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Cascade and Fritiof models in analyzing forward-backward multiplicities of (4.1-4.5) A GeV/c 22 Ne and 28 Si interactions with emulsion target nuclei

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Abstract. The multiplicity and correlations of the forward ($\theta<90^o$) and backward ($\theta\geq90^o$) secondary particles emitted in ^{22}Ne- and ^{28}Si-emulsion interactions are calculated according to the modified cascade and modified Fritiof models. The predictions of the two models are compared with experimental data at incident momentum of (4.1-4.5) GeV/c per nucleon. Both models depend on the Monte Carlo techniques where the modified cascade model implies the superposition of nucleon-nucleon interactions, and the modified Fritiof model utilizes the Regge theory for the description of the cascading process. Comparison with data shows no clear preference of one model over the other. However, the modified Fritiof model seems to be nearer to the experimental data than the modified cascade model, which appear to overestimate the number of the intranuclear cascade.

1 Introduction

During the last few years the backward production of pions and protons scattered off nuclei has attracted much attention (Adamovich, 1990; El-Nadi et al., 1998). This is because the emission of such backward hadrons may be beyond the kinematics limit allowed in free nucleon-nucleon collisions. Although there are some works (e.g., Frankfurt, 1979 and references therein) in order to interpret such phenomena, but the theoretical description is still insufficient.

On the other hand, reliable models for a simulation of reactions are carried out to provide the necessary data. Most of these models use the ideas of the cascade evaporation model (e.g., Toneev, 1983).Traditional cascade model of hadron-nucleus hA and nucleus-nucleus AA interactions, in which multiparticle production is a result of nucleon-nucleon NN and meson-nucleon interactions, gives a satisfactory agreement with data at intermediate energies (up to few GeV). But this classical picture overestimates the multiparticle production at higher energies.

In the recent parton models of hA and AA collisions, the multiparticle production is considered as two-step process in which partons are firstly created before the final hadron emerges (Bialas, 1991). The consequence of this two-step process mechanism is that the creation of a hadron is not instantaneous but it takes time, which is called the formation time. Developing the cascade model with the concept of the formation time is referred to as the modified cascade model, MCM.

The Fritiof model, on the other hand is another Monte Carlo simulation program for inelastic hN, hA and AA interactions. Its basic assumptions are based on the model presented in (Andersson et al., 1987). It assumes an excitation of hadrons into continuous mass spectra in hh collisions, while in hA and AA interactions the excited hadrons can suffer an additional collisions with nuclear nucleons and go to more excited states. The excited hadrons are considered as quark strings, and thus the quark model (Sjostrand et al., 1987) is used for the description of their decay. The probabilities of multiple collisions are calculated within the Glauber model (Glauber, 1959). Cascading of secondary particles is omitted in the model. For that reason no characteristics of slow target associated particles are reproduced. Quantum mechanical description of cascading particles in nuclei can be achieved within the framework of the Regge theory (Boreskov et al., 1990). The combination of the original Fritiof NN scattering with the Regge cascade theory is developed in (Abdel-Waged and Uzhinskii, 1997) and is referred to as the modified Fritiof model, MFM.

The main goal of the present paper is to study the applicability of the two codes, namely the MCM and MFM in describing the forward-backward particle emission in AA interactions at high-energy. Experimental data (El-Naghy et al., 1997) on the multiplicity distribution of

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charged particles and their correlations in forward and backward hemispheres for (4.1 4.5) A GeV/c ^{22}Ne and ^{28}Si interactions with emulsion target nuclei are used in the comparison.

2 Description of the basic models

2.1 The modified cascade model MCM

According to the model, when one of the projectile nucleons interacts with one of the target nucleons the creation of a new particle takes place. The participating target nucleon acquires momentum and begins to move in the nucleus. Such cascade particles can interact with other target / projectile nucleons to produce new particles or elastically scatter. The nucleons, which can participate in elementary interactions, are chosen randomly from the initial configuration system. All the nucleons of the colliding nuclei with mass numbers A and B are identified by the coordinates (x_i ,y_i , z_i, i=1,2, ,A) and (x_j, y_j, z_j, j=1,2, ,B) in the initial configuration state. Taking into account the Lorentz contraction of the projectile nucleus A in the rest frame of the target nucleus B, the corresponding coordinates are redefined as $z_i \rightarrow \frac{z_i}{\gamma} - \frac{R_A}{\gamma} - R_B$, where γ is the Lorentz factor of the projectile nucleus and R_A (R_B) is the projectile (target) nuclear radii. Nucleons whose coordinates satisfy the condition:

$$(b_x + x_i - x_j)^2 + (b_y + y_i - y_j)^2 \leq (R_{\text{int}} + \lambda_D)^2$$

are considered to participate in the elementary interactions, where (b_x, b_y) are the components of the impact parameter vector, R_{int} is the strong interaction range (~1.3 fm) and λ_D is the de Brogli wavelength of the projectile nucleon. The time evolution of the system is determined by considering many independent simulations of the collision process and taking average over the values of those quantities calculated in each run. All the collisions that take place in the closest time interval are independently processed. A nucleon involved in the interaction is treated as a cascade particle as soon as it undergoes its first interaction.

The momenta of the colliding particles are determined randomly according to the differential cross section. After the first nucleon-nucleon collision has been completed, straight-line motion is resumed and the next possible collision is followed in a similar manner and so on. The process continues until all moving particles either escape from the nucleus or are absorbed. At the end of the fast stage of the process, the number of charges of spectator nucleons as well as the charges of the absorbed mesons determine the nuclear residual mass number and charge.

The excitation energy of the nuclear residual is the sum of the energies of absorbed particles and the holes counted from the Fermi energy. In addition, Pauli exclusion principle and the energy-momentum conservation are obeyed in each intra-nucleon interaction. Also the trailing effect (rearranging the density) is included; a target nucleon is scattered as a result of collision with the projectile, the whole target density is depleted by one nucleon.

The model overestimates the meson production and several efforts were tried to overcome the problem. The concept of formation time of secondary particles was introduced (Kawrakow et al., 1992). It is assumed that, during the time required for the formation of a self-mesonic cloud, product particles can not interact. The formation time, which depends on hadron properties, is considered as a free parameter and the problem is reduced to choosing this parameter.

Generated events consists of 5000 interactions are simulated for each projectile-target combination using the code developed in (Barashenkov et al., 1984).

2.2 The modified Fritiof model MFM

The model, in its original form, applies the Glauber approach to calculate the number of the inelastic NN collisions. The hadron is treated as a vortex line. It consists of a hard core surrounded by an exponentially damped field. When two hadrons interact, two longitudinally excited string states are formed and then they are hadronize according to the Lund model of jet fragmentation (Andersson et al., 1983). The hadronization is assumed to take place outside the nuclei and thus the intranuclear cascade is neglected.

In order to introduce cascading in the Fritiof model, the primary interacting nucleons are allowed to rescatter through Regge cascading theory (Abdel-Waged and Uzhinskii, 1998). According to this approach, each interaction of incident hadron with nucleons of a target nucleus initiates a cascade of reggeon exchanges. The amplitudes and cross sections for cascading processes are calculated using enhanced graphs i.e., graphs with an interaction between rggeons. The yield of the enhanced graphs leads to increase the slow particle contribution in the target fragmentation region. The method is explained in detail in (Abdel-Waged and Uzhinskii, 1997). This picture looks like the classical cascade evaporation model. However, the main difference between these two approaches is that the latter developed a cascade in three-dimensional space of the target nucleus, while the former assumes the cascade of regge exchanges in two-dimensional space on the impact parameter plane.

MFM simulates the events according to the following steps:

i. Nucleon coordinates (x,y,z) of the two colliding nuclei were simulated to a Gaussian distribution for the nuclei with A≤ 14 or according to a Wood- Saxon distribution for nuclei with A> 14.

ii. Wounded nucleons of nuclei were determined by the Glauber approximation (Shmakov et al., 1989).

iii. Target and projectile spectator nucleons are now followed. If the i-th spectator of nucleus A is at $b_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ distance from the j-th wounded nucleon of A, the i-th nucleon is considered as a participant of the collision with the probability of $w = C\exp(-b^2{}_{ij})$, C= 0.35.

iv. If the number of newly nucleon participants is not zero, step (iii) is repeated for the newly participants. Otherwise, the interaction will be rejected.

v. The number of spectator nucleons and their charges are determined. These quantities represent the mass number and charge of the nuclear residue, which is normally excited.

vi. The excited residue is allowed to emit nucleons and light fragments if the excitation energy of the residual nucleus is higher than the separation energy.

A sample consists of 5000 simulated events for each projectile-target combination is generated using the MFM code.

3. Comparison with data

Experimental multiplicities of forward emitted particles (those with θ <90^o) and backward emitted particles (those with $\theta \geq 90^o$) are used to show the preference of one simulated code over the other (namely, MCM and MFM), where θ is the emission angle in the laboratory system. Two samples (El-Naghy et al., 1997) consist of 2000 ^{22}Ne- Em interactions at 4.1 AGeV/c and 1322 ^{28}Si-Em interactions at 4.5 AGeV/c are used in the study. The emitted particles are classified into shower, with multiplicity N_s, grey, with multiplicity N_g and black, with multiplicity N_b according to the emulsion terminology. Shower particles are mainly pions, grey particles contain a large fraction of fast protons, and black particles are dominant by evaporated protons emitted from residual nuclei. The average charged multiplicities of shower, grey and black particles in the forward and backward cones, for the considered reactions are listed in table (1) with the predictions of MCM and MFM. As seen from the table, the mean multiplicity of shower particles in the forward cone, $\langle N_s\rangle_{forward}$ is well reproduced by both models in Ne-Em data, however they over exceed it in Si-Em data. Also, while MCM overestimates $\langle N_g\rangle_{forward}$ for both data, the MFM seems to be better. This may indicate that the MCM enriches the spectrum by a large number of intranuclear collisions. $\langle N_b\rangle_{forward}$ are in good agreement with both models for both data groups. In the backward cone, MCM and MFM are in fair agreement with the mean values of different multiplicities. However, the MFM seems to better than the MCM in describing $\langle N_s\rangle_{backward}$ and $\langle N_b\rangle_{backward}$, while MCM is the best for reproducing $\langle N_g\rangle_{backward}$.

Table 1. The average multiplicities for ^{22}Ne- and ^{28}Si- Em data in forward and backward cones in comparison with the predictions of MCM and MFM

Reaction		$\langle N_s\rangle$	$\langle N_g\rangle$	$\langle N_b\rangle$
^{22}Ne-Em Forward	Exp.	9.71 ± 0.23	4.79 ± 0.10	2.31 ± 0.07
	MCM	9.55	6.70	3.02
	MFM	10.86	5.87	2.18
Backward	Exp.	11.43 ± 0.35	1.38 ± 0.03	1.84 ± 0.03
	MCM	13.62	1.32	2.26
	MFM	14.81	0.74	1.71
^{28}Si-Em Forward	Exp.	11.43 ± 0.35	4.96 ± 0.81	2.45 ± 0.07
	MCM	13.62	7.91	3.43
	MFM	14.81	6.92	2.43
Backward	Exp.	0.35 ± 0.02	1.42 ± 0.06	1.99 ± 0.05
	MCM	0.88	1.69	2.56
	MFM	0.79	0.87	1.88

The correlation between different types of charged particles in both forward and backward cones are more sensitive for testing the two models. Figs.(1 and 2) show $\langle N_g\rangle$ and $\langle N_b\rangle$, respectively as function of N_s for (a) forward and (b) backward cone in Ne- and Si-Em data. It can be observed that, the MCM describes satisfactorily $\langle N_g\rangle_{forward}$ and $\langle N_b\rangle_{forward}$ up to $N_s \approx$ 20-25. For N_s > 25, the model predicts an increase in multiplicity of grey particles. The MFM, on the other hand underestimates $\langle N_g\rangle_{forward}$ at N_s>10 in Ne data and gives better agreement in Si data. Also, it, in general represents $\langle N_b\rangle_{forward}$ as function of N_s for both data groups.

In the backward cone (figs. 1b and 2b), both models fail to reproduce $\langle N_g\rangle_{backward}$ in Ne and Si data. But MFM succeeds to describe $\langle N_b\rangle_{backward}$ in Ne and Si data up to $N_s \approx$ 5.

In conclusion, the comparison of the present data with the predictions of the MCM and MFM in the forward and backward cones, for the considered reactions at momentum (4.1-4.5)A GeV/c, shows no clear preference of one mode over the other. However, the MFM seems to be nearer to the experimental data than the MCM, while MCM appears to overestimate the number of the intranuclear cascade.

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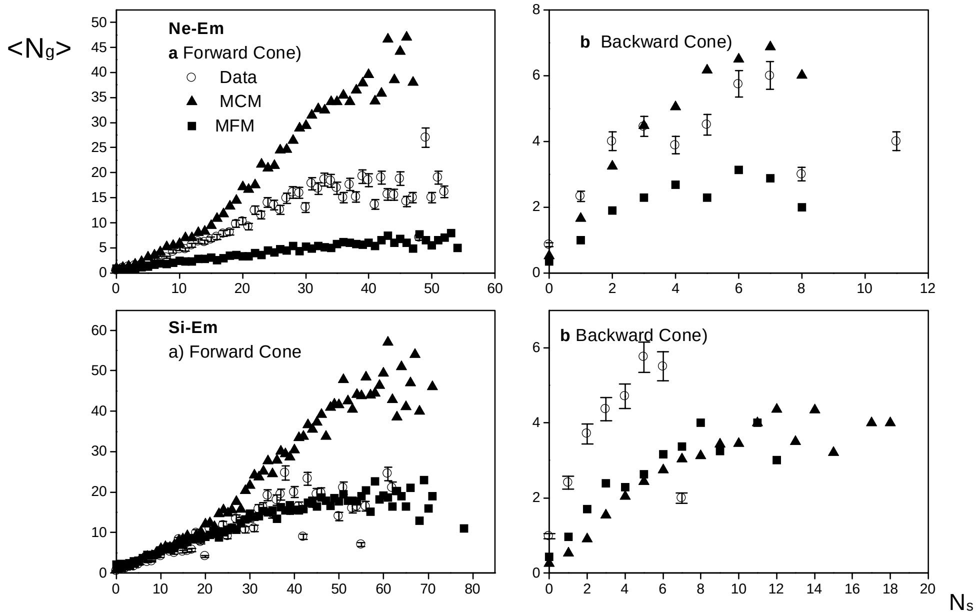

Fig.1. Correlation between N_s and $\langle N_g \rangle$ for Ne- and Si-Em data in a) Forward and b) Backward cones in comparison with the predictions of MCM and MFM

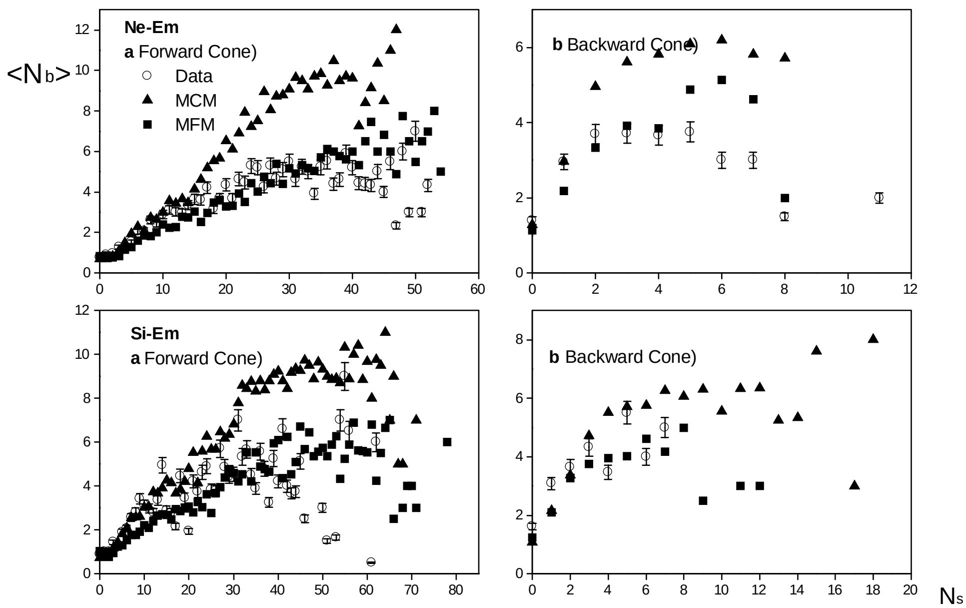

Fig.2. Correlation between N_s and $\langle N_b \rangle$ for Ne- and Si-Em data in a) Forward and b) Backward cones in comparison with the predictions of MCM and MFM