PHYSICS

Axion dark matter: How to see it?

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The axion is a highly motivated elementary particle that could address two fundamental questions in physics—the strong charge-parity (CP) problem and the dark matter mystery. Experimental searches for this hypothetical particle started reaching theoretically interesting sensitivity levels, particularly in the micro–electron volt (gigahertz) region. They rely on microwave resonators in strong magnetic fields with signals read out by quantum noise limited amplifiers. Concurrently, there have been intensive experimental efforts to widen the search range by devising various techniques and to enhance sensitivities by implementing advanced technologies. These orthogonal approaches will enable us to explore most of the parameter space for axions and axion-like particles within the next decades, with the 1- to 25-gigahertz frequency range to be conquered well within the first decade. We review the experimental aspects of axion physics and discuss the past, present, and future of the direct search programs.

INTRODUCTION

As discussed in the companion theoretical review, the Peccei-Quinn mechanism offers a dynamic solution to the CP (combination of charge conjugation and parity transformation) symmetry problem in quantum chromodynamics (QCD) of particle physics. The mechanism involves a new global U(1) symmetry with an associated pseudo-scalar field permeating all space. The symmetry is assumed to have been spontaneously broken at a certain energy scale, while the universe was evolving at its early stages. This spontaneous process of symmetry breaking is supposed to be accompanied by the production of a pseudo–Nambu-Goldstone boson, the axion (*1–3*). The null results from searches for the standard axion with a mass of order of a few hundred kilo–electron volts have quickly diverted attention to "invisible" axions with very small masses (*4*). The QCD axion has theoretically well-defined properties: (i) its mass determined by the symmetry-breaking energy scale and (ii) its interactions to Standard Model particles depending on models, Kim-Shifman-Vainshtein-Zakharov (KSVZ) (*4, 5*) and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) (*6, 7*). There is a more generic type of axions, called the axion-like particle (ALP), which is not necessarily related to QCD but favored by certain theoretical models including string theory (*8–10*). The QCD axions and ALPs, together referred to as axions, could also account for cold dark matter (CDM) in our galactic halo, the mysterious substance that is believed to constitute ~85% of the matter in the universe (*11–13*).

Not yet revealed, the axion models have been extensively studied over the past 40 years with growing attention, and tremendous efforts have been made to test them experimentally. Several experimental searches are presently underway mainly exploiting the axion field interaction with the electromagnetic (EM) fields (*14*). The emergence of EM radiation, i.e., photons, out of vacuum in the presence of magnetic fields can be a distinctive signature of the axion in the galactic dark matter halo floating around us. Direct conversion searches require a strong magnetic field to have a chance with the weak axion signal. The Axion Dark Matter eXperiment (ADMX) at the University of Washington uses a resonant cavity immersed in a superconducting (SC) magnet to detect the weak

conversion of axions to microwave photons. Axions or ALPs produced by astrophysical objects could be detected by terrestrial telescopes. The CERN Axion Search Telescope (CAST) at CERN, European Organization for Nuclear Research, was designed to detect axions produced in the Sun's core where x-rays scatter off strong electric fields. Axions could also resonantly convert into photons in the magnetosphere of neutron stars that can leave distinct features in the spectra detectable by current space or ground telescopes. Another technique exploits the photon-axion-photon oscillation to produce and detect the axion signal in the laboratory using a strong light source and a pair of magnets. The Any Light Particle Search (ALPS) at DESY, Deutsches Elektronen-Synchrotron, shines a laser beam into the vacuum on one side of a magnet setup to convert the light into axions, which pass through an optical wall to enter the other side, where they are converted back into light to shine out of vacuum.

The main challenge of finding the axion is that the particle mass is not theoretically predictable but has to be experimentally determined by scanning a vastly wide energy range. Some constraints on mass of axions as dark matter can be made by cosmological arguments and astrophysical observations (*15*). Despite these constraints, the search range spans several orders of magnitude between micro–electron volts and electron volts, with the lower bound possibly extended down to nano–electron volts in certain cosmological models (see section 4 of the accompanying theory paper for more details). In addition, the axion signal is expected to be very narrow with an equivalent quality factor of $Q \approx 10^6$ (*16*) and extremely feeble due to very weak couplings to the Standard Model particles and fields. Recalling equation 5 in the theory paper, the interactions of the axion field, a, with the Standard Model fields are categorized into three types proportional to

$$g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B},\, g_{aff}\, \nabla a \cdot \hat{\mathbf{S}},\, \text{and}\, g_{\text{EDM}}\, a\, \hat{\mathbf{S}} \cdot \mathbf{E} \tag{1}$$

respectively, for EM fields, fermion spins, and nuclear electric dipole moments (EDMs). The first type of interaction is examined with cavity resonators in strong magnetic fields [RBF–UF (Rochester-Brookhaven-Fermilab–University of Florida) (*17, 18*), ADMX (*19*), HAYSTAC (Haloscope at Yale Sensitive to Axion CDM) (*20*), CAPP (Center for Axion and Precision Physics Research) (*21*), etc.], the second interaction with magnetometry [GNOME (Global Network of

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Optical Magnetometers for Exotic physics) (22), QUAX (QUest for AXions) (23), ARIADNE (Axion Resonant InterAction Detection Experiment) (24), etc.] and storage ring EDM methods (25), and the third one with nuclear magnetic resonance (NMR) spectroscopy [CASPEr (Cosmic Axion Spin Precession Experiment) (26)] and storage ring EDM methods (27). The probable axion mass range under various cosmological scenarios and the search regions by on-going and upcoming experiments is given in Fig. 1.

Since the search range spans over several decades, it is inevitable that the technologies involved are also very different depending on the targeted mass range. In broad terms, the range of 10^{-6} to 10^{-3} eV involves the use of microwave resonators in a solenoid magnetic field and/or multilayer dielectric resonators in a dipole magnetic field (28). A higher mass range up to $\sim 10^{-2}$ eV can be covered by experiments sensitive to monopole-dipole interactions (29), similar to techniques used in experiments looking for deviations from Newtonian mechanics at micrometer scales (30). The search can be further extended above $\sim 10^{-2}$ eV by looking for solar axions, complementary to the astrophysical observations. Below $\sim 10^{-6}$ eV, lumped element circuits with toroidal/solenoidal magnetic fields and NMR techniques are involved. Experiments looking for static or oscillating nuclear EDM, e.g., neutron and proton EDM, can also provide independent information about the relation between the axion field and the $\bar{\theta}$ parameter of the Standard Model in low-mass regions.

This article reviews major experimental endeavors to unveil the axion physics while offering shorter descriptions for other efforts. The "Search strategies" section introduces the detection principle and search strategies and gives an overview of direct searches. Through the "Haloscope searches," "Helioscope searches," and "LSW searches" sections, the individual searches will be described in more detail including a brief history and key features of the experimental research, as well as their present status and future prospects. A critical remark is made in the "EDM, CP violation, and axion" section on the fact that most experimental attempts assume that axions compose 100% of the dark matter halo and an interesting approach is suggested, on the basis of the correlation of two independent experimental results, to look into axion physics without relying on such an assumption.

SEARCH STRATEGIES

The most common experimental searches for axions rely on the EM interaction mediating the axion-photon coupling. The presence of

a coherently oscillating axion field a in free space modifies Gauss' law and Ampère's law of Maxwell's equations as

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma}\nabla a \cdot \mathbf{B}$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = j + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a \times \mathbf{E})$$

where ρ and j are the ordinary charge and current, while the additional interaction terms, $g_{a\gamma\gamma}\nabla a \cdot \mathbf{B}$ and $g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a \times \mathbf{E})$, correspond to the axion-induced charge and current densities, respectively. The spatial coherence length (i.e., de Broglie wavelength) of the oscillating axion field is large, e.g., about 1 km for 1 µeV, and inversely proportional to the axion mass. For invisible axion dark matter, therefore, $\nabla a \approx 0$ is valid, and thus, only the time-dependent current source term is in effect. In 1983, a promising detection principle was proposed on the basis of the axion-photon interaction to use this remaining source term, i.e., the axions are converted into photons in the presence of a magnetic field (14), as illustrated in Fig. 2.

First of all, the axions in the micro–electron volt mass range are a plausible cold dark matter candidate, and the converted photons are in the microwave frequency region. The haloscope, a technique for detecting the dark matter halo signal, has provided the most sensitive searches for axions in our galactic halo using microwave resonators. ADMX, HAYSTAC, and CAPP use cylindrical cavities in an SC solenoid, while MADMAX (Magnetized Disc and Mirror Axion eXperiment) uses a periodic array of dielectric planes in a dipole magnet.

Second, the axions can emerge abundantly from the stars by Primakoff scattering in the EM fields of charged particles in the stellar plasma. The helioscope, a dipole magnet directed toward the Sun, is designed to observe x-rays converted from the axion flux originating from the solar core. The CAST project at CERN has finalized its mission to search for the solar axion in 2015. It will be taken over by a future international program, IAXO (International Axion Observatory), to continue this successful program.

Third, the ALPs can also be sought in the laboratory by converting photons to axions and regenerating them behind a wall based on the so-called light-shining-through-wall (LSW) method. A combination of high-intensity laser beams and strong magnetic fields have been successfully used by OSQAR (Optical Search of QED vacuum magnetic birefringence, Axion, and photon Regeneration) at CERN and ALPS at DESY. The latter experiment is currently being scaled up with improved sensitivity.

Apart from these, there has been steady progress in the direction of indirect searches for dark matter axions, which are not discussed in this review, using terrestrial radio telescopes to look for spectral lines originating from the resonant conversion of axions to photons by magnetized astrophysical sources, particularly neutron stars (31–36). These radio telescope searches were reported to set constraints on the existence of axion dark matter in the micro–electron volt mass ranges (37–39). Recently, major theoretical uncertainties have also been addressed on the basis of advanced simulation and modeling to estimate the expected signal in a more reliable fashion (40–42).

The search results from these various types of experiments are reflected in a single two-dimensional (2D) parameter space defined by the axion coupling to photon, $g_{a\gamma\gamma} = \alpha_{em}C_\gamma/2\pi f_a$ (equation 16 in the theory paper) or equivalently C_γ, and the axion mass m_a or its Compton frequency ν_a satisfying $m_a \simeq h\nu_a$. For invisible axions, a
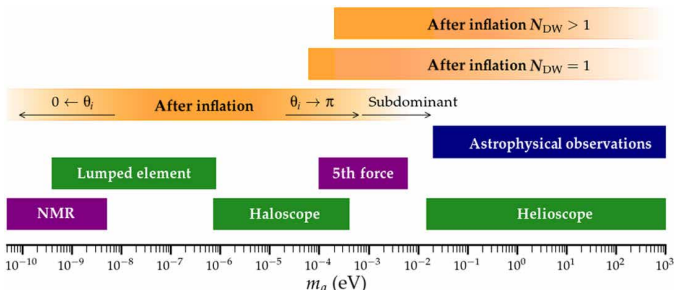

Fig. 1. Allowed mass ranges for dark matter axions by various cosmological scenarios (in orange) and astrophysical observations (in navy). Different experimental approaches are involved to cover different mass ranges depending on the axion couplings (e.g., to photons in green or to nuclear spins in purple).
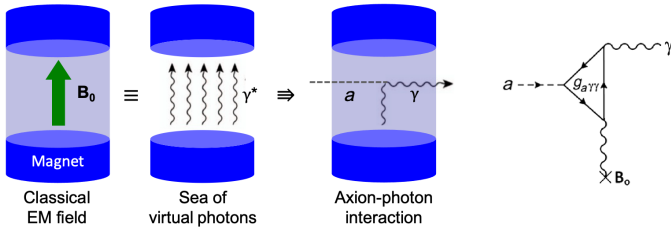
Fig. 2. Principle of axion detection. A classical strong magnetic field generates a sea of virtual photons with which axions interact to be converted to real photons. The corresponding Feynman diagram is also shown. The axion de Broglie wavelength is much larger than the detector sizes, enabling coherent conversion within the detectors.

linear relation holds between the mass and the Compton frequency, e.g., 1 μeV corresponds approximately to 0.25 GHz. Experiments use diverse detection strategies to explore different mass regions with different sensitivities, which are typically compared with the theoretically interesting axion models, e.g., KSVZ and DFSZ. Null results exclude the search regions from the parameter space. Figure 3 summarizes the exclusion limits on the axion-photon coupling set by individual experiments to date and projected sensitivities for major search methods. A recent review also discussed search methods for invisible axions and ALPs along with theoretical derivations of their experimental signatures (43), and a committee report provided a comprehensive overview of the experimental programs of direct searches for dark matter candidates (44).

HALOSCOPE SEARCHES

The axion haloscope was designed to scope microwave photon signals from the axions in our galactic halo, hence the name. The signal power can be enhanced by the resonance effect that occurs when the axion mass matches the natural frequency of the detection system. This technique has provided the most sensitive approach to testing the theoretical models in the microwave regime.

Cavity haloscopes

Microwave cavities have well-defined eigenmodes (resonant modes) determined by the cavity geometry. The cavity haloscope uses a microwave cavity resonator immersed in a strong magnetic field. When the frequency of the axion-induced photon matches the frequency of the cavity eigenmode under consideration, the conversion power is resonantly enhanced by orders of magnitude given by the cavity quality factor Q_c. The power deposited in the cavity due to the axion-photon conversion is given, using typical parameter values, by

$$P_{a\gamma\gamma} = 5.0 \times 10^{-23}\,\text{W} \left(\frac{C_\gamma}{0.75}\right)^2 \left(\frac{\rho_a}{0.45\,\frac{\text{GeV}}{\text{cm}^3}}\right) \left(\frac{\nu_a}{1\,\text{GHz}}\right) \left(\frac{B_0}{10\,\text{T}}\right)^2$$
$$\left(\frac{V}{30\,\text{liters}}\right) \left(\frac{G}{0.5}\right) \left(\frac{Q_c}{10^5}\right) \quad (2)$$

where C_γ is the model-dependent coupling coefficient with a value of −1.92 and 0.75 for the KSVZ and DFSZ model, respectively, ρ_a is the mass density of dark matter axions as discussed in section 1 of the theory review, ν_a is the axion Compton frequency, and B_0 is the externally applied magnetic field. The geometrical factor G is a measure of the amplitude of axion-induced photon field coupled to the cavity mode.
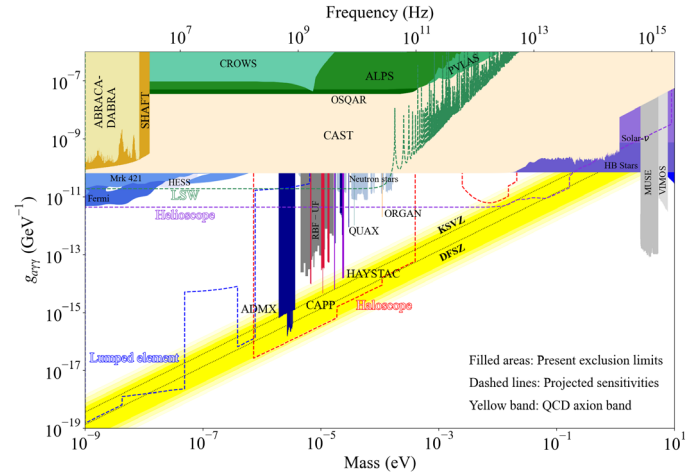

Fig. 3. Up-to-date experimental exclusion limits on the axion-photon coupling versus axion mass. The projected sensitivities are represented by dashed lines. Two theoretical models are represented by the diagonal dashed lines with the uncertainty band in yellow. Major features of the individual experiments are described in the text. The acronyms of the experiments which are not discussed in the review include CROWS (CERN Resonant Weakly interacting sub-electron volt particle Search), PVLAS (Polarization of the Vacuum with Laser), HESS (High Energy Stereoscopic System), HB (horizontal branch) stars, MUSE (Multi Unit Spectroscopic Explorer) and VIMOS (Visible Multi-Object Spectrograph).

The experimental sensitivity is determined by the signal-to-noise ratio (SNR)

$$\text{SNR} \equiv \frac{P_{a\gamma\gamma}}{\delta P_{\text{sys}}} \quad (3)$$

where δP_{sys} is described as fluctuations in system noise power, which is dictated by the Johnson-Nyquist formula, $P_{\text{sys}} = k_B T_{\text{sys}} \Delta\nu$, with the Boltzmann constant k_B and the equivalent noise temperature T_{sys}. Since the axion mass is a priori unknown, all possible mass ranges need to be explored. A relevant figure of merit for experimental design is the scanning rate, i.e., how fast one can scan a mass region with a given sensitivity. This quantity is obtained by plugging Eq. 2 into Eq. 3 as

$$\frac{d\nu}{dt} = 1.2\,\frac{\text{GHz}}{\text{year}} \left(\frac{5}{\text{snr}}\right)^2 \left(\frac{0.15\,\text{K}}{T_{\text{sys}}}\right)^2 \left(\frac{P_{a\gamma\gamma}(B_0, V, G, Q_c)}{5.0 \times 10^{-23}\,\text{W}}\right)^2 \left(\frac{10^5}{Q_c}\right) \quad (4)$$

where snr is the target SNR value. Major R&D efforts are made to increase the scanning rate by maximizing $B_0^2 V G Q_c$ and minimizing T_{sys}. The up-to-date exclusion limits made by individual haloscope experiments, which will be described in detail in this section, and their projected sensitivities are shown in Fig. 4.

The first experimental search for axion dark matter was carried out by the RBF Collaboration using an SC solenoid magnet, a copper cavity in a liquid helium reservoir and a transistor-based radio frequency (RF) amplifier. The sensitivity, however, was not high enough to reach the axion theory band. The system noise was reduced by a subsequent experiment at the UF to make the search more effective. The ADMX, established in 1990, designed a larger scale detector to explore new ways forward. Several critical improvements were involved to increase the sensitivity to the theoretically interesting levels. These include the employment of an SC quantum interference device (SQUID) and/or a Josephson parametric amplifier (JPA) to reduce the electronic noise near to the quantum limit and the
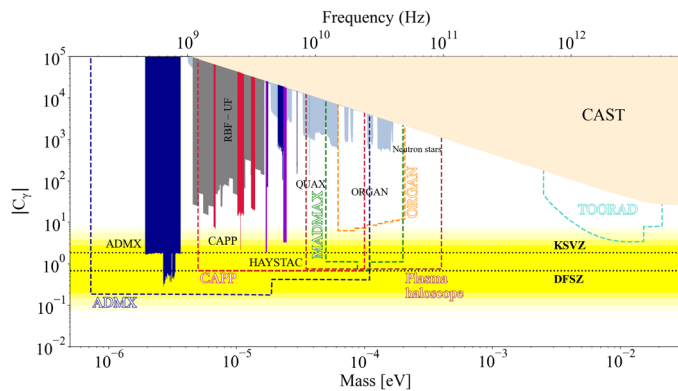
Fig. 4. Experimental exclusion limits and projected sensitivities by the halo-scopes. The limits are set in terms of the axion-photon coupling C_γ as a function of axion mass, presuming the local dark matter halo is made up solely of axions. The projection by CAPP includes the scenario of axions making a partial contribution to the dark matter halo density as discussed in the text.

operation of a dilution refrigerator to lower the system temperature to the sub-kelvin level. However, the advantages of such a large-scale detector with the quantum noise–limited technology would run out quickly at higher frequencies because the large cavity diameter limits the search to low frequencies below 1 GHz and the quantum noise grows linearly with frequency. In addition, overall progress in the axion field has been time-consuming, and one would think that the task is just too daunting to carry out. The CAPP of the Institute for Basic Science (IBS) launched a massive, parallel R&D program to push the limits of current technology to extend the search range toward higher frequency regions with enhanced detection efficiency. The breakthroughs contain (i) the successful operation of multiple experiments simultaneously, (ii) the development of functional high-temperature SC (HTS) and low-temperature SC (LTS) magnets capable of reaching higher than 9 T (the limiting value of traditional LTS magnets), (iii) the development of efficient high-frequency microwave resonators with large volume, (iv) developed practical SC cavities based on HTS tapes with large quality factors, and (v) the full use of the most effective quantum noise–limited amplifiers. In the meantime, the cavity haloscope searches based on cylindrical cavities in an SC solenoid became popular such that many other collaborations have proposed and demonstrated their new ideas. Separate efforts, on the other hand, have been made to recycle the existing resources, such as the prototype SC dipole magnets at CERN, for axion dark matter search using arrays of small rectangular cavities placed inside the long magnet bores.

Rochester-Brookhaven-Fermilab–University of Florida
The first microwave cavity experiment looking for axion dark matter was conducted by the RBF Collaboration at Brookhaven National Laboratory in 1987 (*17*). The experimental setup, providing the basic structure for even today's most sensitive experiments, includes an SC solenoid magnet with a maximum field of 8.5 T, a copper resonant cavity immersed into liquid helium, heterostructure field-effect transistor (HFET) RF amplifiers, and a computer-aided automated data acquisition system. The cavity was operated at two different resonant modes tuned by insertion of a dielectric or conducting rod, accompanying a study of mode localization. Several experimental configurations set limits in the range of 4.5 μeV < m_a < 16.3 μeV on the axion-photon coupling. The sensitivity level was about a

factor of 10^2 to 10^3 away from the QCD axion models mainly due to the high system noise temperature of about 16 K (*45*). A subsequent search performed at the UF was rapidly reported with reduced system noise using a commercially available amplifier with a noise temperature of about 3 K, which improved sensitivity by an order of magnitude for masses around 5.5 μeV (*18*).

Axion Dark Matter eXperiment
ADMX is the first large-scale cavity experiment searching for QCD dark matter axions with realistic masses and couplings to microwave photons. The detector consists of a cylindrical tunable high-Q microwave cavity placed in a 7.6-T magnetic field produced by a 0.6-m-wide and 1-m-long SC solenoid. The large size of the apparatus featuring a high value of B^2V naturally fits sensitive searches for axions in relatively low-mass regions, particularly between 1 and 10 μeV. During the first operation period, the detector was cooled down to 1.5 K, and the EM power spectrum was obtained by a low-noise microwave receiver. The experiment has achieved a power sensitivity better than 10^{-23} W to probe the KSVZ axions in the mass range of 1.9 to 3.3 μeV (*19*, *46*). The subsequent run implemented a quantum technology, SQUID, whose intrinsic noise is subject to the standard quantum limit. A frequency tunable microstrip SQUID amplifier replacing the HFET amplifier has broadened the search range with an improved detection rate by two orders of magnitude (*47*).

The second-generation detector is featured by deploying a dilution refrigerator, enabling the experiment to operate at sub-kelvin temperatures. A substantial reduction in thermal background noise and the excess noise from the quantum-limited SQUID amplifier resulted in many-fold improvement in the system noise temperature, providing the capability to achieve unprecedented sensitivity to the DFSZ model (*48*). Recently, they extended the search range to higher frequencies using an ultralow-noise JPA with a tunable resonance developed by the University of California, Berkeley (*49*). Ongoing searches are expected to provide crucial tests of the invisible axion models over a wider mass range.

Meanwhile, ADMX has been putting substantial research and development effort to expand searches beyond 10 μeV. A prototype of a small-scale cavity mounted on top of the main cavity system exploited multimode searches to attain new mass limits in three distinct frequency regions (*50*). A multiple-cavity system is currently under construction to compensate for volume reduction in high-mass axion searches with a refined design from the proof-of-concept study performed earlier using an array of four cavities (*51*). The principal challenge of this design, maintaining frequency matching among the cavities in every frequency step, needs to be carefully addressed and realistically demonstrated (*52*).

To further increase sensitivity to the microwave signal detection, the Fermilab group has been developing a qubit-based single-photon detector that allows for repeated nondemolition measurements of cavity photons to reduce the noise (*53*). They claimed a noise reduction of more than 15 dB at near 25 μeV (6.0 GHz) below the quantum limit with the detector performance being limited by residual background of real photons. A new experimental exclusion limit on hidden photon dark matter has proven that this photon counting technique can greatly enhance the searching speed for dark matter axions.

Haloscope at Yale Sensitive to Axion CDM
The HAYSTAC experiment was designed to search for dark matter axions with masses above 20 μeV, an order of magnitude higher in mass than naturally accessible by ADMX. A 2-liter copper-plated stainless steel cylindrical cavity is housed in a cryogen-free dilution

refrigerator integrated with a 9-T SC solenoid. HAYSTAC is the first microwave cavity haloscope search with deployment of a JPA, developed by the Joint Institute for Laboratory Astrophysics at the University of Colorado, that owes its inductance to an array of SQUIDs to achieve near-quantum limited performance. The parametric amplification is attained by a coherent pump field that modulates the resonant frequency, which can be tuned by DC flux through the SQUID array. The experiment has completed its first data production at around 24 μeV and excluded the possibility of axion conversion into two photons at slightly higher level than the KSVZ coupling (20, 54), demonstrating that a small-scale axion haloscope will still be able to probe the axion physics at higher mass regions.

Recently, the HAYSTAC Collaboration used a pair of JPAs to realize squeezed vacuum states to circumvent the fundamental quantum-noise limit. One of them was dedicated to prepare a photon field in a squeezed state, while the other was used to read out only the squeezed quadrature with nearly noiseless amplification. This quantum squeezing technique effectively increased the bandwidth over which the apparatus is sensitive to an axion obtained at a given cavity resonant frequency. By coupling the HAYSTAC cavity to the squeezed-state receiver, they yielded a twofold enhancement in scanning rate relative to optimal unsqueezed operation and set a new limit on axion coupling at around 4 GHz (17 μeV) (55).

Center for Axion and Precision Physics Research

IBS-CAPP was established with the aim of building a laboratory equipped with the world's best infrastructure for cavity haloscope searches with enhanced sensitivities over a boarder range in the microwave region. The laboratory is featured by multiple state-of-the-art axion experiments—three already built and in operation mode, one being under construction, and another in the planning stage—based on high-field SC magnets, powerful dilution refrigerators mounted on low vibration pads, and quantum noise limited amplifiers. The individual experiments were designed to run in parallel targeting at different mass ranges to explore the axion parameter space as quickly as possible.

Since the field of axion dark matter search requires highly developed technologies and advanced scientific skills from a number of different research areas, the CAPP's strategies were set accordingly early on with a major emphasis placed in the Center's devotion to diverse R&D areas rather than a single project. The ongoing R&D endeavors focus on the following:

1) Launch of a pioneering program of axion dark matter search using HTS magnets based on ReBCO (rare-earth barium copper oxide) tapes, capable of withstanding fields up to 100 T with adequate current density (56).

2) Establishment of an experiment for definitive tests of the QCD axion models above 1 GHz making use of the high field and large volume of a 12-T/320-mm LTS magnet and ultralow temperature achievable by a powerful dilution refrigerator.

3) Design and construction of high-efficiency high-frequency microwave resonators in the most advantageous ways (57).

4) Development of practical SC resonators with quality factors larger than normal conductor by at least an order of magnitude (58).

5) Optimal use of a series of the most effective JPAs (and traveling-wave JPAs if available) covering from 1 to 8 GHz to bring the electronic noise near the quantum limit (59).

6) Implementation of a phase-matching scheme—coherent combination of individual signals from multiple local systems running at the same frequency.

7) Last, development of a tunable microwave-photon detector based on quantum technologies using Rydberg atoms, particularly for high-frequency searches above 10 GHz.

At the current stage, the ground at CAPP was prepared for sensitive searches for axions in the 5- to 30-μeV mass range on a time scale of 5 years, presuming that dark matter in the local halo is solely made up of axions. Recently, three experiments, CAPP-8TB, CAPP-9T, and CAPP-PACE (pilot axion cavity experiment), have carried out their pioneering operation to yield meaningful scientific results around 6.7, 13.5, and 10.7 μeV, respectively (60–62). CAPP-8TB and CAPP-PACE set up similar experimental designs consisting of an 8-T SC magnet installed in a dilution refrigerator to produce the first result and scan more than 1 μeV with sensitivities close to the KSVZ model. CAPP-9T used a 9-T (?) SC magnet and a ^{3}He refrigerator to demonstrate the performance of the new cavity concept, featured by a multiple-cell structure in a single cavity (57), which will promote high-mass axion searches. These experiments are currently being upgraded for improved sensitivities with adoption of high-performance JPAs from the University of Tokyo, and implementation of high-Q cavities was uniquely developed by CAPP using HTS tapes and/or dielectric arrays.

The CAPP-12TB experiment, presently under commissioning, will take advantage of the high field and large volume of the customized LTS-12T/320-mm magnet, which was fully tested in 2020, expecting to lead the cavity haloscope search program. The large aperture of the magnet allows for nearly 40 liters of detection volume, and a powerful dilution refrigerator brings the experimental system to an extreme environment below 100 mK. Using a series of JPAs with different dynamic ranges, CAPP-12TB is expected to deliver unprecedented experimental sensitivities above 1 GHz, probing the DFSZ axion physics, in a wider mass range. An additional experiment plans to join the parallel search program in 2022 to extend the search range beyond 10 GHz using a 12-T SC magnet with a smaller aperture. With successful integration of the R&D efforts into these experimental setups, CAPP desires in the next decade to be sensitive enough to examine the supposition that the QCD axion partially composes the local dark matter halo density, over a range between 1 and 25 GHz (4 and 100 μeV).

Other cavity haloscopes

The QUAX Collaboration puts an effort to bring a cavity experiment mining the axion-photon coupling around 10 GHz. In particular, they performed an axion search at 9 GHz using a NbTi SC resonant cavity to achieve a quality factor $Q_c = 4 \times 10^5$, a factor of 4 higher than a copper cavity, under a 2-T magnetic field. This is the first search for galactic axions using an SC haloscope (23). The QUAX Collaboration also simulated a single-photon counter based on an underdamped Josephson junction, claiming that the switching voltage measurement can register microwave single photons with a dark count rate of 4×10^{-4} Hz (63).

An Australian group designs an experiment, named ORGAN (Oscillating Resonant Group AxioN), to probe high-mass regions considering a unique cavity configuration (64). Consisting of a variety of thin, long cylindrical cavities of various dimensions packed in a 14-T SC magnet, similar in arrangement to a pipe organ, the experiment desires to access different regions in a single operation to cover a wide range of 60 to 200 μeV.

A Large Hadron Collider (LHC) test dipole magnet, which had been used to look for solar axions at CERN, was recycled for dark matter axion searches benefiting from the high field and large length

of the magnet. A joint project, CAST-CAPP, placed a series of 40-cm-long tunable rectangular cavities inside one of the magnet twin bores to exploit the phase-matching scheme for an initial dark matter axion search above 5 GHz (65). The RADES (Relic Axion Detector Exploratory Setup) project plans to use the same dipole magnet to explore masses of several tens of micro–electron volt using an array of small microwave cavities connected by rectangular irises, whose characteristics were recently studied (66).

Dielectric haloscopes
Relying on closed resonant structures, microwave cavity haloscopes are sensitive to dark matter axions with relatively low frequencies up to several gigahertz, but they would face difficulties in scaling to higher frequencies for which the cavity size needs to be smaller. An alternative method for efficient searches for high-frequency axions is based on a detector architecture consisting of strategically config-ured dielectric materials in an open resonator. In particular, peri-odic structures of dielectric planes with a high dielectric constant ϵ_r are expected to allow for an observable emission of EM waves in-duced by axions with frequencies (masses) between 10 (40) and 100 (400) GHz (μeV).

Open resonator
The first version of an open resonant system introduced a series of current-carrying wire planes in an RF Fabry-Perot (FP) resonator that provides an alternating magnetic field with the same polarity as the axion-induced electric field to maximize the geometry factor. The Orpheus experiment demonstrated this technique using cop-per wire planes for a search for dark matter ALPs with masses around 70 μeV (67). A new design was proposed with the wire planes replaced by high-ϵ_r dielectric planes to modify the axion-induced electric field yielding nonvanishing geometry factors under a static magnetic field. These two approaches are conceptually simi-lar to each other, but the latter is more beneficial in acquiring higher quality factors.

Magnetized Disc and Mirror Axion eXperiment
The MADMAX Collaboration proposed a new strategy to search for dark matter axions that can explore a similar mass range of 40 to 400 μeV (28, 68). The scheme is characterized by the so-called "booster" that is composed of a periodic structure of high-ϵ_r dielec-tric disks with an RF mirror on one side, all of which are placed in an external magnetic field parallel to the surfaces. The changing dielectric media induce discontinuity in the axion-induced electric field in the interface, resulting in generation of EM waves propagat-ing perpendicular to the dielectric surface in both directions. By exploiting constructive interference of the emitted waves from the precisely aligned interfaces and the reflected waves from the mir-ror, the radiated EM signal is boosted, hence the name, by the num-ber of disks in quadrature. Analogous to the quality factor in a cavity haloscope, this boosting effect acts as an enhancement factor in a dielectric haloscope, which is a nonresonant open system. The expected signal power from such a boosting haloscope received by an antenna placed on the other side of the system is given by

$$P = 1.3 \times 10^{-21} \text{ W} \left(\frac{B_0}{10 \text{ T}}\right)^2 \left(\frac{C_\gamma}{1.92}\right)^2 \left(\frac{\beta}{400}\right)^2 \left(\frac{A}{1 \text{ m}^2}\right) \quad (5)$$

where β is the boosting factor and A is the disk surface area. Since the search frequency is determined by the space between neighboring disks, the detector configuration facilitates access to high-frequency

regions without major loss of detection volume in contrast to con-ventional cavity experiments.

For realistic sensitivity to reach the QCD axion models, the MADMAX Collaboration proposed to build a large-scale dielectric haloscope experiment that features a 2-m-long 10-T dipole magnet, a boosting system consisting of 80 dielectric disks with 1-m^2 area, and a low-noise receiver chain. Recently, they demonstrated a first proof-of-principle realization of the booster setup of the haloscope using a copper mirror and up to five sapphire disks (69) and performed a dedicated 3D simulation study to investigate design require-ments for the dielectric disk system (70).

Other haloscopes
Ferromagnetic haloscope
Another experiment in the QUAX Collaboration accepts a variant of cavity haloscope, named QUAX-ae, exploiting the interaction of the cosmic axion with the spin of electrons in a magnetized sample placed inside a resonant cavity. The resonant interaction of the axion-induced EM field at the Larmor frequency, determined by an external magnetic field, would flip the electron spin states (magnons) coherently, which subsequently emits microwave photons (71). QUAX-ae is unique in probing the axion-electron coupling directly, giving excellent prospects for model discrimination in the event of discovery. A preliminary axion dark matter search demonstrated the scheme using a photon-magnon hybrid system consisting of a series of Yttrium iron garnet spheres coupled to the TM_{110} mode of a cylindrical copper cavity (72). A subsequent scientific run with an upgraded photon-magnon system coupled to a quantum-limited JPA resulted in the best limit on the axion-electron coupling near 43 μeV (73). The QUAX Collaboration also plans further upgrades using hundreds of spheres with the goal of DFSZ sensitivity.

Plasma haloscope
A proposed search strategy for dark matter axions, known as plasma haloscope, considers the coupling of the axions to bulk plasmons, quanta of plasma oscillation, rather than photons (74). It uses the resonant conversion between the two particles by matching the axion mass to the plasma frequency. A metastructure of conducting wires is identified as a promising candidate for tunable plasma with the frequency varying with interwire space. A key advantage of this concept is that the resonant frequency and, hence, the signal enhancement are unrelated to boundary conditions, allowing for a large conversion volume over a wide frequency range. For realistic experimental sizes, plasma haloscopes can offer a plausible alterna-tive to dielectric haloscopes, providing competitive sensitivity in the mass region of 35 to 400 μeV.

Topological insulator
An experimental idea was suggested on the basis of topological phenomena in condensed matter physics. The existence of hypo-thetical axion-like quasiparticles in topological insulators allows the mathematical description to be identical to axion electrodynamics. Antiferromagnetically doped topological insulators predict these dynamical quasiparticles that are resonantly driven by the axion-induced field under an external magnetic background and subse-quently converted into photons in the terahertz range (75). This presents a viable route to detect axion dark matter with a mass of order of 1 meV, currently inaccessible by other dark matter de-tection methods. The independence of sample volume of the reso-nance allows for high sensitivity at high frequencies with broad tunability provided by varying the external magnetic field. A recent

proposal called TOORAD (TOpolOgical Resonant Axion Detection) has developed the theory of axion quasiparticles in topological magnetic insulators and characterized a realistic experimental setup with an antiferromagnetic insulator (Fe-doped Bi_2Se_3 or $Mn_2Bi_2Te_5$) to realize these axion quasiparticles assuming a wide bandwidth single-photon detector highly efficient in terahertz (76). Besides, there are many other interesting ideas that have been put forth recently for axion detection in condensed matter systems (77, 78).

Low-mass axion searches

Complementary to the cavity or dielectric haloscope method, searches for axions in low-mass regions $m_a < 10^{-6}$ eV require different strategies. Dark matter axions can cause an oscillating electric current by an external magnetic field that subsequently induces a small magnetic field. This axion-induced field can be detected exploiting a lumped element circuit and a sensitive magnetometer to probe axion-photon couplings weaker than those accessible by haloscope searches (79). Magnetic resonance techniques can also be used to detect a time-varying torque on nuclear spins exerted by an oscillating axion field and be sensitive to ALP dark matter with masses $m_a < 10^{-9}$ eV (26).

Lumped element searches

An LC (inductor-capacitor) circuit–based axion search was performed by the pilot experiment ADMX SLIC (SC LC Circuit Investigating Cold Axions), which was designed to probe lighter-axion mass parameter space difficult to reach with microwave cavity haloscopes. The prototype circuit consists of a large rectangular SC loop antenna placed in a solenoid magnet bore and a parallel plate capacitor with a movable dielectric sheet in between to tune the resonant frequency. The experiment demonstrated this new strategy by exploring three consecutive mass regions near 10^{-7} eV with different magnetic fields (80).

ABRACADABRA (A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus) is an experiment proposed to search for axion-photon coupling over a broad mass range of 10^{-12} eV $< m_a < 10^{-6}$ eV (81). It uses a static toroidal magnetic background to source a time-varying effective electric current along the magnetic field, $\mathbf{J}_{\text{eff}} = g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\mathbf{B}$, that gives rise to an oscillating magnetic flux through the center of the toroid, which can eventually be sensed by an SQUID magnetometer. The readout circuit can be designed for resonant/broadband searches with/without a tunable capacity in the input coil. Recently, a small-scale prototype demonstrated the detection scheme, which made an advance toward a full-scale experiment that can examine the QCD axions with low masses (82).

A dual search program, DM Radio (Dark Matter Radio), for axion and hidden photon dark matter is a solenoid version of the lumped element search (83). Using an optimized tunable SC LC resonator, it found the potential sensitivity of many orders of magnitude beyond current limits over an extensive frequency range from 100 Hz to 300 MHz. The prototype DM Radio pathfinder experiment, designed to probe hidden photons in the 100-kHz to 10-MHz mass range, is currently under construction (84). The full-scale program plans to instrument a sample of ~1 m^3 at 10 mK to test the pre-inflation dark matter scenario.

SHAFT (Search for Halo Axions with Ferromagnetic Toroids) is a new experimental program using a similar concept to ABRACADABRA. A main difference is to make use of toroidal magnets with ferromagnetic material in the core to enhance the magnetic field. The experimental apparatus is configured with two pairs of stacked toroids each of which has a separate pickup coil a SQUID magnetic flux sensor. The toroid pairs generate magnetic fields in the opposite direction such that two independent detection channels reduce the correlated systematic noise. The experiment was able to reach a magnetic field of 1.5 T at 6 A using a set of toroids with Fe-Ni powder cores and achieved magnetic sensitivity of 150 aT/$\sqrt{\text{Hz}}$ using a dual-channel readout chain at 4.2 K. On the basis of this configuration, they reported on a direct search for EM interactions of ALPs in a broad low-mass region that spans from 10^{-11} to 10^{-8} eV (85).

NMR-based search

The presence of the oscillating cosmic axion background could produce a time-varying nuclear EDM (26). If the axion-induced EDM oscillates at the nuclear Larmor frequency, then this will result in the enhancement of the transverse magnetization with time that can be measured with a sensitive magnetometer such as SQUID. CASPEr is an NMR experiment seeking for such oscillating EDM signals using two different measurement schemes via different couplings. CASPEr-Wind, the originally proposed scheme, searches for dark matter ALPs by considering their pseudo-magnetic coupling to nucleons, referred as the ALP-nucleon coupling. The scheme offers a resonant search via continuous-wave NMR spectroscopy and yields the highest sensitivity for frequencies ranging from a few hertz to hundreds of megahertz, corresponding to masses of 10^{-14} to 10^{-6} eV. A new search method, called CASPEr-Electric, on the other hand, is sensitive to experimental signatures of the axion-gluon coupling. The concept makes use of a static electric field to implement a nonresonant frequency-modulation detection scheme, suitable for searches below hertz down to millihertz (masses of 10^{-17} to 10^{-14} eV), extending the detection bandwidth by three decades.

A similar approach is considered with storage ring experiments designed to measure the proton EDM by looking for the time-varying spin precession induced by ultralight dark matter relying on the axion-gluon coupling. A combination of external magnetic and electric fields tunes the $g - 2$ frequency of polarized proton beams to be in resonance with the oscillation frequency of the background axion field, which brings the enhancement in the oscillation amplitude of the axion-induced EDM with time (27). The proton is given the so-called magic momentum to keep the spin and momentum always aligned, and if the proton has an EDM, then its spin will precess in the presence of an external electric field. The effect will add up for each proton orbit around the ring and boost the signal over the entire particle storage time in the ring, about 1000 s for the proton EDM experiment (25). Since a relativistic proton sees a much larger spatial gradient of the axion field, the storage ring EDM method can, in principle, provide a sensitive probe particularly to low-mass regions from 10^{-24} to 10^{-17} eV.

HELIOSCOPE SEARCHES

The high-mass regions have been looked into by either astrophysical telescopes or laboratory-based experiments. As a matter of fact, most of the regions where the axion could exist without being dark matter have been already excluded, so it is not unnatural to assume that it may constitute the dark matter in our galactic halo. This assumption, however, plausible as it may be, is still an assumption. If the axion physics takes place in nature, then stars are the strongest sources of the axion production via the Primakoff conversion of the plasma photons, reducing the uncertainty about their production

mechanism. Helioscopes were designed to detect the copious flux of axions emitted from our Sun based on the axion-to-photon conversion using a dipole magnet directed toward the Sun. No matter what the axion mass is, the total axion energy would reflect the temperature of the Sun's interior of a few kilo–electron volts, as they would be efficiently produced in the solar core within 10% of the solar radius. Therefore, the solar axions searches use photon detectors with high efficiency in the x-ray region. The probability of axions conversion into photons is given by

$$\mathcal{P}_{a \to \gamma} = 2.6 \times 10^{-17} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\, \text{GeV}^{-1}}\right)^2 \left(\frac{B_0}{10\, \text{T}}\right)^2 \left(\frac{L}{10\, \text{m}}\right)^2 \mathcal{F} \quad (6)$$

where L is the magnet length. The enhancement factor $\mathcal{F}$ accounts for the coherence of the process, whose value is preserved ($\mathcal{F} \simeq 1$) for axion masses up to $\sim 10^{-2}$ eV.

Historically, the first helioscope search was performed at Brookhaven National Laboratory (86), then at the University of Tokyo (87), and lastly at CERN with CAST (CERN Axion Solar Telescope) (88). CAST recycled an LHC dipole prototype magnet with a magnetic field of up to 9 T over a length of 9.3 m and has been operational for more than a decade. With improved detectors and novel x-ray optics, the final phase of the experiment set the most restrictive constraint on the axion-photon coupling below 10^{-10} GeV^{-1} for masses $m_a < 0.02$ eV, competing with the most stringent limits from astrophysics (88). IAXO, the fourth-generation axion helioscope, was proposed to improve CAST's performance by more than an order of magnitude by building a large-scale magnet and x-ray focusing devices coupled to low background detectors (89, 90). The new magnet design, inspired by the ATLAS toroids (91), considers a multibore configuration in a large toroid comprising eight 21-m-long and 1-m-wide racetrack coils, which can generate an intense magnetic field of 5.4 T inside eight 600-mm aperture bores placed between two neighboring coils. Baby-IAXO, a demonstration version of the proposed large-scale IAXO with a 10-m single-bore magnet, has recently been approved (in 2020) for construction at DESY. The projected sensitivity of Baby-IAXO is shown in Fig. 5, as well as the possible limits with the full-size IAXO and its updated version. For the experiment to become sensitive in a wider axion mass range, the vacuum chamber needs to be filled with a gas to match the axion mass with the gas plasma frequency (88).

LSW SEARCHES

The axion or ALP, if it exists, could also be produced and detected in the laboratory without relying on extraterrestrial sources. One of the straightforward laboratory schemes is the photon regeneration, dubbed "light shining through a wall." Photons emitted by a strong light source are exposed in an SC dipole magnet where axions are produced via photon-axion mixing and continue to propagate through an optical wall. A similar magnet system behind the wall converts the axions back into photons with the original energy, detected by an optical sensor. A high-finesse FP optical resonator is introduced in the production magnet to increase the probability of photon-to-axion conversion. The coherence length of the mixed state depends on the axion mass and the photon energy. Since the axions need to first be produced and then be reconverted to photons, the process is proportional to the fourth power of the axion-to-photon coupling. The experimental figure of merit is given by the probability of the double conversion $a \to \gamma \to a$ as

$$\mathcal{P}_{a \to \gamma \to a} = 6 \times 10^{-34} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\, \text{GeV}^{-1}}\right)^4 \left(\frac{B_0}{10\, \text{T}}\right)^4 \left(\frac{L}{10\, \text{m}}\right)^4 \mathcal{F}_P \mathcal{F}_R \quad (7)$$

where $\mathcal{F}_P$ and $\mathcal{F}_R$ are the enhancement factor representing power built-up by the optics systems in the production and reconversion regions, respectively.

The first LSW experiment was performed by the Brookhaven-Fermilab-Rochester-Trieste Collaboration using a pair of 4.4-m-long dipole magnets to search for light scalar or pseudo-scalar particles for $m_a < 10^{-3}$ eV (92, 93). OSQAR used a buffer gas at a specific pressure to amplify the photon-axion conversions in LHC dipole magnets at CERN (94). The most stringent laboratory limits for $m_a < 0.3$ meV was achieved using 9-T transverse magnetic fields over the unprecedented length of 2×14.3 m (95). Meanwhile, the ALPS Collaboration recycled several SC dipole magnets from HERA (Hadron-Electron Ring Accelerator) to set up an experiment at the site of DESY. An upgraded laser system for increased power and incorporation of a low-noise high-efficiency charge-coupled device camera allowed for experimental constraints comparable to OSQAR on the existence of low-mass ALP (96).

A new breakthrough idea was proposed with an additional FP resonator built on the reconversion side (97). This second resonator is actively phase-locked together with the first FP resonator in the production magnet, significantly increasing the probability of the inverse Primakoff process in the reconversion region. On the basis of this concept, the next generation of ALPS, named ALPS II, is currently under construction in a straight section of the HERA tunnel. Using dual optical cavities installed in two strings of 12 SC dipoles, each of which has 8.8 m in length (i.e., the total length of a string is about 100 m) and 5.3-T field strength, the experiment aims at a substantial improvement of the current laboratory bound on $g_{a\gamma\gamma}$ by a factor of $\sim 10^3$ in the near future (98), potentially making it more sensitive than the Sun.

EDM, CP VIOLATION, AND AXION

The existence of the axion field can address an important question in particle physics; why is the neutron EDM so small? i.e., why the
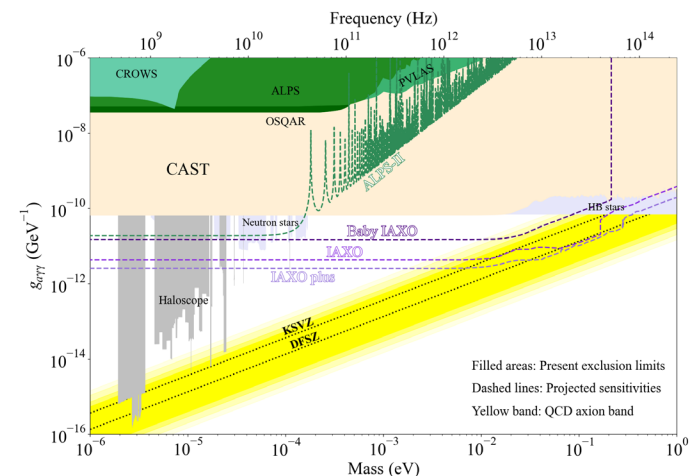

Fig. 5. Current exclusion limits and projections by the helioscope and LSW searches. The present limits were set by the past experiments (CAST for the helioscope and OSQAR and ALPS for the LSW experiment). The projected sensitivities from their next-generation experiments (IAXO and ALPS II) are represented by the dashed purple and green lines.
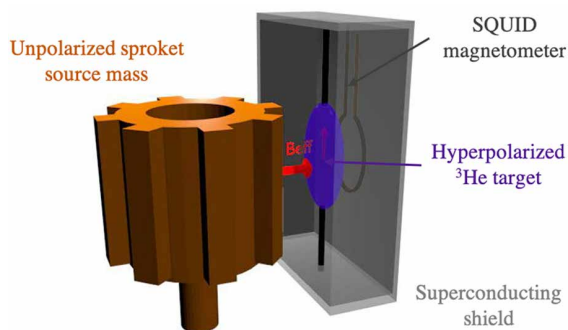
Fig. 6. Schematic view of the ARIADNE setup. The rotation of the unpolarized segmented cylinder sources a modulating effective magnetic field that acts on the laser-polarized ^{3}He gas. Synchronization of the modulating frequency with the Larmor precession of ^{3}He will accumulate its transverse nuclear spin, which can be sensed by the SQUID magnetometer.

Fig. 7. Future projections of the ARIADNE and storage ring proton EDM searches. The limits are shown in terms of the nuclear monopole-dipole coupling as a function of axion mass. The desired sensitivities by the prototype and upgraded ARIADNE experiments are represented by the dashed and dotted lines in red overlapped on the QCD axion band (in the orange area). The purple solid lines correspond to the current experimental upper limit on neutron EDM and theoretical lower bound imposed by the EW CP-violating phase.

experimental limit is more than 10 orders of magnitude smaller than anticipated from QCD. This field dynamically cancels the $\bar{\theta}$ term out of the QCD Lagrangian and hence effectively brings the EDM value of hadrons very close to zero. However, any CP violation in nature slightly shifts the EDM value away from zero due to nonperturbative QCD effects. With the CP-violating phase already observed in the electroweak (EW) interactions, represented by the Cabibbo-Kobayashi-Maskawa (CKM) phase, a nonzero (albeit small) hadronic EDM is expected. Additional CP-violating phases beyond the Standard Model will move its value further away. A new, much larger CP-violating source is believed to exist since the observed EW CP violation is too small to account for the prevalence of matter over antimatter in the present universe, one of the biggest questions in physics today. Therefore, once there is an EDM observed in a hadronic system, a number of other similar systems are needed to be examined to uncover the CP-violating source.

The storage ring method can improve the sensitivity for direct measurements of the hadronic EDM by three to four orders of magnitude over the present limits (*25*, *27*, *99–107*). The method uses a high-intensity beam of longitudinally polarized protons (order of 10^{11}) stored in a circular ring with electric bending fields to accurately gauge the proton spin precession over the spin coherent time (about 1000 s). The proton beam is set up to be at the so-called magic momentum, along which the proton spin is aligned at all times, freezing the average spin precession on the horizontal plane (*108*). In this configuration, the presence of a nonzero EDM develops the spin precession on the vertical plane under the influence of the radial electric field. To realize the concept, the beam and spin dynamics have been simulated with high precision, and beam position monitoring systems have been developed using SQUID gradiometers. A new hybrid ring design, featured by a highly symmetric configuration of the magnetic focusing systems, was proposed to enable simultaneous storage of the clockwise and counterclockwise beams such that the systematic errors can be greatly reduced (*109*), enabling the experiment to be performed using only currently available technology.

A generic experiment searching for axion-mediated CP-violating forces is currently under development by an international collaboration, ARIADNE (*24*). In the presence of an anomalous CP-violating phase, CP-odd axion fields can mediate short-range monopole-dipole interactions between matter objects. The proposal is based on the resonant
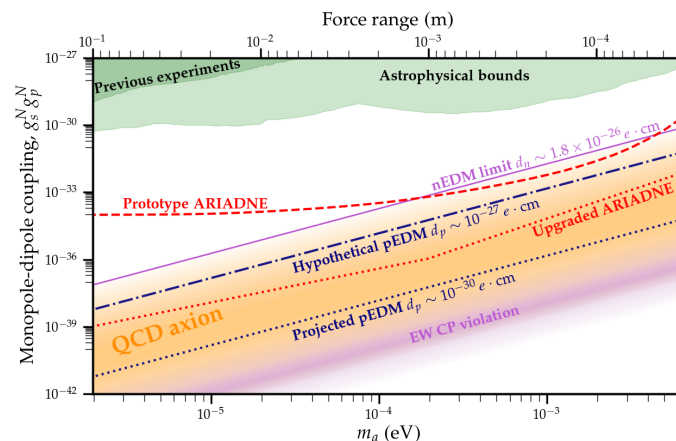
coupling between the rotational frequency of a source mass and an NMR sample with a matching Larmor spin precession frequency. The experimental scheme, shown in Fig. 6, involves an unpolarized sprocket mass as a monopole source, polarized ^{3}He nuclei for a dipole spin system, and an SQUID magnetometer to pick up the resonantly enhanced precession signal (*110*). The sensitive mass (frequency) range by this spin-dependent interaction is 0.1 to 10 meV (25 GHz to 2.5 THz), which is practically unreachable by the haloscope experiments. The ARIADNE Collaboration plans to perform the experiment using hyperpolarized ^{3}He gas as the NMR target with a future upgrade for ultimate sensitivity by scaling the size of the apparatus and increasing the sample density (liquid phase of ^{3}He). The projected sensitivities of the ARIADNE and storage ring EDM experiments are shown in Fig. 7.

Although the underlying principle of the axion-mediated spin-dependent interactions does not necessarily demand the axion to be dark matter, it requires new CP-violating phases in order for the proposed experiment to be sensitive enough to detect a signal. Therefore, any signal observed by ARIADNE can reveal both the axion mechanism and the existence of new CP-violation within its sensitive mass range. If the physics of QCD axions is realized in nature, then the ARIADNE signal is expected to lie above the Standard Model limit set by the EW CKM CP-violating phase and below the current experimental limit on the neutron EDM (*111*) in Fig. 7. In the absence of new *CP*-violation beyond the Standard Model, on the other hand, the experiment is supposed to observe a signal within the area in purple on the bottom of the figure, depending on the axion mass.

Last, as mentioned earlier, most of the sensitive experiments looking for the axion signal presume that the axions solely compose the local dark matter halo. This implies that null results do not really exclude the hypothesis of existence of this particle, but they merely rule it out as a dominant contributor to dark matter within the search range. However, the simultaneous consideration of the experimental results between ARIADNE and nucleon EDM measurements could provide decisive information. For example, if a proton or neutron EDM were measured to be 10^{-27} $e \cdot$ cm (represented by the navy dash-dotted line in Fig. 7), while the ARIADNE

experiment failed to see any signal down to the ultimate sensitivity level (corresponding to "Upgraded ARIADNE" in the same figure), then one could declare that axions do not exist in that accessible mass range. On the other hand, a combination of the resonant signal observed by ARIADNE and vain attempts by the storage ring EDM measurements up to the projected limit (the navy dotted line) could be used to claim the existence of the axion as a new force mediator, which does not solve the strong CP problem. In this regard, the combination of the two independent experiments would provide a unique capability to shed light on the axion physics in the related axion mass range.

DISCUSSION

During the past few decades, substantial experimental efforts have been made to search for the invisible axion, which is believed to address two fundamental questions in physics—the strong CP problem and the dark matter mystery. Different detection schemes have been developed to probe different mass ranges and various new ideas, and concepts have been proposed on the basis of newly emerging technologies and interdisciplinary research. The haloscope experiments have entered a very exciting phase, reaching the theoretically interesting territory to test the favored axion models and extending the search range to cover a large fraction of the microwave region. In particular, the cavity haloscopes have provided the most sensitive experimental approach so far. For instance, ADMX and HAYSTAC have approached interesting sensitivity levels within relatively low-mass regions below 20 μeV. CAPP has been performing intensive R&D projects in various areas and demonstrated its capability of exploring the axion physics up to 100 μeV and even testing the QCD axions as a partial composition of the local dark matter halo. MADMAX is expected to expand the search range up to 100 GHz (400 μeV) by exploiting dielectric properties.

Apart from them, a number of interesting search programs relying on lumped element circuits (e.g., DM Radio) and NMR techniques (e.g., CASPEr) seem promising to cover a broad range below the QCD-band regions within the next few operation phases. Solar axions can also reveal the axion physics particularly above the milli–electron volt range, leading to an international proposal of a next-generation large-scale helioscope, IAXO. ALPS II is currently under upgrade to provide an independent search method with increased sensitivity of the LSW scheme for ALPs. Last, a combined interpretation of search results from the ARIADNE and nucleon EDM experiments could address the axion physics in a decisive manner particularly in the high-mass regions, which are not easily reachable by any other terrestrial experiment. Overall, it is foreseen that the next decade is going to be very interesting and exciting in the axion field and indeed could see the discovery of the axion in any part of the parameter space.

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