CAST – A CERN EXPERIMENT TO SEARCH FOR SOLAR AXIONS

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Abstract. The CAST experiment at CERN is the only running solar axion telescope. The first results obtained so far with CAST – PHASE I is presented, which compete with the best astrophysically derived limits of the axion-to-photon coupling. The ongoing PHASE II of the experiment as well as the scheduled upgrades, which improve the axion discovery potential of CAST, are discussed.

Keywords: axion, dark matter, solar particles and photons.
PACS: 14.80.Mz, 95.35.+d, 96.50.Vg

QCD predicts the existence of a CP violating term in the standard equations which does not agree with any experiment. For example, the neutron electric dipole moment is expected to be ~10 orders of magnitude larger than its measured upper limit. Axions were proposed to solve this so-called strong CP problem. Introducing an additional global Peccei-Quinn (PQ) symmetry [1] solves the strong CP problem. To break this symmetry spontaneously at some energy scale $f_{\mathrm{PQ}} > 10^7$ GeV, an associated pseudo-scalar boson (axion) is needed [2]. Axion coupling to particles is inversely proportional to f_{PQ}. The mass of the axion is given by

$$m_{PQ} = 6\,\mathrm{eV}\,\frac{10^6 GeV}{f_{PQ}}. \qquad (1)$$

Axion-photon coupling, via the Primakoff process [3], has the form: $g_{a\gamma}(\vec{E}.\vec{B})a$ where $g_{a\gamma} \sim \frac{\alpha}{2\pi\, f_{PQ}}$.

WMAP data [4] reveals that the content of the universe is 4% atoms, the building blocks of stars and planets, 22% dark matter, 74% dark energy. Dark matter, does not emit or absorb light. It has only been detected indirectly by its gravity. Most of the mass of the Milky Way is contributed by its halo, presumably in the form of non-interacting dark matter. Owing to their potential abundance in the early universe, axions are the best candidates for cold dark matter. Dark energy, that acts as a sort of an anti-gravity, is responsible for the present-day acceleration.

CP899, *Sixth International Conference of the Balkan Physical Union,* edited by S. A. Cetin and I. Hikmet

Photons converting into axions in the extragalactic magnetic fields may be altering our astronomical observations. Axions can modify the apparent brightness of distant astronomical sources which may be an alternative scenario to the accelerating universe model. There is a mysterious X-ray glow that surrounds the sun. Surface of the sun is not hot enough to produce such X-ray glow. This may be an evidence for the existence of axions [5].

Several axion models exist. They all agree that it is a neutral, spin-parity 0^-, very light particle, interacting very weakly with ordinary matter. Cosmological and astrophysical considerations give some constraints on the axion mass and couplings to fermions, nucleons and photons. According to these bounds, axions are allowed to exist only in the mass range of meV to some tens of meV. Sun should be a source of axions, similar to solar neutrinos in flux.

CAST [6] is designed to detect axions produced in the sun via the Primakoff process. The detection mechanism also relies on the same effect [7]. The Primakoff effect is basically the conversion of an axion into a photon and vice versa in a strong magnetic field (see Fig. 1). The conversion probability for axions is proportional to $(BL)^2$ where B is the transverse magnetic field and L is the conversion region length. In CAST, B = 9 T field is produced by a superconducting, prototype LHC magnet (at 1.8 K) with two parallel pipes of L = 9.26 m length, 43 mm diameter each.

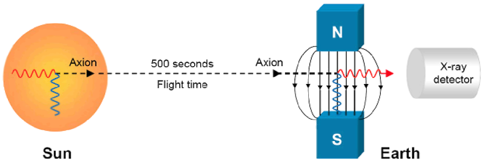

FIGURE 1. Conversion and detection of solar axions.

X-rays are detected at the two ends of the magnet by background optimized X-ray detectors: TPC (Time Projection Chamber) covering the one end of the pipes, MicroMEGAS (μM) and CCD coupled with an X-ray telescope covering the other end of the pipes. Figure 2 shows a schematic view of the CAST experimental setup.

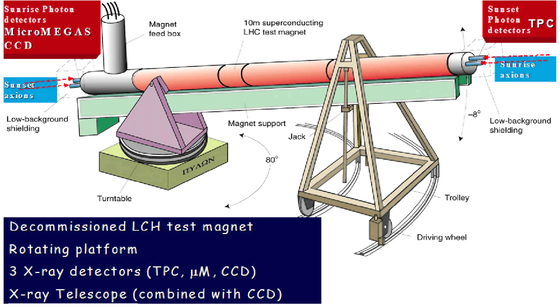

FIGURE 2. Schematic view of the CAST experiment.

The magnet is mounted on a platform with ±8° vertical movement, ±40° horizontal movement, allowing for observation of the sun for 1.5 h both at sunrise and sunset. The time the sun is not reachable is devoted to background measurements. X-ray telescope (XRT) with a CCD camera and μM detector, each occupying one bore at one end of the magnet, look for sunrise axions TPC, occupying both bores on the other end, looks for sunset axions. The actual layout of the experiment is seen in Fig. 3.

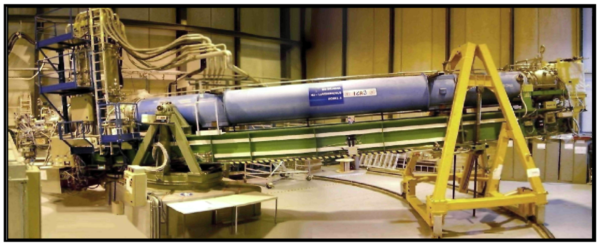

FIGURE 3. Detector system of the CAST experiment.

The XRT is a spare unit from ABRIXAS space mission. It has 1.7 m focal length, consists of 27 nested gold coated nickel mirror shells with 35% transmission. As seen in Fig. 3, only one sector of the full aperture (16 cm) is used for the CAST magnet. It focuses the sun spot to ~ $6 mm^2$ spot on the CCD. The CCD has an excellent energy and space resolution (< 0.5 keV, pixel size: 150 μm x 150 μm). It has ~100% efficiency over the full energy range.

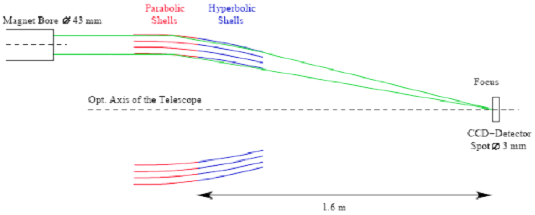

FIGURE 4. XRT and CCD coupling to the magnet bore.

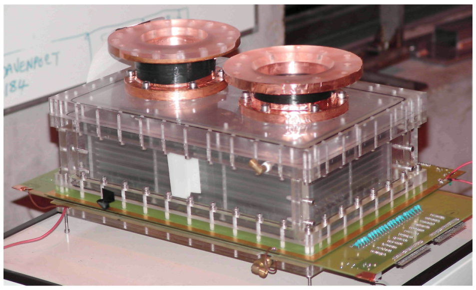

FIGURE 5. The TPC used in CAST experiment.

The TPC (see Fig. 5) is a conventional gas (Ar) chamber with 48 anode wires (x) and 96 cathode wires

(y) with 3mm spacing. Figure 6 shows the principle of photon detection with TPC.

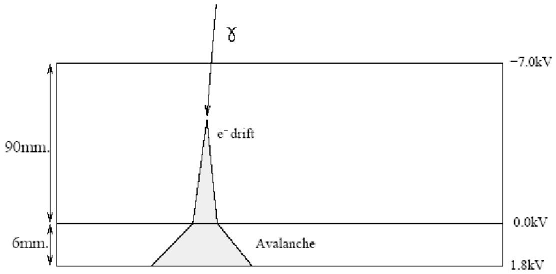

FIGURE 6. Conversion of a photon in the TPC.

The μM is also a gas chamber (95% Ar with 5% Isobutane). It has 192 charge collection strips in x and in y which are read out individually. (see Figs. 7-10).

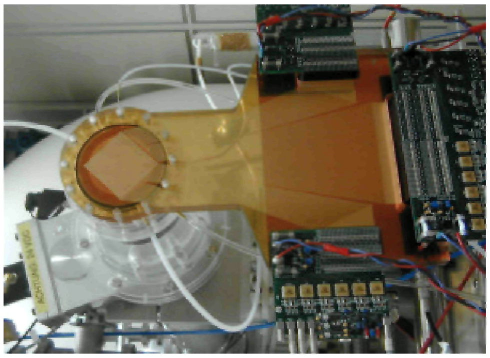

FIGURE 7. The μM and its readout electronics.

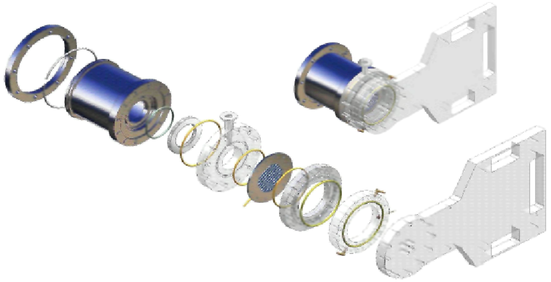

FIGURE 8. Assembly of the μM chamber.

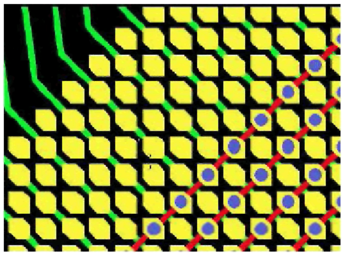

FIGURE 9. The strip geometry of the μM chamber.

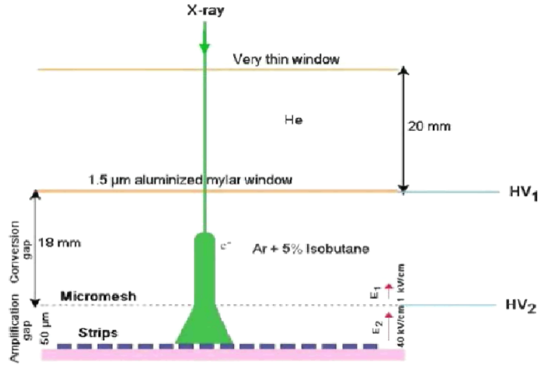

FIGURE 10. Conversion of a photon in the μM chamber.

GRID measurements, done with the surveyors of CERN, define the position of the magnet and XRT at ~ 100 points (cold and warm). The tracking system is calibrated and correlated with celestial coordinates. In March and September, the sun can be observed with an optical telescope through the small window of the building, and it is filmed for alignment cross check.

Figure 11 shows the expected solar axion flux [8] at the earth as a function of energy. The total flux is estimated as

$$\Phi_a = (g_{10})^2 \, 3.8\times10^{11}\,\mathrm{cm^{-2}s^{-1}} \tag{2}$$

where $g_{10} \equiv g_{a\gamma} \times 10^{10}\,\mathrm{GeV}$. The axion-photon conversion probability is given by

$$P_{a\gamma} = 1.74\times10^{-17}\left(\frac{B}{9.0T}\right)^2\left(\frac{L}{9.26m}\right)^2 g_{10}^2\,|M|^2 \tag{3}$$

where the matrix element squared becomes unity in case of coherence ($qL << 1$):

$$|M|^2 = \left(\frac{\sin(qL/2)}{(qL/2)}\right)^2 \to 1 \;\cdot \tag{4}$$

The difference between photon and axion momenta is $q = p_\gamma - \sqrt{\omega^2 - m_a^2} \approx p_\gamma - \omega + \frac{m_a^2}{2\omega} = \frac{m_a^2}{2\omega}$ in vacuum ($p_\gamma = \omega = E_a$). In order to have coherence, the phase difference qL should be less than π. Expected number of conversion photons at an area S in time t will be

$$N_\gamma \approx (g_{10})^4\left(\frac{B}{9.0T}\right)^2\left(\frac{L}{9.26m}\right)^2 St\times(0.51)\ \mathrm{cm^{-2}d^{-1}}.$$

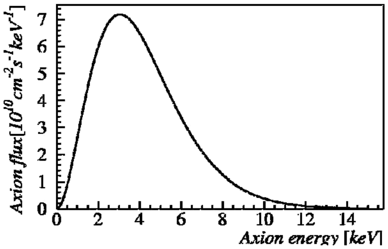

FIGURE 11. Axion flux spectrum at the Earth.

In vacuum, coherence is lost for $m_a > 10^{-2}$ eV. In order to scan higher mass values, one needs to use He gas instead of vacuum. Photon's speed in He is smaller than c, $p_\gamma \neq \omega$ and it gains an effective mass m_γ. The momentum difference becomes $q \approx \frac{|m_a^2 - m_\gamma^2|}{2\omega}$ where $m_\gamma \approx \sqrt{0.02\frac{p(mbar)}{T(K)}}$ can be increased by increasing He pressure and still keeping $qL << 1$. This allows CAST to scan axion masses up to 0.4 eV with ^{4}He, up to 0.8 eV with ^{3}He.

Figure 12 illustrates evolution of the experiment. During PHASE I there was vacuum inside the magnet. In PHASE II the conversion region is filled with He gas.

The analysis of 2003 data showed no axion signal above background and set a new upper limit on the axion-photon coupling: $g_{a\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} [9].

In 2004, there were many detector improvements to reduce the background and improve the data quality. 2004 data was 1.5 – 3 times more than the 2003 data and no axion signal was obseerved. The preliminary value of the upper limit set on the coupling is $g_{a\gamma} < 0.9 \times 10^{-10}$ GeV^{-1} for $m_a < 0.02$ eV (see Fig.13).

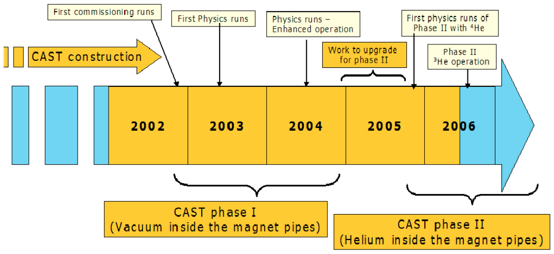

FIGURE 12. The history and the future plans of CAST.

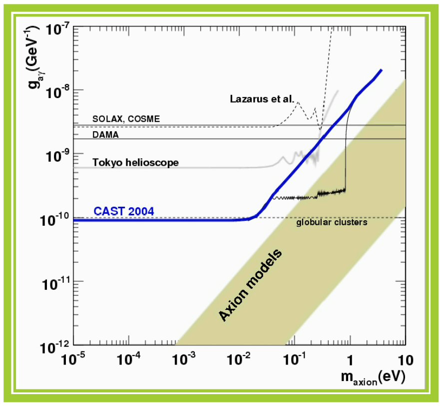

FIGURE 13. 95% CL exclusion limit from the 2004 data.

In preparation for PHASE II, special windows (15 µm polyproplene thin film on strongback) were installed to seal the He inside the magnet pipes (see Figs. 14-15). A new gas system is designed to control the pressure and temperature of He. PHASE II data taking started in November 2005. Initially the magnet pipes were filled with ^{4}He. Starting in 2007, the magnet pipes will be filled with ^{3}He. The gas pressure, increasing from 0 to 60 mbar (at T = 1.8 K) in 0.083 mbar steps, enables CAST to cover axion masses up to ~ 0.8 eV, CAST is the first laboratory experiment to probe the favoured region by the theory as seen in Fig. 16.

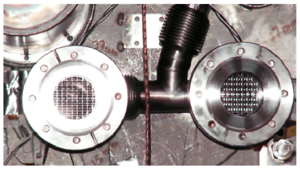

FIGURE 14. Cold windows installed at one end of the pipes.

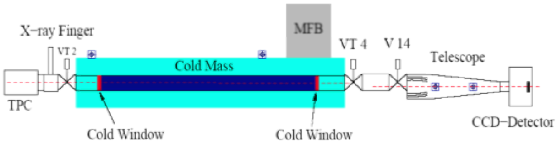

FIGURE 15. The side view of one of the pipes with cold windows.

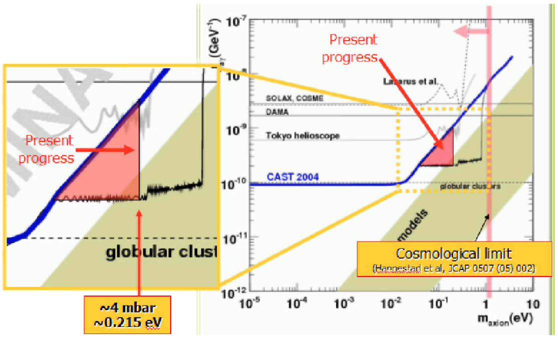

FIGURE 16. Present status of the exclusion limit set by the CAST PHASE II data.

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