The low energy frontier of fundamental physics

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- Who is me

- Early stages ... Thesis: PVLAS issue

- Hidden photons

- The low energy frontier

- Axions and Dark matter
'bout me

- Degree: Zaragoza U.
- PhD: UAB (Eduard Massó)
- PD: DESY
- PD: Max Planck für Physik
- PD: Munich U.
The PVLAS experiment ...

Vacuum magnetic birefringence & dichroism

Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field


(PVLAS Collaboration)

We report the experimental observation of a light polarization rotation in vacuum in the presence of a transverse magnetic field. Assuming that distribution is Gaussian, the average measured rotation is $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass. at 5 T with 44 000 passes through a 1 m long magnet, with $\lambda = 1064$ nm. The relevance of this result in terms of the existence of a light, neutral, spin-zero particle is discussed.

$
\Delta n = 4 \times 10^{-24} \left( \frac{B_{\text{ext}}}{T} \right)^2$

$
\Delta n = \Delta n(g, m_\phi, B_{\text{ext}}) \sim g^2 B^2$

Standard model

Axion-like particle

$\gamma \rightarrow e^+ e^-$

$\gamma_{\text{laser}} \rightarrow B_{\text{ext}}$

(a)

$E_{\perp}$

(b)

$E_{\parallel}$

(c)

$E_{\perp}$

(d)
The problem, a complicated solution...

Our solution ... 2 paraphotons, 1 MCP

High mom. transfer is penalised!

PVLAS
\[\Delta q \sim \mu eV\]

Astrophysical bounds
\[\Delta q \sim \text{keV}\]

5th force searches (for scalar ALP)
\[\Delta q \sim m_p\]
(Virtuality of a photon)
Editorial Note: Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field


(PVLAS Collaboration)

(Received 7 August 2007; published 20 September 2007)


The observed vacuum optical rotation signal reported in [1] has now been excluded by more recent results from the PVLAS Collaboration [2], which show that it was due to an instrumental artifact and was not of physical origin. These new data therefore also exclude the possible interpretation of the signal reported in [1], as caused by the existence of a light, neutral, spin-zero particle.

- Axion-like particles (ALPs), paraphotons, minicharged particles (weakly interacting sub-eV particles - WISPs)

- Astrophysics, small laboratory experiments are relevant

- HE experiments are mostly irrelevant

- New experiments proposed and running (LSW @ DESY, Fermilab...)

- Growing community at this low energy frontier

- Many questions ... (theory embedding, paraphoton pheno...)

why not continuing a bit?
Paraphotons... (sounds paranormal)

- Solar suppression (low mass paraphotons decouple)
Paraphotons... (sounds paranormal)

- Solar suppression (low mass paraphotons decouple)
- From Okun to Holdom to Okun again
- Hidden photons

\[
\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2}m_{\gamma'}^2(A'_{\mu})^2 + j_{\text{em}}^\mu(A_{\mu} - \chi A'_{\mu})
\]

redefine \( A \rightarrow A + \chi A' \)

Standard sector
\[
\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + j_{\text{em}}^\mu A_{\mu}
\]

hidden sector
\[
\mathcal{L} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2}m_{\gamma'}^2(A'_{\mu})^2
\]

kinetic mixing portal

call it hidden photon... (Ringwald)
Hidden photons from string theory

- Extra U(1)s by the score
- Hidden sectors
- Mixing computable (string, QFT)
- Stueckelberg or Hidden Higgs masses

\[ \mathcal{L} = -\frac{1}{4} (F_{\mu \nu})^2 + j_{em}^\mu A_\mu + \frac{1}{2} \chi F^{\mu \nu} F'_{\mu \nu} - \frac{1}{4} (F'_{\mu \nu})^2 + \frac{1}{2} m_{\gamma'}^2 (A'_\mu)^2 \]

standard sector \quad \text{hidden sector}

kinetic mixing portal
Solar Hidden photons and the greatest blunder of my career

Production rate

\[ \Gamma(\gamma') = \text{Im} \frac{1}{K^2 - \Pi} \chi^2 m^4 \]

Vertex renormalisation

\[ \Gamma(\gamma') = \text{Im} \frac{Z}{K^2 - Z\Pi} \chi^2 m^4 \]

Transversely polarised

\[ \Gamma_T(\gamma') = \Gamma_T(\gamma) \frac{1}{(m_{\gamma'}^2 - \omega_P^2)^2 + (\omega\Gamma_T(\gamma))^2} \chi^2 m^4 \]

Longitudinally polarised

\[ \Gamma_L(\gamma') = \Gamma_T(\gamma) \frac{Z_L}{(\omega^2 - \omega_P^2)^2 + (\omega\Gamma_T(\gamma))^2} \chi^2 m^4 \]

\[ Z_L \approx \omega^2 / m_{\gamma'}^2 \]

huge enhancement at low m

I forgot this one
Solar Hidden photons and the greatest blunder of my career
The transverse flux (paper to come)

\[ \Gamma_T(\gamma') = \Gamma_T(\gamma) \frac{1}{(m_{\gamma'}^2 - \pi_r)^2 + (\omega \Gamma_T(\gamma))^2} \chi^2 m^4 \]

resonances just below the photosphere

Neutral atoms make \( \pi_r = \pi_r(\omega) \)

\[ \frac{\pi_i}{\omega} = \Gamma_T(\gamma) \]

\[ \pi_r = \pi_r(\omega) \]

\[ \rho = 5 \times 10^{-7} \text{ g/cm}^3 \]

\[ m_{e}^2 \text{[total]} \]

\[ m_{H}^0 \text{[free]} \]

\[ \omega [\text{eV}] = 0.5 \]

\[ \rho = 5 \times 10^{-7} \text{ g/cm}^3 \]
HP T flux, larger at low energies, search in the visible (infrared...)

Results (appear next week?)

New helioscopes for HPs?
Light shining through walls: The ALPS experiment

Okun ‘82 (search for paraphotons)

Sikivie ‘86 (for axion-like particles)

Axion-light Particle Search (later Any Light Particle Search) ALPS @ DESY
The Axion-like particles panorama improved a bit too...
ALPS useful for ‘non-standard models’ like mine but not sensitive to ‘standard’ axion-likes
Resonant regeneration: ALPS II

Cavities in the production and regeneration side (Hoogeveen, Tanner)

ALPS

ALPS-IIa (commissioning)

ALPS-IIb ?

ALPS-IIc ?

how to lock the second cavity without light?
Resonant regeneration: ALPS II

use double frequency light...

things became a bit more complicated...
Interlude: The low energy frontier (WISPs)
Beyond the SM

... at low energies

Energy

Answers are awaiting in the high energy frontier where more symmetric beautiful theories arise

... and often imply physics at low energies
Beyond the SM

Energy

... at low energies

Weakly Interacting Slim Particles
WISPs

Standard Model
Paradigmatic example: Strong CP problem

\[ \mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G^\mu\nu_a \tilde{G}_{a\mu\nu} \right\} \theta \]

Violates P and T

\[ \theta_{QCD} \in (-\pi, \pi) \]
\[ \arg \det M_q \sim \mathcal{O}(1) ? \]

 neutron EDM

Prediction:

\[ d_n \sim 10^{-15}\theta \text{ ecm} \]
Paradigmatic example: Strong CP problem

\[ \mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G^\mu_\nu \tilde{G}^\mu_\nu \right\} \theta \]

**Violates P and T**

\[ \theta_{\text{QCD}} \in (-\pi, \pi) \]

\[ \text{arg det } M_q \sim \mathcal{O}(1)? \]

**neutron EDM**

\[ d_n < 2.6 \times 10^{-26} \text{ ecm} \]

\[ \theta \lesssim 10^{-11} \]

**Non Observation:**

**Why ????**

**Prediction:**

\[ d_n \sim 10^{-15} \theta \text{ ecm} \]
Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a high energy scale, >>>>> TeV

**Massless Goldstone Boson: the axion**

\[
\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G_{a\mu\nu} \tilde{G}^{a\mu\nu} \right\} \left( \theta + \frac{a}{f_a} \right)
\]

**Free parameter**

The QCD induced potential is minimized for ...

\[
\theta_{\text{eff}} = \theta + \langle a \rangle \frac{1}{f_a} = 0
\]

**Peccei-Quinn Symmetry and the axion**
Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a high energy scale.

\[ \mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G_a^{\mu\nu} \tilde{G}_a^{\mu\nu} \right\} \left( \theta + \frac{\alpha}{f_a} \right) \]

Free parameter

The QCD induced potential is minimized for ...

\[ \theta_{\text{eff}} = \theta + \frac{\langle a \rangle}{f_a} = 0 \]

The axions adjust its v.e.v. to cancel the effects of any theta!
QCD axion mixes with mesons and gets its couplings

Typical from Nambu-Goldstone Bosons

Mass

\[ m_a \sim m_\pi \frac{f_\pi}{f_a} \sim 6 \text{ meV} \frac{10^9 \text{GeV}}{f_a} \]

Bare models

Extended models also feature couplings to leptons

WISPs
Axions and Axion-like particles ubiquitous BSM

Axion-like particles (ALPs) $0^-$

pseudo Goldstone bosons

Global continuous symmetry spontaneously broken at high energy scale $f$

String ‘axions’

Sizes and deformations of extra dimensions, gauge couplings

$\pi^0 \eta' \eta \alpha$

MAJORONS

R-AXION

FAMILONS

DILATONS

MODULI

RADION
Axion landscape, micro-eV and meV frontier
White dwarf cooling

M5 globular cluster

CAS A (neutron s)

they all cool faster than expected (just a trifle)

SN1987A

Diffuse SN axion background

IAXO

neutrino pulse ok

diffuse SN axion background

solar axions, Betelguese, axion DM? see Igor's talk!!!
microeV frontier

Axion dark matter

V_{QCD}

string contribution?

Cavity experiments

Dish antenna

New experiments

- LC circuits
- NMR spin precession
- Atomic transitions (Rydberg)
- 5th forces NMR

ADMX, ADMX-HF, Yale, WISPDMX, CARRACK, IAXO, RADES...
- There is a low energy frontier of fundamental particle physics

- Input from astrophysics and cosmology (stellar ev. DM, DR, DE, ...)

- Low energy, high precision experiments

- Plenty of things/experiments to do...

- Theory: WISP embedding, VQCD, DM abundance, inflation
- Experiment: pushing the frontier

- Axion very well motivated, also prime DM candidate