Future axion searches with the International Axion Observatory (IAXO)

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Abstract. The International Axion Observatory (IAXO) is a new generation axion helioscope aiming at a sensitivity to the axion-photon coupling of $g_{a\gamma} \gtrsim$ few$\times 10^{-12}$ GeV^{-1}, i.e. 1-1.5 orders of magnitude beyond the one achieved by CAST, currently the most sensitive axion helioscope. The main elements of IAXO are an increased magnetic field volume together with extensive use of x-ray focusing optics and low background detectors, innovations already successfully tested in CAST. Additional physics cases of IAXO could include the detection of electron-coupled axions invoked to explain the white dwarf cooling, relic axions, and a large variety of more generic axion-like particles (ALPs) and other novel excitations at the low-energy frontier of elementary particle physics.

1. Introduction

The Peccei-Quinn (PQ) mechanism of dynamical symmetry restoration [1, 2] stands out as the most compelling solution of the strong CP problem. Central to the PQ mechanism is the axion [3, 4], the Nambu-Goldstone boson of a new spontaneously broken symmetry $U(1)_{PQ}$. The properties of axions allow them to be produced in the early universe as coherent field oscillations and as such to provide all or part of the cold dark matter [5, 6].

It is still possible to find these "invisible axions" in realistic search experiments and in this way test a fundamental aspect of QCD. The generic $a\gamma\gamma$ vertex allows for axion-photon conversion in external electric or magnetic fields in analogy to the Primakoff effect for neutral pions. As shown in 1983 by Pierre Sikivie, the smallness of the axion mass allows this conversion to take place coherently over macroscopic distances, compensating for the smallness of the interaction strength [7]. Especially promising is to use the Sun as a source for axions produced in its interior by the Primakoff effect. Directing a strong dipole magnet toward the Sun allows one to search for keV-range x-rays produced by axion-photon conversion, a process best visualized as a particle oscillation phenomenon [8] in analogy to neutrino flavor oscillations. Three such helioscopes have been built, in Brookhaven [9], Tokyo [10] and at CERN [11]. The CERN Axion Solar Telescope (CAST) has just finished a 8-year long data taking period, having strongly improved on previous experiments and even surpassed astrophysical limits in some range of parameters, although axions have not been found.

We have shown [12] that large improvements in magnetic field volume, x-ray focusing optics and detector backgrounds with respect to CAST are possible. Based on these improvements, and on the experience gathered within CAST, we propose the International Axion Observatory (IAXO), a new generation axion helioscope. IAXO could search for axions that are 1–1.5 orders of magnitude more weakly interacting than those allowed by current CAST constraints. It appears conceivable to surpass the SN 1987A constraint on the axion mass, $m_a \lesssim 20$ meV, test the white-dwarf (WD) cooling hypothesis [13], and explore a substantial part of uncharted axion territory experimentally. Moreover, IAXO would explore other more generic models of weakly interacting sub-eV particles (WISPs) [14, 15], in particular some models for axion-like particles (ALPs) that have been invoked in the context of several unexplained astrophysical observations. Equipped with microwave cavities or antennas, this setup could also aim at detecting relic axions [16, 17, 18].

2. Experimental setup and expected sensitivity

IAXO will follow the basic conceptual layout of an enhanced axion helioscope seen in figure 1, implemented to a toroidal design for the magnet, together with x-ray optics and detectors attached to each of the magnet bores. The improvements anticipated for each of the experimental parameters of the helioscope were quantified in [12], organized in four scenarios (IAXO 1 to 4) ranging from most conservative to most optimistic values (see table 1 of [12]). These values are justified by several considerations of the magnet, x-ray optics and detectors, that are briefly outlined in the following, but we refer to [12] for a detailed discussion.

The magnet parameters are the ones contributing mostly to the helioscope's figure of merit. The CAST success has relied, to a large extent, on the availability of the first class LHC test magnet which was recycled to become part of the CAST helioscope. While going beyond CAST magnet's B or L is difficult, the improvement may come however in the cross section area, which in the case of the CAST magnet is only 3×10^{-3} m^2. Substantially larger cross sections can be achieved, although one needs a different magnet configuration. It is an essential part of our proposal that a new magnet must be designed and built specifically for this application, if one aims at a substantial step forward in sensitivity. A toroidal configuration for the IAXO magnet is being studied with a total cross section area A of up to few m^2, while keeping the product of BL close to levels achieved for CAST [19].

Another area for improvement will be the x-ray optics. Although CAST has proven the concept, only one of the four CAST magnet bores is equipped with optics. The use of focusing power in the entire magnet cross section A is implicit in the figures of merit defined in [12], and therefore the improvement obtained by enlarging A comes in part because a correspondingly large optic is coupled to the magnet. The optics challenge in this case is two-fold: not only must we optimize the optic figure of merit, but we must also consider the availability of cost-effective x-ray optics of the required size. IAXO's optics specifications can be met by a dedicated fabrication effort based on segmented glass substrate optics like the ones of HEFT or NuSTAR [20].

Finally, CAST has enjoyed the sustained development of its detectors towards lower

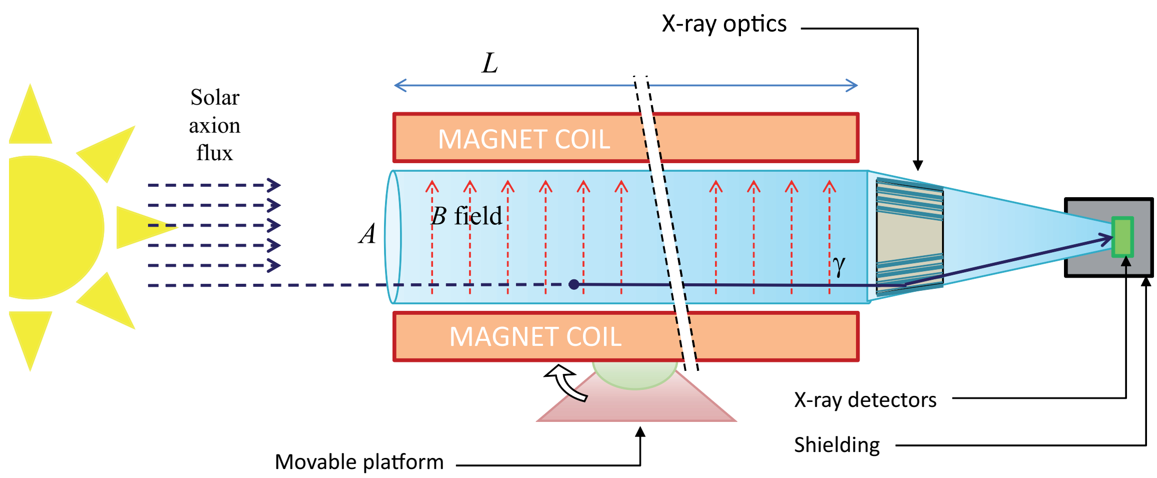

Figure 1. Conceptual arrangement of an enhanced axion helioscope with x-ray focalization. Solar axions are converted into photons by the transverse magnetic field inside the bore of a powerful magnet. The resulting quasi-parallel beam of photons of cross sectional area A is concentrated by an appropriate x-ray optics into a small spot area a in a low background detector. The envisaged design for IAXO includes eight such magnet bores, with their respective optics and detectors.

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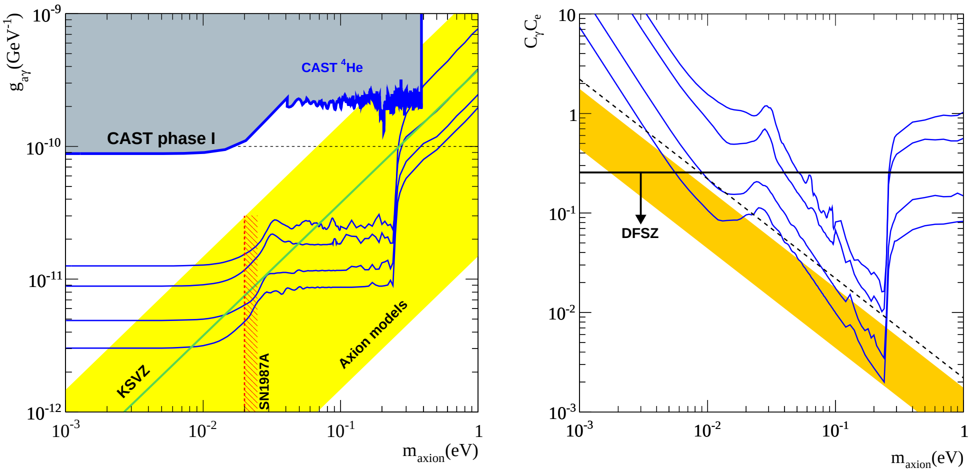

Figure 2. LEFT: The parameter space for hadronic axions and ALPs. The CAST limit, some other limits, and the range of PQ models (yellow band) are also shown. The blue lines indicate the sensitivity of the four scenarios discussed in the text. RIGHT: The expected sensitivity regions of the same four scenarios in the parameter space of non-hadronic axions with both electron and photon coupling. The orange band represents the region motivated by WD cooling, and the dashed line along the diagonal the red giants bound on the electron coupling. See [12] for details.

backgrounds during its lifetime. The latest generation of Micromegas detectors in CAST are achieving backgrounds of $\sim 5 \times 10^{-6}$ counts keV^{-1} cm^{-2} s^{-1}. This value is already a factor 20 better than the backgrounds recorded during the first data-taking periods of CAST. Prospects for reducing this level to 10^{-7} counts keV^{-1} cm^{-2} s^{-1} or even lower appear feasible [21, 22].

The computed sensitivities of each of the four IAXO scenarios are represented by the family of blue lines in figure 2, both for hadronic axions (left) and non-hadronic ones (right). They include two data taking campaigns for each of the scenarios: one three years long performed without buffer gas (analogous to CAST I), and another three years long period with varying amounts of ^{4}He gas inside the magnet bore (analogous to CAST II, although without the need to use ^{3}He). In general, IAXO sensitivity lines go well beyond current CAST sensitivity for hadronic axions and progressively penetrate into the decade 10^{-11}–10^{-12} GeV^{-1}, with the best one approaching 10^{-12} GeV^{-1}. They are sensitive to realistic QCD axion models at the 10 meV scale and exclude a good fraction of them above this. For non-hadronic axions, IAXO sensitivity lines penetrate in the DFSZ model region, approaching or even surpassing the red-giant constraints. Most relevantly, the IAXO 3 and IAXO 4 scenarios start probing the region of parameter space highlighted by the cooling of WDs.

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