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Strangeness asymmetry of the nucleon in the statistical parton model

Claude Bourrely [a], Jacques Soffer [b,*], Franco Buccella [c]

[a] Centre de Physique Théorique, UMR 6207, [1] CNRS-Luminy, Case 907, 13288 Marseille Cedex 9, France
[b] Le Zenon (A) Ave Campagne Berger, 13009 Marseille, France
[c] Dipartimento di Scienze Fisiche, Università di Napoli, Via Cintia, I-80126, Napoli and INFN, Sezione di Napoli, Italy

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Abstract

We extend to the strange quarks and antiquarks, the statistical approach of parton distributions and we calculate the strange quark asymmetry $s - \bar{s}$. We find that the asymmetry is small, positive in the low x region and negative in the high x region. In this framework, the polarized strange quarks and antiquarks distributions, which are obtained simultaneously, are found to be both negative for all x values.

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1. Introduction

Although strange quarks and antiquarks s and $\bar{s}$ play a fundamental role in the nucleon structure, they are much less known than the parton distribution functions (PDF) for the light quarks u and d. The measurements of the structure functions in deep inelastic scattering (DIS) of charged leptons on hadrons provide the best informations on u, d, whereas neutrino DIS and lepton-pair production in hadron collisions put some constraints on the sea quark distributions $\bar{u}$ and $\bar{d}$. Concerning the strange quarks, due to the fact that the structure functions are largely dominated by u and d, the extraction of the small components s and $\bar{s}$ is rather difficult. Therefore most of the phenomelogical models for the PDF studies use the simplifying assumption $s(x) = \bar{s}(x) = \kappa(\bar{u} + \bar{d})/2$ (with $\kappa \sim 0.5$). However, nothing prevents $s(x) \neq \bar{s}(x)$ and we will see how to achieve this inequality in the statistical parton model [1–4].

An experiment on neutrino (antineutrino)-nucleon charged-current DIS by the CCFR Collaboration [5] at the Fermilab Tevatron has measured the production of dimuon final states coming from a charm quark fragmentation. This process involves the interaction of a neutrino (antineutrino) with an s ($\bar{s}$) or d ($\bar{d}$) quarks, via a $W^{\pm}$ exchange, which can be used to isolate their distributions. Since the contribution of the down to charm production is Cabibbo suppressed, scattering off a strange quark is responsible for most of the total dimuon rate. Unfortunately, only an average value of $s + \bar{s}$ was extracted from this experiment, but the size of strange quark distribution was known for the first time. Later, the NuTeV Collaboration [6] has reached a greater accuracy by a high-statistics dimuon measurement, allowing to study independent information on s and $\bar{s}$ and the difference $s - \bar{s}$.

On the theoretical side one of first attempt to separate the s and $\bar{s}$ distributions was investigated in a light-cone model [7] and more recently, other models based on nonperturbative mechanisms were proposed [8,9]. A global QCD fit to the CCFR and NuTeV dimuon data has shown a clear evidence that $s \neq \bar{s}$ [10]. In another approach based on perturbative evolution in QCD at three loops [11], one is able to generate a strange-antistrange asymmetry although at the input scale $s = \bar{s}$.

* Corresponding author.
E-mail address: jacques.soffer@gmail.com (J. Soffer).
[1] Unité Mixte de Recherche du CNRS et des Universités Aix-Marseille I et Aix-Marseille II et de l'Université du Sud Toulon-Var, Laboratoire affilié à la FRUMAM.

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In this Letter, we will show how to construct the strange and antistrange quark distributions in the statistical parton model. Since according to our method, the basic distributions are the helicity dependent ones, $s^\pm$ and $\bar{s}^\pm$, we will obtain simultaneously the unpolarized, $s = s^+ + s^-$, $\bar{s} = \bar{s}^+ + \bar{s}^-$, and the polarized PDF, $\Delta s = s^+ - s^-$, $\Delta\bar{s} = \bar{s}^+ - \bar{s}^-$. We will also explain how to determine the few parameters involved. Our results will be compared with other theoretical predictions.

2. Strange quark and antiquark distributions

In the statistical approach the nucleon is viewed as a gas of massless partons (quarks, antiquarks, gluons) in equilibrium at a given temperature in a finite size volume. Like in our earlier work on the subject [1], we propose to use a simple description of the parton distributions $p(x)$ proportional to $[\exp[(x - X_{0p})/\bar{x}] \pm 1]^{-1}$, the *plus* sign for quarks and antiquarks, corresponds to a Fermi–Dirac distribution and the *minus* sign for gluons, corresponds to a Bose–Einstein distribution. Here X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton p and $\bar{x}$ is the *universal temperature*, which is the same for all partons. Since quarks carry a spin-1/2, it is natural to consider that the basic distributions are $q_i^\pm(x)$, corresponding to a quark of flavor i and helicity parallel or antiparallel to the nucleon helicity. From the chiral structure of QCD, we have two important properties which allow to relate quark and antiquark distributions and to restrict the gluon distribution:

- The potential of a quark q_i^h of helicity h is opposite to the potential of the corresponding antiquark $\bar{q}_i^{-h}$ of helicity $-h$, therefore $X_{0q}^h = -X_{0\bar{q}}^{-h}$.
- The potential of the gluon G is zero $X_{0G} = 0$.

The sum rules, coming from the quantum numbers of the proton, $u - \bar{u} = 2$ and $d - \bar{d} = 1$, give rise to higher values for the potentials of the u's than for the d's. In fact we have found $X_{0u}^+ > X_{0d}^- \sim X_{0u}^- > X_{0d}^+$, which is also consistent with the known facts that $\Delta u(x) > 0$ and $\Delta d(x) < 0$. This ordering leads immediately to some important consequences for the light antiquarks, namely

(i) $\bar{d}(x) > \bar{u}(x)$, the flavor symmetry breaking, which also follows from the Pauli exclusion principle, whose effects are incorporated in the statistical model.
(ii) $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$.

We now turn to the procedure to construct the strange quark distributions. In the original version of the statistical parton model [1] we have assumed that the unpolarized strange quark and antiquark distributions are equal and they can be described by a linear combination of light antiquark distributions at the input scale Q_0^2, namely

$$xs\left(x, Q_0^2\right) = x\bar{s}\left(x, Q_0^2\right) = \frac{1}{4}\left[x\bar{u}\left(x, Q_0^2\right) + x\bar{d}\left(x, Q_0^2\right)\right], \tag{1}$$

where the coefficient 1/4 is an average value of some current estimates. For the corresponding polarized distributions a similar assumption was made, more precisely

$$x\Delta s\left(x, Q_0^2\right) = x\Delta\bar{s}\left(x, Q_0^2\right) = \frac{1}{3}\left[x\Delta\bar{d}\left(x, Q_0^2\right) - x\Delta\bar{u}\left(x, Q_0^2\right)\right], \tag{2}$$

which leads to a large negative distribution, since $\Delta\bar{d} < 0$ and $\Delta\bar{u} > 0$ (see Fig. 18 of Ref. [1]). In order to introduce a difference between s and $\bar{s}$, here we follow the procedure used earlier to built the light quarks PDF, with the recent improvement obtained from the extension to the transverse momentum of the PDF [4]. So the strange quark distributions $s^h(x, Q_0^2)$ of helicity $h = \pm$, at the input energy scale $Q_0^2 = 4\ \mathrm{GeV}^2$, have the following expressions

$$xs^h\left(x, Q_0^2\right) = \frac{AX_{0u}^+ x^{b_s}}{\exp[(x - X_{0s}^h)/\bar{x}] + 1} \frac{\ln(1 + \exp[kX_{0s}^h/\bar{x}])}{\ln(1 + \exp[kX_{0u}^+/\bar{x}])} + \frac{\tilde{A}_s x^{\tilde{b}}}{\exp(x/\bar{x}) + 1}, \tag{3}$$

and similarly[2] for the antiquarks $\bar{s}^h(x, Q_0^2)$

$$x\bar{s}^h\left(x, Q_0^2\right) = \frac{\bar{A}(X_{0d}^+)^{-1} x^{2b_s}}{\exp[(x + X_{0s}^{-h})/\bar{x}] + 1} \frac{\ln(1 + \exp[-kX_{0s}^{-h}/\bar{x}])}{\ln(1 + \exp[-kX_{0d}^+/\bar{x}])} + \frac{\tilde{A}_s x^{\tilde{b}}}{\exp(x/\bar{x}) + 1}. \tag{4}$$

The value of the input energy scale is arbitrary and should not affect the results which satisfy the Q^2 QCD evolution. Our choice was dictated in Ref. [1] by the existence of many accurate data at $Q^2 = 4\ \mathrm{GeV}^2$. The first term in the right-hand side corresponds to the nondiffractive part, while the second is associated with a diffractive component common to all distributions. The ratio of the

[2] As mentioned above, quarks and antiquarks are not independent due to the relation between the potentials $X_{0s}^h = -X_{0\bar{s}}^{-h}$.