CAST: A search for solar axions at CERN

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ABSTRACT

The new axion helioscope at CERN started acquiring data during September of 2002: CAST (Cern Axion Solar Telescope) employs a decommissioned LHC dipole magnet to convert putative solar axions or axion-like particles into detectable photons. The unprecedented dipole magnet intensity and length (9.5 T, 10 m) results in a projected sensitivity that surpasses astrophysical constraints on these particles for the first time, increasing the chance of discovery. The use of X-ray focusing optics and state-of-the-art detector technology has led to an extremely low background for an experiment above ground. A brief status report is given, with emphasis on the tracking and control system and possible future extensions.

Keywords: Solar Axions, Pseudoscalars, Superconducting Magnets, LHC, Primakoff effect, Strong CP Problem

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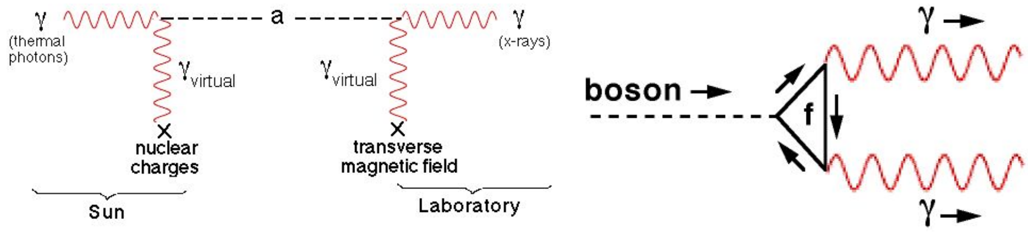

Figure 1. Left: The Primakoff effect (the coupling of an axion to two photons) at work in the Solar core and in the laboratory. Right: A new scalar particle coupling to charged particles is subject to this effect. For this reason, experiments such as CAST are generic searches, not limited to Peccei-Quinn invisible axions in their discovery potential.

1. INTRODUCTION

Axions entered the particle physics arena as a possible solution to the so-called strong CP problem.[?] They soon became more attractive with the realization that for some mass ranges they are prime galactic Dark Matter candidates.[?] To add to their interest, if axions exist, they should be copiously produced in stellar interiors primarily via the Primakoff effect in the scattering of thermal photons off nuclei.[?,?] In the case of our Sun, theoretical expectations are for a low-energy axion emission spectrum peaked around a mean energy of $\sim$4.4 keV and dying off at $\sim$10 keV, while in supernova explosions they could carry up to a much larger $\sim$160 MeV.[?,?] Axions can participate in stellar energy dissipation mechanisms, affecting stellar evolution to the point that useful (but somewhat uncertain) theoretical limits have been obtained from, for instance, the life span of Horizontal Branch (HB) stars.[?,?] The Sun is, due to its closeness to the Earth, the astrophysical source of choice for axion searches. The solar neutrino problem added a humbling dash of uncertainty to our knowledge of a star's inner mechanisms: more to the point, the role that yet undiscovered particles might play, be those axions or axion-like (i.e., participating of some axion couplings) is still the subject of great theoretical and experimental interest. In this sense it is important to emphasize that any new scalar particle can couple to two photons via fermion (quark and lepton) vacuum loops[?] (Fig. 1). Experiments exploiting the Primakoff mechanism are therefore capable of discovering any of a large number of proposed particles arising from broken or unbroken symmetries (Majoron, Familon, Paraphoton, and so on).

2. CERN AXION SOLAR TELESCOPE (CAST)

The detailed conceptual design of a solar axion telescope, including a description of previous experiments, calculations of expected sensitivity, detector background estimates, etc., is described in.[?,?] In essence, the working principle is as follows: An incoming axion couples to a virtual photon provided by the transverse field (B) of an intense dipole magnet, being transformed into a real, detectable photon that carries the energy and momentum of the original axion ($axion + \gamma_{virtual} \rightarrow \gamma$, Fig. 1). Hence, the magnetic field B plays the role of a catalyst. Low-background X-ray detectors at the far end of the magnet are sensitive to the conversion photons, yet exclusively at times of alignment between the magnet and the Sun, providing a unique axion signature.

For the axion energies and rest masses of concern in such searches, the above interaction is coherent, i.e., the axion-to-photon conversion probability is proportional to $(B \cdot L)^2$, where L is the active length of the magnet bore.[?] A decommissioned straight-bore LHC test magnet of $B \sim 9.6$ T, $L \sim 9.5$ m and ~ 10 mrad angular opening has provided a rare opportunity for the construction of a high-sensitivity axion telescope, the CAST experiment at CERN[?,?] (Fig. 2). A single one of these magnets ($B \cdot L = 91\ T \cdot m$) is ~ 100 times more efficient as an axion-to-photon converter than the best competing setup, presently in operation at the University of Tokyo ($B \cdot L = 9.2\ T \cdot m$).[?] The achievable Primakoff coupling sensitivity for light axion masses (< 1 eV) is approximately given by:

$$g_{a\gamma\gamma} \leq 1.4 \cdot 10^{-9}[\mathrm{GeV}^{-1}]\ \frac{b^{1/8}}{t^{1/8}\ B[\mathrm{T}]^{1/2}\ L[\mathrm{m}]^{1/2}\ A^{1/4}}\ , \tag{1}$$

Figure 2. Members of the CAST collaboration in front of the helioscope during the first week of data acquisition (September 2002). Visible to the left are the flexible cryogenic pipelines that allow a free magnet motion. The TPC is visible on the right end.

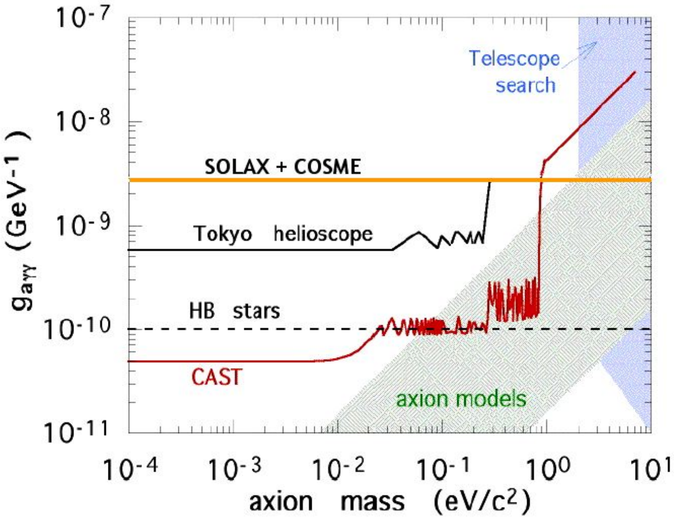

Figure 3. Expected sensitivity for CAST. Also shown: limits obtained using low-background germanium detectors (SOLAX, COSME[?]), those from the Tokyo helioscope,[?] the theoretical red giant bound,[?] the region excluded from the absence of an axion-decay photon line in galactic clusters,[?] and the region favored by theoretical axion models. A further increase in CAST's sensitivity by a factor ∼2 seems feasible from the combined use of X-ray focusing optics and micropattern detectors (see text).

where b is the detector background in counts/day in the energy region $\sim 1-10$ keV, t [days] is the time of alignment of the magnet bore with the Sun and $A[cm^2]$ is the bore opening area (14 cm^2 for this magnet). In view of the weak dependence on all factors other than B and L, it will be extremely hard to improve the axion sensitivity of CAST with present or foreseeable magnet technology. For the first time and over many orders of magnitude in axion mass, the experimental sensitivity will surpass the astrophysical axion constraints (Fig. 3).

Three different detectors have been installed, all of them sensitive to the X-rays that might originate in the conversion of axions inside the magnet: a time projection chamber (TPC), a CCD and a MICROMEGAS chamber.[?] The TPC exhibits the robustness of a well-tested technique, even if its spatial resolution (and

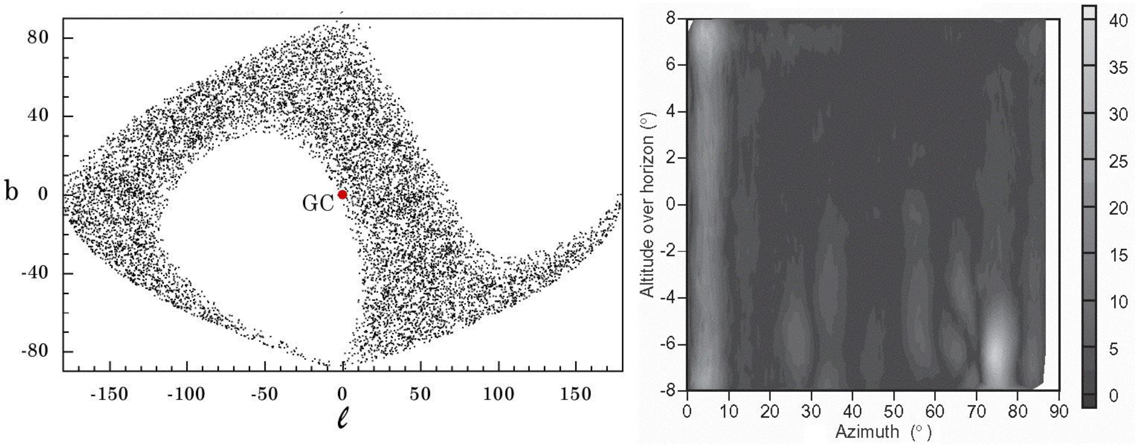

Figure 4. *Left:* Patch of sky scannable with CAST's final range of motion ($\pm 40^\circ$ horizontal, $\pm 8^\circ$ vertical), in galactic coordinates. The automatic platform control system is able to track any user-defined reachable set of galactic coordinates during the hours when solar tracking is impossible. Solar tracking can be followed live at[?] (webpage updated every hour) *Right:* Maximum tracking precision attainable by the platform control system as a function of spatial direction. The grey-scale units are thousands of a degree. The azimuth origin in the figure is offset to the NE direction.

consequently background rejection capability) is inferior to the other two. It is constructed of selected low-background materials and covers both magnet bores sensitive to "sunset" axions. Facing "sunrise" axions, the CCD detector and MICROMEGAS chamber work in conjunction with a mirror system able to focus any X-rays streaming out of the magnet bores. This system is yet another example of recycling, as it employs an engineering unit left behind by the ABRIXAS X-ray astronomy mission. The mirror concentrates the sought signal into a $\sim$1 mm^2 spot. This allows to use a small detector (or one with high spatial resolution) therefore increasing the signal-to-background ratio by roughly two orders of magnitude. The expectations in these conditions are essentially those of a "zero-background" experiment: in the absence of axions, only $\sim$1 count/month is expected after energy and spatial cuts. The detectors and mirror are already installed on their corresponding ends of the magnet. At the time of this writing, several hours of data have been taken with the TPC in "axion-sensitive" conditions, i. e., with the magnet on (9.4 T) and active tracking of the Sun. Routine operation with all detectors online is expected to start in February of 2003, spanning a period of three years under different running conditions (with vacuum or He gas in the bores[?]).

The solar tracking system has been checked using a small alignment telescope mounted on top of the magnet (and carving windows on the otherwise solid walls of the experimental hall). Footage from these satisfactory tests is available at.[?] The first step in this critical part of the project was to measure the orientation of the magnet in the relevant set of topocentric coordinates (azimuthal angle AZ and zenith distance ZD) for ninety platform positions, creating a look-up table of AZ and ZD values correlated to position encoder readings. The collaboration of the EST division at CERN has proven invaluable for this. These measurements will be repeated along the duration of the project to account for possible settling or flexure of the structure. They are performed with a precision better than 0.001°. As a reference, the angle subtended by the magnet bore is $\sim 0.25^\circ$, while the solar core spans $\sim 0.05^\circ$ (the bulk of axion emission is expected from this inner $\sim$1/10 of the solar radius). The second step is to generate reliable solar AZ and ZD predictions with better than 0.01° accuracy[?] and to direct the platform (via control of two motors) to the corresponding encoder values using a non-cartesian spline interpolation of the look-up tables ("Hardy's multiquadrics"[?]). Finally, all components are merged into a stand-alone LABVIEW application also able to log all environmental parameters of interest. The precision goal ($< 0.01^\circ$ error) of the resulting fully-automatic tracking system has been met in both topocentric and galactic coordinates (Fig. 4). The evolution of the experiment can be followed live (with hourly updates).[?]

An interesting possible future direction is the development of low-background detectors able to perform parasitic searches for cosmological higher-energy axion-like particles. While a mapping of the sky in galactic coordinates looking for an excess signal along the galactic plane or center might be of interest *per se* ("axion astronomy"?), a more realistic high-energy boson search should continue to rely on the Sun as a source: If a new boson couples to nucleons, it can substitute for a photon in a number of solar plasma and nuclear processes.[?] Weak experimental limits already exist from the observed flux of solar gamma-rays below 5.5 MeV, to which axion decay ($a \rightarrow \gamma\gamma$) following $p + d \rightarrow {}^3He + a$ might contribute.[?] Other unexplored interesting channels exist[?,?,?] and a generic search should not be limited to pseudoscalar particles (i.e., M1 transitions like the one mentioned). This question has not been examined in all its generality, leaving room for surprises.[?] It must be kept in mind that astrophysical constrains still allow axions to partake of a non-negligible fraction (few %) of the total solar luminosity.[?] In particular, the absence of a 511 keV excess signal (from $e^+ + e^- \rightarrow \gamma + a$) in these additional CAST detectors at times of solar alignment may impose tighter bounds than similar searches for anomalous production of single photons in accelerator experiments.[?] Other ideas are presently under study (e.g., study of solar emission of light pseudoscalars in the visible or UV, etc.).