DESY 06-068

We need lab experiments to look for axion-like particles

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The PVLAS signal has renewed the interest in light bosons coupled to the electromagnetic field. However, astrophysical bounds coming from the lifetime of the sun and the CAST experiment are seemingly in conflict with this result. We discuss effective models that allow to suppress production of axion-like particles in the sun and thereby relax the bounds by some orders of magnitude. This stresses the importance of laboratory searches.

1 Introduction

Recently the PVLAS collaboration has reported a rotation of the polarization plane of an originally linearly polarized laser beam propagating through a magnetic field [1]. This signal could be explained by the existence of a light neutral spin zero boson with a coupling to two photons, e.g. a pseudoscalar ϕ,

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{g}{4}\phi\tilde{F}^{\mu\nu}F_{\mu\nu}, \tag{1}$$

with

$$m_\phi^{\rm PVLAS} = (1-1.5)\,{\rm meV}, \quad g_\phi^{\rm PVLAS} = (1.7-5)\times 10^{-6}\,{\rm GeV}^{-1}. \tag{2}$$

The favorite candidate for such a light and neutral particle is the axion, the pseudo-Goldstone boson of the Peccei-Quinn symmetry that was proposed to solve the so called strong CP problem[2,3,4]. However, the PVLAS measurements are not compatible with the expectations for a standard axion, for which one has a relation that essentially determines $m_\phi g_\phi^{-1}$ in terms of QCD quantities. All natural axion models are located in the green vertically shaded strip in Fig. 1. As we can see from the same figure, the PVLAS result is far outside this region. Hence, it is probably not an axion. We will call it an axion like particle (ALP) due to its similar properties.

The troubling point of the particle interpretation of the PVLAS data is that the action (1) with parameters (2) already is in conflict with observations. Astrophysical considerations based on the production of ϕ's from photons via the coupling $g\phi F\tilde{F}$ in Eq. (1) actually give the strong bounds depicted in Fig. 1. We will briefly review these bounds in Sect. 2.

The motivation for our work[a] is the question: Can we resolve the conflict between the astrophysical bounds and the particle interpretation of PVLAS[b] and how can this be tested? We attack the first part of this question in Sect. 3. In our final Sect. 4 we argue that laboratory

[a]This note is based on a talk given by J. Jaeckel at the "Rencontres des Moriond: Contents and structures of the universe" in La Thuile, Italy in March 2006. For more details see [5].

[b]For other attempts in this direction see [6,7].

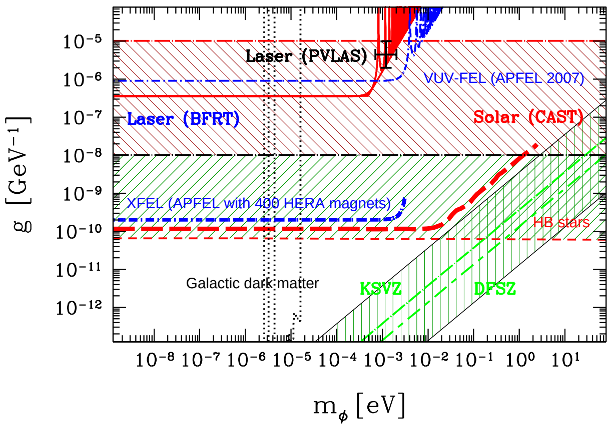

Figure 1: Various bounds on the coupling g and mass m_ϕ of a (light) boson coupled to two photons (areas above single lines are excluded). The green vertically shaded strip gives the range of all reasonable axion models. The two lines within its boundaries give a typical KSVZ and DFSZ model. The green and red diagonally shaded areas give the additional area allowed when we suppress the production of ALP's in the sun (the green smaller one is a little bit more conservative).

experiment are the prime tool to give a conclusive answer if the particle interpretation of PVLAS is invalid or if astrophysical bounds are evaded and PVLAS has detected signals of new exciting physics.

2 Astrophysical bounds revisited

The basic problem of the particle interpretation of the PVLAS data is that it is in conflict with astrophysical bounds. For a better understanding of the problem let us briefly review these bounds.

2.1 Energy loss of stars

The simplest bound comes from the energy loss argument. If any weakly interacting particle is produced in a star and escapes, it takes a certain amount of energy with it, thus contributing to the stellar luminosity. The amount of energy in exotic particles can contribute to shorten the duration of the different phases of stellar evolution, which can be observed (for a review see [8]).

Here, we focus on the sun, for which we have a solid standard solar model from which we can accurately calculate emission of ALPs.

The lifetime of the sun is known to be around 10 billion years from radiological studies of radioactive isotopes in the solar system (see [9]). Solar models reproduce this quantity (among others). From this one concludes that the exotic contribution to the luminosity cannot exceed the standard solar luminosity in photons. For our purposes this means

$$L_{\rm ALP} < L_\odot = 3.8\times 10^{26}\,{\rm W} \approx 1.6\ 10^{30}\,{\rm eV}^2. \tag{3}$$

We compute the ALP emission in the standard solar model BP2000 [10] using Eq. (1) and no further assumptions. We obtain a slightly bigger value than that of [11], where the calculation was done using an older solar model.

$$L_{\rm ALP} = 0.063\, g_{10}^2\, L_\odot, \tag{4}$$

where $g_{10} = g\,10^{10}\,{\rm GeV}$. Together with Eq. (3) this gives a bound on the coupling. A somewhat strengthened bound[8] including data from so called horizontal brach (HB) stars is shown in Fig. 1.

Another bound comes from the CAST experiment[12]. The CAST experiment tries to detect the axion flux (4) by reconverting the axions in the strong magnetic field generated by an LHC test magnet. The rate of photons in the detector is

$$\text{rate} \sim g^2 L_{\rm ALP} \sim g^4. \tag{5}$$

$R_0/R_\odot$	$\rho_0/(\mathrm{g\,cm^{-3}})$	T_0/eV	$S(R_0)$
0	150	1200	1
0.79	0.1	120	10^{-4}
0.97	0.003	12	10^{-20}

Table 1: Several values for suppression factors.

So far no significant photon flux has been measured. The resulting bound is depicted in Fig. 1.

3 Evading astrophysical bounds

Our strategy to evade the astrophysical bounds is rather simplistic. In the center of the sun where most ALPs are produced the environment is different from the environment of the PVLAS experiment. If the parameters m_ϕ and M_ϕ depend on the environment

$$m_\phi \to m_\phi(\text{environment}), \quad M_\phi \to M_\phi(\text{environment}), \tag{6}$$

in a suitable way the production of the ϕ particles inside the sun is strongly suppressed. In particular, we consider the following:

1. The density ρ inside the sun is quite high.
2. Inside the sun the temperature T is high.
3. The average momentum transfer $\langle q \rangle$ in the Primakoff processes generating the ALP's is high.

We will not try to construct micro physical explanations but rather write down simple effective models and fix their parameters in order to be consistent with PVLAS as well as the astrophysical bounds.

For simplicity we allow in this note only a variation of the coupling g. Suppression via a high mass term in the sun environment is more difficult since it involves a strong coupling to generate the high mass (for more details see [5]). In addition, we will restrict the dependence to a single parameter $\alpha = \rho$, T, etc.. We are mainly interested in giving conservative bounds for g and the suppression scales involved, so instead of guessing possible dependencies $g = g(\alpha)$ we make the calculations with the most optimistic suppression, a step function, i.e. if $\alpha > \alpha_{\text{crit}}$, $g = 0$, and the generation of ALP's in this region is completely suppressed.

The macroscopic quantities ρ, T depend more or less only on the radius. Therefore, we get the following simple picture. In the center of the sun (where naively most ALP's would be produced) the suppression is switched off while in the remaining shell we have no suppression at all. Using this we only need to calculate the production in the outer shell and compare it with the production within the whole volume happening in a scenario without suppression[c],

$$S(R_0) = \text{suppression factor} = \frac{\text{production}(R > R_0)}{\text{production}(\text{full sun})}. \tag{7}$$

We treat the emission of ALP's as a small perturbation of the solar model and therefore can compute the emission of these particles from the unperturbed solar model. We have chosen the BP2000 of Bahcall et al [10]. The suppression factor S for some radii is given in Tab. 3.

Similar reasoning can be applied to $\langle q \rangle$. However, writing down a model it is preferable to use directly the microscopic quantity q. In this situation one has to perform the thermal average

[c]For CAST actually one has to take into account that the CAST detector measures a number and not an energy flux and is only sensitive in a certain energy range. This gives a slightly modified suppression factor $\tilde{S}$ (see [5]).

over the scattering processes (see [5]). For the suppression factors in the range $10^{-4} - 10^{-20}$ the resulting critical q lie in the meV – eV range.

Using Eqs. (4) and (5) we find that a suppression

$$S_{\text{loss}} = g_{\text{supp}}^2/g_{\text{loss}}^2, \quad S_{\text{CAST}} = g_{\text{supp}}^4/g_{\text{CAST}}^4, \tag{8}$$

is needed to achieve a less restrictive bound g_{supp}.

The necessary critical values for the temperature, density and momentum transfer for certain suppression factors can be read off from Tab. 3. It is rather obvious that none of these values is very extreme. However, one has to compare to the values in PVLAS. These are even smaller,

$$\rho_{\text{PVLAS}} < 2 \times 10^{-5}\text{g cm}^{-3}, \quad T < 300\,\text{K} \approx 0.025\,\text{eV}, \quad q \sim 10^{-6}\,\text{eV}. \tag{9}$$

Hence, we have room for some *exotic* possibilities. Even a suppression factor of 10^{-20} is marginally possible, allowing for the PVLAS result. This gives the red (large) shaded region in Fig. 1. For a somewhat more conservative suppression factor we find the green (smaller) shaded region in Fig. 1.

4 Conclusions: We need lab experiments!

Naively, the particle interpretation of the PVLAS data is in conflict with astrophysical bounds. If we allow for an interaction between photons and axion like particles (ALP's) that depends on other physical quantities (density, temperature and momentum are candidates), the production of ALP's can be suppressed and the astrophysical bounds can be evaded. However, the typical scales appearing in these models are rather low (typically eV and smaller) and the physics must be exotic in this sense. Nevertheless, one cannot rule out these exotic possibilities from the start and PVLAS is a good motivation to look more closely. Since astrophysical bounds can be evaded, a true test can only come from laboratory experiments where we have control of the environmental parameters. A conclusive answer about the particle interpretation of PVLAS can come in particular from so called light shining through walls experiments, where the photon not only disappears but is regenerated. It is exciting that experiments of this type, with enough sensitivity to test PVLAS, could be built in the next one or two years. An example of such an experiment is APFEL (Axion Production at a Free-Electron Laser) which has been proposed at DESY (see also Fig. 1) and is sensitive enough to test PVLAS[13].

J. Jaeckel would like to thank the organizers for the wonderful conference.

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