Esperimento PVLAS per la misura della birifrangenza magnetica del vuoto

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"Hands holding the void"

Alberto Giacometti

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Summary

• Introduction:
  • Aim of the PVLAS experiment
  • Experimental technique

• PVLAS
  • Overview of published results

• Development phases
  • Improvements with respect to PVLAS-LNL
  • Ferrara Test apparatus
  • Final experiment
Classical vacuum has no structure.

The superposition principle is valid

with $c = 1/\sqrt{\varepsilon_0 \mu_0}$
Heisenberg’s Uncertainty Principle

\[ \Delta E \Delta t \geq \frac{\hbar}{2} \]

Vacuum is the **minimum** energy state and can fluctuate into anything compatible with vacuum.

Vacuum has a **structure** which can be observed by perturbing it and probing it.

- QED tests in bound systems - Lamb shift
- QED tests in charged particles - \((g-2)\)
- QED tests with photons is missing
- Macroscopically observable (small) non linear effects have been predicted since 1936 but have never been directly observed yet.

Propagation of light

Photon propagation in vacuum as depicted with Feynman diagrams

Without external field

Real photon  Bare photon  Virtual pairs

With external field

Real photon  Bare photon  Virtual pairs  Radiative corrections

\[ c = \text{depends on polarization and external field!} \]

Euler-Heisenberg Effective Lagrangian

For fields much smaller than the critical field \( B \ll 4.4 \times 10^9 \, \text{T} \); \( E \ll 1.3 \times 10^{18} \, \text{V/m} \) one can write

\[
L = L_{em} + L_{HE} = \frac{1}{2 \mu_0} \left( \frac{E^2}{c^2} - B^2 \right) + \frac{A_e}{\mu_0} \left[ \left( \frac{E^2}{c^2} - B^2 \right)^2 + 7 \left( \frac{E}{c} \cdot \vec{B} \right)^2 \right] + \ldots
\]

\[
A_e = \frac{2}{45 \mu_0} \left( \frac{\alpha^2 \kappa_e^3}{m_e c^2} \right) = 1.32 \times 10^{-24} \, \text{T}^{-2}
\]

\( \text{CPT and Lorentz invariant} \implies \text{Coefficients determined by theory} \)

\( \text{Are neglected:} \)
- \( \alpha^3 \) and higher order terms
- virtual pairs with particles different from \( e^+ e^- \)

W Heisenberg and H Euler, Z. Phys. 98, 714 (1936)
H Euler, Ann. Phys. 26, 398 (1936)

Induced Magnetic Birefringence of Vacuum

By applying the constitutive relations to $L_{EH}$ one finds

$$
\vec{D} = \frac{\partial L_{EH}}{\partial \vec{E}} = \varepsilon_0 \vec{E} + \varepsilon_0 A_e \left[ 4 \left( \frac{E^2}{c^2} - B^2 \right) \vec{E} + 14 \left( \vec{E} \cdot \vec{B} \right) \vec{B} \right]
$$

$$
\vec{H} = - \frac{\partial L_{EH}}{\partial \vec{B}} = \mu_0 \vec{H} + A_e \left[ 4 \left( \frac{E^2}{c^2} - B^2 \right) \vec{B} - 14 \left( \vec{E} \cdot \vec{B} \right) \vec{E} \right]
$$

Light propagation is still described by Maxwell’s equations in media but they no longer are linear due to E-H correction.

Index of refraction

Linearly polarized light passing through a transverse external magnetic field perpendicular to $\vec{k}$.

$$
\begin{align*}
\varepsilon_\parallel &= 1 + 10 A_e B_{Ext}^2 \\
\mu_\parallel &= 1 + 4 A_e B_{Ext}^2 \\
n_\parallel &= 1 + 7 A_e B_{Ext}^2 \\
\varepsilon_\perp &= 1 - 4 A_e B_{Ext}^2 \\
\mu_\perp &= 1 + 12 A_e B_{Ext}^2 \\
n_\perp &= 1 + 4 A_e B_{Ext}^2
\end{align*}
$$

\( \Delta n = 2.5 \cdot 10^{-23} \) for \( B = 2.5 \) T

\[ \Delta n = \Delta n_{(\alpha^2)} = 3A_e B^2 \]

\[ \Delta n = \Delta n_{(\alpha^3)} = 3A_e B^2 \left( 1 + \frac{25}{4\pi} \alpha \right) = \frac{2}{15} \frac{\alpha^2 \hbar^3}{m_e c^5} \left( 1 + \frac{25}{4\pi} \alpha \right) \frac{B^2}{\mu_0} \]

\( \Delta n = (4.031699 \pm 0.000002) \cdot 10^{-24} \left( \frac{B}{1T} \right)^2 \)

\( A_e \) can be determined by measuring the magnetic birefringence of vacuum.

\( \cdot v \neq c \)

\( \cdot \text{anisotropy} \)

O(\( \alpha^4 \)), O(\( \alpha^5 \))? Also a theoretical challenge
Vacuum behaves like a gas: Cotton-Mouton effect

\[ \Delta n_{CM} = CM \frac{P}{P_{atm}} B_0^2 \]

<table>
<thead>
<tr>
<th>Gas</th>
<th>CM constant (atm Tesla(^{-2}))</th>
<th>vacuum equiv. pressure (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(_2)</td>
<td>-2.45 \cdot 10^{-13}</td>
<td>1.6 \cdot 10^{-8}</td>
</tr>
<tr>
<td>Ar</td>
<td>6.8 \cdot 10^{-15}</td>
<td>5.8 \cdot 10^{-7}</td>
</tr>
<tr>
<td>Kr</td>
<td>9.9 \cdot 10^{-15}</td>
<td>4 \cdot 10^{-7}</td>
</tr>
<tr>
<td>Ne</td>
<td>2.8 \cdot 10^{-16}</td>
<td>1.4 \cdot 10^{-5}</td>
</tr>
<tr>
<td>He</td>
<td>1.8 \cdot 10^{-16}</td>
<td>2.2 \cdot 10^{-5}</td>
</tr>
<tr>
<td>H(_2)</td>
<td>8.5 \cdot 10^{-15}</td>
<td>4.7 \cdot 10^{-7}</td>
</tr>
</tbody>
</table>

For He:
Vacuum is 'equivalent' to 5.8 \cdot 10^{11} He atoms/cm\(^3\)

Light-Light scattering

Very low energy photon-photon scattering is proportional to $A_e^2$.

For non polarized light:

\[
\sigma_{\gamma\gamma} = \frac{973 \mu_0^2}{20\pi} \frac{E_\gamma^6}{\hbar^4 c^4} A_e^2
\]

From Euler-Heisenberg Lagrangian (S.I. units)

- For light at 1064 nm this predicts a value of $\sigma_{\gamma\gamma} = 1.8 \cdot 10^{-65}$ cm$^2$
- Experimentally Bernard et al.[**] have published $\sigma_{\gamma\gamma} < 1.5 \cdot 10^{-48}$ cm$^2$


Summary of possible 4 photon processes

- Described by the Euler-Heisenberg Lagrangian. Should be there. Also includes MCPs
- Radialtive correction 1.45%
- Hadronic contribution. Difficult to extract from indirect measurements. g-2 open problem.
- Contribution from hypothetical new particles coupling to two photons.

Aim of PVLAS

• We want to study the speed of light in the perturbed vacuum and therefore study changes in the refractive index.

\[ n_{\text{vacuum}} = 1 + (\delta n_r - i\kappa)_{\text{field}} \]

• Absolute changes of \( n_{\text{vacuum}} \) are too difficult to measure so we study anisotropies due to the perturbing field.
• Linear birefringence and linear dichroism
• Linear dichroism (photon splitting) results to be exceedingly small
Propagation of the photon in an external field

**Dichroism** $\Delta \kappa$
- (Photon splitting)
- Real particle production

**Birefringence** $\Delta n$
- QED dispersion
- Virtual particle production
- MCPs
- Hadrons

Both $\Delta n$ and $\Delta \kappa$ are defined with **sign**

Summing up

Experimental study of the quantum vacuum with:

- magnetic field perturbation
- linearly polarised light beam as a probe
- changes in the polarisation state are the expected signals

Key Ingredients

- high magnetic field
  - superconducting dipole magnet or high field permanent magnet
- long optical path
  - delay line cavity or very-high Q Fabry-Perot resonator
- ellipsometer with heterodyne detection for best sensitivity
  - periodic change of field amplitude/direction for signal modulation

Ellipticity

\[
\psi = \frac{\pi L}{\lambda} \Delta n \sin 2\theta
\]
Present published results - QED

\[ \Delta n = 3 \, A_e \, B^2 \]
\[ \Delta n_{1064} < 4.6 \times 10^{-20} \text{ @ 1064 nm} \]
\[ \Delta n_{532} < 1.0 \times 10^{-19} \text{ @ 532 nm} \]

\[ A_e^{(FE)} < 2.9 \times 10^{-21} \, \text{T}^{-2} \]
\[ A_e^{(QED)} = 1.3 \times 10^{-24} \, \text{T}^{-2} \]

\[ \sigma_{\gamma\gamma} < 9.5 \times 10^{-59} \, \text{cm}^2 \text{ @ 1064 nm} \]
\[ \sigma_{\gamma\gamma} < 2.7 \times 10^{-56} \, \text{cm}^2 \text{ @ 532 nm} \]

Bregant et al, PRD 78, 032006 (2008)

The figure illustrates the process of signal detection through a polariser, a magnetic field, an ellipticity modulator, and an analyser. The equation for the transmitted intensity $I_{Tr}$ is given by:

$$I_{Tr} = I_0 \left[ \sigma^2 + (\psi(t) + \eta(t) + \beta_s(t))^2 \right]$$

$$= I_0 \left[ \sigma^2 + (\eta(t))^2 + 2\psi(t)\eta(t) + 2\beta_s(t)\eta(t) + \ldots \right]$$

This equation accounts for the signal $\eta(t)$ and the noise contributions from $\psi(t)$ and $\beta_s(t)$. The main frequency components at $\omega_{Mod} \pm 2\omega_{Mag}$ and $2\omega_{Mod}$ are highlighted in the graph, with $\omega_{Mod}$ and $\omega_{Mag}$ representing the modulation and magnetic field frequencies, respectively.
Limitations of the LNL apparatus

- Superconducting magnets produce **stray field** when operated at high fields (saturated iron)

- **Running time limited** due to liquid helium consumption

- Observed **correlation between seismic noise and ellipticity noise**. The Legnaro apparatus is large and therefore difficult to isolate seismically.

- **No zero measurement possible** with field turned ON.
Test apparatus in Ferrara

Two permanent magnets allow a zero measurement.

The Fabry-Perot cavity is a resonant optical cavity that increases the effective optical path. It is composed of two mirrors placed at a separation $d$ which is an integer multiple of the light half wavelength. To obtain this condition a laser is phase locked to the cavity using a feedback circuit.

**Amplification factor**

$$N = \frac{2F}{\pi}$$

**Finesse**

$$F = \frac{\pi c \tau}{d}$$

The Ferrara test apparatus - High finesse successful.

**Amplitude vs. Time**

- **Coefficient values ± one standard deviation**
  - $Amp = 6.1063 \pm 0.0338$
  - $Finesse = 4.9343e+05 \pm 4.85e+03$

**Finesse = 493000**

With a finesse = 245000 and with the magnets perpendicular to each other we demonstrated a reduction of more than a factor 80 of the Cotton Mouton signal.

In red, magnets at 0 degrees
In black, magnets at 90 degrees

Rotating vs non rotating magnets

Rotating Magnets
No peak
Sensitivity = $3.0 \cdot 10^{-7}$ 1/√Hz
$\Delta n$ sensitivity = $1.8 \cdot 10^{-18}$ 1/√Hz
$T = 2.3$ hours

Non rotating Magnets
No peak
Sensitivity = $3.3 \cdot 10^{-7}$ 1/√Hz
$\Delta n$ sensitivity = $1.8 \cdot 10^{-18}$ 1/√Hz
$T = 4.8$ hours

Ellipticity histograms around $2 \Omega_{Mag}$

Rayleigh distribution
Coefficient values ± one standard deviation
Norm = $5.9524e-07 \pm 1.27e-08$
$\sigma = 3.3581e-09 \pm 5.42e-11$

$A_e^{Exp} < \frac{\Delta n}{3B^2} = \frac{\sigma \lambda}{2FL3B^2} = 2.9 \cdot 10^{-21}$ T$^{-2}$

$\sigma_{\gamma\gamma} < 9.5 \cdot 10^{-59}$ cm$^2$ @ 1064 nm

New granite optical bench

Installation in Ferrara clean room

Magnets

\[ \int B^2 dl = 5.501 \, \text{T}^2 \text{ m for magnet #2} \]

\[ \int B^2 dl = 5.502 \, \text{T}^2 \text{ m for magnet #1} \]
Mechanical Design
Parameter space

Our best published limit with PVLAS-LNL

Expected limit with the test setup and present performances:
Sensitivity = $2 \cdot 10^{-7} \text{1/Hz}$ and finesse = 245000
Integration time of $1 \text{e6 s} = 10 \text{ giorni}$

Expected limit with final setup and present performances:
Sensitivity = $2 \cdot 10^{-7} \text{1/Hz}$ and finesse = 245000
Integration time of $1 \text{e6 s} = 10 \text{ giorni}$

Expected QED value
Reachable with the new apparatus if the sensitivity is $< 3 \cdot 10^{-8} \text{1/Hz}$ and finesse 245000

Other world efforts

Q&A experiment - Taiwan
Sensibilità $10^{-6} \, 1/\sqrt{\text{Hz}}$, con $F = 30000$, campo $2.3 \, \text{T}$, $L = 180 \, \text{cm}$, 1 magnete. Banchi ottici separati. Ellitticità $= 2 \cdot 10^{-12}$.

$T_{\text{QED}} = 2 \cdot 10^{11} \, \text{s} = 6500 \, \text{anni}$

BMV experiment - Toulouse
Sensibilità in $\Delta n \approx 5 \cdot 10^{-20} \, 1/\sqrt{\text{Hz}}$ con $F = 529000$, campo impulsato qualche $\approx 3 \, \text{ms}$, 115 $\text{T}^2\text{m}$, 1 colpo/12 min $\Rightarrow$ sensibilità efficace $= 1.7 \cdot 10^{-17} \, 1/\sqrt{\text{Hz}}$. Ellitticità $= 1 \cdot 10^{-10}$.

$T_{\text{QED}} = 1.8 \cdot 10^{13} \, \text{s} = 5 \cdot 10^5 \, \text{anni}$

OSQAR experiment - CERN
Sensibilità = ??? Magnete di LHC lungo 15 m, 10 T, Finesse $\approx 1000$, banchi ottici separati. Magnete non modulabile. Ellitticità $= 1 \cdot 10^{-11}$. Assumendo sensibilità $= 10^{-7} \, 1/\sqrt{\text{Hz}}$. A che frequenza? Presumibilmente mHz .... Difficilmente ottenibile

$T_{\text{QED}} = 10^8 \, \text{s} = 3.2 \, \text{anni}$ ???

PVLAS - Ferrara
Sensibilità $2 \cdot 10^{-7} \, 1/\sqrt{\text{Hz}}$, con $F = 285000$, campo $2.6 \, \text{T}$, $L = 1.8 \, \text{m}$, 2 magneti, 11 $\text{T}^2\text{m}$
Banco unico ottico. Ellitticità $= 2.4 \cdot 10^{-11}$

$T_{\text{QED}} = 7.2 \cdot 10^7 \, \text{s} = 2.2 \, \text{anni}$
Measurement time

\[ \text{Effetto} \propto B2LF \]

\[ \text{Sensitività} \left[ \frac{1}{\sqrt{\text{Hz}}} \right] \]

Grazie!

Post-Maxwellian models - 3

For \( \vartheta \neq 0 \)

\[
\begin{align*}
  f^{(pM)}_{\parallel} (\vartheta, E_\gamma) &\propto \eta_1 E_\gamma^3 \\
  f^{(pM)}_{\perp} (\vartheta, E_\gamma) &\propto (a\eta_1 + b\eta_2) E_\gamma^3
\end{align*}
\]

\( \Rightarrow \) Always \( \neq 0 \)

\[
\Delta n^{(pM)} = 2 \xi (\eta_2 - \eta_1) B^2_{\text{Ext}}
\]

If \( \eta_1 = \eta_2 \Rightarrow \Delta n^{(pM)} = 0 \)

e.g. Born - Infeld

Linear dichroism and birefringence

Dichroism

Ellipticity

Dichroism

Ellipticity

apparent rotation $\varepsilon$

ellipticity $\psi$

Linear Birefringence

- A birefringent medium has $n_{||} \neq n_{\perp}$
- A linearly polarized light beam propagating through a birefringent medium will acquire an ellipticity $\psi$

$$\psi = \frac{a}{b} = \frac{\pi L(n_{||} - n_{\perp})}{\lambda} \sin 2\vartheta$$

Linear Dichroism

• A dichroic medium has different extinction coefficients: \( \kappa_\parallel \neq \kappa_\perp \)

• A linearly polarized light beam propagating through a dichroic medium will acquire an apparent rotation \( \varepsilon \)

\[
\varepsilon = \frac{\pi L (\kappa_\parallel - \kappa_\perp)}{\lambda} \sin 2\vartheta
\]

Absorption coefficient

\[
= \frac{2\pi}{\lambda} K
\]

Axion-like contribution

One can add extra terms \([\ast]\) to the E-H effective lagrangian to include contributions from hypothetical neutral light particles interacting weakly with two photons.

\[ L_\phi = \frac{1}{M} \phi(\vec{E}_\gamma \cdot \vec{B}_{\text{ext}}) \]

**pseudoscalar case**

\(M, M_s\) are inverse coupling constants

\[ L_\sigma = \frac{1}{M_s} \sigma(\vec{B}_\gamma \cdot \vec{B}_{\text{ext}}) \]

**scalar case**

Effects on photon propagation

Absorption

Dispersion

DICHROISM

BIREFRINGENCE


Focused on a general study of the vacuum in the presence of a magnetic field

Major improvements compared to previous efforts:

- Resonant FP cavity (6.4 m) for large amplification factor (> $5 \times 10^4$)
- Rotating cryostat allows high modulation frequency (up to 0.4 Hz)
- Large magnetic field (magnet tested up to 7 T)
- Magnetic system mechanically decoupled from optical system
Past - PVLAS at Lab. Nazionali Legnaro
The CAST experiment at CERN has excluded values of $M < 10^{10}$ GeV. Unreachable with present lab techniques.
Low finesse - seismic isolation

Compact 50 cm long ellipsometer without magnetic field

Flat noise spectrum above ≈ 5 Hz
High finesse – seismic isolation

High finesse: \( F = 414000 \)

\[
L_{\text{eff}} = \left( \frac{2F}{\pi} \right) L = 130 \text{ km}
\]

Compact 50 cm long ellipsometer without magnetic field

Cavity output power = 25 mW
Laser-cavity coupling = 75%
Cavity transmission = 25%

Decadimento della luce in uscita dalla cavità

Record sensitivity with a cavity \( \Psi = 3 \cdot 10^{-8} \text{ } 1/\sqrt{\text{Hz}} \)

Assuming \( B = 2.3 \text{ T} \): Sensitivity in \( \Delta n/B^2 = 1.5 \cdot 10^{-20} \text{ T}^{-2} \text{ } 1/\sqrt{\text{Hz}} \)

Ferrara test apparatus - sensitivity

No cavity - reached expected noise level with rotating magnets

No electronically induced signals in the readout system
Ferrara test apparatus - sensitivity

With high-finesse cavity > 400000
Sensitivity worsened - still under study

Ellipticity spectral density \[1/\sqrt{\text{Hz}}\]

-20 -10 0 10 20
Frequency from carrier [Hz]

Non rotating magnets
Rotating magnets @ 3Hz

Permanent Test Magnets

B.Campo magnetico [kgauss]

B cinesi B corretto

New granite optical bench

Installation in Ferrara clean room

Present - Future

Currently building final apparatus in clean room in Ferrara.

- Magnetic field: 2 x 1 m long magnets with 2.5 T \((\text{arrived})\)
- Magnet support structure \((\text{arrived})\)
- Magnet support mechanics + motor \((\text{ordered})\)
- Optical bench with isolation system \((\text{installed})\)
- Optical enclosures \((\text{arriving})\)
- New laser (2 Watts, 1064 nm) \((\text{arrived})\)
- All optical elements, supports and movements will be non magnetic \((\text{arrived})\)
- Getters will be used as vacuum pumps \((\text{arrived})\)
Main interest is the Euler-Heisenberg birefringence

- $B = 2.5 \, \text{T}$
- $F = 4 \cdot 10^5$
- $\Delta n = 2.5 \cdot 10^{-23}$
- $L = 2 \, \text{m}$

If we assume a maximum integration time of $10^6 \, \text{s} (= 12 \, \text{days})$

Ellipticity sensitivity of $< 3.7 \cdot 10^{-8} \, 1/\sqrt{\text{Hz}}$
Birefringence sensitivity $< 2.5 \cdot 10^{-20} \, 1/\sqrt{\text{Hz}}$

Present sensitivity in
$\Delta n = 1.8 \cdot 10^{-18} \, 1/\sqrt{\text{Hz}}$

\[
\text{Shot noise limit} = \sqrt{\frac{e}{2I_0q}} = 1 \cdot 10^{-9} \, \frac{1}{\sqrt{\text{Hz}}}
\]

for $I_0 = 100 \, \text{mW}$

$(I_0 = \text{output intensity reaching the analyzer})$