GammeV: Fermilab axion-like particle photon regeneration results

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GammeV is an axion-like particle photon regeneration experiment conducted at Fermilab 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 axion-like particles in the milli-eV mass range. We are able to exclude the axion-like particle interpretation of the anomalous PVLAS 2006 result by more than 5 standard deviations.

1   Introduction

The question, *What are the particles that make up the dark matter of the universe?*, is one of the most fundamental scientific questions today. Besides weakly interacting massive particles (WIMPs) such as neutralinos, 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 is of particular interest in modern particle physics since that mass scale may be constructed with a see-saw between the Planck and TeV mass scales, and may be related to neutrino mass differences, the dark energy density expressed in $(\text{milli-eV})^4$, and known dark matter candidates such as gravitinos and axion-like particles. In 2006, the PVLAS experiment reported [1] anomalous polarization effects in the presence of a magnetic field including polarization rotation and ellipticity generation 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. It is noted that additional data recorded by PVLAS no longer observe the anomalous effects [2].

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) [3] technique to set limits on sub-eV axion-like particles [4]. 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 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 anomalous PVLAS result and to extend the search for an axion-like particle in the milli-eV mass scale.

2 GammeV Apparatus

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

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

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 toward one end of the magnet ($L_1 \neq L_2$). This changes the magnetic baseline over which axion-like particles can be generated and regenerated back into photons which is dependent on the mass through the $\sin^2$ terms in the above formula. Thus, the regions of insensitivity will be shifted from each other when the plunger is put in two distinct positions and the entire region of interest in the milli-eV mass range can be probed with high sensitivity. 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 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.

3 Calibration

GammeV recorded calibration data called the "leaky mirror" sample where the wall was removed, photons were generated from the laser, the intense laser burst was attenuated by a factor of $\sim 10^{19}$, and then single photons were recorded by the PMT. The attenuation involved shining the laser onto a highly reflective mirror - that was leaky by a factor approximately 10^{-4}. A second mirror, a 10 μm pin hole, and several neutral density filters completed the attenuation. The end result was that we could observe single photons generated by the laser, 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 regenerated photons from an axion-like particle would have the same relative timing. By putting a polarizing filter before the PMT, we also verified that 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.

4 Data Taking and Results

Data were 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. Our observation of 4 signal candidates is consistent with the expectation of 6 background PMT pulses; hence, the data show no indication of regenerated photons. 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.

The non-observation of an excess signal allows us to set limits at 3σ 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 anomaly. Figures 3, 4 show the resulting limits for the coupling of scalar and pseudoscalar axion-like particles to photons in milli-eV mass region.

5 Acknowledgments

References

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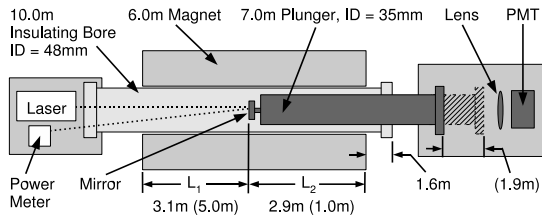
Figure 1: Schematic diagram of the GammeV experimental apparatus showing a Nd:YAG laser sending 20Hz of 10 ns wide laser pulses down the warm bore of a Tevatron dipole magnet. In either the middle of the magnet or toward one end is the "wall" which reflects the laser back onto a power meter. The "wall" 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. If an axion-like particle did traverse the wall, it could regenerate in the plunger back into a detectable photon that could be focused onto the PMT. photocathode.
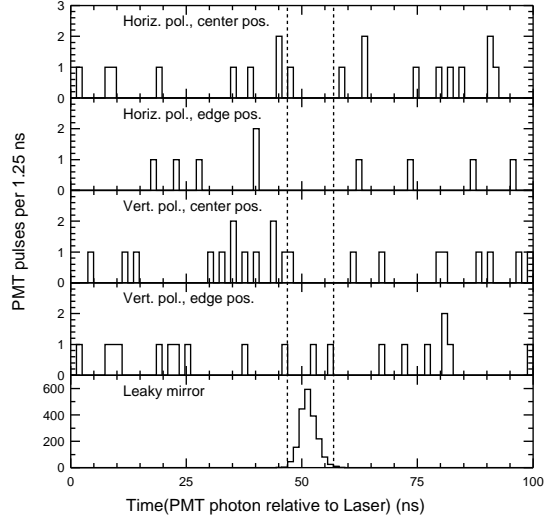

Figure 2: PMT pulse time relative to laser pulse time for the four run configurations shown relative to the expected time distribution of photons form the "leaky mirror" calibration data. The *a priori* search region for signal candidates is between the two dotted lines.
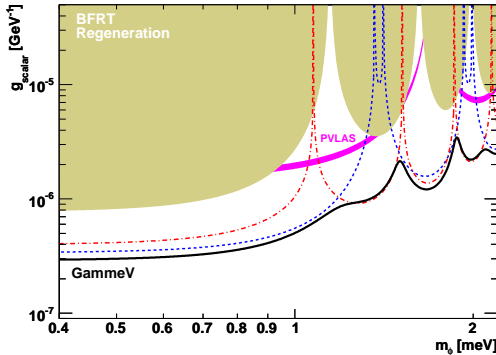

Figure 3: Exclusion region obtained by GammeV for the coupling to photons versus the mass of a scalar axion-like particle. The dashed lines show the limits obtained separately for the data recorded with the "wall" in the middle and near one end of the magnet. Also shown is the anomalous PVLAS region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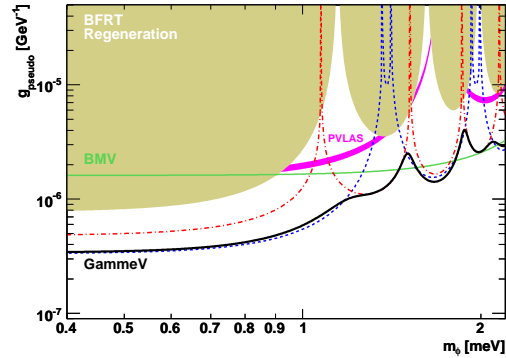

Figure 4: Exclusion region for the case that the axion-like particle couples to photons as a pseudoscalar. Also shown is a recent limit obtained by the BMV [7] experiment.