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The CAST (CERN Axion Solar Telescope) experiment is searching for solar axions by their conversion into photons inside the magnet pipes of an LHC dipole. The analysis of data taken so far has shown no signal above the background, thus implying an upper limit to the axion-photon coupling of  $g_{a\gamma} < 0.85 \times 10^{-10} \text{GeV}^{-1}$  at 95% CL for  $m_a < 0.02 \text{eV}/c^2$ . Ongoing measurements, with the magnet bores filled with a buffer gas ( $^3\text{He}$ ), are improving the sensitivity of the experiment for higher axion masses towards  $1 \text{eV}/c^2$ . Recent results, new ideas for Axion-Like Particle (WISPs) searches with CAST in the near future and the prospects of a new generation Helioscope are presented here.

## 1 Introduction

The CAST (CERN Axion Solar Telescope) experiment is using a decommissioned LHC dipole magnet to convert solar axions into detectable x-ray photons. Axions are light pseudoscalar particles that arise in the context of the Peccei-Quinn [1] solution to the strong CP problem and can be Dark Matter candidates [2]. Stars could produce axions via the Primakoff conversion of the plasma photons. CAST is pointing at our closest star, the Sun, aiming to detect solar axions. The detection principle is based on the coupling of an incoming axion to a virtual photon provided by the transverse field of an intense dipole magnet, being transformed into a real, detectable photon that carries the energy and the momentum of the original axion. The axion to photon conversion probability is proportional to the square of the transverse field of the magnet and to the active length of the magnet. Using an LHC magnet (9 T and 9.26 m long) improves the sensitivity by a factor 100 compared to previous experiments.

The CAST experiment has been taking data since 2003. During 2003 and 2004 the experiment operated with vacuum in the magnet bores (CAST phase I) and set the best experimental limit [3, 4] on the axion-photon coupling constant in the range of axion masses up to  $0.02 \text{eV}/c^2$ . At this mass the sensitivity is degraded due to coherence loss.

In order to extend CAST sensitivity to higher axion masses, the experimental setup was upgraded in 2005 to operate the second phase of the experiment with the magnet bores filled with a buffer gas. The gas density has to be increased in appropriate steps to cover equally a possible range of axion masses above  $0.02 \text{eV}/c^2$ . In the first part of the CAST phase II (2005-2006),  $^4\text{He}$  was used as a buffer gas. During this time, the experiment scanned the range of axion masses from  $0.02 \text{eV}/c^2$  to  $0.39 \text{eV}/c^2$  and set the most restrictive limit on the axion-photon coupling constant for masses that are, for the first time, in the theoretically favored region [5], which has been used by the Particle Data Group (2010).

In 2007, the system was thoroughly upgraded to use  $^3\text{He}$  as a buffer gas. The ongoing second part of CAST phase II started in 2008 with the goal to cover the range of axion masses up to  $1.16 \text{eV}/c^2$ . So far, the experiment scanned the range up to  $0.88 \text{eV}/c^2$ .

## 2 $^3\text{He}$ as a buffer gas

In the presence of a buffer gas the coherent axion to photon conversion condition is restored for a very narrow mass range, which depends on the gas density [5]. The precise knowledge and reproducibility of each density setting and the density homogeneity along the magnet bore during tracking are essential. Cooling the magnet with superfluid  $^4\text{He}$  at 1.8 K guarantees temperature stability along the cold bore. The amount of gas ejected into the magnet bores is measured precisely with a metering volume kept at stable temperature (typically 36 °C). These allow the reproduction of any desired density setting given the stable conditions of the superconductive magnets.

However, there are parts of the magnet bores, outside the magnetic field region, that are in higher temperatures. These temperatures can vary during tracking causing variations on the buffer gas density. In order to estimate the effect of those variations on the axion to photon conversion probability, a number of temperature and pressure sensors have been placed in several points of the magnet and the gas system. A series of Computational Fluid Dynamics (CFD) simulations with the sensors data as bounding conditions was performed and is still going on, both for the static and dynamic case (magnet movement).

Monitoring the evolution of the  $^3\text{He}$  gas at CAST and comparing it to results from simulations have helped to understand the real nature of the gas, as well as effects such as buoyancy and convection. It has also revealed that CAST is now operating in conditions where the Van der Waals effects are significant; neglecting them can lead to deviations as large as 11%. The simulations performed have allowed the extraction of a precise formula for gas density calculation, being in agreement with experimental data within 200-300 ppm [6]. Also, they have verified that the desired density homogeneity across the magnet bore is achieved. Furthermore, they have allowed the precise knowledge of the gas density during tracking, which is essential for the data analysis.

## 3 First preliminary result from $^3\text{He}$ phase

During the 2007 shutdown, CAST replaced the TPC [7] and the conventional Micromegas [8] with new technology Micromegas detectors, built with the Bulk [9] or Microbulk [10] technology. The enhanced performance of the new detectors [11] in combination with the installation of shielding resulted in a reduction of the background level by a factor of 5-10 in comparison with the past situation. During September 2008 the Bulk detectors were replaced by the more stable Microbulks which showed a background level of  $5 \times 10^{-6} \text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ , equivalent to 1-2 counts per pressure setting. This performance, together with the already very low count rate of the CCD detector [12], makes interesting the use of an unbinned likelihood function in the analysis for the  $^3\text{He}$  phase, instead of the binned version used in  $^4\text{He}$  phase [5]. The unbinned likelihood function can be defined as:

$$\log(L_{m_a}) \propto -R_T + \sum_i^N \log R(t_i, E_i, d_i)$$

where the sum runs over each of the N detected counts and  $R(t_i)$  is the event rate expected at the time  $t_i$ , energy  $E_i$  and detector  $d_i$  of the event  $i$ , while  $R_T$  is the integrated expected number of counts over all exposure time, energy and detectors:

$$R(t, E, d) = B_d + S(t, E, d)$$

being  $B_d$  the background rate of the detector  $d$  and  $S(t, E, d)$  the expected rate from axions in detector  $d$ , which depend on the axion properties  $g_{a\gamma}$  and  $m_a$ :

$$S(t, E, d) = \frac{d\Phi}{dE} P_{a\gamma} \epsilon_d$$

where  $d\Phi/dE$  is the solar axion solar flux spectrum,  $P_{a\gamma}$  the axion photon conversion probability in the CAST magnet and  $\epsilon_d$  the detector efficiency.

Furthermore, the unbinned likelihood is more suitable for situations where the detection conditions are changing. The presence of a small  $^3\text{He}$  leak during 2008 period makes the density of the cold bore to be continuously varying with time. Moreover the analysis of the gas behavior in this phase revealed that the effective cold bore density is affected by cold windows temperatures and convection which change during tracking movement. This effect is especially strong during 2008 data due to the configuration of the boundary conditions. In order to obtain a first exclusion limit on the mass region covered during 2008, the measured value of  $^3\text{He}$  pressure ( $P_{gas}$ ), corrected for the actual cryostat temperature, is assumed to be directly related to the core density, allowing in this approach to obtain the axion mass directly from the  $P_{gas}$  measurement. Then,  $R_T$  is calculated by using the time periods the detectors were in tracking conditions and obtaining the effective exposure time as a function of  $P_{gas}$  or what is equivalent the axion mass determined by the relation:

$$m_a = \sqrt{\frac{0.0201 P_{gas}}{1.8}}$$

Introducing into the unbinned likelihood the expected signal contribution for a given axion mass coming from the total exposure time of the 3 Micromegas detectors, and introducing the tracking counts measured by each detector in the region of sensitivity of the specific axion mass to be calculated, we have obtained a preliminary upper limit to  $g_{a\gamma}$  by integration of the Bayesian probability from zero up to 95% of its area in  $g_{a\gamma}^4$ .

A preliminary limit has been derived [13] from the data taken in CAST in 2008 by the Micromegas detectors and is shown in Figure 1. The total exposure time was about 600 hours, covering axion masses between 0.39 and 0.65  $eV/c^2$ . As soon as the analysis of the CCD data is completed the final combined limit of all detectors will be calculated and published.

## 4 Future outlook

CAST is planning to continue exploiting high axion masses with  $^3\text{He}$  as buffer gas until July 2011. In case that no direct axion signal is observed, the CAST collaboration is preparing a proposal to CERN to extend its scientific program. Developments both in instrumentation and theoretical models, together with enhancements and additions to the existing CAST experimental equipment could enable, in the near-term future, best-in-class searches for several types of particles, including QCD-inspired axions, chameleons, paraphotons or any other exotic WISPs.

The possibility of a significant further reduction of the background level of the Micromegas detectors [11] by optimizing their design, would allow CAST to improve the  $^4\text{He}$  and phase I results. In the first case the search would be oriented towards lowering the sensitivity for axion

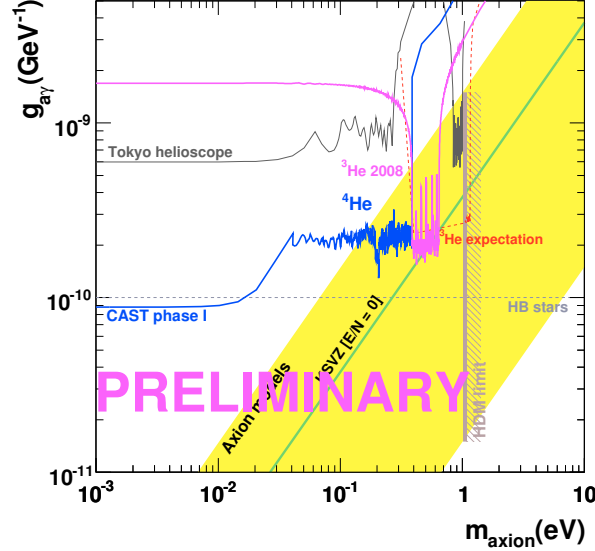


Figure 1: Preliminary exclusion limit (95% CL) from the three Micromegas detectors for axion masses between  $0.39$  and  $0.65 \text{ eV}/c^2$  (2008 data).

masses in the range  $0.02$  to  $0.39 \text{ eV}/c^2$  at the level of  $10^{-10} \text{ GeV}^{-1}$ . In the second case, a sensitivity of the level of  $g_{a\gamma} \approx 5 \times 10^{-11} \text{ GeV}^{-1}$  for  $m_a < 0.02 \text{ eV}/c^2$  could be achieved, after one year data tacking.

Returning to the vacuum phase and lowering the detector threshold at the level of  $0.5 \text{ keV}$ , CAST will become sensitive to solar chameleons [14], a dark energy candidate. This can be achieved in parallel with the axion searches, by using a new, low threshold *Frame Store CCD* [6] and transparent windows for the Micromegas detectors, constructed from nanotube materials [15].

The use of new techniques such as a Glan-Thompson Polarization Beam Splitter can exploit the nature of linearly polarized photons of axion origin. Provided we use very low background photo detectors, the CAST sensitivity for WISP searches in the visible energy range will be significantly enhanced. Furthermore, an extreme UV sensitive Micromegas can be used in order to cover the whole sub-keV range, together with the rest of the CAST detectors.

Besides the searches for WISP conversions in the presence of a magnetic field, CAST infrastructure can be used for parallel search for solar paraphotons (hidden-sector  $U(1)$  gauge bosons). CAST can be used for paraphoton searches either by using the magnet cold bores and the attached detectors or by mounting a dedicated paraphoton conversion vessel and photon detector onto the CAST magnet support structure [16].

In addition to considering various investigations for the near-term, the CAST collaboration has also begun consideration of a *next-generation axion helioscope* aiming to achieve at least an order of magnitude improvement in coupling constant sensitivity, compared to the result obtained by CAST. Such an experiment would require significant investments in developing the required X-ray optics and detectors and the design and construction of a new magnet, specifically optimized for axion searches.

## 5 Conclusions

CAST, during its 10 years of existence has put the strictest experimental limit on axion searches for a wide mass range, while currently is testing axion masses inside the region favored by QCD models. The first preliminary results of the  $^3\text{He}$  data analysis show that high rest mass range ( $\leq 1.16\text{eV}/c^2$ ) can be investigated with the targeted sensitivity. CAST has not observed a direct solar axion signal but has provided world class limits for axions and axion-like particles including paraphotons.

The CAST Collaboration is planning to start new searches for WISPs by mid-2011 when  $^3\text{He}$  phase is going to be completed. Detector development and research on superconducting magnets in combination with the experience gained on solar axion searches can lead to more sensitive future helioscopes.

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