The IAXO Helioscope

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Abstract.
The IAXO (International Axion Experiment) is a fourth generation helioscope with a sensitivity, in terms of detectable signal counts, at least 10^4 better than CAST phase-I, resulting in sensitivity on $g_{a\gamma}$ one order of magnitude better. To achieve this performance IAXO will count on a 8-coil toroidal magnet with 60 cm diameter bores and equipped with X-ray focusing optics into 0.20 cm^2 spots coupled to ultra-low background Micromegas X-ray detectors. The magnet will be on a platform that will allow solar tracking for 12 hours per day. The next short term objectives are to prepare a Technical Design Report and to construct the first prototypes of the hardware main ingredients: demonstration coil, X-ray optics and low background detector while refining the physics case and studying the feasibility studies for Dark Matter axions.

1. Introduction

The Standard Model (SM) of particle physics is a very successful theory that explains with a high level of accuracy the fundamental constituents of matter and their interactions, especially since the Higgs Boson was discovered at the Large Hadron Collider (LHC) in 2012.

Yet the SM is not a complete theory as there are still a number of unanswered questions among them the origin of Dark Matter (DM) and Dark Energy (DE), the matter-antimatter asymmetry of the universe, and why gravity can not be included in this theory...The search of signs of physics beyond the Standard Model at high energy will continue with the LHC run II from summer 2015 to 2018 at 13 TeV. However in a large number of more general theories, embedding the SM, low mass and very weakly interacting particles, the so called WISPs (Weakly Interacting Slim Particles) are predicted. Axions and axion-like particles (ALPs) are salient examples of WISPs. Axions are light pseudoscalar particles that arise in the context of the Peccei-Quinn[1] solution to the strong CP problem and can be Dark Matter candidates[2]. The Primakoff effect which allows the conversion of axions into photons in the presence of a strong magnetic field is used in all experimental searches. In helioscopes, the Sun as source of axions, can be scrutinised by directing a strong dipole magnet towards it and searching for the axion-photon conversion in the keV range. The CAST (Cern Axion Solar Telescope) experiment has been using a decommissioned LHC dipole magnet to convert solar axions into detectable x-ray photons since 2003. The CAST experiment data taking has provided the most restrictive experimental limits on the axion-photon coupling for a broad range of axion masses[3, 4, 5, 6, 7]. In order to reach further sensitivities a new axion helioscope, IAXO (International AXion Observatory)[9], is being designed and is described in the following sections.

2. Experimental set-up

The aim of IAXO is to improve the sensitivity in terms of axion-photon coupling, $g_{a\gamma}$, by a factor of ~ 20 with respect to the CAST experiment, meaning about 4-5 orders of magnitude in terms of signal intensity. The key ingredients are: a large and strong magnet, focusing optics and low background detectors. In order to justify the choices made for the different systems i.e. the magnet, the X-ray focusing optics and the X-ray detectors, the dependence of the sensitivity of IAXO with respect to each system is now discussed.

The discovery potential of the experiment depends on $N_\gamma/\sqrt{N_b}$ where the number of axion signal counts N_γ and background counts, N_b can be written as follows [9]:

$$N_\gamma \sim N^* \times g_{a\gamma}^4 = B^2L^2A\epsilon t \times g_{a\gamma}^4 \tag{1}$$

and

$$N_b = ba\epsilon_t t \tag{2}$$

where B, L and A concern the magnetic field, the length and the cross sectional area respectively. ϵ is the total efficiency $\epsilon = \epsilon_d\epsilon_o\epsilon_t$ taking into account the detector efficiency, ϵ_d, the optics throughput ϵ_o and the data taking efficiency ϵ_t, which is the amount of time where the magnet is following the sun. The background of the detector is denoted by b and given in counts $\mathrm{keV}^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a is the total focusing spot area and t is the duration of the data taking. We can define a figure of merit that takes into account the contribution of the different systems to the total sensitivity:

$$f = \frac{N_\gamma}{\sqrt{N_b}} = f_M f_{DO} f_t \tag{3}$$

with

$$f_M = B^2L^2A;\; f_{DO} = \frac{\epsilon_d\epsilon_o}{\sqrt{ba}};\; f_t = \sqrt{\epsilon_t t}. \tag{4}$$

These relations assume that the axion-photon conversion is fully coherent throughout the length of the magnet L and that background counts are in the Gaussian regime. From these expressions, one can see that the sensitivity of a helioscope is mainly driven by the magnet parameters. In order to surpass CAST performances, it does not seem feasible to build a dipole that would outperform the CAST LHC dipole parameters in a significant manner. Instead the toroidal configuration might enable to keep a BL close to the levels achieved by CAST while increasing significantly the cross sectional area. Moreover it is desirable to have X-ray focusing optics in most of the magnet bores with an entrance that fits the magnet bore and with a large throughput ϵ_o and a small spot area a. The background level of X-ray detectors should be 10^{-7} counts $\mathrm{keV}^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ or lower. With the present performance of the Micromegas detectors this should not be a problem especially after the 2014 data taking during which a new state-of-the-art microbulk detector was tested. The tracking efficiency should also be improved with a platform that allows tracking the sun for at least 30 or 50% of the day.

With these considerations and after a preliminary study, a conceptual design has been proposed with an 8-coil toroidal magnet with 60 cm diameter bores equipped with optics focusing X-rays into $0.20\,\mathrm{cm}^2$ spots coupled to ultra-low background Micromegas X-ray detectors. The magnet would be on a platform that would allow solar tracking for 12 hours per day. A sketch of the conceptual design is given in figure 1 as well as a possible implementation.

The concept of a new generation of helioscope was proposed in [9] with ultra-low background Micromegas detectors as the baseline option for the X-ray detectors. A letter of intent was proposed to CERN [11] and the conceptual design is described in [12]. In the next sections we

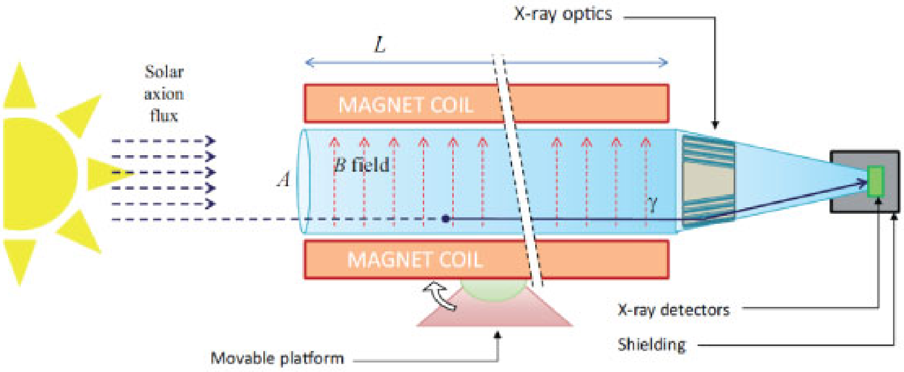

Figure 1. Sketch of the principle of IAXO.

will describe shortly the main ingredients: the magnet, the low background detectors and the focusing optics. The expected sensitivity will be given in section 3.

2.1. Magnet

After a prospective study of the available magnets on the various accelerators and experiments, the CERN magnet group concluded that a new magnet is required in order to achieve the required sensitivity. A well-known proven engineering technology has been chosen, the NbTi technology. With this technology, the attainable peak magnetic field is 5-6 T. Therefore, in order to reach the required magnet FOM $f_m = L^2B^2A$, the aperture is the parameter that can be enlarged easily.

The first optimisation of the geometry of the IAXO superconducting magnet based on simulations has shown that the toroidal geometry, inspired by the ATLAS barrel and end-cap toroids, is the preferred one [9]. These simulations have been realised within the CERN magnet group. The study has shown the optimal configuration is a toroid with 8 magnet bores each 1 m wide and 25 m in length reaching a peak magnetic field of 5.4 T and an averaged field in the bores of 2.5 T (critical magnetic field 8.8 T). The study of the magnet takes into account the implementation options of the other of the systems. For instance, the optimisation of the different parameters will not be the same depending on whether the optics are positioned as close as possible to the inner radius of the the toroid ("field dominated") or between each pair of racetrack coils ("area dominated"). The study also shows that is better to have an increased fraction of the aperture of the optics exposed to X-rays favouring the "area dominated" options as shown in figure 2.

The toroidal magnet consists of eight coils and their casing within an inner cylindrical support for the magnetic forces. The operational current is 12.3 kA with a stored energy of ~500 MJ. Safety margins have been taken into account in the operational current and temperature to allow proper operation. The operational temperature will be 4.5 K. For safety it is also necessary to design a quench protection system to allow the safe release of the stored energy.

The magnet needs to follow the sun as long as possible requiring a horizontal and vertical movement. In order to track for a half day a horizontal movement of 360° will be required with a vertical movement of 25°. The rotation system can be seen in figure 1: the whole system is supported by the central post with an inclination system that allows the vertical movement sitting on a rotating platform allowing the full horizontal rotation.

In order to validate the design of the IAXO magnet, it is envisaged to build and test a single short (2 m) prototype coil in the short term to demonstrate the feasibility of the IAXO toroid

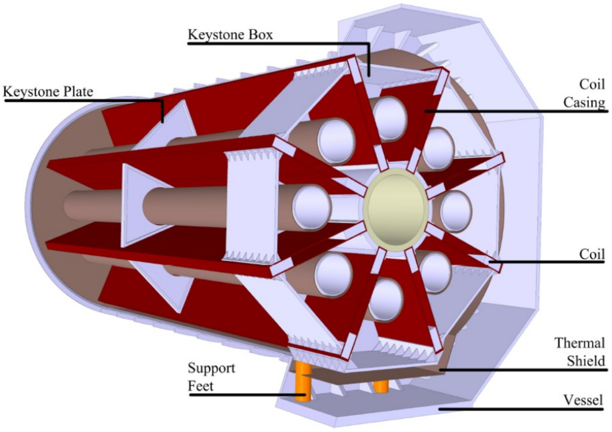

Figure 2. Transverse section of the magnet cryostat, showing the cold mass and its supports, surrounded by a thermal shield and the vacuum vessel.

magnet.

2.2. *Focusing X-ray optics*

The use of X-ray telescopes allows IAXO to enhance the signal to background ratio by concentrating the potential signal in a small spot. The main requirements of helioscope optics are high efficiency in the 1–10 keV range and an aperture that fits the area of the magnet bore with a solid angle acceptance that is greater than the 0.3 arcmin (the extent of the solar core where axions are produced). Taking into account these requirements, using reflective X-ray optics seems to be the most appropriate choice.

The parameters of the optics need to be optimised in order to have the smallest spot, a, and the highest reflectivity. To have a small spot, the optics should have a small focal length, f, since $a \propto f^2$. However the reflectivity increases with decreasing graze angle, α and since $f \propto \frac{1}{\alpha}$, to achieve the highest throughput (efficiency) the optics should have the maximum possible focal length. In addition, the design has to take into account that the performance of the optics have a complex dependence on the incident photon energy and α. Moreover the reflectivity also depends on the coating material and in the number of reflections.

The fabrication technology that has been chosen is a segmented, slumped glass optics were several individual pieces of substrate make a single layer. The reasons are that the technology is mature and not expensive, it has been developed by members of IAXO for the NuStar Satellite mission [10], it is easy to deposit a single layer or multi-layers reflective coatings and the imaging requirements can be satisfied.

The design studies have taken into account the axion spectrum and the detector efficiency in order to achieve the highest figure of merit, f_{DO} with the optimisation of the optics parameters (f, a, number of layers, single and multilayer coatings). The optimal figure of merit is found for 5 m focal length with 123 layers with W/B_4C multilayers coating and with a spot of ~ 4 mm.

2.3. *Low background X-ray detectors*

The Micromegas detectors developed for the CAST experiment are the baseline technology for the X-ray detectors of IAXO. The levels achieved resulted from a global approach where the improvement has come from different fronts: from the manufacturing technique leading to highly intrinsically radiopure detectors with high performance, from the optimisation of the passive and

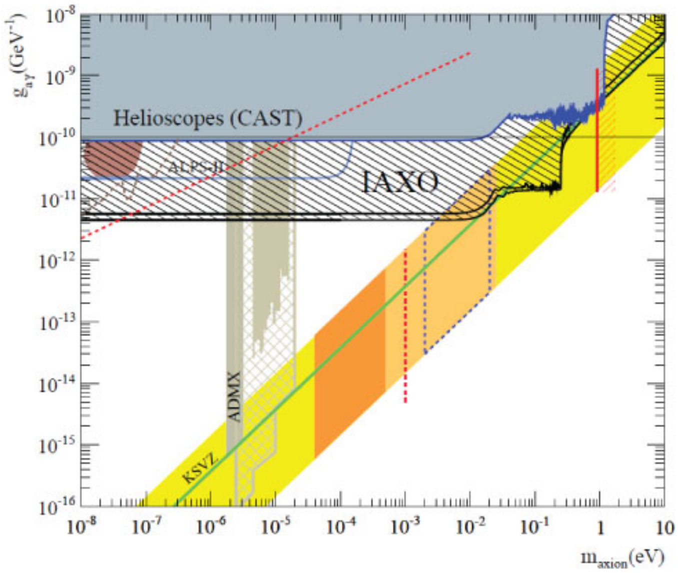

Figure 3. Expected IAXO sensitivity compared to CAST and ADMX limits. Future prospects of ADMX (dashed brown) and ALPS-II (light blue line) are shown. The nominal scenario takes into account the figures of merit described in the text while the enhanced scenario expects a lower background level (10^{-8}counts keV^{-1} cm^{-2}s^{-1} instead of 5×10^{-8}) for the Micromegas detector and an increased efficiency for the optics (70% instead of 50%) with a smaller spot size a (0.15 cm^2 instead of 0.2 cm^2).

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active shielding thanks to an understanding of the background and from the refinement of the selection algorithms. The detector installed in the 2014 CAST data taking campaign in the sunrise side coupled to the X-ray telescope achieved levels 0.85×10^{-6}counts keV^{-1} cm^{-2}s^{-1} [16]. It can be considered as the first Micromegas prototype for IAXO. Further improvements are still expected:

- Use of segmented mesh microbulks[14] with auto-trigger electronics[15];
- more stringent radioactive requirements for the components of the detectors;
- upgrade of the active muon and gamma shielding;
- improvement of the selection algorithms.

3. Expected sensitivity

IAXO sensitivity, in terms of detectable signal counts, is at least 10^4 better than CAST phase-I, resulting in a sensitivity of $g_{a\gamma}$ one order of magnitude better. Simulated sensitivities for different set of parameters are given in figure 3. This exclusion plot is obtained by considering different scenarios of the expected performances of the different sub-systems of IAXO (magnet, optics, X-ray detectors). To obtain this plot a vacuum run of 3 years effective data taking, IAXO run I, is considered with sensitivities to $m_a < 0.1$ eV followed by IAXO run II that will use a buffer gas, ^{4}He, inside the magnet bores to reach higher masses up to $m_a \sim 0.25$ eV. In this way, a large unexplored region of the QCD axion phase space will be scanned reaching a few $\sim g_{a\gamma}$ 10^{-12} GeV^{-1} for masses up to 0.25 eV. At high masses, the expected sensitivity will supersede the SN 1987 energy loss limit. This region is interesting because it is favoured for DM candidates.

3.1. Additional equipment for extended sensitivity

Additional equipment can be considered to enhance the physics goals of the experiment. GridPix detectors [17], Transition Edge Sensors (TES) [18] and Charged Coupled Devices (CCD) [19] could be interesting to search for signatures requiring lower energy thresholds like hidden photons, chameleons or other ALPs. Furthermore possibilities to search for relic axions in IAXO with microwave cavities or dark matter axions with dish antennas have also been explored [11, 20]. In this way, the IAXO sensitivity could be extended to very low masses entering the region of interest for Dark Matter axions.

4. Conclusions and Status

The increasing experimental and theoretical efforts in the axion searches demonstrate that the axion search has a strong physics case. The CAST experiment has been a very important milestone in axion research during the last decade. IAXO, the fourth generation helioscope, will allow the community to deeply probe into the unexplored axion-ALP parameter space becoming a generic axion facility with discovery potential. The next short term objectives are to prepare a Technical Design Report and to construct the first prototypes of the hardware main ingredients: demonstration coil IAXO-T0, X-ray optics IAXO-X0 and low background detector IAXO-D0 while refining the physics case and studying the feasibility studies for Dark Matter axions.

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