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GammeV is an experiment conducted at Fermilab that employs the light shining through a wall technique to search for axion-like particles and employs a particle in a jar technique to search for dilaton-like chameleon particles. We obtain limits on the coupling of a photon to an axion-like particle that extend previous limits for both scalars and pseudoscalars in the milli-eV mass range. We are able to exclude the axion-like particle interpretation of the anomolous PVLAS 2006 result by more than 5 standard deviations. We also present results on a search for chameleons and set limits on their possible coupling to photons.

1. Introduction

What are the particles that make up the dark matter of the universe?, is one of the most fundamental scientific questions today. Axion-like particles or other weakly interacting sub-eV particles (WISPs) are highly motivated dark matter particle candidates since they have properties that might explain the cosmic abundance of dark matter. The milli-eV mass scale arises in several areas of modern particle physics with a see-saw between the Planck and TeV mass scales, neutrino mass differences, the dark energy density expressed in milli-eV^4, and known dark matter candidates. In 2006, the PVLAS experiment reported [1] (although no longer observes [2]) anomolous polarization effects on an incident laser in the presence of a magentic field which could be interpretated as being due to an axion-like particle in the milli-eV mass range with a unexpectantly strong coupling to photons.

A previous laser experiment (BFRT) in the early 1990's used a "light shining through a wall" (LSW) [3] technique to set limits on sub-eV axion-like particles [4]. Because this experiment used available 4.4m long magnets, they had regions with no sensitivity for an axion-like particle in the mass range suggested by the anomolous PVLAS result. The GammeV experiment [5] has been proposed to examine the milli-eV mass scale for an axion-like particle that couples to photons to resolve the possible mystery of the anomolous PVLAS result and to extend the search for an axion-like and chameleon particles in the milli-eV mass region.

2. GammeV Apparatus

The GammeV LSW apparatus is shown schematically in Fig. 1 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 back into a detectable photon. The formula for the probability of this regeneration is given by the following:

$$\begin{aligned} P_{regen} &= \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right) \cdot \sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right) \\ &= (2.25 \times 10^{-22}) \times \frac{(B_1/\text{Tesla})^2 (B_2/\text{Tesla})^2 (\omega/\text{eV})^4}{(M/10^5\ \text{GeV})^4 (m_\phi/10^{-3}\ \text{eV})^8} \\ &\quad \times \sin^2\left(1.267\frac{(m_\phi/10^{-3}\ \text{eV})^2 (L_1/\text{m})}{(\omega/\text{eV})}\right) \sin^2\left(1.267\frac{(m_\phi/10^{-3}\ \text{eV})^2 (L_2/\text{m})}{(\omega/\text{eV})}\right) \end{aligned}$$

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 towards one end of the magnet ($L_1 \neq L_2$). Regions of insensitivity will be shifted when the plunger is put in two distinct positions and the entire milli-eV mass range can be probed with high sensitivity. The second aspect is to utilize time correlated single photon counting techniques where regenerated photons are searched in a 10 ns wide window that is intrinsically low noise since the appropriate overlap of a laser pusles with dark pulses from the PMT is low over the duration of the experiment.

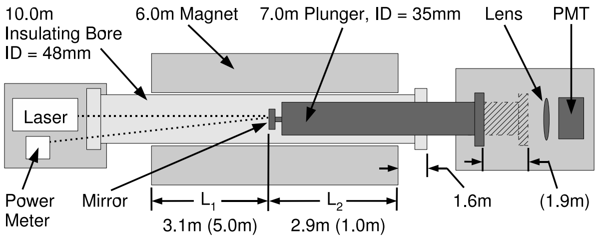

Figure 1: Schematic diagram of the GammeV experimental apparatus showing a frequency-doubled Nd:YAG laser sending 20Hz of 10 ns wide laser pulses down the warm bore of a Tevatron dipole magnet. In either the middle of the magnet or towards one end is the "wall" which reflects the laser back onto a power meter. The "wall" is mounted on a sliding vacuum tube, the plunger, which is welded light-tight inside the magnet and which extends into a PMT dark box. For the particle in a jar chameleon search, the wall is removed and the mirror is placed in the PMT box. The laser is then turned off, the mirror removed, and the PMT is turned on to search for an afterglow of possible regenerated photons.

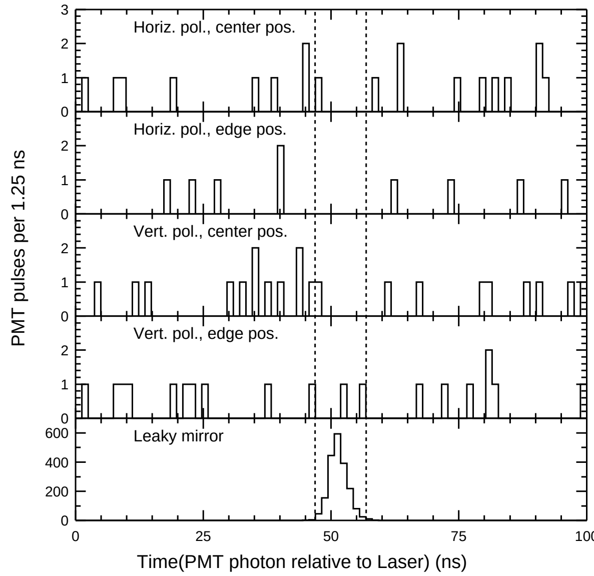

Figure 2: PMT pulse time relative to laser pulse time for the four run configurations shown relative to the expected time distribution of photons form the "leaky mirror" calibration data.

3. Data Taking and Axion-like Particle Results

GammeV has recorded calibration data called the "leaky mirror" sample where the wall was removed and the each laser pulse was attenuated by $\sim 10^{19}$ so that single photons could be recorded by the PMT. The end result was that we confirm the speed of light travel of those photons through the GammeV apparatus, and establish a 10 ns wide window *a priori* for our search region since regnerated photons from an axion-like particle would have the same relative timing. By putting a polarizing filter before the PMT, we also verified that the polarization of the laser light was parallel or perpendicular to the magnetic field depending on whether we inserted a 1/2-wave plate into the optical path. We would thus be able to probe either scalar or pseudoscalar axion-like particles which differ in that the coupling requires the polarization to be aligned or perpendicular to the magnetic field.

Data was acquired in four configurations: two polarizations and two positions of the "wall." In each configuration, approximately 20 hours of data was acquired - nearly 1.5M pulses with 4×10^{17} photons per pulse. The time of each laser pulse was recorded along with the time of each pulse detected by the PMT. In an offline analysis of the data, the timing of PMT pulses relative to the laser pulse could be examined in the temporal region where the "leaky mirror" calibration photons were also recorded. Fig. 2 shows the data recorded in the four configurations where 1, 0, 1, and 2 signal candidates are observed in the 10 ns wide search window. The expected background is obtained from the data by looking at the number of PMT pulses within 10000 ns of the laser firing and indicates that we should have expected approximately 1.5 events of expected background in each of the four configurations. The data show

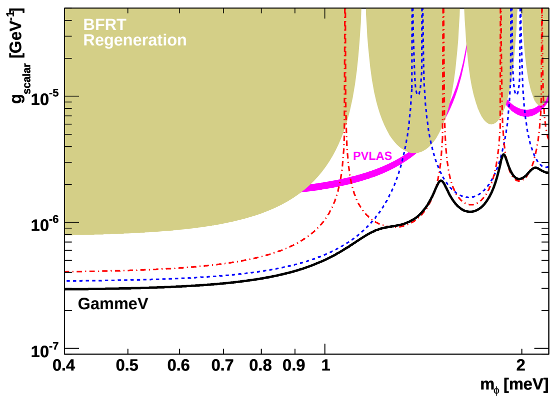

Figure 3: Exclusion region obtained by the GammeV for the coupling to photons versus the mass of a scalar axion-like particle. The dashed lines show the limits obtained separately for the data recorded with the "wall" in the middle and near one end of the maget. Also shown is the anomolous PVLAS region of interest. Finally,the shaded region indicates the previous exclusion from BFRT.

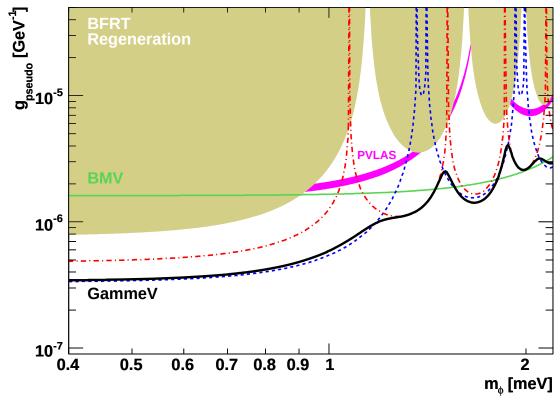

Figure 4: Exclusion region for the case that the axion-like particle couples to photons as a pseudoscalar. Also shown is a recent limit obtained by the BMV [8] experiment.

no indication of regenerated photons above this background. We use the determined efficiencies of the PMT and optical transport along with the measured laser power for each pulse to obtain the normalization on the number of incident photons and the expectation of the signal rate. We account for systematic uncertainties in these quantities in the derrived limits.

The non-observation of an excess signal allows us to set limits at 90% C.L. of the axion-like particle coupling to photons versus the mass that extend the previously excluded region. In addition, we exclude at more than 5σ the axion-like particle interpretation of the PVLAS anomoly. Figures 3, 4 show the resulting limits for the coupling of scalar and pseudoscalar axion-like particles to photons in milli-eV mass region. Other recent experiments that also probe this region of interest have also reported null results [7].

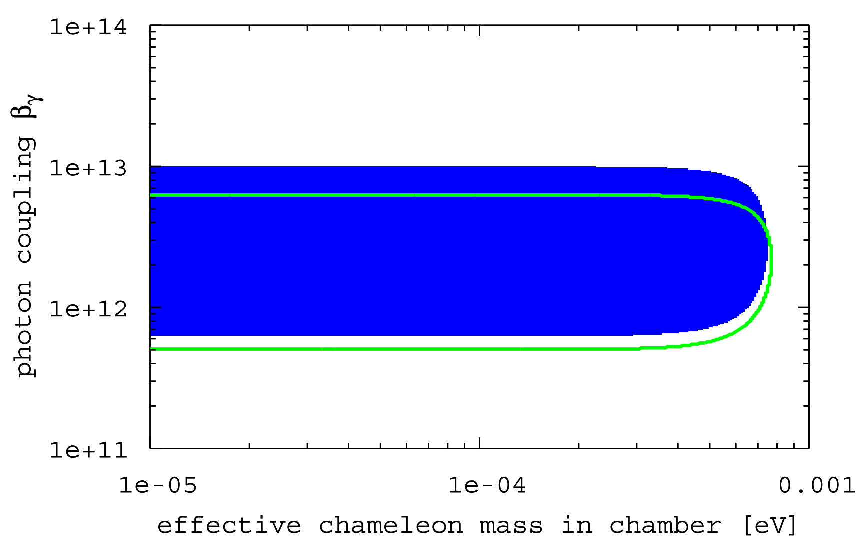

Figure 5: Chameleon exclusion region obtained by the GammeV for the coupling to photons (expressed relative to the reduced Planck mass) versus the effective mass of the chameleon in the vacuum of the GammeV apparatus.

4. Chameleons

Chameleons are possible fundamental (pseudo-)scalars that might explain the dark energy of the unvierse with a property that they couple to the stress energy tensor [9] which allows them to change their properties depending on their environment. If chameleons couple to photons they could be generated by a laser shining through a magnetic field and be 100% reflective upon encountering ordinary matter. Thus they could be trapped in a jar as they bounce between the windows and vacuum tubes of the GammeV apparatus. After turning off the laser and removing the wall, the PMT can be turned on to see whether the trapped chameleons might produce a detectable afterglow by having a rate for regenerating back into photons. GammeV searched for such an afterglow and set limits under various assumptions of the form of the chameleon potential on the possible coupling to photons versus an effective chameleon mass [10]. These limits are shown in Fig. 5. More details on the region of validity for these limits can be found in [10].

5. Future Prospects

There is continued motivation to search for possible sub-eV (pseudo-)scalars that couple to photons as a possible contribution to the dark matter of the universe. A next generation chameleon experiement will use a modified vacuum system. For "light shining through a wall" experiments, one would like to improve limits by more than three orders of magntitude to probe a region previously unexplored by laboratory or astrophysical data. This might be possible by utilizing two phased matched Fabry-Perot optical cavities on both the generation and regeneration sides of the wall in order to resonnantly enhance the axion-like particle to photon regeneration. [11].

Acknowledgments

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