How to measure the pion structure function at HERA

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Abstract

We suggest a method of determination of the pion structure function down to $x \simeq 10^{-4}$ based on semi-exclusive deep inelastic scattering off protons. The idea is to exploit the nonperturbative πN and $\pi \Delta$ Fock components of the nucleon, which contribute significantly to deep inelastic scattering and dominate the fragmentation of protons into fast neutrons and deltas. The intrinsic factorization properties of the semi-exclusive cross section give a good test for the validity of this approach.

Up to now the only feasible method to extract the pion structure was the πN Drell–Yan production. The disadvantages of this method are that the attainable luminosity is low and that only the valence part of the pion structure function at rather large x ($\gtrsim 0.2$) can be studied. An extension of our knowledge of the pion structure function is possible by using virtual pions around the nucleon as targets in deep inelastic scattering. These pions arise naturally as a consequence of the pion–nucleon coupling which leads to an admixture of the πN Fock state in the light-cone nucleon. Interaction of high-energy projectiles (nucleons, pions, leptons) with the virtual pion of the πN Fock state of the proton is a typical stripping reaction, in which the momentum distribution of the spectator nucleon reflects the momentum distribution in the πN (meson–baryon) Fock state. For instance, the differential cross section of the inclusive reaction $\pi p \rightarrow nX$ takes the form (Fig. 1a)

$$\frac{d\sigma(\pi p \rightarrow nX)}{dz\,dp_\perp^2} = \frac{2}{3} f_{N/p}(z, p_\perp^2)\sigma_{\pi\pi}(s_{\pi\pi}), \qquad (1)$$

where $f_{N/p}(z, p_\perp)$ is the flux of nucleons with the transverse momentum $p_\perp$ and the fraction z of the proton's light-cone momentum. The $\pi\pi$ total cross section enters at the center of mass energy squared $s_{\pi\pi} = (1 - z)s_{\pi p}$ and the factor $\frac{2}{3}$ comes from the isotopic Clebsch–Gordan coefficients.

The salient feature of Eq. (1) is that the flux $f_{N/p}(z, p_\perp)$, as well as its counterpart $f_{\Delta/p}(z, p_\perp)$ for the $p \rightarrow \Delta$ inclusive fragmentation, is a universal property of the πN, $\pi\Delta$ Fock state, which does not depend on the projectile. In the light-cone representation they read (see [1,2])

$$f_{N/p}(z, p_\perp^2) = \frac{3g_{p\pi^0 p}^2}{16\pi^2}$$
$$\times \frac{[(1 - z)^2 m_N^2 + p_\perp^2]}{z^2(1 - z)(m_N^2 - M_{\pi N}^2)^2}|F(z, p_\perp^2)|^2, \qquad (2)$$
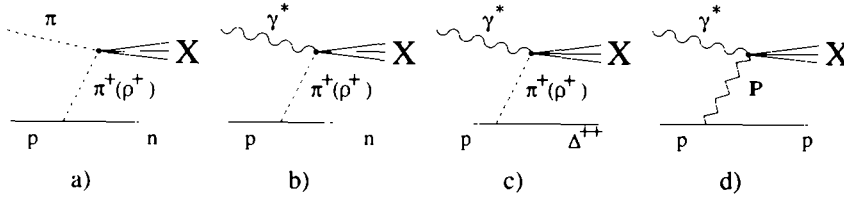
Fig. 1. The pion-exchange contribution to the inclusive production of neutrons in (a) πp scattering and (b) deep inelastic scattering and to the inclusive production of Δ^{++} (Δ^0) (c) in deep inelastic scattering. Diagram (d) shows the diffractive production of N^*'s by pomeron exchange.

and

$$f_{\Delta/p}(z, p_\perp^2) = \frac{2g^2_{p\pi^-\Delta^{++}}}{16\pi^2}$$

$$\times \frac{[(zm_N + m_\Delta)^2 + p_\perp^2]^2[(zm_N - m_\Delta)^2 + p_\perp^2]}{6z^4(1-z)m_\Delta^2(m_N^2 - M_{\pi\Delta}^2)^2}$$

$$\times |F(z, p_\perp^2)|^2, \tag{3}$$

These fluxes are nonperturbative quantities. Their absolute normalization is fixed by the nonperturbative strong couplings known from low-energy physics: $g^2_{p\pi^0p}/4\pi = 13.6$ [3] and $g^2_{p\pi^-\Delta^{++}}/4\pi = 12.3$ GeV^{-2} [4]. The vertex light-cone form factors $F(z, p_\perp^2)$ are parameterized as [1,2,5]

$$F(z, p_\perp^2) = \exp\left[-\tfrac{1}{2}R_{MB}^2(M_{MB}^2(z, p_\perp^2) - m_N^2)\right] \tag{4}$$

in terms of still another nonperturbative parameter – the radii R_{MB} of the meson–baryon Fock state. Here $M_{MB}(z, p_\perp^2)$ is the invariant mass of the intermediate two-body meson–baryon Fock state

$$M_{MB}^2(z, p_\perp^2) = \frac{m_B^2 + p_\perp^2}{z} + \frac{m_M^2 + p_\perp^2}{1-z}. \tag{5}$$

The nonperturbative radius R_{MB} is the only adjustable parameter and it describes the z and $p_\perp$ distribution of the observed neutrons (deltas). The pion exchange is a well defined nonperturbative dynamical model for the $p \to n$, Δ fragmentation processes, and it has been shown [1,5–8] that the simple formulas (2), (3) give an excellent quantitative description of the experimental data on high energy neutron and Δ^{++} production in a broad range of z. (Near the kinematical boundary $1 - z \ll 1$ the fluxes Eqs. (2), (3) must be modified for the reggeization of pions [9], but we shall not

consider this region of z.) The pion-exchange contribution exhausts the observed cross section at $z \sim 0.7$–0.8. This agreement shows that the production of fast nucleons and deltas with $z \sim 0.7$–0.8 is a small background to the pion-exchange contribution. The recent analysis [5] gave $R_{\pi N} = 0.93$ GeV^{-1} and $R_{\pi\Delta} = 1.02$ GeV^{-1}. Notice, that once the fluxes $f_{N/p}(z, p_\perp)$ and $f_{\Delta/p}(z, p_\perp)$ are known, one can use the data on the $\pi p \to n(\Delta)X$ inclusive reactions for the determination of the high-energy pion–pion total cross section (see [10,11] and references therein).

Elaborating on this remarkable success of the pion exchange in hadronic reactions, we expect that the semi-inclusive reactions

$$\text{(a)} \quad ep \to e'nX \qquad \text{(b)} \quad ep \to e'\Delta X \tag{6}$$

in the properly chosen kinematical domain also will be dominated by the pion exchange ([12]) mechanism of Fig. 1. If this is the case, then the straightforward generalization of Eq. (1) to semi-inclusive deep inelastic scattering is

$$\frac{d\sigma(ep \to e'nX)}{dxdQ^2dzdp_\perp^2} = \tfrac{2}{3}f_{N/p}(z, p_\perp^2)$$

$$\times K(x, Q^2)F_2^{e\pi}(x_\pi, Q^2), \tag{7}$$

where $F_2^{e\pi}(x_\pi, Q^2)$ is the structure function of the pion; $x_\pi = x/(1-z)$ is the Bjorken variable in the electron–pion deep inelastic scattering with the obvious kinematical restriction $0 < x < 1 - z$, and $K(x, Q^2)$ is the standard kinematical factor

$$K(x, Q^2) = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[1 - y + \tfrac{1}{2}y^2\right], \quad y = \frac{Q^2}{xs}, \tag{8}$$

assuming for the sake of simplicity $2xF_1^{e\pi}(x) = F_2^{e\pi}(x)$. Knowing all kinematical variables and trusting the theoretical prediction for $f_{N/p}(z, p_\perp^2)$, one can

invert Eq. (7) and determine the pion structure function from the experimentally measured semi-inclusive cross section. In the HERA experiments, one can go down to the region of very small $x_\pi \gtrsim 10^{-4}$. This will be an enormous expansion of the studied kinematical region compared to the πN Drell-Yan experiments, which cannot go much below $x_\pi \sim 0.1$ [13]. Besides, such a determination of the pion structure function at HERA will allow the study the scaling violations in the pion structure function in a broad range of (x_π, Q^2), which hardly is possible in the Drell-Yan experiments. The aim of the present communication is to analyze kinematical conditions under which the pion structure function can be extracted.

From the purely experimental point of view, the semi-inclusive reaction $ep \rightarrow e'nX$ is being studied already by the ZEUS collaboration, which has installed a test forward neutron calorimeter (FNC) to complement its leading proton spectrometer [14]. This FNC was tested with neutrons from inclusive proton beam-gas interactions, and an excellent agreement between the measured spectra and the pion-exchange predictions was found.

From the theoretical point of view, the principal issue is the relevance of the pion-exchange mechanism to deep inelastic scattering off protons. The pion-exchange diagrams of Fig. 1 correspond to deep inelastic scattering off the nonperturbative pion-induced sea in nucleus. There is ample experimental evidence for such a nonperturbative sea in nucleons, which presently can be evaluated parameter-free making use of the pion structure function as determined from the πN Drell-Yan data [13] and the universal fluxes, Eqs. (2), (3). Further evidence for the importance of the pion-induced (and ρ-induced) sea in DIS comes from the observed Gottfried sum rule violation, connected to the $\bar{u}$-$\bar{d}$ asymmetry [1,15–20], which can be calculated parameter-free and agrees with the experimental data [1,5]. The predicted $\bar{u}$-$\bar{d}$ asymmetry was confirmed [21] by the measurement of the $\bar{u}(x)/\bar{d}(x)$ ratio in the recent NA51 Drell-Yan experiment [22]. Furthermore, the nonperturbative meson-induced sea was shown [21] to dominate the nucleon sea at $x \gtrsim 0.1$.

Our principal task is to find the kinematical domain in which the semi-inclusive reaction $ep \rightarrow enX$ is dominated by the pion-exchange contribution. The semi-inclusive production of neutrons with $z \sim 0.8$
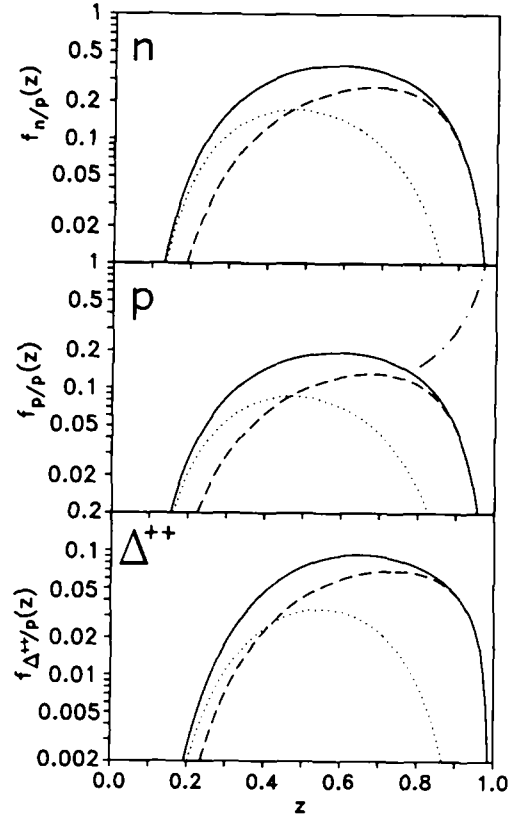

Fig. 2. Longitudinal momentum distribution of (a) neutrons, (b) protons and (c) Δ^{++}. The contributions of the π and ρ exchange mechanisms are shown by the dashed and dotted line, respectively. The contribution from the pomeron exchange mechanism to the $p \rightarrow p$ fragmentation is shown by the dash-dotted line.

turns out to be the optimal kinematical domain, and it also corresponds to the domain in which the semi-inclusive cross section is largest. Then, we suggest tests of the pion-exchange dominance and evaluate some of background reactions which also lead to production of fast neutrons.

Let us start with the charge-exchange reaction $p \rightarrow n$ and let us consider first the $p_\perp$-integrated semi-inclusive cross sections. The corresponding flux of neutrons $f_{n/p}(z) = \frac{2}{3} f_{N/p}(z)$ is shown in Fig. 2. The salient feature of the pion-exchange mechanism is that the corresponding neutrons are fast and the spectrum of neutrons has its maximum at $z \sim 0.6$–0.8. This important property can easily be understood: evidently, heavy nucleons carry a larger fraction of momentum z than light pions. The expected counting rates can be judged by the total number of virtual pions in the nu-
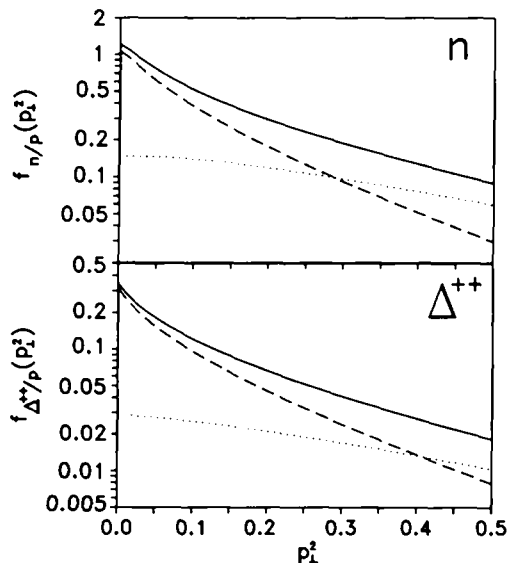
Fig. 3. Inclusive perpendicular momentum distribution of (a) neutrons and (b) Δ^{++}. The contributions corresponding to the π and ρ exchanges are shown by the dashed and dotted line, respectively.

cleon: $n_\pi(\pi N) \approx 0.18$, $n_\pi(\pi \Delta) \approx 0.06$ [5], which shows that the deep inelastic scattering on pions, accompanied by $p \to n$, Δ fragmentation, will have a statistics only by one order in magnitude lower than for the ep scattering.

The background to the pure pion exchange comes from interaction with Fock states which contain heavier mesons $M = K, \rho, \omega, \ldots$. Evidently, in such states the heavy mesons M will carry a larger fraction of the momentum of the MN state, and the heavy meson exchange will contribute to the spectrum of neutrons at smaller z as compared to the pion exchange (we do not discuss here the region of $1 - z \ll 1$ where the reggeization of mesons becomes important). In Fig. 3 we show the effect of the ρN Fock state, which was found to be important at small z [5]. Because of many spin couplings the formulas for the corresponding fluxes are too lengthy to be reproduced here; they can be found elsewhere [2]. Evidently, zooming at $z \sim 0.7$–0.8 one can eliminate much of the ρ-exchange background. A still better separation of the π and ρ exchange can be achieved if one compares the $p_\perp$ distributions for the two mechanisms. With the radii R_{MN} as determined in [5], the ρ exchange gives a broader $p_\perp$ distributions than the pion exchange (Fig. 2). If one selects only events with $p_\perp^2 <$
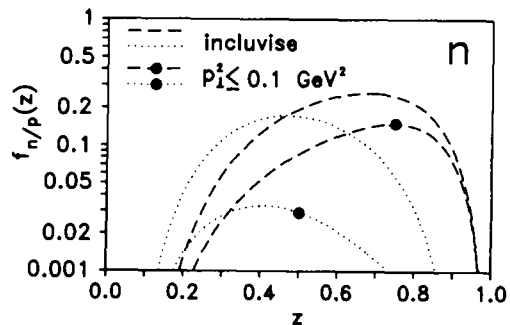

Fig. 4. Longitudinal momentum distribution of neutrons (see Fig. 2a.) with the extra condition $p_\perp^2 < 0.1 (GeV/c)^2$ (lower curves) compared to the unconstrained one (upper curves, see Fig. 2a.). The π exchange contributions are shown by dashed lines; the ρ exchange contributions by the dotted lines.

$0.1 (GeV/c)^2$, then, without much loss of statistics, one can significantly enhance the relative contribution of the pion exchange, which is demonstrated in Fig. 4.

We wish to emphasize that, as a matter of fact, the ρ-exchange contribution is not a real background, because it is natural to expect that structure functions of the pion and the ρ-meson are close to each other. Because of the different spin structure, the ρ and π contributions do not interfere, and the total semi-inclusive cross section will be proportional to

$$f_{N/p}^{(\pi N)}(z) F_2^\pi(x_\pi, Q^2) + f_{N/p}^{(\rho N)}(z) F_2^\rho(x_\pi, Q^2)$$

$$\approx [f_{N/p}^{(\pi N)}(z) + f_{N/p}^{(\rho N)}(z)] F_2^\pi(x, Q^2). \qquad (9)$$

Therefore, Eq. (7) will hold in a broader range of z, if the flux of nucleons $f_{N/p}(z)$ in Eq. (7) is generalized to include the effect of $N\rho$ states as well. Still, we feel it is safer to concentrate on $z \sim 0.7$–0.8, which is also the region from where the dominant part of the semi-inclusive cross section is coming.

Above we have considered the *elastic* fragmentation $p \to n$. One can also consider the excitation of the proton into resonances and continuum states, which then will decay into the observed neutron. The prominent excitation channel is the production of Δ states, which is also dominated by the same pion (and ρ) exchange mechanism; we shall comment more on this reaction below. Another type of background is the diffractive excitation of the proton into the prominent N^* resonances and/or the low mass $N\pi$, $N\pi\pi$, ... continuum states, whose decays can produce fast neutrons with large z. Such diffractively

produced states carry $\approx 100\%$ of the protons momentum. The underlying mechanism is the pomeron ($\mathbb{P}$) exchange process of Fig. 1d, in which the photon interacts with the pomeron. The relative fraction of the pomeron-exchange and pion-exchange reactions must not change from the pp scattering to the deep inelastic scattering energy region. In pp scattering, the total cross section of diffractive excitation of N^* resonances and $N\pi$, $N\pi\pi$ continuum states is $\lesssim 1$ mb [23], which is much smaller than the $p \rightarrow n$ charge-exchange cross section of ~ 10 mb [6–8,10,11]. Thus, we conclude that the background from the diffractive excitation of protons is negligibly small. Furthermore, the pion and pomeron exchange reactions differ by the rapidity distributions of secondary hadrons: in the pion-exchange reaction the rapidity gap between the observed neutron and the hadronic debris from the $\gamma^*\pi$ collision is small, $\Delta\eta \sim \log(1/(1 - z)) \sim 1$, whereas in the diffractive pomeron-exchange reaction there will be a large rapidity gap between the decay products of N^* and hadrons from the $\gamma^*\mathbb{P}$ interaction, which will allow one to experimentally separate the two reaction mechanisms.

In the suggested mechanism of the semi-inclusive neutron production, the differential cross section (7) is a product of the universal flux factor which only depends on z and the structure function $F_2^\pi(x_\pi, Q^2)$ which is a function of $x_\pi = x/(1 - z)$. This factorization property allows an important cross check of the model: binning the semi-inclusive cross section data as a function of z at different fixed values of x_π one can verify that the shape of the flux factor as a function of z does not depend on x_π. Furthermore, this z-dependence must come out identical to the z-dependence of the inclusive spectra of neutrons from the hadronic pN interactions. Remarkably, the FNC of the ZEUS collaboration enables the latter cross check to be performed in situ , directly comparing the spectra of neutrons from inclusive beam-gas interactions and from deep inelastic ep scattering. Such a comparison of the two spectra will allow to verify that the background contribution to $z \sim 0.7$–0.8 from deep inelastic scattering off the baryonic core is as small as in hadronic reactions. Reversing the argument, one can determine the x_π dependence of the pion structure function changing x at fixed values of z and verify that this x_π dependence comes out the same at all val-

ues of z. Our conclusion is that the separation of the pion-exchange contribution and determination of the pion structure function is experimentally feasible, the possible backgrounds to the pion exchange are under reasonably good control, and important in situ cross checks of the pion-exchange mechanism are possible.

The above discussion is fully applicable to the semi-inclusive production of Δ^{++}. The longitudinal momentum distribution of Δ^{++} is shown in Fig. 2c. As in the $p \rightarrow n$ case, the contributions from the π and ρ exchange mechanism are fairly well separated with the π-exchange contribution dominating large z. Measuring the Δ^{++} production at HERA will require good experimental resolution of both proton and π^+ resulting from the Δ^{++} decay, which requires multitrack identification of the leading proton spectrometer. The ZEUS collaboration has such a device operating at HERA [24]. The measurements of the Δ^{++} production are important for the direct evaluation of the contribution of the two-step process $p \rightarrow \Delta \rightarrow n\pi$ to the spectrum of neutrons. The Δ decay background to the spectrum of neutrons is small. Isospin symmetry considerations imply that the relative contamination of the neutron spectra $n_\pi(\pi\Delta) / (3n_\pi(\pi N)) \approx 0.1$ is significantly smaller than that for the proton spectra $(7n_\pi(\pi\Delta)) / (9n_\pi(\pi N)) \approx 0.3$.

The dominance of the isovector exchange mechanism, both π and ρ exchange, predicts very definite ratios of cross sections for the n/p and Δ^{++}/Δ^0 production: $\sigma(p \rightarrow n)/\sigma(p \rightarrow p) = 2$ and $\sigma(p \rightarrow \Delta^{++})/\sigma(p \rightarrow \Delta^0) = 3$. The leading-proton spectrometer (LPS) installed at the ZEUS detector allows measurement of the spectrum of protons in the interesting region of $z \sim 0.6$–0.8. Here one must be aware of the competitive pomeron-exchange contribution of Fig. 1d. to the spectrum of leading protons. The salient feature of pomeron-exchange is the approximately factorizable cross section of excitations of large masses

$$\frac{1}{\sigma_{tot}(ap)} \frac{d\sigma(ap \rightarrow Xp)}{M^2 \, dt}\bigg|_{t=0} \simeq \frac{A_{3\mathbb{P}}}{M^2 + Q^2}. \qquad (10)$$

Here $A_{3\mathbb{P}} \simeq 0.16$ GeV^{-2} [25] is the so-called triple-pomeron constant which must be approximately the same in the hadronic reactions, the real photoproductions and the deep inelastic scattering [26,27]. The reaction of Fig. 1d can be interpreted as a convolution of the flux of pomerons in the $p\mathbb{P}$ system with

the structure function of the pomeron. Both normalization of the flux of pomerons in the proton and of the pomeron structure function are convention dependent, because for the observable cross section only the product of these two factors is needed. The analysis [26–28] has shown that the (anti)quark–gluon content of the pomeron is similar to that of the π^0. If we choose the pomeron structure function to have the same absolute normalization as the pion structure function, then the observed flux of proton due to pomeron exchange can be estimated as

$$f_{P/N}(z) = \frac{1}{1-z} \frac{A_{3P}}{B_{3P}} \tag{11}$$

where B_{3P} is the diffraction dissociation slope parameter. With $A_{3P} \approx 0.16(\text{GeV}/c)^{-2}$ and $B_{3P} \approx 6(\text{GeV}/c)^{-2}$, as borrowed from the Regge phenomenology of real photoproduction [25], $A_{3P}/B_{3P} \approx 0.025$ [26,27]. As clearly seen from the Fig. 2a rather good separation of the pion and pomeron exchange mechanisms can be achieved in the longitudinal momentum spectrum. The pion-exchange mechanism is dominant for $0.6 < z < 0.8$.

In conclusion, we have calculated the longitudinal and perpendicular momentum distributions of leading protons, neutrons and Δ's in high-energy electron-proton collisions with kinematics suitable for HERA. We find that a large part of the phase space is populated predominantly through the one-pion exchange mechanism, which is a dominant and well-defined nonperturbative mechanism of $p \rightarrow n$ and $p \rightarrow \Delta$ fragmentation. The background to the pion exchange was shown to be small. This can be used to study the pion structure function in a very small-x region. The FNC of the ZEUS detector allows one to measure the leading neutrons and is most promising in this respect. Tests of the factorization property of the semi-inclusive cross section and the in situ comparison of the spectra of neutrons from deep inelastic scattering and beam-gas interactions allow independent checks of the pion-exchange mechanism.

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