THE CERN AXION SOLAR TELESCOPE (CAST)


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A decommissioned LHC test magnet is being prepared as the CERN Axion Solar Telescope (CAST) experiment. The magnet has a field of 9.6 Tesla and length of 10 meters. It is being mounted on a platform to track the sun over ±8° vertically and ±45° horizontally. A sensitivity in axion-photon coupling $g_{\alpha\gamma\gamma} < 5 \times 10^{-11}$ GeV$^{-1}$ can be reached for $m_\alpha \leq 10^{-2}$ eV, and with a gas filled tube can reach $g_{\alpha\gamma\gamma} \leq 10^{-10}$ GeV$^{-1}$ for axion masses $m_\alpha < 2$ eV.

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1. Introduction

Since the first introduction of axions [1,2] to address the strong CP problem [3], there have been many experimental searches. There is an excellent pedagogical article by Sikivie [4] and a recent report on axions [5] that contains much of the work on previous searches. The physics involved in searches utilizing the Primakoff process appears in articles by Sikivie [6], Raffelt and Stodolsky [7] and van Bibber et al. [8]. There have been two previous experiments using magnets to search for solar axions [9,10]. The CAST experiment was proposed in an article by Zioutas et al. [11]. In this short note, we give a brief update and status of the experiment. The CAST instrument is a ~10T magnet, 10m in length. It is being mounted on a platform that can track the sun over a vertical angle of ±89°, and horizontal angle of ±45°.

2. Coherence

The probability that an axion going through the transverse magnetic field, B, over a length, L, will convert to a photon is:

\[ P_{a\gamma} = 1.8 \times 10^{-17} \frac{B}{8.4 T} \frac{L}{10 m} \left( g_{a\gamma\gamma} \times 10^{19} \text{GeV}^{-1} \right)^2 |M|^2, \]  

where,

\[ |M|^2 = \left| \int_0^L \Psi_a^*(x) \Psi_a(x) dx \right|^2 = \frac{2(1 - \cos qL)}{(qL)^2}. \]  

In eq.(2), \( q = |k_a - k_\gamma| \), the momentum exchange. If the axion has mass, \( m_a \), \( \Psi_a(x) = L^{\frac{1}{2}} e^{ik_a x} \) will fall out of phase with

\[ \Psi_\gamma(x) = L^{-\frac{1}{2}} e^{ik_\gamma x}, \]  

by \( \lambda/2 \) after traversing \( L_c = 2\pi h c (\omega_\gamma)/m_a^2 c^4 \), the coherence length. This occurs when \( qL = \pi \). For the 10m long CAST magnet, this occurs for an axion energy \( E_a = 4keV \) for a mass of \( \sim 10^{-2}eV/c^2 \). To search for axions more massive, it is necessary to fill the beam pipe inside the magnet with a gas to “slow” the photons, so that they remain in phase with the axions. It is easily shown that the plasma frequency in the gas is \( \omega_p^2 = 4\pi n_e r_e c^2 \), where \( n_e \) is the spatial density of electrons, \( r_e \) is the classical electron radius, and \( c \) is the speed of light in vacuum [12]. One can then write the effective mass of a photon in a gas as

\[ m_{\gamma\text{eff}}^2 = \frac{\hbar c (4\pi r_e n_e)^{\frac{1}{2}}}{(\hbar c - 1.975 \times 10^{-4} eV \cdot cm)}. \]

Accordingly, the momentum exchange, \( q \), in the gas can be written:

\[ q = \left( a^2 n_e - m_{\gamma\text{eff}}^2 \right)/2E_a \hbar c, \]  

were \( a = 3.716 \times 10^{-11} eV cm^2 \), so that \( a^2 n_e = m_{\gamma\text{eff}}^2 \), the effective photon rest energy squared. For a gas of \( ^4He \) at 300K, the required pressure in atmospheres is given by \( P(\text{Atm.}) \approx 14.8 (m_{\gamma\text{eff}}^2 eV^2/1eV^2) \) in agreement with that given in ref.(8). The ideal condition is for \( q = 0 \), or \( m_{\gamma\text{eff}}^2 = a^2 n_e \), where \( n_e \) in \( ^4He \) at STP is \( 5.378 \times 10^{16}/\text{cm}^3 \). Therefore to remain totally coherent for \( m_{\gamma\text{eff}}^2 = 1eV \), \( n_e \) corresponds to \( 14.8 \) Atmospheres at room temperature. The actual pressure would be for example 1 Atmosphere if cooled to 20.3K.

3. Experimental Parameters

An expression for the bound on \( g_{a\gamma\gamma} \) in terms of experimental parameters is given below:

\[ g_{a\gamma\gamma} \leq 1.4 \times 10^{-9} (GeV)^{-1} \frac{b^{\frac{1}{2}}}{t^{\frac{1}{2}} R^{\frac{1}{2}} L^{\frac{1}{2}} A^{\frac{1}{4}}}, \]  

where \( b \) is the background (counts day\(^{-1}\)), \( t \) is the time of alignment with the sun in days, \( B \) is the field in Tesla, \( L \) is the length in meters, and \( A \) is the area of the magnet bore in cm\(^2\). In this case \( B, L, \) and \( A \) are fixed and only \( t \) and \( b \) can be controlled. Actually since the limits of the tilt of the magnet are controlled by the properties of the cryogenic system that keeps it superconducting, we can really only control the background, \( b \).

Detector backgrounds will be from radioactivity in construction materials, in the beam pipe, and from the surroundings, and are proportional to the detector mass. The CAST collaboration is testing an x-ray mirror system, similar to those used in x-ray astronomy, that can focus axion induced x-rays from the sun to a submillimeter spot. This will not only reduce the background by...
using a position sensitive detector, but will also allow the background to be simultaneously measured with far more area $\times$ exposure time than the rate in the small spot in the detector where the axion signal is expected.

Three position sensitive detectors are being developed, a small gas time projection chamber, a p-n CCD, and a micromegas detector. All these are position sensitive and low background. Using our best estimates of the predictions of all of the parameters in equation (4), the predicted exclusion plot is shown in Fig. 1.

![Image](image_url)

Figure 1. Figure 1, a) sensitivity attainable (99.7\% CL) on $g_{a\gamma\gamma}$ as a function of axion mass. b) Present experimental limits of the Tokyo axion helioscope [10]. c) Astrophysical constraints from HB star populations.

4. Conclusion

CAST's LHC magnet is being mounted on a moving platform with X-ray detectors on either end, to observe the Sun an average of 206 minutes per day including sunrise and sunset. The rest of the day will be devoted to background measurements and, through the Earth's motion, observations of a large portion of the sky. CAST's X-ray detectors are under development, with the collaboration looking at gas-filled and solid state options. A chamber using the "micromegas" principle has been tested.

The aperture of the LHC magnet's beam pipes is around five times the predicted solar axion source size, so its X-ray detectors must be correspondingly large, implying a high level of noise. To overcome this problem, the CAST collaboration is considering using X-ray lenses to focus the converted X-rays emerging parallel from the 50 mm magnet aperture to a submillimetre spot. This will bring a vast signal-to-noise improvement.

CAST is a new departure for CERN, relying not on the lab's expertise in accelerators but on its know-how in X-ray detection, magnets and cryogenics. With a discovery potential for axions extending beyond that dictated by astrophysical considerations, the experiment leaves room for surprises and could open up a new field of terrestrial axion astrophysics [13].

REFERENCES