



Recent constraints on axion-photon and axion-electron coupling with the CAST experiment.

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Abstract

The CERN Axion Solar Telescope (CAST) is a helioscope looking for axions arising from the solar core plasma and arriving to Earth. The experiment, located in Geneva (Switzerland) is able to follow the Sun during sunrise and sunset. Four x-ray detectors mounted on both ends of the magnet wait for photons from axion-to-photon conversion due to the Primakoff effect. Up to date, with the completion of Phases I and II, CAST has been looking for axions that could be produced in the Sun by both, hadronic and non-hadronic mechanisms.

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1. Helioscopes axion searches

The strong CP-problem of QCD might be solved by the introduction of a symmetry that leads to the existence of a new pseudo-scalar particle [1]. The physics case of helioscopes has been mainly focused on hadronic axions [2, 3] which are appealing as hot dark matter candidates [4]. Hadronic axions are minimal models where the axion gets its generic interactions with hadrons and photons. The interaction with leptons arises at further loop level [5] and is usually irrelevant. In hadronic models, the bulk of the solar axion flux comes from Primakoff production $\gamma + Z \rightarrow a + Z$ [6, 7, 8], involving the two-photon coupling that also accounts for the detection channel in CAST.

Recently, non-minimal axion and ALP models are receiving increasing attention. For instance, the White Dwarf (WD) cooling hypothesis relies solely on the axion-electron coupling. Non-hadronic axion models have a tree-level axion-electron interaction. In such scenario, the Sun would produce a strong axion flux by bremsstrahlung, Compton scattering, and axio-recombination, the “BCA processes.” Non-hadronic axion models such as that of DFSZ [9, 10] have different and very interesting phenomenological consequences.

2. The CAST experiment

Four x-ray detectors are mounted on both sides of the magnet. Each one of them is aligned daily with the solar core during 1.5 hours expecting photons originating from axion-to-photon conversion due to the

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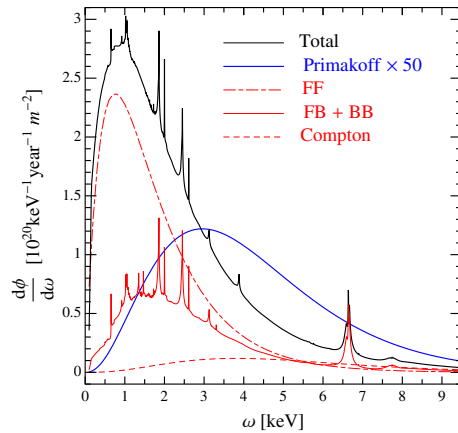


Fig. 1. Solar axion flux on Earth for a typical DFSZ model with interaction strength to photons $g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}$ and electrons $g_{ae} = 10^{-13}$. The blue solid line corresponds to the Primakoff flux and the red lines show the different components of the BCA flux: dash-dotted line (FF = bremsstrahlung), solid line (FB = axio-recombination and BB = axio-deexcitation) and dotted line (Compton). The black solid line is the total flux for non-hadronic models to compare with the solid blue line that is 50 times the total flux for the hadronic models.

Primakoff effect inside its magnet. The detectors are: one sunrise and two sunset MICROMEAS [11], the later two replacing the previously used Time Projection Chamber [12], and a Charge Coupled Device [13] together with an x-ray telescope that improves the signal to background ratio by a factor of about 200 for this detector. The axion flux arriving at CAST is shown in Figure 1.

To extend the experimental sensitivity to larger masses, during its second phase, the conversion region of CAST is filled with a suitable buffer gas, providing the photons with an effective mass m_γ [17], and the axion band for which Primakoff based helioscope experiments are sensitive can be extracted from the coherence condition

$$\left(\frac{m_a^2}{eV^2}\right) \ll \left(\frac{m_\gamma^2}{eV^2}\right) + 2 \cdot \left(\frac{E_a/eV}{L \cdot eV}\right) \quad (1)$$

so that for axion masses m_a in the neighborhood of the chosen effective photon mass m_γ the sensitivity is restored for a magnet of length L . The cryogenic nature of the CAST magnet makes helium-3 and helium-4 suitable gases for the purpose. The CAST data taking procedure stepped ramping over different densities of gas filling the cold bore in order to allow the search of different axion masses.

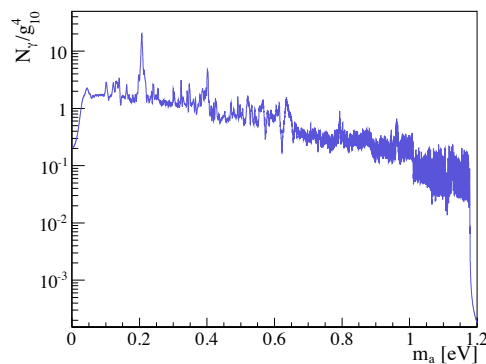


Fig. 2. Effective exposure of CAST to the different axion masses after gravitational and convection effects are taken into consideration.

Achieving the desired density is a challenging task that required computational fluid dynamic simulations of the actual system. Under extreme conditions, like high pressures and extremely low temperatures, helium-3 and helium-4 gases follow the Peng-Robison equation of state. Its use is extended in thermodynamic applications and it is best suited to accurately describe the actual conditions at CAST. Tilting a 10 m magnet full of helium while tracking the Sun has also some consequences on the effective photon mass the experiment is tuned for. Gravitational forces are capable of generating a gradient of densities in the gas column of the magnet region. Such an effect can be corrected by applying an effective density to the whole column, since the movement of the system is symmetric around the polar angle. The expected photons arising from the Primakoff conversion inside the magnet of CAST can be accurately calculated by taking into account the exposure to the Sun together with the instant pressure in the coldbore at different inclinations (see Figure 2).

3. Latest results of CAST

At present, the experiment looked for hadronic-axions with masses up to 1.16 eV. CAST began operation in 2003 and after two years of data taking (Phase I) with vacuum inside the magnet bores achieved a limit of $g_{a\gamma} \lesssim 0.88 \times 10^{-10} \text{ GeV}^{-1}$ at 95 % CL for $m_a \lesssim 0.02 \text{ eV}/c^2$ [15, 16]. CAST analysis for masses up to 0.65 eV was published in [21] and the data analysis for axion masses up to 1.16 eV has been recently published [22]. Refer to the left plot of Figure 3 for the hadronic axion model limits.

CAST has also looked into the non-hadronic axion models and has already extracted limits on the axion-electron Yukawa coupling g_{ae} using the CAST Phase I data [14]. See the right plot of figure 3 for the non-hadronic axion model limits.

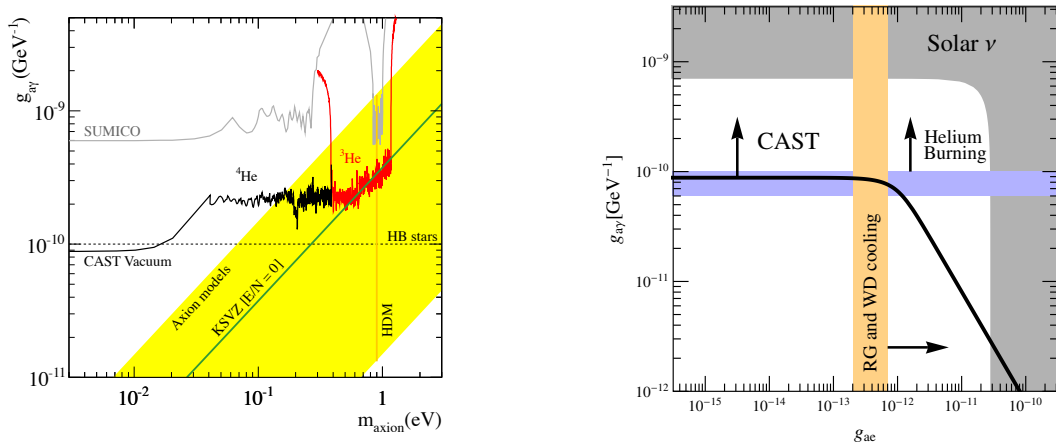


Fig. 3. Left: CAST exclusion plot of the axion-to-photon coupling constant at 95% CL for all data collected in Phase I and Phase II. The achieved limit of CAST is compared with the Horizontal Branch (HB) star limit [18]. The yellow band represents the theoretical QCD axion models and the green solid line corresponds to the KSVZ model with $E/N = 0$. Right: Constraints on g_{ae} and $g_{a\gamma}$ for $m_a \lesssim 10 \text{ meV}$. 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; parameters to the right of this band are excluded. Likewise, helium-burning stars would be perceptibly affected in the horizontal blue band; parameters above it are excluded.

4. Conclusions and outlook

The final results for hadronic axion models in vacuum, helium-4 and helium-3 are displayed in Fig.3 together with the results for non-hadronic axions. Currently, CAST is extending its axion search even further into the unexplored regions of favored axion models. The analysis of these data is ongoing and the

latest results are presented in this contribution. Next-generation axion helioscopes such as the proposed IAXO [19, 20] could significantly push CAST sensitivity for both, hadronic and non-hadronic models.

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