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Scalar and Pseudoscalar Higgs Couplings with Nucleons

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Abstract

The estimation of the cross sections of certain dark matter interactions with nuclei requires a correct evaluation of the couplings between the scalar or pseudoscalar Higgs boson and the nucleons. Progress has been made in two aspects relevant to this study in the past few years. First, recent lattice calculations show that the strange-quark sigma term σ_s and the strange-quark content in the nucleon are much smaller than what are expected previously. However, in view of the conflict between lattice and experimental results for the pion-nucleon sigma term $\sigma_{\pi N}$, the quark sigma terms $\sigma_{u,d,s}$ are still not well determined. Second, the pseudoscalar Higgs coupling with the nucleon is customarily expressed in terms of the axial-vector couplings g_A^a ($a = 0, 3, 8$) or the quark spin components Δu, Δd and Δs. Lattice calculations, semi-inclusive deep inelastic scattering data, and the small $\Delta G/G$ obtained by RHIC, COMPASS and HERMES all indicate a smaller $\Delta s = O(-0.02 \sim -0.03)$, which in turn implies sizable SU(3) breaking effects in the determination of g_A^8 and g_A^0. We re-evaluate the relevant nucleon matrix elements and compute the scalar and pseudoscalar couplings of the proton and neutron.

Keywords: Higgs, Nucleon

1. Introduction

Knowledge of scalar and pseudoscalar Higgs boson interactions with the nucleons at low energies is an important ingredient for computing certain dark matter–nuclei interaction cross sections. To evaluate the effective scalar and pseudoscalar couplings with the nucleons given by

$$g_{\phi NN} = (\sqrt{2}G_F)^{1/2} \sum_q \langle N|\zeta_q m_q \bar{q}q|N\rangle, \tag{1}$$
$$g_{\sigma NN} = (\sqrt{2}G_F)^{1/2} \sum_q \langle N|\xi_q m_q \bar{q}i\gamma_5 q|N\rangle,$$

it amounts to computing the nucleon matrix elements of quark scalar and pseudoscalar densities, namely, $\langle N|m_q\bar{q}q|N\rangle$ and $\langle N|m_q\bar{q}i\gamma_5 q|N\rangle$, where ζ_q and ξ_q are the couplings of the scalar ϕ and the pseudoscalar σ with quarks, respectively. While in the standard model $\zeta_q = 1$ for all q's, they may have values different from unity beyond the standard model.

The coupling $g_{\phi NN}$ was first studied by Shifman, Vainstein and Zakharov (SVZ) [1] who assumed a negligible strange quark contribution to the nucleon mass. Consequently, their scalar-nucleon coupling was dominated by heavy quarks. Based on the pion-nucleon sigma term available in late 80's which implied a sizable strange quark content in the nucleon, it was shown in [2, 3] that the effective coupling $g_{\phi NN}$ was dominated by the s quark rather than by heavy quarks. As a result, the scalar-nucleon coupling was enhanced by a factor of about 2.5 [3].

As for the pseudoscalar-nucleon coupling, it is conventional to express $g_{\sigma NN}$ in terms of the axial-vector couplings g_A^a ($a = 0, 3, 8$) or the quark spin components Δq with $q = u, d, s$. A thorough discussion of generic pseudoscalar-nucleon couplings was given in [3] based on the relation

$$\langle N|\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d + \bar{s}i\gamma_5 s|N\rangle = 0\,, \tag{2}$$

derived from the large-N_c and chiral limits. Contrary to the case of scalar-nucleon couplings, $g_{\sigma NN}$ does receive

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significant contributions from light quarks even in the chiral limit.

Recently, there is some progress in topics relevant to the interactions between the scalar or pseudoscalar Higgs boson and the nucleons. First, there have been intensive lattice calculations of the pion-nucleon sigma term $\sigma_{\pi N}$, the quark sigma term $\sigma_q \equiv m_q\langle p|\bar{q}q|p\rangle$, and the strange quark content in the nucleons characterized by the parameter y. Especially, the lattice calculation of σ_s is not available until recent years. The lattice results indicate that the strange quark fraction in the nucleon and σ_s are getting smaller than what we had one or two decades ago. For example, the new lattice average of $\sigma_s = (43 \pm 8)$ MeV [4] is much smaller than the value of $\sim$ 390 MeV in the late 80's and $\sim$ 130 MeV in the early 90's. Second, recent lattice and model calculations [5, 6] hint at a size of g_A^8 about 20% smaller than the canonical value 0.585 determined from the hyperon β-decays supplemented by flavor SU(3) symmetry. Since g_A^0 is extracted from the measurement of the first moment of the proton polarized structure function g_1^p, a decrease in g_A^8 will lead to an increase in g_A^0. This in turn implies a Δs reduced in magnitude by a factor of 2 to 3.

Motivated by the above-mentioned developments, in this work we would like to revisit the couplings of scalar and pseudoscalar bosons with the nucleons to incorporate the recent progress. Moreover, we wish to investigate if it is possible to evaluate the matrix elements $\langle N|G\tilde{G}|N\rangle$ and $\langle N|\bar{q}i\gamma_5 q|N\rangle$ without invoking the large-N_c chiral relation Eq. (2) as this relation is presumably subject to $1/N_c$ and chiral corrections.

2. Scalar Higgs Couplings to the Nucleons

Consider the effective scalar couplings with the nucleons given by Eq. (1), the relevant nucleon matrix elements are related to the trace of the energy-momentum tensor Θ^μ_μ. Under the heavy quark expansion [1]

$$m_h\bar{q}_h q_h \to -\frac{2}{3}\frac{\alpha_s}{8\pi}GG + O\left(\frac{\mu^2}{m_h^2}\right), \tag{3}$$

where μ is a typical hadron mass scale, the energy-momentum tensor becomes

$$\Theta^\mu_\mu = m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s - \frac{9\alpha_s}{8\pi}GG. \tag{4}$$

Under the light quark mass expansion, the baryon mass has the general expression

$$\begin{aligned} m_{\mathcal{B}} &= m_0 + \sum_q b_q m_q + \sum_q c_q m_q^{3/2} \\ &+ \sum_q d_q m_q^2 \ln\frac{m_q}{m_0} + \sum_q e_q m_q^2 + O(m_q^3), \end{aligned} \tag{5}$$

where the coefficients b_q, c_q, d_q and e_q are baryon state-dependent. To the leading order, the masses of octet baryons can be expressed in terms of the proton matrix elements

$$B_u \equiv \langle p|\bar{u}u|p\rangle, \quad B_d \equiv \langle p|\bar{d}d|p\rangle, \quad B_s \equiv \langle p|\bar{s}s|p\rangle.$$

Under SU(3) symmetry we have

$$\begin{aligned} B_u - B_s &= \frac{2(m_\Xi - m_N)}{2m_s - m_u - m_d} = 3.94, \\ B_d - B_s &= \frac{2(m_\Sigma - m_N)}{2m_s - m_u - m_d} = 2.64 \end{aligned} \tag{6}$$

at $\mu = 2$ GeV.

To determine the parameters B_u, B_d and B_s we need additional information. To proceed, we define two quantities:

$$y \equiv \frac{2B_s}{B_u + B_d}, \tag{7}$$

which characterizes the strange quark content in the proton and

$$\sigma_0 \equiv \hat{m}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle, \tag{8}$$

with $\hat{m} = (m_u + m_d)/2$, which is related to the pion-nucleon sigma term

$$\sigma_{\pi N} \equiv \hat{m}\langle N|\bar{u}u + \bar{d}d|N\rangle \tag{9}$$

by

$$\sigma_{\pi N} = \frac{\sigma_0}{1-y}. \tag{10}$$

At the leading order,

$$\sigma_0 = \frac{3\hat{m}}{m_s - \hat{m}}(m_\Xi - m_\Lambda). \tag{11}$$

Numerically, σ_0 is of order 24 MeV. The experimental and theoretical information of $\sigma_{\pi N}$ will enable us to determine the strange quark fraction y which puts an additional constraint on the parameters B_u, B_d and B_s.

Based on the sigma term $\sigma_{\pi N} = 55 \sim 60$ MeV obtained in the early 80's, one has a large strange quark content $y \approx 0.55$ and

$$\begin{aligned} &\sigma_u \approx 20\,\text{MeV}, \quad \sigma_d \approx 33\,\text{MeV}, \\ &\sigma_s \approx 394\,\text{MeV}, \end{aligned} \tag{12}$$

The strange quark content y and the sigma term σ_s are both unexpectedly large. Nevertheless, they are significantly reduced in 90's. Based on heavy baryon chiral perturbation theory to order $O(m_q^2)$, Borasoy and Meißner [7, 8] obtained

$$\sigma_0 = 36 \pm 7\,\text{MeV}, \quad y = 0.21 \pm 0.20, \tag{13}$$