EDM, Axions, Axion-Like Particles, and The Dark Side

Dmitry Budker
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CP violation workshop
Mahabaleshwar India, February 2013
Stuart J. Freedman
1944-2012
Outline:

• General introduction to EDMs
• Proposed search for oscillating EDM
• Proposed search for cosmic domains of Axion Like Particles

CP violation workshop
Mahabaleshwar India, February 2013
Permanent EDM of a particle contradicts both P- and T-invariance

T violation was not understood in the first EDM experiments!
Prof. Norman F. Ramsey (1915–2011)

“What if we see an EDM?”
But what about polar molecules?

No EDM in a state with a well defined rotational quantum number!
“Permanent” EDM of KRb

“Given the measured B, the fit of the Stark shift (line in lower panel) gives a permanent electric dipole moment of 0.566(17) D.”

T violation and EDM

- Existence of particle EDM implies T reversal invariance violation
- T reversal violation implies CP violation if CPT symmetry preserved
- Std. model $\implies$ immeasurably small EDM
- EDMs are good to look beyond Std. model
EDM causes spin to precess in an electric field
Universal Statistical Sensitivity Formula ("Equation One")

\[ \delta d \approx \frac{\hbar}{E} \cdot \frac{1}{\sqrt{N \tau T}} \]

- Electric field
- Number of Particles
- Coherence Time
- Lifetime of Experimentalist
OSCILLATING AXIONS AND “EDM NMR”

**Theory**: Peter Graham and Surjeet Rajendran (Stanford)

**Experimental dreams**: Micah Ledbetter and D. Budker (UC Berkeley & LBNL); Alex Sushkov (Harvard)

**CP Violation Workshop, Mahabaleshwar, Maharashtra, India, February 2013**
• Introduced to solve strong CP problem in QCD:
• why is n-EDM so small?
• Axions may also solve the Dark Matter problem

**AXIONS**

<table>
<thead>
<tr>
<th>Interactions</th>
<th>Gravity, Electromagnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Hypothetical</td>
</tr>
<tr>
<td>Theorized</td>
<td>1977, Peccei and Quinn</td>
</tr>
<tr>
<td>Mass</td>
<td>$10^{-12}$ to $1$ eV/$c^2$</td>
</tr>
<tr>
<td>Electric charge</td>
<td>0</td>
</tr>
<tr>
<td>Spin</td>
<td>0</td>
</tr>
</tbody>
</table>

http://scienceblogs.com/startswithabang/files/2012/04/rotationCurve.jpeg
http://earthsky.org/space/
• $f_a$ - axion decay constant
• expected to be around $M_{\text{GUT}}(\sim 10^{16} \text{ GeV}) - M_{\text{Pl}}(\sim 10^{19} \text{ GeV})$

$\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$ is the QCD confinement scale

$m_a \sim \frac{\Lambda_{\text{QCD}}^2}{f_a}$

• Axion parameter space:

Theoretically “natural” range

Graham & Rajendran, 2011
Axion dark matter detection with cold molecules

Peter W. Graham
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA

Surjeet Rajendran

- Axion field oscillates
- at a frequency equal to its mass
- $\implies$ time varying CP-odd nuclear moments:
- nEDM, Schiff, …
**NEW IDEAS**

**PHYSICAL REVIEW D 84, 055013 (2011)**

**Axion dark matter detection with cold molecules**

Peter W. Graham

*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*

Surjeet Rajendran

- Existing searches rely on axion-photon conversion via the coupling $\mathcal{L} \supset g_{a\gamma} \frac{a}{f_a} F \tilde{F} = g_{a\gamma} \frac{a}{f_a} \tilde{E} \cdot \tilde{B}$

- Graham & Rajendran: use coupling to gluons instead

- $\implies$ background axions generate nucleon EDM:

$$d_n = 1.2 \times 10^{-16} \theta_{QCD} \text{ e} \cdot \text{cm}.$$  

- in analogy to QCD
NEW IDEAS

PHYSICAL REVIEW D 84, 055013 (2011)

Axion dark matter detection with cold molecules

Peter W. Graham
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Surjeet Rajendran

• What is the local density of axion dark-matter field?
• Nearly constant value everywhere after inflation
• Subsequent evolution governed by the mass term

\[ \mathcal{L} \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} \text{tr} G \tilde{G} + m_a^2 a^2 \]

\[ m_a \sim \frac{(200 \text{ MeV})^2}{f_a} \sim \text{MHz} \left( \frac{10^{16} \text{ GeV}}{f_a} \right) \]

• Oscillating solution: \( a(t) = a_0 \cos(m_a t) \)
• All axion interactions suppressed \( \rightarrow \) no thermalization
• Good cold dark matter candidate

Axion field affected by gravitation $\rightarrow$ galactic speed

$\nu/c \sim 10^{-3}$ $\implies$ finite coherence length $\sim h/mv \sim 500$ km($\frac{f_a}{M_{GUT}}$)

and coherence time $\sim h/mv^2$

$\rightarrow \sim 10^6 \times$ field oscillation period
• Assuming that axions are the dark matter
• and taking \( m_a \sim 10^{-19} \text{ GeV}(M_{\text{GUT}}/f_a) \Rightarrow \theta_a = \frac{a_0}{f_a} \sim \frac{\sqrt{g_{\text{DM}}}}{\Lambda_{\text{QCD}}^2} \sim 3 \times 10^{-19} \).

• This generates oscillating EDM:
• Independent of \( f_a \)
• Nucleons radiate (but no problem)
• “Classic” EDM searches are insensitive to oscill. EDM
• The oscillating EDM is tiny
• But lots of potential advantages over static EDM expts
• For example, can increase $T_2$ via dynamic decoupling
• Easier to fight technical noise at high frequency
• Solid-state NMR seems promising
• Take advantage of large intrinsic fields in polar crystals
• Relates to recent theoretical and experimental work on solid-state non-oscillating EDM searches

$d_n \approx 4 \times 10^{-35} \cos(m_a t) \text{ e} \cdot \text{cm}$

Solid-state “magnetization” experiment:

- Obvious benefit: very large $N$
- But there could be more…

\[ B \approx N\mu \frac{dE}{kT_S} \]

$B$ is measured by a magnetometer.

(F. L. Shapiro, Usp. Phys. Nauk (1968))
The perovskite crystal structure of PbTiO₃
The perovskite crystal structure of PbTiO$_3$
PbTiO$_3$ is a ferroelectric crystal $\rightarrow$ large effective electric field: $E_{\text{int}} \approx 10^8$ V/cm as in diatomic molecules!

A solid-state experiment $\rightarrow$ large number of atoms: $N \approx 10^{22}$ cm$^{-3}$

Nuclear de-magnetization cooling to reach nuclear spin temperature: $T_s \approx 10^{-4}$ K

Other schemes (optical pumping?) may give even lower nuclear spin temperature: $T_s \approx 10^{-8}$ K
Sensitivity of condensed-matter $P$- and $T$-violation experiments

D. Budker,¹,²,* S. K. Lamoreaux,³,† A. O. Sushkov,¹,‡ and O. P. Sushkov⁴,§

PRECESSION EDM EXPERIMENTS

• Single-shot Ramsey-type measurement over coherence time ($\tau$):
  
  \[ S_1 \approx \frac{N}{\tau} \frac{dE}{\hbar} \]

  Signal: \[ S_1 \approx \frac{N}{\tau} \frac{dE}{\hbar} \]

  Noise: \[ N_1 \approx \sqrt{N} \]

  Things get better for longer measurement ($t$):

  \[ \frac{S}{N} \approx \frac{S_1}{N_1} \sqrt{\frac{t}{\tau}} = \sqrt{\frac{N}{\tau}} \frac{dE}{\hbar} \sqrt{t/\tau}. \]

CM MAGNETIZATION EXPERIMENTS

Signal: \[ S_1 \propto \frac{N}{T} \frac{dE}{\mu} \]

Noise: \[ N_1 \propto \sqrt{N \mu} \]

Things still get better for longer measurement ($t$):

\[ \frac{S}{N} \approx \frac{S_1}{N_1} \sqrt{\frac{t}{\tau}} = \sqrt{\frac{N}{T}} \frac{dE}{\mu} \sqrt{t/\tau}. \]

but…

it is better to have a short relaxation time $\tau$
What happens at low temperature?

• Relaxation is determined by dipole-dipole interactions between spins

• Relaxation time scale and energy of the d-d interaction are related:

\[ \mathcal{J} \approx \frac{\hbar}{\tau}. \]

• Induced magnetization scales as \( T^{-1} \) down to:

\[ T_{opt} \approx \mathcal{J}. \]

below that \( \Rightarrow \) (anti)ferromagnetic transition

• Substituting into

\[ \frac{S}{N} \approx \frac{S_1}{N_1} \frac{t}{\tau} = \sqrt{\frac{dE}{T}} \sqrt{t/\tau}. \]

recovers the usual scaling:

\[ \frac{S}{N} \approx \frac{S_1}{N_1} \frac{t}{\tau} = \sqrt{\frac{dE}{\hbar}} \sqrt{\frac{t}{\pi \tau}}. \]
Back to the oscillating EDM story…
Conceptual Setup

Surjeet Rajendran
\[ \delta \theta \sim \frac{d_N B}{2 \mu_N B - m_a} \sin \left( (2\mu_N B - m_a) t \right) \sin \left( 2\mu_N B t \right) \]
Conceptual Setup

Surjeet Rajendran
Rough Estimate

\[ \delta B \sim \pi \rho \mu_N \frac{d_N E}{2 \mu_N B - m_a} \sin ((2 \mu_N B - m_a) t) \sin (2 \mu_N B t) \]

\[ n \sim \frac{10^{22}}{\text{cm}^3} \]

\[ \mu_N \sim \frac{e}{\text{GeV}} \]

\[ d_N \sim 10^{-34} \text{ e-cm} \]

\[ p \sim \mathcal{O}(1) \]

\[ E_{\text{eff}} \sim 10^6 \frac{\text{V}}{\text{cm}} \]

\[ (\mu_N B - m_a)^{-1} \sim (10^{-6} m_a)^{-1} \sim t \sim 1 \text{ s} \left( \frac{f_a}{10^{18} \text{GeV}} \right) \]

\[ \delta B \sim 10^{-2} \text{ fT} \]
Projected Sensitivity in Lead Titanate

\[ \mathcal{L} \supset -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma^5 N F^{\mu\nu} \]

\[ d_N = g_d a \]

\[ p \sim 10^{-3} \]

\[ p \sim 1 \]

\[ \delta B = 0.1 \frac{f_T}{\sqrt{H_2}}, \, n = \frac{10^{22}}{\text{cm}^3}, \, V = 1000 \, \text{cm}^3, \, T_2 = 1 \, \text{s} \]
Solid State Axion Searches

- can most easily search in kHz - MHz frequencies $\rightarrow$ high $f_a$
- technological challenges, similar to early stages of WIMP detection
- axion dark matter is very well-motivated, no other way to search for at high $f_a$
- would be both the discovery of dark matter and a glimpse into physics at very high energies

Surjeet Rajendran
Another story:
How would you know you went through a wall?
All-optical magnetometers

- **Pump**
- **“Precession”**
- **Probe**

*Figure from: D.B. : A new spin on magnetometry*  
*Nature (News&Views) 422, 574 - 575 (2003)*
\[ \delta B \approx \frac{1}{\frac{g \mu}{\sqrt{N \tau T}}} \]

- **Ground-state gyromagnetic ratio**
- **Number of atoms**
- **Spin-relaxation time**
- **Measurement time**
Interlude: breakthrough in coating

Polarized Alkali-Metal Vapor with Minute-Long Transverse Spin-Relaxation Time

M. V. Balabas,¹ T. Karaulanov,² M. P. Ledbetter,²,* and D. Budker²,³

Novel coating type
- \(10^6\) bounces before depolarization!
The Cell
Correlated magnetometers...

- Modern atomic magnetometers are sensitive at the level of $<1 \text{ fT/Hz}^{1/2}$
- Electron and nuclear spin based mags
- What can we learn comparing synchronized separated shielded mags?
Search for exotic fields: GNOME

Global Network Of Magnetometers for Exotic physics
Detecting Domain Walls of Axionlike Models Using Terrestrial Experiments

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(Dated: April 11, 2012)

- Ultralight \((m_a \sim \text{neV})\) axion-like fields forming domain networks
- Wall thickness \(d \sim 2/m_a\)
- Domain size \(L = 10^{-2} \text{ ly}\) consistent with Dark Energy density constraints
- We may be going through a wall every 10 y or so!
- Bottom line: GNOME is quite sensitive to such events!
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Conclusions:

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