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A solar axion search using a decommissioned LHC test magnet

The Solar Axion Telescopic ANtenna

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1. Summary

Axions made their appearance into the particle physics arena as a possible solution to the strong CP problem. They soon became more attractive with the realization that they constitute prime candidates for the galactic dark matter. 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 ~ 4.4 keV, while in supernova explosions they could carry a much larger ~ 160 MeV. Axions, should they exist, would participate in stellar energy dissipation mechanisms, therefore affecting stellar evolution to the point that useful (albeit subject to large uncertainties) theoretical limits have been obtained from, for instance, the lifespan of the Horizontal Branch (HB) stars. The Sun, due to its closeness, is when compared to any other stellar object the astrophysical laboratory of choice for axion searches. The solar neutrino deficit problem adds an alluring dash of doubt to our degree of knowledge of a star's inner mechanisms, specifically to the role that yet undiscovered particles might play in them (be those axions or axion-like, i.e., participating of some of their expected couplings).

The conceptual design of an axion telescope is described in detail in the NIM-A paper [1] that accompanies this proposal. The relevant physics, biography of experimental efforts, calculations of expected sensitivity, detector background estimates, etc., are all presented there; the unfamiliar reader is refered at this point to the paper and its references for a more in-depth introduction. In essence, the working principle of an axion telescope is the Primakoff effect: an incoming axion couples to a virtual photon provided by the transverse field (B) of the telescope's magnet, and is transformed to a real photon which carries the energy and momentum of the original axion ($axion + \gamma_{virtual} \rightarrow \gamma$). Hence, the magnetic field B plays the role of a catalyst. A low-background x-ray detector at the far end of the magnet can detect the conversion photons, 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 this search, the above interaction is coherent, i.e., the axion-to-photon conversion probability is proportional to $(B \cdot L)^2$, where L is the length of the magnetic field. The recently decommissioned straight-bore LHC test magnets, having $B \sim 9.6$ T, $L \sim 9.5$ m and ~ 10 mrad angular resolution provide a rare opportunity for the construction of a high-sensitivity axion telescope. 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 Tokio ($B \cdot L = 9.2\ T \cdot m$) [2]. For two such magnets in series, a combination already thoroughly assayed at the LHC Test String, this efficiency factor becomes ~ 400. However, the axion detection rate depends on the fourth power of the Primakoff coupling $g_{a\gamma\gamma}$ (since the same process describes both axion generation and detection [1]), and therefore, as far as $B \cdot L$ is concerned, the limits on this coupling constant can be improved only by a factor ~ 4 to 10. A more complete vision of the achievable sensitivity is given by an approximate rule-of-thumb :

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

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 (19.6 cm^2 here). This equation applies only to limits obtained with vacuum in the bore [1], but in combination with Fig. 1 gives an idea of how hard it would be with present and envisioned magnet technology to surpass the sensitivity of the proposed telescope.

Fig. 1 shows the expected performance of this telescope (*top*) optimally oriented towards sunset at one of the solstices and *without* a Sun-tracking moving platform, yet taking into account the vertical motion of $\sim \pm 3^o$ already implemented in the existing magnet girder [3] (LHC magnets have been tested simulating maximum LEP tunnel inclinations); (*center*) by adding only a turntable able to sweep at least $\sim \pm 45^o$ horizontally; (*bottom*) appending to this a vertical motion of $\pm 10^o$, within the limits of structural stability of the magnet. The background estimate utilized (6 counts/keV/day in the x-ray region) is conservative in the sense that it corresponds to levels already achieved by members of this collaboration above ground; the installation of the telescope in the ALEPH cavern (140 m underground), as proposed below, can reduce it considerably. As can be seen from Eq. (1), the dependence of the experimental sensitivity on t is weak and simply adding horizontal motion to the existing infrastructure would allow to surpass the best astrophysical limits (Fig. 1, *center*). It must be borne in mind that the theoretically-favored region labeled "axion models" in Fig. 1 is only indicative, since models of hadronic axions with enhanced or suppressed photon couplings are easily constructed [4]. For each calculation in Fig. 1 a total of three years running time was considered, one with vacuum in the bores and two with buffer gas. However, this does not imply a continuous operation of the telescope with the magnetic field switched on, given that the periods of solar alignment sum up to only 0.061, 9.16 and 29.25 days per year, respectively for the cases considered. The detectors will be placed well outside the magnetic field lines; if their functioning is convincingly shown to be impervious to the on/off state of the magnet, collection of background with the magnet switched off in times of solar misalignment is a possibility that could reduce the running costs associated to electricity and helium liquefaction.

2. Equipment, Location and Costs

The following is a list of the material requirements for the construction of the axion helioscope. As can be seen, most are already available or can be recuperated at CERN, greatly reducing the overall costs.

1) One of the 10 m LHC test magnets, its Main Feed Box (MFB) and their girder. They are, along with the necessary flexible cryo-pipes, all available.

Estimated total cost . . . .~ 5 MCHF

2) Refrigerator, Compressor, and cool-box. All available.

Estimated total cost . . . .~ 2.2 MCHF

3) Pumping station, in order to reduce the He-temperature down to 1.8 K. Not yet available.

Cost . . . . 0.2 MCHF

4) Magnet power supply (14 kAmps/low-voltage). An 8 kAmps/600 V/$\sim 5MW$ unit is already available from Saclay. However, with this the axion conversion efficiency would be at 34% of the value attainable with the maximum allowed current. Efforts are underway to find a more adequate unused unit.

Cost . . . . 0.15 MCHF

5) Flexible cables and connectors between power supply and MFB. Not available.

Estimated total cost . . . .~ 0.1 MCHF

6) Extra cryo-piping within the underground area A4 (ALEPH cavern). This site, with its associated cryogenic infrastructure, will be available from July 2001 for at least 2 years. Limited access to the area can start as early as end of 2000 (LEP closing date).

Estimated total cost . . . .~ 0.1 MCHF

(The additional piping necessary in any other location would increase this figure to 0.5 MCHF).

7) Data acquisition system, x-ray detectors and shielding : Two choices of detector (of many possibilities) are presently under consideration : segmented HP germaniums (4.2 mm thick, 53 mm diameter) with OFHP electroformed copper cryostats and reinforced Be windows (members of this collaboration have ample experience in achieving ultra low-backgrounds with HPGe technology), or existing MicroMega Chambers [5] ($15\times15\ cm^2$) from Saclay. The intrinsic background of the second will be investigated in September 1999 in one of the two underground laboratories operated by the collaboration. The lower active mass of the MicroMegas may allow for a satisfactory level of background without rebuilding of the components. These chambers offer the added advantage of a very low energy threshold (few tens of eVs, making them sensitive to the full axion spectral shape) and spatial resolution ($\sim 50\ \mu$m) that can be used for background rejection. Low-background shielding (ancient lead, OFHP Cu) and active muon veto are available from the participating groups. Only if the first option (Ge) is preferred there will be a significant associated cost of:

Estimated total cost . . . .~ 0.1 MCHF

8) Sun-tracking moving platform. A study by a private engineering firm has been commissioned to appraise this expense (see next section). Two options have been contemplated: (a) horizontal motion only, and, (b) combined horizontal and ±10° vertical motion.

The estimated cost for (a) / (b) is . . . .~ 0.16 / 0.28 MCHF

As discussed above, option (a) is deemed sufficient to surpass the astrophysical limits.

Conclusion :

The cost of the equipment required is . . . .~ **8 MCHF**

The already recovered items from CERN sum up to . . . . ~ **7.2 MCHF**

Items not yet available are :

Power supply	150.-kCHF
Pumping station	200.-kCHF
Cryo-piping	100.-kCHF
Flexible cables	100.-kCHF
Moving platform (horizontal movement only)	160.-kCHF

(It is still expected to be able to borrow the two first items. Cryo-piping and cables can be recycled for posterior LHC use).

3. Moving Platform - Conceptual Design[1]

The magnet is fixed on the existing girder and limited vertical inclination poses no structural stability problems (nor cryogenic, for the magnet operates with superfluid He, which creeps up). The magnet and its MFB have to be maintained in position without causing during the motion any stresses to either bodies or their fixations. Cryogenic and power lines will be flexible.

According to the study performed, the horizontal rotation can be implemented by adding a crane-resembling structure at a location close to the center-of-gravity of the system (Fig. 2), consisting of a set of bearings capable of supporting the axial load. The front side of the platform will be fitted with wheels in order to allow motion on rails. Since the weight of the system is supported by the central structure, the wheels carry minimal loads. In order to further minimize this load, the addition of a small weight on the rear of the girder can shift the location of the center-of-gravity to the desired point. Smooth motion will be guaranteed by a hydraulic and/or step motor system.

In order to implement the vertical motion, if desired, the following additional modifications would be called for : a) Construction of a new platform to support the existing system. This platform will connect to the existing girder by a horizontal axle of suitable dimensions and a hydraulic system will allow the vertical motion. b) Modification of the existing girder, in order to reduce the height while maintaining rigidity. Establishment of the connection points to the new supporting platform.

In addition, the tracking platform in the proposed design works as follows: An inner platform supports the magnet with the MFB and allows for the vertical movement by rotating around a horizontal axis. An external platform supports this structure, limits the vertical movement in both directions, and is supported by the crane-like structure on a set of bearings. This platform allows for the horizontal rotation through an adequately powered rail system.

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[1] In collaboration with PYLON, S.A., Athens, Greece

The control of the system will be done by a custom-made software package. All hardware components are commercially available or will be constructed following the completion of the design. The described structure offers the following advantages : a) Makes efficient use of existing supporting equipment and materials, thus reducing the total cost. b) Can be adapted in order to allow construction in stages, i.e., exclusively horizontal motion at first, followed by an eventual complete system, if deemed necessary. c) The load on the front part is minimized, allowing the use of precision, low-power step motors.

4. Financing and division of responsibilities

It may be premature to attempt a clear-cut division of tasks between the involved groups prior to approval of the project. However, some guidelines can be offered at this point : The detectors will be provided by the collaborating institutes, be that USC-PNNL-UZ if HPGe are opted for, or Saclay in the case MicroMegas are favored. The necessary low-activity shielding materials and experience to achieve the lowest possible background conditions are evidently available to participating groups, which have a history of fruitful collaboration in the fields of double-beta decay, dark matter and axion searches. In particular, if rebuilding of the MicroMegas is necessary, UZ operates an underground laboratory for characterization and selection of low-radioactivity materials. The INR group can provide the required competence to operate the magnet and its associated cryogenics. The collaboration includes members able to offer strong theoretical support in the fields of axion and astroparticle physics. Other tasks such as DAQ and software development will be divided according to manpower.

The monetary sum to be raised if the magnet power supply and pumping station can be recovered is of ~400.-kCHF, a viable figure to be shared among the groups and their funding agencies. Support from CERN including running costs, transportation and maintenance of the magnet, etc., is expected. In case of insufficient funding, an option that could be considered is the use of two optimally-oriented stationary magnets in series, which would generate a sensitivity a factor of $\sqrt{2}$ higher (a limit $\sqrt{2}$ lower) than what is shown in Fig. 1 (*top*), i.e., roughly able to match the best astrophysical limits.

5. Other perspectives

During times of solar misalignment the telescope can be used to address aspects that may seem at first sight of secondary importance (albeit the absence of prior experimental searches can make them enticing). For instance, it will have in its field of view the penetrating components of horizontal and slant underground atmospheric showers from cosmic radiation. A parallel can be drawn between this astrophysical "beam-dump" and accelerator ones that have already been used for axion searches, not forgetting their differences in luminosity and energy. No anomalous neutrino observations have been made so far in accelerators, in contrast to the SuperKamiokande results, a thought that can wet the appetite for such serendipitous searches. In addition, the telescope can be pointed occasionally to intriguing places in the sky, such as the Galactic Center (see Fig. 3 and discussion in the attached paper), or Gamma Ray Bursts (GRBs), the most energetic astrophysical events, taking place approximately once per day. An alert-trigger for an ongoing GRB and its rough location can be obtained from NASA [6] within 3 to 5 seconds of its onset; a moving axion-telescope could be rapidly pointed to these objects (note that > 50% of the GRBs last much longer than 5 sec). Finally, ideas on the possible eventual adaptation of the setup to seek a dark matter axion signal are under study.

6. Conclusions

A solar-axion telescope of hard-to-match sensitivity is technically feasible at a reasonable cost thanks to the availability of decommissioned CERN equipment, offering as a side dish a varied astroparticle physics program. Should funding availability exclude the construction of the moving platform, the physics potential of an optimally-aligned stationary telescope composed of one or two 10 m magnets is still interesting (use of two magnets in this case would not imply any additional costs).

The proposed non-accelerator experiment, mostly composed of salvaged CERN equipment, can improve the present limit on the axion-to-photon coupling constant by a factor 4 to 10, exploring theoretically-favored regions. These LHC magnets, given their length and intensity, offer a *unique* opportunity to match or surpass astrophysical limits with a direct search (a cynic might argue that if axions exist and play an important role in stellar evolution, then these limits point at where to look for them). The time gap between the end of LEP and start of LHC provides a likewise unusual window of opportunity to embark in this program.

All in all, the Solar Axion Telescopic ANtena is a singular instrument that could open our eyes to new astrophysical phenomena.

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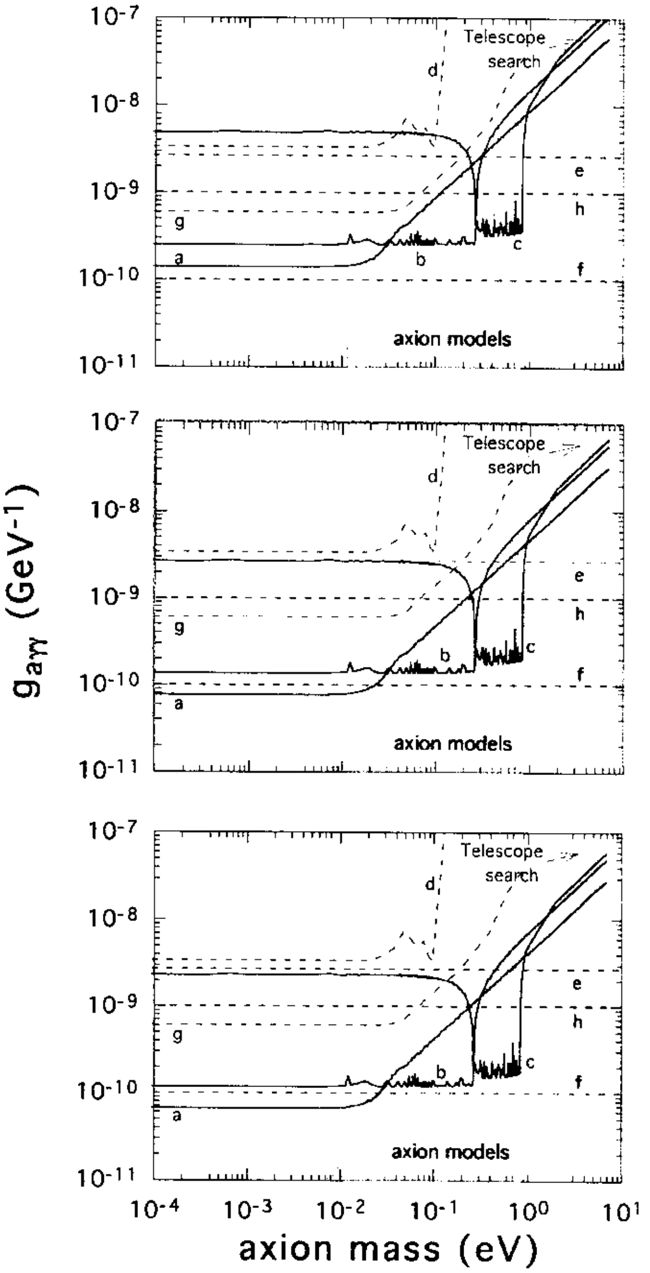

Figure 1: Attainable 3 σ C.L. limits on the coupling strength of axions to two photons as a function of the axion rest mass. The top figure corresponds to an optimally-oriented 9.5 m LHC test magnet with the already implemented ±3° vertical tracking as the only motion. The middle is for the addition to this of ±45° horizontal tracking. The bottom figure represents the limits with an increased vertical tracking of ±10° and ±45° horizontal tracking; **(a)** after 1 y with vacuum in the pipe line, **(b)** an additional 1 y with He gas pressure increased from 0-1 atm in 100 increments, **(c)** an additional 1 y with 1-10 atm in 365 increments. **(d)** Previous limits from ref.[22] in the attached paper, **(e)** limits recently imposed by members of this collaboration using an underground Ge detector [7], **(f)** the *theoretical* HB stars limit (refs. 26, 27 in [1]), **(g)** recent limits from the Tokio axion helioscope (refs. 41, 42 in [1]) and **(h)**, the new helioseismological constraints on solar axion emission (ref. 25 in [1]). (Color printers: red lines denote *experimental* limits).

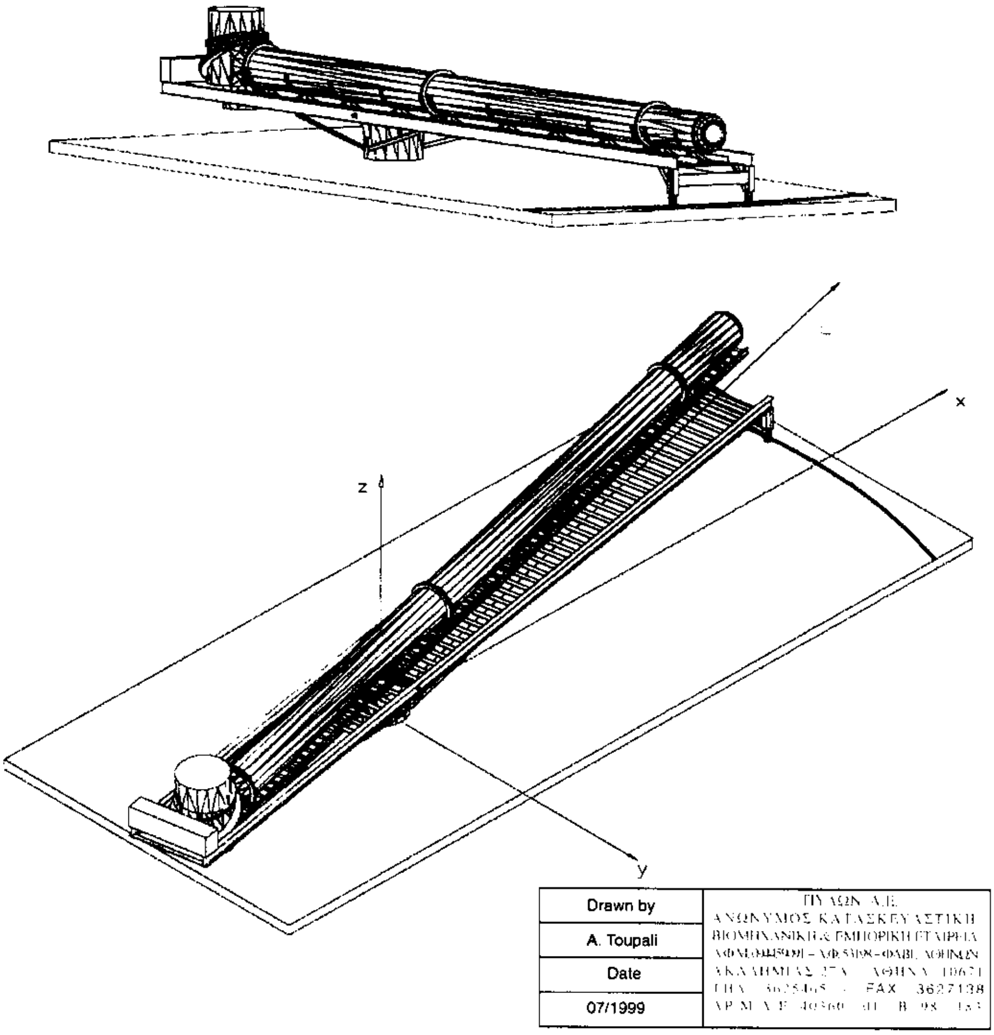

Figure 2: A preliminary design of the Sun-tracking platform