No signal yet:
The elusive birefringence of the vacuum, and whether gravitational wave detectors may help

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CaJAGWR, Caltech
24. Feb. 2015
Horror Vacui?

Otto Von Guerrike 1654/1656
Vacuum

The **physical vacuum**: What is left when all that can be removed has been removed (J.C. Maxwell)

Heisenberg: \[ \Delta E \Delta t \approx \hbar \]

The quantum vacuum

Non-zero ground state of EM field, and virtual particles

Credit: G. Ruoso
The quantum vacuum

Examples that can be associated:
- Lamb shift
- Anomalous magnetic moment of e and μ
- Casimir force (though other interpretations exist)

Here:
- Properties of the quantum vacuum in the presence of an external field

Credit: G. Ruoso
The quantum vacuum

Examples:
- Lamb shift
- Anomalous magnetic moment of e and µ
- Casimir force

Here:
- Properties of the quantum vacuum in the presence of an external field
- Study with light

$\Delta n > 0$?
PART II.

EXPERIMENTS ON THE VELOCITY OF LIGHT IN A MAGNETIC FIELD.¹

BY EDWARD W. MORLEY AND DAYTON C. MILLER.

Phys. Rev. 7, Vol. 5, 283

Light source: Bunsen burner colored with sodium
Light polarized with Nicol prism

Magnetic field solenoidal $B = 0.165$ T

NOT IN VACUUM

Faraday rotation + change of velocity

Looking at fringes by eye, sensitivity:

$\Delta n \sim 10^{-8}$
Motivated by the search for a photon magnetic moment.

No effect measured: $\Delta n < 4 \times 10^{-7} \ T^{-1}$
Consequences of Dirac’s Theory of the Positron

W. Heisenberg and H. Euler in Leipzig

22. December 1935

Abstract

According to Dirac’s theory of the positron, an electromagnetic field tends to create pairs of particles which leads to a change of Maxwell’s equations in the vacuum. These changes are calculated in the special case that no real electrons or positrons are present and the field varies little over a Compton wavelength. The resulting effective Lagrangian of the field reads:

\[ L = \frac{1}{2}(e^2 - m^2) + \frac{e^2}{\hbar c} \int_0^\infty e^{-\gamma} \frac{dz}{\gamma} \left\{ i \eta^2 (\varepsilon \mathbf{\mathbb{B}}) \cdot \frac{\cos (\frac{\eta}{|\varepsilon_k|} \sqrt{\varepsilon^2 - m^2} + 2i (\varepsilon \mathbf{\mathbb{B}}))}{\cos (\frac{\eta}{|\varepsilon_k|} \sqrt{\varepsilon^2 - m^2} - 2i (\varepsilon \mathbf{\mathbb{B}}))} - \text{conj.} \right\} \]

where \(\varepsilon, \mathbf{\mathbb{B}}\) are field strengths

\[ |\varepsilon_k| = \frac{m c^3}{\hbar} = \frac{1}{137} \left( \frac{e}{m c^2} \right)^2 \] = critical field strengths

The expansion terms in small fields (compared to \(\varepsilon\)) describe light-light scattering. The simplest term is already known from perturbation theory. For large fields, the equations derived here differ strongly from Maxwell’s equations. Our equations will be compared to those proposed by Born.

\[ L = L_{\text{em}} + L_{HE} = \frac{1}{2\mu_0} \left( \frac{E^2}{C^2} - B^2 \right) + \frac{A_e}{\mu_0} \left[ \left( \frac{E^2}{C^2} - B^2 \right)^2 + 7 \left( \frac{E}{C} \times \mathbf{B} \right)^2 \right] + \ldots \]
QED Prediction

- Light slows down in vacuum in the presence of a magnetic field (perpendicular to the direction of light propagation).

\[ \Delta n_\parallel = 9.3 \times 10^{-24} \times B^2 \frac{1}{T^2} \]

\[ \Delta n_\perp = 5.3 \times 10^{-24} \times B^2 \frac{1}{T^2} \]

\[ \Delta n_{\parallel\perp} = 4 \times 10^{-24} \times B^2 \frac{1}{T^2} \]

Vacuum is birefringent:
Light propagation in QED

Without external field

Real photon propagation = Bare photon propagation + Virtual pairs interaction

With external field

Real photon propagation = Bare photon propagation + Virtual pairs interaction + Higher order corrections

c depends on external field!

Credit: G. Ruoso
The quantum vacuum as the origin of the speed of light

Marcel Urban\textsuperscript{1}, François Couchot\textsuperscript{1}, Xavier Sarazin\textsuperscript{1,\textsuperscript{a}}, and Arache Djannati-Atai\textsuperscript{2}

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Abstract. We show that the vacuum permeability $\mu_0$ and permittivity $\epsilon_0$ may originate from the magnetization and the polarization of continuously appearing and disappearing fermion pairs. We then show that if we simply model the propagation of the photon in vacuum as a series of transient captures within these ephemeral pairs, we can derive a finite photon velocity. Requiring that this velocity is equal to the speed of light constrains our model of vacuum. Within this approach, the propagation of a photon is a statistical process at scales much larger than the Planck scale. Therefore we expect its time of flight to fluctuate. We propose an experimental test of this prediction.

$\epsilon_0$ and $\mu_0$ may be consequences of ephemeral (virtual) particles, ...and so may c!
QED

- Not tested much in weak field, low energy limit

But some people try hard...
Ellipsometer Method

Absolute phase shift is hard to measure, study anisotropic Changes of refractive index instead. (birefringence, dichroism)
PVLAS Legnaro (1992-2008)

Factor 5000 away from QED prediction
New PVLAS layout (Ferrara)
Isolated optics table

Credit: G. Ruoso
3.75 Hz spinning...
PVLAS: recent progress

Limited by currently unexplained noise:
One suspect: birefringence of mirror coatings
BMV: temporal B-field modulation with pulsed magnets
BMV, new setup (Jan. 2015)

[Image of a BMV setup with labels for Nd:YAG, λ=1064 nm, AOM, EOM, λ/4, PDH lock, P, M1, M2, B, x, y, z, Ph_r, Ph_e, Ph_t, X-coil]

[Diagram of the BMV setup with annotations for laser wavelength, optical components, and magnetic field orientation]
PVLAS, BMV, and others

- Measure *polarization variation* of laser beam induced by a varying magnetic field. The B-field variation can be spatial (PVLAS) or temporal (BMV).
- Typical problem: Bi-refringence of mirror optics?
- Best upper limit today by PVLAS collab.: factor 10-50 away from QED prediction (new PVLAS Exp., improved factor ~100 in 2014)
Field modulation vs. measurement technique

<table>
<thead>
<tr>
<th>Method</th>
<th>Rotate B-field</th>
<th>Modulate strength of B-field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure polarization</td>
<td>PVLAS, others</td>
<td>BMV</td>
</tr>
<tr>
<td>Measure phase</td>
<td>GW detectors?</td>
<td>GW detectors?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Get refractive indices for par. and perp. direction independently! → More implications for particle physics)</td>
</tr>
</tbody>
</table>
Connection to particle physics

- Milli charged particles: Hypothetical particles with mass $< m(e)$, $\rightarrow$ virtual pairs at lower energy, would show up as ellipticity in addition to QED prediction.

- Axions: Effective absorption of photons (due to coupling to axions) would show up as dichroism (linear polarization rotation).
1979: Proposal to use Laser Interferometers

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri
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(Received 21 April 1978; revised manuscript received 9 November 1978)

Laser interferometry combined with present-day electronic techniques now make it possible to test nonlinear-electrodynamics predictions in the weak-field limit, up to a sensitivity of $10^{-23}$ in the relative variation of the velocity of light. The significance of such tests in regard to QED predictions is noted.

I. INTRODUCTION

In the past, nonlinear equations for electromagnetism have often been proposed, on the basis of theoretical motivations of a widely varying nature. Such proposed nonlinearities are either intrinsic or represent the interaction with other fields such as, for instance, the effects of vacuum polarizability deriving from the interaction of the electromagnetic field with the electronic field. However, as far as experimental confirmation is concerned, there is a nearly total lack of direct information because the theoretically anticipated nonlinearities are exceedingly small.

The purpose of the present paper is to suggest that the progress in instrumentation and experimental techniques in recent years now makes it equations predicted by QED should be of some testable case. For clarity, we report the procedure followed rather than stating the resulting figures.

The equations of electromagnetism in the inclusion of nonlinear terms read:

\[
\begin{align*}
\nabla \times \mathbf{E} - \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} &= 0, \\
\nabla \times \mathbf{H} + \frac{1}{c} \frac{\partial \mathbf{D}}{\partial t} &= 0, \\
\n\nabla \cdot \mathbf{B} &= 0, \\
\n\n\nabla \cdot \mathbf{D} &= 0, \\
\n\mathbf{D} &= \mathbf{E} + \gamma [\alpha (E^2 - B^2) \mathbf{E} + \beta (\mathbf{E} \cdot \mathbf{B}) \mathbf{B}], \\
\n\mathbf{H} &= \mathbf{B} + \gamma [\alpha (E^2 - B^2) \mathbf{B} - \beta (\mathbf{E} \cdot \mathbf{B}) \mathbf{E}],
\end{align*}
\]

where all symbols conform to common the coefficients $\alpha, \beta, \gamma$ have the following QED:

FIG. 1. Sketch of laser interferometer with magnetic field perturbation.
2002: Proposal to use GW detectors.

Exploring the QED vacuum with laser interferometers

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February 1, 2008

It is demonstrated that the nonlinear, and as yet unobserved, QED effect of slowing down light by application of a strong magnetic field may be observable with large laser interferometers like for instance LIGO or GEO600.

12.20.Fv, 07.60.Ly, 41.20.Jb, 42.25.Lc, 41.25.Bs, 95.75.Kk

-too optimistic in assuming possible increase in sensitivity
-with increasing cavity Finesse
-neglecting possible integration of signal over time
Probing for new physics and detecting non-linear vacuum QED effects using gravitational wave interferometer antennas

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-pointing out new physics potential
Interferometry of light propagation in pulsed fields

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published online 28 July 2009

PACS 12.20.Fv – Quantum electrodynamics: Experimental tests
PACS 14.80.-j – Other particles (including hypothetical)

Abstract – We investigate the use of ground-based gravitational-wave interferometers for studies of the strong-field domain of QED. Interferometric measurements of phase velocity shifts induced by quantum fluctuations in magnetic fields can become a sensitive probe for nonlinear self-interactions among macroscopic electromagnetic fields. We identify pulsed magnets as a suitable strong-field source, since their pulse frequency can be matched perfectly with the domain of highest sensitivity of gravitational-wave interferometers. If these interferometers reach their future sensitivity goals, not only strong-field QED phenomena can be discovered but also further parameter space of hypothetical hidden-sector particles will be accessible.

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- assumes aperture of O~cm
On the possibility of vacuum QED measurements with gravitational wave detectors

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Quantum electrodynamics (QED) comprises virtual particle production and thus gives rise to a refractive index of the vacuum larger than unity in the presence of a magnetic field. This predicted effect has not been measured to date, even after considerable effort of a number of experiments. It has been proposed by other authors to possibly use gravitational wave detectors for such vacuum QED measurements, and we give this proposal some new consideration in this paper. In particular, we look at possible source field magnet designs and further constraints on the implementation at a gravitational wave detector. We conclude that such an experiment seems to be feasible with permanent magnets, yet still challenging in its implementation.

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PACS numbers: 04.80.Nn, 42.50.Xa, 95.55.Ym, 95.75.Kk

I. INTRODUCTION

Corrections to the Maxwell equations that emerge from the quantum properties of the vacuum have been proposed many decades ago; see, e.g., [1]. Quantum electrodynamics

All of the ongoing experiments make use of the difference $\Delta n_{\parallel-\perp}$ of the predicted refractive index changes for different angles of the magnetic field with respect to the polarization direction of the light; i.e., they attempt to uncover the birefringence of the vacuum. In these experi...
Integration time for sinusoidal signal

$$t_{SNR=1} = \left( \frac{\tilde{n}(f)}{S_{RMS,\|}} \right)^2$$

Displacement signal

Displacement noise
Ampl. spectral density

$$S_\| = \Delta n_\| \times D = 9.3 \times 10^{-24} \times B^2 \left[ \frac{1}{T^2} \right] \times D$$
Measurement time as function of displacement sensitivity

**Diagram:**
- **Y-axis:** Integration time for SNR=1 [years]
- **X-axis:** Displacement Sensitivity [m/sqrt(Hz)]
- Line styles and labels:
  - Green solid line: Spatially modulated magnetic field
  - Blue dashed line: Amplitude modulated magnetic field
- Key points:
  - $1 \, \text{T}^2 \, \text{m}$
  - $4 \, \text{T}^2 \, \text{m}$
  - $16 \, \text{T}^2 \, \text{m}$

**Legend:**
- Adv. LIGO, Virgo, Kagra, 2018/2019
Displacement Sensitivities

![Displacement noise vs. frequency plot]

Displacement noise [m/sqrt(Hz)] vs. Frequency [Hz]

- GEO–HF upgrade
- Adv.LIGO (2018)
- KAGRA (2019)
- Adv.LIGO upgrade
- ET (LF & HF)
Here: Is it feasible? And with what kind of magnet?

- IFO aspect: smallest acceptable aperture: \(~3\) times beam size (\(< 1\text{ppm loss}\))
Some IFO beam sizes

<table>
<thead>
<tr>
<th>Interferometer</th>
<th>Beam radius at waist</th>
<th>Minimal aperture radius (3 x waist radius)</th>
<th>Realistic aperture radius, including vacuum tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO (no arm cavities)</td>
<td>9 mm</td>
<td>27 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Virgo</td>
<td>10 mm</td>
<td>30 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>LIGO</td>
<td>12 mm</td>
<td>36 mm</td>
<td>55 mm</td>
</tr>
<tr>
<td>KAGRA</td>
<td>16 mm</td>
<td>48 mm</td>
<td>70 mm</td>
</tr>
<tr>
<td>ET-LF</td>
<td>29 mm</td>
<td>87 mm</td>
<td>130 mm</td>
</tr>
</tbody>
</table>

Beam waist near middle of arm cavity
Linear magnet

Simple scaling law:
\[ B^2 D \sim \frac{P A}{r^2} \]
Continuous operation of a linear magnet

For $B^2 D = 1 \, T^2 \, m$:
(r=55mm, $A \sim r^2$)

- $P = 300 \, kW$ (thermal dissipation only)
- $Pr = 2.5 \, MW$ (reactive power, $f=25 \, Hz$)
  - 1 MW with ferro-magnetic material surrounding the conductor

Electricity:
1 year * 1 MW = 8.76 M kWh ~ 2 M €
Intermittent operation of a magnet

\[ t_{SNR=1} \sim \left( \frac{\tilde{n}(f)}{P} \right)^2 \]

\[ P = P_p \times \eta_p \]

\[ t_{SNR=1} \sim \eta_p \times \left( \frac{\tilde{n}(f)}{P} \right)^2 \]

\[ P = 20 \text{ kW (average power)} \]
\[ P = 100 \text{ MW (pulse power, 10ms pulse length)} \]
\[ E = 1 \text{ MJ, 240g TNT} \]
\[ 1 \text{ pulse every 50 s.} \]
\[ 600000 \text{ pulses for SNR}=1 \text{ (1 year)} \]
Magnet Aspects

- Electro-magnets: very difficult due to high energy in B-field. Perhaps better with new alloys and lower frequencies. Very large dissipation.

- Pulsed magnets: Limited lifetime seems the main problem. Large apertures do not exist yet. (see 'X-coil' for BMV, long development time)

- Permanent magnets: Field energy does not have to be shifted around...
Magnet as Halbach Cylinder

\[ B = B_r \cdot \ln(\frac{r_o}{r_i}) \]

\[ B_r \sim 1.3 \text{T for NeFeB} \]

Example: \( B = 1.0 \text{T} \) for \( r_o=121 \text{mm}, r_i=55 \text{mm} \) → \( m=328 \text{kg} \) for \( D=1.2 \text{m} \)

NeFeB: 150$ / kg → 50k$ / Magnet
Nested Halbach cylinders for ampl. Modulated B field

Advanced QED measurement!
IFO assembly with valves and baffles

- Chamber for baffle suspension at entry to small-aperture tube
Low displacement noise hard to reach with small beams
LIGO Hanford: Only facility with mid-tube gate valves

~10m space

e.g: install during A+ 2. upgrade phase, or Voyager upgrade...
A QED calibrator?

- Magnetic field excitation stable over years, can be determined to sub-% level
- Only need magnetic excitation and QED prediction (and good vacuum)
- Long integration time: 3% accuracy for ET-HF after 1 year
Conclusion

- VAC QED at GW-IFO: Different method (phase lag signal rather than polarization shift signal)
- Maybe ambitious, yet still looks feasible
- Quasi-parasitic addition to existing facility
- Permanent magnets seem to be an option for now