

Axions and Photons In Terms of “Particles” and “Anti-Particles”

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The axion photon system in an external magnetic field, when for example considered with the 1+1 geometry of the experiments exploring axion photon mixing displays a continuous axion-photon duality symmetry in the limit where the axion mass is neglected. The conservation law that follows from this symmetry is obtained. The magnetic field interaction is seen to be equivalent to first order to the interaction of a complex charged field with an external electric potential, where this fictitious “electric potential” is proportional to the external magnetic field. Generalizing the scalar QED formalism to 2+1 dimensions makes it clear that a photon and an axion split into two components in an inhomogeneous magnetic field.

Introduction.- The possible existence of a light pseudo scalar particle is a very interesting possibility. For example, the axion [1, 2, 3] which was introduced in order to solve the strong CP problem has since then also been postulated as a candidate for the dark matter. A great number of ideas and experiments for the search this particle have been proposed [4, 5].

Here we are going to focus on a particular feature of the axion field ϕ : its coupling to the photon through an interaction term of the form $g\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$. It was recognized by Sikivie that axion detection exploiting axion to photon conversion in a magnetic field was a possibility [6] and afterwards, further developments were carried out in [7, 10].

We will study here properties of the axion-photon system in the presence of a strong magnetic field. By representing axions and photons as particles and anti particles we will show also that photons and axions split in the presence of an external magnetic field, in a way that we will make more precise. By this we mean that from a beam of photons we will get two different kinds of scattered components (plus the photons that do not suffer any interactions), each of the scattered beams has also an axion component, but each of the beams is directly observable due to its photon component and an observable process is obtained to first order in the axion photon interaction (unlike the “light shining through a wall” phenomena).

Action and Equations of Motion.- The action principle describing the relevant light pseudoscalar coupling to the photon is

$$S = \int d^4x \left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{g}{8}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} \right]. \quad (1)$$

We now specialize to the case where we consider an electromagnetic field with propagation along the y and z directions and where a strong magnetic field pointing in the x -direction is present. This field may have an arbitrary space dependence in y and z , but it is assumed to be time independent. In the case the magnetic field is constant, see for example [11] for general

solutions. For the small perturbations, we consider only small quadratic terms in the action for the axion and the electromagnetic fields, following the method of Ref. [11]. This means that the interaction between the background field, the axion and photon fields reduces in our current set-up to

$$S_I = - \int d^4x [\beta \phi E_x], \quad (2)$$

where $\beta = gB(y, z)$. Choosing the temporal gauge for the photon excitations and considering only the x -polarization for the electromagnetic waves (since only this polarization couples to the axion) we get the following 2+1 effective dimensional action (A being the x -polarization of the photon, so that $E_x = -\partial_t A$)

$$S_2 = \int dydzdt \left[\frac{1}{2} \partial_\mu A \partial^\mu A + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 + \beta \phi \partial_t A \right]. \quad (3)$$

Since we consider only $A = A(t, y, z)$, $\phi = \phi(t, y, z)$, we have avoided the integration over x . For the same reason μ runs over t, y and z only. This leads to the equations

$$\partial_\mu \partial^\mu \phi + m^2 \phi = \beta \partial_t A \quad \text{and} \quad \partial_\mu \partial^\mu A = -\beta \partial_t \phi. \quad (4)$$

As is well known, when choosing the temporal gauge the action principle cannot reproduce the Gauss constraint (here with a charge density obtained from the axion photon coupling) and has to be imposed as a complementary condition. However, this constraint is automatically satisfied here just because of the type of dynamical reduction employed and does not need to be considered anymore.

The continuous axion photon duality symmetry and the scalar QED analogy.- Without assuming any particular y and z -dependence for β , but still insisting that it will be static, we see that in the case $m = 0$, we discover a continuous axion photon duality symmetry, since: 1) The kinetic terms of the photon and axion allow for a rotational $O(2)$ symmetry in the axion-photon field space, 2) the interaction term, after dropping a total time derivative, can also be expressed in an $O(2)$ symmetric way as follows:

$$S_I = \frac{1}{2} \int dydzdt \beta [\phi \partial_t A - A \partial_t \phi]. \quad (5)$$

The axion photon symmetry is (in the infinitesimal limit)

$$\delta A = \epsilon \phi, \delta \phi = -\epsilon A, \quad (6)$$

where ϵ is a small number. Using Noether's theorem, this leads to the conserved current, with components given by

$$j_0 = A \partial_t \phi - \phi \partial_t A - \frac{\beta}{2} (A^2 + \phi^2) \quad \text{and} \quad j_i = A \partial_i \phi - \phi \partial_i A. \quad (7)$$

Here $i = y, z$ coordinates. Defining now the complex field ψ as $\psi = \frac{1}{\sqrt{2}}(\phi + iA)$, we see that in terms of this complex field, the axion photon density takes the form

$$j_0 = i(\psi^* \partial_t \psi - \psi \partial_t \psi^*) - \beta \psi^* \psi. \quad (8)$$

We observe that (to first order in β) (5) represents the interaction of the magnetic field with the “axion photon density” 7, (9) and also that this interaction has the same form as that of scalar QED with an external “electric” field to first order. In fact the magnetic field (or more precisely $\beta/2$) appears to play the role of external electric potential that couples to the axion photon density (7), (9) which appears then to play the role of an electric charge density. From this analogy one can obtain without effort the scattering amplitudes, just using the known results from the scattering of charged scalar particles under the influence of an external static electric potential (see for example [13]).

One should notice however that the natural initial states used in a real experiment, like an initial photon and no axion involved, is not going to have a well defined axion photon charge in the second quantized theory (although its average value appears zero), so the S matrix has to be presented in a different basis than that of normal QED. This is similar to the difference between working with linear polarizations as opposed to circular polarizations in ordinary optics, except that here we talk about polarizations in the axion photon space. In fact pure axion and pure photon initial states correspond to symmetric and antisymmetric linear combinations of particle and antiparticle in the analog QED language. The reason these linear combinations are not going to be maintained in the presence of B in the analog QED language, is that the analog external electric potential breaks the symmetry between particle and antiparticle and therefore will not maintain in time the symmetric or antisymmetric combinations.

From the point of view of the axion-photon conversion experiments, the symmetry (6) and its finite form, which is just a rotation in the axion-photon space, implies a corresponding symmetry of the axion-photon conversion amplitudes, for the limit $\omega \gg m$.

In terms of the complex field, the axion photon current takes the form

$$j_k = i(\psi^* \partial_k \psi - \psi \partial_k \psi^*). \quad (9)$$

The Particle Anti-Particle Representation of Axions and Photons and their Splitting in an External Magnetic Field.- Introducing the charge conjugation [14],

$$\psi \rightarrow \psi^*, \quad (10)$$

we see that the free part of the action is indeed invariant under (11). The A and ϕ fields when acting on the free vacuum give rise to a photon and an axion respectively, but in terms of the particles and antiparticles defined in terms of ψ , we see that a photon is an antisymmetric combination of particle and antiparticle and an axion a symmetric combination, since

$$\phi = \frac{1}{\sqrt{2}}(\psi^* + \psi), \quad A = \frac{1}{i\sqrt{2}}(\psi - \psi^*), \quad (11)$$

so that the axion is even under charge conjugation, while the photon is odd. These two eigenstates of charge conjugation will propagate without mixing as long as no external magnetic field is applied. The interaction with the external magnetic field transforms under (11) as $S_I \rightarrow -S_I$. Therefore these symmetric and antisymmetric combinations, corresponding to axion and photon are not going to be maintained in the presence of B in the analog QED language, since the “analog external electric potential” breaks the symmetry between particle and antiparticle and therefore will not maintain in time the symmetric or antisymmetric combinations. In fact if the analog external electric potential is taken to be a repulsive potential for particles, it will be an attractive potential for antiparticles, so the symmetry breaking is maximal.

Even at the classical level these two components suffer opposite forces, so under the influence of an inhomogeneous magnetic field both a photon or an axion will be decomposed through scattering into their particle and antiparticle components, each of which is scattered in a different direction, since the analog electric force is related to the gradient of the effective electric potential, i.e., the gradient of the magnetic field, times the $U(1)$ charge which is opposite for particles and antiparticles.

For this effect to have meaning, we have to work at least in a 2+1 formalism [15], the 1+1 reduction [12, 14] which allows motion only in a single spacial direction is unable to produce such separation, since in order to separate particle and antiparticle components we need at least two dimensions to obtain a final state with particles and antiparticles going in slightly different directions.

This is in a way similar to the Stern Gerlach experiment in atomic physics [16], where different spin orientations suffer a different force proportional to the gradient of the magnetic field in the direction of the spin. Here instead of spin we have that the photon is a combination of two states with different $U(1)$ charge and each of these components will suffer opposite force under the influence of the external inhomogeneous magnetic field. Notice also that since particle and antiparticles are distinguishable, there are no interference effect between the two processes.

Therefore an original beam of photons will be decomposed through scattering into two different elementary particle and antiparticle components plus the photons that have not undergone scattering. These two beams are observable, since they have both photon components, so the observable consequence of the axion photon coupling will be the splitting by a magnetic field of a photon beam.

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