Could Goldstone Bosons Generate an Observable $1/R$ Potential?

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We discuss gauge models in which exchange of Goldstone bosons combined with the QCD anomaly can lead to spin-independent $1/R$ and T-nonconserving $\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}/R^2$ potential. In contrast with axion-exchange forces which lead to new short-range macroscopic forces (range ~ 10 cm), these forces could be observable in Eötvös-Dicke–type experiments involving polarized and unpolarized materials.

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An exactly conserved locally gauged baryon number would generate a long-range $1/r$ force via the exchange of the corresponding massless vector boson. The high-precision Eötvös-type experiments[1] checking the equivalence principle rule out any appreciable coupling for such a force.[2]

This is not the case for the massless spin-0 Goldstone bosons corresponding to the spontaneous breakdown of a global symmetry. Such particles have derivative couplings[3] which vanish in the $q=0$ limit. Their exchange between nucleons or electrons gives rise to $1/r^3$ spin-dependent potentials which are very hard to detect. We would like to point out that this result may change when we have a $\theta F\tilde{F}$ term added to the QCD Lagrangean leading to interesting phenomenological and experimental possibilities.

Let us focus on a Goldstone boson ϕ associated with the spontaneous breaking of some global axial U(1) symmetry, with the corresponding U(1) quantum number carried by quarks. Its coupling to quarks is of a pure γ_5 type,

$$\mathscr{L}^I_{\phi qq} = g_\phi \phi \bar{\psi}\gamma_5\psi, \tag{1}$$

so that at a low energy it is equivalent to the pure derivative coupling

$$\mathscr{L}^I_{\phi qq} \approx F_\phi^{-1}\,\partial_\mu\phi\bar{\psi}\gamma^\mu\gamma^5\psi. \tag{2}$$

F_ϕ and g_ϕ are related via a Goldberger-Treiman relation,

$$g_\phi = 2mg_A/F_\phi = 2m/F_\phi, \tag{3}$$

where m denotes the fermion mass and g_A the axial coupling ($g_A \approx 1$). The ϕ vertex $F_\phi^{-1}(\boldsymbol{\sigma}\cdot\mathbf{q})$ vanishes in the $\mathbf{q}\rightarrow 0$ limit and the potential resulting from the ϕ exchange is

$$V(r) = F_\phi^{-2}(\boldsymbol{\sigma}_1\cdot\nabla)r^{-1}(\boldsymbol{\sigma}_2\cdot\nabla) \approx (S_{12}/F_\phi^2)r^{-3}, \quad S_{12} = \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 - 3(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{r}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{r}}). \tag{4}$$

Astrophysics considerations related to the cooling of red giants imply[4] that

$$F_\phi >> 10^8\ \mathrm{GeV}, \tag{5}$$

and similar bounds are obtained if the ϕ arises from a wider context of spontaneous breaking of a global horizontal symmetry from limits on $K\rightarrow\pi+\phi'$, $\mu\rightarrow e+\phi''$, etc.[3] With such an F_ϕ, the interaction (4) is practically undetectable.[5]

Consider next this theory as part of a realistic theory of quarks and leptons, that contains the nonvanishing but small QCD anomaly term $\theta G\tilde{G}$ (where G is the color gluon field). To study the impact of the anomaly term on the coupling of the Goldstone boson to quarks, let us review the familiar case of the pseudoscalar pion-nucleon coupling: $g_{\pi NN}\bar{N}\gamma_5 N\pi$. It has been shown[6] that in the presence of the anomaly term, an induced scalar coupling of type

$$\mathscr{L}_s = \frac{\theta}{F_\pi}\frac{m_u m_d}{m_u+m_d}\bar{N}N\pi \tag{6}$$

appears. This suggests, by analogy, that if the Goldstone boson ϕ of interest couples as $(m_q/F_\phi)\bar{q}\gamma_5 q\phi$, the anomaly term will induce a scalar coupling

$$\delta\mathscr{L}_{\phi\bar{N}N} \approx \frac{\theta}{F_\phi}\left(\frac{m_u m_d}{m_u+m_d}\right)\bar{N}N\phi \equiv \mu\frac{\theta}{F_\phi}\phi\bar{N}N. \tag{7}$$

One could think of the induced coupling in terms of the diagram in Fig. 1, where the QCD anomaly induces the scalar coupling at the $NN\pi$ vertex in Eq. (6) and the pion propagator cancels the m_π^2 leading to Eq.

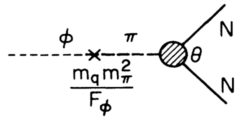

FIG. 1. Typical diagram for the induced scalar coupling in the presence of the QCD anomaly.

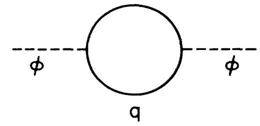

FIG. 2. One-loop graph involving two external Goldstone-boson lines.

(7). Note that both (6) and (7) vanish when any one of the quarks has vanishing mass, since in this case the effect of the θ term is compensated by an appropriate chiral rotation.

The important observation is that since the Goldstone boson ϕ has zero mass (see later), the scalar vertex induces a long-range spin-independent $1/R$ potential

$$V_S^{NN}(R)=\left(\frac{\theta\mu}{F_\phi}\right)^2\frac{1}{R}\equiv\frac{g_S^2}{R}. \tag{8}$$

The strength of the new interaction is very weak. From experimental bounds on the electric dipole moment of the neutron, we know[7] that

$$\theta \leq 10^{-10}, \tag{9}$$

which together with $\mu \approx 4$ MeV and Eq. (5) implies

$$g_S^2 \leq 10^{-41} \tag{10}$$

and a very weak ϕ force.

However, if the ϕ force adds up coherently, i.e., nucleons and leptons possess the U(1) quantum number without exact cancellation as in the case of em charge, then $V_\phi(r)$ could be comparable to the gravitational potential

$$V_G^{NN}\approx\frac{m_N^2}{(m_{\rm Planck})^2}\frac{1}{r}\simeq 10^{-38}\times\frac{1}{r}. \tag{11}$$

Furthermore, $V_\phi(r)$ will not respect the inertial-mass–interaction-strength equivalence. Let us denote by x the degree to which the $V_\phi(r)$-mass proportionality is violated as we vary the isotope (nucleus) considered. x could be as large as 0.1 if ϕ couples only to up or down quarks. Even if the coupling to u and d quarks is equal, nuclear binding, Coulomb, and n-p mass-difference effects will make $x=0.01$.

The new scalar interaction will therefore cause an apparent deviation

$$\delta = xV_S/V_G = xg_S^2/10^{-38} \tag{12}$$

from equivalence in Eötvös-type experiments. The Roll-Krotkov-Dicke experiment[8] limits possible different accelerations towards the Sun of different elements to

$$\delta_{(\rm Sun)} \leq 10^{-11}. \tag{13}$$

The Braginsky-Panov experiment[9] claims a better accuracy for a similar experiment,

$$\delta_{(\rm Sun)} \leq 10^{-12}, \tag{14}$$

and the early Eötvös experiment itself[10] claimed $\delta_{(\rm Earth)} \leq 10^{-9}$. With $x=0.1$, we get from (12) and (13) or (14) stronger bounds,

$$g_S^2 \leq 10^{-48}\text{–}10^{-49}\ \{\text{Sun}\},$$
$$g_S^2 \leq 10^{-46}\ \{\text{Earth}\}, \tag{15}$$

than the one obtained [Eq. (10)] by the bounds on θ and F_ϕ separately.

In the previous discussion we have assumed all along that the ϕ is exactly massless. One would expect, however, that the θ term which leads to violation of the pure derivative coupling will also generate a tiny mass for the otherwise exactly massless Goldstone boson, which can be seen from the following heuristic argument.

Specifically let us consider a quark-loop diagram with two external ϕ legs (Fig. 2). If the interaction at both vertices is of a pure derivative $(\partial_\mu\phi)$ form, then only a wave-function renormalization of the kinetic term $(\partial_\mu\phi)^2$ will be contributed. This, in fact, is a very nice reciprocity between the Goldstone theorem and the derivative-coupling theorem. However, the small scalar coupling g_S may yield a mass correction roughly estimated to be

$$\delta m^2 \simeq g_S^2 m_q^2 \approx \frac{\theta^2 m_u^2 m_q^2}{F_\phi^2} \text{ or } \delta m = \frac{\theta m_q m_u}{F_\phi}. \tag{16}$$

This apparent breakdown of Goldstone's theorem is perhaps related to the nonlocality of instanton effects. (Note that the scalar coupling to fermions of equal mass, unlike the pseudoscalar one, cannot be expressed as a derivative term.) The corresponding Compton wavelength or range of force is

$$\lambda_\phi = F_\phi/\theta m_q m_u. \tag{17}$$

Note that m_q could be as large as the t-quark mass; but because of hadronic uncertainties, we cannot be sure of its magnitude and, therefore, we choose the following plausible range for $m_q = 10$ MeV to 1 GeV. Using separate bounds on F_ϕ and θ, we find

$$\lambda_\phi \gtrsim 20\text{–}10\,000 \text{ km} \tag{18}$$

Thus, it can be as large as the radius of the earth and will, therefore, affect the gravitational fall towards the earth. For the case of gravitational fall towards the Sun, however, since $\lambda_\phi << R_{\text{Earth-Sun}}$, $\delta_{(\text{Sun})}$ will not be affected by V_ϕ. We also wish to point out that similar induced scalar couplings[11] of the invisible axion[12] have been discussed in the literature. However, since the invisible axion has mass,[12] $m_a \approx 10^{-12}$ to 10^{-6} eV, it corresponds to an interaction with range ≤ 10 cm.

In general the force corresponding to massive ϕ,

$$\mathscr{F}_\phi \approx r^{-2} e^{-r/\lambda_\phi}, \tag{19}$$

will operate only on distances $r \leq \lambda_\phi$. Thus if we have an attracting mass of radius R and uniform density ρ the net force due to this on a point object on the surface is

$$\mathscr{F}_\phi \simeq \int^{\lambda_\phi} (g_s^2/r^2) \rho r^2 \, dr \approx \lambda_\phi g_s^2 \rho \tag{20}$$

rather than $\mathscr{F}_\phi \approx R\rho(Gm_p^2)$, and $\mathscr{F}_\phi$ will be smaller by a factor of $(\lambda_\phi/R) g_S^2/Gm_p^2$. Thus for $\lambda_\phi \simeq 1$–10 cm,[13] as is the case for the axion, $\mathscr{F}_\phi$ will be further reduced with respect to the gravitational pull of the earth by 10^{-9}–10^{-8}. A null experiment using a superconducting gravity gradiometer in Earth orbit has recently been proposed by Paik,[14] which can be sensitive to such deviations from gravitational forces at the level of 10^{-11}.

From the above discussion it follows that for the "ϕ force" to be significant at large distances we need m_ϕ to be smaller than the typical estimate for axion mass[12]

$$m_a \approx (f_\pi/F_a) m_\pi \approx 10^{-5}\text{–}10^{-6} \text{ eV}. \tag{21}$$

In the remaining paragraphs, we present two illustrative models, where such a long-range spin-independent potential arises. Consider the class of models where lepton number is spontaneously broken.[15,16] This requires an extension of the standard model by the addition of either[15] (i) a right-handed neutrino and a gauge-singlet Higgs field with $L=2$ or[16] (ii) a left-handed $SU(2)_L$-triplet Higgs multiplet with $L=2$. We do not discuss details of the model except to recall that in both these models, the massless Goldstone boson which couples to leptons only prior to spontaneously breaking acquires a coupling to quarks after symmetry breaking takes place with equivalent F_ϕ given as follows $[q=(u,d)]$:

$$\mathscr{L}_{\phi q\bar{q}} = iF_\phi^{-1} \bar{q}\gamma_5 q\phi, \tag{22}$$

where, for case (i),

$$F_\phi^{-1} \approx (G_F/16\pi^2) m_\nu; \tag{23}$$

for case (ii),

$$F_\phi^{-1} \approx G_F^{1/2} (v_T/v_D), \tag{24}$$

where v_T and v_D denote the vacuum expectation values of Higgs triplet and doublet, respectively. As mentioned, the quark sector is identical to that of the standard model so that it has an arbitrary value for the anomaly parameter, θ, only restricted by the experiments to be less than 10^{-10}. Using present bounds on m_ν and v_T,[17] we find, for case (i),

$$g_S^2 \leq 10^{-54}; \tag{25a}$$

for case (ii),

$$g_S^2 \leq 10^{-44}\text{–}10^{-45}. \tag{25b}$$

These bounds are well within the observable experimental range in Eötvös-type experiments involving the Earth. An upcoming experiment[18] using NASA satellites is expected to improve the precision of Eötvös-type experiments by eight orders of magnitude, which could therefore test both kinds of models.

The next point we wish to note is that exchange of the majoron can also lead to spin-dependent T- and P-nonconserving $1/r^2$-type long-range forces. In this case only one vertex is spin dependent, leading to the following form of the potential ($\lambda_\phi \approx 10^4$ km):

$$V_{\text{SD}} = (f_{\text{SD}}^2/r^2) \boldsymbol{\sigma} \cdot \hat{\mathbf{r}} e^{-r/\lambda_\phi}, \tag{26}$$

where

$$f_{\text{SD}}^2 \simeq \mu\theta/F_\phi^2. \tag{27}$$

The strength of this force for the two cases described here is, for case (i),

$$f_{\text{SD}}^2 \leq 10^{-42} \text{ GeV}^{-1}; \tag{28a}$$

for case (ii),

$$f_{\text{SD}}^2 \leq 10^{-34} \text{ GeV}^{-1}. \tag{28b}$$

The present bounds on these parameters can be inferred from the work of Leitner and Okubo[19] to be

$$f_{\text{SD}}^2 \leq 10^{-27} \text{ GeV}^{-1}. \tag{29}$$

It should be possible in a laboratory experiment to attain sensitivity of the level predicted in Eqs. (28).

In conclusion, we find observable strengths for $1/r$-type potentials (with range $\approx 10^4$ km) in majoron models in the presence of the QCD anomaly term, as well as spin-dependent T-nonconserving $1/r^2$-type terms. Experimental test of these effects by macroscopic experiments would throw light on physics at submicroscopic distance scales.

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