Polarization measurements and their perspectives at the Low Energy Frontier

Giovanni Cantatore

University and INFN, Via Valerio 2, 34127 Trieste, Italy

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Polarization measurements at low energy (1-2 eV) will soon probably be able to directly detect QED processes, such as photon-photon scattering. In principle, these techniques could also be used to probe particle production (Axion-Like Particles, Mini-Charged Particles, Chameleons, to mention a few) at the Low Energy Frontier. Reaching an interesting unexplored zone in the ALP parameter space is, however, currently beyond their power, even in very optimistic scenarios. Photon regeneration experiments, on the other hand, have the potential to extend the reach of laser experiments beyond what is possible with polarization detection schemes. Using the resonant regeneration idea one can exploit the coherence properties of the ALP and photon fields to enhance the ALP-photon conversion probability by a factor which can be as large as 10^{10}, or more, by using two frequency-locked Fabry-Perot optical resonators. The PVLAS-Phase II group in Trieste is attempting to build a table-top resonant regeneration pilot apparatus. At the moment, resonant regeneration appears as the sole purely laboratory-based method capable of investigating a region of the ALP parameter space now accessible, in part, only to astrophysical observations, such as those from the CAST magnetic helioscope for ALPs. In the optimistic, though not a priori excluded, case of a positive signal one would obtain a discovery of great scientific value.

1 Introduction

Precision measurements of the changes in the polarization state of a linearly polarized visible laser beam propagating through a magnetic field were introduced several years ago as a tool to investigate photon-photon scattering at low energies as described by QED [1]. In the course of the development of these techniques it became also clear [2] that the production of nearly massless particles, which we now call WISPs, for Weakly Interacting Sub-eV Particles, has a possible signature in terms of polarization. QCD axions [3] are a prime example of WISPs and remain the main goal of current WISP searches: their polarization signature is an induced birefringence, in the case of the production of a virtual axion, or an induced dichroism in the case of the production of a real particle. More recently, the possibility has emerged to exploit, at least in principle, polarization measurement to investigate other WISP particles such as Mini Charged (MCPs) and Chameleon particles [4]. The basic experimental technique can be thought of as a scattering off a "photon target", normally consisting of the virtual photons provided by a magnetic field, where one analyzes the polarization state of the scattered photons. The simplest way to detect polarization changes is to enclose the interaction region, where the scattering takes place, between two crossed polarizers. This is called static detection and is severely limited by the extinction factor of the polarizers themselves. This number expresses the ratio of the intensity transmitted by a crossed polarizer versus the intensity incident on it. High quality polarizers may reach exctinction factors of 10^{-8}, corresponding to an ellipticity of 10^{-4}, which is orders of magnitude larger than 10^{-11}, the typical ellipticity to be detected in QED experiments[1]. To detect smaller ellipticities one must resort to the heterodyne technique, where the effect is made time-varying by acting on the magnetic field (either changing its intensity as in BFRT [5] of rotating it as in PVLAS [6]) and a carrier ellipticity is superimposed on it by means of an optical modulator. The heterodyne technique, combined with the amplification of the optical path provided by a Fabry-Perot resonant cavity, brings detectable ellipticities in the 10^{-9} range, the challenge now being gaining the two remaining orders of magnitude to access the QED regime.

2 Panorama of current polarization experiments

The current panorama of polarization experiments comprises the efforts in France, by the BMV group [7], at CERN, by the OSQAR collaboration [8], and in Taiwan, by Q&A [9]. These experiments have been active for several years and in the case of BMV are already in the preliminary data-taking phase. As an example of the new start-ups we will mention the PVLAS-Phase II [10] project which is pushing towards a reduction of the dimension of the apparatus down to true table-top level in order to better understand and control noise sources. All these experiments share common features: a low-energy (1-2 eV) linearly polarized laser beam probing a vacuum region where a transverse magnetic field is present, continuous light power with a maximum of 1 W, a time-varying physical effect, an optical path in the interaction region amplified by means of a resonant Fabry-Perot cavity. They also share, unfortunately, the same problem: a noise background limiting the sensitivity, which is defined as the minimum ellipticity angle which can be detected in a measurement lasting 1 s. The current common barrier is a sensitivity around 10^{-7} rad/$\sqrt{\text{Hz}}$, meaning that to detect a 10^{-11} angle one would have to gather data continuously for 10^8 s.

Q&A uses 1 eV photons from a few mW power ND:YAG laser to probe a magnetic region where the time-varying field is provided by a rotating permanent 2.2 T dipole placed horizontally. Amplification of the optical path is given by a resonant Fabry-Perot cavity with the peculiarity of having its mirrors mounted on suspensions in order to attenuate seismic vibrations. Q&A tested relatively recently the performance of its apparatus by measuring the magnetic birefringence of a few gases.

The OSQAR collaboration intends to exploit the strength of two dipole LHC magnets by keeping the field static and applying the time variation to the polarization of the probing laser beam. The experiment is now in the optics development stage.

The BMV group is probably at this time the one nearest the goal of starting actual science runs. The main feature of BMV is relying on pairs of pulsed magnetic coils having a characteristic X shape. These coils provide magnetic pulses lasting a few ms with peak intensities of 12-14 T and give the time-variation needed for heterodyne detection. A high-finesse Fabry-Perot

[1] We distinguish here between the birefringence Δn, which is the difference of the refractive indices relative to two orthogonal polarization states, and the ellipticity Ψ, which is the ratio of the semi-minor to the semi-major axes of the ellipse described by the light electric field. The relation between the two quantities is $\Psi = (\pi L/\lambda)\Delta n$, where L is the length of the interaction region and λ is the light wavelength.

resonator is employed to amplify the optical path, and to insulate its mirrors form contamination BMV houses its optical benches in a clean-room. The experiment has entered the final commissioning phase and they have recently reported the detection of a birefringence as low as $(-9.8 \pm 22.9) \cdot 10^{-17}$ T^{-2}, while the reference value corresponding to the QED photon-photon scattering is $\approx 4 \cdot 10^{-24}$ T^{-2}.

The main challenge for polarization experiments is lowering the noise background. The fact that all optical components exhibit an intrinsic birefringence and that changes in this birefringence are responsible for the least understood part of the background has ushered in the idea that reducing the size of the apparatus might help bringing also this noise under control. PVLAS-Phase II has built an optical ellipsometer sitting on a single optical bench, complete with a rotating 2.3 T permanent dipole magnet and a high finesse Fabry-Perot cavity ($F \approx 200000$). The goal is to achieve a sensitivity of at least 10^{-8} rad/$\sqrt{\text{Hz}}$, which would allow detecting the QED birefringence in a reasonable measurement time of 188 standard 8-hour workdays. Note that a further factor 10 improvement in sensitivity would bring this time down to 0.471 days. Such sensitivities, however, would not help polarization experiments significantly in the search for WISPs. Figure 1, for instance, shows a portion of the parameter space for Axion Like Particles (ALPs) where curves representing upper bounds are plotted for a few polarization experiments. As a reference, the "CAST barrier"', representing the best currently available wide-band experimental limit [2], and the "axion line"[3], giving the locus of points compatible with a QCD axion, are also plotted.

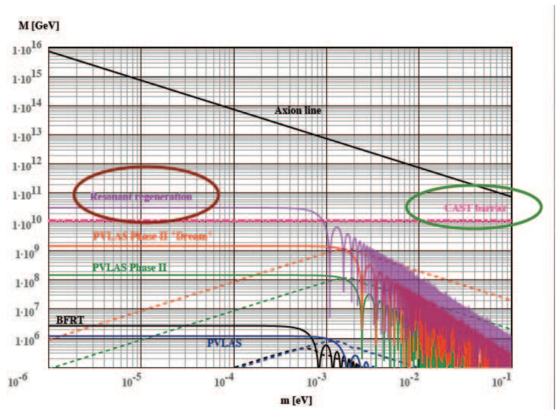

Figure 1: Comparison of upper bounds in the mass-inverse coupling plane for ALPs. "PVLAS" and "BFRT" label curves giving the bounds set by the PVLAS and BFRT, respectively. "PVLAS Phase II" and "PVLAS Phase II dream" label curves corresponding to the bounds reachable with the PVLAS-Phase II table-top apparatus with a sensitivity of 10^{-8}rad/$\sqrt{\text{Hz}}$ and 10^{-9}rad/$\sqrt{\text{Hz}}$, respectively. The curve labelled "Resonant regeneration" gives the bound reachable with a table-top resonant regeneration set-up (see text).

It is apparent from the plot that even in the best "dream" scenario, corresponding to the "PVLAS Phase II dream", where an extremely good sensitivity of 10^{-9} rad/$\sqrt{\text{Hz}}$ is assumed,

[2]The CAST limit is actually valid only up to masses around 1 eV, and is drawn here as a line for simplicity.
[3]The axion line should actually be a band to take into account the spread due to different models for the QCD axion.

polarization experiments cannot even approach the "CAST barrier", let alone the QCD axion line. In fact, the bounds for polarization experiments are plotted using the ellipticity angle that would be necessary to detect to reach the signature of QED photon-photon scattering. An ellipticity generated by axion-photon interactions would then be smaller that the QED effect and basically indistinguishable from it[4]. In conclusion, there is little hope of reaching the CAST barrier with polarization-type experiments unless a fantastic sensitivity is attained, and it can be safely stated that the primary mission of precision ellipsometers was and remains the detection of QED effects.

3 The future of laser experiments: resonant regeneration

The WISP concept encompasses different types of particles, however it is hardly disputable that the "Holy Grail" of WISP searches is still represented by ALPs and in particular by the QCD axion itself. The future of laser experiments, indeed the future of laboratory-type experiments in the field of axion detection, lies with the resonant regeneration concept.

Resonant regeneration was recently proposed [11] as the ultimate evolution of the light-shining-through-a-wall (LSW) scheme for producing and detecting axions in the laboratory. In resonant regeneration, both the magnet where particles are produced from photons and the magnet where the photons are regenerated from the particles are enclosed in resonant Fabry-Perot cavities of finesse F. This increases the overall probability of observing a regenerated photon by a factor proportional to F^2. With the current techniques finesses can routinely reach 10^5, meaning that the probability increases by 10^{10}.

The curve labelled "Resonant regeneration" in Figure 1 shows the bound which could be obtained by a table-top resonant regeneration experiment. Note how this bound is capable of breaking the "CAST barrier" with a purely laboratory-type experiment.

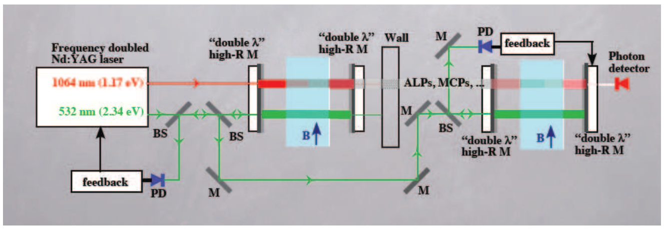

Figure 2: Proposed optical scheme to achieve the frequency-lock of two separate Fabry-Perot cavities. The scheme is based on a laser emitting two beams, one of which is obtained by frequency-doubling the first one, and on high-reflectivity mirrors having maximum reflectance at the two laser wavelengths (see text).

A few challenges must be met on the way to a successful resonant regeneration experiment. The first and most difficult one is meeting the requirement that the two Fabry-Perot must be frequency-locked and must also resonate on the same spatial mode. A possible scheme to meet this challenge, at least for the frequency-locking part, is sketched in Figure 2.

In this scheme, the laser is a ND:YAG solid state device emitting a primary beam in the infrared at 1064 nm and a secondary beam at 532 nm, obtained from the first by passing

[4]If a dichroism is also measured, however, there is the possibility of disentangling the two contributions.

through a non-linear duplicating crystal. These two beams are frequency-locked and coherent. The Fabry-Perot cavities are formed by high-reflectivity multi-layer dielectric mirrors coated for maximum reflectance at the two wavelengths of interest. One of the two beams is used to lock the laser frequency to the first cavity, which then becomes the reference, and then to lock the second cavity to the laser. The other beam, which is now naturally resonant with the cavities, is used for the actual photon regeneration measurement. Other challenges regard the need for a high power laser and for a low background detector capable of counting single-photons at 1-2 eV energies. 10 W lasers emitting continuously in the infra-red are commercially available, while going up to 100 W requires specialized expertise, using however existing technology. The detector challenge is actually a common problem for most WISP search experiments. A resonant regeneration experiment could certainly benefit from a detector such as the cooled APD being developed within the BaRBE project of INFN [12]. A better, but more difficult option, would probably be to use a Transition Edge Sensor (TES) for instance of the type developed by INFN Genova [13].

In conclusion, photon beams are the primary tools to explore the Low Energy Frontier, however of the two main types of experiments, polarization measurements and photon regeneration, only photon regeneration in its fully resonant version has the possibility of impacting significantly on WISP searches by breaking the "CAST barrier" and establishing the new experimental benchmark. Difficult challenges must be met on the road to a successful resonant regeneration experiments, however a handsome reward, in the form of a revolutionary scientific discovery, could be just around the corner.

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