Search for Axionic Dark Matter

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2013-04/tanner_david

The Axion Dark Matter eXperiment (ADMX) searches for axions as part of the halo of our galaxy. These axions have a mass in the range 1–10 μeV and convert to photons in a microwave cavity permeated by a strong magnetic field. ADMX recently incorporated low-noise SQUID amplifiers into the experiment and at present is being upgraded with a dilution refrigerator, permitting operation with noise temperatures of 100–200 mK.

Our understanding of the energy and matter composition of the universe has undergone a revolution in recent years.[1–3] The picture has evolved from a universe dominated by protons, neutrons, and electrons to one where dark matter and dark energy dominate the mass-energy budget. The dark matter is convincingly constrained to be non-baryonic and cold. There are three widely discussed candidates for the dark matter: sterile neutrinos, weakly interacting massive particles (WIMPs), and axions. This paper describes the results and plans for a search for axions: the Axion Dark-Matter eXperiment (ADMX).

A discovery of the axion, or placing unambiguous limits on its existence, would have profound implications for the dark matter problem. Either result would also impact a second important problem in contemporary physics: the origin of parity P and the product of charge conjugation with parity CP symmetry in the strong interactions.[4, 5] The axion is thus motivated by and has the potential to solve two rather important issues in particle physics and astrophysics. Moreover, the fact that the LHC has not produced evidence for supersymmetric particles[6] makes the case for WIMP dark matter more difficult to muster.[7] In contrast, the case for axions remains as strong as ever.[8, 9] The most plausible mass for the axion is in the 1-1000 μeV range. At the low end of this window axions provide the dark matter.[10–14]

ADMX searches for axions that constitute the dark-matter halo of our galaxy. Many observations imply the existence of large halos of non-luminous matter surrounding galaxies.[15, 16] ADMX exploits the fact that axions may be stimulated to convert into microwave photons in a high Q cavity permeated by a large magnetic field. This detection method was proposed thirty years ago[17] and was developed during pilot experiments [18, 19] ADMX was initially located at the Lawrence Livermore National Laboratory (LLNL) but recently relocated to the University of Washington, Seattle. This axion detector,[8, 20, 21] which improved the sensitivity over the pilot detectors by at least a factor of 400, consists of a large superconducting magnet containing one or more microwave cavities. Axions which overlap the high-field region will be stimulated to decay into microwave photons when the resonant frequency of the cavity equals the mass of the axion. An ultra-sensitive microwave receiver, using superconducting electronics in its front end,[21] amplifies the cavity signal to a point where spectral analysis can search for signatures of axion–photon emission. Over the past few years, the detector has scanned the 1.9–3.6 μeV axion mass range with a sensitivity capable of a detection if the axion-photon coupling is near the upper end of theoretical predictions.

In 2003, the DOE approved Phase I of an upgrade to ADMX to give an additional improvement to the sensitivity: incorporation of SQUID amplifiers into the front end of the receiver. This upgrade is based on a remarkable breakthrough in making DC SQUIDs operate as high-gain, low-noise amplifiers up to GHz frequencies.[22] Phase I retrofitted the experiment to operate with SQUID amplifiers at a physical temperature of $T \sim 1.5$ K. In this case the system background temperature is dominated by the physical temperature, $T_s \sim 2$ K. The Phase I construction and commissioning ended in 2008 and was followed by a year-long science data run using the SQUID amplifiers.[23]

Phase II has recently begun as a second-generation dark matter detector. Our incremental approach will continue with the installation of a ^{3}He refrigerator (to cool to 400 mK) and a science run at a sensitivity required to detect weakly-coupled axions. Next, a high-circulation-rate dilution refrigerator will be added to the detector, reducing the physical temperature to $T \sim 100$ mK. The system noise temperature is then expected to be below 200 mK. The upgrade will improve system noise performance to such an extent that ADMX will be sensitive to—or be able to rule out—axions as a component of the halo of our galaxy with *all* plausible coupling strengths over the same mass range as the original detector ($\sim 1 - -10$ μeV) and at the same time to be able to scan the mass range 2–3 times more rapidly than in the past.

The axion arises in particle theory from a mechanism introduced by Peccei and Quinn (PQ)[4] to ensure that the strong interactions conserve P and CP in spite of the fact that the standard model as a whole violates those symmetries. No violation has been observed; the upper limit on the neutron electric dipole moment requires fine tuning to 1 part in 10^9, resulting in the "strong CP problem." The light, pseudo-scalar particle which necessarily results from the PQ mechanism is the axion.[5] Particle theory leaves the value of the axion mass, m_a, arbitrary. All of the couplings of the axion are proportional to m_a, so that a very light axion is also very weakly coupled to other particles and fields.[24, 25] However, astrophysical/cosmological considerations and laboratory searches do constrain these quantities. The constraints from SN1987a[13] and from searches for the axion in high-energy and nuclear physics experiments[26] rule out $m_a > 10^{-2}$ eV. In addition, cosmology places a *lower limit* on m_a of order 10^{-6} eV by requiring that axions do not overclose the universe.[10–12]

Axions are non-relativistic from the moment of their production during the QCD phase transition, making them cold dark matter (CDM). Studies of the cosmic microwave background anisotropy and of large-scale structure formation strongly imply that the dominant fraction of the energy density of the universe is in cold dark matter. There is good reason to believe also that CDM (either axions or WIMPs) is the constituent matter of galactic halos.[27]

There are large uncertainties in the relationship between Ω_a and m_a. Assuming standard concordance cosmology and that inflation happens before the PQ phase transition, the most likely value of the axion mass for which $\Omega_a = 0.23$ is 1.5×10^{-5} eV. This estimate includes the contributions from vacuum realignment, string decay, and wall decay. If inflation happens after the PQ phase transition, the most likely value of the axion mass for which $\Omega_a = 0.23$ is $m_a \sim 3 \times 10^{-6}$ eV. In this case there is no contribution from string or wall decay, but only a vacuum realignment contribution.

Superstring theories generally predict the existence of axion-like particles, one of which would be the QCD axion discussed here. Many superstring theories prefer lighter axions, in the neV range or smaller, although Witten and Svrcek[28] have shown that in some superstring theories the axion mass can be larger than this.

A number of years ago, Ipser and Sikivie[29] discussed the extent to which the phase-space distribution of cold dark matter particles is thermalized in a galactic halo and concluded that many dark matter particles are in distinct flows, with each of these flows producing a peak in the local velocity distribution. Figure 1 shows a cartoon of infalling dark matter. The cold dark matter particles fall from the surrounding space into the galaxy. Those falling into the galaxy for the first time reach the detector with a specific velocity vector and give a narrow peak in the detector response. Other peaks that would be observed are due to particles falling out of the galaxy for the first time, particles falling into the galaxy for the second time, etc. The peaks due to particles that have fallen in and out of the galaxy a large number of times in the past are washed out because of scattering in the gravitational wells of stars, globular clusters and large molecular clouds. But the peaks due to particles which have fallen in and out of the galaxy only a small number of times in the past are not washed out.

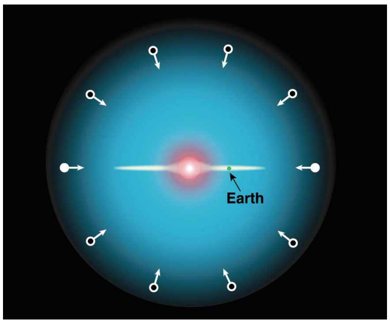


Figure 1: Infall of dark matter into the galaxy. Particles falling in for the first time arrive at the Earth with a well-defined velocity.

If the fraction of the local dark matter density which is in these velocity peaks is sufficiently large, a direct dark matter search may be made more sensitive by having it look specifically for sharp peaks in the energy spectrum. Moreover, it has been pointed out[30] that one or more peaks may be further enhanced because the sun lies close to a caustic ring in the dark matter distribution. In a fit[31] of caustic rings to the galactic rotation curve, it is found that the local density is dominated by a single flow, called the "Big Flow." ADMX has incorporated a high-resolution spectrometer to search for such fine structure in the energy spectrum of axion dark matter.

It was shown recently[32] that cold dark-matter axions must form a Bose-Einstein condensate as a result of their gravitational self-interactions when the photon temperature is of order 500 eV. This result has produced an argument that at least part of the dark matter is axions. The argument has three steps. First, axions behave differently from other dark-matter candidates because a rethermalizing axion BEC tracks the lowest-energy available state. Second, there is a tool to distinguish a BEC from other forms of dark matter on the band of observation, namely the study of the axion caustics of galactic halos. Third, the observational evidence for caustic rings of dark matter is consistent in every aspect with axion BEC, but not with other forms of dark matter.[33]

The ADMX detector is meter-scale cylindrical electromagnetic cavity permeated by a ~ 8 T static magnetic field $\vec{B}_0$. On resonance halo axions can convert to quanta of excitation (photons) of that cavity mode. Only the $\mathrm{TM}_{n\ell 0}$ modes couple in the limit where the cavity is much smaller than the de Broglie wavelength. The signal is proportional to g_γ, the coupling strength of the axion to two photons. The value $g_\gamma = 0.36$ is predicted by the Dine-Fischler-Srednicki-

Zhitnitskii (DFSZ) model.[24] In all other models that have been put forth, the magnitude of g_γ is predicted to be larger than 0.36. For example, $g_\gamma = -0.97$ in the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model.[25]

Modes that can be used for the search are those with form factors $C_{n\ell 0} \neq 0$, those for which the integral of $\vec{E} \cdot \vec{B}_0$ is finite. $C_{n\ell 0}$ is 0.69 for the lowest (TM_{010}) mode and 0.12 for the next (TM_{020}) mode. This decrease in form factor is partially offset by the higher power emitted at the 2.3× higher frequency of the TM_{020} mode, making the ratio of signal powers $P_{020}/P_{010} = 0.41$.

The signal to noise ratio (and search rate) is determined by a thermal and technical background, described by T_n, the sum of the physical temperature of the cavity plus the excess-noise temperature of the microwave receiver. The search rate goes $1/T_n^2$ and both background and technical noise are found[21, 23] to be linear in the physical temperature T, with $T_n \approx 2T$.

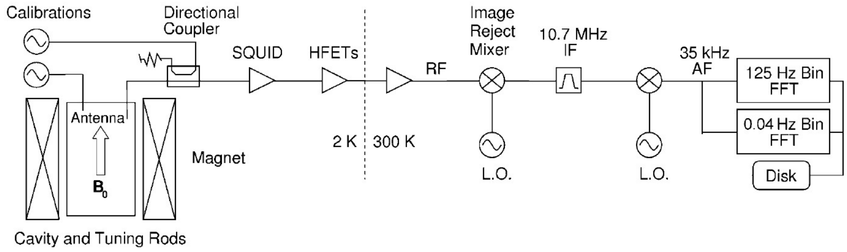


Figure 2: Schematic diagram of the axion detector.

The Axion Dark-Matter eXperiment (ADMX) experiment[20] has placed meaningful limits on axion couplings and densities.[34–39] Figure 2 is a schematic diagram of the axion detector in its present configuration.[21, 23] The magnet is a superconducting solenoid with 7.6 T central field. The cylindrical cavity (50 cm diameter, 100 cm length) has a resonant frequency tunable over 460–860 MHz. The cavity is tuned by moving metallic tuning rods, which run the full length of the cavity, between the wall and center. Initially, the first-stage preamplifiers in the receiver were balanced GaAs high electron mobility transistor (HEMT) with noise temperature $T_n \sim 2.5$ K. These have been replaced by SQUID amplifiers in the phase I upgrade of the experiment.

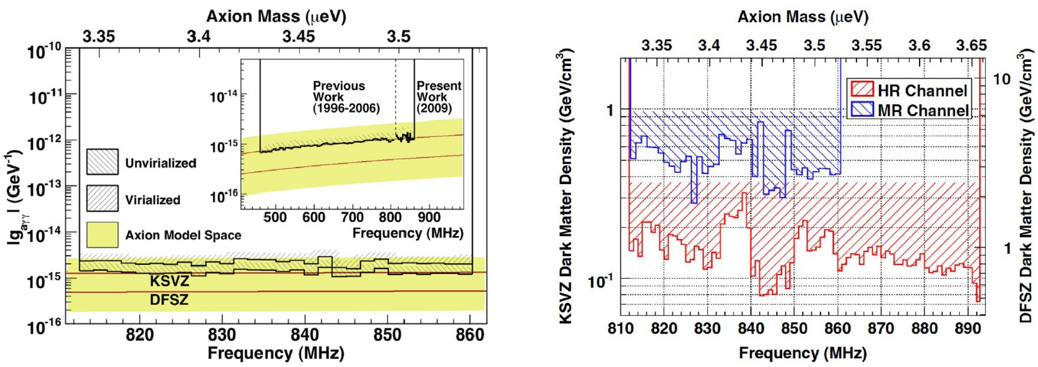
The preamplifiers are followed by additional amplification, after which the signal is converted to the 10.7 MHz intermediate frequency by an image-rejection mixer. An 8-pole crystal filter sets the 30 kHz measurement bandwidth and prevents image power from entering the second mixing stage. The signal is then mixed down a second time, in effect shifting the cavity resonant frequency to 35 kHz. A commercial FFT spectrum analyzer then generates the “medium-resolution” power spectrum, an average of 10^4 spectra at 125 Hz resolution. This resolution is well-matched to a search for the Maxwellian component of the halo, which should be about 6 channels wide.

The analog signal is also processed by a second “high resolution” data analysis channel. There is no averaging; instead, a commercial ADC/DSP PC board acquires and computes one 2,500,000 point, 0.04 Hz/point power spectrum. The resolution is well matched to a search for fine structure having fractional width $\sim 0(10^{-11})$ or less in the power spectrum.

The Phase I upgrade installed superconducting quantum interference device (SQUID) amplifiers[22] as the front end of the receiver. Phase I construction and commissioning took place over 2004–2007, with first cooldown of the insert in fall 2007 and completion of commissioning in early 2008. The Phase I data run scanned the 3.3–3.5 μeV range.[23] It demonstrated that SQUID amplifiers can be produced which (with proper magnetic shielding) function in the high magnetic field environment of the experiment. In addition, the amplifiers can be coupled to the axion cavity, provide adequate gain so that the system noise is the physical noise from the cavity in series with the modest noise from the amplifiers themselves, and can deliver the signal to an automated data acquisition system.

Phase II has recently begun. It will upgrade the cryogenics with (first) a ^{3}He refrigerator (reducing the physical temperature to $\sim$ 400 mK) and then with a dilution refrigerator, (reaching $\sim$ 100 mK). We expect total background (system) noise temperatures to be 50–100% higher than the physical temperature. In addition to reducing the physical and noise temperatures, Phase II will add a receiver second channel to search the TM_{020} in parallel with the TM_{010} mode. Both modes tune in a similar way as the tuning rods are moved. Using metal tuning rods, the collaboration estimates that we will be able to search for axions in the 1.7–3.7 μeV (400–900 MHz) using the TM_{010} mode while *at the same time* scanning 3.7–8.7 μeV (900–2100 MHz) with the TM_{020} mode. The higher frequency search is expected to exceed the sensitivity required to detect DFSZ axions[24] by a small amount; the lower frequency search will exceed this limit by nearly an order of magnitude.

Figure 3 shows the axion couplings and masses excluded at the 90% confidence level by ADMX at the end of the Phase I data run.[23] The inset shows the results of earlier experiments. [34–37] The plot in the right panel shows the axion-to-photon coupling $g_{a\gamma\gamma}$ as a function of the axion mass $m_a = hf/c^2$. ADMX is the first experiment to exclude a realistic axion model: KSVZ axions of mass between 1.9 and 3.55 μeV. If a significant fraction of halo axions are distributed in a few narrow peaks, weaker axion two-photon couplings are excluded.[38–40] (left panel).



(a) (b)

Figure 3: a) Axion couplings and masses excluded at the 90% confidence level by the experiment. The R.F. frequency range is 460–860 MHz. (b) Axion density limits for axions with velocity dispersion less than $3 \times 10^{-6}c$ from 812 MHz to 892.8 MHz. The scale for predictions of the KSVZ and DFSZ models are shown on the left and right axes, respectively. The limit is below the KSVZ prediction. Density limits for the medium resolution channel (for axions with velocity dispersion less than $2 \times 10^{-4}c$) are also shown.

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