The ϕNN coupling from chiral loops

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Abstract

Starting from effective Lagrangians which combine a gauge formulation of Vector Meson Dominance with Chiral Lagrangians, the coupling of the ϕ to the nucleon, which is zero at tree level due to the OZI rule, is calculated perturbatively considering loop contributions to the electric and magnetic form factors. We obtain reasonably smaller values for both form factors than those for ρNN and consistent with the expected order of magnitude of the OZI rule violation.

1 Introduction

A general formulation of vector meson couplings to pseudoscalar mesons and baryons can be constructed combining elements of Vector Meson Dominance and SU(3) chiral Lagrangians [1, 2], hence placing the ϕ and the ρ on the same footing. Yet, the ρ and ϕ couple to the nucleon in a very different way, since the Lagrangians are consistent with the OZI rule and thus the ϕ, which stands for a $s\bar{s}$ state in this formulation, does not couple to the nucleon nor to pions at the tree level. The same Lagrangians, however, allow one to perform perturbative calculations to account for loop contributions to the ϕ couplings, involving kaons and hyperons to which the ϕ couples naturally. One, nevertheless, still expects the couplings to be small since the OZI rule should not be much violated. One of the reactions where the OZI rule shows up, drastically reducing the decay rate, is the $\phi \to \pi^+\pi^-$ reaction [3], where the combination of the OZI rule and isospin symmetry leads to an extremely small branching ratio. This can explicitly be seen in theoretical calculations [4, 5, 6, 7], where one finds large cancellations as a combined effect of isospin symmetry and the OZI rule.

Unlike the ρ coupling to the nucleon which has been the subject of much research from different theoretical points of view [8, 9, 10, 11, 12, 13, 14], the ϕ coupling to the nucleon has comparatively received much less attention. Some studies done using theoretical dispersion relations give a rather large coupling of the ϕ to the nucleon [15, 16] implying a large violation of the OZI rule. A reanalysis of the situation was done in [17], where the consideration in the dispersion-theoretical analysis of the correlated $\rho\pi$ exchange term in the NN potential [18] drastically reduced the former results for the ϕ coupling. At the same time a perturbative calculation by explicitly evaluating the indirect coupling of the ϕ to the nucleon through the K and K^* meson cloud and hyperon excitation was done, and it was concluded that the couplings, although with uncertainties, were indeed small and compatible with the expected OZI rule violation.

New developments in chiral theory and vector meson interaction with nucleons and nuclei have given us more elements to tackle the problem and make a more quantitative evaluation of the ϕ coupling. One of the interesting developments was the combination of chiral symmetry with vector meson dominance formulated within a gauge invariant framework. Thanks to this, vertex corrections of the type of contact terms VPBB (vector-pseudoscalar-baryon-baryon) are generated [2, 19, 20, 21, 22] which introduce new terms in the loop calculations of the vector meson form factors not considered in the past. Such task was undertaken recently in the evaluation of the loop contribution to the ρ electric and magnetic form factors [23], which led to corrections quite stable with respect to moderate changes in the regularizing scale of the theory.

The purpose of the present paper is to make an evaluation of the electric and magnetic form factors of the ϕ coupling to the nucleon for which we follow closely the approach of [23]. There are also other new elements in the present evaluation, like the consideration of the $\Sigma^*(1385)$ in addition to the Λ and the Σ in the intermediate states. This is done for consistency with the study of the ρ coupling where $\Delta(1232)$ intermediate states were also considered. The consideration of Δ intermediate states was advocated in [24, 25, 26] as a way to implement in the chiral perturbative calculations appropriate limits of large N_c. The $\Sigma^*(1385)$ is the element of the SU(3) decuplet which plays to the hyperons the role of the Δ to the nucleons. Hence their inclusion is most advised and the actual calculations show that its contribution is indeed comparable to that of other intermediate hyperons.

The strength which we get for the couplings is small and consistent with a weak violation of the OZI rule. On the other hand the results obtained are quite stable and provide a realistic determination of the size and sign of the ϕNN electric and magnetic form factors for not too large values of the ϕ momentum.

2 Model for the ϕNN coupling

In this section we introduce the Lagrangians needed to calculate the one loop contributions to the ϕNN couplings and perform the calculation. In general, the vertex function of the ϕNN coupling can be written in terms of two Lorentz independent functions, G^V and G^T:

$$-it_{\phi NN} = i\left(G^V(q)\gamma^\mu + \frac{G^T(q)}{2iM_N}\sigma^{\mu\nu}q_\nu\right)\epsilon^*_\mu \qquad (1)$$

being q and ϵ^*_μ the momentum and the polarization vector of the outgoing ϕ. For convenience, we work in the Breit frame, i. e., $q^0 = 0$, $\vec{p}_i = \vec{q}/2$ (initial proton) and $\vec{p}_f = -\vec{q}/2$ (final proton), and also in the non-relativistic limit. Then eq. (1) is written as

$$-it_{\phi NN} = iG^E(q)\epsilon^0 - \frac{G^M(q)}{2M_N}(\vec{\sigma}\times\vec{q})\cdot\vec{\epsilon} \qquad (2)$$

with

$$\begin{aligned} G^E(q) &= G^V(q) \\ G^M(q) &= G^T(q) + G^V(q) \end{aligned} \qquad (3)$$

In order to perform the calculations, we use the effective Lagrangians of refs. [1, 2], which combine chiral $SU(3)$ dynamics with VMD [1]. The basic coupling of the pseudoscalar mesons to the baryons is given by the Lagrangian

$$\mathcal{L}_{BBP} = \frac{F}{2}tr\left(\bar{B}\gamma_\mu\gamma_5[u^\mu, B]\right) + \frac{D}{2}tr\left(\bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\right) \qquad (4)$$

with

$$u^\mu = -\frac{\sqrt{2}}{f}\left(\partial^\mu P + i\frac{g}{\sqrt{2}}[V^\mu, P]\right) \qquad (5)$$

In these two last equations B and P represent the $SU(3)$ matrix fields of the baryon and pseudoscalar meson octets, respectively, $f = 93$ MeV is the pion decay constant, and we take $g = -6.05$, $F = 0.51$ and $D = 0.75$, as done in [2]. The vector mesons have been introduced by means of the minimal substitution scheme, in terms of the matrix V_μ, which, when considering only neutral states, reads

[1] We have modified the formulae of [1, 2] in order to use the normalizations of the P, V_μ and u_μ matrices of ref. [29] which are more commonly used in the literature when using chiral Lagrangians, and the sign of g to agree with the paper of the ρNN coupling of [23].

$$V_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho^0_\mu + \omega_\mu & 0 & 0 \\ 0 & -\rho^0_\mu + \omega_\mu & 0 \\ 0 & 0 & \sqrt{2}\phi_\mu \end{pmatrix} \tag{6}$$

The pseudoscalar meson-vector meson couplings are given in refs. [1, 27], and can be obtained by introducing a gauge-covariant derivative in the lowest order chiral Lagrangian [28]

$$\partial_\mu P \to D_\mu P = \partial_\mu P + i\frac{g}{\sqrt{2}}[V_\mu, P] \tag{7}$$

In this way we obtain the Lagrangian

$$\mathcal{L}_{VPP} = -\frac{ig}{\sqrt{2}} tr\left(V^\mu[\partial_\mu P, P]\right) \tag{8}$$

The Lagrangian of eq. (4) provides the BBP and $BBVP$ vertices but does not provide the direct couplings of the vector mesons to the baryon fields BBV. These vertices are given by the Lagrangian [2]

$$\mathcal{L}_{BBV} = -\frac{g}{2\sqrt{2}}\left(tr(\bar{B}\gamma_\mu[V^\mu, B] + tr(\bar{B}\gamma_\mu B)tr(V^\mu)\right) \tag{9}$$

In order to evaluate the contribution of diagrams d) and e) we need the $BBPP$ and $BBPPV$ vertices. These vertices can be obtained from the chiral Lagrangian [29]

$$\mathcal{L} = i\ tr\left(\bar{B}\gamma^\mu[\Gamma_\mu, B]\right) \tag{10}$$

with

$$\Gamma_\mu = \frac{1}{2}\left\{u^\dagger(\partial_\mu + i\frac{g}{2\sqrt{2}}V_\mu)u + u(\partial_\mu + i\frac{g}{2\sqrt{2}}V_\mu)u^\dagger\right\} \tag{11}$$

where u is defined in reference [29].

It is important to stress that, according to the OZI rule, we do not get any direct coupling of the ϕ to the nucleon from the Lagrangian in eq. (9). As a consequence, all the contributions to the electric and magnetic form factors of the ϕ coupling to the nucleon should come from loop diagrams. The one loop diagrams contributing to these form factors are given in fig. 1. The

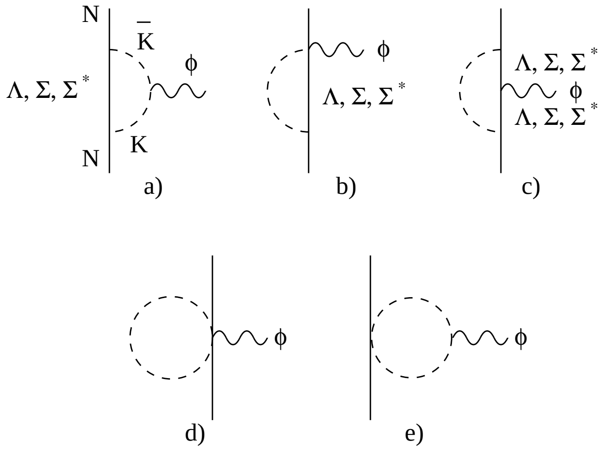


Figure 1: One loop diagrams evaluated.

contribution of each diagram to $G^E_{\phi NN}$ and to $G^M_{\phi NN}$ is given in Appendix B. We will discuss later in more detail the calculations and results obtained.

In the former Lagrangians only baryons from the octet are involved. Here we will consider also the Σ^* as an intermediate state, which belongs to the decuplet. It is worth including this hyperon in our calculations since its contribution to some processes can be as big as (or even bigger than) the one of the Σ, as can be seen in reference [30]. The $\bar{K}N\Sigma^*$ vertex is given by [31]

$$V_{\bar{K}N\Sigma^*} = \frac{2\sqrt{6}}{5}\frac{D+F}{2f}A\vec{S}^\dagger \cdot \vec{k} \tag{12}$$

where $\vec{S}^\dagger$ is the spin transition operator from $S = 1/2$ to $S = 3/2$ and $\vec{k}$ is the momentum of the incoming kaon. The A coefficient takes the values $-1/\sqrt{2}$, -1, -1, $1/\sqrt{2}$ for the $K^- p \to \Sigma^{*0}$, $K^- n \to \Sigma^{*-}$, $\bar{K}^0 p \to \Sigma^{*+}$, $\bar{K}^0 n \to \Sigma^{*0}$ transitions respectively. To evaluate the diagram b) of fig. 1 with intermediate Σ^*, we need also to know the $\phi N\bar{K}\Sigma^*$ vertices. These vertices are given in ref. [31] and have the form

$$V_{\phi\bar{K}N\Sigma^*} = -g\frac{2\sqrt{3}}{5}\frac{D+F}{2f}A\vec{S}^\dagger \cdot \vec{\epsilon}(\phi) \tag{13}$$

where the A coefficients have the same values as in the $\bar{K}N\Sigma^*$ vertex.

Finally, we will need to know the direct $\phi\Sigma^*\Sigma^*$ vertex in order to evaluate diagram c). We can relate this vertex to the $\phi\Sigma\Sigma$ one by means of a quark model (see Appendix A).

Interm. baryon	a)	b)	c)	Sum
Λ	-0.49	—	0.49	0
Σ	-0.05	—	0.05	0
Σ^*	0.40	—	-0.40	0
Total $G^E_{\phi NN}(\vec{q}=\vec{0})$				0

Table 1: Different contributions to $G^E_{\phi NN}$ at $\vec{q}=\vec{0}$.

With the Lagrangians and vertices previously introduced we can evaluate all the diagrams in figure 1. In diagram a) we can have Λ, Σ and Σ^* baryons as intermediate states. The evaluation of these diagrams is straightforward and the results obtained for $G^E_{\phi NN}(\vec{q}=\vec{0})$ and $G^M_{\phi NN}(\vec{q}=\vec{0})$ are shown in table 1 and table 2.

The other diagrams to be considered contain direct couplings of the ϕ to the baryonic leg. In these diagrams we multiply the expressions for $G^E_{\phi NN}(\vec{q})$ and $G^M_{\phi NN}(\vec{q})$ given in Appendix B by the $F_\phi(\vec{Q})$ form factor, defined in eq. (26). The contribution of diagram b) to $G^E_{\phi NN}(\vec{q})$ is of order $\mathcal{O}(1/M)$ and we will not consider it here, as also done in [23], since corrections of order $\mathcal{O}(1/M)$ in other terms have also been neglected. In Appendix B we give the contributions of diagram b) with Λ, Σ and Σ^* as intermediate mesons to $G^M_{\phi NN}(\vec{q})$. The expressions in the Appendix include the sum of both diagrams b) with the ϕ attached to the upper and lower vertices.

Another set of diagrams that contribute to both $G^E_{\phi NN}(\vec{q})$ and $G^M_{\phi NN}(\vec{q})$ is represented by diagram c) in figure 1, where $\phi\Lambda\Lambda$, $\phi\Sigma\Sigma$ and $\phi\Sigma^*\Sigma^*$ vertices appear (we do not have vertices attaching a ϕ to two different baryons, in contrast with the ρ case, since the ϕ is an isoscalar). The $\phi\Lambda\Lambda$ and $\phi\Sigma\Sigma$ vertices can be obtained from Lagrangian (9). However, this Lagrangian does not account for baryons belonging to the decouplet, and we have to resort to a quark model to relate the $\phi\Sigma^*\Sigma^*$ coupling to the $\phi\Sigma\Sigma$, as announced before. This is done in Appendix A in an analogous way as it was done in ref. [23] to relate the $\rho N\Delta$ and $\rho\Delta\Delta$ couplings to the ρNN coupling. Note also that diagrams a), b) and c), in the case of intermediate Σ's, account actually for two diagrams, since the intermediate hyperon can be either a Σ^+ or a Σ^0. The same happens in the case of intermediate Σ^*. Finally, diagrams d) and e) of fig. 1 do not contribute to the ϕNN coupling at $q=0$ and we do not consider them (see Appendix B).

It is worth pointing out that the total contribution to $G^E_\phi(\vec{q})$ at $\vec{q}=\vec{0}$ is null, due to the cancellation between the contributions of diagrams a) and c) of fig. 1 for each intermediate baryon (we have done the calculations using an averaged kaon mass $m_K = 495.7$ MeV). This cancellation is a consequence of the gauge symmetry for vector mesons, whose implications were discussed in detail in [23]. It is interesting to note that the cancellation of G^E at $q=0$ for the case of the ρ required a term with nucleon wave function renormalization.

Interm. baryon	a)	b)	c)	Sum
Λ	-0.75	0.60	-0.17	-0.32
Σ	-0.07	0.06	-0.02	-0.03
Σ^*	0.31	-0.21	1.35	1.45
Total $G^M_{\phi NN}(\vec{q}=\vec{0})$				1.10

Table 2: Different contributions to $G^M_{\phi NN}$ at $\vec{q}=\vec{0}$.

This term is null here since the ϕ does not couple directly to the nucleon, but in spite of that, the requirement $G^E_{NN\phi}(\vec{q}=0)=0$ also holds here and comes from a direct cancellation of the terms associated to diagrams a) and c). We can also see that the contributions of the diagrams with an intermediate Σ are small compared to those of the diagrams with intermediate Λ or Σ^*. This is due to the fact that the contributions of the diagrams with intermediate Σ are proportional to $(D-F)^2 = 0.058$, compared to the factors $(D+3F)^2 = 5.20$ and $(D+F)^2 = 1.59$ in the intermediate Λ and Σ^* cases, respectively (see Appendix B). Another interesting fact is that $G^M_{\phi NN}$ is dominated by the contribution of the diagrams with intermediate Σ^*, specially diagram c) of fig. 1 with two intermediate Σ^*, as we can see in table 2. The value that we get for this coupling is rather large but still a factor 20 smaller than the corresponding factor in the ρ coupling to the nucleon, $G^{M,exp}_{\rho NN} \sim 21$. It is also about a factor 6 smaller than the contribution from loops to $G^M_{\rho NN}$ found in [23].

In fig. 2 we show the q dependence of both couplings. We only present our results up to 500 MeV since we work in the non-relativistic limit and also we have not taken into account the $\mathcal{O}(1/M)$ corrections. These approximations restrict the range of validity of our approach, being the higher energies region out of the scope of this paper. In the figure we see that $G^E_{\phi NN}$ is null at $\vec{q}=\vec{0}$ and keeps to small values in the low momentum region which we study. Similarly, the q dependence of $G^M_{\phi NN}$ is very smooth. Finally, let us stress that the final results have a non negligible dependence on the input of the calculation, mainly on the value of the Λ parameter in the form factors (see Appendix B). A change of 20% in this parameter induces a change of the same magnitude in the couplings.

3 Conclusions

We have evaluated the contributions to $G^E_{\phi NN}(\vec{q})$ and $G^M_{\phi NN}(\vec{q})$ for the OZI violating ϕNN coupling. Since there is no direct coupling of the ϕ to the nucleon, all the contributions come from loop diagrams. The loops are regularized by means of a form factor, introducing an effective cut off of the order of 1.2 GeV. In addition we also restrict the space of intermediate states to the Λ, Σ and Σ^*. This kind of regularization from two sources has

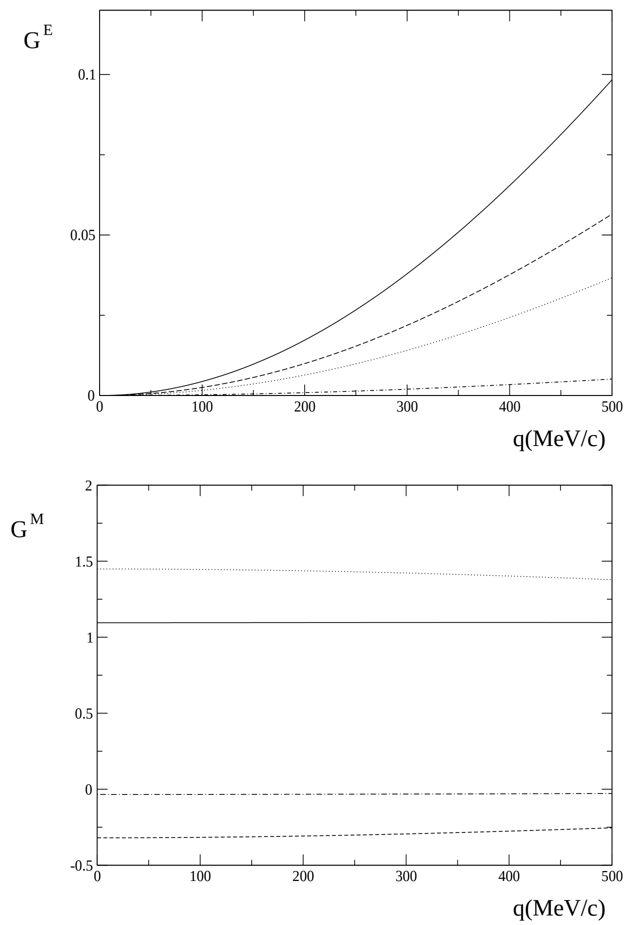


Figure 2: q dependence of $G^E_{\phi NN}$ and $G^M_{\phi NN}$. Dashed line: diagrams with intermediate Λ; dashed-dotted line: diagrams with intermediate Σ; dotted line: diagrams with intermediate Σ^*; solid line: sum of all.

been successfully used in a large number of evaluations of chiral bag models [32].

We find that $G^E_{\phi NN}$ is null at $q = 0$ and grows smoothly in the low energy regime reaching values of around 0.1 at $q = 500$ MeV. In the $G^M_{\phi NN}$ coupling case we find a value of 1.1 at $q = 0$, with a very smooth dependence on the momentum. This coupling is dominated by the contribution of diagrams with intermediate Σ^*. In both $G^E_{\phi NN}$ and $G^M_{\phi NN}$ the contribution of diagrams with intermediate Σ is very small compared to those of the diagrams with intermediate Λ, Σ^*, due to the smallness of the ΣKN, $\Sigma KN\phi$ couplings. The values of the couplings that we have obtained are small compared to the corresponding couplings in the case of the ρNN interaction, $G^E_{\rho NN} = 2.9 \pm 0.3$ and $G^M_{\rho NN} = 20.9 \pm 2.3$, as expected from the OZI rule. However, the one loop calculation of $G^M_{\rho NN}$ of ref. [23] gives a value $G^M_{\rho NN} = 6.05$, only a factor 6 bigger than the one obtained here.

A Quark model for the $\phi\Sigma^*\Sigma^*$ vertex

In this Appendix we relate the $\phi\Sigma^*\Sigma^*$ and $\phi\Sigma\Sigma$ vertices through the $SU(6)$ quark model. Let us define the operator corresponding to the ϕ coupling to the i-th quark for G^M

$$\hat{g}^i_M = -G^M_{(q)} \frac{(\vec{q} \times \vec{\epsilon}) \cdot \vec{\sigma}_i}{2m_q} \tag{14}$$

where m_q is the quark mass, $\vec{q}$ is the momentum of the outgoing ϕ and $G^M_{(q)}$ is the G^M factor corresponding to the ϕ coupling to the quark q. For a Σ baryon with spin up the quark model provides

$$\langle \Sigma^+ \uparrow | \sum_{i=1}^{3} \hat{g}^{(i)}_M | \Sigma^+ \uparrow \rangle = -G^M_{(q)} \frac{(\vec{q} \times \vec{\varepsilon})_3}{2m_q} \tag{15}$$

Here we have used that $\langle \Sigma \uparrow | \sigma_3 | \Sigma \uparrow \rangle$=1, as can be obtained using the Σ wave function in the spin-flavor space

$$|\Sigma^+ \uparrow\rangle = \frac{1}{\sqrt{2}} (\phi_{MS}\chi_{MS} + \phi_{MA}\chi_{MA}) \tag{16}$$

with

$$\phi^{\Sigma^+}_{MS} = \frac{1}{\sqrt{6}}[(us + su)u - 2uus] \qquad \phi^{\Sigma^+}_{MA} = \frac{1}{\sqrt{2}}(us - su)u \tag{17}$$

$$\chi^{(\uparrow)}_{MS} = \frac{1}{\sqrt{6}}[(\uparrow\downarrow + \downarrow\uparrow)\uparrow -2 \uparrow\uparrow\downarrow] \qquad \chi^{(\uparrow)}_{MA} = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)\uparrow \tag{18}$$

Using these wave functions and comparing with the definition of magnetic coupling to the nucleon (see eq. (2)), we easily find that

$$\frac{G^M_{(q)}}{2m_q} = \frac{G^M_\Sigma}{2M_N} = -\frac{g}{\sqrt{2}} \frac{1}{2M_N} \tag{19}$$

where the result $G^M_\Sigma = -\frac{g}{\sqrt{2}}$ can be obtained from the Lagrangian of eq. (9).

In the same way, we can relate $G^M_{\Sigma^*}$ to $G^M_{(q)}$. To do that we must use the Σ^{*+} wave function in the spin-flavor space

$$|\Sigma^{*+}\uparrow\rangle = |\phi_S\rangle|\chi_S\rangle \tag{20}$$

with

$$\phi_{MS}^{(\Sigma^{*+})} = \frac{1}{\sqrt{3}}(uus + usu + suu) \quad \chi_{MS}^{(\uparrow)} = \frac{1}{\sqrt{3}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow) \tag{21}$$

Using this wave function we obtain

$$\langle\Sigma^{*+}\uparrow|\sum_{i=1}^{3}\hat{g}_M^{(i)}|\Sigma^{*+}\uparrow\rangle = -2G_{(q)}^M\frac{(\vec{q}\times\vec{\varepsilon})_3}{2m_q} \tag{22}$$

The magnetic coupling to the Σ^* is defined

$$-it_{\phi\Sigma^*\Sigma^*} = iG_{\Sigma^*}^E\epsilon^0 - \frac{G_{\Sigma^*}^M}{2M_N}(\vec{S}_{\Sigma^*}\times\vec{q})\;\vec{\epsilon} \tag{23}$$

Taking care of the normalization of the couplings, it is straightforward to arrive at

$$\frac{G_{\Sigma^*}^M}{2M_N} = 4\frac{G_{(q)}^M}{2m_q} = 4\frac{G_{\Sigma}^M}{2M_N} = -2\sqrt{2}g\frac{1}{2M_N} \tag{24}$$

The evaluation of $G_{\Sigma^*}^E$ is analogous and even easier since in this case only matrix elements of the identity in both the spin and flavor space must be calculated. We get

$$G_{\Sigma^*}^E = G_{\Sigma}^E = -\frac{g}{\sqrt{2}} \tag{25}$$

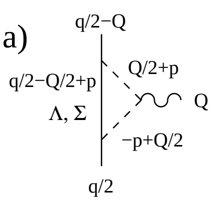
B One loop calculations

In this Appendix we give the explicit expressions of the contributions of the loop diagrams to $G_{NN\phi}^E$ and $G_{NN\phi}^M$. In the following equations and diagrams ϵ_μ denotes the ϕ polarization vector, and:

$$
\begin{aligned}
q &\equiv (E(\vec{q}), \vec{q}) & Q &\equiv (0, \vec{q}) \\
\omega(k) &\equiv \sqrt{\vec{k}^2 + m_K^2} & D(k) &\equiv \frac{1}{k^2 - m_K^2} \\
F_K(\vec{k}) &\equiv \frac{\Lambda^2}{\Lambda^2 + \vec{k}^2} & F_\phi(\vec{k}) &\equiv \frac{\Lambda_\phi^2}{\Lambda_\phi^2 + \vec{k}^2} \\
\Lambda &= 1.2 \text{ GeV} & \Lambda_\phi &= 2.5 \text{ GeV} \\
E(\vec{k}) &\equiv \frac{\vec{k}^{\,2}}{2M_N} + M_N & E_Y(\vec{k}) &\equiv \frac{\vec{k}^{\,2}}{2M_Y} + M_Y
\end{aligned}
\tag{26}
$$

where the subindex Y refers to any of the hyperons considered here (Λ, Σ, Σ^*). We warn the reader that, in order not to complicate excessively the expressions, we have deliberately omitted the form factors and the M/E relativistic corrections to the baryonic propagators in the following equations, although it should be kept in mind that one must include them to perform the numerical calculations.

a)



$$
G_{\phi NN}^{E\ a)}(\vec{q}) = \alpha_Y^{a)} g \int \frac{d^3p}{(2\pi)^3} \left(\vec{p}^{\,2} - \frac{\vec{q}^{\,2}}{4} \right) f_1(\vec{p}, \vec{q}) \tag{27}
$$

$$
\frac{G_{\phi NN}^{M\ a)}}{2M_N} = \alpha_Y^{a)} g \int \frac{d^3p}{(2\pi)^3} \left(\vec{p}^{\,2} - \frac{(\vec{p}\vec{q})^2}{\vec{q}^{\,2}} \right) f_2(\vec{p}, \vec{q}) \tag{28}
$$

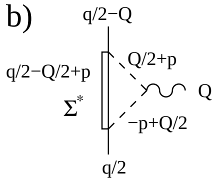
where the α_Y and β_Y coefficients, for Λ and Σ intermediate hyperons, are:

$$
\alpha_\Lambda^{a)} = \frac{1}{3\sqrt{2}} \left(\frac{D + 3F}{2f} \right)^2 \quad ; \alpha_\Sigma^{a)} = \frac{3}{\sqrt{2}} \left(\frac{D - F}{2f} \right)^2 \tag{29}
$$

The f_1 and f_2 functions are defined as:

$$
\begin{aligned}
f_1(\vec{p}, \vec{q}) &= \frac{1}{\omega(\vec{p} + \vec{q}/2) + \omega(\vec{p} - \vec{q}/2)} \frac{1}{E(\vec{q}/2) - \omega(\vec{p} + \vec{q}/2) - E_Y(\vec{p})} \times \\
&\times \frac{1}{E(\vec{q}/2) - \omega(\vec{p} - \vec{q}/2) - E_Y(\vec{p})} \\
f_2(\vec{p}, \vec{q}) &= \frac{1}{\omega(\vec{p} + \vec{q}/2) + \omega(\vec{p} - \vec{q}/2)} \frac{1}{E(\vec{q}/2) - \omega(\vec{p} + \vec{q}/2) - E_Y(\vec{p})} \times \\
&\times \frac{\omega(\vec{p} + \vec{q}/2) + \omega(\vec{p} - \vec{q}/2) + E_Y(\vec{p}) - E(\vec{q}/2)}{E(\vec{q}/2) - \omega(\vec{p} - \vec{q}/2) - E_Y(\vec{p})} \frac{1}{2\omega(\vec{p} + \vec{q}/2)\omega(\vec{p} - \vec{q}/2)}
\end{aligned}
\tag{30}
$$

b)



In the calculation of diagrams with intermediate Σ^*'s one has different spin and isospin factors since the spin and isospin transition operators appearing in the corresponding Lagrangians satisfy the following relations:

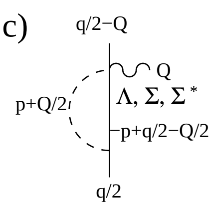
$$S_i S_j^\dagger = \frac{2}{3}\delta_{ij} - \frac{i}{3}\epsilon_{ijk}\sigma_k \tag{31}$$

Taking this into account one finds

$$G_{\phi NN}^{E\ b)}(\vec{q}) = \frac{12\sqrt{2}}{25}\left(\frac{D+F}{2f}\right)^2 g \int \frac{d^3p}{(2\pi)^3}\left(\vec{p}^{\ 2} - \frac{\vec{q}^{\ 2}}{4}\right) f_1(\vec{p},\vec{q}) \tag{32}$$

$$\frac{G_{\phi NN}^{M\ b)}}{2M_N} = -\frac{6\sqrt{2}}{25}\left(\frac{D+F}{2f}\right)^2 g \int \frac{d^3p}{(2\pi)^3}\left(\vec{p}^{\ 2} - \frac{(\vec{p}\vec{q})^2}{\vec{q}^{\ 2}}\right) f_2(\vec{p},\vec{q}) \tag{33}$$

c)



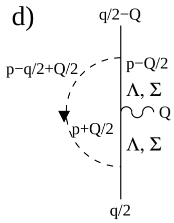
$$G_{\phi NN}^{E\ c)}(\vec{q}) = \mathcal{O}(1/M_N) \tag{34}$$

$$\begin{aligned}\frac{G_{\phi NN}^{M\ c)}}{2M_N} &= - \quad \beta_Y^{c)} g \int \frac{d^3p}{(2\pi)^3}\left(1 + \frac{2\vec{p}\vec{q}}{\vec{q}^2}\right)\frac{1}{2\omega(\vec{p}+\vec{q}/2)} \times \\ &\times \quad \frac{1}{E(\vec{q}/2) - \omega(\vec{p}+\vec{q}/2) - E_Y(\vec{p})}\end{aligned} \tag{35}$$

with

$$\begin{aligned}\beta_\Lambda^{c)} &= -\frac{1}{3\sqrt{2}}\left(\frac{D+3F}{2f}\right)^2 \quad ; \qquad \beta_\Sigma^{c)} = -\tfrac{3}{\sqrt{2}}\left(\tfrac{D-F}{2f}\right)^2 ; \\ \beta_{\Sigma^*}^{c)} &= \frac{6\sqrt{2}}{25}\left(\frac{D+F}{2f}\right)^2\end{aligned} \tag{36}$$

d)

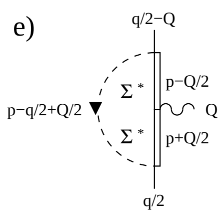


$$G^{E\ d)}_{\phi NN}(\vec{q}) = -\alpha^{d)}_Y g \int \frac{d^3p}{(2\pi)^3} \frac{1}{2\omega(\vec{p})} \times$$
$$\times \frac{\vec{p}^{\,2}}{E(\vec{q}/2) - \omega(\vec{p}) - E_Y(\vec{q}/2 - \vec{p})} \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_Y(-\vec{q}/2 - \vec{p})} \quad (37)$$

$$G^{M\ d)}_{\phi NN}(\vec{q}) = \alpha^{d)}_Y g \int \frac{d^3p}{(2\pi)^3} \frac{(\vec{p}\vec{q})^2}{2\vec{q}^{\,2}\omega(\vec{p})} \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_Y(\vec{q}/2 - \vec{p})} \times$$
$$\times \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_Y(-\vec{q}/2 - \vec{p})} \quad (38)$$

$$\alpha^{d)}_\Lambda = \frac{1}{3\sqrt{2}} \left(\frac{D+3F}{2f}\right)^2 \qquad ; \alpha^{d)}_\Sigma = \frac{3}{\sqrt{2}} \left(\frac{D-F}{2f}\right)^2 \quad (39)$$

e)



$$G^{E\ e)}_{\phi NN}(\vec{q}) = -\frac{12\sqrt{2}}{25} \left(\frac{D+F}{2f}\right)^2 g \int \frac{d^3p}{(2\pi)^3} \frac{1}{2\omega(\vec{p})} \times \quad (40)$$
$$\times \frac{\vec{p}^{\,2}}{E(\vec{q}/2) - \omega(\vec{p}) - E_{\Sigma^*}(\vec{q}/2 - \vec{p})} \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_{\Sigma^*}(-\vec{q}/2 - \vec{p})}$$

$$G^{M\ e)}_{\phi NN}(\vec{q}) = -\frac{36\sqrt{2}}{25} g \left(\frac{D+F}{2f}\right)^2 \int \frac{d^3p}{(2\pi)^3} \left(\vec{p}^{\,2} + \frac{(\vec{p}\vec{q})^2}{3\vec{q}^{\,2}}\right) \frac{1}{2\omega(\vec{p})} \times$$
$$\times \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_{\Sigma^*}(\vec{q}/2 - \vec{p})} \frac{1}{E(\vec{q}/2) - \omega(\vec{p}) - E_{\Sigma^*}(-\vec{q}/2 - \vec{p})} \quad (41)$$

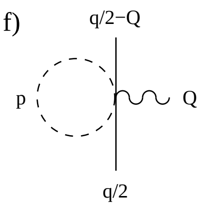
To evaluate this diagram we have used the relation

$$S_i S_j S^\dagger_k = \frac{5}{6} \mathrm{i}\epsilon_{ijk} - \frac{1}{6}\delta_{ij}\sigma_k + \frac{2}{3}\delta_{ik}\sigma_j - \frac{1}{6}\delta_{jk}\sigma_i \quad (42)$$

We do not take into account diagrams f) and g) since they cancel at $\vec{q} = \vec{0}$. At this value of $\vec{q}$ diagram f) is proportional to:

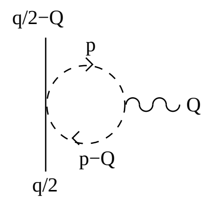
$$\int \frac{d^4p}{(2\pi)^4} 2\gamma^\mu g_{\mu\nu} \epsilon^\nu D(p) \quad (43)$$

f)



and

g)



and diagram g) is proportional to:

$$-\int \frac{d^4p}{(2\pi)^4}\gamma^\mu 4p_\mu \epsilon^\nu p_\nu D(p)D(p) \tag{44}$$

Taking into account the integral identity:

$$\int d^4p \frac{4p^\mu p^\nu}{(p^2+s+i\epsilon)^2} = \int d^4p \frac{2g^{\mu\nu}}{k^2+s+i\epsilon} \tag{45}$$

it is straightforward to see that these diagrams cancel at $\vec{q}=\vec{0}$.

Acknowledgments

One of us, J. P. wishes to ackowledge support from the Ministerio de Educacion. This work is also partly supported by DGICYT contract number BFM2000-1326 and E.U. EURODAPHNE network contract no. ERBFMRX-CT98-0169.

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