Semi-inclusive cross sections for deep-inelastic neutrino scattering on hydrogen and deuterium

Bosveld, GD; Dieperink, AEL; Scholten, O

Published in:
Physics Letters B

DOI:
10.1016/0370-2693(91)90694-L

Semi-inclusive cross sections for deep-inelastic neutrino scattering on hydrogen and deuterium

G.D. Bosveld, A.E.L. Dieperink and O. Scholten

Kernfysisch Versneller Instituut, NL-9747 AA Groningen, The Netherlands

Received 21 March 1991; revised manuscript received 13 May 1991

The production of low energy protons observed in recent deep-inelastic (anti-)neutrino scattering on hydrogen and deuteron targets is interpreted in terms of fragmentation of the spectator di-quark and emission of nuclear spectators.

1. Introduction

In the past, nuclear effects in deep-inelastic scattering have been studied mostly in terms of inclusive reactions. These studies show that the structure function $F_2(x)$ for a nucleon bound in the nuclear medium is different from the one for a free nucleon. Theoretical investigations indicate that for $x > 0.2$ a large part of this so-called EMC effect can be explained by conventional nuclear physics degrees of freedom, such as Fermi motion, nuclear binding and possibly pionic contributions [1]. More detailed information on these mechanisms can be obtained from semi-inclusive experiments. For example, for testing the binding hypothesis for the EMC effect it would be desirable to obtain information on the (excitation) energy of the final $A-1$ nuclear system [2].

Recently, the results of two neutrino-induced deep-inelastic scattering experiments were published in which slow protons ("dark tracks" or "stubs" in a bubble chamber) were detected in coincidence with the muon. In the Fermilab experiment on a freon (i.e. predominantly fluor) target [2] the ratio $R(x)$ of the number of events with a slow proton present (typically with a momentum <0.5 GeV/c) over the events without slow protons showed a dip at intermediate x values. These results were interpreted [3] in terms of emission of a nuclear spectator proton (correlated with the struck one), a mechanism proposed by Frankfurt and Strikman [4]. However, the observation of an even larger effect for deep-inelastic scattering on a free proton by the BEBC Collaboration [5] strongly indicates that in addition to nuclear effects hadronization of the struck nucleon also plays an important role. Recently Ishii et al. [6] proposed a simple model that describes the gross features of the data of ref. [3] by a combination of di-quark fragmentation and rescattering of the struck hadron. They included effects of Fermi motion and binding, but did not consider the spectator contribution.

Motivated by recent data from the BEBC Collaboration [5] we report on a calculation of the so called "tagged" structure functions for deep-inelastic (anti-)neutrino scattering on simple targets ($A=1$, 2). First we consider scattering on a free proton where fragmentation is the only source of slow protons (produced solely in the forward hemisphere) and therefore this case can be used as a valuable test of the fragmentation model. Next for the deuteron we study the competition between the emission of a spectator nucleon and production of protons via the struck nucleon.

2. The free nucleon case

For a free nucleon we basically assume that slow protons in deep-inelastic neutrino scattering are produced either by fragmentation of a spectator di-quark after interaction of the neutrino with a valence d-quark, or by fragmentation of the spectator four-quark system after the interaction of the neutrino with a sea

0370-2693/91/$ 03.50

quark. The probability to find a proton with momentum fraction $\tilde{z}$ from a di-quark can be expressed in terms of the fragmentation function $D^{\mathrm{p}}_{\mathrm{qq}}(\tilde{z})$. Similarly, the fragmentation of the four-quark state is described by a fragmentation function $D^{\mathrm{p}}_{\mathrm{qqq\bar{q}}}(\tilde{z})$. In the extreme parton model the spectator di-quark carries a momentum fraction $1-x$ (x is the Bjorken scaling variable), and hence the detected proton has a momentum fraction $z=(1-x)\tilde{z}$ of the target nucleon.

In practice it is convenient to use a light-cone momentum fraction which is invariant under longitudinal boosts, i.e. $z=(p'^0-p'^3)/(p^0-p^3)$, where p' and p are the momenta and energies of the detected and target nucleon, and $\boldsymbol{q}$ is chosen along the $+z$-axis. In the laboratory system $z=(p'^0-p'^3)/m$, and thus slow protons with $p'^3\approx 0$ correspond to $z\approx 1$.

In the spirit of the fragmentation approach the semi-inclusive cross section (averaged over the angle) for deep-inelastic neutrino scattering on a proton can be factorized as

$$\frac{\mathrm{d}^2\sigma^{\nu\mathrm{p}}(x,z)}{\mathrm{d}x\,\mathrm{d}z}=\frac{G^2mE}{\pi}\frac{2x}{1-x}\left[d_{\mathrm{v}}(x)D^{\mathrm{p}}_{\mathrm{uu}}\left(\frac{z}{1-x}\right)+d_{\mathrm{s}}(x)D^{\mathrm{p}}_{\mathrm{uud\bar{d}}}\left(\frac{z}{1-x}\right)+\tfrac{1}{3}\bar{u}_{\mathrm{s}}(x)D^{\mathrm{p}}_{\mathrm{uuud}}\left(\frac{z}{1-x}\right)\right].\qquad(1)$$

Here $xd_{\mathrm{v}}(x)$ ($xu_{\mathrm{v}}(x)$) and $xd_{\mathrm{s}}(x)$ ($xu_{\mathrm{s}}(x)$) are the valence and sea-quark structure functions for the d-(u-)quark in the proton, respectively, and $D^{\mathrm{p}}_{\mathrm{qq}}(\tilde{z})$ and $D^{\mathrm{p}}_{\mathrm{qqqq}}(\tilde{z})$ the fragmentation functions for the formation of a proton or delta from a di-quark (tetraquark). The cross section for scattering of a neutrino on a neutron is obtained by interchanging d$\leftrightarrow$u and $\bar{\mathrm{u}}\leftrightarrow\bar{\mathrm{d}}$ and appropriately changing of the indices of the D functions. The cross sections for scattering of an anti-neutrino on a proton or a neutron is obtained by replacing quark momentum distributions by antiquark distributions and vice versa. We assume that in leading order all D functions in eq. (1) are equal. Then by defining $F^{\nu\mathrm{p}}(x)=2x[d_{\mathrm{v}}(x)+d_{\mathrm{s}}(x)+\frac{1}{3}\bar{u}_{\mathrm{s}}(x)]$ eq. (1) takes on the simple form

$$\frac{\mathrm{d}^2\sigma^{\nu\mathrm{p}}(x,z)}{\mathrm{d}x\,\mathrm{d}z}=\frac{G^2mE}{\pi}F^{\nu\mathrm{p}}(x)\frac{1}{1-x}D^{\mathrm{p}}\left(\frac{z}{1-x}\right).$$

Experimentally one observes slow protons within a certain momentum bin $p'_{\min}<p'<p'_{\max}$ in the laboratory system, ($p'\equiv|\boldsymbol{p}'|$), corresponding to a $z=p'^-/m$ interval Δz. The coincidence cross section is then proportional to the probability, $P_{\mathrm{d.t.}}(x,\Delta z)$, for finding a slow proton (or dark track (d.t.)) from a di-quark

$$P^{\nu\mathrm{p}}_{\mathrm{d.t.}}(x,\Delta z)=\left(\frac{\mathrm{d}\sigma^{\nu\mathrm{p}}}{\mathrm{d}x}\right)^{-1}\int_{\Delta z}\mathrm{d}z\,\frac{\mathrm{d}^2\sigma^{\nu\mathrm{p}}(x,z)}{\mathrm{d}x\,\mathrm{d}z}=\int_{\Delta z}\frac{\mathrm{d}z}{1-x}D^{\mathrm{p}}\left(\frac{z}{1-x}\right).$$

For the di-quark fragmentation function we have used the leading term of the parametrization given by Bartl et al. [7]. The fact that $P_{\mathrm{d.t.}}$ is a strongly decreasing function of x is mainly caused by the integration limits which restricts the value of z to $z<1-x$. On the other hand, the x dependence of $P_{\mathrm{d.t.}}$ is rather insensitive to the precise form of the fragmentation function and a parametrization based upon counting rules, $D(\tilde{z})\propto(1-\tilde{z})\theta(1-\tilde{z})$ leads to similar results.

The fragmentation into nucleons and delta resonances (when allowed by spin/flavor symmetry) is treated on an equal footing thereby neglecting the mass difference between them. For simplicity we assume that all delta's decay into nucleons with the same velocity, i.e. protons and neutrons according to the standard isospin weighing. A possible contribution from the interaction with a virtual meson (pion) will be neglected.

In the calculation we assumed a transverse component in the hadronization with an exponential probability function and $\langle p_{\mathrm{T}}^2\rangle^{1/2}=300$ MeV/c. Since the magnitude of the transverse component is of the same order of magnitude as the momentum of the slow protons it gives a significant contribution in particular near the kinematic cut-off point.

In fig. 1 we show the comparison of ratios $R(x,\Delta z)=P(x,\Delta z)/[1-P(x,\Delta z)]$ of the (anti-)neutrino cross sections with and without slow protons for two momentum bins with the data of ref. [5] as a function of x. In order to compare we used the same normalization convention as in the data. It is seen that the experimental trend can be described qualitatively. Whereas the difference in the slope of $R(x,\Delta z)$ for events with $150<p'<350$ MeV/c and those with $350<p'<600$ MeV/c can be explained, the theoretical distributions clearly fall off more rapidly than

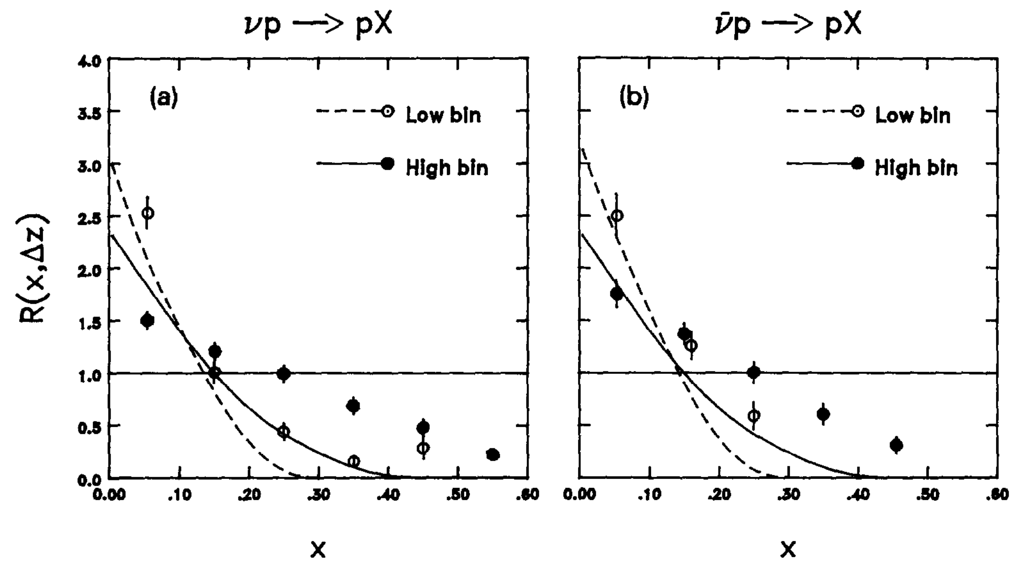

Fig. 1. The (normalized) ratio $R(x, \Delta z)$ of (a) neutrino and (b) anti-neutrino cross sections on H with/without slow protons in the momentum bins $150<p'<350$ MeV/c and $350<p'<600$ MeV/c, compared to the (normalized) ratio of the experimental data of ref. [5].

the observed ones. We note that in the present model no protons can be produced with momenta $p'<350$ (600) MeV/c for events with $x>0.25$ (0.45), due to the kinematic constraints. The slower fall-off of $R(x)$ with increasing x obtained in ref. [6] appears to be due in part to the larger value of the cut-off momentum $p'_{\max}=1$ GeV/c used in refs. [3,6], and in part to the assumption that each four-quark state leads to a slow proton.

The predicted absolute probability for producing slow protons is quite small. Using the leading order of the fragmentation functions of ref. [7] we find that, for $x=0$, the probability for producing a proton in the low (high) momentum bin is 0.4% (2.0%). Although these numbers cannot be compared directly with data, which are x integrated quantities, they are of the same order of magnitude.

3. The deuteron case

To investigate to what extent nuclear effects like Fermi smearing and binding affect the x dependence of the semi-inclusive cross section we now turn to the deuteron. In the impulse approximation one can distinguish two different processes that can give rise to slow protons, the "direct" process which represents the fragmentation of the struck moving proton or neutron in the target (see fig. 2b), and the "spectator" process corresponding to detection of the spectator proton (see fig. 2a).

In the impulse approximation the cross section for the *direct* process can be expressed in terms of a convolution integral over the single-nucleon cross section of eq. (1) (for simplicity we drop all references to transverse momenta)

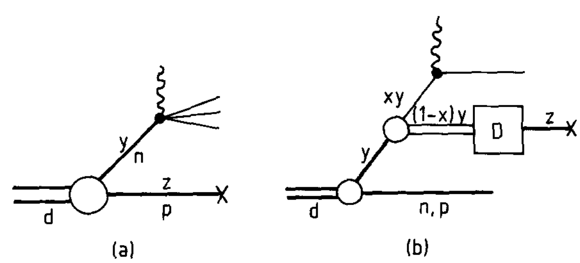

Fig. 2. Diagrammatic illustration of (a) the spectator and (b) the direct processes for deep-inelastic scattering on the deuteron. The cross indicates the detected proton.

$$\frac{d^2\sigma^{\nu d}_{dir.}(x,z)}{dx\,dz}=\frac{G^2mE}{\pi}\times\sum_{N=p,n}\int_{x+z}^{m_d/m}dy\,f_d(y)F^{\nu N}(x/y)\frac{1}{y-x}D^p\left(\frac{z}{y-x}\right), \quad (2)$$

where the convolution function $f_d(y)$ (the light-cone momentum distribution of the hit nucleon) is given in terms of the deuteron momentum distribution $n(p)$

$$f_d(y)=c\int d^3p\,|\phi_d(p)|^2 y\,\delta\left(y-\frac{p^0-p^3}{m}\right)=2\pi cym\int_{p_{min.}}^{\infty}p\,dp\,n(p)\,. \quad (3)$$

In eq. (3) the factor y represents the so called flux factor [8,4], and c is chosen such that $f(y)$ is normalized to unity. For the deuteron momentum distribution we use the parametrization of Machleidt et al. [9]. For light systems like the deuteron it is crucial to take into account the recoil energy, leading to [10] (up to order E_b/m)

$$p_{min.}(y,E_b)=\left|\frac{m^2(y^2-1)+2myE_b}{2(my+E_b)}\right|,$$

where E_b is the deuteron binding energy.

The *spectator* contribution can be written as

$$\frac{d^2\sigma^{\nu d}_{spec.}(x,z)}{dx\,dz}=\frac{G^2mE}{\pi}\times\int_{x}^{m_d/m}dy\,f(y)F^{\nu n}(x/y)\delta\left(z+y-\frac{m_d}{m}\right). \quad (4)$$

Assuming that these contributions may be added incoherently the total probability for finding a slow proton in the interval Δz is

$$P^{\nu d}_{d.t.}(x,\Delta z)=\left(\frac{d\sigma^{\nu d}(x)}{dx}\right)^{-1}\times\int_{\Delta z}dz\left(\frac{d^2\sigma^{\nu d}_{dir.}(x,z)}{dx\,dz}+\frac{d^2\sigma^{\nu d}_{spec.}(x,z)}{dx\,dz}\right), \quad (5)$$

with the inclusive cross section given by

$$\frac{d\sigma^{\nu d}(x)}{dx}=\frac{G^2mE}{\pi}\times\int_{x}^{m_d/m}dy\,f_d(y)\,[F^{\nu p}(x/y)+F^{\nu n}(x/y)]\,.$$

$F^{\nu p}$ and $F^{\nu n}$ are calculated using the parametrizations given by Eichten et al. [11].

In fig. 3 we show the contributions of both processes and their sum to the ratio $R(x,\Delta z)$ of events with slow protons to events without slow protons for neutrino and antineutrino scattering on the deuteron. The direct contribution, which does not depend strongly on z, is only slightly affected by Fermi smearing; as in the free proton case it falls of rapidly with increasing x and is negligibly small for $x>0.5$. On the other hand the spectator contribution is a smooth function of x, but is strongly peaked at $x=1$ and decreases rapidly with increasing $|z-1|$, and thus corresponds mainly to very slow protons. At values of $x>0.4$ the summed probability is dominated by the spectator process, and as a result the ratio $R(x,\Delta z)$ falls off slower and extends to larger x values than for the free proton. This effect is much more pronounced for the low proton momentum bin ($150<p'<350$ MeV/c) than for the higher one, in qualitative agreement with the experimental trend. It should be noted, however, that because of the strong z dependence of the spectator contribution the net result for R is extremely sensitive to the precise value of the empirical lower cutoff in the proton momentum. For example, the use of a 10% higher value than the one reported in ref. [5] would reduce the spectator contribution by 80% and thus lead to a much better fit with the low momentum bin neutrino data.

Another feature worth noting is the appreciable difference between the x dependence of the ratio $R(x,\Delta z)$ for the neutrino and antineutrino scattering. This effect can be attributed to the difference in u- and d-quark momentum distributions entering in the spectator contribution. Namely, compared to the inclusive scattering which averages over neutrons and protons, the observation of the spectator proton in the semi-inclusive neutrino (antineutrino) scattering selectively picks out events in which a d- (u-)quark in the neutron has been struck. It illustrates that semi-inclusive scattering is quite sensitive to the flavor de-

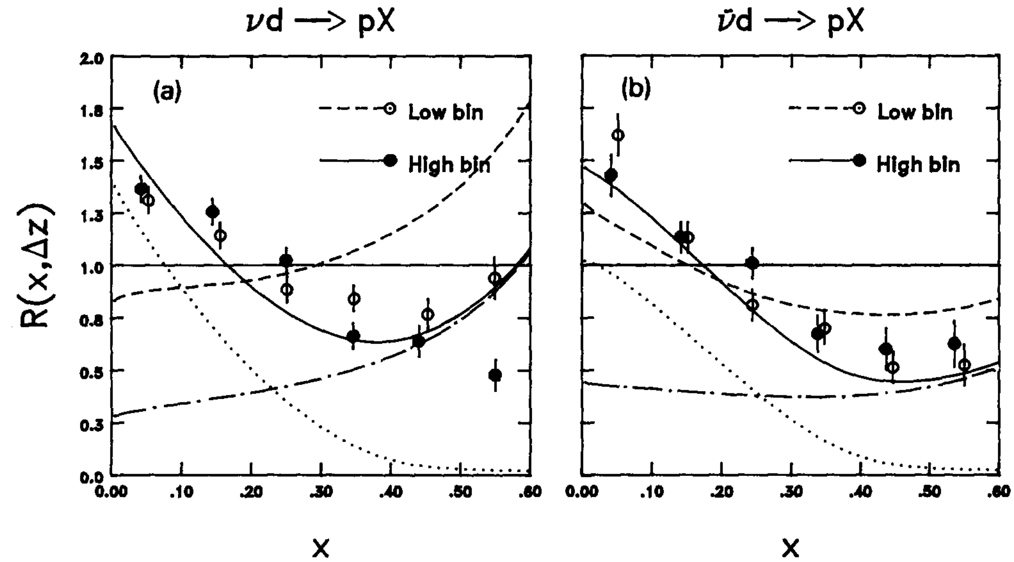

Fig. 3. The ratio $R(x, \Delta z)$ of (a) neutrino and (b) antineutrino cross sections on deuterium with/without slow protons for the same momentum bins as in fig. 1 compared with the data of ref. [5]. Also shown are the separate contributions of the direct (dotted) and spectator (dash-dotted) process for the high bin.

pendence of quark momentum distributions.

4. Discussion and summary

We have interpreted the observation of slow protons in semi-inclusive deep-inelastic neutrino scattering on the free proton in terms of di-quark fragmentation, and that on the deuteron in terms of a competition between fragmentation and spectator processes. We have shown that the observed dilution of the strong x dependence of the ratio of events with/without slow protons going from the free nucleon to the deuteron can be attributed to the detection of spectator nucleons. We expect the latter process to be important also for heavier nuclei, and are planning to investigate its A dependence in more detail. For a quantitative description of tagged structure functions in $A>2$ systems one needs a two-nucleon spectral function, which in general is not available yet.

Another point to be investigated is the role of rescattering. One may argue that the interaction of non color-singlets (quarks and di-quarks) with the observed nucleon is suppressed. Therefore the most important interaction is that of the produced slow nucleon with the target nucleon. To estimate the magnitude of this effect one needs to know the hadronization length. For slow protons it is expected to be of the order of the deuteron size and the rescattering will lead to a smearing of the momentum distribution. We are planning to study the question of rescattering in more detail in the future.

Above we have considered only the absolute value of momenta of slow protons but not the direction. In order to separate the direct and spectator processes it is useful to distinguish events with $z>1$ (backwards with respect to q) and events with $z<1$ (forwards). We find that in the deuteron the direct fragmentation process contributes very little (less than 1%) to backward protons and therefore the backward hemisphere is well suited to study the spectator process. In ref. [12] deuteron events with slow backward protons (in the laboratory system) were selected.

A simple quantity to consider is the expectation value of the scaling variable $\langle xy \rangle$ (where $y=\nu/E_\nu$) as a function of z [4]. Namely, if a proton with momentum fraction z is observed one has

$$\langle xy \rangle_{\text{obs.}} = \frac{Q^2}{2mE_\nu} = (2-z)\langle xy \rangle_{\text{true}}\,, \qquad (6)$$

where $\langle xy \rangle_{\text{true}} = Q^2/2E_\nu p^-$. Thus in the spectator picture the ratio of $\langle xy \rangle$ for events with/without the observation of a slow backward proton is predicted to be $(2-z)$, i.e. a linearly decreasing function of z. Within the accuracy this agrees with the data [12].

Acknowledgement

We thank Dr. A.W. Schreiber for careful reading of the manuscript. This work is supported by the Foundation for Fundamental Research (FOM) and the Netherlands Organization for the Advancement of Scientific Research (NWO).

References

[1] R.P. Bickerstaff and A.W. Thomas, J. Phys. G 15 (1989) 1523.
[2] S. Kumano and F.E. Close, Phys. Rev. C 41 (1990) 1855.
[3] T. Kitagaki et al., Phys. Lett. B 214 (1988) 281.
[4] L.L. Frankfurt and M.I. Strikman, Phys. Rep. 76 (1981) 215.
[5] J. Guy et al., Phys. Lett. B 229 (1989) 421.
[6] C. Ishii, K. Saito and F. Takagi, Phys. Lett. B 216 (1989) 409.
[7] A. Bartl, H. Fraas and W. Majerotto, Phys. Rev. D 26 (1982) 1061.
[8] D. Kusno and M.J. Moravcsik, Phys. Rev. D 20 (1979) 2734.
[9] R. Machleidt et al., Phys. Rep. 149 (1987) 1.
[10] C. Ciofi degli Atti and S. Liuti, Phys. Rev. C 41 (1990) 1100.
[11] E. Eichten et al., Rev. Mod. Phys. 56 (1984) 579.
[12] E. Matsinos et al., Z. Phys. C 44 (1989) 79.