Goldberger-Treiman constraint criterion for hyperon coupling constants

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The generalized Goldberger-Treiman relation is combined with the Dashen-Weinstein sum rule to provide a constraint equation between the $g_{\kappa N}$ and $g_{K N}$ coupling constants. A comprehensive examination of the published phenomenological and theoretical hyperon couplings has yielded a much smaller set of values, spanning the intervals $0.80 \leq g_{\kappa N}/\sqrt{4\pi} \leq 2.72$ and $-3.90 \leq g_{K N}/\sqrt{4\pi} \leq -1.84$, consistent with this criterion. The $SU(3)$ and Goldberger-Treiman hyperon couplings satisfy the constraint along with predictions from a Taylor series extrapolation using the same momentum variation as exhibited by $g_{\pi NN}$.

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I. INTRODUCTION

After a half century of investigating meson-baryon interactions, it is somewhat surprising that there are still several important coupling constants not accurately known. While the $\pi N$ coupling constant, $g_{\pi NN}$, has been determined to within a few percent, significant uncertainty in the two hyperon couplings, $g_{K(\Lambda, \Sigma)N}$, remains and even recently published values for both vary by more than a factor of four. This large variance is due to limited experimental information and also shortcomings in theoretical models. Further, analyses of purely hadronic processes typically yield larger couplings than those obtained from hyperon electromagnetic production studies. Fortunately, with the advent of new accelerator facilities, such as Jefferson Lab and SPring-8, more accurate and abundant data are now becoming available. Related, the recently reported discovery of the exotic strangeness $+1$ pentaquark resonance, $\Theta^+$, is also attracting attention which should spawn additional $K N$ measurements.

The purpose of this work is to detail a potentially useful constraint relation between $g_{K N}$ and $g_{\kappa N}$ which should facilitate future hyperon scattering and production analyses, especially with respect to extracting more accurate coupling constants. The constraint involves the generalized Goldberger-Treiman (GT) relation and the Dashen-Weinstein (DW) sum-rule. The GT relation is exact in the combined chiral and zero momentum limits according to the partially conserved axial vector current (PCAC) hypothesis and the assumed slow momentum variation of the $\pi N$ coupling constant. Even with explicit chiral symmetry breaking, the nucleon GT relation remains valid and is now satisfied to within one percent (see section II). Because of the larger strange quark mass and attending broken $SU_F(3)$ flavor symmetry, the generalized GT relation is not as accurate in the hyperon sector. However the deviation, or hyperon GT discrepancy, $\Delta_Y$, is believed to be reasonably accurately constrained by the DW sum rule since corrections are suppressed by two powers in the heavy baryon chiral perturbation theory expansion. Accordingly, by utilizing the DW sum rule connecting the $N$, $\Lambda$ and $\Sigma$ discrepancies, we have obtained a presumably accurate constraint equation between the hyperon and nucleon coupling constants, involving the known axial charges and hadron masses.

There have been several studies that have implemented the DW sum rule, especially to constrain the $\pi N$ coupling constant. Our approach represents a different view as we submit the hyperon couplings and their discrepancies are the limiting, less accurate quantities and that the reasonably well known $g_{\pi NN}$, through the DW sum rule, provides a constraint for $g_{K N}$ and $g_{\kappa N}$. Because $g_{\pi NN}$ is only determined to within a few percent, the constraint equation produces a band in the $(g_{\kappa N}, g_{K N})$ plane and we document which published couplings, when plotted, fall within this band. Since there is only one equation for the two couplings our constraint will only be useful for analyses involving both couplings. However, this should encompass most phenomenological investigations since models for hyperon reactions and production entail both $\Lambda$ and $\Sigma$ intermediate states and their attending couplings. Because of this interdependence our criterion should be useful even if analyses of purely hadronic processes continue to provide larger hyperon couplings than electromagnetic production (i.e. the constraint should provide a good numerical relation between the two couplings even if there is an effective coupling renormalization due to model dependence). Our result should also be of special interest to the hyperon and hypernuclear community and of timely benefit in the analysis of precision kaon electromagnetic production data recently measured at Jefferson Lab. Obtaining improved hyperon coupling constants will also permit new confrontations with QCD based theoretical approaches which have been successful in calculating $g_{\pi NN}$.

This paper is organized into four sections. The generalized GT relation and the DW sum rule, along with the $SU_F(3)$ coupling relations, are given in section II and the constraint criterion is developed. Published values for $g_{KYN}$ are reviewed in section III and the coupling constraint is imposed producing a subset satisfying this criterion. Finally, conclusions are summarized in section IV.
II. FUNDAMENTAL COUPLING RELATIONS

A. Generalized Goldberger-Treiman relation

To fully appreciate the validity of the GT relation it is illustrative to sketch its derivation. There are several ways to obtain this result such as using PCAC or unsubtracted dispersion relations (pion pole dominance of the axial vector divergence). Here the PCAC approach is adopted. Consider the matrix element of the axial $SU_F(3)$ current operator, $j_\mu^a(x) = \bar{\Psi}(x) \gamma_\mu \gamma_5 \frac{a}{2} \Psi(x)$, between two baryon octet states, $\langle B | j_\mu^a | B' \rangle$. Since the current transforms as a pseudovector, the most general form for this matrix element is

$$\langle B | j_\mu^a (x) | B' \rangle = e^{-i \frac{q \cdot x}{\hbar}} \pi(p) [g_A^B (q^2) \frac{\gamma^\mu \gamma_5}{2} + g_P^B (q^2) i \sigma^{\mu \nu} q_\nu \gamma_5 + g_\rho^B (q^2) q^\mu \gamma_5] u(p'),$$

(1)

where $q = p - p'$, $p^2 = m_B^2$, $p'^2 = m_{B'}^2$, and $g_A^B (q^2)$ and $g_P^B (q^2)$ are the axial vector and induced pseudoscalar form factors, respectively. The induced tensor form factor, $g_\rho^B (q^2)$, violates $G$-parity and will be omitted, consistent with small effects from second class currents. The axial current operator also appears in the definition of the decay constant, $f_M$, for a pseudoscalar octet meson $M^0$ having mass $m_M$

$$\langle 0 | j_\mu^a (x) | M^b (q) \rangle = i \sqrt{2} f_M q^\mu \delta^a_b e^{-i \frac{q \cdot x}{\hbar}}.$$  

(2)

Taking the divergence

$$\langle 0 | \nabla_\mu j_\mu^a (x) | M^b (q) \rangle = \sqrt{2} f_M m_M^2 \delta^a_b e^{-i \frac{q \cdot x}{\hbar}},$$

(3)

yields a conserved axial current in the generalized chiral limit ($\lim_{m_M \to 0} \nabla_\mu j_\mu^a (x) = 0$); this is the PCAC hypothesis. Under this assumption the baryon axial vector current, Eq. (1), is also conserved, and its divergence yields

$$\pi(p) [g_A^B (q^2) \frac{\gamma_5}{2} + g_P^B (q^2) \frac{\gamma_5}{2}] u(p') = 0.$$  

(4)

Then using the free Dirac equation for the first term leads to the form factor relation

$$g_A^B (q^2) = - \frac{q^2}{m_B + m_{B'}} g_P^B (q^2).$$

(5)

To proceed further, consider the leading Feynman diagrams for the weak decay $B \to B^* + \bar{\nu}_e + \nu_e$ depicted in Fig. 1. Only the meson exchange graph c) contributes to $g_P^B$. Direct evaluation gives

$$g_P^B (q^2) = - \frac{\sqrt{2} f_M}{q^2 - m_M^2} g_{MBB'}.$$

(6)

where $g_{MBB'}$ is the strong interaction baryon-meson coupling constant. Including higher order vertex corrections would modify this result by an additional multiplicative form factor, $F(q^2)$, with $F(0) = 1$. Combining Eqs. (5) and (6) finally yields in the combined chiral and zero momentum limits

$$g_A^B (0) = \frac{\sqrt{2} f_M}{m_B + m_{B'}} g_{MBB'} (0),$$

(7)

or rearranging

$$g_{MBB'} \equiv g_{MBB'} (0) = \frac{(m_B + m_{B'})}{\sqrt{2} f_M} g_A^B (0).$$

(8)

This is the generalized GT relation that defines the GT coupling constant and is exact in the zero meson mass and momentum limits, $m_M^2 = q^2 = 0$. We now apply Eq. (8) to evaluate the GT coupling constants $g_{\pi NN}$ and $g_{K^0 N}$. First we specify our coupling constant convention and phase consistent with the usual pseudoscalar Lagrangian

$$\mathcal{L} = i g_{\pi NN} \bar{N} \gamma_5 \tau N \cdot \pi + i g_{K^0 N} \bar{N} \gamma_5 \Lambda K$$

$$+ i g_{\Sigma N} \bar{N} \gamma_5 \Sigma \cdot K + h.c.,$$

(9)

with isospin nucleon, $N = (n, p)$, and kaon, $K = (K^+, K^0)$, doublet, and pion, $\pi$, and sigma, $\Sigma$, triplet fields. The different meson charge couplings are related to the generic coupling constants by

$$g_{\pi NN} \equiv g_{\pi nn} = - \frac{1}{\sqrt{2}} g_{\pi - np},$$

(10)

$$g_{K^0 N} \equiv g_{K^0 - \Lambda p},$$

(11)

$$g_{\Sigma N} \equiv \frac{1}{\sqrt{2}} g_{\Sigma - \Sigma - n}.$$

(12)

With this notation and the most recently measured parameters [10] listed in Table II including the axial charges (note $g_A^N = -g_A^\Lambda$) corresponding to the weak decays $n \to p + e^- + \bar{\nu}_e$, $\Lambda \to p + e^- + \bar{\nu}_e$ and $\Sigma^- \to n + e^- + \bar{\nu}_e$, [10].
the GT coupling constants are
\[
g_{\pi NN}^{GT} = \frac{g_A^N (m_n + m_p)}{f_N} = 12.897 \pm 0.047, \quad (13)
\]
\[
g_{K\Lambda N}^{GT} = \frac{g_A^\Lambda}{\sqrt{2} F} (m_\Lambda + m_p) = -9.228 \pm 0.209, \quad (14)
\]
\[
g_{K\Sigma N}^{GT} = \frac{g_A^{\Sigma}}{f_K} (m_\Sigma + m_n) = 3.215 \pm 0.163. \quad (15)
\]

Using these results and the commonly cited [11] \( m_\pi \) coupling value \( g_{\pi NN} = 13.02 \pm 0.08 \), it is interesting to make a simple Taylor series extrapolation for the hyperon couplings
\[
g_{\pi NN}^{(TS)} = g_{\pi NN}(0) + m_K^2 \frac{dg_{\pi NN}}{dm_K} (m_K^2). \quad (16)
\]

Then assuming that the magnitudes of the GT coupling are lower bounds, as suggested from results in section III, and using the same momentum variation (derivative) as exhibited by the \( \pi N \) coupling, the predicted Taylor series coupling constants are
\[
|g_{\pi NN}^{(TS)}| = |g_{\pi NN}^{(GT)}| + m_K^2 \frac{dg_{\pi NN}^{(GT)}}{dm_K} (m_K^2),
\]
\[
= |g_{\pi NN}^{(GT)}| + 0.123 \frac{m_K^2}{m_N^2} = |g_{\pi NN}^{(GT)}| + 1.539. \quad (17)
\]

This yields \( g_{\pi NN}^{(TS)} = -10.77 \) and \( g_{\pi NN}^{(TS)} = 4.75 \) which will also be assessed in section III along with the published hyperon couplings.

| TABLE I: Hadron masses, axial charges and decay constants. Errors are not listed for the very accurately known masses. |
|---|---|---|
| \( m_\pi \) | 938.272 MeV |
| \( m_\rho \) | 939.565 MeV |
| \( m_\Lambda \) | 1115.683 MeV |
| \( m_\Sigma^+ \) | 1197.449 MeV |
| \( m_\Xi^- \) | 1397.570 MeV |
| \( m_\Xi^0 \) | 493.677 MeV |

B. Dashen-Weinstein sum rule

As stated above, the GT relation is exact in the combined chiral and zero momentum limits. The deviation of \( g_{MBB'}^{GT} \) from the "physical" \( g_{MBB'}(m_M^2) \), defines the Goldberger-Treiman discrepancy (GTD)
\[
\Delta_B \equiv 1 - \frac{g_{MBB'}^{GT}}{g_{MBB'}(m_M^2)}. \quad (18)
\]

There are several relations for \( \Delta_B \), one of which is a sum rule first derived by Dashen and Weinstein [3]. It connects the GTD for the \( \pi N \) and hyperon couplings and is given by
\[
g_{\pi NN} \Delta_N = \frac{1}{2} \frac{m_K^2}{m_N^2} \left( g_{\Sigma N} \Delta_{\Sigma} - \sqrt{3} g_{\Lambda N} \Delta_{\Lambda} \right). \quad (19)
\]

While this relation is an approximation, its appearance does not appear to be widely accepted \[1, 2, 3, 4, 5\] and, as detailed in Ref. 4, corrections are suppressed by two powers in the heavy baryon chiral perturbation theory expansion. From Eq. (19) and the \( \pi N \) coupling \( g_{\pi NN} = 13.02 \), the nucleon discrepancy is \( \Delta_N = 0.094 \) indicating that the GT relation is now satisfied to better than 1%. Because \( \Delta_N \) is much better known than \( \Delta_{\lambda N} \), we regard the DW sum rule as an equation between \( \Delta_{\lambda N} \) and \( \Delta_{\lambda N} \), which permits extracting one of the coupling constants if the other is known. Unfortunately neither is that accurately known so the sum rule only provides a correlated constraint and this is the basis of our hyperon coupling criterion. Rearranging Eq. (19) gives a linear constraint relation between \( g_{\Lambda N} \) and \( g_{\Sigma N} \)
\[
g_{\Lambda N} = \frac{1}{\sqrt{3}} g_{\Sigma N} + b, \quad (20)
\]
where the intercept \( b \) is given by
\[
b = g_{\Lambda N}^{(GT)} - \frac{g_{\Sigma N}^{(GT)}}{\sqrt{3}} + \frac{2}{3} \frac{m_K^2}{m_N^2} \left( g_{\pi NN}^{(GT)} - g_{\pi NN} \right). \quad (21)
\]

Because the small uncertainty in \( g_{\pi NN} \) is magnified by the large meson mass ratio, the constraint only restricts an area in the \( (g_{\Sigma N}, g_{\Lambda N}) \) plane bounded by two parallel lines with the maximum and minimum intercept values corresponding to the error in \( g_{\pi NN} \). Nevertheless, it still provides a new criterion for evaluating the two \( g_{\pi NN} \) couplings, especially when they are analyzed in tandem. This coupling constraint is applied to the published phenomenological and theoretical \( g_{KN} \) in section III.

C. SU(3) relation between coupling constants

Unbroken \( SU_F(3) \) flavor symmetry provides another relation between the baryon-meson coupling constants \[12\]. Using de Swart’s convention, the predictions for the hyperon couplings are
\[
g_{K\Lambda N}^{SU(3)} = -\frac{g_{\pi NN}^{SU(3)}}{\sqrt{3}} (3 - 2\alpha_D), \quad (22)
\]
\[
g_{K\Sigma N}^{SU(3)} = g_{\pi NN}^{SU(3)} (2\alpha_D - 1), \quad (23)
\]
where \( \alpha_D = D/(D + F) \) is the standard fraction involving \( D \) and \( F \) couplings. Using the \( SU(6) \) value, \( \alpha_D = 0.6 \), and \( g_{\pi NN} = 13.02 \), the predicted \( SU_F(3) \) hyperon coupling constants are \( g_{K\Lambda N}^{SU(3)} = -13.53 \) and \( g_{K\Sigma N}^{SU(3)} = 2.60 \). However, flavor symmetry is broken,
typically quoted at least 20% [13], and we prefer using the experimental value $\alpha_D = 0.644$ determined by Donoghue-Holstein [14]. This yields the couplings, $g_{KAN}^{SU(3)} = -12.87$ and $g_{KAN}^{SU(3)} = 3.75$, and broken symmetry ranges, $-15.44 \leq g_{KAN} \leq -10.30$ and $3.00 \leq g_{KAN}^{SU(3)} \leq 4.50$.

We conclude this section by noting that there appears to be an inconsistency in the literature regarding phases. To ensure that Eq. (19) has the appropriate phases, we use the nucleon and hyperon discrepancies. To ensure that the relative sign between the nucleon and hyperon discrepancies. To ensure that Eq. (19) has the appropriate phases, we use the $SU(3)$ relations, Eqs. (22) and (23). Although the sum rule does not respect flavor symmetry, its derivation utilizes the $SU(3)$ representation for the current operator and thus the relative signs between the GT discrepancies must be the same as given in the $SU(3)$ limit. Then eliminating $\alpha_D$ from Eqs. (22, 23) yields

$$-\frac{2}{\sqrt{3}}g_{\pi NN}g_{KAN}^{SU(3)} = \frac{g_{KAN}^{SU(3)} - 2g_{\pi NN}}{\sqrt{3}}.$$ (24)

Combining this result with the $SU(3)$ limit ($m_K \to m_\pi$) of Eqs. (20) and (21) gives for the GT couplings

$$g_{KAN}^{GT(3)} = \left(\frac{g_{KAN}^{SU(3)} - 2g_{\pi NN}}{\sqrt{3}}\right),$$ (25)

which has the same form (and signs) as Eq. (24). Substituting the GT couplings from Eqs. (24) and (25) and taking the $SU(3)$ limit ($f_\pi = f_K, m_B = m_{B'}$), produces

$$(g_{A}^{SU(3)}) = \left(\frac{g_{A}^{SU(3)} - 2g_{\pi NN}}{\sqrt{6}}\right).$$ (26)

Finally, inserting the $SU(3)$ axial charges, $(g_{A}^{SU(3)}) = D + F$, $(g_{A}^{SU(3)}) = -(D + 3F)/\sqrt{6}$ and $(g_{A}^{SU(3)}) = D - F$, Eq. (20) reduces to an identity verifying the phases and coefficients in our sum rule are consistent.

III. APPLICATION OF THE CRITERION

In the past decade there have been numerous analyses of hyperon reactions, most involving electromagnetic processes. Table II summarizes a large class of phenomenological couplings in rationalized, $g_{KAN}/\sqrt{4\pi}$, form. Several theoretical predictions are also included for comparison. The results of Gobbi et al. [15] are based on a Skyrme-type model, while Choe et al. [16] use a QCD sum rule method and Jeong et al. [17] et al. employ the chiral bag model. The broken $SU(3)$ and GT values are presented along with the Taylor series extrapolation.

In Figs. 2 and 3 we compare all tabulated $\Lambda$ and $\Sigma$ couplings, respectively, in histogram form and also indicate the broken $SU(3)$ interval (dark gray), GT (diamond) and Taylor series (inverted triangle) couplings.

![Fig. 2: GT, SU(3), Taylor series and published KAN coupling constants.](image)

Applying the constraint criterion, the intercept $b$ requires specifying $g_{K\Lambda N}$ which is still subject to discussion [11, 15, 32, 33, 35, 36, 37, 38]. Nevertheless, it is generally accepted that $12.90 \leq g_{\pi NN} \leq 13.20$. This uncertainty is the dominant contribution to the variation in the in-
tercept, $\Delta b$, given by

$$\Delta b = \sqrt{\sum_i \left(\frac{\partial b}{\partial x_i} \Delta x_i\right)^2}, \quad (27)$$

where the independent variables $x_i$ and the corresponding errors $\Delta x_i$ are the $\pi N$ coupling, the three axial charges $g_A^3$ and the two meson decay constants $f_M$. Evaluating yields $b = -13.293$ and $\Delta b = 2.281$ which produces the maximum and minimum intercepts, $b_{\text{max}}/\sqrt{4\pi} = -11.011/\sqrt{4\pi} = -3.106$ and $b_{\text{min}}/\sqrt{4\pi} = -15.575/\sqrt{4\pi} = -4.394$. The corresponding constraint lines are shown in Fig. 4. A more stringent constraint can be obtained from the value recommended by de Swart et al. [11], $g_{\pi N N} = 13.02 \pm .08$, which produces the rationalized intercepts $-3.245$ and $-4.011$, represented by the narrower band (dashed lines) in the figure.

Treating the coupling constants as coordinates, $(g_{K\Sigma N}, g_{K\Lambda N})$, the values in Table II are plotted in Fig. 4 (dark circles for phenomenological, triangles for theoretical, box for $SU_F(3)$, diamond for GT and inverted triangle for Taylor series). The couplings satisfying the constraint are those with coordinates within the band. This produces the reduced or filtered set of acceptable values listed in Table III. The histograms for this subset of $\Lambda$ and $\Sigma$ couplings are depicted in Figs. 5 and 6, respectively. $\Lambda$ and $\Sigma$

Because the criterion only applies to hyperon coupling pairs $(g_{K\Sigma N}, g_{K\Lambda N})$, two of the $\Lambda$ analyses [25, 29] were precluded from Table III. This does not necessarily mean that their results are unacceptable. Also note from Fig. 4 that not all of the broken $SU_F(3)$ values are inside the constraint region and if the more stringent constraint (dashed lines) is imposed, the $SU_F(3)$ centroid point would be eliminated from Table III along with the GT couplings. Clearly, determining a more precise $g_{\pi N N}$ will be helpful in obtaining accurate hyperon couplings.

The hyperon couplings consistent with the constraint fall in the ranges $0.80 \leq g_{K\Sigma}/\sqrt{4\pi} \leq 2.72$ and $-3.90 \leq g_{K\Lambda}/\sqrt{4\pi} \leq -1.84$. The -3.90 limit on the $\Lambda$ coupling was obtained from the intersection of the constraint line with the area representing the broken $SU_F(3)$ uncertainty region. Although we summarize our criterion analysis by quoting these ranges, it is important to stress that the constraint does not specify upper or lower bounds for the coupling constants. However, examining the filtered points it is interesting that, with the exception of one $\Lambda$ and one $\Sigma$ value, all couplings have magnitudes above the GT predictions. This suggests that the GT values may be lower bounds, $|g_{K\Sigma N}| \geq |g_{K\Sigma N}^\text{GT}|$, similar to the $\pi N$ coupling result, $g_{\pi N N} \geq g_{\pi N N}^\text{GT}$. If this proves true then the Taylor series extrapolations may be good estimates of the hyperon coupling constants.

IV. CONCLUSION

In summary, a hyperon coupling criterion has been developed using the fundamental Goldberger-Treiman relation and the Dashen-Weinstein sum rule. Because the $\pi N$ coupling constant is not exactly known, the criterion can only restrict an area in the $(g_{K\Sigma N}, g_{K\Lambda N})$ plane. As the precision of $g_{\pi N N}$ improves, this area will decrease providing a stronger constraint. Since the criterion can only be applied to hyperon couplings in pairs,
phenomenological investigations incorporating this constraint should also perform a combined Λ and Σ data analysis, especially since the couplings are interrelated in most models. Even if there is model dependence producing renormalized, effective hyperon couplings, the constraint should still be applicable to all hyperon reactions.

This work has also applied the criterion to a large class of published couplings to produce a reduced number of $g_{KYN}$ parameters satisfying the constraint. This subset spans the intervals $0.80 \leq g_{K\Sigma N}/\sqrt{4\pi} \leq 2.72$ and $-3.90 \leq g_{K\Lambda N}/\sqrt{4\pi} \leq -1.84$ and includes the $SU_F(3)$, GT and extrapolated Taylor series couplings. The range of absolute values in the filtered sets suggests that the GT coupling constants are, in magnitude, lower bounds. Although further study is necessary to rigorously demonstrate this, the constraint as a general guideline should be reasonably useful provided the Dashen-Weinstein sum rule is quantitatively valid.

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