$g_{KN\Lambda}$ and $g_{KN\Sigma}$ from QCD sum rules

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$g_{KN\Lambda}$ and $g_{KN\Sigma}$ are calculated using a QCD sum rule motivated method used by Reinders, Rubinstein, and Yazaki to extract hadron couplings to Goldstone bosons. The SU(3) symmetry breaking effects are taken into account by including the contributions from the strange quark mass and assuming different values for the strange and the up-down quark condensates. We find $g_{KN\Lambda}/\sqrt{4\pi}=-1.96$ and $g_{KN\Sigma}/\sqrt{4\pi}=0.33$.

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I. INTRODUCTION

Over the years, there has been a continuous interest in the field of kaon-nuclear physics, from trying to understand simple processes like kaon nucleon scattering or photokaon production on a nucleon to the spectroscopy and structure of hypernuclei [1]. Compared to pions, the conservation of strangeness leads to very different interactions of the kaons to the nucleon and the nuclei and can therefore yield many exotic states in nuclear physics [1] by either a hadronic or an electromagnetic process.

To understand both these processes and other phenomena in kaon-nuclear physics, it is important to know the hadronic coupling strengths involving the kaons. Among them, $g_{KN\Lambda}$ and $g_{KN\Sigma}$ are the most relevant coupling constants.

For the pions, their hadronic coupling constant $g_{\pi NN}$ is determined quite accurately through either nucleon-nucleon scattering or pion-nucleon scattering experiments. However, the situation for the kaons is not as satisfactory. For example, to theoretically reproduce the experimental kaon-nucleon scattering cross section, one usually calculates the contributions from one-boson exchanges, the resonances in the s channel, such as the Λ and Σ, and the next to leading two meson exchanges [2]. These involves many phenomenologically undetermined coupling constants so that it seems a formidable task to determine the coupling constants related to the kaons separately.

As another approach, there have been many attempts [2–6] to determine these coupling constants from the kaon photoproduction. For instance Adelseck *et al.* [3,4] tried to determine these coupling constants ($g_{KN\Lambda}$ and $g_{KN\Sigma}$) phenomenologically from the data using a least-squares fit method similar to that of Thom [5] and deduced some values. But due to the simultaneous determination of many other unknown coupling constants, these results turned out to have large uncertainties; i.e., their extracted values of $g_{KN\Lambda}/\sqrt{4\pi}$ range from -1.29 to -4.17. Hence, given the uncertainties and difficulties in extracting the strength of these couplings from the experiments, it is necessary to explore theoretical predictions.

In this paper, we will use QCD sum rules [7] to extract these kaon couplings. QCD sum rules are an attempt to understand hadronic parameters in the low energy region in terms of QCD perturbation theory and nonvanishing condensate, which characterizes the nonperturbative QCD vacuum. This is possible by looking at the correlation function between either two or three QCD hadronic currents and studying its dispersion relation, the *real* part of which is calculated in QCD using the operator product expansion (OPE) and the *imaginary* part is modeled with the phenomenological parameters. This method has been applied successfully to the pseudoscalar hadron hadron trilinear couplings by Reinders, Rubinstein, and Yazaki [8], who obtained interesting formulas such as, $g^2_{\pi NN}/4\pi \simeq 2^5\pi^3 f_\pi^2/M_N^2$ and $g_{\omega\rho\pi} \simeq (2/f_\pi)(e/2\sqrt{2})$, which are numerically in good agreement with the experiment. Here, we will try to generalize the method to the kaons and hypernucleons. The generalization can be made either within the SU(3) symmetry or with the explicit SU(3) symmetry breaking effects included. The former case has already been given in Ref. [8] and amounts to calculating the F to D ratio [9] in QCD sum rules within the SU(3) symmetry. The SU(3) symmetry breaking effects in QCD sum rules are taken into account by including the effects of strange quark mass and different values for the strange quark condensate $\langle 0|\bar{s}s|0\rangle = 0.8\langle 0|\bar{u}u|0\rangle$. This prescription gives a good description for the ϕ and K^* meson masses and their couplings [10].

In the following sections, we will derive the QCD sum rule result for the kaon couplings with explicit symmetry breaking and compare the numerical estimates with the results from phenomenological fitting analyses [11–14] and that of other QCD-inspired model calculations [15,16].

II. QCD SUM RULES FOR $g_{KN\Lambda}$

We will closely follow the procedures given in Ref. [8]. Consider the three point function constructed of the two baryon currents η_B, $\eta_{B'}$ and the pseudoscalar meson current j_5 (Fig. 1):

$$A(p,p',q) = \int dx dy \langle 0|T[\eta_{B'}(x) j_5(y) \bar{\eta}_B(0)]|0\rangle \times e^{i(p'\cdot x - q\cdot y)}. \quad (1)$$

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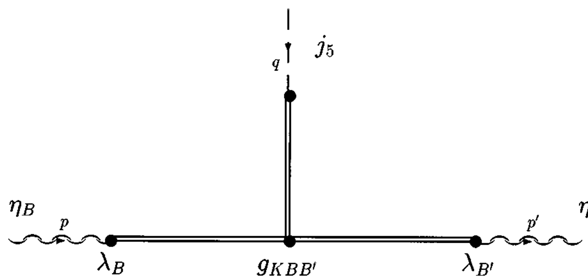

FIG. 1. The three point function. η_B, $\eta_{B'}$ are the baryon currents and j_5 is the pseudoscalar current. λ_B and $\lambda_{B'}$ are the couplings of the baryons to the currents, and $g_{KBB'}$ is the three point coupling.

In order to obtain $g_{KN\Lambda}$, we will use the following extrapolating fields for the nucleon and the Λ:

$$\eta_N = \epsilon_{abc}(u_a^T C \gamma_\mu u_b)\gamma_5 \gamma^\mu d_c, \tag{2}$$

$$\eta_\Lambda = \sqrt{\frac{2}{3}}\epsilon_{abc}[(u_a^T C\gamma_\mu s_b)\gamma_5\gamma^\mu d_c - (d_a^T C\gamma_\mu s_b)\gamma_5\gamma^\mu u_c], \tag{3}$$

where u and d are the up and down quark fields (a, b, and c are color indices), T denotes the transpose in Dirac space, and C is the charge conjugation matrix. For the K^- we choose the current

$$j_{K^-} = \bar{s} i \gamma_5 u. \tag{4}$$

Assuming a pseudovector coupling between the nucleon, the K, and the Λ, we expect the following phenomenological form for Eq. (1):

$$\lambda_N \lambda_\Lambda \frac{M_B}{(p^2 - M_N^2)(p'^2 - M_\Lambda^2)}(\not{q} i\gamma_5) g_{KN\Lambda} \frac{1}{q^2 - m_K^2}\frac{f_K m_K^2}{2m_q}; \tag{5}$$

here, $M_B = \frac{1}{2}(M_N + M_\Lambda)$, where M_N and M_Λ are the masses of the nucleon and the Λ particle, respectively, and λ_N and λ_Λ are the couplings of the baryons to their currents. m_q is the average of the quark masses, which we take to be equal to the strange quark mass m_s in our approximation. $f_K = 160$ MeV is the kaon decay constant and m_K the kaon mass. There are other contributions from excited baryon states that couple to the baryon extrapolating current. However, we will only look at the pole structure $\not{q}/q^2$ at $q \to 0$ and make a Borel transformation to both $p^2, p'^2 \to M^2$. Then, the contributions from the excited baryons will be exponentially suppressed and consequently neglected in our approximation [10].

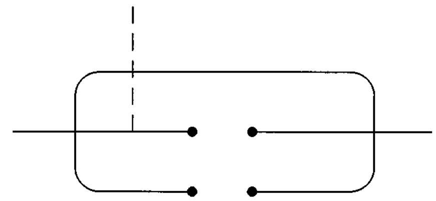

FIG. 2. Contribution from the strange quark mass and quark condensates. Solid lines are the baryon currents and dashed line is the meson current.

As for the OPE side, the perturbative part does not contribute to the $\not{q}/q^2$ structure. This is so because the dimension of Eq. (1) is 4 and $\not{q}$ takes away one dimension such that only the odd dimensional operators can contribute. The lowest dimensional operator with dimension 3 is the quark condensate term with higher dimensional operators having the form of a quark condensate with certain number of gluon operators in between. In fact, for the case of the pions, taking into account only the leading quark condensate $\langle 0|\bar{q}q|0\rangle$ in the OPE gives an excellent value for $g_{\pi NN}$ [10]. Motivated by this result, we will work out similar leading quark condensate contribution as in the pion, which in this case includes the contribution from $\langle 0|\bar{s}s|0\rangle$, and further work out the additional SU(3) breaking terms up to $\mathcal{O}(m_s^2)$ and dimension 7.

First, we will include the contribution proportional to the m_s^2 in the Wilson coefficient of the quark condensate. This will have the form

$$A(p,p',q) = C_u\langle 0|\bar{u}u|0\rangle + C_d\langle 0|\bar{d}d|0\rangle + C_s\langle 0|\bar{s}s|0\rangle + \cdots. \tag{6}$$

One can easily show that $C_d = 0$ and

$$C_u = -\sqrt{\frac{2}{3}}\frac{11p^2}{24\pi^2}\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p^2}, \tag{7}$$

$$C_s = -\sqrt{\frac{2}{3}}\left(\frac{11p'^2}{24\pi^2} + \frac{11m_s^2}{48\pi^2}\right)\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p'^2}, \tag{8}$$

where Λ is the cutoff from the loop integration. Taking the limit $p'^2 \to p^2$ and assuming $\langle 0|\bar{u}u|0\rangle = \langle 0|\bar{d}d|0\rangle = \langle 0|\bar{q}q|0\rangle$ and $\langle 0|\bar{s}s|0\rangle = 0.8\langle 0|\bar{q}q|0\rangle$ we obtain

$$C_u\langle 0|\bar{u}u|0\rangle + C_s\langle 0|\bar{s}s|0\rangle = -\sqrt{\frac{2}{3}}\left(\frac{33p^2}{40\pi^2} + \frac{11m_s^2}{60\pi^2}\right)\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p^2}\langle 0|\bar{q}q|0\rangle. \tag{9}$$

Next, we consider the lowest order terms that are proportional to the strange quark mass m_s, namely, the dimension-7 operators of the type $\sim m_s\langle 0|\bar{s}s|0\rangle\langle 0|\bar{q}q|0\rangle$. The largest contribution among them comes from the tree graph of Fig. 2, which gives the following contribution:

$$+\sqrt{\frac{2}{3}}\frac{m_s}{3}\frac{\not{q}}{q^2}(i\gamma_5)\frac{1}{p^2}\langle 0|\bar{s}s|0\rangle\langle 0|\bar{q}q|0\rangle. \tag{10}$$

After the Borel transformation the typical ratio between the contribution from Eq. (10) and that from Eq. (9) is $4\pi^2 m_s\langle 0|\bar{q}q|0\rangle/m_N^4$ for the relevant Borel mass range $M^2\sim m_N^2$. The factor of $4\pi^2$ originates from the fact that Eq. (9) comes from a loop graph whereas Eq. (10) does not. Despite these loop factors, the additional condensate effect suppresses the overall ratio to less than 5%. Other dimension-7 operators come from graphs which contain at least one loop and then the ratio to Eq. (9) becomes even smaller and can be neglected.

Using Eqs. (9) and (10) for the OPE and Eq. (5) for the phenomenological side, the sum rule after Borel transformation to $p^2=p'^2$ becomes

$$\lambda_N\lambda_\Lambda \frac{M_B}{M_\Lambda^2-M_N^2}(e^{-M_N^2/M^2}-e^{-M_\Lambda^2/M^2})g_{KN\Lambda}\frac{f_K m_K^2}{2m_q}=-\sqrt{\frac{2}{3}}\left(\frac{33}{40\pi^2}M^4+\frac{11m_s^2}{60\pi^2}M^2+\frac{m_s}{3}\langle 0|\bar{s}s|0\rangle\right)\langle 0|\bar{q}q|0\rangle. \tag{11}$$

For λ_N and λ_Λ, we use the values obtained from the following baryon sum rules for the N and the Λ [10]:

$$M^6+bM^2+\tfrac{4}{3}a^2=2(2\pi)^4\lambda_N^2 e^{-M_N^2/M^2}, \tag{12}$$

$$M^6+\tfrac{2}{3}am_s(1-3\gamma)M^2+bM^2+\tfrac{4}{9}a^2(3+4\gamma)=2(2\pi)^4\lambda_\Lambda^2 e^{-M_\Lambda^2/M^2}. \tag{13}$$

Here, $a\equiv-(2\pi)^2\langle 0|\bar{q}q|0\rangle\simeq 0.5$ GeV^3, $b\equiv\pi^2\langle 0|(\alpha_s/\pi)G^2|0\rangle\simeq 0.17$ GeV^4, and $\gamma\equiv\langle 0|\bar{s}s|0\rangle/\langle 0|\bar{q}q|0\rangle-1\simeq-0.2$. We take the strange quark mass m_s = 150 MeV.

It should be noted from Eqs. (12) and (13) that we cannot determine the sign of λ_N and λ_Λ. Consequently, we can only determine the absolute value of $g_{KN\Lambda}$ from our sum rules. The sum rule in Eq. (11) should be used for the relevant Borel mass $M\simeq M_B=\frac{1}{2}(M_N+M_\Lambda)$. Using this we obtain

$$|g_{KN\Lambda}/\sqrt{4\pi}|\simeq 1.96. \tag{14}$$

A more detailed Borel analysis of Eq. (11) gives a similar result with $\pm 30\%$ uncertainty. The uncertainty quoted here comes from neglecting the continuum contribution in the phenomenological side.

III. QCD SUM RULES FOR $g_{KN\Sigma}$

The current of Σ^0 is defined by [17,18]

$$\eta_{\Sigma^0}=\frac{1}{\sqrt{2}}\epsilon_{abc}[(u_a^T C\gamma_\mu d_b)\gamma_5\gamma^\mu s_c+(d_a^T C\gamma_\mu u_b)\gamma_5\gamma^\mu s_c],$$

$$=\sqrt{2}\epsilon_{abc}[(u_a^T C\gamma_\mu s_b)\gamma_5\gamma^\mu d_c+(d_a^T C\gamma_\mu s_b)\gamma_5\gamma^\mu u_c]. \tag{15}$$

The second form is more useful in our calculation. Then, within the same approximation as before, the OPE side looks as follows:

$$C_u\langle 0|\bar{u}u|0\rangle+C_s\langle 0|\bar{s}s|0\rangle=+\sqrt{2}\left(\frac{3p^2}{40\pi^2}+\frac{m_s^2}{60\pi^2}\right)\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p^2}\langle 0|\bar{q}q|0\rangle. \tag{16}$$

In this case there is no term like $\sim m_s\langle 0|\bar{s}s|0\rangle\langle 0|\bar{q}q|0\rangle$. This is so because the contribution of this form coming from the first term in Eq. (15) cancels that coming from the second term. As can be seen from comparing Eq. (16) with Eq. (9), the ratio between the leading term and the correction proportional to m_s^2 is the same for both cases.

Using a similar form in the phenomenological side as in Eq. (5), the sum rule looks as follows:

$$\lambda_N\lambda_\Sigma\frac{M_B}{M_\Sigma^2-M_N^2}(e^{-M_N^2/M^2}-e^{-M_\Sigma^2/M^2})g_{KN\Sigma}\frac{f_K m_K^2}{2m_q}=+\sqrt{2}\left(\frac{3}{40\pi^2}M^4+\frac{m_s^2}{60\pi^2}M^2\right)\langle 0|\bar{q}q|0\rangle. \tag{17}$$

Again for λ_{Σ^0}, we take the value from the following sum rule for the Σ [10]:

$$M^6-2am_s(1+\gamma)M^2+bM^2+\tfrac{4}{3}a^2=2(2\pi)^4\lambda_\Sigma^2 e^{-M_\Sigma^2/M^2}. \tag{18}$$

Within the same approximation as before, we take $M\simeq M_B=\frac{1}{2}(M_N+M_{\Sigma^0})$ in Eq. (17). This gives the following value for the coupling:

$$|g_{K^-N\Sigma^0}/\sqrt{4\pi}|\simeq 0.33. \tag{19}$$

TABLE I. Coupling constants $g_{KN\Lambda}$ and $g_{KN\Sigma}$. Sets I and II are the results from analyses of kaon-nucleon scattering. Set III is the result of Adelseck and Saghai from the analysis of photokaon scattering and set IV is the result of Mart *et al.* from the analysis of charged Σ photoproduction. SM I and II are the Skyrme model predictions. QSR I is a QCD sum rule prediction using $\alpha_D = 7/12$ in the SU(3) symmetric limit. QSR II is our result including the SU(3) symmetry breaking effects.

Coupling constants	I [11]	II [12]	III [13]	IV [14]	SM I [15]	SM II [16]	QSR I	QSR II
$g_{KN\Lambda}/\sqrt{4\pi}$	3.73 [a]	3.53 [a]	-4.17 ± 0.75	0.510	-2.17 [b]	-0.67 [c]	–2.76	–1.96
$g_{KN\Sigma}/\sqrt{4\pi}$	1.82 [a]	1.53 [a]	1.18 ± 0.66	0.130	0.76 [b]	0.24 [c]	0.44	0.33

[a] Sign undetermined.
[b] With $f_\pi = 76$ MeV, $e = 4.84$ which give the experimental values of N and Δ masses.
[c] With the empirical $f_\pi = 133$ MeV, and $e = 4.82$ which gives a $\Delta - N$ mass difference.

In our approximation, we have SU(2) symmetry: i.e., we neglected the up and down quark masses, and assumed $\langle 0|\bar{u}u|0\rangle = \langle 0|\bar{d}d|0\rangle$. Consequently, we can obtain $g_{KN\Sigma}$ using η_{Σ^+} and $j_{\bar{K}^0}$, where

$$\eta_{\Sigma^+} = \epsilon_{abc}(u_a^T C \gamma_\mu u_b)\gamma_5 \gamma^\mu s_c\,, \tag{20}$$

$$j_{\bar{K}^0} = \bar{s} i \gamma_5 d. \tag{21}$$

In this case, $C_u = 0$ and

$$C_d = \frac{p^2}{12\pi^2}\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p^2}, \tag{22}$$

$$C_s = \left(\frac{p'^2}{12\pi^2} + \frac{m_s^2}{24\pi^2}\right)\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p'^2}. \tag{23}$$

Then the final expression in the OPE side is

$$C_d\langle 0|\bar{d}d|0\rangle + C_s\langle 0|\bar{s}s|0\rangle = +\left(\frac{3p^2}{20\pi^2} + \frac{m_s^2}{30\pi^2}\right)\frac{\not{q}}{q^2}(i\gamma_5)\ln\frac{\Lambda^2}{-p^2}\langle 0|\bar{q}q|0\rangle. \tag{24}$$

Again, there is no term proportional to $\sim m_s\langle 0|\bar{s}s|0\rangle\langle 0|\bar{q}q|0\rangle$. Neglecting the difference between M_{Σ^0} and M_{Σ^+} in the phenomenological side, and comparing Eq. (24) with Eq. (16) we obtain the well-known relation from isospin symmetry:

$$g_{K^- N\Sigma^0} = \frac{1}{\sqrt{2}} g_{\bar{K}^0 N\Sigma^+}. \tag{25}$$

Because the contribution of each coefficient is the same, we obtain this relation despite of taking $\langle 0|\bar{s}s|0\rangle = 0.8\langle 0|\bar{q}q|0\rangle$ and including the strange quark mass correction. This reflects the SU(2) symmetry within our approach [see Eqs. (7), (8) and Eqs. (22), (23)].

IV. DISCUSSION

The SU(3) symmetry , using de Swart's convention, predicts

$$g_{KN\Lambda} = -\frac{1}{\sqrt{3}}(3 - 2\alpha_D)g_{\pi NN}\,,$$

$$g_{KN\Sigma} = +(2\alpha_D - 1)g_{\pi NN}\,, \tag{26}$$

where α_D is the fraction of the D-type coupling, $\alpha_D = D/(D+F)$. Using the expression of $g_{\pi NN}$ in Ref. [8] and comparing the OPE sides only, we obtain $\alpha_D = 7/12$ in the SU(3) symmetric limit. This limit is denoted by QSR I in Table I.

Our case (denoted by QSR II in Table I) does not satisfy Eq. (26) because of the additional SU(3) symmetry breaking factors in the OPE and in the phenomenological side. Using the convention by de Swart[1] we get

$$g_{KN\Lambda}/\sqrt{4\pi} = -1.96,$$

$$g_{KN\Sigma}/\sqrt{4\pi} = +0.33. \tag{27}$$

Comparing QSR I and QSR II, we note that the SU(3) symmetry breaking effect for the couplings is of the order of 25–30 %. This order is similar to the SU(3) symmetry breaking effects observed in the vector meson masses or the square of the couplings to the electromagnetic current.

In Ref. [4] the ranges for the coupling constants are given by fitting $g_{\pi NN}$ and α_D to experimental data and allowing for SU(3) symmetry breaking at the 20% level. This gives the following range:

[1] In fact, there is another convention [4,19].

$$g_{KN\Lambda}/\sqrt{4\pi}=-4.4 \text{ to } -3.0,$$

$$g_{KN\Sigma}/\sqrt{4\pi}=+0.9 \text{ to } +1.3. \tag{28}$$

Other experimentally extracted values, which are summarized as I, II, and III in Table I, lie within the limits above, except for the case denoted by IV.

Comparing these limits with our QSR calculations, we observe that our values fall short of the experimental limits, although it is closer than the predictions of the Skyrme model. However, it should be noted that the present experimental extractions of the couplings involve simultaneous determinations of many other unknown parameters and model-dependent subprocesses. Therefore it is necessary to investigate the problem further both theoretically and experimentally. Recently, there have been works by Leinweber and co-workers [20] on a critical reexamination on the QCD sum rule method for the nucleon and the vector meson. Among the conclusions, it was pointed out that the optimal mixing coefficient of the nucleon current was $\beta=-1.2$, whereas the Ioffe current corresponds to $\beta=-1$. We believe that using the optimal coefficient will not change our result too much because our sum rules are based on the values of the residue λ, which is less sensitive to the mixing coefficient [20]. However, it would be necessary and interesting to reanalyze our work using this ‘‘optimal’’ current.

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