BRIEF REPORTS

Brief Reports are accounts of completed research which do not warrant regular articles or the priority handling given to Rapid Communications; however, the same standards of scientific quality apply. (Addenda are included in Brief Reports.) A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.

Probing the polarized sea by inclusive leptoproduction of hadrons

F. E. Close
Physics Department, University of Tennessee, Knoxville, Tennessee 37996-1200;
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6373;
and Rutherford Appleton Laboratory, Chilton, Didcot, OXON OX11 OQX, England

R. G. Milner
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139
(Received 21 May 1991)

We give predictions for the inclusive production of π and K in polarized leptoproduction from polarized nucleons. As $E^{\text{lab}}_{\pi,K}\rightarrow 0$ the hadron inclusive asymmetry equals that of the total cross section; for $E^{\text{lab}}_{\pi,K}>0$ new information obtains. We show that these processes can provide sensitive tests for a polarized sea in a polarized nucleon.

The recent measurement [1] of the proton's polarized structure function $g_1(x,Q^2)$ suggests that the spin content of the proton may be more complicated than hitherto anticipated. The data confirm that the valence quarks are highly polarized but suggest that a significant amount of this polarization is canceled out by other components of the proton substructure [2]. Candidates for this counter polarization include orbital angular momentum, gluon polarization, or a highly polarized sea of quarks and antiquarks. Identifying the culprits, or even confirming the claim [3], is an urgent precursor in developing deeper intuition into the nature of proton substructure. We show that a polarized $q\bar{q}$ sea can give a clear signature in the target polarization dependence of inclusive $\pi^\pm$, $K^\pm$ production and can be probed in forthcoming experiments. From unpolarized deep-inelastic scattering, the probability is estimated to be greater than 70% that the fastest forward-going charged hadron with $z>0.5$ contains a quark of the same flavor as the scattered quark [4].

In principle, the production of $K^-(s\bar{u})$ at large $z(=E_K/E_\gamma)$ in $lp\rightarrow l'K^-\cdots$ is most clear in this regard. The lepton beam interacts with a q (or $\bar{q}$) which subsequently produces the detected hadron. As $z\rightarrow 1$ the most probable occurrence is that the hadron contains the struck q ($\bar{q}$) in its valence Fock state [5]; thus, a fast K^- is a signal for an s or $\bar{u}$ having been struck by the lepton. As $s,\bar{u}$ occur in the proton's sea, a target polarization dependence of fast K^- production would indicate that the s or $\bar{u}$ components of the proton sea are polarized; indeed, the K^- inclusive asymmetry as $z\rightarrow 1$ is a direct measure of the amount and sign of the sea polarization.

Regretably, this simple example is too idealized. The limit $z\rightarrow 1$ is not accessible in practice and production of K^- at $z<1$ is contaminated by the highly polarized valence quarks. However, even for $z\leq 0.5$, we find that there is a distinct dependence on sea polarization both for $K^\pm$ and also for $\pi^\pm$ production. In addition, at $x\geq 0.2$ where valence quarks dominate, inclusive hadroproduction can separate the individual flavor polarizations from a proton target and thus complement the neutron data. In this way, inclusive hadroproduction with polarized beams and targets gives important new information on the spin content of the nucleon. The basic ideas and formalism for polarized hadroproduction in the quark-parton model were described in Ref. [6], where some early limited predictions were also reported.

In the deep-inelastic scattering of longitudinally polarized muons from longitudinally polarized target nucleons [5], one measures the asymmetry

$$a_1(x,Q^2)=\frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}}\ , \tag{1}$$

where $\sigma_{1/2(3/2)}(x,Q^2)$ are the virtual photoabsorption cross sections when the projection of the total angular momentum of the photon-nucleon system along the photon-nucleon direction is $\frac{1}{2}$ ($\frac{3}{2}$). Given the knowledge of the unpolarized (transverse) structure function $F_1(x,Q^2)$, one constructs the polarized structure function [5]

$$g_1(x_1Q^2)=a_1(x,Q^2)F_1(x,Q^2)\ . \tag{2}$$

If $q^{\uparrow\downarrow}(x,Q^2)$ refer to partons with helicity parallel or antiparallel to the target and $\Delta q(x,Q^2)\equiv q^{\uparrow}(x,Q^2)-q^{\downarrow}(x,Q^2)$, then the measurement of $g_1(x,Q^2)$ may be used to determine Δq and $\Delta\bar{q}$ from

$$2g_1(x,Q^2)=\sum_i e_i^2[\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)]\ . \tag{3}$$

Empirically, $a_1(x,Q^2)$ shows no discernible Q^2 dependence and we shall henceforth approximate it as $a_1(x)$.

By analogy we define hadron inclusive structure functions for $lN \to l'H(z) + \cdots$ (where the target four-momentum is P, momentum transfer is q, hadron H momentum is p, and $z \equiv p\cdot P/q\cdot P = E_{lab}/q_0$):

$$2F_1^{p/H}(x,z) = \sum_i e_i^2[q_i(x)D_i^H(z) + \bar{q}_i(x)D_{\bar{i}}^H(z)] , \quad (4)$$

$$2g_1^{p/H}(x,z) = \sum_i e_i^2[\Delta q_i(x)D_i^H(z) + \Delta\bar{q}_i(x)D_{\bar{i}}^H(z)] , \quad (5)$$

$$A^{p/H}(x,z) = \frac{g_1^{p/H}(x,z)}{F_1^{p/H}(x,z)} , \quad (6)$$

where $D_i^H(z)$ is the fragmentation function for parton i to produce hadron H [5] and k_T of the produced hadron is integrated over.

The fragmentation functions are of two classes: those "favored" as $z \to 1$ (e.g., $D_u^{\pi^+}$ and those related by isospin or charge conjugation [5]) and "unfavored" (e.g., $D_u^{\pi^-}$). These have been measured; see, e.g., Ref. [7], which quotes

$$D_u^{\pi^+}(z) = \eta(z) D_u^{\pi^-}(z) = \frac{0.7(1-z)^{1.75}}{z} , \quad (7)$$

where

$$\eta(z) \equiv \frac{1+z}{1-z} . \quad (8)$$

Thus,

$$18 g_1^{p/\pi^+}(x,z) = D_u^{\pi^-}(z)\{\eta(z)[4\Delta u(x) + \Delta\bar{d}(x)] + \Delta d(x) + 4\Delta\bar{u}(x)\} + D_s^{\pi^+}(z)(\Delta s + \Delta\bar{s}) , \quad (9)$$

with F_1^{p/π^+} following if $\Delta q \to q$ and $\Delta\bar{q} \to \bar{q}$ everywhere. One could obtain a probe of the polarized strange sea if the z and x dependences can be separately binned. First note that

$$g_1^{p/(\pi^+ + \pi^-)}(x,z) = [D_u^{\pi^+}(z) + D_u^{\pi^-}(z)] g_1^p(x) + \tfrac{1}{9}(\Delta s + \Delta\bar{s})(x)[D_u^{\pi^-}(z) - D_u^{\pi^+}(z)](z). \quad (10)$$

Thus, by defining the asymmetry

$$A^{p/(\pi^+ + \pi^-)} \equiv \frac{g_1^{p/(\pi^+ + \pi^-)}}{F_1^{p/(\pi^+ + \pi^-)}} \quad (11)$$

(note that this is not equal to $A^{p/\pi^+} + A^{p/\pi^-}$), then if s and $\bar{s}$ are negligible one necessarily has

$$A^{p/(\pi^+ + \pi^-)}(x,z) = A^p(x) . \quad (12)$$

In predicting the hadron inclusive asymmetries we have used the unpolarized distributions of Ref. [8]:

$$q_V(x) = \frac{2}{B(\alpha_q, \beta_q + 1)} x^{\alpha_q - 1}(1-x)^{\beta_q} , \qquad \bar{q}(x) = C(1+\gamma)\frac{(1-x)^\gamma}{x} , \quad (13)$$

where

$\alpha_u = 0.59 \pm 0.06$,

$\beta_u = 2.7 \pm 0.3$,

$\alpha_d = 1.03 \pm 0.22$,

$\beta_d = 6.9 \pm 1.0$,

$C = 0.015 \pm 0.002$,

$\gamma = 14.6 \pm 3.5$,

and $\bar{q}(x) = u_S(x) = \bar{u}_S(x) = \cdots = 2s(x) = 2\bar{s}(x)$.

The polarized valence distributions Δu_V^N, Δd_V^N are obtained using the wave function of Ref. [9]:

$$|p\rangle = u\uparrow|I=0,S=0\rangle \left[\frac{A_0(x)}{x}\right]^{1/2} + [(\tfrac{2}{3})^{1/2} d\,|I=1,I_3=1\rangle - (\tfrac{1}{3})^{1/2} u\,|I=1,I_3=0\rangle] \times [(\tfrac{2}{3})^{1/2}\downarrow|S=1,S_3=1\rangle - (\tfrac{1}{3})^{1/2}\uparrow|S=1,S_3=0\rangle] \left[\frac{A_1(x)}{x}\right]^{1/2} , \quad (14)$$

which is motivated by the successes of quark models in describing low-energy nucleon properties, incorporates spin-dependent effects [$A_0(x) \neq A_1(x)$], and gives a good description of the polarized asymmetry in the valence-quark region ($x \geq 0.2$). Here I and S are the isospin and spin of the two noninteracting valence quarks and $A_0(x)/x$ and $A_1(x)/x$ are the probabilities that a quark with momentum fraction x is hit while the two other valence quarks are in a state with spin 0 or 1, respectively. $A_{0,1}(x)$ are given by data on unpolarized distributions

$$A_0(x) = x[u_V(x) - \tfrac{1}{2}d_V(x)] , \qquad A_1(x) = x\tfrac{3}{2}d_V(x) . \quad (15)$$

The spin-dependent structure functions are then given by (neglecting $\Delta\bar{q}$ effects)

$$2g_1^N(x) = \tfrac{4}{9}\Delta u_V^N + \tfrac{1}{9}\Delta d_V^N , \quad (16)$$

where the polarized valence distributions are

$$\begin{aligned} x\Delta u_V^p &= A_0(x) f_u(0;x) + \tfrac{1}{3}A_1(x)[\tfrac{1}{3}f_u(0;x) - \tfrac{2}{3}f_u(1;x)] , \\ x\Delta d_V^p &= \tfrac{2}{3}A_1(x)[\tfrac{1}{3}f_d(0;x) - \tfrac{2}{3}f_d(1;x)] , \\ x\Delta u_V^n &= \tfrac{2}{3}A_1(x)[\tfrac{1}{3}f_u(0;x) - \tfrac{2}{3}f_u(1;x)] , \\ x\Delta d_V^n &= a_0(x) f_d(0;x) + \tfrac{1}{3}A_1(x)[\tfrac{1}{3}f_d(0;x) - \tfrac{2}{3}f_d(1;x)] , \end{aligned} \quad (17)$$

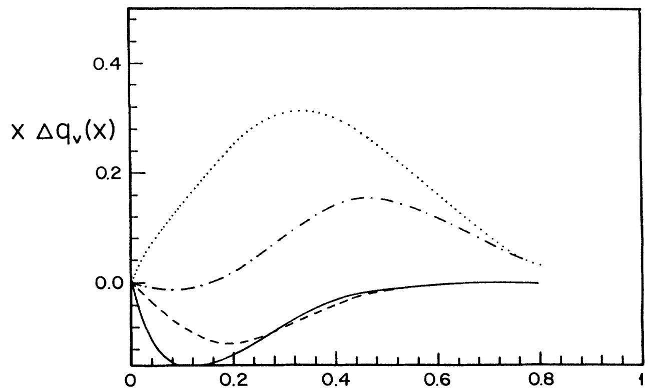

FIG. 1. The valence-quark spin distributions $x\Delta u_V^p(x)$ (dots), $x\Delta d_V^p(x)$ (dashes), $x\Delta u_V^n(x)$ (solid), $x\Delta d_V^n(x)$ (dot-dash) for the proton and neutron, respectively [9]. The large isospin violation shown in the figure arises because in Ref. [9] the probability of spin flip is taken to be proportional to the square of the current quark mass.

and the $f_{u(d)}(S_3;x)$ are spin dilution factors [9] which take into account the differences between up and down quarks as well as the mass difference between spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ baryons. The polarized valence distributions are shown in Fig. 1. The resulting asymmetry $A_1^p(x)$ agrees with the data on the proton [1] (see Fig. 2) and satisfies the Bjorken sum rule [10]. Further, the prediction for $A_1^n(x)$ is shown in Fig. 2 (neglecting $\Delta\bar{q}$ effects).

We can then write

$$A^{p/\pi^+}=\frac{4\eta\Delta u_V+\Delta d_V+(6+5\eta)\Delta\bar{q}}{4\eta u_V+d_V+(6+5\eta)\bar{q}}\ , \tag{18}$$

and A^{p/π^-} is similar but that η multiplies d_v in place of u_V. We find that in the x region where valence quarks dominate $A^{p/\pi^\pm}(x,z\to 0)\approx A_{\rm total}(x)$. This can be used to separate $\Delta u_V(x)$ and $\Delta d_V(x)$ and to provide a test of the underlying formalism. For example, Fig. 3 shows $A^{p/\pi^\pm}(x=0.2,z)$ with the decrease in $A^{p/\pi^-}(x=0.2,z)$ at large z due to the negative sign of Δd_p, as in Fig. 1. At low x, where $\bar{q}(x)$ is significant and $\Delta q_V(x)$ are small as in Fig. 1, $A^{p/\pi^\pm}$ (both $x,z\to 0$) becomes very sensitive to the sea polarization asymmetry. Figure 4 shows $A^{p/\pi^+}(x=0.02,z)$ and demonstrates the sensitivity to the $\bar{d}$ polarization. $A^{p/\pi^-}(x,z)$ at low x and z is sensitive to the $\bar{u}$ polarization in a similar way.

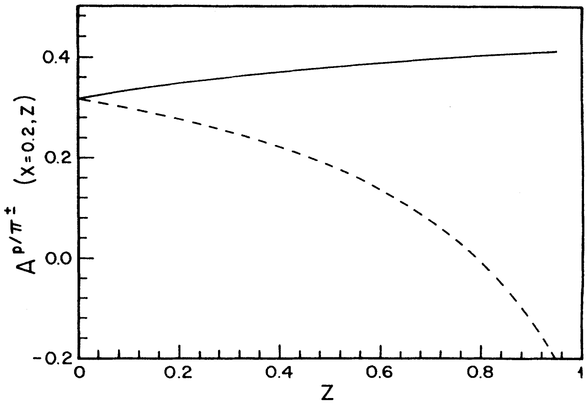

FIG. 3. This shows A^{p/π^+} $(x=0.2,z)$ (solid) and A^{p/π^-} $(x=0.2,z)$ (dashes).

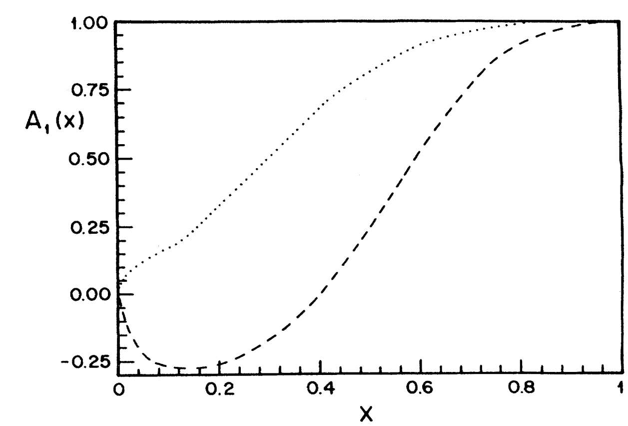

FIG. 2. The total asymmetries $A_1^p(x)$ (dots) and $A_1^n(x)$ (dashes) for the proton and neutron, respectively [9].

For K^- production we allow for the extra strange-quark mass by supposing that $D_{\bar{u}}^{K^-}(z)=RD_s^{K^-}(z)$; $R\approx 0.3$ (as cited in Ref. [4]). (A more detailed $R(z)$ has recently been reported [11] which has $R(z)\approx 0.1+0.4z$ with large errors. This tends to favor the strange-quark fragmentation as $z\to 0$ but does not change our curves within the likely accuracies of forthcoming experiments.) Thus,

$$A^{p/K^-}=\frac{4\Delta u_V+\Delta d_V+\left[\frac{13}{2}\Delta\bar{q}+4\eta\Delta\bar{u}+\frac{1}{R}\eta\Delta s\right]}{4u_V+d_V+\left[\frac{13}{2}\bar{q}+4\eta\bar{u}+\frac{1}{R}\eta s\right]}\ . \tag{19}$$

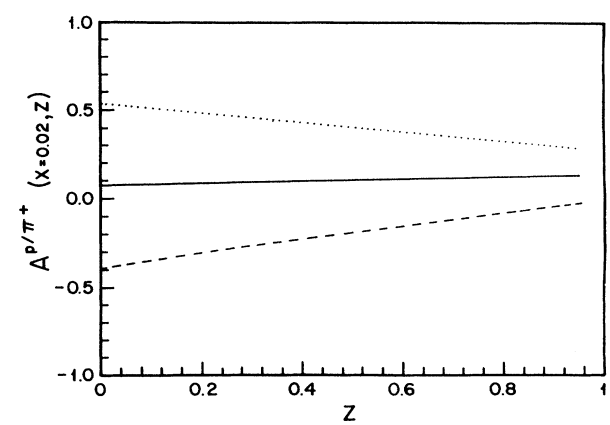

FIG. 4. This shows A^{p/π^+} $(x=0.02,z)$. The dotted line corresponds to maximum positive sea polarization asymmetry ($\Delta\bar{q}=+\bar{q}$), the dashed line to maximum negative sea polarization asymmetry ($\Delta\bar{q}=-\bar{q}$), and the solid line is the prediction for zero sea polarization asymmetry.

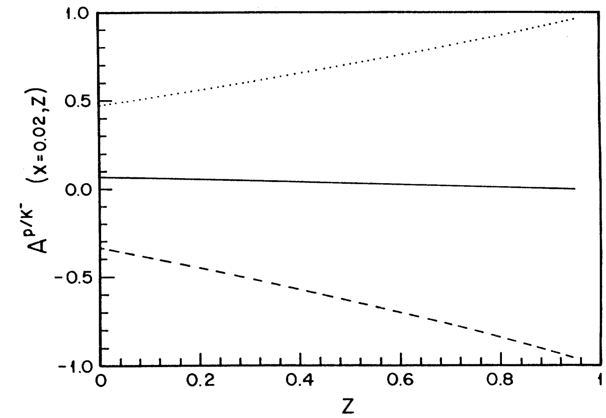

FIG. 5. This shows A^{p/K^-} $(x=0.02,z)$. The dotted line corresponds to maximum positive sea polarization, the dashed line to maximum negative sea polarization, and the solid line is the prediction for zero sea polarization.

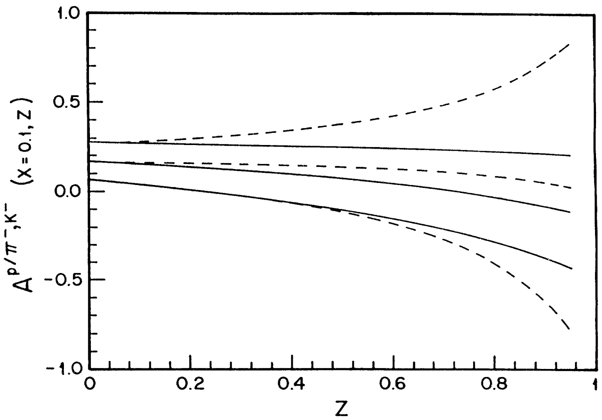

FIG. 6. This shows A^{p/π^-} $(x=0.1,z)$ (solid) and A^{p/K^-} $(x=0.1,z)$ (dashes). In each case the top curve is for maximum positive sea polarization, the center curve is for zero polarization, and the lowest curve is for maximum negative polarization.

Figure 5 shows A^{p/K^-} $(x=0.02,z)$ for the cases of zero and maximum sea polarization asymmetry. Again, at low z there is large sensitivity to the sign and magnitude of the sea polarization asymmetry. Figure 6 shows A^{p/π^-} $(x=0.1,z)$ and a^{p/K^-} $(x=0.1,z)$ and we see that for $z>0$ $|A^{p/K^-}(x=0.1.z)|>|A^{p/\pi^-}(x=0.1,z)|$ if the $q\bar{q}$ sea is highly polarized. In the idealized limit $z\to 1$, K^- production directly probes the sea polarization asymmetry:

$$\lim_{z\to 1} A^{p/K^-}(x,z)=\frac{\Delta\bar{q}}{\bar{q}}(x) \ . \tag{20}$$

At low $x\approx 0.02$, where Δd_V is predicted to be small (see Fig. 1), a comparison of A^{p/K^-} (x,z) and A^{p/π^-} (x,z) will be sensitive to the polarization of the strange sea. If the strange and nonstrange sea polarization asymmetries are the same, then $A^{p/\pi^+}(x=0.1,z)\approx A^{p/K^+}(x=0.1,z)$. A measureable difference between π^+ and K^+ asymmetries will reveal that $\Delta\bar{s}\neq\Delta\bar{d}$.

In the limit $z\to 1$, the K^- is an ideal tag for polarized sea quarks in theory; in practice, however, there is no event rate. Fortunately, these large effects are predicted to apply even for $z\geq 0.5$ (see Fig. 6) where experimentally quark flavor can be identified with high probability and where there are reasonable event rates. Thus, a detailed comparison of inclusive $\pi^\pm$, $K^\pm$ polarization asymmetries on protons can help to constrain models of the proton spin structure. Further, the K^- asymmetry at large z directly probes the polarized sea. For $x\geq 0.2$, $\Delta u_V(x)$ and $\Delta d_V(x)$ in the nucleon are determined by $A^{p/\pi^\pm}$. For low x, the magnitude and sign of the polarized $q\bar{q}$ sea is determined. The A^{p/K^-} $(z\to 1)$ is best in this regard. However, in addition $\Delta\bar{u}$ and $\Delta\bar{d}$ are constrained by A^{p/π^-} (both $x,z\to 0$) and A^{p/π^+} (both $x,z\to 0$), respectively. Also, it is necessary to ensure that the recoil hadronic mass is above the resonance region. Given the formulas and distributions in the text it is trivial to generate curves for arbitrary x and for neutron targets. We have not shown these here. The test for a polarized sea, through possible z dependence of the asymmetry, seems most feasible with K^- production from proton targets. We stress the importance of considering the x and z dependence of inclusive hadron production in the next generation of deep-inelastic asymmetry measurements on the nucleon [12].

The authors would like to acknowledge discussions with D. Geesaman, L. Osborne, and G. Ross. The research has been supported in part (F.E.C) by the State of Tennessee Science Alliance Center and by U.S. Department of Energy Contract No. DE-AS05-76ER04936 and in part (R.G.M.) by U.S. Department of Energy Contract No. DE-AC02-76ER03069.

[1] J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988).
[2] S. J. Brodsky, J. Ellis, and M. Karliner, Phys. Lett. B **206**, 309 (1988); J Ellis and M. Karliner, *ibid.* **213**, 73 (1988); H. J. Lipkin, D. Sivers, B. Ioffe, and F. E. Close, in *Future Polarization Physics at Fermilab,* Proceedings of the Symposium, Batavia, Illinois, 1988, edited by E. Berger, J. G. Morfin, A. L. Read, and A. Yokosawa (Fermilab, Batavia, 1988); H. Fritzsch, Munich Report No. MPI-PAE/PTH 45/88 (unpublished).
[3] F. E. Close and R. G. Roberts, Phys. Rev. Lett. **60**, 1471 (1988).
[4] J. P. Albanese *et al.*, Phys. Lett. **144B**, 302 (1984).
[5] R. P. Feynman, *Photon Hadron Interactions* (Benjamin, Reading, MA, 1972); F. E. Close, *Introduction to Quarks and Partons* (Academic, New York, 1978), Chap. 13.
[6] F. E. Close [5], p. 305; R. L. Heimann, J. Phys. G **4**, 173 (1978).
[7] J. J. Aubert *et al.*, Phys. Lett. **160B**, 417 (1985).
[8] J. J. Aubert *et al.*, Nucl. Phys. **B293**, 740 (1987).
[9] A. Schäfer, Phys. Lett. B **208**, 175 (1988).
[10] J. D. Bjorken, Phys. Rev. **148**, 1467 (1966).
[11] M. Arneodo *et al.*, CERN Report No. EP/89 25 (unpublished).
[12] Proposal of HERMES Collaboration to DESY, 1990.