Axions, QED and Experiments

J. Gamboa

Departamento de Física
Universidad de Santiago de Chile

Zaragoza
June 7-12, 2009

- Adler's theory (S. L. Adler,*Ann. Phys.* **67**, 599 (1971)).
- Heavy excitations as axions (P. Arias, H. Falomir, F. Mendez and J. G. (*Mod. Phys. Lett.* **A24**, *1289 (2009)*).
- Light Shining through a wall setup: Theoretical analysis (S. L. Adler, J. Lopez-Sarrion, F. Mendez and J.G , *Ann. Phys.* **323**, 2851 (2008).
- Designing theoretically new experiments (S. L. Adler, J. Lopez-Sarrion, F. Mendez, P. Sikivie and J.G (in progress)).

plan

- Motivation
- Axions and bounds (QCD and cosmological axions)
- Vacuum Birefringence and QED
- Light shining through a wall: Theoretical analysis
- Heavy bosonic excitations on QED vacuum and experimental possibilities
- Polarization phenomena including axions contributions
- Conclusions

Motivation

- The axions were introduced as a solution to the strong CP problem in QCD (Peccei-Quinn, 1977)
- Axions as particles (Wilczek and Weinberg 1978) but with a very large mass (conflict with observations) (QCD)
- Axions should have a very small mass and coupling constant (invisible axions, P. Sikivie, 1982) and cosmological bounds suggest

$$g < 10^{-10}\mathrm{GeV}^{-1} \qquad\qquad m < 10^{-3}\mathrm{eV}.$$

How to implement technically the axion idea?
One start considering the scalar (or pseudoscalar field) φ coupled to A_μ,

$$\mathcal{L} = \mathcal{L}(\varphi, m^2) + \mathcal{L}(A) + g\varphi\tilde{F}F,$$

The coupling $g\varphi\tilde{F}F$ is known as Primakoff term (~ 1948) and it is reminiscent of the $\pi_0 \rightarrow 2\gamma$ decay!.

Vacuum Birefringence and QED

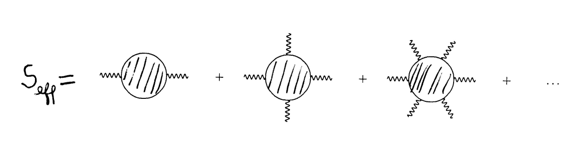
The Adler's theory is the quantum counterpart of a classical phenomenon (Cotton-Moutton effect, 1907).

- Photons pass through a magnetic field region are deviated (although the angle is tiny).
- In a quantum theory (QED), the vacuum could be magnetized with a $\Delta n \neq 0$.

What's the Adler idea? (see Brezin-Itzykson, 1968)

$$\mathbf{B} \rightarrow \mathbf{B} + \mathbf{B}_0,$$

where $\mathbf{B}_0$ (strong) external magnetic field and then one compute the effective Euler-Heisenberg action S_{eff} is



or equivalently

$$S_{eff} = \frac{1}{8\pi}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{e^4}{360\pi^2 m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + (\mathbf{E}\ .\ \mathbf{B})^2\right] + \dots$$

This result implies that :
If $\mathbf{E} \perp \mathbf{B}_0$

- $$n_\perp = 1 + \frac{2\alpha}{4\pi}\left(\frac{B_0}{B_{cri}}\right)^2$$

  where $B_{cri} = m^3c^3/\hbar e$.

If $\mathbf{E}||\mathbf{B}_0$

- $$n_{||} = 1 + \frac{7\alpha}{90\pi}\left(\frac{B_0}{B_{cri}}\right)^2$$

Therefore the refractive index is more larger than one and, therefore, in the presence of an external magnetic field light appears with a (slightly) reduced speed (birefringence).

For linear polarization one can show that

$$\psi = \pi \frac{L}{\lambda} \Delta n$$

where L is the path of lenght and ψ the **ellipticity** and

$$\Delta n = n_{||} - n_{\perp} = \frac{\alpha}{30\pi} \left(\frac{B_0}{B_{cri}} \right)^2,$$

In the experiments B_0 typically is 10T and

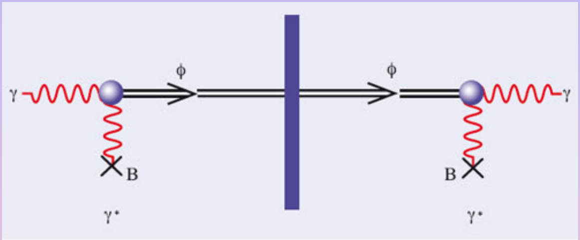
$$\Delta n \sim 10^{-23}$$

Problems

- Δn is four order of magnitude below the background birefringence (and probably negligible for QED).
- New results suggests new ingredients ...e.g coupling with axions (Maiani, Petronzio and Zavattini, 1986). MPZ suggested measure dichroism.
- But ...$\Delta n \leq 10^{-19}$ (BFRT and PVLAS).

Light Shining Through a Wall Setup

The standard setup was proposed by van Bibben et al (1986)



However one must into account the **thickness** of the magnetic region and the mirror, thus in the calculation of axion-photon conversion probability

- one distinguish 7 regions

The explicit calculation of photon-axion conversion probability gives

$$P = \frac{\beta^4 \sin^4\left(\frac{1}{2} mL\right)}{2m^3(\omega - m)}$$

where $\beta = g_{\gamma\varphi} B$.
It is evident that $P \to \infty$ when $\omega = m$.
This special case correspond to a enhancement of the probability. Let's introducing

$$q = \frac{\Delta}{\omega},$$

where Δ is the laser source bandwidth and q is, by definition, the quality factor of the source (laser).
Then

$$P = \frac{\beta^4}{2qm^4} \sin^4\left(\frac{mL}{2}\right) \log\left(\frac{2m^4 q}{\beta^4}\right),$$

For BOSONS at LULI project and BMV experiments (M. Fouche, et al. , arXiv:0808.2800 [hep-ex], *Phys. Rev.* **D78**, 032013 (2008).

They consider

$$m \sim 1.2eV, \quad L \sim 5 \times 10^6 \ eV,$$

then $m.L \sim 5 \times 10^6 \ eV$, therefore, $\sin^4$ oscillates very fast and one replace

$$P = \frac{\beta^4}{2qm^4} \log\left(\frac{2m^4 q}{\beta^4}\right),$$

For LULI and BOSONS project one find

- $P < 10^{-23}$ (from data of the experiments)
- $g_{\gamma\varphi} < 10^{-6}\mathrm{GeV}^{-1}$ which is very far from the standard axion ...people from BMV think that ALP different could be possible.

Heavy bosonic excitations on QED vacuum and experimental possibilities

One start by considering pseudocalar (φ) scalar (χ) fields coupled to the photon field and $\mathcal{G}$ and $\mathcal{F}$ are the invariants given by

$$\begin{aligned} \mathcal{F} &:= -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} = \tfrac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) , \\ \mathcal{G} &:= -\tfrac{1}{4} \widetilde{F}_{\mu\nu} F^{\mu\nu} = \mathbf{E}\cdot\mathbf{B} , \end{aligned} \qquad (1)$$

The conventional QED Lagrangian is replaced by the *total* Lagrangian

$$\mathcal{L} = \mathcal{F} + \bar{\psi}\left[\gamma^\mu \left(\imath\partial_\mu - eA_\mu\right) - m_e\right]\psi + \mathcal{L}_A + \mathcal{L}_S , \qquad (2)$$

where

$$\mathcal{L}_A = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{2}{m_A}^2\varphi^2 - g_A\,\varphi\,\mathcal{G} , \qquad (3)$$

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu\chi\,\partial^\mu\chi - \frac{1}{2}{m_S}^2\chi^2 - g_S\,\chi\,\mathcal{F} . \qquad (4)$$

One compute the effective action

$$\mathcal{L}_{HE} = \frac{e^4}{360\,\pi^2 m_e{}^4}\left\{4\mathcal{F}^2 + 7\mathcal{G}^2\right\} + \cdots . \qquad (5)$$

Since the pseudoscalar is linearly coupled to $\mathcal{G}$, one see that get

$$\int \mathcal{D}\varphi \, \exp\left\{-\frac{i}{2}\int d^4x \left[\varphi\left(\partial^2 + m_A{}^2\right)\varphi + 2g_A\,\varphi\,\mathcal{G}\right]\right\} =$$

$$= \left[\mathrm{Det}\left(\partial^2 + m_A{}^2\right)\right]^{-1/2} \exp\left\{\frac{i}{2}\,g_A^2 \int d^4x \int d^4y\,\mathcal{G}(x)\,K(x,y)\,\mathcal{G}(y)\right\}, \qquad (6)$$

where $K(x,y) = \left(\partial^2 + m_A{}^2\right)^{-1}(x,y)$.

The exponential in the right hand side represents a non-local term in the effective action which, in the infrared limit we will be interested in, admits the asymptotic gradient expansion

$$\frac{i}{2} \qquad g^2 \int d^4x \int d^4y\, \mathcal{G}(x)\, K(x,y)\, \mathcal{G}(y) = \frac{i g_A^2}{2 m_A^2} \sum_{n=0} \frac{(-1)^n}{m_A^{2n}} \times$$
$$\times \int d^4x\, \mathcal{G}(x)\, \partial^{2n}\, \mathcal{G}(x)\,, \qquad (7)$$

which is justified for $m_A \gg \omega$, where ω is an energy scale characteristic of the experiment under consideration.
Therefore, in this approximation, the effective Lagrangian for the electromagnetic field can be written as the (formally local) expression

$$\mathcal{L}_{eff} = \mathcal{F}(x) + \frac{e^4}{360\,\pi^2 {m_e}^4} \left\{ 4\mathcal{F}(x)^2 + 7\mathcal{G}(x)^2 \right\} + \qquad (8)$$
$$+ \frac{g_A^2}{2{m_A}^2} \sum_{n=0}^{\infty} \frac{(-1)^n}{m_A^{2n}} \mathcal{G}(x)\, \partial^{2n}\, \mathcal{G}(x)\,. \qquad (9)$$

Similarly, the coupling with a scalar field $\chi(x)$ as in Eq. (4) adds to the gradient expansion of the effective Lagrangian in Eq. (8) the piece

$$\triangle\mathcal{L}_{eff} = \frac{{g_S}^2}{2{m_S}^2}\sum_{n=0}^{\infty}\frac{(-1)^n}{m_S^{2n}}\,\mathcal{F}(x)\,\partial^{2n}\mathcal{F}(x)\,. \tag{10}$$

Therefore, we get

$$\begin{aligned}\mathcal{L}_{eff} = \mathcal{F}(x) + \frac{1}{2}\Bigg\{\Bigg[4\varrho\,\mathcal{F}(x)^2 + S\sum_{n=0}^{\infty}\frac{(-1)^n}{m_S^{2n}}\,\mathcal{F}(x)\,\partial^{2n}\mathcal{F}(x)\Bigg] + \\ + \Bigg[7\varrho\,\mathcal{G}(x)^2 + A\sum_{n=0}^{\infty}\frac{(-1)^n}{m_A^{2n}}\mathcal{G}(x)\,\partial^{2n}\,\mathcal{G}(x)\Bigg]\Bigg\}\,,\end{aligned} \tag{11}$$

where the parameters ρ, A and S are defined as

$$\varrho := \frac{e^4}{180\,\pi^2 {m_e}^4} = \frac{4\,\alpha^2}{45\,{m_e}^4}\,,$$

$$A := \frac{g_A^2}{{m_A}^2}\,, \tag{12}$$

$$S := \frac{g_S^2}{{m_S}^2}\,.$$

Polarization phenomena in axion-electromagnetic backgrounds

By using these results one can see the following

- $\Delta n = \Delta n_{QED}\left(1+\frac{A-S}{3\rho}\right)$
- For pseudoscalar particles

$$\frac{A}{3\rho} = \frac{15m^4 g^2}{4\alpha m^2} = (4.4 \times \mathrm{e}V^4) \times \left(\frac{g}{m}\right)^2 .$$

If $m \sim 10^{-3}$ eV and $g \sim 10^{-16}$ eV^{-1}, then

$$\Delta n_{QED} \sim 10^{-(21+22)}$$

i.e. could be in agreement with the Adler's calculation. .

- However the important thing is $\left(\frac{g}{m}\right)^2 = constant$

Conclusions

- Maybe axions could provide a solution to the infrared problem in QED (Bloch-Nordsieck is cumbersome!).
- Axions could be identified with paraphotons (i.e. a new class of gauge excitations) ...still it is an open problem (DESY ...).
- Several experiments are running in this moment but theoretical analysis still are necessaries.