DESY 06-228

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PHOTON REGENERATION PLANS*

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Precision experiments exploiting low-energy photons may yield information on particle physics complementary to experiments at high-energy colliders, in particular on new very light and very weakly interacting particles, predicted in many extensions of the standard model. Such particles may be produced by laser photons send along a transverse magnetic field. The laser polarization experiment PVLAS may have seen the first indirect signal of such particles by observing an anomalously large rotation of the polarization plane of photons after the passage through a magnetic field. This can be interpreted as evidence for photon disappearance due to particle production. There are a number of experimental proposals to test independently the particle interpretation of PVLAS. Many of them are based on the search for photon reappearance or regeneration, i.e. for "light shining through a wall". At DESY, the Axion-Like Particle Search (ALPS) collaboration is currently setting up such an experiment.

1. Introduction

The standard model of particle physics is phenomenologically extremely successful. However, there are a number of hints which point to the possibility that there is new physics beyond it. Proposed extensions of the standard model aim at a solution of important problems such as the unification of all forces, including gravity, or at an explanation of the absence of CP violation in strong interactions, among many others.

Many attempts to embedd the standard model into a more general, unified framework, notably the ones based on string theory, predict, apart from new very heavy, $m \gg 100$ GeV, particles also a number of new very light, $m \ll 1$ eV particles, which are very weakly coupled to ordinary matter.

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Prominent candidates for such particles go under the names axions (arising in the course of a solution of the strong CP problem), dilatons, and millicharged particles.

2. Polarization Experiments

Laboratory experiments to search for such particles may be based on the possibility to produce them by shining laser photons along a transverse magnetic field. Searches for a change of the polarization state of initially linearly polarized photons after the passage through the magnetic field, in particular for a possible rotation (dichroism) and ellipticity (birefringence) (cf. Fig. 1), are particularly sensitive to new light particles [2,3].

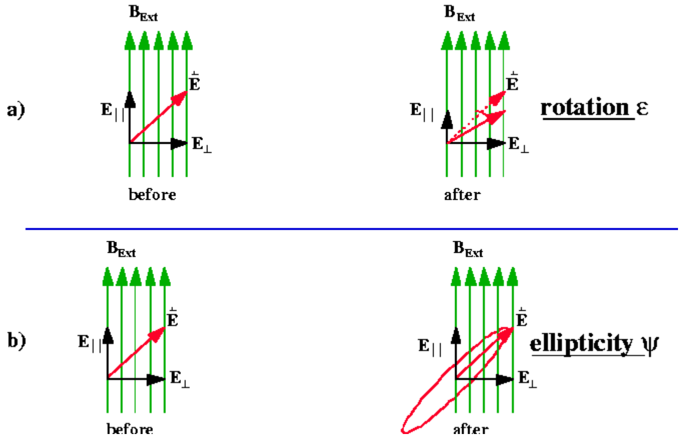

Fig. 1. Possible changes of the polarization state of initially linearly polarized photons after the passage through a magnetic field (adapted from Ref. [1]).

In a pioneering laser polarization experiment, the BFRT collaboration established an upper limit both on a possible vacuum magnetic (VM) dichroism and birefringence [4]. Recently, however, the PVLAS collaboration reported the observation of a VM dichroism [5]. Moreover, preliminary data seem to indicate also evidence for a non-vanishing VM birefringence. These observations have led to a number of theoretical and experimental activities, since the magnitude of the reported signals exceeds the standard model expectations by far.

Two viable particle physics explanations of the reported signals have been proposed: the real and virtual production

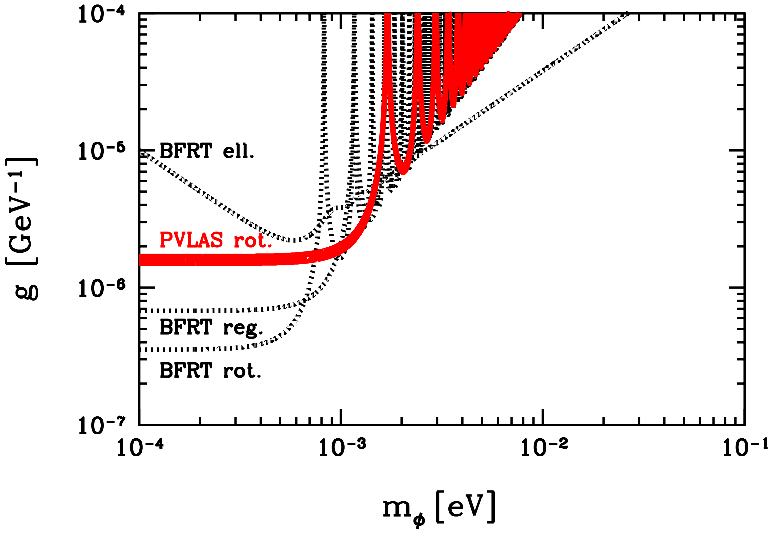

Fig. 2. ALP interpretation of BFRT and PVLAS data: two photon coupling g versus mass m_ϕ. The 95 % confidence level upper limits from BFRT data [4] on polarization (rotation and ellipticity data) and photon regeneration are displayed as dotted lines. The preferred values corresponding to the anomalous rotation signal observed by PVLAS [5] are shown as a thick solid line.

(i) of a neutral spin-0 (axion-like) particle (ALP) ϕ [2] with mass m_ϕ and a coupling to two photons via

$$\mathcal{L}_{\rm int}^{(+)} = -\frac{1}{4} g \phi^{(+)} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} g \phi^{(+)} (\vec{E}^2 - \vec{B}^2), \qquad (1)$$

or

$$\mathcal{L}_{\rm int}^{(-)} = -\frac{1}{4} g \phi^{(-)} F_{\mu\nu} \widetilde{F}^{\mu\nu} = g \phi^{(-)} (\vec{E} \cdot \vec{B}), \qquad (2)$$

depending on its parity, denoted by the superscript (±), or
(ii) of a pair of millicharged, $Q_\epsilon = \epsilon e$, particles (MCP) $\epsilon^+\epsilon^-$ [3] with mass m_ϵ, coupling to photons in the usual way via the minimal substitution $\partial_\mu \to D_\mu \equiv \partial_\mu - {\rm i}\epsilon e A_\mu$ in the Lagrangian.
Indeed, as apparent from Fig. 2, the rotation observed by PVLAS can be reconciled with the non-observation of a rotation and ellipticity by BFRT, if there is an ALP with a mass $m_\phi \sim$ meV and a coupling $g \sim 10^{-6}$ GeV^{-1} [5]. Alternatively, both experimental results are compatible with the existence of an MCP with $m_\epsilon \sim 0.1$ eV and $\epsilon \sim 10^{-6}$ [3] (cf. Fig. 3). These parameter values, however, seem to be in serious conflict with astrophysical bounds, arising for example from energy loss considerations of stars [6,7]. They may

be evaded if the production of ALPs or MCPs is suppressed in astrophysical plasmas [8,9], as realized, for example, in extensions of the standard model involving extra U(1) gauge bosons which kinetically mix with our familiar hypercharge U(1) [10], such as in some realistic string compactifications [11].

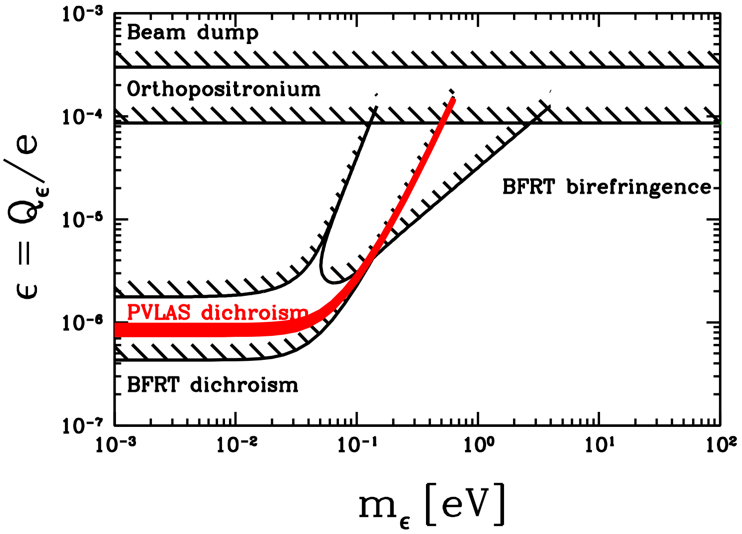

Fig. 3. MCP interpretation of BFRT and PVLAS data: fractional electric charge $\epsilon = Q_\epsilon/e$ versus mass m_ϵ. The preferred values corresponding to the anomalous rotation signal observed by PVLAS [5] are shown as a thick solid line.

It is very comforting that a number of laboratory-based low-energy tests of the ALP and MCP interpretation of the PVLAS anomaly are currently set up and expected to yield decisive results within the upcoming year. For example, in addition to PVLAS, the BMV [12] and Q&A [13] collaborations will run further polarization experiments with different experimental parameter values which finally may lead to a discrimination between the ALP and the MCP hypothesis [14].

3. Regeneration Experiments

The ALP interpretation of the PVLAS signal will crucially be tested by photon regeneration (sometimes called “light shining through walls”) experiments [15–18], presently under construction or serious consideration [12,19–22] (cf. Table 1). In these experiments (cf. Fig. 4), a photon beam is directed across a magnetic field, where a fraction of them turns

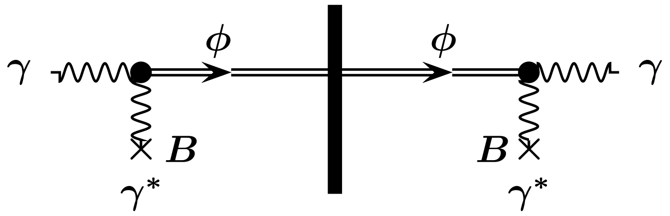

Fig. 4. Schematic view of ALP production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).

into ALPs. The ALP beam can then propagate freely through a wall or another obstruction without being absorbed, and finally another magnetic field located on the other side of the wall can transform some of these ALPs into photons — seemingly regenerating these photons out of nothing. A pioneering photon regeneration experiment has been done also by the BFRT collaboration [4]. No signal has been found and the corresponding upper limit on g vs. m_ϕ is included in Fig. 2.

Table 1. Experimental parameters of proposed photon regeneration experiments: magnetic fields B_i and their length ℓ_i on production ($i = 1$) and regeneration ($i = 2$) side (cf. Fig. 4); and the corresponding probability $P_{\gamma\phi\gamma}$, with $g \sim 2 \times 10^{-6}$ GeV^{-1} in the PVLAS preferred region (cf. Fig. 2).

Name	Laboratory	Magnets	$P_{\gamma\phi\gamma}$ for $g \sim 2 \times 10^{-6}$ GeV^{-1}
ALPS [19]	DESY/D	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m	$\sim 10^{-19}$
BMV [12]	LULI/F	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 0.25$ m	$\sim 10^{-21}$
LIPSS [20]	Jlab/USA	$B_1 = B_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m	$\sim 10^{-23.5}$
PVLAS [21]	Legnaro/I	$B_1 = 5$ T $\ell_1 = 1$ m $B_2 = 2.2$ T $\ell_2 = 0.5$ m	$\sim 10^{-23}$
— [22]	CERN/CH	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 7$ m	$\sim 10^{-17}$

Clearly, crucial experimental parameters for such an experiment are the magnetic fields B_i and their length ℓ_i on the production ($i = 1$) and the regeneration ($i = 2$) side of the apparatus. Indeed, the conversion probability for the process $\gamma \to \phi \to \gamma$ is given by

$$P_{\gamma\to\phi\to\gamma} = P_{\gamma\to\phi}(B_1,\ell_1,q_1)\,P_{\phi\to\gamma}(B_2,\ell_2,q_2)\,,$$
$$P_{\gamma\to\phi}(B,\ell,q) = P_{\phi\to\gamma}(B,\ell,q) = \frac{1}{4}\,(g\,B\,\ell)^2\;F(q\ell)\,, \tag{3}$$

where $F(q\ell) \leq 1$ is a form factor which equals unity, if the photons and the ALPs act coherently over the whole length of the magnet, i.e. for

$$q\ell = \left|\frac{2\,(n_\gamma - 1)\,\omega^2 - m_\phi^2}{2\omega}\right|\ell \ll 1, \tag{4}$$

ω being the photon energy and n_γ being the refraction index of eventual buffer gas in the beam pipe [23]. At small momentum transfer, $q\ell \ll 1$, therefore, the regeneration probability scales as $(B_1\ell_1B_2\ell_2)^4$. Correspondingly, strong and long dipole magnets from high-energy storage rings (e.g. HERA [18] or LHC) are particularly suited for a photon regeneration experiment, as can be seen in Table 1.

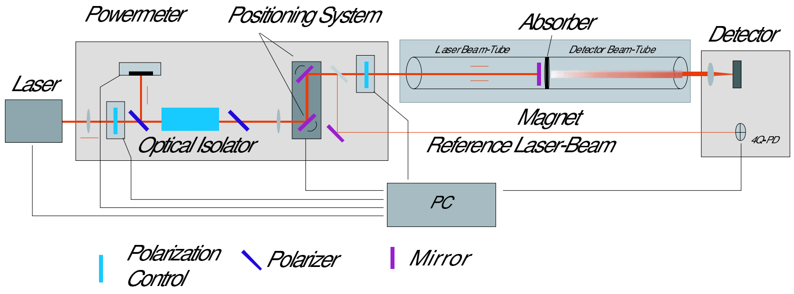

Fig. 5. Schematic view of the experimental setup of the ALPS experiment [19].

Importantly, one may optimize the sensitivity in certain mass regions by essentially tuning q towards small values by adjusting n_γ, i.e. by varying the gas pressure in the magnetic field regions [23]. This effect will be heavily exploited at the Axion-Like Particle Search (ALPS) experiment [19] at DESY (cf. Fig. 5), where the photon beam of a high-power, $\sim$ 200 W, infrared laser, corresponding to an initial flux of $\sim 10^{21}$ photons/s, will be sent along the $\sim$ 5 T, $\sim$ 8.8 m transverse magnetic field of a superconducting HERA dipole magnet (cf. Fig. 6). Filling in a buffer gas with a refractive index $n_\gamma - 1 \sim 10^{-7}$, one will have the maximum sensitivity in the PVLAS preferred parameter region (cf. Fig. 7). ALPS, a collaboration of DESY, the Laserzentrum Hannover and the Sternwarte Bergedorf, has been approved in principle by the DESY directorate and is planning to take data in summer 2007.

Fig. 6. HERA dipole magnet at DESY's magnet test stand. It will be exploited for the ALPS experiment [19].

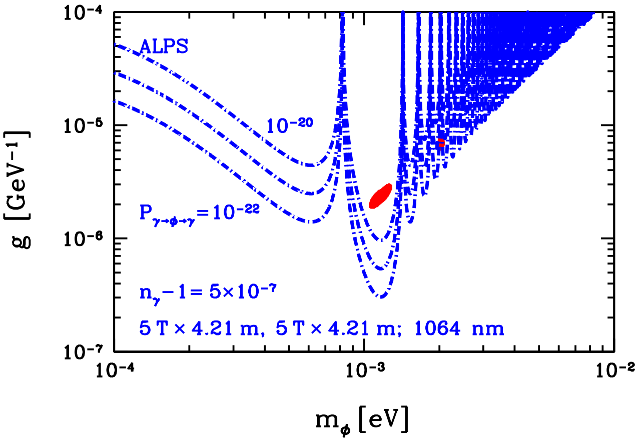

Fig. 7. Isocontours of the probability $P_{\gamma\to\phi\to\gamma}$, Eq. (3), for the parameters of ALPS experiment: $B_1 = B_2 = 5$ T, $\ell_1 = \ell_2 = 4.21$ m, exploiting an infrared photon beam ($\omega = 1.17$ eV) in buffer gas with a refractive index $n_\gamma - 1 = 5\times10^{-7}$ (from Ref. [19]).

4. Conclusions

The evidence for a vacuum magnetic dichroism found by PVLAS has triggered a lot of theoretical and experimental activities. Fortunately, in the upcoming year a number of decisive laboratory based tests both of the axion-like and millicharged particle interpretation will be done. In particular, the planned photon regeneration experiments (cf. Table 1) will firmly establish or exclude the axion-like particle interpretation. In summary, even in the LHC era, small experiments might have a big impact on particle physics!

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