Status of CAST and Solar Chameleon searches

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CERN Axion Solar Telescope (CAST) is the most powerful axion helioscope searching for axions and axion-like particles produced in the Sun. CAST completed its search for solar axions with ^{3}He buffer gas in the magnet bores, covering axion masses up to 1.2 eV. In the absence of excess X-rays it has set the best experimental limit on the axion-photon coupling constant over a broad range of axion masses. In 2013 CAST has improved its sensitivity to solar axions with rest mass below 0.02 eV by using Micromegas detectors and it will continue in 2014 with the implementation of a second X-ray optic and a new type detector (InGrid). In 2013 CAST has extended its sensitivity into the sub-keV energy range using a silicon detector (SDD), to search for solar chameleons, extending its searches to the dark energy sector. This search will be continued in 2014 and 2015 as well with the InGrid detector. Future axion searches can improve the current axion sensitivity by 1 to 1.5 orders of magnitude with a new generation axion telescope (IAXO).

1 Introduction

Axions are stable pseudoscalars that arise from the compelling Peccei-Quinn mechanism [1] to solve the CP problem in quantum chromodynamics. Most of axion experimental searches rely on the axion coupling to two photons, allowing for axion-photon conversion in external electric or magnetic fields.

The CAST experiment is based on the axion helioscope technique [2], orienting a magnet towards the Sun. Axions could be generated in the solar center via the Primakoff effect: a photon converts into an axion in the presence of the electric field of a charged particle. The axion can be back-converted into a photon in the presence of a laboratory magnetic field. The differential solar axion flux at Earth is given by:

$$\frac{d\Phi_a}{dE_a} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 E_a^{2.481} e^{-E_a/1.205} \quad \left[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}\right] \ , \tag{1}$$

where $g_{a\gamma}$ is the axion-photon coupling constant, and E_a is the axion energy (the mean axion energy is 4.2 keV). The probability of axion-photon conversion in the general case of a uniform optical medium inside a transverse and homogeneous magnetic field, which extends for length L is [3]:

$$P_{a\to\gamma} = \left(\frac{B\, g_{a\gamma}}{2} \right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos(qL) \right] \ , \tag{2}$$

with Γ the inverse photon absorption length of the medium, and the momentum transfer q given by

$$q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right| \ , \tag{3}$$

with m_γ being the effective photon mass in the medium,

$$m_\gamma \left[\frac{\mathrm{eV}}{c^2} \right] = 28.77 \sqrt{\frac{Z}{A} \rho \left[\frac{\mathrm{g}}{\mathrm{cm}^3} \right]} \ , \tag{4}$$

given as a function of the density ρ, the atomic number Z and atomic mass A of the medium.

The conversion probability in Eq.(2) becomes maximum when the coherence condition $qL < \pi$ is satisfied. Therefore, the experimental sensitivity is restricted to a range of axion masses. If the medium inside the magnetic field is vacuum ($\Gamma = 0$, $m_\gamma = 0$), the sensitivity is limited to masses $m_a < \sqrt{2\pi E_a/L}$ (for the CAST experimental setup, $m_a < 0.02$ eV). In order to extend the sensitivity to higher axion masses, the conversion region has to be filled with a medium which provides an effective photon mass m_γ. As a result, the coherence is restored for a narrow mass window around $m_a = m_\gamma$.

The expected number of photons reaching an X-ray detector can be calculated as

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma} S\ t\ dE_a \quad , \tag{5}$$

where S is the effective area, and t the observation time.

2 Strategy and scientific program

The main component of the CAST experiment is the 10 m long, twin aperture LHC prototype dipole magnet, with the magnetic field of 9 T. The magnet is mounted on a moving platform which allows it to move it to follow the Sun for approximately 1.5 h during the sunrise and 1.5 h during the sunset, throughout the year. Four low-background X-ray detectors (until the end of 2012 three Micromegas and one pn-CCD/Telescope system [4]) are installed in each end of the cold bore tubes to identify the converted photons exclusively at times of alignment between the magnet and the core of the Sun (tracking), providing an axion signature. The remaining hours of the day the magnet stays idle and reference background measurements are taken.

The CAST experiment has been searching for solar axions since 2003. During 2003 and 2004, it operated with vacuum inside the magnet bores (Phase I). From the absence of excess of X-ray signal, while pointing to the Sun, it set the best experimental limit [5, 6] for the axion-photon coupling constant for axion masses up to 0.02 eV. To extend the sensitivity to higher axion masses, the experiment underwent a large upgrade in 2005 in order to operate with a buffer gas of variable density in the magnet bores (Phase II). The first part of Phase II was completed with ^{4}He as buffer gas. With 160 different pressure settings, CAST scanned the region of axion masses up to 0.39 eV, entering for the first time in the QCD axion model band in the electronvolt range [7]. In 2007 CAST upgraded again the buffer gas system, to accommodate ^{3}He as a buffer gas. In the second part of Phase II, which started in 2008 and finished in 2011, the range of axion masses up to 1.18 eV was scanned [8, 9]. Figure 1 shows the CAST published limits on the axion-photon coupling constant.

3 Status

In the period 2013 - 2015 CAST will revisit the vacuum phase to search for axion-like particles (ALPs) with improved detectors with very low background ($\sim 1\times10^{-6}$ s^{-1} cm^{-2} keV^{-1}). In addition, a new X-ray optics will be installed for the sunrise Micromegas line in 2014. The strategy for achieving low background detectors includes new electronics which provide more information (pulse shape analysis extended to every strip), a cosmic veto with 75% coverage in the sunset line, new shielding design and new generation Micromegas detectors specifically designed for CAST. All the detectors are calibrated in the variable energy X-ray generator line, in the PH-DT detector lab at CERN [10]. Additionally, CAST will continue searching for solar chameleons and axion-like particles, something that no other helioscope has undertaken before.

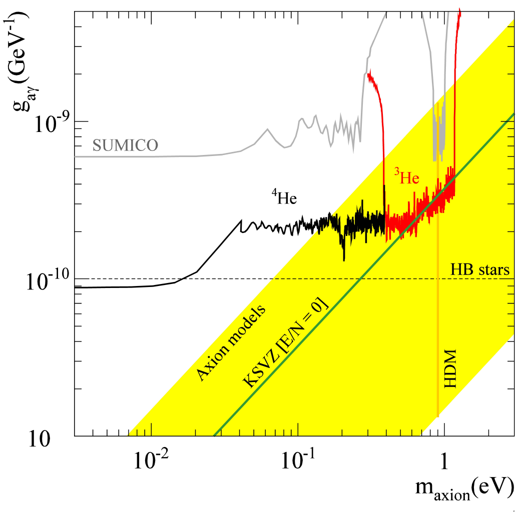

Figure 1: Exclusion regions in the $m_a - g_{a\gamma}$ plane achieved by CAST in the vacuum, ^{4}He, and ^{3}He phase. We also show constraints from the Tokyo helioscope (Sumico), horizontal branch (HB) stars, and the hot dark matter (HDM) limit. The yellow band represents typical theoretical models while the green solid line corresponds to the benchmark KSVZ model.

4 Chameleon searches

Chameleons are dark energy candidates to explain the accelerated expansion of the Universe. Their main characteristic is that their mass depends on the energy density of the environment. They can be created by the Primakoff effect in the presence of a strong magnetic field and can be converted to X-ray photons in CAST via the inverse Primakoff effect (like axions) [11].

In 2013 CAST extended its search to these dark energy particles. For this program, a windowless silicon drift detector (SDD) was chosen with high quantum efficiency, good energy resolution and a relatively large area. The detector collected 15.2 hours of tracking data and 108 hours of background in the energy range of interest from 400-1500 eV. The result of the data analysis is compatible with the null hypothesis. Figure 2 shows the expected number of counts in our detector, the subtracted counts (tracking - background) and the best fit to the data. The compatibility of the data with the absence of excess of X-rays allows the derivation of a preliminary limit to the chameleon to photon coupling constant, over a range of β_m from 1 to 10^6 (Figure 3):

$$\beta_\gamma \leq 9.20 \times 10^{10} \text{ at } 95\% \text{ CL.} \tag{6}$$

In 2014 and 2015, a new InGrid Micromegas detector will be installed on the sunrise side to search for chameleons and ALPs [13]. The effective area of the detector is 2 cm^2 , and the energy threshold well below 1 keV. It will work in combination with the existing X-ray telescope in CAST.

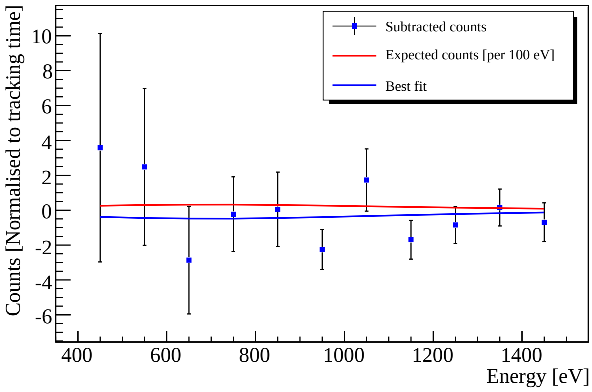

Figure 2: The expected number of photons from chameleon conversion inside the CAST magnet, that reaches the SDD is calculated from the theoretical photon spectrum arriving at the detector, from the conversion of chameleons, taking into account the total tracking time, the quantum efficiency of the detector, the magnetic length that the chameleons travel inside CAST, the absorption phenomena on the cold surface of the bSDD due to the absence of window and the area of the detector.

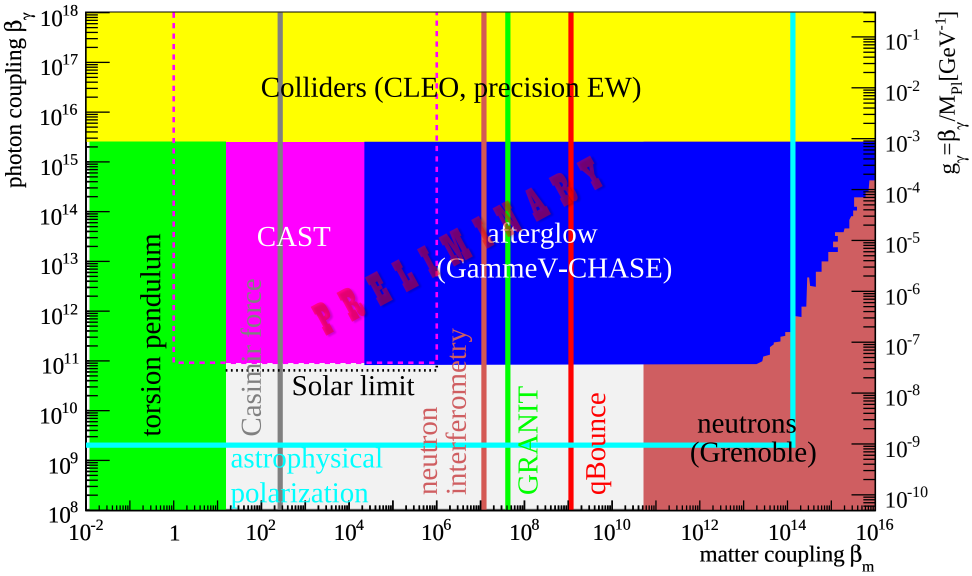

Figure 3: Constraints on the coupling of the chameleons to matter and photons [12]. The current constraints are shown as shaded regions and the future ones as solid lines. The preliminary result of CAST appears as a solid purple area. The black dashed line shows the solar limit whereas the dashed purple one shows the actual limits of sensitivity of CAST.

5 Future searches: CAST and beyond

In the following years the scientific program of CAST involves searches for chameleons and ALPs with improved sensitivity and also the R&D and feasibility study of new types of detectors like a Radiation Pressure detector, a Relic axion dish antenna and dielectric waveguide detectors destined to work inside the cold bores. In the first semester of 2017 CAST could be reconfigured to install Relic axion detectors. In addition a new generation axion telescope, IAXO (International AXion Observatory) [14] is currently at the level of the Conceptual Design. It will look for solar axions or ALPs with about 4-5 orders of magnitude higher sensitivity than CAST.

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