Solar axion search with the CAST experiment

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The CAST (CERN Axion Solar Telescope) experiment is searching for solar axions by their conversion into photons inside the magnet pipe of a LHC prototype dipole. In the phase II, CAST is operating with a buffer gas inside the magnet bore apertures in order to extent the sensitivity of the experiment to larger axion masses. Preliminary results from the analysis of this second phase with ^{4}He inside the magnet pipes excludes axions down to $g_{a\gamma} < 2.2 \cdot 10^{-10}\mathrm{GeV}^{-1}$ at 95% C.L. for $0.02\, eV < m_a < 0.39\, eV$. The data analysis has resulted in the most restrictive experimental limit on the coupling constant of axions to photons and for the first time experimental result has entered the theory motivated axion parameter space. At the beginning of 2008, data started to be taken with ^{3}He in the magnet pipes in order to extend the sensitivity to axion masses up to 1.2 eV.

1 Introduction to Axion Theory

In the Standard Model, the QCD Lagrangian[1] includes a gluon interaction term that violates charge conjugation times parity (CP) and time reversal (T):

$$\mathcal{L}_{CP} = \bar{\theta}\frac{\alpha_s}{8\pi}G\widetilde{G} \tag{1}$$

where G is the color field strength tensor, $\widetilde{G}$ its dual, $\bar{\theta}$ represents the effective QCD vacuum and it can assume any value between 0 and 2π. A non vanishing $\bar{\theta}$ value would imply CP violation.

Evidence of CP violation would be observable by the electric dipole moment of neutrons, that has been theoretically estimated to be[2]:

$$d_n \approx \bar{\theta}\frac{e}{m_n}\frac{m^*}{\Lambda_{QCD}} \propto \bar{\theta}\cdot 3.6 \cdot 10^{-16} e\,\mathrm{cm} \tag{2}$$

where Λ_{QCD} is QCD energy scale $\approx$ 1 GeV and m^* is the reduced mass of the up and down quark defined as $m^* = \frac{m_u m_d}{(m_u+m_d)}$, m_n is the neutron mass, e the unit electrical charge. The present experimental upper limit[3] however, is smaller than

$$d_n < 2.9 \cdot 10^{-26} e\,\mathrm{cm}\,(90\%\, CL) \tag{3}$$

Consequently, the phase parameter $\bar{\theta}$ should be smaller than 10^{-10}. This implies that CP is not very strongly broken in the strong interactions. So the solution of the $U(1)_A$ problem begets a different problem: why is CP not badly broken in QCD? This is known as the strong CP problem.

One solution was proposed by Peccei Quinn in 1977[4] introducing a new global chiral $\mathrm{U}(1)_{PQ}$ symmetry. This symmetry is necessarily spontaneously broken at an unknown scale f_a, and its introduction into the theory effectively replaces the static CP-violating angle $\bar{\theta}$ with a dynamical CP- conserving field - the axion. Formally, to make the Lagrangian of the Standard Model $\mathrm{U}(1)_{PQ}$ invariant this Lagrangian must be increased by axion interaction:

$$\mathcal{L}_a = -\frac{1}{2}\left(\partial a\right)^2 + \frac{\alpha_s}{8\pi f_a}\, a\, G\widetilde{G} \tag{4}$$

where α_s is the strong coupling constant, a is the axion field, f_a the axion decay constant and $f_a \propto \frac{1}{g_{a\gamma\gamma}}$. Color anomaly factors have been absorbed in the normalization of f_a which is defined by this Lagrangian. Non-perturbative effects induce a potential for a whose minimum is at $a = \bar{\theta} f_a$, thereby canceling the $\bar{\theta}$ term in the QCD Lagrangian, and thus allowing for the dynamical restoration of the CP symmetry.

Weinberg [5] and Wilczek [6] realized that a consequence of this mechanism is a new pseudoscalar boson, the axion, which is the Nambu-Goldstone boson of the PQ symmetry. The axion coupling to ordinary matter is proportional to the axion mass m_a and, equivalently, to the inverse of the PQ scale $1/f_a$. The PQ symmetry is explicitly broken at low energies by instantaneous effects so that the axion acquires a small mass:

$$m_a = \frac{z^{1/2}}{1+z} \frac{f_\pi m_\pi}{f_a} \approx 6\ eV \frac{10^6 \mathrm{GeV}}{f_a} \tag{5}$$

where f_π is the pion decay constant and $z = m_u/m_d$ is the mass ratio of up and down quarks (for this numerical estimate [7] we used a canonical value of z=0.56). Depending of their density and mass, axions may constitute a candidate for the cold dark matter in the universe.

One generic property of the axion is a two-photons interaction that plays a key role for most searches:

$$\mathcal{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} F \widetilde{F}\, a = -g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a \tag{6}$$

where F is the electromagnetic field-strength tensor, $\widetilde{F}$ its dual, $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields. The coupling constant is:

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z} \right) \tag{7}$$

where α is the fine structure constant, E and N are the electromagnetic and color anomaly of the axial current associated with the axion field and E/N is a model dependent parameter [8].

2 Solar Axions

Axions could be produced in stellar cores through their coupling to plasma photons, namely by Primakoff conversion [9], with energies in the range of keV. The expected solar axion flux on earth based on a Standard Solar Model (see fig.1) is well approximated by [10]:

$$\frac{d\Phi}{dE} = \left(\frac{g_{a\gamma\gamma}}{10^{-10} \mathrm{GeV}^{-1}} \right)^2 \Phi_0 \frac{E^{2.481}}{e^{E/(1.205)}} \tag{8}$$

where E is in keV and $\Phi_0 = 6.020 \cdot 10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}$. The maximum of the distribution is at 3.0 keV and the average energy is 4.2 keV.

This flux can be searched with the inverse process described by (6) where an axion converts into a photon in a macroscopic magnetic field [12]. The conversion probability in magnetic field region in vacuum is given by [13]

$$P_{a\to\gamma} \approx (B L g_{a\gamma\gamma})^2 \frac{\sin^2(qL/2)}{(qL)^2} \tag{9}$$

where B is the magnetic field strength, L is the path length, q is the momentum transfer between the axion and the X-ray photon $q = \frac{m_a^2}{2E_a}$, E_a is the axion energy. The conversion is coherent over a large propagation distance for $qL \ll 1$.

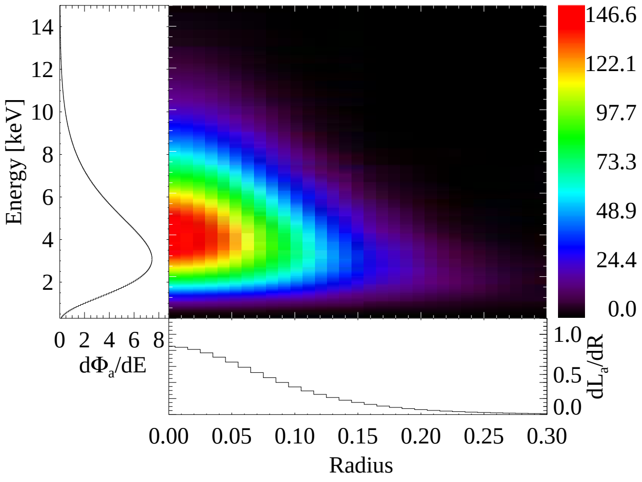

Figure 1: Axion surface luminosity seen from the Earth as a function of axion energy and the radius where the axion are produced in the sun normalized to the solar radius. [11]

One could reach sensitivity for larger axion masses by filling the magnetic field region with a gas, consequently the photon acquires an effective mass, and the conversion probability is [14]

$$P_{a\to\gamma} \propto \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right] \tag{10}$$

where Γ is the inverse photon absorption length for the X-rays in the medium, q is the momentum transfer $q = \frac{m_\gamma^2 - m_a^2}{2E_a}$, E_a is the axion energy, m_γ is the photon effective mass in the buffer gas that depends on the type and density of gas:

$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = \sqrt{\frac{Z}{A}\rho} \tag{11}$$

where Z and A are the atomic and mass number of the gas, m_e is the electron mass, N_e is the number of electron per cm^3 and ρ is the gas density. The coherence $qL < \pi$ can be restored for a narrow mass range:

$$\sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}}. \tag{12}$$

The choice of a specific gas pressure allows the test of a specific axion mass. Scanning over a range of pressure means scanning over a large range of axion mass.

3 CAST

The CAST [15] [16] (CERN Axion Solar Telescope) experiment uses a decommissioned LHC prototype supercoducting magnet with a length of 9.26 m, a magnetic field of about 9 T inside two beam pipes. The magnet is mounted on a moving platform allowing a vertical movement of ±8° and an horizontal movement of ±40°. Different detectors are mounted at the two ends of the magnet cryostat The magnet can point to the sun core for about 1.5 hour at the sunrise and at the sunset, when the magnet is not aligned with the sun the time is dedicated to background measurements. The detectors cover about 1/10th of the solar radius, searching for the axion potentially emitted by the solar core. The CAST tracking system has been accurately calibrated by geometric survey measurements and it is verified by a sun filming. The pointing precision is evaluated to be better than 0.01°.

On one end of the magnet, a conventional plexigas Time Projection Chamber (TPC)[17 18], covering both beam pipes, looks for X-rays coming from axion-to-photon conversion during the sunset. On the opposite magnet end, a Micro-Mesh Gaseous detector (MM)[19] and a Charge Coupled Device (CCD)[20] look for X-rays during the sunrise. The CCD is located at the end of X-ray telescope designed for the German X-ray satellite mission ABRIXAS[21]. This telescope focuses the photons from the magnet bore with a 14.5 cm^2 aperture to a spot size of about 6 mm^2 on the CCD, and thus improving the signal to background ratio by a factor of about 150.

4 Result

During the phase I (2003-2004 data taking) the CAST experiment was operated keeping the magnet pipes evacuated and therefore it was sensitive to the axion mass range up to $m_a = 0.02eV$ due to coherence effects. The results of phase I improved the limit of the axion coupling constant by a factor of 7 with respect to the previous experimental searches and it went beyond the astrophysical limit of globular clusters for coherence masses[11].

The phase II of CAST, where the magnet pipes are filled with a buffer gas, can extend the sensitivity to higher axion rest masses. During 2005, the experiment was upgraded to allow the injection of a buffer gas in the cold bores. A new gas system was built and has been operation since the end of 2005. This system gets a density stability, an accuracy of pressure of about 0.2 mbar and a reproducibility precision of 0.01 mbar. The data taking of phase II with ^{4}He during 2005 and 2006 covered one different pressure per day for a total of 160 density steps (step size is about 0.083 mbar at 1.8 K) up to 13 mbar, near the condensation limit of ^{4}He gas at the

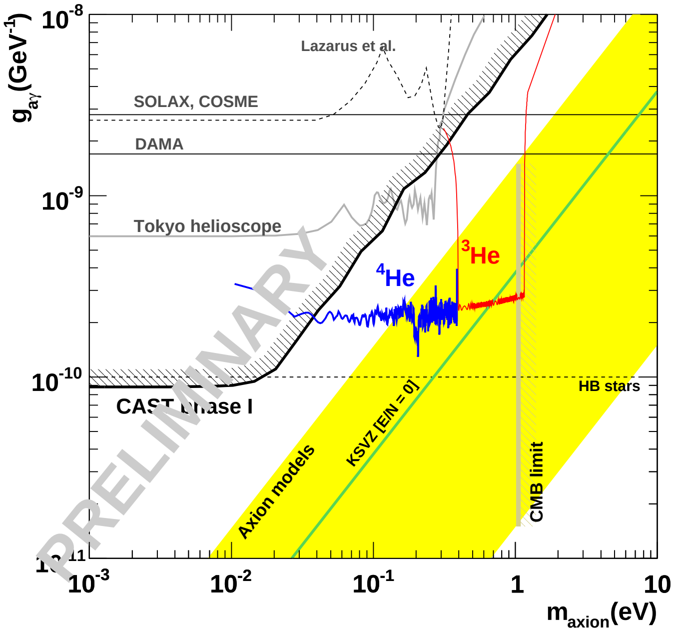

Figure 2: 95% C.L. exclusion line in the axion/photon coupling constant versus the axion mass plane obtained from the complete CAST phase I data[11] (line labeled "CAST Phase I"), from phase II with ^{4}He (blue line labeled "^{4}He") and the foreseen sensitivity for CAST phase II with ^{3}He (red line labeled "^{3}He"). These results are compared with other laboratory limits such as previous helioscopes Lazarus et al.[22], the Tokyo[23] helioscope and those obtained from axion experiments with crystalline detectors located underground (SOLAX[24], COSME[25] and DAMA[26]) and other constraints like the horizontal branch (HB) stars[27]. The grey band labeled "CMB limit" represents the limit evaluated by the amount of Hot Dark Matter deduced by the cosmic microwave background data[28]. 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.

operation temperature of 1.8 K that is about 16 mbar. This corresponds to a scan of axion mass range between 0.02 eV up to 0.39 eV. The preliminary combined results of ^{4}He data for all three detectors are shown in fig.2. The average upper limit to the axion-photon coupling at 95% C.L., in the axion mass range 0.02 eV up to 0.39 eV, is $g_{a\gamma} < 2.2 \cdot 10^{-10}\mathrm{GeV}^{-1}$. For the first time experimental results entered in the QCD theoretically allowed axion models region.

During 2007 the experiment was upgraded to allow the injection of ^{3}He as buffer gas. This gas can reach pressures up to about 135 mbar at 1.8 K, corresponding to axion masses up to about 1.2 eV. The new automatic gas system has the same accuracy and reproducibility of the previous one and moreover it has a high safety and reliability level required to have no leaks of this gas, considerable expensive. The new gas system is operational since end of 2007. In parallel with the above mentioned upgrade, CAST improved the detector system replacing the TPC and MM by MicroMegas detectors based on the new bulk and microbulk technology. These detectors have a better energy resolution and a better background rejection. The new detectors are covered by a shielding composed of copper, lead, cadmium, nitrogen and polyethylene allowing background reduction by a factor 3. The data taking for phase II with ^{3}He started in March 2008. CAST plans to run during the next 3 years to fully exploit the region up to axion mass of 1.2 eV, entering deeper into the QCD theoretically axion models space up to the region excluded by the amount of Hot Dark Matter induced by the cosmic microwave background data[28] (CMB). The expected reachable region is shown in fig. 2.

5 Conclusion

The CAST experiment has been running in phase I (vacuum in the beam pipe in 2003 and 2004) yielding to a lower limit on $g_{a\gamma} < 8.8 \cdot 10^{-11}\mathrm{GeV}^{-1}$ at 95% C.L. for axion masses $m_a < 0.02\,e\mathrm{V}$. During 2005, a major modification to the magnet pipe system was undertaken to fill the beam pipes with ^{4}He during 2005 and 2006. A new system was commissioned and installed in 2007 to use as buffer gas ^{3}He allowing to exploit the region up to axion mass of 1.2 eV. The preliminary results of phase II with ^{4}He has been presented, the average upper limit to the axion-photon coupling is $g_{a\gamma} < 2.2 \cdot 10^{-10}\mathrm{GeV}^{-1}$ at 95% C.L. for axion masses $0.02\,e\mathrm{V} < m_a < 0.39\,e\mathrm{V}$. These results improve the previous constraints given by other experiments by a factor of 7 and have entered the theory motivated axion parameter space. The ^{3}He phase, with data taking started in March 2008, allows to enter deeper in the theoretical axion model allowed phase space and will continue for about three years.

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