No "Light Shining through a Wall": Results from a Photoregeneration Experiment

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Recently, axionlike particle search has received renewed interest. In particular, several groups have started "light shining through a wall" experiments based on magnetic field and laser both continuous, which is very demanding in terms of detector background. We present here the 2σ limits obtained so far with our novel setup consisting of a pulsed magnetic field and a pulsed laser. In particular, we have found that the axionlike particle two photons inverse coupling constant M is $>8 \times 10^5$ GeV provided that the particle mass $m_a \sim 1$ meV. Our results definitively invalidate the axion interpretation of the original PVLAS optical measurements with a confidence level greater than 99.9%.

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The axion was first proposed 30 years ago to solve the strong CP problem [1], but other models also support the existence of such light, neutral, spin-zero bosons [2,3] called axionlike particles. Although no axion has been definitely detected yet, several experiments and astronomical observations have limited the range of possible axionlike particle mass m_a and inverse axionlike particle two photons inverse coupling M [4].

Last year, an Italian collaboration (PVLAS) announced an unexpected observation of a magnetic dichroism in vacuum which they suggested might be due to photoregeneration of axionlike particles [5]. However, their mass and two photon inverse coupling constant inferred from these PVLAS measurements were seriously inconsistent with the CAST limits [6], albeit the latter are model dependent. There was an urgent need for a direct independent experimental test of the observed dichroism [7].

All of that has raised a renewed interest in axionlike particle search, in particular, for model independent purely laboratory-based experiments [8]. The most popular setup, commonly called "light shining through a wall", is a photoregeneration experiment based on the Primakoff effect coupling an axionlike particle with two photons (a real one from the laser field and a virtual one from an external magnetic field) [9]. The experiment consists of converting photons into axionlike particles of identical energy in a transverse magnetic field, then blocking the photon beam with a wall. The axionlike particles hardly interact with the wall and are converted back to photons in a second magnet. Finally, the regenerated photons are counted with an appropriate detector. Such an experiment was conducted in the 1990s by the BFRT Collaboration without detecting any regenerated photon signal, which led to limits on the axion parameters [10]. Mainly motivated by the PVLAS astonishing results, several "light shining through a wall" experiments have been proposed and are currently under construction [11]: at DESY the Axion-Like Particle Search project (ALPS), at CERN, the Optical Search for QED Vacuum Magnetic Birefringence, Axions and Photon Regeneration project (OSQAR), at Jefferson Laboratory, the LIght PseudoScalar Search project (LIPSS), and at Fermilab, the GammeV Particle Search Experiment project. Eventually, the PVLAS Collaboration disclaimed their previous observations [12].

Experimentally, the main difficulty lies in detection. The expected regeneration rate is indeed very weak—less than 10^{-20}—so that optical shielding has to be perfect and the detector background very low.

In this Letter, we detail our project, and we present the limits on the axionlike particle mass and two photons inverse coupling constant we have obtained so far. We have found an original and efficient way to solve the detection problem as both the laser and the magnetic field are pulsed, as well as our detector. Contrary to other similar experiments requiring long integration times, we are not limited by the background of the detector as the photons are concentrated in very intense and short laser pulses. We are the first to present here the results of a pulsed "light shining through a wall" experiment, specially designed to test the PVLAS claims. In particular, we have found that the axionlike particle two photons inverse coupling constant M is $>8 \times 10^5$ GeV provided that the particle mass $m_a \sim 1$ meV. Our results definitively invalidate the axion interpretation of the original PVLAS optical measurements with a confidence level greater than 99.9%.

Our experimental setup shown in Fig. 1 is based on three synchronized pulsed elements: a very energetic laser, two pulsed magnets which are placed on each side of the wall, and a time-gated single photon detector. We have chosen this pulsed approach as it allows us to measure very small conversion rates free from the inevitable background counts of photon detectors.

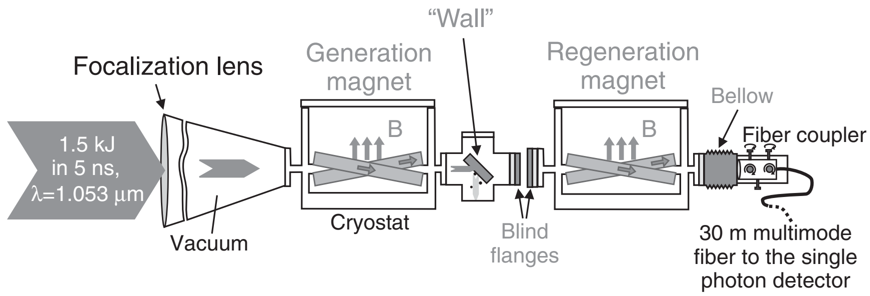

FIG. 1. Scheme of our experimental setup.

The conversion and reconversion transition rate (in natural units $\hbar = c = 1$, with $1\ \mathrm{T} \equiv 195\ \mathrm{eV}^2$ and $1\ \mathrm{m} \equiv 5 \times 10^6\ \mathrm{eV}^{-1}$) after propagating over a distance z in the inhomogeneous magnetic field B writes [13]:

$$P(z) = \left| \int_0^z dz' \Delta_M(z') \exp(i\Delta_a z') \right|^2, \quad (1)$$

where $\Delta_M = \frac{B}{2M}$ and $\Delta_a = -\frac{m_a^2}{2\omega}$ with the photon energy ω. Note that this equation is valid both for pseudoscalar and scalar particles, but pseudoscalar (respectively scalar) particles couple to photons with a polarization parallel (respectively orthogonal) to the magnetic field. We have two identical magnets; the detection rate of regenerated photons is given by

$$R = P^2 \frac{\mathcal{P}}{\omega} \eta, \quad (2)$$

with $\mathcal{P}$ the laser power and η the global detection efficiency.

Studying Eqs. (1) and (2), we can easily see that the number of incident photons, the integral of the transverse magnetic field over the magnet length L:

$$\int_{-L/2}^{+L/2} B dz = B_0 L_{\mathrm{eq}}, \quad (3)$$

and the detection efficiency have to be maximized. We define B_0 as the maximum field and L_{eq} as the equivalent length of a magnet producing a uniform magnetic field B_0. On the other hand, $P(z)$ oscillates for too long magnets. The length leading to the highest conversion rate for a homogeneous magnetic field is $L_{\mathrm{opt}} = 2\pi\omega/m_a^2$. For optical frequencies and an axionlike particle mass on the order of 1 meV, this length is on the order of 1 m.

In order to have the maximum number of incident photons for the laser source at a wavelength that can be efficiently detected, we have chosen to set up the experiment at LULI, Palaiseau, France, on the Nano 2000 chain. It can deliver up to 1.5 kJ over 4.8 ns (FWHM)—as shown in the inset of Fig. 2—with $\omega = 1.17$ eV. This corresponds to $N_{\mathrm{inc}} = 8 \times 10^{21}$ photons per pulse. The repetition rate is 1 pulse every 2 hours. The vertically linearly polarized incident beam has a 186 mm diameter and is almost perfectly collimated. A deformable mirror included in the middle of the amplification chain corrects the spatial phase of the beam to obtain at focus a spot better than two diffraction limits. It is then focused just behind the wall using a lens which focal length is 20.4 m. The beam is apodized to prevent the incoming light from generating a disturbing plasma on the sides of the vacuum tubes. Before the wall where the laser beam propagates, a vacuum better than 10^{-3} mbar is necessary in order to avoid air ionization. Two turbo pumps along the vacuum line give 10^{-3} mbar near the lens and better than 10^{-4} mbar close to the wall. The wall is made of a 15 mm width aluminum plate to stop every incident photon while axionlike particles continue. It is tilted by 45° compared to the axis of the laser propagation in order to increase the area of the laser impact and to avoid backreflected photons. In the second magnetic field region, a vacuum better than 10^{-3} mbar is also maintained.

For the magnets, we use a pulsed technology. The pulsed magnetic field is produced by a transportable generator developed at LNCMP, Toulouse, France, which consists of a capacitor bank releasing its energy in the coils in a few milliseconds [14]. A typical time dependence of the mag-

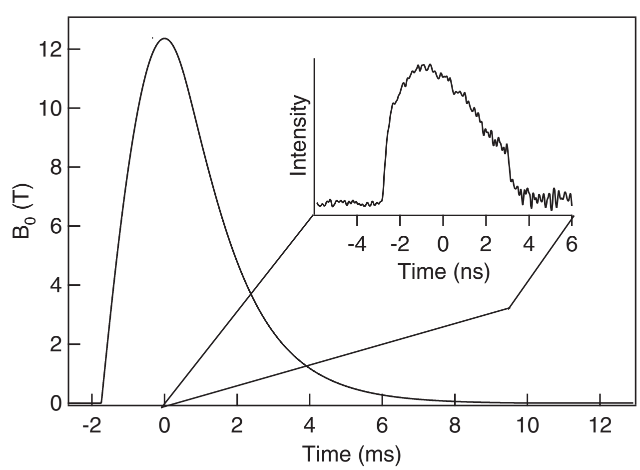

FIG. 2. Magnetic field B_0 at the center of the magnet as a function of time. The maximum is reached within 1.75 ms and can be considered as constant ($\pm 0.3\%$) during $\tau_B = 150\ \mu$s. The 5 ns laser pulse is applied during this interval. Inset: temporal profile of the laser pulse.

netic field in our coils is shown in Fig. 2. Besides, a special coil geometry has been developed in order to reach the highest and longest transverse magnetic field [15]. A 12 mm diameter aperture has been made inside the magnets for the laser beam. As for usual pulsed magnets, the coils are immersed in a liquid nitrogen cryostat to limit the consequences of heating. When the magnetic field is maximum, the repetition rate is set to 5 pulses per hour. A delay between two pulses is necessary to get back to the temperature of equilibrium which is monitored via the coil resistance. During data acquisition, our coils provide $B_0 \geq 12.3$ T over an equivalent length $L_{eq} = 365$ mm. The magnetic field B_0 remains constant ($\pm 0.3\%$) during $\tau_B = 150$ μs, a very long time compared to the 5 ns laser pulse. During operation the magnetic pulse is triggered by a signal from the laser chain which has a stability ensuring that the laser pulse happens within these 150 μs. In order to detect pseudoscalar particles, the transverse magnetic field is parallel to the laser polarization.

The last principal element is the single photon detector that has to meet several criteria. In order to have a sensitivity as good as possible, the regenerated photon detection has to be at the single photon level. The integration time is limited by the 5 ns laser pulse. This imposes a detector with a dark count far lower than 1 over this integration time so that a nonzero regenerated photon counting would be significant.

Our detector is a commercially available single photon receiver from Princeton Lightwave which has a high detection efficiency at 1.05 μm. It integrates a 80×80 μm^2 InGaAs Avalanche Photodiode (APD) thermoelectrically cooled, with all the necessary bias, control, and counting electronics. Light is coupled to the photodiode through a FC/PC connector and a multimode fiber. When the detector is triggered, the APD bias voltage is raised above its reverse breakdown voltage V_{br} to operate in "Geiger mode". For our experiment, the bias pulse width is 5 ns to correspond with the laser pulse.

The APD bias voltage is then adjusted to obtain the best compromise between the detection efficiency and the dark count rate per pulse. The detection efficiency η is measured by illuminating the detector with a calibrated laser intensity, $\eta = 0.50(0.02)$. The dark count rate is about 5×10^{-4} counts per pulse.

After the second magnet, regenerated photons are injected into the detector through a coupling lens plus a graded index multimode fiber with a 62.5 μm core diameter, a 0.27 numerical aperture, and an attenuation lower than 1 dB/km. These parameters ensure that we can easily inject light into the fiber with a high coupling ratio, even when one takes into account the pulse by pulse instability of the propagation axis that can be up to 9 μrad. During data acquisition, a typical coupling efficiency through the fiber was found to be about $\eta_c = 0.85$. This efficiency is measured by removing the wall and the blind flanges (see Fig. 1) and by using the laser beam from the pilot oscillator without chopping nor amplifying it. This procedure ensures that the pulsed kJ beam is perfectly superimposed to the alignment beam.

The only remaining source of misalignment lies in thermal effects during the high energy laser pulse, which could slightly deviate the laser beam, hence generating supplementary losses in fiber coupling. This misalignment is reproducible. This means that it can be corrected by properly changing the initial laser pointing. By monitoring the optical path followed by the high energy beam for each pulse, we were able to take such misalignment losses into account, and we have observed a maximum value of 20% of coupling reduction.

The detector gate is triggered with the same fast signal as the laser, using delay lines. We have measured the coincidence rate between the arrival of photons on the detector and the opening of the 5 ns detector gate as a function of an adjustable delay. We have chosen our working point in order to maximize the coincidence rate (see Fig. 3). To perform such a measurement we used the laser pilot beam which was maximally attenuated and chopped with a pulsed duration of 5 ns, exactly as the kJ beam.

The fiber to inject the detector is 30 m long so that it can be placed far from the magnets to avoid potential electronic noise during magnetic shots. In addition, the detector is placed in a shielding bay to prevent electromagnetic noise during laser pulses.

So far, during data acquisition, a total amount of about 17.4 kJ has reached the wall in 14 different pulses. This corresponds to about 9.3×10^{22} photons. To evaluate the actual number of incident photons that could yield a regenerated photon observable by the detector, we took into account for each pulse the fiber coupling η_c, the misalignment due to thermal effects during the pulse. We have also evaluated the percentage of the whole laser energy (see inset of Fig. 2) actually contained in the 5 ns detection gate, which is 93%. All of these experimental parameters are

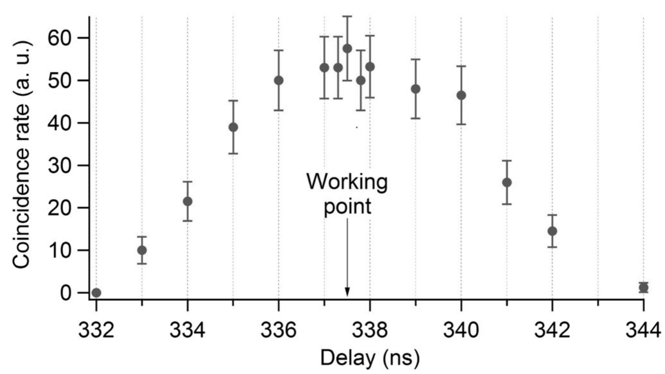

FIG. 3. Coincidence rate between the arrival of photons on the detector and its 5 ns detection gate as a function of an arbitrary delay time. The arrow indicates our working point, chosen in order to maximize the coincidence rate.

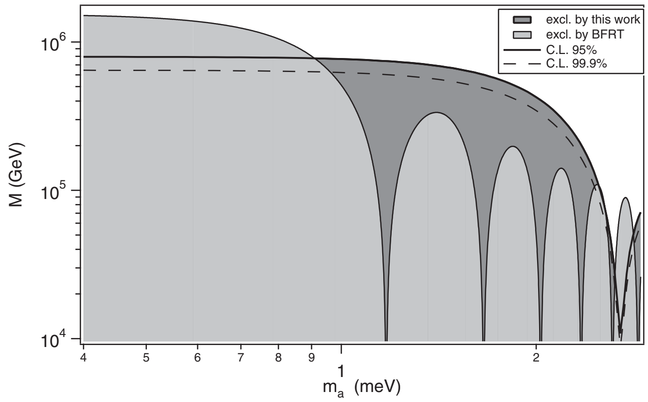

FIG. 4. 95% confidence level limits on the axionlike particle two photons inverse coupling constant M as a function of the axionlike particle mass m_a obtained thanks to our null result (dotted line). The area below our curve is excluded. Our limits are compared to the 95% confidence level exclusion region obtained by the BFRT photon regeneration experiment [10].

known with a few percent errors. The effective number of photons is about 6.7×10^{22}, which corresponds to about 12.5 kJ. No regenerated photon has been detected. In this case, the measurement error is given by the number of photons that could have been missed due to the non perfect detection. The probability P_n that n incident photons have been missed by the detector is $P_n = (1 - \eta)^n$. Dark count is negligible. A standard deviation σ means that a result outside the window $\pm 2\sigma$ corresponds to $P_n < 0.05$, which yields about 4 missed photons for our value of η.

The limits at 95% and 99.9% confidence level that we have reached so far are plotted on Fig. 4. These have been calculated by numerically solving Eq. (1). The area below our curve is excluded by our null result. In particular, the axionlike particle two photons inverse coupling constant M is $>8 \times 10^5$ GeV provided that the particle mass $m_a \sim 1$ meV. This improves the exclusion region obtained on BFRT photon regeneration experiment [10]. In this mass region their results were limited by the axionlike particle photon oscillation due to the length of their magnets. Using shorter magnets, we are able to enlarge the mass range exclusion area.

In Ref. [5], the PVLAS Collaboration suggested that their claimed observation of a vacuum magnetic dichroism could be explained by the existence of an axionlike particle with a two photons inverse coupling constant $1 \times 10^5 \leq M \leq 6 \times 10^5$ GeV and a mass around 1 meV. This is excluded by us with a confidence level greater than 99.9%.

We plan to improve our apparatus so that with about 100 laser pulses, we will be able to give more stringent limits on M than the one given by the BFRT experiment for all the values of m_a.

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[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977).
[2] P. Svrcek and E. Witten, J. High Energy Phys. 06 (2006) 051.
[3] J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. **120B**, 127 (1983); L. F. Abbott and P. Sikivie, *ibid.* **120B**, 133 (1983); M. Dine and W. Fischler, *ibid.* **120B**, 137 (1983); M. S. Turner, Phys. Rev. D **33**, 889 (1986).
[4] G. G. Raffelt, J. Phys. A **40**, 6607 (2007).
[5] E. Zavattini *et al.*, Phys. Rev. Lett. **96**, 110406 (2006).
[6] S. Andriamonje *et al.* (CAST Collaboration), J. Cosmol. Astropart. Phys. 04 (2007) 010.
[7] S. Lamoreaux, Nature (London) **441**, 31 (2006).
[8] J. Jaeckel *et al.*, Phys. Rev. D **75**, 013004 (2007), and references therein.
[9] K. Van Bibber *et al.*, Phys. Rev. Lett. **59**, 759 (1987).
[10] R. Cameron *et al.*, Phys. Rev. D **47**, 3707 (1993).
[11] See, e.g., http://axion-wimp.desy.de/index_eng.html.
[12] E. Zavattini *et al.*, arXiv:0706.3419.
[13] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); Phys. Rev. D **32**, 2988 (1985).
[14] P. Frings *et al.*, Rev. Sci. Instrum. **77**, 063903 (2006).
[15] S. Batut *et al.*, IEEE Trans. Appl. Supercond. (to be published); the coils used in this work have been originally developed by O. Portugall and S. Batut in the framework of the BMV experiment at the LNCMP [R. Battesti *et al.*, Eur. Phys. J. D (to be published)].