AMELIE: An Axion Modulation hELIoscope Experiment

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In this work, I present an innovative idea to search for solar axions using a large volume low background Time Projection Chamber (TPC) immersed in a magnetic field. This technique will be sensitive to axion masses above few hundreds of meV in the theoretically favored QCD-axion parameter space. The detector geometry will be such that will allow to monitor the solar axion flux during the whole day. A stationary detector would produce a daily and annual modulation signal pattern given by the angle of the incident axion flux and the TPC magnetic field which is driven by the earth rotation. Recent progress on large volume low background TPC's for rare event searches motivates the development of such helioscope technique. The principle of detection and prospects on the sensitivity of such an experiment will be shown.

1 Introduction

The axion is a hypothetical neutral pseudoscalar particle which was already predicted in 1977 [1]. This weakly interacting particle came out as a simple solution to the CP problem of strong interactions in Quantum Chromodynamics (QCD) [2]. The particular properties of the axion can be restricted by the actual observational consequences that its existence would imply in astrophysics and cosmology [3, 4]. Their detection principle is based on the Primakoff effect using the interaction of the axion with two photons [5]. Experiments searching for axions use an intense magnetic field that provides one of the photons involved in the interaction, aiming to detect the second photon that, for maximum conversion probability, carries the total energy of the axion. The idea here presented belongs to the axion helioscope searches. If axions exist, they should be produced in the inner core of the Sun. The energy spectrum of these axions is related to the core temperature of the Sun, and thus its energy is in the 1-10 keV region. Axion helioscopes aim to detect the solar axion flux on the earth.

The first solar axion searches provided axion-photon coupling sensitivities for a wide axion mass region (see [6] for a detailed review). The CERN Axion Solar Telescope (CAST) provides today the best sensitivity to the axion-photon coupling for solar axions, being the first helioscope exploring a theoretically favored axion region for axion masses $\lesssim$ eV [7]. CAST uses a 9.6 m-long dipole magnet with an intense magnetic field of 8.9 T, capable to track the Sun 3 hours per day. The International AXion Observatory (IAXO) collaboration is developing the future generation helioscope magnet [8]. IAXO will built a dedicated 8-bore large-aperture superconducting magnet 20 m long, reaching an average field intensity of 2.5 T. Each of the 8 (60 cm diameter) magnet bores will be equipped with x-ray focussing devices that will allow to focus the large aperture area in a spot of just $0.2\,\mathrm{cm}^2$ increasing significatively the signal-to-background ratio. A dedicated tracking system will facilitate taking data during 12 h per day. All these enhancements will allow IAXO to improve by 4-5 orders of magnitude the sensitivity of CAST in terms of signal-to-noise, reaching sensitivities of a few $\times 10^{-12}\mathrm{GeV}^{-1}$.

2 A new helioscope detection technique

We present a new helioscope detection concept that was never before exploited for axion searches, and that could allow to improve actual sensitivities, especially for the $m_a \gtrsim \mathrm{eV}$. To access the higher axion mass region ($\sim$eV) helioscopes use a buffer gas that allows to recover axion-photon conversion probability. The axion field propagates through a long magnetic bore which is filled with helium to minimize the photon re-absorption. The converted photons are transmitted to the end of the bore and detected by low background X-ray detectors. In contrast, the idea proposed here uses a higher-Z (i.e. xenon) buffer gas, allowing to absorb the converted photons directly in the buffer gas. A TPC design immersed in a magnetic field would allow their detection (see Figure 1). Further details for the new helioscope concept presented here can be found at [9].

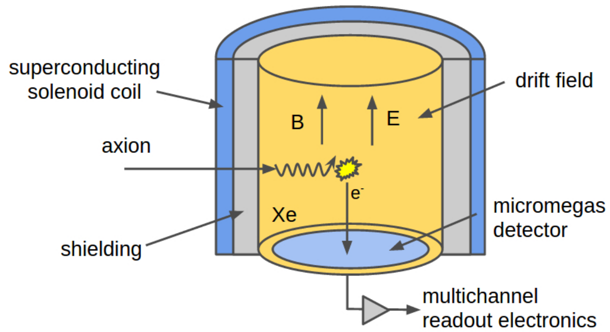

Figure 1: A conceptual drawing showing the TPC drift volume. The axion would convert to a photon inside the TPC, interacting in the gas and producing electrons drifting towards a micropatterned readout, allowing to measure time and spatial event topology. A proper shielding against external radiation should be placed in order to minimize the background level of the detector.

This setup is inspired by an original idea developed in 1989 [10]; the main difference with this work resides on the introduction of a higher-Z buffer gas for axion conversion. The use of higher-Z gases would be possible in this setup thanks to the fact that the buffer gas defining the sensitivity at a given axion mass range and the gas detection volume of the TPC would be the same. Thus, we are interested in using higher-Z gases to maximize the detection efficiency.

The use of a long pipe by actual helioscopes, detecting the transmitted photon component, is justified for the enhancement of the final axion-photon conversion probability that is proportional to B^2L^2 [11], where B the magnetic field and L its length. In the case of a helioscope which aims to detect the absorbed photon component, the conversion probability will be just proportional to B^2L (or to the volume of the TPC, B^2V). This efficiency loss in conversion

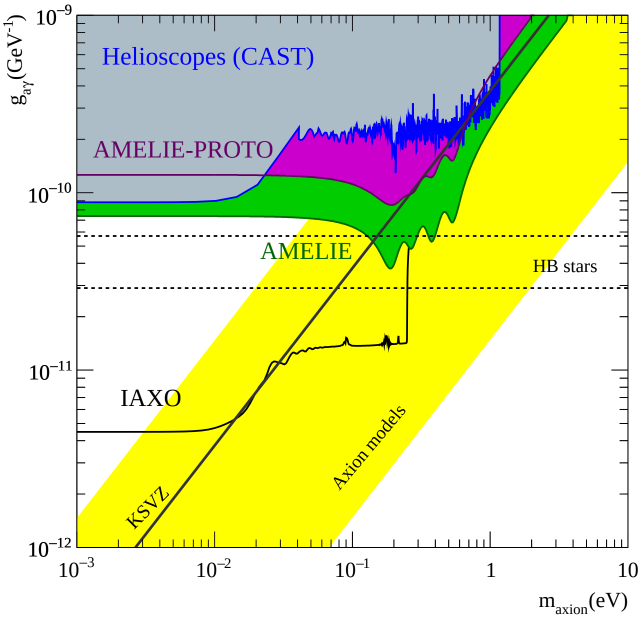

Figure 2: Axion-photon coupling as a function of the axion mass excluded by tracking helioscopes (CAST). The future IAXO sensitivity prospects are also shown. We plot the prospects for a small prototype (AMELIE-PROTO) and a 1 m^3 scale detector (AMELIE). The yellow band represents the favored axion theoretical region.

probability is counter-balanced by using a larger conversion volume, allowing to re-enhance the quantity B^2V, and the longer exposure capability of this type of helioscope.

An obvious implementation maximizing the volume would be a cylindrical shaped TPC. The magnetic field orientation with respect to the incident axion flux would provide a daily modulation pattern due to the change on the effective magnetic field transversal component. The daily average transversal component, B^2, would be about 75% of the absolute field intensity, allowing to track the Sun during 24 hours at the given efficiency. The flexibility of operation of a gaseous TPC at different gas pressures, ranging between few mbar to several bar, would allow to setup the detector to enhance its sensitivity for different axion mass regions, from few hundreds of meV to few eV.

3 Prospects for an AMELIE search

The sensitivity achievable with this type of helioscope will be mainly driven by the quantity B^2V and the background level achievable by a large volume TPC. Recent progress on low background large volume TPCs motivates partially the development of this helioscope technique. Prospects on those TPC developments [12, 13, 14] set the background reachable to be between 0.1-10 keV^{-1} day^{-1} m^{-3}. To reach these levels the detector should be installed at an underground laboratory, certainly possible using this technique since no tracking alignment is required.

We have calculated the axion-photon coupling sensitivity using an Axion Modulation hELIoscope Experiment (AMELIE). Here, we present two different scenarios, a small size prototype of about 21 dm^3 reaching a background level of 1 day^{-1} m^{-3} keV^{-1}, and a larger TPC of about 0.75 m^3 reaching an improved background level of 0.1 day^{-1} m^{-3} keV^{-1}. Both scenarios have been calculated for an absolute magnetic field of 5 T, and *four* pressure settings at 20, 40, 80 and 160 mbar. For this calculation the total exposure used at the first pressure setting is 5 years, at the second pressure setting is 2.5 years, and the *two* remaining pressure settings is 1.25 years. The resulting sensitivity is shown in Figure 2.

The expected sensitivity shown with this technique would allow to explore a region of the axion-photon coupling and axion mass parameter space not previously accessible, and to probe QCD-axions for masses above $\gtrsim$100 meV. The main challenges to reach such sensitivity would be the development of a TPC-magnet design that allows to keep the background level of the detector below the mentioned levels. Another interesting feature of this type of helioscope resides on the wide field of view allowing to scan an extense region of the space. The wider resonance given by the higher-Z gas used would allow to do measurements at a fixed pressure during long data taking periods, still covering an extense region of the axion mass.

References

[1] Steven Weinberg, "A New Light Boson?," Phys. Rev. Lett. **40** 223-226 (1978).

[2] R. D. Peccei and H. R. Quinn, "Constraints imposed by CP conservation in the presence of pseudo-particles," Phys. Rev. D **16** 1791-1797 (1977).

[3] G. G. Raffelt, "Astrophysical axion bounds," Lect. Notes Phys. **741** 51-71 (2008).

[4] P. Sikivie, "Axion cosmology," Lect.Notes Phys. **741** 19-50 (2008).

[5] P. Sikivie, "Experimental Tests of the "Invisible" Axion," Phys. Rev. Lett. **51** 1415 (1983).

[6] K. Baker, "The quest for axions and other new light particles," Ann. Phys. (Berlin) **525**, No. 6, A93-A99 (2013).

[7] CAST Collaboration, M. Arik *et al.*, "Solar axion search with ^{3}He buffer gas: Closing the hot dark matter gap," Phys. Rev. Lett. **112** 091302 (2014).

[8] E. Armengaud *et al.*, "Conceptual design of the International Axion Observatory (IAXO)," JINST **9** T05002 (2014).

[9] J. Galan *et al.*, "Exploring 0.1-10eV axions with a new helioscope concept," submitted to JCAP (2015) [arXiv:1508.03006].

[10] K. van Bibber *et al.*, "Design for a practical laboratory detector for solar axions," Phys. Lett. D **39** 2089-2099 (1989).

[11] G. G. Raffelt and L. Stodolsky, "Mixing of the photon with low-mass particles," Phys. Rev. D **37** 1237-1249 (1988).

[12] A. Dastgheibi-Fard *et al.*, "Background optimization for a new spherical gas detector for very light WIMP detection," Proceedings of Technology and Instrumentation in Particle Physics (2014).

[13] F.J. Iguaz *et al.* "TREX-DM: a low background Micromegas-based TPC for low mass WIMP detection," Proceedings of the 7th Symposium on Large TPCs for low-energy Rare Events Detection (2015).

[14] S. Aune *et al.*, "Low background x-ray detection with Micromegas for axion search," JINST **9** P01001 (2014).