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Probing $SU(2)$ Symmetry Breaking in Nucleon Sea

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Abstract

Investigation of invariant cross-sections for production of K^{*-} and $\overline{K^{*0}}$, in the fragmentation region of proton, in $p-p$ and $\gamma-p$ reactions, gives a direct and unambiguous probe to the symmetry breaking of the nucleon sea. Based on existing data, we clearly found a large asymmetry of the sea. Our result is in excellent agreement with NA51 measurement, signaling lack of any nuclear effect. The measurement can be carried out in a single experimental set up. The ratio $K^{*-}/\overline{K^{*0}}$ is equivalent to $\bar{u}/\bar{d}$, with easy access to the x-dependence of the asymmetry. Here we compare the available experimental data with a calculation made within the valon-recombination model.

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The New Muon Collaboration (NMC) experiment [1] in deep inelastic scattering of muon off hydrogen and deuteron provide the testing ground for the verification of the Gottfried Sum Rule (GSR) [2] which is given as:

$$S_G = \int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = \frac{1}{3}\int_0^1 dx\left[u_v(x) - d_v(x)\right] - \frac{2}{3}\int_0^1 dx\left[\bar{d}(x) - \bar{u}(x)\right] \qquad (1)$$

In the above equation, if the antiquark distributions in proton are SU(2) flavor symmetric, $\bar{u}(x) = \bar{d}(x)$, then the second term in Eq. (1) vanishes and the Gottfried Sum Rule is recovered as $S_G = 1/3$. The NMC measurement, when extrapolated smoothly down to the unmeasured small-x region, found that $S_G = 0.235 \pm 0.026$, which is significantly smaller than the 1/3, expected from GSR.

The discrepancy between the value of GSR and the measurement inspired a considerable theoretical activities [3]. The most obvious place to look for the source of the discrepancy would, of course, be to suspect the validity of $\bar{u}(x) = \bar{d}(x)$ in the proton which appears in the second term of Eq. (1). Theoretical justification for this suspicion is originated from the enhancement of $\bar{d}$ over $\bar{u}$ due to Pauli-blocking effect [4], and the presence of pionic cloud [5]. Other models consider nuclear effects like shadowing in the deuterium as the possible cause of the violation of GSR [6,3]. Yet, it is also possible to attribute the discrepancy to the low Q^2 physics [7] and to non-perturbative effects. All these theoretical considerations are capable to reproduce the experimental results one way or the other. Therefore, it becomes very important to device experiments which can discriminate among the various models and enhance our understanding of the nucleon structure.

Equation (1) shows that the S_G is only sensitive to the integral of $\bar{u} - \bar{d}$ over x and remains silent about the x-dependence of the integrand itself. To investigate the breaking of SU(2) flavor symmetry in the proton sea, it is important and interesting to measure the ratio $\bar{u}/\bar{d}$ as a function of x. One possibility of such an investigation is the proton induced Drell-Yan process, proposed by Ellis and Stirling [8]. In fact, NA51 collaboration [9] has already measured the cross section ratio for muon pair production in $p-p$ and in $p-d$ reactions at rapidity $y = 0$ and found a large asymmetry of $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ at $x = 0.18$. Since this experiment uses the deuterium target to extract the cross-section for the dilepton production in p-n collision, it is subject to the concerns raised over the nuclear effect [6]. Until a wider range in x is explored a firm conclusion about the asymmetry in the proton sea and its x dependence will be hard to reach. This is important because, as it is shown in [10], one may have a symmetric antiquark distribution in the nucleon sea and yet obtain a finite flavor symmetry breaking distribution, $[\bar{u} - \bar{d}]_A \neq 0$ in nucleus, compatible with the NMC data.

New measurements are proposed and in particular, the Relativistic Heavy Ion Collider (RHIC) machine will be able to further investigate into the flavor dependent structure of the nucleon sea. It is well known that the production of W and Z bosons are sensitive to the $\bar{u}/\bar{d}$ asymmetry. The ratio, given by

$$R(x_f) = \frac{d\sigma(W^+)/dx_f}{d\sigma(W^-)/dx_f} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}, \qquad (2)$$

in $p-p$ collision, is obviously sensitive to the sea - quark distribution in proton. In particular, this ratio is interesting for $x_F >> 0$, where it reduces to

$$R(x_f) \sim \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)}. \tag{3}$$

However, the calculation of this quantity also depends on the set of parton distribution chosen and the result can be affected by the choice made.

The purpose of this letter is manyfold. First, to suggest an alternative experiment which relies on a single proton target, avoiding possible concerns on testing $\bar{u} \neq \bar{d}$ due to nuclear effects [6]. Second, accessing a direct measurement of just $\bar{u}(x)/\bar{d}(x)$, as opposed to the quantities in Eqs.(2) and (3). Finally, to advocate a model which is suitable for investigation of sea quark content of the nucleon. We also would like to point out that the proposed experiment can be done with the existing facilities, in particular at HERA machine.

K^{*-} and $\overline{K^{*0}}$ mesons both have identical masses of 892 MeV, but their quark contents are different: the former is composed of $s\bar{u}$ and the latter is composed of $s\bar{d}$. One expects these two particle to be produced with the same rate in an identical setting. In fact, any deviation in their production rate will signify a difference in the quark content of the initial state particles. More specifically, we would like to consider the invariant cross section for the production of these mesons in p - p or $\gamma - p$ interaction in the proton fragmentation region. W. O'Ches discovered [11] that the π^+ X distribution in the proton fragmentation region is very similar to the distribution of valence u-quark in proton. Similarly, one would expect that in the proton fragmentation region the distribution of K^{*-} and $\overline{K^{*0}}$ will also reflect the sea quark distribution in the proton. For K^{*-} and $\overline{K^{*0}}$ having one s-quark in common, any deviation in their invariant cross-section ratio from unity will indicate $\bar{d} \neq \bar{u}$. Moreover, just by inspecting the shape of the ratio of the cross section one can find the x-dependence of the inequality as well.

In the following we will calculate the invariant cross-section in the valon-recombination model [12]. In this model a meson is formed by a combination of a pair of $q - \bar{q}$ from the initial proton. The model was recently applied successfully to the production of D^+ and D^-, where QCD and PYTHIA [13] calculations failed to agree with WA82 [14] and E769 [15] data. However, the calculation can be done in any model and the result should be independent of the calculational scheme chosen, as long as the breaking of the sea symmetry is not assumed from the begining. Many experimental support for this simple model yield valuable clue to the function of the sea quarks in the high energy reactions. As it was noted by Field and Feynman [16], neither deep inelastic scattering nor high-mass muon pair production experiments can give the exact sea quark distribution for individual flavors, the form of the sea quark distributions used is more of conjectural type. In view of such an uncertainty, the determination of the sea quark distribution from the inclusive cross-section of mesons becomes important. Since it is now clear that most of the observed mesons in the experiments are from the resonance decays, the x-distribution has substantial contribution from the decay spectra of the resonance, specially in the small x region where the sea -quark are concentrated. Therefore, we believe that the determination of the shape of the meson resonances will determine directly the distribution of each flavor of the sea-quark.

Since strange quark is a common particle in K^{*-} and $\overline{K^{*0}}$, in the ratio of the cross sections, the strange quark distribution cancels out and essentially leaves the result identical to $\bar{u}/\bar{d}$, without any free parameter. But, for the moment and for the purpose of calculating individual cross - sections, we tentatively assume that the strange and nonstrange quark distributions have the same shape, only the former is suppressed in normalization.

The recombination model assumes that a meson, produced in the fragmentation region of the initial proton, is composed of a quark q_1 and an antiquark $\bar{q}_2$ from the inital proton. Hence, the inclusive distribution of a meson $\mathcal{M}$ can be written as

$$\frac{x}{\sigma}\frac{d\sigma}{dx} \equiv \int\int F(x_1, x_2)\mathcal{R}(x_1, x_2; x)\frac{dx_1}{x_1}\frac{dx_2}{x_2}, \tag{4}$$

where $F(x_1, x_2)$ is the joint probability distribution for finding a quark-antiquark pair with momentum fractions x_1 and x_2 in the initial proton, $\mathcal{R}(x_1, x_2; x)$ is the recombination function for the formation of a meson at x. By time-reversal consideration $\mathcal{R}(x_1, x_2; x)$ for $q\bar{q} \to \mathcal{M}$ is related to the invariant dressed quark (valon) distributions, V_q and $V_{\bar{q}}$ in the meson $\mathcal{M}$, where V_q denotes a valon of flavor q, that is,

$$\mathcal{R}(x_1, x_2; x) = y_1 y_2 G_{\mathcal{M}}(y_1, y_2), \tag{5}$$

with $y_i = x_i/x$ and $i = 1, 2$. With valons of unequal masses, we have in general [17]

$$G_{\mathcal{M}}(y_1, y_2) = [B(a, b)]^{-1} y_1^{a-1} y_2^{b-1} \delta(y_1 + y_2 - 1), \tag{6}$$

where $B(a, b)$ is the beta function. Letting the ratio of average momenta carried by the valons in the meson to be proportional to their masses, for the case of K^{*-} we have

$$\frac{m_{\bar{u}}}{m_s} = \frac{\bar{y}_2}{\bar{y}_1} = \frac{a}{b} = \frac{330}{500} \sim \frac{2}{3}. \tag{7}$$

So, we chose a=1 and b=3/2 and consequently we have

$$\mathcal{R}_{K^{*-}} = \left[B\left(1, \frac{3}{2}\right)\right]^{-1} \left(\frac{x_1^{3/2} x_2}{x^{3/2}}\right) \delta(x_1 + x_2 - x). \tag{8}$$

Of course the choice of a and b is not unique and we have also tried $a = b = 1$ as well as $a = 1$, $b = 2$ and found that our results are not sensitive to the particular choice of a and b.

The difficulty in using Eq.(4) is the determination of $F(x_1, x_2)$. The valon model provides a procedure for doing that [18]. Proton has three valons UUD and the two quarks at x_1 and x_2 can either come from the same valon, or from two different valons. We split $F(x_1, x_2)$ into $F^1(x_1, x_2)$ and $F^2(x_1, x_2)$, such that we have $F = F^1 + F^2$. This means that F^1 is the convolution of a single valon distribution $G_{V/p}(y)$ in the proton and $q - \bar{q}$ distribution in the valon. Similarly, F^2 is a convolution of two-valon distribution in a proton, $G_{VV/p}(y_1, y_2)$, and a single quark distribution in each of the two valons. In general a meson forming quark can be either a valence quark or a sea quark in proton therefore, they will have different distributions. Folowing Ref. [18], let us denote the distribution of the momentum fraction z of the valence quark of flavor q in a valon of the same flavor by $\mathcal{L}_v(z)$ and that of a sea quark in a valon of any flavor by $\mathcal{L}_{sea}(z)$.

To acertain the working of the recombination model, first we calculate the invariant distribution of π^+, for which more accurate data are available.

For the production of a π^+, the probability distribution is as follows:

$$F^1_{\pi^+}(x_1,x_2) = \int dyG_{U/p}(y)\left[\mathcal{S}\left(\frac{x_1}{y}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y-x_1}\right)+\mathcal{S}\left(\frac{x_1}{y-x_2}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y}\right)\right]$$
$$+\int dyG_{D/p}(y)\frac{1}{2}\left[\mathcal{L}_u\left(\frac{x_1}{y}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y-x_1}\right)+\mathcal{L}_u\left(\frac{x_1}{y-x_2}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y}\right)\right] \quad (9)$$
$$F^2_{\pi^+}(x_1,x_2) = 2\int dy_1\int dy_2\left[G_{UU/p}(y_1,y_2)+G_{UD/p}(y_1,y_2)\right]\mathcal{S}_s\left(\frac{x_1}{y_1}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y_2}\right)$$
$$+2\int dy_1\int dy_2 G_{UD/p}(y_1,y_2)\mathcal{L}_u\left(\frac{x_1}{y_1}\right)\mathcal{L}_{\bar{d}}\left(\frac{x_2}{y_2}\right).$$

In Figure 1, we present the calculated invariant cross section for $pp \to \pi^+$ X along with the experimental data from Ref. [19]. As one can see, the result is very good.

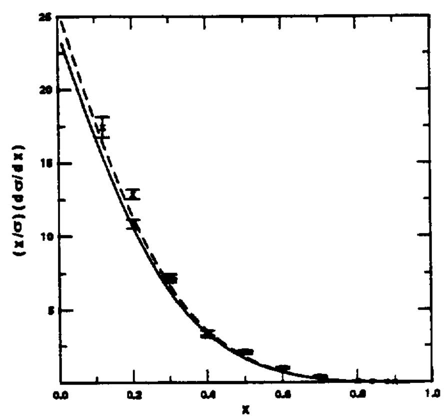

FIG.1 Invariant cross section for π^+ production in pp - collision. Curves are model calculation and data points are from Ref. [19]. Solid curve (full circle) is for 100 GeV/c and dashed curve (cross points) is for 175 GeV/c.

For K^{*-}, the probability distribution is given by:

$$F^1(x_1,x_2) = \int dyG_{U/p}(y)\left[\mathcal{L}_s\left(\frac{x_1}{y}\right)\mathcal{L}_{\bar{u}}\left(\frac{x_2}{y-x_1}\right)+\mathcal{L}_s\left(\frac{x_1}{y-x_2}\right)\mathcal{L}_{\bar{u}}\left(\frac{x_2}{y}\right)\right]$$
$$+\int dyG_{D/p}(y)\frac{1}{2}\{\mathcal{L}_s\left(\frac{x_1}{y}\right)\mathcal{L}_{\bar{u}}\left(\frac{x_2}{y-x_1}\right)+\mathcal{L}_s\left(\frac{x_1}{y-x_2}\right)\mathcal{L}_{\bar{u}}\left(\frac{x_2}{y}\right)\}; \quad (10)$$
$$F^2(x_1,x_2) = 2\int dy_1\int dy_2\left[G_{UU/p}(y_1,y_2)+G_{UD/p}(y_1,y_2)\right]\mathcal{L}_s\left(\frac{x_1}{y_1}\right)\mathcal{L}_{\bar{u}}\left(\frac{x_2}{y_2}\right).$$

The distributions $G_{U/p}(y)$, $G_{D/p}(y)$, $G_{UU/p}(y_1,y_2)$, and $G_{UD/p}(y_1,y_2)$ are known [20]. We adopt the following forms for $\mathcal{L}(z)$ and $\mathcal{S}(z)$:

$$\mathcal{L}_{sea}(z) = 0.31(1-z)^{1.5};\quad \mathcal{L}_v(z) = 1.2z^{1.1}(1-z)^{0.16};\quad \mathcal{S}(z) = \mathcal{L}_{sea}(z)+\mathcal{L}_v(z) \quad (11)$$

for light quarks. For the heavier strange quark, as we mentioned earlier we consider the same shape as light quark distribution but with a normalization suppression factor of λ. So, for the strange quark in the proton, we have $\mathcal{L}_{strange}(z) = \lambda\mathcal{L}_{sea}(z)$.

Figure 2-a, solid curve, gives the model calculation along with all available data known to us for K^{*-} [21,22] and $\overline{K^{*0}}$ [23].

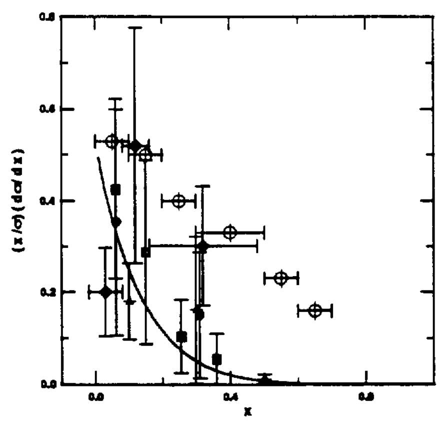

FIG.2A Invariant cross section for K^{*-} and $\overline{K^{*0}}$. Data are from Refs. [21–23]. The curve is our model calculation for K^{*-}. Open circles are for $\overline{K^{*0}}$ [23] and the other experimental points are for K^{*-}. Square from Ref. [22], diamond from Azis et al., triangles from BHMC Col., and solid circles from Kichimi et al. [21].

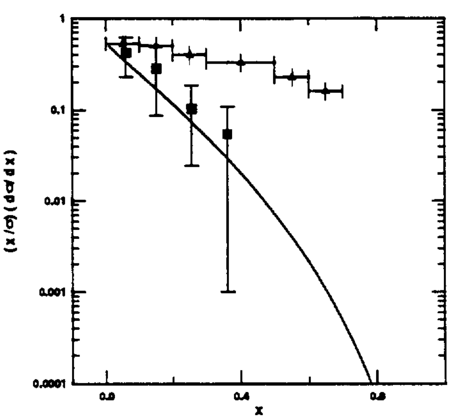

FIG.2B Same as Fig. 2-a, but with only two sets of data points from Refs. [22] and [23].

In Fig. 2-b we use data from Ref. [22] forK^{*-}, which show a clear trend and with error bars relatively small compared with others; and the data from Ref. [23] for $\overline{K^{*0}}$. We present this in a linear plot,for more clarity.

Again, we see that the calculation agrees rather well with the K^{*-} data. Unfortunately, the errors are large, blouring the transparency of the results. Nevertheless the same figures also indicate the asymmetry in the sea, $\overline{K^{*0}}$ data is quite different from those of K^{*-}.

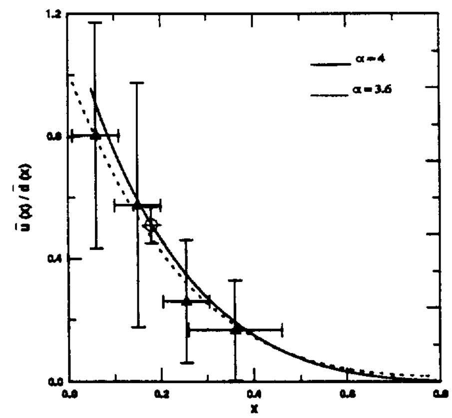

FIG.3 $\bar{u}(x)/\bar{d}(x)$ extracted from the ratio of the corresponding cross sections for K^{*-} [22] and for $\overline{K^{*0}}$ [23]. The curve is a fit for these meson data, as given by Eq.(12). NA51 experimental point [9] is also shown with open circle.

To go one step further, we take the central values of the K^{*-} data from a consistent set which have overlaping x-value with those of $\overline{K^{*0}}$ and calculate their ratio to obtain $\bar{u}/\bar{d}$. The calculated ratio now is ploted in Fig.3 as a function of x, which can be well represented with a simple curve like

$$\frac{\bar{u}(x)}{\bar{d}(x)} = (1-x)^{\alpha}, \tag{12}$$

with $\alpha \sim 4$. As a further check, in Fig.3, we also show the single point from NA51 experiment. It agrees rather nicely with the procedure we have described, rendering further support for the view advocated here.

To conclude, there seems to be a substantial violation of SU(2) flavor symmetry in the nucleon sea.The asymmetry obviously is not originated from the nuclear effects and a fundamental underlying dynamics appears to be responsible for the asymmetry. We have also shown that ratio of the invariant cross section for production of meson resonances can provide valuable insight to the sea content of the nucleon. We would like to emphasise that γ induced reactions on proton is well positioned to investigate the topic further.

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