Experimental overview on axion-like dark matter and time-varying EDM

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UC Berkeley Physics NSD LBNL

EDM Workshop, CERN, 26 March 2018
So what is DM or what mimics it?

- A gross misunderstanding of gravity (MOND, …) 😞?
- Proca MHD (finite photon mass) ?
- Black holes, dark planets, interstellar gas, … 😞
- WIMPS 😊
- Ultralight bosonic particles
  - Axions (pseudoscalar) 😊
  - ALPs (pseudoscalar) 😊
  - Dilatons (scalar) 😊
  - Vector particles 😊
  - Tensor particles ???
“Most Wanted” file on DM
What do we know?

- Galactic DM density: $\sim 0.4$ GeV/cm$^3$ (10 GeV/cm$^3$ d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be \textbf{bosonic} if $m < \sim 20$ eV (1 keV dwarf galaxies)
- "Bosonic Oscillator" with $Q \sim (v/c)^{-2} \sim 10^6$
- Cannot be lighter than $\sim 10^{-22}$ eV
- … (e.g., BEC ?)
Why Axions (ALPs)?

- Big clean-up?
  - Strong CP problem
  - Dark Matter
  - Dark Energy
  - Baryon asymmetry of the Universe
  - Hierarchy?
  - …

http://earthsky.org/space/
How to search for Axions (ALPs)?

Axion (ALP) Interactions

Gravity

P. Graham
S. Rajendran

2017
New Horizons
In Physics Prize

Gauge Fields

Most Searches

(FERMILAB-E)

Fermions

(CASPER-Wind, GNOME, QUAX)

\( \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \)

\( \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \)

\( \frac{\partial \mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma^5 \Psi_f \)
High magnetic fields for fundamental physics

Rémy Battesti\textsuperscript{a}, Jerome Beard\textsuperscript{a}, Sebastian Böser\textsuperscript{b}, Nicolas Bruyant\textsuperscript{a}, Dmitry Budker\textsuperscript{b,c,d,e,*}, Scott A. Crooker\textsuperscript{f}, Edward J. Daw\textsuperscript{g}, Victor V. Flambaum\textsuperscript{h,b,c}, Toshiaki Inada\textsuperscript{i}, Igor G. Irastorza\textsuperscript{j}, Felix Karbstein\textsuperscript{k,l}, Dong Lak Kim\textsuperscript{m}, Mikhail G. Kozlov\textsuperscript{n,o}, Ziad Melhem\textsuperscript{p}, Arran Phipps\textsuperscript{q}, Pierre Pugnat\textsuperscript{r}, Geert Rikken\textsuperscript{a,**}, Carlo Rizzo\textsuperscript{a}, Matthias Schott\textsuperscript{b}, Yannis K. Semertzidis\textsuperscript{m,s}, Herman H. J. ten Kate\textsuperscript{f}, Guido Zavattini\textsuperscript{u}
A new (?) idea on the arXiv today: partially transparent wall, atoms as detectors

Interference-assisted resonant detection of axions

H. B. Tran Tan,¹ V. V. Flambaum,¹,² I. B. Samsonov,¹,³ Y. V. Stadnik,¹,² and D. Budker²,⁴
Helioscopes

<table>
<thead>
<tr>
<th>Experiment</th>
<th>References</th>
<th>Status</th>
<th>B (T)</th>
<th>L (m)</th>
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Haloscopes

ADMX

**Diagram:**
- Bucking Magnet
- SQUID Amplifier
- 8 T Magnet
- Microwave Cavity

**Graph:**
- $g_{sv}/\text{GeV}^{-1}$ vs mass / eV
- Legend:
  - QCD Axions (DFSZ)
  - QCD Axions (KSVZ)
  - ORGAN Projected
  - CAPP Prospects (18T)
  - CAPP Prospects (25T)
  - HAYSTAC
  - ADMX
  - ADMX Prospects

**Table:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>References</th>
<th>Status</th>
<th>$B$ (T)</th>
<th>$V$ (m$^3$)</th>
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<th>Axion/ALP mass range ($\mu$eV)</th>
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</table>
New haloscopes: DM Radio, ABRACADABRA

\( f = \frac{m_\alpha}{2\pi} \)

kHz MHz GHz THz

CAST

SN 1987a \( \gamma \)-ray

30 L DETECTOR
\( T=0.01 \text{K}, B=0.1 \text{T} \)

0.5 T

B=0.1 T

0.5 T

4.0 T

1 m\(^3\) DETECTOR, \( T=0.01 \text{K} \)

QCD axion

DARK MATTER RADIO

peV neV \( \mu \text{eV} \) meV

\( m_\alpha \)
How to search for Axions (ALPs)?

Axion (ALP) Interactions

Gravity

Gauge Fields

\[ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Most Searches

(CASPER-E)

Fermions

\[ \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

(CASPER-Wind, GNOME, QUAX)
Cosmic Axion Spin Precession Experiment (CASPEr)

Proposal:
Peter Graham
Surjeet Rajendran
Alex Sushkov
Micah Ledbetter
Dmitry Budker

CASPEr Overview

Key ideas:

• Axion (ALP) field oscillates
• at a frequency equal to its mass (mHz to GHz)
• \( \rightarrow \) time varying CP-odd nuclear moments:
  • nEDM, Schiff, …
• Also: axion wind (like a magnetic field)
• \( v \sim 10^{-3} c \) (virial velocity)
• Coherence time: \( [m_a (v/c)^2]^{-1} \) \( \rightarrow Q \sim 10^6 \)
Nuclear Magnetic Resonance (NMR)

Resonance: \[ 2\mu B_{\text{ext}} = \omega \]
SQUID pickup loop

Larmor frequency = axion mass $\rightarrow$ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid $^{129}\text{Xe}$, ferroelectric $\text{PbTiO}_3$
Our collaboration

Deniz Aybas (Boston University)
Janos Adam (Boston University)
Sasha Gramolin (Boston University)
Annalies Kleyheeg (Boston University)
Alex Wilzewski (Mainz)
Arne Wickenbrock (Mainz)
John Blanchard (Mainz)
Gary Centers (Mainz)
Nataniel Figueroa (Mainz)
Marina Gil Sendra (Mainz)
Tao Wang (UC Berkeley)

Alex Sushkov (Boston University)
Dmitry Budker (UC Berkeley & Mainz)
Derek Kimball (CSUEB)
Surjeet Rajendran (UC Berkeley),
Peter Graham (Stanford)

Mainz and Stockholm:
CASPEr-wind using liquid Xenon, ZULF

Boston University:
CASPEr-electric using spins in solids

Stanford, Berkeley, CSUEB:
Oscillating-EDM NMR

\[ d_n \approx 10^{-34} \cos (m_a t) e \cdot cm \]

Small, but with potential advantages over static EDM searches

Easier to fight technical noise at high frequency

Solid State NMR seems promising

Large spin density

Large intrinsic fields in polar crystals

Long \( T_2 \) with dynamic decoupling

Relates to work on solid state static EDM searches

Bouchard et al.,
http://doi.org/10.1103/PhysRevA.77.022102
Eckel et al.,
http://doi.org/10.1103/PhysRevLett.109.193003
# EDM enhancement

<table>
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<th>Atoms</th>
<th>Molecules</th>
<th>F/E solids</th>
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<tr>
<td>High electric field</td>
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<td>?</td>
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<tr>
<td>Long $T_2$</td>
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<td></td>
<td>?</td>
<td>✓</td>
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</table>
Sample material

effective interaction: \( H_e = \vec{\sigma} \cdot \vec{B}_1^* \cos \omega_a t \)

1) maximize \( \vec{B}_1^* = g_d a_0 \vec{E}^* \)
2) maximize spin density
3) optimize spin coherence time

1) use a **ferroelectric solid** where nuclear spin are subject to effective electric fields

\[ E^* \approx 10^8 \text{ V/cm} \]

similar to a polar molecule: \[ \text{ACME [Science 343, 269 (2013)]} \]

2) nuclear spin **density**: \( n \approx 3 \times 10^{21} \text{ cm}^{-3} \)

3) nuclear spin **coherence time**: \( T_2^* \approx 1 \text{ ms} \)

materials: \( \text{PbTiO}_3 \)

\( \text{Pb(Zr, Ti)}_3 \text{O}_3 \) (PZT)

\( (1 - x)[\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})_3\text{O}_3]/x[\text{PbTiO}_3] \) (PMN – PT)

\( \text{Pb}_5\text{Ge}_3\text{O}_{11} \)

[Phys. Rev. X 4, 021030 (2014)]

commercially available

used for novel piezoelectric transducers
PMN-PT ferroelectric hysteresis

- we can polarize and depolarize our PMN-PT crystals at room temperature
- ferroelectric polarization persists after thermal cycling

materials:  
\[ \text{PbTiO}_3 \]  
\[ \text{Pb(Zr, Ti)}_3 \text{O}_3 \ (PZT) \]  
\[ (1-x)[\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})_3\text{O}_3]/x[\text{PbTiO}_3] \ (PMN - PT) \]  
\[ \text{Pb}_5\text{Ge}_3\text{O}_{11} \]

\[ T_K \approx 180 \, ^\circ \text{C} \]

[Phys. Rev. X 4, 021030 (2014)]
Measurements

- Interesting hysteresis loop at 77K
Detection

goal: detect sample spins tilting and precessing due to axion dark matter

**inductive (Faraday) detection:**

- pickup coil
- matched tank circuit
- RF amplifier

**SQUID:**

- superconducting pickup coil
- commercial SQUID

used for precision magnetometry in a wide range of frequencies

Slide by Alex Suskov (adapted)
Detection electronics test: SQUID magnetometer noise at 4K

goal: test SQUID electronics and data acquisition

**SQUID:**
superconducting pickup coil + commercial SQUID

---

**intrinsic SQUID noise** (no pickup coil)

**SQUID noise with a pickup coil**

- SQUID noise is on the level of $\mu \Phi_0/\sqrt{\text{Hz}}$
- vibrational peaks are below kHz
- tested SQUID performance in CASPER-like conditions
The experimental reach of CASPER

[Graphical representation showing the experimental reach of CASPER with various scales and labels such as frequency (Hz), axion coupling $g_d$, axion mass (eV), Planck scale, GUT scale, SN1987A, QCD axion, and ADMX.]
The experimental reach of CASPER

CASPER-now at BU:
- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

[Phys. Rev. X 4, 021030 (2014)]
The experimental reach of CASPER-

- **optically enhanced spin polarization**
- **5 cm sample size,**
- **14T magnet, homogeneity 100 ppm**
- **tuned SQUID circuit?**

**CASPER-now at BU:**
- **thermal spin polarization,**
- **0.5 cm sample size,**
- **9T magnet, homogeneity 1000 ppm**
- **broadband SQUID detection**

**phase II:**
- **optically enhanced spin polarization**
- **5 cm sample size,**
- **14T magnet, homogeneity 100 ppm**
- **tuned SQUID circuit?**

[Phys. Rev. X 4, 021030 (2014)]

Slide by Alex Suskov (adapted)
The experimental reach of CASPER

CASPER-now at BU:
- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

phase II:
- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

phase III:
- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

[Phys. Rev. X 4, 021030 (2014)]
"CASPER-Now" and related work

The PSI nEDM result is the only one so far for oscillating EDM! (but several wind results coming up)

Future:

Axion dark matter search with the storage ring EDM method

Seung Pyo Chang$^{ab}$, Selenk Haciomeroglu$^b$, On Kim$^{ab}$, Soohyun Lee$^b$, Seongtae Park$^{ab,*}$, Yannis K. Semertzidis$^{ab}$

$^a$Department of Physics, KAIST, Daejeon 34141, Republic of Korea
$^b$Center for Axion and Precision Physics Research, IBS, Daejeon 34051, Republic of Korea

arXiv:1710.05271
Needed Wanted:

Detailed Theory of Axion/ALP-Induced EDMs and Wind coupling for

n, p, $^{129}$Xe, $^3$He, $^{85}$Rb, $^{87}$Rb, $^{133}$Cs, $^{207}$Pb, ...