Optical production and detection of dark matter candidates

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Abstract

The PVLAS collaboration is at present running, at the Laboratori Nazionali di Legnaro of I.N.F.N., a very sensitive optical ellipsometer capable of measuring the small rotations or ellipticities which can be acquired by a linearly polarized laser beam propagating in vacuum through a transverse magnetic field (vacuum magnetic birefringence). The apparatus will also be able to set new limits on mass and coupling constant of light scalar/pseudoscalar particles coupling to two photons by both producing and detecting the hypothetical particles. The axion, introduced to explain parity conservation in strong interactions, is an example of this class of particles, all of which are considered possible dark matter candidates. The PVLAS apparatus consists of a very high finesse (> 140000), 6.4 m long, Fabry-Pèrot cavity immersed in an intense dipolar magnetic field (\textasciitilde 6.5 T). A linearly polarized laser beam is frequency locked to the cavity and analysed, using a heterodyne technique, for rotation and/or ellipticity acquired within the magnetic field.

Key words: Dark Matter, ellipsometer, Fabry-Pérot cavity, frequency locking

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Since any neutral light particle couples to two photons, with a strength depending on its particular nature, a possible detection strategy can be pursued by optical techniques [1]. Among such particles there could be those considered to be possible dark matter candidates [2]. These interactions are explored by the PVLAS experiment by sending a linearly polarised laser beam through a transverse magnetic field, and by measuring changes in the polarisation state of the light [3–7]. If the electric field of the light is (parallel)perpendicular to the magnetic field both will couple to the (pseudo)scalar particles. Two effects can arise: an induced dichroism and an induced ellipticity [1]. For instance, figure 1a shows the Feynman diagram for real pseudoscalar particle production and the resulting dichroism, while figure 1b shows the retardation mechanism following from virtual particle production. In the case of real production, photons polarised parallel to the external magnetic field will disappear leading to an apparent rotation of the polarisation plane. In the other case, the appearance and successive decay of a virtual massive particle causes retardation between the two components of the electric field of the laser beam. Following ref.[1] the acquired dichroism $\epsilon$ and ellipticity $\psi$ due to a pseudoscalar neutral particle can be written

$$\epsilon = -\sin 2\alpha \left( \frac{\beta L}{\hbar} \right)^2 N \left[ \sin \left( \frac{k}{2} \sqrt{k^2 - k_m^2} \right) \right]^2, \quad \psi = \sin 2\alpha \left( \frac{\beta^2 k L}{4M^2 k_m^2} \right) N \left[ 1 - \sin \left( \frac{L}{2M^2 k_m^2} \right) \right]$$

where $\alpha$ is the angle between the magnetic field and the light polarization, $k$ is the photon wave number, $k_m = mc/\hbar$ is the inverse Compton wavelength of the neutral field, $M$ is the inverse coupling constant, $B$ is the external magnetic induction, $L$ is the length of the magnetic field region and $N$ is the number of passages of the light across the field region. Analogous expressions can be obtained for the dichroism and ellipticity induced by a scalar field.

Fig. 1. a) Dichroism induced by the production of a massive particle coupling to two photons; b) Ellipticity induced by the retardation of one of the electric field components by the virtual production of a massive particle coupling to two photons.
With the PVLAS apparatus, ellipticity and dichroism can be measured independently giving access to both the coupling constant and the mass of the produced particle. It must be noted that this detection method is free from assumptions on an a priori relation between $m$ and $M$. The experimental apparatus, shown schematically in figure 2, consists of an optical ellipsometer and a dipole superconducting magnet. The ellipsometer is based on a vertical high finesse ($\mathcal{F} = 140000$), 6.4 m long, Fabry-Pérot resonator cavity traversing a 1.1 m long dipole magnet which is housed in a warm bore, liquid He, cryostat [7]. The resonator effectively accumulates photons in the magnetic region, thus

![Diagram](image)

Fig. 2. Scheme of the experimental setup. The linearly polarized laser beam is phase-locked to a Fabry-Pérot cavity, which increases the effect by $2\mathcal{F}/\pi$. The cavity passes through the warm bore of a superconducting dipole magnet which rotates around a vertical axis to modulate the effect. The effect is detected as side bands of the modulator carrier frequency in the diode signal.

lengthening the optical path by a factor $N = 2\mathcal{F}/\pi$. The resonant condition is kept by means of a modified Pound-Drever-Hall frequency locking scheme [8,9]. The magnet-cryostat assembly can be rotated so that the magnetic field rotates in a plane normal to the light propagation direction, thus producing a time-modulation of the effect. The magnet has been energized and set in rotation with a field of 6.5 T. An optical modulator placed after the cavity
introduces a carrier frequency necessary for heterodyne detection. The ellipticity and dichroism induced in the light polarisation can be extracted from the photodiode current by Fourier analysis.

A signal due to the existence of a (pseudo)scalar neutral particle, which will appear in the photocurrent spectrum as sidebands separated from the carrier frequency by twice the magnet rotation frequency, must necessarily be dependent on $B^2$ and independent of the magnet rotation frequency. Also, this signal must be in the correct phase relation, depending on whether the particle is scalar or pseudoscalar, with the magnetic field at all rotation frequencies. In fact the (pseudo)scalar field production is maximum for photon polarizations (parallel) perpendicular to the magnetic field.

The apparatus briefly discussed above is installed and functioning as an integrated system at the Laboratori Nazionali di Legnaro of I.N.F.N., near Padova, Italy. A preliminary commissioning run has been successfully completed in the following (not nominal) conditions: Fabry-Pérot cavity finesse $F = 100000$ (corresponding to a quality factor $Q = 10^{12}$), magnetic field $B = 4.0$ T and magnet rotation frequency of 0.43 Hz. This run has shown that the system is stable in time, and that data taking can be continuously performed as long as liquid He is available. Preliminary data collected during commissioning yielded a sensitivity figure for the ellipticity of $2 \times 10^{-7}$ rad/$\sqrt{\text{Hz}}$ which will allow to reach previous limits [10] in a few seconds of measuring time. Taking into account the above experimental parameters, this sensitivity could give access to new physics in the yet unexplored [2,10] particle mass region $10^{-3}$ eV < $m$ < $10^{-1}$ eV.

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