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Probing the eV-Mass Range for Solar Axions with the CAST Experiment

Julia VOGEL[∗†]
Albert-Ludwigs-Universität Freiburg
E-mail: Julia.Vogel@cern.ch

The CERN Axion Solar Telescope (CAST) is searching for solar axions, which could be produced in the core of the Sun via the so-called Primakoff effect. For this purpose, CAST uses a decommissioned LHC prototype magnet. In its magnetic field of 9 Tesla, axions could be reconverted into X-ray photons. The magnet is mounted on a structure built to follow the Sun during sunrise and sunset for a total of about 3 hours per day. The analysis of the data acquired during the first phase of the experiment with vacuum in the magnetic field region yielded the most restrictive experimental upper limit on the axion-to-photon coupling constant for axion masses up to about 0.02 eV. In order to extend the sensitivity of the experiment to a wider mass range, the CAST experiment continued its search for axions with helium in the magnet bores. In this way it is possible to restore coherence for larger masses. Changing the pressure of the helium gas enables the experiment to scan different axion masses. In the first part of this second phase of CAST, ^{4}He has been used and the axion mass region was extended up to 0.4 eV. Therefore the experiment enters the regions favored by axion models. In CAST's ongoing ^{3}He phase the studied mass range is now being further extended. We will present the final results of CAST's ^{4}He phase and give a brief outlook on the experiment's status and its prospects.

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1. Theoretical Motivation

Quantum Chromodynamics (QCD) is expected to violate the so-called CP-Symmetry, but up to now no experiment was able to observe this non-conservation of CP in strong interactions. A possible solution to the strong CP-problem was formulated by R. Peccei and H. Quinn [1] in 1977. They managed to explain the apparent conservation of CP in strong interactions by introducing only one additional symmetry, which is now referred to as the Peccei-Quinn-symmetry. When this new global symmetry is spontaneously broken at a yet unknown breaking scale f_a, it gives rise to a Goldstone boson as Steven Weinberg and Frank Wilczek [2] pointed out independently in 1978. This neutral pseudo-scalar is generally referred to as the axion.

2. Experimental Axion Searches

If they exist, axions could have been created in the very early universe, but they could as well originate from cores of stars like our Sun nowadays. Several constraints from astrophysics and cosmology have been applied in order to prove or rule out the existence of the axion. The mass range, in which axions are still likely to exist, could thus be narrowed down to a window reaching from μeV up to some meV. Several experiments have attempted to detect axions in and close to the remaining mass regions. Although different methods have been applied in the quest for the postulated particle, most of them make use of the so-called Primakoff [3] effect, which allows for a conversion of axions into photons in the presence of a strong electromagnetic field [4]. One possible kind of experiment employing this effect are the helioscopes [5], waiting for axions produced in the closest celestial axion source available: the core of the Sun.

3. The CAST Experiment

The most sensitive existing helioscope is the CERN Axion Solar Telescope (CAST), which utilizes a prototype of a superconducting LHC dipole magnet providing a magnetic field of up to 9 T. CAST is able to follow the Sun twice a day during sunset and sunrise for a total of about 3 h. At both ends of the 10 m long magnet, several X-ray detectors have been mounted to search for photons from Primakoff conversion. Installed on one end of the magnet, two novel MICROMEsh GAseous Structure (MICROMEGAS, MM, [6]) detectors search for the signature of axions during sunset. These detectors replaced the formerly used Time Projection Chamber (TPC, [7]) and thus improved the sensitivity of the experiment. On the other side of the solenoid, two further detectors are mounted waiting for an axion signal during sunrise. One of the ports of the dipole is covered by another MICROMEGAS detector, while the other is occupied by an X-Ray telescope consisting of X-ray mirror optics with a Charge Coupled Device (CCD) as a focal plane detector [8].
In order to investigate different axion mass ranges, the CAST experiment consists of two phases. In its first stage with an evacuated magnetic field region, masses up to 0.02 eV were investigated with very high sensitivity. To extend this range towards higher masses, helium has been filled inside the cold bore, restoring the coherence for axion-to-photon conversion (see Fig. 1). Since the magnet is operated at 1.8 K, ^{4}He gas can only be used up to a pressure of 16.4 mbar, for which it liquefies, and in order to continue the search it has to be substituted by ^{3}He .

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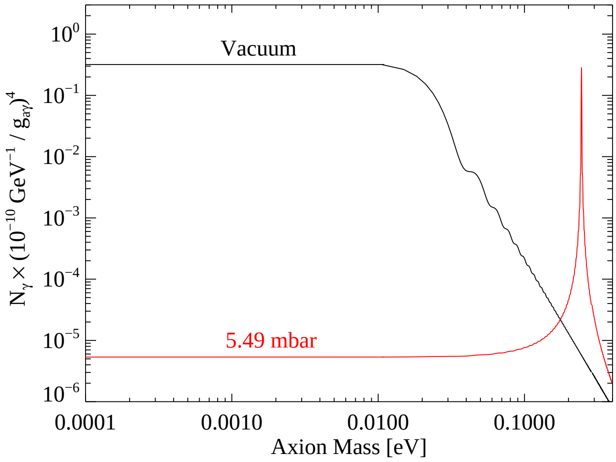

Figure 1: Expected number of photons from axion-to-photon-conversion for CAST with evacuated magnet bores (Phase I, black). An example for a pressure setting measured during Phase II is shown in red.

4. Latest Results of CAST

The first phase of CAST succeeded in 2004 with two years of data. No significant signal above background was observed when following the Sun. Thus, an upper limit on the axion-to-photon coupling of $g_{a\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} (95% C.L.) for axion masses $m_a \lesssim 0.02$ eV [9] was determined. After the completion of Phase I, CAST was upgraded to allow for operation with helium gas at various pressures inside the magnetic field region. For this purpose, a sophisticated gas system and novel cold windows were designed and installed. During the first part of Phase II in 2005 and 2006 the magnet was filled with ^{4}He gas and axion masses up to 0.39 eV have been investigated by measuring 160 different density steps between 0.08 and 13.4 mbar. Since no significant excess of X-rays was observed, when the magnet was pointing to the Sun, a typical upper limit on the axion-photon coupling of $g_{a\gamma} \lesssim 2.2 \times 10^{-10}$ GeV^{-1} at 95% CL for $m_a \lesssim 0.4$ eV was extracted [10]. The exact value depends on the considered pressure setting. The final results for the ^{4}He data are displayed in Fig. 2 together with the prospects for the ^{3}He run, during which axion masses up to 1.2 eV are being studied. At the moment, CAST is taking data with ^{3}He in the magnet bores and over 340 density steps have already been measured. Further upgrades for the experiment are in progress, such as for example the design and construction of a new framestore CCD with enhanced performance in comparison to the present detector.

5. Conclusions and Outlook

The results obtained by CAST from the combination of the Phase I and ^{4}He data allow CAST to enter as the first experiment into so far unexplored regions of the axion parameter space favored by theoretical models. CAST is thus to date the most sensitive experiment looking for axions in a wide and interesting mass range. With ^{3}He in the magnet bores, CAST is currently extending its axion search even further into the unexplored regions of the favored axion models continuing the hunt for the elusive particle. The analysis of these data is ongoing and first results can be expected

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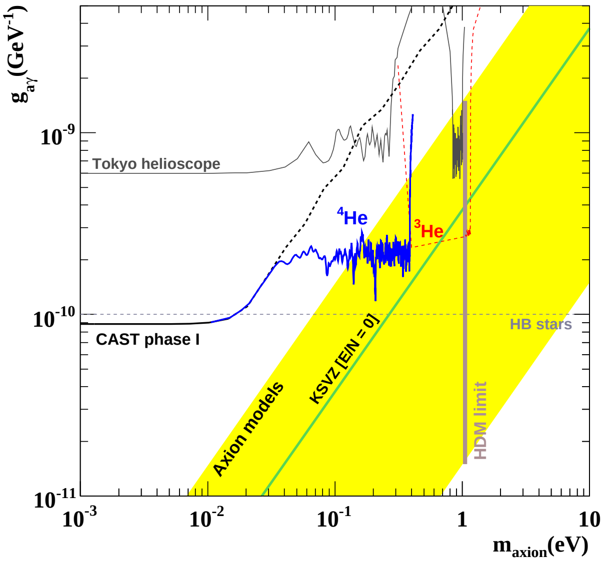

Figure 2: CAST exclusion plot of the axion-to-photon coupling constant at 95% CL for all data obtained in Phase I and Phase II with ^{4}He gas at CAST with the three X-ray detectors of CAST (CCD, MM and TPC). The achieved limit of CAST is compared with the Horizontal Branch (HB) star limit [11] and the hot dark matter (HDM) limit [12]. The yellow band represents the typical theoretical axion models and the green solid line corresponds to the case of the KSVZ model with $E/N = 0$. The prospects for data taking with ^{3}He have been included in red [10].

soon. The goal of present and future axion searches seems to be as clear as it is challenging: Find the hypothetical particle or rule out its existence by closing the allowed mass window once and for all. Either way, CAST will be able to help shedding light on this particular dark matter candidate.

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