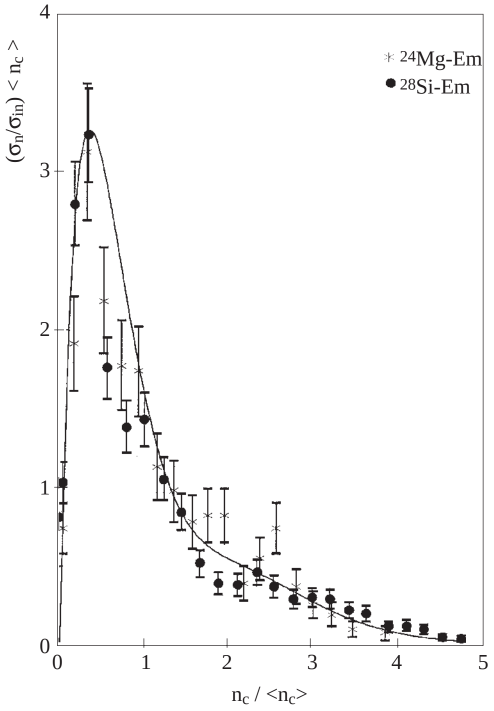

Figure 4. Dependence of $(\sigma_n/\sigma_{in}) < n_c >$ on $n_c/ < n_c >$ for 4.5A GeV/c ^{24}Mg and ^{28}Si interactions with emulsion. The curve is the result of the fitting of experimental data by KNO scaling formula.

5. Dependence of the average compound multiplicity $< n_c >$ on the Target and Projectile Masses

The identification of the target nuclei in the nuclear emulsion is not easy since the medium has a complex composition and a variety of nuclei like H, CNO and AgBr are present. Generally, one classifies the events with light targets as H- events, those with medium targets as CNO- events and those with heavy targets as AgBr- events. The same procedure as that discribed in ref. [30] has been used to separate the ^{24}Mg and ^{28}Si interactions into collisions with H, CNO and AgBr, emulsion nuclei. The average compound multiplicity for the charged secondary particles emitted in the spallation of nuclei with different masses by ^{24}Mg and ^{28}Si nuclei are listed in Table 2. From this table, one can see that the average value of the compound multiplicity increases rapidly with increasing target nucleus mass. However, the ratio $< n_c > /D(n_c)$, within statistical errors, increases slowly with increasing the target mass. This observation agrees with the results obtained by Khan et al. [28]. The dependence of $< n_c >$ on the target mass A_t is displayed in Figure (5.a); the value of $< n_c >$ is also found to increase with the increase of the target mass. The experimental data, shown in Figure (5.a), may be fitted quite satisfactorily with a relation of the form :

$$< n_c >= 2.61 \pm 0.14 {A_t}^{0.49\pm0.01}$$

$$< n_c >= 2.77 \pm 0.18 {A_t}^{0.48\pm0.01}$$

for ^{24}Mg and ^{28}Si, respectively.

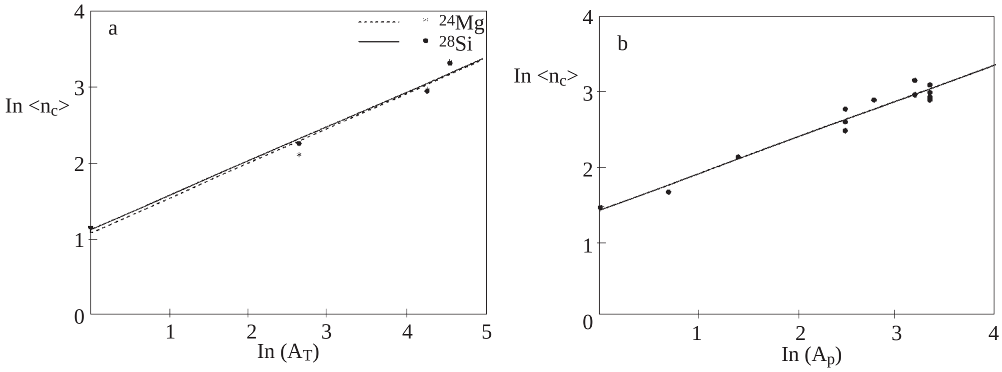

Figure 5. Dependence of $< n_c >$ in nucleus-emulsion collisions at 4.5A GeV/c on *a*) the mass of the target *b*) the mass of the projectile

Table 2. The mean value of $< n_c >$, $D(n_c)$ and $< n_c > /D(n_c)$ for the interactions of ^{12}C[28], ^{24}Mg and ^{28}Si nuclei with emulsion, also with the separate emulsion groups of nuclei (H, CNO, AgBr).

Group	$< n_c >$	$D(n_c)$	$< n_c > /D(n_c)$
^{12}C + H	3.29 ±0.26	2.01 ±0.21	1.64 ±0.21
^{12}C + CNO	9.27 ±0.23	3.88 ±0.21	2.39 ±0.14
^{12}C + Em	16.17 ±0.18	10.51 ±0.34	1.54 ±0.05
^{12}C + AgBr	23.19 ±0.29	9.09 ±0.40	2.55 ±0.14
^{24}Mg + H	3.22 ±0.22	2.99 ±0.13	1.07 ±0.18
^{24}Mg + CNO	8.28 ±0.35	7.21 ±0.24	1.14 ±0.16
^{24}Mg + Em	19.50 ±0.50	19.23 ±0.22	1.01 ±0.05
^{24}Mg + AgBr	28.06 ±0.60	11.29 ±0.42	2.48 ±0.14
^{28}Si + H	3.21 ±0.25	3.20 ±0.17	1.00 ±0.03
^{28}Si + CNO	9.60 ±0.39	6.66 ±0.28	1.44 ±0.05
^{28}Si + Em	19.04 ±0.50	18.80 ±0.80	0.97 ±0.03
^{28}Si + AgBr	27.43 ±0.67	11.99 ±0.47	2.28 ±0.15

Using the data of Table 1, the dependence of the compound multiplicity on the projectile mass A_P has been investigated. In Figure (5.b), the dependence of $< n_c >$ on the projectile mass A_P is shown. It may be observed from the figure that $< n_c >$ increases rapidly with increasing projectile mass. It has been observed that the empirical relation:

$$< n_c >= \alpha A_P^{\beta} \tag{2}$$

represents the experimental data points satisfactorily. The values of the two parameters α and β are found to be (4.26 ± 0.67) and (0.48 ± 0.02), respectively. The value of the parameter β as reported by Singh et al. [17] is (0.47 ± 0.02) in agreement with the value obtained in the present work.

6. Compound Multiplicity Correlations

The study of the compound multiplicity correlations in the heavy-ion interactions has been carried out by several authors [15-17] but not all the possible multiplicity correlations have been studied. Therefore, an attempt was made to investigate the compound multiplicity correlations in the 4.5A GeV/c for ^{24}Mg and ^{28}Si with emulsion nuclei. The variations of $< n_c >$ with n_g, n_b and n_h are exhibited in Figure 6. It can be observed that $< n_c >$ increases linearly with n_g, n_b and n_h. Furthermore, from the study of $< n_c >$ as a function of n_b, n_g and n_h, the following relations have been obtained using the least-square fits for the ^{24}Mg nuclei with emulsion:

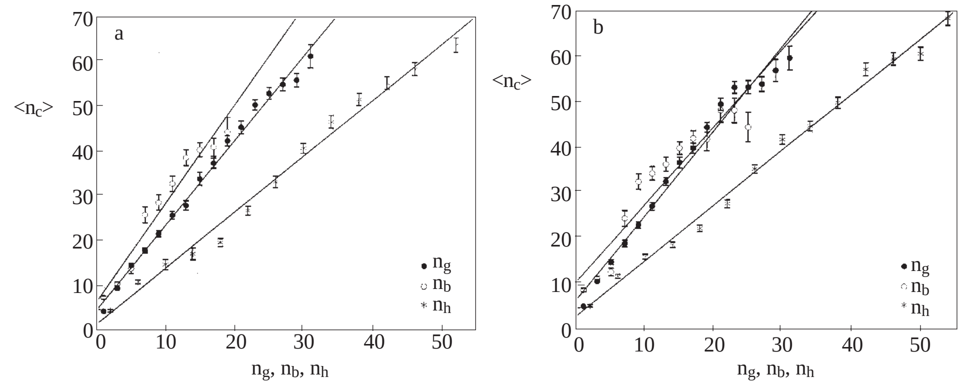

Figure 6. Variations of the average compound multiplicity $< n_c >$ with the grey tracks multiplicities (• n_g) , the black tracks multiplicities (○ n_b) and the heavily ionizing track multiplicities ($*$ n_h) for *a*) ^{24}Mg and *b*) ^{28}Si with emulsion at 4.5A GeV/c.

$$< n_c >= (1.89 \pm 0.10) n_g + (4.89 \pm 0.40) \tag{3}$$

$$< n_c >= (2.19 \pm 0.12) n_b + (6.74 \pm 0.41) \tag{4}$$

$$< n_c >= (1.25 \pm 0.04) n_h + (1.69 \pm 0.60) \tag{5}$$

and for the ^{28}Si nuclei with emulsion, the equations representing these fits are as follows:

$$< n_c >= (1.84 \pm 0.08) n_g + (6.77 \pm 0.12) \tag{6}$$

$$< n_c >= (1.68 \pm 0.10)n_b + (10.74 \pm 0.22) \tag{7}$$

$$< n_c >= (1.21 \pm 0.05)n_h + (3.22 \pm 0.59). \tag{8}$$

Also, from Figure 6, it can be seen that the dependence of $< n_c >$ on n_g, n_b and n_h is strong in the cases of heavy-ion interactions, however, this dependence becomes weak in the case of proton-nucleus collisions [16,31]. The results of the linear fits of the data are given in Table 3. It can be observed that the values of the slope in the case of $< n_c > - n_b$ correlation are almost of the same order.

Table 3. Values of the slope for the average compound multiplicity using $< n_c >= a + kn_i$.

Projectile	n_i	k	Ref.
^{12}C	n_g	1.51 ±0.07	28
^{24}Mg	–	1.89 ±0.10	Present work
^{28}Si	–	2.77 ±0.10	18
^{28}Si	–	1.84 ±0.08	Present work
p	n_b	0.32 ±0.04	16
^{12}C	–	2.00 ±0.16	16
^{12}C	–	2.49 ±0.10	28
^{24}Mg	–	2.10 ±0.12	16
^{24}Mg	–	2.19 ±0.12	Present work
^{28}Si	–	1.68 ±0.10	Present work
p	n_h	0.32 ±0.23	16
^{12}C	–	0.93 ±0.12	16
^{12}C	–	0.94 ±0.04	28
^{24}Mg	–	1.21 ±0.04	Present work
^{28}Si	–	1.22 ±0.06	Present work

Conclusion

The main conclusions which can be drawn from the present study of the nucleus-nucleus interactions at 4.5A GeV/c for ^{24}Mg and ^{28}Si are as follows:

1. The compound multiplicity distribution and the average compound multiplicity $< n_c >$ depend on the target and projectile mass.
2. The value of the ratio $< n_c > /D(n_c)$ is independent of the mass of the projectile.
3. The parameter $D(n_c)$ is found to increase linearly with $< n_c >$ in the same way as that observed in the case of the dependence of $D(n_s)$ on $< n_s >$. This is in accordance with the predictions of KNO scaling.
4. The compound multiplicity distributions for the ^{24}Mg and ^{28}Si interactions obey KNO scaling.
5. The value of the inclination coefficient, in the case of compound multiplicity, is independent of the mass of the projectile.

6. It has been observed that the value of $< n_c >$ depends strongly on n_b in the case of the nucleus-nucleus interactions, whereas this dependence is weak for the proton-nucleus collisions

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