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Next Generation Search for Axion and ALP Dark Matter with the International Axion Observatory

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***Abstract*—More than 80 years after the postulation of dark matter, its nature remains one of the fundamental questions in cosmology. Axions are currently one of the leading candidates for the hypothetical, non-baryonic dark matter that is expected to account for about 25% of the energy density of the Universe. Especially in the light of the Large Hadron Collider at CERN slowly closing in on Weakly-Interacting Massive Particle (WIMP) searches, axions and axion-like particles (ALPs) provide a viable alternative approach to solving the dark matter problem. The fact that makes them particularly appealing is that they were initially introduced to solve a long-standing problem in quantum chromodynamics and the Standard Model of particle physics.**

Helioscopes are a type of axion experiment searching for axions produced in the core of the Sun via the Primakoff effect. The International Axion Observatory (IAXO) is a next generation axion helioscope aiming at a sensitivity to the axion-photon coupling of $1-1.5$ orders of magnitude beyond the current most sensitive axion helioscope, which is the CERN Axion Solar Telescope (CAST). IAXO will be able to challenge the stringent bounds from supernova SN1987A and test the axion interpretation of anomalous white-dwarf cooling. Beyond standard axions, this new experiment will also be able to search for a large variety of axion-like particles and other novel excitations at the low-energy frontier of elementary particle physics. BabyIAXO is proposed as an intermediate-scale experiment increasing the sensitivity to axion-photon couplings down to a few 10^{-11} GeV^{-1} and thus delivering significant physics results while demonstrating the feasibility of the full-scale IAXO experiment. Here we introduce the IAXO and BabyIAXO experiments, report on the current status of both and outline the expected IAXO science reach.

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I. Introduction

While the discovery of the Higgs boson at the LHC experimentally confirms the widely successful Standard Model (SM) of particle physics, the theory still falls short of explaining several fundamental features of our Universe. A major shortcoming is the SM's silence on the nature of Dark Matter (DM). Another problem that cannot be solved within the SM is the fact that strong interactions do not violate charge-parity (CP) symmetry as expected from theory [1]. The most compelling solution to the strong CP problem has been suggested over 30 years ago [2], and results in the appearance of a new extraordinary weakly interacting particle, dubbed

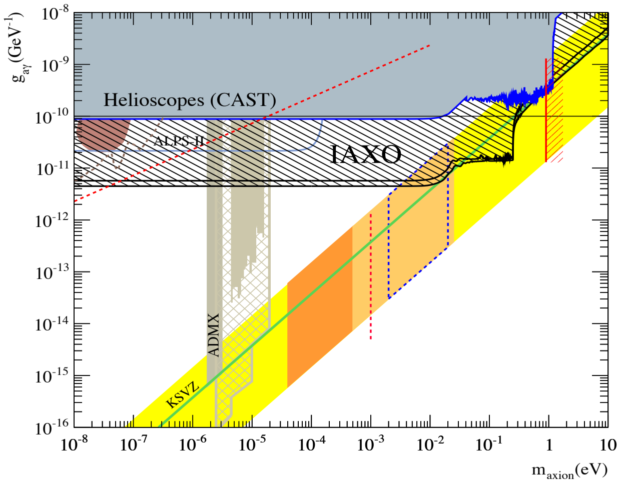

Fig. 1. Exclusion plot with current-best upper limits (CAST [10], ADMX [11], [12]) on the axion-photon coupling constant $g_{a\gamma\gamma}$ as a function of axion mass together with sensitivity prospects for IAXO. The yellow band represents QCD axion models. The interested reader is referred to [13] for additional details.

the axion [3]. Experiments have yet to confirm or refute the existence of the elusive particle, and the search is challenging, since the axion mass is not known a priori. Similar to neutrino oscillations, axions mix with photons in the presence of strong electromagnetic fields leading to axion-photon oscillations [4]-[6]. This $a\gamma\gamma$-coupling brings about the axion production in stellar cores via the Primakoff effect [7] possibly providing the major axion energy loss channel for stars like the Sun, while the inverse Primakoff effect is the favored detection mechanism of axion search experiments, like helioscopes [8] and haloscopes [4]. Apart from providing the most elegant solution to the strong CP problem, axions are favored candidates for the hypothetical, non-baryonic DM along with Weakly Interacting Massive Particles (WIMPs). Both candidates, axions and WIMPs, commonly arise in supersymmetric (SUSY) extensions to the SM and could solve the DM problem either together or alone. Axions may have been produced non-thermally in the early universe (non-relativistic axions) and could still be present in the halo of galaxies. But they could also be continuously created nowadays in the core of stars. Depending on their mass they could provide either a subdominant component, or most to all of the DM. Moreover, axion-like particles (ALPs, [9]) are potentially able to address and solve the DM mystery. Although ALPs are not necessarily related to the QCD-axion they still share a large part of their phenomenology and can therefore be searched for with similar experiments. Figure 1 summarizes the status of current axion searches and future prospects.

To date, the most sensitive instrument searching for solar axions is the CERN Axion Solar Telescope (CAST) experiment [14]- [21]. This helioscope uses a strong magnetic field to reconvert the axions into x-ray photons and studies a large fraction of previously unsearched axion parameter space complementary to present and future microwave cavity experiments looking for halo axions, such as the Axion Dark Matter eXperiment (ADMX) [11], [12]. The International Axion Observatory (IAXO, [22]- [23]) will further push the search into yet unexplored parameter space by increasing the sensitivity by $1-1.5$ orders of magnitude over a wide range of interesting axion masses (see also Fig. 1).

II. The BabyIAXO and IAXO Experiments

Helioscopes use a strong magnetic field to reconvert solar axions into x-ray photons via the inverse Primakoff effect as shown in Fig. 2. Telescopes can be used to focus the putative signal from axions into a small spot on a low-background x-ray detector significantly increasing the experimental sensitivity by allowing for small-area detectors and simultaneous data and background acquisition. The third key component for helioscopes besides magnet and optics are dedicated low-background detectors tuned for low-event searches. BabyIAXO (see Fig. 3, top) has been proposed as a test bench for the IAXO magnet, optics and detectors. This will help to reduce remaining risks of the generally mature technologies and provide the opportunity to implement improvements that might enable IAXO to go beyond its proposed baseline performance (which would then be dubbed IAXO+ and able to reach sensitivities to the axion-photon coupling $g_{a\gamma\gamma}$ down to a few 10^{-12} GeV^{-1}) while delivering new and relevant physics results pushing further into unexplored, yet well-motivated regions of the axion parameter space.

To achieve this goal, BabyIAXO will feature a double-bore, 10 m toroidal magnet in a common coil configuration. The average magnetic field strength will be $2-3$ Tesla within the bore of diameter 0.7 m and the peak magnetic field is envisioned to reach 4.1 T with a stored energy of $40-50$ MJ. While other magnet configuration were under consideration, the choice for BabyIAXO relies on a cost-effective, low-risk approach. The relatively low expenses are due to the possibility to reuse existing tooling for this magnet arrangement and the low risk will allow to move from design to construction rather early. In any case, the bore dimensions will be similar to those of the full-scale IAXO, however, IAXO is expected to consist of 8 bores, each 20 m in length (Fig 3, bottom). The total stored energy will then be 500 MJ, with average and peak fields similar to BabyIAXO ($2-3$ T and $4-5$ T, respectively). Fig. 4 shows the envisioned final IAXO magnet with its eight bores.

Optics and detector for BabyIAXO will be representative of the final IAXO designs and therefore the intermediate-scale experiments provides an ideal testbench for first, fullscale detection systems for the final IAXO configuration. Details can be found in Ref. [23].

In preparation for IAXO and BabyIAXO, a pathfinder system [24], [25] consisting of a prototype x-ray telescope (XRT, shown in the left part of Fig. 5) and a novel low-background Micromegas detector was designed, built, tested and installed at CAST. The XRT is based on the same slumped-glass technology developed for NASA's NuSTAR satellite mission [26] and the optics+detector pathfinder (see right part of Fig. 5) enabled new benchmark limits on solar axions at CAST [10], while demonstrating that this

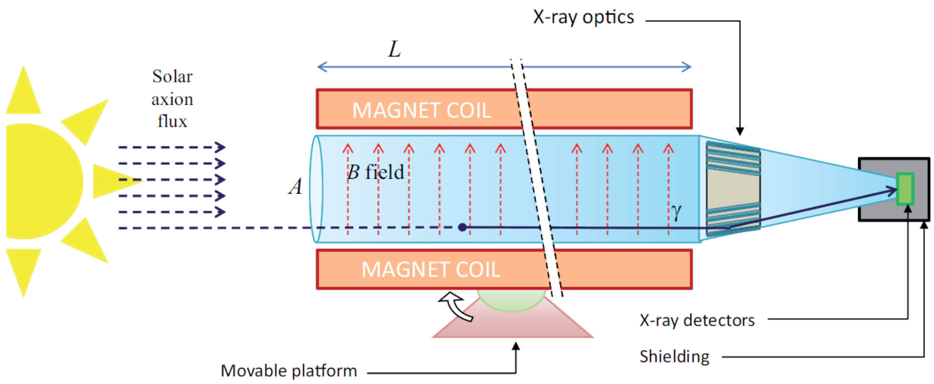

Fig. 2. Detection principle of axion helioscopes. A strong transverse magnetic field is used to reconvert axions originating from the solar core into x-ray photons that can then be focused by an x-ray telescope and detected by low-background x-ray detectors.

approach works well for axion physics experiments and is highly suitable for BabyIAXO and IAXO. The next step in the XRT development for BabyIAXO and IAXO will include building a 60-cm-diameter segmented x-ray optic (see Fig. 6), that will be installed on the end of one of BabyIAXO's bores. For the second bore, it is envisioned that one of ESA's XMM-Newton flight spare telescopes [27] will be used. While not optimized for the BabyIAXO experiment, it is still close enough in its specifications to be able to significantly contribute in obtaining interesting science results.

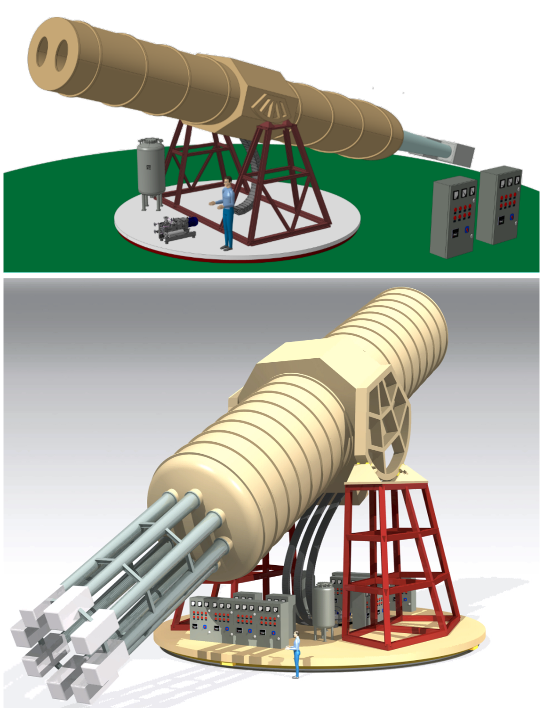

Fig. 3. Schematic experimental setup for BabyIAXO (top) and IAXO (bottom). The main difference is that the intermediate-stage experiment BabyIAXO has only two 10 m long magnet bore, while this will be replaced by 8 coils of 20 m length each for IAXO.

Several detector technologies are under consideration for both BabyIAXO and IAXO with microbulk Micromegas detectors as baseline technology. The use of these detectors generally involves special low-background techniques often developed for experiments conducted deep underground. This includes the use of highly radiopure materials, sophisticated shielding as well as offline background reduction algorithms. Other detector types under consideration include GridPix detectors, Magnetic Metallic Calorimeters, Transition Edge Sensors, and Silicon Drift Detectors. These novel technologies might prove especially promising for specific niche measurements such as search for solar axions via the axion-electron coupling if they exhibit a sufficiently low energy threshold.

III. IAXO Physics Reach

IAXO 's primary science driver is the search for solar axions and ALPs emitted via the generic Primakoff effect for which it will improve the sensitivity with respect to CAST by more than 1 order of magnitude in sensitivity to $g_{a\gamma\gamma}$, which corresponds to a factor of more than 10^4 in terms of signal to noise. The experiment will probe a large fraction of QCD axion models in the meV to eV mass band not accessible to any other proposed technique. In addition to exploring viable QCD axion DM models, IAXO will also probe large

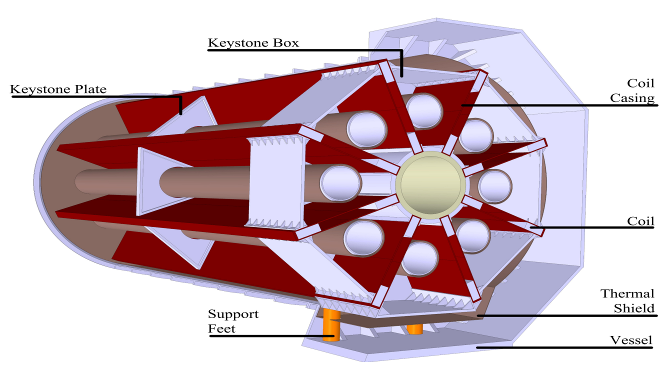

Fig. 4. Design of the IAXO toroidal magnet which will feature 8 bores of 20 m length each producing an average magnetic field of $2-3$ T in the 60 or 70 cm diameter bores.

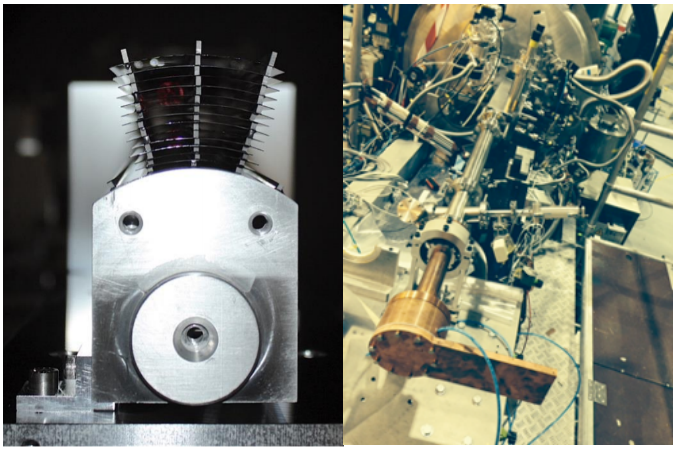

Fig. 5. Left: IAXO segmented-glass pathfinder x-ray optic, based on NuSTAR technology [26]. Right: Full IAXO pathfinder system consisting of optic and novel Micomegas detector (bottom left in image) as installed at CAST.

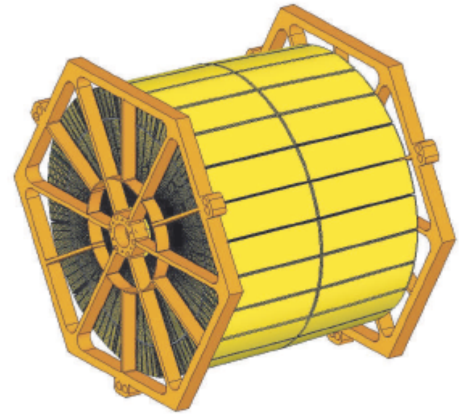

Fig. 6. A side-view of the design for the IAXO telescopes and the spider mounting structures used to support the segmented-glass optic.

regions of theoretically-motivated parameter space for the ”ALP miracle” models [28] solving both DM and inflation. Furthermore IAXO will also be sensitive to non-hadronic axions, i.e. axions coupling to electrons in addition to photons, and could directly measure the solar axion flux produced via BCA processes (Bremsstrahlung, Compton scattering, and axio-recombination) for the first time with sensitivities to values of g_{ae} relevant to test the hypothesis that the cooling of White Dwarfs is enhanced by axion emission [29]. Beyond this, IAXO can also be sensitive to other, more exotic, proposed particles at the low energy frontier of particle physics, such as hidden photons [30] or chameleons [31], and is able to study the ALP region invoked to solve the transparency anomaly [32]. It is worth noting that all these questions can be addressed independent of whether axions are a subdominant DM component or compose all of the DM, while the experiment is largely complementary to other axion and ALP search strategies. BabyIAXO could already start shedding light on some of these aspects and improve the state-of-the-art when it reaches the intended sensitivity to the axion-photon coupling of a few 10^{-11} GeV^{-1}. More detailed prospects for BabyIAXO, IAXO and IAXO+ will be discussed in an upcoming publication [33].

IV. Conclusion

In this contribution, we presented the basic layout of both the IAXO and BabyIAXO experiment and reported on our IAXO pathfinder line that includes an x-ray telescope and a low-background micromegas detector. This setup was successfully tested and aquired data leading to new world-best limits on solar axions. We furthermore outlined the sensitivity prospects for BabyIAXO and IAXO to demonstrate their improvements over current-best helioscope experiments. We are currently working towards the technical design report for the BabyIAXO setup and are preparing to build a first set of magnet, x-ray optic and detector to be the key pieces of the BabyIAXO stage of the IAXO experiment.

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