

Polarization Measurements of Gamma Ray Bursts and Axion Like Particles

André Rubbia¹, Alexander Sakharov^{1,2}

¹Swiss Institute of Technology, ETH-Zürich, 8093 Zürich, Switzerland

²TH Division, PH Department, CERN, 1211 Geneva 23, Switzerland

DOI: http://dx.doi.org/10.3204/DESY-PROC-2008-02/sakharov_alexander

A polarized gamma ray emission spread over a sufficiently wide energy band from a strongly magnetized astrophysical object like gamma ray bursts (GRBs) offers an opportunity to test the hypothesis of axion like particles (ALPs). Based on evidences of polarized gamma ray emission detected in several gamma ray bursts we estimated the level of ALPs induced dichroism, which could take place in the magnetized fireball environment of a GRB. This allows to estimate the sensitivity of polarization measurements of GRBs to the ALP-photon coupling. This sensitivity $g_{a\gamma\gamma} \leq 2.2 \cdot 10^{-11} \text{ GeV}^{-1}$ calculated for the ALP mass $m_a = 10^{-3} \text{ eV}$ and MeV energy spread of gamma ray emission is competitive with the sensitivity of CAST and becomes even stronger for lower ALPs masses.

New very light spin-zero particles are predicted in many extensions of the Standard Model (see this proceedings for the references). Typically, such particles called axion like particles (ALPs) can arise as a result of a spontaneous breakdown of a continuous symmetry. A notable example of such breakdown is the Peccei-Quinn (PQ) mechanism [1], which remains perhaps the most natural solution to the CP problem in QCD. The most important phenomenological property of ALPs is their two-photon vertex interaction, which allows for ALP to photon conversion in the presence of an external electric and magnetic fields [2] through an interaction term

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma\gamma}\mathbf{E} \cdot \mathbf{B}a, \quad (1)$$

where a is the ALP field, F is the electromagnetic field strength tensor, $\tilde{F}$ its dual, $\mathbf{E}$, $\mathbf{B}$ the electric and magnetic fields respectively and $g_{a\gamma\gamma}$ is the ALP-photon coupling strength.

According to [3] the ALP-photon mixing (1) gives rise to vacuum dichroism. This dichroism results in the rotation of the polarization plane of an initially linearly polarized monochromatic beam by angle given in [3, 4]:

$$\epsilon = \frac{g_{a\gamma\gamma}^2 B^2 \omega^2}{m_a^2} \sin^2 \left(\frac{m_a^2 L}{4\omega} \right) \sin 2\phi. \quad (2)$$

It is valid for a uniform magnetic field $\mathbf{B}$ lying at a nonvanishing angle ϕ with the wave vector $\mathbf{k}$ of photons with frequency ω . Here m_a is the mass of ALP, L is the length of the magnetized

region. Such rotation, for instance, in case of ALPs, could be detected in a laser experiment like PVLAS [5, 6]. The validity of the approximation (2) is provided if the oscillation wavenumber

$$\Delta_{\text{osc}}^2 = \left(\frac{m_a^2 - \omega_{\text{pl}}}{2\omega} \right)^2 + B^2 g_{a\gamma\gamma}^2 \quad (3)$$

is dominated by the axion mass term. In fact, (3) pertains to the situation in which the beam propagates in a magnetized plasma, which gives rise to an effective photon mass set by the plasma frequency $\omega_{\text{pl}} = \sqrt{4\pi\alpha n_e/m_e} \simeq 3.7 \cdot 10^{-11} \sqrt{n_e/\text{cm}^{-3}} \text{ eV}$, where n_e is the electron density and m_e is the electron mass.

The polarization of the prompt gamma ray emission has been measured in four bright GRBs: GRB021206, GRB930131, GRB960924 and GRB041219a. The first measurements made in [7] with Ratan High Energy Solar Spectrometer Imager (RHESSI) satellite, found a linear polarization, $\Pi = (80 \pm 20)\%$, of the gamma rays from GRB021206 across the spectral window 0.15–2 MeV. The analysis techniques have been challenged in [8] and defended in [9]. Subsequent analyses made in [10] confirmed the results of [7] but at the lower level of significance. Later, in [11] the BATSE instrument on board of the Compton Gamma Ray Observatory (CGRO) has been used to measure, for two GRBs, the angular distribution of gamma rays back-scattered by the rim of the Earth’s atmosphere: $35\% \leq \Pi \leq 100\%$ for GRB930131 and $50\% \leq \Pi \leq 100\%$ for GRB960924. The analysis technique of [11] is only sensitive to the energy range 3–100 keV. Finally, the analysis [12] of GRB041219a across the spectral window 100–350 keV has been performed using coincidence events in the SPI (spectrometer on board of the INTEGRAL satellite) and IBIS (the Imager on Board of the INTEGRAL satellite). The polarization fraction of $\Pi = 96^{+39}_{-40}\%$ was determined for this GRB.

According to the Hillas [14] diagram showing size and magnetic field strengths of different astrophysical object the typical magnetic field in a GRB’s engine can be estimated as $B \simeq 10^9 \text{ G}$ over a region $L_{\text{GRB}} \simeq 10^9 \text{ cm}$. Moreover, the conservation of magnetic field energy at the rest wind frame of fireball shell model of the GRB’s engine [15] implies at any radial distance r , in the fireball environment, $4\pi r_0^2 B_0^2 = 4\pi r^2 B^2$, leading to the relation $B = B_0(r_0/r)$, where B_0 and r_0 are the magnetic field strength and the size of the central part of the fireball. The minimal time scale of variability of GRBs light curves is estimated to be about 0.1 sec¹. This implies that the typical extension of the GRB’s engine is indeed compatible with $L_{\text{GRB}} \approx 10^9 \text{ cm}$. Typically

¹See, for example, the analysis in [16].

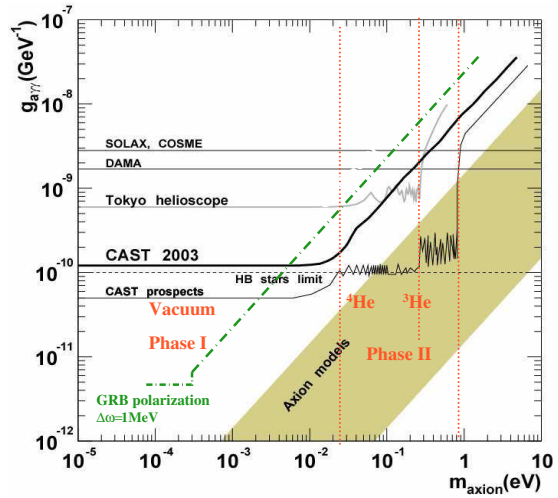


Figure 1: The plot of the regions of $(m_a, g_{a\gamma\gamma})$ space ruled out by various solar axion searches with the bound of the present letter, estimated for the inner part of the energy range 0.2–1.3 MeV applied for the polarization measurements of GRB021206 (dashed dotted line), superimposed.

the central part of the fireball can be represented by a neutron star of radius $r_0 \approx 10^6$ cm with magnetic field of $B_0 \approx 10^{12}$ G. Therefore the strength of the magnetic field at the distance $r = L_{GRB}$ corresponds to $B \approx 10^9$ G, which is in a good agreement with the values taken from [14].

According to (2), the relative misalignment between the polarization planes of gamma radiation at two different energies ω_1 and ω_2 induced by ALPs (see for details [17]) is given by

$$\Delta\epsilon = \frac{L_{GRB}}{2\pi} \frac{g_{a\gamma\gamma}^2}{m_a^2} \Delta\omega B^2, \quad (4)$$

where $\Delta\omega = |\omega_2 - \omega_1|$. Therefore, one can observe that the constraint arises from the fact that if the ALP dichroism induced rotation of polarization plane (4) in the given magnetic field were to differ by more than $\pi/2$ over the energy range 0.2-1.3 MeV, as in the case of GRB021206, the instantaneous polarization in the detector would fluctuate significantly for the net time averaged polarization of the signal to be suppressed. This condition can be transformed into the bound on the ALP-photon coupling as

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B\sqrt{\Delta\omega L_{GRB}}} \approx 2.2 \cdot 10^{-8} \frac{m_a}{1 \text{ eV}} (\text{GeV})^{-1}, \quad (5)$$

where the inner part of the spectral window 0.2-1.3 MeV ($\Delta\omega \approx 1\text{MeV}$) reported in polarization analysis of GRB021206 has been used. This constraint is obtained under the assumption that the correlation length of the magnetic field being initially defined by the typical size of the neutron star in the core of a GRB's engine is getting stretched out by the expansion of the fireball shell. So, at some moment of the expansion the correlation length becomes adjusted to the oscillation length. However, for the ALP's mass

$$m_a \leq m_{cr1} = \sqrt{\frac{2\pi\omega}{L_{GRB}}} \approx 3.5 \cdot 10^{-4} \text{ eV} \quad (6)$$

this condition does not hold anymore and the polarization planes misalignment angle should be calculated as

$$\Delta\epsilon = B^2 g_{a\gamma\gamma}^2 L_{GRB} \left(\frac{L_{GRB}}{16} - \frac{\omega_1}{2\pi m_a^2} \right). \quad (7)$$

The expression (7) holds to be positive down to the mass (see for details [17]): $m_{cr2} = 4\sqrt{\frac{\omega_1}{2\pi L_{GRB}}} \approx 8 \cdot 10^{-5} \text{ eV}$. Requiring again that the misalignment angle (7) does not exceed $\pi/2$ in the axion mass range between m_{cr1} and m_{cr2} one arrives to a bound, which can be well approximated by a constant ²

$$g_{a\gamma\gamma} \leq \frac{2\sqrt{2\pi}}{BL_{GRB}} \approx 5 \cdot 10^{-12} (\text{GeV})^{-1}. \quad (8)$$

In Fig. 1. we show the bounds (5) and (8) superimposed on the recent results of CAST [18] and other axion helioscope experiments [19]. The limit obtained becomes by factor $\sqrt{1\text{MeV}/\Delta\omega_{I,B}}$ weaker if we apply the width $\Delta\omega_I \approx 250 \text{ keV}$ of the energy bands for GRB041219a detected

²The electron number density in a GRB's environment can be estimated as $n_e \simeq 10^{10} \text{ cm}^{-3}$ [15]. Therefore the expression (3) is still ALP mass dominated down to $m_a \approx m_{cr}$ for the energy of the gamma radiation, $\omega \approx 1 \text{ MeV}$, and constraints on $g_{a\gamma\gamma}$ calculated from (5) and (8).

by INTEGRAL or $\Delta\omega_B \approx 100$ keV for GRB930131 and GRB960924 detected by BATSE. This implies that $g_{a\gamma\gamma} \leq 4.4 \cdot 10^{-11} \text{ GeV}^{-1}$ and $g_{a\gamma\gamma} \leq 6.9 \cdot 10^{-11} \text{ GeV}^{-1}$ for INTEGRAL and BATSE measurements respectively calculated for the axion mass $m_a = 10^{-3} \text{ eV}$.

An improvement of the current estimations could be archived in further detection of gamma polarized signals from GRBs in the similar or higher energy ranges. For these reasons the POLAR [20] experiment as well as other numerous efforts to develop instruments with the sensitivity required for astrophysical polarimetry over 100 eV to 10 GeV band [21] become important probes for ALPs beyond Standard Model physics.

We thank K. Zioutas, H. Hofer and N. Produit for useful discussions on CAST, POLAR and related topics.

References

- [1] R.D. Peccei and H. Quinn, Phys. Rev. Lett. **38** (1977) 1440
- [2] D. A. Dicus, E. W. Kolb, V. L. Teplitz and R. V. Wagoner, Phys. Rev. D **18** (1978) 1829; P. Sikivie, Phys. Rev. Lett. **51** (1983) 1415 [Erratum-ibid. **52** (1984) 695].
- [3] L. Maiani, R. Petronzio and E. Zavattini, Phys. Lett. B **175** (1986) 359.
- [4] P. Sikivie, Phys. Rev. Lett. **51** (1983) 1415 [Erratum-ibid. **52** (1984) 695]; G. Raffelt and L. Stodolsky, Phys. Rev. **37** (1988) 1237.
- [5] E. Zavattini *et al.* [PVLAS Collaboration], Phys. Rev. Lett. **96** (2006) 110406 [arXiv:hep-ex/0507107].
- [6] E. Zavattini *et al.* [PVLAS Collaboration], arXiv:0706.3419 [hep-ex].
- [7] W. Coburn and S.E. Boggs, Nature **423**, 415 (2003).
- [8] R. E. Rutledge and D. B. Fox, Mon. Not. Roy. Astron. Soc. **350** (2004) 1272 [arXiv:astro-ph/0310385].
- [9] S. E. Boggs and W. Coburn, arXiv:astro-ph/0310515.
- [10] C. Wigger, W. Hajdas, K. Arzner, M. Gudiel and A. Zehnder, Astrophys. J. **613** (2004) 1088 [arXiv:astro-ph/0405525].
- [11] D. R. Willis *et al.*, arXiv:astro-ph/0505097.
- [12] S. McGlynn *et al.*, arXiv:astro-ph/0702738.
- [13] S. E. Boggs, C. B. Wunderer, K. Hurley and W. Coburn, Astrophys. J. **611** (2004) L77 [arXiv:astro-ph/0310307].
- [14] A. M. Hillas, Ann. Rev. Astron. Astrophys. **22** (1984) 425; L. Anchordoqui, T. Paul, S. Reucroft and J. Swain, Int. J. Mod. Phys. A **18** (2003) 2229 [arXiv:hep-ph/0206072].
- [15] T. Piran, Phys. Rept. **314** (1999) 575 [arXiv:astro-ph/9810256].
- [16] J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos and A. S. Sakharov, Astron. Astrophys. **402** (2003) 409 [arXiv:astro-ph/0210124].
- [17] A. Rubbia and A. S. Sakharov, Astropart. Phys. **29** (2008) 20.
- [18] S. Andriamonje *et al.* [CAST Collaboration], JCAP **0704** (2007) 010 [arXiv:hep-ex/0702006]; K. Zioutas *et al.* [CAST Collaboration], Phys. Rev. Lett. **94** (2005) 121301 [arXiv:hep-ex/0411033].
- [19] For review see: R. Battesti *et al.*, arXiv:0705.0615 [hep-ex]; D. Lazarus *et al.*, Phys. Rev. Lett. **69** (1992) 2089; S. Moriyama *et al.*, Phys. Lett. **B434** (1998) 147; R. Bernabei *et al.*, Phys. Lett. **B515** (2001) 6; F.T. Avignone *et al.*, Phys. Rev. Lett. **81** (1998) 5068; R.J. Creswick *et al.*, Phys. Lett. **B427** (1998) 235.
- [20] N. Produit *et al.*, Nucl. Instrum. Meth. A **550** (2005) 616 [arXiv:astro-ph/0504605];
- [21] For reviews see: J.K. Black, 3rd Symposium on Large TPCs for Low Energy Rare Event Detectors, Journal of Physics, Conference Series **65** (2007) 012005; A. Curioni, Ph.D. Dissertation Thesis, Columbia University (2004), unpublished; A. Rubbia, J. Phys. Conf. Ser. **39**, 129 (2006) [arXiv:hep-ph/0510320].