Status of the Solar Axion Search with CAST

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The CAST experiment is making use of a decommissioned LHC test magnet to look for solar axions by their conversion into photons inside the magnetic field. The data taking of the first phase, with vacuum in the magenet pipes, took place in 2003 and, in improved conditions, in 2004. A preliminary result of the 2004 data is presented here, and it is compatible with absence of signal down to an axion-photon coupling of $g_{a\gamma} \lesssim 9 \times 10^{-11}$ GeV^{-1} for $m_a \lesssim 0.02$ eV. CAST has resumed data taking recently, after being upgraded for operation with He-4 inside the magnet pipes (phase II), in order to extent the sensitivity of the experiment to higher axion masses. Further upgrades are foreseen in the coming months, like the installation of a second X-ray focusing optics.

1. Introduction

Axions are light pseudoscalar particles that arise in theories in which the Peccei-Quinn U(1) symmetry has been introduced to solve the strong CP problem [1]. They could have been produced in early stages of the Universe being attractive candidates to the cold

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Dark Matter (and in some particular scenarios to the hot Dark Matter) that could compose up to ∼1/3 of the ingredients of the Universe.

Axion phenomenology [2] is determined by its mass m_a which in turn is fixed by the scale f_a of the Peccei–Quinn symmetry breaking, $m_a \simeq 0.62$ eV (10^7 GeV$/f_a$). No hint is provided by theory about where the f_a scale should be, so the axion mass is an unconstrained parameter on which all axion couplings depend. In addition, the particular way the axion is implemented in the Standard Model –the axion model– determines the type and magnitude of such couplings. However, only one particular process, the *Primakoff effect*, is present in almost every axion model and is the basis of most axion detection techniques. It makes use of the coupling between the axion field ψ_a and the electromagnetic tensor:

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\psi_a \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} = \\ = -g_{a\gamma}\psi_a \vec{B}\cdot\vec{E} \qquad (1)$$

and allows for the conversion of the axion into a photon –and viceversa– in the presence of an electromagnetic field.

Like all the other axion couplings, $g_{a\gamma}$ is proportional to m_a[3, 4]:

$$g_{a\gamma} \simeq 0.19 \frac{m_a}{\mathrm{eV}} \left(\frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right) 10^{-9} \mathrm{GeV}^{-1} \qquad (2)$$

where E/N is the PQ symmetry anomaly and the second term in parenthesis is the chiral symmetry breaking correction. The anomaly E/N depends on the particular axion model, while the symmetry breaking correction is a function of the parameter $z \equiv m_u/m_d \simeq 0.56$ (m_u and m_d being the up and down quark masses). Two popular models are the GUT–DFSZ axion[5] (E/N=8/3) and the KSVZ axion[6] (E/N=0). However, it is possible to build viable axion models with different values of E/N[7] and the determination of the parameter z is subject to some theoretical uncertainties[8]. This implies that a very small or even vanishing $g_{a\gamma}$ cannot in principle be excluded.

A combination of astrophysical and nuclear physics constraints, and the requirement that the axion relic abundance does not overclose the Universe, restricts the allowed range of viable axion masses[3, 9, 10]. Pure cosmological arguments lead to a conservative, relative model-independent version of the allowed mass range:

$$10^{-6}\mathrm{eV} \lesssim \ m_a \ \lesssim 1 \ \mathrm{eV} \qquad (3)$$

the upper limit being recently set [11], by requiring thermal production of axions to be compatible with recent CMB data. This range and the allowed range of $g_{a\gamma}$ can be further constrained by a number of theoretical arguments that depend on more or less solid astrophysical models. Let's mention the limit $g_{a\gamma} \lesssim 10^{-9}$ GeV^{-1} based on the solar standard model and helioseismological observations [12], or the so-called *globular cluster* limit of $g_{a\gamma} \lesssim 10^{-10}$ GeV^{-1} [13, 14] .

Axions could be produced at early stages of the Universe by the so-called misalignment (or realignment) effect[2]. Extra contributions to the relic density of non-relativistic axions might come from the decay of primordial topological defects (like axion strings or walls). There is not a consensus on how much these contributions account for, so the axion mass window which may give the right amount of primordial axion density (to solve the dark matter problem) spans from 10^{-6} eV to 10^{-3} eV. For higher masses, the axion production via these channels is normally too low to account for the missing mass, although its production via standard thermal process increases. Thermal production yields relativistic axions (hot dark matter) and is therefore less interesting from the point of view of solving the dark matter problem, but in principle axion masses up to ∼ 1 eV, are not in conflict with cosmological observations[11].

Under the assumption that axions are the cold dark matter, they could be detected by using microwave cavities as originally proposed in[15]. In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by $hf = m_a c^2(1 + O(10^{-6}))$. At the lower end of the axion mass window of interest, the frequency of the photons lies in the microwave regime. A high-Q resonant cavity, tuned to the axion mass serves as high sensitivity detector for the converted photons. Such technique is followed by experiments like the Axion Dark Matter Experiment (ADMX)[16, 17], which has implemented the concept using a cylindrical cavity of 50 cm in diameter and 1 m long. So far the ADMX experiment has scanned a small axion mass energy, from 1.9 to 3.3 μeV[17] with a sensitivity enough to exclude a KSVZ axion, assuming that thermalized axions compose a major fraction of our galactic halo ($\rho_a = 450$ MeV/c^2). An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal[18].

But axions could also be copiously produced in the core of the stars by means of the Primakoff conversion of the blackbody photons in the fluctuating electric field of the plasma. In particular, a nearby and powerful source of stellar axions would be the Sun. This axion emission would open new channels of stellar energy drain. Therefore, energy loss arguments constrain considerable axion properties in order not to be in conflict with our knowledge of solar physics or stellar evolution[13].

The solar axion flux can be easily estimated [19, 20] within the standard solar model under the conservative assumption of an axion with no leptonic couplings (hadronic axion)[1]. The resulting axion flux has an average energy of about 4 keV and can be parameterized by the following expresion:

$$\frac{d\Phi}{dE_a} = (g_{(-8)})^2 \frac{\Phi_0}{E_0} \frac{(E_a/E_0)^3}{e^{E_a/E_0} - 1} \quad (4)$$

where $g_{(-8)} = g_{a\gamma} \times 10^8/\text{GeV}^{-1}$, Φ_0=5.95 $\times 10^{14}$ cm^{-2} sec^{-1} and E_0=1.103 keV.

By means again of the photon-axion coupling, solar axions can be converted back into photons in the presence of an electromagnetic field. The energy of the reconverted photon is equal to the incoming axion, so a flux of detectable X-rays with the same energy profile as (4) is expected after the conversion. Crystalline detectors may provide such fields [20, 21], giving rise to very characteristic Bragg patterns that have been looked for as byproducts of dark matter underground experiments [22–24]. However, the prospects of this technique have been proved to be rather limited [25], an do not compete with the experiments called "axion helioscopes" [19, 26], which use magnets to trigger the axion conversion. This technique was first experimentally applied in [27] and later on by the Tokyo helioscope [28], which provided the first limit to solar axions which is "self-consistent", i.e, compatible with solar physics. Currently, the same basic concept is being used by CAST at CERN [29, 30] with some original additions that provide a considerable step forward in sensitivity to solar axions. In the following section we make a short description of the experiment as well as an update of its status and results.

It is worth stressing that "helioscope" experiments like CAST are not based on the assumption of axions being the dark matter. Moreover, although we focus on the axion because of its special theoretical motivations, all this scenario is also valid for a generic pseudoscalar (or scalar) particle coupled to photons [31]. Needless to say that the discovery of any type of pseudoscalar or scalar fundamental particle would have profound implications in Particle Physics.

For the sake of completeness, let us mention that the existence of axions or other axion-like particles may produce measurable effects in the laboratory. A typical example is the "light through wall" experiments, in which a photon beam is converted into axions inside a magnetic field and, after crossing an optical barrier, are converted back into photons by another magnetic field. As a result, light seems to have gone through an opaque wall. This technique was used to derive some early limits on the axion properties [32].

Other subtler effects are the ones induced on the polarization of a laser beam traversing a magnetic field in vacuum. The presence of axion-photon oscillations will produce both a rotation (*dichroism*) and an ellipticity of the beam polarization. Although the ellipticity effect has a Standard Model contribution, by virtue of four-legged fermion loops, the dichroism one does not. Experiments with ultraprecise optical equipment may look for such an effect. The PVLAS experiment[33], designed to measure the QED-predicted magnetic-induced birefringence [34, 35] has recently reported on a positive detection [36] compatible in principle with the presence of a photon-axion oscillation. However, the interpretation of PVLAS observation in terms of axions needs an axion mass of $\sim$ 1 meV and an axion-photon coupling of $\sim 10^{-6}$ GeV^{-1}, far larger than many astrophysical limits and experimental results, in particular that of CAST (although exotic extensions of the standard axion scenario may allow to reconcile all experimental results[37]).

2. The CAST experiment

The CAST experiment is making use of a decommissioned LHC test magnet that provides a magnetic field of 9 Tesla along its two parallel pipes of 2×14.5 cm^2 area and 10 m length. The aperture of each of the bores fully covers the potentially axion-emitting solar core ($\sim$ 1/10th of the solar radius). The magnet is mounted on a platform with $\pm 8^\circ$ vertical movement, allowing for observation of the Sun for 1.5 h at both sunrise and sunset. The rest of the day is devoted to background measurements. The horizontal range of $\pm 40^\circ$ encompasses nearly the full azimuthal movement of the Sun throughout the year. At both ends of the magnet, several detectors look for the X-rays originated by the conversion of the axions inside the magnet when it is pointing to the Sun.

These features makes the axion-photon conversion probability in the CAST magnet be a factor 100 higher than in the previous best helioscope at Tokyo. More specifically, the probability that an axion going through the transverse magnetic field B over a length L will convert to a photon is given by:

$$P_{a\gamma} = 2.4 \times 10^{-17} \left(\frac{B}{9.6\ \text{T}}\right)^2 \left(\frac{L}{10\ \text{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \text{GeV}^{-1}\right) |\mathcal{M}|^2 \quad (5)$$

where the matrix element $|\mathcal{M}|^2$ accounts for the coherence of the process:

$$|\mathcal{M}|^2 = 2(1 - \cos qL)/(qL)^2 \quad (6)$$

[1]particular scenarios with axion couplings to other particles could give rise to additional contributions to the solar axion emission. Following a conservative approach we consider only the axion-photon coupling (Primakoff effect) as source of solar axions, which is present is every axion model –unless accidentally suppressed in Eq. 2–.

being q the momentum exchange. The fact that the axion is not massless, makes the axion and photon waves out of phase after a certain length. For axion energies relevant to us and the length of the magnet, the coherence is preserved ($|\mathcal{M}|^2 \simeq 1$) for axion masses up to $\sim 10^{-2}$ eV, while for higher masses $|\mathcal{M}|$ begins to decrease, and so does the sensitivity of the experiment. To cope with this, a second phase of CAST was planned with the magnet beam pipes filled with a buffer gas to give a mass to the photons $m_\gamma = \omega_p$ (where ω_p is the plasma frequency of the gas, $\omega_p^2 = 4\pi n_e r_0$, being n_e the spatial density of electrons and r_0 the classical electron radius). For axion masses that match the photon mass, the coherence is restored. Changing the pressure of the gas inside the pipe, the photon mass can be changed accordingly, and so the sensitivity of the experiment can be extended to higher axion masses.

A full cryogenic station is used to cool the superconducting magnet down to 1.8 K [38]. The hardware and software of the tracking system have been precisely calibrated, by means of geometric survey measurements, in order to orient the magnet to any given celestial coordinates. The overall CAST pointing precision is better than 0.01° [39].

At both ends of the magnet, three different detectors search for excess X-rays from axion conversion in the magnet when it is pointing to the Sun. Covering both bores of one of the magnet's ends, a conventional Time Projection Chamber (TPC) is looking for X-rays from "sunset" axions. At the other end, facing "sunrise" axions, a second smaller gaseous chamber with novel MICROMEGAS (micromesh gaseous structure – MM) [40] readout is placed behind one of the magnet bores, while in the other one a focusing X-ray mirror telescope is working with a Charge Coupled Device (CCD) as the focal plane detector. Both the CCD and the X-ray telescope are prototypes developed for X-ray astronomy [41]. The X-ray mirror telescope can produce an "axion image" of the Sun by focusing the photons from axion conversion to a $\sim 6\,\mathrm{mm}^2$ spot on the CCD. The enhanced signal-to-background ratio substantially improves the sensitivity of the experiment.

3. Results and status

CAST has been running in phase I (vacuum) configuration both in 2003 and 2004. The results of the analysis of the 2003 data have been published in [30]. No signal above background was observed, implying an upper limit to the axion-photon coupling $g_{a\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} at 95% CL for the low mass (coherence) region $m_a \lesssim 0.02$ eV.

In 2004, considerable improvements were made in the magnet set-up as well as the X-ray detectors. Regarding the magnet, the improvements concentrated on the mechanical platform and cryogenic aspects. These upgrades allowed to minimize to practically zero the shutdown periods for technical maintenance during the 2004 data taking campaign, affecting positively the homogeneity of data taking and therefore improving the data quality. An enhanced system to read out different experimental magnitudes allowed a better continuous monitoring of the experiment. Regarding the detectors, the improvements focused on diverse upgrades of their setups. For the TPC, a differential pumping system for the X-ray windows was installed to increase the robustness of the system against possible leaks through the thin X-ray windows. This upgrade allowed smooth detector operation throughout the 2004 data taking period without one single shutdown for window maintenance. Besides, a passive shielding –composed of copper (5 mm), lead (2 cm), cadmium (1 mm) and polyethylene (20 cm) and clean nitrogen flushing inside– was installed around the detector, yielding a background reduction (down to 4 $\times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}) and homogenization. For the micromegas detector, a new version of the detector read-out was used, which showed to be absent of cross talk effects between strips, as was the one operating in 2003. This increased the data quality, and allowed for more strict software cuts that reduced the background down to 5 $\times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}. Automatic calibrators were installed for both the TPC and Micromegas to continually monitor their stability. For the CCD/telescope system, an additional layer of 17 to 25 mm of ancient lead was added to the shielding, leading to a background level of 7.5 $\times 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}. An improvement on the monitoring of the position and stability of the focusing spot of the telescope was achieved by the installation, on the opposite side of the magnet, of a x-ray source based on a pyroelectric crystal. Thanks to it, the analysis of the CCD could be restricted to the small area where the spot is expected and profit maximally from the focusing power of the X-ray telescope.

The data analysis from 2004 data is almost complete, and a preliminary result has been achieved. The analysis is performed as described in [30]. Data obtained during non-alignment periods are used to estimate the background levels to be subtracted to the data in "axion-sensitive" conditions, i.e., with the magnet pointing to the sun. The CCD may also use for that purpose the data outside the spot region. Each of the subtracted spectra is individually consistent with absence of signal. The excluded value of $g_{a\gamma}^4$ was conservatively calculated by taking the limit encompassing 95% of the physically allowed part (i.e. positive signals) of the Bayesian probability distribution with a flat prior in $g_{a\gamma}^4$. They can be statistically combined by multiplying the Bayesian probability functions and repeating the previous process. The preliminary combined limit for CAST 2004 data is:

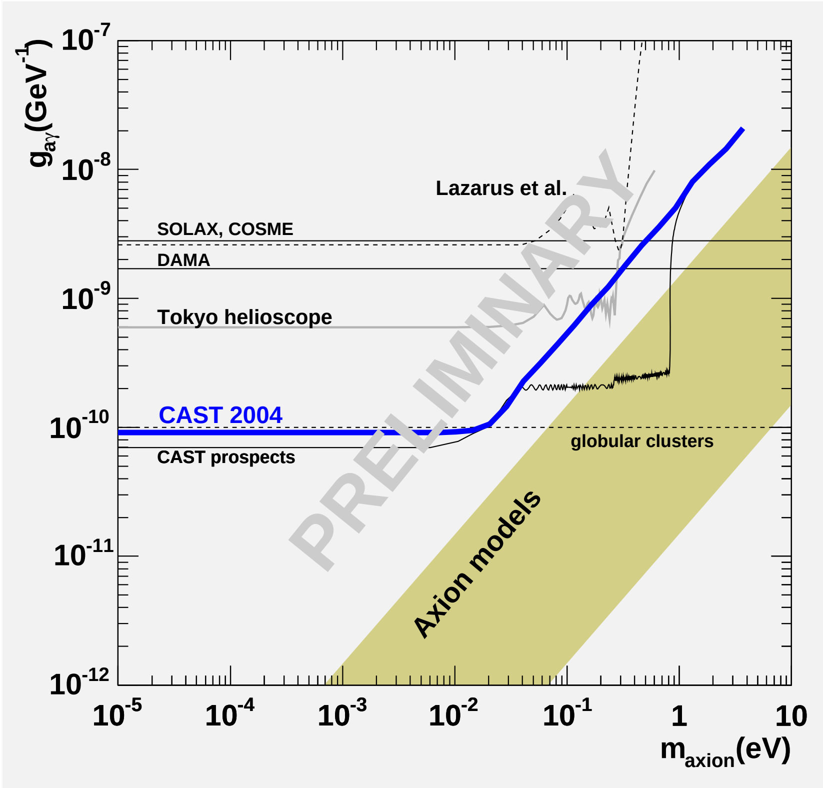

Figure 1: 95% CL exclusion line obtained from the preliminary analysis of the 2004 data (line labeled "CAST 2004"), compared with other laboratory limits such as the Tokyo helioscope and those obtained from axion experiments with crystalline detectors located underground (SOLAX, COSME and DAMA). The shaded area indicates the region of theoretical preference for axion models. Also shown are the limits coming from astrophysical considerations (dashed line) and the expected sensitivity of CAST phase II. See text for references.

$$g_{a\gamma} < 9 \times 10^{-11}\mathrm{GeV}^{-1}(95\%\mathrm{C.L.}) \qquad (7)$$

This limit is valid for the mass range $m_a \lesssim 0.02$ eV where the expected signal is mass-independent because the axion-photon oscillation length far exceeds the length of the magnet. For higher m_a the overall signal strength diminishes rapidly and the spectral shape differs. Our procedure was repeated for different values of m_a to obtain the entire 95% CL exclusion line shown in Fig. 1. As can be seen, the obtained limit is a factor ∼7 more restrictive than the limit from the Tokyo axion helioscope and goes for the first time beyond the limit derived from stellar energy-loss arguments.

During 2005 the experiment has been upgraded to face the needs of phase II operation, which require the injection of a buffer gas in the magnet pipes and the precise control of its pressure. As a result, a system dealing with He-4 gas for that purpose has been built and is currently operational. Data taking with He-4 gas is now ongoing, setting a different pressure every day, so the axion mass range is scanned continuously. This system will allow to swept the axion mass space up to ∼0.15 eV. A further upgrade towards He-3 gas is foreseen next year in order to extent CAST sensitivity to 1 eV axion mass. The expected overall sensitivity of CAST phase II is shown in figure 1.

As an additional upgrade of CAST phase II, a second X-ray focusing optics is going to be installed in the next months. It will be coupled to a new smaller Micromegas detector with enhanced features with respect to the present version, and which is now under construction. The new detection line, whose design is shown in figure 2, will contribute to further increase the sensitivity of CAST by means of several key points. First, the x-ray optics, a concentrator with a 1.3 m focal length and 47 mm diameter, has been designed specifically for CAST, and is being built using new substrate techniques developed at LLNL of Livermore. It will consist of 14 nested polycarbonate conic shells, each 125 mm long and coated with iridium. The optic will transmit and focus ∼36% of the 0.5–10 keV flux emerging from the magnet bore. Second, the shielding, composed of copper, lead, cadmium nitrogen and polyethylene follows the experience of the TPC detector described above, and is expected to reduce the background similarly. Third, the new Mi-

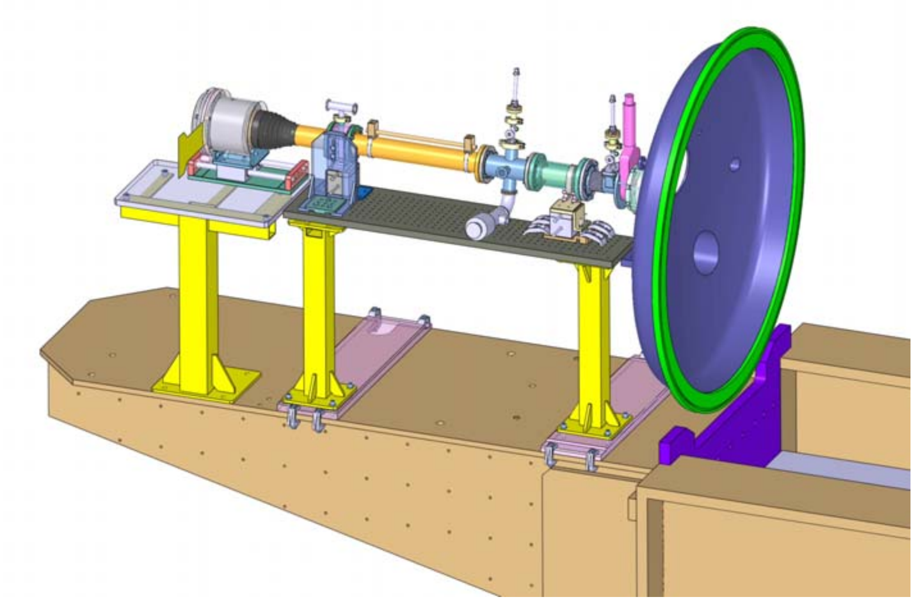

Figure 2: Design of the new Micromegas line with the new x-ray optics, as will be installed in the CAST magnet (on the right, only the end cap is shown).

cromegas chamber will use a gas mixture based on Xenon (instead of Argon as at present), offering an increased photon conversion by ∼10%. The new detector will use the same electronics and acquisition developed for the phase I detector.

4. Conclusions

The CAST experiment is looking for solar axions following the "axion helioscops" concept with a 9.6 Tesla and 10 m long LHC test magnet. A preliminary limit obtained with the phase I 2004 data has been presented: $g_{a\gamma} < 9 \times 10^{-11}$ GeV^{-1} for $m_a \lesssim 0.02$ eV. The phase II of the experiment has already started using He-4 as buffer gas to trigger axion-photon conversion for higher axion masses. He-3 gas will be used subsequently to go up to 1 eV axion mass. A second x-ray focusing optics is in preparation to be installed and used in conjunction with a new Micromegas chamber, to be installed in a few months.

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