Search for axion-like particles and hidden-sector photons in the resonant regeneration experiment SOLA

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Abstract

Photon mixing with new light scalars and pseudoscalars (axion-like particles, ALP), which are predicted in several extensions of the particle-physics Standard Model, may explain several astrophysical problems, in particular those related to long-distance propagation of energetic photons. Astrophysically motivated region of the ALP parameter space includes masses $m < 10^{-6}$ eV and ALP-photon couplings $1/M \sim (10^{-10}...10^{-11})\mathrm{GeV}^{-1}$. The project is sighted on search of ALP with such parameters and further limiting of parameter space with help of laboratory experiment of new kind realising the idea of resonant regeneration. It can allow us to achieve the best for laboratory experiment sensitivity in this range of masses.

1 Introduction

Project SOLA assumes research based on a new type of experiment on search of ALPs in laboratory. Such an experiment can advance sensitivity in 2,5-3 orders compared with existing setups with the same parameters (magnet field and length of conversion). Experiment is based on the idea of resonant regeneration and corresponds to classic scheme "light shining through wall" experiment supplemented with two synchronized cavities - before and after optical barrier. Idea of this experiment was offered in 2007 (Sikivie, Tanner,van Bibber) and was not realized because of difficulties in synchronization of resonators. But with help of colleagues in INFN (Triest) who have started developing a unique pilot project SOLA in 2009, we are planning to resolve this problem. Experiment consists of two Fabry-Perot cavities with length 50 cm inserted in magnet field about 2.2 T with system of cavities synchronization and photon detectors after second resonator. This allows us to achieve limit on reverse coupled constant $\sim 0.6 \cdot 10^8$ GeV with ALPs mass $m < 10^{-4}$ eV for cavity finesse about 10^5. It will be the best limit achieved in such an experiment. Planned increase of finesse leads us to even better constrains. It is supposed that developed in this project methods and engineering results can be used for full-scale experiment. Such an experiment will let us to search for ALPs with reverse coupled constant up to $3 \cdot 10^{10}$ GeV and will give us sensitivity exceeding astrophysical limits and will have a potential discovery of ALPs in astrophysically motivated field of parameters. In the network of this project we suggest to find optimal synchronization of two cavities to select method of detection of regenerated photons.

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2 Motivation

New light particles which could mix with photons are predicted by many extensions of the Standard Model of particle physics. The best known one is the axion, a pseudoscalar particle which is a crucial ingredient of the most popular solution of the $U(1)$ problem in quantum chromodynamics [1]. The effective lagrangian of axion-photon interactions contains a term which gives rise to mixing in the external magnetic field. The coupling constant $1/M$ in front of this term is expressed through the axion mass m in a model-dependent way; numerically model-to-model variations are not so large. A particle with the similar interactions but with arbitrary values of m and M is called axion-like particle (ALP). Scalar particles with photon-mixing term are often also called ALPs. These scalar and pseudoscalar particles appear as a natural consequence of many models which motivate the hierarchy of Standard-Model constants and/or unify quantum field theory and gravitation (string theories – e.g. [2], theories with extra dimensions – e.g. [3], models of supersymmetry breaking - e.g. [4]). Phenomenologically, it makes sense to consider two free parameters, m and M. There exist a series of unsolved problems in the modern high-energy (1 keV - 100 TeV) and ultra-high-energy (10^{18} eV – 10^{20} eV) astrophysics which are related to emission and propagation of photons:

(1) observation of photons with energies in excess of 100 GeV from distant (up to redshift > 0.5 [5]) blazars (the so-called "infrared-TeV crisis", see e.g. [6, 7]): observed spectra fail to agree simultaneously with reasonable mechanisms of the gamma-ray emission in sources and with realistic estimates of intergalactic infrared background on which TeV photons experience intense scattering;

(2) indications to the existence of neutral particles with energies $> 10^{18}$ eV arriving from cosmologically distant sources - BL Lac type objects - in the data of the High Resolution Fly's Eye experiment [8, 9]: the mean free path of known neutral particles with these energies is many times smaller than the distance to these sources;

(3) luminosity function of active galaxies [10];

(4) luminosity function of white dwarfs [11];

(5) large-scale correlations in orientations of polarization planes of quasar emission [12];

(6) excess of the solar X-ray radiation as compared to theoretical models [13];

(7) pulsed emission at dosens GeV from the Crab pulsar [14] which is difficult to explain in classical models of pulsar radiation;

(8) extended sources of cosmic rays at 10^{15} eV [15];

(9) excess of X-ray radiation and the electron-positron annihilation line from the Galactic Center region.

For the problems (1)–(3), quantitative explanations have been suggested which invoke photon mixing with a light ALP (1, Ref. [16]; 2, Ref. [17]; 3, Ref. [10]). In all three cases, the required ALP parameters are similar: mass $m < 10^{-6}$ eV, inverse coupling constant $M \sim (10^{10} - 10^{11})$ GeV. For the problems (4)–(6), qualitative explanations with ALP mixing have been proposed, but the required ALP parameters were not determined (except for a particular scenario for the problem (5), Ref. [18]). ALP mixing may also help to solve the problems (7)–(9).

For the problem (2), the axion explanation has a number of consequences testable in cosmic-ray physics. Search of primary ultra-high-energy photons is a nontrivial task, and only recently considerable progress has been achieved. One of the problems is related to the energy determination of the primary photons (see Ref. [19]). In particular, the largest modern experiment (the surface detector of the Pierre Auger observatory) underestimates photon energies by a factor of a few. The astrophysically motivated part of the parameter space is not constrained by any of the experiments: the coupling constant is weaker than the best CAST limit and is several orders of magnitude weaker than the best laboratory limits (see Fig. 1). A large-scale experiment motivated by axion solutions of the astrophysical problems (1) and (2) of the above list has been suggested in 2009 [22].

3 Method of resonant regeneration

We can see the principal scheme of classic "light shining through wall" experiment on search of ALPs at Fig. 2. Light from high power laser passes through strong magnetic field in which part of photons converts into ALPs. Wall between cavities lets only axions to pass through. Axions pass in second cavity and convert into photons in strong magnetic field after the wall. This photons are registered with photon detectors. Possibility of conversion is very small (for ALPs with mass m and reverse coupling constant $M = \frac{1}{\chi}$, L-length of region occupied with magnetic field, ω-laser frequency):

$$P_0 = [\frac{2\omega B_0}{M_a m_a^2} \sin \frac{m_a^2 L}{4\omega}]^4 \tag{1}$$

The idea of resonant regeneration is based on installing the second cavity after the wall and synchronize both of the cavities. Thus, accordingly to Sikivie, Tanner, van Bibber(2007) the possibility will be:

$$P = 2(F/\pi)^2 [\frac{2\omega B_0}{M_a m_a^2} \sin \frac{m_a^2 L}{4\omega}]^4 \tag{2}$$

Synchronization of two cavities is rather difficult. The group from INFN (Triest) solved this problem(see Fig. 3). For synchronization they use laser beam with doubled frequency(green) and for search for axions - main beam(red). Detector for registration of regenerated photons is sensitive only to main frequency.

4 Search for hidden-sector photons

With help of method of resonant regeneration we can also search for hidden-sector photons. Let us consider the simplest model with two U(1) gauge groups, one being our electromagnetic $U(1)_{QED}$, the other a hidden-sector $U(1)_h$, corresponding to paraphoton.

Using the same theoretical approach as for axion-like particles (only without magnetic field), we will achieve the possibility of photon-paraphoton oscillations in experiment with two Fabry-Perot cavities (Q_1, Q_2-finesses of the cavities):

$$P_{trans}^{max} \approx \chi^4 Q_1 Q_2 \tag{3}$$

The power output P_{out} of the detector cavity will be:

$$P_{out} = P_{trans} P_{in} \tag{4}$$

Let us calculate the amount of photons we can detect after the second Fabry-Perot in case of different P_{in}, maximal $\chi = 10^{-7}$ and $Q_{1,2} = 10^5$, $\lambda = 1064\,nm$. We calculate possibility of oscillations in case of maximal mixing, when $m_{\gamma'}^2 = 2\omega\pi/L$.

P_{in}	P_{trans}	P_{out}	Detected photons
$1W$	10^{-18}	$10^{-18}W$	5
$10W$	10^{-18}	$10^{-17}W$	52
$100W$	10^{-18}	$10^{-16}W$	529

5 Conclusions

- With help of the method of resonant regeneration we can also search for photon-paraphoton oscillations.
- It is supposed that developed in this project methods and its results can be used for a full-scale experiment using magnet from solar axion telescope from CAST ($9\,T$). Such an experiment will allow us to search for ALPs with reverse coupling constant $3 \cdot 10^{10}\, GeV$, thus will give us sensitivity exceeding astrophysical limits and we will have a potential discovery of ALPs in astronomically motivated field of parameters.

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References

[1] Peccei, Quinn 1977, Phys.Rev.Lett.38:1440

[2] Svrcek, Witten 2006, JHEP 0606:051

[3] Rubakov 2001, Phys. Uspekhi 171:913

[4] Gorbunov, Dubovsky, Troitsky, 1999, Phys. Uspekhi 169:705

[5] MAGIC collaboration 2007, Science 320:1752

[6] Protheroe, Meyer 2000, Phys.Lett.B493:1

[7] Aharonian et al. 2006, Nature 440:1018

[8] Gorbunov et al. 2004, JETP Letters 80:167

[9] HiRes collaboration 2005, Astrophys.J.636:680

[10] Burrage, Davis, Show, 2009, arXiv:0902.2320

[11] Isern et al. 2008, arXiv:0812.3043

[12] Payez, Cudell, Hutsemekers 2008, arXiv:0805.3946

[13] Zioutas et al. 2009, arXiv:0903.1807

[14] MAGIC collaboration 2008, Science 322:1221

[15] MILAGRO collaboration 2008, Phys.Rev.Lett.101:221101

[16] Simet, Hooper, Serpico, 2008, Phys.Rev.D77:063001

[17] Fairbairn, Rashba, Troitsky, 2009, arXiv:0901.4085

[18] Piotrovich, Gnedin, Natsvlishvili 2008, arXiv:0805.3649

[19] Kalashev, Rubtsov, Troitsky 2008, arXiv:0812.1020

[20] Harari et al. 2007, arXiv:0706.1715

[21] Troitsky 2008, Mon. Not. Roy. Astron. Soc. 388:L79

[22] Avignone, Creswick, Nussinov, 2009, arXiv:0903.4451

[23] Guido Mueller, Pierre Sikivie, Tanner, Karl van Bibber,2009, arXiv:0907.5387

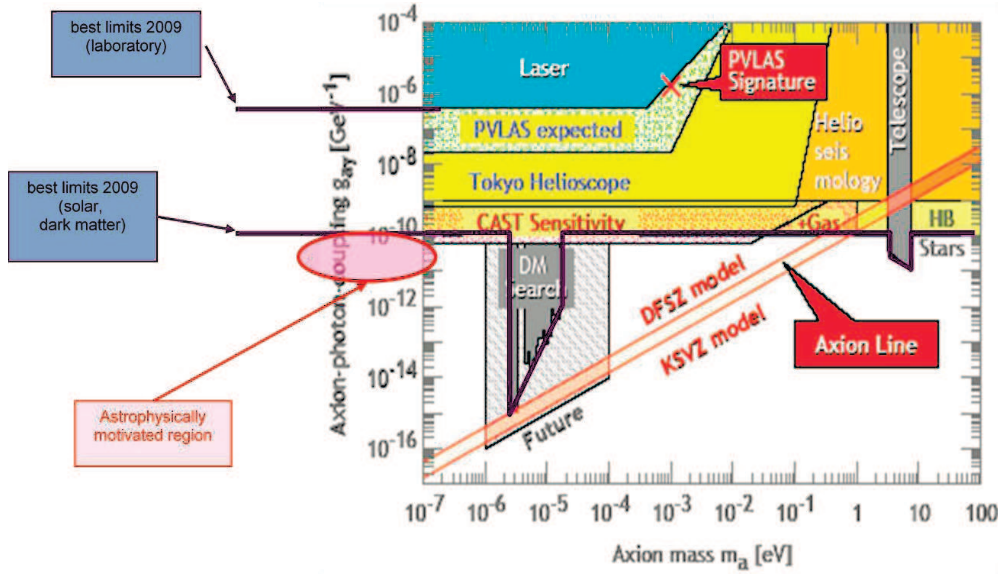

Figure 1: Parameter space of ALPs. The plot with constraints was taken from the webpage of G. Raffelt.

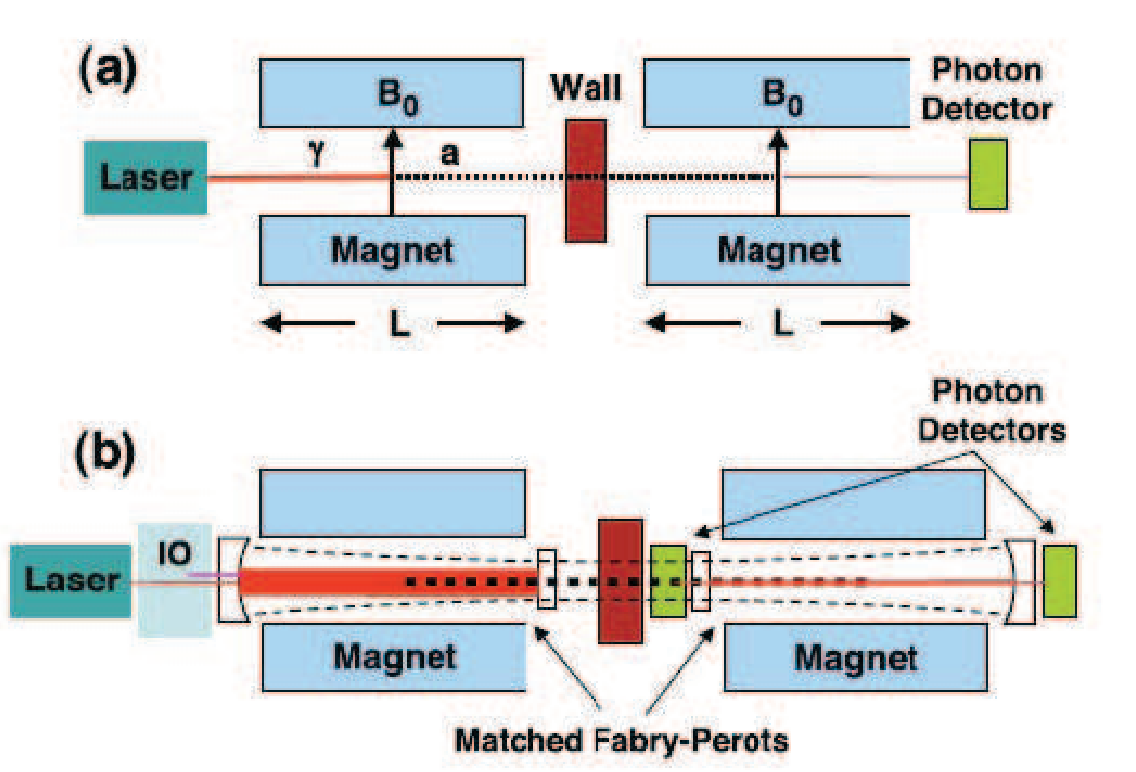

Figure 2: This figure was taken from article [23]

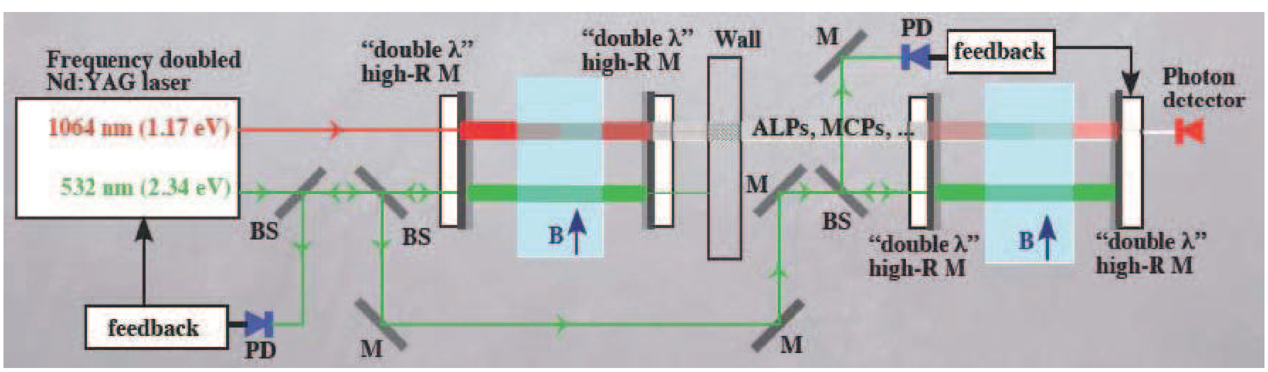

Figure 3: This figure was taken from the presentation of G. Cantatore, Talk at the 1st Axion Strategy Meeting, CERN, January 2008.