Light DM Search with NV Centers in Diamonds

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arXiv: 2302.12756

So Chigusa

11/13/2023 @ UC Davis
Dark Matter as a hint of new physics

“Known”
- DM existence, abundance
- Has gravitational interaction

“Unknown”
- DM mass
- Non-gravitational interactions
DM mass window

- **WIMP miracle** w/ thermal production of $\sim (1)$ TeV
- Other interaction and production mechanisms allow a broader mass range
  - freeze-in
  - misalignment mechanism for light bosonic DM

**Nelson+ ’11, Arias+ ’12**
Light bosonic DM

- QCD axion
- Axion-like particles (ALPs)

- Dark photon
DM-induced electromagnetic field

- QCD axion / axion-like particles (ALPs)
  \[ \mathcal{L} = g_{a f} \frac{\partial \mu a}{2m_f} \bar{f} \gamma^\mu \gamma_5 f \rightarrow H_{\text{eff}} = \frac{g_{a f}}{m_f} \nabla a \cdot S_f \]

- Dark photon
  \[ B_{\text{eff}} \simeq \sqrt{2} \rho_{\text{DM}} e \left( v_{\text{DM}} \times \hat{H} \right) \cos(mt + \delta) \sim 3 aT \left( \frac{g_{a f}}{10^{-10}} \right) \]

- Behaves as an effective EM field with coherence time
  \[ \tau_{\text{DM}} = \frac{2\pi}{m_{\text{DM}} v_{\text{DM}}^2} \sim 6 s \left( \frac{10^{-10} \text{eV}}{m_{\text{DM}}} \right) \]

\[
a(t) \simeq a_0 \cos \left( m_a t + \frac{1}{2} m_a v_a^2 t - \bar{v}_a \cdot \bar{x} + \delta \right)
\]

\[
\rho_{\text{DM}} = \frac{1}{2} m_a^2 a_0^2 \propto m_a^2 / 2
\]

\[
\tau_{\text{DM}} = \frac{2\pi}{m_{\text{DM}} v_{\text{DM}}^2} \sim 6 s \left( \frac{10^{-10} \text{eV}}{m_{\text{DM}}} \right)
\]
Spin dynamics for DM search

- Spin dynamics in various condensed matter systems can be used

**Electron spins**

- Magnons: $g_{aee}$

**Nuclear spins**

- Axions: $g_{ary}$

- Superfluid $^3\text{He}_c$

- Hyperfine interaction

- Application of the NV center magnetometry with diamond samples

**Today's topics**

- Brief summary of my works in this direction

- 2001.10666
- 2102.06179
- 2309.09160
- 2307.08577

- 2302.12756
Magnon as a DM signal

- Light bosonic DM converts into a collective excitation of spin = magnon
Table of contents

- Introduction to light bosonic DM

- Introduction to NV center
  - What is it? How does it work as a quantum sensor?

- NV center magnetometry for DM detection
  - DC magnetometry + application to axion DM
  - AC magnetometry + application to axion DM
  - Shielding effect for dark photon DM

- Experimental status

- Conclusion
Introduction to NV center
NV center in diamond

- The stable complex of substitutional nitrogen (N) and vacancy (V) in diamond
- The charged state NV\(^-\) has two extra e\(^-\)s localized at V
- The ground state: e\(^-\) orbital singlet, e\(^-\) spin triplet \(S = 1\) system
Fluorescence

- Can distinguish spin states \( |m_s = 0\rangle \) and \( |m_s = \pm \rangle \) by fluorescence measurement

- Governed by following processes + selection rules
  - \( ^3A_2 + 532 \text{ nm photon} \rightarrow ^3E \)
  - \( ^3E \rightarrow ^3A_2 + 600 - 850 \text{ nm photon} \)
  - \( ^3E_{S \neq 0} \rightarrow (^1A_1 \rightarrow ^1E) \rightarrow |m_s = \pm \rangle + \text{infrared photon} \)

- The spin state \( |\psi\rangle = \cos \frac{\theta}{2} |0\rangle + \sin \frac{\theta}{2} |\pm \rangle \) is read from strength of the red (pink) fluorescence light

J. F. Barry+ ‘20
NV center as a quantum sensor

- NV center works as a multimodal quantum sensor
  1. Temperature  G. Kucsko+ ’13
  2. Electric field  F. Dolde+ ’11
  3. Strain  M. Barson+ ’17
  4. Magnetic field (explain later)
     - No cryogenics
     - No vacuum system
     - No tesla-scale applied bias fields are required

- Two options
  - Single NV center (high spacial resolution)
  - Ensemble of NV centers (high sensitivity) with \( \sim 1 - 20 \text{ ppm} \) concentration
Applications of NV center magnetometry

- Single NV center
  - $B_{ac} \sim 9.1 \text{ nT Hz}^{-1/2}$
  - $B_{dc} \sim 10 \text{ nT Hz}^{-1/2}$
    D. Herbschleb+ '19

- Ensemble
  - $B_{ac} \sim 210 \text{ fT Hz}^{-1/2}$
  - $B_{dc} \sim 460 \text{ fT Hz}^{-1/2}$
    J. F. Barry+ '23

- DM detection :)

DC magnetometry
Rabi cycle

- Energy gap $\Delta E \sim 2\pi \times 2.87\,\text{GHz}$
- Inject oscillating driving field with frequency $f = D + \frac{1}{2\pi} \gamma_e B_z$
  - $|\ - \rangle$ is irrelevant
  - qubit system of $|0\rangle$ and $|+\rangle$
- Under the transverse magnetic field $B_1 = B_{1y} \hat{y} \sin(2\pi ft)$,
  - Time evolution is described by the Rabi cycle

$$|\psi(t)\rangle = \cos\left(\frac{1}{\sqrt{2}} \gamma_e B_{1y} t\right) |0\rangle + \sin\left(\frac{1}{\sqrt{2}} \gamma_e B_{1y} t\right) |+\rangle$$
Bloch sphere

- Map from SU(2) group elements to the sphere $S^2$

$$|\psi\rangle = \cos \frac{\theta}{2} |0\rangle + \sin \frac{\theta}{2} e^{i\phi} |+\rangle = (|0\rangle |+\rangle) \begin{pmatrix} \cos \frac{\theta}{2} & -\sin \frac{\theta}{2} e^{-i\phi} \\ \sin \frac{\theta}{2} e^{i\phi} & \cos \frac{\theta}{2} \end{pmatrix} (1)$$
Rabi cycle on Bloch sphere

- Rotation around $\vec{B}_1 \propto \hat{y}$

$$|\psi(t)\rangle = \cos \left( \frac{\theta(t)}{2} \right) |0\rangle + \sin \left( \frac{\theta(t)}{2} \right) |+\rangle$$
with $\theta(t) = \sqrt{2} \gamma_e B_{1y} t$
Free precession

- Magnetic field $\vec{B} \propto \hat{z}$ causes free precession = rotation around $\hat{z}$

$$|\psi(\tau)\rangle = \frac{1}{\sqrt{2}} \left( |0\rangle + e^{i\varphi(\tau)} |+\rangle \right) \text{ with } \varphi(\tau) = \gamma_e \int_0^\tau dt B_{DM}^z(t) \simeq \gamma_e B_{DM}^z \tau \text{ (for DC-like signal)}$$
Ramsey sequence

Ramsey sequence for DC magnetometry

1. \((\pi/2)_y\) pulse
   - Rabi cycle with \(\theta = \sqrt{2} \gamma_e B_1 y t = \pi/2\)

2. Free precession under \(B_{DM}\) for duration \(\tau \sim T_2^*/2\)
   - \(T_2^* \sim 1 \mu s\) : spin relaxation (dephasing) time

3. \((\pi/2)_x\) pulse

4. Fluorescence measurement
   - DM signal is population difference between \(|0\rangle\) and \(|+\rangle\)

\[
S \equiv \frac{1}{2} \langle \psi_{\text{fin.}} | \sigma_z | \psi_{\text{fin.}} \rangle \propto \varphi(\tau) = \gamma_e B_{DM}^z \tau \quad (\varphi(\tau) \ll 1)
\]
Sensitivity on axion DM

- Assume spin-projection noise limits the sensitivity

\[ |x\rangle \equiv \frac{1}{\sqrt{2}} (|0\rangle + |+\rangle) \]

\[ \Delta S \equiv \frac{1}{2} \left[ \langle x|\sigma^2_z|x\rangle - (\langle x|\sigma_z|x\rangle)^2 \right]^{1/2} = \frac{1}{2} \]

- Large statistics reduce noise
  - \( N \) : # of NV centers
  - \( t_{\text{obs}} \) : total observation time

- (Roughly) universally sensitive to dc-like signal with \( m \lesssim 2\pi/\tau \sim 10^{-8}\) eV

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\[ N = 10^{12}, t_{\text{obs}} = 1\text{yr} \]
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\[ N = 10^{12}, t_{\text{obs}} = 1\text{yr} \]
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XENONnT
red giant
DFSZ
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SC+ [2302.12756]
Effects of DM coherence time

- $B_{DM}^z$ and $\delta$ change randomly with $\tau_{DM} \sim 2\pi/m_{DM}v_{DM}^2$

- For $t_{obs} \ll \tau_{DM}$
  - Fixed $B_{DM}^z$ and $\delta$
  - (# of observations) $\approx N(t_{obs}/\tau)$
  - (Sensitivity) $\propto N^{1/2}(t_{obs}/\tau)^{1/2}$

- For $t_{obs} \gg \tau_{DM}$
  - We measure the variance of $S_{obs}$
  - Comparison of $\Delta S_{DM}$ and $\Delta S N^{-1/2}(\tau_{DM}/\tau)^{-1/2}$
  - (Sensitivity) $\propto N^{1/2}(\tau_{DM}/\tau)^{1/2}(t_{obs}/\tau_{DM})^{1/4}$

Consistent with Dror+ [2210.06481] in the context of CASPER
Fast oscillation leads to cancellation

\[ S \sim \int_0^\tau dt B_{\text{DM}}^z \sin(mt) \propto \frac{1 - \cos(m\tau)}{m\tau} \]
DM on resonance

If $m/2\pi \approx f$, DM field itself works as a driving field.

“Resonance” sequence for $m/2\pi \approx f$

1. $(\pi/2)_y$ pulse
2. Free precession for duration $\tau \sim T_2^*/2$
3. Fluorescence measurement

$S \propto B_{DM}^y \tau$
On resonance sensitivity

- Resonance position
  \[ \frac{m}{2\pi} \approx 2.87 \text{ GHz} \iff m \approx 11.9 \mu\text{eV} \]
  - Tunable with e.g., external magnetic field \( B \)

- Resonant enhancement of sensitivity w/ 
  \[ m\tau \sim 2 \times 10^4 \left( \frac{\tau}{1 \mu\text{s}} \right) \]
AC magnetometry
Insensitive to fast-oscillating signals

- Fast oscillation leads to cancellation when $m \lesssim 2\pi/\tau$
Hahn echo

Hahn echo for ac magnetometry
1. \((\pi/2)_y\) pulse
2. Free precession for \(\tau/2\)
3. \(\pi_y\) pulse
4. Free precession for \(\tau/2\)
5. \((\pi/2)_x\) pulse
6. Fluorescence measurement

\[
\varphi(\tau) = \gamma_e \left( \int_0^{\tau/2} dt \, B^z_{DM}(t) - \int_{\tau/2}^{\tau} dt \, B^z_{DM}(t) \right) \implies \text{Targeted at the frequency } \sim 1/\tau
\]
Prolonged relaxation time

- No dephasing from inhomogeneous DC fields
- Relaxation time $T_2 \sim 50 \mu s \gg T_2^* \sim 1 \mu s$
- Optimized choice $\tau \sim T_2/2$

- Any DC effect cancels out from $\varphi(t)$
Sensitivity on axion DM

- Peak position
  \[ \frac{m}{2\pi} \sim \frac{1}{\tau} \sim 20 \text{ kHz} \]
  - Better sensitivity around the peak than DC thanks to \( T_2 \gg T_2^* \)

- Tunable peak position with shorter \( \tau \)
Towards sensitivity improvement

- Using more $\pi_y$ pulses prolongs $T_2$
  - Upper limit on $T_2 < T_1$
  - Target frequency $\times N_\pi$

- Lower temperature prolongs $T_2, T_1$
  (With $N_\pi = 1023$)
  - $300$ K: $T_2 = 100\,\mu$s, $T_1 \sim 1$ ms
  - $77$ K: $T_2 = 1$ ms, $T_1 \sim 1$ s
  - $4$ K: $T_2 = 10$ ms, $T_1 \gg 1$ s
  - $0.1$ K: $T_2 = 0.1$ s, $T_1 \gg 1$ s

D. Herbschleb, private communication
Dark photons
Shielding effect

- Electric interaction of the dark photon creates current in the conductor and induces a magnetic field \( \mathbf{B}_{\text{ind}} \)
- The effective magnetic field may be canceled and "shielded" if \( \lambda_{\text{DM}} > L \)

S. Chaudhuri+ [1411.7382] "DM Radio" paper

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NV center works without shielding

- AC magnetometry is insensitive to DC(-like) noises
  - Applicable for $\frac{m}{2\pi} \geq 1$ kHz

- “Low-frequency quantum sensing” possible with Fourier analysis
  - Applicable for $\frac{m}{2\pi} \geq \frac{1}{t_{obs}}$

- Must be careful with AC magnetic noises with the target frequency
Sensitivities on dark photon DM

- DC magnetometry
- AC magnetometry

SC+ [2302.12756]
Assumptions on magnetic shielding

- We put shielding for \( \frac{m}{2\pi} \lesssim \frac{1}{t_{\text{obs}}} \)
  - Sensitivity is significantly suppressed

- Even without magnetic shielding, the inner core of the Earth/ionosphere are conducting and shielding fields
  - M. A. Fedderke+ [2106.00022]
  - Suppression factor \( \propto mR_{\text{Earth}} \)
Experimental status
Standard-deviation quantum sensing

- Working on experimental validation of our statistical treatment
Standard-deviation quantum sensing

- Obtained expected dependence on # of data points $N$
- Can estimate signal amplitude and frequency
Discussions and conclusions

- We explored the potential of NV center magnetometry for DM search

- Benefits of this approach include:
  - Wide dynamic range = broad DM mass range is searched for
  - Not always need magnetic shielding

- Some applications of advanced quantum sensing techniques can be considered
  - e.g.) Use of entanglement  C. L. Degan+ "Quantum sensing"

\[
|\psi\rangle = \otimes_c \frac{1}{\sqrt{2}} (|0\rangle_c + e^{i\phi} |1\rangle_c) \rightarrow |\psi\rangle = \frac{1}{\sqrt{2}} (|000\ldots\rangle + e^{iN\phi} |111\ldots\rangle)
\]

- Now setting up an experimental environment at QUP with NV + cryogenic
Backup slides
Sensitivity estimation

- The outcome of the spin-projection noise

\[ |x\rangle \equiv \frac{1}{\sqrt{2}} (|0\rangle + |+\rangle) \]

\[ \Delta S \equiv \frac{1}{2} \left[ \langle x | \sigma_z^2 | x \rangle - (\langle x | \sigma_z | x \rangle)^2 \right]^{1/2} = \frac{1}{2} \]

- Noise contribution is \( \Delta S_{sp} \sim \begin{cases} 
\frac{1}{2} \frac{1}{\sqrt{N(t_{obs}/\tau)}} & (t_{obs} < \tau_a) \\
\frac{1}{2} \frac{1}{\sqrt{N(\tau_a/\tau)}} \left( \frac{t_{obs}}{\tau_a} \right)^{1/4} & (t_{obs} > \tau_a) 
\end{cases} \]

- Sensitivity curve is \((\text{SNR}) \equiv \frac{S}{\Delta S_{sp}} = 1\)
Sensitivity estimation

- The axion-induced effective magnetic field has an unknown velocity $v_{DM}$ and phase $\delta$

$$B_{DM} \approx \sqrt{2\rho_{DM} g_{ae} e} v_{DM} \sin(m_{DM} t + \delta)$$

Random velocity $v_{DM}$

- The signal is proportional to $(v_{DM}^i)^2$ ($i = x, y, z$), which is averaged to $\sim \frac{1}{3} v_{DM}^2$

Random phase $\delta \in [0, 2\pi)$

- The signal is estimated as a function of $\delta : S(\delta) \propto \cos\left(\frac{m\tau}{2} + \delta\right)$

- We obtain the average $\langle S \rangle_\delta = 0$ and the standard deviation $\sqrt{\langle S^2 \rangle} \neq 0$, which should be compared with the noise
Technical noise mitigation

II. MAGNETOMETRY METHOD

In many high-sensitivity measurements, technical noise such as \(1/f\) noise is mitigated by moving the sensing bandwidth away from dc via upmodulation. One method, common in NV-diamond magnetometry experiments, applies frequency [12,32,41,42] or phase modulation [19,43–45] to the MWs addressing a spin transition, which causes the magnetic-field information to be encoded in a band around the modulation frequency. Here we demonstrate a multiplexed [46–49] extension of this scheme, where information from multiple NV orientations is encoded in separate frequency bands and measured on a single optical detector. Lock-in demodulation and filtering then extracts the signal associated with each NV orientation, enabling concurrent measurement of all components of a dynamic magnetic field.

J. M. Schloss+ ‘18