Status report of
Latest result from the Tokyo axion helioscope experiment

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Axion

What is the Axion?

- QCD $\to \theta$ vacuum $\to$ Strong CP problem (eg. neutron EDM)

- Peccei–Quinn mechanism:
  
  global chiral $U(1) +$ SSB
  
  $\to$ NG boson $+ (1/32\pi^2 f_a) a F_a \tilde{F}_a$

  ↓

  axion resolves Strong CP

Searches/Limits:

- Experiments: Accelerator, Reactor, Nuclear transition, Telescope, Solar axion, Laser, Microwave cavity, …

- Astrophysics: Solar axion, Red giants, SN1987A

- Cosmology: $\Omega_a < 1$
Exclusion plot ($g_{a\gamma}$ vs $m_a$)

Fig. 26. Plot of excluded $g_{A\gamma}$ vs. $m_A$ with all experimental and observational constraints, along with predicted couplings for KSVZ and DFSZ models.

Be a high-priority component of the program in particle astrophysics, and the state of technology is well-prepared for one or more major experiments. Fig. 26 shows all experimental and observational constraints on the axion through the axion-photon coupling, with two prototypical axion models (KSVZ and DFSZ) and the nominally open mass range. Although somewhat schematic, it provokes several key points.

The "first concern is axion models. While it is encouraging that two very different axion models have axion-photon couplings of the same order of magnitude, one should be cautious in drawing conclusions. Should the ratio of the electromagnetic and color anomaly $E/N$ be far away from that corresponding to exact suppression (≈1.95), there could be a pleasant surprise for experimentalists; conversely, a value close to it could make the axion nearly impossible to see. Kim has evaluated numerous models with very different but plausible PQ charges [71], and nevertheless finds their corresponding $g_{A\gamma}$ clustered in roughly two orders of magnitude, mostly more favorable than the implementation of the DFSZ model indicated throughout this review. Second, the open range of axion masses ($m_A \approx 10^{-6}$ to $10^{-2}$ eV) is soft on both ends, particularly on the low-mass side. Taken together, a good point of view on these experiments is that they are principally discovery tools; a negative result is less meaningful even if the mass-coupling region covered is substantial.

Regarding the experiments, it is also interesting that the axion-photon coupling $g_{A\gamma}$ has lent itself to the greatest variety of imaginative and practical search techniques. If the axion is someday found, it will likely be through the $E_B$ interaction. Purely laboratory experiments, such as the precision measurement of vacuum birefringence using lasers and magnets, are elegant and will soon provide beautiful demonstrations of higher-order QED. On the other hand, we do not see any

Solar axion

The sun can be a powerful source of axions. In the solar core, axions can be produced from photons through the Primakoff process.

K. van Bibber et al., PRD39(1989)2089

\text{axion flux \left[10^{10} \text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}\right]} \times \left(g_{\text{eff}}/10^{-10} \text{GeV}^{-1}\right)^2

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{solar_axion_diagram}
\caption{Diagram illustrating the production of axions from photons in the solar core.}
\end{figure}
Axion telescope


The solar axions can be reconverted into x-rays using a strong magnetic field in a laboratory.
Conversion rate

Conversion rate:

\[ P_{a \rightarrow \gamma} = \frac{g_{a\gamma}^2}{2} \left| \int_0^L B e^{iqlz} \, dz \right|^2 = \frac{g_{a\gamma}^2 B^2}{q^2} \sin^2 \frac{qL}{2}, \]

\[ q = \frac{m_a^2}{2E}. \quad \text{(momentum transfer)} \]

The coherence is lost for \( m_a \gtrsim \sqrt{\pi E/L} \ldots \)

But coherence can be restored by filling the conversion region with buffer gas. In buffer gas, the momentum transfer becomes

\[ q = \frac{|m_{\gamma}^2 - m_a^2|}{2E}, \]

\[ m_{\gamma} = \sqrt{\frac{4\pi \alpha N_e}{m_e}}. \quad \text{(effective photon mass)} \]
The Sumico V detector consists of several components:

- Refrigerators
- Superconducting magnet
- PIN photodiodes
- Vacuum vessel
- Turntable

Key specifications include:
- Magnetic field: $B = 4 \text{T}$, length: $L = 2.3 \text{ m}$
-Persistent current: 268A
-16 PIN photodiodes
- Horizontal: $360^\circ$, vertical: $\pm 28^\circ$
Past measurements & results

- **Phase I** — vacuum
  
  \[ m_a < 0.03 \text{ eV} \]
  
  1997 December
  

- **Phase II** — low density He
  
  \[ m_a < 0.27 \text{ eV} \]
  
  \((p < 2 \text{ kPa}, T = 5.2–5.7 \text{ K})\)
  
  2000 July–September
  
CAST @ CERN

[Zioutas et al., PRL94(2005)121301]

- $B = 9\, \text{T}, \, L = 9.26\, \text{m}$
  (LHC test magnet)
- Vertical $\pm 8^\circ$, horizontal $\pm 40^\circ$
- TPC, Micromegas, CCD+mirror

[Irastorza et al.,
Rencontres de Moriond EW2007]

What’s next? — Sumico Phase III

- Phase I — vacuum
  \[ m_a < 0.03 \text{ eV} \]
  1997 December

- Phase II — low density He
  \[ m_a < 0.27 \text{ eV} \]
  \((p < 2 \text{ kPa}, T = 5.2–5.7 \text{ K})\)
  2000 July–September

- Phase III — high density He
  \[ m_a \lesssim 2.2–2.6 \text{ eV} \]
  \((p \lesssim 1–2 \text{ atm}, T = 5–6 \text{ K})\)
How to resist magnet quench?

When the superconducting magnet quenches, its temperature rises up to 50–60 K within a few seconds.

- No good commercial cryogenic relief valve
- Know thy enemy.
  Measured the pressure change after a forced quench.

→ Not as fast as the magnet: use φ1/4” tube
And a rupture disk

- Hydrodyne
- Cryogenic precision burst disc
- 36 psi ±5% @ 5 K
- Exhaust through a normally evacuated 3/8” line.
Resonance width at high $m_a$

$$P_{a\to\gamma} = \frac{g_{a\gamma}^2 B^2}{q^2} \sin^2 \frac{qL}{2}; \quad q = |m_\gamma^2 - m_a^2|/2E$$

- $\delta N_{He}/N_{He} < 0.1\%$
- stabilize $T +$ control $p$. 
  $$N_{He} = \frac{p}{RT}$$
- Many many data points to scan
  → computer control
Temperature stabilization

- DAC
- PC1
- 5N Al strips
- thermal bridge w/ heater
- Lakeshore CGR thermistor
- gas container
- magnet = heat sink
- Kevlar insulating support
- VXI ADC
- TCP/IP
- PC2
Gas container

- Compact design
- Welded 4 × st. steel 304
  21.9 × 17.9 × 2300 mm³ square pipes
- Pure Al (99.999%)
  0.1-mm thick,
  × 2 layers
- Measured thermal conductivity
  $\gtrsim 10^{-2}$ W/K
  @ 5 K, 4 T
Gas controlling system

- He gas
- Horiba PV-1000 piezo valves
- diaphragm pump
- evacuation line
- Yokokawa MU101
- EIA232
- PCI DAC card +amp
- gas container
- heat exchanger (40K, 5K)
- x-ray window
- rupture disc
- vacuum vessel
- PC1
- PC2
- TCP/IP
Test result of $p, T$ control

$p \sim 15$ kPa, $T = 5.75$ K

Excellent!
Other progress / status

- PIN diode dead layer measurement
- Moved to a new site ... again
- Recontruction — almost finished, left final precision alignment
- True north direction by gyrocompass
- Repaired and refined mechanics of altazimuth stage
- Cable handling robot — work in progress, half done
- Repairing broken cables — work in progress
Summary

- Sumico Phase III will explore $m_a \lesssim 2.2 - 2.6$ eV
- Most technical difficulties have been overcome.
- Now the magnet has been cooled.
  \[ T_{\text{mag}} = 6 \text{ K as of 10 September} \]
- Measurement will start soon.