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Search for solar axions with the CAST experiment

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Abstract: Axions are hypothetical particles arising in models which may solve the CP problem of strong interactions. They are practically stable neutral pseudoscalar particles and also viable candidates for the dark matter in the Universe.

Most of the axion experimental searches are based on the axion coupling to two photons. As a consequence of this coupling, axion could transform into photon and vice versa in external electric and magnetic fields. Axions could be produced in the solar core by conversion of thermal photons in the Coulomb fields of nuclei and electrons - the Primakoff process, and back-converted into photons in a laboratory magnetic field.

CERN Axion Solar Telescope (CAST) is designed to search for these axions by using a Large Hadron Collider prototype dipole magnet which follows the Sun during sunrise and sunset throughout the year. To explore as wide as possible range of axion masses, the operation of CAST is divided in two phases. During the phase I the experiment operated with vacuum inside the magnet bores and scanned axion masses up to 0.02 eV. In order to extend the sensitivity to higher axion masses, the magnet bores are filled with a buffer gas at various densities. In the first part of the CAST phase II, ^{4}He was used as a buffer gas. In the ongoing second part of the phase II, CAST has been using ^{3}He to cover axion masses up to 1 eV. So far, no evidence of axion signal has been found and CAST set the most stringent experimental limit on the axion-photon coupling constant over a broad range of axion masses.

Introduction

A long-standing problem in the quantum chromodynamics is the presence of a CP violating term in the Lagrangian:

$$L_{\text{strong CP}} = \bar{\theta}\frac{\alpha_S}{8\pi} G_a^{\mu\nu} \widetilde{G}_{a\mu\nu}, \tag{1}$$

where $G_a^{\mu\nu}$ is the color field-strength tensor, $\widetilde{G}_{a\mu\nu}$ its dual, and $\bar{\theta}$ is given by $\bar{\theta} = \theta + \operatorname{Arg}\det M$. The parameter θ is related to the nontrivial structure of the QCD vacuum, while $\operatorname{Arg}\det M$, with M being the quark mass matrix, is the well known CP violating contribution from the electroweak sector.

The strong CP violation should be easily observed in measurements of the electric dipole moment of the neutron (nEDM). However, the existing experimental limit on nEDM requires $\bar{\theta} \leq 10^{-9}$. The strong CP problem why is this parameter $\bar{\theta}$, coming from the strong and weak interactions, is so small?

In 1977, Peccei and Quinn [1] proposed an elegant solution to the strong CP problem: they introduced a new global chiral $U(1)_{\text{PQ}}$ symmetry spontaneously broken at a scale f_a, and axion emerges as the associated pseudo-Goldston boson. As a result, the parameter $\bar{\theta}$ is re-interpreted as a dynamical variable and is absorbed in the definition of the axion field: $\bar{\theta} \to a(x)/f_a$. There is no more CP violation in the theory, and the CP violating term (1) is replaced with

$$L_a = \frac{\alpha_S}{8\pi f_a} a(x) G_a^{\mu\nu} \widetilde{G}_{a\mu\nu}. \tag{2}$$

The only thing left is to prove experimentally the existence of axions.

Axions

Axion properties

Axions are practically stable neutral pseudoscalars with phenomenology determined by the scale f_a. They generically couple to gluons (2) and mix with neutral pions (see Fig. 1). The axion mass can be expressed in the form $m_a = m_\pi f_\pi / f_a = 6\,\text{eV}(10^6\ \text{GeV}/f_a)$, where m_π and f_π are the pion mass and decay constant, respectively. Axions can couple to photons, nucleons and electrons. Most of the axion experimental searches are based on the axion interaction with two photons:

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a, \tag{3}$$

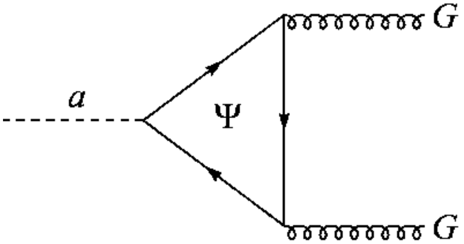

Figure 1: Coupling of axions with gluons via a triangle loop.

where F is the electromagnetic field-strength tensor, $\tilde{F}$ its dual, a the axion field, $\mathbf{E}$ electric and $\mathbf{B}$ magnetic field. The axion-photon coupling constant $g_{a\gamma}$ can be written as

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right) = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92 \pm 0.08\right), \quad (4)$$

where $z \equiv m_u/m_d$ and $w \equiv m_u/m_s$ are quark-mass ratios and E/N is the model-dependent parameter. As a consequence of this interaction, axions could transform into photons and vice versa in external electric and magnetic fields.

In the originally proposed axion model it was assumed that the scale f_a is equal to the electroweak scale $f_{\text{weak}} = 250$ GeV. After ruling out this model experimentally, the idea of "invisible" axions was introduced. If we assume that $f_a \gg f_{\text{weak}}$, axions become very light and very weakly coupled particles. The best known invisible axion models are the KSVZ (Kim, Shifman, Vainshtein, Zakharov) [2] and DFSZ (Dine, Fischler, Srednicki, Zhitnitskiĭ) [3] model. The major difference between the two models is that in the KSVZ model there is no coupling (at the tree level) of axions with electrons.

Cosmological and astrophysical limits

Due to its properties (neutral, low mass, weak coupling), axions are viable dark matter candidates. In the early Universe, they could have been produced by the coherent "misalignment" mechanism or by thermal interactions, leading to both a cold and a hot dark matter component. In order to avoid the overclosure of the Universe, axion mass is limited to the range $10^{-5} \lesssim m_a \lesssim 1$ eV.

Axions, as well as other low-mass weakly-interacting particles, could be produced in hot stellar interiors and transport energy out of stars. The couplings of these particles with matter and radiation are bounded by the requirement that stellar lifetimes do not conflict with the observations. For the axion-photon coupling, the most restrictive astrophysical limit, $g_{a\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$, is derived from globular clusters [4] by comparing the number of horizontal branch (HB) stars with the number of red giants.

Experimental searches ($a - \gamma$ coupling)

Searching for axions is very challenging. The most promising approaches rely on the coupling of axions to two photons, allowing for axion-photon conversion in external electric or magnetic fields. There are several different techniques to search for axion-photon conversion [5]:

1. Laser experiments
    - Photon regeneration (”invisible light shining through walls”): if a laser beam propagates through the bore of a magnet with an optical barrier inside, then photons may be regenerated from the pure axion beam after passing through the barrier.
    - Photon polarization: the polarization of light propagating through a transverse magnetic field suffers dichroism and birefrigence.
2. Search for dark matter axions
    - Microwave cavity experiments (the ADMX experiment): galactic halo axions may be detected by their resonant conversion into a microwave signal in a high-Q cavity permeated by a static magnetic field.
3. Search for solar axions
    - Crystal detectors and Bragg condition: experiments with crystal detectors exploit the coherent conversion of axions into photons when the axion angle of incidence satisfies the Bragg condition with the crystal plane.
    - Helioscope: CERN Axion Solar Telescope (CAST) is the most sensitive experiment of this type (see next section).

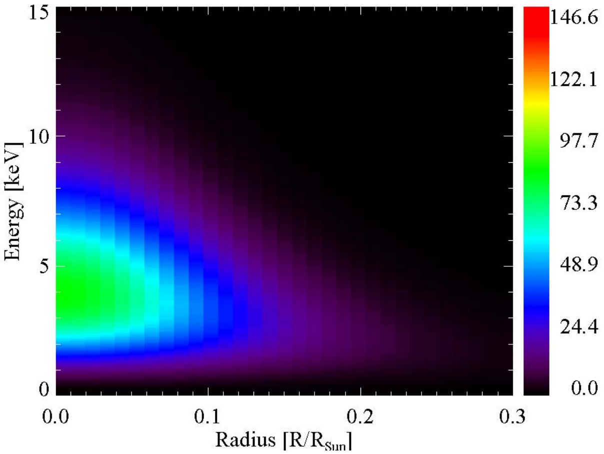

Figure 2: Solar axion flux as a function of energy and solar radius.

CAST physics

The CAST experiment is based on the axion helioscope technique [6] where a dipole magnet is oriented towards the Sun. Axions could be produced in the solar core by conversion of thermal photons in the Coulomb fields of nuclei and electrons - the Primakoff process, and back-converted into photons in a laboratory transverse magnetic field. The expected solar axion flux at the Earth is $\Phi_a = 3.75{\cdot}10^{11}(g_{a\gamma}/(10^{-10}\mathrm{GeV}^{-1}))^2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ with an approximate spectrum

$$\frac{\mathrm{d}\Phi_a}{\mathrm{d}E_a} = 6.02{\cdot}10^{10}\left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \frac{(E_a/\mathrm{keV})^{2.481}}{\exp(E_a/1.205\,\mathrm{keV})}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1} \tag{5}$$

and the average energy $\langle E_a \rangle = 4.2\,\mathrm{keV}$. (see Fig. 2). The expected number of photons (X-rays) reaching a detector is $N_\gamma = \int(\mathrm{d}\Phi_a/\mathrm{d}E_a)P_{a\to\gamma}\,S\,t\,\mathrm{d}E_a$ where $P_{a\to\gamma}$ is the axion-photon conversion probability, S the effective area and t the measurement time. The axion-photon conversion probability in a 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. Therefore, the experimental sensitivity is restricted to a range of axion masses (for example, $m_a \lesssim 0.02$ eV for $L = 10$ m and

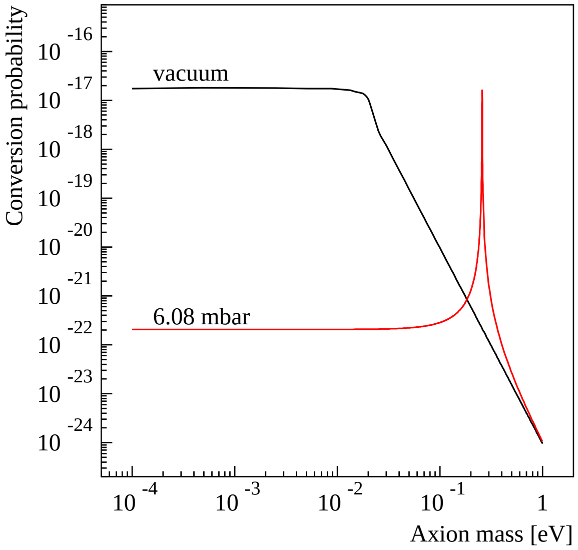

Figure 3: Axion-photon conversion probability versus axion mass. The black line corresponds to the case when vacuum is inside the conversion region and the red line to one particular helium pressure setting. The coupling constant of $1 \cdot 10^{-10}$ GeV^{-1} is assumed.

$E_a = 4.2$ keV). 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 m_γ. In that case, the conversion probability takes the form [7]

$$P_{a\to\gamma} = \left(\frac{B\,g_{a\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left(1+e^{-\Gamma L}-2\,e^{-\Gamma L/2}\cos(qL)\right) \tag{6}$$

where $q = |m_a^2 - m_\gamma^2|/2E_a$ and Γ is the inverse absorption length for photons in a gas. As a result, the coherence is restored for a narrow mass window around $m_a = m_\gamma$ (see Fig. 3).

The first implementation of the axion helioscope principle was performed in Brookhaven [8] and later in a more sensitive search in Tokyo [9, 10, 11]. The most sensitive heliscope experiment CAST [12, 13, 14] has been taking data since 2003, both with vacuum and gas (first ^{4}He and later ^{3}He) inside the conversion region.

Figure 4: CAST magnet.

CAST Experimental setup

The external magnetic field in the CAST experiment is provided by a Large Hadron Collider (LHC) prototype dipole magnet [15] with the magnetic field $B = 9.0$ T (see Fig. 4). Inside the magnet there are two paralell, straight pipes with the length $L = 9.26$ m and cross-sectional area $S = 2 \times 14.5$ cm^2. The operating temperature is 1.8 K which is provided by a full cryogenic station. The magnet is mounted on the rotating platform with $\pm 40^\circ$ horizontal and $\pm 8^\circ$ vertical movement. As a result, the Sun can be tracked for 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. Periodical GRID measurements show that CAST points to the Sun within the required precision. As an additional check, the Sun can be filmed twice per year using a camera placed on the magnet. The overall tracking precision is $\sim 0.01^\circ$.

For the data taking with ^{4}He, a gas system was designed to operate in range $0 - 16.4$ mbar at 1.8 K. The system provided a homogenous and stable density along the magnet bores, with adequate accuracy and reproducibility of density settings. At the ends of the bores, four X-ray windows were installed. The windows were designed to provide high X-ray transmission (polypropylene 15 μm), resistance to sudden rise of pressure (strongback mesh) and minimum helium leakage.

Before 2007, CAST utilized the following X-ray detectors: a conventional Time Projection Chamber (TPC)[16], an unshielded Micromegas detector [17] and an X-ray mirror telescope in combination with a Charged Coupled Device (CCD) [18]. The X-ray focusing system and Micromegas were looking for sunrise axions, while the TPC was occupying both bores on the other end of the magnet looking for sunset axions. The X-ray telescope can focus the photons to a $\sim$ 9 mm^2 spot on the CCD, thus significantly improving the experimental sensitivity.

CAST operation, results and prospects

The operation of the CAST experiment has been forseen to proceed in several phases:

- **Phase I**: during 2003 and 2004 the experiment operated with vacuum inside the magnet bores, thus exploring the axion mass range up to 0.02 eV. Data analysis showed the absence of excess photons when the magnet was pointing to the Sun, and therefore set an upper limit on the axion-photon coupling of $g_{a\gamma} < 8.8 \cdot 10^{-11}$ GeV^{-1} at 95% C.L. [13]. This result is the best experimental limit for the range of axion masses up to 0.02 eV, also superseeding the astrophysical limit derived from energy-loss arguments on horizontal branch stars (Fig. 5).

- **Phase II with ^{4}He**: during 2005 and 2006 the magnet bores were filled with ^{4}He. The gas pressure was increased from 0 to 14 mbar in appropriate steps to cover equally the accessible mass range. With 160 different pressure settings, the range of axion masses up to 0.39 eV was scanned. The resulting upper limit on the axion-photon coupling constant [14] is shown in Fig. 5. The measurement time at each pressure setting was only a few hours, resulting in small event numbers and therefore large statistical fluctuations of the line contour. For the first time, the limit has entered the QCD axion model band in the electronvolt range.

- **Phase II with ^{3}He**: In 2008, CAST started taking data with ^{3}He inside the magnet bores. The data taking will continue until the middle of 2011. The range of axion masses up to $\sim$ 1.2 eV will be scanned. The first preliminary results for the axion mass range 0.39eV $< m_a <$ 0.64 eV are shown in Fig. 5.

Apart from the main line of research, CAST could also be sensitive to axions from M1 nuclear transition [19, 20], Kaluza-Klein [21] and low energy axions [22].

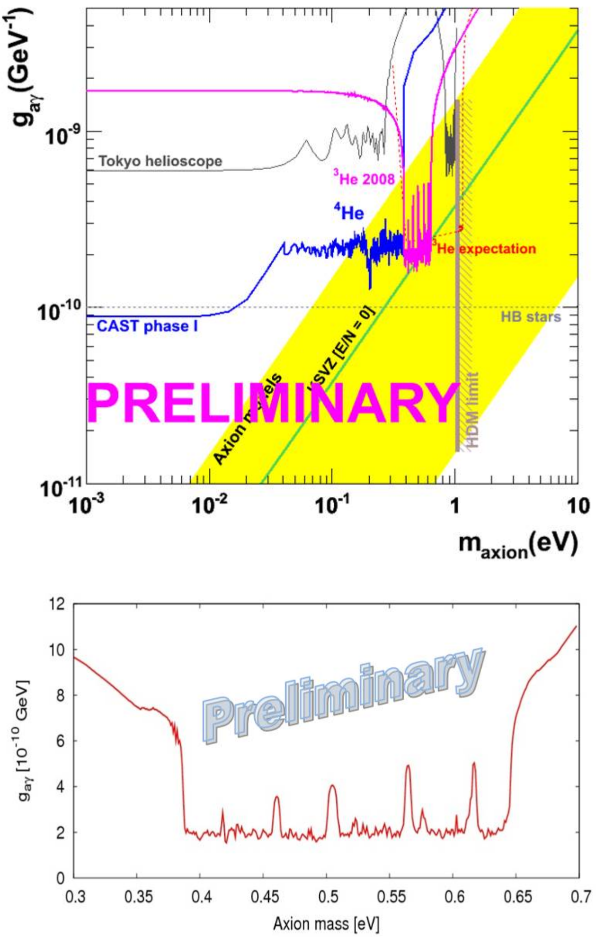

Figure 5: Exclusion limit on the axion-photon coupling constant versus axion mass. Top: Combined result from the CAST phase I and ^{4}He part of phase II (blue line) and preliminary limit from the first part of ^{3}He run (pink line) are compared with results from the Tokyo experiment and horizontal branch stars limit. The HDM line refers to the hot dark matter limit [27, 28]. The yellow band represents typical theoretical models while the red dashed line shows CAST prospects for the ^{3}He run. Bottom: Preliminary ^{3}He limit in linear scale.

Upgrades for the CAST ^{3}He phase

During 2007, the CAST experiment performed several upgrades in order to prepare for the more demanding ^{3}He part of phase II data taking. The most important upgrade was a design and installation of a sophisticated and complex ^{3}He gas system [23]. The system provides high accuracy in measuring the gas quantity, flexible operation modes (stepping and ramping), absence of thermo-acoustic oscillations and protection of cold, thin X-ray windows during a quench. To scan over a range of axion masses, CAST needs to control precisely the gas density in the magnet bores. This required computational fluid dynamics simulations of the system as well as different physical phenomena such as hydrostatic effect, convection and buoyancy.

Before starting ^{3}He data taking, CAST detectors were upgraded as well: a new shielded bulk Micromegas replaced the unshielded one, while the TPC detector was replaced by two shielded Micromegas detectors (bulk and microbulk) [24, 25, 26]. Upgraded detectors have a very low background level, therefore improving the experimental sensitivity in the ongoing ^{3}He part of phase II.

Conclusions and outlook

CAST provides the best experimental limit on the axion-photon coupling constant over a broad range of axion masses. CAST phase II has entered the QCD axion model band and explores the mass range where QCD axions would provide a hot dark matter component similar to neutrinos.

CAST Collaboration has gained a lot of experience in axion helioscope searches. The ongoing R&D on superconducting magnets can lead to much more sensitive helioscopes (see Fig. 6). Future helioscope experiments and microwave cavity searches (e.g. the ADMX experiment) could cover a big part of the QCD axion model region until 2020.

Acknowledgments

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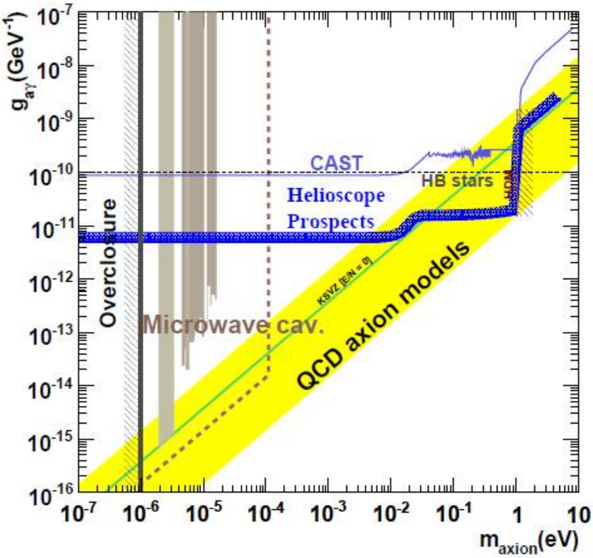

Figure 6: Prospects for future helioscope searches.

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