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Slow proton production in semi-inclusive deep inelastic scattering and the pion cloud in the nucleon

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A b s t r a c t

The semi-inclusive cross section for producing slow protons in charged current deep inelastic (anti-) neutrino scattering on protons and neutrons is calculated as a function of the Bjorken x and the proton momentum. The standard hadronization models based upon the colour neutralization mechanism appear to underestimate the rate of slow proton production on hydrogen. The presence of the virtual mesons (pions) in the nucleon leads to an additional mechanism for proton production, referred to as spectator process. It is found that at low proton momenta both mechanisms compete, whereas the spectator mechanism dominates at very small momenta, while the color neutralization mechanism dominates at momenta larger than 1-2 GeV/c. The results of the calculations are compared with the CERN bubble chamber (BEBC) data. The spectator model predicts a sharp increase of the semi-inclusive cross section at small x due to the sea quarks in virtual mesons.

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1 Introduction

Inclusive deep inelastic lepton scattering off nucleons is a well established tool for investigating the parton distributions [1]. Hadrons, which are not measured in inclusive experiments, are produced mainly in the colour neutralization process; the string models being the state of art. It is expected that the measurement of final state hadrons will lead to a better understanding of the mechanism of hadron production as it contains information about hadronization process.

In semi-inclusive deep inelastic reaction (SIDIS) one observes one or more hadrons in coincidence with the scattered lepton. In the simplest approximation the semi-inclusive cross section is assumed to factorize into an inclusive cross section (proportional to the deep-inelastic structure functions) and a fragmentation function [2, 3].

In the past the study of semi-inclusive deep-inelastic lepton scattering has been restricted mainly to the detection of high energy hadrons, which originate from the fragmentation of the leading (struck) quark. The production of slow protons in coincidence with muons has been studied in the (anti)neutrino induced charged current reactions at CERN [4, 5]. In a more recent analysis of the CERN experiment WA21 [5] the fraction of slow ($p < 0.6$ GeV/c) protons was determined. In Ref.[6] the rate from Ref.[5] was reproduced with a constant fragmentation function, assuming that only protons (no other baryons) are produced. The rate of slow proton production strongly depends on the behaviour of the fragmentation function at the kinematical limit, i.e. the light cone momentum fraction $z = p^-/m$ close to 1. The counting rules [7] suggest for the diquark fragmentation function rather a linear, $D_{2q}(z) = A(1-z)$, than a constant dependence on z. Furthermore, other baryons (neutrons, isobars, etc.) can be produced which leads to a suppression of the relative proton yield.

In order to illustrate this point we show in Table 1 the relative yield of protons and neutrons including both direct and sequential (intermediate Δ) production obtained from a more realistic, yet simple, quark-diquark model [8]. For comparison we give the number of protons/neutrons per event obtained from the Lund string model [9]. Both arguments discussed above suggest that the agreement with experimental rate in Ref.[6] has to be reconsidered. It will be discussed later that a more realistic calculation leads to a deficit of slow protons compared to the experimental rate [5]. The violation of the Gottfried sum rule observed by NMC [10] strongly suggests the flavour asymmetry of the sea of light quarks in the proton. This can be naturally accounted for by the presence of the pion (meson) cloud in the nucleon [11] – [18]. The pion cloud model has also been used successfully in inclusive DIS to explain the antiquark distributions [18, 19].

The presence of the meson cloud may lead to an additional mechanism for the slow proton production in deep inelastic lepton scattering [20, 21, 22, 23]. For instance, in the (anti)neutrino induced reaction the virtual boson W smashes the virtual pion (meson) into debris and the nucleon (baryon) is produced as a spectator of the reaction (see Fig.1). The presence of the $\pi\Delta$ Fock component in the nucleon leads to the production of a spectator Δ which decays into a pion and nucleon.

Up to now no fully consistent treatment of both the standard fragmentation mechanism and the meson exchange mechanism exists. We note that it is inconsistent to add the cross sections for the two processes. In the present paper we discuss in a simple hybrid model how the two mechanisms can be taken into account in a consistent manner which ensures baryon number conservation. It is also not fully consistent to replace the four-quark fragmentation by the meson exchange mechanism due to the following two reasons. First of all, as discussed in Ref.[16], the virtual pions (mesons) give rise both to the sea and valence quark distributions. Secondly [18, 24] the sea generated by mesons constitute only a fraction of the total sea.

It is the aim of this paper to quantitatively predict the contribution of the meson exchange mechanism to the slow proton production rate in (anti-)neutrino charged current deep inelastic scattering from nucleons. In addition the momentum distribution of protons is calculated and compared with existing experimental data [4]. Finally the x-dependence of the coincidence cross section for the experimental momentum bins is calculated and compared with experimental data from Ref.[5].

2 Deep inelastic (anti-)neutrino scattering

2.1 Inclusive scattering

In leading order electroweak theory the inclusive, differential, charged current (cc) cross section for the neutrino/antineutrino scattering $(h(\ell,\ell')X)$ can be expressed in terms of the structure functions F_1, F_2, F_3

$$\frac{d^3\sigma^\ell_{cc}}{dxdydQ^2} = \frac{G_F^2}{\pi(1+\frac{Q^2}{M_W^2})}[y^2xF_1(x,Q^2) + (1-y)F_2(x,Q^2) \pm (y-\frac{y^2}{2})xF_3(x,Q^2)]. \qquad (1)$$

Here $G_F = \pi/(\sqrt{2}\sin^2\theta_W M_W^2)$ is the Fermi coupling constant, M_W is the W-boson mass and $y = (E_{\ell'} - E_\ell)/E_\ell$. Assuming the Callan-Gross relation, $2xF_1 = F_2$ and the standard parton model the y integrated cross section is given by

$$\frac{d^2\sigma^\ell_{cc}}{dxdQ^2} = \frac{G_F^2}{\pi(1+Q^2/M_W^2)} x\mathcal{F}^\ell_{cc}(x,Q^2)\,, \qquad (2)$$

where $\mathcal{F}^\ell_{cc}(x,Q^2)$ can be expressed in terms of the quark distributions

$$\begin{aligned}
\mathcal{F}^\nu_{cc}(x,Q^2) &= d(x,Q^2) + \overline{u}(x,Q^2) + \frac{1}{2}(-y+\frac{y^2}{2})[d(x,Q^2) + 3\overline{u}(x,Q^2)], \\
\mathcal{F}^{\overline{\nu}}_{cc}(x,Q^2) &= \overline{d}(x,Q^2) + u(x,Q^2) + \frac{1}{2}(-y+\frac{y^2}{2})[\overline{d}(x,Q^2) + 3u(x,Q^2)]
\end{aligned} \qquad (3)$$

for neutrino and antineutrino induced reactions, respectively. In the expressions above the distributions of heavier quarks have been neglected. In the scaling limit and transferred four-momenta $Q^2 \ll M_W^2$ the Q^2-integrated cross section is

$$\frac{d\sigma^\ell_{cc}}{dx} = \frac{G_F^2 m_N E_{beam}}{\pi}\mathcal{G}^\ell_{cc}(x), \qquad (4)$$

where

$$\begin{aligned}
\mathcal{G}^\nu_{cc}(x) &= 2x[d(x) + \overline{u}(x)/3], \\
\mathcal{G}^{\overline{\nu}}_{cc}(x) &= 2x[\overline{d}(x) + u(x)/3].
\end{aligned} \qquad (5)$$

This formula will be useful in the further analysis.

2.2 Semi-inclusive scattering: fragmentation approach

Semi-inclusive charged current (anti)neutrino reactions, where a slow proton is measured in coincidence with the muon, are of special interest. The Q^2-integrated cross section for the production of a baryon B (nucleon, delta) can be written as

$$\frac{d\sigma[N(\ell,\ell'B)X]}{dxdzdp_\perp^2} = \frac{G^2 m_N E_{beam}}{\pi} \sum_f [V_f^{N(\ell,\ell')}(x) D_{2q}^{B/f}(\tilde{z},p_T^2) + S_f^{N(\ell,\ell')}(x) D_{4q}^{B/f}(\tilde{z},p_T^2)]/(1-x). \qquad (6)$$

Here $V_f^{N(\ell,\ell')}(x)$ and $S_f^{N(\ell,\ell')}(x)$ are functions proportional to the valence and sea quark distributions, respectively, with coefficients being reaction and flavour (f) dependent, $D^p_{debris}(\tilde{z},p_T^2)$ is the target debris $\rightarrow$ proton fragmentation function, with $z = p^-/m_N$, $\tilde{z} = z/(1-x)$, and p_T is the transverse momentum of the emitted proton (baryon). Usually a factorized form of the fragmentation function is assumed

$$D^p_{debris}(\tilde{z},p_T^2) = D(\tilde{z})\Phi(p_T^2). \tag{7}$$

Then, neglecting a small production of the $B\overline{B}$ pairs, the baryon number conservation requires for each flavour the following sum rules (assuming only one baryon is produced in the target fragmentation region)

$$\begin{aligned} \sum_B \int D_{2q}^{B/f}(z)\, dz = 1, \\ \sum_B \int D_{4q}^{B/f}(z)\, dz = 1, \end{aligned} \tag{8}$$

separately for diquark, $D_{2q}(z)$, and four-quark, $D_{4q}(z)$, fragmentation functions.

In more advanced string models [25, 26, 27, 28, 29] the semi-inclusive cross sections can be calculated with the help of Monte Carlo methods [30, 31, 32, 9].

2.3 Pionic contribution to the semi-inclusive cross section

In the simplest models the nucleon is treated as a system of three quarks. The pion-nucleon interaction leads naturally to an admixture of a πN Fock component in the physical nucleon. In the simplest approximation, the Fock state decomposition of the hybrid proton (neutron) reads

$$\begin{aligned} |p\rangle \;&=\; \cos\theta|(p_0)\rangle + \sin\theta\left[\sin\phi\left(\sqrt{2/3}|\pi^+ n\rangle - \sqrt{1/3}|\pi^0 p\rangle\right)\right. \\ &\left.+\cos\phi\left(\sqrt{1/2}|\pi^-\Delta^{++}\rangle - \sqrt{1/3}|\pi^0\Delta^+\rangle + \sqrt{1/6}|\pi^+\Delta^0\rangle\right)\right] \quad , \end{aligned} \tag{9}$$

$$\begin{aligned} |n\rangle \;&=\; \cos\theta|(n_0)\rangle + \sin\theta\left[\sin\phi\left(\sqrt{1/3}|\pi^0 n\rangle - \sqrt{2/3}|\pi^- p\rangle\right)\right. \\ &\left.+\cos\phi\left(\sqrt{1/2}|\pi^+\Delta^-\rangle - \sqrt{1/3}|\pi^0\Delta^0\rangle + \sqrt{1/6}|\pi^-\Delta^+\rangle\right)\right] \quad , \end{aligned} \tag{10}$$

where only πN and $\pi\Delta$ Fock states are taken into account.

The two mixing angles are related to the number of pions ($n_\pi = n_{\pi N} + n_{\pi\Delta}$) in the pionic cloud

$$\begin{aligned} \sin^2\theta = n_\pi/(1+n_\pi) \\ \sin^2\phi = n_{\pi N}/n_\pi \quad . \end{aligned}$$

The Fock expansion in Eqs. (9, 10) leads to the processes which can be classified as spectator mechanism (see Fig.1), core fragmentation, and intermediate nucleon (and intermediate Δ) fragmentation with the pion produced as a spectator, respectively.

Schematically the total cross section can be expressed as

$$\begin{aligned}\sigma^{tot}(N(\ell,\ell' N')) &= \sigma^{sp}(N\to N') + \sum_{\Delta}\sigma^{sp}(N\to\Delta\to N') \\ &+ Z[\sigma^{h}(N\to N') + \sum_{\Delta}\sigma^{h}(N\to\Delta\to N')] \\ &+ P_{\pi N}[\sum_{N"} f_{N"}\sigma^{h}(N"\to N') + \sum_{N",\Delta} f_{N"}\sigma^{h}(N"\to\Delta\to N')] \\ &+ P_{\pi\Delta}[\sum_{\Delta} f_{\Delta}\sigma^{h}(\Delta\to N') + \sum_{\Delta,\Delta'} f_{\Delta}\sigma^{h}(\Delta\to\Delta'\to N)]\ . \end{aligned} \tag{11}$$

In the formula above σ^{sp} and σ^{h} are cross sections for the spectator and colour neutralization mechanisms, respectively. The factors $Z = \cos^2\theta, P_{\pi N}, P_{\pi\Delta}$ are probabilities of the core, and πN and $\pi\Delta$ Fock components. The $f_{N'}$ and f_{Δ} factors are the relative weights of the nucleons (deltas) in the meson cloud model as dictated by the isospin symmetry. A fully consistent calculation would require to include the momentum distribution of virtual baryons in the nucleon, which goes beyond the scope of the present paper. In the actual calculation we have taken into account only the first two lines in Eq.(11). We note that the nucleon can be produced in the direct way ($M = \pi, B = N$) or as a two step process: direct production of isobar Δ ($M = \pi, B = \Delta$) and subsequent decay of the resonance ($\Delta \to N + \pi$).

In calculating σ^{h} (see Eq.(11)) one should bear in mind that part of the the sea quark distributions in bare nucleons (deltas) is already taken into account by the pionic component. Therefore in Eq.(6) the sea structure functions $S_f(x)$ should be replaced by the difference between the experimental ones and the ones computed in the pion spectator approach. In practice we find that at $Q^2 = 4$ (GeV$/c)^2$ this is equivalent with a reduction of the four quark fragmentation by a factor $0.5 - 0.7$ [18, 24].

The probability density to find a meson with longitudinal momentum fraction y_M and four-momentum of the virtual meson squared, t, (or alternatively transverse momentum p_T^2), referred to as splitting function, quantifies the presence of virtual mesons in the nucleon. The splitting function $f(y_M, t)$ for the first process is

$$f_{\pi N}(y_M, t) = \frac{3g^2_{p\pi^0 p}}{16\pi^2} y_M \frac{(-t)|F(y_M,t)|^2}{(t-m_\pi^2)^2}. \tag{12}$$

The splitting function for the $\pi\Delta$ Fock state is

$$f_{\pi\Delta}(y_M, t) = \frac{2g^2_{p\pi^-\Delta^{++}}}{16\pi^2} y_M \frac{(M_+^2 - t)^2(M_-^2 - t)|F(y_M,t)|^2}{6m_N^2 m_\Delta^2 (t-m_\pi^2)^2}, \tag{13}$$

where $M_+ = m_\Delta + m_N$ and $M_- = m_\Delta - m_N$. The $F(y_M, t)$ are vertex form factors, which account for the extended nature of hadrons involved. The form factors used in meson exchange models are usually taken to be a function of t only. As discussed in Refs.[15, 33] such form factors are a source of momentum sum rule violation.

The pion (meson) emitted by the nucleon can interact with a virtual W-boson. In general the cross section for the semi-inclusive spectator $N(\ell,\ell' B)X$ process depicted in Fig.1 can be written as

$$\frac{d\sigma^{sp}(N(\ell,\ell' B)X)}{dx dQ^2 dy_M dp_T^2} = f_{M/N}(y_M, p_T^2)\frac{d\sigma^{\ell M}}{dx dQ^2}(x/y_M)\ . \tag{14}$$

Integrating over unmeasured quantities one recovers the known one-pion exchange contribution to the inclusive cross section

$$\frac{d\sigma^{\ell N}(x)}{dx} = \int_x^1 dy_M f_\pi(y_M) \frac{d\sigma^{\ell\pi}(x/y_M)}{dx}, \tag{15}$$

where the $\frac{d\sigma^{\ell\pi}}{dx}$ is the Q^2-integrated cross section for the deep inelastic scattering of ℓ from the virtual pion. In practical calculations the on-mass-shell $\ell\pi$ cross section given by Eq.(4) can be used.

The probability to find a nucleon N' associated with the lepton ℓ' at given value of the Bjorken x can easily by calculated as

$$P_{N'}^{\ell N}(x) = |<1t_3^\pi, \frac{1}{2}t_3^{N'}|\frac{1}{2}t_3^N>|^2 \int_x^1 dy_M f_{\pi N'/N}(y_M)\mathcal{G}_{cc}^{\ell\pi}(x/y_M)$$
$$+\sum_{t_3^\Delta} |<1t_3^\pi, \frac{3}{2}t_3^\Delta|\frac{1}{2}t_3^N>|^2 \int_x^1 dy_M f_{\pi\Delta/N}(y_M)\mathcal{G}_{cc}^{\ell\pi}(x/y_M)P(\Delta \to \pi N'). \tag{16}$$

The first term in Eq.(16) describes the direct nucleon production whereas the second term corresponds to the two step mechanism. The Clebsch-Gordan coefficients account for the relative yield of a given isospin channel. The sum involves all charge combinations of the pion and Δ which lead to the final nucleon N'. The probability of the Δ resonance decay into the channel of interest (N') can be calculated assuming isospin symmetry

$$P(\Delta \to \pi N') \; = \; |<1t_3^\pi, \frac{1}{2}t_3^{N'}|\frac{3}{2}t_3^\Delta>|^2. \tag{17}$$

The formula given by Eq.(16) can be easily generalized to the case with the proton (nucleon) in a given momentum range ($p_{min} < p < p_{max}$). In this case the following substitutions are necessary

$$\begin{aligned} f_{\pi N'/N}(y_M) \;&\to\; \int_{t_{min}^N}^{t_{max}^N} f_{\pi N'/N}(t, y_M)\, dt\;, \\ f_{\pi\Delta/N}(y_M) \;&\to\; \int_{t_{min}^\Delta}^{t_{max}^\Delta} f_{\pi\Delta/N}(t, y_M) P(t, p_{min}, p_{max})\, dt\;. \end{aligned} \tag{18}$$

For the direct process the experimental limits on the proton momentum directly correspond to limits for t:

$$\begin{aligned} t_{min}^N &= 2[m_N^2 - m_N\sqrt{p_{max}^2 + m_N^2}], \\ t_{max}^N &= 2[m_N^2 - m_N\sqrt{p_{min}^2 + m_N^2}], \end{aligned} \tag{19}$$

with an extra absolute limit $t < -m_N^2 y_M^2/(1-y_M)$. For the proton production through the intermediate delta resonance one has to integrate over all possible t and include an extra probability function $P(t, p_{min}, p_{max})$. The $P(t, p_{min}, p_{max})$ is the probability that the intermediate isobar Δ produced with momentum

$$p_\Delta^2(t) = \left[\frac{m_\Delta^2 + m_N^2 - t}{2m_N}\right]^2 - m_\Delta^2 \tag{20}$$

decays into a pion and nucleon N' in the given momentum range. It can easily be calculated assuming a sharp Δ resonance and its isotropic decay. Technically it is convenient to calculate $P(t, p_{min}, p_{max})$ as a difference

$$P(t, p_{min}, p_{max}) = P(t, p_{N'} < p_{max}) - P(t, p_{N'} < p_{min}) \tag{21}$$

with self-explanatory notation. In this approximation the probability is

$$P(t, p_{N'} < p_{max}) = \frac{1}{2}\Big[1 - \frac{E_0 E_\Delta/m_\Delta - (p_{max}^2 + m_N^2)^{1/2}}{p_0(E_\Delta/m_\Delta - 1)^{1/2}}\Big] , \tag{22}$$

where p_0, E_0 are momentum and energy of the nucleon in the delta rest frame.

The momentum distribution of the spectator baryon B produced in the $N(\ell, \ell' B)X$ reaction which proceeds via scattering of virtual boson $(\gamma, W_\pm)$ on the virtual meson M can generally be written as

$$\frac{dN(p,Q^2)}{dp} = \frac{\frac{1}{\Delta p}\int dx \int_x^1 dy_M [\int_{t_1}^{t_2} f_{MB/N}(y_M,t)dt] \ \frac{d\sigma_M^{\ell\ell'}}{dx}(\frac{x}{y_M}, Q^2)}{\int dx \frac{d\sigma_N^{\ell\ell'}}{dx}(x,Q^2)} \tag{23}$$

with t_1 and t_2 corresponding to momenta $p \pm \Delta p/2$, respectively. The function $f_{MB/N}(y_M, t)$ can be calculated for different partitions of the nucleon into a meson M (pseudoscalar,vector) and baryon B (octet,decuplet) [33].

3 Results and Discussion

Let us first discuss the probability for production of slow protons as obtained from the hadronization models. (With slow protons we mean hereafter unless specified otherwise, protons with momenta in the interval (0.15 - 0.60 GeV/c), corresponding to the experimental bins defined in Ref.[5]). In Table 2 we list the probabilities calculated in (a) the quark-diquark model from Ref.[8], (b) the quark-diquark model corrected for the presence of the pionic cloud (to be discussed later) and (c) in the Lund string model [9]. In the first two cases the results are rather sensitive to the form of the fragmentation function $D(\tilde{z})$. In this calculation the transverse momentum distribution function $\Phi(p_T^2)$ in Eq.(7) is parametrized by a Gaussian form

$$\Phi(p_T^2) = \frac{1}{\sigma^2} \exp(-p_T^2/\sigma^2) \tag{24}$$

with $\sigma^2 = 0.3$ (GeV/c)^2. We find that the use of a constant fragmentation function (as in Ref.[6]) yields a result almost consistent with the experimental one [5]. The rate obtained with quadratic $D(\tilde{z}) = 1/2 * \tilde{z}(1-\tilde{z})$ and especially with the 'triangular' $D(\tilde{z}) = 2(1-\tilde{z})$ (counting rule motivated for the diquark hadronization) hadronization functions is lower than the experimental rate. The quark-diquark model [8] gives only isospin factors for the valence quark (diquark) hadronization.

To show the sensitivity to details of the sea (4-quark) fragmentation two extreme limits have been used in which protons being produced either with zero probability (only diquark hadronization) or with unit probability (neglecting production of other baryons), respectively. As is seen from the results the contribution of the sea hadronization is rather important for the production of slow protons. The total rate obtained in both extreme limits is, however, below the experimental rate [5]. The Lund string model predicts an even lower rate.

This supports the conjecture that another mechanism plays a role and therefore we now turn to a discussion of the role of pion exchange mechanism as sketched in the previous section.

In all calculations discussed below exponential vertex form factors

$$F(y_M, p_T^2) = \exp[-\frac{M_{MB}^2(y_M, p_T^2) - m_N^2}{2\Lambda^2}] \tag{25}$$

have been used in Eqs.(12,13). In Eq.(25) $M_{MB}(y, p_T^2)$ is the invariant mass of the intermediate meson-baryon system. The cut-off parameters used in the present calculation ($\Lambda_{\pi N} = 1.10$ GeV and $\Lambda_{\pi\Delta} = 0.98$ GeV) have been determined from the analysis of the particle spectra for high-energy neutron ($p(p,n)X$) and Δ ($p(p,\Delta^{++})X$) production [19]. With these cut-off parameters the NMC result for the Gottfried sum rule [10] which depends sensitively on Λ, has been reproduced [17, 19]. Furthermore the model describes $\overline{u}/\overline{d}$ asymmetry extracted recently from the Drell-Yan NA51 experiment at CERN [24]. Finally the deep-inelastic structure functions of pions are taken from Ref.[35] and those for the nucleon from Ref.[34].

A quantity of interest [8] is the probability for finding a slow proton in a momentum bin Δp as a function of x

$$P(x, \Delta p) = \frac{d\sigma(x, \Delta p)}{dx} (\frac{d\sigma}{dx})^{-1}. \tag{26}$$

The quantity calculated in the spectator model is shown in Fig.2 where in addition we show the direct component by the dashed line (the contribution of the intermediate Δ is a complement to the total $P(x)$ given by the solid line) and the contribution from the valence quarks in the pion by the dotted line (the sea contribution is again a complement to the solid line). As seen from the figure the direct component dominates the cross section in the whole range of x. The contribution of the sea in the pion plays an important role only at small Bjorken x. Experimentally this region can only be accessible at high beam energies.

In order to obtain an absolutely normalized "experimental" quantity the following procedure has been applied. In Ref.[5] the ratios of normalized x-distributions with and without secondary protons in the momentum range Δp

$$R(x,\Delta p) = \frac{\frac{d\sigma}{dx}(x,\Delta p)/\sigma(\Delta p)}{\frac{d\sigma}{dx}(x,1-\Delta p)/\sigma(1-\Delta p)} \tag{27}$$

have been given, where $(1-\Delta p)$ refers to the complement of the momentum interval Δp. Taken the absolute normalization $R_{tot} = \sigma(\Delta p)/\sigma_{tot}$ from Table 1 of Ref.[5] at face value one can extract the absolutely normalized quantity (26) as

$$P(x,\Delta p) = \frac{R(x,\Delta p)}{R(x,\Delta p) + (1-R_{tot})/R_{tot}}. \tag{28}$$

The results of the procedure are presented in Fig.3 for low (0.15 -0.35 GeV/c) and high (0.35 -0.60 GeV/c) momentum bins. The results of the spectator model (dashed line) and of the Lund string model[9] (solid line) are shown in Fig.3. As can be seen from the figure the string breaking mechanism underestimates the experimental data. To get more insight into this result it is instructive to consider simpler quark-diquark model [8] for the flavour dependent diquark branching ratio into nucleons and deltas. In this calculation we have taken the QCD motivated fragmentation functions [36]

$$D_{2q}(\tilde{z}) = C\,\tilde{z}^{1/2}(1-\tilde{z}),\ D_{4q}(\tilde{z}) = \text{ const.} \tag{29}$$

Since no realistic model for the four-quark branching ratio exists, one can only consider lower (diquark fragmentation) and upper (maximal proton production in four-quark hadronization) estimates, as for the relative yields in Table 2. The results are shown in Fig.3 as dotted lines. The difference between the lower and the upper limit clearly demonstrates a significant sensitivity to the four-quark hadronization. The presence of the virtual pions leads to a reduction of the perturbative sea by about a factor 2 [24], which would result in the same reduction of the four-quark contribution to $P(x)$. Even the upper limit underestimates the experimental data. This suggests a presence of an extra competing mechanism.

For the proton production on the neutron the situation is somewhat more complicated (see Fig.4). Here the result for the Lund string model falls only slightly below the experimental data [8] extracted from the (ν,μ^-) reaction on the deuteron (Fig.4a,b). The spectator mechanism predicts a very similar result, also almost consistent with the experimental data. For the $(\overline{\nu},\mu^+)$ reaction (Fig.4c,d) the situation is similar, except that here the corresponding cross sections are significantly smaller. Similarly as for the proton production on the proton we present the lower (diquark fragmentation) and the upper (maximal proton production in four-quark hadronization) limits of the model discuss in section 2.2. Again a large difference between the two limits can be observed. The proton production on the neutron , however, differs from that on the proton. It is reasonable to expect here rather the lower limit to be more realistic. The experimental data seems to support this expectation.

In order to better understand the range of proton momenta where the spectator mechanism plays an important role, it is instructive to calculate the momentum distribution of protons produced in the neutrino (anti-neutrino) induced reactions. The proton momentum distributions were determined in the early BEBC experiments at CERN [4]. In order to avoid the resonance contributions and minimize the effect of the proton's sea, the events have been selected with the constraints $W > 3$ GeV and $x > 0.1$.

The cuts are rather important especially for the low-momentum part of the spectrum. In the experiment [4] the wide band (anti-)neutrino beam has been used. In principle, the effect of the beam spread should be taken into account. It has been checked, however, that the results of the Lund string model[9] are not very sensitive to the beam energy. The results of the Monte Carlo simulation for three different beam energies (20, 50, 80 GeV) are shown in Fig.5. The total number of protons per event in the momentum range ($0.15 < p < 0.60$ GeV/c) and corresponding to the experimental cuts[4], calculated in the Lund string model and the spectator model is given in Table 3. Also shown are the experimental results extracted from Ref.[4]. Similarly as for the experiment from Ref.[5] the string mechanism produces too little low energy protons. In this case the spectator mechanism gives almost total missing strength (see Table 3).

In order to get insight into the total proton momentum distribution, it is instructive to consider the simpler quark-diquark model [8] for the flavour dependent diquark branching ratio into nucleons and deltas. The momentum distribution calculated with the QCD motivated fragmentation functions (Eq.(29)) is shown in Fig.6. It was assumed here for simplicity that the four-quark hadronization leads in all cases to proton production. This will lead to an overestimation of this contribution. The diquark and four-quark hadronization contributions are shown separately by the dashed and dotted line, respectively. As clearly seen from the figure, the four-quark hadronization populates the slow proton region, whereas the diquark hadronization is responsible for the production of rather fast protons.

The momentum distribution of protons produced in the spectator mechanism calculated according to Eq.(23) is shown in Fig.7. The solid line includes both protons originating from the $\pi^0 p$ Fock component (direct component) and those originating from the decay of spectator deltas. The direct component is shown separately by the dashed line. In the neutrino induced reaction the sequential mechanism is as important as the direct production of protons, whereas in antineutrino induced reaction its relative contribution is much smaller. This effect is a consequence of the dependence of underlying coupling constants on the charge of pions and of the difference of $F_2^{\nu,\pi}(x)$ and $F_2^{\overline{\nu},\pi}(x)$ structure functions. In order to better understand the underlying reaction mechanism we present also in Fig.7 separately the contribution from the valence quarks in the pion (dotted line). The corresponding contribution from the sea is a complement to the total momentum distribution.

In the experiment of ref.[4] not all protons with low momenta ($p < 0.6$ GeV/c) were identified. In order to make comparison of the model results in the whole momentum range the inclusion of the proton identification efficiency is neccessary. In the present paper the proton identification efficiency has been parametrized as

$$e(p) = \left[1 + \exp[\frac{p - p_0}{\sigma}]\right]^{-n} \tag{30}$$

with $p_0 = 0.86$ GeV/c, $\sigma = 0.1$ GeV/c and $n = 0.25$. The result of the spectator mechanism and the result of the quark-diquark model have been multiplied by the efficiency function $e(p)$ and are shown in Fig.8 by the dashed and dotted line, respectively. One clearly sees that the colour neutralization mechanism (dotted line) is dominant for the proton production in a broad momentum range. The spectator mechanism (dashed line) plays, however, important role at very low momenta. Since in our model the pionic cloud constitutes about half of the nucleon sea [24] for Q^2 of a few GeV^2, for consistency the four-quark hadronization contribution (dotted line in Fig.6) must be reduced by a factor of about 0.5. Therefore the sum

$$N(p) = e(p)\ [N_{2q}(p) + 0.5 N_{4q}(p) + N_{\pi}(p)] \tag{31}$$

consistently includes the two mechanisms. The sum (solid line in Fig.8) almost coincides with the original quark-diquark model and describes the experimental data [4] in a resonable way.

The considered x-distributions $P(x)$ and proton momentum distributions do not give a direct evidence for identifying the meson cloud in the nucleon, although they do not contradict its existence. Therefore one should look for other possibilities. It has been suggested by some authors to consider the production of slow (for the fixed target experiments) pions. Slow pions could be created by a mechanism analogous to that considered in the present paper for the slow proton production, as a spectator of the reaction (see Fig.9). The momentum distribution of pions can be calculated in a fully analogous way to that of the slow protons (see formula (23)). In this case all kinematical variables associated with the meson M (pion) have to be replaced by corresponding variables for the recoil baryon B (nucleon or delta). The momentum distributions of pions (π^+, π^0, π^-) produced in the (ν, μ^-) and ($\overline{\nu}, \mu^+$) reactions calculated in this way are shown in Fig.10, separately for $N\pi$ (solid line) and $\Delta\pi$ (dashed line) mechanisms. For comparison the momentum distribution of pions generated by the Monte Carlo method [9] according to the the Lund string model is shown by the solid line with the centered points. As seen from the figure the spectator pions constitute only a small fraction of all pions, therefore their identification seems to be rather difficult.

The relative fraction of different pions differs between the Lund string model [9] and the spectator model (see Table 4). This is especially visible for the neutrino induced reaction on the proton and antineutrino induced reaction on the neutron. The spectator mechanism predicts a huge asymmetry between π^+ and π^- production. The reason here is very simple. Both π^- in the $\nu + p$ and π^+ in the $\overline{\nu} + n$ reactions cannot be produced in the scattering of the virtual boson $W^{\pm}$ off the nucleon of the πN Fock states. On the other hand their production via scattering of $W^{\pm}$ from the virtual delta of the $\pi\Delta$ Fock state is highly suppressed as here the corresponding structure functions vanish in the valence quark approximation. The huge difference between the predictions of the Lund string model and the spectator mechanism could in principle be tested if one limits the analysis only to the pions produced in the backward directions. This part of the phase space is expected to be dominated via the spectator mechanism. A possible confirmation of the asymmetry in the production of the positively and negatively charged pions would be a strong test of the spectator mechanism and the concept of virtual pions in the nucleon.

4 Conclusions

In the present paper the production of slow protons produced in (anti)neutrino induced reactions on proton and neutron has been studied. We have analyzed the total rate, the Bjorken-x dependence of the slow proton production as well as the momentum distribution of emitted protons.

The analysis of the rate of slow proton production in the neutrino and anti-neutrino charged current reactions shows that "realistic" hadronization models underestimate the cross section measured by the bubble chamber Collaboration at CERN [5]. Although the pion exchange mechanism leads to a rather small contribution to the total proton production, it plays an important role in the production of slow protons and helps us to understand the deficit of the slow proton production as predicted by standard hadronization models based on colour neutralization mechanism.

Even these two mechanisms seem to fail to describe the total rate of slow proton production from Ref.[5]. Comparison of the total rate as extracted here from earlier CERN measurement [4], where more severe restrictions on the Bjorken-x and invariant mass of the produced hadrons have been imposed, suggests that the 'missing' mechanism is related to the region of small x and low invariant mass of the produced hadrons. The considered x-distributions $P(x)$ and proton momentum distributions for (anti-)neutrino charged current reactions do not give direct evidence for identifying the meson cloud in the nucleon, although they do not contradict its existence. Therefore one should look for other possibilities to prove or disprove the whole concept of the meson cloud in the nucleon.

The recent results of deep inelastic electron-proton scattering at HERA, (ref[37]), open such a possibility. The observation of a surprisingly large number of events characterized by a large rapidity gap, strongly suggests the presence of a (up to now not really identified) proton with approximately beam velocity. These so-called diffractive scattering events, which cannot be explained by conventional hadronization codes, have up to now primarily been interpreted in terms of Pomeron exchange. Since the Pomeron by definition has vacuum quantum numbers this approach predicts that only protons are produced in the final state in contrast to the mesonic cloud model which leads to a definite prediction for branchings into proton, neutron and isobars. Therefore the planned search for neutron spectators will provide more information on the mechanism for the production of slow baryons.

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Tables

Table 1. Fraction of protons ($f_p = N_p/(N_p + N_n)$) and neutrons ($f_n = N_n/(N_p + N_n)$) produced in the $e + p$, $\nu + p$ and $\overline{\nu} + p$ reactions. The fractions have been calculated according to the quark-diquark model [8] and the Lund string model [9] for the beam energy 50 GeV. The total number of protons and neutrons per event in the Lund string model exceeds unity which is caused by the explicit production of baryon-antibaryon pairs.

beam	$p \to p$	$p \to n$	$n \to p$	$n \to n$
quark-diquark model				
$\mu^{\pm}$	0.5473	0.4527	0.2160	0.7840
ν	0.9259	0.0741	0.5000	0.5000
$\overline{\nu}$	0.5000	0.5000	0.0741	0.9259
Lund string model				
$\mu^{\pm}$	0.60	0.47	0.43	0.64
ν	0.78	0.29	0.56	0.52
$\overline{\nu}$	0.52	0.54	0.31	0.76

Table 2. Fraction (in percent) of events with low ($0.15 < p < 0.60$ GeV/c) momentum protons for neutral current charged lepton DIS and charged current neutrino and antineutrino reactions.

final state baryons	$D(z)$	$p + \mu^{\pm} \rightarrow p$	$p + \nu \rightarrow p$	$p + \overline{\nu} \rightarrow p$
simple quark-diquark				
model	constant	3.47-5.88	6.70-9.75	2.74-6.57
	quadratic	2.15-3.89	4.22-6.42	1.69-4.45
	triangular	0.89-1.64	1.76-2.70	0.70-1.89
improved quark-diquark				
model	constant	3.43-5.54	5.72-8.04	2.75-6.13
	quadratic	2.13-3.65	3.59-5.26	1.70-4.14
	triangular	0.88-1.54	1.50-2.21	0.70-1.75
Lund string model				
$E = 20$ GeV		2.97	0.89	1.44
$E = 50$ GeV		4.37	1.43	1.95
$E = 80$ GeV		4.60	1.42	1.75
spectator model				
πN		0.97	1.23	1.55
$\pi\Delta$		0.29	0.52	0.27
valence		0.88	1.33	1.28
sea		0.38	0.42	0.53
sum		1.25	1.75	1.81
Exp [5]			10	8

Table 3. Fraction (in percent) of events with protons in the momentum interval $0.15 < p < 0.60$ GeV/c for the neutrino and antineutrino induced reactions. The results from the Lund string model has been obtained with extra limitations: $x > 0.1$ and W > 3 GeV for three different beam energies.

contribution	$p + \nu \to p$	$p + \overline{\nu} \to p$
spectator mech.		
πN	1.23	1.55
$\pi\Delta$	0.52	0.27
sum	1.75	1.81
Lund string model		
E = 20 GeV	0.98	1.39
E = 50 GeV	1.27	1.79
E = 80 GeV	1.17	1.58
Exp.[4]	4.74	5.20

Table 4. Fractions of different pions calculated in the Lund string model [9] for the beam energy 50 GeV and in the spectator mechanism.

	Lund string model			spectator mechanism		
reaction	π^-	π^0	π^+	π^-	π^0	π^+
$\mu^\pm + p$	0.29	0.36	0.35	0.25	0.38	0.37
$\nu + p$	0.23	0.36	0.41	0.01	0.24	0.75
$\overline{\nu} + p$	0.36	0.37	0.27	0.29	0.40	0.31
$\mu^\pm + n$	0.36	0.36	0.28	0.63	0.28	0.09
$\nu + n$	0.28	0.36	0.35	0.29	0.41	0.31
$\overline{\nu} + n$	0.42	0.36	0.22	0.71	0.25	0.04

Figure Captions

Fig.1 The spectator mechanism for the production of slow protons in the (anti)neutrino induced reactions on the nucleon.

Fig.2 $P(x, \Delta p)$ for $0.15 < p < 0.60$ GeV/c calculated within the spectator model (solid line). The contribution of the direct proton production is shown by the dashed line and the contribution from the valence quarks in the pion by the dotted line.

Fig.3 $P(x, \Delta p)$ for $p(\nu, p)X$ and $p(\overline{\nu}, p)X$ reactions, for low ($0.15 < p < 0.35$ GeV/c) and high ($0.35 < p < 0.60$ GeV/c) momentum bins. The "experimental" data has been obtained by the procedure described in the text. The result from the spectator model is shown by the solid and from the Lund string model by the dashed line. In addition the two limits discussed in the text are shown by the dotted lines.

Fig.4 $P(x, \Delta p)$ for $n(\nu, p)X$ and $n(\overline{\nu}, p)X$ for low ($0.15 < p < 0.35$ GeV/c) and high ($0.35 < p < 0.60$ GeV/c) momentum bins. The experimental data are taken from Ref.[8]. The result from the spectator model is shown by the solid and from the Lund string model by the dashed line. In addition the two limits discussed in the text are shown by the dotted lines.

Fig.5 Momentum distribution of protons from the Lund string model for different (anti)neutrino beam energies (E_{beam} = 20 GeV – dashed line, E_{beam} = 50 GeV – solid line and E_{beam} = 80 GeV – dotted line. The experimental [4] cuts: $W >$ 3GeV and $x > 0.1$ have been taken into account. The proton identification efficiency of the experiment is not included here.

Fig.6 Momentum distribution of protons from the quark-diquark model [8]. The diquark fragmentation contribution is shown by the dashed line and the 4-quark fragmentation contribution by the dotted one. The details concerning the fragmentation function used are described in the text.

Fig.7 Momentum distributions of protons produced in the spectator mechanism in the neutrino (a) and antineutrino (b) induced deep inelastic scattering (solid line). The direct πN contribution is shown separately by the dashed line, whereas the contribution from the valence quarks in the pion is shown by the dotted line.

Fig.8 Momentum distributions of protons corrected for the identification efficiency from the quark-diquark model (dotted line) and from the spectator model (dashed line) compared with the CERN experimental data [4]. The solid line includes both mechanisms in the way described in the text.

Fig.9 The spectator mechanism for the production of slow pions in the (anti)neutrino induced reactions on the nucleon.

Fig.10 Momentum distribution of pions produced in the $p(\nu, \pi)X$ and $p(\overline{\nu}, \pi)X$ deep-inelastic processes. The predictions of the spectator model are shown as the solid (πN) and the dashed ($\pi\Delta$) lines. The result of the Monte Carlo simulation according to the Lund string model [9] are shown by the solid line with the centered points.