Microwave Cavity Search for Axions

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Outline

• Brief review of the axion and its dark matter implications
• The Sikivie microwave cavity technique
• The Axion Dark-Matter Experiment (ADMX) – Results
• ADMX – Prospects
• Another approach to axion detection – Photon regeneration
• Summary
A brief review of the axion

- Peccei-Quinn mechanism for strong CP problem $\rightarrow a$
- Like an ultra-light, ultra-weakly interacting pion $\pi^0$
- Decays by two-photon emission $a \rightarrow \gamma\gamma$ (but $\tau > \tau_{\text{universe}}$)
- All couplings proportional to its mass: $g_{a\ii} \sim m_a$
- Abundance roughly inverse to mass: $\Omega_a \sim m_a^{-7/6}$
- Mass limits: $10^{-6} < m_a < 10^{-(2-3)}$ eV
  - (overclosure) (SN1987a)
- Galactic halos may consist of axions (Ipser/Sikivie, PRL 1983)
- At the Earth, $\rho = 0.45$ geV/cm$^3$
Evidence for dark matter: now very compelling

“The rotation curves [of all spiral galaxies] remain high even at large radii.”

Faber and Gallagher
ARAA 1979

Dynamics

NGC 3198

Lensing of background objects as a probe

“..."
The cosmological inventory is now well-delineated

- But we know neither what the “dark energy” or the “dark matter” is
- A cold particle relic from the Big Bang is strongly implied for DM
  — WIMPs?
  — Axions?
Present window for the axion mass

Very light axions forbidden: else too much dark matter

\( \Rightarrow \) Dark matter range: “axion window” very hard to detect “invisible axions”

Heavy axions forbidden: else new pion-like particle

A very light axion (\( \sim 10 \, \mu \text{eV} \)) would be an ideal dark-matter candidate
Cavity axion detector (Sikivie, 1983)

Resonance condition:
\[ h\nu = m_a c^2 [1 + O(\beta^2 \sim 10^{-6})] \]
Signal strength

- Power from the cavity is

\[
P = 2.3 \cdot 10^{-26} \text{Watt} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{Tesla}} \right)^2 C_{nl} \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.5 \cdot 10^{24} \text{g/cm}^3} \right) \left( \frac{m_a}{2\pi \text{GHz}} \right) \min(Q_L, Q_a)
\]

- \( Q_L \sim 10^5 \) and \( Q_a \sim 10^6 \)

- For KSVZ axions, \( g_\gamma \sim 0.97 \) ,[1] whereas for DFSZ axions \( g_\gamma \sim 0.36 \).[2]

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### ADMX hardware @ LLNL

**Magnet with Insert (side view)**

- Stepping motors
- Liquid helium
- Amplifier, refrigerator
- Tuner
- Tuning rods
- Superconducting magnet
  - 8T, 6 tons

**Pumped LHe → T ~ 1.5 k**

**Magnet (Wang NMR Inc.)**

- 8 T, 1 m × 60 cm ø
ADMX hardware (cont’d)

High-Q Cavity (~200,000)

Experimental Insert
Search spectrum

Electromagnetic Spectrum

Recent Axion Search

Frequency (Hz)

Wavelength

Long-waves
Radio TV
Microwaves
Infrared
Visible
Ultraviolet
X-Rays

10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
10^15

Long-waves
Radio TV
Microwaves
Infrared
Visible
Ultraviolet
X-Rays

10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
10^15

1000 m
100 m
10 m
1 cm
1 mm
100 μm
1 μm
1 nm
0.1 nm

micro-eV

TeV

APS@Jax -- Apr 2007

ADMX
Sample data and candidates

<table>
<thead>
<tr>
<th>Environmental</th>
<th>Statistical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subspectra</strong></td>
<td><strong>Subspectra</strong></td>
</tr>
<tr>
<td>Power</td>
<td>Power</td>
</tr>
<tr>
<td>775.72 - 775.77 MHz</td>
<td>772.11 - 772.17 MHz</td>
</tr>
</tbody>
</table>

**Signal maximizes off-resonance:** Radio peak

**Signal distributed over many sub-spectra:** a good threshold candidate (but did not persist in rescan)
Details of data acq. & analysis

- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

→ 6535 candidates > 2.25 \sqrt{\sigma} (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

For a persistent peak, the ultimate test is to turn off the magnet!
Limits on axion models and local axion halo density

**Particle Physics**

![Graph showing m_a (µeV) vs Frequency (MHz)]

- 6-bin analysis
- WF analysis

**Astrophysics**

![Graph showing m_a (µeV) vs Frequency (MHz)]

- DFSZ
- KSVZ

**References**

- PRL 80 (1998) 2043
- PRD 64 (2001) 092003
- PRD 69 (2004) 011101(R)


- RBF: PRL 59 (1987) 839
- UF: PRD 42 (1990) 1297
Could there be sharp features in the axion spectrum?

Late-infall axions pass through our position with specific velocities
Velocity spectrum of axions at our solar system

(a) No angular momentum
(b) Finite angular momentum

\[ E_k = \left( \frac{v_k}{300 \text{ km s}^{-1}} \right)^2 \]
Cavity axion detector (Sikivie, 1983)
High resolution data – $\delta f \sim 0.02$ Hz
Results of the high-resolution analysis

L Duffy et al., *PRL* 95, 091304 (2005); *PRD* 74, 012006 (2006).

Measured power in environmental (radio) peak is the same in Med- & Hi-Res
# ADMX upgrades

<table>
<thead>
<tr>
<th>Stage</th>
<th>ADMX Now</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>HEMT; Pumped LHe</td>
<td>Replace w. SQUID</td>
<td>Add Dil Fridge</td>
</tr>
<tr>
<td>$T_{\text{phys}}$</td>
<td>1.3 K</td>
<td>1.3 K</td>
<td>50 - 100 mK</td>
</tr>
<tr>
<td>$T_{\text{noise}}$</td>
<td>2 K</td>
<td>0.4 K</td>
<td>50 – 100 mK</td>
</tr>
<tr>
<td>$T_{\text{sys}} = T_{\text{phys}} + T_{\text{noise}}$</td>
<td>3.3 K</td>
<td>1.7 K</td>
<td>150 mK</td>
</tr>
<tr>
<td><strong>Scan Rate</strong></td>
<td>$1 @ \text{KSVZ}$</td>
<td>$4 @ \text{KSVZ}$</td>
<td>$10 @ \text{DFSZ}$</td>
</tr>
<tr>
<td>$\propto (T_{\text{sys}})^{-2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sensitivity Reach</strong></td>
<td>$1 x \text{KSVZ}$</td>
<td>$0.5 x \text{KSVZ}$</td>
<td>$0.3 x \text{DFSZ}$</td>
</tr>
<tr>
<td>$g^2 \propto T_{\text{sys}}$</td>
<td></td>
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</tr>
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</table>
“Phase I” upgrade: SQUID amplifiers

Presently the noise temperature of our HFET amplifier is $\sim 1.5K$

**But the quantum limit at 700 MHz is $\sim 33 \text{ mK}$**

Use SQUID amplifier -- a flux-to-voltage transducer

SQUID noise arises from Nyquist noise in shunt resistance - scales linearly with $T$

However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).
Microstrip SQUID amplifiers

More than an order of magnitude quieter than current GaAs HFET amplifier

Our latest SQUIDs are now within 15% of the Standard Quantum Limit
ADMX is in a Phase I upgrade
Addition of SQUID amplifiers: nearing completion

• A challenge: Zero-field region for the SQUID amplifiers
  – SQUIDS DO NOT LIKE MAGNETIC FIELDS
  – Needed “bucking coil” to reduce field in region of the superconducting electronics
  – Field is a few Gauss
  – Passive shielding can then take over
  – Must manage tons of force between opposed magnets
  – Designed, delivered by AMI, installed
Field-free region

Field cancellation coil

Force compensation coil

From outwards-in:
- Bucking coil
- Iron shield
- Cryoperm (mumetal) shields
- Superconducting shields
- SQUID amplifier package

• Compensation coil has 2 opposed windings
• Zero net force between compensation coil and main magnet
• Strain is in the single-piece mandrill on which these coils are wound
• Sensor/servo package minimizes field at center
• $|B_{\text{uncomp}}| \sim 4 \text{ kG}$, far below the 80 kG critical field of NbTi.
• Currents are manageable.
Phase I upgrade nearing completion

Field compensation magnet for SQUIDs

SQUID amplifier

New microwave cavity
Further upgrade and higher frequencies

Incorporate dilution fridge to reduce cavity temperature to 50 mK. (Phase II)

*To get to 10 GHz, and then 100 GHz*

--- Developing new SQUID geometries
--- Developing new RF cavity geometries
There are several experimental searches for axions

- ADMX
- PVLAS
- CAST
- Sun
- CERN
Purely laboratory experiments

**Polarization effects (e.g. PVLAS):**
Vacuum dichroism & birefringence

**Photon regeneration (JLAB and elsewhere):**
"Shining light through walls"

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Photon regeneration enhanced by cavities

(a) Laser
   \[ \gamma \]
   Wall
   Magnet
   \[ B_0 \]
   \[ L \]
   Photon Detector

(b) Laser
   IO
   Magnet
   \[ B_0 \]
   \[ L \]
   Photon Detectors
   Matched Fabry-Perots

P. Sikivie et al., *PRL, in press.*
Excluded $g_{a\gamma\gamma}$ vs. $m_a$
Summary and conclusions

- Peccei-Quinn symmetry remains a promising solution to the strong CP Problem; hence axions are an attractive dark-matter candidate.

- The parameter space where the axion lives is bounded.

- ADMX has scanned a factor of 2 in mass at a sensitivity within the band of model couplings.

- Current experiments are sensitive to realistic axion couplings and masses; they could see an axion at any time.

- Upgrades to ADMX will be sensitive to very feeble axion couplings and will either detect or rule-out Peccei-Quinn axions with $m_a$ in a decade centered around $10^{-5}$ eV.

- Lab experiments could also observe axions.

- This is an exciting time for axion searchers!
THE END