FLAVOR ANALYSIS OF BARYON ELECTROMAGNETIC FORM FACTORS*

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We report some sample results from a detailed study of the electromagnetic structure of baryons with flavors u, d, and s. The individual flavor contributions to the elastic electromagnetic form factors are calculated along a relativistic constituent-quark model and compared to experimental data as well as results from lattice quantum chromodynamics. In the region of momentum transfers up to $\sim$4 GeV^2, the form factor properties are well reproduced with valence-quark degrees of freedom only.

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1. Introduction

Studies of the electromagnetic hadron structure have traditionally produced important insights into the composition of hadrons in terms of quarks and gluons. In the perturbative regime of quantum chromodynamics (QCD), the situation is well under control both theoretically and experimentally. In electron scattering at low momentum transfers, however, the circumstances are not so clear-cut. There, it is still not obvious, which degrees of freedom come into play and assume essential roles. In the case of nucleons, a wealth of experimental data has been accumulated on the elastic electromagnetic form factors. Nevertheless, it has remained largely unclear, if beyond pure valence (three-quark) configurations also other ingredients, like meson clouds or five-quark components bring about noticeable contributions. These uncertainties might soon be resolved due to detailed microscopic studies of the electromagnetic form factors both from experiment and theory. On the one hand, it has recently become possible to extract individual flavor contributions to the total form factors from phenomenology [1] and, on the other

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hand, detailed theoretical studies have been performed and are ongoing, *e.g.*, from lattice QCD, chiral perturbation theory, relativistic constituent-quark models (RCQM), *etc.* Theoretical investigations can, of course, also be extended to baryons other than the nucleons, for which scarce or no experimental data exist so far.

Here, we give a limited account of our own studies of the electromagnetic form factors of the nucleons and all other $\mathrm{SU}(3)_F$ baryon ground states in terms of their flavor compositions. We follow the approach along the RCQM and conduct our analysis on the basis of covariant predictions for the elastic electromagnetic form factors in the momentum-transfer range $0 \sim 4$ GeV^2. The theory is based on exactly the same formalism as developed about a decade ago in Refs. [2–4], *i.e.* the point-form version of relativistic Hamiltonian dynamics [5, 6]. Regarding the nucleons, first results have already been reported in Refs. [7, 8]. From the extension of the investigations to the Δ and the hyperons, we have shown first results already in Ref. [9]. Here, we discuss the flavor decompositions of the nucleon elastic Sachs form factors and produce as an example for the hyperons the ones for the (octet) Σ^+. In the former case, we may compare to experiment [1], in the latter to data from lattice QCD [10, 11]. All the results shown in the current paper are obtained with the RCQM based on Goldstone-boson exchange (GBE) [12, 13].

2. Formalism

The RCQM relies on a mass operator $\hat{M} = \hat{M}_{\mathrm{free}} + \hat{M}_{\mathrm{int}}$, with a free part $\hat{M}_{\mathrm{free}}$ and an interaction part $\hat{M}_{\mathrm{int}}$, which describes the quark dynamics. In the case of GBE RCQM [12, 13], the latter consists of a linearly rising confinement potential, with a strength corresponding to the QCD string tension, and a hyperfine interaction due to GBE. The corresponding eigenvalue equation for a particular baryon B reads

$$\hat{M}\,|M, V, J, \Sigma\rangle_B = M\,|M, V, J, \Sigma\rangle_B \,. \tag{1}$$

Here M represents the mass eigenvalue, and the various baryon eigenstates $|M, V, J, \Sigma\rangle_B$ are further characterized by the (simultaneous) eigenvalues of the 4-velocity $\hat{V}$, intrinsic spin $\hat{J}$, and its z-component $\hat{\Sigma}$. Due to the relations $\hat{P}^\mu = \hat{M}\hat{V}^\mu$ and $\hat{M}^2 = \hat{P}^\mu \hat{P}_\mu$, the baryon states are also eigenstates of the 4-momentum $\hat{P}^\mu$.

The elastic form factors are obtained from the invariant form factors $F^{B\ \mu}_{\Sigma'\Sigma}$ as matrix elements of the electromagnetic current operator $\hat{J}^\mu$

$$F^{B\ \mu}_{\Sigma'\Sigma}\left(Q^2\right) = \frac{1}{2M}\ {}_B\langle M, V', J, \Sigma'|\, \hat{J}^\mu\, |M, V, J, \Sigma\rangle_B \,, \tag{2}$$

where Q^2 is the momentum transfer by the virtual photon. For a spin-$\frac{1}{2}$ baryon the electric and magnetic Sachs form factors then result as

$$G_E^B\left(Q^2\right) = F^{B\;\mu=0}_{\frac{1}{2}\frac{1}{2}}\left(Q^2\right) , \qquad G_M^B\left(Q^2\right) = \frac{2M}{Q} F^{B\;\mu=1}_{\frac{1}{2}-\frac{1}{2}}\left(Q^2\right) . \tag{3}$$

We extract the u-, d-, and s-flavor contributions to the Sachs form factors by means of projection operators in flavor space

$$\hat{J}^{f_j\;\mu} = \hat{J}^{\mu}|f_j\rangle\langle f_j| \tag{4}$$

for a particular flavor $f_1 = u, f_2 = d, f_3 = s$. Thereby, we obtain the flavor components

$$G_E^{f_j\;B}\left(Q^2\right) = \frac{3}{n_{f_jB}}\frac{1}{2M}\left|\;{}_B\!\left\langle M, V', \frac{1}{2}, \frac{1}{2}\left|\hat{J}^{f_j\;0}\right| M, V, \frac{1}{2}, \frac{1}{2}\right\rangle_B\;\right| ,$$

$$G_M^{f_j\;B}\left(Q^2\right) = \frac{3}{n_{f_jB}}\frac{1}{Q}\left|\;{}_B\!\left\langle M, V', \frac{1}{2}, \frac{1}{2}\left|\hat{J}^{f_j\;1}\right| M, V, \frac{1}{2}, -\frac{1}{2}\right\rangle_B\;\right| , \tag{5}$$

where n_{f_jB} is the number of constituent quarks with flavor f_j in baryon B. The total form factors are then constituted by the flavor contributions in the following way

$$G_{E,M}^B\left(Q^2\right) = \frac{n_{uB}}{3}G_{E,M}^{u\;B}\left(Q^2\right) - \frac{n_{dB}}{3}G_{E,M}^{d\;B}\left(Q^2\right) - \frac{n_{sB}}{3}G_{E,M}^{s\;B}\left(Q^2\right) . \tag{6}$$

In the case of nucleons ($B = p, n$), one has *a priori* four independent flavor components for both the electric and magnetic Sachs form factors, namely, $G_{E,M}^{u\;p}$, $G_{E,M}^{d\;p}$, $G_{E,M}^{u\;n}$, and $G_{E,M}^{d\;n}$. They reduce to only two under the assumption of charge symmetry and we can define u- and d-components as follows

$$G_{E,M}^{u\;p}\left(Q^2\right) \;=\; 2G_{E,M}^{d\;n}\left(Q^2\right) := G_{E,M}^{u}\left(Q^2\right) , \tag{7}$$

$$G_{E,M}^{d\;p}\left(Q^2\right) \;=\; \tfrac{1}{2}G_{E,M}^{u\;n}\left(Q^2\right) := G_{E,M}^{d}\left(Q^2\right) . \tag{8}$$

For the other octet as well as decuplet baryons, charge symmetry reduces the independent flavor components in a similar manner. In the case of the octet Σ considered below, only two independent components remain for each Sachs form factor, namely,

$$G_{E,M}^{u\;\Sigma}\left(Q^2\right) = 2G_{E,M}^{d\;\Sigma}\left(Q^2\right) , \qquad G_{E,M}^{s\;\Sigma}\left(Q^2\right) . \tag{9}$$

The same would be true for the decuplet Σ^*. We remark that the GBE RCQM is constructed in a charge-symmetric manner from the very beginning, *i.e.*, its mass operator is invariant under $u \leftrightarrow d$ exchange. Further details on the aspects of charge symmetry in the context of electromagnetic form factors and their flavor decompositions can be found in Ref. [14].

3. Results and discussion

The parameter-free predictions of the GBE RCQM [12, 13] for the nucleon elastic electromagnetic form factors are shown in Fig. 1. Evidently, a very good description of the total form factors as well as their separate flavor contributions is achieved both in comparison with the global world data set and the phenomenological flavor components [1], respectively. Slight deviations occur only in the limit towards vanishing momentum transfer, specifically for the electric radii and the magnetic moments (*cf.* their values reported in Refs. [4, 6]).

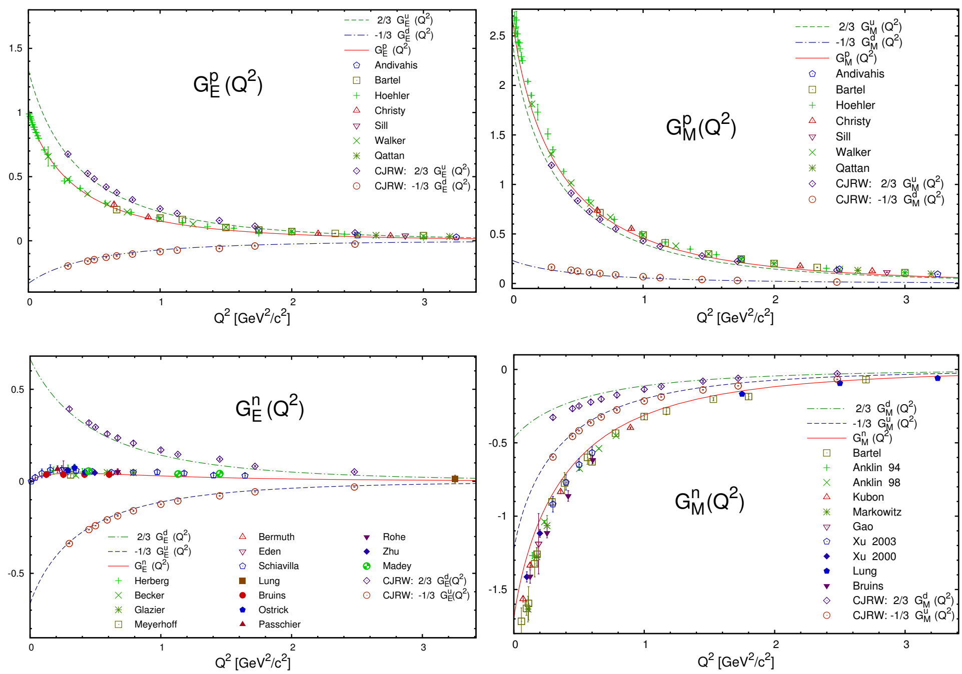

Fig. 1. Predictions of the GBE RCQM for the elastic electric and magnetic form factors of the proton (upper panels) and the neutron (lower panels). Total: solid line, u-contribution: dashed line, d-contribution: dash-dotted line, in comparison to experimental data as indicated; the phenomenological flavor contributions marked by CJRW are from Ref. [1].

In Fig. 2, the analogous results are shown for the example of the octet Σ^+. In this case, the total results and the separate flavor contributions can be compared to lattice-QCD data by Lin and Orginos (LO) [10] and by Boinepalli *et al.* [11], respectively. Except for the momentum dependence of the magnetic form factor *vis-à-vis* the one of LO again a surprisingly good agreement is found. The same is true for other cases of hyperons, like the octet Σ^-, Σ^0, Ξ^-, Ξ^0, the decuplet $\Sigma^{*\pm}$, Σ^{*0}, Ξ^{*-}, Ξ^{*0}, and Ω^- as well as the Δ^+, for which partially lattice-QCD data are available too. These comparisons are contained in a forthcoming paper [15].

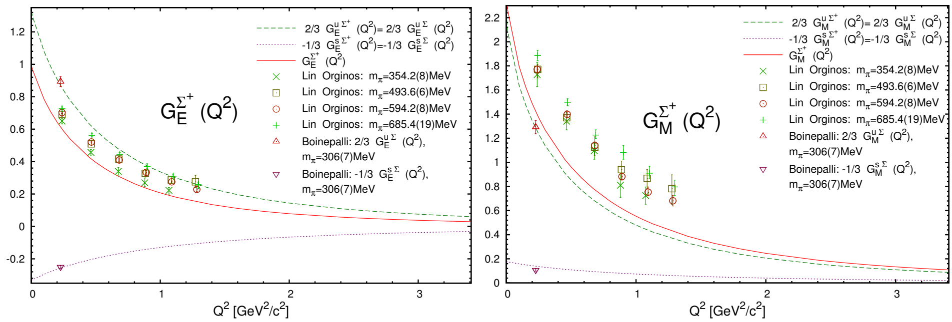

Fig. 2. Predictions of the GBE RCQM for the elastic electric and magnetic form factors of Σ^+. Total: solid line, u-contribution: dashed line, s-contribution: dotted line, in comparison to data from lattice QCD for the total form factor [10] and for the individual u- and s-flavor contributions [11].

In summary, we have found that the predictions of the GBE RCQM for the elastic electromagnetic form factors and their separate u-, d-, and s-flavor contributions agree comfortably well with experiment (in the case of nucleons) and with lattice-QCD data (for the Δ and the hyperons, insofar a comparison is yet possible). We attribute this success mainly to the manifestly covariant results obtained in the point form of Poincarè-invariant quantum mechanics and the implementation of additional symmetry requirements such as time-reversal invariance and current conservation [5, 6] in this approach. It is certainly remarkable that quite a reasonable and consistent description of the baryon form-factor properties is obtained on the basis of three-quark configurations only, and no further ingredients need to be advocated.

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