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Study of Pseudorapidity Distributions of Shower Particles Emitted in Interactions of Nuclei with Emulsion at 4.1- 4.5 A GeV/c

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Abstract

The pseudorapidity distributions of shower particles in interactions of 4.5 A GeV/c ^{12}C, ^{16}O, ^{28}Si and ^{22}Ne at 4.1 A GeV/c with emulsion have been presented. The dependence of these distributions on the target nuclei (AgBr and CNO) have been investigated. The energy density for ^{24}Mg–Pb interactions is calculated using the Bjorken model.

1. Introduction

The special feature which distinguishes the nucleus-nucleus collisions from hadron-hadron and hadron-nucleus collisions is that in the former case, a large amount of energy is released due to numerous nucleon-nucleon interactions, and multiple scattering of the constituents within the nucleus dimensions [1]. In very central collisions the nuclei were found to disintegrate completely into light particles. Underlying the experiments is the search for the evidence that the hadronic matter in these violent collisions made a transition, temporarily, to a deconfined quark-gluon plasma (QGP). It is widely believed that the strong interacting matter undergoes this phase transition at very high temperatures ≈200 MeV/c and/or energy densities ≈ 2–3 ε_o (where ε_o is the energy density of normal nucleus) [2]. A key parameter in the QGP search is the charged particle density ρ, since it can be related to the energy density. By examining how ρ varies with incident energies, projectile and target masses one can extract information that help to improve accelerator based experiments. The dispersion σ of the charged particle density distributions is of interest also for model comparisons [3]. Therefore, high energy pions are considered a valuable tool to test the hot and dense nuclear matter at incident energies around 1 GeV/nucleon [4].

In this paper we will focus on pseudorapidity distributions of secondary relativistic charged particles and their dependence on projectile mass and on target mass have been investigated. Also, the energy density for the ^{24}Mg-Pb interactions have been estimated.

2. Experimental Techniques

Nuclear emulsions of type Br-2 were exposed to 4.5 A GeV/c ^{12}C, ^{16}O, and ^{28}Si beams and ^{22}Ne at 4.1 A GeV/c, at the Dubna Synchrophasotron. The pellicles of emulsion have the dimension of 20 cm × 10 cm

× 600 μm (undeveloped emulsion). Double scanning was carried out along the track, fast in the forward direction and slow in the reverse direction.

In the measured interactions, all the charged secondary particles have been classified according to the range L in the emulsion and the relative ionization $I^* = I \ / \ I_o$where I is the particle track ionization and I_o is the ionization of a relativistic shower track in the narrow forward cone with an opening angle $\theta \leq 3^\circ$, into the following groups:

Shower tracks producing "s-particles" having a relative ionization $I^* \leq 1.4$. Its multiplicity is denoted by $n_s$after the exclusion of tracks having an emission angle $\theta \leq 3°$. Grey tracks producing "g-particles" having $I^* > 1.4$ and $L > 3$ mm. Its multiplicity is denoted by n_g and does not includes those tracks with an emission angle $\theta \leq 3°$. Black tracks producing "b-particles" having $I^* > 1.4$ and $L < 3$ mm and its multiplicity is denoted by n_b and does not include those tracks having an angle $\theta \leq 3°$. The "b" and "g" tracks, together, are called heavily ionizing tracks producing "h-particles," and n_h denotes its multiplicity.

According to the value of n_h [5] the emulsion is divided into two types of target nuclei: light nuclei (CNO) and heavy nuclei (AgBr), so that collisions of the beam with CNO nuclei are events with $0 < n_h < 8$, and events with $n_h \geq 8$ are considered as the collisions of the beam with AgBr nuclei. It should be noted that the classification of events in emulsion is not unique, however there is no perfect method in classifying events due to the limitation of the emulsion technique.

3. Results and Discussions

To study angular distribution of the produced particles (mainly pions) it is common to use the variable pseudorapidity η:

$$\eta = -\ln\tan(\theta/2), \tag{1}$$

where θ is the polar angle, between the direction of the beam and the emitted pion. For light incident beams, the resulting η-distributions have been shown to be well represented by Gaussian function of the form [6]

$$\rho(\eta) = \rho_{\max} e^{-(\eta-\eta_{peak})^2/2\sigma^2}. \tag{2}$$

The distribution is thus described by its height $\rho_{\max}$, width σ and peak position η_{peak}. However, the Gaussian function failed in describing the pseudorapidity distributions of shower particles produced in interactions of relative large projectiles comparing with target nuclei, such as Au with emulsion at energy 10.6 A GeV [7, 8]. For these cases two Gaussian distributions were needed; while, on the other hand, the thermalized cylinder model [9, 10] gave a good description of the experimental data. According to this model the pseudorapidity density distribution is given by [10]:

$$\rho(\eta) = \frac{\langle n_s \rangle - \alpha N_{PP} - N_{PS}}{y_{max} - y_{min}} \int\limits_{y_{\min}}^{y_{max}} f(\eta\,, y_x) dy_x + \alpha N_{pp} f(\eta, y_{\max}) + N_{ps} f(\eta, y_{ps}), \tag{3}$$

and

$$f(\eta\,, y_x) = \frac{1}{2cosh^2(\eta - y_x)}, \tag{4}$$

where $<\mathrm{n}_s >$ is the average number of shower particles, N_{PP}, N_{PS} denote the proton number of projectile participant and spectator, respectively, α is the probability of projectile participant proton appearing as a leading particle and y_{PS} is the mean rapidity of projectile spectator protons. It is assumed in this model that the thermalized cylinder is formed, in nucleus-nucleus collisions, in the rapidity range $(y_{max},\, y_{min})$.

Figure 1(a–d) shows η-distributions of s-shower particles produced in interactions of four incident beams (^{12}C, ^{16}O, ^{22}Ne and ^{28}Si) with emulsion at 4.5 GeV/c, except for ^{22}Ne at 4.1 A GeV/c. The histograms are the experimental data; the dashed and the solid curves are the results of equations (2) and (3), respectively. The values of $\rho_{\max}$, σ and η_{peak}, that are obtained from equation (2), and χ^2/DOF are given in Table 1. In the calculation of thermalized cylinder picture, the values of $y_{max},\, y_{min}, y_{ps}, N_{pp}$ and N_{ps} are obtained by fitting the experimental data. The values of these parameters and the of χ^2/DOF are given in Table 2. The value of α is set to be 0.5, as mentioned in [11]. The symbol $\rho(\eta)$ on the coordinate axis is the pseudorapidity density and satisfies the normalization condition $\int \rho(\eta)\, d\eta = \langle n_s \rangle$.

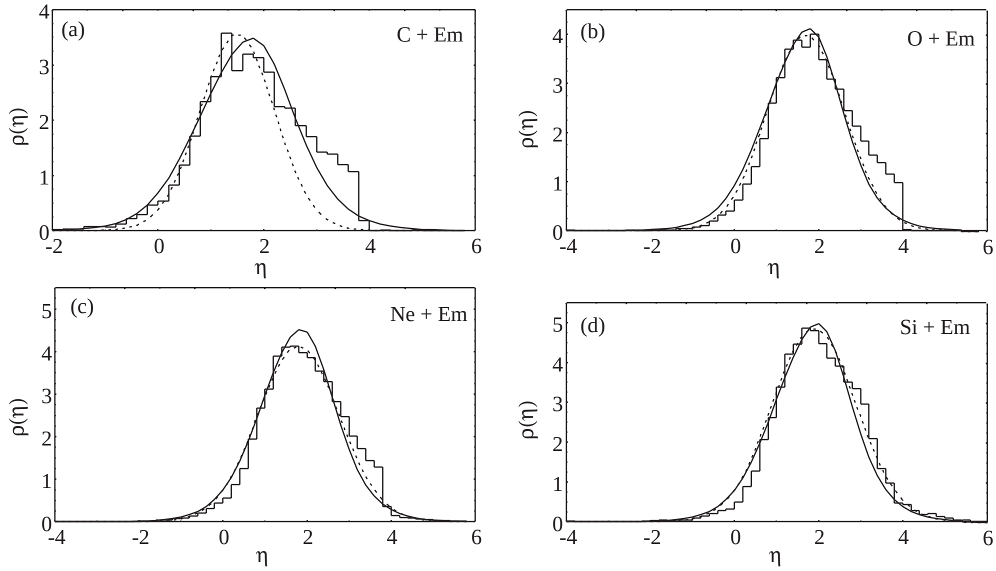

Figure 1. (a–d) The pseudorapidity distributions of shower particles produced in interactions of different incident nuclei with emulsion.

It can be seen from this figure that there is an excess of particles above $\eta = 2.6$ in cases of lighter nuclei (^{12}C and ^{16}O), and that this excess of particles decreases with increasing projectile mass and vanishes in the case of ^{28}Si. This excess is probably caused by the protons from lighter projectiles which appear as s-tracks in the most forward direction, and can not be distinguished from the s-particles. Comparing Tables 1 and 2, the experimental distributions can equally well be represented by both equations (2) and (3), except in the region of $\eta \geq 2.6$, where the excess of particles appears causes the value of χ^2 to increase for lighter projectiles. Also it can be noticed from Table 1, that there is a slight linear increase in the height $\rho_{\max}$, the width σ and the peak position η_{peak} of the distributions with beam masses.

To study the dependence of the pseudorapidity distributions on the target mass, Figure 2(a) and 2(b) shows the experimental results of shower particles emitted in interactions of ^{12}C, ^{16}O, ^{22}Ne and ^{28}Si with different target nuclei, AgBr and CNO, respectively. The histogram for ^{12}C appears as small dashed line, ^{16}O as dot-line, ^{22}Ne as big dashed-line and ^{28}Si as a solid line. These distributions reveal a behavior of particle production, for $\eta < 1$ (that is, in the target fragmentation region) and for $\eta > 2$ (projectile fragmentation region). In the target fragmentation region, the pseudorapidity distributions are seen to scale with the projectile mass for both cases. For the projectile fragmentation region $\eta > 2$, the population of particles increase with the projectile mass, this is more evident for the interactions of beam with AgBr, than with CNO. The heights of the distributions for AgBr (Figure 2a) are greater than those for CNO (Figure 2b). By way of example, Figure 2c shows this distribution for the interactions of ^{28}Si with AgBr and

CNO. It can be seen that, with growing number of intranuclear collisions, the target fragmentation region is increasingly populated, while the projectile fragmentation region remains unaffected. This behavior has been observed in interactions of Au with emulsion at energy 10.6 A GeV [11]. In nucleus-nucleus collisions, the target fragmentation region is populated by particles formed in interactions of secondaries. This indicates that the contribution from re-interactions is largely governed by the number of intranuclear collisions and is independent of energy.

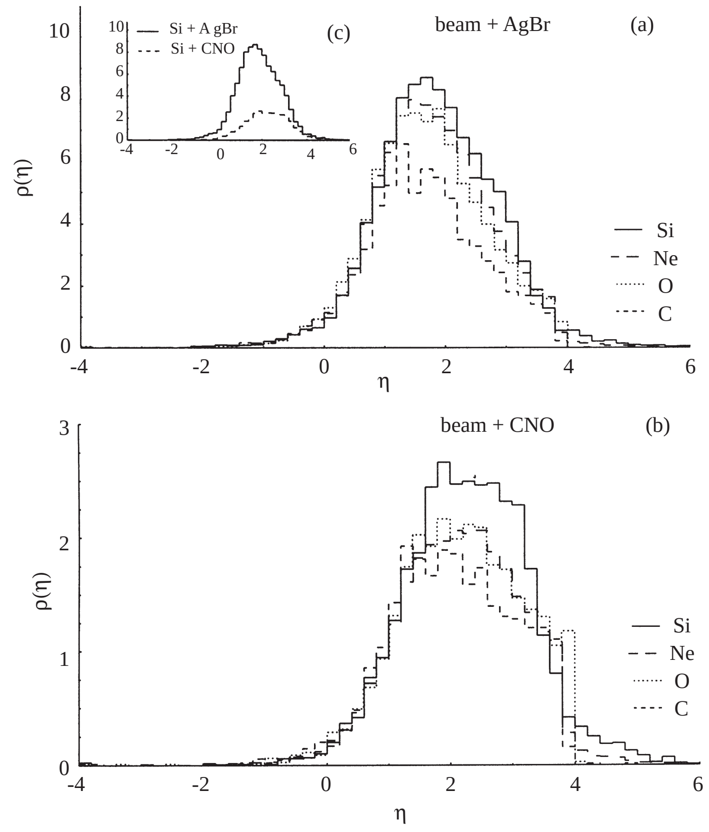

Figure 2. (a–b) The pseudorapidity distributions of shower particles produced in interactions of different incident nuclei with (a) AgBr and (b) CNO.

Table 1. Values of various parameters used in equation (2).

Type of interaction	ρ_{max}	σ	η_{peak}
C + Em	3.54	0.71	1.4
O + Em	3.97	0.92	1.6
Ne + Em	4.13	0.97	1.8
Si + Em	4.84	1.0	1.8

Table 2. Values of various parameters used in equation (3).

Type of interaction	y_{min}	y_{max}	y_{ps}	N_{pp}	N_{ps}
C + Em	0.3	0.9	1.9	4.5	6
O + Em	0.3	0.9	1.9	5.5	7
Ne + Em	0.4	1.1	2	6	7.5
Si + Em	0.5	1.1	2.1	6.5	8.5

To investigate whether hadronic matter would under go a phase transition to QGP, the knowledge of the energy density created in violent collisions is crucial for this type of search. If the two interacting nuclei are completely stopped the energy density will increase strongly with incident energy per nucleon. A common method to estimate the energy density is to use Bjorken's formula [12],

$$\varepsilon = \frac{3}{2}\sqrt{\langle p_T\rangle^2 + m_\pi^2}\left(\frac{dn_s}{d\eta}\right)V^{-1}, \tag{5}$$

assuming a normal average transverse momentum = 0.350 GeV c^{-1} and V = $\pi A^{2/3}(1.18)^2$, where A is the mass number of the smaller nuclei involved in the collision. For this search the interactions of ^{24}Mg with Pb have been used; and on an event-by-event basis the highest multiplicity events, where the pseudorapidity distribution exhibits spike higher than the overall distribution for the same multiplicity, have been selected. These conditions were found to be fulfilled in one of the events having $n_s = 51$ and $n_h = 77$; the pseudorapidity distribution is shown in Figure 3, where η is the normalized pseudorapidity $\eta = (\eta - \eta_{\min})/(\eta_{\max} - \eta_{\min})$, which takes the value from zero to unity. η_{max} and $\eta_{min}$are the maximum and the minimum pseudorapidities for an individual event.

From the value of the spike where the pseudorapidity density $dn_s/d\eta = 21$ in Figure 3, the energy density we calculated from Bjorken's formula gave $\varepsilon = 2.25\varepsilon_o$, which could be considered as the energy required for a transition to quark-gluon plasma. The authors of ref. [13] have reported an energy density $2.5\varepsilon_o$ in the case of their highest shower multiplicity event produced by the 4.1 A GeV/c ^{22}Ne beam, while the author of [14] obtained an energy density $3.2\varepsilon_o$ for the case of ^{28}Si–^{108}Ag event in interactions of 4.5 A GeV/c ^{28}Si with emulsion.

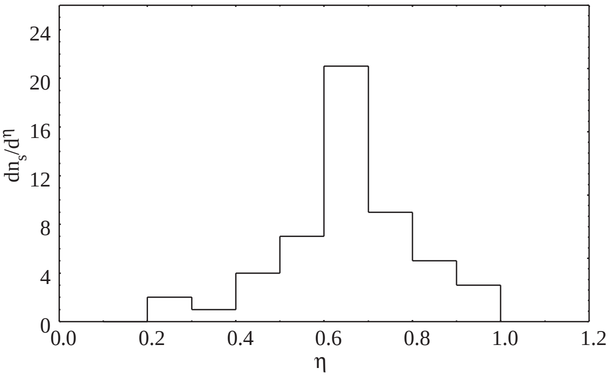

Figure 3. Normalized pseudorapidity distribution of s-particles produced in single event having $n_s = 51$ and $n_h = 77$ in ^{24}Mg–Pb interactions.

4. Conclusion

We find that the η-distributions of s-shower particles produced in interactions of incident beams (^{12}C, ^{16}O, ^{22}Ne and ^{28}Si) with emulsion are well reproduced by the Gaussian and the thermalized cylinder model, except for lighter nuclei, where the proton contamination is high; and that the thermalized cylinder model gives a better picture than the Gaussian maodel. The interactions of ^{24}Mg with Pb gave an evidence for the hadronic matter to transit to quark-gluon plasma.

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