QED / VMB at Gravitational Wave Detectors



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QED workshop @ DESY, Nov. 1.-2. 2015

QED Prediction

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



$$\Delta n_{\parallel} = 9.3 * 10^{-24} * B^2 [1/T^2]$$

$$\Delta n_{\perp} = 5.3 * 10^{-24} * B^2 [1/T^2]$$

Vacuum is birefringent:

$$\Delta n_{\parallel-\perp} = 4 * 10^{-24} * B^2 [1/T^2]$$

Ellipsometer Method





Emilio Zavattini (1927 -2007) Absolute phase shift is hard to measure, study anisotropic Changes of refractive index instead. (birefringence, dichroism)

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI CERN, Geneva, Switzerland

Received 28 May 1979

Volume 85B, number 1

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler-Heisenberg-Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11} .

PHYSICS LETTERS

30 July 1979

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 ?
 (...) (new PVLAS Exp., improved factor >~100 in 2014)

Field modulation vs. measurement technique

	Rotate B-field	Modulate strength of B-field
Measure polarization	PVLAS, others	BMV
Measure phase	GW detectors?	GW detectors? (Get refractive indices for par. and perp. direction independently! → More implications for particle physics)

THE MICHELSON INTERFEROMETER

C

A = GLASS HALF SILVERED ON SURFACE OPPOSED TO B
 B = TRANSPARENT GLASS PLATE OR COMPENSATOR
 NOTE - A & B CUT FROM SAME GLASS ACCURATELY
 PLANE PARALLEL
 C = GLASS HEAVILY SILVERED ON FRONT SURFACE
 D = GLASS HEAVILY SILVERED ON FRONT SURFACE IT IS MOUNTED ON A CARRIAGE SO THAT IT CAN
 BE MOVED ALONG PARALLEL WAYS BY MEANS OF
 A SCREW

L = LENS

8

S

OBSERVER

D

S . MONOCHROMATIC LIGHT SOURCE

Michelson (with additions)





Michelson-Morley experiment: Accuracy: 10^-8 m (10^-9 relative)

10m arm-length

Advanced Interferometer: Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

3-4 km arm-length

Michelson (with additions)





Michelson-Morley experiment: Accuracy: 10^-8 m (10^-9 relative)

10m arm-length

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3-4 km arm-length









Kamioka site

CRYOGENIC, UNDEGROUND interferometer





1979: Proposal to use Laser Interferometers for QED measurement

PHYSICAL PEVIEW D

VOLUME 19, NUMBER 8

15 APRIL 1979

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri

Institute of Physical Sciences of the University and Sezione dell'I.N.F.N., 20133 Milano, Italy (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 polarization 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 pr report the procedure followed rather th stating the resulting figures.

The equations of electromagnetism m the inclusion of nonlinear terms read¹

$$\nabla \times \vec{\mathbf{E}} + \frac{1}{c} \cdot \vec{\mathbf{B}} = 0, \quad \nabla \times \vec{\mathbf{H}} - \frac{1}{c} \cdot \vec{\mathbf{D}} = 0,$$

$$\nabla \cdot \vec{\mathbf{B}} = 0, \quad \nabla \cdot \vec{\mathbf{D}} = 0,$$

$$\vec{\mathbf{D}} = \vec{\mathbf{E}} + \gamma [\alpha (E^2 - B^2) \vec{\mathbf{E}} + \beta (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}}) \vec{\mathbf{B}}],$$

$$\vec{\mathbf{H}} = \vec{\mathbf{B}} + \gamma [\alpha (E^2 - B^2) \vec{\mathbf{B}} - \beta (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}}) \vec{\mathbf{E}}],$$

where all symbols conform to common the coefficients α , β , γ have the followin QED:



FIG. 1. Sketch of laser interferometer with magnetic field perturbation.

2002: Proposal to use GW detectors.

hep-ph/0204207 NIKHEF/2002-001

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

2009: Virgo / Electro-Magnets

Eur. Phys. J. C (2009) 62: 459–466 DOI 10.1140/epjc/s10052-009-1079-y THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

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

2009: LIGO/GEO Pulsed Magnets



A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

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www.epljournal.org

Interferometry of light propagation in pulsed fields

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received 16 April 2009; accepted in final form 30 June 2009 published online 28 July 2009

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 selfinteractions 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

2015: Feasibility / Magnet design

PHYSICAL REVIEW D 91, 022002 (2015)

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.

DOI: 10.1103/PhysRevD.91.022002

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

Integration time for sinusoidal signal

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

Displacement noise Ampl. spectral density

Displacement signal

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

Measurement time as function of displacement sensitivity



Displacement Sensitivities



Here: Is it feasible? And with what kind of magnet?

 IFO aspect: smallest acceptable aperture: ~3 times beam size (< 1ppm loss)



Energy in magnetic field:

$$W=\frac{\pi}{2\mu_0}B^2Dr^2$$

Some IFO beam sizes

Interfero- meter	Beam radius at waist	Minimal aperture radius (3 x waist radius)	Realistic aperture radius, including vacuum tube
GEO (no arm cavities)	9 mm	27 mm	40 mm
Virgo	10 mm	30 mm	45 mm
LIGO	12 mm	36 mm	55 mm
KAGRA	16 mm	48 mm	70 mm
ET-LF	29 mm	87 mm	130 mm

Beam waist near middle of arm cavity



Linear magnet





Simple scaling law: B^2 D ~ P A / r^2

Continuous operation of a linear magnet



For B² D = 1 T² m: (r=55mm, A~r²)

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 kW (average power)
P = 100 MW (pulse power, 10ms pulse length)
E = 1 MJ, 240g TNT
1 pulse every 50 s.
600000 pulses for SNR=1 (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 = Br * In(ro/ri) Br ~ 1.3T for NeFeB

Example: B = 1.0T for ro=121mm, ri=55mm \rightarrow m=328kg for D=1.2m NeFeB: 150\$ / kg \rightarrow 50k\$ / Magnet

Magnet size optimization (signal/cost)



Nested Halbach cylinders for ampl. Modulated B field



Systematic errors...

...and solutions

Baffles



IFO assembly with valves and baffles

Chamber for baffle suspension at entry to small-aperture tube





Where?



Low displacement noise hard to reach with small beams

Questions / Considerations

- Worthwhile even if ellipsometric methods are successful and see expected effect?
- Worthwhile for birefringence signal only (i.e. Spatial B-field modulation)?
- Nested Halbach cylinders vs. pulsed magnets?
- Other systematic errors?
- Interference with science program of GW detectors?
 - Dedicated facility/experiment?