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Nucleon strangeness: intrinsic or extrinsic? ⋆

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Abstract A review of experimental results for the measurement of the strange quark distributions in the nucleon, is given. Contributions of the strange quarks to the nucleon mass, electromagnetic form factors and spin, are discussed.

Keywords Nucleon strangeness · Sigma-term · Strange quark-antiquark asymmetry · Strange sea polarization

1 Introduction

The nucleon is a system with zero strangeness and the influence of the strange quarks on the main characteristics of the nucleon is expected to be small. In this sense the strange degrees of freedom of the nucleon are good markers of non-trivial physics: if in some channel the contribution of the strange quarks turns out to be significant it will be a sign of interesting physics. Following S.Brodsky [1] it is worthwhile to distinguish between the extrinsic and intrinsic nucleon strangeness. The extrinsic strangeness is produced by gluons. These processes of production and annihilation of the $\bar{s}s$ pairs in the nucleon are under control of perturbative QCD. The intrinsic strangeness is an essentially nonperturbative phenomenon, it appears due to an interaction between the strange and valence quarks. Considering the nucleon as a sum of different Fock states

$$|N>= \alpha|uud> + \beta|uud\bar{s}s> + ... \tag{1}$$

we implicitly assume the existence of some interaction between the strange and valence quarks which determines the quantum numbers of the $\bar{s}s$ pair. The magnitude β of the strange quarks admixture to the nucleon wave function is not known. It is up to the experiment to conclude whether the intrinsic strangeness exists.

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The nonperturbative character of the intrinsic nucleon strangeness determines its experimental signatures. B.Ioffe and M.Karliner [2] pointed out that the strange quark contribution in the nucleon could be at the same time small or large, depending on the considered matrix element. The nonperturbative effects should increase the contribution of the strange quarks to the nucleon mass and to the nucleon spin, whereas no significant modification of the electric and magnetic nucleon form factors is expected due to the strange quarks. In general, the signal of the intrinsic strangeness is some enhancement in comparison with the predictions of the perturbative QCD. Intrinsic strangeness may result in a difference between the strange $s(x)$ and antistrange $\bar{s}(x)$ unpolarized distribution functions (x is the Bjorken scaling variable). The polarization of the nucleon strange sea may be also considered as a signal of intrinsic strangeness.

Let us consider the experimental information about the role of the strange quarks in different nucleon characteristics.

2 Strange quark contribution to the nucleon mass

It is worthwhile to remember that in the vacuum the strange quark condensate $\bar{s}s$ is as large as the light quarks $\bar{q}q$. It was shown [3,4] that

$$< 0|\bar{s}s|0 >= (0.8 \pm 0.1) < 0|\bar{q}q|0 > . \tag{2}$$

There is no strong strange quark suppression in vacuum, the amount of the $\bar{s}s$ pairs in vacuum is only slightly less than the light quarks. It is interesting to see what has happened in the nucleon. To what extent the large strangeness of the vacuum will survive in the nucleon?

The scalar strange matrix element of the nucleon

$$\sigma_s = m_s < p|\bar{s}s|p >, \tag{3}$$

where m_s is the strange quark mass, is determined from the nucleon sigma term σ:

$$\sigma = m(< p|\bar{u}u|p > + < p|\bar{d}d|p >) \tag{4}$$

and the value of non-singlet combination σ_0

$$\sigma_0 = m(< p|\bar{u}u|p > + < p|\bar{d}d|p > -2 < p|\bar{s}s|p >), \tag{5}$$

where $m = 1/2(m_u + m_d)$ is the average light quark mass. The relation connecting σ, σ_0 and σ_s is

$$\sigma - \sigma_0 = 2\frac{m}{m_s}\sigma_s. \tag{6}$$

Sometimes to quantify the nucleon strangeness, the ratio

$$y = \frac{2 < p|\bar{s}s|p >}{< p|\bar{u}u|p > + < p|\bar{d}d|p >} \tag{7}$$

is used. It is related with the sigma terms (4) and (5) as follows:

$$\sigma = \frac{\sigma_0}{1 - y}. \tag{8}$$

The nucleon sigma term σ is defined by the scalar form factor $\sigma(t)$ in the limit of vanishing momentum transfer t. The experimental required input is the Born-subtracted, isoscalar $\pi - N$ scattering amplitude $\Sigma_{\pi N}$ evaluated in the unphysical region (at $t = 2m_\pi^2$):

$$\Sigma_{\pi N} = \sigma + \Delta_R + \Delta_{CD}, \tag{9}$$

where Δ_R and Δ_{CD} are corrections due to the extrapolation at $t = 0$. Classical analyses of the pion-nucleon scattering data by Koch [5] and Gasser et al. [6] gave $\Sigma_{\pi N} = (64 \pm 8)$ MeV, which results in a value of σ around 45 MeV after corrections due to extrapolation at $t = 0$. The analysis of the baryon octet mass splittings gave $\sigma_0 = (36 \pm 7)$ MeV and $y = 0.21 \pm 0.20$ [7]. Assuming the strange-to-light quark mass ratio to be about 25, from (6) one could estimate that the contribution of the strange quarks to the nucleon mass is at the level of 110 MeV, though with large uncertainty. It is a bit uncomfortable that the contribution of strange quarks to the nucleon mass σ_s exceeds the contribution of the light quarks σ. It stimulated a number of experiments on πN scattering, which, however, have given unexpected results [8]: the value of $\Sigma_{\pi N}$ increases to $\Sigma_{\pi N} = (79 \pm 7)$ MeV, which results in $y \sim 0.46$ and $\sigma_s \sim 300$ MeV. The other analysis [9] has confirmed this trend with y as large as $y = 0.36 - 0.48$ (for review, see [10]).

Unfortunately, this puzzle of large nucleon strangeness is not solved since no new experimental data have appeared in this century. Recently, the importance of the strange nucleon sigma term has been stressed [11] in connection with the search for supersymmetrical particles. It is shown [11] that the spin-independent interaction of neutralinos with nucleon is determined by their scalar coupling to the light and strange quark sigma terms. Comparing $\sigma \sim 45$ MeV and $\sigma_s \sim 300$ MeV, one may conclude that the neutralinos cross section has been dominated by the strange quark content of the nucleon. Moreover, if σ_s is large, then the cross section of the neutralino-nucleon interaction exceeds the existing experimental limits, (for some values of the MSSM parameters). It indicates that the dark matter is not of the SUSY origin. Naturally, this conclusion is very important and the authors of [11] "plead for an experimental campaign to determine better the π-nucleon σ term".

This appeal has not stimulated new experiments yet, but recently a number of the lattice calculations has been done [12–14]. They have shown an unusually small value of the strange sigma term: $\sigma_s = 31 \pm 15$ MeV [13] and $\sigma_s = 59 \pm 10$ MeV [14]. In [12] it was obtained that $y \sim 0.03$. Since the new experimental data are absent, these lattice calculations raise serious doubts about a large contribution of the strange quarks to the nucleon mass.

3 Strange quark contribution to the nucleon electric and magnetic form factors

The strange quark contribution to the electromagnetic form factors of the nucleon can be expressed in terms of the strange electric and magnetic form factors G_E^s and G_M^s. An elegant idea [15] to measure this contribution in the parity-violating elastic scattering (PVES) of electrons on nucleon, has been used in a number of experiments [16–21]. The asymmetry $A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$ is measured in the elastic scattering cross section of left-and right- handed electrons σ_L and σ_R. The asymmetry must be zero for the pure electromagnetic interaction, however, the admixture of the weak interaction and interference between the electromagnetic and weak amplitudes result in a small but non-zero value. Combining the electromagnetic nucleon form factors with the weak form factors, it is possible to separate the light and strange quark contributions.

Table 1 The strange electric and magnetic form factors G_E^s and G_M^s (at $Q^2 = 0.1\ (GeV/c)^2$).

Analysis	G_E^s	G_M^s
PVA4, [19]	$0.050 \pm 0.038 \pm 0.019$	$-0.014 \pm 0.011 \pm 0.011$
Global data analysis, [26]	-0.008 ± 0.016	0.29 ± 0.21
Global data analysis, [27]	0.002 ± 0.018	-0.01 ± 0.25
Lattice, [28,29]	$0.001 \pm 0.004 \pm 0.004$	-0.046 ± 0.022

First measurements of A_{LR} [21] have shown an unusually large and positive value of G_M^s, though with substantial errors: $G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$ at $Q^2 = 0.1\ (GeV/c)^2$, where the uncertainties are statistical, systematic and the uncertainty due to electroweak radiative corrections, respectively. Most of theoretical calculations at that time predicted a negative value for G_M^s. In particular, the $K\Lambda$ meson cloud model gave negative G_M^s [22].

If the strange quark contribution to the magnetic form factor were indeed large and positive, then, as it was shown in [23], the $|uud\bar{s}s>$ component of the nucleon would have had the $\bar{s}$ quark in the ground S-wave state and the $uuds$ system in the P-wave. The positive value of G_M^s corresponds to the negative polarization of the strange quarks with respect to the nucleon spin $\Delta s = -0.06 \pm 0.02$ and the probability of the strange quark admixture to the nucleon wave function (1) is at the level of $P_{\bar{s}s} = |\beta|^2 = 0.17 - 0.22$.

The conclusion about negative polarization of the nucleon strangeness is in a good agreement with the measurements in deep-inelastic scattering experiments (see, Sect.5). The value of the probability of the strange quark admixture agrees well with $P_{\bar{s}s} \sim 0.19$ obtained from the analysis of the apparent OZI-violation in the antiproton annihilation at rest [24]. This agreement between the results obtained from the measurements of different processes seems to be remarkable. However, the situation changes with new, precise PVES experiments [19,25].

The results of these experiments as well as the global analysis of all PVES experiments [26,27] and the lattice calculations [28,29] are given in Table 1.

One could see that the contribution of the strange quarks to the electric form factor G_E^s is compatible with zero. It means that the spatial distributions of the strange and antistrange quarks in the nucleon are similar. The contribution of the strange quarks G_M^s seems to be also small, less than 10% of the nucleon magnetic form factor and also compatible with zero. However, one could bear in mind that the results of the global data analysis [26,27] for G_M^s have significant errors, which do not exclude the scenario with a small positive G_M^s and small negative Δs.

4 Difference between $s(x)$ and $\bar{s}(x)$

One of the signals of intrinsic strangeness may be the difference between unpolarized strange and antistrange distribution functions $s(x)$ and $\bar{s}(x)$. This difference appears naturally in the meson-baryon models [30] of the nucleon considering ΛK or ΣK components of the Fock wave function of the nucleon. In these models the s quark is in a hyperon whereas the $\bar{s}$ belongs to a strange meson cloud and their momentum distributions should not be the same.

The asymmetry between $s(x)$ and $\bar{s}(x)$ was measured in the neutrino dimuons production in DIS [31]. The first muon is created in the charm production from neutrino charged current (CC) interactions with strange quarks in the nucleon. The second muon comes from the decay of the charm hadron which provides a clear signal to distinguish these events from other CC interactions.The NuTeV experiment recorded 5163(1380) dimuon events in neutrino(antineutrino) interactions with reconstructed neutrino energies 20-400 GeV. The experimental dimuons cross section was fitted assuming the different behaviour of $s(x)$ and $\bar{s}(x)$ using the NLO neutrino charm production cross section [32]. It was obtained

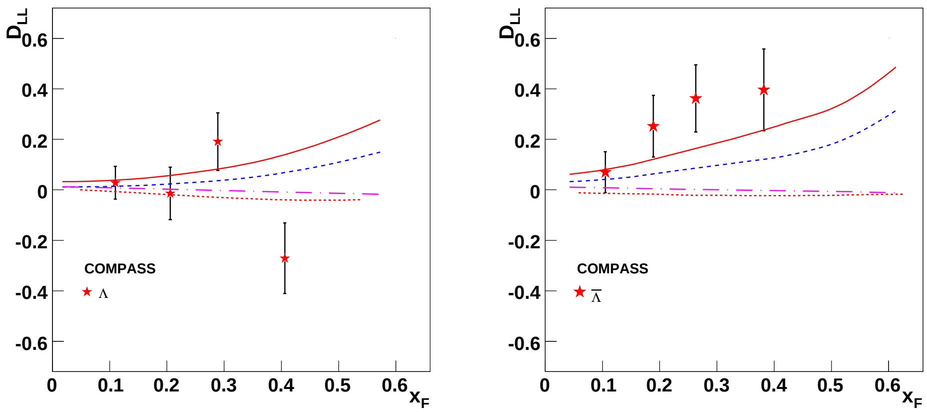
$$S^{-} = \int_{0}^{1} xdx[s(x) - \bar{s}(x)] = (1.96 \pm 0.46 \pm 0.45) \cdot 10^{-3} \tag{10}$$

indicating on some non-zero strange quark-antiquark asymmetry. However, large statistical and systematic uncertainties prevent from considering this result as a firm proof of the existence of the nucleon intrinsic strangeness. The dominant contribution is the large uncertainty in the average semileptonic branching ratio, which is strongly anticorrelated with S^{-}.

It is interesting that the non-zero strange asymmetry S^{-} appears even in the framework of perturbative QCD. In [33] it was shown that the perturbative evolution in QCD at three loops generates the strange quark-antiquark asymmetry at the level of $S^{-} \sim -5 \cdot 10^{-4}$ at $Q^2 = 20\, GeV^2$. Different models of the nucleon intrinsic strangeness predict larger strange quark-antiquark asymmetry, even of a different sign. Thus the statistical parton model [34] gives $S^{-} = -1.93 \cdot 10^{-3}$, the light-cone baryon-meson fluctuation model [35] predicts $S^{-} = (4.2 - 10.6) \cdot 10^{-3}$.

Summarizing, the situation with the strange quark-antiquark asymmetry is inconclusive and needs more experimental input.

An interesting possibility to provide new information about the strange quark-antiquark asymmetry appears in the measurements of the spin transfer from polarized lepton to Λ and $\bar{\Lambda}$ hyperons in DIS. The recent measurements of COMPASS [36] have found that the longitudinal spin transfer to $\bar{\Lambda}$ is large in comparison with Λ (see, Fig.1) and strongly depends on $\bar{s}(x)$. In Fig.1 the degree of the sensitivity to the strange parton distributions is illustrated by the comparison of the results obtained with the CTEQ5L [38](solid line) and GRV98LO [39](dashed line) parton distributions. The GRV98 set is chosen because of its assumption that there is no intrinsic nucleon strangeness at a low scale and the strange sea is of pure perturbative origin. The CTEQ collaboration allows non-perturbative strangeness in the nucleon, which is fixed from the dimuon data of the CCFR and NuTeV experiments. As a result, the $s(x)$ distribution of CTEQ is larger than the GRV98 one by a factor of about two in the region $x = 0.001 - 0.01$. The results in Fig. 1 show that the data on Λ can not discriminate between the predictions since the spin transfer to Λ is small. For the $\bar{\Lambda}$ hyperon the use of CTEQ5L set leads to a prediction which is nearly twice larger than the one with the GRV98LO and much closer to the data. This behaviour reflects the difference in the corresponding $\bar{s}$-quark distributions. If one completely switches off the spin transfer from the $s(\bar{s})$ quarks, the spin transfer to $\Lambda(\bar{\Lambda})$ practically vanishes (dash-dotted line). This feature is independent of the model of Λ spin structure. Calculations in the BJ-model [40], where the spin transfer from the u- and d-quarks(antiquarks) is possible, demonstrate the same absence of the spin transfer to hyperon without contribution from the $s(\bar{s})$-quarks (dotted line). The spin transfer to $\bar{\Lambda}$ could provide an additional experimental



a) b)

Fig. 1 The x_F dependences of the longitudinal spin transfer to Λ (a) and $\bar{\Lambda}$ (b) calculated in [37](model B) for the GRV98LO parton distribution functions (dashed lines), the CTEQ5L pdf (solid lines) and for the CTEQ5L without spin transfer from the s-quark (dash-dotted lines). The SU(6) model for the Λ spin structure is assumed. The dotted lines correspond to the calculations for the CTEQ5L without spin transfer from the s-quark in the BJ-model of Λ spin [40].

information for determination of strange quark distributions in the nucleon. To match this goal the present experimental precision must be increased and the theoretical uncertainties should be clarified.

5 Strange quarks polarization

The first indication that strange quarks in the nucleon may be polarized was obtained in the inclusive DIS experiment by the EMC collaboration [41], which found that $\Delta s = -0.15 \pm 0.09$. The minus sign means that the strange quarks and antiquarks are polarized negatively with respect to the direction of the nucleon spin. Recent measurements with polarized lepton beams and targets for the inclusive DIS performed by HERMES [43] and COMPASS [44] collaborations, are in agreement with the EMC result: $\Delta s = -0.09 \pm 0.01(exp) \pm 0.02(syst)$ [44].

The experiment on elastic neutrino scattering [45] has also concluded that the nucleon strangeness is negatively polarized, though within large uncertainties: $\Delta s = -0.15 \pm 0.07$. Combined analysis of these data and the PVES data, used for the extraction of the strange axial form factor, also suggests a negative strange quark contribution [46]. Finally, global fits of all polarized DIS data favour negative strange quark polarization $\Delta s \sim -0.12$ [47,48].

The different models of the nucleon intrinsic strangeness (see, e.g.[30,34,42]) may quite naturally accommodate for the negative polarization. In this sense the strange sea polarization could be considered as a manifestation of the existence of the intrinsic strangeness.

However, recent measurements of the cross section asymmetries in the semi-inclusive DIS (SIDIS), where in addition to the scattered lepton, pions and kaons are detected,

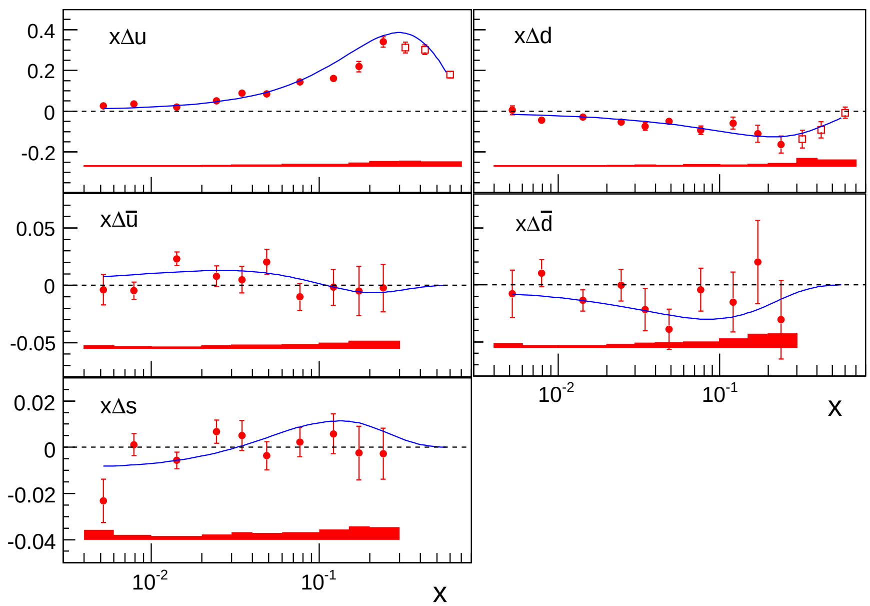


Fig. 2 The quark helicity distributions at $Q^2 = 3(GeV/c)^2$ as a function of x [51]. The bands at the bottom of each plot show the systematic errors. The curves show the predictions of the global fit [47] calculated at NLO.

have put doubts on the conclusion about the strange quark polarization [49,51,53]. Fig.2 shows the quark helicity distributions evaluated at LO analysis of the SIDIS proton and deuteron data [51]. One could see that the Δs is compatible with zero in all the measured interval of x. The first moment of the strange quark helicity distribution is $\Delta s = -0.01 \pm 0.01 \pm 0.01$ in $0.004 < x < 0.3$ at $Q^2 = 3\ GeV^2$. Similar results were obtained by the HERMES collaboration [49].

There are different explanations of this apparent contradiction between the DIS and SIDIS results on Δs. According to [52] the strange quarks are not polarized in the nucleon and the analysis of the DIS data is not correct due to an assumption on exact $SU(3)_f$ symmetry. Another point of view is that the analysis of the SIDIS data strongly depends on the fragmentation functions used [53]. In principle, the variation of the fragmentation functions may lead to appearance of the negative strange quark polarization even at the measured large-x region. Finally, there is an interesting possibility that both DIS and SIDIS analysis are correct and the apparent difference means that the negative strange quark polarization is an effect of small x-physics. Fig. 2 shows that the present SIDIS data do not disagree with the global fit [47]. However, the global fit [47] results in $\Delta s \sim -0.12$, mainly due to negative contribution at small x.

If indeed the polarization of the strange quarks is a small-x effect then it is naturally associated with the gluons rather than with the valence quarks. In this sense, the strange quark polarization is not an intrinsic strangeness effect. Possible mechanism of the strange quark polarization in the limit of the heavy quark mass is suggested in [54].

6 Conclusions

The measurements of the strange quark contribution to different nucleon characteristics have revealed no signs of large effects. The existence of the intrinsic nucleon strangeness connected with valence quarks is under question. However, the present experimental situation is far from the final conclusion. The measurements of the strange quark contribution in the scalar nucleon matrix element are absent, the strange quark-antiquark asymmetry needs confirmation and the problem of polarization of the strange quarks should be solved.

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