SEARCH FOR DARK MATTER PARTICLES WITH JEFFERSON LAB'S FREE ELECTRON LASER*

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Abstract

Cosmology and astrophysics indicate that our Universe contains a considerable amount of `dark matter' that is associated with an unknown elementary particle. LIPSS experiment at Jefferson Lab used a high average-power laser beam from a Free Electron Laser to probe for two-photon coupling of such particles using a `light shining through a wall' technique. Non-observation of a new scalar boson signal and kinetic mixing with hypothetical hidden-sector paraphotons provided new constraints on masses and coupling strength of these particles. We present detailed description of the LIPSS experimental procedure and plans for future measurements.

Cosmology provides evidence that most of the mass of the observable universe cannot be associated with any of the known Standard-Model elementary particles. Evidence of this `dark matter' was also obtained in the recent data from space telescopes. Axions - hypothetical particles proposed to solve a strong CP problem in Quantum Chromodynamics [1] - are dark matter candidates. Although they carry zero electric charge, they can be produced via Primakoff mechanism, resulting in predictable effects in the laboratory. At present, laser-based experiments searching for dark matter particles use two different techniques. One technique analyzes (small) modification of laser light polarization passing through magnetic field [2] that could be caused by virtual light neutral bosons (LNB). In another technique called `light shining through a wall' (LSW) [3] laser photons are sent through a strong magnetic field where some of them can convert into LNB via the Primakoff effect, these bosons then pass through a wall that serves to block the incident laser light, and reconvert into photons in a second magnetic field in a similar manner, as shown in Fig. 1. LIPSS [4] is the first experiment that uses LSW technique with a high average-power beam provided by a Free Electron Laser. This technique also may provide evidence for photon oscillation into a hypothetical hidden-sector `paraphoton' [5], and LIPSS experiment analyzed this possibility, setting new constraints on photon-paraphoton coupling [6].

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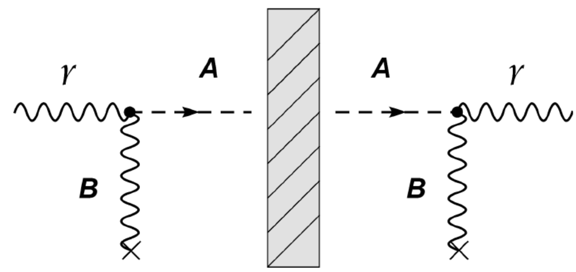

Figure 1: Photon regeneration using the “light shining through a wall” technique. The incident light (g) couples to photons in the magnetic field (B) creating the hypothetical dark-matter particle, a light neutral boson (A). Because of low interaction probability, the LNB passes through the optical barrier (the “wall”) while no incident photons do so. Regenerated photons having the same characteristics as the original photons result from the second magnetic field region downstream of the wall.

The experimental setup is shown in Figure 2. Laser light from the Jefferson Lab’s Free Electron Laser (FEL) facility was used over a period of one week of running. The FEL creates light that is more than 99.9% linearly polarized over a wide range of wavelengths in pulses that are 150 femtoseconds long with a 75 MHz repetition rate. For the LIPSS runs, it was tuned to a wavelength of 0.935 ± 0.010 micrometers with an intensity of 180 watts on average, and collimated to an 8 millimeter beam diameter; all parameters were monitored continuously during the run. The polarization direction of the laser light was verified with an optical polarization filter and chromo-color television cameras. The beam exits the FEL optical transport system and is directed onto the LIPSS beam line through a series of water-cooled turning mirrors (TM's) and collimators, as shown in Figure 2. The TM’s are specially coated to reflect 0.935 micron light and absorb light outside its narrow optical bandwidth (roughly 0.010 micrometers). The LIPSS beam line consists of an upstream (generation) magnetic field region and an identical (regeneration) magnetic field region placed downstream of it. Between the generation and regeneration magnets is an optical beam dump that also serves as a power meter; the beam dump in combination with a stainless steel vacuum flange on the input to the downstream beam line blocks all incident FEL light from the regeneration magnet. Any regenerated photons would be detected by the detector system housed in the Light Tight Box, downstream of the regeneration magnet. Both generation and regeneration magnets had dipole fields of 1.77 ± 0.04 Tesla on average. Each magnet had an effective length of 1.01 ± 0.02 meters. The magnetic field direction was determined from the magnet pole configuration and verified using standard Hall probes. In all of the results presented here, the laser light polarization direction was perpendicular to the magnetic field; the experiment was therefore sensitive to scalar (positive parity) couplings between photons and LNBs. The Light Tight Box in Figure 2 is an aluminum case painted on both inner and outer surfaces with black paint, housed inside a second box of black tape-covered aluminium foil. Inside the Light Tight Box, the photon beam passes a Newport KPX082AR16 50.2 millimeter lens which serves to focus the beam to desired accuracy onto the CCD array; the array sits five centimeters downstream of the lens. The camera system is a Princeton Instrument Spec-10: 400BR with WinView32 software. It consists of a back illuminated CCD with 1340´400 pixels imaging area (a single pixel is 20 mm´20 mm in area) and a controller box for easy integrated measurement using a PC. The CCD array is cooled to –120^{o}C resulting in a typical dark current of less than one single electron per pixel per hour. The system featured onboard grouping (binning) of pixels, where groups of adjacent pixels may be summed before readout to decrease read noise. The detection system also consisted of a light emitting diode (LED) and a convex lens used to provide a beam spot on the CCD; this serves as a reference spot on the CCD.

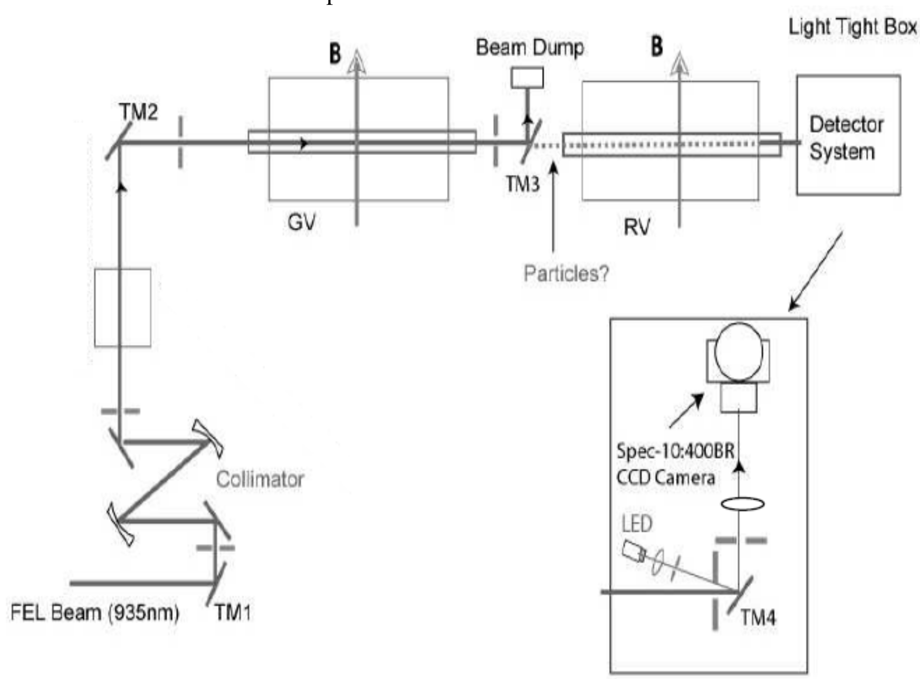

Figure 2: The LIPSS experimental setup. Laser light from the FEL is directed to the LIPSS beam line by Turning Mirror 1 (TM1) and a collimator. Turning Mirror 2 directs the incident light through the generation magnet (GV) and to an optical beam dump (the “wall”) as shown. A second, identical magnet (RV) is used to regenerate any photons that would result from a hypothetical particle (LNB) that passes through the wall; no incident FEL light passes into RV. These regenerated photons would be detected by the detector system in the Light Tight Box. Details of the Light Tight Box are shown in the insert.

The data were analyzed by defining a signal region where any regenerated photons would be observed, and background regions where no signal was expected. Seventeen hours of data were taken and analyzed. No signals from regenerated photons were observed. The results from this run can therefore be used to set the new limits on the scalar coupling of photons to a hypothetical LNB shown in Figure 3. This represents the most stringent limits to date on this scalar coupling in a generation-regeneration experiment in this range of parameters for a long, continuously-running LSW experiment. The region above the S=5 curve (short dashed) and S=2 (full) is ruled out in the present experiment.

At present LIPSS experiment runs in a beam polarization configuration sensitive to production of LNB with negative parity (pseudoscalar mode).

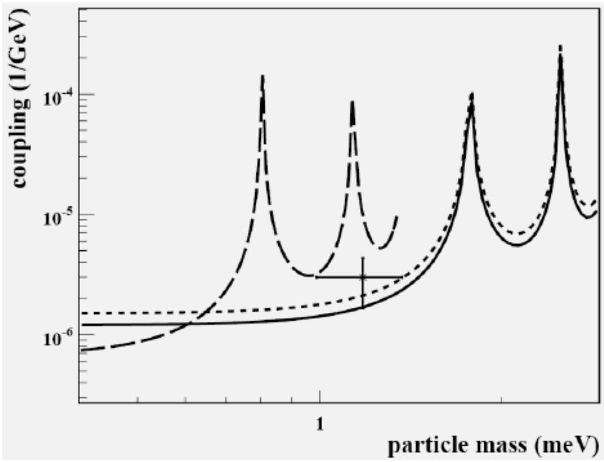

Figure 3: The new limits on scalar coupling of photons to a hypothetical LNB (in inverse giga-electron-volts) versus the LNB mass in milli-electron-volts. The curve shows the results for a significance of five (short dashed) and two (full). The BFRT result [2] is also shown (long dashed). The data point is the region claimed (now disclaimed) by the PVLAS collaboration [2].

Another physics result from this measurement is a new constraint set on a possible oscillation of a photon into a hypothetical paraphoton that is associated with a hidden-sector $U(1)_H$ symmetry [5]. In this scenario a small fraction of photon in the laser beam oscillates into a paraphoton having non-zero mass with a probability governed by a kinetic-mixing parameter χ. The photons are then blocked by a `wall', but weakly-interacting paraphotons pass through the wall, then oscillate back into photons, resulting in an observable signal in the CCD camera [6]. We observed no indication of an excess of events above background for any cuts applied to the data. The results from this run can therefore be used to set the new limits on the mixing χ of photons to hypothetical hidden-sector paraphotons as shown in Fig. 4. The full curve is the new LIPSS result, compared with those from the GammeV [7] and BMV [8] collaborations. The region above the curves is ruled out in each case. This LIPSS result represents the most stringent limits to date on this mixing in a generation-regeneration experiment in this range of parameters. The limits set by the BFRT collaboration [2] are less than those presented in Figure 4 for each case. The new LIPSS limits are approximately a factor of three better than the best previous limit. This result also leads to new constraints on hidden-sector milli-charged fermions [9].

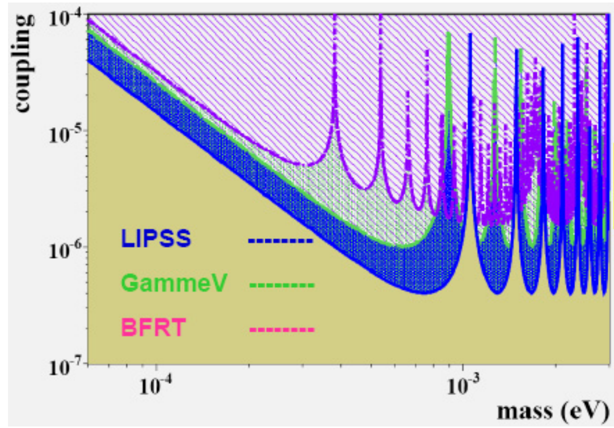

Figure 4: A mixing parameter χ versus hidden sector paraphoton mass. Upper limits (95% confidence) set by the recent "light shining through wall" experiments [6]. The short-dashed curve is from the BMV collaboration, the long-dashed curve is from the GammeV collaboration, and the full curve is the new result from the LIPSS collaboration. The latter is approximately a factor of three better than the previous limit.

LIPSS Collaboration plans to continue measurements with Jefferson Lab's FEL, improve sensitivity of the apparatus, and further extend the search for physics beyond the Standard Model.

REFERENCES

[1] C. Amsler et al. (Particle Data Group), Phys. Lett. B667, 1 (2008)

[2] L. Maiani, R. Petronzio, E. Zavattini, Phys. Lett. B175, 359(1986); BFRT Collaboration (R. Cameron et al.), Phys.Rev.D47, 3707 (1993); PVLAS Collaboration (M. Bregant *et al.*), Phys. Rev. D78, 032006 (2008).

[3] K.V. Bibber et. al., Phys. Rev. Lett. 59, 759 (1987).

[4] A. Afanasev et al. (LIPSS Collab.), Phys. Rev. Lett. 101, 120401 (2008).

[5] L.B. Okun, Sov. Phys. JETP 56, 502 (1982); B. Holdom, Phys. Lett. B 166, 196 (1986); Ahlers et al, Phys.Rev. D 78, 075005 (2008) ; Abel et al, JHEP07, 124 (2008).

[6] A. Afanasev et al., (LIPSS Collab.), arXiv: 0810.4189 [hep-ex], Phys. Lett. B . (in press), doi:10.1016/j.physletb.2009.07.055

[7] A. Chou et al., Phys. Rev. Lett. 100, 080402 (2008)

[8] C. Robilliard et al., Phys. Rev. Lett. 99, 190403 (2007); M. Fouche et. al., Phys. Rev D78, 032013 (2008)

[9] K.Ehret et al., Report DESY 09-058, arxiv:0905.4159