Status and Perspectives of the CAST Experiment

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CERN Axion Solar Telescope (CAST) is currently the most sensitive axion helioscope designed to search for axions and axion-like particles produced in the Sun. CAST is using a Large Hadron Collider prototype magnet where axions could be converted into X-rays. So far, no evidence of signal has been found and CAST set the best experimental limit on the axion-photon coupling constant over a broad range of axion masses up to ~ 1 eV.

1 Introduction

Axions are hypothetical particles arising in models which may solve the CP problem of strong interactions. The underlying Peccei-Quinn (PQ) mechanism [1] introduces a new global U(1) symmetry that is spontaneously broken at a large energy scale f_a. Axions are neutral pseudoscalars with phenomenology determined by the scale f_a. They generically couple to gluons and mix with neutral pions. The axion mass can be expressed in the form $m_a = m_\pi f_\pi / f_a = 6\ \mathrm{eV}(10^6\ \mathrm{GeV}/f_a)$, where m_π and f_π are the pion mass and decay constant, respectively. Axions couple to photons, nucleons and electrons. Most of the axion experimental searches rely on the axion interaction with two photons, allowing for axion-photon conversion in external electric or magnetic fields.

The CAST experiment is based on the axion helioscope technique [2] where a dipole magnet is oriented towards the Sun. Axions could be produced in the solar plasma via the Primakoff process, and back-converted into photons in a laboratory magnetic field. The expected solar axion flux at the Earth would have a continuous energy spectrum peaked near the mean energy $\langle E_a \rangle = 4.2$ keV and dying off above 10 keV. The expected number of photons (X-rays) reaching a detector is $N_\gamma = \int (d\Phi_a/dE_a) P_{a\to\gamma} S\, t\, dE_a$ where $(d\Phi_a/dE_a)$ is the differential axion flux at the Earth, $P_{a\to\gamma}$ the axion-photon conversion probablilty, S the effective area and t the measurement time. The axion-photon conversion probability in vacuum can be written as $P_{a\to\gamma} = (g_{a\gamma} B/q)^2 \sin^2(qL)$ where L is the magnet length, B the magnetic field and $q = m_a^2/2E_a$ the axion-photon momentum difference. The probability is maximal if the axion and photon remain in phase over the magnet length, i.e. when the coherence condition $qL < \pi$ is satisfied. As a consequence, the experimental sensitivity is restricted to a range of axion masses. In order to extend the sensitivity to higher axion masses, the conversion region has to be filled with a buffer gas which provides an effective photon mass.

The first implementation of the axion helioscope technique was performed in Brookhaven [3] and later a more sensitive search in Tokyo [4, 5, 6]. The most sensitive heliscope experiment CAST has been taking data since 2003, both with vacuum and gas (helium) inside the conversion region.

2 Experimental setup

CAST utilizes a Large Hadron Collider (LHC) prototype dipole magnet as the source of external magnetic field ($B = 9$ T). Inside the magnet there are two paralell pipes with the length $L = 9.26$ m and cross-sectional area $S = 2\times 14.5\ \mathrm{cm}^2$. The magnet is mounted on a rotating platform with $\pm 40^\circ$ horizontal and $\pm 8^\circ$ vertical movement. As a result, the Sun can be followed for about 1.5 hours both at sunrise and sunset during the whole year. At both ends of the magnet, different detectors are searching for X-rays coming from axion conversion inside the magnet when it is pointing to the Sun. The time the Sun is not reachable is used for background measurements. Two different X-ray detectors are used presently. Three Micromegas detectors [7, 8, 9] cover two bores on the sunset side and one of the bores of the sunrise side. A Charged Coupled Device (CCD) [10] is covering the other bore on the sunrise side. The CCD is working in combination with an X-ray telescope which can focus the photons to a few mm^2 spot, thus significantly improving the experimental sensitivity.

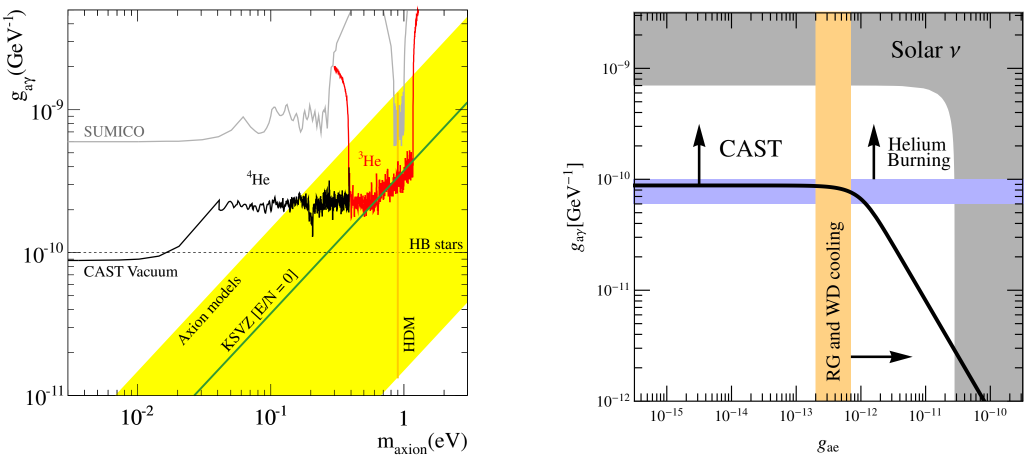

Figure 1: *Left*: Exclusion regions in the $m_a - g_{a\gamma}$ plane achieved by CAST in the vacuum, ^{4}He, first part of the ^{3}He phase and our new preliminary results (all in red). We also show constraints from the Tokyo helioscope (Sumico), horizontal branch (HB) stars, and the hot dark matter (HDM) bound. The yellow band represents typical theoretical models while the green solid line corresponds to the KSVZ model. *Right*: CAST constraints on g_{ae} and $g_{a\gamma}$ for $m_a \lesssim 10$ meV. The region above the thick black line is excluded by CAST. The gray region is excluded by solar neutrino measurements. In the vertical orange band, axion emission strongly affects white dwarf cooling and the evolution of low-mass red giants; the region to the right of this band is excluded. Likewise, helium-burning stars would be affected in the horizontal blue band; parameters above it are excluded.

3 CAST operation, results and prospects

The CAST experiment has been taking data since 2003. During 2003 and 2004 the experiment operated with vacuum inside the magnet bores, and set the best experimental limit on the axion-photon coupling constant for the axion mass range up to 0.02 eV [11, 12]. In order to extend the sensitivity to higher axion masses, the conversion region had to be filled with a buffer gas. By changing the pressure of the buffer gas in steps, one can scan an entire range of axion mass values. During 2005 and 2006 the magnet bores were filled with ^{4}He, and the range of axion masses up to 0.39 eV was scanned. For the first time, the obtained limit [13] entered the QCD axion model band in the electroweak range. From 2008 to 2011, with ^{3}He as the buffer gas, CAST covered the range of axion masses up to 1.18 eV. The results of the first part of ^{3}He data, with the sensitivity up to 0.64 eV, were published in [14]. Figure 1 (left) shows the CAST published limits on the axion-photon coupling constant for axion masses up to 0.64 eV, as well as the preliminary limit for masses up to 1.18 eV.

Apart from the main line of research, CAST has also performed searches from M1 nuclear transitions [15, 16] and low energy axions [17]. The most recent search investigated non-hadronic axion models, which have a tree-level axion-electron interaction. In these models, axions would be abundantly produced in the Sun via bremsstrahlung, Compton scattering, and axio-recombination. Figure 1 (right) shows the obtained constraints [18] on the axion-electron (g_{ae}) and axion-photon coupling constant ($g_{a\gamma}$) for the range of axion masses up to 0.01 eV.

In the immediate future, CAST is planning to revisit the vacuum phase with significantly improved low-background Micromegas detectors and new X-ray optics for the sunrise Micromegas. With the improved sensitivity, CAST will be able to scan a new region of the parameter space searching for axion-like particles. These particles appear in many extensions of the standard model (including string theory) and are viable candidates for the dark matter of the universe. In parallel, CAST will be able to search for other proposed particles at the low energy frontier, like hidden photons or chameleons.

The challenge for the long-term future is to move down in the $m_a - g_{a\gamma}$ parameter space. This goal could be achieved with significant improvements of magnet and detector properties, and extensive use of X-ray optics [19]. A new generation of axion helioscope, IAXO (International AXion Observatory), is currently at the level of the Conceptual Design.

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References

[1] R. D. Peccei, Lect. Notes Phys. **741**, 3 (2008) [hep-ph/0607268].

[2] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983) [Erratum-ibid. **52**, 695 (1984)].

[3] D. M. Lazarus *et al.*, Phys. Rev. Lett. **69**, 2333 (1992).

[4] S. Moriyama *et al.*, Phys. Lett. B **434**, 147 (1998) [hep-ex/9805026].

[5] Y. Inoue *et al.*, Phys. Lett. B **536**, 18 (2002) [astro-ph/0204388].

[6] Y. Inoue *et al.*, Phys. Lett. B **668**, 93 (2008) [arXiv:0806.2230 [astro-ph]].

[7] P. Abbon *et al.*, New J. Phys. **9**, 170 (2007) [physics/0702190].

[8] S. Aune *et al.*, J. Phys. Conf. Ser. **179**, 012015 (2009).

[9] T. Dafni *et al.*, Nucl. Instrum. Meth. A **628**, 172 (2011).

[10] M. Kuster *et al.*, New J. Phys. **9**, 169 (2007) [physics/0702188].

[11] K. Zioutas *et al.* [CAST Collaboration], Phys. Rev. Lett. **94**, 121301 (2005) [hep-ex/0411033].

[12] S. Andriamonje *et al.* [CAST Collaboration], JCAP **0704**, 010 (2007) [hep-ex/0702006].

[13] E. Arik *et al.* [CAST Collaboration], JCAP **0902**, 008 (2009) [arXiv:0810.4482 [hep-ex]].

[14] M. Arik *et al.* [CAST Collaboration], Phys. Rev. Lett. **107**, 261302 (2011) [arXiv:1106.3919 [hep-ex]].

[15] S. Andriamonje *et al.* [CAST Collaboration], JCAP **0912**, 002 (2009) [arXiv:0906.4488 [hep-ex]].

[16] S. Andriamonje *et al.* [CAST Collaboration], JCAP **1003**, 032 (2010) [arXiv:0904.2103 [hep-ex]].

[17] G. Cantatore *et al.* [CAST Collaboration], arXiv:0809.4581 [hep-ex].

[18] K. Barth *et al.*, JCAP **1305**, 010 (2013) [arXiv:1302.6283 [astro-ph.SR]].

[19] I. G. Irastorza *et al.*, JCAP **1106**, 013 (2011) [arXiv:1103.5334 [hep-ex]].