THE CERN AXION SOLAR TELESCOPE

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The CAST experiment at CERN is using a decommissioned LHC prototype magnet to search for solar axions through their Primakoff conversion into x-ray photons. The magnet (B = 9.0 Tesla, L = 10 m) can track the sun each day for a total exposure time of ∼180 minutes (sunrise + sunset). We expect to reach a sensitivity in axion-photon coupling, $g_{a\gamma\gamma} \lesssim 5 \times 10^{-11}$ GeV^{-1} for $m_a \lesssim 10^{-2}$ eV after ∼1 year's running time. By filling the beam tube with ^{4}He or ^{3}He gas we should be able to extend the sensitive axion mass region into the eV mass range.

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1. Introduction

The Standard Model of Electroweak Physics has had remarkable success explaining all the existing experimental data. Its extension to strong interactions, Quantum Chromodynamics, has also proven remarkably successful. However, QCD does have one loose end–its non-Abelian nature introduces T-, P- and CP-violating effects, and, in its basic form, it predicts a substantial CP-violating electric dipole moment (edm) for the neutron – in rather sharp disagreement with experiment ($d_{theory} \sim 10^{-15} e \cdot cm$ and $d_{exp} \sim 10^{-25} e \cdot cm$). The simplest and most elegant solution to this problem is the one proposed by Peccei and Quinn[1]. They showed that a mimimal extension of the Higgs sector endows the SM with a global U(1) symmetry, the Peccei-Quinn(PQ) symmetry, which is broken at some new scale, f_{PQ}. Subsequently Weinberg[2] and Wilzeck[3] pointed out that, since a continuous symmetry has been broken, there must be an associated Goldstone boson (the AXION). Although the axion starts out as a massless Goldstone boson, it eventually acquires an effective mass through intermediate states coupled to its axial colour anomaly.

Axions are attractive candidates for Cold Dark Matter since they could have been produced in the early stages of the Universe. Higher energy axions might also contribute to Hot Dark Matter and help to produce a flat Universe. Axions could also be produced in the core of stars by means of the Primakoff conversion of the blackbody photons in the fluctuating electromagnetic fields of the hot dense plasma. The solar axion flux from our own Sun can easily be estimated[4] using the standard solar model and the conservative assumption of a "hadronic" axion with very small leptonic couplings. The resulting axion flux has a broad spectrum which peaks at about 4 keV as shown in Figure 1.

These solar axions can then be converted back into real photons in the presence of an intense magnetic field here in the laboratory. This is the basic principle of the CERN Axion Solar Telescope (CAST) experiment[5] described in the next section. Although the motivation given above for our experiment has been centred on the axion because of its special theoretical significance, our telescope will search for any type of low mass pseudoscalar or scalar particles which couple to photons and such a discovery would have profound implications in Particle Physics.

A combination of astrophysical and nuclear physics constraints, plus the requirement that the relic axion abundance does not overclose the Universe, restricts the allowed range of viable axion masses to the region

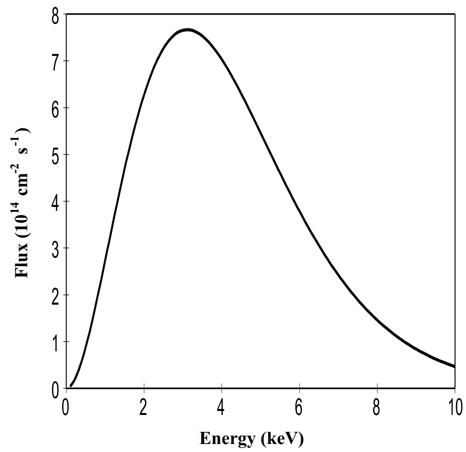

Figure 1. Differential solar axion flux at the Earth assuming Primakoff conversion of the blackbody photon as the only way of solar axion production (hadronic axions).

$10^{-6} \leq m_a \leq 20$ eV[6]. This mass range and the allowed range of $g_{a\gamma\gamma}$ can be further constrained by theoretical arguments based on various astrophysical models. For example, the standard solar model and helioseismological observations[7] limit $g_{a\gamma\gamma} \leq 10^{-9}\ GeV^{-1}$.

Raffelt[8] has written extensively on how these cosmic relic axions could have been produced in the early stages of the Universe and therefore provide some fraction of the Cold Dark Matter required to explain the gravitational measurements and the observed spectrum of the Cosmic Microwave Background anisotropies. Moroi and Murayama[9] have also considered a scenario in which higher mass axions (~ 1 eV) also contribute to the Hot Dark Matter.

There have been two previous magnetic axion searches–a fixed magnet experiment at BNL[10] and a tracking magnet measurement at Tokyo[11],[12] resulting in an upper limit on $g_{a\gamma\gamma} \lesssim 10^{-9}\ GeV^{-1}$ for $m_a = 0.05$–0.27 eV.

2. Experimental Method

The experimental search for axions has focussed on their predicted interaction with the electromagnetic field (F) that would be of the form

$$\mathrm{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} \phi_a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} \phi_a \vec{\mathbf{E}} \cdot \vec{\mathbf{B}} \tag{1}$$

where ϕ_a is the axion field and the coupling strength is

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right) 10^{-9}\ GeV^{-1}. \tag{2}$$

The quantity, E/N is the PQ symmetry anomaly which is the ratio of the electromagnetic and colour anomalies, a model-dependent ratio of small integers. Two popular models are the GUT axion[13] (E/N = 8/3) and the KSVZ[14] model (E/N = 0). The second term in the parenthesis is the chiral symmetry breaking correction which is a function of z = m_u/m_d, the up and down quark masses.

The probability that an axion passing through a transverse magnetic field B over a length L will convert to a photon is given by

$$P_{a\gamma} = 2.4 \times 10^{-17} \left(g_{a\gamma\gamma} \times 10^{10}\ GeV^{-1}\right)^2 |\mathrm{M}|^2 \left(\frac{B}{9.6T}\right)^2 \left(\frac{L}{10m}\right)^2 \quad (3)$$

where the matrix element $|\mathrm{M}|^2 = 2(1 - cos\ qL)/(qL)^2$ accounts for the coherence of the process and q is the momentum exchanged between the axion and the magnet. Since $m_a \neq 0$, the axion and photon waves become out-of-phase after a certain length of travel in the magnet. For the keV energies for solar axions this coherence is preserved up to m_a values $\sim 10^{-2}$ eV over a length of 10 m. For larger axion masses $|M|$ becomes < 1 and we lose sensitivity so we plan to fill the beam pipe inside the magnet with ^{4}He or ^{3}He gas to give an effective mass to the photon through the index of refraction of the gas. Then the photon mass becomes equal to the plasma frequency of the gas, $m_\gamma = \omega_p = \sqrt{4\pi n_e r_0}$ where n_e is the spatial density of the electrons in the plasma and r_0 is the classical electron radius. When $m_a \sim m_\gamma$ coherence is once again restored. By changing the pressure of the gas inside the beampipe m_γ can be varied and so the sensitivity of the experiment can be extended to higher m_a values as shown in Figure 3. The diagonal band indicates the range allowed by the various model-dependent E/N values. Given the improvement of ×10 in our B·L value our sensitivity should be $\sim 5 - 10\times$ better than the Tokyo axion helioscope result[11],[12].

3. The CAST Experiment

The decommissioned LHC super-conducting prototype magnet (B = 9.0 Tesla, L = 10 m) has twin-apertures with an effective cross sectional area = 2 x 14 cm^2. It is mounted on a girder capable of moving ±8° vertically and ±40° horizontally; hence we can track the sun for about 90 minutes at sunrise and also 90 minutes at sunset. The vertical limitation is determined by the cryogenic system which supports the cold mass and the horizontal limitation is a result of the size of the hall. Because of this horizontal limitation we have chosen to mount detectors at both ends of the magnet

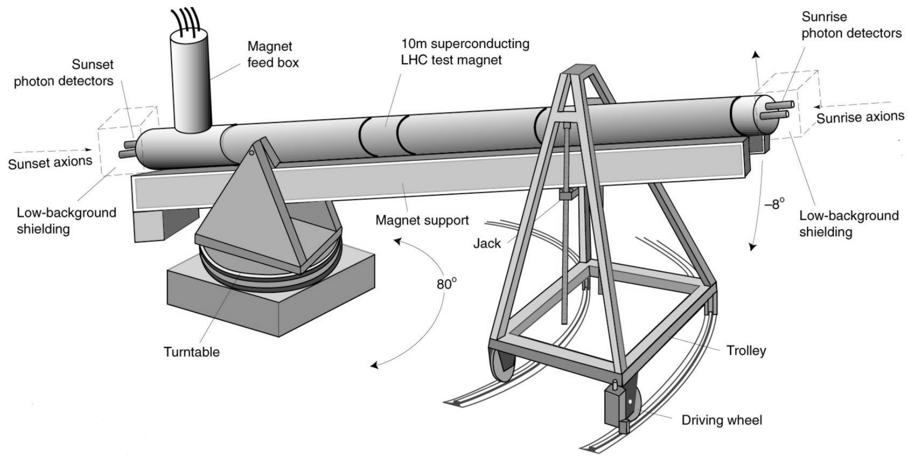

Figure 2. Schematic view of the CAST experimental setup. The 10 m long LHC prototype magnet can move ±8° vertically and ±40° horizontally.

in order to double our observing time. A schematic view of the CAST experimental setup is shown in Figure 2.

The solar axion flux can be computed for a given axion-photon coupling, $g_{a\gamma\gamma}$; hence the expected limit on $g_{a\gamma\gamma}$ in terms of the experimental parameters (assuming total coherence) becomes:

$$g_{a\gamma\gamma} \leq 1.4 \times 10^{-9} \, \frac{b^{1/8}}{t^{1/8}(BL)^{1/2}A^{1/4}} \, GeV^{-1} \tag{4}$$

where b is the background of the x-ray detector (in counts/day), t is the time of alignment with the sun (in days), BL (in Tesla meters) and A is the area of the magnet beampipe (in cm^2). All these quantities are already fixed for CAST except for the background, b, which we have tried to make as low as possible by using very low radioactivity materials for the construction of the detectors. Fortunately the dependence of $g_{a\gamma\gamma}$ on the background is only to the 1/8 power.

We have developed three different types of detectors to detect the low-energy x-rays: a small plexiglass time projection chamber (TPC), a position sensitive CCD detector, and a small MicroMegas detector(MM) – also constructed from plexiglass. The TPC has 48 anode wires and 96 cathode wires placed perpendicular to each other at 3 mm wire spacing. Each wire is readout by a 10 MHz flash ADC so that very accurate positions can be obtained. In this way we can easily separate the spatially localized x-ray events from the long tracks produced by cosmic-rays. The TPC has an active volume = 30 x 15 x 10 cm^3 and is operated with a 95:5 Ar:Ethane

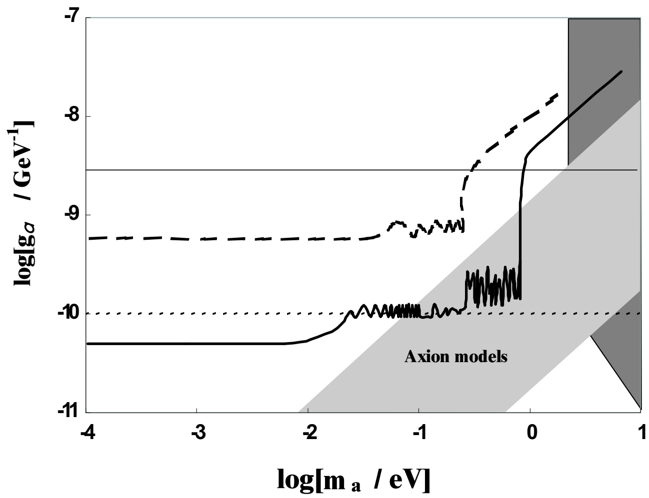

Figure 3. Expected exclusion limit of CAST (solid line) taking into account both data taking phases (vacuum and gas). Also shown are the limits obtained by the SOLAX[15] and COSME[16] experiments using solid state detectors (thin line), and the Tokyo helioscope[11],[12] (dashed line) which uses the same principle as CAST. The region favoured by theoretical axion models is indicated by the light grey band. The dotted line represents the theoretical red giant bound[17] and the dark grey region on the right is excluded by the absence of an axion-decay quasi-monochromatic photon line from galactic clusters[18].

gas mixture at a drift field of 700 V/cm. The energy resolution for an ^{55}Fe source is about 12% (σ) and the noise threshold is about 300 eV. Using various software cuts we have obtained a background counting rate $\sim 10^{-5}$ counts/keV/cm^2/s and we expect this to improve by another factor of 5-10 once the shielding of copper/cadmium/lead/polyethelyne has been installed around the detector. This is roughly equal to the background level estimated in the original proposal.

The TPC detector covers both of the magnet exit windows and will observe the sunset axions. At the other end of the magnet, the sunrise axions will be detected by a CCD + and a MicroMegas detector. In order to improve our signal/noise ratio we have obtained a focussing mirror system which can focus the x-ray beam from the 43 mm beampipe diameter down to a 1 mm spot, thereby greatly improving the signal/noise ratio. A position sensitive CCD detector or a second MicroMegas detector will be mounted behind this focussing telescope.

4. Present Status and Future Plans

The magnet was cooled down to 1.8K in August and it reached full current (13,330 amps) on Sept 9. The first solar data was collected by the TPC detector on Sept 19. The installation of the focussing telescope and the MM detector will take place during October and we expect to collect data with all 3 detectors in a full Engineering run in November. The background shielding for the TPC detector will be installed during the CERN Winter shutdown and we should then be able to run continuously from March until Dec'03. We expect to install the thin Be windows necessary for the implementation of the low pressure gas measurements during the Dec'03 shutdown and we will then run during 2004 with ^{4}He gas and 2005 with ^{3}He gas in the beam tubes in order to extend the axion mass range into the eV region. This will allow CAST to challenge the various theoretical model predictions (see Figure 3). The possibility of adding a high energy γ-ray calorimeter behind the MM detector on the sunrise side of the magnet in order to search for higher mass pseudoscalar particles is also being discussed.

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