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Experimental Test for Arion $\leftrightarrows$ Photon Oscillations in a Homogeneous Constant Magnetic Field

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In references[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 reference[4]). Many of the properties of the arion are quite similar to that of the axion, the main difference is that its mass exactly equals zero. This property allows to suggest experiments where long-range forces mediated by exchange of arions could be detected by the methods similar to that for the detection of a very weak magnetic field.[2] Some of these experiments have been actually performed [5–6] and yielded the negative result which rules out the possibility of the interaction of the arion with quarks and leptons with the strength (m_f/V) with $V \sim 5 - 10$ TeV (m_f is the mass of the fermion).

It is, however, well known that the energy loss of stars by emission of pseudoscalar particles of that type gives much more stringent restrictions on the existence of axions and/or arions.[7–11] In the work[12] much more sensitive experiment of different type has been suggested based on the fact that being degenerated in masses arion and photon oscillate into each other in a homogeneous constant magnetic field. In reference[12] it was proposed to use laser beam in a magnetic filed as a source of arions and then transform the arions back to photons after they penetrate a screen. Quite recently exactly the same device has been suggested for search of axions[13] but it should be stressed that the difference is essential. While for arions there are oscillations arion $\leftrightarrows$ photon in a homogeneous magnetic field there are no such oscillations for axions because 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 V is the scale of Peccei-Quinn symmetry breaking while M determines the interaction of the axion (arion) with the photon, presumably $M \sim \alpha^{-1}V, \alpha = 1/137$; B is the magnetic field and ω is the energy of the beam. Because of this reason for the case of axions inhomogeneous magnetic field should be applied and production (not oscillation) of axions must be considered. The same difference relates also to Sikivie's work[14] who was the first to suggest to use the trilinear interaction of axions with the photons for production of axions in an external magnetic field.

The purpose of this letter is to reconsider from the practical point of view the phenomenon of arion $\leftrightarrows$ photon oscillations as a possible test in search of arions. We shall see that using the sun as a source of arions (as was suggested by Sikivie for axions[14]) one can easily over-pass the limit placed by the emission of arions from the sun (the latter was substantially weakened recently[11]), and even the case of $M \simeq 5.10^{10}$ GeV which might correspond to $V \sim 10^9$ GeV does not seem completely inconceivable. This value of V is discussed sometimes for the invisible axion [15] and there are good reasons to believe that the arion symmetry may be broken at the same scale. Some concrete models actually support such an assumption.[16]

At the end of this letter we shall discuss qualitatively the difference of production of axions and arions and shall see that there exist a smooth transition to the case $m_a \to 0$, i.e. from the case of axions to arions. The oscillations arion $\leftrightarrows$photon in the electric field and some new proposal of an experiment with a laser beam[17] will be also briefly mentioned.

The interaction of the arion with the electromagnetic field [12,4] is described by the effective interaction of the same type as for the axion:

$$L = \frac{1}{4M} F_{\mu\nu} \tilde{F}_{\mu\nu} \alpha = \frac{1}{M} \vec{E}.\vec{B} \alpha \ . \qquad (.1)$$

Here $F_{\mu\nu}$ is the electromagnetic field, $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}$, $\vec{E}$ and $\vec{B}$ are the electric and the magnetic fields and α is the arion field.

The quantity M is determined by the scale V at which the arion symmetry is broken

$$M^{-1} = V^{-1} \frac{\alpha}{\pi} \sum_f x_f e_f^2 \ \ , \alpha = \frac{1}{137} \ . \qquad (.2)$$

An extra factor in eq.(2) comes out of the usual calculation of the triangle loop, x_f are the numbers which distinguish the interaction of the arion with the different fermions ($x_f \sim 1$), e_f is the electric charge of the fermion f in units of the elementary charge.

Recently the new limit was placed for the parameter M following from the calculation of the axion (arion) emission from the sun, which takes into account a plasma screening effect:[11]

$$M > 4.2.10^8 GeV \ . \qquad (.3)$$

It is interesting that because of the screening the dominant process for the solar emission of arions may become bremsstrahlung [11,3] while the previously thought Primakoff effect (leading directly to restriction(3)) is now suppressed.

For the strength of the interaction of the arion with the electrons one has (the coupling constant is m_e/V)[11]:

$$V > 1.1.10^7\ \text{GeV} \ . \tag{.4}$$

We do not know the numerical relation between V and M since parameters x_f in eq. (2) are unknown. However if we put arbitrarily all $x_f = 1$ we get for the three generations of fermions

$$M \simeq 50V \ , \tag{.5}$$

so that (3) and (4) more or less match each other. In other words Primakoff process and bremsstrahlung might be comparable.

With the value of M given by eq. (3) the energy loss from the sun due to arion emission by the Primakoff process is equal to the photon flux, that is at the surface of the earth:

$$F_\alpha = 1.3.10^6 erg \cdot cm^{-2} \cdot sec^{-1} \ . \tag{.6}$$

The Lagrangian (1) leads to an effect of arion $\leftrightarrows$ photon oscillations in a homogeneous constant magnetic field. This mechanism has been described in some details in reference[12]. 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 $\vec{B}$ and $\vec{k}$). In fact this is not really a restriction since $B/Mk \sim 10^{-19}$. The eigenvectors of the Hamiltonian are

$$\Psi_1 = \frac{1}{\sqrt{2}}(\alpha + i\gamma), \qquad \Psi_2 = \frac{1}{\sqrt{2}}(\alpha - i\gamma) \ , \tag{.7}$$

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

$$\omega_{1,2} = \left[k^2 + \frac{B^2}{2M^2} \pm \frac{B}{M}\left[\frac{B^2}{4M^2} + k^2\, sin^2\theta\right]^{1/2}\right]^{1/2} \simeq k \pm \frac{Bsin\theta}{2M} \tag{.8}$$

An arion moving into a magnetic field perpendicular to the direction of its motion ($sin\theta = 1$) begins to oscillate $\alpha \leftrightarrows \gamma$. 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

$$W_\gamma(t) = sin^2\frac{\Delta\omega t}{2}, \quad W_\alpha(t) = cos^2\frac{\Delta\omega t}{2} \quad , \Delta\omega = \omega_1 - \omega_2 = \frac{B}{M} \ . \tag{.9}$$

For $BL/M \ll 1, L$ is the distance, the probability to find γ is

$$W_\gamma(L) = \frac{B^2L^2}{4M^2} \ . \qquad (.10)$$

An experiment can be imagined of the type described in reference[14] for search of axions. The arions coming from the sun acquire photon component as a result of travelling a distance L with a perpendicular magnetic field switched on. Using (10) and the flux (6) one can obtain the following expression for the number of x-rays (black body radiation with the average energy of the x-ray $\sim$ 1KeV):

$$N_\gamma = \left(\frac{10}{sec}\right)\left(\frac{S}{1m^2}\right)\left(\frac{L}{1m}\right)^2\left(\frac{B}{1T}\right)^2\left(\frac{4.10^8 GeV}{MGeV}\right)^4 \ . \qquad (.11)$$

For the solar limit, $M = 4.10^8$ GeV, the observation of the photons appears to be rather an easy problem. It is, of course, much more difficult for, say, $V \simeq 10^9$ GeV which might correspond to $M \simeq 4.10^{10}$ GeV. But even so, it seems that one can imagine $B = 2T$, $S = 1m^2$ and $L = 50m$. Then there is about 1 event in 15 minutes.

It is interesting to compare these results to the production of axions with a mass m_a in an inhomogeneous magnetic field. It is quite obvious, and also immediately seen from references[13,14], that in this case a formfactor appears:

$$N_\gamma \sim \left|F(q)\right|^2 = \left|\int e^{i\vec{q}\vec{r}} B(\vec{r}) d^3r\right|^2, \quad \vec{q} = \vec{k}_\gamma - \vec{k}_a \ . \qquad (.12)$$

If the direction of motion is Z one has for the field B which is inhomogeneous along Z direction:

$$F(q) \sim \int e^{i\frac{m_a^2}{2E_a}Z} B(z)dz, \quad q_z = \frac{m_a^2}{2E_a} \ . \qquad (.13)$$

So one can not effectively use a length L bigger than $q_z^{-1} = 2E_a/m_a^2$.

Consider first the solar limit $V \simeq 10^7$ GeV (eq.(4)) and $E_a \simeq 1$ KeV. Then $m_a \simeq m_\pi f_\pi / V \simeq 1$eV and the decrease in counting would be of order*)

$$\left(\frac{1}{Lq_z}\right)^2 \simeq \left(\frac{0.04cm}{L}\right)^2 \ . \qquad (.14)$$

*We consider the length of inhomogeneity $d \sim L$. For $d \ll L$ d enters (11) instead of L.[14]

From that point of view the situation is better for bigger V, that is for smaller m_a. For $V \simeq 10^9$ GeV,$m_a \simeq 0.01eV$ one has

$$(1/Lq_z)^2 \simeq \left(\frac{4m}{L}\right)^2 \quad . \tag{.15}$$

As to the case of laser-type experiment, when $E_a \simeq 0.1eV$, the decrease starts at very small L indeed. Only for $m_a \sim 10^{-4}eV$ ($i.e. V \simeq 10^{11}$ 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 it is done in reference [13], then there is still some hope for $V < 10^7$ GeV but $m_a < 10^{-4}eV$.

Let us now mention the possibility of arion $\leftrightarrows$ photon oscillations in an external electric field. In this case oscillations take place between arion and photon 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:

$$\omega_{1,2} = \sqrt{k^2 \pm \frac{kE}{M}} \simeq k \pm \frac{E}{2M} \tag{.16}$$

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

In conclusion let us mention also another possibility of using a laser beam travelling through a perpendicular magnetic field. Due to the interaction (1) one can expect a small rotation of the polarization plane and an appearance of the ellipticity of the light.*Recently it was shown[17] that these phenomena actually give the possibility to go as far as to $M \simeq 10^{10}$ GeV for the case of arions while, but exactly because of the reasons described in this paper, it is still impossible to reach the same limit for the axions with $m_a = m_\pi f\pi/V$.

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*This possibility has been first mentioned to me by E. Zavattini as an alternative to the experiment[12] with the laser beam "penetrating" through a shield due to photon $\leftrightarrows$ arion oscillations at CERN in January 1986.

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