Possible new long-range interaction and methods for detecting it

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The possible existence of a stable, massless, 0^{-+} Goldstone particle exhibiting a semiweak interaction with fermions (an arion) is discussed. An arionic long-range interaction could be detected by any method suitable for detecting a weak magnetic field in an experiment with oriented spins, if the magnetic field produced by these spins is suppressed by a superconducting shield.

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The possible existence of a massless Goldstone particle corresponding to a spontaneous breaking of the chiral lepton symmetry (a "massless axion") was pointed out in Ref. 1. As a specific model that paper adopted a model with three doublets of Higgs fields, each of which imparts a mass to fermions with a given electric charge. In principle, however, Higgs fields which do not interact with fermions might exist. In this case there is the possibility that some additional (spontaneously broken) symmetries might appear, so that new, massless Goldstone particles might arise.

In this paper we will consider three cases: a—that in which all the fermions acquire mass from a single Higgs doublet φ_1 (the minimal model); b—that in which φ_1 imparts a mass to quarks with a charge of $-1/3$ and to leptons, while φ_2 imparts a mass to quarks with a charge of 2/3 (this is the usual assumption in the theory of the standard axion and it is prescribed by the grand unification theories); c—that in which φ_1 imparts a mass to the lower quarks, φ_2 imparts a mass to the upper quarks, and φ_3 imparts a mass to leptons (as in Ref. 1). We will furthermore assume that there is an arbitrary number of other doublets $\varphi_i, i \leqslant n$, which do not interact with fermions. In this case it is a straightforward matter to show that if all the phases of the Higgs field can be rotated independently, then the theory will acquire, in addition to the axion with a mass, $\alpha(x)$, some massless Goldstone particles $\alpha(x)$, $\alpha'(x)$ with the following Lagrangians describing the interaction with fermions [for cases a, b, and c, respectively]:

$$\mathcal{L} = \frac{i}{v}\left[m_d(\bar{d}\gamma_5 d) - m_u(\bar{u}\gamma_5 u) + m_e(\bar{e}\gamma_5 e)\right]\sqrt{\frac{v^2}{v_1^2} - 1}\; a\,, \tag{1a}$$

$$\mathcal{L} = \frac{i}{v}\left[m_d(\bar{d}\gamma_5 d) + m_e(\bar{e}\gamma_5 e)\right]\left[\frac{v v_2}{v_{12} v_1} a + \sqrt{\frac{v^2}{v_{12}} - 1}\, a\right] + \frac{i}{v} m_u(\bar{u}\gamma_5 u)\left[\frac{v v_1}{v_{12} v_2} a - \sqrt{\frac{v^2}{v_{12}^2} - 1}\, a\right], \tag{1b}$$

$$\mathcal{L} = \frac{i}{v} m_d(\bar{d}\gamma_5 d)\left[\frac{v v_2}{v_{12} v_1} a + \sqrt{\frac{v^2}{v_{12}^2} - 1}\, a\right] + \frac{i}{v} m_u(\bar{u}\gamma_5 u)\left[\frac{v v_1}{v_{12} v_2} a - \sqrt{\frac{v^2}{v_{12}^2} - 1}\, a\right]$$

$$+ \frac{i}{v} m_e(\bar{e}\gamma_5 e)\left[-\frac{1}{\sqrt{\frac{v^2}{v_{12}^2} - 1}} a + \frac{v}{v_3}\frac{\sqrt{v^2 - v_{123}^2}}{\sqrt{v^2 - v_{12}^2}} a'\right], \qquad (1c)$$

$$v_k = \sqrt{2} < \varphi_k^{\circ} >, \; v_{12}^2 = v_1^2 + v_2^2, \; v_{123}^2 = v_1^2 + v_2^2 + v_3^2, \; v^2 = \sum_{k=1}^{n} v_k^2 = (G_F\sqrt{2})^{-1}.$$

To save space, we have written out only the fermions of the first generation in Eqs. (1). The Goldstone particle $\alpha(x)$ in (1c) is the "massless axion" of Ref. 1. The case (1a) illustrates the fact that a massless Goldstone particle can exist even in the absence of an axion having a mass, regarding which the situation remains unclear: Although indications for its existence have been reported in some well-known papers,[2] some serious objections have also been raised (see Ref. 3, for example). At any rate, regardless of the details of the theory, it is interesting to examine the possible existence of a stable, massless, 0^{-+} Goldstone particle α which exhibits a semiweak interaction with fermions which is diagonal in the flavors with a coupling constant $x_f m_f/v$, where $v = (G_F\sqrt{2})^{-1/2}$, m_f is the fermion mass, and x_f is a parameter ~ 1. To distinguish this hypothetical problem from the axion with a mass, we will call it an "arion." Although the standard arguments which led to the hypothesis of the axion do not extend to the case of symmetries corresponding to the appearance of arions, these symmetries are actually present in several theories. These are the many technicolor models, for example, in which a large number of Goldstone bosons (and pseudo-Goldstone bosons) almost unavoidably arise, constructed from the various techniquarks.[4]

What is the experimental status of the arion? Since arions are stable, all the experimental searches for axions from 2γ decay are irrelevant. The greatest danger *to* the arion hypothesis is posed by the absence of the decays $\phi \to a\gamma$ (Ref. 5) and $K^+ \to \pi^+ a$ (Ref. 6) and astrophysical considerations based on the estimated rate of axionic emission of energy by the sun and the red giants.[7] The restriction on the rate of the decay $\psi \to a\gamma$, however, as asserted in Ref. 5, means only that the condition $x_c < 1$ holds (if the coupling constant describing the coupling of the arion with the c quark is defined as $x_c m_c/v$), while the experimental limit[6] on the decay $K^+ \to \pi^+ a$ is much less restricted for the arion than for the ordinary axion. The arions interact with the divergence of an isovector axial current, so that the selection rule $\Delta I = 1/2$ applies to the decay $K^+ \to \pi^+ a$.

An extremely serious objection to the existence of the arion is the loss of energy from the sun. Curiously, however, the usual estimate of the mean free path of the arion, determined from the reaction $a + e \to \gamma + e$, is three orders of magnitude larger than the mean free path associated with ternary collisions, in which Coulomb exchange with a third particle—a proton or electron—occurs. Although this situation is not sufficient to lead to a strong absorption of arions, it appears that the picture is still somewhat fuzzy and requires a more careful look. In particular, the arions produced in relatively cold layers of the sun might be absorbed extremely strongly.

In this letter I wish to discuss the possibility of observing a static, long-range arion field. The exchange of arions leads to a tensor interaction potential between two fermions f_1 and f_2 (quarks or leptons) of the type

$$V_a(r) = x_{f_1} x_{f_2} \frac{G_F}{8\pi\sqrt{2}} \frac{1}{r^3} \left(\vec{\sigma}_1\vec{\sigma}_2 - 3(\vec{\sigma}_1\mathbf{n})(\vec{\sigma}_2\mathbf{n})\right). \quad (2)$$

Here x_f are the factors, of order unity, which are the coefficients of the α and α' fields in Eqs. (1). It is a simple matter to transform from an interaction of quarks to an interaction of nucleons in (2); it is sufficient to introduce in (2) $x_{p,n} = x_{u,d}(-g_A)$, where $g_A = -1.25$ is a weak axial form factor.[1]

Interaction (2) is completely analogous to the interaction of two magnetic moments. Two magnetized ferromagnets have an arion interaction which amounts to $x_e^2 G_F m_e^2/2\pi\sqrt{2}a = 4.7\times 10^{-11} x_e^2$ of the ordinary magnetic interaction; the dependence on the distance, the orientation of the magnetizations, etc., is completely the same as for ordinary magnetism. Interestingly, the arionic nucleon–nucleon, nucleon–electron, and electron–electron interactions are all of the same order of magnitude, in contrast with their magnetic counterparts.

Can the ordinary magnetic interaction of two permanent magnets be shielded carefully enough to permit the detection of an arion interaction? Apparently the only possibility here is to surround the magnets with superconducting shields, so that the magnetic field does not penetrate through the shield (because of the Meissner effect). A decisive circumstance here is that the superconducting layer will not shield the arion field, since the latter interacts only with spins $[\mathscr{L}_{\text{int}} = (x_f/2v)\vec{\nabla} a(\psi^* \vec{\sigma}\psi)]$, while the Meissner effect for an ordinary magnetic field arises from an interaction involving the exchange $\mathbf{p} \rightarrow \mathbf{p} - eA$.

Schematically, we might imagine a Cavendish experiment in which a magnetic needle shielded by a superconducting screen and attached to a torsion balance interacts with a massive magnet. A torsional (or ordinary) pendulum might be driven into oscillation by reversing the magnetization of an attached massive magnet. The moment of force acting on the needle can be easily found by using the value given above $(4.7\times 10^{11}\, x_e^{\,2})$ for the ratio of the magnetic and arionic interactions:

$$M = 4.7\times 10^{-11} x_e^2\, \mu_{Bohr}\, NH = 4.37\times 10^{-31} NH x_e^2 \left(\frac{\text{dyn}\cdot\text{cm}}{\text{G}}\right) \quad (3)$$

where N is the number of oriented spins in the needle, and H is the magnetic field. With $x_e = 1$, $N = 10^{23}$, and $H = 10^3$ G we find $M = 5\times 10^{-5}$ dyn cm, which appears to be detectable.

Let us compare the arionic and gravitational forces. The ratios of these forces for two small iron samples is given by the following expression, where we are taking into account the fact that for each Fe atom there are 58 nucleons involved in the gravitation, while in the arionic interaction there are ~ 2 electrons with oriented spins:

$$F_a / F_g = x_e^2 \left(\frac{9\text{cm}}{r} \right)^2 . \tag{4}$$

The arionic interaction is thus comparable to the gravitational interaction at about 10 cm. Realistic objects, with finite dimensions, would have the same scale dimensions.

Generally, since the arionic forces are absolutely equivalent to weak magnetic forces in a spin-spin interaction, any method available for detecting a weak magnetic field (a magnetometer) can be used to detect the arionic long-range interaction, provided that the magnetic fields produced by the spins can be suppressed by a superconducting shield. In principle, if the arionic long-range interaction did exist, then the study of this interaction by both macroscopic and microscopic methods might become a broad research field, comparable to the physics of magnetic phenomena. A quantitative discussion of the various effects that arise here, e.g., an arionic Zeeman effect, spin precession in an arion field, etc., requires consideration of the specific experimental possibilities and goes beyond the scope of the present paper. We will simply point out that in all cases the magnitude of the effect is determined by the product of the "arion magnetic moments" of the particles involved, which are equal to $x_f(G_F/8\pi\sqrt{2})^{1/2}$. Here are the ratios of the arionic and actual magnetic moments for the electron, the proton, and the neutron:

$$\rho_e = -x_e \left(\frac{G_F m_e^2}{2\pi\sqrt{2}a} \right)^{1/2} = -x_e \times 0.685 \times 10^{-5} ,$$

$$\rho_p = x_u \left(\frac{-g_A}{\mu_p} \right) \left(\frac{G_F m_p^2}{2\pi\sqrt{2}a} \right)^{1/2} = x_u 0.563 \times 10^{-2}, \tag{5}$$

$$\rho_n = x_d \left(\frac{-g_A}{\mu_n} \right) \left(\frac{G_F m_p^2}{2\pi\sqrt{2}a} \right)^{1/2} = -x_d \times 0.823 \times 10^{-2} , \quad x_u = -x_d .$$

Interestingly, in version (1c) of the theory the unknown factor $(x_e = x_u{}^{-1})$ cancels out in the arionic interaction of an electron with nucleons. In this case, in units of the corresponding magnetic moments, we would have

$$\rho_e \rho_n = -0.564 \times 10^{-7}, \quad \rho_e \rho_p = -0.386 \times 10^{-7}. \tag{6}$$

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