FIRST RESULTS FROM THE CERN AXION SOLAR TELESCOPE (CAST)

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Hypothetical axion-like particles with a two-photon interaction would be produced in the Sun by the Primakoff process. In a laboratory magnetic field ("axion helioscope") they would be transformed into X-rays with energies of a few keV. Using a decommissioned LHC test magnet, CAST has been running for about 6 months during 2003. The first results from the analysis of these data are presented here. No signal above background was observed, implying an upper limit to the axion-photon coupling $g_{a\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} at 95% CL for $m_a \lesssim 0.02$ eV. This limit is comparable to the limit from stellar energy-loss arguments and considerably more restrictive than any previous experiment in this axion mass range.

1. Introduction

Axions and other hypothetical axion-like particles with a two-photon interaction have been invoked in a number of well-motivated scenarios. In particular, they may provide a solution for the strong CP problem and are viable dark matter candidates[1,2]. They can transform into photons in external electric or magnetic fields[3]; an effect that may lead to measurable consequences in laboratory or astrophysical observations[1,4,5,6,7,8,9,10]. For example, axions would contribute to the magnetically induced vacuum birefringence, interfering with the corresponding QED effect[11,5]. The PVLAS experiment[12] apparently observes such an effect far in excess of the QED expectation, although an interpretation in terms of axion-like particles requires a coupling strength far larger than existing limits.

Stars could produce these particles by transforming thermal photons in the fluctuating electromagnetic fields of the stellar plasma[13,14]. Anomalous stellar energy loss by axion emission is constrained by the observed properties of globular cluster stars, implying[14] $g_{a\gamma} \lesssim 10^{-10}$ GeV^{-1} for the axion-photon coupling, where the axion-photon interaction is written in the usual form $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$. Therefore, the Sun would be a strong axion source and thus offers a unique opportunity to actually detect these particles by taking advantage of their back-conversion into X-rays in laboratory magnetic fields[4]. The expected solar axion flux at the Earth due to the Primakoff process[a] is $\Phi_a = g_{10}^2\, 3.67 \times 10^{11}$ cm^{-2} s^{-1} (where $g_{10} \equiv g_{a\gamma}\, 10^{10}$ GeV) with an approximate spectrum $d\Phi_a/dE_a = g_{10}^2\, 3.821 \times 10^{10}$ cm^{-2} s^{-1} keV^{-1} $(E_a/\mathrm{keV})^3/(e^{E_a/1.103\ \mathrm{keV}} - 1)$ and an average energy of 4.2 keV [15].

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[a] Axion interactions other than the two-photon vertex would provide for additional production channels, but in the most interesting scenarios these channels are severely constrained, leaving the Primakoff effect as the dominant one[14]. In any case, it is conservative to use the Primakoff effect alone when deriving limits on $g_{a\gamma}$.

The conversion probability in a B-field in vacuum is[4] $P_{a\to\gamma} = (g_{a\gamma}B/q)^2\sin^2(qL/2)$, where L is the path length and $q = m_a^2/2E_a$ is the axion-photon momentum difference. For $qL \lesssim 1$ where the axion-photon oscillation length far exceeds L we have $P_{a\to\gamma} = (g_{a\gamma}BL/2)^2$, implying an X-ray flux of

$$\Phi_\gamma = 0.51\ \mathrm{cm}^{-2}\ \mathrm{d}^{-1}\, g_{10}^4 \left(\frac{L}{9.26\ \mathrm{m}}\right)^2 \left(\frac{B}{9.0\ \mathrm{T}}\right)^2 . \qquad (1)$$

For $qL \gtrsim 1$ this rate is reduced due to the axion-photon momentum mismatch. The presence of a gas would provide a refractive photon mass m_γ so that $q = |m_\gamma^2 - m_a^2|/2E_a$. For $m_a \approx m_\gamma$ the maximum rate can thus be restored[18].

The Tokyo axion helioscope[19] of $L = 2.3$ m and $B = 3.9$ T has provided the limit $g_{10} < 6.0$ at 95% CL for $m_a \lesssim 0.03$ eV (vacuum) and $g_{10} < 6.8$–10.9 for $m_a \lesssim 0.3$ eV (using a variable-pressure buffer gas)[20]. Limits from crystal detectors[21,22,23] are much less restrictive.

2. CAST experiment

In order to detect solar axions or to improve the existing limits on $g_{a\gamma}$ an axion helioscope has been built at CERN by refurbishing a de-commissioned LHC test magnet[24] which produces a magnetic field of $B = 9.0$ T in the interior of two parallel pipes of length $L = 9.26$ m and a cross–sectional area $A = 2 \times 14.5\ \mathrm{cm}^2$. The magnet is mounted on a platform with ±8° vertical movement, allowing for observation of the Sun for 1.5 h at both sunrise and sunset. The horizontal range of ±40° encompasses nearly the full azimuthal movement of the Sun throughout the year. The time the Sun is not reachable is devoted to background measurements. A full cryogenic station is used to cool the superconducting magnet down to 1.8 K[25]. The hardware and software of the tracking system have been precisely calibrated, by means of geometric survey measurements, in order to orient the magnet to any given celestial coordinates. The overall CAST pointing precision[26] is better than 0.01°. At both ends of the magnet, three different detectors have searched for excess X-rays from axion conversion in the magnet when it was pointing to the Sun. Covering both bores of one of the magnet's ends, a conventional Time Projection Chamber (TPC) is looking for X-rays from "sunset" axions. At the other end, facing "sunrise" axions, a second smaller gaseous chamber with novel MICROMEGAS (micromesh gaseous structure – MM)[27] readout is placed behind one of the magnet bores, while in the other one a focusing X-ray mirror telescope is

Table 1. Data sets included in our result.

Data set	Tracking exposure (h)	Background exposure (h)	$g_{a\gamma}(95\%)$ $(10^{-10}\ \mathrm{GeV}^{-1})$
TPC	62.7	719.9	1.55
MM set A	43.8	431.4	1.67
MM set B	11.5	121.0	2.09
MM set C	21.8	251.0	1.67
CCD	121.3	1233.5	1.23

working with a Charge Coupled Device (CCD) as the focal plane detector. Both the CCD and the X-ray telescope are prototypes developed for X-ray astronomy[28]. The X-ray mirror telescope can produce an "axion image" of the Sun by focusing the photons from axion conversion to a $\sim 6\,\mathrm{mm}^2$ spot on the CCD. The enhanced signal-to-background ratio substantially improves the sensitivity of the experiment. A detailed account of the technical aspects of the experiment will be given elsewhere.

3. Data Analysis and First Results

CAST has been in operation for about 6 months from May to November in 2003, during which time most detectors were taking data. The results presented here were obtained after the analysis of the data sets listed in Table 1. An independent analysis was performed for each data set. Finally, the results from all data sets are combined.

For a fixed m_a, the theoretically expected spectrum of axion-induced photons has been calculated and multiplied by the detector efficiency curves. These spectra, which are proportional to $g_{a\gamma}^4$, are directly used as fitting functions to the experimental subtracted spectra (tracking minus background) for the TPC and MM. For these data, the fitting is performed by standard χ^2 minimization. Regarding the CCD data, the analysis is restricted to the small area on the CCD where the axion signal is expected after the focusing of the X-ray telescope. The resulting low counting statistics in the CCD required the use of a likelihood function in the minimization procedure, rather than a χ^2-analysis. For more details on the analysis we refer to [29].

Each of the data sets is individually compatible with the absence of any signal. The 95% CL limits on $g_{a\gamma}$ for each of the data sets are shown in the last column of Table 1. They can be statistically combined by multiplying the Bayesian probability functions to find the global result for the 2003 CAST data:

$$g_{a\gamma} < 1.16 \times 10^{-10}\mathrm{GeV}^{-1}(95\%\mathrm{CL}).$$

Thus far our analysis was limited to the mass range $m_a \lesssim 0.02$ eV where the expected signal is mass-independent because the axion-photon oscillation length far exceeds the length of the magnet. For higher m_a the overall signal strength diminishes rapidly and the spectral shape differs. Our procedure was repeated for different values of m_a to obtain the entire 95% CL exclusion line shown in Fig. 1.

4. Summary

Our limit improves the best previous laboratory constraints [19] on $g_{a\gamma}$ by a factor 5 in our coherence region $m_a \lesssim 0.02$ eV. This result excludes an important part of the parameter space not excluded by solar age considerations [30] and is comparable, in this range of masses, to the limit derived from stellar energy-loss arguments. A higher sensitivity is expected from the 2004 data with improved conditions in all detectors, which should allow us to surpass the astrophysical limit. In addition, starting in 2005, CAST plans to take data with a varying-pressure buffer gas in the magnet pipes, in order to restore coherence for axion masses above 0.02 eV. The extended sensitivity to higher axion masses will allow us to enter into the region shown in Fig. 1 which is especially motivated by axion models [31].

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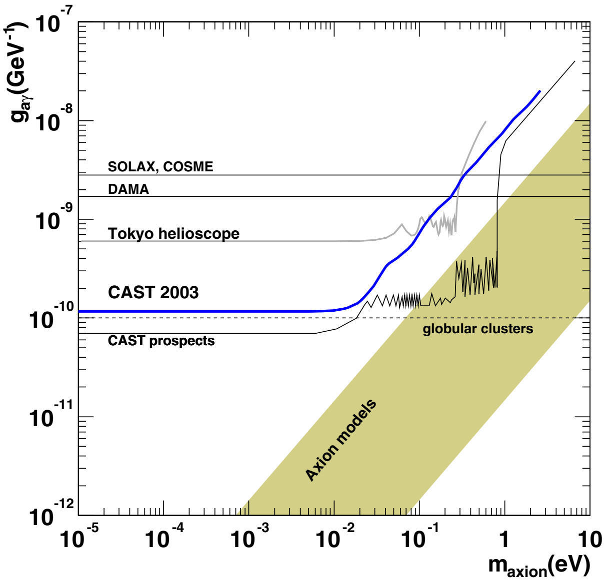

Figure 1. Exclusion limit (95% CL) from the CAST 2003 data compared with other constraints discussed in the introduction. The shaded band represents typical theoretical models. Also shown is the future CAST sensitivity as foreseen in the experiment proposal.

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