Experimental test for arion ↔ photon oscillations in a homogeneous constant magnetic field

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The oscillations between photon and arion in a constant homogeneous magnetic field are considered, the arion being a strictly massless pseudoscalar Goldstone particle. It is shown that using the Sun as a source of arions it is easy to surpass the astrophysical limit for its existence in a laboratory experiment, while it is practically impossible for axions. The connection between the arion ↔ photon oscillations in a homogeneous magnetic field and the production of photons by axions in an inhomogeneous field is discussed. The oscillations in a medium with a refraction index $n \neq 1$ are also considered.

In Refs. 1–3 we have discussed the possibility of the existence of a strictly massless Goldstone particle (the arion) corresponding to the spontaneous breaking of an exact symmetry similar to the chiral Peccei-Quinn pseudosymmetry (for a review, see Ref. 4). Many of the properties of the arion are quite similar to those of the axion; the main difference is that its mass exactly equals zero. This property allows us to suggest experiments where long-range forces mediated by exchange of arions could be detected by methods similar to those for the detection of a very weak magnetic field.[2] Some of these experiments have actually been performed[5,6] and yielded a negative result which rules out the possibility of the interaction of the arion with quarks and leptons with the strength m_f/V with $V \sim 5$ TeV and m_f is the mass of the fermions.

The main purpose of this paper is to analyze the possibilities of the search for the arion in a much more sensitive experiment than the type suggested previously for the search for the axion, but with somewhat different physics involved. Before we discuss the experiment itself let us recall the simplest model for the arion[1] and some of its general (model-independent) properties.[4]

In the simplest model we consider the possibility that all the fermions with different charge (up and down quarks and leptons) acquire their masses from three different Higgs bosons. As is well known this is the most general form of Yukawa interaction which conserves flavors naturally in neutral-Higgs-boson exchange. In this model the total Lagrangian may be invariant to the chiral rotation of leptons alone, without any transformation of quarks, if the Higgs-boson potential is invariant to the phase transformation of the single Higgs-boson field which gives mass to leptons. Unlike the axion symmetry this "arion" symmetry is not spoiled by an anomaly and its spontaneous breaking gives rise to a Goldstone-boson arion. In fact, as was pointed out in Ref. 1, the possibility of the independent chiral rotations of quarks and leptons is the only possibility that had not been considered before.

Among the model-independent properties of the arion we mention the following.[4]

(1) The arion coupling to the fermion f with the mass m_f is pseudoscalar and has the form (α is the arion field)

$$\mathcal{L}=\frac{m_f}{V_f}(\bar{f}i\gamma_5 f)\alpha = x_f\frac{m_f}{V}(\bar{f}i\gamma_5 f)\alpha \; . \tag{1}$$

Here V is the scale of the arion symmetry breaking; for different fermions the scales V_f may differ, so $V_f = V/x_f$. In the simplest model mentioned above, the scale V is of the order of the weak scale $V=(G_F\sqrt{2})^{-1/2}=246$ GeV. However it can also be much larger if, for example, the Higgs-boson potential contains an additional weak singlet with a large vacuum expectation value (VEV) which transforms nontrivially under the arion symmetry ("invisible arion").

(2) Exchange of arions leads to an interaction of two fermions similar to that of two spin magnetic moments with an "arion magneton" of each fermion being equal to

$$\mu_f = \frac{x_f}{4\sqrt{\pi}}\frac{1}{V} \; . \tag{2}$$

This suggests the possibility of "magnetic-type" experiments which were realized in Refs. 5 and 6.

(3) The interaction of the arion with the electromagnetic field is described by the effective interaction of the same type as for the axion:

$$L=\frac{1}{4M}F_{\mu\nu}\tilde{F}_{\mu\nu}\alpha=\frac{1}{M}E\cdot H\alpha \; , \tag{3}$$

where $F_{\mu\nu}$ is the electromagnetic field, $F_{\mu\nu}=\frac{1}{2}\epsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}$, and E and B are the electric and the magnetic fields, respectively. The value of M is given by

$$M^{-1}=V^{-1}\left|\frac{\alpha}{\pi}\sum_f x_f q_f^2\right|, \quad \alpha=\tfrac{1}{137} \; . \tag{4}$$

q_f are the electric charges of the fermions.

In the model mentioned above, for the "standard" (not "invisible") arion we get $x_u=-x_d=x_e^{-1}$ with $V=(G_F\sqrt{2})^{-1/2}=246$ GeV (Refs. 1 and 4). As for the realistic case of the invisible arion the equation $x_u=-x_d$ is still valid since it corresponds to the absence of the anomaly in the arion current.[1,4] The equation $x_a=x_e^{-1}$ in this case can be obtained by using an uncertainty in the choice of V. To have $x_u = x_e^{-1}$ one should choose $V = \sqrt{V_u V_e}$. However, it requires that $V_u V_e > 0$ which is not correct in some models. So we get for three generations of fermions:

$$M^{-1} = V^{-1}\frac{\alpha}{\pi}3(x_u + 1/x_u), \quad M \leq \frac{\pi}{6\alpha}V \simeq 50V \ . \tag{5}$$

The interaction (3) leads to an interesting phenomenon of the arion⇄photon oscillations in a homogeneous constant magnetic field since these particles are degenerate in masses.[7] In Ref. 7 it was proposed to use a laser beam in a magnetic field as a source of arions and then transform arions back to photons after they penetrate a screen. Quite recently the same device has been suggested for the search of axions[8] although the physics is somewhat different. While for arions there are oscillations arion⇄photon in a homogeneous magnetic field there are no such oscillations for axions because of the difference in masses with the photon: $m_a^2 \sim (m_\pi f_\pi / V)^2$ is much bigger than the mixing mass term ($\omega B/M$). There B is the magnetic field and ω is the energy of the beam. Because of this, for the case of axions an inhomogeneous magnetic field should be applied and production (not oscillation) of axions must be considered. The same difference also relates to Sikivie's work[9] which was the first to suggest the use of the trilinear interaction of axions with photons for production of axions in an external magnetic field. In spite of this obvious difference we shall see in what follows that when the length of oscillations is much smaller than the size of the magnetic field, the probability of oscillation arion→photon is the same as the probability of creation of the photon by the axion for $m_a \to 0$. This is because in this case a magnetic field is actually inhomogeneous due to its finite length.

The most stringent restrictions on the existence of axions and/or arions come out of energy loss of stars by emission of pseudoscalar particles.[10–14] Recently it was shown that (i) the limit arising from consideration of the Sun is comparable to that of the red giants (previously it was believed that the latter give much stronger limit) and (ii) that the plasma screening effects essentially change the limit for the parameter M, directly connected to the Primakoff-type production of axions and/or arions. We have, from the most recent investigation,[14]

$$V_e > 1.1 \times 10^7 \text{ GeV}, \quad M > 4.2 \times 10^8 \text{ GeV} \ . \tag{6}$$

If we assume that $M \sim 50V$, as is suggested by (5), the limits for M and V more or less match each other. It is interesting that the restriction (6) for M, following from the calculation of axion (arion) emission from the Sun, is not weaker than the limit from red giants. Eventually we can adopt the point of view that the Primakoff effect gives more or less the same flux of axions from the Sun as other processes, such as, for example, bremsstrahlung.[14] The value of $M = 4.2 \times 10^8$ GeV corresponds to this flux equal to the photon flux. The latter, at the surface of the Earth, is

$$F_\alpha = 1.3 \times 10^6 \text{ erg cm}^{-2}\text{sec}^{-1} \ . \tag{7}$$

Let us now consider the phenomenon of arion-photon oscillations as a possible test in a search of arions using the Sun as a source of arions as it was suggested by Sikivie for axions.[9] We shall see that for arions one can easily surpass the limit (6) for M, while for axions it is practically impossible to reach an astrophysical limit.

The mechanism of arion⇄photon oscillations has been described in some detail in Ref. 7. The result has the simplest form under the mild assumption that $B/Mk \sin\theta \ll 1$ (k is the momentum of the particle, θ is the angle between B and k). In fact this is not really a restriction since $B/Mk \sim 10^{-19}$. The eigenvectors of the Hamiltonian are

$$\psi_1 = \frac{1}{\sqrt{2}}(\alpha + i\gamma), \quad \psi_2 = \frac{1}{\sqrt{2}}(\alpha - i\gamma) \ , \tag{8}$$

where γ is the photon field with the polarization along the magnetic field B. The eigenvalues corresponding to $\psi_{1,2}$ are

$$\omega_{1,2} = \left[k^2 + \frac{B^2}{2M^2} \pm \frac{B}{M}\left[\frac{B^2}{4M^2} \pm k^2 \sin^2\theta\right]^{1/2}\right]^{1/2} \simeq k \pm \frac{B\sin\theta}{2M} \ . \tag{9}$$

An arion moving into a magnetic field perpendicular to the direction of its motion ($\sin\theta = 1$) begins to oscillate $\alpha \rightleftarrows \gamma$. If at the initial time the state $\psi(0) = \alpha$ then for $t > 0$ the probabilities of the arion and photon states are equal to

$$W_\gamma(t) = \sin^2\frac{\Delta\omega t}{2} \ , \quad W_\alpha(t) = \cos^2\frac{\Delta\omega t}{2} \ , \quad \Delta\omega = \omega_1 - \omega_2 = \frac{B}{M} \ , \tag{10}$$

i.e.,

$$W_\gamma(L) = \sin^2 BL/2M \ , \tag{10$'$}$$

where L is the distance.

In order to observe real oscillations the magnetic field should be homogeneous at least for several oscillation lengths, i.e., at a distance $L > M/B$. At $M = 4.2 \times 10^2$ GeV and $B = 1$ T, $M/B \simeq 4 \times 10^5$ km, so that condition $L > M/B$ may be realized only in astrophysical phenomena but not in laboratory experiments. For the latter, it is always $L \ll M/B$ and we can expand (10′) getting the probability to find γ:

$$W_\gamma(L) = B^2 L^2 / 4M^2 \ . \tag{11}$$

This expression coincides with the result which is obtained by the standard calculation of the cross section for photon production by arions in an inhomogeneous magnetic field, whose inhomogeneity is due to its finite length L. A more general expression for this cross section for production of particles with a mass $m_a \neq 0$ (axions) is[9]

$$\sigma = \frac{1}{4M^2}\int d^2p \ \left| \int_0^L dz \, e^{iq_z z} B(z,p) \right|^2, \quad q_z = \frac{m_a^2}{2E_a} \ . \tag{12}$$

It is also seen from (12) that if the magnetic field is inhomogeneous at the length $d \ll L$ one has, roughly speaking, d instead of L in Eq. (11). For example, for $B(z)=B_0\cos(z/d)$, $L \to d\sin(L/d)$ in this equation.

An experiment can be imagined of the type described in Ref. 9 for the search for axions. The arions coming from the Sun acquire a photon component as a result of traveling a distance L with a perpendicular magnetic field switched on. To estimate the number of expected photons we use Eq. (11) and the flux (7) and take into account that this flux corresponds to $M=4\times10^8$ GeV and decreases as $\sim 1/M^2$. One gets the following result for the number of x rays (blackbody radiation with a temperature $T\sim1$ keV):

$$N_\gamma=(12\times4/\text{sec})(S/1\ \text{m}^2)(L/1\ \text{m})^2(B/1\ \text{T})^2[4\times10^8\ \text{GeV}/M(\text{GeV})]^4\ . \tag{13}$$

For the solar limit $M=4\times10^8$ GeV the observation of the photons appears to be rather an easy problem.

It is interesting to compare these results to the production of axions with a mass m_a in an inhomogeneous magnetic field. We see from Eq. (12) that in this case one cannot effectively use a length L bigger than $q_z^{-1}=2E_a/m_a^2$.

Consider, for example, the solar limit $V\simeq10^7$ GeV [Eq. (6)] and $E_a\simeq1$ keV. Then $m_a\simeq m_\pi f_\pi/V\simeq1$ eV and the decrease in counting would be of order

$$(1/Lq_z)^2\simeq(0.04\ \text{cm}/L)^2\ . \tag{14}$$

From this point of view the situation is better for bigger V, that is, for smaller m_a. For $V\simeq10^9$ GeV, $m_a\simeq0.01$ eV one has

$$(1/Lq_z)^2\simeq(4\text{m}/L)^2\ . \tag{15}$$

As for the case of laser-type experiments,[7,8] when $E_a\simeq0.1$ eV, the decrease starts at very small L indeed. Only for $m_a\sim10^{-4}$ eV (i.e., $V\simeq10^{11}$ GeV) one reaches the effective length given by (15). Of course, if one does not take into account the relation between m_a and V, as is done in Ref. 8, then there is still some hope for $V<10^7$ GeV but $m_a<10^{-4}$ eV.

In planning the solar experiment it may be useful and in some circumstances even necessary to deal with a "spoiled" vacuum when a tube, in which arions are transformed into photons, is filled with some gas at low pressure. Suppose that the refraction index of this medium $n-1\ll1$ (which is the only interesting case), then one can readily show that the probability of transformation of an arion into a photon is given by [instead of (10′)]

$$W_\gamma=(l_1^2/l_o^2)\sin^2 L/2l_1,\quad l_1^{-2}=l_o^{-2}+l_c^{-2}\ ,$$
$$l_o^{-1}=H/M,\quad l_c^{-1}=k(n-1)\ . \tag{16}$$

Here l_o is the oscillation length and l_c is the length of coherency (the length at which phases of arion and photon waves become different). If $l_c\ll l_o$ one obtains, from (16),

$$W_\gamma=(l_c^2/l_o^2)\sin^2 L/2l_c\ . \tag{17}$$

Actually, this formula is correct not only in the case of $l_c\ll l_o$, since for $l_c \gtrsim l_o$ for the laboratory experiments it is still $L\ll l_o$ and both expressions (16) and (17) are reduced to $W_\gamma=L^2/4l_o^2$.

At last it may be useful to give the result for the production of photons by axions (with $m_a\neq0$). In this case Eq. (17) should be replaced by

$$W_\gamma=(l_2^2/l_o^2)\sin^2 L/2l_2\ ,$$
$$l_2^{-1}=l_c^{-1}+q_z,\quad q_z=m_a^2/2k\ . \tag{18}$$

Let us mention the possibility of arion⇄photon oscillations in an external electric field. In this case oscillations take place between arions and photons with the polarization perpendicular to the electric field (which is, in turn, transverse to the direction of motion). The eigenvalues of energy in this case are

$$\omega_{1,2}=\sqrt{k^2\pm kE/M}\simeq k\pm E/2M\ , \tag{19}$$

so that one should simply replace $B\to E$ in all the equations. It is, however, very difficult to obtain sufficiently large external electric fields.

In conclusion let us also mention another possibility of using a laser beam traveling through a perpendicular magnetic field. Because of the interaction (3) one can expect a small rotation of the polarization plane and the appearance of the ellipticity of the light.[15] (This possibility was first mentioned to me by E. Zavattini as an alternative to the experiment[7] with the laser beam "penetrating" through a shield due to photon⇄arion oscillations at CERN.)

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