Korean Physical Society meeting

Ultrasensitive Searches for the Axion

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Monterey, California

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Outline

Some basics about the axion

Microwave-cavity searches for dark matter axions

Other axion searches

What if the axion be found?

(See Physics Today, August 2006, KvB & Les Rosenberg)
TSP’s* fine-tuning problem

*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)
TSP’s hypothesis, and first unsuccessful experiment
The key insight
A high-Q search for relic oscillations
The Axion

### The Strong-CP Problem

- $\mathcal{L}_{\text{QCD}} = \ldots + \frac{\theta}{32\pi^2} \, G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m.
  - $|d_n| < 10^{-25} \text{ e} \cdot \text{cm}$
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving

$$\text{CP} \left( \begin{array}{c} \mu_n \downarrow d_n \\ \uparrow -\mu_n \\ \downarrow d_n \end{array} \right) = \begin{array}{c} \text{neutron} \\ \neq \text{antineutron} \end{array}$$

- Why?

### Peccei-Quinn / Weinberg-Wilczek

- $\theta$ a dynamical variable
- $T = f_a$ spontaneous symmetry breaking
- $T \lesssim 1 \text{ GeV}$

$$V(\bar{\theta})$$

- $\bar{\theta}$ dynamically $\to 0$
- Remnant oscillation $= \text{Axion}$
Completing the analogy $f \leftrightarrow l$.

<table>
<thead>
<tr>
<th></th>
<th>PQ-symmetry breaking scale</th>
<th>Pendulum length</th>
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<tbody>
<tr>
<td><strong>Quanta</strong> $m_a (\omega)$</td>
<td>$\sim f^{-1}$</td>
<td>$\sim l^{-1/2}$</td>
</tr>
<tr>
<td><strong>Couplings</strong> $g_{a i i}$</td>
<td>$\sim f^{-1}$</td>
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</tr>
<tr>
<td><strong>Total energy</strong> $\Omega_a (E)$</td>
<td>$\sim f^{7/6}$</td>
<td>$\sim l$</td>
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**Diagram:**

- **Quanta** $m_a (\omega)$: $\sim f^{-1}$, $\sim l^{-1/2}$
- **Couplings** $g_{a i i}$: $\sim f^{-1}$, $\sim l^{-1}$
- **Total energy** $\Omega_a (E)$: $\sim f^{7/6}$, $\sim l$
Axion basics *(What you learn for free)*

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

One of the pioneers in the theory of the axion

Prof. Jihn E. Kim

Seoul National University

Thank you, Prof. Kim!
Axion-photon mixing provides the key  [P. Sikivie, PRL 51, 1415 (1983)]

$$L_{\text{int}} = a g_{a\gamma\gamma} E \cdot B$$

Coherent mixing of axions and photons over large spatial regions of strong magnetic fields (a sea of virtual photons) compensates for the extraordinarily small value of $g_{a\gamma\gamma}$

The Primakoff Effect

Classical EM field  $\equiv$  Sea of virtual photons  $\equiv$  Primakoff Effect

$\gamma^*$

Magnet

B
The microwave cavity experiment: Listening to dark matter
The cosmological inventory is now well-delineated

- But we know neither what the “dark energy” or the “dark matter” is

- A particle relic from the Big Bang is strongly implied for DM
  - WIMPs?
  - Axions?

![Pie chart showing the distribution of dark energy, dark matter, luminous matter, and other nonluminous components.]

- Dark energy (identity unknown) 73%
- Dark matter (identity unknown) 23%
- Other nonluminous components:
  - Intergalactic gas 3.6%
  - Neutrinos 0.1%
  - Supermassive BHs 0.04%
- Luminous matter:
  - Stars and luminous gas 0.4%
  - Radiation 0.005%
The Microwave Cavity Search for DM Axions (Pierre Sikivie, 1983)

\[ P_{\text{sig}} \propto (B^2 V Q_{\text{cav}})(g^2 m_a \rho_a) \sim 10^{-23} W \]

\[ s/n = \frac{P_{\text{sig}}}{kT_{\text{sys}}} \sqrt{\frac{t}{\Delta v}} \]
Axion Dark Matter eXperiment (ADMX)

University of California, Berkeley
John Clarke

University of Florida
Jeffrey Hoskins, Junseek Hwang, C. Martin, Pierre Sikivie, Neil Sullivan, David Tanner

Lawrence Livermore National Laboratory
Stephen Asztalos, Gianpaolo Carosi, Christian Hagmann, Darin Kinion, Karl van Bibber

National Radio Astronomical Observatory
Richard Bradley

University of Washington
Michael Hotz, Leslie Rosenberg, Gray Rybka, Andrew Wagner
Axion hardware

**Magnet with Insert (side view)**

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

Pumped LHe $\rightarrow$ T $\sim$ 1.5 k

**Magnet (Wang NMR Inc.)**

8 T, 1 m $\times$ 60 cm $\varnothing$
Axion hardware (cont’d)

High-Q Cavity (~200,000)

Experimental Insert
dc SQUID basics

When flux biased at $(n + 1/4) \Phi_0$ the SQUID is a very sensitive flux to voltage transducer.
Microstrip SQUID amplifiers

More than an order of magnitude quieter than current GaAs HFET amplifier
ADMX is the world’s quietest spectral receiver

Dicke Radiometer equation:

$$\frac{S}{n} = \frac{P_s}{kT_n} \sqrt{\frac{t}{\Delta \nu}}$$

Systematics-limited for signals of $10^{-26} \text{ W} - 10^{-3}$ of DFSZ axion power. Last signal received from Pioneer 10 (6 billion miles away) $\sim 10^{-21} \text{ W}$. 
Signal maximizes in the wings, and furthermore is episodic $\rightarrow$ Radio peak

Distributed over many subspectra (good), but didn’t repeat $\rightarrow$ Statistical peak
So far, no axion over an octave in mass! 

(1.9 - 3.6 μeV)

Need to push the experiment on two fronts:

- **Reduce System Temperature**
  - ADMX Phase II: add Dilution Refrigerator

- **Go up (& down) in Frequency**
  - ADMX-HF (High Frequency):
    - smaller microwave cavities

\[
T_{sys} = T + T_N, \quad T_{N, Squid} \propto T
\]
ADMX Phase II & ADMX-HF Coverage

\[ \Omega_a \approx 0.23 \]

\[ f \text{ (GHz)} \]

\[ m_a \text{ (\(\mu\text{eV}\))} \]

ADMX (complete)
ADMX (Phase II)
ADMX (Higher TM)
ADMX - HF
KVSZ
DFSZ
RBF
UF
Rydberg-atom single-quantum detectors

Atoms with a single electron promoted to a large principal quantum number, \( n \gg 1 \). Superposition of Rydberg states yields “classical atoms” with macroscopic dimensions (e.g. \( \sim 1 \) mm).

Potential for highly sensitive microwave photon detectors (“RF photo-multiplier tubes”) realized by Kleppner and others in the 1970’s. The axion experiment is an ideal application for Rydberg atoms:

- **Large transition dipole moments**  
  \( \langle n \pm 1 | e r | n \rangle \propto n^2 a_0 \)

- **Long lifetimes**  
  \( \tau_n \propto n^3 \quad (l << n) ; \quad \tau_{100} \approx 1 \) m sec

- **Transitions span microwave range**  
  \( \Delta E_n = E_{n+1} - E_n \approx 2R/n^2 ; \quad \Delta E_{100} \approx 7\) GHz

Most importantly, being a phaseless detector (photons-as-particles), the Rydberg-atom detector can evade the standard quantum limit:

\( h\nu = kT \)
Rydberg single-quantum detection (S. Matsuki et al., Kyoto)

The blackbody spectrum has been measured at 2527 MHz, a factor of ~2 below the standard quantum limit (~120mK).
Searches for Solar Axions
Produced by a Primakoff interaction, with a mean energy of 4.2 keV

\[ E \text{ [ keV]} \]

\[ \text{Flux [10}^{10} \text{ m}_a(\text{eV})^2 \text{ cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}] \]

\[ 16 \]

\[ 0 \]

\[ 10 \]

\[ T_{\text{central}} = 1.3 \text{ keV, but plasma screening suppresses low energy part of spectrum} \]

\[ \Phi_a = 7.44 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1} (m_a / 1\text{eV})^2 \]

The dominant contribution is confined to the central 20% of the Sun’s radius
Principle of the experiment *(Sikivie’s PRL 1983 again!)*

\[ L_{a\gamma\gamma} = ag_{a\gamma\gamma} E \cdot B \quad \rightarrow \quad \Pi(a \leftrightarrow \gamma) = \frac{1}{4} (g_{a\gamma\gamma} B_0 L)^2 |F(q)|^2 \]

where \[ F(q) = \frac{\sin(qL/2)}{(qL/2)} \quad , \quad F(0) = 1 \quad \text{and} \quad q = k_\gamma - k_a \approx m_a^2 / 2\omega \]
The CERN Axion Solar Telescope (CAST)

Prototype LHC dipole magnet, double bore, 50 tons, L~10m, B~10T

Tracks the Sun for 1.5 hours at dawn & 1.5 hours at dusk

Instrumented w. 3 technologies: CCD w. x-ray lens; Micromegas; TPC
CAST has published limits equaling those from Horizontal Branch Stars

The Phase II run with $^3$He is pushing the mass limit up into the region of axion models, 0.1-1 eV

Fill the magnet bore with gas (e.g. helium), and tune the pressure

When the plasma frequency equals the axion mass, full coherence and conversion probability are restored:

$$\omega_p = \left(4\pi\alpha N_e / m_e\right)^{1/2} \equiv m_\gamma$$

KvB et al. PRD 1989

A Next Generation Axion Helioscope is being proposed at CERN
The Sun’s photosphere has its own magnetic field, and ongoing analyses of RHESSI, Yohkoh & Hinode x-ray satellite data may yield a competitive limit on solar axions (or - who knows - see something)

**Synthetic axion signal superimposed onto Hinode ‘quiet sun’ image**

Google “RHESSI Science Nuggets” for April 30, 2007

Hinode/XRT Solar Image (> 12/06, approaching solar minimum)

Copious features and activity even in the quiet Sun!
How does one look for axions with e.g. RHESSI?

The magnetic field of the Sun’s photosphere replaces the CAST magnet on the earth

Potentially \((B \cdot L)_{\text{Sun}}^2 \approx 10^5 \times (B \cdot L)_{\text{CAST}}^2 \) … But:

- The x-rays must be detected above the atmosphere
- The Sun’s photospheric magnetic field is poorly known
- The photosphere is a plasma of exponentially falling density, complicating the analysis

Having said that, the Sun in the several keV range is very quiet at solar minimum conditions

RHESSI analysis at this point still only claims upper limits on hard x-rays in the > 3 keV range

If one ultimately concludes there is a real signal, are they consistent with standard processes & uniform across the disk, or localized within the central 10%?

Fourier-type imagers (i.e. not true imagers) such as RHESSI are poor for very low contrast applications

<table>
<thead>
<tr>
<th>Detector</th>
<th>FOM</th>
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<tbody>
<tr>
<td>CAST</td>
<td>1.0</td>
</tr>
<tr>
<td>RHESSI</td>
<td>0.0005</td>
</tr>
<tr>
<td>(^{57}\text{Fe}^*)</td>
<td>2\times10^3</td>
</tr>
<tr>
<td>X-ray**</td>
<td>7\times10^4</td>
</tr>
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</table>

Both assume SMEX level spacecraft

*14.4 kev photonuclear \(\gamma\)-ray

**1000 cm\(^2\), \(B = 2\times10^{-4} \text{(cm}^2\text{.sec.keV)}^{-1}\)
RHESSI (Berkeley SSL; launched 2002, still operating)

Nine different collimator pairs; each optimized to a different characteristic angular size. Image is Fourier-reconstructed from temporal data as RHESSI spins around its axis.

Yohkoh is a true imager; but sensitive at lower energies; ceased operation 1999.

Hinode, also true imager; launched ~ 2006; better suited for axion search.

An x-ray satellite dedicated to a solar axion search may be a very interesting possibility for the Korean space program!
At this point, the analysis only supports upper limits to hard x-rays from the quiet Sun.

Iain Hannah et al., Durham 5th “Patras” workshop on Axions etc. (July 2009)
Purely laboratory experiments
**Vacuum birefringence & dichroism**  
(Maiani, Zavattini, Petronzio, Phys. Lett. 1986)

**Vacuum dichroism**

\[ \varepsilon = N \cdot (1/4 \, gB_0L)^2 \cdot |F(q)|^2 \]

\( (N = \text{number of passes}) \)

**Vacuum birefringence**

**QED:**

\[ n_\perp = 1 + 4/2 \cdot \xi, \quad n_\parallel = 1 + 7/2 \cdot \xi \]

\[ \xi = \alpha/45\pi \, (B/B_{\text{crit}})^2, \quad B_{\text{crit}} = m_e^2/e \approx 4.41 \times 10^{13} \, \text{G} \]

**Axion:**

\[ \Psi = N \cdot (1/96) \cdot (g B_0 m_a)^2 \cdot L^3/\omega \]

No one has ever measured the non-linear QED effect, much less seen an axion!
Photon regeneration – simple ("shining light through walls")

KvB et al., PRL 59 (1987) 759

\[ \Pi^2 = \frac{1}{16} (gB_0L)^4 \left| F(q) \right|^4 \]

Published measurements to date:
\( g < 6.7 \times 10^{-7} \text{ GeV}^{-1} \) for \( m_a < 1 \text{ meV} \)
BMV collaboration (2007); GammeV (2007)
Several new photon regeneration experiments were launched around the world – the best limit to date being “GammeV” at FNAL.


FNAL Tevatron dipole, used as two halves (3m+3m, 5T); Nd:YAG 2w (532 nm) with PMT

These limits however are still orders of magnitude weaker than the limits established by astrophysics (Horizontal Branch Stars), and CAST.
Resonantly-Enhanced Photon Regeneration

Basic concept – encompass the production and regeneration magnet regions with Fabry-Perot optical cavities, actively locked in frequency


\[ P^{\text{Resonant}} (\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\eta \eta'} \cdot P^{\text{Simple}} (\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\pi^2} FF' \cdot P^{\text{Simple}} (\gamma \rightarrow a \rightarrow \gamma) \]

where \( \eta, \eta' \) are the mirror transmissivities & \( F, F' \) are the finesses of the cavities

For \( \eta \sim 10^{(5-6)} \), the gain in rate is of order \( 10^{(10-12)} \) and the limit in \( g_{a\gamma\gamma} \) improves by \( 10^{(2.5–3)} \)
We’re forming up to do this experiment at Fermilab (Project “GRIM REPR”).

“Time we mow the axion down for good”

Point-design 6+6 Tev magnets - 36m x 5T each leg

Collaboration of FNAL, LLNL, Florida & Michigan, including LIGO optics & lasers experts
Excluded $g_{A\gamma\gamma}$ vs. $m_A$ with all experimental and observational constraints
Summary and Conclusions

- The role of axions in particle physics and cosmology is just only now being widely recognized and appreciated.

- Solid progress has been made in the search for the axion on all fronts.

- The microwave cavity experiment in particular is on the cusp of major acceleration in pace, with ADMX Phase II.

- But it is strategically important to cover multiple mass decades in parallel, i.e. with ADMX-HF (Yale).

- We must take an experimental approach; ultimately we do not know where the axion may be lurking, and we should look in every region of parameter space, by any means.

- A major center for axion research here in Korea would immediately advance the global position of axion research.

- A significant discovery here is very possible!