The OVAL experiment:
Search for vacuum magnetic birefringence with pulsed magnet and high-finesse Fabry-Pérot cavity

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What is **Vacuum Magnetic Birefringence**?

- QED predicts light interacts with magnetic field even in the vacuum mediated by virtual e⁻e⁺ pair
- As a result, a refractive index of vacuum could become anisotropic (**VMB**)
- Predicted since 1930s

\[ \Delta n = n_{||} - n_{\perp} = k_{CM} \times B^2 \]

QED predicts \( k_{CM} = 4.0 \times 10^{-24} [T^{-2}] \)

Not observed yet!!
Contributions from new physics

- Axion-like particles (ALPs) and milli-charged particles (MCP) could mediate an interaction between light and magnetic field.

- ALPs and MCP could also induce VMB

VMB search is one of the best probe for sub-eV ALPs as a terrestrial experiment.
Concept of the OVAL experiment

- Sensitivity $\propto B^2 \times F \times L_B \times T_{DAQ}^{1/2}$

High repetitive pulsed magnet

Observe Vacuum with Laser experiment since 2015

Polarizer

Analyzer

Photo detector

High finesse Fabry-Pérot cavity = 2 high reflective mirrors

$\Delta n$ changed the polarization of incident light.

Fabry-Pérot cavity enhances the interaction length by $2F/\pi$ (F: finesse)
Key technologies: Magnet & Fabry-Pérot cavity

**Pulsed Magnet**

- 9T and -4.5T along 20cm, $f_{\text{rep}} = 0.05\text{Hz}$
- Timing profile → separate signal from BG

**Fabry-Pérot cavity**

- $L = 1.4\text{m}$ & $R > 99.999\%$
- Cavity finesse: $F \sim \pi/(1-R)$
- $F_{\text{measured}}$ is 350,000 !!
  - High finesse → sever resonance condition
  - Laser frequency feedback

**Experimental setup**

- Magnetic field shape
  - $B=9.0\text{T}$
  - $1.2\text{ms}$

- Mirror displacement [nm]
  - FWHM 3pm....
The Challenge of OVAL experiment

With great magnetic field comes great disturbance..

If the magnet is broken...

Magnet in LqN$_2$

Experimental setup

Ele-mag stress: 40MPa
Current: 10kA
Stabilization effort

- Large disturbance from magnet
  ✔ vibration isolation
  ✔ magnetic shield
  ✔ precise feedback is necessary
- After many trial and error, the stable operation is established
N₂ Measurement

- Polarization change induced by N₂ is measured at 3 different pressures.
- A validation of the current system and analysis procedure.

Typical result of 300 Pa N₂

\[ k_F(N₂) = (1.64 \pm 0.03\,\text{stat} \pm 0.15\,\text{sys}) \times 10^{-15} \, \text{T}^{-1}\text{Pa} \]

Pressure dependence of polarization change

Theoretical value \( k_F = 1.8 \times 10^{-15} \, \text{Pa} \)
Test run / Analysis

- Last year, test run of OVAL experiment was performed
- 6000 pulses during 1 day → Strongest B(t) as VMB experiment
- Polarization change is fitted by $B^2(t)$, then $k_{CM}$ is obtained.

No significant signal is observed.

From the distribution of $k_{CM}$, $k_{cm} < 6.5 \times 10^{-20} \text{ [T}^{-2}]$

Polarization change = $2L_B F k_{CM}/\lambda \times B^2$
✓ Stale operation of the cavity with magnet is succeeded
✓ The sensitivity is needed to be improved 3500 times
→ The experiment is just started...
Current works

- The upgrade of magnet and Fabry-Pérot cavity is ongoing!

### Test run

- **Magnet**
  - $B = 9T$
  - $L_B = 0.2m$
  - $\Delta t_{\text{pulse}} = 1ms$
  - $f_{\text{rep}} = 0.05 \text{ Hz}$

- **Fabry-pérot**
  - $L = 1.4m$
  - RIN $= -80dB$

### New setup

- **Magnet**
  - $B = 16T$
  - $L_B = 0.2m \times 4$
  - $\Delta t_{\text{pulse}} = 4ms$
  - $f_{\text{rep}} = 0.05 \text{ Hz}$

- **Fabry-pérot**
  - $L = 3.2m$
  - RIN $= -110dB$

QED predicted VMB is observed in 200 days
Summary

• VMB is a non-linear effect of the QED in the vacuum and the good probe for ALPs.

• The OVAL experiment is searching for VMB with strong pulsed magnet and high-finesse Fabry-Pérot cavity.

• Test run of OVAL experiment is performed, the stable operation of the whole system is established.

• The obtained result is $k_{cm} < 6.5 \times 10^{-20} \ [T^{-2}]$

• The upgrade of a Fabry-pérot cavity and pulsed magnets is ongoing.

• QED predicted VMB can be observed in 200 days.
Thank you

• Many interesting experiments in tabletop team including...
  • Development of a laser towards BEC of Positronium
  • Light Shining through the Wall with XFEL
  • Search for Vacuum Birefringence with XFEL
  • Search for hidden photon with Gyrotron

• Ask me anytime if you are interested!!
Back up
Which magnet is the best?

• Requirement
  ✓ Strong
  ✓ Higher frequency modulation
  ✓ Less disturbance to cavity

<table>
<thead>
<tr>
<th></th>
<th>Strong field</th>
<th>modulation</th>
<th>Disturbance</th>
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<tbody>
<tr>
<td>SC mag</td>
<td>◯</td>
<td>×</td>
<td>△</td>
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<td>Pulsed mag</td>
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<td>Dipole mag</td>
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高速繰り返しコンデンサバンク

・われわれは放電スイッチを逆並列に2つ接続

放電スイッチ×2

Charging apparatus

C

Magnet coil

R

L
高速繰り返しコンデンサバンク

・最初、普通に電圧$V_0$まで充電

放電スイッチ×2

充電

- $CV_0$

$+CV_0$

Magnet coil
高速繰り返しコンデンサバンク

- 上側の放電スイッチのみONにすることとでパルスが1発発生
- コンデンサは$V_1$の電圧で逆充電される

放電スイッチ×2

実測例
高速繰り返しコンデンサバンク

・今度は下側の放電スイッチのみONにして逆向き磁場のパルスが1つ発生

・コンデンサは$V_2$の電圧で充電される

実測例

放電スイッチ×2

図：高速繰り返しコンデンサバンクの原理

Charging apparatus

$+CV_2$

$-CV_2$

逆放電

Magnet coil

$R$

$L$
高速繰り返しコンデンサバンク

・その後、磁石での発熱で失われた分を再充電。これの繰り返し。

・これにより充電にかかる時間を大幅に短縮と順・逆磁場の両方のデータを取り系統誤差を減らす。

![電気回路図](image)
漏れ磁場

磁石の中心から3軸方向に離れていた時のシミュレーション

• ダイポール輻射なので、距離の3乗へたるのを確認
  • 例えば7-8T@10kAの時、1m離れると1ガウス
• あとは5号機で実測してOKなら書類出します。
バンク写真 1/2
バンク写真 2/2