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Chapter III

Examples of Quantum Sensors

A. Neutral Atoms • B. Trapped Ions • C. Rydberg Atoms • D. Atomic Clocks • E. Solid-State Spins (Ensemble)

May 22, 2026 | Yusuke Takeuchi

Chapter III A–E at a Glance

Quantum systems → measured quantities → fundamental-physics examples

- The review classifies quantum sensors by implementation, measured quantity, initialization, and readout.
- I summarize the key points of each implementation and add selected connections to particle / fundamental physics.

Adopted from Table 1

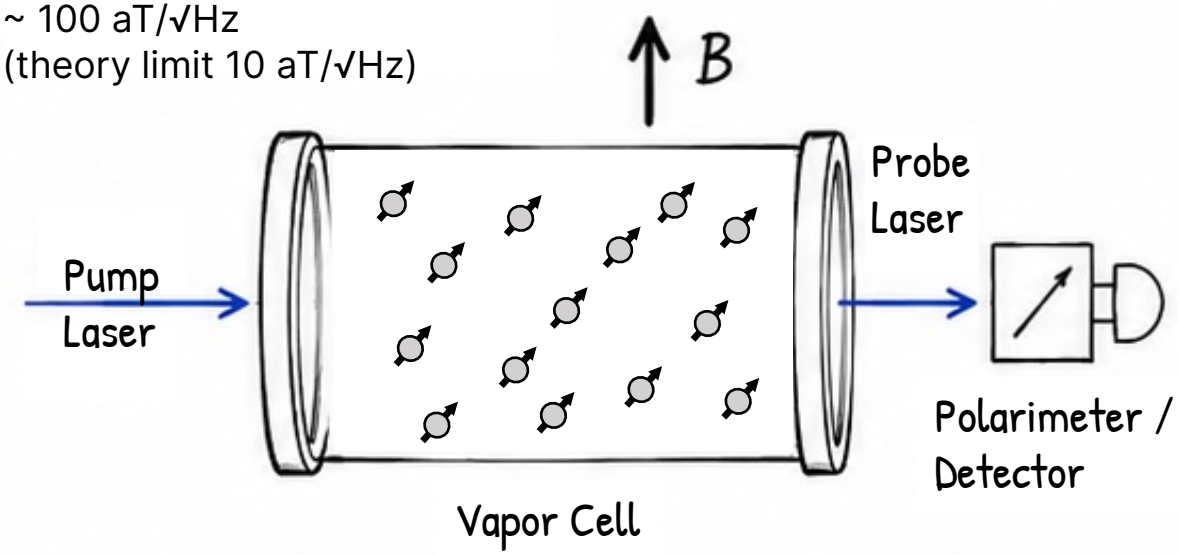
Section	Implementation	Quantum system	Measured quantity
III-A	Atomic vapor	atomic spin	magnetic field, rotation
III-A	Cold atomic clouds	atomic spin	magnetic field, acceleration
III-B	Trapped ions	electronic / spin / vibrational states	rotation, electric field, force
III-C	Rydberg atoms	Rydberg states	electric field, including GHz/microwave fields
III-D	Atomic clocks	clock transitions	oscillator phase / time/frequency
III-E	NMR ensembles	nuclear spins	magnetic field
III-E	NV ensembles	electron spins	magnetic field, electric field, temperature

- Goal:
  Compare the sensor implementations in Chapter III A–E by their quantum system, measured quantity, limitations, and selected fundamental-physics applications.

Atomic Vapors

Spin precession in an optically pumped vapor

The most sensitive magnetometers to date
~ 100 aT/√Hz
(theory limit 10 aT/√Hz)



Magnetic-field-sensitive spin precession

Main sensing quantities:

- **Magnetic field B**
  → Larmor precession ($\omega_L = \gamma B$)
- **Rotation Ω**
  → Rotation-induced spin precession ($\omega_\Omega \simeq \Omega$)

Key characteristics:

- **Collective spin-phase sensing**
  The ensemble phase is the sensing variable.
- **Large atomic ensembles**
  Typically, 10^9–10^{12} polarized atoms → projection noise $\propto 1/\sqrt{N}$
- **Long spin coherence**
  Coherence times from ms to s → long phase accumulation time
- **SERF operation in near-zero magnetic fields**
  Spin-exchange relaxation strongly suppressed
  → enables long coherence and high sensitivity

Practical issue:

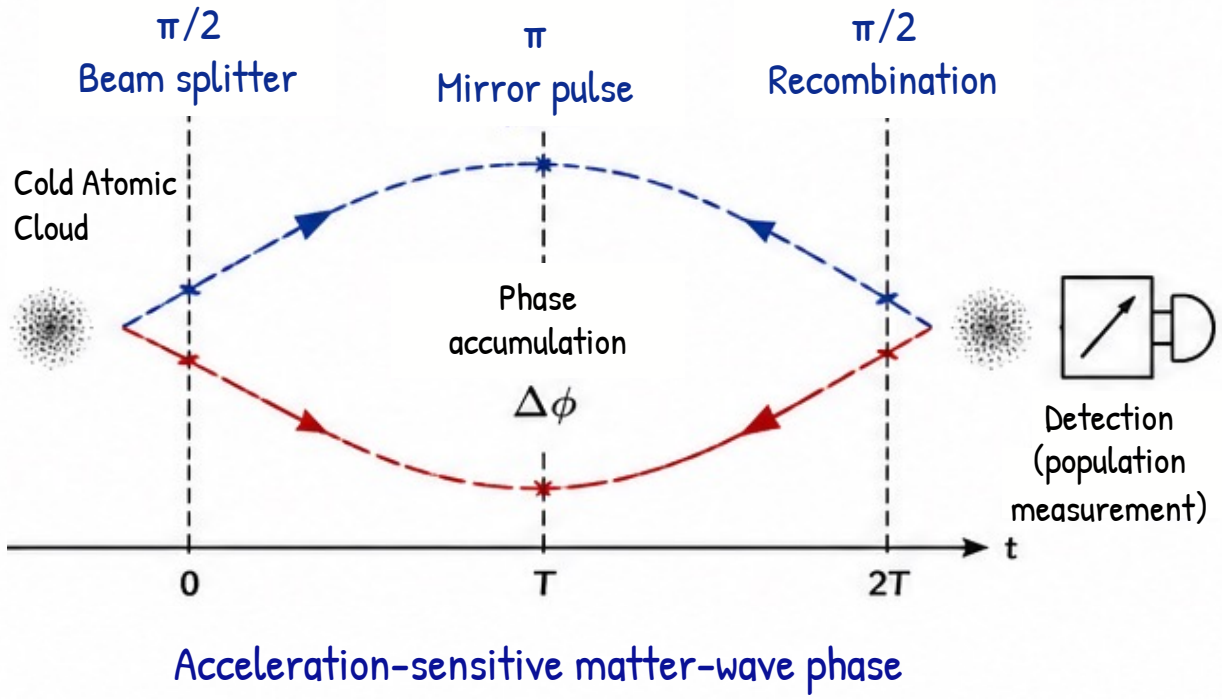
- Best sensitivity often requires near-zero field, magnetic shielding, and careful control of gradients / light shifts

Particle physics applications (examples):

- **Spin-dependent exotic interactions [Exp: 1]**
  → effective pseudo-magnetic fields
- **Lorentz / CPT violation with ^{21}Ne–Rb–K comagnetometer [Exp: 2]**
  → anomalous spin precession
- **Axion-like dark matter with SERF comagnetometer [Exp: 3]**
  → oscillating pseudo-fields
- **Magnetometry for neutron EDM experiments [Exp: 4]**
  → ultra-precise magnetic-field control (co-magnetometry)

Cold Atomic Clouds

Matter-wave phase as a probe of acceleration



Acceleration-sensitive matter-wave phase

Main sensing quantities:

- **Acceleration a**
  → Inertial matter-wave phase shift ($\Delta\varphi_a = k_{eff}\, a\, T^2$)

Key characteristics:

- **Matter-wave phase sensing**
  Interferometric phase is the sensing variable.

- **Long interrogation time**
  Cold atoms enable long free-fall or trapped evolution
  → large phase accumulation

- **Small velocity spread**
  Laser cooling reduces thermal motion and Doppler noise
  → high phase stability

- **High sensitivity to acceleration**
  Phase scales as T^2 for acceleration
  → excellent inertial sensitivity

Practical issue:

- Best sensitivity requires: Maybe expensive
  ultrahigh vacuum, stable lasers, and vibration control

Particle physics applications (examples):

- **Equivalent-principle tests with atom interferometry [Exp: 5]**
  → differential acceleration measurements

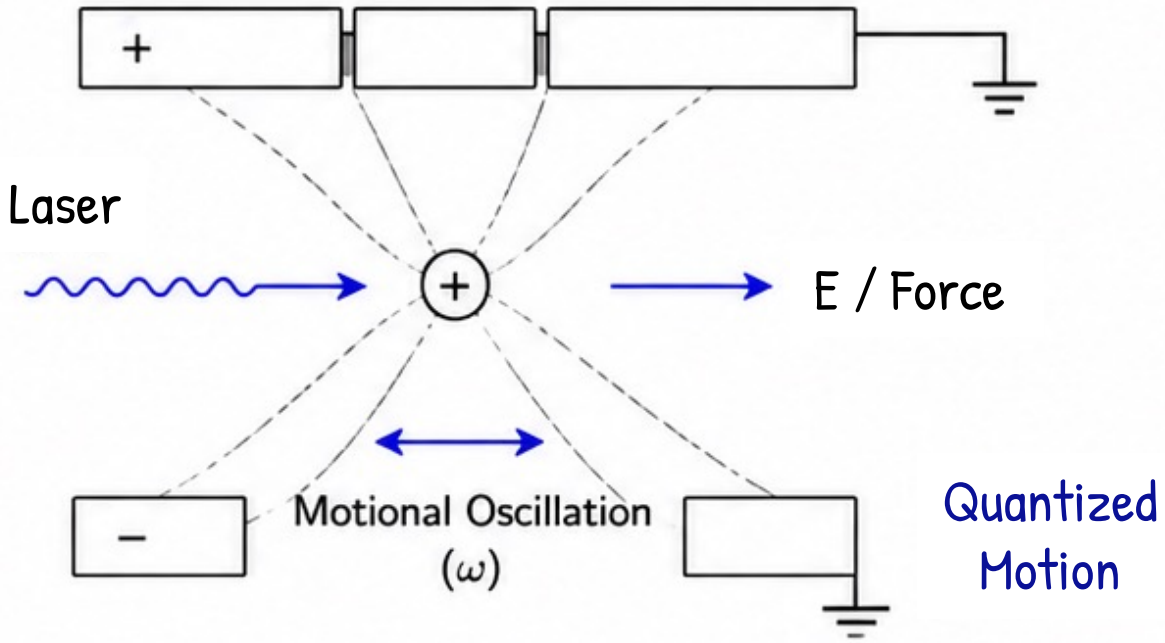
- **Fine-structure constant from atom-recoil interferometry [Exp: 6]**
  → precise determination via recoil phase

- **QED / electron g-2 consistency test via α [Exp: 6]**
  → recoil frequency and mass measurements

- **Long-baseline atom interferometers for DM/GW searches [Prop: 7,8]**
  → sensitive to phase oscillations/transients

Trapped Ions

Clean, controllable quantum probes in vacuum



Electric-field-sensitive spin and motion

Main sensing quantities:

- **Electric field E / force**
  → motional excitation of trapped ions
- **Magnetic field B**
  → spin-state energy splitting / phase evolution
- **Rotation**
  → matter-wave Sagnac phase shift

Key characteristics:

- **Quantized motional states**
  Sensitive to weak electric fields and forces.
- **Magnetic-field-sensitive spin states**
  Ground-state spin sublevels act as magnetic-field-sensitive qubits.
- **Extremely clean isolated quantum system**
  Ultra-low environmental decoherence in vacuum.
- **Excellent coherent control**
  Internal and motional states can be precisely manipulated.

Practical issue:

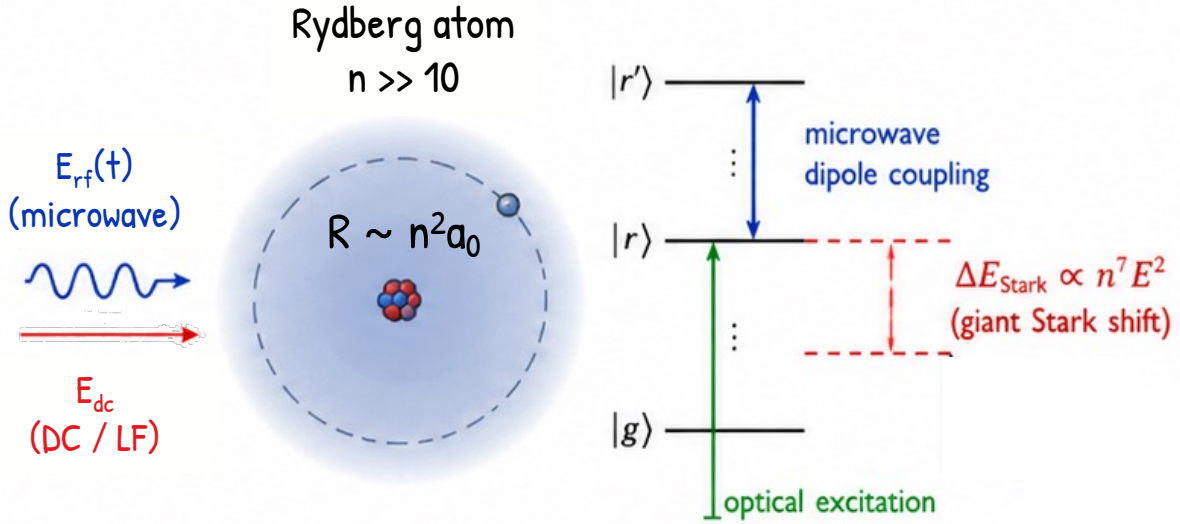
- Surface electric-field noise causes decoherence.
- Single-ion sensitivity is limited compared with ensemble sensors
- Operation close to surfaces remains challenging.

Particle physics applications (examples):

- **Light DM detection with trapped-ion motional states [Prop: 9]**
  → weak DM-induced electric fields drive vibrational excitation
- **Fifth-force / new-boson bounds with Ca^+ isotope shifts [Exp: 10]**
  → deviations from expected isotope-shift patterns
- **Lorentz-symmetry tests with trapped Ca^+ ions [Exp: 11]**
  → sidereal modulation of transition frequencies
- **Improved Lorentz-violation bounds with trapped Yb^+ ions [Exp: 12]**
  → ultra-stable frequency comparison

Rydberg Atoms

Large electric dipoles for weak electric and RF fields



Microwave electric-field sensing

Main sensing quantities:

- **Electric field E**
  → Large Stark shift of Rydberg levels ($\Delta E_{Stark} \propto n^7 E^2$)
- **Microwave / RF field E_{rf}**
  → Resonant dipole transitions between Rydberg states ($R \sim n^2 a_0$)

Key characteristics:

- **Huge electric dipole moments**
  Dipole moments scale strongly with principal quantum number n.
- **Extremely large polarizability**
  → giant Stark shifts from weak electric fields ($\Delta E \propto n^7 E^2$)
- **Strong microwave / GHz coupling**
  Resonant transitions between nearby Rydberg states enable sensitive detection of RF fields.
- **Optical preparation and readout**
  Laser excitation and spectroscopy convert RF signals into optical signals for high-sensitivity detection.

Practical issue:

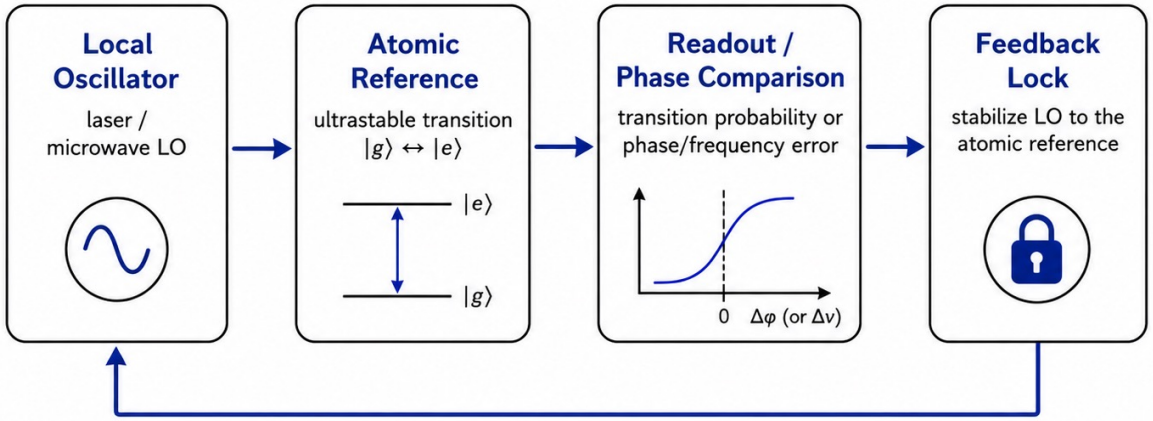
- Extremely sensitive to stray electric fields, surface charges, and field inhomogeneities
- Blackbody-radiation-induced transitions and dephasing broaden the spectroscopy signal
- Cryogenic cavity integration and stable field control are experimentally demanding

Particle physics applications (examples):

- **Axion haloscope readout with Rydberg atoms [Prop: 13]**
  → single microwave-photon detection from axion conversion
- **Dark matter detection with Rydberg tweezer arrays [Prop: 14]**
  → DM-induced electric fields drive transitions between Rydberg states

Atomic Clocks

Frequency references viewed as quantum sensors



Precision frequency comparison

Main sensing quantities:

- **Frequency / phase drift**
  → repeated comparison between atomic transition and LO
- **Tiny transition-frequency shifts**
  → caused by external perturbations or new physics

Key characteristics:

- **Ultrastable clock transitions**
  Narrow atomic transitions provide an absolute frequency reference.
- **Long coherence and high frequency stability**
  Long phase accumulation enables precise frequency comparison.
- **Optical lattice, trapped-ion, and quantum-logic clocks**
  State-of-the-art platforms realize optical-frequency precision.

Practical issue:

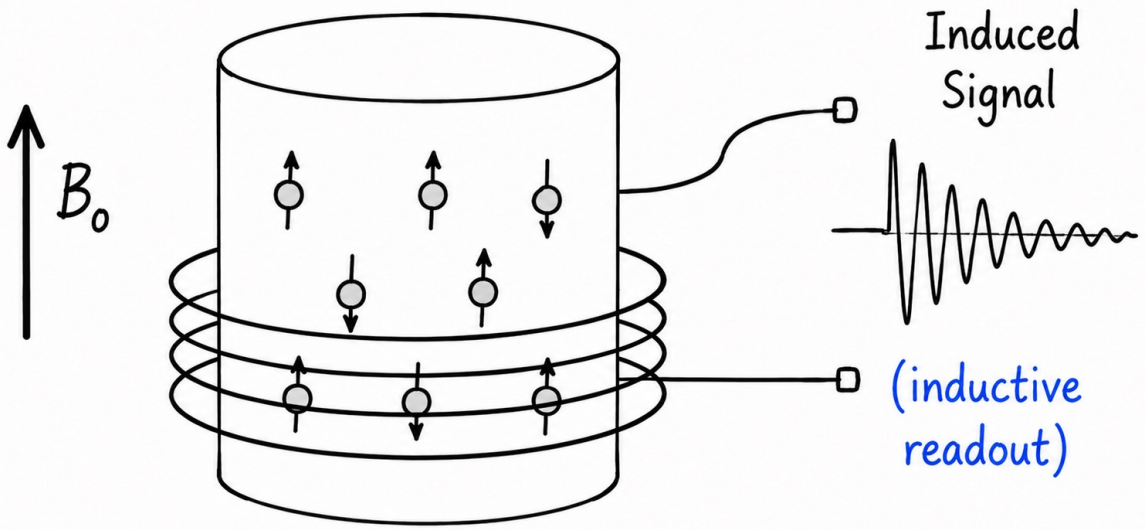
- **Systematic shifts: blackbody radiation, Zeeman / Stark shifts**
  Environmental perturbations shift the clock transition frequency.
- **LO noise, laser stability, and frequency transfer**
  Clock performance depends on stable interrogation and comparison.
- **Complex control of environment and apparatus**
  Vacuum, temperature, fields, and trapping conditions must be controlled.

Particle physics applications (examples):

- **Ultralight dark matter from optical/MW clock comparisons [Exp: 15]**
  → oscillating fundamental constants
- **Atom–cavity frequency comparison searches [Exp: 16]**
  → dark-matter-induced frequency modulation
- **Transient dark matter with clock networks [Prop: 17]**
  → correlated timing/frequency excursions across Earth-scale networks

NMR Ensembles

Nuclear-spin precession in robust ensembles



Nuclear-spin precession sensing

Main sensing quantities:

- **Magnetic field B**
  → Larmor precession ($\omega_L = \gamma B$)
- **Rotation Ω**
  → Rotation-induced spin precession ($\omega_\Omega \simeq \Omega$)

Key characteristics:

- **Robust nuclear-spin ensembles**
  Weak environmental coupling → stable operation
- **Long spin coherence**
  Nuclear spins can maintain coherence for long durations
- **Mature low-noise detection techniques**
  High-Q inductive detection and precision RF techniques
- **Natural platform for precision precession measurements**
  Direct frequency-based sensing

Practical issue:

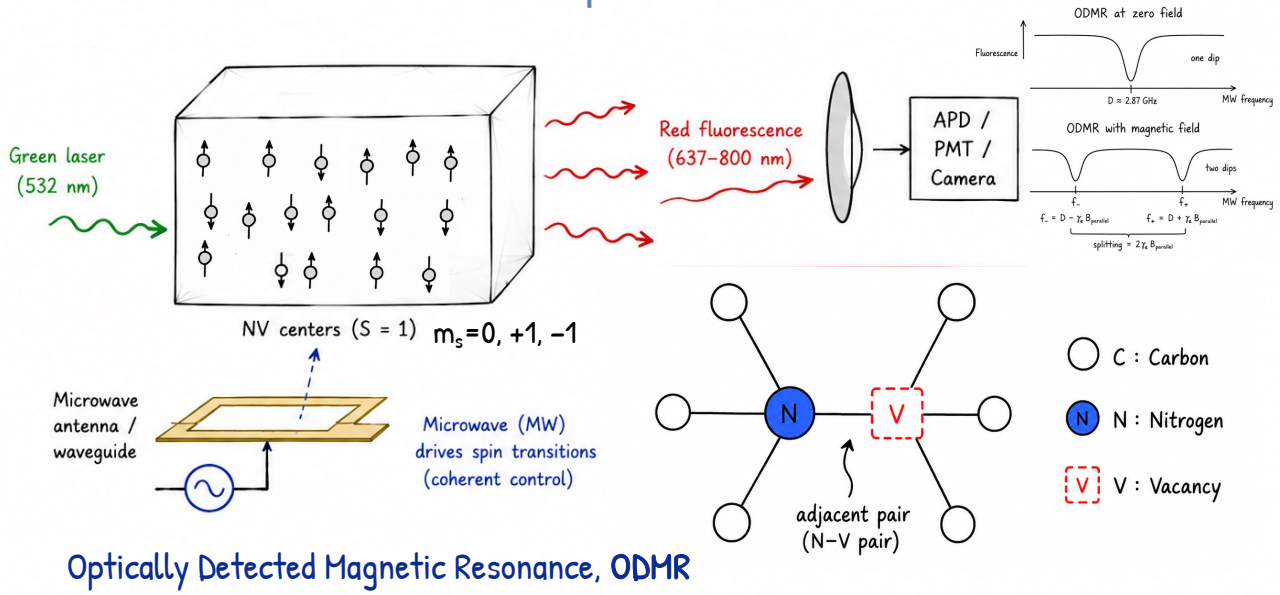
- **Small nuclear magnetic moments**
  Intrinsically weaker signals than electron-spin systems
- **Weak thermal polarization**
  Often requires strong magnetic fields or hyperpolarization
- **Low-frequency inductive readout limitations**
  Small samples are difficult to detect efficiently

Particle physics applications (examples):

- **CASPEr axion / CASPEr-ZULF DM searches [Prop:18,Exp:19]**
  → resonant pseudo-magnetic spin precession (B_0 scan)
- **Liquid-state nuclear-spin comagnetometer [Exp: 20]**
  → axion-induced anomalous spin coupling
- **Muon g−2 magnetic-field metrology [Exp: 21]**
  → precision proton NMR frequency measurement

NV Center Ensembles

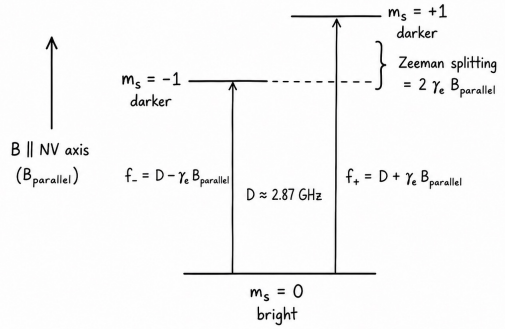
Solid-state electron-spin ensembles in diamond



Optically Detected Magnetic Resonance, ODMR

Main sensing quantities:

- **Magnetic field B**
  → Zeeman shift of NV electron spin transitions ($\Delta\omega=\gamma_e B$)
- **Electric field E**
  → Stark shift of NV levels ($\Delta\omega=kE$)
- **Temperature T**
  → Zero-field splitting shift ($\Delta D/D$)
- **Strain, Microwave**



Key characteristics:

- **Optical spin readout**
  High-contrast fluorescence enables sensitive detection
- **Room-temperature solid-state operation**
  Practical and robust with minimal cryogenic requirements
- **High-density spin ensemble possible**
  Many NVs in a small volume → large signal
- **Magnetic imaging with micrometer-scale pixels**
  High spatial resolution and wide-field capability

Practical issue:

- **Nitrogen-related defects and spin–spin interactions**
  Introduce decoherence and background signals
- **Fluorescence collection and contrast are difficult**
  Photon shot noise and collection inefficiency limit sensitivity

Particle physics applications (examples):

- **Exotic spin-dependent interactions [Exp: 22]**
  → new physics via spin-coupled backgrounds (single NV)
- **Light dark matter searches with NV centers [Prop: 23]**
  → oscillating pseudo-magnetic or electric fields
- **Axion / dark-photon searches with NV centers [Prop: 24,25]**
  → resonant spin coupling to ultralight fields

DIY Portable NV Center Magnetometer

Pulsed magnetic resonance in diamond with Arduino Uno

A home-made portable device based on Arduino Uno for pulsed magnetic resonance of NV centers in diamond

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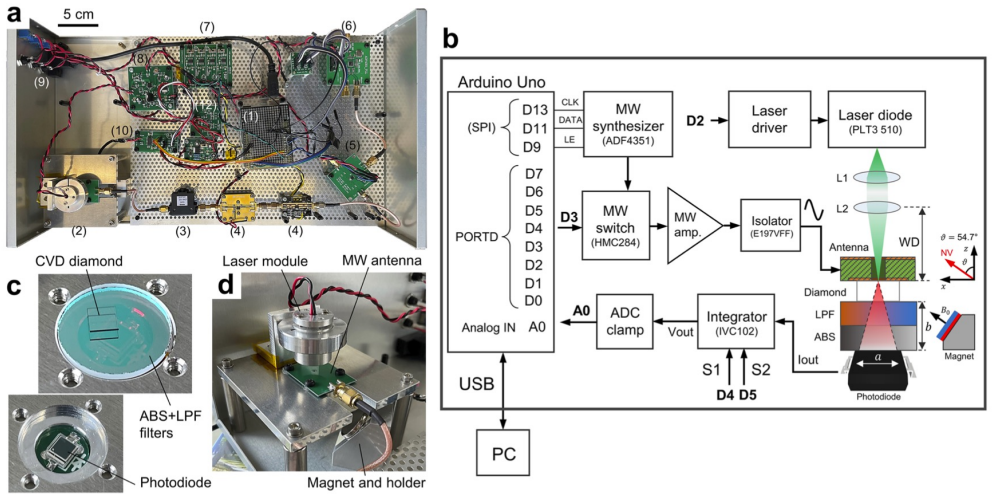

FIG. 1. (a) Interior of the experimental setup: (1) Arduino Uno, (2) sample holder, (3) MW isolator, (4) MW amplifiers, (5) MW switch, (6) MW synthesizer, (7) 5, 3.3 V voltage regulators, (8) laser driver, (9) input of AC/DC converters and USB, (10) switched integrator, (11) ADC clamp, and (12) integrator's ±12 V regulator. (b) Schematic of the setup. The Arduino board controls the modules by using the digital pins D2–D5, D9, D11, and D13. The laser beam is collimated by a lens (L1) and focused by a lens (L2), with a working distance WD = 16 mm from the surface of the diamond. The distance between the diamond and the photodiode (PD) is $b = 2$ mm. The active area of the PD is $a^2 = 2.65 \times 2.65$ mm^2. (c) Sample holder. The diamond sample with a size of $3 \times 3 \times 0.25$ mm^3 is placed on the top of the reflective (LPF) and the absorptive glass (ABS) filters. The PD mounted on a PCB is placed on the back side of the filters and fixed to the aluminum plate with screws. (d) Attachment of the MW antenna and alignment system of the laser diode on the sample holder.

Compact & portable

20 × 40 × 10 cm³
Weight: ~1.8 kg

Low cost

~98,861 JPY
(excluding diamond)
~$650 USD

Diamond sample

~70,000 – 300,000 JPY ??
(depending on quality)
e.g., CVD type IIa, 3×3×0.25 mm³

It may be interesting and educational to build a setup like this as a hands-on introduction to NV-center (quantum sensing) experiments.

Summary

Quantum sensors turn weak perturbations into measurable quantum evolution

1. Different implementations use different quantum systems
spins, motional states, Rydberg states, clock transitions, and solid-state defects.

2. The measured quantity is usually a phase, frequency, level shift, or population change
magnetic fields, electric fields, acceleration, rotation, and time/frequency can be sensed.

3. For particle physics, the key is not only sensitivity but also the matching of the signal signature
spin precession → axion / Lorentz tests
frequency shift → ultralight dark matter / varying constants
level shift → fifth forces / isotope-shift anomalies
RF response → dark photon / axion-photon searches

Further Reading

No.	Type	System	Reference
[1]	Exp	Atomic vapor	W. Xiao et al., "Femtotesla Atomic Magnetometer Employing Diffusion Optical Pumping to Search for Exotic Spin-Dependent Interactions," *Phys. Rev. Lett.* **130**, 143201 (2023).
[2]	Exp	Atomic vapor	M. Smiciklas et al., "New Test of Local Lorentz Invariance Using a ^{21}Ne–Rb–K Comagnetometer," *Phys. Rev. Lett.* **107**, 171604 (2011).
[3]	Exp	Atomic vapor	I. M. Bloch et al., "Constraints on axion-like dark matter from a SERF comagnetometer," *Nature Communications* **14**, 5784 (2023).
[4]	Exp	Atomic vapor	C. Abel et al., "Optically pumped Cs magnetometers enabling a high-sensitivity search for the neutron electric dipole moment," *Phys. Rev. A* **101**, 053419 (2020).
[5]	Exp	Cold atoms	P. Asenbaum et al., "Atom-Interferometric Test of the Equivalence Principle," *Phys. Rev. Lett.* **125**, 191101 (2020).
[6]	Exp	Cold atoms	L. Morel et al., "Determination of the fine-structure constant with an accuracy of 81 parts per trillion," *Nature* **588**, 61–65 (2020).
[7]	Prop	Cold atoms	L. Badurina et al., "AION: An Atom Interferometer Observatory and Network," *Journal of Cosmology and Astroparticle Physics* **2020**(05), 011 (2020).
[8]	Prop	Cold atoms	M. Abe et al., "Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)," *Quantum Sci. Technol.* **6**, 044003 (2021).
[9]	Prop	Trapped ions	A. Ito et al., "Quantum entanglement of ions for light dark matter detection," *JHEP* **2024**(02), 124 (2024).
[10]	Exp	Trapped ions	A. Wilzewski et al., "Nonlinear Calcium King Plot Constrains New Bosons and Nuclear Properties," *Phys. Rev. Lett.* **134**, 233002 (2025).
[11]	Exp	Trapped ions	T. Pruttivarasin et al., "Michelson-Morley analogue for electrons using trapped ions," *Nature* **517**, 592–595 (2015).
[12]	Exp	Trapped ions	L. S. Dreissen et al., "Improved bounds on Lorentz violation from composite pulse Ramsey spectroscopy in a trapped ion," *Nature Communications* **13**, 7314 (2022).
[13]	Prop	Rydberg atoms	E. Graham et al., "Rydberg-atom-based single-photon detection for haloscope axion searches," *Phys. Rev. D* **109**, 032009 (2024).
[14]	Prop	Rydberg atoms	S. Chigusa et al., "Detecting Dark Matter Using Optically Trapped Rydberg Atom Tweezer Arrays," *Phys. Rev. Lett.* **136**, 151801 (2026).
[15]	Exp	Atomic clocks	T. Kobayashi et al., "Search for Ultralight Dark Matter from Long-Term Frequency Comparisons of Optical and Microwave Atomic Clocks," *Phys. Rev. Lett.* **129**, 241301 (2022).
[16]	Exp	Atomic clocks	C. J. Kennedy et al., "Precision Metrology Meets Cosmology: Improved Constraints on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons," *Phys. Rev. Lett.* **125**, 201302 (2020).
[17]	Prop	Atomic clocks	A. Derevianko and M. Pospelov, "Hunting for topological dark matter with atomic clocks," *Nature Physics* **10**, 933–936 (2014).
[18]	Prop	NMR	D. Budker et al., "Proposal for a Cosmic Axion Spin Precession Experiment," *Phys. Rev. X* **4**, 021030 (2014).
[19]	Exp	NMR	A. Garcon et al., "Constraints on bosonic dark matter from ultralow-field nuclear magnetic resonance," *Science Advances* **5**, eaax4539 (2019).
[20]	Exp	NMR	T. Wu et al., "Search for Axionlike Dark Matter with a Liquid-State Nuclear Spin Comagnetometer," *Phys. Rev. Lett.* **122**, 191302 (2019).
[21]	Exp	NMR	T. Albahri et al. (Muon g−2 Collaboration), "Magnetic-field measurement and analysis for the Muon g−2 Experiment at Fermilab," *Phys. Rev. A* **103**, 042208 (2021).
[22]	Exp	NV centers	X. Rong et al., "Searching for an exotic spin-dependent interaction with a single electron-spin quantum sensor," *Nature Communications* **9**, 739 (2018).
[23]	Prop	NV centers	S. Chigusa et al., "Light dark matter search with nitrogen-vacancy centers in diamond," *JHEP* **03**, 083 (2025).
[24]	Prop	NV centers	S. Chigusa et al., "Nuclear spin metrology with nitrogen vacancy center in diamond," *Phys. Rev. D* **111**, 075028 (2025).
[25]	Prop	NV centers	A. Guo et al., "Searching for exotic spin-dependent interactions with diamond-based vector magnetometer," *Phys. Rev. D* **109**, 055034 (2024).