Inclusive characteristics of neutrino scattering at the nuclei of a photographic emulsion at energies of $E_\nu = 3-30$ GeV (The E-128 Experiment)

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This paper presents the results of studies of inclusive neutrino–nuclear reactions for $E_\nu < 30$ GeV, carried out on the SKIF neutrino spectrometer in the E-128 experiment (Serpukhov). Values are obtained for the integrals of the nucleon structure functions, and the contributions of quarks, antiquarks, and gluons to the nucleon momentum are determined. © *1996 American Institute of Physics.* [S1063-7761(96)00108-4]

Most of the experimental data obtained so far on inclusive neutrino scattering at nuclei relate to the region of high neutrino energies, $E_\nu > 30$ GeV, and consequently to large values of the square momentum Q^2 transferred from the lepton vertex to the hadronic system. These experimental results are well described by QCD.

However, in the region of comparatively low neutrino energies ($E_\nu < 30$ GeV), the perturbation methods of QCD become inapplicable because of the increase of the effective color charge $\alpha_s(Q^2)$ with decreasing Q^2 and the asymptotic character of the series for the Gell-Mann–Low function,

$$\beta(\alpha_s(Q^2)) = \frac{d\alpha_s(Q^2)}{d \ln Q^2},$$

which diverges.[1] Therefore, one has to use semiphenomenological techniques to adequately describe deeply inelastic scattering processes in the range[1)] $Q^2 \leq 1$ GeV^2. One mainly uses the quark–parton model of Refs. 2 and 3 and its modifications[4] with Q^2-dependent distribution functions, which describe the nucleon structure functions in the form of Lipatov–Altarelli–Parisi evolution equations.[4]

An important feature of lepton–nucleon scattering is also that it is not the quark–gluon structure that is experimentally studied, but the associated hadronic state, whose field is formed over a long time and is described by large values of the effective charge $\alpha_s(Q^2)$. In this case, even when Q^2 is large and it is possible to use perturbation theory, the nucleon mass M cannot be neglected, because of the $M \to 0$ singularity in the mass logarithms $\ln(Q^2/M^2)$, which in the end causes the Bjorken scaling to break down.

By accumulating experimental data by various techniques and over the largest possible ranges of the kinematic variables, it becomes possible to determine the parameters of specific models. This paper analyzes the data obtained in the E-128 experiment on the SKIF spectrometer, for which the neutrino-beam energy of the IFVÉ accelerator was $E_\nu = 3-30$ GeV. The experiment was based on a hybrid technique: a nuclear photographic emulsion was used as a vertex detector–target, while a streamer chamber in a magnetic field, in combination with a muon identifier, was used as a target-indicating and spectrometric detector. The physical problems of the experiment are explained in detail in Ref. 6, and descriptions are given of the streamer chamber in Ref. 7, of the emulsion target in Ref. 8, and of the spectrometer as a whole in Ref. 9.

To study the inclusive characteristics in neutrino–nuclear interactions, 670 neutrino-interaction events in the charge current process

$$\nu N \to \mu^- X \tag{1}$$

were selected on the SKIF spectrometer, where N is a nucleon of the target atom, and X is the final hadronic state. To reduce the contribution of background processes to the specimen being studied, we also required that the following selection criteria on the muon momentum and the neutrino energy be fulfilled:

$$|\mathbf{p}_\mu| > 0.5 \text{ GeV}/c, \quad E_\nu > 3.0 \text{ GeV}.$$

The restriction on the muon momentum makes it possible to eliminate background neutrino interactions that occur via the neutral-current channel, while the restriction on the neutrino energy eliminates the neutron background.

For a kinematic description of the process (1), it is sufficient to use any three kinematic variables from the following set of Lorentz invariants:

the reconstructed neutrino energy,

$$E_\nu = E_\nu^{\text{vis}} + \Delta\nu = E_\mu + \nu^{\text{vis}} + \Delta\nu; \tag{2}$$

the energy transferred to the hadrons,

$$\nu=\frac{P_N q}{M}=\frac{P_N(P_\nu-P_\mu)}{M}; \quad (3)$$

the square of the momentum transferred from the lepton vertex to the hadronic system,

$$Q^2=-q^2=-(P_\nu-P_\mu)^2; \quad (4)$$

the square of the invariant interaction energy,

$$S=(P_N+P_\nu)^2; \quad (5)$$

the square of the invariant mass of the hadronic system,

$$W^2=[P_N+(P_\nu-P_\mu)]^2=M^2+2M\nu-Q^2; \quad (6)$$

the dimensionless Bjorken scaling variables,

$$x=\frac{Q^2}{2M\nu}=\frac{Q^2}{2P_N(P_\nu-P_\mu)}, \quad (7)$$

$$y=\frac{\nu}{E_\nu}=\frac{P_N(P_\nu-P_\mu)}{ME_\nu}. \quad (8)$$

Equations (2)–(8) employ the following notation: E_ν^{vis} is the total energy of all the recorded particles; ν^{vis} is the total energy of the recorded hadrons; $\Delta\nu$ is the correction to the unrecorded energy; E_μ is the muon energy; $P_\nu=(E_\nu, c\mathbf{p}_\nu)$, $P_\mu=(E_\mu, c\mathbf{p}_\mu)$, and $P_N=(M,0)$ are the 4-momenta of the neutrino, the muon, and the nucleon, respectively; and M is the nucleon mass.

The hadron energy was determined as the sum of the energies of all the hadrons reconstructed in the event, taking into account energy corrections from unrecorded neutral and low-energy particles, intranuclear energy losses, and also the conditions under which the experiment was carried out. In determining corrections for undetected energy, the results of Ref. 10 were used. Corrections for the energy expended in exciting the nucleus were introduced from an analysis of the total energy of the "evaporative" particles experimentally measured in the events found from the target designations in the photographic emulsion. A correction was also introduced for the incomplete angle of coverage by the target-indicating track detector of the kinematically attainable region for the escape of secondary particles. The total value of the corrections was 20% of the energy of the recorded hadrons.

Figure 1 shows the distribution of the selected neutrino interactions in Q^2. Good agreement of the experimental and calculated results is observed. It follows from this distribution that a large part of the experimental data lies in the interval $Q^2=0.2$–$2.0\ \text{GeV}^2$, where the quark–parton model is directly applicable. If the source of the scaling breakdown in the region of small Q^2 is the nonzero mass of the target, the deviation from scale invariance can be reconstructed by converting the scaling variable x, which assumes that the nucleon mass is zero, into the variable $x'=x/(1+M^2x^2/Q^2)$.

The inclusive differential cross section of neutrino scattering from a nucleon is expressed in a charged-current process in terms of three nucleon structure functions, which in general are functions of two variables, x and Q^2 (or ν):

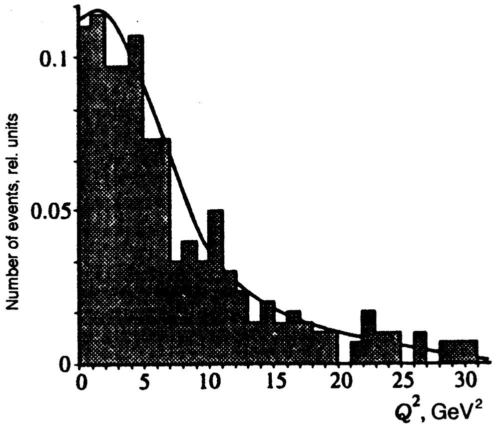

FIG. 1. Normalized distribution over Q^2 of neutrino interactions in the charged-current process. The curve corresponds to a Monte Carlo calculation.

$$\frac{d^2\sigma_{cc}^{\nu N}}{dx\,dy}=\frac{G_F^2 M E_\nu}{\pi}\left[\frac{y^2}{2}2xF_1^{\nu N}(x,Q^2)+\left(1-y-\frac{Mxy}{2E_\nu}\right)\times F_2^{\nu N}(x,Q^2)+y\left(1-\frac{y}{2}\right)xF_3^{\nu N}(x,Q^2)\right]. \quad (9)$$

In the framework of the four-quark (u, d, s, c) parton model, the structure functions depend only on one variable, expressed in terms of the distributions over the fraction x of the momentum of the quarks and antiquarks in the nucleon:

$$F_2^{\nu N}(x)=q(x)-\bar{q}(x), \quad (10)$$

$$xF_3^{\nu N}(x)=q(x)-\bar{q}(x)+2x[s(x)-c(x)], \quad (11)$$

$$2xF_1^{\nu N}(x)=F_2^{\nu N}(x), \quad (12)$$

where

$$q(x)=x[u(x)+d(x)+s(x)+c(x)], \quad (13)$$

$$\bar{q}(x)=x[\bar{u}(x)+\bar{d}(x)+\bar{s}(x)+\bar{c}(x)]. \quad (14)$$

Integrating the structure functions of Eqs. (10) and (11) while neglecting the contributions of the s and c quarks, we get

$$B=\frac{\int(q-\bar{q})dx}{\int(q+\bar{q})dx}=\frac{\int xF_3^{\nu N}(x)dx}{\int F_2^{\nu N}(x)dx}, \quad (15)$$

$$a=\frac{1-B}{2}=\frac{\int\bar{q}dx}{\int(q+\bar{q})dx}, \quad (16)$$

$$R=1-\frac{\int 2xF_1(x)dx}{\int F_2(x)dx}. \quad (17)$$

In the quark–parton model, it follows from the Callan–Gross relation, given by Eq. (12), that the parameter $R=0$, parameter B characterizes the relative contribution of the valence quarks to the cross section, and the parameter a is the relative contribution of the antiquarks.

Equations (10)–(14) make it possible to write the differential cross section of Eq. (9), neglecting the $Mxy/2E$ term, as

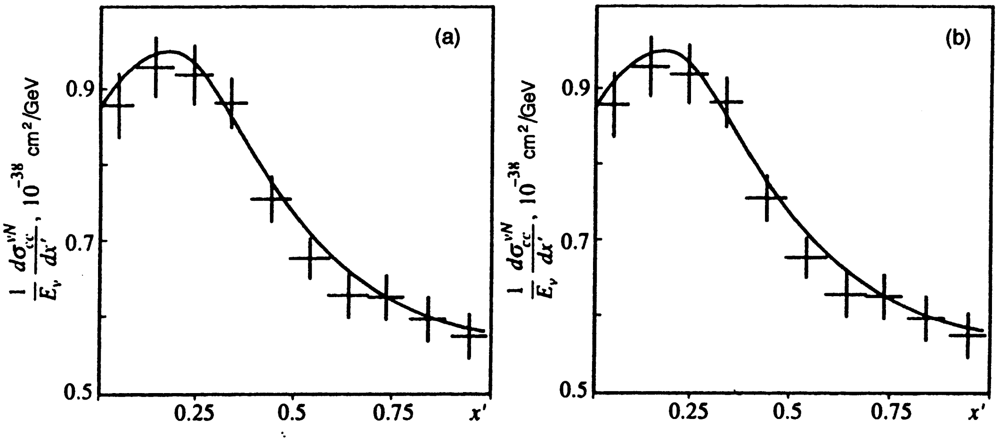

FIG. 2. Inclusive spectra over the variables y (a) and x' (b).

$$\frac{d^2\sigma^{\nu N}_{cc}}{dx\,dy}=\frac{C_F^2 M E_\nu}{\pi}[q(x)+\bar{q}(x)(1-y^2)]. \tag{18}$$

Independently integrating Eq. (18) over y and x between zero and infinity, we get the differential cross sections for neutrino scattering from a nucleon:

$$\frac{d\sigma^{\nu N}_{cc}}{dx}=\frac{C_F^2 M E_\nu}{\pi}\left[q(x)+\frac{1}{3}\bar{q}(x)\right], \tag{19}$$

$$\frac{d\sigma^{\nu N}_{cc}}{dy}=\frac{C_F^2 M E_\nu}{\pi}\int F_2^{\nu N}(x)dx\left[\frac{1+B}{2}+\frac{1-B}{2}(1-y)^2\right]. \tag{20}$$

The approximation of Eq. (20) by

$$\frac{1}{E_\nu}\frac{d\sigma^{\nu N}_{cc}}{dy}=A[(1-a)+a(1-y)^2], \tag{21}$$

as can be seen from Fig. 2a, gives a good description of our experimental results. A calculation using Eq. (21) gives the following values of parameters B and a:

$$B=0.88\pm0.04, \quad a=0.06\pm0.02.$$

It then follows from Eqs. (15) and (16) that

$$\int\left(q+\frac{1}{3}\bar{q}\right)dx=0.96\int F_2(x)dx. \tag{22}$$

The integral on the left-hand side of Eq. (22) is determined by computing the area under the curve in the distribution $d\sigma^{\nu N}_{cc}/dx'$ (Fig. 2b). Using Eq. (15) as well, we have

$$\int F_2(x)dx=0.52\pm0.10, \tag{23}$$

$$\int xF_3(x)dx=0.42\pm0.10. \tag{24}$$

In terms of the quark–parton model, Eq. (23) determines the fraction of the nucleon momentum in the total that is transferred by quarks and antiquarks, while Eq. (24) determines the fraction of the nucleon momentum transferred by valence quarks. The difference between Eq. (23) and unity is evidence that the remaining part of the nucleon momentum ($\sim$50%) is transferred by gluons.

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[1)]The system of units with $\hbar=c=1$ is used.

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