Abstract: I will discuss the wide-range of new physics that can be probed with nuclear-spin comagnetometers, from EDM measurements to dark matter direct detection experiments.

I will outline the potential for improvement in these measurements, and how improved quantum control could have a significant impact in our sensitivity. I will present some new dark matter detection results using comagnetometers.
Searching for dark matter and new physics with nuclear spins

William Terrano, ASU
New Physics with Nuclear Spins

- Prepare highly-coherent state
  - $10^{21}$ particles
  - Lifetimes of hours or days
- Readout with quantum sensors
- Study nuclear-spin symmetries and interactions:
  - Baryogenesis (CP-violation)
  - Dark matter couplings (low mass axions)
  - New high-energy symmetries
  - 5th forces (goldstone boson exchange)
Highly Coherent Nuclear Spins

Simple but Powerful

Great for testing new physics!

- Measure energy difference between spin-up and spin-down nuclei
  \[ \mathcal{H}_{\text{spin}} = \mathcal{H}_{\text{mag}} + \mathcal{H}_{\text{BSM}} + \ldots = \vec{\mu}_N \cdot \vec{B} + \vec{\sigma}_N \cdot \vec{\beta} + \ldots \]

- Best \textit{absolute} sensitivity to date for measuring energy splitting of quantum states @ \(10^{-25}\text{eV}\) or \(O(100\ \text{pHz})/10\ \text{Hz}\)

Atomic Clocks best \textit{fractional} uncertainty \(O(\text{mHz})/\text{THz}\)

- Typical magnetic field stability \(O(10^{-4})\): must compare two spins
Spin Exchange Optical Pumping 2

Noble gas nuclei: intrinsically well isolated! Need optical control

Collisional mixing

$\text{Collisional mixing} \quad m_J = -1/2 \quad m_J = 1/2$

$\text{795 nm pump laser (}\sigma_+\text{)}$

Radiative decay

Spin destruction

$\text{Radiative decay} \quad m_s = -1/2 \quad m_s = 1/2$

Circularly polarized laser carries spin 1: selectively pump alkali electron $S_z$
(if decay non-radiative)
Spin Exchange Optical Pumping 1

Noble gas nuclei: intrinsically well isolated! Closed electron shell

How to align the spins?

Alkali Vapors have single valence electron!

Can optically pump

Can turn on and off

— Vapor temp 100°C

From Walker Rev. Mod. Phys., Vol. 69, No. 2, April 1997
Spin Exchange Optical Pumping 2

Noble gas nuclei: intrinsically well isolated!
Need optical control

Circularly polarized laser carries spin 1:
selectively pump alkali electron $S_z$
(if decay non-radiative)
Spin Exchange Optical Pumping 3

Noble gas nuclei: intrinsically well isolated!
Need optical control
Spin Exchange Optical Pumping 3

Biomedical Advance #1

Medical Imaging applications

• MRI image lungs
• Study blood flow
• Developed high-powered lasers for high pressure
Measuring Energy Splitting 1

- Transfer **both ensembles** to spin-up/spin-down superposition (excite density matrix coherence)

\[ \mathcal{H}_{\text{mag}} = \vec{\mu}_N \cdot \vec{B} \quad \mathcal{H}_{\text{BSM}} = \vec{\sigma}_N \cdot \vec{\beta} \quad \mathcal{T}(t) = \exp(iS_z \omega t) \]
Measuring Energy Splitting 2
Biomedical Advance #2

\[ H_{\text{mag}} = \mu_N \cdot \vec{B} \quad H_{\text{BSM}} = \sigma_N \cdot \vec{\beta} \quad T(t) = \exp(iS_z \omega t) \]

- Measure oscillation frequency of \( S_x \) or \( S_y \) in 2 nuclei
- Need different mag and BSM terms

SQUID

Quantum Interference Effects in Josephson Tunneling
R. C. Jaklevic, John Lambe, A. H. Silver, and J. E. Mercereau
Ford Scientific Laboratories, Dearborn, Michigan
(Received 16 January 1964)

Pro: Cheaper & easier to use,
Con: lower bandwidth and in-situ

SERF/Optical rotation

![Image of SQUID and SERF/Optical rotation](image-url)
Measuring Energy Splitting 1

- Transfer **both ensembles** to spin-up/spin-down superposition (excite density matrix coherence)

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Wide range of new physics

**Major Puzzles in SM**
- Baryon asymmetry
- Gravity and quantum theory

**Clues from Spins**
- CP-violation
- Testing Lorentz invariance
Fuzzy Dark Matter:

- DM with $m_a = 10^{-22}$ eV explains minimum size of Dwarf galaxies

Hu, Barkana, Gruzinov Phys. Rev. Lett. 85, 1158

- Natural scale for axion is GUT scale $\sim 10^{16}$ GeV

- With $m_a = 10^{-22}$ eV and $F_a = 10^{16}$ GeV:

  $\rightarrow$ Generic density $= \text{relic dark matter density}$

Hui, Ostriker, Tremaine and Witten; Phys. Rev. D 95, 043541
Quantum weirdness at galactic scales

- Tunneling out of dwarf galaxies
- Soliton at center of galaxy
- Interference fringes
Energy-splitting of Spin along velocity of DM
Doubly-modulated at Earths rotation rate and axion Debroglie frequency

\[ \mathcal{L} = (\partial \mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi \quad \alpha = a_0 \cos \omega_C t \quad H_{\text{ax}} \sim \sqrt{2\rho_{\text{DM}}} \bar{v} \cdot \vec{\sigma}_\psi \cos \omega t. \]

Magnitude \sim \text{axion velocity in lab frame}
DM signal:
huge number of modes — velocity spread matters

w Matt Moschella and Mariangela Lisanti
DM signal: velocity spread matters

Dark Matter Direction changes stochastically!

w Matt Moschella and Mariangela Lisanti
Limits on Axion Dark Matter

![Graph showing limits on axion dark matter](image)

- **Experiment**
- **MC ± 5σ**
- **MC median**
- **SN1987**

**b)** Magnetic power (pT²)

![Second graph showing magnetic power](image)
K-He comagnetometer

![Diagram showing the components of a K-He comagnetometer, including a pump and a probe.]

- $v_E$, $v$, $u$, $\omega_e$, $\hat{m}$
- Theoretical average, sample, and Monte Carlo average are indicated by different markers.
New Data: Measurement in the dark

Pump — Probe cycles
Detection/Precession measurements

Replaced Xenon with Neon (lower Rb interactions)

Rb depolarized with RF fields
Dark Matter Limits

Ne-He Data 30 days  
K-He Data 40 days  
(analysis by Junyi Li & Matt Moschella)
30 Days of Data

Sidereal fit coefficients: χ-level: 5. Fraction of shots dropped: 0.072

Signal rotated with B0: True

mean: 1.1e-10 ± 3.1e-10  χ^2/d.o.f: 1.84

mean: -6.3e-10 ± 3.2e-10  χ^2/d.o.f: 2.99
2019 Xe-EDM — Setup

Separate Pumping station (~10% polarization)

Prepared cells placed in magnetically shielded room near SQUID (~6 fT/rt(Hz))

Spins tipped, Electric fields applied (6-9kV)
CP-violation and spins

Baryogenesis requires new CP-violation

Intrinsic EDM

\[ \vec{\sigma} \sim \vec{v} \times \vec{r} \]

\[ \vec{d} \sim \vec{\sigma} \]

\[ \mathcal{H} = \mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E} \]

- Energy of spin perturbed by relative orientation of electric field
2019 Xe-EDM measurement — Raw Data

![Graph showing signal and amplitude against frequency.]

- Signal [pT]
- Amplitude [pT/√Hz]
- Frequency [Hz]
2019 Xe-EDM — Setup

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Spins tipped, Electric fields applied (6-9kV)
2019 Xe-EDM measurement — EDM extraction
2019 Xe-EDM measurement — Error Table

<table>
<thead>
<tr>
<th></th>
<th>2017 (e cm)</th>
<th>2018 (e cm)</th>
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<tbody>
<tr>
<td>EDM</td>
<td>$7.2 \times 10^{-28}$</td>
<td>$0.9 \times 10^{-28}$</td>
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<tr>
<td>Statistical error</td>
<td>$23.5 \times 10^{-28}$</td>
<td>$6.8 \times 10^{-28}$</td>
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<tr>
<td><strong>Systematic Source</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leakage current</td>
<td>$1.2 \times 10^{-28}$</td>
<td>$4.5 \times 10^{-31}$</td>
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<tr>
<td>Charging currents</td>
<td>$1.7 \times 10^{-29}$</td>
<td>$1.2 \times 10^{-29}$</td>
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<tr>
<td>Cell motion (rotation)</td>
<td>$4.2 \times 10^{-29}$</td>
<td>$4.0 \times 10^{-29}$</td>
</tr>
<tr>
<td>Cell motion (translation)</td>
<td>$2.6 \times 10^{-28}$</td>
<td>$1.9 \times 10^{-28}$</td>
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<tr>
<td>Comagnetometer drift</td>
<td>$2.6 \times 10^{-28}$</td>
<td>$4.0 \times 10^{-29}$</td>
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<tr>
<td>$</td>
<td>\vec{E}</td>
<td>^2$ effects</td>
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<tr>
<td>$</td>
<td>\vec{E}</td>
<td>$ uncertainty</td>
</tr>
<tr>
<td>Geometric phase</td>
<td>$\leq 2 \times 10^{-31}$</td>
<td>$\leq 2 \times 10^{-31}$</td>
</tr>
<tr>
<td><strong>Total Systematic Error</strong></td>
<td>$3.9 \times 10^{-28}$</td>
<td>$2.0 \times 10^{-28}$</td>
</tr>
</tbody>
</table>
2019 Xe-EDM measurement — Raw Data

![Graph showing signal vs. frequency]

**Signal [pT]**

- 2000
db 4000
db 6000
db 8000
db 10000
db 12000
db 14000

**Frequency [Hz]**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

**Amplitude [pT/√Hz]**

- $10^0$
- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
2019 Xe-EDM measurement — EDM extraction
Non-linear Interactions: \[ H_{\text{Scalar}} = \kappa_0 \vec{\sigma}_N \cdot \vec{\sigma}_N \]

Neon amplitude (proxy for state)

Energy Splitting
Non-linear Frequency Instabilities:

\[ \mathcal{H}_{\text{Scalar}} = \kappa_0 \bar{\sigma}_N \cdot \bar{\sigma}_N \]

- Imperfect state transfer to
  - Random
    - \( \mathcal{H}_{\text{Scalar}} \) changes between measurements
  - Systematic
    - \( \mathcal{H}_{\text{Scalar}} \) evolves during measurements
    - \( S_z \) decoheres back to thermal level
Quantum Control
(w V. Batista and L. Santos)

- **Optimal and robust control**: protocol to minimize error in target state in the presence of experimental errors.

- **Dynamical decoupling**: invert unwanted terms in the Hamiltonian (spin-echo for magnetic gradients).

Has been done for a scalar term; need to develop sequence for \(\sim4\) equal sized scalars:

\[
I(\tau/2) - \pi_X - I(\tau) - \pi_Y - I(\tau) - \pi_X - I(\tau/2) \\
I(\tau/2) - \pi_{\pi/6+\phi} - I(\tau) - \pi_\phi - I(\tau) - \pi_{\pi/2+\phi} - I(\tau) - \pi_\phi - I(\tau) - \pi_{\pi/6+\phi} - I(\tau/2)
\]
• Diffeomorphic modulation under observable response preserving homotopy (D-MORPH) gradient and the Broyden Fletcher Goldfarb Shannon (BFGS) iterative scheme for nonlinear optimization.

• Measure and minimize state-asymmetry
ASU system
Rb-free system
SQUID readout (more expensive, more complicated)

- Compact shielding
- In-situ SEOP
- closed cycle liquid Helium system
- Aligned with Earths rotation axis
ASU system
Rb-free system
SQUID readout (more expensive, more complicated)

- Must control nuclear self-interactions (collisional and geometric couplings)
  - Controlled cell geometry
  - Precise quantum state initialization
  - Decouple self-interaction Hamiltonian
- Rotation rate of lab itself
- Maintain or monitor magnetic field direction (Earth's rotation effect)
- Operate SQUID without disturbing Nuclei
ASU System
Great time to get involved :)

- Separate slab for helium reliquification and mechanicals
- Separate room for control system
ASU System

Design Underway — SQUID gradiometer and magnetic shielding

- Limiting noise source in SQUID: magnetic shielding (Johnson Eddy Currents)

- Calculations (by Keaten Wood) of gradiometer options
  - Extended to nth order, and varying radii
  - Optimize Signal to Noise — don’t cancel signal!

- 35x improvement in SNR
ASU System
Design Underway — Magnetic control fields

- Limitation on spin precession lifetime
- Extend formalism to 2nd order gradients
Potential for Ultra-light Axion search

Reach

Astro-current

~ 3 \cdot 10^8 \text{ GeV (?)}

2 \cdot 10^9 \text{ GeV}  \quad 10^{-27}

6 \cdot 10^{10} \text{ GeV}  \quad 3 \cdot 10^{-27}

1 \cdot 10^{12} \text{ GeV}  \quad 2.9 \times 10^{-30}

3 \cdot 10^{13} \text{ GeV}  \quad 1.1 \times 10^{-31}

7 \cdot 10^{14} \text{ GeV}  \quad 4 \times 10^{-33}

Optimistic/Speculative

Density & Polarization:

Same / 1 atm & 50%

Cell size: 6 cm/same

SQUID-spin coupling: same

Spin life time: 2x longer/same

SQUID noise: 0.1 fT/same

SQUID distance: 4.1 cm/same

Within 20x of GUT and SM prediction respectively

Technical requirements already achieved; systematics and self-interactions are the obstacle
High proton-spin sources

Naphthalene doped with Pentacene
Electron polarized optically
Microwave transfer to protons
Thank You

Romalis Group: MVR, Mark Limes, Yukai Lu, Junyi Lee

Tim Chupp, Jonas Meinel

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