A Search for Halo Axions

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A SEARCH FOR HALO AXIONS

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A collaboration of MIT, LLNL, Univ. of Florida, FNAL, UC Berkeley and INR Moscow have built a large-scale RF cavity axion detector. The experiment has been taking production data since February of 1996 and is sensitive enough to detect plausible dark matter axions comprising a reasonable fraction of the mass in our galactic halo. After a brief introduction to axion physics, I discuss details of our instrumentation, our analysis methodology, our run plan and future goals of the experiment.

1. Introduction

Axions result from the solution to the strong CP problem first proposed by Peccei and Quinn [1,2] in the late 1970s. Their solution forces CP conservation in the strong interactions through the introduction of a new U(1) symmetry of QCD which is broken at an unknown energy scale f_PQ. The axion is the pseudo-Goldstone boson resulting from the symmetry breaking. If axions exist, enough would have been produced shortly after the big bang at the energy scale f_PQ to make relic axions a good cold dark matter candidate. The axion mass and all of its couplings are inversely proportional to f_PQ, and although theory does not supply a prediction for f_PQ, observational evidence from cosmology and astrophysics has constrained the axion mass to a range of 10^{-6} - 10^{-3} eV. The lower bound arises from requiring that axions not overclose the universe, the upper bound from the effect that axion cooling would have had on the neutrino pulse from SN1987A. At masses below about 10^{-5} eV, the density of axions would be sufficient to close the universe and solve the dark matter problem.

2. Experimental Method

Our axion detector is based on the resonant cavity detection scheme first proposed by Sikivie [3]. The experiment has been described in detail elsewhere [4]. Figure 1a is a diagram of the axion detector. The axion has the same spin-parity as a neutral pion, hence it has a coupling to two photons (figure 1b). In our experiment, one of the photons is provided by a static 7.6T magnetic field, with which a halo axion can 'collide', producing a second photon (similar to the decay of a neutral pion into a photon in the electric field of a nucleus). The magnetic field threads a tunable high Q cavity in which the final state photons resonate when the cavity resonant frequency v is related to the axion mass m by hv=mc^2.
To Roots Blower

Cryostat vessel

Liquid Helium reservoir for microwave cavities

Liquid Helium reservoir for magnet

Amplifiers + RF mixers, cooled to 1.3 Kelvin.

Frequency tuning mechanism

The copper RF - Cavity is at about 1 torr Helium gas

Sapphire tuning rod

Metal tuning rod

Superconducting magnet coil, 60cm ID, 110cm long
8.5 Tesla field at 4.2 Kelvin
Weight: 6 tons.

figure 1a

figure 1b
If axions are an appreciable fraction of the dark matter in our galactic halo, their density at our detector is large enough that photons from axion decays are detectable as excess noise in the cavity over a bandwidth of about 700Hz, for v=700MHz. This noise is detected using an electric field probe which critically couples the cavity TM$_{010}$ mode to ultra-low-noise electronics. Figure 2 is a schematic of the cavity coupled to the receiver electronics.

Noise and possible signal from around the cavity resonant frequency is amplified and mixed down to audio frequencies in a double heterodyne receiver designed and built at MIT, and a power spectrum of the noise is produced using fast-Fourier-transform hardware. The axion signal is excess power in a few adjacent bins of a power spectrum taken at a cavity resonant frequency corresponding to the axion mass.

3. Data Analysis

Figure 3 shows a single power spectrum from our data set. Each power spectrum has 400 125Hz wide bins. The centre bin is at the frequency of the cavity TM$_{010}$ resonance. The steep sides of the power spectrum around bins 70 and 320 are the edges of the passband of a bandwidth-critical crystal filter in the receiver. The inset is a magnified section of the power spectrum. Notice that the average power level is
a slowly varying function of frequency. This modulation is due to ripple in the transfer function of the crystal filter and the variation in the effective impedance of the cavity across the resonance. The fluctuations about the average power are Gaussian distributed. The rms of the fluctuations drops as the square root of the integration time over which the power spectrum was taken and as the square root of the bin width, by the Dicke radiometer equation. If axion decays were present, positive fluctuations would be seen in several neighboring bins, on top of the Gaussian background noise from the detector. The signal from axions is stronger if it appears near the centre of a power spectrum than near the edges, since the frequency of the decay photons are closer to the cavity resonant frequency.

A Single Power Spectrum from the Raw Data

After a power spectrum is taken, a tuning rod is moved, altering the cavity resonant frequency, then the next power spectrum is taken. To ensure that our sensitivity is uniform across frequency, there is considerable overlap between the frequency ranges covered in successive power spectra. Figure 4 is a plot of several power spectra taken in succession.

This overlap means that several power spectra will contain a signal from axion to photon conversion. We must therefore combine the raw spectra into a single table of power per 125Hz bin vs frequency in a manner which maximizes the signal to noise ratio in the combined data. We have developed an algorithm which yields a
combined data set with an optimized signal to noise ratio at each frequency which is consistent with our total integration time at that frequency and the noise temperature of our detector. Figure 5 (1st plot) is an example of this combined data.

Adjacent Raw Spectra from Axion Experiment Data

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Relative Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>658.98</td>
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<tr>
<td>658.99</td>
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<tr>
<td>659.00</td>
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<td>659.01</td>
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<td>659.04</td>
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</tr>
<tr>
<td>659.05</td>
<td></td>
</tr>
<tr>
<td>659.06</td>
<td></td>
</tr>
</tbody>
</table>

Each point represents the fluctuation about average power in a 125Hz bin with contributions from many raw power spectra. For clarity, only every 20th bin is plotted, so there are about 18,000 points plotted in this 45MHz frequency interval. The gaps in the combined data represent mode crossings; these gaps are filled later in the run. Figure 5 (2nd plot) is the cavity resonant frequency as a function of time during the data taking. Notice from the 1st plot that at frequencies below 665MHz, the rms of the points is larger than in the rest of the frequency interval. Referring to the 2nd plot, notice that we only swept this frequency region once. In fact, this scan was a test run at the start of data taking, hence the large rms scatter and correspondingly low sensitivity. An axion signal at a power level of $2 \times 10^{-22}W$ in a single bin would be easily discernible against the noise background at 685MHz; at 660MHz it would be indistinguishable from a positive fluctuation in the thermal noise. This is how our sensitivity is linked to the noise temperature of our electronics and integration time. Longer integration time or a lower noise temperature lead to smaller rms noise fluctuations and greater sensitivity to axion signals.
4. The Axion Signal

The signature for axion decay in our combined data is a narrow peak at frequency $v$ where $hv = mc^2$ and $m$ is the axion mass. This excess power is due to photons from...
axion decay in the presence of the magnetic field. The shape and width of this peak is model dependent; one popular model is that proposed by Turner [5] and others. This model suggests that axions produced as a cold gas at the time of the QCD phase transition should since have fallen towards the centres of galaxies and have become thermalized in the galactic gravitational potential. The fractional axion line width will be $(v/c)^2$ where $v$ is the axion virial velocity. In our neighborhood, this virial velocity is $\sim 10^3c$, so the line width is $\sim 10^{-6}$. Figure 5 is a plot of the predicted line shape in the Turner model, for $v=700\text{MHz}$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Graphical representation of the predicted line shape in the Turner model.}
\end{figure}

5. Experimental Sensitivity

The sensitivity of our experiment is set by thermal noise fluctuations in the combined data (see figure 4). The smaller the fluctuations, the smaller the power excess signal indicating axion decay that will be discernible amongst them. The size of these fluctuations are determined by 1) the noise temperature of our cavity and electronics and 2) the integration time over which the power spectrum was taken. The experiment has been taking production data for almost a year. The data from this first run allows us to search for KSVZ [6] axions in the mass range 2.8-3.3\text{meV}. Figure 6 is a typical section of our combined data to which I have added a fake 'axion' peak. The total power in the peak is that which we calculate would be present in our detector for KSVZ axions. The shape of the peak is that of the Turner model. The axion signal is easily discernible in the presence of the background thermal noise.
6. Plan for our Current Data Taking Run

First, we must step through cavity resonant frequency from 670 to 800MHz and generate the combined data set for this frequency range. This process is now complete. In this data set are gaps (see figure 5 plot 1) caused by mode crossings where the TM010 resonant frequency is near the resonant frequency of another mode. We have now filled in these gaps by running with the cavity filled with liquid helium, and are in the process of searching for candidates. One powerful search method is to look for power excess in 6 neighbouring bins of combined data. Each candidate peak is then re-scanned to see if the power excess persists. As a further test, the magnetic field is ramped down. For a peak due to axion decay the power should be modulated as the square of the B field. We have good enough sensitivity to either discover KSVZ axions in this mass range, or rule them out at 90% confidence or better.

7. Future Goals of the Axion Search Experiment

During our first data run we have searched for axions in the mass range 2.8-3.3μeV. The detector is sensitive to KSVZ axions assuming a halo density consistent with the predictions of established cosmological models [6]. The hatched region in figure 8 represents the range of axion masses and couplings for which we have almost completed data taking, and on which we will submit our findings for publication in
early 1997. Also indicated on figure 8 are the areas of the parameter space which were excluded in the pilot experiments at the University of Florida [7] and Brookhaven [8]. The boxed region between masses of 1.3 and 13\mu eV represents the parameter space to be explored at our current sensitivity or better using our present receiver electronics with a noise temperature of 3.5-6K.

![Cosmic Axion Exclusion Plot](image)

In addition, the collaboration is committed to research into ultra-low-noise RF amplifiers designed around DC SQUIDs. Prototypes of such amplifiers operating around 100MHz have demonstrated noise temperatures as low as 0.3K [9]. There is good reason to believe that this type of performance might be reproducible at higher frequencies. This improvement in noise temperature would increase our sensitivity by a factor of about 10, allowing us to probe even the most feebly coupled axion models in the mass range important for axion cold dark matter.

Figure 9 (next page) is a schematic of a DC SQUID, and its current-voltage characteristic. A constant DC current \( I_B \) biases the Josephson junction pair at close to their critical current \( I_C \). An RF signal in the input coil causes an additional circulating current around the SQUID ring, effectively modulating the critical current of the SQUID, \( I_C \). With \( I_B \) held fixed, the modulation in \( I_C \) causes modulation of the voltage \( V_{OUT} \) across the SQUID. Thus a small RF current through the input coil can lead to a large output voltage across the SQUID ring. The energy necessary for power gain is from the constant current source supplying the fixed bias current \( I_B \).
Our collaborators at UC Berkeley headed by Prof. J Clarke are in the process of fabricating and testing DC SQUIDS for use as an ultra-low-noise replacement for the HEMT amplifiers used in our current receiver electronics. First tests of the SQUIDS at RF frequencies will be underway within the next few months.

8. Conclusion

Due to space constraints, I have only very briefly outlined the current status of our axion search experiment. We have taken data for nearly a year, and analysis of this data is well underway. We should have our first limit on KSVZ axions by early 1997. The detector has achieved its design specifications and is running with a duty cycle in excess of 90%. We aim to cover the mass range 3-13µeV in a total of 3 years. Possible upgrades of the detector include use of DC SQUID amplifiers with greatly improved noise temperatures and 3He refrigeration with consequent improvement in sensitivity.

9. Acknowledgements

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*by LL/L

10. References
