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S.M.Eliseev

SPACE-TIME PICTURE OF DEEP INELASTIC LEPTON-NUCLEUS COLLISIONS (CUMULATIVE NUCLEON PRODUCTION AND HADRON FORMATION TIME)

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1. Introduction

One question of fundamental importance in QCD is the hadronisation - mechanism which converts quark and gluon quanta into integrally-charged final state hadrons. According to the parton model, a high energy lepton interacts with a nucleon transferred a considerable amount of the momentum to one of the quarks of the nucleon. As a result, lepton-nucleon scattering allows us to study the hadronisation of quark-diquark jets (or strings) in vacuum. For lepton-nucleus scattering these jets may interact with spectator nucleons. In other words lepton-nucleus scattering provides a nontrivial possibility to study space-time evolution of jets inside a nuclear matter. Clearly, a full Monte Carlo study with a realistic simulation should be done to verify these opportunity. In contrast with hadroprodaction, intranuclear cascading can be studied without complicate effects of projectile rescattering or interactions of projectile constituent.

The physics of such reactions [1-6] is very interesting. However, at the present time it is not possible to calculate accurately all peculiarities of such reactions according to 'first principles' of QCD. Instead of this we apply a simple phenomenological concept of the formation zone. This phenomenon was studied by Landau and Pomeranchuk [7] and Nikolaev [8]. The QCD analysis was performed by Brodsky, Bodwin and Lepage [9].

The aim of this work is to examine a multiproduction process of charged-current deep inelastic ν_μ-emulsion scattering and to estimate quantitatively the value of a formation length. We also concentrate on the cumulative protons (i.e. the final state protons from backward angles).

2. The model

The conceptual ideas of our model are very straightforward and transparent. We assume that the interaction between incident an lepton and a target nucleus takes place in a lepton-nucleon interaction. The nucleus is excited by a series of collisions between secondaries (produced in the first lepton-nucleon interaction) and the intranuclear nucleons. At high energies the secondaries traverse the nucleus in such a short time that nucleons cannot rearrange themselves until the probe has left. In the main the target nucleons are just static spectators,so that the scattering problem is in the first approximation a sequence of two-body ones. This process continues until all secondaries escape target nucleus. A part of the energy is spread through the nucleus to produce a fully-equilibrated nucleus which then decays statistically [10]. The process of generation of particles is simulated by the Monte Carlo method.

The cross sections of intranuclear interactions and the characteristics of secondary particles (multiplicities, rapidity and transverse momentum distributions) at different energies are taken from experiments with free nucleons [1-6]. Elastic and inelastic interactions, charge exchange and absorption of slow pions inside the nucleus are taken into account. Nuclear effects such as the Fermi motion and Pauli blocking are all taken into consideration as before [10].

Since the interaction cross section of neutrino with a nucleon is small, we assume that the neutrino can interact with any nucleon of the nucleus with equal probability, i.e.

$$\sigma(\nu + A) = \sum_{i=1}^{A} \sigma_i(\nu + N) \tag{1}$$

where $\sigma_i(\nu + N)$ is the interaction cross section of a neutrino with a separate nucleon. Following experiments and the quark parton model, we take into account that the interaction cross section of neutrino with

a neutron is twice that with a proton, i.e.
$\sigma(\nu + n)/\sigma(\nu + p) \approx 2$

The Fermi gas model of the nucleus is utilized. The nuclear density is taken from the Woods-Saxon expression

$$\rho(r) \sim 1/(1 + e^{(r-c)/\alpha}) \tag{2}$$

with the parameters $\alpha = 0.57$ fm and $c = 1.19A^{1/3} - 1.61A^{-1/3}$ fm. Moreover, three-dimensional geometry is used in our calculations.

According to the emulsion composition, a nucleus (of mass number A) with which the neutrino would interact is drawn randomly. Then, knowing the nuclear density, we can place A nucleons inside the nucleus. For each simulation of A nucleons, we fix the coordinates of the center of intranuclear nucleons throughout the process of developing the cascade. The characteristics of charged particles produced in the first νN interaction inside the nucleus, are taken from experimental data [1-6]. These input data were obtained from reactions induced by the same neutrino beam used in the present work. The multiplicities of neutral particles (pions) are taken from the experiment [10]. These multiplicities for νn and νp are respectively

$$n_{\pi^0} = 0.72 + 0.22 n_{\pi^-} \tag{3}$$

and

$$n_{\pi^0} = 0.14 + 0.73 n_{\pi^-} \tag{4}$$

where n_{π^-} is the multiplicity of negatively charged particles. The angular and momentum distributions of neutral particles are assumed to be the same as those of positively and negatively charged particles. The calculations were carried out with some program and assumptions of our previous work [10]. The space-time characteristics of lepton-nucleon interactions inside the target nucleus were taken into consideration. After time τ from the intranuclear collision the cross section for the next collision of a secondary particle with a nucleon inside the nucleus is given by

$$\sigma_{hN} = \sigma_{hN}^{exp}(1 - e^{-\tau/\tau_0}) \tag{5}$$

where σ_{hN}^{exp} is the experimentally determined total interaction cross section of a hadron with a free nucleon at the corresponding energy of the secondary particle produced. Thus, only after a relatively long time τ does the cross section of intranuclear interaction reach the value σ_{hN}^{exp}. In our equation, the parameter τ_0 is equal to $1/m_0$ and is a certain characteristic mass corresponding to the formation time of the secondary generated hadron in its rest frame of reference. The time τ is equal to $L/\beta\gamma$ where L is the secondary particle range inside the nucleus(the distance traversed by the secondary particle of velocity $\beta(=v/c)$ from its generation point to the point of interaction with a nuclear nucleon). The Lorentz factor of the generated particle is $\gamma = (1-\beta^2)^{-1/2}$. The equation for σ_{hN} can be rewritten in the form

$$\sigma_{hN} = \sigma_{hN}^{exp}(1 - e^{-m_0 L/\beta\gamma c}) \tag{6}$$

It is to be noted that when $m_0 \to \infty$, our model will reduce to the old - fashioned cascade model in which secondary hadrons are produced instantly in the intranuclear interactions. In the present model, at a finite value of m_0,secondary particles (e.g. pions) are not formed instantly but after a certain time.According to equation (6), the cross section of the intranuclear interaction is calculated as a function of the mean free path L and the velocity β. From (6) it is seen that slow secondary particles interact inside the target nucleus more frequently than the fast ones. The most rapid secondary particles produced in the first νN interaction may fly out without interaction with the subsequent nucleon inside the target nucleus.

3. Experiment

The present data discussed below have been obtained in the Fermilab experiment. In this experiment, the nuclear emulsion was exposed in the wide-band neutrino beams. The neutrino energy spectrum peaks at about 15 GeV, and extends to about 200 GeV. Nuclear emulsion offers a higher effective target mass ($< A >\sim 80$) than other track-sensitive targets. This allow us to study different striking phenomena(the interaction of quark-gluon jets and cascading of soft particles in nucleus, formation zone effects etc).

The secondary particles in high-energy experiments with emulsion has been divided into three classes [6]. The first includes relativistic

particles or shower s (s-particles) of velocity $\beta > 0.7$. These particles are almost all charged pions of kinetic energy ≥ 60 MeV and fast protons of kinetic energy ≥ 400 MeV. The second class consists of grey track particles g (g-particles) of range $0.23 \leq \beta \leq 0.7$. They are mainly protons in the energy range 27-400 MeV. The third class is black track particles b (b-particles). They are low energy particles emitted mainly due to evaporation.

4. Results and discussion

The average multiplicities of shower and grey particles, produced in charged-current ν_μ-emulsion interaction, compared with the corresponding quantities calculated in our model at different values of m_0 are presented in Table 1.

Table 1. The average multiplicities of s and g particle produced in charged-current ν_μ-emulsion interactions obtained in the experiment compared with the values calculated according to our model.

Experimental data[1-6]	Calculations of the model		
	$m_0 = \infty$	$m_0 = 0.94$ GeV	$m_0 = 0.40$ GeV
N_s 5.28±0.26	6.45±0.06	5.60±0.04	5.12±0.03
N_g 1.33±0.15	2.08±0.03	1.71±0.02	1.35±0.02

One can see from this table that the experimental and calculated data at $m_0 = 0.4$ GeV are in good agreement.

Figure 1 shows the multiplicity distribution of shower particles for charged-current ν_μ-emulsion interactions. The dotted curve corresponds to calculation according to our model with formation zone parameter $m_0 = \infty$. The solid line is the prediction with m_0=0.4 GeV. The experimental data are taken from [6].

Figure 2 compares for $m_0 = 0.4$ GeV the ratio, R_η of average multiplicity of shower particles in $\nu - Em$ collisions over that in $\nu - N$ collisions, versus pseudorapidity.

In figure 3, the pseudorapidity distribution of s-particles is compared with expectations [6]. Once again, the calculated distribution for $m_0 = 0.4$ GeV adequatly explains the major features of ν_μ - emulsion interactions.

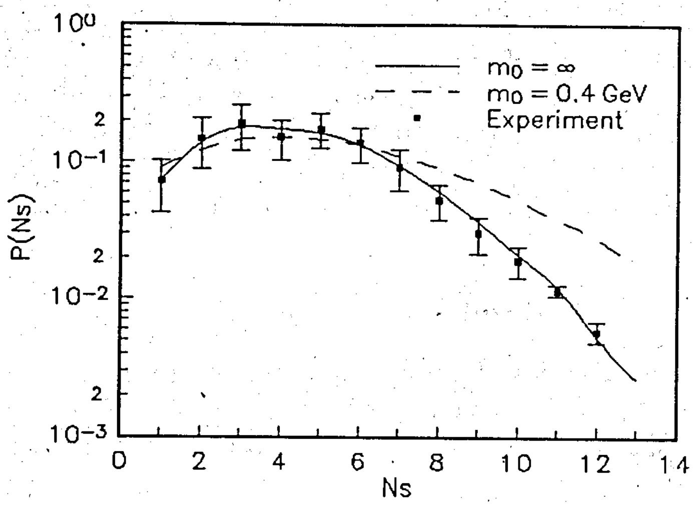

Figure 1: The multiplicity distribution of shower particles produced in neutrino - emulsion collisions

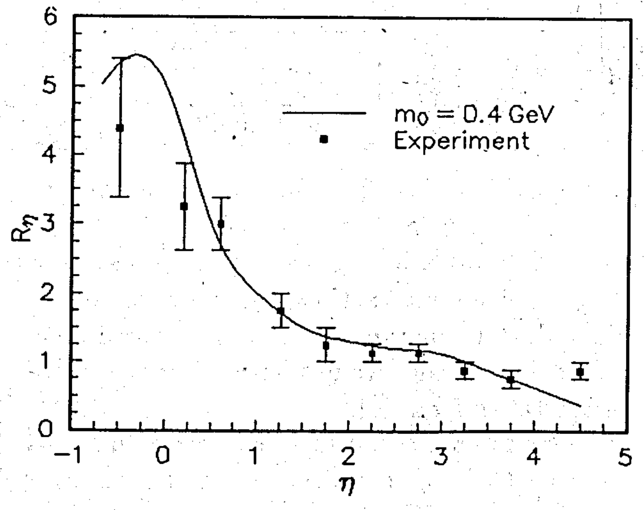

Figure 2: The ratio, R_η of average produced multiplicity in neutrino - emulsion collisions over that in neutrino - nucleon, as a function of pseudorapidity η

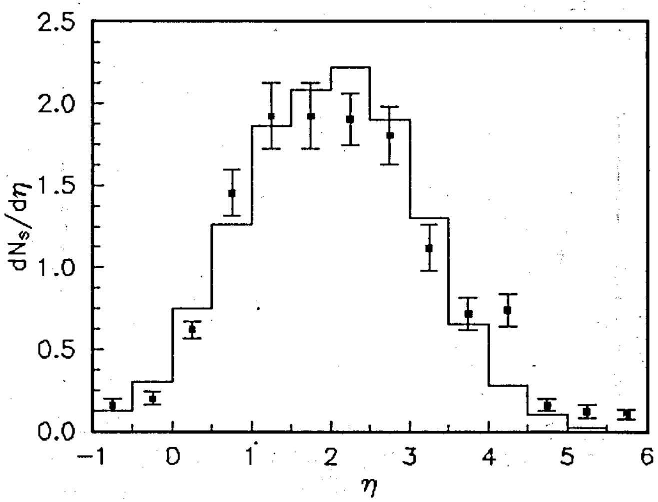

Figure 3: Pseudorapidity distribution of shower particles

The model predicts also the angular distributions. As an example of the results obtained, angular distributions of g-particles are displayed in figure 4. The agreement between all the measured and calculated values is impressive.

It is important to note that in our approach the evolution of quark-gluon jets in nuclei is accompaned by a nucleon emission at backward angles and momentum $\geq$ 300 MeV/c. In our model the underlying mechanism responsible for energetic particles production was quasideuteron intranuclear absorption process. Such cumulative protons(cp) were observed in deep inelastic charged - current neutrino - emulsion interactions[5]. The experimental multillicity of cp 0.33$\pm$0.07 are in good agreement with the calculated one equal to 0.29.

In Table 2 we compare calculated maltiplicities of g and b particles accompanied by a different number k of cp with data [11]. Figure 5 displays the spectrum of protons at backward angles. The solid curve indicate our calculation. The parameter is $m_0 = 0.4$ GeV. We see that the nucleon emission process at backward angles can be divided into two parts with a different slope parameter of the spectra. In our approach the evaporation mechanism is responsible for production of protons with momentum $\leq$ 300 MeV/c. However, highly energetic nucleons are emitted in a direct process of neutrino - nucleus collision.

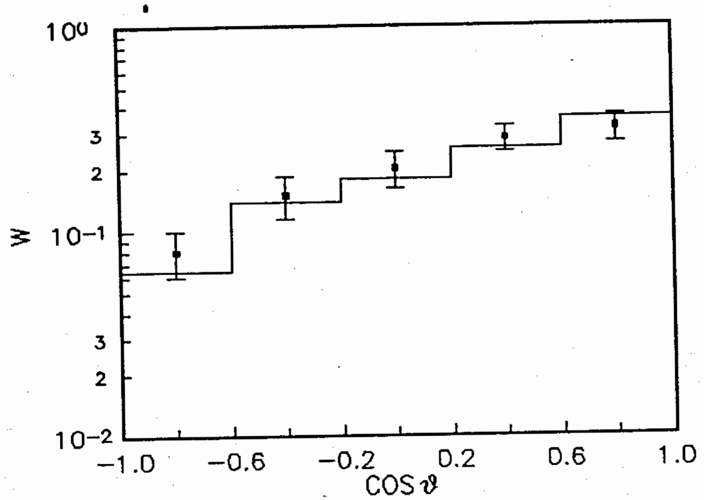

Figure 4: Angular distribution of gray protons

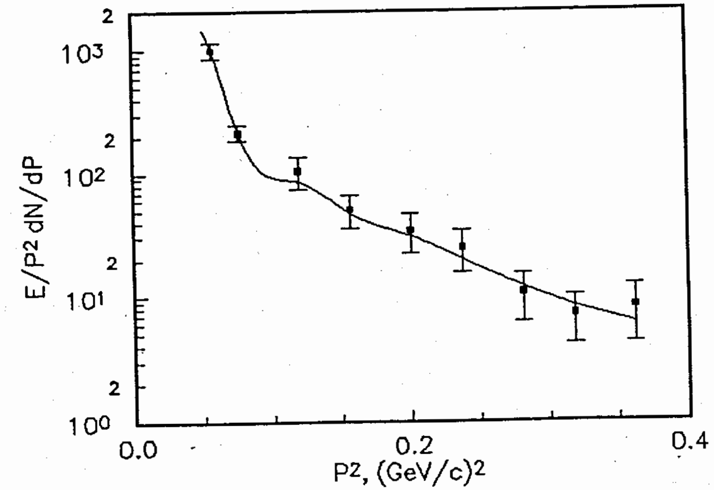

Figure 5: Momentum distribution of cumulative protons

Table 2. The average multiplicity of N_g and N_b particles associated with a different number k=0,1 and ≥ 2 of final state cumulative protons produced in charged-current ν_μ-emulsion interactions. The experimental data [11] are given in parentheses.

k	N_g $(\vartheta \leq \pi)$	N_g $(\pi/2 \leq \vartheta \leq \pi)$	N_b
0	1.1 (1.4±0.1)	1.1 (1.4±0.1)	3.9 (4.4±0.2)
1	2.8 (3.0±0.3)	1.8 (2.0±0.3)	5.2 (5.4±0.6)
≥ 2	5.6 (5.6±0.5)	3.0 (3.1±0.6)	9.0 (10.±1.0)

In this way we can also introduce in our simple model some exotic states (for example intranuclear multiquarks bags) to produce more energetic cumulative protons. Any discussion of this possibility and a more detailed investigation of the formation zone effect are, however, beyond the scope of the present analysis. Work along these lines is in progress. Our calculations roughly agrees with the previous estimates [12] while providing a lot of additional information concerning production of cumulative nucleons. We have shown that our model could be very useful not only to reveal the main physical effects of deep inelastic scattering, but also to perform accurate quantitative analyses and large systematics.

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