Letter of Interest Snowmass 2021: Focusing on Axions: Optics for the International Axion Observatory (IAXO) and BabyIAXO

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On behalf of the IAXO optics team and the IAXO collaboration

I. INTRODUCTION

As the nature of dark matter remains one of the big open questions of cosmology, axions [1] have taken the spotlight in recent years and are currently one of the leading candidates.These hypothetical particles were initially introduced as a solution to the strong CP problem in QCD [2]. Especially in the light of dedicated dark matter experiments searching for weakly-interacting massive particle (WIMP) coming away empty-handed, axions and axion-like particles (ALPs, [3]) provide a viable alternative to address the dark matter problem. Helioscopes [4] are one of three major types of axion experiments and search for axions produced via the Primakoff effect [5] in the core of the Sun. The International Axion Observatory (IAXO[1], [8], [9], [10]) is a 4th-generation axion helioscope aiming at a sensitivity to the axion-photon coupling $g_{a\gamma}$ that is $1-1.5$ orders of magnitude beyond that of the CERN Axion Solar Telescope (CAST, [11], [12]), which is the current most sensitive axion helioscope. BabyIAXO (BIAXO, [13]) is proposed as a first stage towards IAXO and aims at extending the sensitivity to $g_{a\gamma}$ down to a few 10^{-11} GeV^{-1}, thus delivering significant physics results while demonstrating the feasibility of the full-scale IAXO experiment.

X-ray telescopes (XRTs) play a crucial role in pushing helioscopes to superior sensitivities since they focus the putative signal from axions on a small focal area. This enables the the use of the full potential of the most powerful, large-aperture magnets and the most sensitive, small-area, low-background x-ray detectors which boosts signal-to-noise ratios significantly. Optics technology inherited from decade-long developments for space applications can be efficiently leveraged and further enhanced to meet the needs of axion helioscopes. For IAXO and BabyIAXO two different approaches are being considered: (1) segmented-glass optics based on technology developed for NASA's Nuclear Spectroscopic Telescope Array (NuSTAR, [14]) and (2) Aluminum foil optics as flown on the joint JAXA/NASA mission ASTRO-H/Hitomi and implemented in the X-ray Imaging and Spectroscopy Mission (XRISM [15]). Additionally, BabyIAXO will take advantage of already existing optics – a flight spare module of the XMM-Newton XRTs – to maximize the BabyIAXO science return.

TABLE I
REQUIREMENTS FOR OPTICS TECHNOLOGY OF BABYIAXO AND IAXO

Specs	IAXO
Energy Range	$0.5-10$ keV
Spatial resolution (HPD)	<2.5 arcmin
Efficiency	$40-60\%$
Focal Length	$5-7.5$ m
Optics Diameter	$60-70$ cm

II. OPTICS REQUIREMENTS FOR IAXO

The determining factor for optimizing XRTs for axion helioscopes is the optics figure of merit FOM_{Optic} [8]

$$FOM_{\mathrm{Optic}} = \frac{\epsilon_o}{\sqrt{a}} \tag{1}$$

with telescope efficiency ϵ_o and focal spot area a. Therefore in order to maximize the helioscope sensitivity, XRTs with large effective areas (i.e. large throughput) and small focal spot areas are required. All optimizations of the optic performance must be done simultaneously taking into account the XRT, the expected axion spectrum, and the detector performance. Even though the requirements are rather straightforward, optimizations can be challenging, since the two requirements drive the optics design in opposite directions: to obtain the smallest possible spot area a, a short focal length, f, is preferred since the focal spot area grows quadratically with f, but longer focal lengths are advantageous to maximize the throughput. This is due to the fact that reflectivity increases with decreasing graze angle α. The optimization of the optical design is further complicated by fact that throughput, point spread function and

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[1] For additional details on the BabyIAXO and IAXO experiment as well as the detector development for these helioscopes can be found in two LOIs submitted to the Snowmass 2021 process ([6], [7]).

field of view of an XRT have a complex dependence on both the incident photon energy E and the graze angle α. Apart from technical requirements, cost-efficiency is a driving factor to build highly nested, high-efficiency optics, since the full-scale experiment will require eight, one for each of IAXO's bores. Table I summarizes the IAXO optics requirements.

III. OPTICS FOR IAXO AND BABYIAXO

In preparation for IAXO and BabyIAXO, a first pathfinder system [16], [17] consisting of a prototype x-ray telescope coupled to a novel low-background Micromegas detector was designed, built, tested and installed at CAST. The optic is based on the same slumped-glass technology developed for NASA's NuSTAR satellite mission [14] and the pathfinder enabled new benchmark limits on solar axions from CAST [12], while demonstrating that this approach works well for axion physics experiments and is highly suitable for BIAXO and IAXO. This NuSTAR technology uses flat-panel glass that has been thermally formed (i.e. slumped) into cylindrical shapes. Multilayer (ML) coatings to enhance x-ray reflectivity are then deposited on the curved pieces of glass. By cutting the coated substrates into conical (truncated cone) shapes and epoxying them into a precision assembly, this results in a reflective x-ray optic that approximates a Wolter-I geometry. For BIAXO a NuSTAR-like optic (~ 40 cm diameter) need to be extended to measuring $60-70$ cm across by an outer shell using a cold-slumping approach based on technology developed for ATHENA [18]. This hybrid approach is shown in Fig. 1 and enables verification of both slumping technologies for IAXO. A second approach to build a custom-designed IAXO XRT will follow the Astro-H/Hitomi/XRISM technology [15] to fabricate Aluminum foil optics. These lightweight and low-cost x-ray mirrors are able to produce large collecting areas. While first realizations of this type of XRTs struggled with poor angular resolution (3-4 arcmin), state-of-the-art implementations using a novel technique referred to as *epoxy replication* of the reflective coating onto the thin Al substrate [19] have successfully addressed this previous issues. This method involves two types of mandrels: an Aluminum forming mandrel (FM) and a conventional (inexpensive) Pyrex glass replication mandrel (RM). In a first step, 150-300 micron thick sheets of Al are thermally shaped into a conical approximation to a Wolter-I optic using the FM. Following this, a thin Au layer is deposited on the RM for smooth surface replication and a thin epoxy layer is applied to the back of the coating. The pre-shaped Al substrate and the Au coating are then permanently bonded via the epoxy yielding one of the shells to be mounted in each of 8 quadrants that compose the double-bounce optic for incident photons. The Astro-H soft XRT (45 cm diameter) fabricated in this manner is shown in Fig. 2. For IAXO, the goal is to extend this approach to radii of 35 cm to cover a full bore.

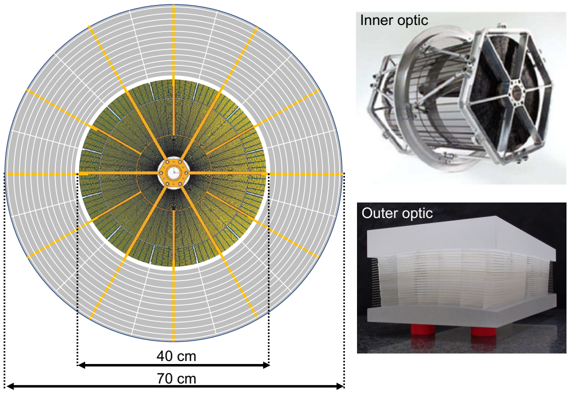

Fig. 1. Left: Schematic view of the BabyIAXO optic, including the hexagonal spider structure that will be used to mount the optic to the magnet bores. The optic consists of an inner and outer part using two different glass-slumping and optics assembly technologies. Right: the top image shows the NuSTAR optic which forms the base of the inner part of the BabyIAXO optic, while the bottom image displays the cold-slumped glass technology that is going to be used to build the outer part of the axion telescope.

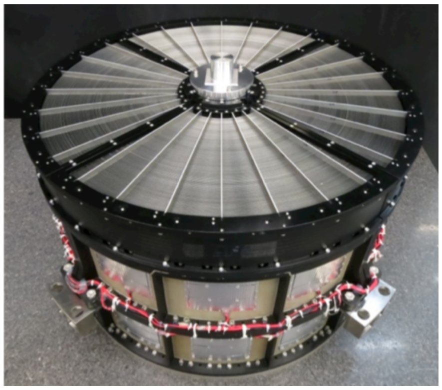

Fig. 2. Full-revolution replicated x-ray optic as built for ASTRO-H/Hitomi and XRISM.

In order to obtain the highest sensitivity to detect solar axions with BabyIAXO, the experiment has been designed to comprise two large diameter bores (70 cm diameter each). While one bore is expected to be covered by a custom-designed optic, the second available bore will be connected to existing flight spare telescope from ESA's XMM Newton [20] mission. This optic, that consists of 58 Wolter I grazing-incidence mirrors with shells nested in a co-axial and co-focal configuration, matches the BabyIAXO bore dimensions well. It is also a reasonable match to the experimental requirements, even though the FOM_{Optic} would be reduced by a factor of ~ 2 compared to a dedicated IAXO design optic. Should two custom-made optics become available during the BabyIAXO run, adjustments can be made to accommodate the two best-performing telescopes.

IV. CONCLUSIONS

The US consortium for IAXO is currently leading the optics development performed together with optics experts among the European IAXO collaborators. As the optics are a key part of the future helioscope experiments, this is a crucial task and requires advances in several areas of otherwise mature technologies to build cost-efficient, high-throughput XRTs with small focal spot areas and large diameters matching the BabyIAXO and IAXO requirements. Ideally new optics would be fabricated, characterized and ready for the BabyIAXO commissioning phase, which is anticipated to commence in calendar year 2023/24.

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