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Can the meson cloud explain the nucleon strangeness?

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We use a version of the meson cloud model, including the kaon and the K^* contributions, to estimate the electric and magnetic strange form factors of the nucleon. We compare our results with the recent measurements of the strange quark contribution to parity-violating asymmetries in the forward G0 electron-proton scattering experiment. We conclude that it is very important to determine experimentally the electric and magnetic strange form factors, and not only the combination $G_E^s + \eta\, G_M^s$, if one does really intend to understand the strangeness of the nucleon.

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As new experimental data appear, our picture of the nucleon evolves continually. Our knowledge about the sea quarks in the nucleon has been changing dramatically and, in particular, our ideas about the strange sea quarks have been modified very rapidly. The famous EMC experiment [1] and other polarized DIS experiments [2] could be interpreted as showing that the quarks carry only a small fraction of the total angular momentum of the proton. A further conclusion was that the strange sea quarks in the proton are strongly polarized opposite to the polarization of the proton [3]. The recent results of the HERMES Collaboration [4] indicated that there is a SU(3) symmetry breaking in the nucleon sea. Most of these findings could be well understood with a meson cloud model (MCM) [5–9]. In any version of the meson cloud model, the physical nucleon contains virtual meson-baryon components, that "dress" the bare nucleon. The meson cloud mechanism provides a natural explanation for symmetry breaking among parton distributions [10]. In Ref. [6], it has been shown that the inclusion of the meson cloud significantly lowers the value of the total spin carried by quarks and antiquarks. In Ref. [6] the strange cloud was composed by ΛK and ΣK components in the Fock wave function of the proton and the authors obtained a very small polarization of the strange sea. Later on, in Ref. [11,12], it was shown that the higher mass components ΛK^* and ΣK^* could have important effects on the strange sea. These components are kinematically suppressed but have large couplings to the nucleon and may lead to a numerically significant contribution to some observables. In particular, the states containing K^* affect the quark-antiquark symmetry breaking in the polarized strange sea. When only K mesons were considered it was observed that $x[\Delta s(x) - \Delta\bar{s}(x)] > 0$. When both contributions of K and K^* were included, as it was shown in [12], $x[\Delta s(x) - \Delta\bar{s}(x)] < 0$.

Complementary to the high energy regime of Refs. [1,2,4] the nucleon strange sea can be probed in the low energy parity violating experiments carried out at TJNAF, where it is possible to measure the strange electric and magnetic form factors of the nucleon. The first measurements of these quantities (and combinations of them) were performed by the SAMPLE [13] and HAPPEX [14] Collaborations. In this low energy regime the strange component of the nucleon sea is expected to have a nonperturbative origin. One of the possible nonperturbative mechanisms of strangeness production is given precisely by the meson cloud. Indeed, these data were studied in a number of approaches, including the MCM.

Already in the first kaon-cloud models the nucleon strangeness distribution was generated by fluctuations of the "bare" nucleon into kaon-hyperon intermediate states that were described by the corresponding one-loop Feynman graphs [15]. Since then, some concerns have been raised in the literature regarding the implementation of the loop model of the nucleon. In particular, it has been pointed out that truncations of the Fock space, which stop at the one-loop order, violate unitarity [16]. Although this is true in principle, the region where rescattering should become important is above the production threshold, which is at high momenta compared with those most relevant to the current process. Concerns have also been raised about the omission of contributions from higher-lying intermediate states in the meson-hyperon fluctuations [17,18]. Although the effects of heavier hyperons, such as the Σ^*, have been shown to be negligible [18], the contribution of the $K^* - Y$ pairs were found to be large [17]. Nevertheless, the results of Ref. [19] pointed to a "slow convergence" of the intermediate state sum.

The very recent results from G0 Collaboration at TJNAF [20], provide information on the nucleon strange vector form factors over the range of momentum transfers $0.12 \leqslant Q^2 \leqslant 1.0\,\mathrm{GeV}^2$. The data indicate nontrivial, Q^2-dependent, strange quark distributions inside the nucleon, and present a challenge to models of the nucleon structure.

In view of these new data we think that it is interesting to update our previous calculations of the strange form factors with the meson cloud model. One of the central issues will be the role played by the K^* contribution. Our previous results indicated that the K and K^* loops lead to an opposite Q^2 dependence of the combination $G_E^s(Q^2) + 0.39 G_M^s(Q^2)$. This conclusion is qualitatively consistent with the findings of Ref. [12], where an analogous statement concerning the quantity $x[\Delta s(x) - \Delta\bar{s}(x)]$ could be made.

In this brief report we will compute the momentum dependence of the strange vector form factors in the loop model at momentum transfers $0 \leqslant Q^2 \leqslant 3\,\mathrm{GeV}^2$, evaluated in Ref. [19], to compare with the results from G0 Collaboration [20]. Although we believe that the results of this version

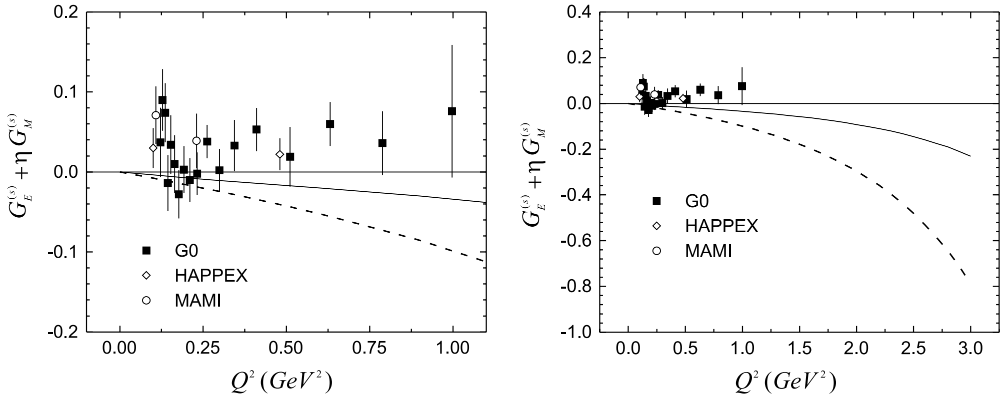

FIG. 1. The combination $G_E^s + \eta\, G_M^s$ as measured by the G0 Collaboration. The solid and dashed lines show our results with $\Lambda_K = \Lambda_{K^*} = 0.9\,\text{GeV}$ and $\Lambda_K = 0.9\,\text{GeV},\ \Lambda_{K^*} = 1.1\,\text{GeV}$ respectively. In the left panel we show our results only up to $Q^2 = 1\,\text{GeV}^2$ to give a better view of the experimental data.

of the MCM are more suitable for the momentum region $Q^2 \leqslant 1\,\text{GeV}^2$, we extend our analysis up to $Q^2 = 3\,\text{GeV}^2$ because new experiments are being planned to cover this higher region of momentum transfer.

The nucleon matrix element of the strangeness current is parametrized by two invariant amplitudes, the Dirac and Pauli strangeness form factors $F_{1,2}^{(s)}$:

$$\langle N(p')|\bar{s}\gamma_\mu s|N(p)\rangle = \bar{U}(p')\left[F_1^{(s)}(Q^2)\gamma_\mu + i\frac{\sigma_{\mu\nu}q^\nu}{2m_N}F_2^{(s)}(Q^2)\right]U(p), \quad (1)$$

where $U(p)$ denotes the nucleon spinor and $F_1^{(s)}(0) = 0$, because of the absence of an overall strangeness charge of the nucleon. The electric and magnetic form factors are defined through

$$\begin{aligned} G_E^{(s)}(Q^2) &= F_1^{(s)}(Q^2) - \frac{Q^2}{4m_N^2}F_2^{(s)}(Q^2), \\ G_M^{(s)}(Q^2) &= F_1^{(s)}(Q^2) + F_2^{(s)}(Q^2). \end{aligned} \quad (2)$$

We consider a hadronic one-loop model containing K and K^* mesons as the dynamical framework for the calculation of these form factors. This model is based on the meson–baryon effective Lagrangians

$$\mathcal{L}_{MB} = -g_{ps}\bar{B}i\gamma_5 BK, \quad (3)$$

$$\mathcal{L}_{VB} = -g_v\left[\bar{B}\gamma_\alpha BV^\alpha - \frac{\kappa}{2m_N}\bar{B}\sigma_{\alpha\beta}B\partial^\alpha V^\beta\right], \quad (4)$$

where $B\ (= N, \Lambda, \Sigma)$, K, and V^α are the baryon, kaon, and K^* vector meson fields, respectively, $m_N = 939$ MeV is the nucleon mass and κ is the ratio of tensor to vector coupling, $\kappa = g_t/g_v$. To account for the finite extent of the above vertices, the model includes form factors from the Bonn-Jülich $N - Y$ potential [21] at the hadronic KNY and K^*NY $(Y = \Lambda, \Sigma)$ vertices, which have the monopole form

$$F(k^2) = \frac{m_M^2 - \Lambda_M^2}{k^2 - \Lambda_M^2} \quad (5)$$

with meson momenta k and the physical meson masses $m_K = 495$ MeV and $m_{K^*} = 895$ MeV.

Because the nonlocality of the meson-baryon form factors (5) gives rise to vertex currents, gauge invariance was maintained in Ref. [17] by introducing the photon field via minimal substitution in the momentum variable k [22]. The resulting nonlocal seagull vertices are given explicitly in Refs. [17,19].

The diagonal couplings of $\bar{s}\gamma_\mu s$ to the strange mesons and baryons in the intermediate states are straightforwardly determined by current conservation, i.e., they are given by the net strangeness charge of the corresponding hadron. The situation is more complex for the nondiagonal (i.e., spin-flipping) coupling $F_{KK^*}^{(s)}(0)$ of the strange current to K and K^*, which is defined by the transition matrix element

$$\langle K_a^*(k_1, \varepsilon)|\bar{s}\gamma_\mu s|K_b(k_2)\rangle = \frac{F_{KK^*}^{(s)}(Q^2)}{m_{K^*}}\epsilon_{\mu\nu\alpha\beta}\,k_1^\nu\,k_2^\alpha\,\varepsilon^{*\beta}\,\delta_{ab}. \quad (6)$$

This coupling was estimated in Ref. [17] with the result $F_{KK^*}^{(s)}(0) = 1.84$. The other couplings in the effective Lagrangians are taken from the Nijmegen NY potential [23, 24]: $g_{ps}/\sqrt{4\pi} = -4.005$, $g_v/\sqrt{4\pi} = -1.45$, $\kappa = 2.43$, and we will consider the cutoff parameter values $\Lambda_K = 0.9\,\text{GeV}$ and $0.9\,\text{GeV} \leqslant \Lambda_{K^*} \leqslant 1.1\,\text{GeV}$ [25]. A smaller value for g_{ps} was found in Ref. [26].

From the difference between the experimental asymmetry, measured by the G0 Collaboration, and the "no-vector-strange" asymmetry, the combination

$$G_E^s(Q^2) + \eta(Q^2)G_M^s(Q^2), \quad (7)$$

was obtained in Ref. [20]. In Eq. (7) $\eta(Q^2) = \tau G_M^p/\epsilon G_E^p$, with $\epsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$, $\tau = Q^2/4m_N^2$ and $G_{E,M}^p$ being the electromagnetic form factors of Kelly [27].

In Fig. 1 we show the results of the loop model obtained by using $\Lambda_K = \Lambda_{K^*} = 0.9\,\text{GeV}$ (solid line) and $\Lambda_K = 0.9\,\text{GeV},\ \Lambda_{K^*} = 1.1\,\text{GeV}$ (dashed line). We see that, although not completely inconsistent with the G0 data (which seems to be consistent with zero), our results are negative and drecreasing with Q^2. The cutoff value $\Lambda_{K^*} = 0.9$ GeV is very

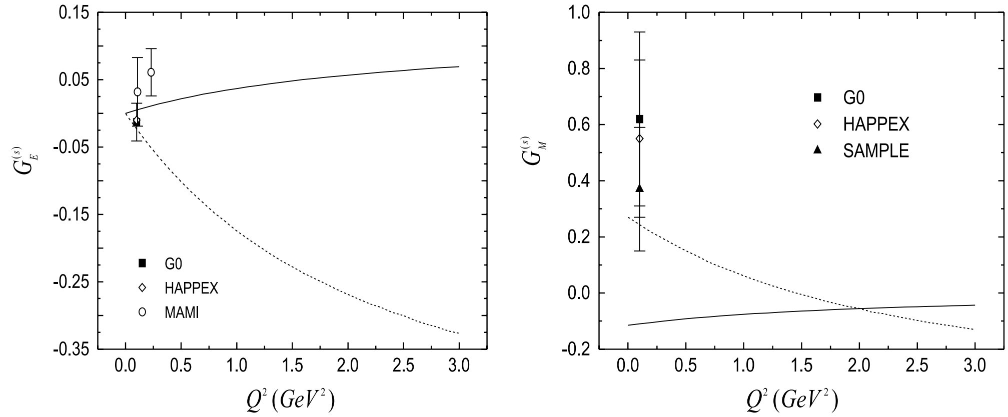

FIG. 2. The electric (left panel) and magnetic (right panel) strange form factors. The solid and dashed lines show our results with $\Lambda_K = \Lambda_{K^*} = 0.9\,\mathrm{GeV}$, $F^{(s)}_{KK^*}(0) = 1.84$ and $\Lambda_K = 0.9\,\mathrm{GeV}$, $\Lambda_{K^*} = 1.1\,\mathrm{GeV}$, $F^{(s)}_{KK^*}(0) = 8.0$ respectively.

close to the K^* mass. As a consequence, for this cutoff value the contributions from the K^* and the K/K^* transition are completely negligible relative to the kaon contribution. Using a bigger value for Λ_{K^*} makes the agreement with the G0 data worse, as can be seen by the dashed line in Fig. 1. In Fig. 1 we also show the new HAPPEX [28] and MAMI [29] data, which are in a very good agreement with the G0 data.

The HAPPEX Collaboration [28] has also estimated the values of the electric and magnetic strange form factors at $Q^2 \sim 0.1\,\mathrm{GeV}^2$. They found $G_E^s = -0.01 \pm 0.03$ and $G_M^s = 0.55 \pm 0.28$. Using the SAMPLE result for G_M^s: $G_M^s(Q^2 = 0.1) = 0.37 \pm 0.22$ [30], the A4 Collaboration at MAMI [29] got $G_E^s(Q^2 = 0.108) = 0.032 \pm 0.051$ and $G_E^s(Q^2 = 0.23) = 0.061 \pm 0.035$. Our calculation gives for these form factors at $Q^2 \sim 0.1\,\mathrm{GeV}^2$ (with $\Lambda_K = \Lambda_{K^*} = 0.9\,\mathrm{GeV}$): $G_E^s = 0.0053$ and $G_M^s = -0.11$. Therefore, although we get G_E^s compatible with data, our G_M^s is negative for the choice of parameters given above. A negative value for G_M^s was also obtained in a recent lattice calulation [31].

Taking a closer look at the results obtained for the strange magnetic moment of the nucleon obtained in Ref. [19], we see that although the contributions from the kaon and K^* are negative, the K/K^* transition contribution is positive. Therefore, if one allows the $F^{(s)}_{KK^*}(0)$ coupling in Eq. (6) to be bigger, it is possible to get a positive value for $G_M^s(Q^2)$. Just to give an example, using $F^{(s)}_{KK^*}(0) \sim 8.0$, $\Lambda_{K^*} = 1.1\,\mathrm{GeV}$ and keeping the other parameters fixed we get at $Q^2 \sim 0.1\,\mathrm{GeV}^2$: $G_E^s = -0.023$ and $G_M^s = 0.24$. What is even more interesting is the fact that the result for the combination $G_E^s + \eta\, G_M^s$ remains almost unchanged, up to $Q^2 \sim 1\,\mathrm{GeV}^2$, as compared with the dashed line in Fig. 1. This shows that it is very important to determine experimentally each one of the strange for factors, and not only the combination $G_E^s + \eta\, G_M^s$, if one does really intend to understand the strangeness of the nucleon. In Fig. 2 we show, together with the available experimental data, our results for the electric and magnetic strange form factors using $\Lambda_K = \Lambda_{K^*} = 0.9\,\mathrm{GeV}$, $F^{(s)}_{KK^*}(0) = 1.84$ (solid line) and $\Lambda_K = 0.9\,\mathrm{GeV}$, $\Lambda_{K^*} = 1.1\,\mathrm{GeV}$, $F^{(s)}_{KK^*}(0) = 8.0$ (dashed line).

In summary, we have calculated the electric and magnetic strange form factors of the nucleon with a version of the meson cloud model, which includes the kaon and the K^* contributions. In contrast to other situations, in the present case the K^* contribution did not cancel the kaon contribution. Instead it reinforced it. In our approach the combination in Eq. (7) is negative and decreasing with Q^2. However, it is important to point out that other version of the MCM, like the light-cone chiral cloud model in Ref. [32], gives a positive value to the combination in Eq. (7).

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