New Results in Axion Physics

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Abstract

We comment on the recent experimental results from the PVLAS and CAST collaborations that search for axion-like particles. We propose a particle physics model in which their apparent inconsistency is circumvented.

PACS numbers: 12.20.Fv,14.80.Mz,95.35.+d,96.60.Vg
I. INTRODUCTION

The search for new very weakly interacting light particles was motivated by the theoretical idea of the axion, a particle arising\footnote{1, 2} when one introduces the Peccei-Quinn symmetry\footnote{3, 4} in order to solve the strong CP-problem. When allowing the breaking scale of the symmetry to be a very high energy scale one obtains the so called invisible axion, named this way because of its very weakly interactions. Also, the theory of the axion predicts a very small mass for it. A milestone in axion physics was the realization by Sikivie that it was not impossible to probe the existence of the axion with feasible experiments\footnote{5}.

In\footnote{5} there are some proposals to look for axions. All are based on the axion-photon conversion in a magnetic field, an effect that is described by the interaction term

\[ \mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4M} F^{\mu\nu} \tilde{F}_{\mu\nu} \phi. \]

Here \( F^{\mu\nu} \) is the electromagnetic field tensor, \( \tilde{F}_{\mu\nu} \) its dual, and \( \phi \) the axion field. One may envisage to detect axions if they constitute the galactic dark matter halo (haloscope). Another type of experiment (helioscope) is based on the fact that light particles should be produced in the interior of the Sun, and subsequently leave it in the form of a continuous flux. At the Earth, we can try to detect this solar flux by looking at axion conversion to X-rays in a magnetic field. Finally, there is the remarkable effect of light shining through a wall: in a magnetic field, light oscillates into axions, these cross a wall and afterwards they convert back into photons.

Here we will be concerned with helioscopes and also with another detection method that was proposed in\footnote{7}. It consists in letting a polarized laser to propagate in a magnetic field. The real conversion of photons to axions produces a selective absorption of one of the two laser polarization (dichroism), and the virtual conversion photon-axion-photon produces a phase retardation of one of the polarizations (birefringence). If we write \( \mathcal{L}_{\phi\gamma\gamma} \) as

\[ \mathcal{L}_{\phi\gamma\gamma} = \frac{1}{M} \vec{E} \cdot \vec{B} \phi \]  

we see that it is the polarization (taken as the direction of the electric field in the laser) parallel to the external magnetic field that gets affected.

Let us mention that any light particle coupled to two photons could be able to give a positive signal in these experiments. This general situation has been studied in\footnote{6}. In the case that the particle is a pseudoscalar, we would have a Lagrangian similar to \( \mathcal{L}_{\phi\gamma\gamma} \). Notice that a light scalar particle, with a lagrangian given by

\[ \mathcal{L}'_{\phi\gamma\gamma} = \frac{1}{4M} F^{\mu\nu} F_{\mu\nu} \phi \]  

also may be detected in an helioscope, may induce light shining through walls and also may be responsible of dichroism and birefringence, although it is now the polarization perpendicular to the magnetic field that intervenes, since \( \mathcal{L}'_{\phi\gamma\gamma} \) can be written as

\[ \mathcal{L}'_{\phi\gamma\gamma} = \frac{1}{2M} \left( \vec{E}^2 - \vec{B}^2 \right) \phi. \]

I will refer to these hypothetical particles, either pseudoscalar or scalar, as axion-like particles.

Recently, there have been two groups that have announced experimental results on axion-like particles coupled to photons. First, there is the helioscope of the CAST collaboration that has not observed any signal coming from the Sun and has put the limit\footnote{8}

\[ M > 0.9 \times 10^{10} \text{ GeV} \]  

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valid for a mass of the light particle \( m < 0.02 \) eV.

The second result is by the PVLAS collaboration. They have a positive signal consistent in a rotation of the plane of the polarization of a laser propagating in a magnetic field\(^9\). Their result can be interpreted in terms of an axion-like particle. It is consistent with a scale

\[ M \sim 4 \times 10^5 \text{ GeV} \]  \( (6) \)

and with a light particle mass \( m \sim 10^{-3} \) eV.

We notice that the two results are in strong contradiction. In fact the PVLAS result is also in contradiction with the stellar energy loss bounds. These bounds are obtained when noticing that light \( \phi \) particles would be produced by the Primakoff-like effect due to the interaction \( (1) \) or \( (3) \). If the produced \( \phi \)'s escape freely from the star the whole process constitutes a non-standard channel of energy-loss, which is limited by observational data on stellar evolution time scales. These arguments lead to the bound\(^10\)

\[ M > 10^{10} \text{ GeV} . \]  \( (7) \)

If all these results are confirmed of course we will need to find a model where we can understand \( (6) \), \( (5) \), and \( (7) \) at the same time.

II. OUR MODEL

Let us start discussing two possible ways to evade \( (7) \) as discussed in\(^11\). First, we may assume that \( \phi \)'s are indeed produced in the Sun core, but they get trapped because of some additional interactions and diffuse with extremely small mean free path up to the solar surface. This could in principle evade the astrophysical bounds. Unfortunately a satisfactory model has yet to be found\(^11, 12\). A second possibility is that there is much less production in the Sun than expected. We shall here report recent work we have done\(^13\) along this second line. For related approaches see\(^14\).

We shall assume that the neutral \( \phi \) particle couples to two photons through a triangle with a new fermion \( f \); see Fig.(1).

\[ \phi - - - \begin{array}{c} \phi \end{array} \begin{array}{c} f \end{array} \begin{array}{c} \gamma \end{array} \begin{array}{c} \gamma \end{array} \begin{array}{c} \gamma \end{array} \]

**FIG. 1:** Triangle diagram for the \( \phi \gamma \gamma \) vertex.

We wish that this new particle \( f \) has small electric charge on the one hand, and on the other hand we want this charge to decrease when going from the momentum transfer involved in the PVLAS experiment, \( |k^2| \sim 0 \), to the typical momentum transfer in the solar processes, \( |k^2| \sim \text{keV}^2 \). In order for this second condition to happen it is already clear that we need to advocate for new physics with a very low energy scale.

We can meet both conditions in the context of paraphoton models\(^15, 16\). To start with, these models are the only ones, as far as we know, where the effective electric charge of some particles can be naturally very small. The idea is that particles with paracharge get an induced electric charge proportional to some small mixing angle \( \epsilon \) between photons and paraphotons. To satisfy the second condition, i.e., to get a variation of the effective electric charge with energy, we use a model with two light but massive paraphotons with the same mixing with the photon. If the fermion \( f \) couples to the two paraphotons with
opposite paracharge, the resulting effective electric charge for \( f \) decreases with energy or temperature \( T \),

\[
q_f(T) \simeq \frac{\mu^2}{T^2} q_f(0)
\]  

(8)

where \( \mu \) is the mass scale of the paraphoton masses (in [8] we assume \( T \gg \mu \)). With \( \mu \simeq 10^{-3} \text{ eV} \) and \( \epsilon \) such that \( q(0) \epsilon \simeq 10^{-8} \epsilon \), our model is able to accommodate the strength of the PVLAS signal and yet have a very suppressed emission in the Sun. Notice that in our model the CAST limit [5], which is based on a standard solar \( \phi \)-flux, does not hold.

Summarizing, we have presented a paraphoton model that evades the astrophysical bounds on axion-like particles and is consistent with the CAST and the PVLAS experimental results.

### III. ACKNOWLEDGEMENTS

We would like to congratulate Mario Greco as well as Giorgio Bellettini and Giorgio Chiarelli for the superb organization of the XXth session of the workshop. EM thanks Alvaro De Rújula for asking him the right question in the workshop. We acknowledge support by the CICYT Research Project FPA2005-05904 and the Departament d’Universitats, Recerca i Societat de la Informació (DURSI), Project 2005SGR00916.

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