LATEST RESULTS OF THE CAST AXION SEARCH

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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 magnet pipes, took place in 2003 and, in improved conditions, in 2004. The final phase I result has been recently released, excluding axions down to $g_{a\gamma} \lesssim 8.8 \times 10^{-11}$ GeV^{-1} for $m_a \lesssim 0.02$ eV. CAST is now immersed in its phase II, operating with a buffer gas inside the magnet pipes, in order to extent the sensitivity of the experiment to higher axion masses. During the 2006 data taking ^{4}He was used, and now the system is being upgraded to use ^{3}He. The latest status of the experiment will be presented. A brief overview of the situation of other axion experiments and in general of the field will be given.

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 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:

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} g_{a\gamma\gamma} \psi_a \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} = \\ &= -g_{a\gamma} \psi_a \vec{B} \cdot \vec{E}\end{aligned} \tag{1}$$

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]:

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

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 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:

$$10^{-6}\mathrm{eV} \lesssim \quad m_a \quad \lesssim 1\ \mathrm{eV} \tag{3}$$

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] Currently the collaboration has completed a development involving high sensitivity squids amplifiers, which will allow them to scan the full decade $10^{-6} - 10^{-5}$ eV in the near future. Plans are also ongoing both to increase the sensitivity of the experiment to lower axion-photon couplings as well as extending the reachable axion mass range.

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)[f]. The resulting

[f] particular scenarios with axion couplings to other particles could give rise to additional contributions to the

axion flux has an average energy of about 4 keV and can be parameterized by the following expresion [30]:

$$\frac{\mathrm{d}\Phi_a}{\mathrm{d}E} = 6.02 \times 10^{10}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ \mathrm{keV}^{-1}\, g_{10}^2\, E^{2.481} e^{-E/1.205}\,. \tag{4}$$

where $g_{10} = g_{a\gamma}/10^{-10}$ GeV^{-1}.

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,[21,20] giving rise to very characteristic Bragg patterns that have been looked for as byproducts of dark matter underground experiments.[22,23,24] However, the prospects of this technique have been proved to be rather limited,[25] and do not compete with the experiments called "axion helioscopes",[26,19] 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 [29,31,30,32,33,34] 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.[37] 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.[38]

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 ultra-precise optical equipment may look for such an effect. The PVLAS experiment,[39] designed to measure the QED-predicted magnetic-induced birefringence [41,40] has recently reported on a positive detection [42] compatible in principle with the presence of a photon-axion oscillation[g]. However, the interpretation of PVLAS observation in terms of axions needs an axion mass of ~ 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.[43]) The current situation of these type of experiments and theoretical efforts was reviewed in this same conference by J. Jaeckel, and we refer to his contribution for further information and references.

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–.

[g] Although during the preparation of this paper we have learnt the announcement by the PVLAS group indicating that the effect disappears after the latest improvements of the experimental setup.[48]

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 ($\sim 1/10$th of the solar radius). The magnet is mounted on a platform with $\pm8°$ 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 $\pm40°$ 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:

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

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

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

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.[44] 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°.[45]

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) [46] 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.[47] 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.

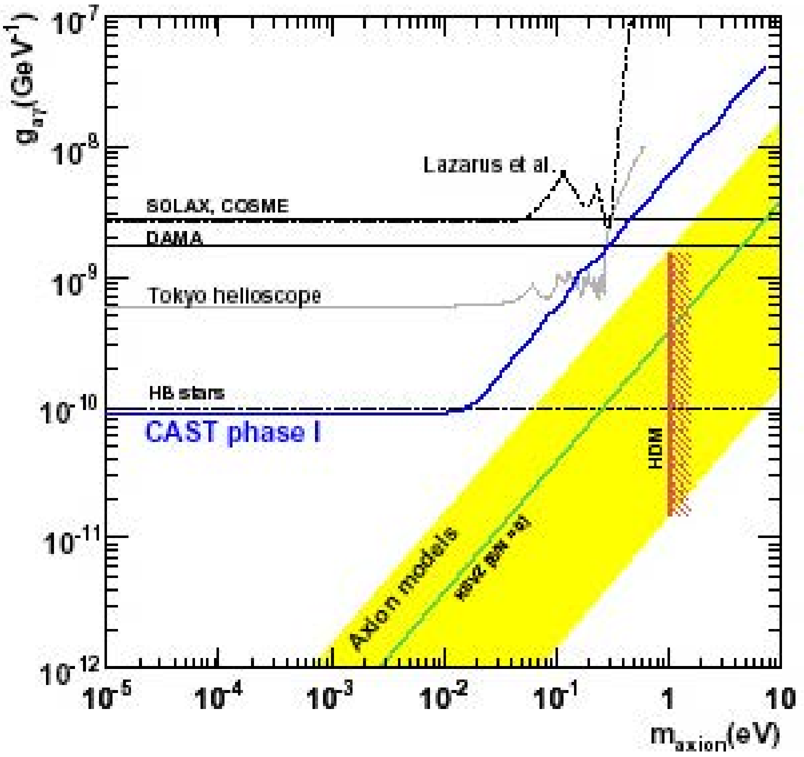

Figure 1: 95% CL exclusion line in the axion-photon coupling versus the axion mass plane obtained from the complete (2003 and 2004) CAST phase I data (line labeled "CAST Phase I"), compared with other laboratory limits such as the Tokyo helioscope and those obtained from axion experiments with crystalline detectors located underground (SOLAX, COSME and DAMA) and other constraints like the HB stars, all discussed in the introduction. The yellow band represents typical theoretical models with $|E/N - 1.95|$ in the range 0.07–7 while the green solid line corresponds to the case when $E/N = 0$ is assumed. See text for references.

3 CAST phase II: status

CAST has been running in phase I (vacuum) configuration both in 2003 and 2004. The combined results of these data for all three detectors have been recently released.[30] From the absence of signal in the data a 95% CL upper limit to the axion-photon coupling was derived:

$$g_{a\gamma} < 8.8 \times 10^{-11} \mathrm{GeV}^{-1} (95\% \mathrm{C.L.}) \tag{7}$$

This limit is valid for the mass range $m_a \lesssim 0.02$ eV where the expected signal is mass-independent because, as was explained in the introduction, the axion-photon oscillation length far exceeds the length of the magnet and hence coherence is preserved in the conversion. For higher m_a the overall signal strength diminishes rapidly and the spectral shape differs. The limit to the axion-photon coupling was derived also for axion masses above this range so that the entire 95% CL exclusion line shown in Fig. 1 was obtained. This result improves the previous CAST published result,[31] and constitutes the final official CAST phase I limit. As can be seen, it 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 was 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 ^{4}He gas for that purpose was built and has been operational since end of 2005. Data taking with ^{4}He gas in the magnet pipes took place all throughout 2006,

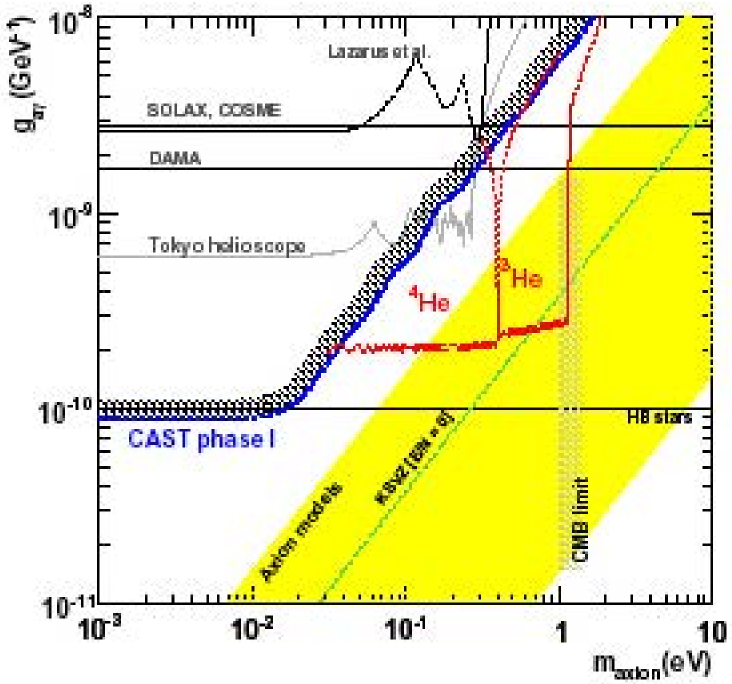

Figure 2: Sensitivity of CAST phase II. The red line labelled ^{4}He indicates the axion parameter region reachable by the ^{4}He phase which took place in 2006 (actual data being analyzed). The red line labelled ^{3}He shows the region reachable in the upcoming 3 years data taking period with ^{3}He .

setting a different pressure every day, so the axion mass range was scanned continuously up to the condensation limit of this gas at the operation temperature of 1.8 K, which is $\sim$13 mbar. This has allowed CAST to scan a new axion mass range up to $\sim$ 0.39 eV, exploring the region indicated in fig. 2. The ^{4}He data is currently under analysis, the region shown in figure 2 being the expected exclusion plot.

Currently the experiment is being further upgraded to be able to deal with ^{3}He as the buffer gas. This gas can reach pressures up to $\sim$ 135 mbar at 1.8 K, corresponding to axion masses up to $\sim$1.2 eV. The experimental setup to use ^{3}He, supposes a considerable effort due to the high safety and reliability level required by the fact of not tolerating leaks of this gas, considerable expensive. The system is expected to be ready for data taking by mid 2007.

For the realization of the ^{3}He experimental program and to exploit fully the potential of the new upgraded system, CAST plans to run during the next 3 years, scanning axion masses up to $\sim$1.2 eV, and closing the window presently allowed (axions with masses above 1.1 eV are excluded by the amount of Hot Dark Matter induced by the cosmic microwave background data). The expected reachable region is depicted in figure 2. As can be seen, the second phase of CAST is allowing sensitivity to QCD axion models at the 0.1 – 1 eV mass scale, which was out of reach for previous experiments (including CAST phase I).

In parallel with the above mentioned upgrades, CAST is exploring possible improvements in the detector systems that could lead to an increased overall sensitivity. A very appealing possibility is to add a second X-ray focusing optics to the experimental setup. A design has been done specifically for CAST, and tests are ongoing to assess whether construction under specification is possible. It consists of a concentrator with a 1.3 m focal length and 47 mm diameter built using new substrate techniques developed at LLNL of Livermore. The concentrator will have 14 nested polycarbonate conic shells, each 125 mm long and coated with iridium. It will be coupled to a new smaller Micromegas detector with enhanced features with respect to the present version, in particular it will enjoy a shielding composed of copper, lead, cadmium nitrogen and polyethylene following the experience of the TPC detector described above, and is expected to reduce the background similarly.[35]

4 Conclusions

The CAST experiment is looking for solar axions following the "axion helioscope" concept with a 9.6 Tesla and 10 m long LHC test magnet. A final result from the phase I data taken in 2003 and 2004 data has been presented: $g_{a\gamma} < 0.88 \times 10^{-11}$ GeV^{-1} for $m_a \lesssim 0.02$ eV. The phase II of the experiment has already started using ^{4}He as buffer gas to trigger axion-photon conversion for higher axion masses. With this upgrade CAST has entered the theory motivated axion parameter space. Currently the collaboration prepares the transition to ^{3}He which will allow to extend the sensitivity of the experiment to axion masses up to $\sim$ **1**.2 eV, closing the window allowed by cosmological limits. The ^{3}He phase should start in the coming months and last for about three years.

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