

Polarized light-flavor antiquarks from Drell-Yan processes of $h + \vec{N} \rightarrow \vec{l}^\pm + l^\mp + X$

H. Kitagawa*

Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaragi 305-0801, Japan

Y. Sakemi†

Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

T. Yamanishi‡

Department of Management Science, Fukui University of Technology, Gakuen, Fukui 910-8505, Japan

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We propose a formula to determine the first moment of difference between the polarized \bar{u} and \bar{d} quarks in the nucleon, i.e., $\Delta\bar{u} - \Delta\bar{d}$ from the Drell-Yan processes in collisions of unpolarized hadrons with longitudinally polarized nucleons by measuring outgoing lepton helicities. As coefficients in the differential cross section depend on the u - and d -quark numbers in the unpolarized hadron beam, the difference $\Delta\bar{u} - \Delta\bar{d}$ can be independently tested by changing the hadron beam. Moreover, a formula for estimating the K factor in Drell-Yan processes is also suggested.

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Several experiments have been devoted to investigating the nucleon structures. In the large momentum transfer region, the nucleon (generally hadron) can be regarded as composed of almost free pointlike constituents with spin 1/2, i.e., partons. It seems quite natural to identify partons as (almost) massless quarks. Then, how do quarks construct the nucleon? Inclusive deep inelastic scatterings (inclusive DIS) off lepton beams on nucleon targets have revealed some combinations of valence and sea quark distributions in the nucleon. Traditionally, the light-antiquark distributions, $\bar{u}(x)$ and $\bar{d}(x)$, have been taken to be flavor symmetric in phenomenological analyses for structure functions of nucleons from a point of view, which the strong interaction is independent of the quark flavor for light quark-pair creations from gluons. However, the asymmetry of $\bar{u}(x)$ and $\bar{d}(x)$ has been predicted [1], and in 1991 the New Muon Collaboration (NMC) at CERN has reported on the violation of the Gottfried sum rule [2] from the unpolarized structure functions of the proton and the neutron [3]. This implied a significant flavor asymmetry for the unpolarized light-antiquark distributions, $\bar{u}(x) \neq \bar{d}(x)$. Furthermore, this asymmetry was confirmed independently by the NA51 at CERN [4] and the E866 at Fermilab [5,6] through the Drell-Yan (DY) processes with proton beam and proton and deuteron targets at rapidity $y=0$ and for a large x_F (i.e., small x) region. At present, from these experimental results several approaches such as chiral quark model, Skyrme model, Pauli blocking effects, etc., are proposed to understand light-flavor antiquark asymmetry [7]. However, the discussions are still ongoing. Since the strong interaction does not depend on the quark flavor for perturbative QCD, the mechanism for its flavor asymmetry may be addressed to nonperturbative QCD effect [8]. Therefore, the

studies of its mechanism are related to disclose how quarks build up the hadron, and are a challenging subject in particle and nuclear physics.

We also come to mind a question whether the longitudinally polarized light-antiquark distributions have this asymmetry or not. Unfortunately, we have no idea to estimate the first moment of $\Delta\bar{u} - \Delta\bar{d}$ such as the Gottfried sum rule for the unpolarized light-antiquark flavor asymmetry. It makes the analysis on the light-flavor antiquark polarization difficult. The experimental data for the longitudinally polarized semi-inclusive DIS [9–11] have been reanalyzed recently for $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ [12]. The result implied the asymmetry between $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$, but had ambiguities because of insufficient information on the fragmentation functions and of statistical error. At present we cannot derive any conclusion on $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ from data, though several models with this asymmetry were proposed [13,14]. Thus, it is important to find a formula for the first moment of $\Delta\bar{u} - \Delta\bar{d}$, and to measure it directly without ambiguities.

So far, several approaches for polarized light-flavor antiquark distributions in the DY process [14,15] and the weak boson production [16] have been proposed, but these processes can only probe $\Delta\bar{u}$ and $\Delta\bar{d}$ in a limited kinematic region.

Here we propose a formula for the first moment of $\Delta\bar{u} - \Delta\bar{d}$ from the DY process with longitudinally polarized nucleon targets and unpolarized hadron beams by measuring the helicity of one of the produced lepton pair.

Let us consider a process of $h + \vec{N} \rightarrow \vec{l}^\pm + l^\mp + X$. The spin-dependent cross section is defined by [17,18]

$$\frac{d^3\Delta\sigma}{dx_1 dx_2 d\cos\theta_\mu} \equiv \frac{d^3\sigma_{++}}{dx_1 dx_2 d\cos\theta_\mu} - \frac{d^3\sigma_{+-}}{dx_1 dx_2 d\cos\theta_\mu}, \quad (1)$$

where the subscript $(+-)$ means the target nucleon helicity

*Email address: khisashi@post.kek.jp

†Email address: sakemi@rcnp.osaka-u.ac.jp

‡Email address: yamanisi@ccmails.fukui-ut.ac.jp

and that of one of the outgoing leptons are parallel and antiparallel, respectively. This cross section is expressed as

$$\begin{aligned} \frac{d^3\Delta\sigma}{dx_1 dx_2 d\cos\theta_\mu} &= K_{pol} \frac{d\Delta\hat{\sigma}}{d\cos\theta_\mu} \sum_i e_i^2 [\bar{q}_i^h(x_1, Q^2) \\ &\quad \times \Delta q_i^N(x_2, Q^2) + q_i^h(x_1, Q^2) \Delta \bar{q}_i^N(x_2, Q^2)] \\ &\equiv K_{pol} \frac{d\Delta\hat{\sigma}}{d\cos\theta_\mu} \Delta P^{hN}(x_1, x_2, Q^2), \end{aligned} \quad (2)$$

with $x_1 \equiv x_{beam}$ and $x_2 \equiv x_{target}$ in the leading order (LO) of QCD. K_{pol} , $\Delta q_i^{(-)N}$ and $q_i^{(-)h}$ in Eq. (2) are the K factor of this DY process, the polarized quark (antiquark) and the unpolarized quark (antiquark) distributions with flavor i , respectively. Also θ_μ is the lepton production angle in the center-of-mass frame of hN collisions. In the LO QCD, the differential cross sections of the subprocess in Eq. (2) is given by [17]

$$\begin{aligned} \frac{d\Delta\hat{\sigma}}{d\cos\theta_\mu} &= \mp \Delta f(x_1, x_2, Q^2, \cos\theta_\mu), \\ \Delta f(x_1, x_2, Q^2, \cos\theta_\mu) & \\ &= \frac{\pi\alpha^2}{Q^4} \frac{8x_1^2 x_2^2 p_N^2}{\{(x_1+x_2)-(x_1-x_2)\cos\theta_\mu\}^3} \\ &\quad \times \{x_1^2(1-\cos\theta_\mu)^2 - x_2^2(1+\cos\theta_\mu)^2\}, \end{aligned} \quad (3)$$

with $Q^2 = x_1 x_2 s$ and p_N being the nucleon momentum. Here the initial $-$ and $+$ signs refer to $\Delta q \bar{q} \rightarrow \tilde{l}^+ l^-$ and $\Delta \bar{q} q \rightarrow \tilde{l}^+ l^-$ for measuring the positive lepton helicity, respectively. For negative lepton, $-$ and $+$ refer to $\Delta \bar{q} q \rightarrow l^+ \tilde{l}^-$ and $\Delta q \bar{q} \rightarrow l^+ \tilde{l}^-$, respectively.

When the target is the longitudinally polarized proton target, $\Delta P^{hN}(x_1, x_2, Q^2)$ in Eq. (2) can be written by

$$\begin{aligned} \Delta P^{hp}(x_1, x_2, Q^2) & \\ &= \frac{4}{9} [\bar{u}^h(x_1, Q^2) \Delta u^p(x_2, Q^2) - u^h(x_1, Q^2) \Delta \bar{u}^p(x_2, Q^2)] \\ &\quad + \frac{1}{9} [\bar{d}^h(x_1, Q^2) \Delta d^p(x_2, Q^2) - d^h(x_1, Q^2) \Delta \bar{d}^p(x_2, Q^2)] \\ &\quad + \frac{1}{9} [\bar{s}^h(x_1, Q^2) \Delta s^p(x_2, Q^2) - s^h(x_1, Q^2) \Delta \bar{s}^p(x_2, Q^2)] \\ &\quad + (\text{contributions from heavy quark distributions}). \end{aligned} \quad (4)$$

Similarly, $\Delta P^{hn}(x_1, x_2, Q^2)$ for the neutron target can be also obtained. Assuming the isospin symmetry for the target nucleon, one has an interesting equation such as

$$\begin{aligned} \frac{d^3\Delta\sigma^{hp}}{dx_1 dx_2 d\cos\theta_\mu} - \frac{d^3\Delta\sigma^{hn}}{dx_1 dx_2 d\cos\theta_\mu} &= K_{pol} \frac{d\Delta\hat{\sigma}}{d\cos\theta_\mu} \{ \Delta P^{hp}(x_1, x_2, Q^2) - \Delta P^{hn}(x_1, x_2, Q^2) \} = \mp K_{pol} \Delta f(x_1, x_2, Q^2, \cos\theta_\mu) \\ &\quad \times \left[\frac{1}{9} [\Delta u_v^p(x_2, Q^2) - \Delta d_v^p(x_2, Q^2) + 2\{\Delta \bar{u}^p(x_2, Q^2) - \Delta \bar{d}^p(x_2, Q^2)\}] \{4\bar{u}^h(x_1, Q^2) \right. \\ &\quad \left. - \bar{d}^h(x_1, Q^2)\} - \frac{1}{9} \{\Delta \bar{u}^p(x_2, Q^2) - \Delta \bar{d}^p(x_2, Q^2)\} [4u_v^h(x_1, Q^2) - d_v^h(x_1, Q^2)] \right. \\ &\quad \left. + 2\{4\bar{u}^h(x_1, Q^2) - \bar{d}^h(x_1, Q^2)\} \right], \end{aligned} \quad (5)$$

where the initial $-$ and $+$ signs in the right-hand side of the above equation correspond to the measurement of the positively charged lepton and the negatively charged one, respectively. Integrating over x_1 and x_2 on Eq. (5), we obtain the following relation:

$$\begin{aligned} \int_0^1 \int_0^1 \frac{d^3\Delta\sigma^{hp}/dx_1 dx_2 d\cos\theta_\mu - d^3\Delta\sigma^{hn}/dx_1 dx_2 d\cos\theta_\mu}{K_{pol} \Delta f(x_1, x_2, Q^2, \cos\theta_\mu)} dx_1 dx_2 & \\ &= \frac{1}{9} [\Delta u_v^p(Q^2) - \Delta d_v^p(Q^2) + 2\{\Delta \bar{u}^p(Q^2) - \Delta \bar{d}^p(Q^2)\}] \{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\} \\ &\quad - \frac{1}{9} \{\Delta \bar{u}^p(Q^2) - \Delta \bar{d}^p(Q^2)\} [4u_v^h - d_v^h + 2\{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\}] \\ &= \frac{1}{9} \left| \frac{g_A}{g_V} \right| \{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\} - \frac{1}{9} \{\Delta \bar{u}^p(Q^2) - \Delta \bar{d}^p(Q^2)\} [4u_v^h - d_v^h + 2\{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\}] \end{aligned} \quad (6)$$

for the measurement of the l^- helicity. In Eq. (6), g_A and g_V are the nucleon axial and vector coupling constants, respectively, and u_v^h and d_v^h are numbers of the valence u and d quarks in the beam particle h , respectively. Here, we drop the label Q^2 , since the valence quark numbers in the hadron are independent of Q^2 . Therefore, appraising $4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)$ in the unpolarized beam hadron h and the K factor of this polarized DY process, we get information on the first moment of $\Delta\bar{u}^p - \Delta\bar{d}^p$ from the cross sections for $h + \{\vec{p} \text{ and } \vec{n}\} \rightarrow \vec{l}^\pm + l^\mp + X$ with wide ranges of both x_1 and x_2 .

If the polarized light-flavor antiquark distribution is symmetric, i.e., $\Delta\bar{u}^p - \Delta\bar{d}^p = 0$, the right-hand side of Eq. (6) reduces to $1/9|g_A/g_V|\{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\}$. For instance, choosing the proton as the unpolarized hadron beam h and taking $x_{1\min} = 10^{-5}$ and $Q^2 = 4 \text{ GeV}^2$, it becomes $1/9 \times 1.267 \times 0.14 \times 10^2 = 19.7$ with 0.141×10^2 or 0.139×10^2 for $4\bar{u}^p(Q^2) - \bar{d}^p(Q^2)$ by the parametrization of Glück-Reya-Vogt 1998 (GRV98) LO [19] or Martin-Roberts-Stirling-Thorne 1998 (MRST98) LO [20], respectively. Also, the difference between the spin-dependent differential cross sections of pp and pn collisions as a function of x_2 for several x_1 values is shown in Fig. 1 by taking $K_{pol} = 1.8$. We use AAC [21] with $\Delta\bar{u} = \Delta\bar{d}$ and GRV98LO parametrizations as polarized and unpolarized distribution functions, respectively. Therefore, we can conclude that the behavior of $\Delta\bar{u}$

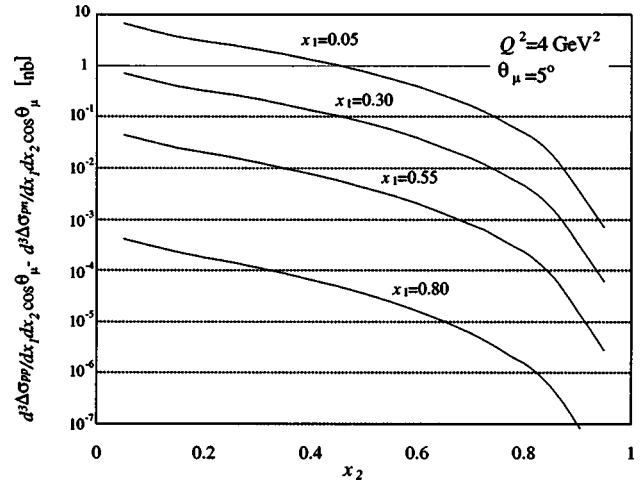


FIG. 1. The difference between the spin-dependent differential cross sections of pp and pn collisions for the measurement of the l^- helicity as a function of x_2 with $K_{pol} = 1.8$.

and $\Delta\bar{d}$ in the nucleon is asymmetric if we find a discrepancy between the measured values and above predicted ones.

For other unpolarized hadron beams, for example charged pions, kaons and so on, it is not difficult to estimate $4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)$ in Eq. (6) from experiments. The value of $4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)$ in the unpolarized beam hadron h can be obtained from data in the same way as above. With unpolarized nucleon targets, the same procedure as Eq. (6) leads to

$$\int_0^1 \int_0^1 \frac{d^3\sigma^{hp}/dx_1dx_2d\cos\theta_\mu - d^3\sigma^{hn}/dx_1dx_2d\cos\theta_\mu}{K_{unpol}d\hat{\sigma}/d\cos\theta_\mu} dx_1dx_2 = \frac{1}{9}\{\bar{u}^p(Q^2) - \bar{d}^p(Q^2)\}(4u_v^h - d_v^h) + \frac{1}{9}[u_v^p - d_v^p + 2\{\bar{u}^p(Q^2) - \bar{d}^p(Q^2)\}]\{4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)\}, \quad (7)$$

where K_{unpol} is the K factor of the unpolarized DY process, and the differential cross sections of the subprocess is written as

$$\frac{d\hat{\sigma}}{d\cos\theta_\mu} = \frac{\pi\alpha^2}{Q^4} \frac{8x_1^2x_2^2p_N^2}{\{(x_1+x_2) - (x_1-x_2)\cos\theta_\mu\}^3} \{x_1^2(1-\cos\theta_\mu)^2 + x_2^2(1+\cos\theta_\mu)^2\}.$$

Since the value of $\bar{u}^p(Q^2) - \bar{d}^p(Q^2)$ in Eq. (7) was obtained by the NMC and other experiments and also has been studied intensively, one can extract $4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)$ from the combination of the differential cross sections, $d\sigma^{hp}$ and $d\sigma^{hn}$, for the unpolarized DY processes. Using the NMC result, namely $\bar{u}^p(Q^2) - \bar{d}^p(Q^2) = -0.147 \pm 0.039$ at $Q^2 = 4 \text{ GeV}^2$ [3], and choosing the proton as the hadron h , we obtain

$$4\bar{u}^h(Q^2) - \bar{d}^h(Q^2) = \left[\int_0^1 \int_0^1 \frac{d^3\sigma^{hp}/dx_1dx_2d\cos\theta_\mu - d^3\sigma^{hn}/dx_1dx_2d\cos\theta_\mu}{K_{unpol}d\hat{\sigma}/d\cos\theta_\mu} dx_1dx_2 + 0.114 \right] / 0.0784. \quad (8)$$

For K_{pol} and K_{unpol} appeared in Eqs. (6)–(8), in general, it is important to find an equation where the K factor cancels out in order to extract physical quantities from DY processes. However, we do not have enough information derived from such equation. In order to get absolute values of the physical quantities induced from the DY processes, the K factor must be estimated exactly. Using unpolarized antihadron beams together with unpolarized hadron beams, the mean value of K_{pol} in terms of x for this polarized DY process is given as follows:

$$\int_0^1 \int_0^1 \frac{\left\{ \frac{d^3 \Delta \sigma^{\bar{h}p}}{dx_1 dx_2 d \cos \theta_\mu} - \frac{d^3 \Delta \sigma^{\bar{h}n}}{dx_1 dx_2 d \cos \theta_\mu} \right\} - \left\{ \frac{d^3 \Delta \sigma^{hp}}{dx_1 dx_2 d \cos \theta_\mu} - \frac{d^3 \Delta \sigma^{hn}}{dx_1 dx_2 d \cos \theta_\mu} \right\}}{\Delta f(x_1, x_2, Q^2, \cos \theta_\mu)} dx_1 dx_2 = \mp K_{pol} \frac{1}{9} \left| \frac{g_A}{g_V} \right| (4u_v^h - d_v^h), \quad (9)$$

with \mp being similar to Eq. (5), where we assume the reflection symmetry along the V-spin axis, the isospin symmetry and the charge conjugation invariance for the unpolarized beam hadron with the polarized nucleon target. For K_{unpol} of the unpolarized DY process, we also have

$$\int_0^1 \int_0^1 \frac{\left\{ \frac{d^3 \sigma^{\bar{h}p}}{dx_1 dx_2 d \cos \theta_\mu} - \frac{d^3 \sigma^{\bar{h}n}}{dx_1 dx_2 d \cos \theta_\mu} \right\} - \left\{ \frac{d^3 \sigma^{hp}}{dx_1 dx_2 d \cos \theta_\mu} - \frac{d^3 \sigma^{hn}}{dx_1 dx_2 d \cos \theta_\mu} \right\}}{d\hat{\sigma}/d \cos \theta_\mu} dx_1 dx_2 = K_{unpol} \frac{1}{9} (u_v^p - d_v^p)(4u_v^h - d_v^h). \quad (10)$$

Since each term of the right-hand side in Eqs. (9) and (10) is constant, K_{pol} and K_{unpol} can be evaluated from the relevant differential cross sections.

Thus, measuring the K factors by using unpolarized hadron and antihadron beams, and evaluating $4\bar{u}^h(Q^2) - \bar{d}^h(Q^2)$ from the unpolarized DY experiment, the polarized DY process for an unpolarized hadron beam and a polarized nucleon target allows to provide the first moment of $\Delta\bar{u}^p(Q^2) - \Delta\bar{d}^p(Q^2)$ by measuring the helicity of one of the produced lepton pair. Note that it does not require measurements with high precision for large x_1 and x_2 region in order to determine the value of $\Delta\bar{u}^p - \Delta\bar{d}^p$, though differential cross sections for the proton and the neutron targets are combined. Because each differential cross section for large x_1 and x_2 is quite small as shown in Fig. 1, a contribution from this region to the integral is small.

In summary, we have proposed a formula for the difference between the polarized light-flavor antiquark density, $\Delta\bar{u}^p - \Delta\bar{d}^p$, from DY processes. It is given by a combination of the cross sections with an unpolarized hadron beam and a longitudinally polarized proton target by measuring one of the produced lepton helicity and that with a neutron target. Then, the formula is described in terms of the neutron β -decay constant and the difference between $\Delta\bar{u}^p$ and $\Delta\bar{d}^p$. As coefficients of these terms depend on u - and d -quark numbers in the unpolarized beam hadron, we can independently get information on the behavior of $\Delta\bar{u}^p$ and $\Delta\bar{d}^p$ by changing the beam hadron.

Recently, the DY process in the next-to-leading order (NLO) of QCD has been discussed and compared with that in the LO, though it is the DY process for the longitudinally polarized nucleon and the longitudinally polarized nucleon

collisions [14]. The relevant differential cross section has an additional term including contributions from gluons. However, in the difference $d\Delta\sigma^{hp} - d\Delta\sigma^{hn}$ the contributions from gluons will be canceled. Accordingly, Eq. (6) is expected to be also kept in the NLO.

Now experiments to solve the nucleon spin problems start at Relativistic Heavy Ion Collider (RHIC) at BNL with colliding polarized protons at high energy, $\sqrt{s} = 200$ GeV. Also, the Japan Hadron Facility (JHF) is under construction. It provides 50 GeV high intensity proton and antiproton beams, and also can produce high intensity charged π/K meson beams. One expects that future experiments for processes proposed here will be carried out at RHIC and/or JHF with the detector measuring the helicity of high energy leptons over wide ranges of x_1 and x_2 . It is certainly difficult to measure the high energy lepton helicity. However, the measurement of the helicity of the μ^+ produced in charged current interactions has already been carried out at high-energy antineutrino experiments at CERN Super Proton-Synchrotron (SPS) [22]. The polarimeter used there was composed of the marbles for stopping the muon, the scintillators for detecting the positron from muon decay and the proportional drift tubes for observing the muon track [22]. This makes use of the fact that high energy positron is preferentially emitted in the direction of the muon spin because of the V-A interaction in muon decay. Accordingly, it seems possible to do experiments on the processes discussed here. We wish to get new information on $\Delta\bar{u}^p - \Delta\bar{d}^p$ at RHIC and/or JHF.

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