The Precision Frontier of Particle Physics

Peter Graham

Stanford
Cosmic Axion Spin Precession Experiment (CASPER)

with

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Axions with NMR

NMR resonant spin flip when Larmor frequency

\[ 2\mu B_{\text{ext}} = \omega \]
Cosmic Axion Spin Precession Experiment (CASPER)

NMR techniques + high precision magnetometry

Larmor frequency = axion mass $\Rightarrow$ resonant enhancement

SQUID measures resulting transverse magnetization
Resonant Enhancement

resonance → scan over axion masses by changing $B_{ext}$

magnetization signal increases linearly in time (axion periods)

resonant enhancement limited by axion coherence time $\tau_a \sim \frac{2\pi}{m_a v^2}$

and nuclear spin transverse relaxation time $T_2$

local B-field inhomogeneities:

$\vec{B}(\vec{r}_1) \neq \vec{B}(\vec{r}_2)$

and spin-spin interactions source transverse spin dephasing

naturally: $T_2 \sim \left( \mu_N \left( \frac{\mu_N}{A^3} \right) \right)^{-1} \sim 1$ ms

designed NMR pulse sequences can improve (dynamic decoupling)
demonstrated $T_2 = 1300$ s in Xe
Cosmic Axion Spin Precession Experiment (CASPER)

NMR techniques + high precision magnetometry

ferroelectric (e.g. PbTiO$_3$) for large $E^*$

NMR pulse sequences (spin-echo, …) for longer $T_2$

NMR techniques for high polarization fraction

quantum spin projection (magnetization) noise small enough
Magnetization Noise

Magnetization (quantum spin projection) noise:

\[ S(\omega) = \frac{1}{8} \left( \frac{T_2}{1 + T_2^2 (\omega - 2\mu_N B)^2} \right) \]

an approximate estimate, in a particular sample magnetization noise must be measured
Axion Limits on $\frac{a}{f_a} G \tilde{G}$

$d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 NF^{\mu\nu}$
\[ d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu} \]
CASPEr-Wind

spin coupling: \((\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi \rightarrow H \propto \nabla a \cdot \vec{\sigma}_N\)

axion DM field gradient torques electron and nucleon spins
oscillates with axion frequency
proportional to axion momentum ("wind")

Similar to CASPEr-Electric but no Schiff suppression, no polar crystal → can use LXe or \(^3\text{He}\)

makes a directional detector for axions (and gives annual modulation)
Cosmic Axion Spin Precession Experiment (CASPER)

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under construction at Mainz and BU

New field of axion direct detection, similar to early stages of WIMP direct detection

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies \(\sim 10^{16} - 10^{19}\) GeV

Targeted Grants in Mathematics and Physical Sciences

The Simons Foundation’s Mathematics and Physical Sciences (MPS) division invites applications for its new Targeted Grants in MPS program.

Rationale:
The program is intended to support high-risk projects of exceptional promise and scientific importance on a case-by-case basis.

How to Apply:
Applicants may submit a Letter of Intent (LOI) through proposalCENTRAL (https://proposalcentral.altum.com/default.asp) beginning August 1, 2015. The deadline is rolling and an applicant can submit at any time. Please coordinate submission of the proposal with the appropriate officials in accordance with institution policies. Please refer to the Application Instructions for further information on and requirements for submitting an application.

For projects with Principal Investigator (PIs) at different institutions, the LOI should be signed and submitted by the PI designated as the main PI and his/her institution.

LOI Requirements Include:
- Research plan (two-page limit, plus up to one page for references and figures): Signed by the main PI on letterhead, which includes a brief summary of the support requested, including the names of the other PI(s) involved, if applicable, the scientific goals, background relevant to the application, and a brief budget justification.
- A tentative yearly budget (two-page limit) indicating total amount and major expense categories with proposed start and end dates.

Applicants will be notified within two months of the LOI submission. Please note that the volume of interest in this program is such that the foundation is not able to provide advance guidance on potential proposals. We use the LOI stage to assess suitability and novelty. The foundation recommends submitting an LOI if an applicant believes his/her research meets the criteria outlined in the RFA.

Full Proposal: A review of the LOI may lead to a request for a full proposal. Full proposals must be submitted through proposalCENTRAL.
QCD Axion Dark Matter

May be able to cover all of QCD axion dark matter:

QCD coupling

EM coupling

NMR

LC circuit
cavities

ADMX

new ideas?
open resonators

many more new ideas beyond these for axion detection in general!
Other Couplings & Techniques
Possibilities for Light Dark Matter

Only really 4 different types of effects, 4 types of experiments needed

- Scalar
- Vector
- Pseudo-scalar (axion)
- Axial-vector

E&M - drive currents
QCD - change nuclear properties
Spin - cause precession
Scalar - new force/change SM properties (e.g. electron mass)

Can cover all these possibilities!
Axion DM Effects

spin coupling: \((\partial_\mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi \rightarrow H \equiv \nabla a \cdot \vec{\sigma}_N\)

axion DM field gradient torques electron and nucleon spins
dooscillates with axion frequency
proportional to axion momentum ("wind")

axion DM field gradient can exert a force
oscillatory and violates equivalence principle

scalar coupling: \(a H^\dagger H\) e.g. change electron mass

same effects allow searches for hidden photons
Force/Torque from Dark Matter


New oscillatory force/torque from dark matter

New Direct Detection Experiments:

Torsion Balances
scalar balance for force
spin-polarized for torque

Atom Interferometers
split + recombine atom wavefunction
measure atom spin and acceleration

Pulsar Timing Arrays
DM and gravitational wave
detection similar

Eot-Wash analysis underway
with Will Terrano

In construction Kasevich/Hogan groups
covers frequency range ~10 Hz down to yr⁻¹
DM Direct Detection

DM mass: $10^{-22}$ eV - $10^{-2}$ eV

- $10^{-8}$ Hz - $10^{-4}$ Hz
- 1 Hz - $10^4$ Hz
- $10^8$ Hz - $10^{12}$ Hz

Coupling:

- E&M
- QCD
- Spin
- Scalar

- Eot-Wash (spin)
- Eot-Wash (scalar)
- Atom Interferometry (spin)
- Atom Interferometry (scalar)
- CASPEr-Electric
- CASPEr-Wind
- ADMX
- HAYSTAC
- LC Circuit
- DM Radio
- ABRACADABRA

+ many important new force/transmission experiments (e.g. ARIADNE)
New Force and Transmission Experiments
DM expts:

- Microwave cavity (e.g. ADMX)
  - Resonance optimal, need to scan frequencies to reach smaller couplings, limited mass range

New force/transmission expts:

- Light-through-walls (e.g. ALPS)
  - Covers all masses (below expt cutoff), not as sensitive in coupling

Amplitude proportional to:

- DM: \( \propto g \)
- New force/transmission: \( \propto g^2 \)
Possibilities for New Fields

4 types of couplings

Scalar
- $\phi h^+ h$, $\phi O_{SM}$
- $A_\mu ' \bar{\psi} \gamma^\mu \psi$
- $F'_\mu\nu F^{\mu\nu}$
- $A_\mu ' \bar{\psi} \gamma^\mu \gamma^5 \psi$

Pseudo-scalar (Axion)
- $a F \bar{F}$
- $a G \bar{G}$
- $(\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi$
- \[ (\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi \]

Vector
- $A_\mu \bar{\psi} \gamma_5 \psi$
- $F'_\mu\nu F^{\mu\nu}$
- $F'_\mu\nu \psi \sigma^{\mu\nu} \psi$
- $A_\mu ' \bar{\psi} \gamma^\mu \gamma^5 \psi$

Axial-Vector
- $A_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$
- $F'_\mu\nu \psi \sigma^{\mu\nu} \psi$
- $A_\mu ' \bar{\psi} \gamma^\mu \gamma^5 \psi$

SM properties
- (electron mass)
- (axion)
- (matter (spin))
- (charged)
- (DM-photon mixing)
- (dipole moment)
- (spin)

E&M - drive currents
QCD - change nuclear properties
spin - cause precession
scalar - new force/
change SM properties
(e.g. electron mass)

arXiv:1512.06165
Possible New Forces
Moody and Wilczek (PRD 1984)

search for a new scalar with a few types of new forces:

Scalar (monopole field)  \( \phi h^\dagger h, \phi \mathcal{O}_{\text{SM}} \)  SM properties (electron mass)

Pseudoscalar (dipole field)  \((\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi\)  matter (spin)

monopole-monopole (scalar-scalar)  \( V \sim \frac{g_1 g_2}{r} e^{-mr} \)

if \( \phi \) has nonzero mass \( m \)

monopole-dipole (scalar-pseudoscalar)  \( V \sim \frac{g_1 g_2}{r^2} \hat{\sigma} \cdot \hat{r} (1 + mr) e^{-mr} \)

spin-dependent forces

dipole-dipole (pseudo-pseudo)  \( V \sim \frac{g_1 g_2}{r^3} (\hat{\sigma} \cdot \hat{\sigma} + \hat{\sigma} \cdot \hat{r} \ \hat{\sigma} \cdot \hat{r}) (1 + mr + m^2 r^2) e^{-mr} \)

effective field theory \( \rightarrow \) only a few possibilities
Experimental Strategies for New Forces

- **Scalar force**
  - Equivalence principle violation: two different test masses
    - will see infinite range (zero mass) force
    - suppressed by composition difference (usually $\sim 10^{-1} - 10^{-2}$)
  - deviations from $r^{-2}$: move test mass around
    - only sensitive at masses $\sim$ distance scale of expt

- **Spin-dependent force**: control spins of source and test masses
  - limited by shortest distance achievable ($V \sim r^{-2}$ or $r^{-3}$), bad backgrounds (EM) at short distances
Motivations

new light particles/deviations from gravity well motivated by many theories: axions, moduli (SUSY), extra dimensions…

e.g. twin Higgs has a new photon, will pick up some (small) kinetic mixing, but potentially testable by high precision experiments/astrophysics

Cosmological Constant Problem:

Raman Sundrum

great, vague, idea: turn off graviton coupling to loops (once far enough off-shell)

\[ \propto \Lambda^4 \quad \Rightarrow \text{require cutoff at momenta} \quad \Lambda \sim \text{meV} \sim (100 \mu\text{m})^{-1} \]

\[ \Rightarrow \text{Newtonian gravity } \frac{1}{r^2} \text{ will cut off below } 100 \mu\text{m} \]
Eot-Wash Torsion Pendulums

high sensitivity possible: use laser readout of angle

backgrounds:
- fiber thermal noise,
- laser readout noise,
- EM forces (Casimir),
- gravity gradients

spin-polarized pendulums:
Deviations from $1/r^2$

\[ \alpha = \text{strength relative to gravity} \quad \lambda \sim m^{-1} \]
Equivalence Principle

Best current limits $\sim 10^{-13}$ and will likely improve from:
- Lunar Laser Ranging: earth - moon falling towards sun
- Torsion balances: two masses (e.g. Al-Be) toward earth

$10^{-13}$ so good it bounds how antimatter falls can only see forces $\sim 6000$ km or longer

HW: is a short-range EP test interesting?

New techniques coming:
- Satellite Test of Equivalence Principle (STEP)
- Atom interferometry

Figure 4: 95%-confidence-level constraints on ISL-violating Yukawa interactions with $\lambda > 1c$ m. The LLR constraints do not the anomalous perigee precession; the remaining constraints are based on Keplerian tests. This plot is based on Figure 2.13 of Reference (14) and updated to include recent LLR results.
Spin-Dependent Forces

$g_{aNN}(\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N$

generally hard for lab measurements to beat astro bounds in spin-dependence
new experiment for axion detection though new force (monopole-dipole) uses NMR as detection technology
The challenge for LSW searches is that for each photon incident on the first (production) magnet to be detected at the end of the second (regeneration) magnet is 

\[ P_{\gamma a} \gamma \propto (g_{\gamma a})^4, \]

and thus the sensitivity in the axion-photon coupling improves only as 

\[ g_{\gamma a} \propto I^{-1/4} t^{-1/8}, \]

where \( I \) is the laser intensity, and \( t \) the integration time, assuming the detector is not background-free.

On the other hand, \( g_{\gamma a} \propto (B)^{-1} \), thus the most effective way to improve the limits of LSW experiments is to increase the product of the magnets' length and strength.

In regard to extending the length of the magnetic field, however, note that when \( q_\ell \sim 1 \), the sensitivity of the experiment degrades significantly and becomes highly oscillatory as a function of mass.

For axions or other pseudoscalars, the incoming light must be polarized parallel to the magnetic field; production of scalars require the orthogonal polarization. A significant virtue of photon regeneration is that the signal can in principle be background-free as the primary beam is blocked at the optical barrier.

Such experiments were first envisioned both for massless (b) and massive (c) pseudoscalars; the latter described how even the intrinsic noise of the photodetector could be rendered negligible by homodyning the signal with the original beam.

A contemporary discussion of photon regeneration, including its applicability for a broad array of axion-like particles, including hidden photons, is found in (116); such LSW experiments can even search for mini-charged particles as is further developed in (117,118).

5.2. Current status of photon regeneration experiments

The ALPS-I experiment (Any Light Particle Search) at DESY has set the strongest published limits to date from an optical LSW experiment (127). This experiment utilized two 4.3 m long magnets of 5 T field strength, and a 532 nm laser of 0.5 W power. An optical cavity encompassing the production magnet boosted the effective laser power to 150 W. A limit on axion-like particles of \( g < 6.5 \times 10^{-8} \) GeV\(^{-1}\) was established, valid for masses \( m < 600 \mu eV \).

A slightly improved limit in the optical regime by the OSQAR collaboration at CERN is awaiting publication (128).

A photon regeneration experiment (CROWS) in the microwave has also been performed utilizing two resonant cavities in a 2.9 T field, setting a slightly weaker limit, \( g < 9.9 \times 10^{-8} \) GeV\(^{-1}\), for masses \( m < 7 \mu eV \).

Both ALPS-I and CROWS have published searches for hidden photons as well, where significantly stronger limits have been set by the microwave experiment, although they probe different mass ranges.

LSW experiments have also been carried out in the x-ray regime at synchrotron light sources (129, 130), probing regions of mass \( m > 1 \) eV.
Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

GRG 43 (2011) arXiv:1009.2702
Every new EM band opened has revealed unexpected discoveries, gravitational waves give a new spectrum.

Advanced LIGO can only detect GW’s > 10 Hz ➜ How look at lower spectrum?

New detectors?
Atomic Clock

\[ |\text{atom}\rangle = |1\rangle \]

1
\[ \frac{1}{\sqrt{2}} \left( |1\rangle + |2\rangle \right) \]

wait time \( t \)

1
\[ \frac{1}{\sqrt{2}} \left( |1\rangle + e^{i(\Delta E)t} |2\rangle \right) \]

beamsplitter

2
\[ \frac{1}{2} \left[ \left( 1 - e^{i(\Delta E)t} \right) |1\rangle + \left( 1 + e^{i(\Delta E)t} \right) |2\rangle \right] \]

beamsplitter

output ports

\( N_1 \)

\( N_2 \)

can measure times \( t \sim \frac{1}{\Delta E} \sim 10^{-10} \text{ s} \)
Atom Interferometry

Space-time Interferometry

\[ \frac{1}{\sqrt{2}} (|2, p + k\rangle + e^{i\Delta\phi} |1, p\rangle) \]

\[ \frac{1}{\sqrt{2}} (|1, p\rangle + e^{i\Delta\phi} |2, p + k\rangle) \]

|atom\rangle = |1, p\rangle

cancels clock shift exactly, what is left?
Sensitivity of Atom Interferometry

A constant gravitational field produces a phase shift:

$$\Delta \phi = \int L dt = \int m d\tau = \int p_\mu dx^\mu$$

The interferometer can be as long as $T \sim 1$ sec $\sim$ earth-moon distance!

$$\Delta \phi \sim mg(\Delta h)T \sim mg \left(\frac{k}{m}T\right) T = kgT^2 \sim 10^8 \text{ rad}$$

The interferometer can be as long as $T \sim 1$ sec $\sim$ earth-moon distance!

$$\Delta \phi \sim \frac{1}{\sqrt{N_{\text{atoms}}}} \frac{1}{\sqrt{N_{\text{shots}}}}$$

each shot $\sim 1$ s $\Rightarrow$ $N_{\text{shots}} \sim 10^7$

$N_{\text{atoms}} \sim 10^6$ per shot $\Rightarrow$ sensitivity in one year $\sim 10^{-7}$ rad

Have sensitivity to forces as small as $\sim 10^{-15} g$
Raman Transition

\[ \psi = c_1 |1, p\rangle + c_2 |2, p + k\rangle \]

\[ |c_1|^2, |c_2|^2 \]

\[ \pi/2 \text{ pulse is a beamsplitter} \]

\[ \pi \text{ pulse is a mirror} \]
measures differential acceleration between two atoms: removes seismic noise
Laser Phase Noise

remove laser noise using multiple baselines
Laser Phase Noise Insensitive Detector

run atom interferometer as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL 110 (2013)

atoms act as clocks, measure light travel time

Removes laser noise, allows single baseline detection
Atom Interferometry for Gravitational Waves

run atom interferometer as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL 110 (2013)

atoms act as clocks → remove laser noise

accelerometer → atoms are good inertial test masses, removes many noise sources
(seismic, thermal vibrations, vacuum gas collisions, charging….)
### Gravitational Wave Detection

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<td>laser</td>
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<td>good clock</td>
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![Diagram of Gravitational Wave Detector](image1)

![Diagram of Atom Interferometry](image2)
100 m Detector Proposal at Fermilab

- MINOS, MINERνA and NOνA experiments use the NuMI beam
- 100 meter access shaft
- Atom DM detector (small scale project)
- 100 m atom interferometer (accelerometer) drop tower
- >3 s drop time to split and recombine atomic wavefunctions
- Detect dark matter through oscillatory force
- Also gravitational waves from unknown sources
- Lead to ~km scale detector for GW’s (e.g. BH mergers) and DM, opens band below LIGO and above LISA (~ 0.1 - 10 Hz)
Atom Interferometry for Gravitational Waves

Atoms could access mid-frequency band

![Image of LISA satellite]

- Earth orbit allows polarization measurement with single detector

For example, this band allows:

- Localize sources on the sky (e.g., sub-degree accuracy) and predict BH and NS binary mergers for other telescopes to observe
- May measure initial BH spins and orbital eccentricity

With Sunghoon Jung
Angular Localization

Phase advance across orbit (between detectors) dominates angular resolution

$$\Delta \theta \sim \text{SNR} \cdot \frac{L}{\lambda}$$

- Highest frequencies where source lasts 6 months are best

Atoms could access mid-frequency band ideal for angular localization

with Sunghoon Jung
Initial Black Hole Spins

Gravitomagnetic BH binary spin-spin effects fall rapidly with distance, seen only in highest frequencies before merger.

LIGO can’t measure well, needs lower frequencies ⇒ atoms (terrestrial or satellite) could measure? gives info on formation history (primordial?), etc. of BH’s.
Recent Experimental Results
(Kasevich and Hogan groups)

Stanford Test Facility

Macroscopic splitting of atomic wavefunction:

atom cooling

→ 50 pK

Summary

Precision measurement is a powerful tool for particle physics and cosmology
new technologies beyond traditional particle detection
e.g. combination of several experiments will cover QCD axion dark matter fully

Light dark matter (axions) and gravitational wave detection similar:
detect coherent effects of entire field, not single particles

- laser interferometry
- atom interferometry (clocks)
- EM resonators (e.g. cavities)
- NMR
- high-precision magnetometry (SQUIDs, atomic systems)
- torsion pendulums
- optically-levitated dielectric spheres
- ...

Many more possibilities we haven’t thought of yet…