LIPSS Results for Photons Coupling to Light Neutral Scalar Bosons

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The LIPSS search for a light neutral scalar boson coupling to optical photons is reported. The search covers a region of parameter space of approximately 1.0 meV and coupling strength greater than 10^{-6} GeV^{-1}. The LIPSS results show no evidence for scalar coupling in this region of parameter space.

1 Introduction

Several theories in particle physics as well as cosmology predict the existence of at least one scalar, that is, spin-zero, boson [1, 2, 3, 4, 5, 6, 7, 8]. Many theories of physics beyond the SM (BSM) can accommodate scalars with very small masses and weak couplings to SM fields [9, 10, 11]. For the latter, there is renewed interest in experimental searches for sub-electron volt mass, spin-zero, weakly interacting particles, triggered in large part by the recent PVLAS collaboration claims [12], now disclaimed [13], of an anomalous rotation of polarized laser light when it propagates through a magnetic field. The experimental programs that explore the parameter space of weakly interacting, light, spin-zero, bosons by and large all use the "light shining through a wall" (LSW) technique of photon regeneration [14]: laser photons are sent through a strong magnetic field where some of them can convert into low-mass, weakly interacting bosons. 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.

The Light Pseudoscalar and Scalar Particle Search (LIPSS) collaboration searched for evidence of photons coupling to light, neutral bosons (LNBs) in a series of measurements that took place at Jefferson Lab (JLab) in the Spring of 2007. The results reported here are the LIPSS collaboration's direct search for the scalar coupling of photons to a hypothetical LNB in an LSW experiment. This is contrasted to the search for pseudoscalar couplings between photons and a LNB that has already recently been reported by the BMV collaboration [15], and as carried out originally by the BFRT collaboration [16]. The GammeV collaboration at Fermi National Accelerator Laboratory (FNAL) [17] and the OSQAR collaboration at the European Center for Nuclear Research (CERN) [18] reported first results for both scalar and pseudoscalar couplings to photons in this same region of coupling-mass parameter space. It is to be emphasized that the LIPSS collaboration took data using near-infrared photons continuously over extended periods as compared with the previously reported LSW experiments. Thus, it is most sensitive to phenomena discussed in the context of hypothetical chameleon particles [19]. The limits presented here can also be compared with the results from the CAST collaboration [20] that searches for solar produced axions (light, weakly interacting, pseudoscalar bosons, [6]) using the regeneration technique, to sensitive searches for dark matter halo axions in the galaxy [21], and to constraints on BSM couplings and masses from tests of the gravitational inverse-square law [22].

2 Experimental setup and data analysis

The experimental setup is described in [23]. Laser light from the JLab 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 in pulses that are 150 fs long with a repetition rate of up to 75 MHz. For the LIPSS runs, it was tuned to a wavelength of 0.935 ± 0.010 microns with an intensity of 180 watts on average.

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. Both generation and regeneration magnets had dipole fields of 1.77 ± 0.04 Tesla and effective lengths of 1.01 ± 0.02 meters. 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 camera system was a Princeton Instruments Spec-10:400BR with WinView32 software. It consisted of a back-illuminated CCD with 1340×400 pixels imaging area (a single pixel was $20\ \mu \times 20\mu$ in area). The CCD array was cooled to -120^o C resulting in a typical dark current of less than one single electron per pixel per hour. Stray light from all sources was shown to be less than one count per pixel per hour during the experiment. The read noise was determined to be 2.7 ± 0.2 counts per pixel per readout. Cosmic rays (CRs) that strike the pixel array leave clear ionization signals in the pixels that they strike and are easily subtracted from the data. Runs that contain a CR hit on any pixel within an area of 100×100 pixels around the signal region were discarded.

The data were analyzed by defining a signal region where any regenerated photons would be observed, and background regions where no signal was expected. The signal region for the pixel array was taken to be a 3×3 pixel area at the aligned-beam location. Tests performed subsequent to the data runs confirmed that the beam focus on the signal region wandered by at most one pixel vertically and horizontally; the 3×3 pixel area defined as the signal region did not change during the data runs.

The nine pixels in the signal area were binned together in software for each run. All other pixels and pixel groupings outside the signal region were used to define the background region(s). The difference between the counts in the signal region and the counts in the background region (normalized to the number of pixels in the signal region) was determined for all data runs [24]. No excess events above background were seen in any single run, or if all runs were combined.

3 Results and conclusions

The rate of regenerated photons is given by [14]

$$\mathrm{R} = \mathrm{r}_\gamma\ \mathrm{P}_{\gamma\to\mathrm{LNB}}\ \mathrm{P}_{\mathrm{LNB}\to\gamma}\ \frac{\Delta\Omega}{\Omega}\ \epsilon_\mathrm{c}\ \epsilon_\mathrm{d} \tag{1}$$

where r_γ is the FEL (incident) photon rate, $\Delta\Omega$ is the solid angle for detection, ϵ_c is the photon collection efficiency, ϵ_d is the detector quantum efficiency, and

$$\mathrm{P}_{\gamma\to\mathrm{LNB}} = \mathrm{P}_{\mathrm{LNB}\to\gamma} = \frac{(\mathrm{gB})^2}{\frac{\mathrm{m}^4}{4\omega^2}}\ \sin^2\!\left(\frac{\mathrm{m}^2\mathrm{L}}{4\omega}\right) \approx \frac{1}{4}(\mathrm{gBL})^2 \tag{2}$$

is the probability of scalar boson generation from the incident photons for magnets not too long for a given wavelength of light; photon regeneration from these scalar particles is given by the identical expression as shown. Here ω is the photon energy, m (g) is the LNB mass (coupling strength to photons), and B (L) is the magnetic field strength (length). The significance of the result is defined as $\mathrm{S} = \mathrm{signal}/\sqrt{\mathrm{background}}$ where signal is the number of events expected based upon Equation (1) and that would show up in the signal region as described above. The results indicate no coupling of photons to a LNB at any significance..

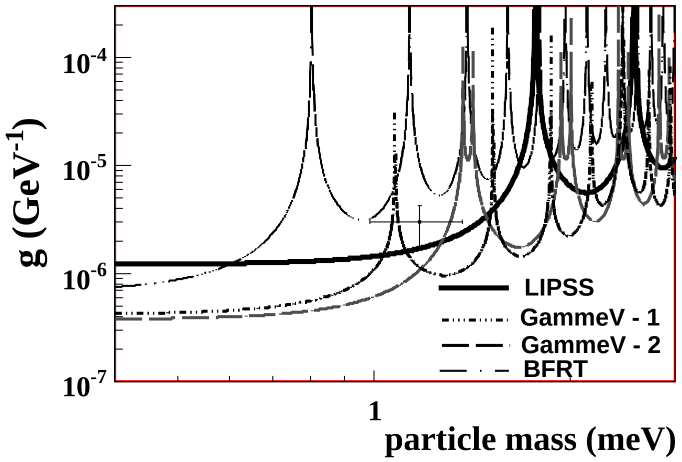

Figure 1: The new LIPSS limits on scalar coupling, g, of photons to a hypothetical LNB (in inverse giga-electron-volts) versus the LNB mass in milli-electron-volts. The curves show the LIPSS result for a significance of 2.2 (full) along with the results from previous measurements at different photon energies: GammeV-1 (using magnet lengths 5.0 m and 1.0 m), GammeV-2 (using magnet lengths 3.1 m and 2.9 m), and BFRT, as indicated. The data point is the region claimed (now disclaimed) by the PVLAS collaboration [12, 13]. The LIPSS photon energy was 1.33 eV while those of GammeV and BFRT were 2.34 eV and 2.44 eV, respectively.

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 1. 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 using optical photons. The region above the S=2.2 (full) is ruled out in the present experiment. These are similar limits already set by the BMV [15], BFRT [16], GammeV [17], and OSQAR [18] collaborations for pseudoscalar and scalar couplings, but under slightly different LSW experimental conditions. The LIPSS measurement was made with photons closest to that of the original PVLAS wavelength. This result therefore would rule out any energy dependence of the result at this level for this energy range.

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References

[1] M. Ahlers *et. al.*, Phys. Rev. D**75**, 035011 (2007); A. Ringwald, J. Phys. Conf. Ser. **39**, 197 (2006).

[2] J. Khoury and A. Weltman, Phys. Rev. Lett. **93**, 171104 (2004), Phys. Rev. D**69**, 044026 (2004); D.F. Mota and D.J. Shaw, Phys. Rev. D**75**, 063501 (2007), Phys. Rev. Lett. **97**,151102 (2006).

[3] Ph. Brax, C. van de Bruck, A.-C. Davis, J. Khoury, and A. Weltman, Phys. Rev. D**70**, 123518 (2004); Ph. Brax, C. van de Bruck, A.-C. Davis, J. Khoury, and A.M. Green, Phys. Lett. B**633**, 441 (2006).

[4] K. Choi, Phys. Rev. D **62**, 043509 (2000).

[5] I. Waga and J. Frieman, Phys. Rev. D**62**, 043521 (2000); J. Frieman *et. al.*, Phys. Rev. Lett. **75**, 2077 (1995); J.A. Frieman, C.T. Hill, and R. Watkins, Phys. Rev. D**46**, 1226 (1992).

[6] R.D. Pecci and H.R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D**16**, 1791 (1977); S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[7] G.G. Raffelt, in W.-M. Yao *et. al.*, (Particle Data Group), J. Phys. G**33**, 1 (2006).

[8] P.W. Higgs, Phys. Lett. **12**, 132 (1964).

[9] B. Holdom, Phys. Lett. B**166**, 196 (1986); R. Foot and X. G. He, Phys. Lett. B**267**, 509 (1991); K.R. Dienes *et. al.*, Nucl. Phys. B**492**, 104 (1997); S.A. Abel and B.W. Schofield, Nucl. Phys. B**685**, 150 (2004); L.B. Okun, Sov. Phys. JETP **56**, 502 (1982).

[10] J. Jaeckel and A. Ringwald, Phys. Lett. B**659**, 509 (2008); M. Ahlers *et. al.*, Phys. Rev. D**77**, 095001 (2008).

[11] V.V. Popov and O.V. Vasil'ev Europhys. Lett. **15**, 7 (1991); D. Maity, S. Roy, and S. SenGupta, Phys. Rev. D**77**, 015010 (2008).

[12] E. Zavattini *et. al.*, Phys. Rev. Lett. **96**, 110406 (2006).

[13] E. Zavattini *et. al.*, Phys. Rev. D**77**, 032006 (2008); http://axion-wimp.desy.de/index_eng.html (2007).

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

[15] C. Robilliard *et. al.*, Phys. Rev. Lett. **99**, 190403 (2007).

[16] R. Cameron *et. al.*, Phys. Rev. D**47**, 3707 (1993).

[17] A.S. Chou *et. al.*, Phys. Rev. Lett. **100**, 080402 (2008); GammeV collaboration http://gammev.fnal.gov.

[18] R. Ballou *et. al.*, CERN Report CERN-SPSC-2007-039 (2007); SPSC-M-762 (2007).

[19] M. Ahlers *et. al.*, Phys. Rev. D**77**, 015018 (2008); H. Gies *et. al.*, Phys. Rev. D**77**, 025016 (2008).

[20] S. Andriamonje *et. al.*, J. Cosmol. Astropart. Phys. **04**, 010, (2007).

[21] R. Bradley *et. al.*, Rev. Mod. Phys. **75**, 777 (2003); P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

[22] G.L. Smith *et. al.*, Phys. Rev. D**61**, 022001 (2000); R. Schlamminger *et al.*, Phys Rev. Lett. **100**, 041101 (2008); A. Dupays, E. Masso, J. Redondo, and C. Rizzo, Phys. Rev. Lett. **98**, 131802 (2007).

[23] LIPSS collaboration, Phys. Rev. Lett. (accepted for publication) (2008).

[24] K.B. Beard, Jefferson Laboratory Technical Note, JLAB-TN-07-012 (2007).