CAST solar axion search with $^3$He buffer gas: Closing the hot dark matter gap

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Introduction.—The most promising method to search for axions and axion-like particles (ALPs) [1, 2], low-mass bosons with a two-photon interaction vertex, is their conversion to photons in macroscopic magnetic fields [3, 7]. This approach includes the search for solar axions by the helioscope technique [8–15], photon regeneration experiments (“shining light through a wall”) [16, 18], axion-photon conversion in astrophysical $B$ fields [19, 22], and the search for galactic axion dark matter [23, 27].

One limiting factor in any of these efforts is the momentum difference between freely propagating photons and axions caused by the axion mass $m_a$. It limits the magnetic field volume over which the conversion is coherent. In solar axion searches one can extend the search to larger $m_a$ values by providing the photons with a refractive mass [28]. The conversion pipe is filled with a low-$Z$ buffer gas; the search mass is chosen by adjusting the gas pressure. In this way, the CERN Axion Solar Telescope (CAST), the largest axion helioscope to date, has successively pushed its search range to higher $m_a$ values (see Fig. 1 for a summary of results). We here report on the final search range based on $^3$He buffer gas.

Within the ALP family of hypothetical bosons, the original axion is the best-motivated case because it...
emerges from the compelling Peccei-Quinn mechanism to explain the absence of CP-violating effects in QCD. In the two-dimensional $g_{a\gamma}$-$m_a$ ALP parameter space, the QCD axion must lie somewhere on the line $g_{a\gamma} \propto m_a$ which is anchored to $\pi^0$. After allowing for model-dependent numerical factors, the axion may be found anywhere in the yellow band indicated in Fig. 1. The CAST vacuum result ($g_{a\gamma} < 0.88 \times 10^{-10}$ GeV$^{-1}$ at 95% CL for $m_a < 0.02$ eV [13]) remains a milestone in the ALP landscape. However, a major objective of CAST has been to find or exclude QCD axions and thus to push as far as possible to higher $m_a$ values. Our first $^3$He limits [15] have for the first time crossed the axion line appropriate for the KSVZ model (Fig. 1) [32, 33].

QCD axions with parameters in this range thermalize in the early universe after the QCD phase transition by interactions with pions [34] and would thus exist with a present-day number density of around 50 cm$^{-3}$, comparable to 0.5 neutrino species, and thus are susceptible to hot dark matter bounds [31, 32, 36]. Assuming neutrino masses to be negligible, the latest axion hot dark matter bound is $m_a \lesssim 0.9$ eV, leaving a small gap to our earlier $^3$He search range which we now close.

The recent Planck measurements of the cosmic microwave background (CMB) significantly improve our knowledge of many cosmological parameters. In contrast to earlier CMB results, Planck alone now constrains the axion mass and provides a limit $m_a < 1.01$ eV (95% CL). The inclusion of other data sets, notably the matter power spectrum and the HST measurement of the Hubble parameter, have only a small impact, providing limits between 0.67 and 0.86 eV, depending on the combination of data sets [37]. In other words, concerning a possible axion hot dark matter contribution to the universe, the situation after Planck is almost the same as before.

Data taking strategy.—CAST uses an LHC test dipole magnet ($L = 9.26$ m, $B \sim 9.0$ T) mounted on a movable platform to follow the Sun for about 1.5 h both at sunrise and sunset. One of the apertures of the magnet is covered by a CCD/Telescope system [38] and the other three by three Micromegas detectors of the microbulk type [39, 42].

The axion-photon conversion probability when the conversion volume is filled with a buffer gas ($^3$He in our case) is

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

where $\Gamma$ is the inverse photon absorption length in the buffer gas, and the axion-photon momentum transfer provided by the magnetic field is $q = |m_a^2 - m_\gamma^2|/2E$. The maximum conversion probability is reached for $m_a \simeq m_\gamma$ where $m_\gamma$ is the photon refraction mass which depends on the buffer gas density. For $m_a \neq m_\gamma$, the probability rapidly decreases due to the axion-photon momentum mismatch.

Throughout CAST Phase II, the data taking strategy was to increase the density in the cold bore circuit in small steps chosen to partially overlap the intrinsic mass acceptance (~1 meV FWHM) of the previous setting and so scan smoothly over the whole available mass range. The original step size and exposure time have been modified on a number of occasions in order to complete the physics program more efficiently without compromising continuity, but at the expense of reduced sensitivity at higher masses.

The central gas density inside the cold bore, with the magnet horizontal, was calculated from the cold bore pressure ($P_{cb}$) measured at one end of the cold bore, the magnet temperature $T_{mag}$ and the equation of state (EoS) of $^3$He gas [13]. During solar tracking, $P_{cb}$ changed continuously due to the changing hydrostatic pressure of the $^3$He gas column and due to a slow characteristic temperature transient in the magnet (10-15 mK) caused by the tilting affecting the regulation and efficiency of the 1.8 K heat exchanger. In addition, because of the presence of short warm link regions, $^3$He temperature and density are not uniform in the system and regions with lighter vapour are present at the extremities, where
buoyancy-driven flows occur. The magnet tilting affects such phenomena, giving rise to a redistribution of the $^3$He mass and a consequent further pressure change. Computational Fluid Dynamics (CFD) simulations are required to describe the complex fluid dynamics involved which results in the measured pressure and the density profile along the cold bore.

The actual density profile cannot be measured directly but the experimental pressure variation on tilting is a key indicator which the CFD simulation must reproduce. An extensive and on-going program of CFD simulations has been undertaken. The CFD simulations take into account all requisite physical phenomena, such as gravity, natural convection and turbulence together with the geometry of the cold bores, link volumes and the cold windows and the buffer gas EoS. The boundary conditions are defined by the number of moles of $^3$He gas in the system, $T_{\text{mag}}$ and several temperatures measured around the link volumes and cold windows.

The predicted pressure variations are in satisfactory agreement with those observed experimentally when tilting. This result justifies the method used in the data analysis for calculating the central density during tracking, where we use a continuously re-evaluated value for the central density, calculated from $P_{\text{cb}}$, the hydrostatic correction, $T_{\text{mag}}$ and the EoS.

The density profiles derived from the CFD simulations made with the magnet horizontal and over the full range of Phase II density settings were subjected to a simple and conservative coherence criterion ($\Delta \rho < 0.001$ kg m$^{-3}$). The resulting dependence of the effective coherence length $L_{\text{eff}}$ with density was parametrised and applied to all data independent of photon energy and tilt angle. $L_{\text{eff}}$ decreases from about $\sim 9$ m to $\sim 6$ m in the range $m_a=0.4$ eV to $m_a=1.15$ eV, compared with the magnetic length of 9.26 m. The CFD simulations made with magnet tilted allow an estimate to be made that the final effect on the limit on the $\gamma$ conversion from applying this simple criterion to be well below 10%.

Data analysis and results.—The data presented in this paper correspond to 1100 hour$\times$detector taken by the three Micromegas detectors from 2009 to 2011 with $^3$He in the system in axion-sensitive conditions (i.e. with the magnet tracking the Sun). Background levels are determined from a larger body of data taken during non tracking time. The data acquired by the CCD/Telescope of this period is under analysis and will be presented in a later publication. The present data correspond to about 418 effective axion mass steps that, together with the first 252 $^3$He steps already released in a previous paper, continuously cover an axion mass range between 0.39 eV and 1.17 eV. Due to the density excursions experienced during a single tracking, data from each actual density step contribute to the neighbouring mass steps, specially for the larger densities used. The effective average exposure time per mass step is approximately 0.75 h per detector for masses from 0.64 eV to 1 eV, while it was reduced to $\sim 0.4$ h per detector for masses above 1 eV.

The data analysis is performed in a manner similar to our previous results. We use an unbinned likelihood function that can be expressed as

$$\log \mathcal{L} \propto -R_T + \sum_{i} \log R(t_i, E_i, d_i).$$

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

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

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

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

where $P_{a\rightarrow\gamma}$ is the axion photon conversion probability in the CAST magnet given by Eq. (1) and $\epsilon_d$ the detector effective area. Finally, the solar axion spectrum is

$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} g_{10}^2 \frac{E^{2.81}}{E/1.205} \text{ cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$$

with $g_{10} = g_{a\gamma}/(10^{-10} \text{GeV}^{-1})$ and energies in keV.

As explained in [14], the $m_a$ dependence of the above expression is encoded in the probability $P_{a\rightarrow\gamma}$, which is coherently enhanced for values of $m_a$ matching the refractive photon mass $m_{\gamma}$ induced by the buffer gas density, while it is negligible for values away from $m_{\gamma}$. Therefore, only the counts observed with the gas density matching a given axion mass $m_a$ will contribute to $\log \mathcal{L}$ (and the exclusion plot) for that mass $m_a$. We stress that the value of $m_{\gamma}$ to be introduced is time-dependent even within a single density step, due to the pressure excursions explained above.

Maximization of $\mathcal{L}$ (for a fixed value of $m_a$) leads to a best-fit value of $g_{10}^2$. The obtained value is compatible with the absence of a signal in the entire mass range, and therefore an upper limit on $g_{10}^2$ is obtained by integration of the Bayesian probability from zero up to 95% of its area in $g^2$. This is computed for many values of the axion mass $m_a$ in order to configure the full exclusion plot shown in Fig. A. A close up of the same exclusion plot is shown in Fig. 2 focused specifically in the axion mass range which has been explored in the data presented here.

As can be seen in Fig. CAST extends its previous range towards higher axion masses, excluding the interval 0.64–1.17 eV down to an average value of the axion-photon coupling of $3.3 \times 10^{-10}$ GeV$^{-1}$. The actual
limit contour has a high-frequency structure that is a result of statistical fluctuations that occur when a limit is computed for a specific mass using only a few hours of data. The green solid line corresponds to $E/N = 0$ (KSVZ model).

Conclusions.—CAST has finished its phase of using $^3$He buffer gas, continuing the search to its limiting pressure setting corresponding to a search mass of $m_a = 1.17$ eV. In this way, the search range now generously overlaps with the current cosmic hot dark matter bound of $m_a \lesssim 0.9$ eV and there would be little benefit in pushing to yet larger masses with the buffer-gas technique. CAST has not found axions and the next challenge is to move down in the $m_a-g_{a\gamma}$ plot to reach the “axion band” of theoretical models in a broader range of masses. Such a goal cannot be achieved with the existing CAST apparatus and will require significant improvements of detector and magnet properties, such as the proposed International AXion Observatory (IAXO) or a completely new approach.

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