Tokyo axion helioscope

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Collaborators

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← Logo designed by Yuki Akimoto
What is the Axion?

• Strong CP problem:
  CP violating term in QCD
  \[ \mathcal{L}_{\text{CP}} = \frac{\bar{\theta}}{32\pi^2} F_{a}^{\mu\nu} \tilde{F}_{a\mu\nu} \quad (\bar{\theta} \sim O(\pi)?) \]

  Neutron EDM: \( d_n < 2.9 \times 10^{-26} \text{ e cm} \) \( (\bar{\theta} < 10^{-10}) \)

• Peccei–Quinn mechanism:

  \[ \text{U}(1)_{\text{PQ}} + \text{SSB} \longrightarrow \begin{cases} \text{“Axion”} & \text{(NG boson)} \\ \bar{\theta} = \frac{\langle a \rangle}{f_a} = 0. \end{cases} \]
Principle of Axion helioscope


\[ \mathcal{L}_{a\gamma\gamma} = g_{a\gamma} a \vec{E} \cdot \vec{B} \]
Principle of Axion helioscope


Conversion rate:

\[ P_{a\rightarrow\gamma} = \frac{1}{2} g_{a\gamma}^2 \left| \int_0^L B e^{iqa} dz \right|^2 \]

\[ \lesssim \frac{1}{4} g_{a\gamma}^2 B^2 L^2 \]

\[ q = k_{\gamma} - k_a \]
Sumico V detector

- Refrigerators
- Superconducting magnet
- PIN photodiodes
- Gas container
- Vacuum vessel
- Turntable
  - $B = 4\,\text{T}$, $L = 2.3\,\text{m}$
  - 268A persistent current
  - 16 PIN photodiodes
  - Track the sun $\sim 12\,\text{hours/day}$
Sensitive to heavier axions by buffer gas

Conversion rate:

\[ P_{a \rightarrow \gamma} = \frac{g_{a\gamma}^2}{2} \left| \int_0^L B e^{iqz} \, dz \right|^2 \sim \frac{g_{a\gamma}^2 B^2}{q^2} \sin^2 \frac{qL}{2} \leq \frac{g_{a\gamma}^2 B^2 L^2}{4} , \]

\[ q = k_\gamma - k_a \approx \frac{m_\gamma^2 - m_a^2}{2E} . \]

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

\[ \downarrow \]

The effective photon mass in buffer gas:

\[ m_\gamma = \sqrt{\frac{4\pi \alpha N_e}{m_e}} . \]

\( N_e \): electron density
- X-ray window (detector side)
- Ensure temperature uniformity along the container by:
  - Suspending container body in vacuum
  - Thermal contact at one end ← Active temperature control
  - High thermal conductivity layer
Buffer gas container

- Welded $4 \times$ st. steel 304
  $21.9 \times 17.9 \times 2300 \text{ mm}^3$
  square pipes

- Wrapped with
  99.999% pure Al
  0.1-mm thick $\times 2$ layers

- Thermal conductivity
  (measured)
  $\gtrsim 10^{-2} \text{W/K @ 5 K, 4 T}$
X-ray window

- $25 \mu m$ Be foils with $1 \mu m$ polyimide coating
- Supported by Ni grid
- Withstands up to $0.3 \text{ MPa}$
- Transmits $\gtrsim 80\%$ for $E > 3 \text{ keV}$
Gas handling system

- He gas
- Evacuated line
- Rupture disc
- X-ray window
- Gas container
- Heat exchanger (40K, 5K)
- Diaphragm pump
- Piezo valves
- Yokogawa MU101
- PCI DAC card +amp
- EIA232
- TCP/IP
- PC1
- PC2
- Vacuum vessel
Helium density time chart

Helium density [mol/m³]
Photon mass [eV]

start
encoder broken
end
quench
end of the 1st unmanned tracking
2nd unmanned tracking

Dec Jan Feb Mar Apr
2007 2008
PIN photodiode X-ray detector

- Inside OFHC shield @ $T = 60$ K
- 16 PIN photodiodes
  4 PIN/module
- chip: Hamamatsu S3590-06-SPL
- size:
  $11 \times 11 \times 0.5$ mm$^3$/PIN
- active area $> 9 \times 9$ mm$^2$/PIN
- inactive surface $< 0.35 \mu$m

[T. Namba et al., NIMA 489(220)224]
[Y. Akimoto et al., NIMA557(2006)684]
Data acquisition system

- 16 input channels
- Waveform recording:
  - PIN photodiode ➔ Charge sens. preamp. ➔ Flash ADC
- Offline shaping
- Trigger:
  - shaper + leading edge discr.
- Precise live time
- Control: CAMAC
## Sumico & CAST side-by-side

<table>
<thead>
<tr>
<th>Sumico</th>
<th>CAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hongo, U. Tokyo</td>
<td>CERN</td>
</tr>
<tr>
<td>$4 , T \times 2.3 , m @ 5 , K$</td>
<td>$9 , T \times 9.26 , m @ 1.9 , K$</td>
</tr>
<tr>
<td>12 hours/day</td>
<td>2 $\times 1.5$ hours/day</td>
</tr>
<tr>
<td>$^4\text{He} \ (m_a \lesssim 2 , \text{eV})$</td>
<td>$^4\text{He}+^3\text{He} \ (m_a &lt; 1.1 , \text{eV})$</td>
</tr>
</tbody>
</table>
Exclusion plots

- Lazarus et al. (PRL69 (1992) 2333)
- SOLAX, COSME, CDMS
- DAMA
- Solar age
- Sumico (95%CL)
- Phase I—vacuum (PLB434 (1998) 147)
- Phase II—low density (PLB536 (2002) 18)
- Phase III latest (PLB668 (2008) 93)
- CAST I (PRL94 (2005) 121301)
- CAST II $^4$He (JCAP0902:008, 2009)
- CAST II $^3$He preliminary
- Axion models $(E/N = 8/3)$
Exclusion plots

- **Lazarus et al.** (PRL69, 1992, 2333)
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- **Phase III latest** (PLB668, 2008, 93)

Axion models (E/N = 8/3)

- **CAST I** (PRL94, 2005, 121301)
- **CAST II** (JCAP0902:008, 2009)
- **CAST II** 4He (preliminary)
- **Lazarus et al.** (PRL69, 1992, 2333)

**Solar age**

- **CAST II** 3He
- **SOLAX**, COSME, CDMS
- **CDMS**
- **DAMA**

**Axion models**

- **(E/N = 8/3)**

**Sumico** (95% CL)
Future plan

Sumico (95% CL)

Solar age

SOLAX, COSME, CDMS

DAMA

CAST I CAST II

CAST II 4He
CAST II 3He preliminary

Lazarus et al.

Axion models

\( g_{a\gamma} \propto (BL)^{-1/2} \left( \frac{\text{bg rate}}{\text{time} \times \text{area}} \right)^{1/8} \)
Sumico Phase III upgrades

Gas density control has been quite successful so far. We want to make $^4$He density higher and higher! But higher density caused new problems...

- Reworked internal and external pipelines for safer operation.
- But a thermoacoustic oscillation set in at higher densities.
  - Introduced a fast pressure gauge to monitor oscillation and bellows in the room temperature section.
- Unacceptable elevation-angle dependent temperature difference observed at higher densities.
  - Introduced new heat exchangers. (Now testing)
Sumico Phase III upgrades

New heat exchangers
Summary

• Sumico, aka Tokyo axion helioscope, results:
  Phase I: vacuum
  \[ g_{a\gamma} < 6.0 \times 10^{-10} \text{GeV}^{-1}, \quad m_a < 0.03 \text{ eV} \]
  
  Phase II: low density \(^4\text{He}\)
  \[ g_{a\gamma} < 6.8-10.9 \times 10^{-10} \text{GeV}^{-1}, \quad 0.05 < m_a < 0.27 \text{ eV} \]
  
  Phase III: cold dense \(^4\text{He}\)
  \[ g_{a\gamma} < 5.6-13.4 \times 10^{-10} \text{GeV}^{-1}, \quad 0.84 < m_a < 1.00 \text{ eV} \]
  
• Sumico Phase III will explorer further up to \(m_a \lesssim 2 \text{ eV}\).
  Now started cooling!
Thank you
Notes on buffer gas

- "Helium-4" is used
- Temperature is kept high enough above the critical point \((p_c = 0.227 \text{ MPa}, T_c = 5.1953 \text{ K})\)
- X-ray absorption and decoherence due to gravity are not fatal even at \(m_\gamma \sim 2 \text{ eV}\)

\[
m_\gamma = \sqrt{\frac{4\pi \alpha N_e}{m_e}}
\]
Resonance width at higher axion masses

\[ P_{a\to\gamma} = \frac{g_{a\gamma}^2 B^2}{q^2} \sin^2 \frac{qL}{2}; \quad q \approx \frac{m_{\gamma}^2 - m_a^2}{2E}; \quad m_{\gamma}^2 = \frac{4\pi\alpha N_e}{m_e} \]

\[ |qL| < 2\pi \quad \rightarrow \quad \frac{\delta N_e}{N_e} < \frac{4\pi E}{m_a^2 L} \sim O(10^{-3}) \quad \text{for } m_a \sim 2 \text{ eV}. \]

- stabilize $T + \text{control } p$.  
  \[ N_{He} \sim \frac{p}{RT} \]
- Many data points to scan  
  \[ \rightarrow \text{computer control} \]
After quench, before explosion...

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

- Pressure change is slower:
  \[
  \begin{align*}
  \times 3 & \text{ in 2 minutes} \\
  \times 7 & \text{ in 2 hours}
  \end{align*}
  \]

\[
\rightarrow \quad \text{pipe line design}
\]
Pressure change after quench on Apr 23 2008
• Hydrodyne cryogenic precision burst disc
• Protects X-ray window from over pressure
• Breaks at 0.25 MPa±5% @ 5 K
Energy spectrum

\[ \chi^2(m_\alpha) = \sum_{m_\gamma=m_\gamma,\text{min}}^{m_\gamma,\text{max}} \sum_{20 \text{ keV}}^{20 \text{ keV}} \left( \frac{N_{\text{solar}}(E, m_\gamma) - N_{\text{bg}}(E, m_\gamma) - N_{\text{theo}}(E, q)}{\sigma(E, m_\gamma)} \right)^2 \]