A European Strategy Towards Finding Axions and Other WISPs

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Abstract
Since the last update of the European strategy on particle physics (ESPP) the interest in hypothetical very weakly interacting slim particles, dubbed WISPs, has gained significant momentum. Searches for WISPs with masses below about 1 eV require new approaches beyond accelerator experiments. This document summarizes the physics case, the experimental status and its prospects for the coming 10-20 years. Its focus is on larger scale experiments with European leadership requiring a more strategic approach for their potential realization. This document will be submitted in December 2018 as an input to the update process of the European Strategy on Particle Physics (ESPP).

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1 Introduction

Particle physics is getting more diverse. New experiments have started or are being proposed to search for new particles at very low masses as signatures of physics beyond the Standard Model (BSM). Frequently such experiments search for axion and axion-like particles (ALPs), but also other kinds of WISPs might show the path to BSM physics. For simplicity, we will focus on axions and ALPs in the following.

Basically, the experimental approaches can be categorized in three groups:

1. Purely laboratory based experiments do not rely on astrophysical or cosmological assumptions.
2. Helioscopes search for WISPs emitted by the sun.
3. Haloscopes look for WISPs as local dark matter constituents.

Typically, WISP search experiments with great discovery potential can be performed with investments much below the scale of accelerator based detectors. This feature is re-vitalizing the experimental landscape, attracts both young as well as established physicists and also new institutes into the field. At the same time, with the advancement of technologies and based on experiences with smaller scale efforts, new proposals for experiments potentially sited in Europe, with an investment above 50 million Euro exist. A necessary condition to further proceed with these proposals is their support in the future European strategy on particle physics. Therefore this document, while being mindful of smaller scale efforts, puts a particular emphasis on these larger scale initiatives (IAXO, MADMAX, JURA), demonstrating their roles in the world-wide WISP efforts.

2 The physics case for axions and ALPs

The Standard Model (SM) of elementary particle physics explains all the constituents and interactions of known matter to a remarkable accuracy. Its predictions have been checked by collider and other particle physics experiments - in many cases down to the precision of quantum corrections. So far, no significant deviations have been observed. Nevertheless, the SM is known to be far from being complete. Indeed there are two types of problems with the Standard Model. First, and perhaps most urgently, there are observations that cannot be explained within the Standard Model. Famously, it does not feature a viable particle candidate for the non-baryonic dark matter which constitutes about 85% of the matter content of the universe. Moreover, it cannot generate the primordial exponential expansion of the universe - known as inflation - that is needed to explain the statistically isotropic, Gaussian and nearly scale-invariant temperature fluctuations of the cosmic microwave background radiation. The SM also lacks enough CP violation to explain why the universe contains a larger fraction of baryonic matter than of antimatter. Also it fails to give masses to neutrinos and thus can not explain the observed neutrino oscillations. Second, there are also more subtle problems: free parameters of the Standard Model take on very unnatural values. This includes the well known hierarchy problem, i.e. the smallness of the electroweak vacuum expectation value compared to the Planck scale, but importantly also the strong CP problem: the smallness of the θ angle of quantum chromodynamics (QCD), which induces CP-violation in flavour-diagonal interactions, notably a non-zero electric dipole moment of the neutron. In fact, the non-observation of the latter leads to the very strong upper limit $|\theta| < 10^{-10}$, requiring an extreme fine-tuning. In contrast to the hierarchy problem this cannot be justified even by anthropic reasoning.

The solution to some - if not all - of these problems of the SM may arise from the spontaneous breaking of one or several new global symmetries at an energy scale $\gtrsim 10^8$ GeV - much above the scale of electroweak symmetry breaking. The high scale would explain naturally why collider experiments - which are presently sensitive up to the TeV scale - have not seen signs of BSM physics. In addition, an inevitable prediction of the spontaneous breaking of a global symmetry is the existence of Nambu-Goldstone bosons whose mass is much smaller than the symmetry breaking scale. At the same time their interactions are suppressed by the high scale of spontaneous symmetry breaking and therefore very small. Crucially, such Nambu-Goldstone bosons are candidates for cold dark matter [1]. Therefore, it appears to be mandatory to widen the focus also on experiments searching for such elusive Nambu-Goldstone bosons or similar WISPs, complementary to the collider and dark matter direct detection experiments searching for Weakly Interacting Massive Particles (WIMPs) [2].

The prime example of such a Nambu-Goldstone boson is the axion [3], which arises from the spontaneous breaking of a colour anomalous global $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry and solves the strong CP problem since its field acts like a space-time dependent θ angle [4]. Its mass is predicted as $m_A = 57.0(7)\,\mathrm{meV}\,(10^8\,\mathrm{GeV}/f_a)$, where $f_a = v_{\mathrm{PQ}}/N$ is the axion decay constant, in terms of the symmetry breaking scale v_{PQ} and an integer N [5]. The former is typically a free parameter, since neither the solution of the strong CP problem nor the solution of the dark matter problem fixes this scale. It is firmly predicted only in specific models, such as for example in certain $\mathrm{U}(1)_{\mathrm{PQ}}$ extensions of grand unified theories where it is fixed to the scale of grand unification [6, 7]. Further examples are the majoron [9] to explain neutrino masses by the seesaw mechanism and the familon or flavon [8] to understand the family or flavor structure of the SM. In the following we will dub all Nambu-Goldstone bosons apart from the axion as axion-like particles.

In addition to the problems in particle physics and cosmology mentioned above, there are also some observations in astrophysics that can be interpreted as direct indications for the existence of axions or ALPs. Most notably, this concerns the apparent excessive cooling of stars in almost all stages of their evolution - from Red Giants (RGs), via Helium Burning stars (HBs), to White Dwarfs (WDs) (see [10] for an overview and Refs.). Remarkably, axions and more generally ALPs, with a mass below a few keV and couplings both to photons and electrons, with an interaction strength $g_{ae} \equiv |C_{ae}| m_e/f_a = 1.5 \times 10^{-13}$ and $g_{a\gamma} \equiv |C_{a\gamma}| \alpha/2\pi f_a = 1.4 \times 10^{-11}$ GeV^{-1}, respectively, could nicely explain the cooling anomalies of RGs, HBs, and WDs at once [10]. More specifically, good fits to the stellar cooling observables have been obtained in two well-motivated classes of axion models: DFSZ-type models [11] and KSVZ-type [12] axion/majoron models [13]. These fits generically prefer an axion decay constant around 10^8 GeV [10], corresponding to an axion mass around 60 meV (ALP masses are not constrained).

There is also an indication for another anomaly in astrophysics: the universe appears to be too transparent for gamma rays. In fact, exploiting published data points of spectra from Active Galactic Nuclei (AGN) obtained with imaging air Cherenkov telescopes (IACTs), several authors found that state-of-the-art models of the Extragalactic Background Light (EBL) over-predict the attenuation of gamma rays. Photon-ALP conversions in cosmic magnetic fields between the source and the earth have been proposed as a possible solution of the anomaly, requiring a photon coupling $g_{a\gamma} \gtrsim 10^{-12}\,\mathrm{GeV}^{-1}$ and a mass $m_a \lesssim \mu$eV (see, e.g.for a summary and refs. [14, 15]). Intriguingly, the photon coupling required by the solution of the stellar cooling anomaly is compatible with this range. It should be mentioned, however, that there are also analyses which did not find hints for a spectral hardening [16].

Beyond these more phenomenological or “bottom-up” motivations the existence of axions and ALPs is also favored by fundamental extensions of the Standard Model following a “top-down” approach. In particular low energy effective field theories obtained from string compactifications generically feature a plethora of Nambu-Goldstone bosons [17, 18]. Indeed it is very suggestive that in any fundamental theory that has no (or only a very small number of) free fundamental parameters the sizeable number of Standard Model couplings must be given by vacuum expectation values of scalar fields that may also be connected to accompanying ALPs.

3 Axions in the laboratory

Purely laboratory based experiments searching for axions and other WISPs do not rely on any cosmological or astrophysical assumptions and thus offer model independent measurements of particle properties. A drawback is their limited sensitivity, as they cannot compete with the large fluxes from natural sources. Therefore present or future pure laboratory experiments will be hardly able to probe for the QCD axion, but will concentrate on other WISPs, mostly on axion-like particles (ALPs). Mainly two techniques are exploited to search for WISPs in the laboratory: 1) searches for 5th macroscopic forces resulting from the WISP coupling to nucleons and spins, and 2) searches for effects in the propagation of light in magnetic fields, such as changes in the polarization or "light shining through wall" (LSW).

3.1 5th force searches

Axions (or ALPs) could mediate long range (as given by their low mass) forces related to dipole-dipole (spin polarized matter), monopole-dipole or monopole-monopole interactions. The latter two forces require some CP-violating axion/ALP-nucleon interactions, which is not the case in all models. Nevertheless most experiments concentrate on these forces, because dipole-dipole interaction searches suffer from backgrounds of magnetic interactions.

Different experimental approaches like torsion-balances, $1/r^2$ tests of gravitation or depolarization studies in presence of large masses have not shown any hint for ALPs. The limits on the strength of the CP violating ALP-nucleon interaction are several orders of magnitude above the CP violating limits from EDM searches [19]. Within the next five to 10 years this might change with the ARIADNE proposal [20]. Building on resonance effects it could reach parameter regions well below the limits from EDM measurements thus probing for the QCD axion in a mass range of roughly 0.01 to 1 meV. However, as noted above, ARIADNE would not allow for a firm model independent exclusion of the axion in this mass interval due to the above mentioned assumptions on the CP violating interactions.

3.2 ALP-photon couplings

Caused by the ALP-photon mixing in a magnetic field transversal to the moving direction, some fraction of light polarized parallel to the magnetic field might convert to ALPs or axions and vice versa. This gives rise to distinct observational phenomena:

- Linearly polarized light passing through a transversal magnetic field might develop an elliptical polarization due to virtual ALP production related to the light component polarized parallel to the magnetic field. A similar vacuum magnetic birefringence is predicted also by QED due to virtual e^-e^+ production.
- Linearly polarized light passing through a transversal magnetic field might face a rotation of the polarization due to on-shell ALP/axion production depleting the light component polarized parallel to the magnetic field, resulting in a vacuum magnetic dichroism.
- By combining the production of real ALPs with a second experimental compartment allowing for a re-conversion of ALPs to photons, where both experimental compartments are separated by a light-tight wall, ALPs would give the impression of "light shining through walls" as WISPs would not be affected by any wall.

Experiments measuring light polarization changes in magnetic fields have been able to exclude any ALPs with photon couplings larger than a few 10^{-7} GeV^{-1} and masses below 1 meV [21]. LSW experiments have probed for ALPs in roughly the same mass region with photon-ALP coupling sensitivities up to an order of magnitude larger [22–24]. It seems unlikely at present that polarization measurements will allow to reach ALP sensitivities comparable to future LSW experiment. Note that these experiments can probe for the existence of ALPs from zero up to a maximum mass depending on the photon energy and the length of the apparatus.

The next big jump in sensitivity will be performed by ALPS II presently under construction at DESY in Hamburg. ALPS II will be based on 20 dipole magnets from the former HERA proton accelerator and incorporate mode-matched optical resonators before and behind the wall [25, 26]. This will allow to boost the sensitivity for ALP-photon couplings to $2{\cdot}10^{-11}$ GeV^{-1} allowing to probe for the astrophysical hints mentioned in the previous section. Data taking is scheduled to start in 2020.

R&D is ongoing for STAX [27] which would be based on THz photons and could allow surpassing the

ALPS II sensitivity by nearly an order of magnitude in a second step.
On a time scale of around 15 years the JURA project based on the ALPS II optics technologies and accelerator dipole magnets under development at CERN for future proton accelerators could allow to even go beyond the sensitivity of future helioscopes for masses below 0.1 meV. In the context of the update of the European particle physics strategy a stepwise approach from ALPS II to JURA is discussed. Such intermediate experiments could be based on strings of 8 and 14 LHC dipole magnets for example. The sensitivities aimed for are lined out in Fig. 1.

4 Helioscopes

If axions exist, they would be produced in large quantities in the solar interior. Photons from the solar plasma would convert into axions in the Coulomb fields of charged particles via the Primakoff axion-photon conversion. If axions couple to electrons, additional production channels are possible. Once produced, axions get out of the star unimpeded and travel to the Earth, offering a great opportunity for direct detection in terrestrial experiments. The axion helioscope concept [28] invokes the conversion of the solar axions back to photons in a strong laboratory magnet. The resulting photons are X-rays that can be detected behind the magnet when it is pointing to the Sun. This strategy was followed by the CERN Axion Solar Telescope (CAST) using a decommissioned LHC test magnet. CAST has been active for more than 15 years at CERN and represents the state-of-the-art in the search for solar axions. The latest result is shown in Fig. 1. This limit competes with the strongest bound coming from astrophysics. Advancing beyond this bound is highly motivated as outlined in the introduction.

The International Axion Observatory (IAXO) [29] (see also the report [30] of the BSM working group in the context of the "Physics Beyond Colliders" study which in large parts parallels the discussion in this section) is a new generation axion helioscope, aiming at the detection of solar axions with sensitivities to the axion-photon coupling $g_{a\gamma}$ down to a few 10^{-12} GeV^{-1}, a factor of 20 better than the current best limit from CAST (a factor of more than 10^4 in signal-to-noise ratio). This leap forward in sensitivity is achieved by the realization of a large-scale magnet, as well as by extensive use of X-ray focusing optics and low background detectors.

The main element of IAXO is a new dedicated large superconducting magnet, designed to maximize the helioscope figure of merit. The IAXO magnet will be a superconducting magnet following a large multi-bore toroidal configuration, to efficiently produce an intense magnetic field over a large volume. The design is inspired by the ATLAS barrel and end-cap toroids, the largest superconducting toroids ever built and presently in operation at CERN. Experience of CERN in the design, construction and operation of large superconducting magnets is a key aspect of the project.

X-ray focusing relies on the fact that, at grazing incident angles, it is possible to realize X-ray mirrors with high reflectivity. IAXO envisions newly-built optics similar to those used onboard NASA's NuSTAR satellite mission, but optimized for the energies of the solar axion spectrum. Each of the eight $\sim$60 cm diameter magnet bores will be equipped with such optics. At the focal plane of each of the optics, IAXO will have low-background X-ray detectors. Several detection technologies are under consideration, but the most developed ones are small gaseous chambers read by pixelised microbulk Micromegas planes. They involve low-background techniques typically developed in underground laboratories, like the use of radiopure detector components, appropriate shielding, and the use of offline discrimination algorithms. Further X-ray detection technologies are also considered, like GridPix detectors, Magnetic Metallic Calorimeters, Transition Edge Sensors, or Silicon Drift Detectors. All of them show promising prospects to outperform the baseline Micromegas detectors in aspects like energy threshold or resolution, which are of interest, for example, to search for solar axions via the axion-electron coupling, a process featuring both lower energies than the standard Primakoff ones, and monochromatic peaks in the spectrum.

An intermediate experimental stage called BabyIAXO is the near term goal of the collaboration.

BabyIAXO will test magnet, optics and detectors at a technically representative scale for the full IAXO, and, at the same time, will be operated and take data as a fully-fledged helioscope experiment, with sensitivity beyond CAST and potential for discovery. It will likely be located at DESY, and it is expected to be built in 2-3 years, entering into data taking in 3-4 years. Apart from CERN and DESY, 15 other institutions currently form the IAXO collaboration, encompassing about $\sim$75 physicists, and it is likely to grow in the near future. TASTE [31] is another proposal for a helioscope with a sensitivity close to BabyIAXO.

The physics reach of IAXO is highly complementary to all other initiatives in the field, with sensitivity to motivated parts of the axion parameter space that no other experimental technique can probe. As solar axion emission is a generic prediction of most axion models, solar axion searches represent the only approach that combines relative immunity to model assumptions plus a competitive sensitivity to parameters largely complementary to those accessible with other detection techniques. The unique physics potential of IAXO can be summarized by the following statements:

- IAXO follows the only proposed technique able to probe a large fraction of QCD axion models in the meV to eV mass band. This region is the only one in which astrophysical, cosmological (DM) and theoretical (strong CP problem) motivations overlap.
- IAXO will fully probe the ALP region invoked to solve the transparency anomaly, and will largely probe the axion region invoked to solve observed stellar cooling anomalies.
- IAXO will partially explore viable QCD axion DM models, and largely explore a subset of predictive ALP models (dubbed *ALP miracle*) recently studied to simultaneously solve both DM and inflation.
- The above sensitivity goals do not depend on the hypothesis of axion being the DM.
- IAXO relies on detection concepts that have been tested in the CAST experiment at CERN. Risks associated with the scaling up of the subsystems will be mitigated by the realization of BabyIAXO.
- IAXO will also constitute a generic infrastructure for axion/ALP physics with potential for additional search strategies (e.g. the option of implementing RF cavities to search for DM axions).

5 Haloscopes: Searches for DM axions

If axions are the dark matter in our Universe, the number density of axions all around us would be huge. This can facilitate detection of even very weakly coupled axions, because the small coupling needs to be invoked only for the detection and not for the production. Moreover, the huge number density combined with their non-relativistic velocity (roughly the virial velocity inside our galaxy) implies that occupation numbers for available modes are very high and consequently they behave like a classical field that is coherent over a length approximately equal to the typical de Broglie wavelength, which for typical axion masses is macroscopic and often on meter or even larger scales. This allows to employ a variety of coherent and resonant techniques for their detection, further enhancing sensitivities. In the following we will briefly outline the existing techniques and efforts. For details we refer the reader to [15] on which this summary is based.

5.1 Cavity experiments

The conventional *axion haloscope* technique [28] involves a microwave high quality factor, Q, cavity, placed inside a magnet. Inside the magnetic field the axion dark matter induces tiny E-field oscillations effectively driving the cavity. If the axion energy matches the cavity frequency within their respective bandwidth there is resonant enhancement by the Q factor. Since axions are non-relativistic their energy is essentially equal to their mass and the width of the axion signal is very small $\sim v^2 \sim 10^{-6}$. This puts the maximal usable Q into the range of 10^6. While this corresponds to an enormous enhancement of the signal, it requires a scanning of frequencies, since the axion mass is unknown. Covering a wide mass range poses an experimental challenge.

Efforts in this direction have been led by the ADMX collaboration, who have pioneered many relevant technologies (high Q-cavities inside magnetic fields, RF detection close to the quantum limit and others). Applying this they have achieved sensitivity to axion models in the μeV range [32] and are currently taking data to cover a wider mass range. Over recent years a number of new groups have entered this field making this one of the most dynamical areas of experimental exploration in the field (see [15] for details and an overview).

Reaching much lower masses than ADMX, while feasible, requires larger magnets. To start in this direction the use of large existing (or future) magnets has been proposed in this regard (e.g. the KLASH proposal at LNF [33] or ACTION in Korea [34]).

On the other hand going to significantly higher frequencies and therefore larger masses than probed by ADMX is challenging. The most obvious reason is that the natural size of a cavity in its lowest mode (which naively is best for axion searches) rapidly decreases with the frequency, therefore capturing fewer axions. In addition there are further reasons such as lower achievable Q. Significant efforts are underway to address these challenges, by using more intense magnetic fields, cavities designed for higher quality factors, noise reduction at detection, etc.. An example of this is HAYSTAC at Yale [35], having provided first results at $\sim$24 μeV, or CULTASK, the flagship project of the recently created Center for Axion and Precision Physics (CAPP) in Korea [36]. CAPP also hosts several other projects and R&D lines, with the general long-term goal of exploring DM axions in the mass range 4-40 μeV.

To probe even higher frequencies attempts are being made to increase the usable volume of the cavities. This can be done by combining many similar phase-matched cavities, or by implementing more complex extended resonant structures that effectively decouple the detection volume V from the resonant frequency. The former is being attempted by the CAST-CAPP project, that plans to combine several long-aspect-ratio rectangular (i.e. waveguide-like) cavities inserted in CAST dipole magnet at CERN. The latter is investigated by the RADES project [37], also implemented in the CAST magnet. RADES is exploring the use of arrays of many small rectangular cavities connected by irises, carefully designed to maximally couple to the axion field for a given resonant mode. A similar concept, better adapted to a solenoidal magnet, is being followed at CAPP, with the concept of a sliced-as-a-pizza cavity, which consists on dividing the cylindrical cavity in sections connected by a longitudinal iris along the cylinder's axis of symmetry. The ORGAN project in Australia [38] is also exploring similar concepts to push the haloscope technique to higher masses.

5.2 Dielectric haloscopes

For the case of Peccei Quinn symmetry breaking after inflation the axion mass is predicted to be around 100 μeV. As explained above cavity experiments deteriorate in sensitivity in this mass range. Dielectric haloscopes could get around the limitations due to problems with small volumes and low Q.

Conceptually the simplest idea is to magnetize a spherical mirror and place a detector in the center. However, in order to detect dark matter axions within one week with a detector sensitive to 10^{-23}W a parabolic mirror with $\approx$10.000 m^2 would need to be magnetized with 10T. This currently seems unfeasible and improvements are needed.

One possibility is to use many transparent dielectric discs placed in front of a metallic mirror. This increases the number of surfaces from which power is emitted. Moreover, suitably adjusting the distance of the discs the emitted waves of each disc can be made to constructively interfere for a given frequency range. Both effects increase the power emitted by such a system. Calculations have shown that deploying for example 80 discs of $LaAlO_3$ with 1 m^2 area in a 10 T B-field can lead to a boost in power emitted by the system of factor greater than 10.000 with respect to a single metallic mirror in a quasi-broad-band frequency range of 50 MHz. Larger frequency ranges can be covered by adjusting the spacing between the discs [46].

The Magnetized Disc and Mirror Axion Experiment (MADMAX) collaboration is following this approach. Its goal is to detect dark matter axions in the mass range between 40 and 400 μeV as predicted by most models describing the post inflationary PQ symmetry breaking scenario. The experiment will consist of three main parts: The magnet, the booster (mirror and 80 adjustable discs) and the receiver. It has been shown in earlier measurements that the receiver technology to detect 10^{-23}W power within one week is available for the mass range up to $\approx 100\mu$eV. For higher axion masses further R&D will be necessary. R&D regarding the booster is presently focusing on designing a system able to adjust the discs with the required precision and in obtaining discs with the needed size and low enough dielectric loss. Presently a magnet design study is ongoing. It revealed that it is feasible to build the required dipole magnet with $\approx$1.3m aperture and $\approx$9 T B-field using NbTi as superconductor. DESY has offered to host the MADMAX experiment.

5.3 Other haloscope approaches

Not exhaustively, other recently proposed detection methods include the use of LC circuits inside magnetic fields to generate the resonance (ABRACADABRA [40], DM-radio [41], or the search for DM-induced spin precession in magnetized samples (CASPER [42], QUAX [43]), both with promise to achieve good sensitivity at much lower masses that the conventional haloscopes, and the latter invoking the interaction of the axions with electrons or nuclei, instead of $g_{a\gamma}$. In addition, the effect of the DM axion field in atomic transitions (AXIOMA) [44] could lead to observable effects at much larger m_a than previous techniques. All these concepts still require substantial demonstrative R&D in small test setups.

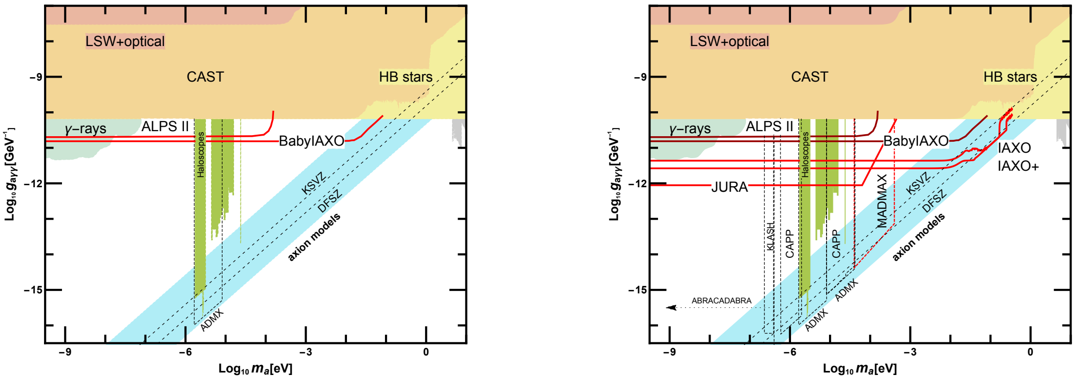

Fig. 1: Overview of the relevant ALP parameter space as well the experiments exploring it in the near future (the two panels show a 5 and 15 year timescale, respectively). For an explanation of the shaded regions see for example [2, 15].)

6 Readiness and technological developments

6.1 ALP-photon couplings

The technological requirements and developments to probe the ALP-photon coupling has recently also been investigated in a working group in the ‘physics beyond collider context’ [47]. The goal of this working group was primarily to facilitate exchange of technology between CERN and experiments possibly located outside CERN with respect to technology, the report can be found in [48]. Key requirements are

1. photon detection: This can e.g. concern single photon detection for eV-scale photons in LSW, detection of keV photons in Helioscopes as well sensitive E-field measurements in microwave resonators.

2. high magnetic fields: All axion-search experiments have their history of re-using magnets built for other purposes (notably accelerator magnets). The Baby-IAXO and MADMAX magnets will be the first magnets being designed specifically for an axion-search experiment.
3. high-finesse resonators: This can concern resonators in the optical, THz or microwave regime. While optical resonators have among their biggest challenge, length stability requirements across large distances, THz and microwave resonators must be built such that their modes and resonant frequencies can be tuned at cryo-temperatures.

6.2 ALP-electron couplings

The axion-electron coupling can be probed by helioscopes [49] although for them it is a challenge to overcome astrophysical limits. One of the promising avenues explored to test axion-electron couplings is through coupling with the electron spin. This is currently pursued by the QUAX experiment [43] and has similar requirements on the detection of microwave photons and high-Q resonators as ‘conventional’ haloscopes with the additional complication of producing large volumes of ferro-magnetic materials with high spin densities and line-widths compatible with the axion.

6.3 ALP-nucleon couplings

Axions can be searched using NMR-techniques, e.g. at CASPEr at Mainz [50] or HeXenia at Heidelberg. Technological challenges concern the question on how well a material can be fabricated free of paramagnetic impurities and the sensitivity limit is set by the nuclear spin noise of the sample.

6.4 ALP-flavor couplings

The QCD axion is not necessarily flavor-diagonal [8]. Consistent realizations of such models are testable at flavor factories and most sensitive channels like $K \to \pi + a$ (with an axion a) to be tested at high-intensity rare-decay machines like NA62 [51]. Technological requirements here are on the side of excellent timing resolution, low in-efficiencies at high rates for MeV-scale particle detection.

7 Roles of laboratories of different sizes in WISP searches

Due to their very low mass and due their generic coupling to the electro-magnetic field, axions and ALPs allow for a multitude of different experimental approaches to search for their effects. Numerous techniques for precision experiments in quantum atomics, atom interferometry, precision magnetometry as well as classic microwave cavity based experiments have been proposed and are pursued. Many of these can typically be performed in experimental environments available at universities or at smaller research laboratories. The continuation and support of these smaller-scale experiments is required and strongly recommended.

The next generation of LSW experiments, haloscopes, and helioscopes, offer unique possibilities and decisive progress, as described above. These experiments are beyond the size which can be accommodated at universities or small research laboratories. They require significant infrastructure and expertise typical of large-scale, accelerator-based particle physics experiments. The requirement of high large-volume magnetic fields, as required e.g. by MADMAX and IAXO are very similar to the requirements found for large experimental magnets in collider detectors. In particular, the long-standing expertise in the design and construction of large experimental magnets as available at CERN and CEA Saclay is of utmost importance for the next generation of axion experiments. The requirement of a long flight path in a transverse magnetic field, as required for ALPS II and JURA, is (almost) the same requirement as for large storage rings. Large mechanical structures and their minute control are also in the expertise of large particle physics laboratories like CERN and DESY. Project management, required for the larger experiments and corresponding collaborations is also best available at these laboratories.

In experimental axion physics the mixture of small-, mid and large-scale projects, all with the potential for break-through discoveries, offers a very stimulating environment also for students and young scientists. In this context the large international projects provide cornerstones for axion research and that is why we seek for support of these in the European strategy on particle physics.

Summary

Searching for WISPs and especially for axion and axion-like particles has developed from a niche activity to a world-wide effort with significant competition. With experiments taking data, being under construction or planned a promising part of the parameter space could be explored within the next 10-20 years. These prospects are shown in Fig. 1 for ALP-photon couplings as an example. To realize this potential, the international community also needs support by integrating WISP searches in the future European strategy on particle physics. Such a step is a pre-requisite to further strive for the challenging realizations of larger scale flagship projects like IAXO and MADMAX and, at a later stage, perhaps JURA. These endeavors would complement the rich variety of smaller scale experiments in all parts of the world and offer discovery potential to the theoretically and phenomenologically best motivated candidates for light particles, including a potential discovery of a dark matter candidate.

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