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Comparative study for nucleus-nucleus interactions and modified cascade evaporation model aT (4.1-4.5) A GeV/c

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Abstract. The characteristics of the interactions of ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{28}Si and ^{32}S with emulsion at momentum (4.1-4.5)A GeV/c have been investigated. It has been found that the modified cascade evaporation model can describe the multiplicity characteristics of the different emitted particles and the correlation between them. The calculated pseudorapidity distributions of the produced shower particles are typically gaussian shaped in the mid-rapidity region and agree well with the experimental data. The angular distributions of the grey particles show a universal shape independent of the type of projectile. The angular distributions of the black particles are nearly isotropic.

1 Introduction

Many models have been introduced to describe the multiparticle production in the nucleus-nucleus (A-A) interactions (EL-Naghy et al., 1994; EL-Naghy et al., 2000 and Ghosh et al., 1992). One of these models, is the cascade evaporation model (CEM) based on the assumption that the nuclear collision can be described simply as the superposition of nucleon-nucleon interactions (e.g.Toneev and Gudima, 1983). In the simplest version of the CEM, the nucleons are assumed to travel in straight trajectories between any two collisions. Also, the collisions are calculated neglecting any possible phase relationship with previous or following collisions, i.e., the multiparticle interactions are neglected. The cascade evaporation model (CEM) has been modified into MCEM, given, in the next section, in order to describe the relativistic nuclear collisions.

In the present work, the multiplicity and angular characteristics of the interactions of (4.1-4.5) A GeV/c ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{28}Si and ^{32}S with emulsion have been studied. The results of the calculations, performed according to MCEM, are presented.

2 Modified Cascade Evaporation Model

The cascade evaporation model for A-A collision has been developed into MCEM to include a formation time parameter in the multiparticle production process (Kawrakow et al., 1992). The fast produced particles have no chance to undergo any secondary interaction inside the nucleus and according to the uncertainty principle, the creation of a hadron in the proper rest frame needs a certain time, which is equal to:

$$t_o = \frac{1}{m_t} = \frac{1}{(m^2 + p_t^2)^{1/2}} \qquad (1)$$

where m_t , m and p_t are the transverse mass, the rest mass and the transverse momentum of the produced particle, respectively. In the laboratory frame, this time is multiplied by the Lorentz factor, γ,of the generated secondary particle.

The general physical features of the MCEM are similar to the collision of two gas clouds. Each of the two colliding nuclei is considered as a Fermi gas of nucleons bounded in a definite volume with a potential well

$$V(r) = E_B + P_F^2 / 2\,m \qquad (2)$$

where m is the mass of a free nucleon, E_B is the average binding energy of a nucleon inside the nucleus (nearly equals 7 MeV) and P_F is the Fermi momentum.

The inelastic interactions of two nuclei can be classified into four groups: Interaction of the nucleon from the projectile nucleus with those from the target nucleus. Interaction of the cascade particles with the nucleons of the projectile nucleus. Interaction of the cascade particles with the nucleons of the target nucleus. Interaction of the cascade particles with each other, the so-called cascade-cascade interactions.

The dynamics of the interaction were followed in time with the help of the Monte-Carlo method. Thus, for a collision of two chosen particles, the reaction characteristics are selected at random and the validity of

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the Pauli exclusion principle is checked. The cascading stage ends when all the cascade particles have left the interacting nuclei or have been absorbed by them. In MCEM, the only parameter that needs to be adjusted is the formation time parameter, which represents the mean formation time in the rest frame of the secondary particle.

3 Results and discussions

The characteristics of the high-energy A-A collisions have been investigated by studying the interactions of the projectiles ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{28}Si and ^{32}S at 4.5A GeV/c and ^{22}Ne at 4.1A GeV/c with emulsion. The experimental data have been taken from the data bank of the high-energy laboratory at Cairo University.

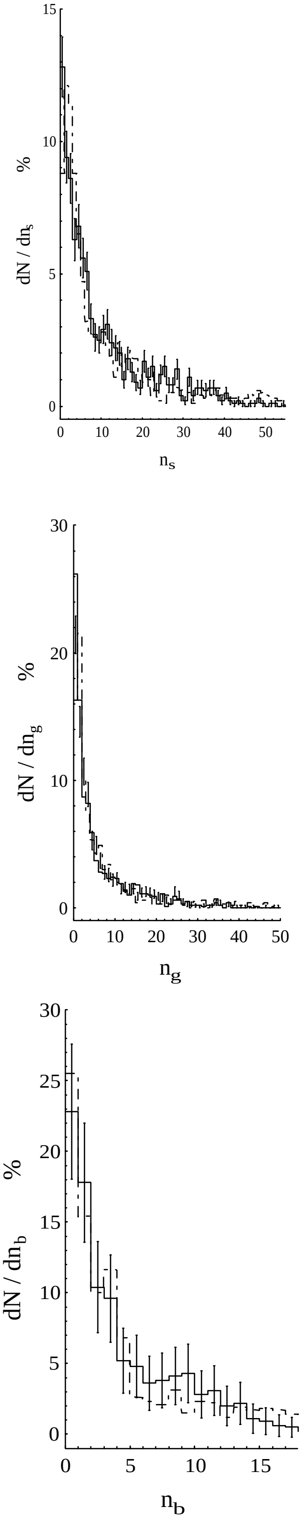
In emulsion experiments, the emitted particles are mainly divided into three classes (Adamovich et al., 1979) : i- Projectile fragments or projectile spectators, ii- Shower, s, particles, iii-Target fragments subdivided into: grey, g, particles and black, b, particles.

3.1 Multiplicity distributions

A systematic study has been carried out for the multiplicity characteristics of the shower, grey and black particles emitted in the interactions of (4.1 - 4.5) A GeV/c ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{28}Si and ^{32}S with emulsion. The average multiplicities of the shower, $\langle n_s \rangle$, grey $\langle n_g \rangle$, and black, $\langle n_b \rangle$ particles calculated by generating 1000 events at the best estimated formation time and taking into consideration the emulsion composition and the cross-section of the interactions, together with the corresponding experimental values have been found to be in fair agreement, within errors, with the experimental data. For example, for ^{12}C, $\langle n_s \rangle_{exp}=7.70 \pm 0.20$ while $\langle n_s \rangle_{MCEM}=7.46 \pm 0.30$, $\langle n_g \rangle_{exp}=5.90 \pm 0.20$ while $\langle n_g \rangle_{MCEM}=6.11 \pm 0.20$ and $\langle n_b \rangle_{exp}=4.50 \pm 0.20$ while $\langle n_s \rangle_{MCEM}=4.42 \pm 0.20$. From the calculations, it has been found that as the number of interacting projectile nucleons increases, the values of n_s increases, which leads to an observable increase in the average multiplicity of the produced shower particles, $\langle n_s \rangle$.This indicates the possibility of describing the A-A interactions as a superposition of nucleonnucleon interactions.

The average number of grey tracks, $\langle n_g \rangle$, increases with the increase of the projectile mass number, A_p, This may be due to the increase in the number of collisions and consequently an increase in the number of recoil nucleons as the projectile mass number increases. Also, the average multiplicities of the black tracks, $\langle n_b \rangle$, are nearly constant, within errors. Since the black tracks are evaporation particles from the target nuclei, then the constant value of $\langle n_b \rangle$ with increasing the projectile mass number, A_p, means that the excitation energy given to the target nucleus is independent of the projectile mass number.

Figure 1 shows, as an example, the normalized multiplicity distributions for the n_s-, n_g- and n_b- particles for the interactions of 4.1A GeV/c ^{22}Ne-emulsion nuclei in a, b,and c, respectively. The solid curve represents the experimental (exp) data while the dashed one gives the corresponding distribution calculated according to MCEM. Different criteria have been applied in order to investigate the consistency between the theoretical and experimental distributions such as the Pearson`s $\chi^2$ , Romanovskii's and Kolmogorov`s criteria.



From the analysis,, it can be seen that, in general, the calculated multiplicity distributions, using the MCEM, are consistent with the corresponding experimental ones. This indicates that the MCEM, which implies both the superposition of the nucleon-nucleon collisions and the formation time for the produced particles, reproduces satisfactorily the multiplicity distributions of s-, g- and b-particles and thus describes successfully the inelastic nuclear interactions.

3.2 Multiplicity correlation

One of the effective methods for verifying the adequacy of a model for describing the nuclear interactions is to obtain the correlations among the secondary particles emitted in these interactions.

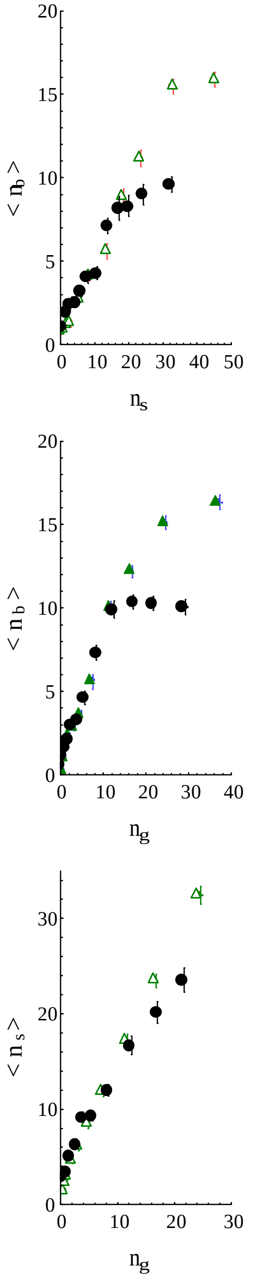
For the interactions of 4.5A GeV/c ^{16}O-Em, as an example, Fig.2a represents $\langle n_b \rangle$ plotted as a function of n_s for the calculations done according to MCEM and the corresponding experimental correlations while the theoretical and experimental correlations $\langle n_b \rangle$ as function of n_g is shown in Fig.2b and Fig.2c displays the theoretical and experimental correlations between $\langle n_s \rangle$ and n_g. In these Figs, the experimental data are represented by circles while the MCEM calculations by triangles and both the theoretical and experimental correlations have been fitted to a straight line, given by the formula: $\langle n_i \rangle = a + b\, n_j$ where i and j stand for s-, g- or b- particles and $i \neq j$ and where b is the slope. The values of the slopes calculated according to MCEM agree, within errors, with the experimental values, particularly for the heavier projectiles. From Fig.2a, one can observe that $\langle n_b \rangle$ increases linearly with n_s. Then, at a certain value of n_s , $\langle n_b \rangle$ reaches a constant value almost equal to 10. This may be interpreted as follows: at a certain value of n_s , the residual target nucleus attains a constant excitation energy and temperature. At higher values of n_s , an excess amount of energy may be pumped to the system to be consumed into a phase transition in the target nucleus system. The constancy of the plateau value of $\langle n_b \rangle$, for the interaction of the above mentioned projectiles at 4.5A GeV/c, may indicate that the critical temperature for the phase transition is independent of the mass number of the projectile nucleus.

It can be seen from Fig.2b that $\langle n_b \rangle$ increases linearly with n_g. The result of this correlation shows the close relation between the cascade stage which is characterized by the emission of grey particles (recoil nucleons) and the subsequent stage (evaporation) during which the black particles (evaporation particles) are emitted.

Figure.2c shows that $\langle n_s \rangle$ increases linearly with n_g, i.e., $\langle n_s \rangle$ increases with the increase of the number of interacting projectile nucleons, since n_g can be considered as a measure of the number of interacting projectile nucleons and of their intranuclear collisions. It may be concluded that the MCEM describes qualitatively well the studied experimental correlations.

3.3 Pseudo-rapidity distributions for shower particles

To study the angular distributions of the produced particles, it is common to use the pseudo-rapidity variable η , which has the advantage that it depends only on the angle of emission θ. It has been found that each distribution includes three main regions: the projectile fragmentation region which is $\eta>4$, the central region which extends from $\eta=0$ to $\eta=4$ and the target fragmentation region for $\eta<0$ and that most of the produced shower particles lay in the mid-pseudorapidity region (pionization region) while very small numbers lay in both the target and the projectile fragmentation regions.



3.4 Angular distributions of grey and black particles

The angular distribution of the grey particles, as a function of cosθ_g, has been found to exhibit a universal shape with a forward peak. This distribution is nearly independent of the variation of the projectile's mass, energy or target mass. This universal shape, observed in the A-A collisions, has the form:

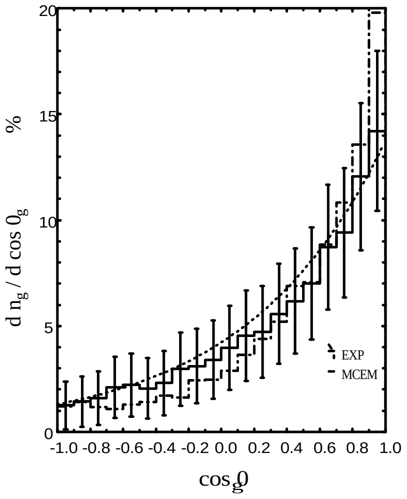
$$\frac{1}{N}\frac{dn_g}{d\cos\theta_g} \cong C\exp(D\cos\theta_g) \qquad (3)$$

Where D takes values from 0.97 up to 1.18.

It is a remarkable feature that the same angular distribution of the grey particles and its universality, observed in A-A collisions, has a corresponding one in the hA collisions and also in the neutrino collisions (ν-Em) .

The theoretical angular distributions, calculated according to the MCEM, for the grey tracks emitted in the interactions of ^{28}Si at 4.5A GeV/c with emulsion nuclei, as a function of cos θ_g, compared with the corresponding experimental distributions are shown in Fig.3,as an example . From this figure, one can observe that the experimental distributions are in fair agreement (within errors) with the calculated ones.

The theoretical angular distribution, as a function of cos θ_g, have been calculated according to MCEM, for the black particles emitted in the studied interactions and compared with the corresponding experimental distributions. It has been observed that the experimental distributions are in fair agreement, within errors, with the calculated ones. One can conclude that the theoretical angular distributions calculated according to the MCEM for grey and black tracks emitted in the above mentioned interactions describe satisfactorily the corresponding experimental distributions.



4 CONCLUSIONS

From the present study, the experimental multiplicity distributions of the shower, grey and black particles emitted in the studied interactions and their average values are well reproduced by the considered code of the modified cascade evaporation model. The multiplicity distributions of the shower particle change with the projectile mass number, the dependence of the multiplicity distributions of the grey particles on the projectile mass number is weak and the multiplicity distributions of the black particles are independent of the projectile mass number.

The comparison of the average multiplicity of the produced shower particle show that the A-A interaction may be described as a superposition of the nucleon-nucleus interactions.

The modified cascade evaporation model has reproduced the correlations observed experimentally between the multiplicities of the different types of the emitted particles. The correlations between the average number of black particles and the number of produced shower particles or grey particles show that the average multiplicity of the black particles may reach a constant value at high values of the number of shower or grey particles, which may be interpreted as a phase transition in the target system.

The strong correlation between the average number of the produced shower particles and the number of the emitted grey particles indicates that the number of grey particles can be used as a measure of the number of intranuclear collisions. The theoretically determined pseudo-rapidity distributions of the produced shower particles are typically Gaussian and are consistent with the corresponding experimental ones. The angular distribution of the grey particles in terms of the emission angle of the grey particle has a universal exponential shape. The distribution does not depend on the projectile mass number or on its energy. The angular distributions of the black particles are nearly isotropic with a small asymmetry in the forward direction. The angular distributions of the grey and black particles are well reproduced by MCEM calculations.

The present analysis shows that the experimental data of the interactions of ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{28}Si and ^{32}S with emulsion at momentum (4.1-4.5) A GeV/c can be reproduced by the MCEM, which includes a finite formation time of the secondary produced hadrons inside the target nucleus.

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