UCRL-PROC-225847

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Finding the Axion: The Search for the Dark Matter of the Universe

G. Carosi

November 3, 2006

Balkan Physical Union 6th International Conference
Istanbul, Turkey
August 22, 2006 through August 26, 2006

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Updated October 14, 2003

Finding the Axion: The Search for the Dark Matter of the Universe

G. Carosi

LLNL, L-270, 7000 East Ave, Livermore, CA, USA, 94550

Abstract. The nature of dark matter has been a mystery for over 70 years. One plausible candidate is the axion, an extremely light and weakly interacting particle, which results from the Peccei-Quinn solution to the strong CP problem. In this proceedings I will briefly review the evidence for dark matter as well as the motivation for the existence of the axion as a prime dark matter candidate. I will then discuss the experimental methods to search for axion dark matter focusing on a sensitive cavity experiment (ADMX) being run at Lawrence Livermore National Laboratory.

Keywords: Document processing, Class file writing, LaTeX 2_ε
PACS: 43.35.Ei, 78.60.Mq

DARK MATTER AND THE AXION

Dark matter was first observed by Fritz Zwicky in the 1930s when he noticed that member galaxies of the Coma cluster had velocities too high to be gravitationally bound by the cluster's luminous matter alone [1]. There had to be an additional "dark matter" component which did not interact appreciably with photons, leptons or baryons. Since then evidence for dark matter has accumulated on scales as small as dwarf galaxies (kiloparsecs)[2] to the size of the observable universe (Gigaparsecs)[3] and is now thought to make up 22% of the energy density in the universe.

Currently the best candidates for dark matter appear to be undiscovered non-baryonic particles left over from the big bang[1]. Studies of structure formation require that these candidates be "cold", i.e. non-relativistic at the beginning of galactic formation, otherwise they would have smoothed out initial density perturbations in the early universe. Observations of the Milky Way constrain the local dark matter halo density to be roughly $\rho_{CDM} \approx 0.45$ GeV/cm^3 [6].

The two most popular dark matter candidates are the general class of Weakly Interacting Massive Particles (WIMPs), one example being the supersymmetric neutralino, and the axion, predicted as a solution to the "Strong CP" problem. This discussion will focus exclusively on the axion. The axion is a light pseudo-scalar boson (negative parity, spin-zero particle) predicted from the breaking of the Peccei-Quinn symmetry. This symmetry was originally introduced in the late 1970s to explain why charge (C) and parity (P) appear to be conserved in strong interactions, even though the QCD Lagrangian has an explicitly CP violating term. Experimentally this term should lead to an easily detectable electric dipole moment in the neutron but none has been observed to very high precision [7]. It was realized that the axion would be produced in large amounts, via a non-thermal mechanism, in the early universe making it an ideal cold dark matter candidate.

The key parameter defining most of the axions characteristics is the spontaneous symmetry breaking (SSB) scale of the Peccei-Quinn symmetry, f_a, which defines the axion mass (m_a) as

$$m_a \simeq 0.6\, eV \left(\frac{10^7\, GeV}{f_a}\right) \tag{1}$$

and the axions coupling to photons as

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}. \tag{2}$$

The dimensionless model dependent parameter g_γ is thought to be ~ 0.97 for the class of axions denoted KSVZ (for Kim-Shifman-Vainshtein-Zakharov) and ~ -0.36 for the more pessimistic grand-unification-theory inspired DFSZ (for Dine-Fischler-Srednicki-Zhitnitshii) models. Since interactions are proportional to the square of the couplings these values of g_γ give an order of magnitude difference between axion to photon conversion rates of the two models. Given that heavier axions couple more strongly to photons limits have been placed on their upper mass ($m_a \leq 3meV$) from effects that would have been observed in super nova 1987a. Lighter axions, though, would have been produced in greater quantities

[1] Even without the limits from Big Bang Nucleosythesis searches for baryonic dark matter in cold gas clouds or MAssive Compact Halo Objects (MACHOs), like brown dwarfs, have not detected nearly enough to account for the majority of dark matter [4]. Attempts to modify the laws of gravity at larger scales have also had difficulties matching observations [5].

in the big bang putting a lower limit on the axion mass of $m_a \geq \mu eV$, lest the universe be overclosed with axions.

Today the axion dark matter in the galaxy would consist of a large halo of particles moving with relative velocities of order $10^{-3}c$. In addition to thermalized axions it's possible that a non-thermalized component could still be oscillating into and out of the galaxy's gravitational well. These axions would have extraordinarily tiny velocity dispersions (of order $10^{-17}c$) [8] and the differences in velocity from various infalls could shed light on the history of the galaxy.

AXION DETECTION EXPERIMENTS

Currently all axion detection experiments utilize the coupling of axions to two photons (the Primakoff Effect) given by

$$L_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} \tag{3}$$

where $\vec{E}$ and $\vec{B}$ are the standard electric and magnetic field, α is the fine structure constant and g_γ is the model dependent coefficient mentioned earlier [9]. The free space lifetime for an axion to decay into two photons is irrelevantly long (10^{50} seconds for a 1 μeV axion) so most experiments utilize a strong magnetic field to provide a source of virtual photons that an axion can scatter off of and convert into a real photon. This photon then carries the entire energy of the converted axion. Essentially all ongoing axion experiments come in three categories. Microwave cavity experiments look for low mass axions (relevant for dark matter) to resonantly convert into microwaves and be detected by sensitive receivers (ADMX) or single-photon Rydberg atom detectors (CARRACK). Solar observatories look for much higher coupling axions that would be produced in the sun and either pass through a dipole magnet and convert to X-rays (CAST) or be seen in Germanium detectors. Finally there is the general class of lab experiments which use lasers to convert photons to axions in a magnetic field. This can either be detected as changes in the polarization of the laser or the axions can travel through a wall and be reconverted to photons on the other side (photon regeneration experiments) [10]. For the rest of this talk I will focus on the microwave cavity searches.

THE ADMX EXPERIMENT

The basic concept of the ADMX experiment was first outlined by Pierre Sikivie in 1983 [11]. He observed that axions whose mass matched the resonant frequency of a microwave cavity permeated by an axial magnetic field could resonantly convert into photons. The predicted halo axion velocities of order $\beta = 10^{-3}$ predict a spread in the axion energy, from $E_a = m_a c^2 + \frac{1}{2}m_a c^2\beta^2$, of order 10^{-6}. For 5 μeV axions this would translate into converted photons at 1.2 GHz with a frequency spread of 1.2 kHz. The power of axions converting to photons on resonance in a microwave cavity is given by

$$P_a = \left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right)^2 V B_0^2 \rho_a C_{lmn} \frac{1}{m_a} Min\left(Q_L, Q_a\right) \tag{4}$$

where V is the cavity volume, B_0 is the magnetic field, Q_L is the cavity's loaded quality factor (defined as center frequency over frequency bandwidth), $Q_a = 10^6$ is the quality factor of the axion signal (axion energy over spread in energy or $1/\beta^2$), ρ_a is the axion mass density at the detection point (earth) and C_{lmn} is the form factor for one of the transverse magnetic (TM_{lmn}) cavity modes. This form factor is essentially the percent of the cavity volume in which the external static magnetic field $\vec{B}_0(\vec{x})$ overlaps with that mode's oscillating electric field $\vec{E}_\omega(\vec{x})e^{i\omega t}$. For a cylindrical cavity with a homogeneous longitudinal magnetic field the TM_{010} mode provides the largest form factor ($C_{010} = 0.69$) [9]. Expected power levels from axion-to-photon conversions are an extremely tiny $\sim 10^{-22}$ Watts.

First generation microwave cavity experiments were carried out at Brookhaven National Laboratory (BNL) [12] and at the University of Florida [13] in the mid 1980s and got within factors of 100 - 1000 of the sensitivity required to detect plausible dark matter axions [9]. ADMX was designed with much quieter receiver electronics and a larger cavity volume in order to look at the lowest mass axions (most interesting dark matter candidates). A schematic of ADMX can be seen in figure 1. The experiment consists of a cylindrical copper-plated steel cavity containing two axial tuning rods. These can be moved transversely from the edge of the cavity wall to its center allowing one to perturb the resonant frequency. Metallic rods raise the cavity frequency while dielectric rods lower it. The cavity itself is located in the bore of a superconducting solenoid providing a strong constant axial magnetic field. The electromagnetic field of the cavity is coupled to low-noise receiver electronics via a small adjustable antenna[9]. These electronics initially amplify the signal using two ultra-low noise cryogenic amplifiers arranged in series. The signal is then boosted again via a room temperature post-amplifier and injected into a double-heterodyne receiver. The receiver consists of an image reject mixer to reduce the signal frequency from the cavity resonance (hundreds of MHz - GHz) to an intermediate frequency (IF) of 10.7 MHz. A crystal bandpass filter is then employed to reject noise power outside of a 35 kHz window centered at the IF. Finally the sig-

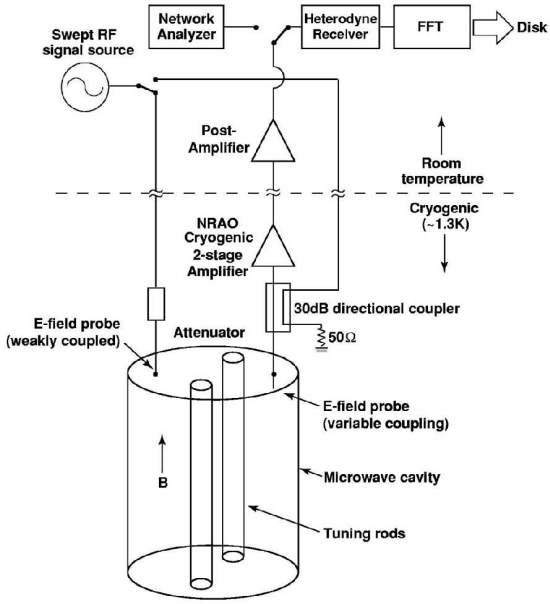

FIGURE 1. Schematic diagram of ADMX experiment including both the resonant cavity (which sits in the bore of a superconducting solenoid) and receiver electronics chain.

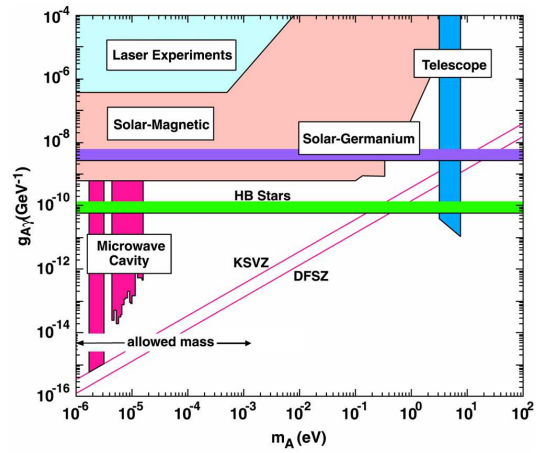

FIGURE 2. Combined exclusion limits for various experiments. The ADMX results can be seen to have reached the sensitivity of the KSVZ axion models at the lowest mass range.

nal is mixed down to almost audio frequencies (35 kHz) and analyzed by fast-Fourier-transform (FFT) electronics which compute the 50 kHz bandwidth centered at 35 kHz into 400 bins with 125 Hz width. The FFT takes 10,000 8 msec samples which are then co-added giving a total exposure time of 80 seconds per tuning rod position. Since the tuning rods are only moved 1 kHz at a time each frequency bin appears in a number of sub-spectra and they are multiplied by the detector response function and co-added yielding roughly a 25 minute exposure for each frequency bin. This is referred to as the medium resolution channel. An additional high resolution channel takes the 35 kHz audio signal and sends it through an LC filter with a 6.5 kHz passband before amplifying and mixing the signal down to a 5 kHz center frequency. This signal is then sampled at 20 kHz for 53 seconds before being sent to a FFT which produces a power spectrum with 19 mHz resolution.

The medium resolution analysis is carried out using two methods. The first is a single bin analysis in which 125 Hz bins are selected if their power is greater than an initial threshold. These selected bins are then rescanned to the see if the signal persists. Each is then checked to see if the signal is the result of external radio interference. The second method is a six-bin analysis used to search for thermalized axions. Here candidates are kept if all six adjacent bins are above a specified threshold. The analysis then proceeds the same way as the single bin analysis. The high resolution analysis follows a similar method in which n-bin searches are also performed where n =1,2,4,8,64,512, and 4096 adjacent combined 19 mHz bins. Here care must be taken rescanning a candidate as the frequency will have shifted from the Doppler effect of the earth's rotation and orbit. If a signal is seen in either channel that can't be identified with an external source a simple check would be to see if the signal persists when the magnet is turned off. If it does not that is a strong indicator that axions are involved.

So far no axions have been detected in any experiment. ADMX currently provides the best limits from microwave cavity experiments in the lowest mass range (most plausible if axions are the major component to the dark matter). Results from both the medium and high resolution channels, as well as other experiments, can been seen in figure 2.

FUTURE DEVELOPMENTS

In order to carry out a definitive axion dark matter search experiments need to become sensitive enough to detect even the most pessimistic axion couplings (DFSZ) at fractional halo densities while quickly scanning over the potential mass range (up to hundreds of GHz).

To determine the best improvement strategy one can use the Dicke radiometer equation [14] which defines the signal-to-noise in an experiment as

$$SNR = \frac{P_a}{\bar{P}_N}\sqrt{Bt} = \frac{P_a}{k_B T_S}\sqrt{\frac{t}{B}}. \qquad (5)$$

Here P_a is the axion conversion power, $\bar{P}_N = k_B B T_S$ is the average thermal noise power, B is the bandwidth, T_S is the total system noise temperature (cavity plus elec-

Stage	ADMX Now	Phase I	Phase II
Technology	HEMT; Pumped LHe	Replace w. SQUID	Add Fridge
T_{phys}	1.3 K	1.3 K	100 mK
T_{amp}	2	0.4	100
$T_{sys} = T_{phys} + T_{amp}$	3.3	1.7	200
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ **OR**	5 @ DFSZ **AND !**
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	0.5 x KSVZ	DFSZ

FIGURE 3. Current and upgrade phases of ADMX.

tronics) and t is the signal integration time [9]. With the bandwidth of the experiment essentially set by the axion mass and anticipated velocity dispersion ($\beta^2 \sim 10^{-6}$) the SNR can be raised by either increasing the signal power ($P_a \propto B_0^2 V$), lowering the noise temperature or integrating for a longer time. Increasing the magnetic field or the cavity volume can get prohibitively expensive fairly quickly. Given the large range of possible masses the integration time needs to remain relatively short (of order 100 seconds integration for every kHz) in order to scan an appreciable amount in a year or so. As a result attention has focused on developing ultra-low noise amplifiers to lower the receiver's noise temperature.

The sensitivity of ADMX is currently limited by the noise in the first stage cryogenic HFET amplifiers. Even though they have a noise temperature under 2 K the quantum limit (defined as $T_Q \sim h\nu/k$) is almost two orders of magnitude lower (25 mK at 500 MHz). As a result SQUID (Superconducting Quantum Interference Device) amplifiers have been developed which have noise temperatures that can get within 30 % of the quantum limit and can be tuned to the resonant frequency of the cavity. These amplifiers are currently being installed in an upgrade to ADMX. Since the SQUIDs are ultra-sensitive to magnetic fields an additional superconducting magnet has being installed above the cavity to negate the magnetic field from the main magnet. This upgrade is anticipated to be completed by the beginning of 2007 with data taking starting a few months later. The first phase will scan between 800 - 900 MHz and be sensitive enough to detect axions with half the coupling strength of the KSVZ models. The next phase of operations envisions using a dilution refrigerator to get the current operating temperatures down from 1.4 K (pumped LHe) to 100 mK and will be sensitive to DFSZ couplings with 5 times the current scanning speed. The various ADMX phases are outlined in figure 3.

While ADMX runs under the upgraded configurations R&D efforts will be underway to develop the technology for higher mass axion searches. Since the cavity frequency is directly related to its size techniques are being developed to combine the signals from multiple smaller cavities as well as from cavities with arrays of metallic rods inserted vertically. Additional SQUID geometries, such as "in-line" SQUIDs, are also being developed to reach the 10s of GHz range.

SUMMARY, CONCLUSIONS

Discovery of the axion would not only solve the Strong-CP problem and perhaps the nature of dark matter but could offer a new window into astrophysics, cosmology and quantum physics. Details of the axion spectrum, especially if fine structure is found, could provide new information of how the Milky Way was formed. The large size of the axions de Broglie wavelength ($\lambda_a \sim 10m - 100m$) could even allow for interesting quantum experiments to be performed at macroscopic scales. These possibilities combined with the limited axion parameter space, much of which within reach of current or near future technology, make the axion an exciting dark matter candidate.

ACKNOWLEDGMENTS

This work was supported under the auspices of the U.S. Department of Energy under Contract W-7405-Eng-48 at Lawrence Livermore National Laboratory.

REFERENCES

1. F. Zwicky, *Helvetica Physica Acta* **6**, 110–127 (1933).
2. G. Jungman, M. Kamionkowski, and K. Griest, *Phys. Reports* **267**, 195–373 (1996).
3. D. S. et. al., *ApJ Supplement Series* **148**, 175–194 (2003).
4. C. A. et. al., *ApJ* **542**, 281–307 (2000).
5. J. T. K. et. al., *ApJ Letters* **563**, 115–118 (2001).
6. E. I. Gates, G. Gyuk, and M. S. Turner, *ApJ Letters* **449**, 123–126 (1995).
7. P. H. et. al., *Phys. Rev. Letters* **82**, 904–907 (1999).
8. P. Sikivie, *Phys. Letters B* **567**, 1–8 (2003).
9. R. B. et. al., *Rev. of Mod. Phys.* **75**, 777–817 (2003).
10. S. A. et. al., *Annu. Rev. Nucl. Part. Sci.* **56**, 293–326 (2006).
11. P. Sikivie, *Phys. Rev. Letters* **51**, 1415–1417 (1983).
12. S. D. et. al., *Phys. Rev. Letters* **59**, 839–842 (1987).
13. C. H. et. al., *Phys. Rev. D* **42**, 1297–1300 (1990).
14. R. Dicke, *The Rev. of Sci. Instr.* **17**, 268–275 (1946).