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Status update of the axion helioscope BabyIAXO

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The International Axion Observatory (IAXO) is a large-scale axion helioscope that will look for axions and axion-like particles (ALPs) produced in the Sun. It is conceived to reach a sensitivity on the axion-photon coupling in the range of 10^{-12} GeV^{-1}. An intermediate experiment, BabyIAXO, is already in the construction phase. BabyIAXO will be important to test all IAXO subsystems (magnet, optics and detectors) and at the same time, as a fully-fledged helioscope, will reach a sensitivity on the axion-photon coupling of 1.5×10^{-11} GeV^{-1} for masses up to 0.25 eV, covering a very interesting region of the parameter space. Important milestones have been reached in the past years in the development of the different components of the experiment. In particular for low background X-ray detectors, X-ray optics as well as for the design of the large magnet hosting two 10 m long bores with a diameter of 0.7 m for axion to photon conversion. The design of the mechanical infrastructure allowing for Sun monitoring during half of the day has been defined. We report on the recent characterization of BabyIAXO subsystems and discuss how the achieved results compare to the requirements.

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1. Introduction

Axions are hypothetical particles that are well motivated by theory as they arise as a solution to the strong CP problem of the Standard Model of particle physics. The most compelling solution is the Peccei-Quinn (PQ) mechanism [1], involving a new global $U(1)$ symmetry that is spontaneously broken at a large energy scale f_a. The oscillations of this field give rise to a new pseudo Nambu-Goldstone boson: the axion. The phenomenology of axions is mainly defined by f_a, being the axion mass m_a and axion couplings to photons, electrons and nucleons inversely proportional to f_a, which, based on accelerator experiments, must be much greater than the electroweak scale. Axions are thus light, long-lived and very weakly interacting, which makes them excellent dark matter candidates without being an ad-hoc solution.

Most of the experimental searches rely on the axions and axion like particles (ALPs) coupling to two photons, $g_{a\gamma}$, together with the use of strong magnetic fields in which axions can convert into photons. In particular, the helioscope technique is based on the axion production via Primakoff effect. Thermal photons interacting with the solar nuclei would produce axions that can travel to Earth and be transformed back to photons, the so called inverse Primakoff effect, inside a strong magnetic field. The expected solar axion emission spectrum from the Primakoff effect follows the black body spectrum from the solar core, with average energy at 4.2 keV [2], which translates into X-ray photons.

2. Experimental searches with helioscopes

To detect solar axions, a helioscope needs a powerful and large magnet designed for this particular case as well as X-ray optics optimized for the expected axion energy to focus the signal to a small spot. Finally, it requires the use of ultra-low background X-ray detectors. The figure of merit f of an axion helioscope [3] has contributions from the different subsystems: magnet (f_M), detector and optics (f_{DO}), and effective time running in axion sensitive conditions (f_T), such that $f \equiv f_M f_{DO} f_T$, and

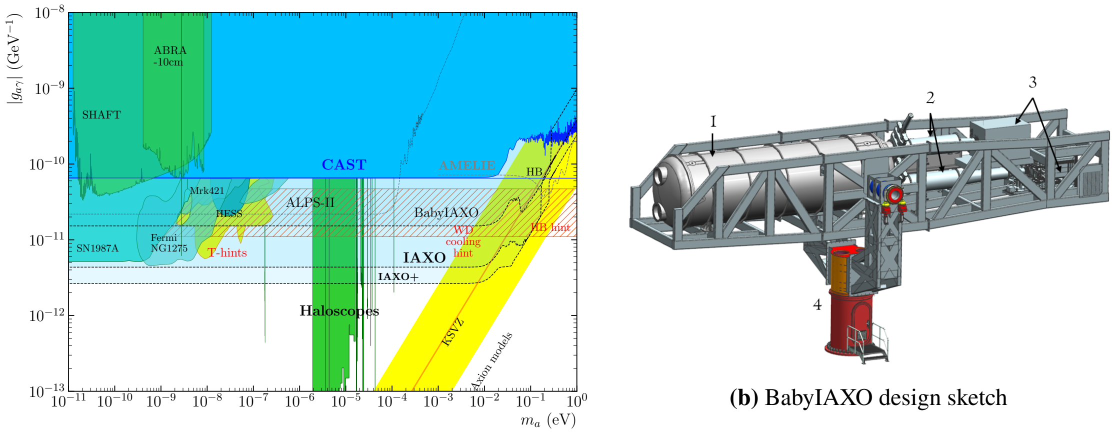
$$f_M = B^2 L^2 A \qquad f_{DO} = \frac{\epsilon_d \epsilon_o}{\sqrt{ba}} \qquad f_T = \sqrt{\epsilon_t t}, \tag{1}$$

where B is the magnetic field, L the length and A the aperture of the bores; ϵ_d, ϵ_o and ϵ_t are the detector, optics and time or data taking efficiency respectively. b is the normalized background, a is the size of the focusing area and t the duration of the data taking campaign.

The CERN Axion Solar Telescope (CAST) [4] is the most powerful axion helioscope to date. Although in the final years it was used to explore other techniques as well, CAST has been operating as an axion helioscope for more than 20 years using a decommissioned prototype dipole 9 m long magnet of the LHC and a magnetic field of 9 T. The period of data taking from 2013 to 2015 is considered the IAXO pathfinder, when X-ray focusing optics were installed to work together with an ultra-low background microbulk Micromegas detector, the baseline detector technology for the future IAXO helioscope. This period of data gave the best experimental limit on axion-photon coupling over a broad axion mass range. It reached similar levels to the most restrictive astrophysical bounds, setting a limit to $g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ (95% C.L.) for $m_a \leq 0.02\,\mathrm{eV}$ [5].

3. A fourth generation helioscope: IAXO and BabyIAXO

The International Axion Observatory (IAXO) [6] is a fourth generation enhanced helioscope that was proposed to search for solar axions. It is based on mature and state-of-the-art technology. It will have a 20 m long magnet with a magnetic field of up to 5.9 T, which will vastly improve the f_M of CAST. It will consist of eight 60 cm diameter conversion bores, each coupled to a detection line with X-ray telescopes and low background detectors and will be able to track the sun during 50 % of the day. Non-tracking operation is also needed for calibration and background measurements. The BabyIAXO [7] helioscope has been proposed as a technological prototype for IAXO and it will be located at DESY (Hamburg, Germany). It is a smaller helioscope with only two detection lines instead of eight, but that will be able to obtain relevant physics results. Its building and operation will mitigate risks for IAXO and will provide the collaboration with hands-on experience. Furthermore, it will probe the IAXO baseline experimental parameters, which can lead to an improvement to the final experiment. The sensitivity and physics potential of these and other experiments can be conveniently represented in the parameter space relating $g_{a\gamma}$ to the axion mass m_a (Fig. 1a). BabyIAXO probes part of the QCD band as well as some of the astrophysical hints, making it relevant for physics discovery, and it improves the signal-to-noise ratio (SNR) by a factor $> 10^2$ that of CAST [7]. IAXO probes large generic unexplored ALP space, QCD axion models in the meV to eV mass band and astrophysically hinted regions. It improves SNR by a factor $> 10^4$ and sensitivity in $g_{a\gamma}$ by more than one order of magnitude [6], [8]. Furthermore, it has been recently shown that both IAXO and BabyIAXO will have the potential to detect solar axions from the ^{57}Fe nuclear transition at 14.4 keV [9].



(a) Parameter space

(b) BabyIAXO design sketch

Figure 1: (a) $g_{a\gamma} - m_a$ parameter space showing the sensitivity of IAXO and BabyIAXO, compared to the sensitivity of other experiments that scan the same region. The yellow band represents the standard QCD axion models. Both IAXO and BabyIAXO get well into this QCD axion region. (b) Design of BabyIAXO, including (1) cylindrical cryostat containing the magnet, (2) optics, (3) detectors, and (4) support frame and structure drive system. The overall system length is about 19 meters.

Each of the relevant subsystems for BabyIAXO, namely magnet, optics and detector (Fig. 1b), that will allow to reach this sensitivity, are described in the following sections. For a complete description, the reader is referred to [7].

3.1 The BabyIAXO magnet

It consists of two 10 m long flat racetrack coils with strands of Aluminum-stabilized NbTi superconducting cable. It has two bores of 70 cm centimeters diameter, and they are designed to be eventually filled with a buffer gas to extend the axion mass reach. The position of the bores with respect to the coils is designed to maximize the magnetic field in the volume of the bores. The design is following conservative choices to minimize the risk, being cost effective and still following a prototyping approach for the proposed toroidal magnet for IAXO.

3.2 The BabyIAXO optics

The use of X-ray optics is crucial to maximize the figure of merit f_{DO} of an axion helioscope, as it allows focusing the axion signal into a small spot of area a (eq. 1), increasing the SNR on that spot while allowing to simultaneously measure background in the regions of the detector out of the focal area. The other relevant parameter is the throughput or optics efficiency ϵ_O. Optimization can be challenging as ϵ_0 is maximized by reducing the grazing angle, which implies longer focal distance F. But $F \propto a^2$, creating a conflict with the focusing requirement. The optimal compromise is found for $F = 5$ m (see fig. 26 in [7]). BabyIAXO requires two X-ray telescopes, one for each detection line. They are Wolter type I optics and can focus the signal from the 0.7 m diameter bore to a 0.2 cm^2 area. Our approach is to cover one of the bores with a custom-designed BabyIAXO optic with $F = 5$ m an the other one with an already available flight-spare module from ESA's X-ray Multi-mirror Mission (XMM) Newton [10], with $F = 7.5$ m and which is compatible with the BabyIAXO design.

3.3 The BabyIAXO detectors

The IAXO project is meant to be an axion observatory where different detector technologies can work at the same time. Based on eq. 1, one can define a detector figure of merit $f_D = \frac{\epsilon}{\sqrt{b}}$. This shows that detectors must have high detection efficiency in the energy range of interest of the experiment (0 keV to 10 keV), and must be able to achieve a very low background in that range. The aim of the IAXO collaboration is to have a background level below 10^{-7} c keV^{-1} cm^{-2} s^{-1}. This involves the use of active and passive shielding as well as very radiopure materials and advanced event discrimination strategies.

The baseline detector technology for BabyIAXO is a Time Projection Chamber (TPC) based on the microbulk Micromegas technology [11], as it is the technology closest to the background requirements while achieving a good energy resolution in the range of interest, thus maximising the probability of discovery. Microbulk Micromegas detectors are gaseous detectors with a gas chamber where an electric field is applied. Ionizing radiation creates primary electrons that drift towards the readout, where a higher electric field is applied so that an electron avalanche process occurs, creating detectable signals. These detectors have been proven to be suitable for axion detection. Their readouts have high granularity, which allows signal recognition and background rejection. Also, they present good energy and spatial resolution for the axion signal and they are capable to reach sub-keV energy thresholds. Moreover, they are built with radiopure materials, which is crucial to reach the very low backgrounds required for axion detection. The performance of these detectors has already been proven with the IAXO pathfinder at CAST, where they have shown and overall detection efficiency of 60 % to 70 %.

Other alternative detection technologies are under study by several teams of the IAXO collaboration, such as the GridPix [12], Metallic Magnetic Calorimeters [13], and also Transition Edge Sensors and Silicon Drift Detectors [14]. These detectors would be particularly useful in a post-discovery scenario as they would allow for high precision measurements to determine the axion parameters.

From the CAST experience and also from other independent studies both at the lab and with simulations, we have developed a very good understanding of what the main background sources in our detectors are, and how to avoid or identify them. A critical background source is that of cosmic muons and neutrons. The current experimental results show that a single plastic scintillator placed above the detector as a cosmic veto halves the background rate. However, a more complex 4π active muon veto and a new cosmic neutron tagger system are being designed and tested. Underground tests are planned to start in October 2022, and will help us determine the intrinsic radioactivity of the detector components and the inner shielding. All these data will be supported by simulations studies, which will allow to acquire insight on the individual components of the background.

4. Conclusions

Axions and ALPs are very well motivated hypothetical particles. Furthermore, they are excellent dark matter candidates. The axion-photon coupling is exploited in experimental searches such as the helioscope technique. We have presented the state of the BabyIAXO helioscope, an intermediate stage towards IAXO, to be hosted at DESY. The project relies on state-of-the-art technologies and on the experience gained at CAST during the last two decades. BabyIAXO is a technological prototype for IAXO, but it will be able to produce relevant physics results by scanning an unexplored region of the QCD axions models. We have presented the key components currently under development: the large volume magnet and cryostat, the two X-ray telescopes and the ultra-low background detectors, being microbulk Micromegas the baseline detector technology.

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