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NEUTRINO-NUCLEON INTERACTION THROUGH INTERMEDIATE VECTOR BOSON

N. M. HASSAN

Cairo University, Fayoum Branch, Faculty of Science, Fayoum, Egypt
E-mail address: hussein1@frcu.eun.eg

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A model is proposed to prospect the general features of the weak interaction of the neutrino with the nucleons. The interaction is viewed via intermediate vector boson. The deep inelastic differential cross section is calculated in terms of the leptonic and hadronic weak currents. A perturbation technique is used to evaluate the leptonic current that explains the cross section dependence on the four-vector momentum transfer square q^2. The leptonic current is considered as a complex quantity, the imaginary part of which represents the rate of absorption. On the other hand, the wave functions of the quarks forming the target nucleon are extracted from experimental data for neutrino-nucleon and electron-nucleon collisions. An empirical method is applied to analyse the data and used to evaluate the quark functions and hence to calculate the weak hadronic current. It is found that the sea-quark wave functions show substantial increase at very low x values, while the quark functions extend to higher values. The hadronic current carries the lineaments of the reaction that depend on the Bjorken scaling variable x as well as q^2. The prediction of the model can explain fairly the experimental data at the neutrino energy range $120-250$ GeV and Bjorken variable $x < 0.5$.

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1. *Introduction*

The problem of weak interactions through the charged and neutral currents has been dealt by many different approaches. A classical picture of lepton neutral current by James L. Carr [1] considered that the neutral current weak interaction is formally similar to ordinary electromagnetism with a massive photon. In this spirit, the Maxwell equations for the fields of the Z-boson are derived from the standard model. For neutral current events, electrons (or neutrinos) remain as electrons (or neutrinos). In the charged current case, an initial electron state emerges as a final neutrino state or vice-versa. A non-relativistic weak-field Hamiltonian for the electron is developed which allows computing the interaction energy of an electron in the presence of a classical Z-boson field. The Maxwell equations derived in this case can be used to describe the (albeit small) Z-boson field generated at macroscopic scale [2]. They may also be used to visualize the Z-boson fields surrounding classical point-like electrons and neutrinos. An alternative method was developed by T. Siiskonen et al. [3], where the phenomenological structure of the weak hadronic current between the proton and neutron states is well determined by its properties under the Lorentz transformation. The resulting interaction Hamiltonian consists of vector (V), axial vector (A), induced weak magnetism (M) and induced pseudoscalar (P) terms together with the associated form factors C_α, $\alpha =$ V, A, M or P. These form factors are called the coupling constants at zero momentum transfer. The present experimental knowledge does not exclude the presence of the scalar and tensor interactions. However, their contribution is expected to be small due to the weak coupling [4]. The induced pseudoscalar and weak magnetic parts are essentially inactive, since their contributions are proportional to q/M, where q is the energy release and M is the nucleon mass (in units where $\hbar = c = 1$) [5]. The most interesting information that can be extracted from such studies are the parton distributions. These can, in principle, be determined from analyzing a set of standard experiments, deep inelastic scattering (DIS), lepton-pair production (LPP), high-p_t direct-photon production, W- and Z-production, high-p_t jet-production, heavy flavour production . . . etc. CTEQ Collaboration [6] obtained features of new sets of parton distributions based on a comprehensive QCD analysis of the available data. The precision of the generation of DIS experiments exceeds the size of next-to-leading order QCD contributions to these processes [7].

In the present work, we shall use the intermediate vector boson (IVB) to calculate the weak leptonic current and the hadronic current in neutrino-nucleon interactions. Consequently, the square of the total interaction transition matrix can be easily calculated and compared with the recently available experimental data. The paper is organized in four sections. Besides the Introduction, we give in Sect. 2 a brief discussion of the theory of weak current in the frame of the intermediate vector boson. In Sect. 3, we present the hypothesis of a model for weak interactions of ν- with nucleons as well as the results and discussion. Finally conclusive remarks are given in Sect. 4.

2. *Intermediate vector boson*

In Fermi theory, it is known that the photon emitted in a radioactive transition is the quantum of the electromagnetic field. The theory is then developed to postulate the existence of a weak intermediate vector boson and suppose that weak interactions are mediated by the exchange of IVB's as the electromagnetic ones are mediated by photon exchange. This was the first step toward an eventual unification of the weak and electromagnetic fields. In the presence of currents, the wave equation for the photon has the form

$$\Box A^{\mu} = j^{\mu}_{em} \,. \tag{1}$$

The propagator associated to the process is just the inverse of the differential operator in Eq. (1). Applying this to the free particle, we get $-q^2 A^{\mu} = j^{\mu}_{em}$, hence the photon propagator is $-g^{\mu\nu}/q^2$. As for a massive spin-1 particle, in a general gauge, the Maxwell equations read

$$\Box A^{\mu} - \partial^{\mu}\partial^{\nu} A_{\nu} = j^{\mu} \,. \tag{2}$$

We make the natural replacement $\Box \Longrightarrow \Box + M^2$ to get

$$(\Box + M^2) W^{\mu} - \partial^{\mu}\partial^{\nu} W_{\nu} = j^{\mu} \,. \tag{3}$$

With the same analogy, it is expected that the propagator in this case has the form

$$\frac{-g^{\mu\nu} + q^{\mu}q^{\nu}/M^2}{q^2 - M^2} \,. \tag{4}$$

2.1. Leptonic and hadronic currents

A series of experiments [8] have shown that neutrinos have the following properties:

(a) They are massless (or nearly so)

(b) There are at least two and probably three distinct types of neutrino each associated with its own charged lepton: (e^-, ν_e), (μ^-,ν_μ) and probably (τ^-,ν_τ).

(c) They have spin -1/2 but only the negative helicity state (left-handed) participates in weak interactions.

(d) The weak interactions neither conserve the parity **P**, nor do they respect invariance under the charge conjugation.

The Lorentz covariance of Dirac equations defines the vector current as $\overline{u}\gamma_\mu u$ and the axial vector current as $\overline{u}\gamma_\mu\gamma_5 u$, where u is a 4-component wave function and γ_5 is a 4×4 matrix that defined in terms of the Dirac γ matrices as $\gamma_5 = \mathrm{i}\gamma^0\gamma^1\gamma^2\gamma^3$. Writing the parity operator **P** in the form $P = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, and the right and left-handed helicity operators $\mathbf{P}_{\mathrm{R}}, \mathbf{P}_{\mathrm{L}}$ are defined as $\mathbf{P}_{\mathrm{R}} = (1+\gamma_5)/2$ and $\mathbf{P}_{\mathrm{L}} = (1-\gamma_5)/2$, which satisfy the relations, $\mathbf{P}_{\mathrm{L}}^2 = \mathbf{P}_{\mathrm{L}}$, $\mathbf{P}_{\mathrm{R}}^2 = \mathbf{P}_{\mathrm{R}}$, $\mathbf{P}_{\mathrm{L}}\mathbf{P}_{\mathrm{R}} = \mathbf{P}_{\mathrm{R}}\mathbf{P}_{\mathrm{L}} = 0$, $\mathbf{P}_{\mathrm{L}}+\mathbf{P}_{\mathrm{R}} = 1$. So that, for massless spin 1/2 neutrinos, the combination $\frac{1}{2}(1-\gamma_5)u_\nu(p)$ contains only a left-handed component. The leptonic weak current for each lepton and its neutrino has the form

$$\begin{aligned} J(\nu\nu') &= \langle \nu' | J^{wk}_{\mu} | \nu \rangle \\ &= (g/\sqrt{2}) N N' \overline{u}(\nu') \gamma_\mu \frac{1}{2}(1-\gamma_5) u(\nu) \,, \end{aligned} \tag{5}$$

where g is the coupling constant for the Z or W boson that exchanges in weak processes. The hadronic current has a similar form, but instead, the valence quarks u and d play the role of the running particles producing the current, and sum is carried out over all possible permutations of quark flavours in the inlet and outlet channels. The total interaction matrix element is given by the product of the leptonic current, the weak propagator and the weak quark current. It is written as

$$M = (g^2/2)\overline{u}(\nu')\gamma_\mu \frac{1}{2}(1-\gamma_5)u(\nu)\frac{-g^{\mu\nu} + q^\mu q^\lambda/M_W^2}{q^2 - M_W^2} \sum_{i \neq j} \overline{u}(q_j^{'})\gamma_\lambda \frac{1}{2}(1-\gamma_5)u(q_i)\,. \tag{6}$$

3. A model for weak interactions of neutrinos with nucleons

In this model we assume that the neutrino interacts with nucleons through the IVB which may be the W or Z with effective mass about 80 GeV. The Feynman diagram as in Fig. 1 represents the interaction. The scattering amplitude is then calculated according to Eq. (6). The implementation of Eq. (6) requires the determination of the neutrino and quark wave functions that are necessary to calculate the weak leptonic and hadronic currents.

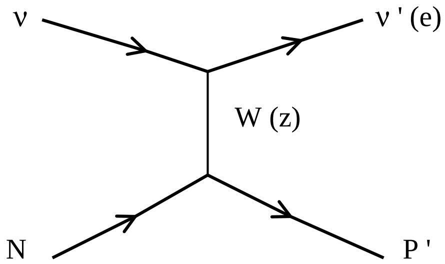

Fig. 1. Feynman representation of the ν-nucleon interaction.

3.1. Calculation of the leptonic weak current

The weak leptonic current is defined as

$$\langle \nu' | J_\mu^{wk} | \nu \rangle = (g^2/2) N N' \overline{\Psi}(\nu')\gamma_\mu \frac{1}{2}(1-\gamma_5)\Psi(\nu)\,, \tag{7}$$

where $\Psi(\nu)$ and $\overline{\Psi}(\nu')$ are the neutrino wave functions before and after scattering at the first vertex of Fig. 1. As a good approximation, it is possible to consider the incident neutrino's wave function as a plane wave in a four-vector component as

$$\Phi_j(r,t) = u_j e^{\mathrm{i}(k.r - \omega t)} \tag{8}$$

The 4-component matrix u describes the neutrino with spin 1/2 is

$$u = \begin{pmatrix} 1 \\ 0 \\ \dfrac{P_Z}{E+m} \\ \dfrac{P_X + \mathrm{i}P_Y}{E+m} \end{pmatrix}. \tag{9}$$

Since the neutrino is massless and moves initially in the z-direction, then $u = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$. On the other hand, we used the perturbation technique to find the scattered wave function of the neutrino as

$$\Psi(k', r) = \left\{ \Phi(k', r) + (2\pi)^{3/2} f \frac{\exp(\mathrm{i}k'r)}{r} \right\} \begin{pmatrix} 1 \\ 0 \\ \cos\theta \\ \sin\theta + \mathrm{i}\sin\theta\cos\varphi \end{pmatrix}. \tag{10}$$

The scattering amplitude f is expanded in a perturbation series [9] as

$$f = \sum f_j \tag{11}$$

$$\begin{aligned} f_j \quad &= \quad -2\pi^2 \int \mathrm{d}k_1 \mathrm{d}k_2 \cdots \mathrm{d}k_{j-1} \langle k_f | U | k_{j-1} \rangle \frac{1}{k^2 - k_{j-1}^2 + \mathrm{i}\epsilon} \\ &\times \langle k_{j-1} | U | k_{j-2} \rangle \frac{1}{k^2 - k_{j-2}^2 + \mathrm{i}\epsilon} \langle k_{j-2} | U | k_{j-3} \rangle \cdots \\ &\times \langle k_2 | U | k_1 \rangle \frac{1}{k^2 - k_1^2 + \mathrm{i}\epsilon} \langle k_{j-2} | U | k_i \rangle \, . \end{aligned} \tag{12}$$

Since the scattering is due to weak field, then it is sufficient to consider only one term in the series that corresponds to the impulse approximation, so that $f_1 = -\dfrac{1}{2\pi} \dfrac{g}{M^2 + q^2}$, hence

$$\begin{aligned} \Psi(k', r) \quad &= \quad \left\{ (2\pi)^{-3/2} e^{\mathrm{i}k' r\cos\theta} + (2\pi)^{1/2} \frac{g}{M^2 + q^2} \frac{e^{\mathrm{i}k'r}}{r} + \cdots \right\} \cdot \\ & \begin{pmatrix} 1 \\ 0 \\ \cos\theta \\ \sin\theta + \mathrm{i}\sin\theta\cos\varphi \end{pmatrix}, \end{aligned} \tag{13}$$

then the first component of the leptonic current J_x, corresponding to $\mu = 1$ in Eq.(7), is given by

$$J_x = \int_0^R \int_0^{2\pi} \int_0^{\pi} \left[\frac{-1 + 2\cos\theta + \sin\theta + \mathrm{i}\sin\theta\cos\varphi}{2\pi(M^2+q^2)r} \right] g r^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\varphi \, \mathrm{d}r \,. \tag{14}$$

The integrals in Eq. (14) are regarded as the average of the current alloved in the available space inside the nucleon of radius R. This leads to an analytical form of the current J_x as

$$J_x = -g \frac{-1 + e^{\mathrm{i}qR} - \mathrm{i}qR}{6\pi(M^2+q^2)} e^{-\mathrm{i}qR} \,. \tag{15}$$

Similarly, J_y and J_z corresponding to $\mu = 2, 3$ respectively, are found to be

$$J_y = g \frac{\mathrm{i}(-1 + e^{\mathrm{i}qR}) + qR}{6\pi(M^2+q^2)} e^{-\mathrm{i}qR} \,, \tag{16}$$

$$J_z = -g \frac{-1 + e^{\mathrm{i}qR} - \mathrm{i}qR}{12\pi q^2(M^2+q^2)} e^{-\mathrm{i}qR} \,. \tag{17}$$

It is clear that the weak leptonic current density is a complex function of the momentum transfer q. The imaginary part measures the absorption rate. The absolute values of the current components J_x and J_y are equal due to the azimuthal symmetry of the problem. Fig. 2 displays the current components J_x and J_z, while the total leptonic current is displayed in Fig. 3.

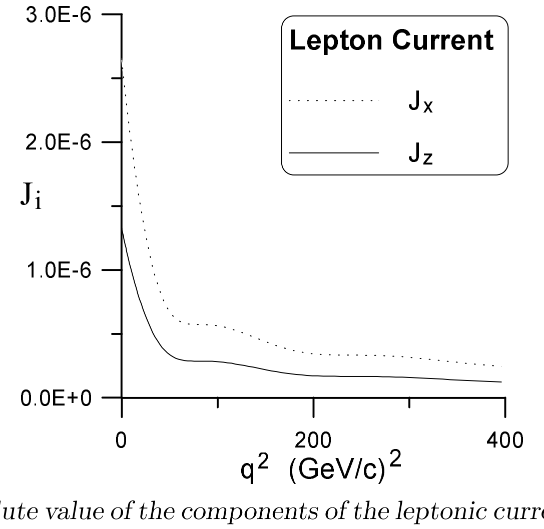

Fig. 2. The absolute value of the components of the leptonic current of the ν-nucleon collisions as seen in the azimuthal plane (J_x, J_y) and the normal component J_z. The components J_x and J_y are equal due to the azimuthal symmetry of the problem.

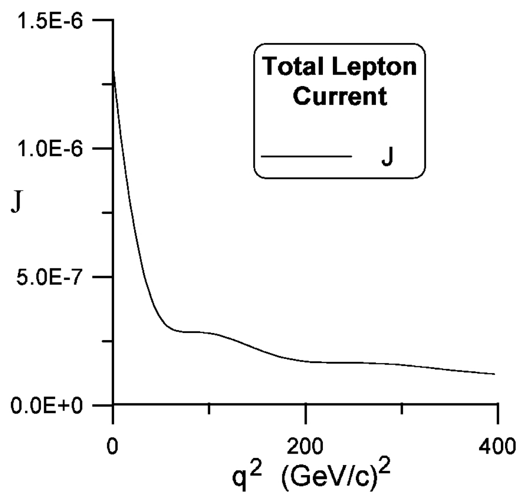

Fig. 3. The absolute value of the total leptonic current in ν-nucleon collision.

3.2. Calculation of the quark weak current

In this part, we shall determine the wave functions for the u, d and s quarks that form the nucleon by an empirical method. In other words, we shall use the features of the structure functions $F_2(x)$ and $xF_3(x)$ that have been extracted from the deep inelastic scattering experiments of both neutrino and electron with nucleons to stand for the quark wave functions u, d and s and their anti-quarks. Making the approximation of setting the Cabibbo angle to zero, we obtain the correspondence

$$F_2^{\nu p} = 2x[d(x) + \overline{u}(x)]\,,$$
$$xF_3^{\nu p} = 2x[\overline{u}(x) - d(x)]\,, \tag{18}$$

where $F_2^{\nu p}$and $F_3^{\nu p}$ are the structure functions for ν-proton scattering. Using the hadronic isospin invariance, we get

$$F_2^{\nu n} = 2x[\overline{d}(x) + u(x)]\,,$$
$$xF_3^{\nu n} = 2x[\overline{d}(x) - u(x)]\,, \tag{19}$$

where $F_2^{\nu n}$and $F_3^{\nu n}$ are the structure functions for ν-neutron scattering. Solving Eqs. (18,19) algebraically, it is easy to define the quark and the anti-quark wave functions as

$$u(x) = \frac{F_2^{\nu n} - xF_3^{\nu n}}{4x}\,, \qquad \overline{u}(x) = \frac{F_2^{\nu p} + xF_3^{\nu p}}{4x}\,,$$
$$d(x) = \frac{F_2^{\nu p} - xF_3^{\nu p}}{4x}\,, \qquad \overline{d}(x) = \frac{F_2^{\nu n} + xF_3^{\nu n}}{4x}\,. \tag{20}$$

Moreover, the s distribution function as well as those concerning the sea quarks are determined from information by the muon-nucleon or electron-nucleon [10] deep inelastic scattering. Following again the Cabibbo approximation, one finds

$$F_2^{ep} = \frac{4}{9}x[u(x)+\overline{u}(x)]+\frac{1}{9}[d(x)+\overline{d}(x)+s(x)+\overline{s}(x)]\,, \tag{21}$$

$$F_2^{en} = \frac{4}{9}x[d(x)+\overline{d}(x)]+\frac{1}{9}[u(x)+\overline{u}(x)+s(x)+\overline{s}(x)]\,, \tag{22}$$

then

$$s(x)=\frac{9}{4x}(F_2^{ep}+F_2^{en})-\frac{5}{4x}(F_2^{\nu p}+F_2^{\nu n})\,. \tag{23}$$

Figures 4 and 5 show the structure functions F_2 and xF_3 which are appreciably dependent on the scaling variable x and slightly dependent on the 4-momentum

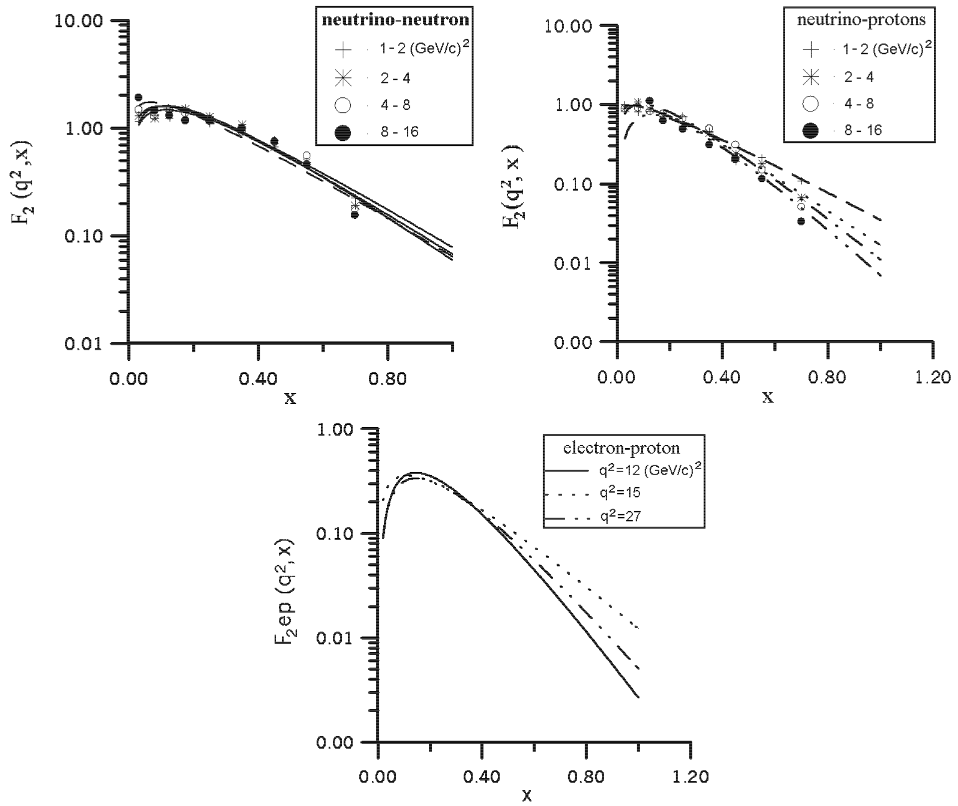

Fig. 4. The structure function $F_2(x,q^2)$ for the target nucleon extracted from data of deep inelastic ν-neutron, ν-proton and electron-proton collisions. The line curves are due to the linear regression fitting of the parametric form $F_2(x) = Ax^{\alpha}\exp(-\beta x)$.

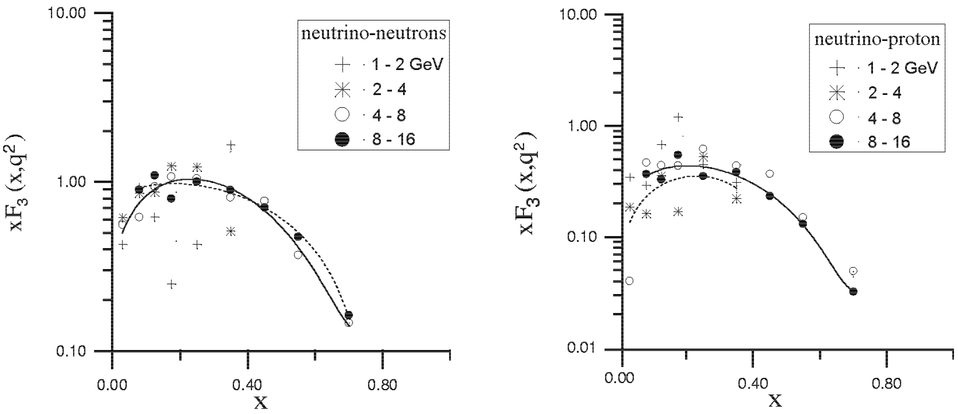

Fig. 5. The structure function $xF_3(x, q^2)$ for the target nucleon extracted from data of deep inelastic ν-neutron and ν-proton collisions. The line curves are due to the linear regression fitting of the parametric form $xF_3(x) = Ax^\alpha \exp(-\beta x^2)$.

square q^2. The data of the experiments CERN-WA-025 [11], CERN-WA-059 [12] and FNAL-616 [13] are used to put the functions F_2 and xF_3 in parametric forms in the variable x. A linear regression program is executed by the MATHEMATICA 3.0 software to parameterize the function F_2 for neutrino interactions with protons and neutrons in the form

$$F_2(x) = Ax^\alpha \exp(-\beta x) , \tag{24}$$

while xF_3 is considered as

$$xF_3 = Ax^\alpha \exp(-\beta x^2) . \tag{25}$$

The analysis was made for data concerning neutrino of q^2 ranges 1:2, 2:4, 4:8 and 8:16 GeV^2. In Table 1 we display the values of the coefficients A, α and β for the family of curves corresponding to ν-protons and ν-neutron interactions. The q-dependence of the structure functions are implicitly included in the parameters A, α and β.

Table 1. q-dependence of the structure functions $F_2(x)$ for protons and neutrons expressed by the parameters A, α and β.

q^2(GeV)^2	$F_2(x)$ for protons			$F_2(x)$ for neutrons		
	A	α	β	A	α	β
1:2	2.89	0.231	4.235	8.151	0.549	4.659
2:4	3.83	0.363	5.448	10.776	0.603	5.216
4:8	8.109	0.616	6.651	7.58	0.472	4.717
8:16	15.844	1.003	7.736	5.085	0.297	4.364

Table 2. q-dependence of the structure functions $xF_3(x)$ for protons and neutrons expressed by the parameters A, α and β.

$q^2(\text{GeV})^2$	$xF_3(x)$ for protons			$xF_3(x)$ for neutrons		
	A	α	β	A	α	β
1:2	0.702	0.174	0 .937	0.805	0 .166	0.980
2:4	0.397	0 .235	0 .1868	1.111	0.119	0.799
4:8	0.599	0 .393	2.205	0.663	-0.064	1.302
8:16	0.121	-0.626	1.113	0.421	-0.435	0.756

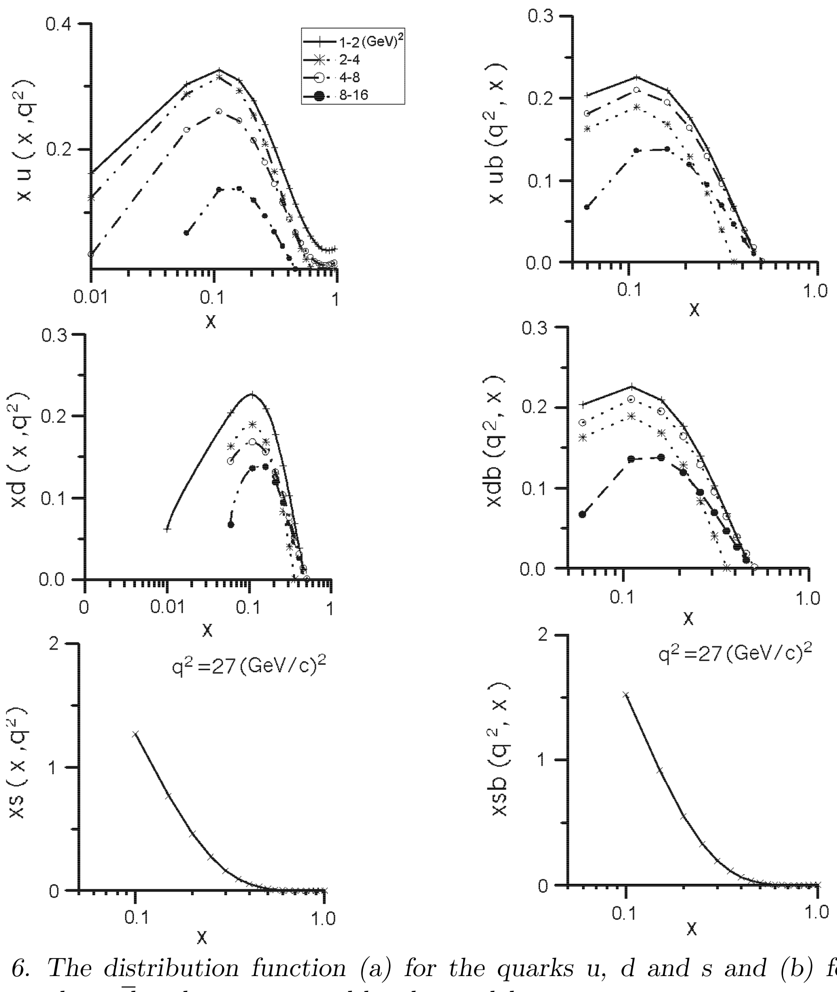

Fig. 6. The distribution function (a) for the quarks u, d and s and (b) for the anti-quarks $\overline{u}$, $\overline{d}$ and $\overline{s}$ as expected by the model.

Consequently, the quark functions $u, d, s, \overline{u}$, $\overline{d}$ and $\overline{s}$ are computed according to Eqs. (20 − 23) and the results are presented in Fig. 6a for the quarks u, d, s and in Fig. 6b for the anti-quarks $\overline{u}$, $\overline{d}$ and $\overline{s}$ as functions of both x and q. The quark wave functions show peak values around $x = 0.1$. The u and d distributions slowly decrease with q^2, while the function of the s quark has a peak value at $x = 0$ and falls off rapidly as x approaches the unity. On the other hand, the anti-quark wave functions show substantial increase at very low x values and do not extend to the high values of x. The general feature of the results seems comparable to those produced by CTEQ collaboration [14] and MRS collaboration [15] at adjacent energy values, although in their analysis, they used a different form of quark function: $f(x; q_0) = A_0 x^{A_1} (1 - x)^{A_2} (1 + A_3 x)^{A_4}$. It is not quite fair to compare the present analysis with those of Ref. [14, 15] because of the different source of data. In Ref. [14], the data were selected at fixed energy value while in the present work the data are classified into classes of different ranges of energy. The quark currents are then calculated as

$$J_q(x, q^2) = \sum_{i \neq j} \overline{u}(x, q_j'^2) \gamma_\mu \frac{1}{2}(1 - \gamma_5) u(x, q_i^2) \,. \tag{26}$$

The results are plotted in Fig. 7 for the u and d currents which seem approximately similar. Finally, the total matrix element, Eq. (6), is evaluated, and the differential cross section is represented in Fig. 8 as a function of q^2, for values of x in the range $0.05 < x < 0.5$.

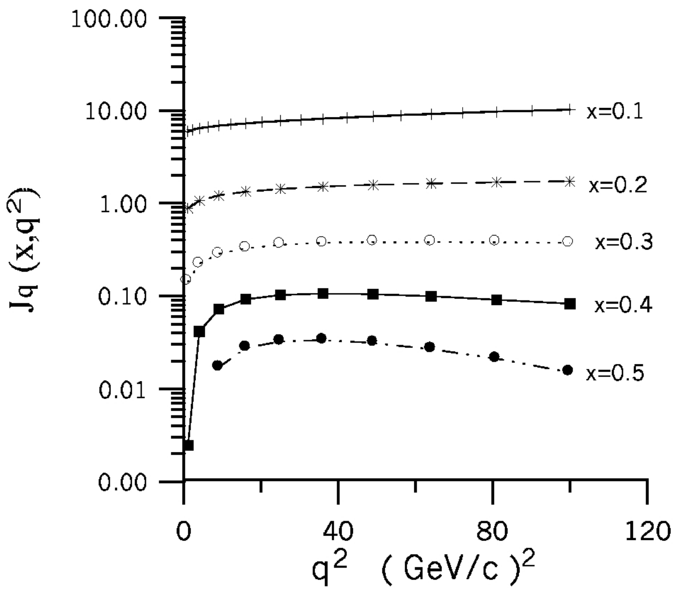

Fig. 7. The total quark current as expected by the model.

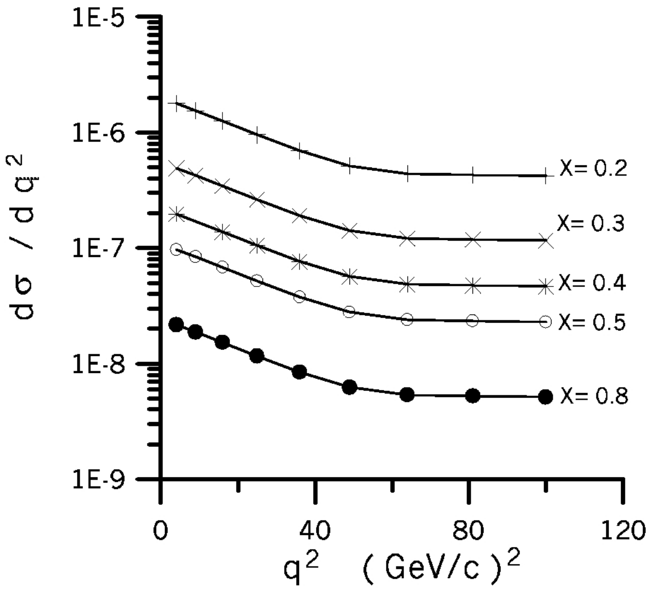

Fig. 8. The differential cross section for ν-nucleon deep inelastic interaction corresponding to Bjorken scaling variable $0.2 < x < 0.8$.

4. *Summary and conclusive remarks*

- It is assumed that weak interactions are mediated by the exchange of IVB´s as the electromagnetic ones are by photon exchange.
- The propagator associated to the process has the form $\dfrac{-g^{\mu\nu} + q^\mu q^\nu / M_W^2}{q^2 - M_W^2}$
- The total interaction matrix element includes, beside the boson propagator, a weak leptonic current and a hadronic (quark) current.
- The $\nu(\nu')$ wave functions are calculated with perturbation technique, and the weak leptonic current is momentum dependent.
- The weak leptonic current is complex, the imaginary part of which represents the rate of absorption of the reaction.
- The quark wave functions are determined by empirical method, and the weak hadronic current depends mainly on the Bjorken variable and lightly dependent on q^2.
- The sea-quark wave functions show substantial increase at very low x values, while the quark functions extend to higher values up to $x \backsim 1$ with peak value at $x \backsim 0.1$.

- The predictions of the model show globally a fair agreement with experimental data in the energy range E_ν from 120 to 250 GeV.

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MEĐUDJELOVANJE NEUTRINO-NUKLEON POSREDSTVOM VEKTORSKIH BOZONA

Predlažemo model za istraživanje općih svojstava slabog međudjelovanja neutrina s nukleonima. Pretpostavlja se međudjelovanje posredstvom vektorskih bozona. Računamo udarne presjeke duboko neelastičnog raspršenja za leptonske i hadronske slabe struje. Primjenjujemo račun smetnje za određivanje leptonske struje koja objašnjava ovisnost udarnih presjeka o kvadratu prijenosa 4-impulsa, q^2. Pretpostavlja se kompleksna leptonska struja, čiji imaginaran dio opisuje apsorpciju. Valne se funkcije kvarkova koji tvore nukleon izvode iz eksperimentalnih podataka za sudare neutrino-nukleon i elektron-nukleon. Primjenjujemo empirijsku metodu za analizu podataka koji se rabe za izvođenje kvarkovskih funkcija i time za računanje slabe hadronske struje. Našli smo da se valne funkcije kvarkovskog mora bitno povećavaju za vrlo male vrijednosti x, dok se kvarkovske funkcije šire do većih vrijednosti. Hadronska struja ima značajke reakcija koje ovise o Bjorkenovoj varijabli x kao i o q^2. Predviđanja modela prilično dobro objašnjavaju eksperimentalne podatke u području energije neutrina $120-250$ GeV i Bjorkenove varijable $x < 0.5$.