INFN-LNL-213(2006)
October 2006

Experimental observation of vacuum birefringence

E. Zavattini[1], G. Zavattini[2], P. Temnikov[3], G. Ruoso[3], G. Raiteri[1], E. Polacco[4], E. Milotti[1], M. Karuza[1], U. Gastaldi[3], G. Di Domenico[2], F. Della Valle[1], R.Cimino[5], S. Carusotto[4], G. Cantatore[1] and M. Bregant[1]

(PVLAS Collaboration)

1-INFN Sezione di Trieste and University of Trieste,Italy

2-INFN Sezione di Ferrara and University of Ferrara, Italy

3-INFN Laboratori Nazionali di Legnaro, Legnaro (Pd), Italy

4-INFN Sezione di Pisa and University of Pisa, Italy

5-INFN Laboratori Nazionali di Frascati, Frascati, Italy

Abstract

The PVLAS experiment operates an ellipsometer based on a Fabry-Perot optical cavity that embraces a superconducting rotating dipole magnet and can measure the ellipticity induced by the magnetic field onto linearly polarized laser light. With a residual pressure less than 10^{-7} mbar the apparatus gives ellipticity signals at the level of 10^{-11}rad per passage through 1m of 5 Tesla transverse magnetic field of 532nm wavelength laser light. These signals can be interpreted as being generated largely by vacuum birefringence. If this interpretation is valid, a tool has become available to characterize physical properties of vacuum as if it were an ordinary transparent medium. The main source of the induced ellipticity could be the existence of ultralight bosons with mass of the order of 10^{-3} eV that would couple to two photons and would be created in the experiment by interactions of photons of the laser beam with virtual photons of the magnetic field. The apparatus is calibrated in amplitude and in phase by measuring Cotton-Mouton ellipticity in gases. The ellipticity induced in vacuum has phase opposite to that of the CME ellipticity induced with noble gases in the interaction region. If the ellipticity signals observed in vacuum are due to authentic quantum vacuum birefringence and not to the apparatus, and a microscopic interpretation of the effect in terms of existence of spin zero ultralight bosons is valid, the observed phase of the ellipticity implies a positive parity of the bosons. The ultralight bosons would then be scalars.

Presented by Ugo Gastaldi at QCD 06
13th High-Energy Physics Internat. Conf. in Quantum Chromodynamics (QCD)
Montpellier, France, 3-8 July 2006

Experimental observation of vacuum birefringence

E. Zavattini[1], G. Zavattini[2], P.Temnikov[3], G. Ruoso[3], G.Raiteri[1],E.Polacco[4], E. Milotti[1], M. Karuza[1], U. Gastaldi[3*], G. Di Domenico[2], F. Della Valle[1], R.Cimino[5], S. Carusotto[4], G. Cantatore[1] and M. Bregant[1]

(PVLAS Collaboration)

1-INFN Sezione di Trieste and University of Trieste,Italy

2-INFN Sezione di Ferrara and University of Ferrara, Italy

3-INFN Laboratori Nazionali di Legnaro, Legnaro (Pd), Italy

4-INFN Sezione di Pisa and University of Pisa, Italy

5-INFN Laboratori Nazionali di Frascati, Frascati, Italy

Abstract

The PVLAS experiment operates an ellipsometer based on a Fabry-Perot optical cavity that embraces a superconducting rotating dipole magnet and can measure the ellipticity induced by the magnetic field onto linearly polarized laser light. With a residual pressure less than 10^{-7} mbar the apparatus gives ellipticity signals at the level of 10^{-11}rad per passage through 1m of 5 Tesla transverse magnetic field of 532nm wavelength laser light. These signals can be interpreted as being generated largely by vacuum birefringence. If this interpretation is valid, a tool has become available to characterize physical properties of vacuum as if it were an ordinary transparent medium. The main source of the induced ellipticity could be the existence of ultralight bosons with mass of the order of 10^{-3} eV that would couple to two photons and would be created in the experiment by interactions of photons of the laser beam with virtual photons of the magnetic field. The apparatus is calibrated in amplitude and in phase by measuring Cotton-Mouton ellipticity in gases. The ellipticity induced in vacuum has phase opposite to that of the CME ellipticity induced with noble gases in the interaction region. If the ellipticity signals observed in vacuum are due to authentic quantum vacuum birefringence and not to the apparatus, and a microscopic interpretation of the effect in terms of existence of spin zero ultralight bosons is valid, the observed phase of the ellipticity implies a positive parity of the bosons. The ultralight bosons would then be scalars.

Keywords: Axion; Boson; Scalars; Birefringence; Dichroism; Polarization

---

The PVLAS experiment has been set up to study physical properties of quantum vacuum by using linearly polarized light as a probe and by measuring variations of the polarization characteristics of the light injected into the apparatus after traversal of an interaction region where is present a transverse magnetic field of intensity B up to 5.5 Tesla and the

---

[*] Corresponding author. e-mail: gastaldi@lnl.infn.it.

residual gas pressure can be set below 10^{-7} mbar[1-3].

We have recently published evidence for dichroism induced in vacuum by a transverse magnetic field on linearly polarized 1064 nm wavelength infrared laser light[4].

We report here the observation of a very large ellipticity induced in vacuum by a transverse magnetic field on linearly polarized 532 nm wavelength green laser light.

A second surprising observation is that the phase of the ellipticity induced in vacuum is opposite to the phase of the ellipticity induced in noble gases.

A complementary report [5] describes the main experimental aspects of our observations. Here emphasis is given to physics aspects not covered in [5] because of page limits. For extended sets of references to relevant literature see refs. [1–6].

We have performed ellipticity measurements in 2004 with 1064nm wavelength infrared light and in 2005 with 532nm green light with basically the same apparatus configuration, apart the change of the laser source and of the FP mirrors. We have observed in the ellipticity polar plot the signals of CME with Ne in the FP cavity at the same angle of 15^0 with both infrared and green light. The vacuum ellipticity signals of 2004 and 2005 have always appeared with phase opposite to the Ne CM ellipticity signal.

During 2005 we have performed dedicated runs to measure ellipticities first in vacuum and then with increasing values of the pressure of a same gas in the FP, without any intervention on the optics, taking care to make measurements at pressure values where zero crossing may occur if the ellipticity induced in vacuum could balance the CM ellipticity of the gas, in case the two media induced ellipticities of opposite sign.

We have sequentially performed ellipticity measurements with N_2, He and Ne, always preceeding a set of gas measurements by a measurement in vacuum. Figs. 1 and 2 show the results with vacuum, N_2 and He.

With vacuum in the FP cavity the amplitude of the ellipticity signal is of the order of 10^{-11} rad per pass of 532nm laser light, and is reproducible within a factor 2; the phase is the same as the phase with N_2 and opposite to the phase with He.

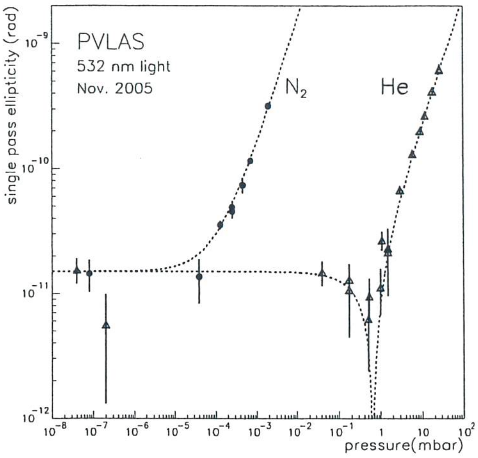

Figure 1. Amplitude of ellipticity signals measured in high vacuum (residual gas pressures below 10^{-6}mbar) and with increasing pressures of N_2 and He. The dotted curves in the bilogaritmic plot correspond to straight lines in a picture with linear coordinates. The slopes of the two rising portions of the two curves represent the moduli of the Cotton-Mouton coefficients of the two gases. The hole in the He data correspond to zero crossing at a pressure value where the negative ellipticity induced in vacuum balances the positive CM ellipticity induced in He. The N_2 curve does not feature zero crossing because the ellipticity induced in vacuum has the same phase as that induced in the gas.

Data with Ne have similar features of data with He, namely they show zero crossing in the amplitude plot and phase jump by 180^0 at the zero crossing pressure [5].

The amplitude of the vacuum ellipticity signals with infrared laser light is about half that with green light, the phase is still opposite to that with noble gases in the FP.

The vacuum ellipticity signals are about four orders of magnitude larger than expected from QED vacuum polarization effects and cannot be explained with known physics, if they are not an artefact of the apparatus. All the checks done so far [1-5] lead however to the conclusion that the signals are generated within the FP cavity.

One could explore the hypothesis of an anomalous contribution from hadronic corrections to the vacuum polarization diagrams [7]. However the experiment has also measured with IR light vacuum dichroism at the level of 4 10^{-11}rad per light transit [4]. Hadronic terms contributing to generate ellipticity through virtual processes do not generate dichroism. So even if hadronic effects would account for the observed ellipticity, the observed rotation would remain unexplained.

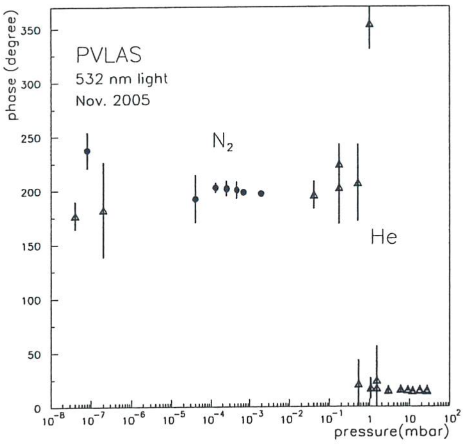

Figure 2. Phase of the ellipticity signals measured in high vacuum (residual gas pressures below 10^{-6}mbar) and with increasing pressures of N_2 and He The phase measured in vacuum remains stable when N_2 is introduced in the FP cavity. When He is introduced in the FP cavity the phase changes suddenly by 180^0 from about 195^0 to 15^0 when moving from 4 10^{-1} to 5 10^{-1} mbar and than remains stable at 15^0 when the pressure is further increased.

Ultralight bosons with mass well below the energy of the laser photons could account for both the ellipticity and rotation effects, because their virtual production could explain the ellipticity and their real production in interactions of the laser photons with virtual photons of the magnetic field could explain the dichroism.

Ultralight spin zero bosons would generate positive ellipticity if they are pseudoscalars, and negative ellipticity if they are scalars [8]. Cotton-Mouton effect generates positive ellipticity in noble gases and negative ellipticity in gases like N_2 [9]. On the basis of the experimental results reported above, if the ellipticity signal in vacuum is dominantly generated by true vacuum effects and a microscopic interpretation of the ellipticity data in terms of existence of spin zero very light bosons is valid, the bosons are scalars.

Ultralight spin zero bosons would generate negative dichroism if they are pseudoscalars, and positive dichroism if they are scalars [8]. We do not know at present the sign of dichroism generated in vacuum with 1064 nm IR light, since the absolute position of the principal axis of the QWP was recorded with an ambiguity of 90^0 in the measurements exploited in ref [4]. It is therefore not possible to crosscheck with the dichroism data of ref [4] the result emerging from the ellipticity data that the ultralight bosons that could explain the PVLAS observations ought to be scalars.

Under the hypothesis that ultralight bosons generate dominantly the observed ellipticity and rotation signals, the crossing of the bands of isoellipticiy and isodichroism in the (m,M) plane of boson mass m and inverse coupling constant to two photons M selects a region of possible values of m and M. In absence of systematic errors the three crossings of the bands of the 1064nm isoellipticity, 1064nm isodichroism and 532nm isoellipticity should occur around a common point. In view of the present uncertainties one can prudendly state only that m should be found in the window 0.8-1.8meV and M in the window 2-5 10^5 GeV. While the mass value m is compatible with current limits for light bosons coupled to two photons, the inverse coupling M is more than 4 orders of magnitude inside the desert of values excluded by CAST and by cosmological constraints [10-13].

In order to complete and improve our measurements, work is in progress along several lines.

A new amagnetic access structure is being installed to reduce possible couplings of the rotating magnet to the optics.

A 2 Tesla permanent dipole magnet 0.5m long has been ordered and will be installed with horizontal magnetic field below the ellipsometer with the bore aligned to the FP axis for a regeneration test. If the source of the dichroism of about $4\ 10^{-11}$rad per 1064 nm light pass through the FP [4] is indeed the production of bosons in the superconducting magnet, in the reconversion magnet a fraction proportional to $4\ 10^{-11}$ of the bosons directed downwards should reconvert into photons of the same energy of the FP photons. The proportionality factor is given by the scaling of the boson-photon oscillation probability with the field intensities and lengths of the magnets. A reduction factor 4/30 comes from the ratio of the magnetic fields and a factor in excess of 1/4 comes from the ratio of the lengths of the two magnets. With a typical number of reflections in the cavity N=50000, a photon detector positioned below the reconversion magnet along the FP beam axis would be invested by a fraction of about 10^{-18} of the photons that traverse the FP. With a laser providing 20 mW of light emerging from the FP, about 10^{17} photons sec^{-1} traverse the FP and then $\sim 10^{-1}$ photons sec^{-1} should invest the photon detector. This regeneration check will be carried out in parallel to normal runs.

Two boson beams of identical intensity and emittance and opposite directions emerge from the FP in the scenario where ultralight bosons exist. An identical rate of regenerated photons is therefore expected in a permanent magnet positioned above the experiment along the bosons beam line of the same length and field intensity of the bottom regeneration magnet[6]. This would be a powerful check of the regeneration test, after having observed signal in the bottom magnet.

By installing above the ellipsometer a permanent magnet longer than the bottom one, the ratio of the rates of regeneration photons detected in the two regeneration photodetectors would provide a precise measurement of the mass m of the ultralight bosons independent on the value of M and of errors in the measurement of the laser intensity and FP finesse[6].

In order to improve dramatically the quality of the polarization measurements we plan to substitute the superconducting magnet with a set of three 1m long permanent magnets. This will provide three essential advantages. The duty cycle will improve by more than one order of magnitude, because at present typically at most 4 hrs of data taking per day are possible and the rest of the time is necessary for cryogenics operations. There will be no stray field on the optics elements. It will be possible to change the magnet length and so to sample with three different lengths the photon boson oscillation curve.

References

[1] E.Zavattini et al. (PVLAS Collaboration) in *XI Int. Workshop on Neutrino Telescopes* , 22–25 Feb. 2005 Venezia, M. Baldo Ceolin edr., Papergraf Piazzola sul Brenta (I), 433 (2005)

[2] E.Zavattini et al. (PVLAS Collab.) in *2005 Electroweak Interactions and Unified Theories*, J. Tran Thanh Van edr., The Gioi Publishers Vietnam, 151 (2005)

[3] E.Zavattini et al. (PVLAS Collab.), PVLAS: probing vacuum with polarized light, INFN-LNL(Rep) 208-05, arXiv hep-ex 0512022(2005), to be published in *QCD05* Int. Conf. Montpellier France, 4-9 July 2005

[4] E.Zavattini et al. (PVLAS Collaboration), *Phys. Rev. Lett.* 96, 110406 (2006)

[5] E.Zavattini et al. (PVLAS Collab.), Observation of vacuum birefringence induced by a transverse magnetic field, presented by U. Gastaldi at ICHEP'06, Moscow 26 July-02 August, 2006

[6] U.Gastaldi, Spectroscopy of ultralight bosons by photon-boson-photon conversion-reconversion:experimental aspects, INFN-LNL(Rep)211-06, arXiv hep-ex/0605072 (2006)

[7] J. Rafelski, in *Frontier Tests of QED and Physics of the Vacuum,* E.Zavattini et al.edrs., Heron Press, Sofia 425 (1998)

[8] L.Maiani, R. Petronzio and E. Zavattini, *Phys. Lett.* **B175,** 359 (1986)

[9] C. Rizzo et al., *Int. Rev. Phys. Chem.* **16**, 81 (1997)

[10] K.Ziutas et al., (CAST Collab.) *Phys.Rev.Lett.* **94,** 121301(2005)

[11] G.Raffelt, in *XI Int. Workshop on Neutrino Telescopes* , 22–25 Feb. 2005 Venezia, M. Baldo Ceolin edr., Papergraf Piazzola sul Brenta (I), 419(2005)

[12] P.Sikivie, Axions 05, arXiv:hep-ph 0509198 (2005)

[13] J. Ellis et al., *Phys. Lett.* **B194,** 291 (1986)