BabyIAXO proposal review report
DESY, 20 May 2019

Members of the review panel:

1. Physics: Yannis K. Semertzidis, IBS/CAPP and KAIST
2. Detectors: Heinz Graafsma (DESY)
3. Cryogenics and infrastructure: Bernd Petersen (DESY)
4. Positioning system: Michael Panter (MPI-HD)
5. X-ray optics: Paul Reid (Harvard-Smithsonian, CfA)
6. Magnet: Lionel Quettier (CEA)
7. General helioscope implementation: Wolfgang Funk (CERN)
8. Ultra-low backgrounds: Stefan Schoenert (TU Munich)

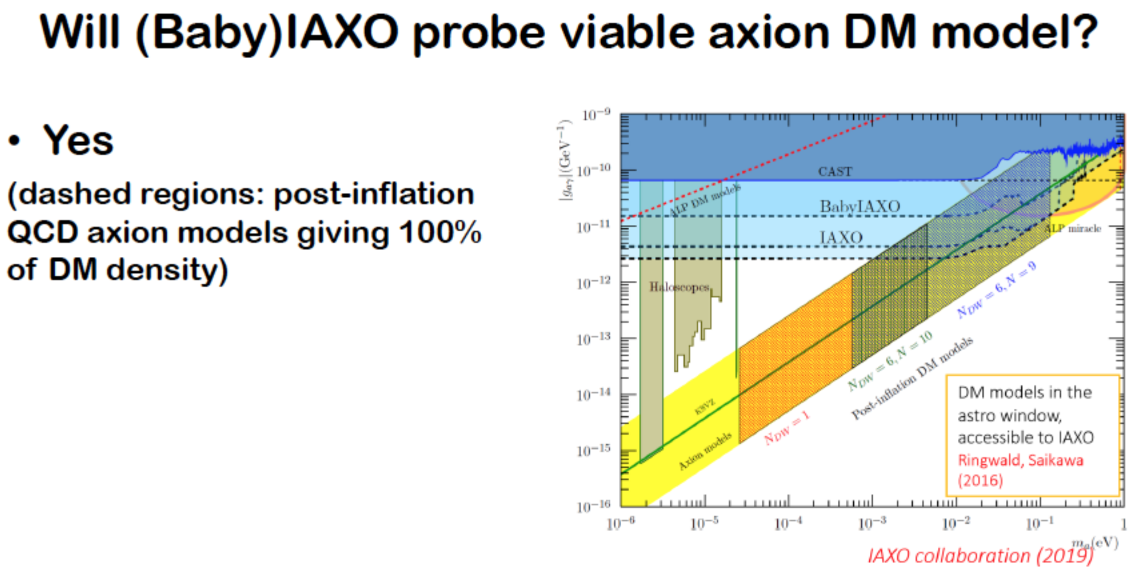
The committee was impressed by the physics potential of BabyIAXO, which is current and unique, potentially positioning DESY at the center of axion physics research in Europe. This experiment, together with a possible future upgrade IAXO will probe an axion mass range which is currently not accessible by any other experimental concept. The technical feasibility of the BabyIAXO as presented, seems to be well under control with presently available techniques which may require small, but also important extrapolations. Even though there are important issues to address, which could significantly delay the project if not addressed properly, the committee unanimously and enthusiastically endorses the approval of this proposal. It asks the DESY management to start immediately discussions with potential and critical partners to enable and/or secure the collaborations. It also asks the collaboration leadership to clarify all technical issues stated below as soon as possible in order not to place obstacles in the buildup of momentum at the start of the project.

Issues to be addressed with urgency:

1. Careful test of the tracking system in Adlershof, prior to moving the tracking system to DESY.
2. Address all the outstanding issues regarding the alignment system with the detector, optics and magnet
3. Check whether there are currently available systems, e.g., X-ray optics, that fit into the planned magnet as well as whether other detectors fit and can be mounted later without significant changes
4. Engineering estimate of the operation costs as well as the modification cost and timeline for the gas-phase of the experiment.
5. Installation schedule needs to be shown in detail, in particular with respect to conflicting activities at DESY.
6. Demonstrate that the low noise detectors work on surface to specifications.
7. The timeline needs to be much more realistic by using professionals and resource loaded schedules, which need to be reviewed carefully.
8. The magnet questions below need to be addressed as soon as possible with a detailed document.
9. The collaboration needs to explore new technologies to complement the presently chosen one and to strengthen the collaboration with strong groups.
10. The suitability of the presently selected Hall in terms of background counting rate should be assessed as soon as possible.

1. Physics

The axion physics is currently the subject of intense competition around the world. Axions are the result of the solution to the strong CP-problem, i.e., why neutrons do not exhibit a large electric dipole moment (EDM). A particle spin creates a magnetic dipole moment, and if it also generates an EDM, then this would mean a violation of time reversal symmetry (T-violation), which is not observed experimentally, by at least nine to ten orders of magnitude. The strong interactions theory, which was spectacularly confirmed at very high precision, mostly with experiments at DESY, nonetheless would fail by at least nine to ten orders of magnitude when it comes to T-violation! A new dynamic field came to the rescue, from the so-called U(1) Peccei-Quinn symmetry, which is spontaneously broken at a very large scale f_a. It, however, also comes with a price of requiring the existence of a pseudo-Goldstone, the axion particle. The theory accommodates axions with a wide range of masses, which have a coupling constant related to its mass. Heavy axions were quickly excluded by experiments or astrophysical observations, so only masses below 1 eV are allowed. Special parameters predict various axion masses; Figures 1 and 2 show the axion masses that are probed by different methods and experiments. The hadronic axion model, KSVZ, shown as a line relating the axion to two photons coupling constant and the axion mass, is in the middle of the band indicating the theoretical uncertainties.



Will (Baby)IAXO probe viable axion DM model?

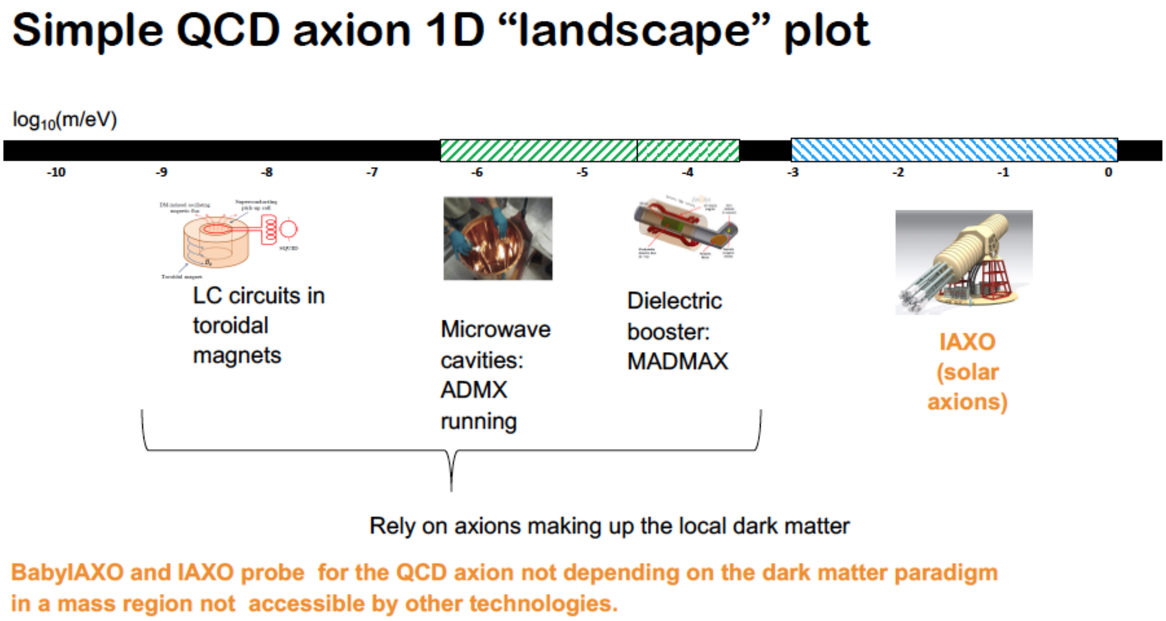
- **Yes**

(dashed regions: post-inflation QCD axion models giving 100% of DM density)

DM models in the astro window, accessible to IAXO
Ringwald, Saikawa (2016)

IAXO collaboration (2019)

Figure 1. BabyIAXO and IAXO probe the hadronic axion models for axion masses between 1 meV to 1 eV, which is not accessible by other experiments.



Simple QCD axion 1D “landscape” plot

Rely on axions making up the local dark matter

BabyIAXO and IAXO probe for the QCD axion not depending on the dark matter paradigm in a mass region not accessible by other technologies.

Figure 2. Various experimental methods are sensitive to a range of axion masses, with IAXO dominating the high-mass range without competition and with minimal assumptions.

Additional models predict coupling constants that are much larger than the hadronic ones and those are probed by BabyIAXO even for much smaller axion masses. The same is true for axion-like-particles (ALPs), which are the same as axions but they don’t require the axion coupling strength to be related to the axion mass. Most of the sensitive axion probing experiments depend on the assumption that the axions are a large fraction of the local dark matter halo. However, the risk associated with the choice of BabyIAXO as an experiment is much smaller as the sun is a natural source of axions provided that they have a certain mass and follow the axion prescribed physics.

2. Detectors

The proposed baseline detectors for the BabyIAXO experiment are using Micro-Megas in its Time Projection Chamber (TPC) version; the same type of detectors as used in the CAST experiment. This choice is very reasonable, since the Micro-Megas based TPC are well understood, and have proven to be low background / noise, and thus present a relatively low risk solution. However, it is not yet proven that they can achieve yet another order of magnitude lower noise as required by BabyIAXO (10^{-7}cts/keV/s/cm^2). Changing the gas from Ar to Xe promises to help, but how much remains to be proven. This seems to be a crucial performance parameter that needs to be achieved for BabyIAXO to be successful.

The IAXO team also presented some alternative detector technologies, which have, for instance, much higher energy resolution, which could be important for the case the axions couple to electrons (producing a spiky spectrum with a clear fingerprint). The research on these detectors appear at the moment to be lower priority. However, since the BabyIAXO is a test case for the larger IAXO, it might be worth putting more emphasis on the further development of these more advanced detectors. In any case the layout of the detector setup should be made such that an easy implementation of new detectors is possible (weight and required infrastructure).

In summary:

- The choice of the baseline detectors is reasonable
- The consortium still needs to prove that a one order of magnitude improvement in the noise / background performance is possible (crucial for the success)
- The consortium should stimulate relevant detector groups in Europe and the world to become as active as possible in the project
- The layout of the detector stages has to take into account possible future upgrades of the detector.

3. Cryogenics and infrastructure

The BabyIAXO experiment will be hosted at DESY Hamburg. The experiment will be installed in one of the HERA halls south or east. The decision, which hall will be chosen, is still pending. The BabyIAXO installations will require support from DESY infrastructure groups. In particular, support from some M-division groups will be needed. The start of the installations is scheduled for end of 2020.

The cryogenic supply of the experiment will be realized by stand-alone cryo-cooler devices at the experiment. External supply of LN2 might be required for pre-cooling of the magnet. The costs for the cryo-coolers are listed in the infrastructure budget.

Comments

The final choice of the HERA hall will affect the requirements for the infrastructure support requested from DESY. The M-division groups are involved in several accelerator and experimental activities at DESY. Any accelerator shut-down activities will always have first priority. In particular the MEA group – responsible for transportation and alignment beside other activities- is and will be frequently over-booked.

Recommendations

The decision for the HERA hall should be made asap. The collaboration should list all support measures requested from DESY and should deliver a schedule for these activities in line with the overall schedule for the experiments. The organization for general supervising on DESY site and working safety should be set in place asap.

4. Positioning system

Tracking

The collaboration of BabyIAXO hopes to take the prototype of the first CTA (Cerenkov Telescope Array) telescope of the MST (Middle Size Telescopes) type installed at Adlershof as the mount of their magnet. The potentially useful part would be the tower, the connection to the foundation, and the two drive systems for 360° azimuth and ± 25° altitude movement.

The requirements on a drive system for a Cherenkov telescope and BabyIAXO are not entirely the same. The Cherenkov telescopes should track a source in a way that the source stays in the center of the field of view. A deviation of about a degree will still be sufficient to save the data during analysis. On the other hand, the pointing accuracy, the precision to locate the source of an event after calibration should be at least 10''. For BabyIAXO it is important to track the sun precisely ($\leq 0.01°$) in order to see a signal. Short interruption, oscillations or deviations would spoil the quality of the data.

The data shown in the review didn't prove a sufficient quality of the system. The BabyIAXO collaboration should evaluate and test the drive system carefully by itself.

A particular worry is the measurement of the position in the two coordinates azimuth and altitude. Precise shaft encoders mounted directly on the axes are necessary. Shaft encoders only showing the position of the motors are not sufficient. They may be governed by the quality of gears and gear rims.

The axes of the mount are driven by two motors each with a bias in order to avoid play. The motors drive worm gears which are running on the large tooth wheels. This is a quite unusual combination since worm gears are self-locking devices. Maybe this is the cause for oscillations which are reported in initial tests. The drive systems have dumping systems to stop these oscillations but it is not clear, if a different layout of the drives would avoid the oscillations to first order.

Alignment

Another very important issue with the BabyIAXO experiment is the precise alignment of the detector. The collaboration seems to be aware of the relevance but is not very advanced in a solution of the connected problems.

The first step will be the definition and control of the axes of the detector, the optical axis which should point to the sun and the two axes of the drive systems, the vertical and the horizontal one.

In a second step the detector has to be aligned inside the experimental hall. The precision of the experiment demands sensitivity to small changes of the floor and the walls of the environment it is mounted to. A system of fiducial marks on the walls together with an aligned optical telescope on the detector or a laser system should be developed for this task.

The last step is the alignment of the detector with the sun. Unfortunately, the experimental hall is deep underground and a direct visibility of the sky is excluded. The only safe reference is the verticality given by gravitation. Even so tracking of the sun is certainly possible in theory, a possibility to directly verify it would be highly desirable.

5. X-ray optics

BabyIAXO serves two purposes; (1) as a technology pathfinder for IAXO, and (2) as a stand-alone leading-edge solar axion observatory aimed at providing the first-ever unambiguous detection of high mass solar axions. Its design incorporates an X-ray telescope to significantly improve the instrument signal-to-noise, which, when compared with earlier axion helioscopes, is expressed as a figure of merit. The X-ray telescope performance requirements are not stringent, being approximately 2 orders of magnitude looser than current technology limits. In addition, the design incorporates two telescopes which are already pre-built or partially built, both of which have performance meeting or surpassing BabyIAXO needs. Existing X-ray telescope technology, and the perceived path to building the two X-ray telescopes, do not represent a limitation to achieving BabyIAXO performance.

It is a concern that the helioscope system lacks a visual (telescopic) reference to several points in the sky to *verify* that the helioscope, sitting ~ 20 m below ground level inside a building, actually is pointing at the solar core. The IAXO team noted that surveying will provide alignment of the telescope to the sky, which coupled with knowledge of the Sun's position, will enable accurate enough pointing. Unfortunately, since axion count rates will be extremely low to zero, there will be no way to verify that the helioscope is indeed aligned to the solar core, from which most axion flux is anticipated to originate. It is strongly advised that a plan be developed to include the capability to visually (via a telescope in the BabyIAXO lab and aligned to BabyIAXO) verify alignment to the sky. This will allow unambiguous confirmation that, within alignment and tracking errors, the instrument is in fact pointed to the correct point in space. Note that this may require two or three portals to the sky to confirm alignment of the BabyIAXO scanning axes.

6. Magnet

The BabyIAXO magnet is one of the core parts of the BabyIAXO helioscope. After several months of iterations and calculations, the design is well advanced and a first concept has been defined. The current version is a superconducting NbTi magnet, indirectly cooled and operated in persistent mode.

The conceptual design presented during the review looks convincing, although all the technical solutions and the associated calculations were not presented in detail.

- Magnetic design and conductor

The magnet is based on a simple design, which limits the technical risks. The magnet consists of a long quadrupole, with a common coil configuration. Each coil is composed of a set of flat double pancakes enclosed into an aluminum casing.

The conductor is made of a Rutherford NbTi cable embedded into an aluminum channel.

The BabyIAXO superconducting NbTi cable is identical to the cable developed for the Panda magnet for FAIR-GSI. This is a very valuable option, as the only difference should be the size of the aluminum channel (and a possible reinforced aluminum grade). Production of the Panda cable is still on-going, but the project plans to reuse cabling, extrusion and insertion tools currently under development in Russia (tooling and process qualification is on-going). The BabyIAXO conductor, as designed, can be considered as nearly defined and specified, and it should remain valid even in case of minor modifications of the magnetic configuration.

- Cryogenics

The magnet is indirectly cooled, with a set of 5 cryocoolers, plus a specific loop for the cool-down phase. The estimated cryogenics budget is mainly driven by the radiation losses due to the large overall surface (more than $100m^2$ for the aluminum thermal shield and the cold mass). But this budget looks optimistic and it is strongly dependent of the manufacturing work quality. In addition, thermal losses from the current leads may also be much higher, even with High Temperature Superconducting (HTS) current leads.

Cryogenic design and associated calculations should be detailed at the next stage of the design phase, with a better evaluation of local thermal resistances and local thermal gradients. Also, it would be good to verify that the sole conduction through the aluminum casing is sufficient and that there is no need of additional thermal drains nor thermosiphon to reinforce the cooling inside the coils.

In order to operate the magnet with a sufficient temperature margin, a larger number of cryocoolers will be required in case of an insufficient cooling, which will increase the initial cost of the magnet.

- Electrical design and protection

The persistent mode operation is a very attractive option. The field drift specification should be reached, assuming the few resistive joints are done according to the state of the art. In case of problem, the magnet could be operated in driven mode, but the details of this operation mode have not been presented.

The magnet protection is correctly addressed. It relies on a classical protection method, and maximum voltages in case of quench and hot spot are acceptable. A more detailed fault scenario analysis is expected at the next step of the design phase.

- Mechanical design

Only very few results were presented during the review. The mechanical supports of the thermal shield and of the cold mass looks ok but a more detailed structural analysis is missing.

- Coil manufacturing and magnet integration

The magnet design is based on classical manufacturing techniques and it does not require any specific development. Most of them have been already used for the other magnets. The magnet fabrication will be entirely managed at CERN, by CERN, with a possible support of external subcontractors for the winding and the final integration. The project will benefit from existing tools from the Atlas magnet fabrication.

The strategy is to build only a small demonstrator to validate the winding tooling and the procedures, but there is no plan of dummy nor spare coil. Besides, there will be no individual test of the coils at cryogenic temperature before the integration into the cryostat.

CERN is offering to develop in-house HTS currents leads for this project, which contributes to minimize the technical risks. A full characterization of the performances (especially of the cryogenic consumption) is still to be done.

Finally, a detailed manufacturing plan, including inspection tests and acceptance criteria, should be established.

- Project organization and next steps

The CERN team has already completed a lot of design work. Even if all the results and the detailed technical solutions were not presented during this review, there is no potential short-term showstopper for the magnet configuration.

A technical design review should be held once the project will be officially approved to validate the final magnet design. The project overall schedule will strongly depend on the procurement of the conductor, on the aluminum casing, on the shield, and of the stainless-steel cryostat. It is suggested to organize this technical design review before launching the main orders. In addition to technical topics, a detailed schedule and a WBS should be presented, as well as a better definition of the interaction between all parties (DESY, CERN, Russia, + tbd…). It would be good to also clarify the magnet interfaces (supporting tower, building and ancillaries at DESY…).

The BabyIAXO magnet project is well advanced, and the current design is based on reliable techniques, which help to get an affordable cost. However, the project relies on the strong involvement of CERN, and especially of the magnet detector group, and this CERN commitment should be officially formalized. In parallel, the project is strongly encouraged to explore additional supports and possible collaborations from other European institutes.

7. General helioscope implementation

1) The alignment procedure especially a way of “sun-filming” has to be developed. If a direct “sun-filming” is not possible, then a second independent procedure needs to be developed as well, in order to exclude a mistake.

2) The fringe field along the z-axis (we were told that this plot exists) needs to be used to verify that all equipment like gate valves, vac gauges and parts of the online alignment system, e.g., X-ray fingers are compatible with those conditions. In addition, any fringe field effects on the electroplated Ni XMM mirror assembly needs to be considered/analyzed.

3) The calculation about the static and dynamic stability of the support column and the frame needs to be verified in detail. A “fatigue” calculation which takes into account the regular movements needs to be prepared.

4) A detailed schedule for the site installation is required to verify the given very-rough time estimate for this and to understand possible conflicting schedule items.

5) What will be the sensitivity gain using Xe instead of Ar for the Micro-Megas?

6) A detailed schedule and planning for the preparation of the He gas phase needs to be established including costing.

7) The continuation of using the experiment CAST at CERN for the next 2-3 years is essential for testing several important BabyIAXO design choices like the IAXO-pathfinder, and Micro-Megas design issues with its electronics.

8) Without the support of CERN, the magnet development and its construction is on extremely high risk for schedule, cost and quality.

8. Ultra-low backgrounds

The stated goal for BabyIAXO is to achieve a low counting rate of 10^{-7} counts/keV/cm^2/s, while the pathfinder already achieved, under realistic operations at the CAST magnet at CERN, 10^{-6} counts/keV/cm^2/s. The collaboration feels confident that it will achieve the stated goal since they have already achieved this goal in an underground lab under more pristine conditions. The collaboration has a well-defined plan to achieve their goals by changing to Xe from Ar gas, and implementing a 4π muon veto (99%) detector. We need to see a more complete study of the Xe vs. Ar gas choices.

A longer target goal for the collaboration is to achieve 10^{-8} counts/keV/cm^2/s, which will bring them closer to actually be improving their sensitivity linearly with time rather than with its square root. The suggested Micro-Megas time projection chamber (TPC) may not be the most promising detector given the required energy resolution when probing for axion-electron coupling. The collaboration itself has a vast experience with the Micro-Megas TPC and it is natural to continue this way, however, they also need to make a serious effort to include a strong group or groups with promising technologies that can also fulfill the energy resolution goal.

The committee feels that the stated goals are reasonable, given the experience of the collaboration in the field and the present state of art. Finally, it is prudent to assess the suggested Hall in terms of suitability for low detector counting as soon as possible.