Search for Relic Axions with the CAST Dipole magnet at CERN

Lino Miceli
IBS Center for Axion and Precision Physics Research (CAPP/IBS)
At the Korea Advanced Institute of Science and Technology (KAIST)
Daejeon, Republic of Korea

University of Geneva
Physics Department
7 December 2016
Center for Axion and Precision Physics Research at KAIST, Daejeon, South Korea

Established October 2013. Goal: ~ 60 people within the first 3-5 years
- 15 research fellows
- Visitor program
- 20 grad. Students
- Engineers, Technicians
- 10 junior/senior staff
Outline

• Axion search motivation
• A common DM axion detection method
• Status of cold dark matter axion searches
• Search in a dipole magnetic field
• The CAST-CAPP/IBS Project at CERN
CAPP Program

Focus is on two key issues of contemporary physics:

• **Nature of dark matter**
  - Comprehensive axion search program (~75%)

• **Baryon asymmetry of the universe**
  - R&D towards a proton EDM measurement in a storage ring (~25%)
CAPP main goals in axion search

• Establish state of the art axion dark matter experimental program at KAIST

• R&D program to improve on all experimentally accessible parameters

• Promote/contribute-to international collaborations

  CAPP is leading a new experiment (CAST-CAPP/IBS project), within the CERN Solar Axion Telescope (CAST) collaboration at CERN, to search for cold dark matter axions with rectangular cavities in the CAST dipole magnet
The axion is a good cold dark matter candidate if its mass is in the range $\approx (1 - 100) \, \mu\text{eV}$.

An axion discovery would solve the so called strong CP problem.
The composition of our universe

- Dark Energy: 68.3%
- Dark Matter: 26.8%
- Ordinary Matter: 4.9%

http://www.esa.int/spaceinimages/Images/2013/03/Planck_cosmic_recipe
Evidence for DM

Rotational curves in spiral galaxies. At large distances from the center of galaxies, stars have higher than expected orbital velocities.

\[ v = \left( \frac{G M(r)}{r} \right)^{1/2} \]

Circular orbit

F. Zwicky, Helv. Phys. Acta. 6, 110 (1933)
The strong CP problem

\[ \mathcal{L}_{QCD} = \ldots + \theta \frac{\alpha_s}{8\pi} G \tilde{G} \]

this term violates CP

Measuring the EDM of a particle is a good test of CP violation
An estimate of the neutron EDM:

\[ d_n \approx 3.6 \times 10^{-16} \theta e \cdot cm \]

Whereas the experiment sets a limit at

\[ d_n < 2.9 \times 10^{-26} e \cdot cm \]

\[ \theta < 10^{-10} \]

The measured value of the \( \theta \) parameter is \( \sim 10 \) orders of magnitude smaller than QCD predictions


C. A. Baker, et al, hep-ex/0602020
Solution to the strong CP problem

• Peccei-Quinn: $\theta_{\text{QCD}}$ is a dynamical variable (1977).
• Wilczek and Weinberg: axion particle (1977)
• J.E. Kim: Hadronic (invisible) axions (1979)

• Axions: pseudoscalars, similar to pions, but much lighter

\[ m_a \approx 6 \times 10^{-6} \text{ eV} \frac{10^{12} \text{ GeV}}{f_a} \]
The link between axion and DM

• Dark matter density: 0.3-0.5 GeV/cm$^3$
• Axions in the 1-100 μeV range: $10^{12}$-$10^{14}$/cm$^3$
  • Light axion would have condensed with the right density to be DM
• Lifetime $\sim 7 \times 10^{44}$s $(100\mu\text{eV} / m_a)^5$.
• Axions interact very weakly
• Kinetic energy $\sim 10^{-6} m_a$ ("cold") very narrow line in spectrum.

  can be treated as a classical system.
Common detection method

Based on the axion coupling to two photons.

In the presence of a strong magnetic field the conversion probability is enhanced (similar to Primakoff (*) effect)

\[ \mathcal{L} = -g_{\alpha\gamma\gamma} a(t) E(t) \cdot B \]

- \( g_{\alpha\gamma\gamma} \) coupling constant
- \( a(t) \) axion field
- \( B \) provides a virtual photon enhancing the conversion probability
- \( E(t) \) electric field associated with the outgoing photon

(*) H. Primakoff, Phys. Rev. 81, 899 (1951)
Axion experiments: two parameter searches

(*) One missing experiment. See later.
Axion detection with microwave cavities

Axion-to-photon conversion probability further enhanced in a microwave cavity that resonates to the frequency of the axion mass (Sikivie (*)).

On-resonance axion conversion power in a microwave cavity:

\[ P \approx g_{a\gamma\gamma}^2 \left( \frac{\rho_a}{m_a} \right) B^2 \cdot Q \cdot V \cdot C \]

\[ Q = 2\pi f \frac{\text{Stored Energy}}{\text{Power Loss}} \quad \text{Quality factor} \]

\[ C = \frac{1}{B_0^2V} \frac{\left| \int \mathbf{B} \cdot \mathbf{E} d^3x \right|^2}{\int \mathbf{E} \cdot \mathbf{E} d^3x} \quad \text{Geometry factor} \]

Tunable cavities

CAPP/IBS axion target plan

• Major improvement elements:
  • High field solenoid magnets, B: 9T→25T→40T
  • High volume magnets/cavities, V: 5l→50l
  • High quality factor of cavity, Q: \(10^5\)→\(10^6\)
  • Low noise amplifiers, \(T_N: 2K\)→0.25K
  • Low physical temperature, \(T_{ph}: 1K\)→0.1K

Scanning rate improvement: \(25\times10^6\)

Improvement in coupling constant: 70

Axion dark matter in the mass range \(\sim1\mu\text{eV}\) to 100\(\mu\text{eV}\). Plan to either detect or exclude axions down to 10% of dark matter.
Rectangular cavity resonant frequencies

\[ f_{lmn} = \frac{c}{2\pi \sqrt{\mu_r \varepsilon_r}} \sqrt{\left( \frac{l}{w} \right)^2 + \left( \frac{m}{h} \right)^2 + \left( \frac{n}{L} \right)^2} \]

Resonant E field aligned with the external B field: \( TE_{l0n} \) modes

\[ E_y \sim \sin \left( \frac{l\pi}{h} x \right) \sin \left( \frac{n\pi}{L} z \right) \]

\[ E_x = E_z = 0 \]

First experiment using rectangular cavities in a dipole magnet

CAST-CAPP/IBS Search: The CAST Dipole Magnet

- **LHC prototype**
- **8.8 T field**
- **1.8 K operating temper.**
- **9.25 m magnetic length**
- **43 mm twin bores**

Magnet front end
Cavity installed here
Resonant power

\[ P = \left( g_{\gamma\gamma} \right)^2 \rho_a \frac{1}{m_a} B^2 CV \min [Q_c, Q_a] \]

\[ = 1.6 \times 10^{-23} W \times \left( g_{\gamma\gamma} 10^{14} \text{GeV} \right)^2 \left( \frac{\rho_a}{300 \text{ MeV/cm}^3} \right) \left( \frac{2.4 \times 10^{-5} \text{eV}}{m_a} \right) \]

\times \left( \frac{B}{9 \text{T}} \right)^2 \left( \frac{C}{0.66} \right) \left( \frac{V}{5 \text{l}} \right) \left( \frac{Q}{5 \times 10^3} \right) \]

- \( m_a = 24 \mu\text{eV} \ (f = 5.8 \text{ GHz}) \)
- \( B = 9 \text{T}, \text{CAST magnet} \)
- \( V = 5 \text{ liters} \)
- \( Q = \min [Q_c, Q_a] = Q_0/2 \sim 5,000; \text{critical coupling} \)
  - \( Q_c \) loaded quality factor
  - \( Q_0 \) cavity quality factor
Time required for a single measurement (example)

\[
t = 9 \times 10^5 s \left( \frac{\text{SNR}}{4} \right)^2 \left( \frac{T}{3.8 \text{ K}} \right)^2 \left( \frac{C}{0.66} \right)^{-2} \left( \frac{B}{9 \text{ T}} \right)^{-4} \left( \frac{V}{5 \text{ l}} \right)^{-2} \times \left( g_{\gamma\gamma} 10^{14} \text{ GeV} \right)^{-4} \left( \frac{\rho_a}{300 \text{ MeV/cm}^3} \right)^{-2} \left( \frac{2.4 \times 10^{-5} \text{ eV}}{m_a} \right)^{-3} \times \left( \frac{Q}{5 \times 10^3} \right)^{-2} \left( \frac{10^6}{Q_a} \right) \sim 10 \text{ days}, g_{\gamma\gamma} = 10^{-14} \text{ GeV}^{-1}
\]

\[\text{SNR} = \frac{P}{K_B T} \sqrt{\frac{t}{b}}\]

\[m_a = 24 \mu\text{eV} \ (f = 5.8 \text{ GHz}) \ ; \quad B = 9 \text{ T} \ , \ \text{CAST magnet}\]

\[V = 5 \text{ liters}\]

\[Q = \min[Q_c, Q_a] = Q_0/2 \sim 5,000; \text{ critical coupling}\]

\[Q_c \text{ loaded quality factor}\]

\[Q_0 \text{ cavity quality factor}\]

\[T = \text{System Temperature} = \text{physical temperature} + \text{receiver\&amplifier\-chain equivalent noise temperature}. \ \text{Commercial HEMT amplifiers.}\]
Scanning rate (example)

\[
\frac{df}{dt} = \frac{f}{Q \cdot t} \approx \frac{3.4 \text{ KHz}}{\text{year}} \left( g_{a\gamma \gamma} \times 10^{15} \text{GeV} \right)^4 \left( \frac{5.8 \text{ GHz}}{f} \right)^2 \left( \frac{4}{\text{SNR}} \right)^2 \left( \frac{3.8 \text{ K}}{T} \right)^2 \\
\times \left( \frac{B}{9 \text{T}} \right)^4 \left( \frac{C}{0.66} \right)^2 \left( \frac{V}{5 \text{l}} \right)^2 \left( \frac{Q}{5 \times 10^3} \right)
\]

\approx 90 \text{ MHz/year at } g_{a\gamma \gamma} \times 10^{-14} \text{GeV}^{-1}

m_a = 24 \mu\text{eV (}f = 5.8 \text{ GHz)} ; \quad B = 9 \text{T, CAST magnet;}

V = 5 \text{ liters}

Q = \min[Q_c, Q_a] = Q_0/2 \sim 5,000; \text{ critical coupling}
\begin{itemize}
  \item Q_c \text{ loaded quality factor }
  \item Q_0 \text{ cavity quality factor }
\end{itemize}

T: System Temperature = physical temperature + receiver&amplifier-chain equivalent noise temperature.
Sensitivity

Cavity Frequency (GHz)

Axion Coupling $|g_{aY}|$ (GeV$^{-1}$)

Axion Cold Dark Matter

CAST-CAPP
Potential mass range

Axion Published Limits
Univ F1
RBF

Non RF-cavity Techniques

White Dwarf and Supernova Bounds

ADMX-HF

ADMX Published Limits

Too Much Dark Matter

$10^{-10}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$

$10^{-10}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$

Axion Mass (μeV)

$10$  $20$  $30$  $100$  $1000$

4.8  7.3
CAST-CAPP sensitivity

**ADMX-HF**(*)
- 110 days (50% eff.)
- 0.4 μeV

**CAST-CAPP**
- 110 days, one bore matched cavities (70% efficiency)
  - 0.8 μeV
- 110 days, 1.5 bores matched cavities
  - 0.8 μeV (70% eff.)
- Future?
  - 200 days, ~ 17 μeV
  - 1.35 μeV (70% eff.)

Status: One year since project started

- **November 2015**: Project start after CERN SPSC approval
- **Jan-May 2016**: cavity prep, integration with magnet, vessel design and construction, OK to install
- **June 2016**: cavity installation and testing
  - Resonance measured after installation, before and after start of vacuum pumping
  - Resonant frequency shifted up by ~ 1.8 MHz, roughly corresponding to the change in electrical permittivity of the medium, at room temperature.
Cavity resonance before and after vacuum pumping

Cold flange with feedthroughs

Resonant frequency shifted up by ~ 1.8 MHz, corresponding to the change in electrical permittivity of the medium, at room temperature.
Status: One year since project started

- **August/September 2016:**
  - Magnet cold (1.8 K)
  - Fundamental resonant frequency re-measured: shifted up from to \( \sim 6.078 \text{ GHz} \) → the cavity behaves as expected.
  - Magnet ramped to 13,000 A (operating field): no significant changes in the resonance
  - **Quench tests:**
    - Magnet quenched from low and operating field (\( \sim 9 \text{ T} \)): Cavity unaffected.
      → cavity mechanically and electrically stable
- **November 28:** ~ 1 week data acquisition before magnet shut down
Cavity unchanged and stable before and after magnet quench

Center freq. = 6.078 GHz

Magnet cold

Before magnet quench (full field)  After magnet quench

Resonant frequency unchanged  Frequency
A closer look at the resonance with and without the magnetic field

Center freq. = 6.078 GHz

Magnet off

Magnet cold

Magnet on

Resonant frequency shifted by –136 KHz, 2 parts in 100,000.
Installed Cavity

- Fundamental mode $f \approx 6.078$ GHz (low-T)
- $Q \approx 10,000$ (room-T)
- Dimensions: 138 mm X 25 mm X 23 mm.
- Material: stainless steel 10-micron thick electrodeposited copper layer
- Longitudinally split
- Magnetically coupled
Setup

• Cavity signals to a cryogenic low noise HEMT amplifier outside of the cold bore, inside a vacuum vessel

• Two temperature sensors: one on cavity, one near the cryogenic amplifier

• Cavity temperature 3.8 K

• Amplifier temperature 2.5 K

• 2-axis Hall probe near the cavity; 3-axis Hall probe near the amplifier
The RF cavity installed inside the bore

“Inspired” by LHC beam screen design and testing, but 7 times thinner copper plating
Installation

2. Insertion tube

3. Cavity

4. VACUUM VESSEL

5. Low-temperature electronics in vac. vessel
A sample from recent data acquisition
A sample from recent data acquisition
CAST-CAPP R&D

• Design and fabrication of longer rectangular cavities.
• Amplifiers in high magnetic fields.
• Cavity tuning and coupling for multi-cavity operation.
• Multi-cavity operation
Next: Cavity tuning with dielectric bars
Cavity tuning with dielectric bars

With hinges

Without hinges

Horz. axes: bar insertion distance from longitudinal wall
Alternative tuning: Split cavity
Cavity engineering:
Mechanical tolerances vs. mode localization.
Cavity: 2.5cm X 2.4cm X 50cm

- **TE$_{101}$ Resonant Frequency (GHz)**
  - Red: Undeformed resonator
  - Green: Varying resonator width

- **Geometry factor (C)**
  - Red: Undeformed resonator
  - Green: Varying resonator width

Horizontal axis: varying resonator width on one side (mm)
Summary:

• For the first time, a microwave cavity has been installed in a dipole magnet for axion search
• The cavity is stable inside the magnet, unaffected by quench forces
• We have taken a few days of data
• This feasibility study shows that an axion search experiment using the Sikivie technique is sustainable in a large dipole magnet
• We plan to move to multiple cavities for higher sensitivity