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Isospin-symmetry breaking effects on the strange electric and magnetic form factors of the nucleon

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We examine the electric and magnetic strange form factors of the nucleon in the pseudoscalar-vector SU(3) Skyrme model, with special emphasis on the effects of isospin symmetry breaking (ISB). It is found that ISB has a nontrivial effect on the strange vector form factors of the nucleon and its contribution to the nucleon strangeness is significantly larger than one might naively expect. Our calculations and discussions may be of some significance for the experimental extraction of the authentic strangeness.

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Deep-inelastic lepton scattering experiments, Drell-Yan processes, and νN scattering experiments demonstrate a much more complex nucleon well beyond its naive quark-model description [1]. In the case of the SU(3) flavor, since the nucleon contains no net strangeness, any strangeness contribution to nucleon observables must be exclusively the result of quantum vacuum fluctuations in the strange direction. The strangeness effects can directly probe the nonperturbative dynamics of strong interaction, and they have been one of the prominently open issues for long and presently are the focus of modern hadron physics [2,3].

Electromagnetic and weak form factors, among the most basic observables of the nucleon, are of fundamental importance for the understanding of the underlying structure and dynamics of the nucleon and other more complex hadrons. Much of the original impetus for examining strange form factors of the nucleon was triggered by the EMC (European Muon Collaboration) experimental results [4], which appeared to indicate that a large fraction of the proton's spin might be due to the strangeness contribution. The initial attempt to describe the strange form factors of the nucleon was performed by Jaffe [5] in terms of the pole-fit analysis based on dispersion theory. Since the first measurement of the proton's neutral weak magnetic form factor reported in 1997 [6], a series of precise measurements of the parity-violating elastic scattering of polarized electrons have been conducted intensively or gotten underway to exploit the strangeness effects on the nucleon structure and properties [7]. Recent results of the parity-violating electron scattering experiments from SAMPLE, PVA4, HAPPEX, and G0 Collaborations [8,9] on the nucleon strange vector form factors have indicated nontrivial strangeness distributions inside the nucleon. However, the rather large experimental uncertainties imply the difficulty of such type of experiments. Presently there is no measurement independently shows compelling evidence for nonzero strangeness and no definitive conclusion can as yet be made regarding the experimental scale of the strange matrix element [10].

Two basic principles play a crucial role in the analysis of the nucleon form factors. The first is relativistic invariance, and it fixes the form of the nucleon currents. The second is isospin invariance. The isospin symmetry holds only approximately in the real world and recent flavor asymmetry measurements indicate a considerable isospin symmetry breaking (ISB) in the nucleon sea [11]. The contributions of ISB and strangeness to nucleon observables interfere with each other and actually cannot be separated experimentally [12]. It is not yet clear whether the ISB effects on the nucleon's electromagnetic and weak form factors are negligible with respect to the strangeness effects. Perhaps the strange electric and magnetic form factors are even small enough to require a serious consideration of the intrinsic ISB [13]. There have been many theoretical attempts to calculate the electric and magnetic strange form factors of the nucleon, each approach emphasizing different aspects and with its particular merits and limitations, but these calculations yield a rather broad spectrum of results which vary considerably in magnitude and sign [3]. In particular, several experiments on parity-violating electron-proton scattering suggest that the strange magnetic form factor of the proton is positive [9], contrary to the negative values resulting from most of the theoretical studies, except that of Refs. [14,15]. However, all of the strangeness calculations in this context to date have not taken into account the ISB effects [16]. In fact, the present experimental precision is approaching the level at which ISB effects become important [13], and the increasingly accurate strangeness data expected in the near future will clarify the role of ISB in the extraction of the authentic strangeness from lepton-nucleon scattering. It is especially timely to see a consolidated treatment of the strange form factors with the ISB effects, and the ability to describe and predict them correctly is of critical importance for the stringent test of any theory or model of the strong interaction.

Several experimental hints of hidden strangeness in the nucleon are expected in the chiral soliton models [17], and they suggest that the strangeness component plays a more important role in the low-energy properties of the nucleon than one might expect. The characteristic feature of the almost linear drop with increasing momentum transfer in the ratio of the proton electric to magnetic form factor [18] was predicted within the framework of chiral soliton models [19] before the polarization transfer data became available. We also note that the works of Ref. [14] are just based on the chiral soliton models. Considering the above-mentioned indications that

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the strange magnetic moment of proton is positive, Zou and Riska recently suggest that the strangeness in the nucleon is most likely in the form of pentaquark configurations [20] and that the specific flavor structure of these exotic components in turn gives a considerable influence on the nucleon form factors [21]. However, in the chiral soliton models or Skyrme models these pentaquarks come naturally as members of the next multiplets of the conventional rotation excitations [22]. Moreover, the latest relativistic χEFT (chiral effective field theory) calculations find that only upon inclusion of explicit vector meson degrees of freedom they can properly describe the form factors [23]. Since the SU(3) Skyrme model with vector mesons provides a fair description of many static properties of the baryons and works rather well for the isospin-conserving case [24], it is interesting to employ it further to the investigation of the strange form factors with ISB. On the other hand, in parity-violating electron scattering the axial strangeness effects are heavily suppressed and the radiative corrections to the axial form factors are significantly larger than anticipated [25], and thus the determination of the strange axial form factors are impeded. Neutrino scattering experiment is usually regarded as an excellent tool for extracting information on the axial strangeness, whereas strong influence from the vector strangeness on the (anti)neutrino cross-section ratios makes it a challenging task [26]. Although a combined analysis of parity-violating electron scattering and (anti)neutrino scattering will make it possible to extract the electric, magnetic and axial strange form factors of the nucleon simultaneously [27], the present paper will only discuss the ISB effects on the electric and magnetic strange form factors of the nucleon.

In the pseudoscalar-vector SU(3) Skyrme model, we introduce vector mesons through external gauging to set up the mesonic action and then construct the classical soliton for the baryon sector [24]. Substituting one set of *ansätze* in terms of the best fits into the action and expanding up to quadratic order in the angular velocities as well as linear order in isospin breaking yields the collective Lagrangian. We then quantize the soliton canonically to get the collective Hamiltonian, which consists of an isospin-symmetry conserving term and a breaking term such that

$$H = H_{I=0} + H_{I=1}, \tag{1}$$

$$\begin{aligned} H_{I=0} = {}& M_{\rm cl} + \frac{1}{2}\left(\frac{1}{\alpha^2} - \frac{1}{\beta^2}\right) J(J+1) - \frac{3}{8\beta^2} \\ & + \frac{1}{2\beta^2}\Bigg\{ C_2(SU(3)) + \beta^2\gamma(1 - D_{88}) \\ & + \beta^2\frac{\alpha_1}{\alpha^2}\sum_{i=1}^{3} D_{8i}(2R_i + \alpha_1 D_{8i}) \\ & + \beta_1\sum_{\alpha=4}^{7} D_{8\alpha}(2R_\alpha + \beta_1 D_{8\alpha}) + \beta^2\gamma_S\big(1 - D_{88}^2\big) \\ & + \beta^2\gamma_T\sum_{i=1}^{3} D_{8i}D_{8i} + \beta^2\gamma_{TS}\sum_{\alpha=4}^{7} D_{8\alpha}D_{8\alpha}\Bigg\}, \end{aligned} \tag{2}$$

$$\begin{aligned} H_{I=1} = {}& \Gamma_3 D_{38} + \Delta_3\sum_{i=1}^{3}(D_{3i}D_{8i} + D_{38}D_{88}) \\ & + \frac{\alpha_3}{\alpha^2}\sum_{i=1}^{3} D_{3i}(R_i + \alpha_1 D_{8i}) \\ & + \frac{\beta_3}{\beta^2}\sum_{\alpha=4}^{7} D_{3\alpha}(R_\alpha + \beta_1 D_{8\alpha}). \end{aligned} \tag{3}$$

Here we refer to Ref. [22] for the details on operators and D-matrices and to Refs. [24,28] for the expressions and determinations of the parameters. The perturbative nucleon wave functions in terms of mixtures of SU(3) multiplets are similar to that of Ref. [22]. By the way, the higher-order calculations are unlikely to be of high numerical relevance compared to the strangeness dynamics considered here.

The vector currents can be obtained by gauging the action with an external vector field (e.g., for the local part that is replacing the ordinary derivatives by covariant ones), and its corresponding expression is given as the coefficient of the term linear in the external field [24]. Identifying the four-momentum transfer squared Q^2 in the Breit frame and considering the Fourier transformations of the time and spatial components of the vector current respectively allow us to extract the electric and magnetic strange form factors of the nucleon:

$$\begin{aligned} G_E^s(Q^2) = {}& -\frac{8\pi}{\sqrt{3}}\int_0^\infty drr^2 j_0(r|Q|) \\ & \times\Bigg\{\frac{2}{\sqrt{3}}V_9(r)\left[\langle D_{88}\rangle_N - \frac{\sqrt{3}}{2}\right] \\ & + \frac{1}{\alpha^2}V_{10}(r)\,[\langle D_{8i}R_i\rangle_N + \alpha_3\langle D_{8i}D_{3i}\rangle_N] \\ & + \frac{1}{\beta^2}V_{11}(r)\,[\langle D_{8\alpha}R_\alpha\rangle_N + \beta_3\langle D_{8\alpha}D_{3\alpha}\rangle_N] \\ & + \left[\frac{\alpha_1}{\alpha^2}V_{10}(r) - V_{12}(r)\right]\langle D_{8i}D_{8i}\rangle_N \\ & + \left[\frac{\beta_1}{\beta^2}V_{11}(r) - V_{13}(r)\right]\langle D_{8\alpha}D_{8\alpha}\rangle_N\Bigg\}, \end{aligned} \tag{4}$$

$$\begin{aligned} G_M^s(Q^2) = {}& \frac{16\pi}{\sqrt{3}}M_N\int_0^\infty drr^2\frac{r}{|Q|}j_1(|Q|r) \\ & \times\Bigg\{\left[V_1(r) + \frac{\alpha_1}{\alpha^2}V_2(r)\right]\langle D_{83}\rangle_N \\ & - \frac{1}{\alpha^2}V_2(r)[\langle R_3\rangle_N + \langle D_{88}R_3\rangle_N + \alpha_3\,(\langle D_{33}\rangle_N \\ & + \langle D_{88}D_{33}\rangle_N)] - \frac{1}{\beta^2}V_3(r)[\langle d_{3\alpha\beta}D_{8\alpha}R_\beta\rangle_N \\ & + \beta_3\langle D_{8\alpha}D_{3\beta}\rangle_N] + V_4(r)\langle D_{83}(1 - D_{88})\rangle_N \\ & - V_5(r)\langle D_{83}\rangle_N + \left[V_5(r) + \frac{\alpha_1}{\alpha^2}V_2(r)\right]\langle D_{88}D_{83}\rangle_N \\ & + \left[V_6(r) + \frac{\beta_1}{\beta^2}V_3(r)\right]\langle d_{3\alpha\beta}D_{8\alpha}D_{8\beta}\rangle_N\Bigg\}, \end{aligned} \tag{5}$$

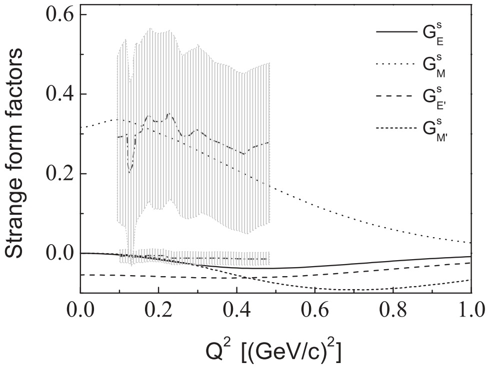

FIG. 1. Momentum-transfer dependence of the electric and magnetic strange form factors of the proton with (G^s_E, G^s_M) and without ($G^s_{E'}, G^s_{M'}$) ISB. The dash-dotted curve, with the 1σ error bars shown as a shaded band, represents the global fit of Ref. [29].

where the repeated indices are summed and the radial functions can be consulted in Ref. [24].

Figure 1 shows that our strange electric form factor G^s_E barely deviates from zero and remains small, with $-0.038 \leqslant G^s_E \leqslant 0$, in the whole momentum transfer range considered. The value of G^s_E changes very little and its Q^2 dependence is essentially weak and insensitive. Our G^s_M estimations ($0.026 \leqslant G^s_M \leqslant 0.336$) initially rise with Q^2 from 0.32 to a shallow maximum at 0.10 (GeV/c)^2 and then fall almost linearly until 0.70 (GeV/c)^2, and in the following there is a significant trend to close to zero at higher Q^2 beyond 1.0 (GeV/c)^2. As our results indicate, there is a clear support for a nonzero strangeness in the nucleon.

The global Q^2-dependence behavior for our G^s_E and G^s_M prediction can also be compared with the existing older results of the same model but without ISB contribution [24], i.e., $G^s_{E'}$ and $G^s_{M'}$ in Fig. 1. The differences or changes between correspond to the additional ISB effects on the electric and magnetic strange form factors without them. Our calculations yield a numerically larger value with an opposite sign for G^s_M as well as a flatter G^s_E curve. It demonstrates that the ISB contribution, albeit formally small, plays an important role in the electric and magnetic strange form factors as evidenced by the non-negligible changes of the curves induced by the ISB. We conclude that the vector strangeness of the nucleon gets an isospin-breaking correction of approximately $5\% \sim 10\%$ in this model, with G^s_M affected more deeply than G^s_E.

To put these predictions into perspective concerning the measurements of the strange form factors, we compare them with the global fit to the current world data of Refs. [26,29], which is a recent attempt to perform a best fit for the strangeness results by combing all available data on parity-violating electron scattering. Each of these measurements is carried out in a narrow range of momentum transfer and the data extracted so far have rather large errors, so the fits are not accurate enough to pin down the nucleon strange form factors successfully. As we see from Fig. 1 the error band of the fitted G^s_M curve is much broader than that of the fitted G^s_E, and the latter is much better constrained and remains almost unchanged. The two G^s_E curves almost coincide with each other from 0.10 to 0.16 (GeV/c)^2, then ours falls gently below the fitted one and tend to be nearly flat in the intermediate region. At 0.30 (GeV/c)^2 our G^s_E curve begins to go beyond the shaded area gradually but only deviates slightly away from its lower boundary at least in this very range. Subsequently, our G^s_E curve rises gradually toward zero. On the whole, our G^s_E result is consistent with the G^s_E fit to a large extent. The fitted G^s_M curve develops a few extrema at 0.13 (a very sharp minimum), 0.18 and 0.24 (GeV/c)^2, etc., and a sudden rise appears from 0.43 (GeV/c)^2 in the corresponding Q^2 range. There remains a strong embarrassment about the interpretation of these apparently irregular structures of the fitted curve of G^s_M, and it suggests that there is a clear need for more data of high accuracy in this range, not to mention the lower and the higher Q^2 region such as from 0 to 0.1 (GeV/c)^2, from 0.5 to 1.0 (GeV/c)^2 and the higher. Although our G^s_M curve lies mostly below and crosses the fitted G^s_M curve only at 0.16 (GeV/c)^2, it remains within the central region of the error bands and they are consistent with the general Q^2-behavior of the available data as a whole. Therefore, there seems not to be a significant disagreement. At this stage of the investigation, those that predict $G^s_M(Q^2) > 0$ [9] and $G^s_E(Q^2) \lesssim 0$ [10] are favored at a high level of confidence, in support of the usefulness of our model in making realistic predictions.

A quantitative understanding of the unavoidable contamination from isospin breaking is increasingly becoming a necessary ingredient in the precise extraction of the nucleon's strange form factors from experimental data. The ISB pieces were early expected to be minor effects and missed in most model calculations. The present work discusses the electric and magnetic strange form factors of the nucleon plus the isospin-breaking contribution in the pseudoscalar-vector SU(3) Skyrme model, which are of direct relevance to the ongoing experimental studies of strangeness. However, the ISB corrections are still smaller than the present experimental error of the strangeness results and their possible impact may be covered by the sizable error bands. The active experimental programs at various facilities world-wide in the next few years, together with the background field technique and high-precision method of evaluating the all-to-all propagator recently employed in the lattice-QCD calculation of strange form factors [30], will offer strangeness data of the nucleon with significantly improved precision [30,31] over a much wider range of momentum transfer. When combined with even more stringent analysis, they could improve our knowledge of the nucleon structure and dynamics.

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