# An initial search for a light spin-zero particle using the JLab FEL

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3/24/2006

**Abstract**

An experiment is proposed to make an initial search for a light, neutral, spin-zero boson (SZB) coupling to two photons, using a generation-regeneration technique. The experiment will focus on the boson mass range in which the PVLAS collaboration has observed an effect (1 meV $\leq m_b \leq$ 1.5 meV). It will reach a coupling scale of approximately $6\times10^5$ GeV (coupling constant $g_{b\gamma\gamma} = 1.7\times10^{-6}$ GeV$^{-1}$), confirming or refuting the SZB explanation of the PVLAS effect in that region of parameter space; a more definitive experiment that covers a larger area of parameter space will be proposed at a later date. This initial search will use the special characteristics of the Jefferson Lab (JLab) infrared (IR) Free Electron Laser (FEL).

## 1. Motivation

The PVLAS collaboration has reported [1] a measurement of the rotation of the polarization direction of light that passes through a magnetic field in a vacuum, quoting a value of $(3.9 \pm 0.5)\times10^{-12}$ radians per pass. This dichroism is much greater than can be caused by any Standard Model interaction; it is almost four orders of magnitude larger than is expected from light by light scattering in quantum electrodynamics. This same group using the same experimental apparatus observed an ellipticity induced presumably by the same effect that caused the dichroism. The PVLAS group suggests an interpretation of these effects as due to the existence of a light, neutral, spin-zero boson (SZB) of mass 1 meV $\leq m_b \leq$ 1.5 meV, coupling to two photons with a coupling constant $g_{b\gamma\gamma} = 1/M_b$, of $2\times10^5$ GeV$\leq M_b \leq 6\times10^5$ GeV. This boson presumably couples to two photons in the same way as the previously proposed axion [2]. In common with the axion, this new boson would have very weak coupling to other particles, otherwise it would have been observed previously in other sensitive experimental searches.

The PVLAS polarization measurement does not by itself put any limit on the range of $m_b$, but only on the relation of $M_b$ to $m_b$. The limitation to a specific range comes from a series of previous experiments by the Brookhaven-Fermilab-Rochester-Trieste (BFRT) collaboration [3][4][5]. The PVLAS collaboration has also reported the ellipticity results in conferences [6][7]. Their newly published work refers to the optical rotation of polarized light [1].

The existence of a boson with properties as suggested by PVLAS would have many implications. It would be a candidate for a component of the dark matter that pervades our universe. It is not in the parameter range expected for a QCD axion, so it may indicate a new low-mass field in particle physics. There may be more than one member of the family, with other unexpected properties. Confirmation or refutation of this interpretation of the PVLAS result is of high importance. Several other groups are expected to design and implement experiments to test this result [8].

## 2. Need for the FEL and Feasibility

The Jefferson Lab FEL has many properties which make it unique as a source to probe this mass range. These features include:

- High average power, required to give the required signal rate
- Stable operation, allowing data collection over extended periods
- Low-emittance beam, useful to separate signal from background
- Bunched beam, also useful to reduce background
- Coherence between bunches, that may be useful to determine axion parameters
- High polarization, necessary to enhance the polarization-dependent production
- Tuneability, to explore effect of different photon energies
- Infrastructure, to support high-field magnets, and other experimental requirements.

The proposers have, over the last few months, investigated ways of taking advantage of these properties to design an experiment that would give conclusive evidence one way or the other. This collaboration has developed the configuration detailed below that is suitable for an initial measurement covering the interesting PVLAS region.

## 3. Source requirements

As noted, in this initial search 1064 nm FEL light at 75 MHz is requested. The average power assumed is 3 kilowatts (kW), however the collaboration plans to implement a scheme that will increase this to approximately 30 kW effective power in an external cavity. This experiment needs the maximum power that the FEL can deliver. If higher power laser light is possible, it is requested at this wavelength in this initial run.

## 4. Beam time required

As noted, approximately three 8-hour shifts this cycle, for data-taking. Some beam time at low power will be needed (at 75MHz) for alignment and calibration. The experiment would benefit from a continuous running period of several shifts (ensuring experimental parameters are stable for data taking) if possible. However, the collaboration will work with whatever beam schedule the FEL personnel deliver.

## 5. Experimental details and experience

As in the case of the neutrino, where direct observation proved the reality of a particle invented to conserve energy in $\beta$ decay, the reality of the SZB interpretation of the PVLAS result can be demonstrated by observing the process of photon production (via regeneration) by these bosons. (An experiment of this kind was performed by the BFRT collaboration [3] with negative results; these results help constrain the PVLAS range of values.) Figure 1 indicates the physics process explored in the proposed experiment.

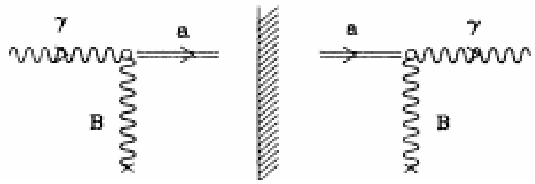



Figure 1. The physics process of the proposed generation-regeneration measurement. FEL photons couple to the virtual photons in a high field magnet to create the spin-zero particles (labeled *a*). These weakly interacting bosons travel through a light shield to a second high field magnet where photons of light are regenerated.

In this layout, photon bunches from the FEL are stored in the external cavity between the mirrors (as a single bunch). The bunch passing through the generation magnet of field strength *B* and length *L* produces bosons (labeled *a* in the figure) that then pass through the mirror and the wall (the wall stops any photons) and proceed to the regeneration magnet. Regenerated photons are focused on the detector system. Note that the regenerated photons have the same properties as the original photons and can be focused to a small spot at the detector.

The rate of regenerated photon events, *R*, is given by:

$$R = r_\gamma P_{\gamma\to\varphi} P_{\varphi\to\gamma} \varepsilon_c \varepsilon_d \tag{1}$$

where $r_\gamma$ is the FEL (incident) photon rate, $\varepsilon_c$ is the photon collection efficiency (solid angle for detection), $\varepsilon_d$ is the detector quantum efficiency, and

$$P_{\gamma\to\varphi} \approx \frac{1}{4}(gBL)^2 \left\{ \frac{\sin\left(\frac{m_b{}^2 L}{4\omega}\right)}{\frac{m_b{}^2 L}{4\omega}} \right\}^2 \tag{2}$$

is the probability of boson generation from the incident photons of frequency $\omega$. An identical expression is used for photon regeneration from these SZBs. In this initial search, the GW magnets that are on hand will be used. Adequate LCW and the required power supplies already exist at the FEL for these magnets.

The proposed experiment will be set up in Laboratory 1 of the FEL building, coexisting with other experiments. A schematic of the experimental layout is shown in Figure 2.

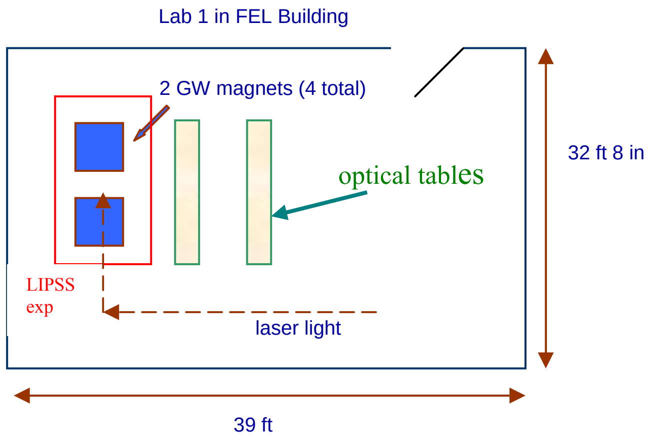



Figure 2. The experiment will be mounted in Laboratory 1 in the FEL Building. There will be two GW magnets used for SZB generation, and two for photon regeneration.

Table 1 shows the rates expected with the setup proposed. The mass reach specified in the last column of Table 1 makes no assumption about the intrinsic detector noise. The low noise detector that will be used will allow a five sigma measurement to be made in roughly one day. The Rockwell Scientific PICNIC pixel array has a dark noise of less than approximately 2 electrons/second and is adequate for this measurement. Sources of noise other than intrinsic detector noise include cosmic rays, radioactivity in the detectors and surrounding apparatus, thermal background (at 1064 nm), and electrical noise. These are mostly unknown and will require study with the actual apparatus. The rate shown assumes a detector quantum efficiency of 50% and a geometric acceptance of 0.8 with 3 kW of laser power at 1.064 micron wavelength.

Table 1: Experimental parameters

| B (Tesla) | L (meters) | coupling scale (GeV) | rate (Hz) |
|---|---|---|---|
| 1.7 | 1.0 | $6.0 \times 10^5$ | 0.1 |

Imaging detectors are chosen to give the ability to reject background by exploiting the low emittance of the beam in an optical cavity: a spot size of 15 μm or less is expected to be achieved. This allows detailed examination and subtraction of backgrounds by looking at adjacent pixels, and by using timing (if timing information is available). The experiment will begin by using a Santa Barbara Instruments Group (SBIG) ST-237 CCD detector; this detector is already on hand. A Rockwell Scientific PICNIC detector with ultra-low noise and good quantum efficiency will be used in the latter running period of the experiment.

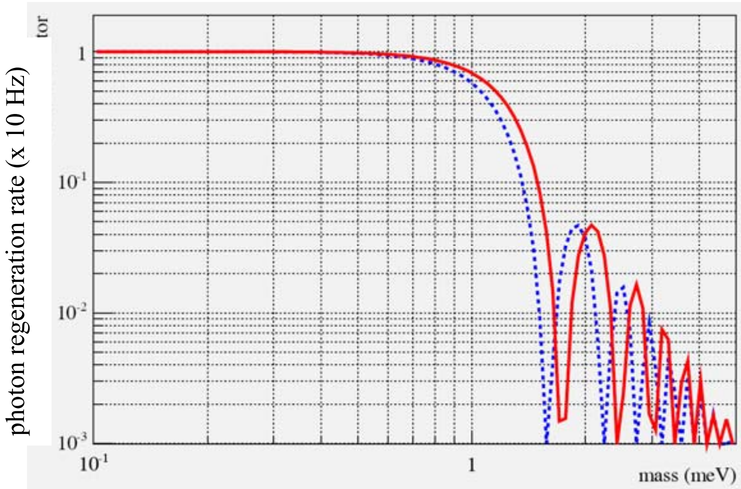



Figure. 3. The regenerated photon detection rate versus boson mass. The rate assumes a 50% detector quantum efficiency and 80% detector acceptance with 3 kW incident power. The solid (red) curve is for a 1.0 meter long magnet; the dashed curve is for 1.2 m.

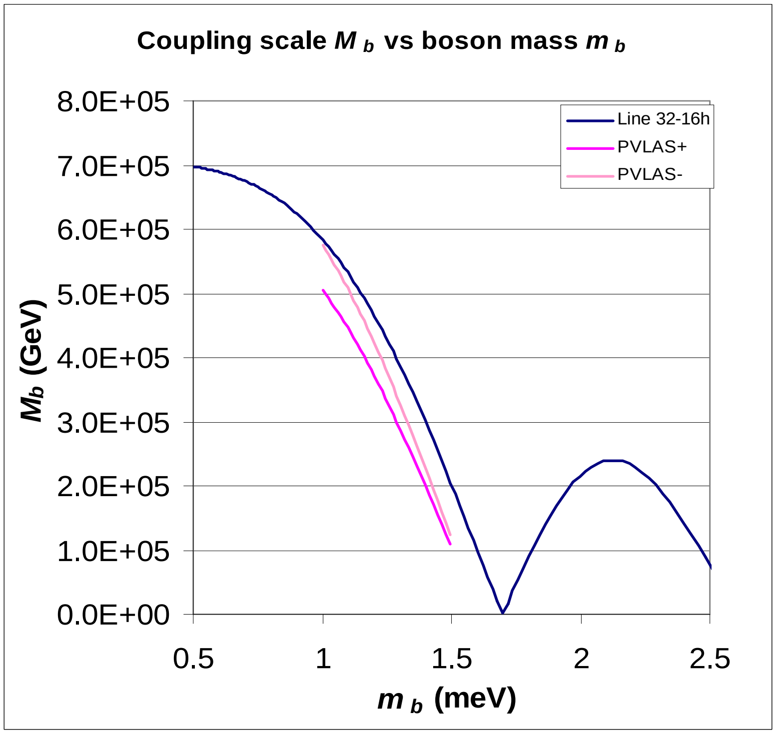
Shown in Figure 3 is the detection rate for the regenerated photons versus the mass of the spin-zero boson. This rate assumes that we use the ultra-quiet Rockwell Scientific PICNIC focal plane array (FPA) (dark noise < 2 electrons/second; quantum efficiency 0.5). The rate is essentially constant over the mass range covered by the PVLAS experiment. The solid red curve shows the rate for a 1.0 m long magnet. The dashed blue curve shows the result with a 1.2 meter long magnet (with reduced magnetic field). Only the magnet of length 1.0 meters or less is useful for this measurement.

The collaboration include two experienced particle and nuclear physicists and a theoretician (OKB, KMcF, and AA), as well as FEL physicists (JB, GB, and MS) with many years of experience in optics, magnets, and FEL operations. This combination brings together the necessary skills to complete this project successfully; other collaborator will be added as needed.

**6. Goals and Scope**

The configuration described above can achieve the goal of testing part of the interesting region where PVLAS claims to see an effect, in this interpretation of their result (the mass reach given in Table 1 exceeds the PVLAS result error bars, as seen in Figure 4). We chose to use 1.064 micron wavelength since that was used by the PVLAS collaboration; there is the possibility that the effect is wavelength dependent. There are many questions to be addressed, especially for backgrounds to the low-rate signal. However, the predicted performance is sufficiently good that we believe the axion (or SZB) interpretation of the PVLAS result may tested with this initial search experiment. The region to be explored (for a five standard deviation measurement) is shown in Figure 4 for a day-long run given the calculated rates with the low noise detector described above; the allowed region from previous experiments is indicated.

Figure 4. The region of parameter space covered by this initial LIPSS search using the GW magnets as described in the text is shown as the area under the Line 32 curve. The PVLAS allowed region is shown as the area between the two short curves PVLAS+ and PVLAS-. The results indicate that the PVLAS interesting region may be accessed in the initial experiment with GW magnets in a 16 hour run.

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