AXIONS AND OTHER VERY LIGHT BOSONS, PART III (EXPERIMENTAL LIMITS)

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In this section we review the experimental methodology and limits on light axions and light pseudoscalars in general. (A comprehensive overview of axion theory is given by H. Murayama in the Part I of this Review, whose notation we follow [1].) Within its scope are searches where the axion is assumed to be dark matter, searches where the Sun is presumed to be a source of axions, and purely laboratory experiments. We restrict the discussion to axions of mass $m_A < O(\mathrm{eV})$, as the allowed range for the axion mass is nominally $10^{-6} < m_A < 10^{-2}$ eV. Experimental work in this range predominantly has been through the axion-photon coupling $g_{A\gamma}$, to which the present review is confined. As discussed in Part II of this Review by G. Raffelt, the lower bound derives from a cosmological overclosure argument, and the upper bound from SN1987A [2]. Limits from stellar evolution overlap seamlessly above that, connecting with accelerator-based limits which ruled out the original axion. There it was assumed that the Peccei-Quinn symmetry-breaking scale was the electroweak scale, *i.e.*, $f_A \sim 250$ GeV, implying axions of mass $m_A \sim O(100\,\mathrm{keV})$. These earlier limits from nuclear transitions, particle decays, *etc.*, while not discussed here, are included in the Listings.

While the axion mass is well determined by the Peccei-Quinn scale, *i.e.*, $m_A = 0.62$ eV $(10^7\,\mathrm{GeV}/f_A)$, the axion-photon coupling $g_{A\gamma}$ is not: $g_{A\gamma} = (\alpha/\pi f_A)\, g_\gamma$, with $g_\gamma = (E/N - 1.92)/2$, where E/N is a model-dependent number. It is noteworthy however, that two quite distinct models lead to axion-photon couplings which are not very different. For the case of axions imbedded in Grand Unified Theories, the DFSZ axion [3], $g_\gamma = 0.37$, whereas in one popular implementation of the "hadronic" class of axions, the KSVZ axion [4], $g_\gamma = -0.96$. The Lagrangian $L = g_{A\gamma}\, \mathbf{E} \cdot \mathbf{B}\, \phi_A$, with ϕ_A the axion field, permits the conversion of an axion into a single real photon in an external electromagnetic field, *i.e.*, a Primakoff interaction. In the case of relativistic axions, $k_\gamma - k_A \sim m_A^2/2\omega \ll \omega$, pertinent to several experiments below, coherent axion-photon mixing in long magnetic fields results in significant conversion probability even for very weakly coupled axions [5].

Below are discussed several experimental techniques constraining $g_{A\gamma}$, and their results. Also included are recent but yet-unpublished results, and projected sensitivities for experiments soon to be upgraded.

III.1. Microwave cavity experiments: Possibly the most promising avenue to the discovery of the axion presumes that axions constitute a significant fraction of the dark matter halo of our galaxy. The maximum likelihood density for the Cold Dark Matter (CDM) component of our galactic halo is $\rho_{\text{CDM}} = 7.5 \times 10^{-25}\text{g/cm}^3(450\,\text{MeV/cm}^3)$ [6]. That the CDM halo is in fact made of axions (rather than *e.g.* WIMPs) is in principle an independent assumption, however should very light axions exist they would almost necessarily be cosmologically abundant [2]. As shown by Sikivie [7], halo axions may be detected by their resonant conversion into a quasi-monochromatic microwave signal in a high-Q cavity permeated by a strong magnetic field. The cavity is tunable and the signal is maximum when the frequency $\nu = m_A(1 + O(10^{-6}))$, the width of the peak representing the virial distribution of thermalized axions in the galactic gravitational potential. The signal may possess ultra-fine structure due to axions recently fallen into the galaxy and not yet thermalized [8]. The feasibility of the technique was established in early experiments of small sensitive volume, $V = O(1\,\text{liter})$ [9,10] with High Electron Mobility Transistor (HEMT) amplifiers, which set limits on axions in the mass range $4.5 < m_A < 16.3\,\mu\text{eV}$, but at power sensitivity levels 2–3 orders of magnitude too high to see KSVZ and DFSZ axions (the conversion power $P_{A\to\gamma} \propto g_{A\gamma}^2$). A recent large-scale experiment ($B \sim 7.5\,\text{T}, V \sim 200\,\text{liter}$) has achieved sensitivity to KSVZ axions over a narrow mass range $2.77 < m_A < 3.3\,\mu\text{eV}$, and continues to take data [11]. The exclusion regions shown in Fig. 1 for Refs. [9–12] are all normalized to the best-fit Cold Dark Matter density $\rho_{\text{CDM}} = 7.5 \times 10^{-25}\text{g/cm}^3(450\,\text{MeV/cm}^3)$, and 90% CL. Recent developments in DC SQUID amplifiers [12] and Rydberg atom single-quantum detectors [13] promise dramatic improvements in noise temperature, which will enable rapid scanning of the axion mass range at or below the DFSZ limit. The region of the microwave cavity experiments is shown in detail in Fig. 2.

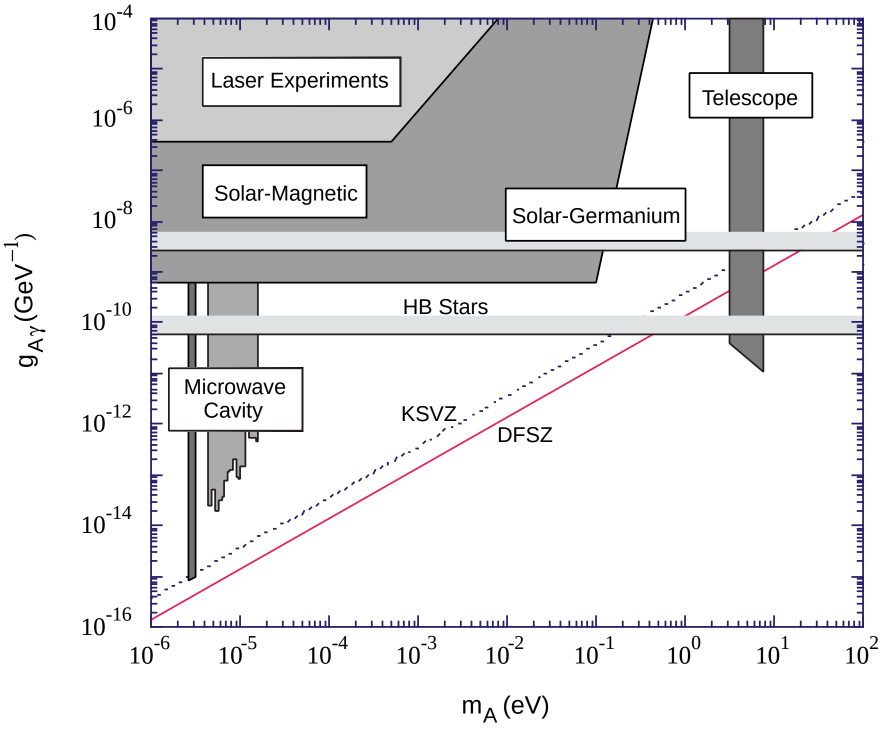

Figure 1: Exclusion region in mass vs. axion-photon coupling $(m_A, g_{A\gamma})$ for various experiments. The limit set by globular cluster Horizontal Branch Stars (“HB Stars”) is shown for Ref. 2.

III.2. Telescope search for eV axions: For axions of mass greater than about 10^{-1} eV, their cosmological abundance is no longer dominated by vacuum misalignment or string radiation mechanisms, but rather by thermal production. Their contribution to the critical density is small, $\Omega \sim 0.01\,(m_A/\mathrm{eV})$. However, the spontaneous-decay lifetime of axions, $\tau(A \rightarrow 2\gamma) \sim 10^{25}\mathrm{sec}(m_A/\mathrm{eV})^{-5}$ while irrelevant for μeV axions, is short enough to afford a powerful constraint on such thermally produced axions in the eV range, by looking for a quasi-monochromatic photon line from galactic clusters. This line, corrected for Doppler shift, would be at half the axion mass and

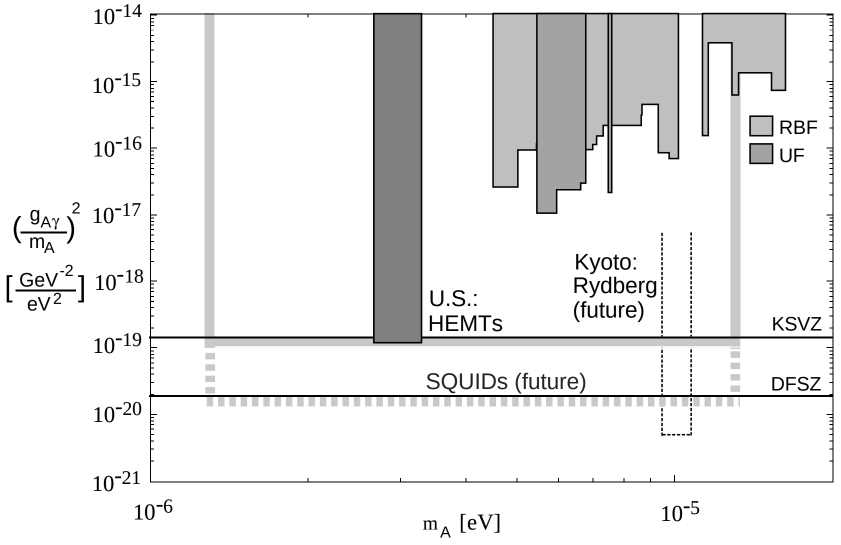

Figure 2: Exclusion region from the microwave cavity experiments, where the plot is flattened by presenting $(g_{A\gamma}/m_A)^2$ vs. m_A. The first-generation experiments (Rochester-BNL-FNAL, "RBF" [9]; University of Florida, "UF" [10]) and the US large-scale experiment in progress ("US" [11]) are all HEMT-based. Shown also is the full mass range to be covered by the latter experiment (shaded line), and the improved sensitivity when upgraded with DC SQUID amplifiers [12] (shaded dashed line). The expected performance of the Kyoto experiment based on a Rydberg atom single-quantum receiver (dotted line) is also shown [13].

its width would be consistent with the observed virial motion, typically $\Delta\lambda/\lambda \sim 10^{-2}$. The expected line intensity would be of the order $I_A \sim 10^{-17}(m_A/3\,\mathrm{eV})^7 \mathrm{erg\,cm^{-2}arcsec^{-2}\AA^{-1}sec^{-1}}$ for DFSZ axions, comparable to the continuum night emission. The conservative assumption is made that the relative density of thermal axions fallen into the cluster gravitational potential reflects their overall cosmological abundance. A search for thermal axions in three rich Abell clusters was carried out at Kitt Peak National Laboratory [14]; no such line was observed between 3100–8300 Å (m_A = 3–8 eV) after "on-off field" subtraction of the atmospheric molecular background spectra. A limit everywhere stronger than $g_{A\gamma} < 10^{-10}\mathrm{GeV}^{-1}$ is set, which is seen from Fig. 1 to easily exclude DFSZ axions throughout the mass range.

III.3. A search for solar axions: As with the telescope search for thermally produced axions above, the search for solar axions was stimulated by the possibility of there being a "1 eV window" for hadronic axions (*i.e.*, axions with no tree-level coupling to leptons), a "window" subsequently closed by an improved understanding of the evolution of globular cluster stars and SN1987A [2]. Hadronic axions would be copiously produced within our Sun's interior by a Primakoff process. Their flux at the Earth of $\sim 10^{12}\mathrm{cm}^{-2}\mathrm{sec}^{-1}(m_A/\mathrm{eV})^2$, which is independent of the details of the solar model, is sufficient for a definitive test via the axion reconversion to photons in a large magnetic field. However, their average energy is $\sim$ 4 keV, implying an oscillation length in the vacuum of $2\pi(m_A^2/2\omega)^{-1} \sim O(\mathrm{mm})$, precluding the mixing from achieving its theoretically maximum value in any practical magnet. It was recognized that one could endow the photon with an effective mass in a gas, $m_\gamma = \omega_{\mathrm{pl}}$, thus permitting the axion and photon dispersion relationships to be matched [15]. A first simple implementation of this proposal was carried out using a conventional dipole magnet with a conversion volume of variable-pressure helium gas and a xenon proportional chamber as the x-ray detector [16]. The magnet was fixed in orientation to take data for $\sim$ 1000 sec/day. Axions were excluded for $g_{A\gamma} < 3.6 \times 10^{-9}\mathrm{GeV}^{-1}$ for $m_A < 0.03\,\mathrm{eV}$, and $g_{A\gamma} < 7.7 \times 10^{-9}\mathrm{GeV}^{-1}$ for $0.03\,\mathrm{eV} < m_A < 0.11$ eV (95% CL). A more ambitious experiment has recently been commissioned, using a superconducting magnet on a telescope mount to track the Sun continuously. A preliminary exclusion limit of $g_{A\gamma} < 6 \times 10^{-10}\mathrm{GeV}^{-1}$ (95% CL) has been set for $m_A < 0.03$ eV [17].

Another search for solar axions has been carried out, using a single crystal germanium detector. It exploits the coherent conversion of axions into photons when their angle of incidence satisfies a Bragg condition with a crystalline plane. Analysis of 1.94 kg-yr of data from a 1 kg germanium detector yields a bound of $g_{A\gamma} < 2.7 \times 10^{-9}\mathrm{GeV}^{-1}$ (95% CL), independent of mass up to $m_A \sim 1$ keV [18].

III.4. Photon regeneration ("invisible light shining through walls"): Photons propagating through a transverse field (with $\mathbf{E}\|\mathbf{B}$) may convert into axions. For light axions with $m_A^2 l/2\omega \ll 2\pi$, where l is the length of the magnetic field, the axion beam produced is colinear and coherent with the photon beam, and the conversion probability Π is given by $\Pi \sim (1/4)(g_{A\gamma}Bl)^2$. An ideal implementation for this limit is a laser beam propagating down a long, superconducting dipole magnet like those for high-energy physics accelerators. If another such dipole magnet is set up in line with the first, with an optical barrier interposed between them, then photons may be regenerated from the pure axion beam in the second magnet and detected [19]. The overall probability $P(\gamma \rightarrow A \rightarrow \gamma) = \Pi^2$. Such an experiment has been carried out, utilizing two magnets of length $l=$ 4.4 m and $B=$ 3.7 T. Axions with mass $m_A < 10^{-3}$ eV, and $g_{A\gamma} > 6.7 \times 10^{-7}\mathrm{GeV}^{-1}$ were excluded at 95% CL [20,21]. With sufficient effort, limits comparable to those from stellar evolution would be achievable. Due to the $g_{A\gamma}^4$ rate suppression however, it does not seem feasible to reach standard axion couplings.

III.5. Polarization experiments: The existence of axions can affect the polarization of light propagating through a transverse magnetic field in two ways [22]. First, as the $E_{\|}$ component, but not the $E_{\perp}$ component will be depleted by the production of real axions, there will be in general a small rotation of the polarization vector of linearly polarized light. This effect will be a constant for all sufficiently light m_A such that the oscillation length is much longer than the magnet ($m_A^2 l/2\omega \ll 2\pi$). For heavier axions, the effect oscillates and diminishes with increasing m_A, and vanishes for $m_A > \omega$. The second effect is birefringence of the vacuum, again because there can be a mixing of virtual axions in the $E_{\|}$ state, but not for the $E_{\perp}$ state. This will lead to light which is initially linearly polarized becoming elliptically polarized. Higher-order QED also induces vacuum birefringence, and is much stronger than the contribution due to axions. A search for both polarization-rotation and induced ellipticity has been carried out with the same magnets described in Sec. (III.4) above [21,23]. As in the case of photon regeneration, the observables are boosted linearly by the number of passes the laser beam makes in an optical cavity within the magnet. The polarization-rotation resulted in a stronger limit than that from ellipticity, $g_{A\gamma} < 3.6 \times 10^{-7}\mathrm{GeV}^{-1}$ (95% CL) for $m_A < 5 \times 10^{-4}$ eV. The limits from ellipticity are better at higher masses, as they fall off smoothly and do not terminate at m_A. There are two experiments in construction with greatly improved sensitivity which while still far from being able to detect standard axions, should measure the QED "light-by-light" contribution for the first time [24,25]. The overall envelope for limits from the laser-based experiments in Sec. (III.4) and Sec. (III.5) is shown schematically in Fig. 1.

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