

## Emission of Shower Particles in High-Energy Neutrino-Emulsion Collisions

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The pseudorapidity distributions of shower particles produced in neutrino-emulsion collisions at high energy are studied by the thermalized cylinder model. It is shown that a thermalized cylinder is formed in neutrino-emulsion collisions. The calculated results are in agreement with the experimental data over an energy range from 3 to 210 GeV.

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Multiparticle production is an important experimental phenomenon in high-energy nuclear collisions. Since neutral leptons interact only through the weak interaction, they have very small cross sections. This renders experiments more difficult. It also explains why there are a smaller number of studies of multiparticle production of neutral lepton-induced reactions with nuclei than studies of hadron-induced reactions. Recently, we have studied the multiparticle production of shower particles (relativistic singly charged particles) in high-energy neutrino-emulsion collisions [1, 2]. The pseudorapidity distributions of shower particles have been obtained for three types of target nuclei H, C/N/O and Ag/Br in emulsion.

It is convenient for us to study the production process of shower particles by the pseudorapidity distribution. Based on the one-dimensional string model [3] and the fireball model [4], we have developed a thermalized cylinder model [5-7] and described the pseudorapidity (or rapidity) distributions of relativistic singly charged particles in nucleus-nucleus collisions at high energy.

In this paper, we use the thermalized cylinder model [5-7] to describe the pseudorapidity distribution of shower particles produced in high-energy neutrino-emulsion collisions. The calculated results are compared with our previous experimental data [2].

Let us consider the simplest pictures of the one-dimensional string model [3] and the fireball model [4]. In a high-energy nucleon-nucleon collision, a string is formed consisting of two endpoints acting as energy reservoirs and the interior with constant energy per length. Because of the asymmetry of the mechanism, the string will break into many substrings along the direction of the incident beam. The distribution length of substrings will define the width of the pseudorapidity distribution. According to the fireball model, the incident nucleon penetrates through the target nucleon, then a firestreak is formed along the direction of the incident beam. The length of the firestreak will define the width of the pseudorapidity distribution. In high-energy nucleus-nucleus collisions, many strings or firestreaks are formed along the incident direction. Finally, a thermalized cylinder is formed. In the case of neutrino-emulsion collisions, we think that a thin thermalized cylinder (or a firestreak) is formed.

In the laboratory reference frame, we assume that the thermalized cylinder formed in collisions is in the rapidity range  $[y_{\min}, y_{\max}]$ . The emission points with the same rapidity,  $y_x$ , in the thermalized cylinder form a emission source in rapidity space. Under the assumption that the particles are emitted isotropically in the rest frame of the emission source, we know that the pseudorapidity distribution of the particles produced in the emission source with rapidity  $y_x$  in the laboratory reference frame is

$$f(\eta; y_x) = \frac{1}{2 \cosh^2(\eta - y_x)} \frac{1}{\sigma} \exp\left[-\frac{(\eta - y_x)^2}{2\sigma^2}\right]; \quad (1)$$

where  $\sigma = 0.91$  is the standard deviation, as Ref. [8] pointed out that the pseudorapidity distribution of the particles produced in an isotropic emission source obeys Gaussian distribution. The pseudorapidity distribution of shower particles in neutrino-emulsion collisions can be written as

$$f(\eta) = \frac{1}{y_{\max} - y_{\min}} \int_{y_{\min}}^{y_{\max}} f(\eta; y_x) dy_x; \quad (2)$$

Let  $y_c$  denote the rapidity of the thermalized cylinder center. Generally speaking,  $y_c$  is the rapidity of the center-of-mass system of collisions, the peak position of particle rapidity distribution, or the mean value of particle rapidities. Let  $2\Delta y$  denote the thermalized cylinder length in rapidity space. We have

$$y_{\min} = y_c - \Delta y; \quad (3)$$

and

$$y_{\max} = y_c + \Delta y; \quad (4)$$

In our calculation,  $y_c$  and  $\Delta y$  are regarded as two parameters and can be obtained by fitting the experimental data.

We have two methods to obtain the pseudorapidity distribution: a direct calculation and a Monte Carlo simulation. We have used the Monte Carlo method in this paper.

In our simulation, the emission source is randomly distributed in  $[y_{\min}, y_{\max}]$ . Particles are isotropically emitted in the emission source. We have

$$y_x = R_1(y_{\max} - y_{\min}) + y_{\min}; \quad (5)$$

and

$$\eta = \frac{p_T}{2 \ln R_2 \cos(2R_3)} + y_x; \quad (6)$$

where  $R_1$ ,  $R_2$  and  $R_3$  are random variables in  $[0, 1]$ .

Figure 1 presents the pseudorapidity distribution of shower particles produced in neutrino-emulsion ( $\pi$ -Em) collisions over an energy range from 3 to 210 GeV. The histograms with error bars are the experimental data [2]. The number of events, the mean multiplicity of shower particles and the average number of target fragments are 325,  $5.51 \pm 0.14$  and  $4.48 \pm 0.29$ , respectively. The black circles in the figure are our Monte Carlo calculated results with  $\Delta y = 1.0$ . In our

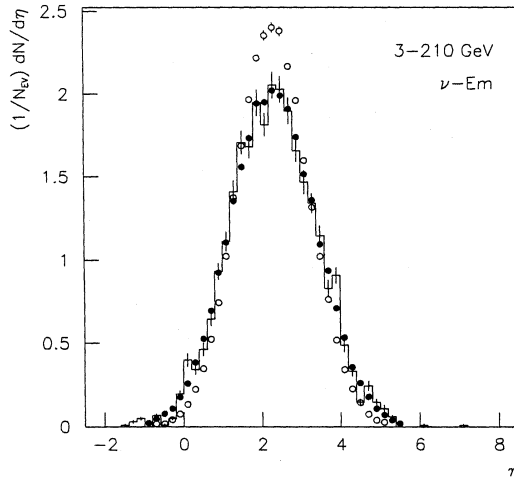


FIG. 1. Pseudorapidity distribution of shower particles produced in  $\nu$ -Em collisions over an energy range from 3 to 210 GeV. The histograms are the experimental data [2]. The white and black circles are our Monte Carlo calculated results with  $\zeta y = 0:0$  and 1.0, respectively.

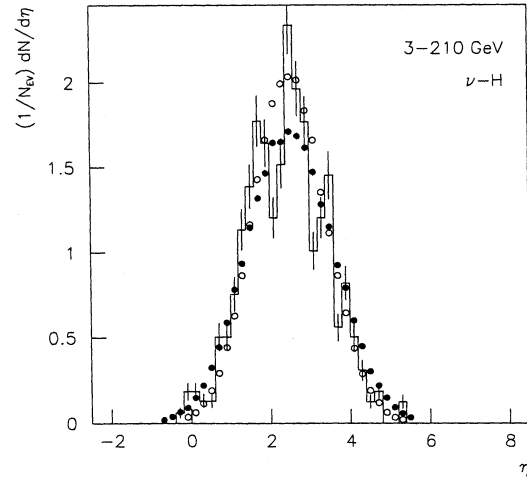


FIG. 2. As for Fig. 1, but showing the result for  $\nu$ -H collisions.

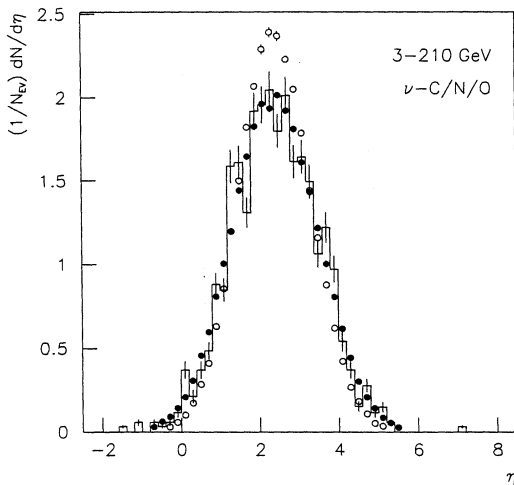


FIG. 3. As for Fig. 1, but showing the result for  $\nu$ -C/N/O collisions.

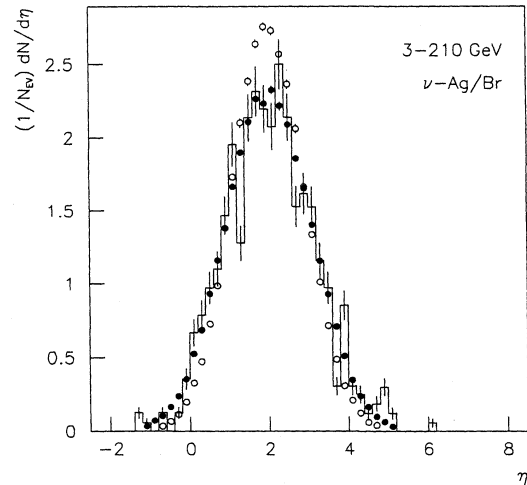


FIG. 4. As for Fig. 1, but showing the result for  $\nu$ -Ag/Br collisions.

calculation,  $y_c = 2:3$ , the simulated particle number is  $1 \text{ E } 10^5$ . The values of  $\hat{A}^2/\text{degree of freedom (DOF)}$  is 0.39. For the purpose of comparison, the result with  $\zeta y = 0:0$ , i.e. the result of an isotropic emission fireball, is given in the figure by the white circles with  $\hat{A}^2/\text{DOF}=3.34$ .

It should be noted that there is no energy dependence of physical effects in  $\nu$ -Em collisions to be investigated in this paper. The neutrinos produced in the FNAL accelerator were so-called

“wide band beam” neutrinos with energies from 3 to 210 GeV, a most probable energy of 20 GeV and mean energy of 43.5 GeV. The effects studied in this paper are averaged over this energy range, without the possibility of studying their energy dependence.

Figures 2-4 presents the pseudorapidity distributions of shower particles produced in interactions of neutrinos with target nuclei H, C/N/O and Ag/Br in emulsion, respectively. The histograms with error bars are the experimental data [2]. The event numbers corresponding to target nuclei H, C/N/O and Ag/Br are 79, 164 and 82, respectively. The black circles in the figures are our Monte Carlo calculated results with  $\langle y \rangle = 1:0$ . In our calculation, the simulated particle number for each type of target is  $1 \times 10^5$ . The values of  $y_c$  for target nuclei H, C/N/O and Ag/Br are 2.5, 2.4 and 2.0, respectively. The values of  $\hat{A}^2/\text{DOF}$  for the above three targets are 0.84, 0.56 and 1.14, respectively. For the purpose of comparison, the results of an isotropic emission fireball for the three targets are plotted in Figs. 2-4 by the white circles with  $\hat{A}^2/\text{DOF}=1.84, 2.21$  and 6.04, respectively.

We have to point out that the division into three subsets (H, C/N/O and Ag/Br) was done using the number  $N_h$  of fragments emitted from the struck target nuclei. We consider all events with  $N_h = 0$  as  $\nu$ -H interactions, with  $1 \leq N_h \leq 6$  as  $\nu$ -C/N/O collisions and all events with  $N_h \geq 7$  as collisions with Ag/Br. Of course, such criteria are very raw. It has to be stressed that interactions characterized by  $N_h = 0$  contain interactions with hydrogen as well as peripheral collisions with C/N/O and Ag/Br. Interactions with  $1 \leq N_h \leq 6$  contain collisions with C/N/O but also peripheral collisions with Ag/Br. Interactions with  $N_h \geq 7$  contain semicentral and central collisions with Ag/Br [2]. We can also divide  $\nu$ -Em collisions into two groups: the first group characterized by  $N_h \leq 7$  which includes interactions with hydrogen, C/N/O nuclei, and peripheral collisions with Ag/Br nuclei, and the second group characterized by  $N_h > 7$  which contains semicentral and central  $\nu$ -Ag/Br collisions [1]. In fact, there is no perfect method of classifying events due to the limitation of the emulsion technique. The value of  $N_h$  is also a measurement of the impact parameter. Figures 2-4 can be also regarded as the dependence of pseudorapidity distribution on target fragment multiplicity.

From Figs. 1-4 one can see that the thermalized cylinder model gives a good description of the pseudorapidity distribution of shower particles produced in neutrino-emulsion collisions over an energy range from 3 to 210 GeV. An isotropic emission fireball gives a narrower and higher distribution in the concerned energy range. It is possible to describe the data by an isotropic emission fireball with flows [9].

We see different  $y_c$  for different target nuclei. The heavy target nuclei (Ag/Br) have a small  $y_c$  and the light target nuclei (H, C/N/O) have a large  $y_c$ . This means that the effect of secondary collisions in heavy target nuclei is greater than that in light target nuclei. Secondary collisions between shower particles and spectator nucleons, as well as shower particles and shower particles, in neutrino-emulsion collisions lead to an increasing emission angle and decreasing pseudorapidity. This effect displays the extension of the pseudorapidity distribution towards the target fragmentation region (low- $\eta$  region).

The values of  $\langle y \rangle$  for the three types of target nuclei are the same. This reflects that the three types of target nuclei have the same stopping power, i.e. the same participant nucleon number for the given incident neutrinos. We can say only one nucleon joins the interaction directly. Other nucleons in the target are the spectators in which the secondary collisions had happened.

In neutrino-induced reactions, there is no contribution of leading hadrons. The shower particle pseudorapidity distribution is qualitatively symmetrical. In hadron-induced reactions, the

leading hadrons contribute in a higher pseudorapidity region. The pseudorapidity distribution has a peak or a long tail in the high pseudorapidity region [6]. The pseudorapidity distribution of shower particles in neutrino-emulsion collisions is approximately of the Gaussian type [2]. If the contributions of leading hadrons can be neglected over a similar energy range, the experimental results show that the pseudorapidity distributions of shower particles in pion-emulsion, proton-emulsion, and nucleus-emulsion collisions are approximately of the Gaussian type as well [10-12]. The thermalized cylinder model can describe the pseudorapidity distribution of the Gaussian type [6].

We can describe qualitatively the thickness of the thermalized cylinder. The geometrical cross section of the participant is regarded as the transverse size of the cylinder. In high-energy nucleus-nucleus collisions, a thick thermalized cylinder is formed because many firestreaks are formed along the direction of the incident beam. In hadron-induced reactions, a thin thermalized cylinder is formed because a few hadrons participate in the collisions. In neutrino-induced reactions, a thinner thermalized cylinder is formed because the participants are only the incident neutrino and the target nucleon. The length of the thermalized cylinder can be described by  $2\zeta y$ . The width of the pseudorapidity distribution can be described by  $\frac{3}{4} + 2\zeta y$ . In the neutrino-emulsion collisions, the thermalized cylinder length is 2.0, and the pseudorapidity distribution width is about 2.9.

In conclusion, the thermalized cylinder model gives a good description of the pseudorapidity distributions of shower particles produced in neutrino-emulsion collisions over an energy range from 3 to 210 GeV. An isotropic emission fireball gives a narrower and higher distribution for the reaction system. The effect of secondary collisions in heavy target nuclei is greater than that in light target nuclei. The three types of target nuclei in emulsion have the same stopping power for the given incident neutrinos.

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