Dark Matter Axion Search Experiments Using 18T HTS Magnet at CAPP/IBS in KAIST

Byeong Hun Min

Center for Axion and Precision Physics Research
IBS
1. Axion as dark matter
2. Important factors for Axion search
   • HTS Magnet (18T)
   • Cryostat (4K)
   • Cavity
   • DAQ system
3. Results from our present setup
4. Factors improvement
   • Dilution refrigerator (~20 mK) with 18 T magnet
   • JPC : First stage amplifier
   • Cancellation magnet
5. Our Project
Axion as a Dark Matter

Invented to solve the strong-CP problem in QCD

- Non-thermal mechanism of producing axion dark matter in the early Universe
- The initial axial angle $\Theta$ determines the potential energy to be released.
- The potential energy density (order of $\Lambda_{QCD}^4$) is converted into cold dark matter
- Axion dark matter mass is determined by the harmonic oscillator frequency

$$m_a \approx \frac{\Lambda_{QCD}^2}{f_a} < 10^{-3} \text{ eV}$$
Axion Dark Matter Search

Axion potential energy decays at time $t \sim 1/m_a$.
If this is too late (too small $m_a$) in cosmological time
the dark matter can be overproduced relative to the photons
Assume: \( m_a \approx \mu \text{eV} \)

\[
\rho_{\text{DM}} = 3 \times 10^8 \text{eV/cc} = 2.4 \times 10^{-6} \text{eV}^4
\]

\[
\beta = 10^{-3} \quad \text{or} \quad < v_a > = 10^{-3} c
\]

\[
L_{\text{coh}} = \frac{1}{\rho} \approx 10^9 \text{eV}^{-1} \approx 200 \text{ m}
\]

\[
t_{\text{coh}} = \frac{1}{E} \approx 10^{12} \text{eV}^{-1} \approx \text{msec}
\]

\[
\mathcal{L} \equiv -\frac{1}{4} g a F \bar{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \bar{F}
\]

\[
= g a \bar{E} \cdot \bar{B}
\]

Oscillating source current \( \rightarrow \) RF photons

RF photon frequency = axion mass

\[
P_a = g^2 \frac{\rho a}{m_a} B_0^2 V \times \min(Q_{\text{cav}}, Q_{\alpha})
\]

\(~ 10^{-21} \text{W} \text{ at } m_a = \mu \text{eV} \)

(assuming \( B = 8 \text{T}, V = 0.2 \text{ m}^3 \) magnet and cavity \( Q = 10^5 \))
CAPP’s Dark Matter Axion Search Strategy

Strong magnetic field (18T)

\[
\frac{df}{dt} = \frac{70 \text{ MHz}}{\text{year}} \left( \frac{4}{[g/n]} \right)^2 \left( \frac{V}{10 \text{ l}} \right)^2 \left( \frac{B_0}{10 \text{ T}} \right)^4 \\
\times C \left( \frac{g_a}{0.36} \right)^4 \left( \frac{\rho_a}{0.3 \text{ GeV/cc}} \right) \left( \frac{1 \text{ K}}{T_n} \right)^2 \left( \frac{f}{\text{GHz}} \right)^2 \left( \frac{Q}{Q_a} \right)
\]

Lower the thermal noise temperature of first stage amplifier

High Q cavity (Q~10^6)
A strong B-field and large bore HTS magnet can be commercially produced by SuNAM Co. Ltd.

2G HTS Superconducting Magnet
Magnetic field: 18 Tesla
Dimension: 70 mm ID / 168mm OD
   200 mm uniform field (>90%)
   552 mm length
Quench free design (No-Insulation winding)
Compact and easy to operate

The magnet delivery by summer 2017

Initial DM axion mass range to probe: 17 to 36 μeV

(Later we will apply multiple cavity method to probe higher mass range search)
18 T no insulation magnet

- non insulation type
- No quench in LHe

18 T was delivered in 2017.

- 44 double pancake coils
- 18 T magnet
- Bore size 70 mm
- 476 mm

25 Tesla magnet

- Bore size 100 mm
- 341.6 mm

1st coil for 25 T magnet to be delivered in 2020
Cavity resonance frequency is tuned by tuning rod which is controlled by stepper motor.

**Measurement program**

- Uniformity: 93% (±100 mm)
- Stability: <0.05% in 2 weeks

*Very high quality of our HTS magnet.*

**Related Poster:** JongKuk Kim (6 July 2018, 18:30)
Simulation of frequency in cavity

- The third factor for axion search is high Q-value cavity

- The dielectric rod has lower frequency than conducting rod.
- We use the red line (TM010 mode) for axion search.

- Related Poster: YoungJae Lee (6 July 2018, 18:30)
• Scanning Rate vs. Length of Cavity

\[
\frac{df}{dt} = \left( \frac{1}{snr} \right)^2 \left( \frac{P_{signal}}{k_B T_{syst}} \right)^2 \frac{Q_a}{Q_L} = g_{\alpha\gamma}^4 \left( \frac{\rho_a}{m_a} \right)^2 \left( \frac{B^2 V_C}{k_B T_{syst}} \right)^2 Q_0 Q_a \frac{\beta^2}{(1 + \beta)^3}
\]

\[C = \frac{\left| \int_V \bar{E} \cdot \bar{B}_0 \, dV \right|^2}{\int_V |\bar{E}|^2 \, dV \cdot \int_V |\bar{B}_0|^2 \, dV}\]

assuming uniform C

\[\text{max rate} \quad \frac{df}{dt} = 0.87 \frac{df}{dt_0}\]

Detailed simulation of E and B

length of magnet (467.8mm)

Scan Rate (A.U.)

\[L = 438 \text{ mm} \quad \text{vs.} \quad 466 \text{ mm}\]

% degradation

Q(300K) = ~24,000  Q(4K) = ~73,000
RF chain configuration

- Signal Generator (SG)
- Switch A
- Switch B
- Switch C
- Switch D
- Cavity
- Circulator
- Low noise amplifier (LNA)
- Weak Coupling
coupler

Cryo- and room temp. DAQ system

- Room temperature amplifier
- Spectrum analyzer
- Network analyzer
- Signal generator
- Room T. amp.

- It can be switched with 4 states by program (S11, S21, S22, SA)
We measured the resonant frequency of our cavity with dielectric tuning rod. 

Temp: 4 K
B : 18 T
Background Noise at 4 K (under 18 T)

$f = 4.227655 \text{ GHz}$

Signal power (dBm)

Frequency (Hz) $\times 10^7$

(Down converted IF)

From signal generator($f$)

Noise measure

$T : 4 \text{ K}$

$H : 18 \text{ T}$
At present, we are going to improve our experimental setup. The new cryostat for the dilution unit and cavity is under development.
Josephson Parametric Converter (JPC : Quantum Limit Amplifier)

4 K exp. : HEMT amp. (2 K Noise Temp.)

Improve the 1st stage amp.

Flux maps were measured from our JPC.

From this maps, we find the two frequency range.

<table>
<thead>
<tr>
<th>Gain (20 dB min)</th>
<th>$F_{\text{min}}$ (GHz)</th>
<th>$F_{\text{max}}$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High frequency</td>
<td>7.72</td>
<td>8.802</td>
</tr>
<tr>
<td>Low frequency</td>
<td>4.757</td>
<td>5.01</td>
</tr>
</tbody>
</table>

Related Poster: JiYoung Lee

Next plan: Measure the noise temperature of JPC
Cancellation Magnet Development

Need the cancellation magnet for JPC operation in 18 T

Delivered in Nov 2017

Cancellation Coil

- Cancel out \(\sim kG\) of stray field to a few G
- Field stability \(\sim 25\text{ppm/hr}\)
- Field profile test & quench test passed

The main purpose of it is cancellation of magnetic field around the JPC

5 gauss
Installation of improvement factors for experiment

Our experimental setup will be installed with this condition.

Magnetic field : 18 T
Noise temperature : $\sim 500$ mK
Q-factor : $\sim 70,000$
Real time DAQ : $\sim 80\%$ (efficiency)
(Physical temperature : $\sim 20$ mK)
Projected Axion Search Goal

We will probe the axion with Dilution and JPC and so on.
• We use 18 T HTS solenoid magnet for Axion Haloscope research.

• We measured the TM modes in the cavity at 4 K(under 18 T)

• We will install the dilution refrigerator and 18 T magnet in October.

• We will sure probe the dark matter Axion in the range of 17 ~ 36 μeV. 
  \( (f : 3.7 \sim 8.8 \text{ GHz}) \)