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OBSERVATION OF VACUUM BIREFRINGENCE INDUCED BY A TRANSVERSE MAGNETIC FIELD

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The PVLAS experiment operates an ellipsometer based on a Fabry-Perot optical cavity that embraces a superconducting dipole magnet and can measure ellipticity and rotation 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 light passage through 1m of 5 Tesla transverse magnetic field of 532nm wavelength green laser light. These signals can be interpreted as being generated largely by vacuum birefringence. If this interpretation of the observed signals 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.

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Keywords: Axion; Boson; Scalars; Dark matter; Birefringence; 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 and the residual gas pressure can be lowered below 10^{-7} mbar.

We have recently published evidence for dichroism induced in vacuum by a transverse magnetic field on linearly polarized 1064 nm wavelength infrared laser light.[1-4]

We report the observation of a surprisingly large ellipticity (of the order of 10^{-11} rad per pass) induced in vacuum by a transverse magnetic field on linearly polarized 532 nm wavelength green laser light. This ellipticity is four orders of magnitude larger than expected from QED effects.

A second surprising observation is that the phase of this ellipticity induced in vacuum is opposite to the phase of the ellipticity induced in noble gases. We emphasize in this report the main experimental aspects of our observations. Physics aspects are discussed more extensively in a complementary report.[5] For extended sets of references to relevant experimental and theoretical literature see refs [1–6].

The PVLAS ellipsometer consists basically of two polarizers set orthogonally for maximum extinction (see fig.1 of ref.[4]) and positioned respectively below and above a superconductive dipole magnet 1.2m long mounted with the bore vertical and horizontal field lines in the bore. The magnet can rotate along a vertical axis corresponding to the bore axis. Laser light is sent into the ellipsometer through the polarizer below the magnet. Light traversing the ellipsometer is detected by a photodiode positioned above the magnet behind the output polarizer. With the ellipsometer set for maximum extinction, in absence of magnetic field the detector is reached only by background light and by light due to ellipticities generated in the apparatus by background sources. When the magnet is powered, ellipticities generated in the ellipsometer by the action of the magnetic field cause a signal in the detector due to the component of the elliptical polarization parallel to the polarization of the output polarizer. In order to enhance the signal of ellipticity induced in vacuum by the magnetic field, a Fabry-Perot optical cavity (constituted by two high reflectivity interferential mirrors positioned above and below the magnet) is mounted inside the ellipsometer. Light that traverses the entrance polarizer and reaches the output polarizer will have typically made N reflections in the FP cavity and traversed N times the magnet. This causes an enhancement of the induced ellipticity by a factor N, that was typically about $5\ 10^4$. In order to improve the ratio of signal over background a heterodyne technique is used: an optical modulator positioned behind the output mirror of the FP cavity and before the output polarizer introduces artificially an ellipticity on the light beam that reaches the output polarizer. This ellipticity has an amplitude typically of the order of $2\ 10^{-3}$ rad and it is time modulated at a frequency ω_{SOM}=506 Hz. The magnet is put in rotation with a typical frequency ω_M=0.3Hz. The ellipticity induced by the magnet is modulated at a frequency $2\omega_M$. The ellipticities generated by the SOM modulator and by the magnet beat and generate two peaks at the frequencies $\omega_{SOM}-2\omega_M$ and $\omega_{SOM}+2\omega_M$. The amplitudes of these peaks are proportional to the magnet induced ellipticity. A Fourier analysis of the output of the photodiode detector permits to determine the amplitude and the phase of the magnet induced ellipticity from the signals of the two peaks at $\omega_{SOM} \pm 2\omega_M$.

By introducing gas in the FP cavity it is possible to calibrate directly the ellipsometer both in amplitude and in phase by the measurement of ellipticity induced by the magnetic field because of the Cotton-Mouton effect (for a review see ref [7]). The amplitude of the CME induced ellipticity is proportional to the gas pressure and to the square of the magnetic field intensity B, and the phase depends on the angle between the direction of the magnetic field and the polarization of the entrance polarizer. In measurements performed with fixed configuration of the optics there are only two possible phases for measurements with gases. These two phases differ by 180^0 because any gas can feature only positive or negative Cotton-Mouton coefficient. Noble gases as He and Ne generate positive ellipticity, while N_2 gas generates negative ellipticity.[7] The CME ellipticity signals at $\omega_{SOM}\pm 2\omega_{SOM}$ are extremely clear. At relatively high pressures the signal over background ratio exceeds 10^3 and the phase is measured with an error less than 1^0. This feature of the apparatus permits to determine experimentally on the basis of the calibration data the two opposite directions in the polar plot (where the signal amplitude is given by the radius and the signal phase by the angle) where can be observed the signal from vacuum induced ellipticity, independently from a detailed knowledge of apparatus and software settings.

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

We have checked the B^2 dependence of the CM ellipticity signal amplitude during 2004 runs with 18 mbar Ne in the FP cavity and IR 1064 nm wavelength light (see Fig.1).

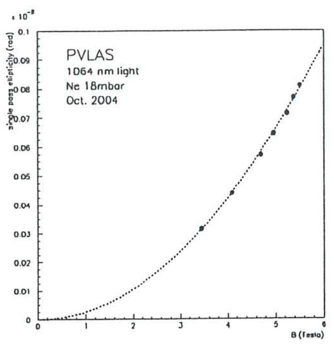

Fig.1. B^2 dependence of the ellipticity signal with Ne

We have checked the compatibility with a B^2 dependence of the signal amplitude of vacuum birefringence in a sequence of runs in December 2004 with residual pressure below 10^{-7} mbar in the FP cavity and IR 1064 nm laser light (see Fig.2).

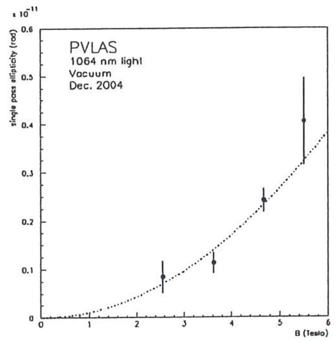

Fig.2. Dependence on B(Tesla) of the ellipticity signal in vacuum

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

We have sequentially performed ellipticity measurements with N_2, He and Ne, always preceeding a set of gas measurements with a measurement in vacuum.

Figs. 3 and 4 show the results with vacuum, N_2 and Ne. Data with He (see ref [5]) have similar features of data with Ne, namely they show zero crossing in the amplitude plot and phase jump by 180^0 at the zero crossing pressure.

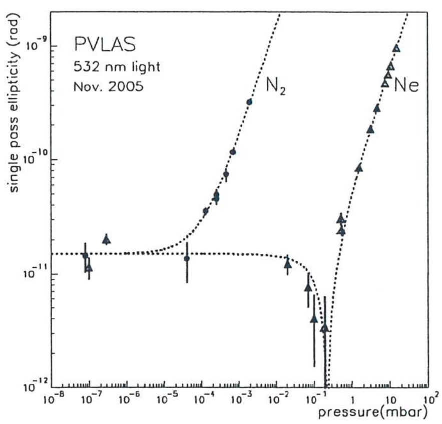

Fig.3. Amplitude of ellipticity signals measured in high vacuum (residual gas pressures below 10^{-6}mbar) and with increasing pressures of N_2 and Ne. The dotted curves in the bilogaritmic plot correspond to straight lines in a picture with linear coordinates. The slopes of the two rising portions of the two curves represent the moduli of the Cotton-Mouton coefficients of the two gases. The hole in the Ne data correspond to zero crossing at a pressure value where the negative ellipticity induced in vacuum balances the positive CM ellipticity induced in Ne. 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.

The amplitude in vacuum is about 10^{-11} rad per pass and it is reproducible within a factor 2. The phase in vacuum is similar to the phase of N_2 and opposite to the phase of He and Ne.
We have checked that the CM ellipticity signal undergoes a phase variation by 180^0 when the ellipticity modulator is rotated by 90^0, and that the same effect occurs in vacuum runs.

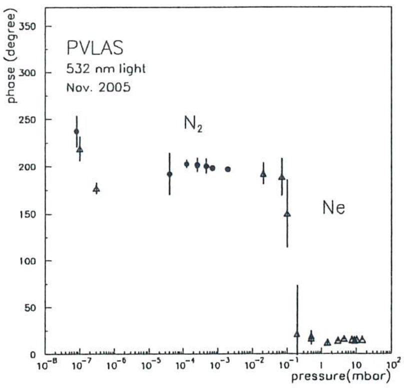

Fig.4. Phase of the ellipticity signals measured in high vacuum (residual gas pressures below 10^{-6}mbar) and with increasing pressures of N_2 and Ne. The phase measured in vacuum remains stable when N_2 is introduced in the FP cavity. When He is introduced in the FP cavity the phase changes suddenly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

We have checked that the ellipticity phase of runs with vacuum and gas rotates by an angle 2α, when the polarizer is rotated by an angle α. We have verified, by exploiting amplitudes and phases of the $n\omega_M$ sidebands of ω_{SOM} and of $2\omega_{SOM}$, that combinations of pairs of background effects each modulated at the frequency ω_M contribute only marginally to the signal observed at $\omega_{SOM} \pm 2\omega_M$.

Measurements with a FP cavity inserted inside a 1 Tesla magnet[8] have shown that the PVLAS ellipticity signal cannot be generated by birefingence of the FP mirrors induced by the stray rotating magnetic field.

Ultralight spin zero bosons would generate positive ellipticity if they are pseudoscalars, and negative ellipticity if they are scalars.[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.

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