Status and perspectives of the CAST experiment

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Abstract. The CERN Axion Solar Telescope (CAST) is currently the most sensitive axion helioscope designed to search for axions produced by the Primakoff process in the solar core. CAST is using a Large Hadron Collider (LHC) test magnet where axions could be converted into X-rays with energies up to 10 keV. During the phase I, the experiment operated with vacuum inside the magnet bores and covered axion masses up to 0.02 eV. In the phase II, the magnet bores were filled with a buffer gas (first ^{4}He and later ^{3}He) at various densities in order to extend the sensitivity to higher axion masses (up to 1.18 eV). The phase II data taking was completed in 2011. So far, no evidence of axion signal has been found and CAST set the most restrictive experimental limit on the axion-photon coupling constant over a broad range of axion masses. The latest CAST results with ^{3}He data in the mass range 0.39 eV $< m_a <$ 0.64 eV will be presented.

1. Introduction

Axions are hypothetical particles arising in models which may solve the CP problem in quantum chromodynamics, the so-called strong CP problem. The underlying Peccei-Quinn mechanism [1, 2, 3] introduces a new global chiral $U(1)$ symmetry that is spontaneously broken at a large energy scale f_a, and the axion is the associated Nambu-Goldstone boson. Axions are practically stable neutral pseudoscalar particles and also viable candidates for both cold [4, 5] and hot [6, 7] dark matter. The phenomenology is determined by the scale f_a. The axion mass can be expressed as $m_a = 6\ \mathrm{eV}(10^6\ \mathrm{GeV}/f_a)$.

Most of the axion experimental searches are based on the axion interaction with two photons given by Lagrangian $\mathcal{L}_{a\gamma} = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,a$ where $\mathbf{E}$ is the electric and $\mathbf{B}$ the magnetic field while the axion-photon coupling constant can be written as $g_{a\gamma} = (\alpha/2\pi f_a)\,[E/N - 2(4+z)/3(1+z)]$. Here $z = m_u/m_d$ with the canonical value 0.56 and E/N is a model-dependent parameter (the KSVZ model [8, 9], where $E/N = 0$, is our benchmark case). As a consequence of this interaction, axions could transform into photons and vice versa in external electric or magnetic fields [10]. While the ongoing ADMX experiment [11] is searching for dark matter axions, the CAST experiment has been using a dipole magnet oriented towards the Sun looking for hot dark matter axions. Axions could be produced in the hot solar interior by converting thermal photons in the Coulomb fields of nuclei and electrons (the Primakoff process), and be back-converted into photons in a strong laboratory magnetic field.

After the first implementation of the "axion helioscope" principle in Brookhaven [12], a more sensitive experiment was built in Tokyo [13, 14, 15]. The most sensitive axion helioscope yet is the CAST experiment, using a test LHC magnet ($L = 9.26$ m, $B = 9$ T) mounted on a platform to follow the Sun for about 1.5 h at sunrise and sunset [16, 17, 18, 19, 20, 21].

CAST began operation in 2003 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 conversion volume was filled with a buffer gas (first ^{4}He and later ^{3}He). In the presence of the buffer gas, the axion-photon conversion probability is

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

where Γ is the inverse photon absorption length in the buffer gas, while the axion-photon momentum difference is given by $q = |(m_a^2 - m_\gamma^2)/2E_a|$ where m_γ is the effective photon mass in a gas. For axions and photons to be in phase along the magnet length, the coherence condition $qL < \pi$ has to be satisified. Therefore, the experimental sensitivity is restricted to a range of axion masses (in the CAST vacuum phase, $m_a \leq 0.02$ eV). With the presence of the buffer gas, the sensitivity is restored for a narrow mass window around $m_a = m_\gamma$ [22]. In order to cover equally the accessible mass range, the gas density had to be increased in appropriate steps.

2. CAST operation and results

The operation of the CAST experiment was performed in several phases:

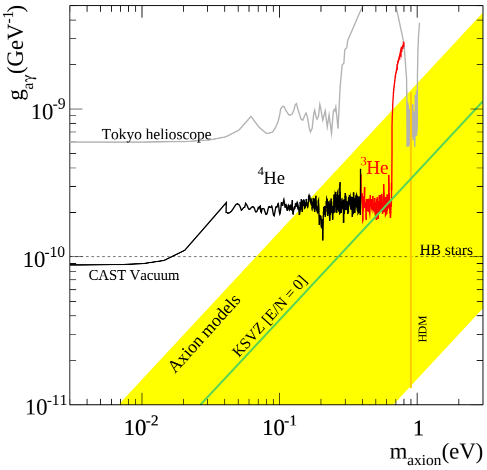

Figure 1. Exclusion plot in the m_a–$g_{a\gamma}$–plane achieved by CAST in the vacuum, ^{4}He and ^{3}He phase. We also show constraints from the Tokyo helioscope, horizontal branch (HB) stars, and the hot dark matter (HDM) bound. The yellow band represents typical theoretical models with $|E/N - 1.95| = 0.07$–7. The green solid line corresponds to $E/N = 0$ (KSVZ model).

- **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. With the absence of signal over background, an upper limit on the axion-photon coupling constant of $g_{a\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} at 95% C.L. was set [16, 17]. This result superseeds the astrophysical limit derived from energy-loss arguments on horizontal branch stars (Fig.1).
- **Phase II with ^{4}He**: during 2005 and 2006 the magnet bores were filled with ^{4}He. 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 is shown in Fig.1 [18]. The measurement time at each pressure setting was only a few hours, resulting in large statistical fluctuations of the exclusion limit. For the first time, the limit entered the QCD axion model band in the electronvolt range.
- **Phase II with ^{3}He**: From 2008 to 2011, CAST was taking data with ^{3}He inside the magnet bores and scanned the range of axion masses up to 1.18 eV. The first results for the axion mass range 0.39 eV $< m_a <$ 0.64 eV are shown in Fig.1 [21]. CAST is the first axion helioscope experiment that crossed the KSVZ axion line.

Apart from the main line of research, CAST has also performed searches for axions from M1 nuclear transition [19, 20] and low energy axions [23].

3. Upgrades for the ^{3}He phase

In order to prepare for the ^{3}He phase, the CAST experiment performed several upgrades. The most important upgrade was the design and installation of a complex ^{3}He gas system. The system has provided high accuracy in measuring the gas quantity, absence of thermoacoustic oscillations, flexible operation modes, and protection of cold, thin X-ray windows during a quench. In order to calculate the amount of gas needed to achieve the desired gas density, a set of computational fluid dynamic (CFD) simulations have been performed. The simulations take into account the actual system as well as different physical phenomena.

The CAST detectors were upgraded as well. The Time Projection Chamber (TPC) [24] that had covered both bores on the sunset end of the magnet was replaced by two shielded Micromegas detectors (bulk and microbulk) [25, 26, 27]. On the sunrise end a new shielded bulk (and later on microbulk) Micromegas replaced the unshielded one [28]. The upgraded detectors have provided improvements in terms of background level, energy resolution, stability and homogeneity of response. The X-ray mirror telescope with a pn-CCD chip [29] covering the other bore on the sunrise end remained unchanged.

4. Prospects

In the immediate future, CAST is planning to revisit a part of the ^{4}He phase with high performance detectors and to continue R&D towards the "ultra-low background" Micromegas detectors. With these detectors and new optics, CAST will be able to revisit the vacuum phase with significantly improved sensitivity and in parallel to search for other exotic particles like chameleons, paraphotons and relic (cold dark matter) axions.

The challenge for the long-term future is to move down in the $m_a - g_{a\gamma}$ parameter space. This goal could be achieved with significant improvements of magnet and detector properties [30]. The design of a new experiment, IAXO (International AXion Observatory), is in preparation.

5. Conclusions

The CAST experiment completed the original program in July 2011 and provided the best experimental limit on the axion-photon coupling constant over a broad range of axion masses. The CAST collaboration has gained a lot of experience in axion helioscope searches. The ongoing R&D on magnets could lead to much more sensitive helioscopes. Future helioscope experiments and microwave cavity searches could cover a significant part of the QCD axion model region in the following decade.

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