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GammeV: results and future plans at Fermilab

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GammeV is an axion-like particle photon regeneration experiment that employs the light shining through a wall technique. We obtain limits on the coupling of a photon to an axion-like particle that extend previous limits for both scalar and pseudoscalar particles in the milli-eV mass range. We have reconfigured our apparatus to search for chameleon particles. We describe the current results and future plans for similar activities at Fermilab.

1 Introduction

Weakly interacting sub-eV particles (WISPs) may exist as physics beyond the Standard Model and help explain fundamental questions such as what is the nature of dark matter or even shed insight into the underlying nature of dark energy. WISPs are a general class of new particles that include axions, axion-like particles, hidden sector photons, milli-charged particles, chameleons etc. In 2006, the PVLAS experiment reported [1] and then no longer observed [2] anomalous polarization effects of light traversing a magnetic field that could be interpreted as being mediated by an axion-like particle in the milli-eV mass range with a unexpectedly strong coupling to photons. New efforts world-wide [3] have started to investigate the possible existence of WISPs as much of the possible parameter space has been unexplored and experiments searching for these possible new particles can be mounted at modest cost.

2 Axion-like particle search

For axion-like particles, a previous laser experiment conducted in the early 1990's by a collaboration Brookhaven, Fermilab, Rochester, and Trieste (BFRT) used a "light shining through a wall" (LSW) [4] technique to set limits on sub-eV axion-like particles [5]. However, their utilization of existing 4.4m long magnets happened to result in a minimum with no sensitivity for an axion-like particle in the mass range suggested by the anomalous PVLAS result (the sine terms in Eq. 1 went to zero). The GammeV experiment [6] at Fermilab was designed to cover this missing region of insensitivity to directly test the axion-like particle interpretation of the anomalous result.

The GammeV apparatus is shown schematically in Fig. 1(a) and is used in a LSW configuration where, in the presence of an external magnetic field, a laser photon might oscillate into an axion-like particle that can traverse a "wall" and then have a small probability to regenerate

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back into a detectable photon. The formula for the probability of this regeneration process is given by the following:

$$P_{regen} = \frac{16B_1^2B_2^2\omega^4}{M^4m_\phi^8}\sin^2\left(\frac{m_\phi^2L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2L_2}{4\omega}\right) \tag{1}$$

where ω is the photon energy, M is a high mass scale inverse to the coupling to photons $g_{a\gamma\gamma}$, m_ϕ is the mass of the axion-like particle, and B_1, L_1, B_2 and L_2 are the magnetic field strengths and lengths in the photon conversion and regeneration regions, respectively.

The GammeV experiment utilizes two novel aspects in order to have increased sensitivity over the region of interest. The plunger is constructed so that it can place the "wall" either in the middle ($L_1 = L_2$) of the magnet or toward one end of the magnet ($L_1 \neq L_2$). Thus, the regions of insensitivity will be shifted in the two configurations. The second aspect is to utilize time correlated single photon counting techniques in order to have high efficiency for signal and very low noise. In this technique, the time of each 10 ns wide laser pulse (pulsed at 20 Hz) is recorded and correlated to the time of PMT pulses (also about 10 ns wide) which include dark pulses at approximately 100 Hz. The chance of a random PMT pulse being in time with a laser pulse is very small compared with the expected rate of in-time signal events if the PVLAS anomalous signal was due to an axion-like particle with large coupling to photons.

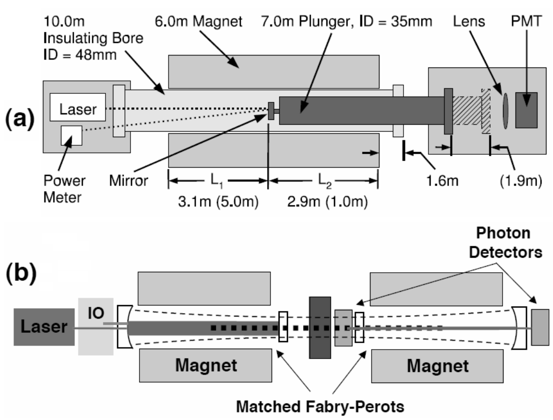

Figure 1: (a) Schematic diagram of the GammeV experimental apparatus showing a Nd:YAG laser frequency doubled to send 532 nm pulses down the warm bore of a Tevatron dipole magnet. The "wall" is mounted on a sliding vacuum tube, the plunger. (b) Schematic diagram of an enhanced LSW experiment using resonanant regeneration with matched optical cavities.

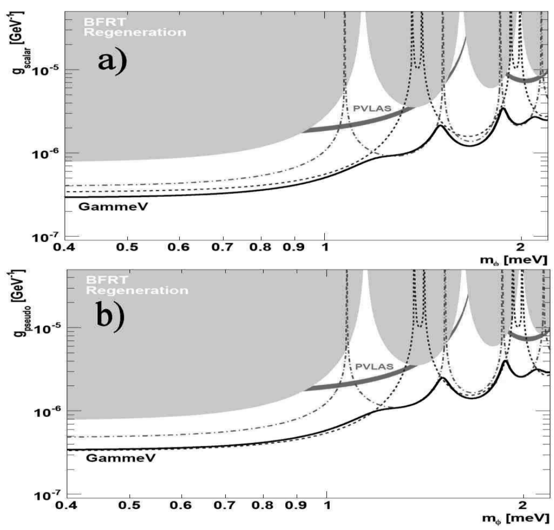

Figure 2: Published 3 σ exclusion region of mass versus photon coupling obtained by GammeV for (a) scalar and (b) pseudoscalar axion-like particles. The PVLAS anomolous region of interest is shown along with the separate limits (dashed) for the wall in the center and the wall near one end.

No signal above background is observed. Figures 2(a),(b) show the resulting 3 σ limits for the coupling of scalar and pseudoscalar axion-like particles to photons in milli-eV mass region.

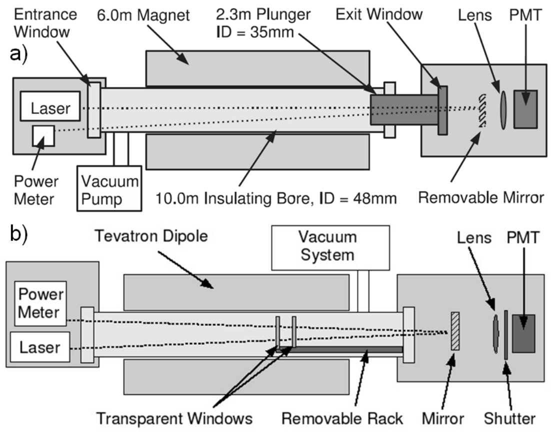

Figure 3: Schematic of the particle in a jar configuration for (a) GammeV and (b) the on-going GammeV-CHASE experiments.

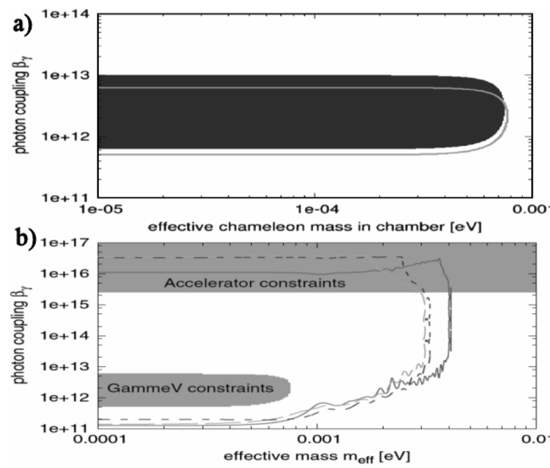

Figure 4: Exclusion region of the coupling normalized to the Planck mass to photons versus the effective chameleon mass (a) as published for the GammeV along with (b) prospects for GammeV-CHASE.

Figure 1(b) shows an enhanced LSW experiment that employs phased locked optical cavities on both the generation and regeneration side of the wall [8]. The '**G**ammeV **r**econsituted and **i**nstrumented with **m**agnets for **r**esonnantly **e**nhanced **p**hoton **r**egeneration" (GRIM REPR [9]) project is in an R&D phase to develop the phase locking scheme between the cavities and to explore the achievable finessee, $\mathcal{F}$, of the long baseline cavities. The sensitivity to the $g_{a\gamma\gamma}$ coupling constant in this configuration scales as the product of the two $\mathcal{F}$'s and linearly with the magnetic field length. With at least 12 Tevatron magnets in length and $\mathcal{F} \sim 10^5$, a sensitivity of $g_{a\gamma\gamma} < \sim 10^{-11}$ would be achievable. R&D is expected to continue for the next couple of years while Fermilab also explores a laser interferometer experiment that might be sensitive to "holographic noise" [10] - a possible jitter in space-time due to Planck scale effects.

3 Chameleon search

Chameleons are WISPs that usually take the form of a scalar particle coupled to the stress energy tensor in a potential such that their properties depend on the matter density of their environment. The GammeV apparatus was rearranged as shown in Fig. 3(a). In this configuration, a laser is shown through the chamber such that photons might oscillate into chameleons which reflect off of the exit vacuum windows or vacuum walls estenially building up a gas of such particles within the vacuum region. The laser is turned off and the PMT is turned on to look for an expontential signal above background as chameleons reconvert back into photons resulting in a detectable afterglow.

GammeV searched for chameleons using the apparatus shown in Fig. 3(a) where separately 5-hr runs of horizontal and vertical polarized laser light were shown through the magnetic field. After possibly building a population of chameleons, a 1-hr data taken period followed after turning off the laser and turning on the PMT. No afterglow was observed and an exclusion region in the chameleon coupling to photons vs effective chameleon mass was obtained under the assumption that the chameleon potential had a characteristic mass dependence on matter density $m_{eff} \propto \rho^{\alpha}$ with $\alpha > 0.8$. The limitations on stronger coupling to photons were set by the fact that such strong couplings would have resulted in the regenerated photons appearing and decaying away before the PMT could be turned on. Weak couplings were limited by the noise of the PMT. Large effective masses were constrained by the long magnetic field length. The region of validity for $\alpha > 0.8$ was conservatively set due to the estimate of the vacuum level near the mechanical roughing pump.

A new effort, **GammeV - CHASE** (**ch**ameleon **a**fterglow **se**earch), is on-going and should result in data recorded in 2010. In this re-incarnation, shown in Fig. 3(b), the limitations of the original chameleon search will all be addressed. Data taking at reduced magnetic field will allow a probe for very strong chameleon couplings to photons. A lower noise PMT will help improve the sensitivity for weak couplings. A "dish rack" that holds optical windows such that the 6 m magnetic field region is divided into regions of approximately 4.7 m, 1.0 m, and 0.3 m, will probe higher effective masses. Finally, removing the mechanical pump and utilitizing very low vacuum enabled by cryopumping will allow for sensitivity of an extended range of α such that potentials consistent with various chameleon dark energy models can be probed [11].

4 Conclusions

A new research program at Fermilab has obtained published results for axion-like particle and chameleon searches. Next generation experiments have started or are undergoing R&D. The possibility that WISPs or other phenomenon might be observable using relatively inexpensive experimental optical set-ups allows for searches of physics beyond the Standard Model. Who knows, such crazy experiments might just reveal a new weirdness of nature.

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