PVLAS – search for the Polarization of Vacuum with LASer light

Aldo Ejilli, Ugo Gastaldi, Guido Zavattini (Dipartimento di Fisica – Univ. di Ferrara and INFN-Ferrara); Ruggero Pengo, Giuseppe Ruoso (INFN-LNL);
Federico Della Valle, Edoardo Milotti (Dipartimento di Fisica – Univ. di Trieste and INFN-Trieste) – **WWW: http://pvlas.ts.infn.it**

1. Under the right circumstances the vacuum of Quantum ElectroDynamics (QED) behaves like an optically birefringent medium

Consider the EM field Lagrangian with quantum corrections from the electronic field (Heisenberg and Euler, 1936 – Schwinger 1951)

the integration variable is the "proper time" variable (fully developed later by Stückelberg, Feynman and Schwinger)

subtraction of the infinite free-field effective action

this corresponds to a log term in the integrated Lagrangian: it is an embryonic form of charge renormalization

$$\mathcal{L} = 4\pi^2 mc^2 \left(\frac{mc}{h}\right)^3 \int_0^\infty \frac{d\eta}{\eta^3} e^{-\eta} \left[-a\eta \cot(a\eta) b\eta \coth(b\eta) + 1 + \frac{\eta^2}{3}(b^2 - a^2) \right]$$

$$\text{where} \quad a^2 - b^2 = (\mathbf{E}^2 - \mathbf{B}^2)/\mathcal{E}_c^2 \quad \text{and} \quad ab = (\mathbf{E}\cdot\mathbf{B})/\mathcal{E}_c^2$$

scalar invariant
(in units of the critical electric field)

pseudoscalar invariant related to axial symmetry


The Physics Department in Ferrara, the present site of the PVLAS experiment.

The lowest order expansion of this Lagrangian yields the Maxwell form of the Lagrangian + a scalar correction term + a pseudoscalar correction term. As a consequence we obtain a new form of the Maxwell's equations. These new equations can be recast in their standard form with the introduction of new effective D and H fields: this means that we can think of QED vacuum as an effective medium with its own properties, which depend on the external fields

$$\mathcal{L} = -\frac{1}{2}(\mathbf{E}^2 - \mathbf{B}^2) + \frac{2\alpha^2}{45 m_e^4}\left[(\mathbf{E}^2 - \mathbf{B}^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$

Modified EM field Lagrangian with the lowest order terms from the Heisenberg-Euler Lagrangian

$$\varepsilon_{ij} = \delta_{ij} + \frac{4\alpha^2}{45 m_e^4}\left[2(\mathbf{E}^2 - \mathbf{B}^2)\delta_{ij} + 7B_iB_j\right]$$

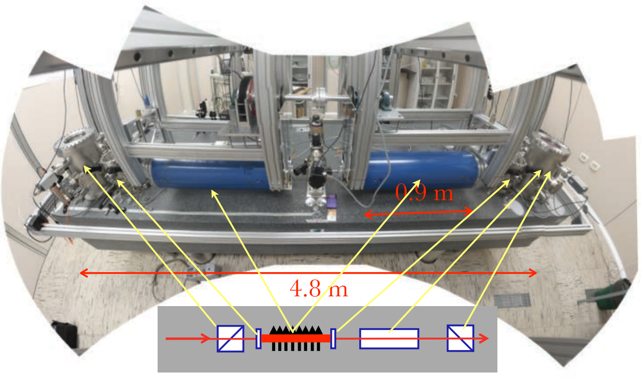
$$\mu_{ij} = \delta_{ij} - \frac{4\alpha^2}{45 m_e^4}\left[2(\mathbf{E}^2 - \mathbf{B}^2)\delta_{ij} - 7E_iE_j\right]$$

Effective values of vacuum polarizabilities when external fields are present

$$\begin{aligned} n_\parallel &= 1 + 7A_eB_0^2 \\ n_\perp &= 1 + 4A_eB_0^2 \\ A_e &= \frac{2\alpha^2\lambda\!\!\!^{-2}}{45\mu_0 m_e c^2} \\ &\approx 1.32 \times 10^{-24}\ \mathrm{T}^{-2} \end{aligned}$$

In a strong magnetic field region vacuum becomes birefringent, with different refractive indexes parallel and perpendicular to the field. However, the A_e parameter that determines the birefringence – and therefore the QED effect – is extremely small.

2. The predicted QED effect is extremely small and requires an exceedingly sensitive apparatus: the PVLAS experiment in Ferrara



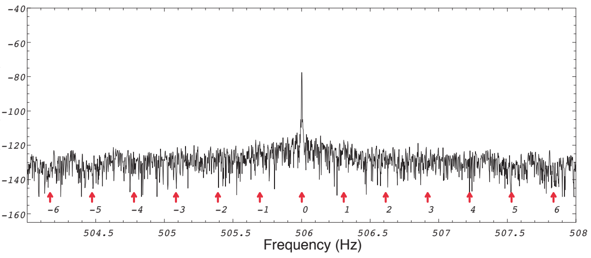
- We use the intense dipole field from permanent magnets (blue cylinders in the picture, field intensity about 2.5 T). This yields the birefringence

$$\Delta n|_{B=2.5\ \mathrm{T}} \approx 2.5\ 10^{-23}$$

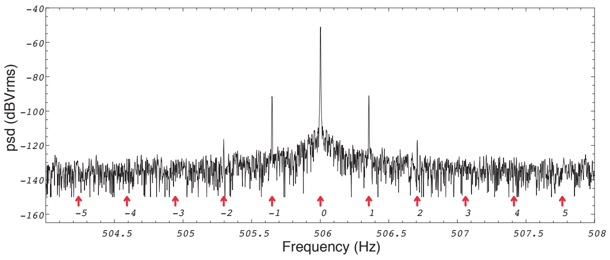
- We inject linearly polarized LASER light perpendicular to the magnetic field, and try to detect the tiny ellipticity due to the birefringence of QED vacuum
- The effect is extremely small and we modulate it and force it to emerge from the ever present noise background by rotating the magnets
- The magnetic field modulation is not enough, we must add a additional controlled ellipticity which is modulated as well at its own pace
- On top of all this we amplify the effect as much as we can by folding the path of LASER light inside the magnetic field region by means of a high-finesse Fabry-Perot resonator. In this way we have been able to achieve an amplification factor almost as large as 10^6
- Finally, the polarized light is analyzed with a precision analyzer, and the final light intensity is detected by a low-noise photodiode

3. The seemingly endless fight against systematics and noise

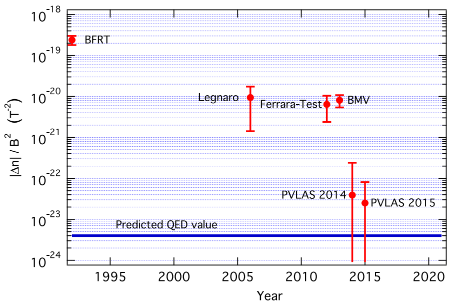
How should the power spectrum of the photodiode signal look like? This is an example of the power spectrum close to the frequency of the ellipticity modulator. The only signal that emerges from noise is the peak from the ellipticity modulator. **Any physics should show up at the second harmonic of the magnetic field modulation** (positions of the harmonics are marked here by the red arrows)



The spectrum on the right displays peaks at the positions of the first and second harmonics, but in this case this is due to the indirect action of the strong magnetic field on parts of the apparatus. **The detection and elimination of systematics such as this and the lowering of the noise floor are a constant worry and amount to most of the experimental work.**



4. Current status of the experiment

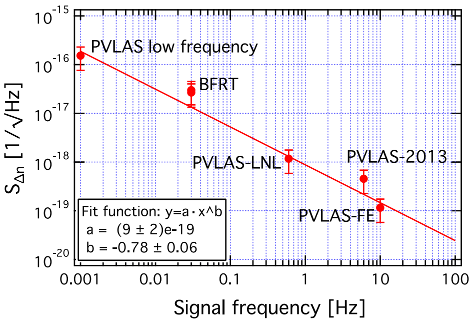


The PVLAS experiment is leading the small pack of brave physicists who are treading this difficult but potentially rewarding path.

We have a record breaking FP resonator, and we have achieved the best bounds on the magnetic birefringence of vacuum

$$\Delta n = (-1.5 \pm 3.0) \times 10^{-22}$$

Figure from PVLAS coll. EPJ **C76** (2016) 24.



Birefringence noise in several experiments vs. the field modulation frequency. The spectral density has a power-law behavior that is not yet understood.

This plot indicates that raising the modulation frequency decreases a fundamental noise process, and it challenges us to increase the modulation frequency while keeping in check dangerous systematics. It also cries for an explanation that has yet to be found.

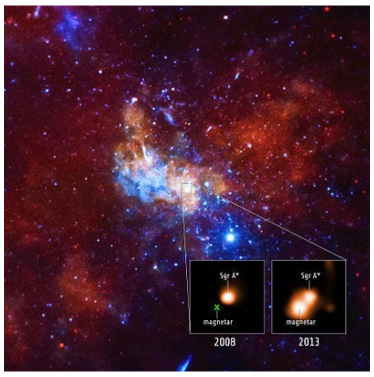
Figure from Zavattini et al. EPJ **C76** (2016) 294

5. Future perspectives and physics goals

We are confident that in the near future we shall reach the sensitivity level required to detect the magnetic birefringence of vacuum predicted by QED.

The birefringence of vacuum may have other sources in addition to QED, and fully understanding this minuscule effect has a large relevance in a cosmic context (such as in the physics of magnetars, where the magnetic birefringence of vacuum – and the associated process of photon splitting – influences the spectrum of the emitted light).

Moreover, any results at odds with the QED prediction could point to the existance of exotic particles and to new and exciting physics.



Additional information and contacts

This work is supported by the Commission 2 – INFN.
For more information on MSc theses and PhD projects please contact Prof. Edoardo Milotti (room 228, e-mail: edoardo.milotti@ts.infn.it)