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Weak vector and axial-vector form factors in the chiral constituent quark model with configuration mixing

Neetika Sharma,[1] Harleen Dahiya,[1] P. K. Chatley,[1] and Manmohan Gupta[2]

[1]*Department of Physics, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar, 144011, India*

[2]*Department of Physics, Centre of Advanced Study in Physics, Panjab University, Chandigarh 160014, India*

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The effects of SU(3) symmetry breaking and configuration mixing have been investigated for the weak vector and axial-vector form factors in the chiral constituent quark model (χCQM) for the strangeness changing as well as strangeness conserving semileptonic octet baryon decays in the nonperturbative regime. The results are in good agreement with existing experimental data and also show improvement over other phenomenological models.

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The measurements in the deep inelastic scattering (DIS) experiments [1] indicate that the valence quarks of the proton carry only about 30% of its spin and also establishes the asymmetry of the quark distribution functions [2]. Further, these measurements relate the spin dependent Gamow-Teller matrix elements to the weak vector and axial-vector form factors ($f_{i=1,2,3}(Q^2)$ and $g_{i=1,2,3}(Q^2)$) of the semileptonic baryon decays [3]. These form factors provide vital information on the interplay between the weak interactions (low-Q^2) and strong interactions (large-Q^2) and are an important set of parameters for investigating in detail the dynamics of the hadrons particularly at low energies.

The baryons are usually assigned to a SU(3)-flavor octet to deduce the spin densities and their relation with the weak matrix elements of the semileptonic decays [3]. The data to study the form factors was earlier analyzed under the assumptions of exact SU(3) symmetry [4]. However, the experiments performed in the late eighties were more precise and the assumption of SU(3) symmetry could no longer provide a reliable explanation of the form factors indicating that SU(3) symmetry breaking effects are important. This was first observed for the $\Sigma^- \to n e^- \bar{\nu}_e$ decay with the measurement of $|(g_1 - 0.133 g_2)/f_1| = 0.327 \pm 0.007 \pm 0.019$ giving $\frac{g_1}{f_1} = -0.20 \pm 0.08$ and $\frac{g_2}{f_1} = -0.56 \pm 0.37$ [5]. These values were quite different from the results obtained assuming SU(3) symmetry. The importance of SU(3) symmetry breaking has been further strengthened from the $\frac{g_1}{f_1}$ ratio of the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ decay measured by the KTeV (Fermilab E799) experiment [6] giving $1.32^{+0.21}_{-0.17} \pm 0.05$, with the assumption of SU(3) symmetry and $1.17 \pm 0.28 \pm 0.05$, in the limit of SU(3) breaking. Recently, this decay has been studied by the NA48/1 Collaboration [7] giving $\frac{g_1}{f_1} = 1.20 \pm 0.05$ which is more in agreement with the results of the KTeV experiment in the limit of SU(3) symmetry breaking.

Theoretically, the question of SU(3) symmetry breaking has been investigated by several authors using various phenomenological models. Calculations have been carried out for the weak form factors in the Cabibbo model [8] assuming exact SU(3) symmetry, chiral quark-soliton model (CQSM) [9,10], relativistic constituent quark model (RCQM) [11], Yamanishi's model using mass splitting interactions (MSI) [12], $1/N_c$ expansion of QCD [13,14], chiral perturbation theory (ChPT) [15,16], lattice QCD [17], covariant chiral quark approach (CCQ) [18], etc. The predictions of these models are, however, not in agreement with each other in terms of the magnitude as well as the sign of these form factors. Therefore, it would be interesting to examine the spin structure and the weak form factors of the baryons at low energy, thereby giving vital clues to the nonperturbative effects of QCD.

It has been shown recently that the chiral constituent quark model (χCQM) [19] has been successful in explaining various general features of the quark flavor and spin distribution functions [20] and baryon magnetic moments [20]. Also, it has been shown that configuration mixing generated by spin-spin forces [21], known to be compatible with the χCQM (henceforth to be referred as $\chi\text{CQM}_{\text{config}}$), improves the predictions of χCQM regarding the spin polarization functions [22] and is able to give an excellent fit [23] to the baryon magnetic moments. The purpose of the present work is to carry out a detailed analysis of the weak vector and axial-vector form factors at low energies for the semileptonic decays of baryons within the framework of $\chi\text{CQM}_{\text{config}}$. In particular, we would like to calculate the individual vector and axial-vector form factors ($f_{i=1,2,3}(Q^2)$ and $g_{i=1,2,3}(Q^2)$) as well as the ratios of these form factors for both the strangeness changing ($\Delta S = 1$) as well as strangeness conserving ($\Delta S = 0$) decays. Further, it would be interesting to understand in detail the role of SU(3) symmetry breaking in the weak axial-vector form factors.

The effective Lagrangian in the χCQM formalism describes the interaction between quarks and a nonet of Goldstone bosons (GBs) where the fluctuation process is $q^{\pm} \to \text{GB} + q'^{\mp} \to (q\bar{q}') + q'^{\mp}$ [20,22]. The GB field is written as

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} + \zeta\frac{\eta'}{\sqrt{3}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} + \zeta\frac{\eta'}{\sqrt{3}} & \alpha K^0 \\ \alpha K^- & \alpha \bar{K}^0 & -\beta\frac{2\eta}{\sqrt{6}} + \zeta\frac{\eta'}{\sqrt{3}} \end{pmatrix}. \tag{1}$$

The $SU(3) \times U(1)$ symmetry breaking is introduced by considering $m_s > m_{u,d}$ as well as by considering the masses of GBs to be nondegenerate ($M_{K,\eta} > M_\pi$ and $M_{\eta'} > M_{K,\eta}$) [20]. The parameter $a(=|g_8|^2)$ denotes the probability of chiral fluctuation $u(d) \to d(u) + \pi^{+(-)}$, whereas $\alpha^2 a$, $\beta^2 a$, and $\zeta^2 a$, respectively denote the probabilities of fluctuations $u(d) \to s + K^{-(0)}$, $u(d,s) \to u(d,s) + \eta$, and $u(d,s) \to u(d,s) + \eta'$.

Further, to make the transition from χCQM to $\chi\text{CQM}_{\text{config}}$, the nucleon wave function is modified because of the configuration mixing generated by the chromodynamic spin-spin forces [21,22] and the modified spin polarization functions $\Delta q = q^+ - q^-$ of different quark flavors can be taken from Ref. [22]. It would be important to mention here that the SU(3) symmetric calculations can easily be obtained by considering $\alpha, \beta = 1$ and $\zeta = -1$.

The matrix elements for the vector and axial-vector current in the case of weak hadronic current J_h^μ for the semileptonic hadronic decay process $B_i \to B_f + l + \bar{\nu}_l$ are given as [24,25]

$$\langle B_f(p_f)|J_V^\mu|B_i(p_i)\rangle = \bar{u}_f(p_f)\left(f_1(Q^2)\gamma^\mu - i\frac{f_2(Q^2)}{M_i + M_f}\sigma^{\mu\nu}q_\nu + \frac{f_3(Q^2)}{M_i + M_f}q^\mu\right)u_i(p_i), \tag{2}$$

$$\langle B_f(p_f)|J_A^\mu|B_i(p_i)\rangle = \bar{u}_f(p_f)\left(g_1(Q^2)\gamma^\mu\gamma^5 - i\frac{g_2(Q^2)}{M_i + M_f}\sigma^{\mu\nu}q_\nu\gamma^5 + \frac{g_3(Q^2)}{M_i + M_f}q^\mu\gamma^5\right)u_i(p_i), \tag{3}$$

where M_i (M_f) and $u_i(p_i)$ ($\bar{u}_f(p_f)$) are the masses and Dirac spinors of the initial (final) baryon states, respectively. The four momenta transfer is given as $Q^2 = -q^2$, where $q \equiv p_i - p_f$. The functions $f_i(Q^2)$ and $g_i(Q^2)$ ($i = 1, 2, 3$) are the dimensionless vector and axial-vector form factors.

Since we are interested in calculating the form factors at low Q^2, in this context the generalized Sachs form factors at $Q^2 \approx 0$ can be introduced following Ref. [24] and the vector as well as axial-vector functions can be expressed in terms of these generalized form factors. Similarly, the generalized Sachs form factors at $Q^2 \approx 0$ at the quark level can be introduced following Ref. [24]. In the nonrelativistic limit, the current operators act additively on the three quarks in the baryons, therefore the Sachs form factors for the quark currents can be used to obtain the corresponding Sachs form factors for the baryons. The vector and axial-vector form factors can, respectively, be expressed as

$$f_1 = f_1(0), \qquad f_2 = \left(\frac{\Sigma M}{\Sigma m}\frac{G_A}{G_V} - 1\right)f_1(0), \qquad f_3 = \frac{\Sigma M}{\Sigma m}\left(E\frac{G_A}{G_V} - \epsilon\right)f_1(0), \tag{4}$$

$$g_1 = g_1(0), \qquad g_2 = \left(\frac{\Sigma M}{\Sigma m}\epsilon - \frac{1}{2}\left(1 + \frac{\Sigma M^2}{\Sigma m^2}\right)E\right)g_1(0),$$
$$g_3 = \left(\frac{1}{2}\left(1 - \frac{\Sigma M^2}{\Sigma m^2}\right) + \frac{\Sigma M^2}{\Sigma m^2}g_3^q\right)g_1(0), \tag{5}$$

where $\Sigma M = M_i + M_f$, $\Delta M = M_i - M_f$, $\Sigma m = m_q + m_{q'}$, $\Delta m = m_q - m_{q'}$ and g_3^q is the induced pseudoscalar form factor at the quark level. Only the linear part of symmetry breaking terms are being calculated where the higher order terms involving $E \equiv \frac{\Delta M}{\Sigma M}$ and $\epsilon \equiv \frac{\Delta m}{\Sigma m}$ can be neglected. The baryon decays considered in the present work are $n \to p$, $\Sigma^{\mp} \to \Lambda$, $\Sigma^- \to \Sigma^0$, and $\Xi^- \to \Xi^0$ corresponding to the strangeness conserving decays and $\Sigma^- \to n$, $\Xi^- \to \Sigma^0$, $\Xi^- \to \Lambda$, $\Lambda \to p$, and $\Xi^0 \to \Sigma^+$ corresponding to the strangeness changing decays.

We now discuss the input parameters used in the calculations. To begin with, we discuss the parameters involved in the calculation of quark spin polarization functions. The $\chi\text{CQM}_{\text{config}}$ involves five parameters, four of these a, $a\alpha^2$, $a\beta^2$, $a\zeta^2$ representing, respectively, the probabilities of fluctuations to pions, K, η, η', following the hierarchy $a > \alpha > \beta > \zeta$, while the fifth representing the mixing angle. The mixing angle ϕ is fixed from the consideration of neutron charge radius [21], whereas for the other parameters, we use the latest data [26]. In this context, it is found convenient to use Δu, Δ_3 asymmetries of the quark distribution functions ($\bar{u} - \bar{d}$ and $\bar{u}/\bar{d}$) as inputs with their latest values given in Table I. Before carrying out the fit to the above-mentioned parameters, we determine their ranges by qualitative arguments. To this end, the range of the symmetry breaking parameter a, α, β, and ζ are found to be $0.09 \lesssim a \lesssim 0.15$, $0.2 \lesssim \alpha \lesssim 0.5$, $0.2 \lesssim \beta \lesssim 0.7$, and $-0.65 \lesssim \zeta \lesssim -0.08$, respectively. After finding the ranges, we have carried out a fine grained analysis using the above ranges as well as considering $\alpha \approx \beta$ leading to $a = 0.12$, $\zeta = -0.15$, $\alpha = \beta = 0.45$ as the best-fit values. For the u, d, and s quarks, we have used their widely accepted values in hadron spectroscopy [20], viz., $m_u = m_d = 0.330$ GeV, and $m_s = 3m_u/2 = 0.495$ GeV. For evaluating the contribution of GBs, we have used their on mass shell value in accordance with several other similar calculations [27].

In Table I, we have given the individual values of vector and axial-vector form factors in the $\chi\text{CQM}_{\text{config}}$ using the input values discussed earlier. Even though there is no

TABLE I. Weak vector and axial-vector form factors for the semileptonic octet baryon decays in the χCQM$_{\rm config}$.

Decay	f_1	f_2	f_3	g_1	g_2	g_3
$n \to p e^- \bar{\nu}$	1.00	2.612	0.003	1.270	−0.004	−232.9
$\Sigma^- \to \Sigma^0 e^- \bar{\nu}$	1.414	1.033	0.005	0.676	−0.010	−201.3
$\Sigma^- \to \Lambda e^- \bar{\nu}$	0	2.265	0.080	0.646	−0.152	−271.4
$\Sigma^+ \to \Lambda e^- \bar{\nu}$	0	2.257	0.072	0.646	−0.136	−245.9
$\Xi^- \to \Xi^0 e^- \bar{\nu}$	−1.00	2.253	0.003	0.314	−0.007	113.8
$\Sigma^- \to n e^- \bar{\nu}$	−1.0	1.813	0.616	0.314	0.017	−9.2
$\Xi^- \to \Sigma^0 e^- \bar{\nu}$	0.707	2.029	−0.291	0.898	0.310	−29.1
$\Xi^- \to \Lambda e^- \bar{\nu}$	1.225	−0.450	−0.658	0.262	0.047	−8.9
$\Lambda \to p e^- \bar{\nu}$	−1.225	−1.037	0.415	−0.909	−0.170	20.7
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}$	1.0	2.854	−0.414	1.27	0.446	−40.7

experimental data available for these form factors, the individual values are important to compare our results with other model calculations. It can be clearly seen from the results that the contributions of second class currents f_3 and g_2 are very small for the same isospin multiplets, for example, $n \to p$, $\Sigma^- \to \Sigma^0$, and $\Xi^- \to \Xi^0$. This is because of the small mass difference between the initial and final decay particles. Also, for all other decays, the second class currents are having a comparatively smaller contribution than the other first class currents as expected.

In Table II, we have presented the values of $\frac{g_1}{f_1}$ at $Q^2 = 0$ and compared our results with other model calculations as well as the available experimental data. The ratio of g_1 and f_1 is the nonsinglet combination of the quark spin polarizations given as $\Delta_3 = \Delta u - \Delta d = \frac{G_A}{G_V} = \frac{g_1(0)}{f_1(0)}$. We have also investigated in detail the implications of SU(3) symmetry breaking and presented the results, both with and without SU(3) symmetry breaking. We are able to give a fairly good account for most of the weak form factors (where the experimental data is available), in line with the success of χCQM$_{\rm config}$ in describing the spin dependent polarization functions. Our results, in the case of $\frac{G_A}{G_V}^{\Sigma^- \to n}$, $\frac{G_A}{G_V}^{\Xi^- \to \Lambda}$, $\frac{G_A}{G_V}^{\Lambda \to p}$, and $\frac{G_A}{G_V}^{\Xi^0 \to \Sigma^+}$, show a clear improvement over the results of other calculations. It is also interesting to consider the ratio $\frac{(g_1/f_1)^{\Lambda \to p}}{(g_1/f_1)^{\Sigma^- \to n}}$, which comes out to be -2.34 in our calculation and is quite close to the experimental value -2.11 ± 0.15 [10].

In the case of weak magnetism form factor ratio $\frac{f_2}{f_1}$, experimental data is available only for two strangeness changing decays. The results have been presented in Table III. In this case also, the predictions of different models differ significantly from each other. Our prediction for the $\Xi^0 \to \Sigma^+$ decay matches well with the experiment. In the case of $\Sigma^- \to n$ decay, it seems that our prediction for the $\frac{f_2}{f_1}(= -1.81)$ is not in agreement with the experimental value (0.96 ± 0.15) listed in Ref. [5]. However, it would be important to mention here that the above-mentioned experimental value has been obtained with the assumption of $g_2 = 0$ or SU(3) symmetry. A better agreement can be found for $|(g_1 - 0.133 g_2)/f_1| = 0.327 \pm 0.007 \pm 0.019$ where our prediction for this quantity is 0.31, in fair agreement with the data, which is clearly due to the SU(3) breaking effect. Pending further experimental data, we have predicted the value of $\frac{f_2}{f_1}$ for all other baryon decays with and without SU(3) symmetry.

TABLE II. The axial-vector form factors G_A/G_V in χCQM$_{\rm config}$ with and without SU(3) symmetry breaking.

Decay	Data [26]	RCQM [11]	CQSM [10]	MSI [12]	ChPT [16]	CCQ [18]	χCQM [24]	χCQM$_{\rm config}$ with SU(3) symmetry	χCQM$_{\rm config}$ with SU(3) symmetry breaking
$\frac{G_A}{G_V}^{n \to p}$	1.2695 ± 0.0029	1.25	1.18	5.3×10^{-7}	1.27	1.27	1.26	0.95	1.27
$\frac{G_A}{G_V}^{\Sigma^- \to \Sigma^0}$	···	0.49	0.46	···	···	···	0.5	0.39	0.48
$\frac{G_A}{G_V}^{\Sigma^- \to \Lambda}$	$\frac{f_1}{g_1} = 0.01 \pm 0.1$	0.74	0.73	···	0.62	0.62	0.62	0.45[a]	0.65[a]
$\frac{G_A}{G_V}^{\Sigma^+ \to \Lambda}$	···	0.74	0.73	···	0.65	0.62	0.62	0.45[a]	0.65[a]
$\frac{G_A}{G_V}^{\Xi^- \to \Xi^0}$	···	−0.24	−0.27	···	···	···	−0.25	−0.16	−0.31
$\frac{G_A}{G_V}^{\Sigma^- \to n}$	-0.340 ± 0.017	−0.28	−0.27	0.38	0.38	0.26	−0.25	−0.16	−0.31
$\frac{G_A}{G_V}^{\Xi^- \to \Sigma^0}$	···	1.36	1.16	···	0.87	0.91	1.26	0.95	1.27
$\frac{G_A}{G_V}^{\Xi^- \to \Lambda}$	0.25 ± 0.05	0.27	0.21	0.21	0.14	0.32	0.21	0.21	0.21
$\frac{G_A}{G_V}^{\Lambda \to p}$	0.718 ± 0.015	0.83	0.68	0.18	−0.90	−0.94	0.76	0.58	0.74
$\frac{G_A}{G_V}^{\Xi^0 \to \Sigma^+}$	1.21 ± 0.05	1.36	···	0.38	1.31	1.28	1.26	0.95	1.27

[a]Since $f_1 = 0$ for $\Sigma^\pm \to \Lambda$ in the present case, predictions are given for g_1 values rather than g_1/f_1.

TABLE III. The weak magnetism form factors $\frac{f_2}{f_1}$ in χCQM$_{\rm config}$ with and without SU(3) symmetry breaking.

Decay	Data [26]	CVC [25]	Cabibbo [8]	CQSM [10]	MSI [12]	χCQM [24]	χCQM$_{\rm config}$ with SU(3) symmetry	χCQM$_{\rm config}$ with SU(3) symmetry breaking
$\frac{f_2}{f_1}\, n\to p$	$\cdots$	3.71	1.86	1.57	1.86	3.53	1.70	2.61
$\frac{f_2}{f_1}\, \Sigma^-\to\Sigma^0$	$\cdots$	0.84	0.53	0.55	$\cdots$	1.31	0.43	0.73
$\frac{f_2}{f_1}\, \Sigma^-\to\Lambda$	$\cdots$	2.34	1.49	1.24	0.81	2.73	1.59[a]	2.27[a]
$\frac{f_2}{f_1}\, \Sigma^+\to\Lambda$	$\cdots$	2.34	1.49	1.24	0.80	2.72	1.58[a]	2.26[a]
$\frac{f_2}{f_1}\, \Xi^-\to\Xi^0$	$\cdots$	−2.03	−1.43	−1.08	$\cdots$	−2.27	−1.64	−2.25
$\frac{f_2}{f_1}\, \Sigma^-\to n$	−0.97 ± 0.14	−2.03	−1.30	−0.96	−0.88	−1.82	−1.42	−1.81
$\frac{f_2}{f_1}\, \Xi^-\to\Sigma^0$	$\cdots$	3.71	2.61	2.02	1.12	3.85	1.89	2.87
$\frac{f_2}{f_1}\, \Xi^-\to\Lambda$	$\cdots$	−0.12	0.09	−0.02	0.18	−0.06	−0.38	−0.37
$\frac{f_2}{f_1}\, \Lambda\to p$	$\cdots$	1.79	1.07	0.71	1.07	1.38	0.44	0.85
$\frac{f_2}{f_1}\, \Xi^0\to\Sigma^+$	2.0 ± 1.3	3.71	2.60	$\cdots$	1.35	3.83	1.88	2.85

[a]Since $f_1 = 0$ for $\Sigma^\pm \to \Lambda$ in the present case, therefore only f_2 values rather than f_2/f_1.

To summarize, the chiral constituent quark model with configuration mixing (χCQM$_{\rm config}$) and SU(3) symmetry breaking is able to provide a fairly good description of the weak vector and axial-vector form factors for the semileptonic octet baryon decays. Our results are consistent with the latest experimental measurements as well as with the lattice QCD results and also show improvement over other phenomenological models in some cases. A refinement in the case of the measurements with the assumption of SU(3) symmetry breaking would have important implications for the basic tenets of χCQM. In conclusion, we would like to state that SU(3) symmetry breaking and configuration mixing in the χCQM are the key in understanding the hadron dynamics in the nonperturbative regime.

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[1] J. Ashman *et al.* (European Muon Collaboration), Phys. Lett. B **206**, 364 (1988); Nucl. Phys. **B328**, 1 (1989).
[2] M. Arneodo *et al.*, Phys. Rev. D **50**, R1 (1994); R. S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001).
[3] L. B. Okun, *Lepton and Quarks* (Elsevier, New York, 1984); F. E. Close and R. G. Roberts, Phys. Lett. B **316**, 165 (1993).
[4] M. Bourquin *et al.*, Z. Phys. C **12**, 307 (1982); **21**, 17 (1983); **21**, 27 (1983).
[5] S. Y. Hsueh *et al.*, Phys. Rev. D **38**, 2056 (1988).
[6] A. Alavi-Harati *et al.* (KTeV Collaboration), Phys. Rev. Lett. **87**, 132001 (2001).
[7] J. R. Batley *et al.* (NA48/1 Collaboration), Phys. Lett. B **645**, 36 (2007).
[8] N. Cabibbo, E. C. Swallow, and R. Winston, Phys. Rev. Lett. **92**, 251803 (2004).
[9] H.-Ch. Kim, M. V. Polyakov, M. Praszalowicz, and K. Goeke, Phys. Rev. D **57**, 299 (1998).
[10] T. Ledwig, A. Silva, H.-Ch. Kim, and K. Goeke, J. High Energy Phys. 07 (2008) 132.
[11] F. Schlumpf, Phys. Rev. D **51**, 2262 (1995).
[12] T. Yamanishi, Phys. Rev. D **76**, 014006 (2007).
[13] R. Flores-Mendieta, Phys. Rev. D **70**, 114036 (2004).
[14] V. Mateu and A. Pich, J. High Energy Phys. 10 (2005) 041.
[15] A. Lacour, B. Kubis, and U. G. Meissner, J. High Energy Phys. 10 (2007) 083.
[16] R. Flores-Mendieta and C. P. Hofmann, Phys. Rev. D **74**, 094001 (2006).
[17] D. Guadagnoli, V. Lubicz, M. Papinutto, and S. Simula, Nucl. Phys. **B761**, 63 (2007).
[18] A. Faessler *et al.*, Phys. Rev. D **77**, 114007 (2008).
[19] S. Weinberg, Physica A (Amsterdam) **96**, 327 (1979); A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).
[20] E. J. Eichten, I. Hinchliffe, and C. Quigg, Phys. Rev. D **45**, 2269 (1992); T. P. Cheng and Ling Fong Li, Phys. Rev. Lett. **74**, 2872 (1995); **80**, 2789 (1998); J. Linde, T. Ohlsson, and H. Snellman, Phys. Rev. D **57**, 452 (1998).
[21] A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. D **12**, 147 (1975); A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Rev. D **15**, 844 (1977); N. Isgur and G. Karl, Phys. Rev. D **21**, 3175 (1980).
[22] H. Dahiya and M. Gupta, Phys. Rev. D **64**, 014013 (2001); **67**, 074001 (2003).
[23] H. Dahiya and M. Gupta, Phys. Rev. D **66**, 051501(R) (2002); **67**, 114015 (2003).
[24] T. Ohlsson and H. Snellman, Eur. Phys. J. C **6**, 285 (1999); **12**, 271 (2000).
[25] P. Renton, *Electroweak Interactions* (Cambridge University Press, Cambridge, England, 1990).
[26] C. Amsler *et al.*, Phys. Lett. B **667**, 1 (2008).
[27] D. A. Dicus, D. Minic, U. van Klock, and R. Vega, Phys. Lett. B **284**, 384 (1992); Y. B. Dong, K. Shimizu, A. Faessler, and A. J. Buchmann, J. Phys. G **25**, 1115 (1999).