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Results from the OSQAR photon-regeneration experiment: No light shining through a wall

Pierre Pugnat,[1,*] Lionel Duvillaret,[2] Remy Jost,[3] Guy Vitrant,[2] Daniele Romanini,[3] Andrzej Siemko,[1] Rafik Ballou,[4] Bernard Barbara,[4] Michael Finger,[5] Miroslav Finger,[5] Jan Hošek,[6] Miroslav Král,[1,6] Krzysztof A. Meissner,[7] Miroslav Šulc,[8] and Josef Zicha[6]

(OSQAR Collaboration)

[1]*CERN, CH-1211 Geneva-23, Switzerland*
[2]*IMEP-LAHC, UMR CNRS 5130, Minatec-INPG, 3 parvis Louis Néel, BP 257, 38016 Grenoble Cedex-1, France*
[3]*LSP, UMR CNRS 5588, Université Joseph Fourier, BP 87, 38402 Saint-Martin d'Hères, France*
[4]*Institut NEEL, CNRS and Université Joseph Fourier, BP 166, 38042 Grenoble Cedex-9, France*
[5]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[6]*Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic*
[7]*Institute of Theoretical Physics, University of Warsaw, Poland;*
[8]*Technical University of Liberec, Czech Republic*
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A new method to amplify the photon-axion conversions in a magnetic field is proposed using a buffer gas at a specific pressure in a photon-regeneration experiment. As a first result, new bounds for mass and coupling constant for laboratory experiments aiming to detect any hypothetical scalars and pseudoscalars, which can couple to photons were obtained, excluding with 95% confidence level, the recently withdrawn PVLAS result.

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Recent intensive theoretical [1–6] and experimental [7–11] studies shed light on possible new physics beyond the standard model of particle physics, which can be probed with sub-eV energy experiments. Most of them were triggered by the observation of the PVLAS collaboration [12] of a rotation of polarization for light propagating in the vacuum permeated by a transverse magnetic field, which could be due to an Axion-Like Particle (ALP) that couples to the photon. Even if the rotation signal was recently attributed to an instrumental artefact [13,14] no longer reproducible after several upgrades of the PVLAS apparatus, an ellipticity signal still remains and was not clearly interpreted. Couplings of ALPs to photons are in principle constrained by star cooling mechanisms and PVLAS result is in strong contradiction with the experimental limits set by the CAST axion helioscope [15]. More recently, BMV [8] and GammeV [10] laboratory experiments have reported negative results.

The axion is a neutral pseudoscalar particle predicted independently by S. Weinberg [16] and F. Wilczek [17] from the Peccei and Quinn [18] symmetry breaking. It remains the most plausible solution to the strong-*CP* problem [19], i.e. the answer to the following question: Why the *CP* symmetry (Charge and Parity conservation), in view of the negative measurement results of the neutron electric dipolar moment [20], seems not to be broken by the strong interaction? Recently, it has also been emphasized that the axion constitutes a fundamental underlying feature of string theory in which a great number of axions or ALPs is naturally present [19]. In addition, interest in axion searches lie beyond particle physics since such hypothetical light spin-zero particles are considered as one of the most serious dark-matter candidates [21], and the only nonsupersymmetric one. Within this scope and in agreement with previous measurement results excluding heavy axions [22], the allowed range for the axion mass is nominally $10^{-6} < m_A < 10^{-2}$ eV.

From the experimental point of view, the hunt for light axions can be classified in two complementary ways with one relying on cosmological assumptions or solar models whereas the other one being experiments of laboratory type (for a review see [22,23]). Nearly all of these experimental approaches are based on the Lagrangian interaction term $L_{A\gamma\gamma} = g_{A\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\phi_A$, with ϕ_A the axion field, $g_{A\gamma\gamma}$ the coupling constant of axion to two photons, $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields, respectively. For scalar particles, the interaction Lagrangian is $L_{S\gamma\gamma} = g_{S\gamma\gamma}(\mathbf{E}^2 - \mathbf{B}^2)\phi_S$, with ϕ_S the scalar field. Both these Lagrangians permit the conversion of an axion or ALP into a single real photon in an external electromagnetic field, i.e. the so-called Primakoff effect, as well as the inverse process.

This letter reports the first results from OSQAR [11], a new 2-in-1 laboratory experiment at CERN. Its main objectives are to achieve two complementary approaches based on the Primakoff interaction to search for axions or ALPs as well as to measure for the first time the vacuum magnetic birefringence predicted by QED. The state-of-

*Corresponding author.
Pierre.Pugnat@cern.ch

the-art superconducting dipoles developed for the Large Hadron Collider (LHC) are combined with innovative optical techniques to provide unique opportunities in the emerging field of laser-based particle physics. The first OSQAR experiment aims at measuring the magneto-optical properties of the vacuum [11] and more precisely the birefringent and dichroic signals induced by the conversion of photons to Axions or ALPs [24]. The second one is considered as the simplest and most unambiguous way to search in laboratory light scalar or pseudoscalar particles and is based on the detection of "a shining light through a wall" due to the photon-regeneration effect [25]. Results presented in this letter come from the OSQAR photon-regeneration experiment and provide one of the first independent crosschecks to the interpretation of PVLAS data within the scope of the discovery of a new light boson [12]. For this, a new way to detect axions using a buffer of neutral gas as a resonant amplifier medium was used and will now be presented.

In a photon-regeneration experiment, a polarized laser beam propagates in a pipe permeated by a transverse magnetic field before being absorbed by an optical barrier. Only photons converted to axions or ALPs will propagate after being regenerated on the other side of the barrier via the Primakoff effect [25,26] (Fig. 1). They have the same wavelength as the laser beam and for their detection a high sensitivity detector is used in general with a chopper for better photon discrimination. When the light is polarized parallel to the magnetic field, the experiment is sensitive to pseudoscalar particles whereas with a polarization in the perpendicular direction, scalar particles can be detected. If a region of length L is permeated by a transverse magnetic field B, the photon-to-axion ($\gamma \rightarrow A$) conversion probability, as well as the axion-to-photon ($A \rightarrow \gamma$) one, are given by [25,26]:

$$P_{\gamma\leftrightarrow A} = \frac{1}{4\beta_A\sqrt{\varepsilon}}(g_{A\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2 \qquad (1)$$

with $\hbar = c = 1$. Here ε is the dielectric constant of the gas, β_A the axion or ALP velocity and $q = |k_\gamma - k_A|$ the momentum transfer. The energy ω is the same for photons and axions, $k_A = (\omega^2 - m_A{}^2)^{1/2}$, $\beta_A = k_A/\omega$ and $k_\gamma = \omega/\sqrt{\varepsilon}$ within the corpuscular description of light [27,28] as its wavelength can reasonably be assumed to be much larger than the size of the photon-photon-ALP vertex. It should be emphasized that the new proposed method is based on a group velocity matching and is fundamentally different from the phase matching condition described in an early proposed axion search experiment [29]. The form factor of the conversion probability (1) is at maximum for $qL \rightarrow 0$ whereas for $qL \gg 1$ incoherence effects emerge from the axion-to-photon oscillation reducing the conversion probability. For $m_A \ll \omega$ and propagation in a gaseous medium characterized by an index of refraction $n = \sqrt{\varepsilon}$ close to 1, the momentum transfer can be approximated to the first order by:

$$q \approx \frac{m_A^2}{2\omega} - (n-1)\omega. \qquad (2)$$

In this expression, the momentum transfer in vacuum can be deduced by setting $n = 1$ in the last term, which comes from the effective mass acquired by the photon with the presence of a gas, i.e. $m_\gamma{}^2 = 2(n-1)\omega^2$. An important point is that by varying the gas pressure, the value of n can be tuned to realize the coherence condition, i.e. $qL = 0$, and this allows optimization of the experiment sensitivity to probe various axion mass regions.

For the photon-regeneration experiment sketched in Fig. 1, the expected counting rate can be expressed as a function of $P_{\gamma\leftrightarrow A}$:

$$\frac{dN_\gamma}{dt} = \frac{P}{\omega}\eta P_{\gamma\leftrightarrow A}{}^2 \qquad (3)$$

where P is the optical power, ω the photon energy and η the detector efficiency. It varies as the fourth power of the field integral along the magnet length. In this respect, the LHC main superconducting dipole magnets constitute the state-of-the-art and one of them was dedicated to the OSQAR photon-regeneration experiment. To operate, a LHC dipole is cooled down to 1.9 K with superfluid He and provides in two apertures a transverse magnetic field which can reach 9.5 T over a magnetic length of 14.3 m. The superconducting winding is made with Nb-Ti and is clamped in a stainless-steel collar. The collared coil is surrounded by a ferromagnetic yoke, which contributed to ~18% of the magnetic field. The so-called cold mass assembly is enclosed by a shrinking cylinder and filled with about 300 liters of superfluid He constituting a static bath pressurized slightly above 1 bar. This static bath is kept at the temperature of 1.9 K by a tubular heat exchanger containing boiling superfluid He at a pressure of ~15 mbar. As for all LHC superconducting magnets, the dipole used for this experiment was thoroughly tested at 1.9 K. In addition, the field strength and field errors were precisely characterized. The integrated transfer function over the magnet length is equal to 10.009 Tm/kA at 9 T. The nonlinearity at high field due to the saturation of the

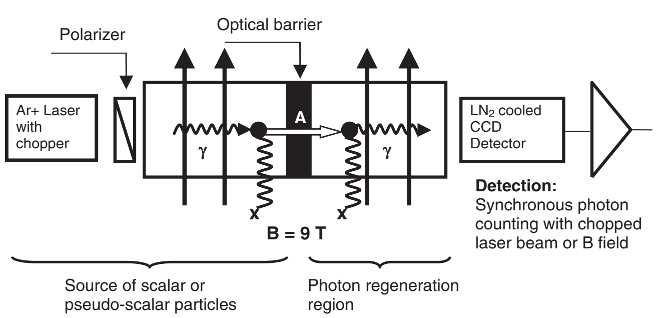

FIG. 1. Scheme of the experimental setup (not to scale) and principle of the OSQAR photon-regeneration experiment.

ferromagnetic yoke was taken into account and the integrated field is known with a relative precision better than 10^{-4}.

The light source used is an ionized argon (Ar +) laser which can deliver in multiline mode up to 18 W of optical power. The optical beam is linearly polarized with a vertical orientation. To rotate the polarization of the light into the horizontal direction, a $\lambda/2$ wave-plate is inserted between the laser and the LHC dipole. It introduces an optical power loss of 20% at the laser wavelengths i.e. in the range 488–514 nm. The Ar+ laser was operated in multiline mode with approximately $2/3$ of the optical power at 514 nm (2.41 eV) and $1/3$ at 488 nm (2.54 eV). Each of these atomic lines is made of about 50 equidistant longitudinal modes. The laser beam profile was measured at the location of the photon detector with a photodiode. It can be well fitted with a Gaussian curve giving rise to a full width half maximum (FWHM) of 6.46 mm. For photon counting, a LN_2 cooled CCD detector from Princeton Instruments is used. It is composed of an array of 1100 pixels of 5 mm height densely packed over a length of 27 mm and intercepting 65% of the laser intensity distribution at the detector location. The quantum efficiency of the CCD detector is $50 \pm 2\%$ for the Ar+ laser wavelengths and this gives an overall detector efficiency $\eta \approx 32.5 \pm 2\%$. The number of dark counts per pixel is lower than 0.1 cts/ min.

To have the beam light chamber thermalized at the ambient temperature (working point at $20 \pm 1\ ^\circ$C), each aperture of the LHC dipole is equipped with an anticryostat, a thermally optimized coaxial tube system of 19.6 m containing a resistive heater [11]. The magnet aperture chosen for the photon-regeneration experiment is enclosed by two optical glass windows in BK7 and the laser beam is precisely aligned with its axis. Then the optical absorber mounted at the extremity of a dark cylindrical chamber is inserted and positioned in the middle of the magnetic length. In this configuration, the magnetic field can permeate the beam pipe over a length $L = 7.15$ m on each side of the absorber (see Fig. 1). A pumping and gas insertion tube is connected at each magnet end.

If one considers the PVLAS result [12] combined with previous ones [30], a remaining island in the parameters space for laboratory experiments settles around $m_A = 10^{-3}$ eV and $M = 1/g_{A\gamma\gamma} = 5 \times 10^5$ GeV [31] (domain hereafter called the PVLAS window). With such values, the coherence condition of the OSQAR photon-regeneration experiment corresponds to $(n - 1) = 8.61 \times 10^{-8}$ for the dominant wavelength of the Ar+ laser. Such a refraction index can be obtained with dry air at a pressure of 0.317 mbar and a temperature of 20 °C. It allows reaching the maximum of the photon counting rate given by the Eq. (3) equal to $\sim$140 photon/s for the targeted island of the axion/ALP parameters space and 10 W of effective optical power at 514 nm.

The OSQAR photon-regeneration experiment was performed using dry nitrogen gas at the pressure level satisfying this coherence condition. The pressure was measured with a Pfeiffer Compact Capacitance Gauge with a precision better than $\pm 5 \times 10^{-4}$ mbar. The standard errors of pressure and temperature measurements of the dry nitrogen gas can typically produce a decrease of the photon flux of $\sim$0.03 photon/s. The optical power of the laser was fixed to about 15 W and was recorded during the measurements. The integration time for the CCD detector was limited to 180 s to avoid too many parasitic counts coming from cosmic rays. When switched on, the magnetic field was tuned to 9 T. The acquisition of photons was repeated 2 times for each of the 3 steps of the experiment which are now defined. The step without optical power and magnetic field allows characterizing the true background signals including their possible drift. The step with optical beam but no magnetic field gives the background signal chosen to be subtracted. The recorded data with optical beam on, magnetic field $\boldsymbol{B}$ on, and polarization of the light aligned either parallel or perpendicular to $\boldsymbol{B}$ allow probing the existence of pseudoscalar and scalar particles, respectively.

Results are given in Fig. 2(a) and 2(b) for the polarizations of the light parallel and perpendicular to the magnetic field respectively [32]. The expected signal de-

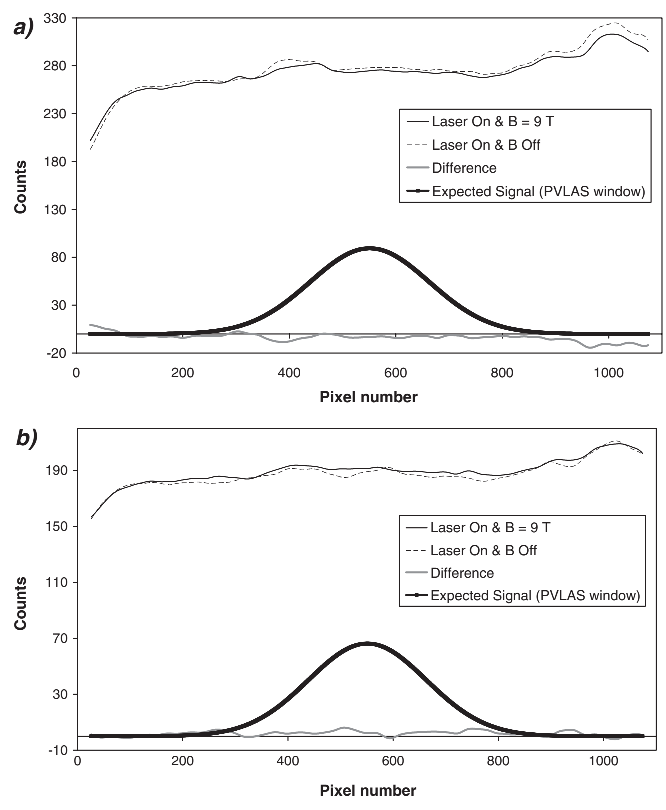

FIG. 2. Measurement results after the filtering of cosmic signals. (a) The coupling of photons with pseudoscalar particles was probed with the polarization of the light parallel to the magnetic field. (b) The coupling of photons with scalar particles was probed with the polarization of the light perpendicular to the magnetic field.

duced from the PVLAS results and the measured Gaussian beam profile is also shown in both cases assuming a counting rate integrated over 180 s of 2520 photons per watt of input optical power. The loss introduced by the $\lambda/2$ wave-plate was also taken into account to construct the expected signal in Fig. 2(b). The uniform background signals coming mainly from the CCD readout noise gives an integrated value of 95 ± 2 cts/pixel. Larger values of the photon counting were obtained for both polarization states of the light because of a slight optical leakage of the dismountable dark chamber of 7.15 m long, which was introduced in the anticryostat of the magnet aperture. When the difference between signals with and without magnetic field is performed, both with the optical beam on, no additional number of counts correlated with the optical beam profile were recorded (Fig. 2(a) and 2(b)). The limit of sensitivity of this experiment can be obtained from a conservative statistical approach applied to the signals after background subtraction. The minimum photon flux which can be detected at 95% confidence level is found to be 1.85 photons/s. It corresponds after the integration of signals over 180 s to the Gaussian beam profile with a maximum exceeding the threshold of 3 counts given by the 5% probability level of the noise distribution of the filtered differential signals.

In summary, this paper proposes a new experimental method to amplify the axion-to-photon and photon-to-axion conversion probability based on group velocity matching in a buffer gas. Interpretation of PVLAS results in terms of ALPs were excluded at 95% confidence level from a photon-regeneration experiment based on such approach. The other experiments searching for light scalar and pseudoscalar particles that couple to photons [8,10] could also profit from this enhancement mechanism to further extend their sensitivity to larger particle masses.

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[32] For each acquisition file, contributions coming from cosmic rays were removed when the signal amplitude of a single pixel exceeded 3 standards deviation above the global mean. The rejected points were replaced by a local averaging of the signal coming from neighbor unaffected pixels. The number of cosmic rays detected during 180 s was between 6 and 21 and the number of replaced points as described above, is typically 3 to 4 times larger. Signals were also filtered using a high order low pass filter to reject high spatial frequencies corresponding to wavelengths smaller than $\sim$20 pixels. For the analysis, differences between relevant signals were performed to substract the background contribution. The limit of sensitivity given for this experiment is based on a standard statistical analysis using the probability distribution of the remaining noise amplitude coming from the 600 central pixels of the CCD detector.

[33] Transparencies at http://axion-wimp.desy.de/e30/index_eng.html.