THE SEARCH FOR DARK MATTER AXIONS

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Abstract

The axion, a hypothetical elementary particle, originally emerged from a solution to the strong CP problem in QCD. Later, axions were recognized as good dark matter candidates. Dark matter axions have only feeble couplings to matter and radiation, so their detection offers considerable challenges. Nonetheless, a new generation of exquisitely sensitive searches is underway. Should axions exist, they have a good chance of being discovered soon.

1. Overview

Confounding expectations, the strong interactions appear to conserve the product CP of charge conjugation and parity. This "strong CP problem" in QCD is resolved in an elegant way by invoking a new symmetry of nature, Peccei-Quinn (PQ) symmetry. When PQ symmetry is spontaneously broken, a new elementary particle—the axion—is born [1].

There is abundant evidence for the existence of large halos of nonluminous matter—dark matter—surrounding galaxies. The density of dark matter near Earth is not very well determined; it is usually given as 0.3 GeV/cm^3 or less. The nature of halo dark matter remains a mystery, and unraveling this mystery is a central challenge of science today. It seems likely from the success of models of nucleosynthesis and inflation that the baryonic mass density can be no more than 10–20% of critical density and the universe is nearly exactly flat, therefore requiring a substantial amount of dark matter. Some of the non-baryonic dark matter candidates, accounting for the remaining 80–90% of the mass density, are exotic objects like finite-mass neutrinos, weakly interacting massive particles (such as the lightest supersymmetric particle), primordial black holes, and axions. Axions are an example of "cold dark matter" whereas light finite-mass neutrinos are "hot dark matter," the hot and cold modifiers referring to their greater- or less-than thermal velocity dispersion at their birth in the early universe.

Axions are then doubly well motivated: they find important roles in resolving the strong CP problem and as a candidate for dark matter. Current laboratory, astrophysical and cosmological considerations constrain the axion mass to the three decade window 1–1000 μeV, with laboratory experiments now underway to probe the first and perhaps most promising decade of mass. This article is an overview of dark matter axions from an experimentalist's perspective. For the sake of brevity, some important topics were omitted. It is particularly unfortunate that there is insufficient space for reevaluated stellar and supernovae bounds, axion clustering, and assorted clever experimental ideas. For more details, there is no better starting point than Kolb and Turner's book *The Early Universe* [2].

2. The Axion and QCD

QCD, the theory of the strong interactions, has amassed an impressive string of successes. Its non-Abelian nature is experimentally established. Decay rates and quantum statistics support the notion of color. Cross sections and branching ratios are in accord with perturbative predictions. There is, however, one annoying loose end, the strong CP problem. The non-Abelian nature of QCD, now seen in experiments, should introduce T, P and CP violating effects and, in particular, there should be a substantial CP violating neutron electric dipole moment. However, sensitive experiments see no such moment, and its lack is a genuine mystery. Naively, it seems surprising, at first, for QCD to have CP violating interactions. The source of such interactions is traced to the complexity of the QCD vacuum. The QCD vacuum has gluon fields in their lowest energy configuration, and in QCD there are many degenerate vacuua. The various vacuua can be classified by winding number n—the non-Abelian nature allows non-zero n—and gauge transformations can change one winding number vacuum into another. In order to preserve gauge invariance, we construct a gauge invariant vacuum by a Bloch-wave-like superposition of vacuua, like so:

$$|\Theta\rangle = \sum_n e^{-in\Theta}\,|n\rangle \qquad (1)$$

Such a vacuum, the Θ vacuum, is gauge invariant and is the physical vacuum of QCD. Effects of the Θ vacuum on vacuum transition amplitudes can be subsumed in a new effective non-perturbative term in the QCD Lagrangian proportional to $\overline{\Theta}G\tilde{G}$, with G and $\tilde{G}$ the gluon field strength tensor and its dual, and (with M the quark mass matrix) $\overline{\Theta} = \Theta + \arg\det M$. The parameter Θ

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takes contributions from the QCD vacuum Θ and phases from the quark mass matrix. The $G\tilde{G}$ term in the Lagrangian is a total derivative and does not contribute to classical equations of motion or perturbative effects. However, the term is explicitly CP violating and can induce non-perturbative effects. With a $\bar{\Theta}$ of order 1, the neutron can be shown [3] to have an electric dipole moment of order 10^{-15} e-cm. Current limits are pushing 10^{-25} e-cm [4], and these limits in the context of the Θ vacuum restrict the magnitude of $\bar{\Theta}$ to less than 10^{-10}.

This immeasurably small value of $\bar{\Theta}$ is the strong CP problem. Of course, a parameter equal to zero is no cause for alarm. After all, the photon mass may very well be zero, and a zero mass neutrino would not be too surprising. However, this immeasurably small $\bar{\Theta}$ is of greater concern. Recall that $\bar{\Theta}$ has contributions from QCD (through the Θ vacuum) and weak interactions (through the quark mass matrix). Likely the weak contribution is non-zero, so, then, is the Θ vacuum contribution. Since the two contributions are independent, the zero in the strong CP problem is therefore more than just a zero, it is the near perfect cancellation of two independent but finite effects. Among the ideas for evading this problem [5], I find most compelling the one invoking the axion.

It seems inescapable that the QCD vacuum is complicated and gives rise to interesting physical effects. However, in taking the vacuum seriously, we are left with the strong CP problem. The solution involving the axion developed from an idea proposed by Peccei and Quinn [6]. They showed that a slight extension of the Higgs sector endows the standard model with a global U(1) symmetry, the Peccei-Quinn (PQ) symmetry. Weinberg and Wilczek then noticed that since the symmetry is broken at some scale f_{PQ}, there must also be a Goldstone boson—the axion [7]. Although the axion starts out as a massless Goldstone boson, it eventually acquires an effective mass (as does, e.g., the η) through intermediate states coupled through its color axial anomaly. Besides mass, other effects of the axial anomaly can be considered as arising from a new effective term in the Lagrangian proportional to $(a/f_{PQ})\bar{\Theta}G\tilde{G}$, with a the axion field, and constant of proportionality dependent on the value of the axion color anomaly. The sum of Θ and anomaly terms, taken as a classical potential, is minimized at some axion vacuum expectation value proportional to $\bar{\Theta}f_{PQ}$. At this value of the axion field, the CP violating $G\tilde{G}$ terms, including those giving rise to a neutron electric dipole moment, vanish.

3. Interactions of the Axion with Matter and Radiation

For experiments, a crucial consideration is the interaction of axions with ordinary matter and radiation. The axion mass and the PQ symmetry breaking scale f_{PQ} are related through

$$m_\alpha = \frac{\sqrt{z}}{1+z}\frac{f_\pi m_\pi}{f_{PQ}/N}, \qquad (2)$$

with z is the ratio of u- and d-quark masses (a ratio presumed near 0.5), and N the axion color anomaly. The model dependence—that is, the particular scheme for introducing the PQ symmetry—enters axion interactions through N (and the axion electromagnetic anomaly, as well). I avoid detailing the various schemes for establishing PQ symmetry and I give greater weight to the PQ symmetry itself. After all, there must be a solution to the strong CP problem, and PQ symmetry could very well be it, even when the symmetry's origin is unknown.

The strength of the axion's couplings to normal matter and radiation are given by effective coupling constants $g_{a\gamma\gamma}$, g_{aee}, g_{app}, etc., for the axion coupling to photons, electrons and protons. Since the elementary axion couplings are model dependent, these effective couplings are model dependent as well. For instance, the effective two photon coupling constant is

$$g_{a\gamma\gamma} = \frac{\alpha/2\pi}{f_{PQ}/N}|(E/N - 2(4+z)/3(1+z)|, \qquad (3)$$

where E is the electromagnetic anomaly, and the factor $2(4 + z)/3(1 + z)$ containing ratios of light quark masses is approximately 2. The tree level coupling of axions to color is fundamental to the axion's role in solving the strong CP problem. The tree level coupling of axions to charged leptons is optional; here, different theories allow different couplings. Extremes of lepton couplings are cases with no tree level axion coupling to electrons (dubbed hadronic axions [8]), and axions where tree level quark and electron couplings are of the same strength (an example is axions layered on a simple GUTs scenario, dubbed DFSZ axions [9]). All the effective coupling constants of axions with normal matter and radiation depend on the inverse of the symmetry breaking scale f_{PQ}, with heavier axions having stronger couplings. With the axion very light, the couplings are very weak and the axion is hard to detect. Such axions are termed invisible axions. The current round of axion searches looks for these invisible axions through their coupling with two photons. There is nothing to forbid the anomaly ratio *E/N* from having the unfortunate value where the axion has effectively no photon coupling. However, in one example, *E/N* in the simple DFSZ GUTs model has value 8/3, and there is no reason to think *E/N* in other models would have the special zero coupling value.

4. Astrophysical and Laboratory Constraints on the Axion Mass

One powerful class of axion search looks for effects of invisible axions on stellar dynamics and cosmological evolution.

4.1 Axions and Stellar Dynamics

The evolution of a star is throttled by the rate at which thermal energy can be dissipated. The interaction length of nuclear reaction photons at the center of the sun is only a few centimeters, so photons bounce around inside the sun for millions of years before they escape. Viewed in this context, electromagnetic interactions are quite strong. In contrast, invisible axions (neutrinos, as well) efficiently transport energy out of a star, thereby accelerating its evolution.

At the center of the sun, about $10(m_a/\mathrm{eV})^2$erg/g/sec DFSZ axions of mass m_a would be created through Compton processes like $e + \gamma \rightarrow e + a$, to be compared with the nuclear energy release of a few erg/g/sec. Naively then, DFSZ axions more massive than about 1 eV transport more energy out of the star than produced in nuclear reactions. Actually, the star would contract, raising its temperature and nuclear reaction rate and thereby accelerating its evolution. Based on our understanding of solar dynamics and the sun's measured ^{4}He content and luminosity, it is unlikely that axions are at this moment removing more than about half of the nuclear energy, thereby constraining the DFSZ axion mass to less than about 1 eV [10]. Another way to arrive at this limit is to remember how solar neutrino production is exquisitely sensitive to the solar temperature. Should there be an axion-induced temperature rise, the observed solar neutrino event rate would increase. If anything, there is evidence for a ''solar neutrino deficit,'' certainly no evidence for an excess, and these considerations ultimately constrain the DFSZ axion mass to below about 1 eV. These solar limits taken together forbid DFSZ axion masses between about 1 eV and the solar central temperature of a few keV.

Red giants are excursions from main sequence stars with relatively low surface temperature, but with large diameter and luminosity. The central temperature of red giants, driven by helium burning, approaches 10^8 K. The evolution of red giants out of the main sequence is extensively modeled [11], and the red giant population relative to main sequence populations is well understood. The evolution of a star into a red giant occurs relatively quickly. Also relatively quickly, a red giant exhausts its helium fuel and continues evolving into a compact object. As in the case of the sun, the effect of hadronic axions on red giants is to raise the central temperature, thereby increasing the helium burning rate and reducing the time a star spends as a red giant. The fraction of red giants in a stellar population thereby declines, and these considerations result in an upper limit to the hadronic axion mass of around a few eV [12].

For DFSZ axions, the $\gamma + e \rightarrow a + e$ Compton coupling to electrons dominates. As a star evolves into a red giant, waste from hydrogen burning becomes a helium core supported by electron degeneracy pressure. As material in the core builds up, it shrinks in size, thereby liberating gravitational binding energy and raising its temperature. When the core becomes sufficiently hot, the helium ignites, and the star continues its evolution as a red giant. Without axions, core cooling is throttled by neutrino radiation. However, DFSZ axions, produced by Compton coupling to electrons, readily transport energy out of a star. The axion production rate is proportional to an inverse power of the axion mass, and much like the neutrino production, is proportional to a high power of the core temperature [13]. Assuming axions dominate energy transport, the core temperature then varies as an inverse power of the axion mass. This is somewhat surprising: for DFSZ axions, the higher the axion mass, the lower the core temperature and a sufficiently massive DFSZ axion inhibits helium ignition. Such considerations constrain DFSZ axions to masses less than about 10^{-2} eV. Also, as for the sun, these limits do not apply to axion masses greater than the red giant core temperature near 10 keV.

4.2 Axions and Supernovae

In 1987, a nearby star in the LMC exploded as a supernova. Dubbed SN1987A, this event had an enormous impact on particle and astrophysics. The impulsive release of the approximately 10^{53} ergs of gravitational binding energy eventually emerged as neutrinos with characteristic temperature near 10 MeV. The Kamiokande and IMB detectors together recorded 19 neutrinos spread over about 10 seconds, a result consistent with our understanding of supernovae dynamics and the number of light neutrino flavors. The supernova cooling is limited by neutrino interactions; a light axion would efficiently remove energy from the explosion and reduce the spread in neutrino arrival times. Nucleons in the core have an effective coupling to axions, and since for axion-nucleon interactions the electromagnetic anomaly does not directly enter, the DFSZ and hadronic axions couple with similar strength. For axions of mass near 10^3 eV [14], axion and neutrino energy transport from the core are about equal. Effects of axion scattering become significant near axion mass 20×10^{-3} eV, and by 2 eV, the relatively strongly interacting axions transport less power from the core than any one neutrino species. These considerations forbid axions with mass between about 10^{-3} eV and 2 eV.

5. Production of Relic Axions

The laboratory and astrophysics upper bounds on the axion mass depend on creation and detection of new axions. If axions are dark matter, they are a relic of the early universe. We know of several scenarios by which a substantial amount of relic axions can be created. A particular scenario coupled with the requirement that the axion mass density not severely overclose the universe results in a lower bound to the axion mass.

5.1 Relic Axions: Misalignment Production

In our Θ vacuum picture of QCD, CP conservation is a consequence of the classical $\overline{\Theta}$ parameter driven to zero through the axion acquiring mass. Recall, however, that the axion did not start out with mass—it acquired mass at the temperature Λ_{QCD}—and the CP violating $\overline{\Theta}$ parameter has arbitrary value in early times. We say the initial value of $\overline{\Theta}$ is misaligned with its present near-zero value. An analogy is found in the simple pendulum: Without gravity, there is no special pendulum angle. Turn on gravity though, and the average pendulum angle is driven to zero. Although the pendulum average angle is zero, the pendulum oscillates with a non-zero RMS angle. There is energy stored in oscillations, and, returning from the pendulum analogy, quanta of these oscillations are axions. This is the mechanism or misalignment production [15]. You can carry this analogy too far—in particular, this simple pendulum does not include Hubble expansion damping—but as for the pendulum case, the quanta form a Bose condensate with minuscule velocity dispersion. Misalignment axions are cold dark matter. The present density of misalignment axions is [16]

$$\Omega_a = 0.85 \times 10^{\pm 0.4}(\Lambda_{QCD}/200\ \mathrm{MeV})^{-0.7} (m_a/10^{-5}\mathrm{eV})^{-1.18}/h^2, \quad (4)$$

where the Hubble factor h enters through expansion driven damping, and the QCD scale enters as the temperature where mass appears. This prediction for the present axion energy density assumes an initial misalignment angle of $\pi\sqrt{3}$—the RMS of the interval $-\pi$ to π. This is a reasonable value as, without inflation, the initial misalignment angle is a composite of independent misalignment angles from a great number of causally disconnected volumes. With these assumptions and typical values for the Hubble and QCD scales, axions with mass near 10^{-5} eV form closure density and much lower axion masses would severely overclose the universe. This misalignment mechanism therefore provides a lower limit to the axion mass. Should inflation have occurred after axions appear, there is just the one initial misalignment angle corresponding to the angle in out particular pre-inflation volume. Here, the statistics of many causally disconnected volumes cannot be invoked, and the argument is the somewhat weaker one that a misalignment angle very near zero is highly improbable.

5.2 Relic Axions: String Decay

The axion is the Goldstone boson of a spontaneously broken global U(1) symmetry, and such broken symmetries have strings as solutions to the equation of motion. These strings are nearly one-dimensional objects, either closed loops or infinitely long, arising from the mismatch between the arbitrary choice of vacuum in neighboring volumes [17]. Assuming no inflation or that inflation occurred before the breaking of PQ symmetry, a network of strings develop carrying an appreciable amount of energy. These strings interact, and in doing so form loops. These loops evaporate via axion radiation, and these radiated axions could form a substantial component of dark matter [18]. There is no consensus as the relative importance of string radiation to the relic axion density. However, even proponents of substantial string radiation advise cautious interpretation. Also unresolved is the question of the phase space structure of string axions; the issue here is how their primordial velocity spectrum compares to a thermal distribution.

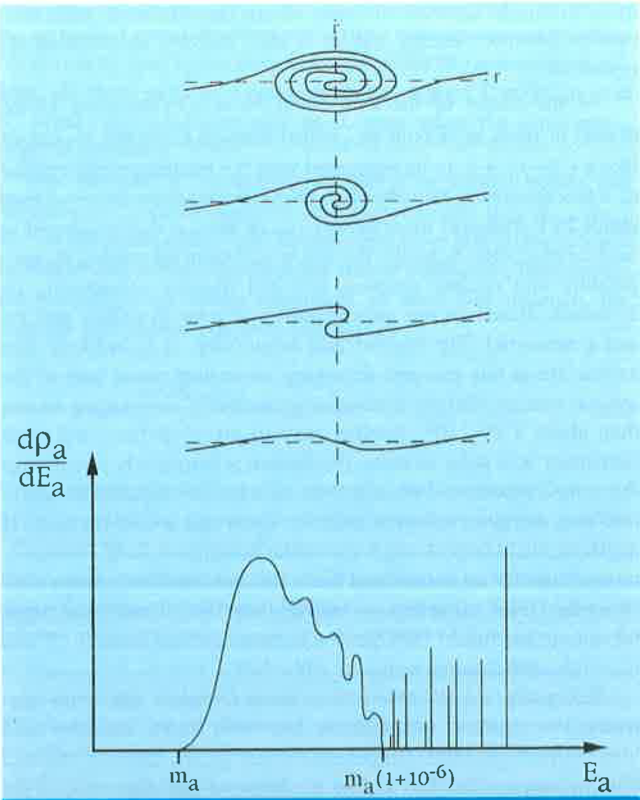

FIGURE 1

(upper) Phase space of halo axions at various stages of galaxy formation. The origin of the distance coordinate is the galactic center. (lower) Energy spectrum of axions near Earth.

5.3 Relic Axions: Phase Space Structure

Axions, whether string or misalignment produced, are subject to gravitational forces, and in what is an overly simplistic picture, relax with normal matter into something resembling an isothermal halo around our galaxy. As for normal matter, the peculiar velocity of isothermal halo axions is of order 10^{-3} c. In addition, halo axions exhibit large deviations from a thermal distribution, most notably in that the highest energy particles have discrete values of velocity. The phase space structure of radial infall halo axions is shown in upper Figure 1, where the radial coordinate is distance from the center of the galaxy [19]. The energy spectrum of axions at our radius from the center of the galaxy is shown in lower figure 1. The isothermal peak is to the left, and the newer infall peaks are to the right. Perhaps 10% of the axions are in the first infall peak, a narrow structure with fractional width less than 10^{-19}.

5.4 Relic Axions: Summary

There is near unanimous agreement that thermal axions would probably not contribute greatly to closure density. However, axions from misalignment or string radiation could be significant. Uncertainties remain, most notably the issue of the density and velocity spectrum of string axions, as well as usual uncertainties of Λ_{QCD} and the Hubble constant. The summary of the various laboratory, astrophysical and cosmological constraints on axion mass is shown in figure 2.

6. Detection of Relic Axions

Besides the 1–1000 μeV window, the combined stellar evolution and cosmological bounds allow a small window of axion mass near 2 eV. These axions live long enough so that there are still significant numbers of them in halos, yet decay frequently enough into photons to be detected as a narrow optical line on the overall sky glow [20]. These decays are not seen, leaving the range $10^{-\varepsilon}$ to 10^3 eV as the sole axion mass window.

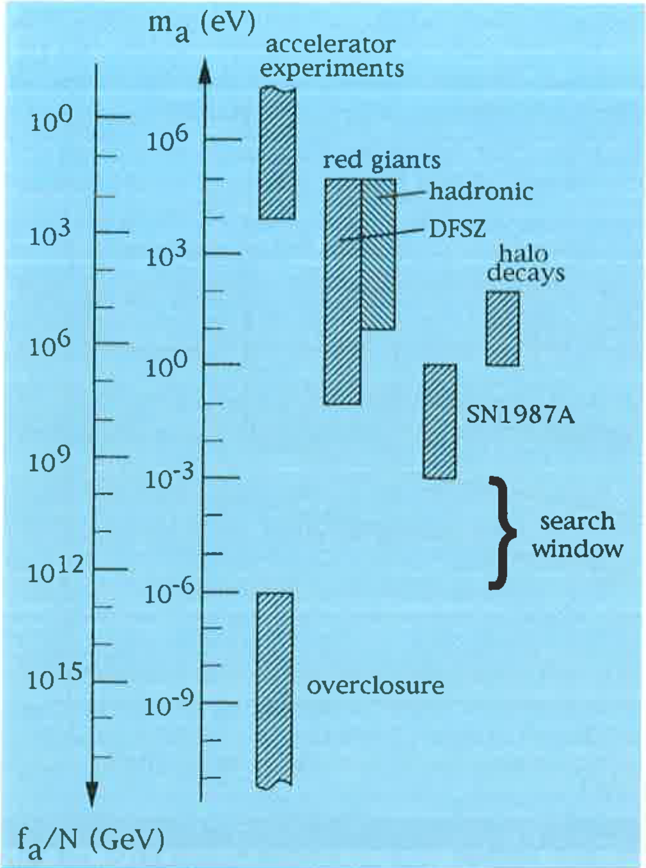

FIGURE 2

Summary of laboratory, astrophysical and cosmological constraints on the axion mass.

6.1 Detection of Relic Axions: Sikivie-Type Axion Detectors

Halo axions in this mass window can be seen through their resonant conversion into photons in a high Q cavity threaded by a magnetic field. In practice, a tunable helium-cooled high Q cavity is placed in the bore of a superconducting solenoid, and the resonant frequency of its lowest TM mode is slowly changed while cavity output is monitored for excess power from resonant axion conversions [21]. The excess power is

$$P = 4.10^{-26}\mathrm{Watt}\left(\frac{V}{0.22\,\mathrm{m}^3}\right)\left(\frac{B_0}{10\mathrm{Tesla}}\right)^2 \times C_{nl}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.5\cdot 10^{24}\ \mathrm{g/cm}^3}\right)\left(\frac{m_a}{2\pi\mathrm{GHz}}\right)\min(Q_L,Q_a)$$

with V the volume of the cavity, B_0 the magnetic field strength, C a mode-dependent form factor of order unity, ρ_a the density of galactic halo axions at the Earth, m_a the axion mass, Q_L the loaded Q of the cavity and $Q_a \sim 10^6$ the ''quality factor'' of the galactic halo axions (the ratio of their energy to their energy spread near Earth). Finally, g_γ is the coupling of axions to two photons. A value $g_\gamma \sim 0.36$ is predicted for DFSZ axions, and 0.97 for a model of hadronic axions. This is a tiny amount of power; consider that with the nominal value of constants in the above expression, the black body power in the Q_a bandwidth from a 1 K cavity is ten times larger than the power from axion conversions.

Unfortunately, the axion mass is unknown, as is the corresponding resonant frequency $f = m_a c^2/h$. It is known, however, that misalignment axions with mass near 4 μeV are near critical density. This is what makes the first decade of the axion search window so promising. The search rate for a constant signal to noise ratio (s/n) is

$$\frac{df}{dt} = \frac{72\ \mathrm{GHz}}{\mathrm{year}}\left(\frac{4}{s/n}\right)^2\left(\frac{V}{0.22\ \mathrm{m}^3}\right)^2\left(\frac{B_0}{10\ \mathrm{Telsa}}\right)^4 \times C^2\left(\frac{g_\gamma}{0.97}\right)^4\frac{\rho_a}{0.5\cdot 10^{-24}\ \mathrm{g/cm}^3}\left(\frac{5\ K}{T_n}\right)^2 \times \left(\frac{f}{1\ GHz}\right)^2\left(\frac{Q_w}{Q_a}\right)$$

with T_n the total noise (the linear sum of cavity black body plus electronic noise) of the microwave detector.

Pilot experiments (also called first generation experiments) have been carried out using relatively small volume magnets and—by current standards—somewhat noisy amplifiers, at Brookhaven National Laboratory (BNL) and at the University of Florida (UF). These experiments had B_0^2V values of 0.36 and 0.45 T^2m^3, respectively. Figure 3 shows the regions in the coupling-squared versus axion mass plane eliminated by these searches, assuming axions saturate the halo, compared with predictions from DFSZ and a range of axion models. The pilot experiments have demonstrated the principle of cosmic axion detection over a wide range of frequencies, but they lacked by factors of 100–1000 the needed sensitivity to detect plausible couplings of halo dark matter axions.

A second-generation axion search, to be operated initially at the Lawrence Livermore National Laboratory, is now under construction in the U.S. The spokespersons are Leslie J Rosenberg (MIT) and Karl van Bibber (LLNL). The capability of this experiment to either detect axions (with *s/n* of 4) or exclude them (at the 97.7% C.L.) is shown in Figure 3 as the region extending into hadronic axion couplings. The key goals of the experiment are (1) to attain a power sensitivity which is conservatively a factor of 40 improvement (and probably closer to a factor of 100) over the pilot experiments–achieved by increasing the magnet volume and incorporating recent advances in low noise microwave amplification, and (2) to search the entire mass range 1.5 $\mu eV < m_a < 12.6\ \mu eV$—achieved through filling the magnet volume with multiple higher frequency cavities.

The key parts of the U.S. experiment are sketched in Figure 4. The experiment will utilize a superconducting magnet with a central field of 8.5 T. The experimental volume has inner diameter 50 cm and length 100 cm. Hence, $B_0^2V = 12\ T^2m^3$, about a factor of 25 better than the pilot experiments. The experimental volume is separated from the magnet cryostat by a cold-vacuum wall. The vacuum wall allows exchanging cavity arrays and electronics while the magnet is energized and cooling the cavity arrays to below the magnet temperature of 4.2 K. Initially, the cavity will be operated at about 1.5 K, somewhat lower than the noise temperatures of the best amplifiers available today in the UHF through S-bands (0.5 through 3 GHz). The expected total noise temperature near 3 K (physical plus electronic) yields another factor 1.6 in improved sensitivity over the pilot experiments.

The U.S. experiment features arrays of multiple cavities to extend the mass search range. Each cavity is separately tuned by moving dielectric or metallic rods within the cavity, and in this way the experiment will search the range 1.5 $\mu eV < m_a < 12.6\ \mu eV$. Additionally, the U.S. experiment looks for narrow peaks in the halo axion velocity spectrum. This has the potential to greatly increase sensitivity as the signal to noise power ratio improves with decreasing bandwidth. In the U.S. experiment, there are separate processing paths for the isothermal and narrow peak searches. Data

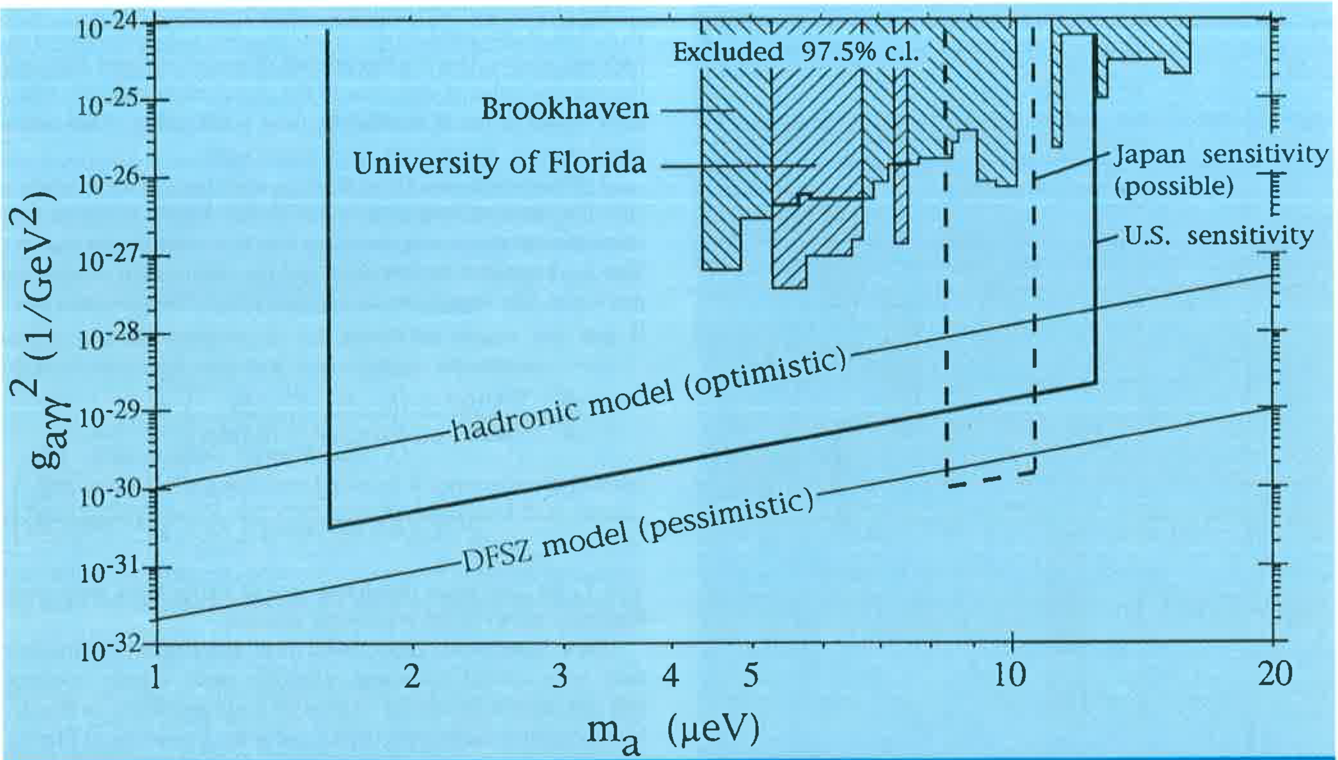

FIGURE 3

Regions in the axion mass versus two photon coupling constants plane excluded by the pilot cavity experiments. Also shown are coupling constants expected in a range (DFSZ and hadronic) of axion models. The area extending into the hadronic axion region is the expected sensitivity of the U.S. experiment. The narrow region extending into the DFSZ axion region is the potential sensitivity of the Japanese experiment.

taking starts after a shake-down run in mid-1995, with the experiment thereafter running continuously for three years.

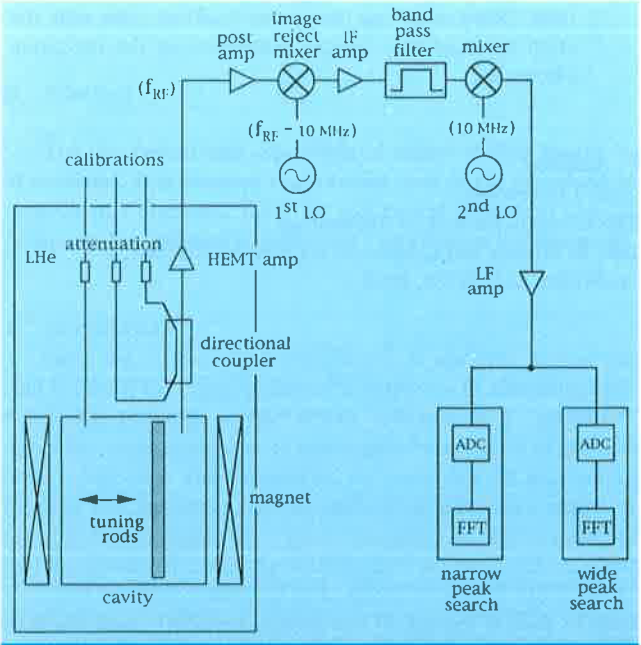

FIGURE 4

Sketch of the major components of the U.S. axion search experiment.

Another second generation axion search is to be operated in Japan. The spokesperson is Seishi Matsuki (Kyoto). It is similar to the U.S. design, except for its dilution refrigerator and Rydberg atom beam system. Rydberg atoms are atoms in states of high principal quantum number n; they are the subject of intense study [22]. Among their other interesting properties, Rydberg atoms have the following features: The interval between energy levels is very small, for example, $\Delta E_{100} \sim 7$ GHz. The electric dipole transition moment between $\Delta n = 1$ states is very large, for example, the absorption cross section with $n = 100$ can approach 1 cm^2. These two above features suggest Rydberg atoms with principal quantum number $n \sim 100$ are sensitive microwave photon counters.

The Japanese realization of a Rydberg atom microwave single photon counter is sketched in figure 5. Here, ground state atoms are excited into a Rydberg state by a semiconductor laser, where the $n \rightarrow n + 1$ transition frequency is tuned to the conversion cavity microwave frequency by a weak external magnetic field. Rydberg atoms that have absorbed a microwave photon are then selectively ionized, [23] and the ionization electrons are detected and counted.

The conversion cavity, a right circular cylinder 7 cm in diameter and 80 cm long, is threaded by a 7 T magnetic field, with approximate tuning range 2.4 GHz ± 10–20%. Extrapolating from their earlier experience with Rydberg atom counting, they hope for a sensitivity in a year of operation—even with the relatively small cavity volume—below the DFSZ model over a narrow mass range, as shown by the lower excluded region in Figure 3.

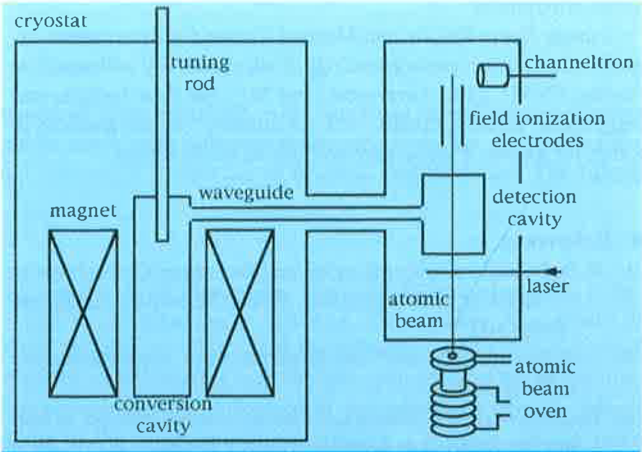

FIGURE 5

Sketch of the major components of the Japanese axion search experiment.

7. Conclusions

The axion, still a likely solution to the strong CP problem, is also a likely candidate for dark matter. The primordial nucleosynthesis upper bound to the baryon density of 0.2 critical density has survived years of scrutiny and the bound is unlikely to topple soon. A near critical density universe plus the nucleosynthesis bound implies substantial amounts of dark matter. The amount of visible mass is substantially less than 0.2, allowing room for some baryonic dark matter. Observationally, it is unlikely MACHOs are the dominant dark matter in our halo. Also, the Hubble telescope did not find substantial mass in the form of low mass stars. These two recent results considerably weaken the case for baryons as the principal dark matter. Measurements of the microwave background quadrupole anisotropy suggest that while pure cold dark matter—for example, axions—is not an ideal dark matter candidate, pure hot dark matter is a horrific candidate. The following is contentious, but I believe the anisotropy data tells us that dark matter—like axions—is substantially cold. The present window of allowed axion mass—10^{-6} to 10^{-3} eV—has likewise been under intense scrutiny and remains for now substantially unchanged, though reasoned voices sound for both shrinking and enlarging the window. It is intriguing that misalignment axions in the first decade of the mass window have just the mass needed to close the universe. Sikivie-type RF cavity experiments are underway to probe this window with reasonable sensitivity, and other ideas for experiments are in lesser stages of development. It looks promising for the axion: (1) they are on firm theoretical ground; (2) the data calls for substantial amounts of non-baryonic halo dark matter; (3) the data hints a substantial comment of dark matter is cold, say, as axions; (4) experiments are underway to look for these halo axions.

Acknowledgment

I thank Pierre Sikivie and Michael Turner for their patient explanations of axion phenomenology. I also thank my colleagues at Florida, FNAL, LBL, Livermore, and MIT for their insights and suggestions. Finally, I thank MIT for allowing me the freedom to search for axions; I sense they will not be disappointed.

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