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Deep inelastic scattering of leptons on nuclei: Hadron formation, cumulative particles production

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Abstract. We introduce a space-time model for propagation of quark and gluon jets in nuclear matter, taking into account the formation zone phenomena (Landau-Pomeranchuk-Migdal, LPM, effect) and cascading of soft particles in a nucleus. The measured final-state hadrons, including cumulative nucleons produced in neutrino interactions with nuclei are investigated and the formation length of hadrons is obtained.

PACS. 13.60.Le Meson production – 13.15.+g Neutrino interactions – 25.30.Pt Neutrino scattering

1 Introduction

Recently, there has been considerable interest in the study of highly relativistic ion collisions. Such an interest stems from the possibility of creating hadron matter of high-energy density. The creation of a domain of high-energy density may allow one to study matter under unusual state, *i.e.*, quark-gluon plasma. In order to investigate the possible emergence of quark-gluon plasma, it is necessary to understand the properties of ordinary multiparticle productions mechanisms in more simple conditions than in the relativistic collisions of heavy ions (see, *e.g.*, [1,2]).

In addition, the question of fundamental importance in QCD is the hadronization-mechanism which converts quark and gluon quanta into integrally charged final-state hadrons. Landau, Pomeranchuk and Migdal [3,4] investigated the classical radiation process in the random field inside the medium. They showed that after the first scattering the electron “shakes off” its field and until this field is re-established the scattering takes placed without emission of a photon leading to suppression of the radiation. The role of long distances in physics of strong interactions was noted by Feinberg [5].

Lepton-nucleus scattering provides a nontrivial possibility to study space-time evolution of jets inside a nuclear matter. In contrast with hadron production, intranuclear cascading can be studied without complicate effects of projectile rescattering or interactions of projectile constituent [6,7]. The physics of such reactions [6,7] is very interesting. However, at the present time it is not possible to calculate accurately all peculiarities of such reactions according to “the first principles” of QCD. Instead of this we apply a simple phenomenological concept of the formation zone (see, *e.g.*, ref. [6]). The last few years have witnessed a great revival of interest in inclusive DIS (HERMES, NOMAD and other collaborations) [8–10].

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 production of cumulative protons (CP), *i.e.* the final-state protons from backward angles.

2 The model

For the time being, the explicit theoretical description of hadronization is difficult, as it is impossible to treat the soft fragmentation processes in the framework of QCD. Consequently, one has to a address this process with model calculation. We developed a cascade model of multiproduction from neutrino-nuclei interaction. (More detailed description of the model can be found in ref. [11]).

We assume that the interaction between an incident lepton and a target nucleus takes place via a lepton-nucleon interaction. The nucleus is excited by a series of collisions between secondaries, produced in the first lepton-nucleon interaction. At high energies the secondaries traverse the nucleus in such a short time that the nucleons cannot rearrange themselves until the probe has left. In short, the target nucleons are just static spectators, so that the scattering problem is in first approximation a sequence of two-body scattering processes. This process continues until all secondaries escape the target nucleus. A part of the energy is spread through the nucleus to produce a nucleus in equilibrium, which then decays statistically [11]. The process of particle generation is simulated by a Monte Carlo method.

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The characteristics of the interactions of the neutrino and of the produced particles with nucleons in nucleus are taken from experiments with free nucleons [11–13]. 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. 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, $\sigma(\nu + n)/\sigma(\nu + p) \approx 2$. Nuclear effects such as the Fermi motion and Pauli blocking are also taken into consideration [11]. The space-time characteristics of lepton-nucleon interactions inside the target nucleus are taken into consideration. After a 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

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

where $\sigma_{hN}^{\exp}$ 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 the cross-section of intranuclear interaction reaches the value $\sigma_{hN}^{\exp}$. In our equation, the parameter τ_0 is characteristic for the formation time of the secondary generated hadron. The equation for σ_{hN} can be rewritten in a formation parameter L. It should be noted that for $L \to 0$ ($\tau_0 \to 0$), our model will reduce to the old fashioned cascade model in which secondary hadrons are produced instantly. In the present model, at a finite value of L, secondary particles (*e.g.*, pions) are formed after a certain time.

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

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

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

According to the matter composition, a nucleus (of mass number A) with which the neutrino would interact is chosen 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-particle production in the first νN interaction inside the nucleus are taken from experimental data [11–13], which were obtained from reactions induced by the same neutrino beam used in the present work. The multiplicities of neutral particles (pions) are also taken from the experiment (see [11–13]). These multiplicities for νn and νp are

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

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.

Table 1. The average multiplicities of s- and g-particles, produced in charged-current ν_μ-emulsion interaction.

	Experimental	Calculations of the model		
	data	$L = 0.2\,\mathrm{fm}$	$L = 0.5\,\mathrm{fm}$	$L = 1\,\mathrm{fm}$
N_s	5.28 ± 0.26	5.60 ± 0.04	5.12 ± 0.03	4.08 ± 0.02
N_g	1.33 ± 0.15	1.71 ± 0.02	1.35 ± 0.02	0.82 ± 0.01

Table 2. The average multiplicity of N_g and N_b particles associated with a different number $k = 0, 1$ and $k \geq 2$ of final-state cumulative protons. The experimental data 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 ($10. \pm 1.0$)

3 Results and discussion

In this section we present the theoretical results for neutrino-emulsion interaction and compare with experimental data [11–13]. (The full list of the references of experimental data can be found in ref. [11].) The neutrino energy spectrum peaks at about 15 GeV, and extends to about 200 GeV.

Secondary particles in high-energy experiments with emulsion are divided into three classes [11]. The first includes relativistic, hot *shower* particles (s-particles) of velocity $\beta > 0.7$. These particles are almost all charged pions of kinetic energy $\geq 60\,\mathrm{MeV}$ and fast protons of kinetic energy $\geq 400\,\mathrm{MeV}$. The second class consists of *grey*-track particles (g-particles) with $0.23 \leq \beta \leq 0.7$. Those are mainly protons in the energy range 27–400 MeV. The third class consists of *black*-track particles (b-particles). They are low-energy particles emitted mainly due to evaporation.

The average multiplicities of s- and g-particles, produced in charged-current ν_μ-emulsion interactions are compared with the corresponding quantities calculated in our model at different values of L and are presented in table 1. One can see from table 1 that the experimental and calculated data at $L = 0.5\,\mathrm{fm}$ are in good agreement.

It is important to note that in our approach the evolution of quark-gluon jets in nuclei is accompanied by a nucleon emission at backward angles and with momentum $\geq 300\ \mathrm{MeV}/c$. In our model the underlying mechanism responsible for energetic particle production is as quasi-deuteron intranuclear absorption process. Such cumulative protons were observed in deep inelastic charged-current neutrino-emulsion interactions. The experimental multiplicity of CP 0.33 ± 0.07 is in good agreement with the calculated one and equal to 0.29 [11–13].

In table 2 we compare our calculated multiplicities of g- and b-particles accompanied by a different number k of cumulative protons with data.

Figure 1 shows the multiplicity distribution of particles for charged-current ν_μ-emulsion interactions. The dotted

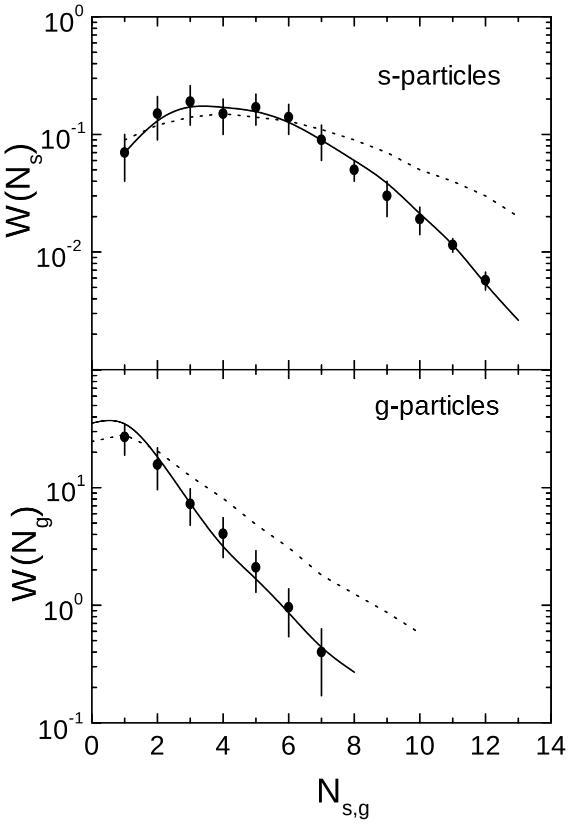

Fig. 1. Multiplicity distribution of s- and g-particles. See main text for details.

curve corresponds to calculation according to our model with a formation zone parameter $L = 0$. The solid line is the prediction with $L = 0.5\,\text{fm}$. The experimental data are taken from refs. [11–13].

Figure 2 displays invariant momentum distributions for backward going protons. The solid line is the prediction with $L = 0.5\,\text{fm}$. 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 $\leq 300\ \text{MeV}/c$. However, highly energetic nucleons are emitted in a direct process of neutrino-nucleus collision (the absorption of pions in nucleus by a correlated pair of nucleons along with rescattering).

In this way, we can include 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.

In summary, the cascade-evaporation model for the description of produced particles from deep inelastic collisions of neutrino with nuclei was developed. The model can be used for the extraction of the information of space-time property of the process of the formation of the secondary particles. Note that the formation time of particles plays a leading role in the various present-day investigations of the different nuclear reactions [14–17]. Moreover, the effect of the formation time is essential for the search of a powerful signature for quark-gluon plasma formation (see, *e.g.*, ref. [14]). We have shown that our model can 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.

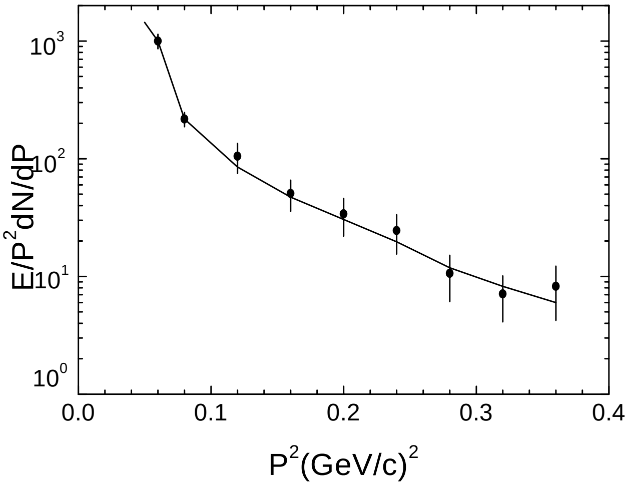

Fig. 2. Invariant momentum distributions for backward-going protons. See main text for details.

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