# Production and Detection of Very Light Spin-zero Bosons at Optical Frequencies

A. V. Afanasev, O. K. Baker,<sup>\*</sup> and K. W. McFarlane

Department of Physics, Hampton University, Hampton, Virginia 23668, U.S.A.

G. H. Biallas, J. R. Boyce, and M. D. Shinn

Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, U.S.A

(Dated: July 3, 2018)

The PVLAS collaboration has observed rotation of the plane of polarization of light passing through a magnetic field in vacuum and has proposed that the effect is due to interaction of photons with very light spin-zero bosons. This would represent new physics beyond the Standard Model, and hence it is of high interest to test this hypothesis. We describe a proposed test of the PVLAS result, and ways of producing, detecting, and studying such bosons with light in the optical frequency range. Novel features include methods for measurements of boson mass, interaction strengths, and decay- or oscillation-lengths with techniques not available in the x-ray region.

PACS numbers: 14.80.Mz, 12.20.Fv, 07.60.Ly, 29.90.+r

#### INTRODUCTION

The PVLAS collaboration's measurement[1], of the rotation of the plane of polarization of light passing through a magnetic field in a vacuum, is many orders of magnitude larger than expected from light-by-light scattering in quantum electrodynamics [2]. They suggest that this effect is due to the existence of a very light, neutral, spinzero boson (LNB) of mass 1 meV  $\leq m_b \leq 1.5$  meV, coupling to two photons with a coupling constant  $g_{b\gamma\gamma} =$  $1/M_b$ , such that  $2 \times 10^5$  GeV  $\leq M_b \leq 6 \times 10^5$  GeV. This boson would have properties similar to the previously proposed axion [3, 4], including very weak coupling to other particles. The ranges quoted for  $m_b$  and  $M_b$  come from combining the PVLAS result with results from previous experiments by the BFRT collaboration [5, 6, 7].

The existence of such a LNB would have many implications. It would be a candidate for a component of dark matter. It is not in the parameter range expected for an axion [8], so it may indicate a new mass scale in particle physics [9]. There may be more than one member of the family, with other unexpected properties [10]. Confirmation or refutation of this interpretation of the PVLAS result is of high importance.

Since the effect has not been observed in astrophysical studies [8], a laboratory experiment is the most direct test. Several groups are planning to carry out such experiments (see, e.g., [11, 12]). There are advantages in using light in the visible and near-visible frequency range: high-power coherent sources are available (such as the Jefferson Lab FEL [13]), as are a variety of sensitive detectors, and signals can be manipulated with optical techniques.

Here we consider methods for production, detection, and study, of LNBs in the specific mass and coupling constant range of the PVLAS result. Ideas behind the methods were put forward in Refs. [14, 15] and some were employed by the BFRT collaboration. The approach uses production of LNBs by light in a static magnetic field (generation), followed by conversion of LNBs to photons (regeneration), also in a static magnetic field. The generation-regeneration (G-R) apparatus that we consider is shown in Figure 1. The regeneration magnet can be moved along the axis of the apparatus.



FIG. 1: Schematic layout of apparatus showing input laser beam, LNB generation magnet 1, photon regeneration magnet 2, and detector. The magnetic fields are transverse to the beam direction. The main beam elements are a polarization rotator B1, a possible optical cavity (B2,B3), a turning mirror B4 that also transmits a fraction of the beam for alignment purposes, and a "wall" W that prevents primary laser light from reaching the regeneration magnet. Optical elements E1-E2-E3 and E1-D1-D3-E3 form an interferometer.

If the coupling of the LNB to ordinary matter is extremely weak, the regenerated photons will have the same optical characteristics as the original beam, except for a phase shift due to the mass of the intermediate state, and hence should have predictable optical proporties, such as being focusable to a very small area. A low-noise imaging detector can be used, where the photons are focused on one or a few pixels, the remaining pixels giving an automatic background measurement. An imaging detector can also observe beam properties other than rate.

The probability of a photon energy  $\omega$  generating a LNB

mass  $m_b$  in a homogeneous magnetic field  $B_1$  length  $\ell_1$ , followed by regeneration by the LNB of a photon in a field  $B_2$  length  $\ell_2$  can be written, using notation and units as in Refs. [1, 7, 16], as:

$$P_{GR} = \left(\frac{B_1\ell_1}{2M_b}\right)^2 \frac{\sin^2(y_1)}{y_1^2} \left(\frac{B_2\ell_2}{2M_b}\right)^2 \frac{\sin^2(y_2)}{y_2^2} \tag{1}$$

where  $y_{1,2} = \Delta_b \ell_{1,2}/2$ , and when  $\omega \gg m_b$ ,  $|\Delta_b| = m_b^2/2\omega$  in vacuum.

The interaction depends on the the photon's polarization, the direction of the magnetic field, the parity of the LNB, and the parity properties of the interaction. For a pseudoscalar LNB, Eqn. 1 applies when the photon polarization is parallel to the field of the generation magnet, the photon direction is perpendicular to the field, and the interaction is parity conserving. With similar provisos, the polarization of the regenerated photons will be parallel to the field of the regeneration magnet. Rotation of the initial polarization, or measurement of the polarization of regenerated photons, relative to the direction of the relevant magnetic field, will reveal the combination of the parity of the boson and the parity-conserving properties of the interaction.

The probability has zeros at  $\Delta_b \ell_{1,2}/2 = \pi, 2\pi, ...$  and rapidly declines beyond the first zero, so that effective G-R requires  $\Delta_b \ell_{1,2}/2 < \pi$ . The PVLAS result sets a scale for constant-field G-R experiments: the product  $\ell_{1,2}\lambda$ should be  $\leq 1 \text{ m} \cdot \mu \text{m}$ , or  $\ell_{1,2}/\omega \leq 1 \text{ m/eV}$ . Magnets with periodic fields [14] avoid this limitation and rates can grow as the fourth power of the length of the apparatus.

For a constant-field G-R arrangement, and a rate N of photons traveling in the beam direction in an apparatus with overall efficiency  $\eta$ , the number of regenerated photons observed at rate r in time t is  $rt = Nt\eta P_{GR}$ . With a noise or background rate n, the significance reached is  $S = r\sqrt{t/n}$  where the variance of the background rate is taken as n. A search experiment should achieve  $S \ge 5$ . As an example, two 1.0-m, 1.5-T magnets with 3 kW of beam at 900 nm and a low-noise ( $\sim 0.1 \,\mathrm{s}^{-1}$ ) detector, would reach the  $S \ge 5$  confirmation level in the PVLAS region in about 200 hours, as shown in Figure 2.

## PHASE MEASUREMENT AND SIGNAL ENHANCEMENT (PSE)

The signal-to-noise ratio can be enhanced using interference between regenerated photons and light from the incident beam [15]. Measurement of the phase can also result in a mass measurement. Figure 1 includes a PSE device; in format it is a Mach-Zender interferometer. This technique relies on the interaction of the LNB with matter being small enough, and its lifetime long enough, that the regenerated photons have a phase relationship to the generating photons. If a signal were observed but



2.0

2.5

FIG. 2: Coupling scale performance of proposed apparatus, versus LNB mass, compared with the PVLAS upper and lower 3- $\sigma$  limits. The 'Simple' curve gives the 5- $\sigma$  confirmation level for a 200-h run, while the 'Enhanced' curve is for a 4-h run using the signal enhancement technique described here.

1.5

boson mass m, (meV)

1.0

8.0x10

6.0x10

4.0x10

2.0x10

0.0

0.5

Coupling scale (M<sub>b</sub>, GeV)



FIG. 3: Sample simulation of use of PSE method. Points are simulated data, curve is least-squares fit.

interference was not, that would indicate that the LNB has significant interactions.

Adding a reference beam of amplitude A to a LNB amplitude a with relative phase  $\phi$  will result in a combined observed rate  $n + \eta (A^2 + 2aA \cos \phi + a^2)$ . The signal rate without enhancement would be  $r = \eta a^2$ . By varying the length of one arm, with the adjustable element D3, the relative phase and amplitude can be measured. For a simple estimate of the signal enhancement, take the effective signal to be  $2\eta aA$ , and the rate from the reference beam to be  $\sim 3n$ . The significance obtained in time t is now  $S' = \sqrt{3rt}$ . As noted in Ref. [15], this result is noiseindependent. For a signal-to-noise ratio of  $\sim 1 : 100$ , the improvement in significance will be  $\sim 20$ . Even in the absence of background or noise, a significance enhancement of a factor of two can be obtained, equivalent to a reduction of time by a factor of four.

A simulation of the process was made using  $r = 0.01 \,\mathrm{s}^{-1}$  and  $n = 10 \,\mathrm{s}^{-1}$ , with a relative phase of 0.1 periods. Runs consisted of 41 data points each corresponding to 100 s of data. The result of one such simulated run is plotted in Figure 3. An ensemble of runs gave a mean for the modulation amplitude of  $(1.13 \pm 0.15) \,\mathrm{s}^{-1}$ , compared with  $1.1 \,\mathrm{s}^{-1}$  expected. The mean fitted pathlength shift was  $(0.10 \pm 0.012)$  wavelengths. (Both uncertainties are rms deviations of the individual run results from the mean of all runs.)

The LNB mass can be measured by changing the spacing between the generation and regeneration field centers and measure the resulting phase shift. For example, the simulated results described above imply that a 1-m movement of the regeneration magnet with 900-nm light would give measurement of the mass of a 1 meV boson to  $\sim 0.02 \text{ meV}$ .

## PERIODIC FIELDS

The use of periodic fields to detect and produce axions has been proposed [14, 15]. Periodic-field magnets can be extended as far as beam divergence allows, overcoming the limitation  $\ell \leq 2\pi/\Delta_b$ . We propose novel ways of implementing these ideas with magnets with adjustable periods, that can be used to make precise measurements of LNB mass and resolve components if there is more than one LNB. For masses in the PVLAS region and photons near the visible range, the required period is of the order of meters, making it practical to consider periodic fields for a variety of experiments (and for LNB production facilities). In the x-ray region, the required period is of the order of kilometers.

Figure 4 shows examples of how an adjustable periodic field could be produced. The magnet in Figure 4(a) consists of rotatable elements that can be arranged with alternating parallel fields, or at any angle to form a helical field, as in Figure 4(b).

We extend the alternating-field concept [15] to segmented magnets with periods incommensurate with the segment length. The probability of generation or regeneration in a magnet with alternating field magnitude  $B_m$ is:

$$P'_{G,R} = \left(\frac{B_m d}{2M_b}\right)^2 \frac{\sin^2 y_0}{y_0^2} \left| \sum_{k=1}^n \delta_k \exp i(2k-1)y_0 \right|^2 \qquad (2)$$

where  $y_0 = \Delta_b d/2 = m_b^2 d/4\omega$ , d is the length of each of n segments, and  $\delta_k = \pm 1$  indicates the polarity of the



FIG. 4: Example of magnets to produce periodic fields: (a) alternating magnetic fields produced by rotatable magnet segments, (b) similar magnets used to form a helical field.



FIG. 5: Regenerated photon rates from adjustable-period alternating-field magnet systems, for a coupling scale of  $M_b = 5 \times 10^5$  GeV. The magnets are length 10 m and field amplitude 1.5 T, with a 900-nm beam at 10 kW. The peaks, from left to right, are for masses of 0.9, 1.1, 1.3, 1.5, and 1.7 meV. The points are for a segment length of 0.2 m, the lines for 0.01 m.

kth segment. The width of the resonant production is  $\delta m_b \approx 2\omega/m_b \ell$ , with the maximum occurring at a period of  $4\pi\omega/m_b^2$ .

Figure 5 shows the photon rates of G-R apparatuses using identical alternating-field magnets. These calculations used  $\delta_k = \operatorname{sgn}[\sin \Delta_m (2k-1)d/2]$ , where  $\Delta_m$  is the desired spatial frequency of the field.

Another approach is to use variable-pitch helical magnets as in Figure 4(b); this design allows better matching to the desired magnet period, and gives similar rates. However, the azimuthal symmetry does not allow tests of parity, and spin-zero bosons will generate photons with circular polarization. For ideal helical magnets with an incident linearly-polarized beam, the resonant portion of the probability for a regenerated photon is

$$P_{GR}'' = \frac{1}{4} \left(\frac{B_1'\ell_1}{2M_b}\right)^2 \frac{\sin^2(y_1')}{y_1'^2} \frac{1}{2} \left(\frac{B_2'\ell_2}{2M_b}\right)^2 \frac{\sin^2(y_2')}{y_2'^2} \qquad (3)$$

where  $B'_{1,2}$  is the magnitude of the field, and  $\ell_{1,2}$  the length, of each magnet,  $y'_{1,2} = (\Delta_b - \Delta_{m1,2})\ell_{1,2}/2$ , and  $\Delta_{m1} = \Delta_{m2} = \Delta_b$  at resonance. Segmented helical magnets give similar rates for periods longer than several segments.

Either arrangement would allow measurement of the boson mass to  $\sim 0.001 \text{ meV}$ , and the detection of multiple LNBs within the accessible mass range. Using light from 10 to  $0.25 \,\mu\text{m}$  and periods from 0.1 to 20 m, a boson mass range from 0.1 to 10 meV could be explored, bracketing the PVLAS range.

If the PVLAS hypothesis is confirmed, a future 'LNB factory' could be built using alternating fields. To generate and detect LNBs in the PVLAS region, one could use a magnet length of 100 m with a field amplitude of 7 T. A 100-m long optical cavity in the production magnet pumped with 355 nm laser light could provide an intracavity photon flux of 100 kW with a Rayleigh range of > 200 m [17] and work in magnet apertures of a few cm, giving rates in excess of 10<sup>9</sup> detected photons/s.

#### PHYSICS STUDIES

In case of observation of a confirmed signal rate, a first study of interaction strengths with ordinary matter could be made by adding material at the wall, and measuring phase shifts or changes in rates. Given that the energy and wavelength of the LNBs would be in the optical region, interaction with matter would likely be in the form of coherent forward scattering and hence could be described by an effective scattering length, providing a connection with theoretical models. With a measurement to the accuracy described above (of the phase shift due to a thick wall), the scattering length per nucleon or electron could be measured to  $\sim 10^{-10}$  fm. Decay or oscillation lengths at the 1-m scale can be also studied by moving the regeneration magnet. The proposed use of an imaging detector that can detect changes in angular distributions may be relevant to physics studies.

# SUMMARY

Optical wavelengths are well suited to studies of light neutral bosons in the PVLAS mass and coupling strength region, using the generation-regeneration technique. High power sources are available, and constantfield and periodic-field magnets can produce significant fluxes. Optical detectors with high efficiency are available, with imaging and timing capabilities. The expected coherence of regenerated photons with the incident photons, assuming very weak coupling to ordinary matter, allow optical techniques of study to be used. Some of these techniques will be applied in a forthcoming experiment by a Hampton University-Jefferson Lab collaboration [18].

#### ACKNOWLEDGEMENTS

We acknowledge the help of the Jefferson Lab FEL staff, especially Gwyn Williams and George Neil. Authored in part by The Southeastern Universities Research Association, Inc. under U.S. DOE Contract No. DE-AC05-84150 and the U.S. Office of Naval Research. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes. This work was supported in part by U.S. National Science Foundation awards PHY-0114343 and PHY-0301841.

- \* Electronic address: oliver.baker@hamptonu.edu; URL: http://cosm.hamptonu.edu/
- E. Zavattini et al. (PVLAS), Phys. Rev. Lett. 96, 110406 (2006), hep-ex/0507107.
- [2] W. Heisenberg and H. Euler, Z. Physik 98, 714 (1936).
- [3] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
- [4] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- [5] R. Cameron et al., Phys. Rev. D47, 3707 (1993).
- [6] R. E. Cameron, Ph.D. thesis, University of Rochester (1992), uR-1262.
- [7] G. Ruoso et al., Z. Phys. C56, 505 (1992).
- [8] S. Eidelman, K. Hayes, K. Olive, M. Aguilar-Benitez, C. Amsler, D. Asner, K. Babu, R. Barnett, J. Beringer, P. Burchat, et al., Physics Letters B 592, 1+ (2004), URL http://pdg.lbl.gov.
- [9] E. Massó and J. Redondo, J. Cosmol. Astropart. Phys. 2005, 015 (2005), hep-ph/0504202 v3.
- [10] K. R. Dienes, E. Dudas, and T. Gherghetta, Phys. Rev. D 62, 105023 (2000), hep-ph/9912455.
- [11] R. Rabadan, A. Ringwald, and K. Sigurdson, Phys. Rev. Lett. 96, 110407 (2006), hep-ph/0511103.
- [12] L. Duvillaret et al., Tech. Rep., CERN (2005), CERN-SPSC-2005-034.
- [13] G. R. Neil et al., Nucl. Inst. and Meth. in Phys. Resrch. A 557, 9 (2006).
- [14] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1981).
- [15] K. Van Bibber et al., Phys. Rev. Lett. 59, 759 (1987).
- [16] G. Raffelt and L. Stodolsky, Phys. Rev. D 37, 1237 (1987).
- [17] N. Hodgson and H. Weber, Optical resonators, fundamentals, advanced concepts and applications (Springer-Verlag, 1997), ISBN 3-540-76137-3.
- [18] A. Afanasev, O. K. Baker, and K. W. Mc-Farlane, An initial search for a light spinzero particle using the JLab FEL (2006), URL http://cosm.hamptonu.edu/research/lipss.html.