Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 61 (2015) 193 – 200

Physics Procedia

The next generation of axion helioscopes: The International Axion Observatory (IAXO)

J. K. Vogel[a,*], E. Armengaud[b], F. T. Avignone[c], M. Betz[d], P. Brax[e], P. Brun[b], G. Cantatore[f], J. M. Carmona[g], G. P. Carosi[a], F. Caspers[d], S. Caspi[h], S. A. Cetin[i], D. Chelouche[j], F. E. Christensen[k], A. Dael[b], T. Dafni[g], M. Davenport[d], A.V. Derbin[l], K. Desch[m], A. Diago[g], B. Döbrich[n], I. Dratchnev[l], A. Dudarev[d], C. Eleftheriadis[o], G. Fanourakis[p], E. Ferrer-Ribas[b], J. Galán[b], J. A. García[g], J. G. Garza[g], T. Geralis[p], B. Gimeno[q], I. Giomataris[b], S. Gninenko[r], H. Gómez[g], D. González-Díaz[g], E. Guendelman[s], C. J. Hailey[t], T. Hiramatsu[u], D. H. H. Hoffmann[v], D. Horns[w], F. J. Iguaz[g], I. G. Irastorza[g], J. Isern[x], K. Imai[y], A. C. Jakobsen[k], J. Jaeckel[z], K. Jakovčić[aa], J. Kaminski[m], M. Kawasaki[ab], M. Karuza[ac], M. Krčmar[aa], K. Kousouris[d], C. Krieger[m], B. Lakić[aa], O. Limousin[b], A. Lindner[n], A. Liolios[o], G. Luzón[g], S. Matsuki[ad], V. N. Muratova[l], C. Nones[b], I. Ortega[g], T. Papaevangelou[b], M. J. Pivovaroff[a], G. Raffelt[ae], J. Redondo[ae], A. Ringwald[n], S. Russenschuck[d], J. Ruz[a], K. Saikawa[af], I. Savvidis[o], T. Sekiguchi[ab], Y. K. Semertzidis[ag], I. Shilon[d], P. Sikivie[ah], H. Silva[d], H. ten Kate[d], A. Tomas[g], S. Troitsky[r], T. Vafeiadis[d], K. van Bibber[ai], P. Vedrine[b], J. A. Villar[g], L. Walckiers[d], A. Weltman[aj], W. Wester[ak], S. C. Yildiz[i], K. Zioutas[al]

[a] *Physics Division, Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory, Livermore, CA, USA*
[b] *CEA Irfu, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
[c] *Physics Department, University of South Carolina, Columbia, SC, USA*
[d] *European Organization for Nuclear Research (CERN), Genève, Switzerland*
[e] *IPHT, Centre d'Études de Saclay (CEA-Saclay), Gif-sur-Yvette, France*
[f] *Instituto Nazionale di Fisica Nucleare (INFN), Sezione di Trieste and Università di Trieste, Trieste, Italy*
[g] *Laboratorio de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain*
[h] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[i] *Dogus University, Istanbul, Turkey*
[j] *Physics Department, University of Haifa, Haifa, 31905 Israel*
[k] *Technical University of Denmark, DTU Space Kgs. Lyngby, Denmark*
[l] *St. Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[m] *Physikalisches Institut der Universität Bonn, Bonn, Germany*
[n] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[o] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[p] *National Center for Scientific Research Demokritos, Athens, Greece*
[q] *Instituto de Ciencias de las Materiales, Universidad de Valencia, Valencia, Spain*
[r] *Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia*
[s] *Physics department, Ben Gurion University, Beer Sheva, Israel*
[t] *Columbia Astrophysics Laboratory, Columbia University, New York, USA*
[u] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan*
[v] *Technische Universität Darmstadt, IKP, Darmstadt, Germany*

*Corresponding author
Email address: `vogel9@llnl.gov` (J. K. Vogel)

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory
doi:10.1016/j.phpro.2014.12.031

[w] Institut fur Experimentalphysik, Universität Hamburg, Hamburg, Germany
[x] Institut de Ciències de l'Espai (CSIC-IEEC), Facultat de Ciències, Campus UAB, Bellaterra, Spain
[y] Advanced Science Research Center, Japan Atomic Energy Agency, Tokai-mura, Ibaraki-ken, Japan
[z] Institut fur theoretische Physik, Universitat Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
[aa] Rudjer Bošković Institute, Zagreb, Croatia
[ab] Institute for Cosmic Ray Research, University of Tokyo, Tokyo, Japan
[ac] University of Rijeka, Croatia
[ad] Research Center for Low Temperature and Materials Sciences, Kyoto University, Kyoto, 606-8502 Japan
[ae] Max-Planck-Institut fur Physik, Munich, Germany
[af] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[ag] Physics Department, Brookhaven National Lab, Upton, NY, USA
[ah] Department of Physics, University of Florida, Gainesville, FL 32611, USA
[ai] Department of Nuclear Engineering, University of California Berkeley, Berkeley, CA, USA
[aj] University of Cape Town, South Africa
[ak] Fermi National Accelerator Laboratory, Batavia, IL, USA
[al] Physics Department, University of Patras, Patras, Greece

Abstract

The International Axion Observatory (IAXO) is a proposed 4$^{\text{th}}$-generation axion helioscope with the primary physics research goal to search for solar axions via their Primakoff conversion into photons of $1-10$ keV energies in a strong magnetic field. IAXO will achieve a sensitivity to the axion-photon coupling $g_{a\gamma}$ down to a few $\times 10^{-12}$ GeV^{-1} for a wide range of axion masses up to ~ 0.25 eV. This is an improvement over the currently best (3$^{\text{rd}}$ generation) axion helioscope, the CERN Axion Solar Telescope (CAST), of about 5 orders of magnitude in signal strength, corresponding to a factor ~ 20 in the axion photon coupling. IAXO's sensitivity relies on the construction of a large superconducting 8-coil toroidal magnet of 20 m length optimized for axion research. Each of the eight 60 cm diameter magnet bores is equipped with x-ray optics focusing the signal photons into ~ 0.2 cm^2 spots that are imaged by very low background x-ray detectors. The magnet will be built into a structure with elevation and azimuth drives that will allow solar tracking for 12 hours each day. This contribution is a summary of our papers [1, 2, 3] and we refer to these for further details.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: dark matter, axion, strong CP problem, helioscopes, IAXO, ALP, astroparticle physics

1. Introduction to the International Axion Observatory (IAXO)

1.1. Theory of Axions

The strong CP-problem has been around for more than 35 years [4] and the answer to the question why strong CP violation in flavor-conserving interactions is not observed experimentally even though theoretically expected is yet to be found. In 1977, R. Peccei and H. Quinn (PQ) proposed a potential solution [5] to the strong CP-problem. By introducing an additional global gauge symmetry the apparent conservation of CP in strong interactions can be explained. Breaking this new symmetry spontaneously at a yet unknown breaking scale f_a gives rise to a Nambu-Goldstone boson, the axion [6, 7]. Furthermore axions -together with Weakly Interacting Massive Particles (WIMPs)- are favored candidates to solve the Dark Matter (DM) problem. Like WIMPs, axions are especially interesting to solve the DM mystery since they have not been introduced as an ad hoc solution for this case. Some theories also find mixed axion-WIMP DM to be a viable option [8]. The axion concept has been generalized to other particles (axion-like particles, ALPs) which may arise as Nambu-Goldstone bosons from the breaking of other global symmetries. These particles appear naturally in several extensions of the Standard Modell (SM) of particle physics, such as for example string theory [9]-[11] and could also account for the DM in the Universe. They have as well been used to explain certain astrophysical observations [12]-[17].

1.2. Previous and Current Axion Experiments

Axion experiments can be categorized into three (mostly) complementary classes: (1) Haloscopes [18] searching for relic axions lingering in the galactic halo, (2) Helioscopes [18] looking for axions originating from the solar

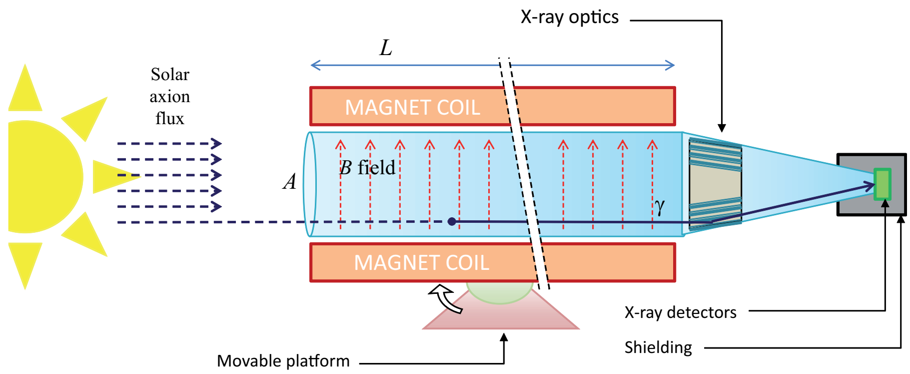

Figure 1. Basic setup of an axion helioscope converting solar axions in a strong laboratory magnetic field of cross-sectional area A and length L via the inverse Primakoff effect. The putative axion signal is then focused on the detector plane by x-ray optics. Figure taken from Reference [3].

core and (3) laboratory light-shining-through-walls experiments (LSW) [19] searching for axions generated in the laboratory environment. All three types make use of the axion-photon interaction, an axion property generic to all axion models. The axion helioscopes stand out as the most mature approach of these technologies and are the one that promises to be most easily scaled to larger sizes.

Helioscopes focus on axions produced from blackbody photons in the solar core via the Primakoff effect [20] in the presence of strong electromagnetic fields in the plasma. Since the interaction of these axions with ordinary matter is extraordinarily weak, they can escape the solar interior, stream undisturbed to Earth and reconvert in the presence of a strong laboratory transverse magnetic field via the inverse Primakoff effect [18, 21, 22] (see Figure 1). In the specific case of non-hadronic axions that exhibit a coupling to electrons on tree-level in addition to the generic axion-photon coupling, further production channels become more important and start competing with or even surpass the Primakoff contribution. Such processes are mainly the ”BCA processes”: bremsstrahlung, compton and axio-recombination.

The minimum requirements for a powerful helioscope experiment of high sensitivity are a powerful magnet of large volume and an appropriate x-ray sensor covering the exit of the magnet bore. Ideally, the magnet is equipped with a mechanical system enabling it to follow the Sun and thus increasing exposure time. Sensitivity can be further enhanced by the use of x-ray optics that focus the putative signal and therefore reduce detector size and background levels.

The first axion helioscope search was carried out at Brookhaven National Lab in 1992 with a static dipole magnet [23]. A second-generation experiment, the Tokyo Axion Helioscope, uses a more powerful magnet and dynamic tracking of the Sun [24]-[26]. The CERN Axion Solar Telescope (CAST), a helioscope of the third generation and the most sensitive solar axion search to date, began data collection in 2003. It employs an LHC dipole test magnet of 10 m length and 10 T field strength [27] with an elaborate elevation and azimuth drive to track the Sun. CAST is the first solar axion search exploiting x-ray optics to improve the signal to background ratio (a factor of 150 in the case of CAST) [28]. For $m_a \lesssim 0.02$ eV, CAST has set an upper limit of $g_{a\gamma} \lesssim 8.8 \times 10^{-11}$ GeV^{-1} and a slightly larger value of $g_{a\gamma}$ for higher axion masses [29]-[33]. CAST has also established the first helioscope limits for non-hadronic axion models [34].

1.3. IAXO Physics Potential

So far each subsequent generation of axion helioscopes has resulted in an improvement in sensitivity to the axion-photon coupling constant $g_{a\gamma}$ of about a factor 6 over its predecessors. To date, all axion helioscopes have used ”recycled” magnets built for other purposes. The IAXO collaboration has recently shown [1] that a further substantial step beyond the current state-of-the-art represented by CAST is possible with a new fourth-generation axion helioscope, dubbed the International AXion Observatory (IAXO, see Figure 2). The concept relies on a purpose-built ATLAS-like magnet capable of tracking the sun for about 12 hours each day, focusing x-ray optics to minimize detector area, and low background x-ray detectors optimized for operation in the 0.5 – 10 keV energy band.

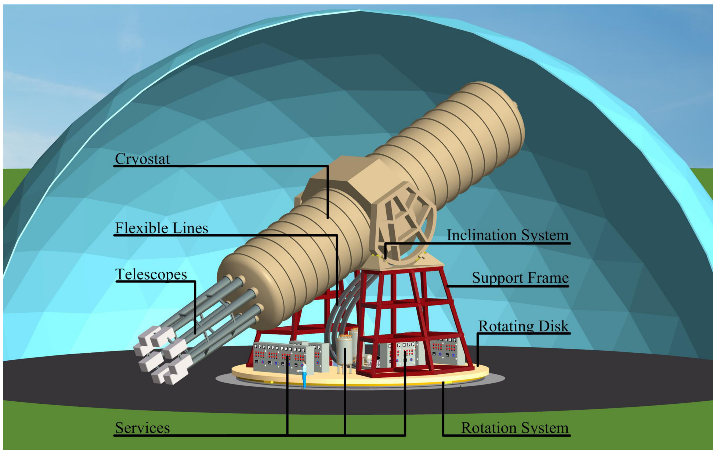

Figure 2. Schematic view of the IAXO setup. The magnet, the eight x-ray telescopes and detectors are shown along with the movable tracking system of the magnet, cryogenics and the power supply system.

The primary physics goal of IAXO is to look for axions and ALPs originating from the Sun via the Primakoff conversion of the solar plasma photons and to substantially surpass all previous best solar searches. IAXO will be about $4-5$ orders of magnitude more sensitive in terms of signal-to-background ratio than CAST, which translates into a factor of ~ 20 in terms of the axion-photon coupling constant $g_{a\gamma}$ and will allow this instrument to reach the few $\times 10^{-12}$ GeV^{-1} regime for a wide range of axion masses up to about 0.25 eV. IAXO will therefore enter deeply into completely unexplored ALP and axion parameter space. IAXO will exclude a large region of the unexplored QCD axion parameter space and the discovery of a new pseudoscalar would be a groundbreaking result for particle physics.

More specifically, at high masses this experiment would explore a broad range of realistic PQ axion models. Its sensitivity would cover axion models with masses down to the few meV range, superseding the SN 1987A energy loss limits ($m_a \lesssim 16$ meV for hadronic axions). Axion models in this region are of high cosmological interest as favored dark matter candidates and they could compose all or part of the cold dark matter of the Universe. In non-standard cosmological scenarios, more generic ALP frameworks [35] or mixed DM scenarios [8], the range of ALP parameters of interest as DM is enlarged and most of the region at reach for IAXO contains possible dark matter candidates. At much lower masses, below $\sim 10^{-7}$ eV, the region attainable by IAXO includes ALP parameters invoked repeatedly to explain anomalies in light propagation over astronomical distances [36]-[39]. IAXO would provide a definitive test of this hypothesis. All above mentionned regions of the axion parameter space that are testable by IAXO are shown in Figure 3.

Additional physics cases for IAXO include the possibility of detecting more specific models of axions or ALPs from the Sun. Most remarkable is the possibility to detect the flux of solar axions produced by axion-electron coupling g_{ae} induced phenomena. Although the existence of these production channels for standard axions is model-dependent, axions with a g_{ae} of few $\sim 10^{-13}$ have been invoked to solve the anomalous cooling observed in white dwarfs. Similarly IAXO will be sensitive to models of other proposed particles like hidden photons, or chameleons [41], scalars with an environment-dependent mass proposed in the context of dark energy models. Although still at an early stage of theoretical development, the possibility of directly testing the particle physics nature of dark energy is an exciting possibility.

Further potential experimental programs for IAXO may include: 1) the search for axionic dark radiation [42], 2) the realization of microwave LSW experiments among different bores of the IAXO magnet [43], and 3) the direct detection of relic cold DM axions [44] or ALPs using microwave cavities or antennas in different configurations within the IAXO magnet. The physics potential of all these options is under study, but they certainly offer possibility for IAXO to become a first-class multi-purpose generic facility for axion research.

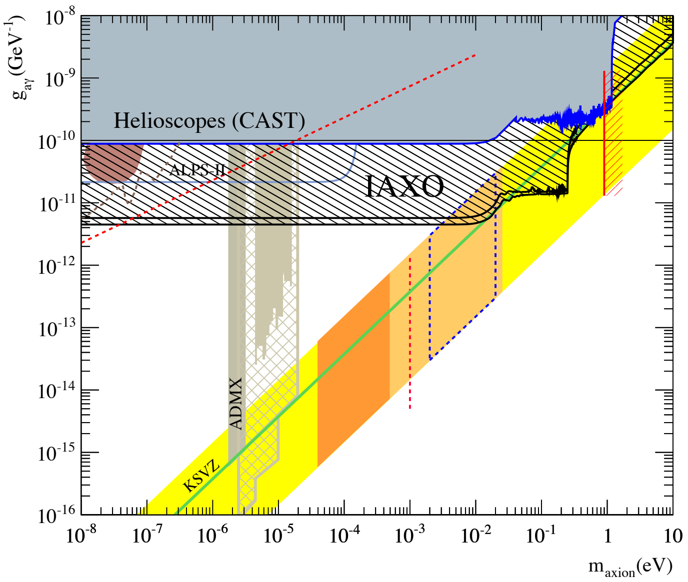

Figure 3. Expected sensitivity of IAXO compared with current bounds from CAST and ADMX. Future prospects of ADMX (dashed brown region) and ALPS-II [40] (light blue line) are also shown. Additionally, theoretically favored regions are shown for axions within the yellow model band (classical axion window in dark orange, mixed axion-WIMP DM in light orange, white dwarf cooling hint within the area surrounded by the dashed blue line) and for ALPs at low masses (brown dashed line for transparency hint, red dashed diagonal line for ALP cold DM). For more details on these well motivated regions of the axion paramter space see Reference [2].

2. Experimental Setup

2.1. Superconducting Magnet for IAXO

The IAXO magnet [3, 45] was designed with the optimization of the IAXO figure of merit (FOM) [1] in mind. For practical reasons as well as cost and risk reduction the only parameter of the magnet's FOM (MFOM, $f_m = L^2B^2A$) that can be significantly increased is the magnet aperture A, since the most suitable magnet technology is based on NbTi superconducting magnets yielding magnetic fields of up to $B = 6$ T. Increasing the length complicates the movement of the experiment to track the Sun and also reduces the accessible axion mass range due to the coherence condition [31]. Already early design studies showed a preference for a toroidal configuration similar to the ATLAS magnet. The envisioned 250 t IAXO magnet will have eight magnet coils of 21 m length and have a diameter of 1 m leading to overall cryostat dimensions of about 25 m in length and 5.2 m outer diameter. When operated at nominal currents of 12.3 kA, peak fields of 5.4 T will be reached storing 500 MJ of energy. With this properties the achievable MFOM is $f_m = 300$ relative to the one obtained for CAST's 21 T^{2}m^4 ($f_{m(\mathrm{CAST})} = 1$). Details on the magnet design and its layout optimization can be found in Reference [3]. A detailed description of the conductor, its peak magnetic field and forces as well as the analysis of the operation stability can be found in the same reference along with layouts of the electrical circuit powering the toroid, the cryogenic systems needed for operation and the compatibility of the complete system with movement requirements. Furthermore the magnet system reliability has been studied and various fault scenarios have been developed together with basic operational strategies to be followed in case of such operational failures. A plan for the assembly of the cryostat and its integration into the rest of the experiment has been mapped out and the construction of a prototype coil is envisioned to validate the design and to reduce risks remaining even though the current design is based on extensive experience from the ATLAS magnets, since the IAXO peak fields are high (non-trivial superconductor development and training of the coils).

2.2. Reflective X-Ray Optics for IAXO

The choice for the eight IAXO telescopes that will focus any x-ray signal from axion-to-photon conversion in the cold bore onto the detectors are reflective x-ray telescopes utilizing segmented, slumped glass optics as the basic

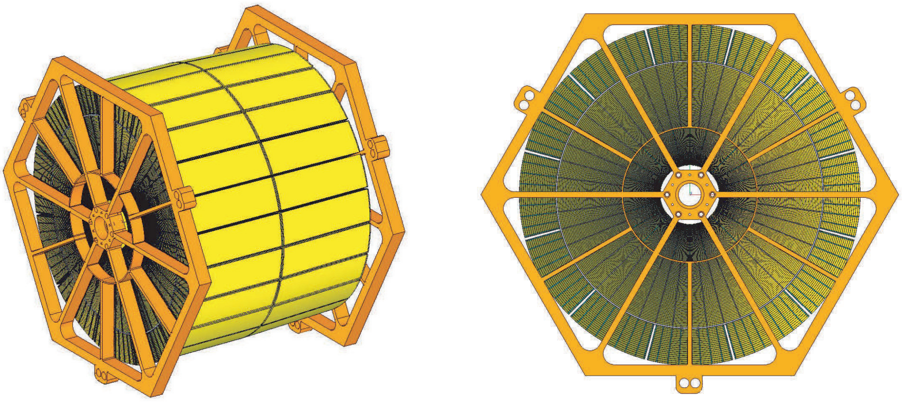

Figure 4. Side (left) and edge-on view (right) of one IAXO optic including the hexagonal suport structure that is intended to be used to mount the telescopes into the magnet bores. The optic consists of more than two thousand individual mirror segments arranged in 123 layers.

fabrication approach. This mature technology has been developed for the NuSTAR satellite mission [46, 47] and relies on multiple individual substrate pieces to form a single shell of a nested Wolter-I-like telescope. The substrates can be coated with multilayers, i.e. alternating layers of low- and high-density materials, such as e.g. W/Si or W/B_4C, increasing the reflectivity of the mirrors and extending the energy range accessible to the optics. Another advantage of this type of optics is that they are low-cost and can leverage existing experience of IAXO collaborators as well as state-of-the-art assembly technology inherited from NuSTAR. The imaging requirements for IAXO are rather modest in terms of focusing the central $3''$ core of the Sun and segmented, slumped glass optics have sufficient resolution while focusing the core in a very compact focused spot. The telescope prescription and reflective coatings have been optimized such that the optic's FOM (OFOM, $f_o = \epsilon_o/\sqrt{s}$) was maximized implying a large focusing efficiency ϵ_o and a minimized focusing spot size s while taking into account practical constraints, such as for example a feasible focal length, necessary field of view (FOV), i.e the extent to which the optic can focus photons arriving off-axis. The current IAXO optics design (see Figure 4) foresees 8 telescopes (one per magnet bore) with 123 layers per optic, which implies the use of a total of 2172 mirror segments per telescope.The optimal focal length f is 5 m, a tradeoff between a spot size as small as possible, i.e., small f, and the highest possible throughput, i.e. large f. The shell radii range from $50 - 300$ mm yielding a total geometric mirror area of 0.38 m^2 per optic. W/B_4C multilayers are the best current option to cover the $1 - 10$ keV passband for the IAXO axion search combining high reflectivities with well-studied material properties which is important for a precise multilayer deposition.

2.3. Low-Background X-Ray Detectors for IAXO

The most promising contenders for the IAXO x-ray detectors are small Time Projection Chambers (TPC) with a thin entrance window and a Micromegas readout that is pixelated. The employed manifacturing technique is the microbulk technology, as currently used at the CAST experiment. Extensive R&D work on this type of detector over recent years [48, 49] has contributed to achieving extremely low background levels of the order of 10^{-6} counts $\mathrm{keV^{-1}cm^{-2}s^{-1}}$ with this type of detector. An even better background reduction down to 10^{-7} counts $\mathrm{keV^{-1}cm^{-2}s^{-1}}$ seems feasible using appropriately designed active vetos. The key parameters to achieve these very low levels of background as compared to earlier Micromegas generations are (1) an improved fabrication technology over more conventional techniques (microbulk technology), (2) high radiopurity of all raw materials used for the construction of the detectors and any nearby support structure, (3) efficient active and passive shielding adopted from underground experiments and adjusted for IAXO constraints (e.g., space and weight restrictions due to the moving platform), and (4) powerful offline background rejection algorithms capable of reducing the raw backgrounds by two to three orders of magnitude in the energy range of interest. Like for the magnet and the optics, the detector FOM (DFOM, $f_d = \epsilon_d/\sqrt{b}$) has been optimized to obtain a maximal efficiency ϵ_d at minimal background rates b. Currently work is progressing to build and test a prototype detector and test optics system for IAXO. This system will be installed and tested at CAST in Summer 2014 delivering operational experience that can feed back into the final IAXO design process while it simultaneously increases the sensitivity of the CAST experiment.

2.4. Other Equipment and Infrastructure

Apart from the key parts for IAXO (magnet, optics, detectors) several additional parts of the general infrastructure are under investigation, including but not limited to the general assembly of the experimental setup, its rotating platform and a gas system for a second data taking campaign after the initial vacuum phase to extend the axion search in the mass parameter space. The IAXO collaboration is also investigating additional equipment that even though based on less mature technology promises potential improvements for the experiment beyond its base performance requirements. An example are alternative detector technologies such as GridPix detectors, Transition Edge Sensors (TES) as well as low-noise CCDs and microwave cavities or antennas. More details on these technologies and their portential application for IAXO can be found in Reference [3].

3. Conclusions

In summary, IAXO is a fourth-generation axion helioscope concept that envisions the construction of a dedicated magnet and x-ray optics to dramatically increase its sensitivity compared to CAST, currently the most powerful axion helioscope. IAXO also has the potential to serve as multi-purpose facility for generic axion and ALP research in the next decade. Together helioscopes, haloscopes and laboratory searches can provide a complementary approach to close in on axions and other dark matter candidates.

Acknowledgements

Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 with support from the LDRD program through grant 10-SI-015. The LLNL IM release number of this document is LLNL-PROC-652380. We acknowledge support from the Spanish Ministry of Science and Innovation (MICINN) under contract FPA2008-03456 and FPA2011-24058, as well as under the CPAN project CSD2007-00042 from the Consolider-Ingenio 2010 program of the MICINN. Part of these grants are funded by the European Regional Development Fund (ERDF/FEDER). We also acknowledge support from the European Commission under the European Research Council T-REX Starting Grant ERC-2009-StG-240054 of the IDEAS program of the 7th EU Framework Program. We also acknowledge support from the CAST collaboration. The design work on the magnet system was supported by CERN, Physics Department as well as the ATLAS Collaboration. Partial support by the Deutsche Forschungsgemeinschaft (Germany) under grant EXC-153, by the MSES of Croatia and the Russian Foundation for Basic Research (RFBR) is also acknowledged. F. I. acknowledges the support from the Eurotalents program.

References

[1] I. Irastorza *et al.*, "Towards a new generation axion helioscope ," Journal of Cosmology and Astroparticle Physics **2011**, 013 (2011).

[2] I. Irastorza *et al.* (IAXO Collaboration), "The International Axion Observatory IAXO. Letter of Intent to the CERN SPS committee," Tech. Rep. CERN-SPSC-2013-022. SPSC-I-242, CERN, Geneva, (Aug 2013).

[3] E. Armengaud *et al.* (IAXO Collaboration), "Conceptual Design of the International Axion Observatory (IAXO)," in press, JINST (2014) [arXiv:1401.3233].

[4] H.-Y. Cheng, "The Strong CP Problem Revisited," Phys.Rept. 158 1 (1988).

[5] R. D. Peccei and H. R. Quinn, "CP Conservation In The Presence Of Pseudoparticles," Phys. Rev. Lett. **38**, 1440 (1977).

[6] S. Weinberg, "A New Light Boson?," Phys. Rev. Lett. **40**, 223 (1978).

[7] F. Wilczek, "Problem Of Strong P And T Invariance In The Presence Of Instantons," Phys. Rev. Lett. **40**, 279 (1978).

[8] H. Baer, A. Lessa, S. Rajagopalan, W. Sreethawong, "Mixed axion/neutralino cold dark matter in supersymmetric model," JCAP **1106** 031 (2011) [arXiv:1103.5413].

[9] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, "String Axiverse," Phys.Rev. D81 (2010) 123530, [arXiv:0905.4720].

[10] M. Cicoli, M. Goodsell, A. Ringwald, M. Goodsell, and A. Ringwald, "The type IIB string axiverse and its low-energy phenomenology," JHEP 1210 (2012) 146, [arXiv:1206.0819].

[11] A. Ringwald, "Searching for axions and ALPs from string theory," arXiv:1209.2299.

[12] C. Csaki, N. Kaloper, M. Peloso, and J. Terning, "Super-GZK photons from photon axion mixing," JCAP0305(2003) 005, [hep-ph/0302030].
[13] A. De Angelis, O. Mansutti, M. Persic, and M. Roncadelli, "Photon propagation and the VHE gamma-ray spectra of blazars: how transparent is really the Universe? " (2008) [arXiv:0807.4246].
[14] M. Roncadelli, A. De Angelis, and O. Mansutti, "Evidence for a new light boson from cosmological gamma-ray propagation?," AIP Conf. Proc. 1018 (2008) 147156, [arXiv:0902.0895].
[15] G. G. Raffelt, "Axion constraints from white dwarf cooling times," Phys. Lett. B 166 (1986) 402.
[16] J. Isern, E. Garcia-Berro, S. Torres, and S. Catalan, "Axions and the cooling of white dwarf stars," Astrophys. J 682 (2008) L109, [arXiv:0806.2807].
[17] J. Isern, S. Catalan, E. Garcia-Berro, and S. Torres, "Axions and the white dwarf luminosity function," J. Phys. Conf. Ser. 172 (2009) 012005, [arXiv:0812.3043].
[18] P. Sikivie, "Experimental tests of the invisible axion," Phys. Rev. Lett. 51 (1983) 1415.
[19] J. Redondo and A. Ringwald, "Light shining through walls," Contemp. Phys. 52 (2011) 211236, [arXiv:1011.3741].
[20] H. Primakoff, "Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson," Phys. Rev. **81**, 899 (1951).
[21] P. Sikivie, "Detection rates for 'invisible'-axion searches," Phys. Rev. D **32**, 2988 (1985).
[22] K. van Bibber, P. M. McIntyre, D. E. Morris, and G. G. Raffelt, "Design for a practical laboratory detector for solar axions," Phys. Rev. D **39**, 2089 (1989).
[23] D. M. Lazarus *et al.*, "Search for solar axions," Phys. Rev. Lett. **69**, 2333 (1992).
[24] S. Moriyama *et al.*, "Direct search for solar axions by using strong magnetic field and x-ray detectors," Phys. Lett. B **434**, 147 (1998).
[25] Y. Inoue *et al.*, "Search for sub-electronvolt solar axions using coherent conversion of axions into photons in magnetic field and gas helium," Phys. Lett. B **536**, 18 (2002).
[26] Y. Inoue *et al.*, "Search for solar axions with mass around 1 eV using coherent conversion of axions into photons," Phys. Lett. B **668**, 93 (2008).
[27] K. Zioutas *et al.*, "A decommissioned LHC model magnet as an axion telescope," NIM A **425**, 480 (1999).
[28] M. Kuster *et al.*, "The x-ray telescope of CAST," New Journal of Physics **9**, 169 (2007).
[29] CAST Collaboration, K. Zioutas *et al.*, "First Results from the CERN Axion Solar Telescope," Phys. Rev. Lett. **94**, 121301 (2005).
[30] S. Andriamonje *et al.*, "An improved limit on the axionphoton coupling from the CAST experiment," Journal of Cosmology and Astroparticle Physics **2007**, 010 (2007).
[31] E. Arik *et al.*, "Probing eV-scale axions with CAST," Journal of Cosmology and Astroparticle Physics **2009**, 008 (2009).
[32] CAST Collaboration, M. Arik *et al.*, "Search for Sub-eV Mass Solar Axions by the CERN Axion Solar Telescope with 3He Buffer Gas," Phys. Rev. Lett. **107**, 261302 (2011) [arXiv:1106.3919].
[33] CAST Collaboration, M. Arik *et al.*, "CAST solar axion search with 3He buffer gas: Closing the hot dark matter gap," Phys. Rev. Lett. 112 091302 (2014).
[34] K. Barth *et al.*, "CAST constraints on the axion-electron coupling," JCAP **1305**, 010 (2013).
[35] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo *et. al.*, "WISPy Cold Dark Matter," JCAP **1206** 013 (2012), [arXiv:1201.5902].
[36] A. De Angelis, G. Galanti, M. Roncadelli, Relevance of axion-like particles for very-high-energy astrophysics, Phys. Rev D **84**, 105030 (2011) [arXiv:astro-ph/1106.1132].
[37] D. Horns, M. Meyer, Indications for a pair-production anomaly from the propagation of VHE gamma-rays, JCAP **1202**, 033 (2012) [arXiv:astro-ph/1201.4711].
[38] M. Simet, D. Hopper, P. D. Serpico, The Milky Way as a Kiloparsec-Scale Axionscope, Phys. Rev. D **77**, 063001 (2008).
[39] I.F.M. Albuquerque, A. Chou, A Faraway Quasar in the Direction of the Highest Energy Auger Event, JCAP **1008**, 016 (2010).
[40] K. Baker, A. Lindner, A. Upadhye, and K. Zioutas, "A chameleon helioscope," [arXiv:1201.0079] (2012).
[41] P. Brax and K. Zioutas, "Solar chameleons," Phys. Rev. D **82**, 043007 (2010).
[42] J. P. Conlon and M. C. D. Marsh, "The Cosmophenomenology of Axionic Dark Radiation," [arXiv:1304.1804].
[43] M. Betz and F. Caspers, "A microwave paraphoton and axion detection experiment with 300 dB electromagnetic shielding at 3 GHz," Conf. Proc. IPAC 2012 (2012) 33203322, [arXiv:1207.3275].
[44] T. Hiramatsu, M. Kawasaki, K. Saikawa, and T. Sekiguchi, "Production of dark matter axions from collapse of string-wall systems," Phys.Rev. D **85** (2012) 105020, [arXiv:1202.5851].
[45] I. Shilon, A. Dudarev, H. Silva, U. Wagner, H. H. J. ten Kate "The Superconducting Toroid for the New International AXion Observatory (IAXO)," IEEE Transactions on Applied Superconductivity 09/2013, 24(3):4500104 (2013).
[46] F. A. Harrison *et al.* " The Nuclear Spectroscopic Telescope Array 9NuSTAR) High-Energy X-Ray Mission," ApJ 770, 103 (2013).
[47] C. J. Hailey *et al.*, The Nuclear Spectroscopic Telescope Array (NuSTAR): optics overview and current status, Proc. SPIE Int. Soc. Opt. Eng. 7732 77320T (2010).
[48] I. Irastorza *et al.* "Status of R&D on micromegas for rare event searches : The T-REX project," EAS Publications Series 53 (2012) 147154.
[49] T. Dafni *et al.* "Rare event searches based on micromegas detectors: The T-REX project," J.Phys.Conf.Ser. 375 (2012) 022003.