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Covariant spectator quark model description of the $\gamma^*\Lambda \to \Sigma^0$ transition

G. Ramalho[1] and K. Tsushima[2]

[1]*CFTP, Instituto Superior Técnico, Universidade Técnica de Lisboa, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal*
[2]*CSSM, School of Chemistry and Physics, University of Adelaide, Adelaide SA 5005, Australia*
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We study the $\gamma^*\Lambda \to \Sigma^0$ transition form factors by applying the covariant spectator quark model. Using the parametrization for the baryon core wave functions as well as for the pion cloud dressing obtained in a previous work, we calculate the dependence on the momentum transfer squared, Q^2, of the electromagnetic transition form factors. The magnetic form factor is dominated by the valence quark contributions. The final result for the transition magnetic moment, a combination of the quark core and pion cloud effects, turns out to give a value very close to the data. The pion cloud contribution, although small, pulls the final result towards the experimental value. The final result, $\mu_{\Lambda\Sigma^0} = -1.486\mu_N$, is about one and a half standard deviations from the central value in PDG, $\mu_{\Lambda\Sigma^0} = -1.61 \pm 0.08\mu_N$. Thus, a modest improvement in the statistics of the experiment would permit the confirmation or rejection of the present result. Small but nonzero values for the electric form factor in the finite Q^2 region are also predicted, as a consequence of the pion cloud dressing.

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I. INTRODUCTION

There is presently strong motivation to understand the structure of light baryons in terms of the quark and gluon dynamics, or quantum chromodynamics (QCD). Experimentally, however, we have no direct access to the quarks and gluons. The experimental studies of the baryon electromagnetic and weak internal structure is based on measurements of their form factors. The measured form factors encode the deviation of a baryon structure from a pointlike particle, with the same quantum numbers. Theoretical studies are often performed using effective degrees of freedom revealed in the low Q^2 region, such as a baryon core with meson cloud excitations, where the core is described by constituent quarks as a first approximation.

Of particular basic interest is the study of the internal electromagnetic structure of the low-lying spin $1/2$ baryons, the octet baryons. However, except for the proton and neutron, the electromagnetic structure of the octet baryons has not yet been uncovered experimentally. Only magnetic moments of some members of the octet baryons were measured. See Ref. [1] for a detailed bibliography.

Among the octet baryons the reaction $\gamma^*\Lambda \to \Sigma^0$ is the only one that is allowed in the electromagnetic transition between the two different members in the octet under the limit of isospin symmetry. The available experimental information is restricted to the magnitude of the magnetic moment (at $Q^2 = 0$): $|\mu_{\Lambda\Sigma^0}| = 1.61 \pm 0.08\mu_N$, where μ_N is the nuclear magneton [2]. Although the sign of $\mu_{\Lambda\Sigma^0}$ is not known experimentally, $SU(6)$ symmetry suggests that $\mu_{\Lambda\Sigma^0} = \frac{\sqrt{3}}{2}\mu_n \simeq -1.66\mu_N$ [3] (μ_n is the neutron magnetic moment), supporting the negative sign. Estimates based on quark models depend on the model conventions and cannot predict the sign unambiguously. The implications of the sign will be discussed later.

In this work we study the $\gamma^*\Lambda \to \Sigma^0$ reaction using the covariant spectator quark model which was successfully applied to investigate the electromagnetic structure of the octet baryons [1,4]. Using the parametrization determined in Ref. [4] for the octet baryon electromagnetic form factors, we predict in this work the electromagnetic transition form factors for the $\gamma^*\Lambda \to \Sigma^0$ reaction. We calculate the contributions from the quark core as well as the pion cloud dressing. This reaction was studied in the past using chiral perturbation theory [5–9], Skyrme models [10,11], chiral quark models [12–17], other quark models [18–25], QCD sum rules [26–28], lattice QCD [29], and some other methods [30–32].

The $\gamma^*\Lambda \to \Sigma^0$ reaction is very interesting to study, since the initial and final states are different and have different masses, contrary to the case of the elastic reactions of octet baryons. As a consequence, the Dirac-type form factor $F_1(Q^2)$ and the electric form factor $G_E(Q^2)$ vanish at $Q^2 = 0$, and only the magnetic form factor $G_M(0)$ survives. In addition, because of $G_E(0) = 0$, we can expect that the absolute value of $G_E(Q^2)$ is small as a function of Q^2, as it happens for the neutron. This creates extra interest in studying the Q^2 dependence of the electric and magnetic form factors. Another important reason to study the $\gamma^*\Lambda \to \Sigma^0$ transition is to identify which degree of freedom gives dominant contributions for the form factors: the valence quark (quark core) or the quark-antiquark contribution, namely, the meson cloud, where the pion excitations are expected to be dominant. The covariant spectator quark model, supplemented with the pion cloud dressing, is therefore particularly convenient to study the $\gamma^*\Lambda \to \Sigma^0$ reaction.

In the covariant spectator quark model, derived from the covariant spectator theory [33], a baryon is described as a three-constituent quark system where one quark is free to interact with the photon field, and a pair of noninteracting quarks is treated as a single on-mass-shell spectator diquark with an effective mass m_D [34–36]. The quark current is parametrized based on a vector meson dominance mechanism as explained in Refs. [1,4,34,36]. The model was later improved by the inclusion of the pion cloud effects [1,4,37]. The formalism of the model will be presented in the next section. The model was also successfully applied to study the excitation of resonances such as Δ, the Roper, $N^*(1535)$, and others [38–42].

This article is organized as follows: In Sec. II we present the definitions of the form factors and explicit expressions of the valence and pion cloud contributions. In Sec. III we present numerical results. Finally, in Sec. IV we give a summary and conclusions.

II. TRANSITION FORM FACTORS

The $\gamma^*\Lambda \to \Sigma^0$ electromagnetic current between the Λ (mass M_Λ and momentum P_+) and the Σ^0 (mass M_Σ and momentum P_-) can be represented by

$$J^\mu_{\Lambda\Sigma} = \bar{u}_\Sigma(P_+)\Big\{F_{1\Lambda\Sigma}(Q^2)\Big(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\Big) + F_{2\Lambda\Sigma}(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{M_\Lambda + M_\Sigma}\Big\}u_\Lambda(P_-), \quad (1)$$

where $F_{1\Lambda\Sigma}$ and $F_{2\Lambda\Sigma}$ are, respectively, the Dirac-type and Pauli-type form factors. The subindex $\Lambda\Sigma$ labels the reaction to distinguish from the elastic one.

From Eq. (1) one can see that $F_{2\Lambda\Sigma}(0)$ gives the transition anomalous magnetic moment in units of $\frac{e}{M_\Lambda + M_\Sigma}$ (analogous to the nucleon case, $\mu_N = \frac{e}{2M_N}$, the nuclear magneton with M_N the nucleon mass). It is therefore convenient to define the average mass of the initial (Λ) and final (Σ^0) baryon masses,

$$M = \frac{1}{2}(M_\Lambda + M_\Sigma). \quad (2)$$

We can also define the Sachs form factors for the transition:

$$G_{E\Lambda\Sigma}(Q^2) = F_{1\Lambda\Sigma}(Q^2) - \tau F_{2\Lambda\Sigma}(Q^2), \quad (3)$$

$$G_{M\Lambda\Sigma}(Q^2) = F_{1\Lambda\Sigma}(Q^2) + F_{2\Lambda\Sigma}(Q^2), \quad (4)$$

with $\tau = \frac{Q^2}{4M^2}$. To express $G_{M\Lambda\Sigma}(Q^2)$ in the nuclear magneton, we need to convert by $\frac{M_N}{M}G_{M\Lambda\Sigma}(Q^2)$.

In the covariant spectator quark model the transition current can be decomposed as [1,4,37]

$$J^\mu_{\Lambda\Sigma} = Z_{\Lambda\Sigma}[J^\mu_0 + J^\mu_\pi + J^\mu_\gamma], \quad (5)$$

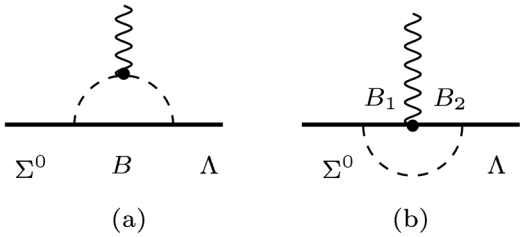

FIG. 1. Electromagnetic interaction within the one-pion loop level (pion cloud) through the intermediate baryon states B, B_1, and B_2. In diagram (a) $B = \Sigma^\pm$, while in diagram (b) $(B_1, B_2) = (\Sigma^-, \Sigma^-)$, (Σ^+, Σ^+), or (Λ, Σ^0).

where J^μ_0 is the current associated with the direct coupling of the photon field to the quark core, J^μ_π the current resulting from the photon coupling with the pion [Fig. 1(a)], and J^μ_γ the current related to the photon interaction with the intermediate baryon state (Λ or Σ) when one pion is in the air [Fig. 1(b)]. The factor $Z_{\Lambda\Sigma}$ arises from the Λ and Σ^0 wave functions when the pion cloud contributions are included, to be discussed later.

The final expressions for the form factors can be written as

$$F_{1\Lambda\Sigma}(Q^2) = Z_{\Lambda\Sigma}[F^0_{1\Lambda\Sigma}(Q^2) + \delta F_{1\Lambda\Sigma}(Q^2)], \quad (6)$$

$$F_{2\Lambda\Sigma}(Q^2) = Z_{\Lambda\Sigma}[F^0_{2\Lambda\Sigma}(Q^2) + \delta F_{2\Lambda\Sigma}(Q^2)], \quad (7)$$

where $F^0_{i\Lambda\Sigma}$ ($i = 1, 2$) are the contributions from the quark core, and $\delta F_{i\Lambda\Sigma}$ ($i = 1, 2$) the contributions resulting from the pion cloud dressing.

A. Valence quark contributions

In the valence quark sector, we have

$$F^0_{1\Lambda\Sigma}(Q^2) = \frac{\tau}{1+\tau}R_{\Lambda\Sigma}(Q^2)\mathcal{I}(Q^2), \quad (8)$$

$$F^0_{2\Lambda\Sigma}(Q^2) = \frac{1}{1+\tau}R_{\Lambda\Sigma}(Q^2)\mathcal{I}(Q^2), \quad (9)$$

where

$$R_{\Lambda\Sigma}(Q^2) = -\frac{1}{\sqrt{3}}\Big\{f_{1-}(Q^2) + \frac{M}{M_N}f_{2-}(Q^2)\Big\}, \quad (10)$$

$$\mathcal{I}(Q^2) = \int_k \psi_\Sigma(P_+, k)\psi_\Lambda(P_-, k). \quad (11)$$

In Eq. (10) the functions f_{i-} ($i = 1, 2$) are the isovector quark form factors defined in Appendix A. (See Refs. [1,4] for details.) By definition, $f_{1-}(0) = 1$ and $f_{2-}(0) = \kappa_-$, where $\kappa_- = 1.803$ as defined by the model for the octet baryons in Ref. [4]. The dependence on the factor $R_{\Lambda\Sigma}$ in Eqs. (8) and (9) reflects the isovector character of the reaction.

In Eq. (11) ψ_Λ and ψ_Σ represent, respectively, the Λ and Σ^0 radial wave functions written in a covariant form using two momentum range parameters, which characterize the spacial short- and long-range behavior of the wave functions. The explicit expressions are given in Appendix A. The symbol $\int_k$ stands for the covariant integration in the diquark momentum k: $\int_k = \int \frac{d^3\mathbf{k}}{(2\pi)^3 2E_D}$, where $E_D = \sqrt{m_D^2 + \mathbf{k}^2}$ is the diquark energy with the mass m_D.

From Eq. (8) we can conclude that $F^0_{1\Lambda\Sigma}(0) = 0$, as required by the definition of the form factors (1), when the pion cloud is absent.

So far, the signs of the form factors are not determined, since the overlap integral (11) depends on the normalization constants of the Σ^0 and Λ radial wave functions, ψ_Σ and ψ_Λ, respectively. However, we have a way to deduce the signs as to whether the normalization constants have the same or a different relative sign, as will be discussed later. This relative sign is also important for the other reactions such as $\gamma^* Y \to \Lambda(1670)$ with $Y = \Lambda, \Sigma^0$ [42]. In the following, we start by assuming the same sign for both wave function normalization constants. The choice determines the sign of $F^0_{2\Lambda\Sigma}(0)$, since $F^0_{1\Lambda\Sigma}(0) = 0$. Ultimately, the relative sign of the wave functions can be determined by experiments for the sign of the transition magnetic moment.

Using Eqs. (8) and (9), we can also calculate the valence quark contributions for the electric and magnetic form factors:

$$G^0_{E\Lambda\Sigma}(Q^2) = 0, \tag{12}$$

$$G^0_{M\Lambda\Sigma}(Q^2) = R_{\Lambda\Sigma}(Q^2)\mathcal{I}(Q^2). \tag{13}$$

We can now estimate the valence quark contribution for the transition magnetic moment. The result in the equal mass limit is $G^0_{M\Lambda\Sigma}(0) = -1.82$, where Σ^0 and Λ have exactly the same radial wave functions in their rest frame at $Q^2 = 0$ [in this case $\mathcal{I}(0) = 1$]. This leads to $\mu_{\Lambda\Sigma^0} = -1.53\mu_N$.

Note, however, that we have not yet taken into consideration the effect of the pion cloud dressing. From one side, this will require a redefinition of the valence quark contribution by the renormalization factor $Z_{\Lambda\Sigma}$ according to Eqs. (6) and (7), and on another side, we have additional contributions for both form factors from the pion cloud dressing.

B. Pion cloud contributions

Now we consider the decomposition (5), and focus particularly on the contributions J^μ_π and J^μ_γ. Following Refs. [1,4,37] we write

$$J^\mu_\pi = \left(\tilde{B}_1\gamma^\mu + \tilde{B}_2\frac{i\sigma^{\mu\nu}q_\nu}{2M}\right)G_{\pi\Lambda\Sigma}, \tag{14}$$

$$J^\mu_\gamma = \left(\tilde{C}_1\gamma^\mu + \tilde{C}_2\frac{i\sigma^{\mu\nu}q_\nu}{2M}\right)G_{e\Lambda\Sigma} + \left(\tilde{D}_1\gamma^\mu + \tilde{D}_2\frac{i\sigma^{\mu\nu}q_\nu}{2M}\right)G_{\kappa\Lambda\Sigma}, \tag{15}$$

where $G_{\pi\Lambda\Sigma}$ is the coefficient that includes the coupling of the photon with the pion, and $G_{z\Lambda\Sigma}$ ($z = e, \kappa$) are the coefficients from the couplings between the photon and the intermediate baryon states, including the charge coupling $z = e$ and the magnetic coupling $z = \kappa$, where e and κ stand, respectively, for the charge and anomalous magnetic moment. We follow the notations in Refs. [1,4,37] except that we now need a double baryon index ($\Lambda\Sigma$) instead of just B, since the initial and final states are different. The dependence on the global coupling constant, πNN, is included in the coefficients $\tilde{B}_i$, $\tilde{C}_i$, and $\tilde{D}_i$ ($i = 1, 2$), which represent integrals of the corresponding Feynman diagrams, each as a function of Q^2. Here the tilde is a short notation to remind us that they are functions of Q^2. Therefore, the coefficients $G_{\pi\Lambda\Sigma}$ and $G_{z\Lambda\Sigma}$ depend only on the ratio of the coupling constants $g_{\pi BB'}/g_{\pi NN}$, with $g^2_{\pi NN}$ being absorbed in the respective integral coefficients. As before [1,4,37], we assume that the integrals $\tilde{B}_i$, $\tilde{C}_i$, and $\tilde{D}_i$ ($i = 1, 2$) are only weakly dependent on the mass of the octet baryon members B, and therefore the values of the coefficients hold for all the octet members. The expressions for $\tilde{B}_i$, $\tilde{C}_i$, and $\tilde{D}_i$ ($i = 1, 2$) are given in Appendix B.

The explicit calculation of $G_{\pi\Lambda\Sigma}$ and $G_{z\Lambda\Sigma}$ gives

$$G_{\pi\Lambda\Sigma} \equiv 0, \tag{16}$$

$$G_{z\Lambda\Sigma} = -\beta_{\Lambda\Sigma}(z_{\Sigma^-} + z_{\Sigma^+}) + \beta_\Lambda z_{\Lambda\Sigma^0}, \tag{17}$$

with $\beta_{\Lambda\Sigma} = \sqrt{\beta_\Lambda}\sqrt{\beta_\Sigma}$, and

$$\beta_\Lambda = \frac{4}{3}\alpha^2, \qquad \beta_\Sigma = 4(1-\alpha)^2, \tag{18}$$

where $\alpha \equiv \frac{D}{F+D}$ is defined in terms of the $SU(3)$ symmetric (D) and antisymmetric (F) couplings [43], and we use the $SU(6)$ quark model value, $\alpha = 0.6$. In Eq. (17) z stands for, again, the charge (e) or the anomalous magnetic moment (κ) couplings corresponding to the bare, undressed case. This means that z is replaced by a function of Q^2 given by $F^0_{1B}(Q^2)$ for $z = e$, and $F^0_{2B}(Q^2)$ for $z = \kappa$, where $F^0_{iB}(Q^2)$ ($i = 1, 2$) are the bare elastic form factors[1] for the baryon B. In the case of $z_{\Lambda\Sigma^0}$ it represents the $\gamma^*\Lambda \to \Sigma^0$ bare form factors given by Eqs. (8) and (9). The bare elastic form factors for Σ^+ and Σ^- were already obtained in the previous works [1,4].

The result $G_{\pi\Lambda\Sigma} = 0$ is a consequence of the cancellation of the diagrams with Σ^+ and Σ^- intermediate states.

[1]In Ref. [1] we used $\tilde{e}_B$ and $\tilde{\kappa}_B$ to represent, respectively, $F^0_{1B}(Q^2)$ and $F^0_{2B}(Q^2)$.

Let us now discuss the normalization factor $Z_{\Lambda\Sigma}$, which is a consequence of the Σ^0 and Λ wave function modification due to the pion cloud effect. In the elastic reactions it is easy to see that Z_B is related to the charge correction due to the pion cloud [37]. A simple example is the nucleon case. The correction from the pion cloud to the proton charge is $3B_1$ with $B_1 = \tilde{B}_1(0)$. In this case we can write $G_E(0) = Z_N(1 + 3B_1)$, where "1" corresponds to the proton bare charge. The correct, dressed charge $G_E(0) = 1$ is ensured by setting $Z_N = 1/(1 + 3B_1)$.

In general, we can relate the normalization factor Z_B with the derivative of the baryon self-energy [37]. This feature also appears in the cloudy bag model [44]. The results for the octet baryons Z_B were obtained in Refs. [1,4,37]. In particular, for Λ and Σ, we have

$$Z_\Lambda = [1 + 3\beta_\Lambda B_1]^{-1}, \tag{19}$$

$$Z_\Sigma = [1 + (2\beta_\Sigma + \beta_\Lambda)B_1]^{-1}. \tag{20}$$

For the $\gamma^*\Lambda \to \Sigma^0$ transition we cannot relate $Z_{\Lambda\Sigma}$ with the form factor $F_{1\Lambda\Sigma}(Q^2)$ at $Q^2 = 0$. In this case, we include a factor $\sqrt{Z_B}$ for the initial and final state baryons, which leads to the factor $Z_{\Lambda\Sigma} = \sqrt{Z_\Lambda Z_\Sigma}$.

C. Total result

With the results for the currents J^μ_π and J^μ_γ together with the definition of $J^\mu_{\Lambda\Sigma}$, we get

$$F_{1\Lambda\Sigma} = Z_{\Lambda\Sigma}\{F^0_{1\Lambda\Sigma} + [\beta_\Lambda F^0_{1\Lambda\Sigma} - \beta_{\Lambda\Sigma}(F^0_{1\Sigma^-} + F^0_{1\Sigma^+})]\tilde{C}_1 + [\beta_\Lambda F^0_{2\Lambda\Sigma} - \beta_{\Lambda\Sigma}(F^0_{2\Sigma^-} + F^0_{2\Sigma^+})]\tilde{D}_1\}, \tag{21}$$

$$F_{2\Lambda\Sigma} = Z_{\Lambda\Sigma}\{F^0_{2\Lambda\Sigma} + [\beta_\Lambda F^0_{1\Lambda\Sigma} - \beta_{\Lambda\Sigma}(F^0_{1\Sigma^-} + F^0_{1\Sigma^+})]\tilde{C}_2 + [\beta_\Lambda F^0_{2\Lambda\Sigma} - \beta_{\Lambda\Sigma}(F^0_{2\Sigma^-} + F^0_{2\Sigma^+})]\tilde{D}_2\}. \tag{22}$$

The expressions above show that we also need to know the Σ^- and Σ^+ form factors to calculate the Λ to Σ^0 transition form factors. As mentioned already, the Σ^- and Σ^+ form factors were evaluated in Ref. [4] in the same framework. For completeness, we give their expressions in Appendix A.

Note that, in Eq. (21), $\Lambda - \Sigma^0$ contributions from the quark core vanish for $Q^2 = 0$ [$F^0_{1\Lambda\Sigma^0}(0) = 0$], and the same is true for the terms with Σ^+ and Σ^- [$F^0_{1\Sigma^+}(0) + F^0_{1\Sigma^-}(0) = 0$], and for the Pauli-type form factor contributions [$\tilde{D}_1(0) = 0$]. Therefore, the pion cloud contribution for $F_{1\Lambda\Sigma}(Q^2)$ vanishes at $Q^2 = 0$, the same as for the bare contributions. As a consequence, $F_{1\Lambda\Sigma}(0) = 0$, as expected.

We now calculate the transition magnetic moment given by $G_{M\Lambda\Sigma}(0) \equiv F_{2\Lambda\Sigma}(0)$. From Eq. (22), we have

$$F_{2\Lambda\Sigma}(0) = Z_{\Lambda\Sigma}\{\kappa_{0\Lambda\Sigma} + [\beta_\Lambda \kappa_{0\Lambda\Sigma} - \beta_{\Lambda\Sigma}(\kappa_{0\Sigma^-} + \kappa_{0\Sigma^+})]D_2\}, \tag{23}$$

where κ_{0B} and $\kappa_{0\Lambda\Sigma}$ are the bare anomalous magnetic moments, and D_2 is the value of $\tilde{D}_2$ at $Q^2 = 0$. With the results $\kappa_{0\Lambda\Sigma} = -1.817$ (determined before), and $\kappa_{0\Sigma^+} = 2.137$, $\kappa_{0\Sigma^-} = -0.249$, and $D_2 = 0.0821$ (from Ref. [4]), and $Z_{\Lambda\Sigma} = 0.9246$, we obtain $G_{M\Lambda\Sigma}(0) = -1.826$, or $\mu_{\Lambda\Sigma^0} = -1.486\mu_N$. Here the pion cloud contribution is $-0.12\mu_N$. Comparing the magnitude of the experimental value of $-1.61 \pm 0.08\mu_N$, our result differs $0.12\mu_N$ from the central value. The deviation is almost within the range of error bars.

III. RESULTS

The results for the Dirac-type ($F_1 \equiv F_{1\Lambda\Sigma}$) and Pauli-type ($F_2 \equiv F_{2\Lambda\Sigma}$) form factors, and also the Sachs form factors, are, respectively, presented in Figs. 2 and 3. In both figures the solid lines give the final results from Eqs. (21) and (22) including the pion cloud effects, while the dotted lines give the contributions from the quark core (setting $\tilde{C}_1 = \tilde{D}_1 = \tilde{C}_2 = \tilde{D}_2 = 0$). The calculations are performed including the $\Lambda - \Sigma$ mass difference, although the approximation, $M_\Lambda = M_\Sigma = M$, leads to a small deviation of $\sim 0.5\%$.

In Fig. 2 one can see that the pion cloud effects (the difference between the solid and dotted lines) are small but lead the total contribution in the direction of

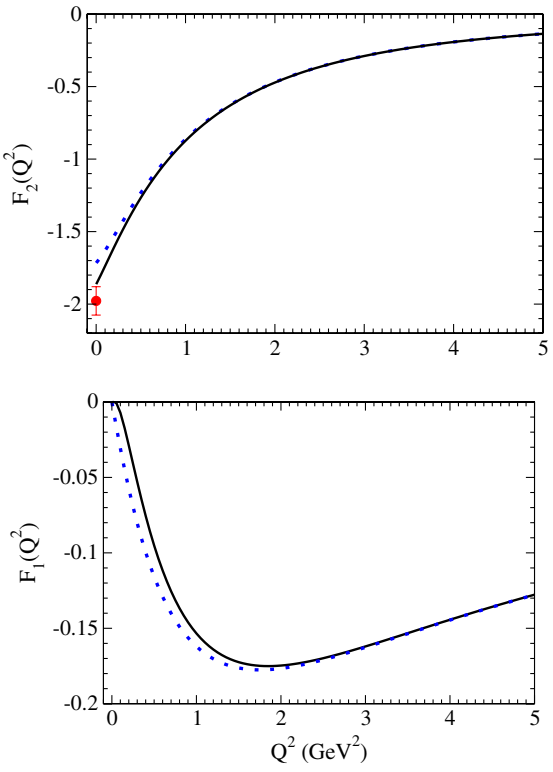

FIG. 2 (color online). Dirac- and Pauli-type form factors. The total and quark core contributions are shown by the solid and dotted lines, respectively.

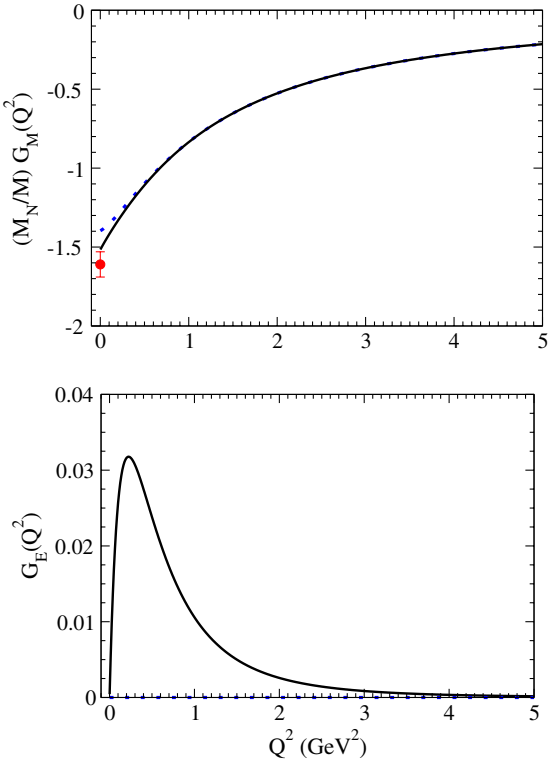

FIG. 3 (color online). Electric and magnetic form factors. The total and quark core contributions are shown by the solid and dotted lines, respectively.

the experimental value $F_2(0) \equiv F_{2\Lambda\Sigma}(0) = -1.98 \pm 0.10$, extracted from $\mu_{\Lambda\Sigma^0}$.

As for $G_E \equiv G_{E\Lambda\Sigma}$ in Fig. 3, only the total result is visible because the quark core contribution vanishes. Therefore, $G_{E\Lambda\Sigma}$ is determined exclusively by the pion cloud effects. We note, however, based on the scale presented, that the electric form factor is small and about 1/3 of the neutron electric form factor in the similar Q^2 range. As for the magnetic form factor $G_M \equiv G_{M\Lambda\Sigma}$, corrected by the factor $\frac{M_N}{M}$ to be compared with $\mu_{\Lambda\Sigma^0}$ in Fig. 3, it is dominated by the valence quark contributions.

For F_2 and G_M we can observe the fast falloff of the pion cloud effects. For F_1 and G_E the falloff is slower and has a larger finite range, although the magnitude of the form factors differs from F_2 and G_M by an order of magnitude.

The results presented here show that we can study the $\gamma^*\Lambda \to \Sigma^0$ reaction once we know the Λ and Σ^0 systems. It is very important to study the Q^2 dependence of the $\Lambda - \Sigma^0$ transition form factors, since most of the studies were restricted to the point $Q^2 = 0$. Some exceptions are Refs. [7,24]. Our result for $\mu_{\Lambda\Sigma^0} = -1.49\mu_N$ can well be compared with the other estimates, $1.4\mu_N < |\mu_{\Lambda\Sigma^0}| < 1.9\mu_N$ [5–28,30–32], and is also close to the $SU(6)$ result of $\mu_{\Lambda\Sigma^0} \simeq -1.66\mu_N$. In addition, the available result from lattice QCD in the quenched approximation is $\mu_{\Lambda\Sigma^0} = -1.15(16)\mu_N$ [29], and it underestimates the experimental result.

We note that some other works have a different sign for $\mu_{\Lambda\Sigma^0}$. The difference in sign can be a consequence of the convention of the relative sign between the Λ and Σ^0 wave functions (in particular, the Λ and Σ^0 quark flavor states). In our model the contribution from the quark core (negative) has the same sign as the pion cloud contribution and is additive.

The relative phase between the Λ and Σ^0 states, which we call $\eta_{\Lambda\Sigma^0}$, is very important also for other reactions. So far in the discussion, we have assumed that $\eta_{\Lambda\Sigma^0} = +1$. In Ref. [42] it is suggested that the study of the reactions $\gamma^* Y \to \Lambda(1670)$ ($Y = \Lambda, \Sigma^0$) can also be used to *deduce* the phase $\eta_{\Lambda\Sigma^0}$. In this case the results for the form factors are dependent on the two phases: $\eta_{\Lambda\Sigma^0}$ and $\eta_{\Lambda\Lambda(1670)}$; the latter is the relative sign between the Λ and $\Lambda(1670)$ wave functions. Once the phase $\eta_{\Lambda\Lambda(1670)}$ is determined by one of the reactions, for instance, the case $Y = \Lambda$, $\eta_{\Lambda\Sigma^0}$ can be fixed by the other reaction. In the case $\eta_{\Lambda\Sigma^0} = -\eta_{\Lambda\Lambda(1670)}$, the suppression of the Pauli-type form factor is expected in the reaction with $Y = \Sigma^0$ [42].

Alternatively, an independent determination of $\eta_{\Lambda\Sigma^0}$, as in the reaction $\gamma^*\Lambda \to \Sigma^0$, can be used in the study of the $\gamma^* Y \to \Lambda(1670)$ ($Y = \Lambda, \Sigma^0$) reactions.

We can also use the present model to calculate the decay width of $\Sigma^0 \to \gamma\Lambda$, using our result for $G_{M\Lambda\Sigma}(0)$. We obtain $\Gamma = 7.9$ keV, which is close to the experimental value of 8.9 ± 0.9 keV [2].

IV. SUMMARY AND CONCLUSIONS

In this work we have studied the $\gamma^*\Lambda \to \Sigma^0$ transition form factors using the covariant spectator quark model including the pion cloud effects. The parameters of the model, including the pion cloud contribution, are all determined in the previous studies of the electromagnetic form factors of the octet baryons.

We conclude that the Dirac- and Pauli-type form factors are dominated by the valence quark contributions. However, the relative contributions from the quark core and the pion cloud change when we consider the Sachs form factors. The magnetic dipole form factor is largely dominated by the valence quark contributions as F_2. As for the electric form factor, the contribution from the quark core is zero; therefore, G_E is determined exclusively by the pion cloud contributions. In all cases the pion cloud effects fall off faster than those of the valence quarks with increasing Q^2. We predict that the magnitude of G_E is at most $\sim 2\%$ of that of G_M in the low Q^2 region. Note that G_E/G_M gives a rough estimate for the ratio between the pion cloud and valence quark contributions in our model. It will be interesting to explore if the proportion can somehow be accessed by experiment in the near future.

About the transition magnetic moment $\mu_{\Lambda\Sigma}$, although the magnitude of the pion cloud contribution is small compared to that of the valence quark core, it pulls the final result towards the experimental value. The final result,

$\mu_{\Lambda\Sigma^0} = -1.486\mu_N$, is nearly within the experimental error bars, about 1.5 standard deviations from the central value in PDG ($\mu_{\Lambda\Sigma^0} = -1.61 \pm 0.08\mu_N$). Thus, a modest improvement in the statistics of the experiment would permit the confirmation or rejection of the present result.

Finally, we recall that the sign of $\mu_{\Lambda\Sigma^0}$ is given by the phase $\eta_{\Lambda\Sigma^0}$ between the Λ and Σ^0 wave functions [$\mu_{\Lambda\Sigma^0} \propto -\eta_{\Lambda\Sigma^0}$]. This phase can also be determined by experimental measurements of the $\gamma^* Y \to \Lambda(1670)$ ($Y = \Lambda,\ \Sigma^0$) transition form factors. Thus, the sign of $\mu_{\Lambda\Sigma^0}$ can be determined consistently with the $\gamma^*\Lambda \to \Lambda(1670)$ and $\gamma^*\Sigma^0 \to \Lambda(1670)$ reactions.

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APPENDIX A: VALENCE QUARK FORM FACTORS

1. Wave functions

Following Ref. [1] we consider a generic wave function ψ_B for the octet baryon member B in terms of the baryon momentum P and diquark momentum k,

$$\Psi_B(P,k) = \frac{1}{\sqrt{2}}[\phi_S^0|M_A\rangle_B + \phi_S^1|M_S\rangle_B]\psi_B, \tag{A1}$$

where $\phi_S^{0,1}$ are the spin wave functions, and $|M_A\rangle_B$ and $|M_S\rangle_B$ are, respectively, the mixed-antisymmetric and mixed-symmetric flavor states with respect to quarks 1 and 2. For simplicity, spin and polarization indices are suppressed.

The spin wave functions are expressed by

$$\phi_S^0 = u_B(P), \tag{A2}$$

$$\phi_S^1 = -(\varepsilon_P^*)_\alpha(\lambda)U_B^\alpha(P), \tag{A3}$$

where u_B is the Dirac spinor, $\varepsilon_P(\lambda)$ with $\lambda = 0, \pm$ is the diquark polarization state [34,45] and U_B^α is the vector spinor given by [34,38]

$$U_B^\alpha(P) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma^\alpha - \frac{P^\alpha}{M_B}\right)u_B(P). \tag{A4}$$

The flavor wave functions are listed in Table I based on $SU(3)$ symmetry, and were also given in Ref. [1].

The spin and flavor states are expressed in terms of the states of quark 3 [1,34,36,37]. The total wave function is obtained by the permutations of the quark states. However, for the present case it is not explicitly necessary because all the diquark pairs (12), (23) and (13) give equal contributions for the transition current.

2. $\gamma^*\Lambda \to \Sigma^0$ form factors

The form factors associated with the photon coupling with the quarks in the spectator quark model are calculated by the relativistic impulse approximation [1,4,34,36],

$$J_0^\mu = 3\sum_\Gamma \int_k \Psi_\Sigma(P_+,k) j_q^\mu \Psi_\Lambda(P_-,k), \tag{A5}$$

where P_+ (P_-) is the momentum of the final (initial) state, and $\Gamma = \{s, \lambda_D\}$ holds for the sum in the scalar (spin-0) and vectorial (spin-1) polarizations $\lambda_D = 0, \pm 1$ of the diquark. The factor 3 assures equal contributions from the three independent diquark states (12), (23) and (13). The quark current operator j_q^μ can be decomposed as

$$j_q^\mu = j_1\left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\right) + j_2\frac{i\sigma^{\mu\nu}q_\mu}{2M_N}, \tag{A6}$$

where M_N is the nucleon mass. The quark form factors j_i ($i = 1, 2$) act on the third quark state. The inclusion of the term $-\not{q} q^\mu/q^2$ in the quark current (A6) is equivalent to using the Landau prescription [46,47] for the final electromagnetic current. The term restores current conservation but does not affect the results of the observables [46].

The operators j_i ($i = 1, 2$) can be decomposed into the sum of operators in flavor $SU(3)$ space [1,36],

$$j_i = \frac{1}{6}f_{i+}\lambda_0 + \frac{1}{2}f_{i-}\lambda_3 + \frac{1}{6}f_{i0}\lambda_s, \qquad (i = 1, 2), \tag{A7}$$

where $\lambda_0 = \mathrm{diag}(1, 1, 0)$, $\lambda_3 = \mathrm{diag}(1, -1, 0)$, and $\lambda_s = \mathrm{diag}(0, 0, -2)$. The operators act on the quark wave function $q = (uds)^T$ of the third quark.

The functions $f_{i\pm}(Q^2)$ ($i = 1, 2$) define the quark electromagnetic form factors. They are normalized as $f_{1n}(0) = 1$ ($n = 0, \pm$), $f_{2\pm}(0) = \kappa_\pm$, and $f_{20}(0) = \kappa_s$. The isoscalar (κ_+) and isovector (κ_-) anomalous magnetic moments are related to the u and d quark anomalous magnetic moments

TABLE I. Flavor wave functions for Λ and Σ^0.

B	$\lvert M_S\rangle_B$	$\lvert M_A\rangle_B$
Λ	$\frac{1}{2}[(dsu - usd) + s(du - ud)]$	$\frac{1}{\sqrt{12}}[s(du - ud) - (dsu - usd) - 2(du - ud)s]$
Σ^0	$\frac{1}{\sqrt{12}}[s(du + ud) + (dsu + usd) - 2(ud + du)s]$	$\frac{1}{2}[(dsu + usd) - s(ud + du)]$

TABLE II. Mixed-symmetric and mixed-antisymmetric coefficients for Σ^+ and Σ^- [1].

B	j_i^S	j_i^A
Σ^+	$\frac{1}{18}(f_{i+} + 3f_{i-} - 4f_{i0})$	$\frac{1}{6}(f_{i+} + 3f_{i-})$
Σ^-	$\frac{1}{18}(f_{i+} - 3f_{i-} - 4f_{i0})$	$\frac{1}{6}(f_{i+} - 3f_{i-})$

by $\kappa_+ = 2\kappa_u - \kappa_d$ and $\kappa_- = \frac{1}{3}(2\kappa_u + \kappa_d)$ [34]. As for κ_s, it is the strange quark anomalous magnetic moment [36].

The effect of the flavor space overlap results in the projection of the final and initial states in the operator j_i ($i = 1, 2$). We then define

$$j_i^A = {}_\Sigma\langle M_A|j_i|M_A\rangle_\Lambda, \qquad j_i^S = {}_\Sigma\langle M_S|j_i|M_S\rangle_\Lambda. \tag{A8}$$

Using the current (A5) with the wave functions defined by Eq. (A1), one obtains after some algebra the form factors defined by Eq. (1) for the valence quark part:

$$F^0_{1\Lambda\Sigma} = \left[\frac{3}{2}j_1^A + \frac{1}{2}\frac{3-\tau}{1+\tau}j_1^S - 2\frac{\tau}{1+\tau}\frac{M_\Lambda + M_\Sigma}{2M_N}j_2^S\right]\mathcal{I}, \tag{A9}$$

$$F^0_{2\Lambda\Sigma} = \left[\left(\frac{3}{2}j_2^A - \frac{1}{2}j_2^S\right)\frac{M_\Lambda + M_\Sigma}{2M_N} - 2\frac{1}{1+\tau}j_1^S\right]\mathcal{I}, \tag{A10}$$

where $\mathcal{I}$ is the overlap integral defined by Eq. (11).

We note that Eqs. (A9) and (A10) are equivalent to the expressions obtained for the octet baryon electromagnetic form factors in Refs. [1,4] if we replace M_B by the average masses of the Λ and Σ^0, $M = \frac{1}{2}(M_\Lambda + M_\Sigma)$. This is interesting since the definitions of the elastic form factors for the octet baryons and those for the inelastic reaction $\gamma^*\Lambda \to \Sigma^0$ as in Eq. (1) are in fact different [see *correction* term in the Dirac form factor].

To get the final results we need only to use the explicit expressions for j_i^A and j_i^S for $i = 1, 2$ given by Eq. (A8). They can be expressed as

$$j_i^S = -j_i^A = \frac{1}{\sqrt{12}}f_{i-} \qquad (i = 1, 2). \tag{A11}$$

Using these relations, we convert Eqs. (A9) and (A10) into Eqs. (8) and (9).

3. Elastic form factors

For the baryons Σ^- and Σ^+ we use the expressions derived previously [1,4],

$$F^0_{1B} = \left[\frac{3}{2}j_1^A + \frac{1}{2}\frac{3-\tau}{1+\tau}j_1^S - 2\frac{\tau}{1+\tau}\frac{M_B}{M_N}j_2^S\right]\mathcal{I}_B, \tag{A12}$$

$$F^0_{2B} = \left[\left(\frac{3}{2}j_2^A - \frac{1}{2}j_2^S\right)\frac{M_B}{M_N} - 2\frac{1}{1+\tau}j_1^S\right]\mathcal{I}_B, \tag{A13}$$

where

$$\mathcal{I}_B = \int_k \psi_B(P_+, k)\psi_B(P_-, k). \tag{A14}$$

The coefficients $j_i^{A,S}$ ($i = 1, 2$) are presented in Table II.

4. Parametrizations for quark form factors

To parametrize the quark current, we adopt the structure inspired by the vector meson dominance mechanism as in Refs. [34,36],

$$\begin{aligned}
f_{1\pm} &= \lambda_q + (1-\lambda_q)\frac{m_\rho^2}{m_\rho^2 + Q^2} + c_\pm\frac{M_h^2Q^2}{(M_h^2+Q^2)^2},\\
f_{10} &= \lambda_q + (1-\lambda_q)\frac{m_\phi^2}{m_\phi^2 + Q^2} + c_0\frac{M_h^2Q^2}{(M_h^2+Q^2)^2},\\
f_{2\pm} &= \kappa_\pm\left\{d_\pm\frac{m_\rho^2}{m_\rho^2+Q^2} + (1-d_\pm)\frac{M_h^2}{M_h^2+Q^2}\right\},\\
f_{20} &= \kappa_s\left\{d_0\frac{m_\phi^2}{m_\phi^2+Q^2} + (1-d_0)\frac{M_h^2}{M_h^2+Q^2}\right\},
\end{aligned} \tag{A15}$$

where m_ρ, m_ϕ, and M_h are the masses, respectively, corresponding to the light vector meson (ρ meson), the ϕ meson (associated with an $s\bar{s}$ state), and an effective heavy meson with mass $M_h = 2M_N$ to represent the short-range phenomenology. The coefficients c_0, $c_\pm$ and d_0, $d_\pm$ were determined in the previous studies for the nucleon (model II) [34] and Ω^- [36]. The values are, respectively, $c_+ = 4.160$, $c_- = 1.160$, $d_+ = d_- = -0.686$, $c_0 = 4.427$, and $d_0 = -1.860$ [36]. The constant $\lambda_q = 1.21$ is obtained so as to reproduce correctly the quark number density in deep inelastic scattering [34].

5. Parametrizations for radial wave functions

The radial wave functions for the Λ and Σ^0 (denoted by B below) are defined in terms of the dimensionless variable [1,34,36]

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{m_D M_B}, \tag{A16}$$

where P is the baryon momentum and k the diquark momentum. The radial wave functions are then given by

$$\psi_B(P, k) = \frac{N_B}{m_D(\beta_1 + \chi_B)(\beta_3 + \chi_B)}, \tag{A17}$$

where β_i ($i = 1, 3$) are two parameters that define the momentum scale (in units of m_D) of the radial wave function in momentum space. The normalization constant N_B is determined by the condition $\int_k |\psi_B(\bar{P}, k)|^2 = 1$, where $\bar{P} = (M_B, 0, 0, 0)$ is the baryon rest frame momentum. As in Ref. [4] we use $\beta_1 = 0.0532$ and $\beta_3 = 0.6035$. In simple terms, β_1 characterizes the long-range region in position space in the radial wave functions, while β_3 shows the short-range region.

APPENDIX B: PION CLOUD DRESSING

1. Lagrangian

The relevant part of the Yukawa-type Lagrangian density for the octet baryons and pseudoscalar octet mesons without the Dirac structure is given by [48]

$$\mathcal{L}_{PB} = g_{\pi NN}\bar{N}\vec{\tau}N\cdot\vec{\pi} + g_{\pi\Lambda\Sigma}[\bar{\Lambda}\vec{\Sigma}\cdot\vec{\pi} + \text{H.c.}] + g_{\pi\Sigma\Sigma}[-i(\vec{\bar{\Sigma}}\times\vec{\Sigma})\cdot\vec{\pi}], \tag{B1}$$

$$\begin{aligned} &= g_{\pi NN}[\sqrt{2}\bar{p}n\pi^+ + \sqrt{2}\bar{n}p\pi^- + (\bar{p}p - \bar{n}n)\pi^0 \\ &+ \sqrt{\beta_\Lambda}(\bar{\Lambda}\Sigma^-\pi^+ + \bar{\Lambda}\Sigma^+\pi^- + \bar{\Lambda}\Sigma^0\pi^0 + \text{H.c.}) \\ &+ \sqrt{\beta_\Sigma}(\bar{\Sigma}^0\Sigma^-\pi^+ - \bar{\Sigma}^+\Sigma^0\pi^+ + \bar{\Sigma}^-\Sigma^0\pi^- \\ &- \bar{\Sigma}^0\Sigma^+\pi^- + \bar{\Sigma}^+\Sigma^+\pi^0 - \bar{\Sigma}^-\Sigma^-\pi^0)], \end{aligned} \tag{B2}$$

where $\beta_\Lambda = 4\alpha^2/3$ and $\beta_\Sigma = 4(1-\alpha)^2$ with $\alpha = \frac{D}{F+D}$. D and F correspond, respectively, to the $SU(3)$ symmetric and antisymmetric couplings.

2. Pion cloud parametrization functions

We consider the following parametrizations for the functions $\tilde{B}_i$, $\tilde{C}_i$, and $\tilde{D}_i$ in Eqs. (14) and (15),

$$\tilde{B}_1 = B_1(1+t_1Q^2)\left(\frac{\Lambda_1^2}{\Lambda_1^2+Q^2}\right)^5, \tag{B3}$$

$$\tilde{C}_1 = B_1\left(\frac{\Lambda_1^2}{\Lambda_1^2+Q^2}\right)^2, \tag{B4}$$

$$\tilde{D}_1 = D_1'\frac{Q^2\Lambda_1^4}{(\Lambda_1^2+Q^2)^3}, \tag{B5}$$

$$\tilde{B}_2 = B_2(1+t_2Q^2)\left(\frac{\Lambda_2^2}{\Lambda_2^2+Q^2}\right)^6, \tag{B6}$$

$$\tilde{C}_2 = C_2\left(\frac{\Lambda_2^2}{\Lambda_2^2+Q^2}\right)^3, \tag{B7}$$

TABLE III. Parameters associated with the pion cloud [4].

B_1, B_2	C_2	D_1', D_2	b_1', b_2'	Λ_1, Λ_2 (GeV)
0.0510		−0.1484	1.036	0.786
0.2159	0.00286	0.08214	−1.987	1.132

$$\tilde{D}_2 = D_2\left(\frac{\Lambda_2^2}{\Lambda_2^2+Q^2}\right)^3, \tag{B8}$$

where B_1, B_2, C_2, D_2 are constants given, respectively, by $\tilde{B}_1(0)$, $\tilde{B}_2(0)$, $\tilde{C}_2(0)$, $\tilde{D}_2(0)$, and Λ_1, Λ_2 are two cutoffs; D_1' is also a constant defined by $D_1' = \frac{1}{\Lambda_1^2}\frac{dD_1}{dQ^2}(0)$. The coefficients t_1 and t_2 are defined next. The parametrization for Eqs. (B3)–(B8) is chosen to reproduce the charge of the dressed nucleon [which requires $\tilde{C}_1(0) = \tilde{B}_1(0)$ and $\tilde{D}_1(0) = 0$] [1,4,37] and also to simulate the chiral behavior of the nucleon radii in the limit of the very small pion mass m_π [4]. The coefficients t_1 and t_2 are obtained as [4]

$$t_1 = \frac{1}{Z_N B_1}\left(\frac{1}{24}\frac{5g_A^2+1}{8\pi^2F_\pi^2}\log m_\pi + b_1'\right), \tag{B9}$$

$$t_2 = \frac{1}{Z_N B_2}\left(-\frac{1}{24}\frac{g_A^2}{8\pi F_\pi^2}\frac{M_N}{m_\pi} + b_2'\right), \tag{B10}$$

where Z_N is the nucleon renormalization factor $Z_N = 1/(1+3B_1)$, g_A the nucleon axial vector coupling constant, and F_π the pion decay constant. As for b_1' and b_2' they are two additional parameters determined by the nucleon isovector radii [4].

All the parameters were determined in Ref. [4] in the study of the octet baryon electromagnetic form factors, and the values are listed in Table III.

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