International Axion Observatory (IAXO) status and prospects

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Abstract. International Axion Observatory (IAXO) is a new generation axion helioscope aiming to search for solar axions and axion-like particles (ALPs) with a signal to background ratio of about 5 orders of magnitude higher than the one achieved by currently the most sensitive axion helioscope, CAST. IAXO relies on large improvements in magnetic field volume and extensive use of X-ray focusing optics combined with low-background detectors. IAXO will probe a substantial unexplored region of the axion and ALP parameter space which is theoretically and cosmologically motivated, and thus will have significant discovery potential. IAXO could also be used to test models of other proposed particles at the low energy frontier of particle physics, like hidden photons or chameleons. In addition, the IAXO magnet could accommodate new equipment to search for relic axions or ALPs potentially composing the galactic halo of dark matter.

1. Introduction

The axion is a hypothetical neutral pseudoscalar particle postulated in order to resolve the strong CP problem: in the quantum chromodynamcs there is a CP violating term, but the CP violation in strong interactions does not occur in experiments. The most elegant solution to the strong CP problem was proposed by Peccei and Quinn in 1977. They introduced a new global chiral $U(1)_{PQ}$ symmetry spontaneosly broken at a large energy scale f_a. The associated pseudo-Goldstone boson is the axion. The CP violating term is absorbed in the definition of the axion field thus solving the strong CP problem [1, 2, 3, 4].

Axions could interact with ordinary particles like photons, electrons, and nucleons. The coupling constants, as well as the axion mass, are inversely proportional to the scale f_a. Since the axion models predict that $f_a >> f_{weak}$, axions have weak couplings and small mass. These properties make them candidates for the dark matter as well.

Axion-like particles (ALPs) are predicted by many extensions of the standard model [5], notably string theory. For ALPs, the coupling constants and the mass are generally independent parameters. Axion-like particles are also viable dark matter candidates.

Most of the experimental searches for axions and ALPs are based on their coupling to two photons, allowing for axion-photon conversion in external electric or magnetic fields [6, 7, 8]. There are three main experimental approaches, depending on the source of axions/ALPs: 1) *light-shining-through-wall* experiments use lasers and strong magnetic fields to produce ALPs in a laboratory; 2) *haloscopes* search for the dark matter in the galactic halo using microwave cavities; 3) *helioscopes* search for axions and ALPs emmited from the center of the Sun using strong magnetic fields.
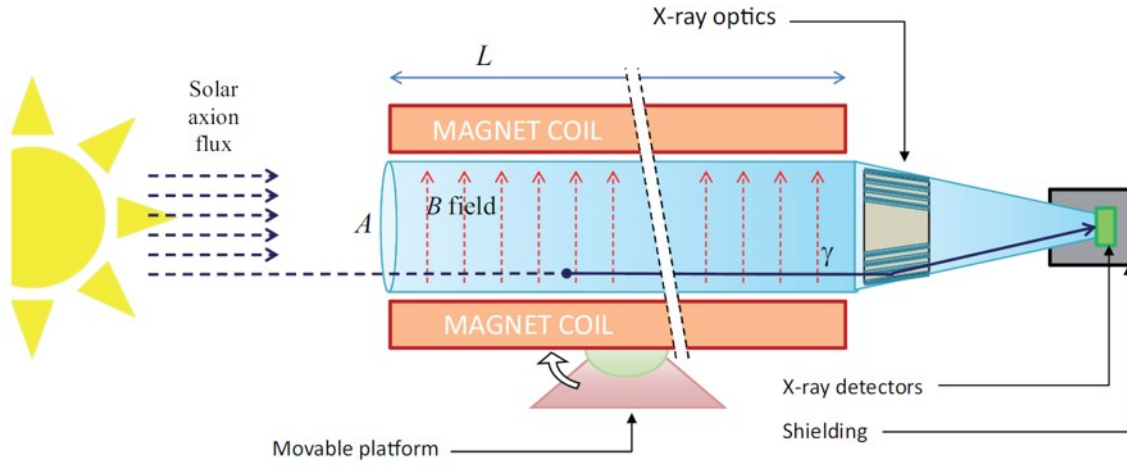
Figure 1. Axion helioscope principle. Axions and ALPs are produced in the solar core via the Primakoff process and converted into photons in a strong magnetic field in laboratory. For IAXO, photon detection systems will include X-ray optics specifically built for axion searches and low-background X-ray detectors.

2. Axion helioscopes

Axions and axion-like particles could be produced in the center of the Sun via the Primakoff process, i.e. conversion of photons to axions in the electromagnetic fields of electrons and nuclei. In a laboratory, axions and ALPs could be back-converted into photons in a strong transverse magnetic field (figure 1). The expected number of photons reaching a detector at the magnet end is given by

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} \, P_{a \to \gamma} \, S \, t \, dE_a \,, \tag{1}$$

where $d\Phi_a/dE_a$ is the differential solar axion flux at the Earth, $P_{a \to \gamma}$ is the axion-photon conversion probability in the magnet, S the cross-sectional area of the magnet bore, and t the measurement time. The differential axion flux at the Earth can be parametrised as:

$$\frac{d\Phi_a}{dE_a} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10} \, \text{GeV}^{-1}} \right)^2 \frac{E_a^{2.481}}{e^{E_a/1.205}} \quad \left[\text{cm}^{-2} \, \text{s}^{-1} \, \text{keV}^{-1} \right] \tag{2}$$

with the average energy $\langle E_a \rangle = 4.2$ keV. The conversion probability (with vacuum inside the magnet bores) is given by

$$P_{a \to \gamma} = \left(\frac{g_{a\gamma} B}{q} \right)^2 \sin^2 \left(\frac{qL}{2} \right) \,, \tag{3}$$

where B is the magnetic field, L the magnet length, and $q = m_a^2/(2E_a)$ the axion-photon momentum transfer.

Currently the most sensitive axion helioscope is CAST (CERN Axion Solar Telescope) [9]. The CAST experiment has set the most stringent limit on the axion-photon coupling constant over a broad range of axion masses. The most recent result [10] is $g_{a\gamma} < 6.6 \times 10^{-11} \text{GeV}^{-1}$ for $m_a < 0.023$ eV. IAXO (International Axion Observatory) [11, 12] is a new generation axion helioscope (currently in the Technical Design phase) aiming for the sensitivity to the axion-photon coupling constant $1 - 1.5$ orders of magnitude better than CAST.

3. IAXO experiment

The IAXO experiment will be designed to search for solar axions and ALPs with the axion-photon coupling $g_{a\gamma}$ down to a few 10^{-12} GeV^{-1} for axion masses $m_a \leq 0.016$ eV, more than 1 order of magnitude beyond the current astrophysical and helioscope upper bounds. The stated IAXO sensitivity relies on the construction of a large scale multi-bore superconducting magnet capable to track the Sun for about 12 hours each day. In the original Conceptual Design (figure 2) [12] the magnet design was inspired by the toroidal magnet geometry used by the ATLAS experiment at CERN. The new toroid would provide 2.5 T magnetic field inside eight 60 cm diameter and 20 m long magnet bores. The magnet design opens the way for the significant sensitivity improvement, with respect to CAST, mainly through a larger cross-sectional area (the CAST magnet has two 4.3 cm diameter bores). Each of large-aperture magnet bores will be equipped with X-ray optics focusing the signal photons into few mm^2 areas. The baseline fabrication approach for the IAXO optics will be slumped glass technology with multilayers, the technollogy which has been successfully used for the NuSTAR satellite mission. With the focal length of 5 m, the signal photons will be focused into few mm^2 areas that are imaged by ultra-low background X-ray detectors. The baseline technology for the low background detectors are gaseous Micromegas detectors with pixelated readout, manufactured with the microbulk technique. The latest generation of Micromegas detectors in combination with the prototype X-ray optics has alreday been used in the CAST experiment [10]. This IAXO pathfinder detection system achieves background levels of 0.003 counts/hour. More detector technologies will be used in the IAXO experiment: gaseous InGRID detectors, MMC (Magnetic Metallic Calorimeter) detectors etc.
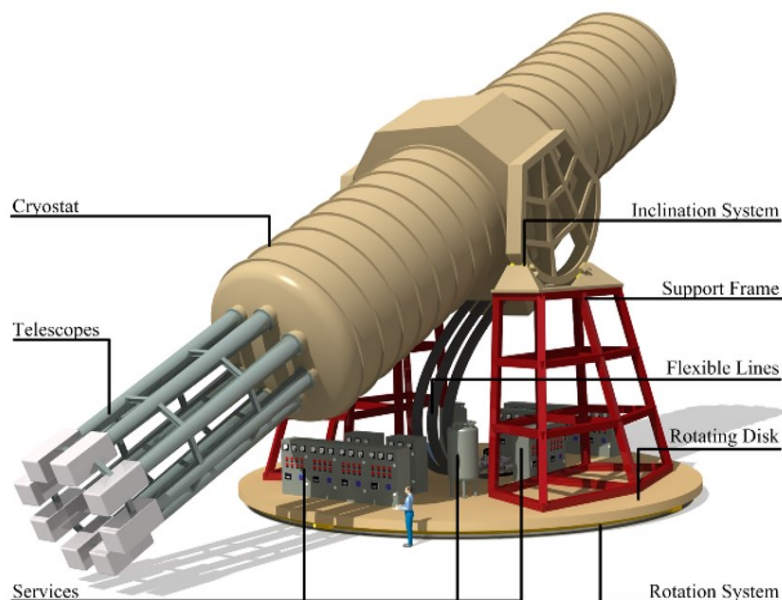

Figure 2. The IAXO setup scheme.

3.1. BabyIAXO experiment

Alternative and more challenging design for the IAXO magnet was proposed recently and therefore a magnet prototype needs to be constructed. The prototype will have one 60 cm diameter and 10 m long magnet bore with 2.5 T magnetic field inside the bore. The magnet will

have figure of merit 10 times better than the CAST magnet. This magnet combined with the X-ray optics and low-background detector will serve as intermediate step (so called BabyIAXO) towards the final IAXO setup. The BabyIAXO experiment will provide sensitivity suitable for exploring yet unexplored part of the axion/ALP parameter space.

3.2. IAXO physics cases and sensitivity

The main goal of the IAXO experiment is to search for solar axions and ALPs produced by the axion-photon coupling. The predicted IAXO sensitivity will enter into completely unexplored axion/ALP parameter space (figure 3). The most important task for IAXO will be to explore a broad range of realistic QCD axion models at high-mass end of the parameter region. Also, IAXO will be able to test some yet unexplained astrophysical observations. At the low-mass end (below 10^{-7} eV) the region attainable by IAXO includes ALP parameters invoked to explain anomalies in high-energy gamma ray propagation over astronomical distances. IAXO would provide a definitive test of this hypothesis. At the high-mass part of the parameter space, IAXO will be able to test the hypothesis that axions/ALPs could explain many astrophysical observations of anomalous cooling of different types of stars. From cosmological point of view, most of the region reachable by IAXO contains possible dark matter candidates. Also, the high-mass end could be of great importance in describing both inflation and dark matter.
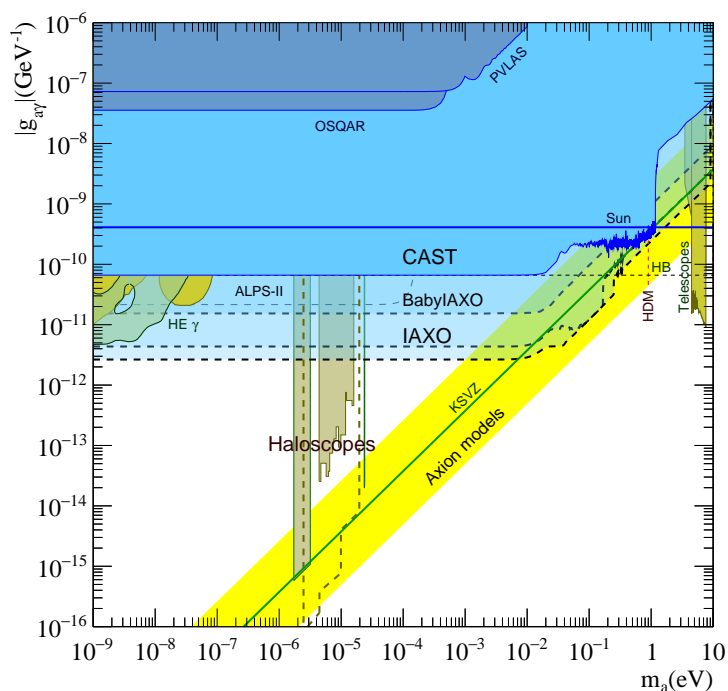

Figure 3. The axion/ALP parameter space. The yellow band represents the QCD axion models. Already excluded regions by laser experiments, haloscopes, and helioscopes (CAST) are shown. The dashed lines show prospects for future searches with haloscopes, laser experiments (ALPS-II) and helioscopes (BabyIAXO and IAXO). The lower IAXO line shows the improved sensitivity, compared to the original design, when the new magnet design (to be tested in BabyIAXO) is included.

Additional physics cases for IAXO include searches for solar axions or ALPs produced by the axion-electron coupling. Similarly IAXO will test models of other proposed particles at the low energy frontier of particle physics, like hidden photons or chameleons. In addition, the IAXO magnet will be conceived to easily accommodate new equipment (e.g., microwave cavities or antennas) to search for relic axions (dark matter axions in the galactic halo).

4. Conclusions

The IAXO experiment is a new generation axion helioscope aiming to search for solar axions and ALPs with the axion-photon coupling $g_{a\gamma}$ down to a few 10^{-12} GeV^{-1} for axion masses $m_a \leq 0.016$ eV. An intermediate experiment, BabyIAXO, will be constructed with the IAXO magnet prototype. Both BabyIAXO and especially IAXO will enter into a completely unexplored region of the axion/ALP parameter space. This region is relevant for several theoretical, astrophysical and cosmological considerations.

Acknowledgements

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