Latest results from the CERN Axion Solar Telescope

Igor G Irastorza\textsuperscript{1} for the CAST collaboration

Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, Zaragoza, Spain

Abstract. The CERN Axion Solar Telescope (CAST) experiment searches for axions from the Sun converted into few keV photons via the inverse Primakoff effect in the high magnetic field of a superconducting Large Hadron Collider (LHC) decommissioned test magnet. After results obtained with vacuum in the magnet pipes (phase I of the experiment) as well as with \(^2\)He the collaboration is now immersed in the data taking with \(^3\)He. The status of the experiment will be presented, including a preliminary indication of the axion parameter space explored up to now. CAST is currently sensitive to realistic QCD axion models at the sub-eV scale, and with axion-photon couplings in the range down to the \(\sim 2 \times 10^{-10}\) GeV\(^{-1}\), compatible with solar life limits.

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 \cite{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 \(\sim 1/3\) of the ingredients of the Universe.

The axion-photon coupling \(g_{a\gamma}\), unlike other axion couplings\cite{2}, is automatically present in every QCD axion model, and allows for the conversion of axions into photons (and vice versa) in the presence of electromagnetic fields, being the base of almost every axion detection strategy.

A combination of astrophysical and nuclear physics constraints, restricts the allowed range for axion mass and couplings\cite{3, 4, 5}. Pure cosmological arguments lead to a conservative, relatively model-independent allowed mass range of \(10^{-6}\) eV \(\lesssim m_a \lesssim 1\) eV, the upper limit being recently set \cite{6}, by requiring thermal production of axions to be compatible with last CMB data. \(g_{a\gamma}\) can be constrained independently by astrophysical observations, namely \(g_{a\gamma} \lesssim 10^{-9}\) GeV\(^{-1}\) based on the solar standard model and helioseismological observations \cite{7}, or the so-called globular cluster limit of \(g_{a\gamma} \lesssim 10^{-10}\) GeV\(^{-1}\) \cite{8, 9}. This scheme is usually generalized to any axion-like particle of a given mass \(m_a\) and a photon coupling \(g_{a\gamma}\).

Axions could be produced at early stages of the Universe by the so-called misalignment (or realignment) effect\cite{2}, plus in some cases also from decay of primordial topological defects like axion strings or walls. These relic axions could be a substantial part of the cold dark matter (CDM) if \(m_a \sim 10^{-6} - 10^{-3}\) eV, and could be detected by microwave cavities as originally proposed in\cite{10}. Such technique is followed by experiments like the Axion Dark Matter Experiment (ADMX)\cite{11, 12}, which is actively scanning the low axion mass range mentioned

\textsuperscript{1} Attending speaker. Email: Igor.Irastorza@cern.ch

\textsuperscript{2} One should not forget that some of the limits above are set using other properties of the QCD axions and therefore do not hold for axion-like particles.
above. 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. Solar axions have energies of 1-10 keV, and could be detected by looking for x-rays of those energies coming from their conversion in a strong laboratory magnetic field. This helioscope concept [10, 13], was first experimentally applied in [14] and later on by the Tokyo helioscope [15], before CAST.

2. Status of CAST and latest results
The CAST experiment is making use of a decommisioned LHC test magnet that provides a magnetic field of 9 Tesla along its two parallel pipes of 2×14.5 cm² area and 10 m length, increasing the corresponding axion-photon conversion probability by a factor 100 with respect to the previous best implementation of the helioscope concept [16]. The magnet is able to track the Sun by about 3 hours per day, half in the morning and half in the evening. At its two ends x-ray detectors are placed, at the "sunrise" side, a Micromegas detector [17] and a CCD [18], and at the "sunset" side two additional Micromegas detectors, installed in 2007 replacing the former TPC [19]. All of the detector setups are conceived following low background techniques (shielding, radiopure materials). The CCD is coupled to a focusing X-ray device (X-ray telescope) [18] that enhances its signal-to-background ratio by two orders of magnitude. Both the CCD and the X-ray telescope are prototypes developed for X-ray astronomy.

The experiment already released its phase I results from data taken in 2003 and 2004 with vacuum in the magnet bores [16, 20]. No signal above background was observed, implying an upper limit to the axion-photon coupling \( g_{a\gamma} < 8.8 \times 10^{-11}\text{ GeV}^{-1}\) at 95\% CL for the low mass (coherence) region \( m_a \leq 0.02\text{ eV}\) (Fig. 1). Since 2006 the experiment runs its second phase, which makes use of a buffer gas inside the magnet bores to recover the coherence of the conversion for specific axion masses matching the effective photon mass defined by the buffer gas density. The pressure of the gas is changed in discrete small steps to scan the parameter space above \( m_a \sim 0.02\text{ eV}\). The \(^4\text{He}\) Run taken in 2006 [21], allowed to scan axions masses up to 0.39 eV, for axion-photon couplings down to about \(2.2 \times 10^{-10}\text{ GeV}^{-1}\), entering into the QCD axion model band, as shown in Fig. 1. Due to gas condensation, in order to go to higher pressures, the experiment switched to \(^3\text{He}\) as buffer gas in 2007. The experiment is currently immersed in the \(^3\text{He}\) Run since beginning of 2008. It should last until end of 2010 and should allow us to explore up to 1.2 eV in axion mass approximately, overlapping with the CMB upper limit on the axion mass discussed above.

At the moment of writing this paper, the experiment has explored a region of axion masses up to about \( m_a \sim 0.70\text{ eV}\), as indicated in the plot 1. Everyday a new thin slice of untouched parameter space is being explored. Due to the sharp coherence effect, and to the fact that the parameter space to which we are sensitive now is populated by realistic QCD axion models and not excluded by previous experiments, a clear positive signal in CAST may appear at any moment.

The collaboration has performed by-product analysis of the data taken, to look for non-standard axion scenario to which CAST would also be sensitive. Using data from the TPC in the CAST phase I, a search for 14 keV axions coming from M1 transitions in the Sun has been recently released [22]. In addition, data taken with a calorimeter during the phase I, were used to search for high energy (MeV) lines from high energy axion conversion [23]. More recently a few days of data were taken with a visible detector coupled to one end of the CAST magnet, in search for axions with energy in the "visible" range, possibly produced in the surface magnetic field of the Sun. A preliminary result was presented recently [24], but more extended data taking is foreseen without interfering with the standard program of CAST by means of a permanent setup that will be installed in the next weeks in CAST.
3. Conclusions and prospects

The CAST experiment is going through the $^3$He phase of data taking, and will fully complete its original program by the end of 2010. CAST will have explored a substantial region of axion-like parameter space beyond previous limits, including a part populated with realistic QCD models.

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
[2] M. S. Turner, Phys. Rept. 197, 67 (1990).
[3] E. Kolb and M. Turner, The Early Universe (, 1990).
[4] A. Burrows, M. T. Russell, and M. S. Turner, Phys. Rev. D42, 3297 (1990).
[5] J. Engel, D. Sedel, and A. C. Hayes, Phys. Rev. Lett. 65, 960 (1990).
[6] S. Hannestad, A. Mirizzi, and G. Raffelt, JCAP 0507, 002 (2005), hep-ph/0504059.
[7] H. Schlattl, A. Weiss, and G. Raffelt, Astropart. Phys. 10, 353 (1999), hep-ph/9807476.
[8] G. G. Raffelt, Ann. Rev. Nucl. Part. Sci. 49, 163 (1999), hep-ph/9903472.
[9] G. G. Raffelt, Phys. Rev. D33, 897 (1986).
[10] P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983).
[11] S. J. Asztalos et al., Phys. Rev. D64, 092003 (2001).
[12] S. J. Asztalos et al., Phys. Rev. D69, 011101 (2004), astro-ph/0310042.
[13] K. van Bibber, P. M. McIntyre, D. E. Morris, and G. G. Raffelt, Phys. Rev. D39, 2089 (1989).
[14] D. M. Lazarus et al., Phys. Rev. Lett. 69, 2333 (1992).
[15] S. Moriyama et al., Phys. Lett. B434, 147 (1998), hep-ex/9805026.
[16] CAST, K. Ziotas et al., Phys. Rev. Lett. 94, 121301 (2005), hep-ex/0411033.
[17] P. Abbott et al., New J. Phys. 9, 170 (2007), physics/0702100.
[18] M. Kuster et al., New J. Phys. 9, 169 (2007), physics/0702188.
[19] D. Antier et al., New J. Phys. 9, 171 (2007), physics/0702189.
[20] CAST, S. Andriamonje et al., JCAP 0704, 010 (2007), hep-ex/0702006.
[21] CAST, E. Arik et al., JCAP 0902, 008 (2009), 0810.4482.
[22] CAST, S. Andriamonje et al., (2009), 0906.4488.
[23] CAST, S. Andriamonje et al., (2009), 0904.2103.
[24] CAST, G. Cantatore et al., (2008), 0809.4381.

Figure 1. 95% CL exclusion line obtained from the published CAST data, both phase I (black line) and $^4$He Run (red line), compared with other laboratory limits such as the Tokyo helioscope and the cosmological upper limit on the axion mentioned in the text. The shaded area indicates the region of theoretical preference for axion models. The thick vertical dashed red line indicates approximately the current progress of CAST data taking with $^3$He.