Search for solar axions: the CAST experiment


1DAPNIA, Centre d’Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France
2European Organization for Nuclear Research (CERN), Genève, Switzerland
3Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia
4Instituto de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain
5Max-Planck-Institut für extraterrestrische Physik, Garching, Germany
6Enrico Fermi Institute and KICP, University of Chicago, Chicago, IL, USA
7Technische Universität Darmstadt, Institut für Kernphysik, Schlossgartenstrasse 9, 64289 Darmstadt
8Aristotle University of Thessaloniki, Thessaloniki, Greece
9National Center for Scientific Research “Demokritos”, Athens, Greece
10Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
11Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada
12Gesellschaft für Schwerionenforschung, GSI-Darmstadt, Planckstr. 1, 64291 Darmstadt
13Johann Wolfgang Goethe-Universität, Institut für Angewandte Physik, Frankfurt am Main, Germany
14Rudjer Bošković Institute, Zagreb, Croatia
15Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
16Physics Department, University of Patras, Patras, Greece.

Abstract. Hypothetical axion-like particles with a two-photon interaction would be produced in the sun by the Primakoff process. In a laboratory magnetic field they would be transformed into X-rays with energies of a few keV. The CAST experiment at CERN is using a decommissioned LHC magnet as an axion helioscope in order to search for these axion-like particles. The analysis of the 2003 data [1] showed no signal above the background, thus implying an upper limit to the axion-photon coupling of \( g_{a\gamma} < 1.16 \times 10^{-10} \text{ GeV}^{-1} \) at 95% CL for \( m_a \leq 0.02 \text{ eV} \). The stable operation of the experiment during 2004 data taking allowed us to lower down this parameter to a preliminary value of \( g_{a\gamma} < 0.9 \times 10^{-10} \text{ GeV}^{-1} \).

Keywords: Axions, Dark matter, Solar Physics, Low background
INTRODUCTION

QCD is the universally accepted theory for describing the strong interactions, but it has one serious blemish: the so-called “strong CP problem”. QCD predicts the existence of a CP violating term in the standard equations, yet Nature has never exhibited this behavior in any experiment [2, 3]. Various theoretical attempts to solve this strong CP problem have been postulated [2, 4], being the most elegant solution the one proposed by Peccei and Quinn in 1977 [5, 6]. For this they introduced an additional global symmetry, known as the Peccei-Quinn symmetry $U(1)_{PQ}$, to the Standard Model Lagrangian which is spontaneously broken at a scale $f_{PQ}$. Immediately and independently, Weinberg [7] and Wilczek [8] realized that, because $U(1)_{PQ}$ is spontaneously broken, there should be a pseudo-Goldstone boson, “the axion” (or as Weinberg originally referred to it, “the higglet”). Because $U(1)_{PQ}$ suffers from a chiral anomaly, the axion acquires a small mass of the order of $m_a \approx 6 \mu eV (10^{12} GeV / f_{PQ})$.

A priori the value of the mass of the axion (or equivalently the $f_{PQ}$ scale) is arbitrary, but it can be constrained using data from various experiments, astrophysical considerations (cooling rates of stars) and cosmological arguments (overclosure of the Universe) [9, 10]. Nowadays it is believed to fall inside the so-called “axion mass window”: $10^{-6} eV < m_a < 10^{-3} eV$.

The interaction strength of axions with ordinary matter (photons, electrons and hadrons) scales [3] as $1 / f_{PQ}$ and so the larger this number, the more weakly the axion couples. The present constraints on its mass make the axion a weakly interacting particle, therefore a nice candidate for the Dark Matter of the Universe [10].

One generic property of the axions is a two-photon interaction of the form:

$$\mathcal{L}_{\alpha\gamma} = -\frac{1}{4}g_{\alpha\gamma}F_{\nu\mu}\tilde{F}^{\nu\mu}a = g_{\alpha\gamma}E \cdot B a$$

(1)

where $F$ is the electromagnetic field-strength tensor, $\tilde{F}$ is its dual, and $E$ and $B$ the electric and magnetic fields. As a consequence axions can transform into photons in external electric or magnetic fields [11], an effect that may lead to measurable consequences in laboratory or astrophysical observations. For example, stars could produce these particles by transforming thermal photons in the fluctuating electromagnetic field of the stellar plasma [12, 9], or axions could contribute to the magnetically induced vacuum birefringence, interfering with the corresponding QED effect [13, 14]. The PVLAS [15]

1 Attendant speaker, Berta.Beltran@cern.ch, Present address: Department of Physics, Queen’s University, Kingston, Ontario K7L 3N6 Canada
2 Present address: DAPNIA, Centre d’Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France
3 Present address: Scuola Normale Superiore, Pisa, Italy
4 Present address: Instituto de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain
5 Deceased
experiment apparently observes this effect, although an interpretation in terms of axion-like particles requires a coupling strength far larger than existing limits.

The sun would be a strong axion source and thus offers a unique opportunity to actually detect such particles by taking advantage of their back-conversion into X-rays in laboratory magnetic fields [16]. The expected solar axion flux at the Earth due to the Primakoff process is:

\[ \Phi_a = g_{a\gamma}^2 \times 3.67 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}, \]

with an approximately thermal spectral distribution given by:

\[ \frac{d\Phi_a}{dE_a} = g_{a\gamma}^2 \times 3.821 \times 10^{30} \frac{(E_a/\text{keV})^3}{(eE_a/1.103 \text{ keV} - 1)} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \]  

(2)

and an average energy of 4.2 keV.

**PRINCIPLE OF DETECTION**

A particularly intriguing application of magnetically induced axion-photon conversions is to search for solar axions using an “axion helioscope” as proposed by Sikivie [16]. One looks at the sun through a “magnetic telescope” and places an X-ray detector at the far end. Inside the magnetic field, the axion couples to a virtual photon, producing a real photon via the Primakoff effect: \( a + \gamma_{\text{virtual}} \rightarrow \gamma \). The energy of this photon is then equal to the axion’s total energy. The expected number of these photons that reach the X-ray detector is:

\[ N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a \rightarrow \gamma} S T dE_a \]  

(3)

where \( d\Phi_a/dE_a \) is the axion flux at the Earth as given by eq.(2), \( S \) is the magnet bore area (cm\(^2\)), \( T \) is the measurement time (s) and \( P_{a \rightarrow \gamma} \) is the conversion probability of an axion into a photon. If we take some realistic numbers \( (g_{a\gamma} = 10^{-10} \text{ GeV}^{-1}, T = 100 \text{ h} \) and \( S = 15 \text{ cm}^2 \) ) this number of photons would be nearly 30 events.

The conversion probability in vacuum is given by:

\[ P_{a \rightarrow \gamma} = \left( \frac{B g_{a\gamma}}{2} \right)^2 \frac{1}{2L^2} \frac{1 - \cos(qL)}{(qL)^2} \]  

(4)

where \( B \) and \( L \) are the magnetic field and its length (given in natural units), and \( q = m_a^2/2E \) is the longitudinal momentum difference between the axion and an X-ray of energy \( E \). The conversion process is coherent when the axion and the photon fields remain in phase over the length of the magnetic field region. The coherence condition states that [20, 21] \( qL = \pi \) so that a coherence length of 10 m in vacuum requires \( m_a \lesssim 0.02 \text{ eV} \) for a photon energy 4.2 keV.

Coherence can be restored for a solar axion rest mass up to \( \sim 1 \text{ eV} \) by filling the magnetic conversion region with a buffer gas [17] so that the photons inside the magnet

\[^{1}\text{The spectrum in [17] has been changed to that proposed in [18], however with a modified normalization constant to match the total axion flux used here, which is predicted by a more recent solar model [19].}\]
pipe acquire an effective mass whose wavelength can match that of the axion. For an appropriate gas pressure, coherence will be preserved for a narrow axion mass window. Thus, with the proper pressure settings it is possible to scan for higher axion masses.

The first implementation of the axion helioscope concept was performed at BNL [20]. More recently, the Tokyo axion helioscope [22] with $L = 2.3$ m and $B = 3.9$ T has provided the limit $g_{a\gamma} < 6.0 \times 10^{-10}$ at 95% CL for $m_a \lesssim 0.03$ eV (vacuum) and $g_{a\gamma} < (6.8 - 10.9) \times 10^{-10}$ for $m_a \lesssim 0.3$ eV (using a variable-pressure buffer gas) [23]. Limits from crystal detectors [24, 25, 26] are much less restrictive.

CAST EXPERIMENT

In order to detect solar axions or to improve the existing limits on $g_{a\gamma}$ an axion helioscope (Fig 1) has been built at CERN by refurbishing a decommissioned LHC test magnet [21] 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 $S = 2 \times 14.5$ cm$^2$. The aperture of each of the bores fully covers the potentially axion-emitting solar core ($\sim 1/10$th of the solar radius). The magnet is mounted on a platform with $\pm 8^\circ$ vertical movement, allowing for observation of the sun for 1.5 h at both sunrise and sunset. The azimuth range of $80^\circ$ 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 needed for its superconducting operation [27]. 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 the reachable celestial coordinates. The overall CAST pointing precision is better [28] than 0.01° including all sources of inaccuracy such as astronomical calculations, as well as spatial position measurements. At both ends of the magnet, three different detectors search for excess X-rays from axion conversion in the magnet when it is 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) [29] readout is placed behind one of the magnet bores, while in the other one, a X-ray mirror telescope [30] is used with a Charge Coupled Device [31] (pn-CCD) as the focal plane detector. Both the pn-CCD and the X-ray telescope are prototypes developed for X-ray astronomy [32]. The X-ray mirror telescope can produce an “axion image” of the sun by focusing the photons from axion conversion to a ∼ 6 mm² spot on the pn-CCD. The enhanced signal-to-background ratio substantially improves the sensitivity of the experiment.

DATA ANALYSIS AND RESULTS

2003 data tacking

CAST operated for about 6 months from May to November in 2003, during most of which time at least one detector was taking data. An important feature of the CAST data treatment is that the detector backgrounds are measured with ∼10 times longer exposure during the non-alignment periods. The use of these data to estimate and subtract the true experimental background during sun tracking data is the most sensitive step in the CAST analysis. To assure the absence of systematic effects, the main strategy of CAST is the use of three independent detectors with complementary approaches.

These data were compatible with the absence of any signal, thus allowing us to extract the following limit to the axion-to-photon coupling constant [1]:

\[ g_{a\gamma} < 1.16 \times 10^{-10} \text{GeV}^{-1} (95\% \text{CL}). \] (5)

2004 data tacking

All detectors and the magnet moving platform were operating with improved conditions during 2004, which lead to a very stable operation during that year, and therefore to a wider set of data. Because of this the calculated upper limit to the axion-to-photon coupling constant was lowered to the preliminary value of:

\[ g_{a\gamma} < 0.9 \times 10^{-10} \text{GeV}^{-1} (95\% \text{CL}). \] (6)

Thus far, our analysis in both years was limited to the mass range \( m_a \lesssim 0.02 \text{ eV} \) 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 as it can bee seen in figure 2.

SUMMARY

The origin of the axion as a particle that solves the strong CP problem has been reviewed. Some properties of this pseudoscalar particle have been pointed out, among them the fact that it can transform into a photon in external electric or magnetic fields, this being
the only property of the axion on which CAST relies. The CAST experiment and its first results [1] have been presented.

Our 2004 limit improves the best previous laboratory constraints [22] on $g_{a\gamma}$ by a factor $\sim 6.5$ in our coherence region $m_a \lesssim 0.02$ eV and surpass the astrophysical limit set by the globular clusters.

In 2005 the so-called second phase of CAST started, where data are taken 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 shaded region shown in Fig. 2, which is especially motivated by axion models [33], as shown by the “CAST prospects” line.

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