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PARTICLE INTERPRETATIONS OF THE PVLAS DATA*

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ABSTRACT

Recently the PVLAS collaboration reported the observation of a rotation of linearly polarized laser light induced by a transverse magnetic field – a signal being unexpected within standard QED. In this review, we emphasize two mechanisms which have been proposed to explain this result: production of a single light neutral spin-zero particle or pair production of light minicharged particles. We discuss a class of models, involving, in addition to our familiar "visible" photon, further light "hidden paraphotons", which mix kinematically with the visible one, and further light paracharged particles. In these models, very strong astrophysical and cosmological bounds on the weakly interacting light particles mentioned above can be evaded. In the upcoming year, a number of decisive laboratory based tests of the particle interpretation of the PVLAS anomaly will be done. More generally, such experiments, exploiting high fluxes of low-energy photons and/or large electromagnetic fields, will dig into previously unconstrained parameter space of the above mentioned models.

1. Introduction

We are entering a new era in particle physics: Next year, the Large Hadron Collider (LHC) will start to probe, through the collision of 7 TeV protons, the structure of matter and space-time at an unprecedented level. There is a lot of circumstantial evidence that the physics at the TeV scale exploited at LHC and later at the International Linear Collider (ILC) will bring decisive insights into fundamental questions such as the origin of particle masses, the nature of dark matter in the universe, and the unification of all forces, including gravity. Indeed, most proposals to embed the standard model of particle physics into a more general, unified framework, notably the ones based on string theory or its low energy incarnations, supergravity and supersymmetry, predict new heavy, $m \gg 100$ GeV, particles which may be searched for at TeV colliders. Some of these particles, prominent examples being neutralinos, are natural candidates for the constituents of cold dark matter in the form of so-called weakly interacting massive particles (WIMPs).

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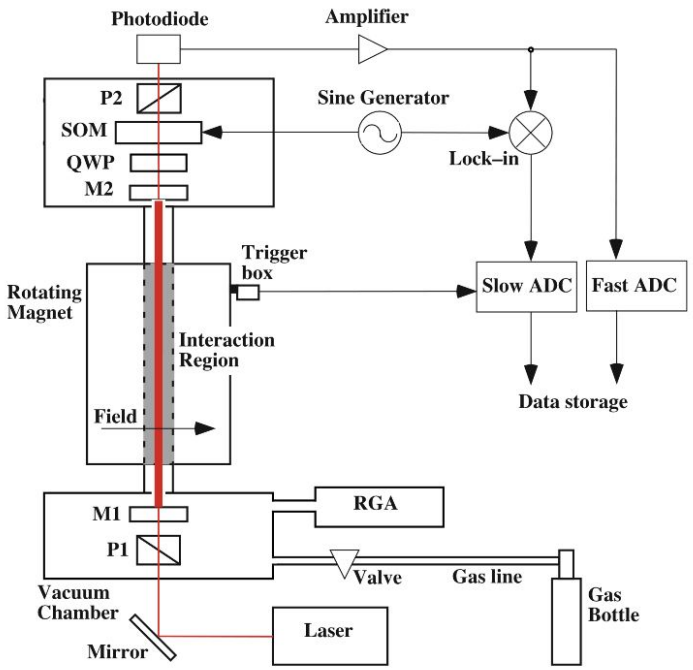

Figure 1: Schematic illustration of the PVLAS experiment[1)].

However, there is also evidence that there is fundamental physics at the sub-eV scale. Indeed, atmospheric, reactor, and solar neutrino data strongly support the hypothesis that neutrinos have masses in the sub-eV range. Moreover, the vacuum energy density of the universe, as inferred from cosmological observations, points to the sub-eV range, $\rho_\Lambda \sim \mathrm{meV}^4$. As a matter of fact, many of the above mentioned extensions of the standard model not only predict WIMPs, but also WILPs, i.e. weakly interacting light particles, some of them even having possibly a tiny electric charge (so-called minicharged particles). Prominent candidates for such particles go under the names axions, dilatons, and moduli. Unlike for WIMPs, TeV colliders are not the best means to search for WILPs. For this purpose, small, high-precision experiments, exploiting high fluxes of low-energy photons and/or large electromagnetic fields, seem to be superior.

2. Vacuum Magnetic Dichroism and Birefringence

The PVLAS collaboration is running a prime example for such an experiment at the INFN Legnaro in Italy[1)]. Similar experiments have been performed in the early

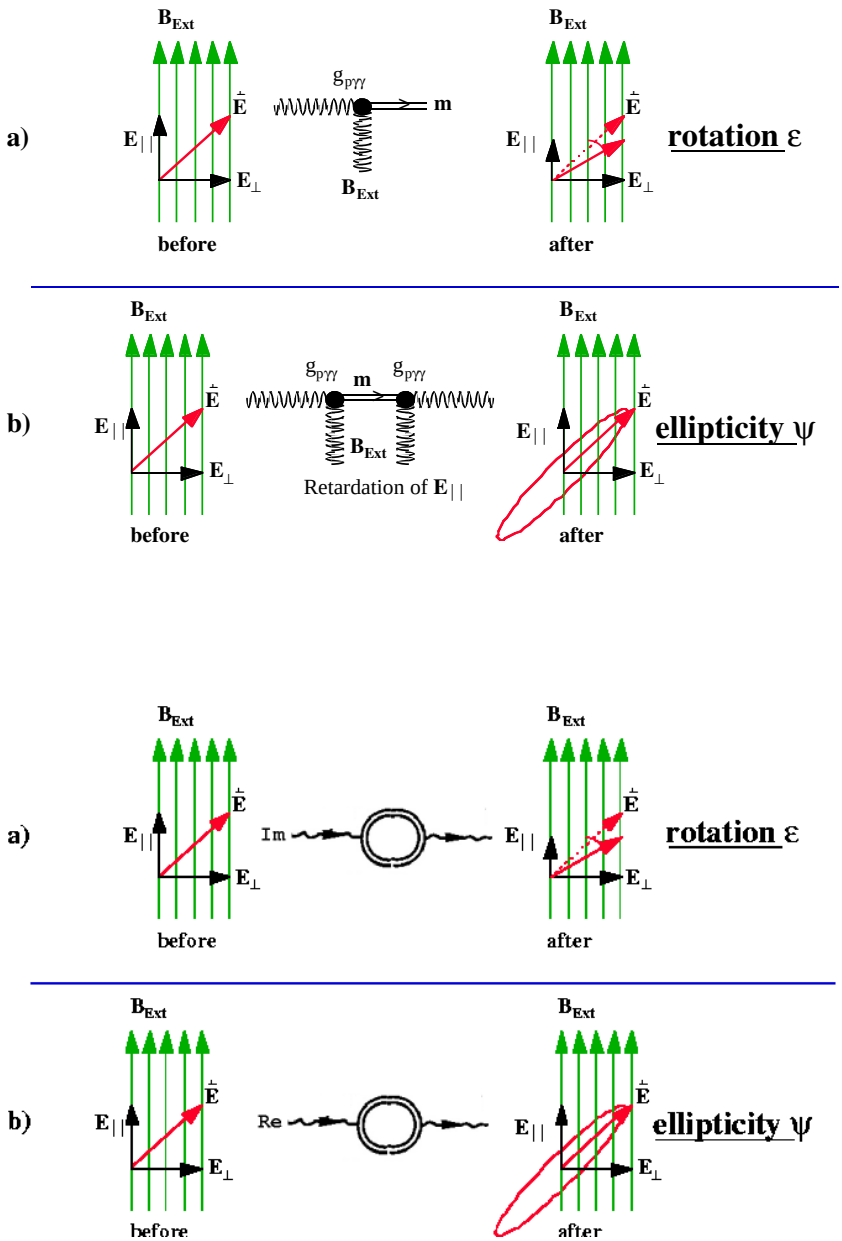

Figure 2: Changes of the polarization state of initially linearly polarized photons after the passage through a magnetic field, due to real and virtual conversion into an axion-like particle (from Ref. [6]) (top panel) or into a pair of minicharged particles (bottom panel). The double lines in the bottom panel denote the exact propagator of the minicharged particle in the background of the magnetic field.

Table 1: Current experimental data on vacuum magnetic dichroism, birefringence, and on photon regeneration.
Top: The vacuum rotation $\Delta\theta$, ellipticity ψ and photon regeneration rate from the BFRT[3)] experiment. For the polarization data, BFRT used a magnetic field with time-varying amplitude $B = B_0 + \Delta B \cos(\omega_m t + \phi_m)$, where $B_0 = 3.25$ T and $\Delta B = 0.62$ T. For photon regeneration, they employed $B = 3.7$ T.
Middle: The vacuum rotation $\Delta\theta$ and ellipticity ψ per pass measured by PVLAS, for $B = 5$ T. The rotation of polarized laser light with $\lambda = 1064$ nm is published in Ref. [1)]. Preliminary results are taken from Refs. [7,8,9)] and are used here for illustrative purposes only.
Bottom: The vacuum rotation $\Delta\theta$ from the Q&A experiment[4)] ($B = 2.3$ T).

BFRT experiment		
Rotation	($L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4}$)	
$N_{\rm pass}$	$\lvert\Delta\theta\rvert$ [nrad]	$\Delta\theta_{\rm noise}$ [nrad]
254	0.35	0.30
34	0.26	0.11
Ellipticity	($L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4}$)	
$N_{\rm pass}$	$\lvert\psi\rvert$ [nrad]	$\psi_{\rm noise}$ [nrad]
578	40.0	11.0
34	1.60	0.44
Regen.	($L = 4.4$ m, $\langle\lambda\rangle = 500$ nm, $N_{\rm pass} = 200$)	
θ [rad]	rate [Hz]	
0	-0.012 ± 0.009	
$\frac{\pi}{2}$	0.013 ± 0.007	

PVLAS experiment	
Rotation	($L = 1$ m, $N_{\rm pass} = 44000$, $\theta = \frac{\pi}{4}$)
λ [nm]	$\Delta\theta\,[10^{-12}$ rad/pass]
1064	$(\pm?)3.9 \pm 0.2$
532	$+6.3 \pm 1.0$ **(preliminary)**
Ellipticity	($L = 1$ m, $N_{\rm pass} = 44000$, $\theta = \frac{\pi}{4}$)
λ [nm]	$\psi\,[10^{-12}$ rad/pass]
1064	-3.4 ± 0.3 **(preliminary)**
532	-6.0 ± 0.6 **(preliminary)**

Q&A experiment	
Rotation	($L = 1$ m, $\lambda = 1064$ nm, $\theta = \frac{\pi}{4}$)
$N_{\rm pass}$	$\Delta\theta$ [nrad]
18700	-0.4 ± 5.3

nineties in Brookhaven (Brookhaven-Fermilab-Rochester-Trieste (BFRT) collaboration[2,3]) and are currently pursued also in Taiwan (Q&A collaboration[4]) and in France (BMV collaboration[5]). In these experiments, linearly polarized laser photons are send through a superconducting dipole magnet (cf. Fig. 1), with the aim of measuring a change of the polarization state in the form of a possible rotation (vacuum magnetic dichroism) and ellipticity (vacuum magnetic birefringence) (cf. Fig. 2). Quite surprisingly and in contrast to the other experiments mentioned, PVLAS reported recently the observation of a quite sizeable vacuum magnetic dichroism[1] (cf. Table 1). Moreover, preliminary data seem to indicate also evidence for an anomalously large vacuum magnetic birefringence (cf. Table 1). These observations have led to a number of theoretical and experimental activities, since the magnitude of the reported signals exceeds the standard model expectations[10,11,12] by far (see however Ref. [13]).

3. Possible Explanations

Among possible particle physics explanations[14,15,16,17,18] of the reported signals two are particularly appealing in the sense that they can easily be embedded in popular extensions of the standard model:

The real and virtual production of

(i) a neutral spin-0 (axion-like) particle[14] (ALP) ϕ with mass m_ϕ and a coupling to two photons via

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

or

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

depending on its parity[†], denoted by the superscript $(\pm)$ (cf. Fig. 2 (top)), or

(ii) a pair of minicharged, $Q_\epsilon = \epsilon e$, particles[16] (MCP) $\epsilon^+\epsilon^-$ 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 (cf. Fig. 2 (bottom)).

Indeed, as apparent from Fig. 3 (top), the rotation observed by PVLAS can be reconciled with the non-observation of a signal by BFRT and Q&A, if there is an ALP with[1] a mass $m_\phi \sim$ meV and a coupling $g \sim 10^{-6}$ GeV^{-1}. Alternatively, the currently published experimental data are compatible with the existence of an MCP with[16] $m_\epsilon \lesssim 0.1$ eV and $\epsilon \sim 10^{-6}$ (cf. Fig. 3 (middle)).

This degeneracy can be lifted eventually by including more data from different experimental settings from the PVLAS collaboration. As an illustration, one may

[†]For an analysis, where the ALP is not assumed to be an eigenstate of parity, see Ref. [19].

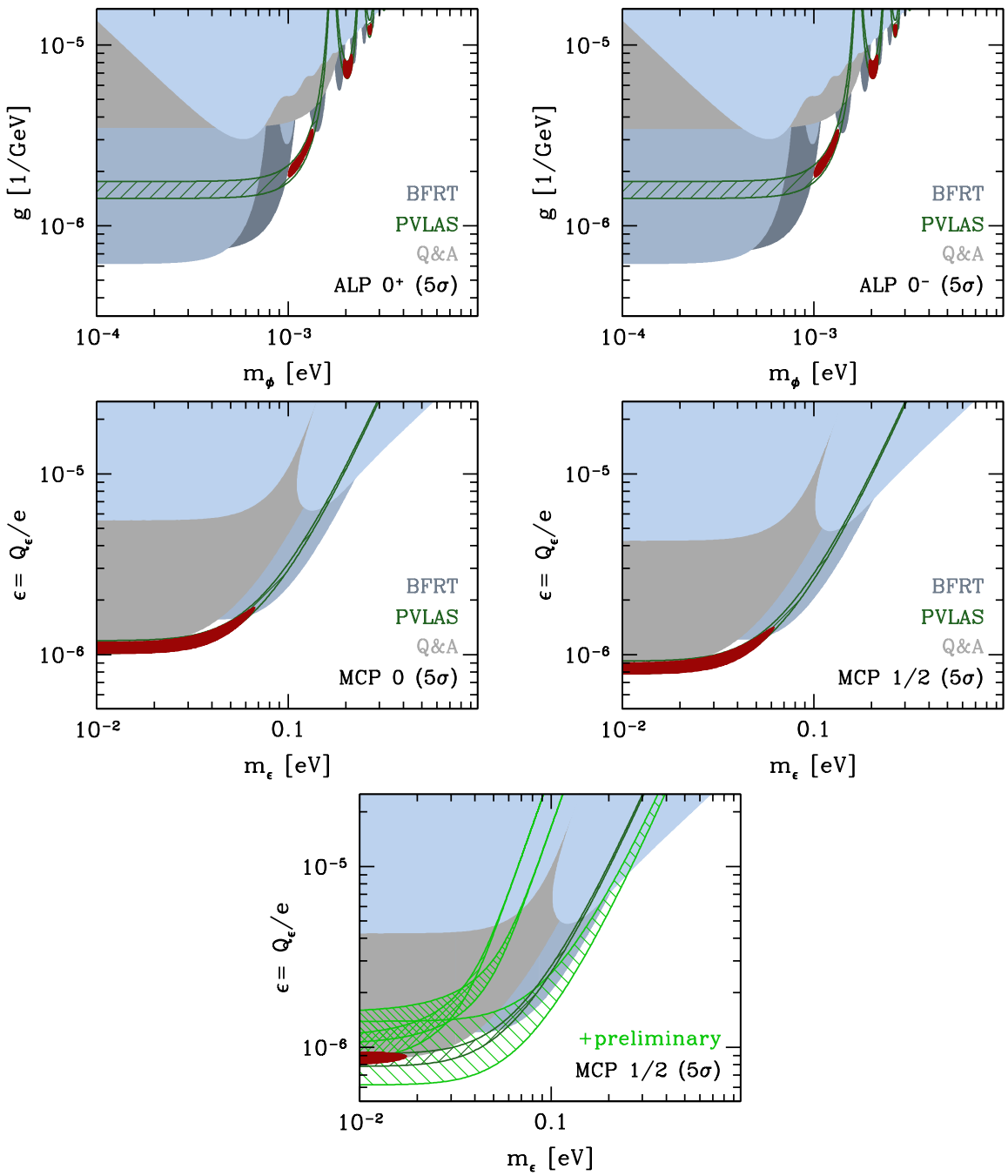

Figure 3: Pure ALP scalar (pseudo-scalar) (top left (right)) and pure MCP spin-0 (1/2) (middle left (right) and bottom) interpretation of the data on vacuum magnetic dichroism, birefringence and photon regeneration[20]: 5σ confidence level of the model parameters (red). The blue-shaded regions arise from the BFRT upper limits[3] for regeneration (dark blue), rotation (blue) and ellipticity (light blue). The gray-shaded region is the Q&A upper limit[4] for rotation. The dark-green band shows the published result of PVLAS for rotation[1] with $\lambda = 1064$ nm. The bottom panel includes also the 5σ C.L.s for rotation (coarse hatched) and ellipticity (fine hatched) with $\lambda = 532$ nm (left hatched) and $\lambda = 1064$ nm (right hatched), respectively, from the preliminary PVLAS data (cf. Table 1).

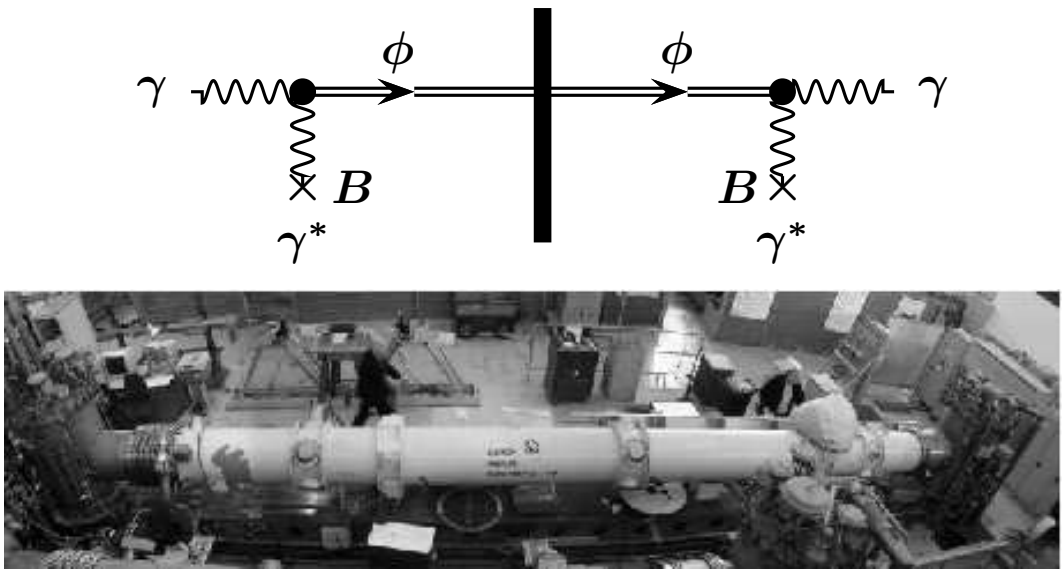

Figure 4: Light shining through a wall. *Top:* Schematic view of ALP production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right). *Bottom:* Superconducting HERA dipole magnet exploited for light shining through a wall in the Axion-Like Particle Search (ALPS) experiment[34], a collaboration between DESY, Laser Zentrum Hannover and Sternwarte Bergedorf.

include the preliminary PVLAS data from Table 1. It is easily seen that the signs of the rotation and the ellipticity are incompatible with a pure scalar (0^+) ALP, a pure pseudo-scalar (0^-) ALP, and a pure MCP spin-0 interpretation[20]. They prefer a pure MCP spin-1/2 interpretation (cf. Fig. 3 (bottom)). A slightly better fit is found[21] from a combination of ALP 0^+ plus MCP 1/2.

4. Crucial Laboratory Tests

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 Q&A[4], BMV[5], and later the OSQAR[26,27] 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[20].

4.1. Light Shining Through a Wall

The ALP interpretation of the PVLAS signal will crucially be tested by photon re-

[‡]For astrophysics-based tests of the ALP interpretation of the PVLAS anomaly see Refs. [22,23,24].

[§]High-energy collider-based tests do not seem to be competitive in the near future[25].

Table 2: Experimental parameters of upcoming 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 photon conversion and reconversion probability $P_{\gamma\phi\gamma}$, for $g \sim 2 \times 10^{-6}$ GeV^{-1}.

Name	Laboratory	Magnets	$P_{\gamma\phi\gamma\|g\sim 2\times 10^{-6}/\mathrm{GeV}}$
ALPS[34]	DESY/D	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m	$\sim 10^{-19}$
BMV[5]	LULI/F	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 0.25$ m	$\sim 10^{-21}$
LIPSS[35]	Jlab/USA	$B_1 = B_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m	$\sim 10^{-23.5}$
OSQAR[27]	CERN/CH	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 7$ m	$\sim 10^{-17}$
PVLAS[36]	Legnaro/I	$B_1 = 5$ T $\ell_1 = 1$ m $B_2 = 2.2$ T $\ell_2 = 0.5$ m	$\sim 10^{-23}$

generation (sometimes called "light shining through walls") experiments[28,29,30,31,32,33], presently under construction or serious consideration[5,27,34,35,36] (cf. Table 2). In these experiments (cf. Fig. 4), a photon beam is directed across a magnetic field, where a fraction of them turns 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[3,37]. No signal has been found and the corresponding upper limit on g vs. m_ϕ is included in Fig. 3 (top). In Hamburg, the Axion-Like Particle Search (ALPS) collaboration between DESY, Laser Zentrum Hannover and Sternwarte Bergedorf is presently setting up such an experiment (cf. Fig. 4 (bottom)) which will take data in summer 2007 and firmly establish or exclude the ALP interpretation of the PVLAS data.

As an incidental remark let us note an obvious, but remarkable spin-off if a positive signal is detected in one of the light shining through a wall experiments mentioned above. It would provide the proof of principle of an "ALP beam radio" – based on the possibility to send signals through material which is untransparent to photons – as a means of long-distance, possibly world-wide telecommunication. With presently available technology, however, only a very low signal transmission rate may be achieved[38].

4.2. Dark Current Flowing Through a Wall

Clearly, light shining through a wall in the above set up will be negligible in pure MCP models, since the probability that the $\epsilon^{\pm}$ pairs produced before the wall meet again and recombine behind the wall will be negligible. However, one may exploit in this case Schwinger pair-production of MCPs in the strong electric fields available in accelerator cavities[39]. This will lead to a new form of energy loss. In fact, one of the best current laboratory limits on very light MCPs, $\epsilon < 10^{-6}$ for $m_{\epsilon} \lesssim 0.1$ meV, arises from the fact that the superconducting cavities of the type developed for the Tera Electronvolt Superconducting Linear Accelerator (TESLA) have a very high quality factor[40], corresponding to a very low energy loss. A more direct approach to infer the existence of such particles may be based on the detection of the macroscopic electrical current comprised of them in the form of a "dark current flowing through a wall" experiment[39]. In Fig. 5 (top), we show schematically how one could set up an experiment to detect this current. In fact, a collaboration between DESY, GSI, and the University of Jena has already developed[41] a so-called cryogenic current comparator (CCC) (cf. Fig. 5 (bottom)) for the absolute measurement of the dark currents leaving the TESLA cavities down to values of pA. Placing an absorber between the TESLA cavity in Fig. 5 (bottom) and the CCC, one may realize easily a dark current flowing through a wall experiment. An exclusion of a dark current of size μA (nA) will result in a limit[43] $\epsilon < 10^{-6}$ (10^{-7}) for very light MCPs, $m_{\epsilon} < 0.1$ meV.

We note in passing that the eventual experimental demonstration that a dark current, produced in an accelerator cavity, flows through a wall and can be detected behind the wall would indicate the exciting possibility of an "MCP beam radio" as a new-type of telecommunication, in analogy to the ALP beam radio mentioned above,

4.3. Search for Invisible Orthopositronium Decay

A classical probe for MCPs is the search for invisible orthopositronium (OP) decays[44,45]. Recently, the ETH-INR collaboration published[46] a new stringent limit on the branching ratio $\mathrm{Br}(\mathrm{OP} \to \text{invisible}) < 4.2 \times 10^{-7}$, which translates, on account of the prediction $\mathrm{Br}(\mathrm{OP} \to \epsilon^{+}\epsilon^{-}) \simeq 371\,\epsilon^{2}$, for $m_{\epsilon} \ll m_{e}$, into a limit $\epsilon < 3.4 \times 10^{-5}$ on the fractional charge of the MCPs $\epsilon^{\pm}$. Further improvements and other experiments are being developed[47,48], which may reach finally a sensitivity of 10^{-10} in the branching ratio $\mathrm{Br}(\mathrm{OP} \to \text{invisible})$, corresponding to a sensitivity of

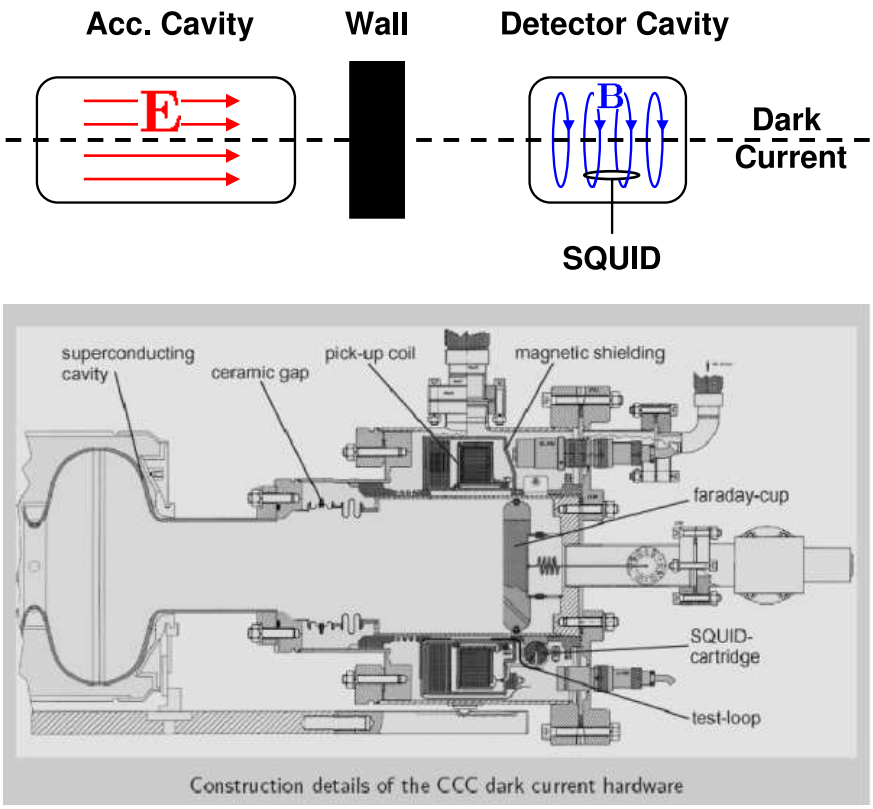

Figure 5: Dark current flowing through a wall. *Top:* Schematic set up for a "dark current flowing through a wall" experiment. The alternating dark current (frequency ν), comprised of the produced millicharged particles (dashed line), escapes from the accelerator cavity and traverses also a thick shielding ("wall"), in which the conventional dark current of electrons is stopped. The dark current induces a magnetic field in a resonant (frequency ν) detector cavity behind the wall, which is detected by a SQUID[39]. *Bottom:* Proposed set up for an absolute measurement of the dark current from a TESLA superconducting accelerator cavity with the help of a cryogenic current comparator[41,42].

5×10^{-7} in ϵ, seriously probing the MCP interpretation of the PVLAS data[¶].

4.4. Searches Near Nuclear Reactors

Another method to infer the existence of MCPs is the search for excess electrons from elastic $\epsilon^{\pm}$ scattering in a detector near a nuclear reactor. Indeed, nuclear reactors with power exceeding 2 GW emit more than 10^{20} photons per second, which may partially convert into $\epsilon^{\pm}$ pairs within the reactor core. A small fraction of these particles could lead to an observable excess of electrons via the above mentioned elastic scattering process. Recent corresponding results from the TEXONO experiment set up at the Kuo-Sheng Nuclear Power Station (2.8 GW), originally given in terms

[¶]The search for the Lamb shift contribution of light MCPs does not seem to be competitive with the search for invisible OP decays: it yields a weaker limit[49], $\epsilon < 10^{-4}$, for $m_{\epsilon} \lesssim 1\,\mathrm{keV}$.

of bounds on the magnetic dipole moment of neutrinos, can be translated into a bound[50] $\epsilon < 10^{-5}$, for $m_\epsilon \lesssim$ keV, which is only about one order of magnitude below the required sensitivity to test the pure MCP interpretation of PVLAS. This bound may be improved in the near future by exploiting a massive liquid Argon detector.

5. Problems of Particle Interpretations

5.1. Constraints from Astrophysics and Cosmology

Both, the ALP as well as the MCP interpretation of the PVLAS data seem to be in serious conflict with astrophysical bounds, arising from energy loss considerations of stars[51,52].

ALP production due to Primakoff processes $\gamma Z \to \phi Z$ in the stellar plasma and subsequent ALP escape would lead to drastic changes in the timescales of stellar evolution, placing a bound $g < 8 \times 10^{-11}$ GeV^{-1} for $m_\phi \lesssim$ keV, slightly stronger than the published bound arising from the non-observation of photon conversion of ALPs, eventually produced in the sun, by the CERN Axion Solar Telescope CAST[53] (cf. Fig. 6 (top)). These bounds on g are more than four orders of magnitude smaller than the values suggested by a pure ALP interpretation of PVLAS. This serious conflict may be solved if the production of ALPs is heavily suppressed[‖] in astrophysical plasmas[62,63,64,65], i.e. if $g_{|\mathrm{plasma}} \ll g_{\mathrm{vacuum}}$. Interestingly enough, microphysical models achieving such a suppression require typically even more sub-eV particles and fields[66,67].

In the case of MCPs, a prominent production mechanism in stellar plasmas is plasmon decay, $\gamma^* \to \epsilon^+\epsilon^-$, which is effective as soon as the plasma frequency $\omega_\mathrm{p} \sim$ few keV exceeds the threshold for pair production, $2m_\epsilon$. The lifetime of red giants leads to the most stringent bound $\epsilon < 2 \times 10^{-14}$, for $m_\epsilon \lesssim 5\,$keV, on the fractional electric charge, considerably stronger than the bound arising from big bang nucleosynthesis (cf. Fig. 6 (bottom)). The red giant bound on ϵ is thus more than seven orders of magnitude below the value required by a pure MCP interpretation of PVLAS. Again, a reconciliation can be achieved if the effective charge in the plasma is much smaller than in vacuum, i.e. $\epsilon_{|\mathrm{plasma}} \ll \epsilon_{\mathrm{vacuum}}$ – as for example in the models[66,68,69] discussed in the next section.

Recently, it has been pointed out that the production of sub-eV mass MCPs through collisions of cosmic microwave background (CMB) photons, $\gamma + \gamma \to \epsilon^+ + \epsilon^-$, may distort the CMB energy spectrum[70]. From a comparison with the observed spectrum, a limit $\epsilon < 10^{-7}$ is inferred. This is about one order of magnitude below the value required in a pure MCP interpretation of PVLAS (cf. Fig. 3 (middle and

[‖]For alternative proposals to solve this conflict based on trapping of ALPs within stellar cores see Refs.[60,61].

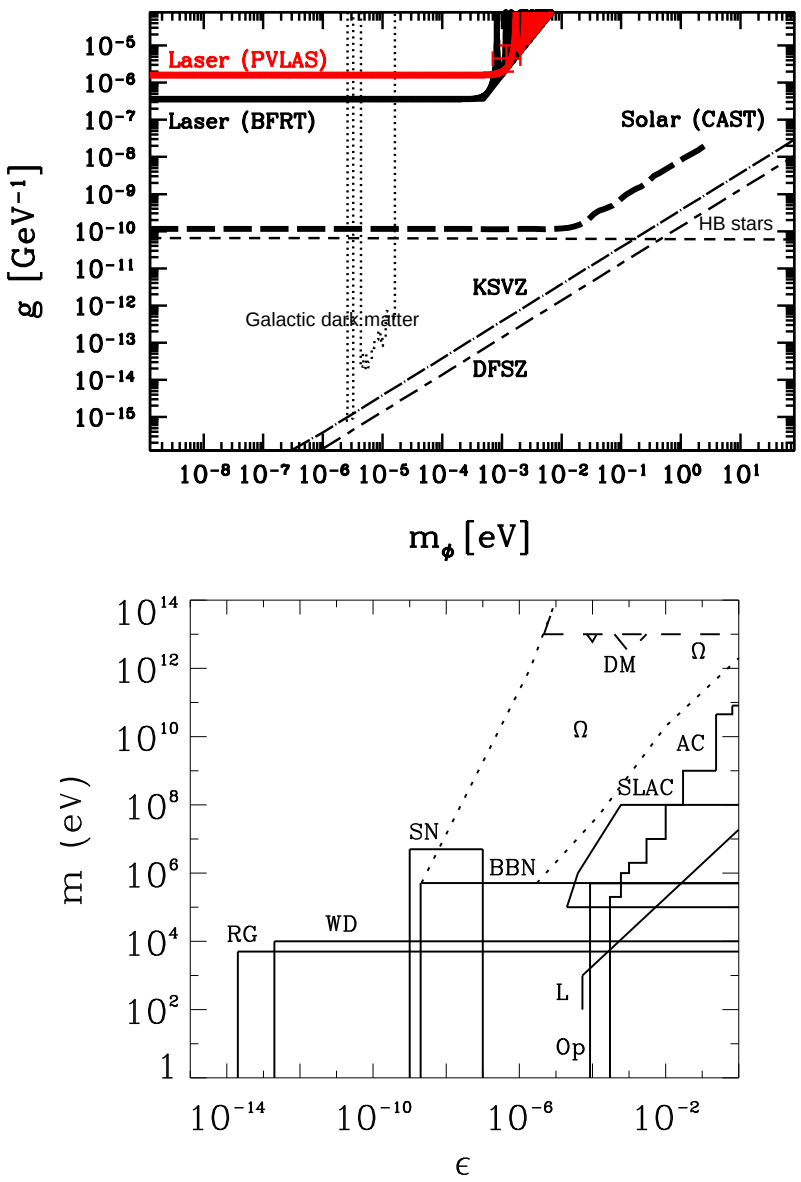

Figure 6: Constraints on ALP (top) and MCP (bottom) parameters. *Top:* Upper limits on ALP coupling g vs. its mass m_ϕ. The laser experiments[1,3)] aim at ϕ production and detection in the laboratory. The galactic dark matter experiments exploit microwave cavities to detect ALPs under the assumption that they are the dominant constituents of our galactic halo[54)], and the solar experiments search for ALPs from the sun[53)]. The constraint from horizontal branch (HB) stars[51)] arises from a consideration of stellar energy losses through ALP production. The predictions from two quite distinct QCD axion models, namely the KSVZ[55,56)] (or hadronic) and the DFSZ[57,58)] (or grand unified) one, are also shown. *Bottom:* Exclusion regions in MCP fractional electric charge ϵ vs. mass $m = m_\epsilon$ (from Ref. [52)]). The bounds arise from the following constraints: AC – accelerator experiments; Op – the Tokyo search for the invisible decay of orthopositronium[45)]; SLAC – the SLAC minicharged particle search[59)]; L – Lamb shift; BBN – nucleosynthesis; Ω – $\Omega < 1$; RG – plasmon decay in red giants; WD – plasmon decay in white dwarfs; DM – dark matter searches; SN – supernova 1987A.

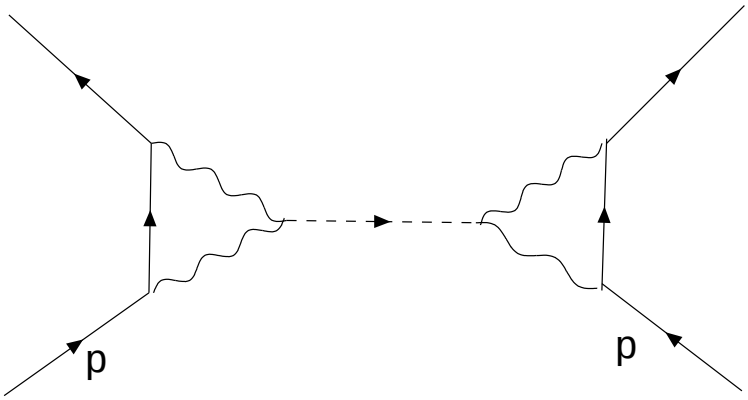

Figure 7: Exchange of a scalar ALP, coupled two photons via Eq. (1), between two protons, giving rise to a Yukawa-type non-Newtonian force between two neutral test bodies (from Ref. [72]).

bottom)). It remains to be seen whether this apparent conflict can be reconciled in certain models.

5.2. Constraints from Searches for Non-Newtonian Forces

A scalar ALP will couple radiatively to protons, leading to a spin-independent non-Newtonian force between test bodies of the Yukawa-type, $\propto (g m_p)^2 \exp(-m_\phi r)$ (cf. Fig. 7). From the non-observation of such a force in sensitive torsion-balance searches for Yukawa violations of the gravitational inverse-square law one may put a very stringent limit[71,72], $g < 4 \times 10^{-17}$ GeV^{-1}, for $m_\phi = 1$ eV and assuming that the effective interaction Eq. (1) is valid up high energies $\Lambda \gg m_p \sim 1$ GeV. This limit seemingly rules out completely the ALP 0^+ interpretation of the PVLAS data, which requires a coupling in the 10^{-6} GeV^{-1} range. However, in models where new physics arises already at sub-eV scales, $\Lambda \sim$ meV, this strong conflict may relax very much, as we will see in the next section.

6. WILPs in Models with Light Extra-U(1)'s

Finally, let us consider in this section a class of models

- in which MCPs with $\epsilon \ll 1$ arise naturally,
- which may be easily embedded in popular extensions of the standard model,
- in which most of the conflicts with astrophysics, cosmology, etc. can be evaded.

Particles with small, unquantized charge arise very naturally in so-called para-photon models[73], containing, beyond the usual "visible" electromagnetic U(1) gauge factor additional "hidden" U(1) factors, which may kinetically mix with the visible

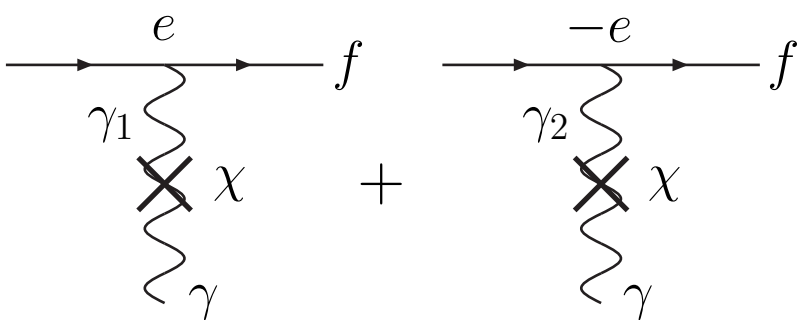

Figure 8: Gauge-kinetic mixing induced coupling of a hidden-sector particle f, with charge assignments $(0, e, -e)$ under the gauge group $\mathrm{U}_0(1) \times \mathrm{U}_1(1) \times \mathrm{U}_2(1)$, to a photon[21].

one. Such hidden-sector U(1)'s and their mixing occur in many extensions of the standard model, in particular in those coming from string theory. The crucial observation is that particles charged under the hidden U(1)'s get an induced visible electric charge proportional to the kinetic mixing parameter[74].

As a specific enlightening example[66], let us consider a gauge theory model with three light Abelian gauge fields A_i, $i = 0, 1, 2$, described by three U(1) factors, $\mathrm{U}_0(1) \times \mathrm{U}_1(1) \times \mathrm{U}_2(1)$, which interact with charged matter fields, entering the currents j_i, $i = 0, 1, 2$. Exploiting a matrix notation for the gauge fields, $A \equiv (A_0, A_1, A_2)^T$, and their field strength, $F \equiv (F_0, F_1, F_2)^T$, the Lagrangian, in the basis where the interactions with charged fields is diagonal, can be written as

$$\mathcal{L} = -\frac{1}{4}\, F^T \mathcal{K}_F\, F + \frac{1}{2}\, A^T \mathcal{M}_A^2\, A + e \sum_i j_i A_i \,. \tag{3}$$

Here, j_0 is assumed to be constructed from the fields corresponding to our visible charged standard model particles, whereas j_1 and j_2 are assumed to be constructed from the fields corresponding to the hidden-sector exotic particles. We assume that there are small mixing terms in the gauge kinetic matrix $\mathcal{K}_F$ and that the masses of the paraphotons entering the mass matrix $\mathcal{M}_A^2$ are small. Specifically,

$$\mathcal{K}_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix} , \qquad \mathcal{M}_A^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \mu^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} , \tag{4}$$

with small mixing parameters, $\chi \ll 1$. From here, it is easily seen that a hidden-sector charged particle will experience a tiny visible-sector electric charge. Indeed, the effective coupling of a hidden-sector particle f with charge assignment $(0, e, -e)$ to a visible-sector photon with four-momentum squared q^2 can be easily read-off from Fig. 8, leading to an effective fractional electric charge[66]

$$\epsilon_f \simeq \frac{\mu^2}{q^2 - \mu^2}\, \chi \simeq \begin{cases} -\chi & \text{for} \quad q^2 = 0 \\ (\mu^2/q^2)\, \chi & \text{for} \quad q^2 \gg \mu^2 \end{cases} , \tag{5}$$

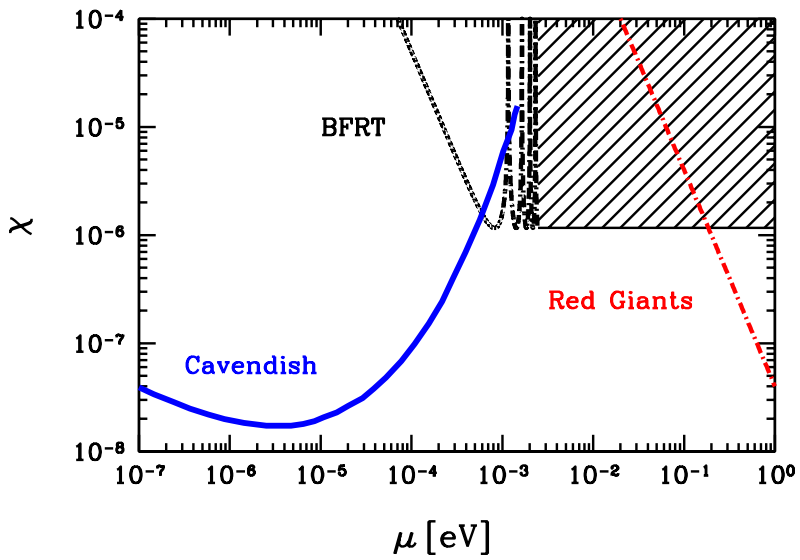

Figure 9: Upper limit on the mixing parameter χ as a function of the mass μ of a light hidden-sector paraphoton. The limits arise from: Cavendish – searches for deviations from Coulomb's law[75,76]; BFRT – light shining through a wall[3] (in vacuum, without magnetic field); Red Giant – plasmon decay $\gamma^* \to f\bar{f}$.

which is naturally small, as long as the gauge kinetic mixing parameter $\chi \ll 1$.

This model, for $\chi \sim 10^{-6}$, therefore, readily reproduces the MCP interpretation of PVLAS. Moreover, the conflict with the lifetime of stars can be relaxed by chosing μ in the sub-eV range[68], $\mu \lesssim 0.1\,\mathrm{eV}$. In fact, in the stellar plasma, the four-momentum squared $q^2 = \omega_\mathrm{p}^2 \sim \mathrm{keV}^2$ of the plasmon γ^* is in this case large enough that the additional suppression factor $\mu^2/\omega_\mathrm{p}^2 \lesssim 10^{-8}$ in Eq. (5) leads to a reconciliation of the PVLAS suggested value for $|\epsilon_f(q^2 = 0)| \simeq \chi \sim 10^{-6}$ with the requirement that in stellar plasma $\epsilon_f \lesssim 10^{-14}$. Further constraints on the paraphoton parameters of such a model can be obtained from Cavendish-type searches for deviations from Coulomb's law and from searches for light-shining through a wall, exploiting vacuum oscillations of photons into hidden-sector paraphotons[73]. As apparent from Fig. 9, the pioneering experiments of this type have already nearly reached the sensitivity to probe for the required paraphotons. Values of $\chi \lesssim 10^{-6}$ in the meV – 0.1 eV mass range may readily be probed by the next-generation of light shining through a wall experiments, which, in the case of photon-paraphoton oscillations and in contrast to the case of photon-ALP oscillations, require only high initial photon fluxes, but no external magnetic field, since they occur, for finite paraphoton mass, already in vacuum. Therefore, should light paraphotons exist, the corresponding "paraphoton beam radio" seems to offer the cheapest way of WILP-based telecommunication.

This class of minimal[68] models for explaining PVLAS may be extended[66] by introducing a light hidden sector spin-0 boson ϕ, with a Yukawa coupling y_f to the hidden-sector paracharged particle f. The corresponding radiatively induced coupling

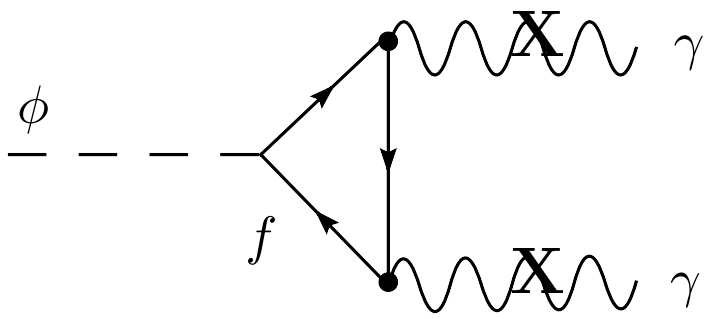

Figure 10: Effective coupling of a hidden-sector spin-0 boson ϕ to two photons via a loop of hidden-sector paracharged fermions f in a model with gauge kinetic mixing[66].

to two photons (cf. Fig. 10) can be arranged to be in the PVLAS range,

$$g(q^2=0) \sim \frac{\alpha}{2\pi}\chi^2\frac{y_f}{m_f} \sim 2\times 10^{-6}\ \mathrm{GeV}^{-1}\ \left(\frac{\chi}{10^{-6}}\right)^2\left(\frac{y_f\ \mathrm{eV}}{m_f}\right)\ . \tag{6}$$

Interestingly enough, the effective form factor appearing in the fractional electric charge (5) for large photon virtualities, $q^2 \gg \mu^2$, leads to the fact that, for a scalar ϕ, the effective Yukawa coupling to the proton is suppressed. Therefore, by chosing the paraphoton mass small enough, $\mu \sim$ meV, this hidden sector scalar ϕ can be a viable candidate for an ALP 0^+ interpretation of PVLAS, while nevertheless contributing negligibly to deviations from Newtonian gravity in torsion-balance experiments[71].

Finally, let us point out that the required multiple U(1) factors, the size of gauge kinetic mixing[77,78,79,80,81,82], and suitable matter representations to explain the PVLAS data occur very naturally within the context of realistic embeddings of the standard model based into string theory, in particular in brane world scenarios[68].

7. Conclusions

The evidence for a vacuum magnetic dichroism found by PVLAS has triggered a lot of theoretical and experimental activities:

- Particle interpretations alternative to an axion-like particle interpretation have been developed, e.g. the minicharged particle interpretation.

- Models have been found which evade very strong astrophysical and cosmological bounds on such weakly interacting light particles. These models, typically, require even more weakly interacting light particles than just the ones introduced for the solution of the PVLAS puzzle, a particular example being additional light vector particles (paraphotons).

- In the upcoming year, a number of decisive laboratory based tests of the particle interpretation of the PVLAS anomaly will be done. More generally, these ex-

periments will dig into previously unconstrained parameter space of the above mentioned models.

Small, high-precision experiments, exploiting high fluxes of low-energy photons and/or large electromagnetic fields, may give important information about fundamental particle physics complementary to the one obtainable at high energy colliders!

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