Axion-like dark matter search using ferromagnetic toroids

Alexander Gramolin, Deniz Aybas, Dorian Johnson, Janos Adam, and Alexander Sushkov

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Northeastern University
Boston, MA
• Dark matter (DM) accounts for $\approx 1/4$ of the total energy density of the Universe

• The local DM energy density is

$$\rho_{DM} \approx 0.4 \text{ GeV/cm}^3$$

• QCD axions and axion-like particles are excellent DM candidates

• The number density of axions per de Broglie volume is large: $n_a/\lambda^3 \gg 1$

• As a result, axions form an oscillating classical field

$$a(t) = a_0 \sin (m_a t), \quad a_0 \approx \sqrt{2\rho_{DM}/m_a}$$  \text{(in natural units, i.e., } \hbar = c = 1)$$

• Coherence time of these oscillations is limited by the virial velocity $v_{vir} \approx 10^{-3} c$:

$$\frac{\Delta \omega_a}{m_a} \approx v_{vir}^2 \approx 10^{-6}, \quad \tau_c \approx 10^6 \frac{2\pi}{m_a}$$
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Axion electrodynamics

In the presence of a background axion field

\[ a(t) = a_0 \sin(m_a t), \]

inhomogeneous Maxwell’s equations take the form (in natural units, i.e., \( \varepsilon_0 = \mu_0 = 1 \))

\[
\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \quad \text{(Gauss’s law)},
\]

\[
\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} + g_{a\gamma\gamma} \left( \frac{\partial a}{\partial t} \mathbf{B} + \nabla a \times \mathbf{E} \right) \quad \text{(Ampère’s law)}.
\]

Under static magnetic field \( B_0 \), DM axions source an effective current density

\[
\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} B_0 = g_{a\gamma\gamma} \sqrt{2 \rho_{\text{DM}}} B_0 \cos(m_a t).
\]

\[ P. \ Sikivie, \ PRL \ 51, \ 1415 \ (1983) \]

\[ P. \ Sikivie, N. \ Sullivan, \ D. \ B. \ Tanner, \ PRL \ 112, \ 131301 \ (2014) \ — \ LC \ Circuit \ proposal \]
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Experimental approach

- Toroidal coil creates an azimuthal static magnetic field $B_0$
- Axion field $a(t)$ sources an azimuthal effective current $J_{\text{eff}}$
- $J_{\text{eff}}$ generates an axial oscillating magnetic flux $\Phi_a$
- $\Phi_a$ can be detected by a SQUID coupled to a pickup coil
- Similar to ABRACADABRA, but we use ferromagnetic core material to enhance $B_0$: $B_0 = H_0 + M$ (natural units)
- We tried two core materials: gadolinium-iron garnet (GdIG) and Fe-Ni alloy powder

\[ a(t) = a_0 \sin(m_at) \]

\[ J_{\text{eff}} = g_{a\gamma} \frac{\partial a}{\partial t} B_0 \]

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Experimental apparatus

Fe-Ni alloy powder core toroids:

- magnetizing coil
- pickup coil
- calibration loop
- permeability sensing coil

\[ r = 24 \text{ mm}, \quad R = 39 \text{ mm}, \quad h = 16 \text{ mm} \]
SQUID magnetometers

SQUIDS from Magnicon GmbH (Germany)

Flux noise at 4 K: \( \approx 1 \mu\Phi_0/\sqrt{\text{Hz}} \)

Broadband readout circuit

\[ \Phi_{\text{SQUID}} = \frac{N_p M_{\text{in}}}{L_p + L_{\text{tp}} + L_{\text{in}}} \Phi_a \]

\( M_{\text{in}} = 9 \, \text{nH}, \ L_{\text{in}} = 1.8 \, \mu\text{H}, \ L_p = 3 \, \mu\text{H} \)

Optimal number of turns: \( N_p = 6 \)
Magnetization measurements

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**Magnetizing coil**

- **Current [A]**
  - Values: -10, -5, 0, 5, 10

- **Magnetic permeability**
  - Values: 10^-2, 10^-1, 10^0, 10^1, 10^2

**Permeability sensing coil**

- **B field [T]**
  - Values: 0, 1, 2

- **H field [A/m]**
  - Values: -8, -6, -4, -2, 0, 2, 4, 6, 8

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DPF2019 — July 31, 2019
Magnetization measurements

![Graph of Magnetizing coil](image1)

![Graph of Permeability sensing coil](image2)

**Magnetizing coil**

- Magnetic permeability vs. Current [A]

**Permeability sensing coil**

- Inductance vs. Current [A]
Sensitivity scaling

- Axion flux scales with the static magnetic field and the toroid effective volume as

\[ \Phi_a = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} H_{\text{min}} V \]

- For 6 A current in the magnetizing coil:

\[ H_{\text{min}} = 41 \text{ kA/m}, \quad V = 396 \text{ cm}^3 \]

- A factor of 30 enhancement compared to an air-core toroid \((V = 13.4 \text{ cm}^3)\)

- Sensitivity scales with the integration time, \(t\), as

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\text{sensitivity } \propto \begin{cases} 
\sqrt{t}, & \text{if } t \ll \tau_c \text{ (coherent averaging)}, \\
\frac{4}{\sqrt{\tau_c}} t, & \text{if } t \gg \tau_c \text{ (incoherent averaging)}, 
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where \(\tau_c\) is the axion coherence time \((\tau_c \approx 10^3 \text{ s for } f_a = 1 \text{ kHz})\)

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\[ D. \ Budker \ et \ al., \ Phys. \ Rev. \ X \ 4, \ 021030 \ (2014) \quad \text{— CASPER proposal} \]
Sensitivity reach of the experiment

\[ \Phi_{\text{SQUID}} < \frac{1}{4} \frac{\mu \Phi_0}{\sqrt{\text{Hz}}} \frac{1}{\sqrt{\tau_c} t} \]

\[ g_{a\gamma\gamma} < \frac{1}{4} \frac{\mu \Phi_0}{\sqrt{\text{Hz}}} \frac{1}{\sqrt{\tau_c} t} \times \frac{L_p + L_{tp} + L_{in}}{N_p M_{in}} \times \frac{1}{\sqrt{2 \rho_{DM} H_{\text{min}} V}} \]

\[ \text{CAST (2017)} \]

1 day

10 days

\[ \text{Axion coupling } g_{a\gamma\gamma} \text{ (GeV}^{-1}) \]

\[ \text{Axion mass (eV)} \]

V. Anastassopoulos et al. (CAST Collaboration),

Nature Physics 13, 584 (2017)
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arXiv:1811.03231
Summary and outlook

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- It generates an oscillating magnetic field in the presence of a static one
- Using SQUIDs we can search for axion DM in peV–neV mass range
- We enhance the static magnetic field with ferromagnetic toroidal cores
- Fe-Ni alloy powder cores provide a factor of 30 increase in sensitivity
- Projected sensitivity of the experiment surpasses the existing laboratory limits
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