Quantum Sensing
(condensed matter perspective)

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Wisconsin Summer School for Quantum Science, UW Madison

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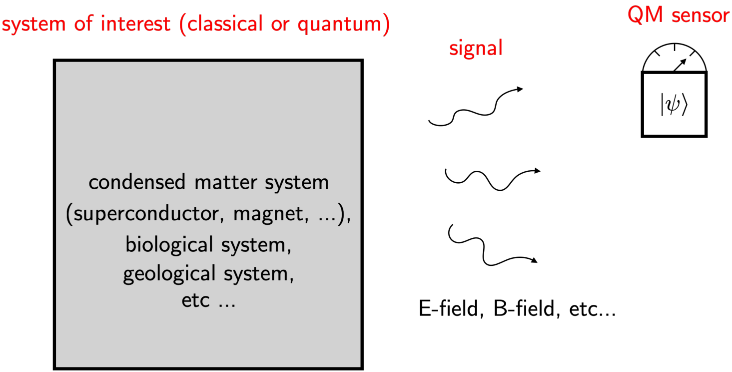
What is quantum sensing?

Quantum sensing = utilizing of a quantum mechanical (QM) system as a sensor for physical quantities



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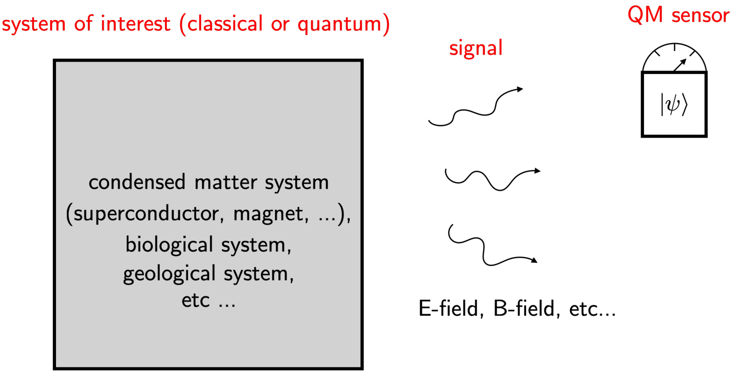
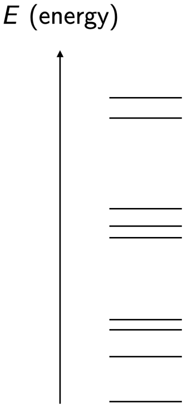


Quantum sensors capitalize on extreme sensitivity of quantum systems to their environment

Properties of a quantum sensor

1. QM system with discrete energy levels



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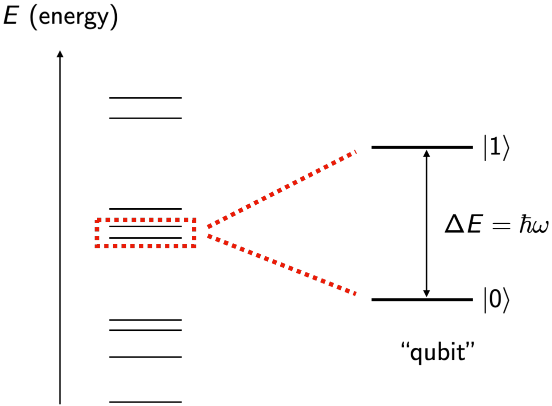

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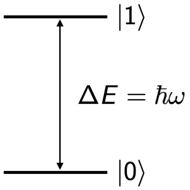
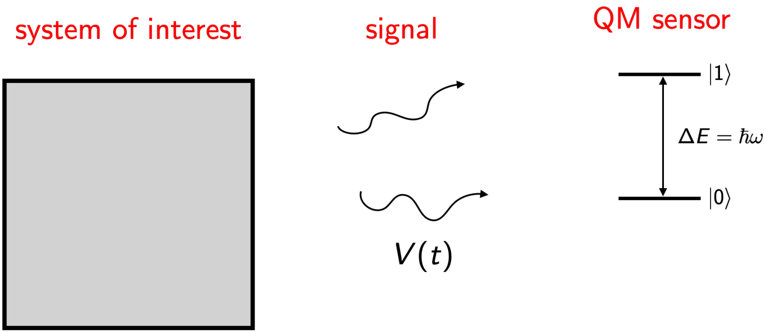


2. Ability to initialize and "read out" quantum state

3. Ability to manipulate quantum state: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad \alpha, \beta \in \mathbb{C}$

Properties of a quantum sensor

4. QM sensor should interact with the system of interest.
Ex: charged ions couple to E-fields, spins couple to B-fields, etc...



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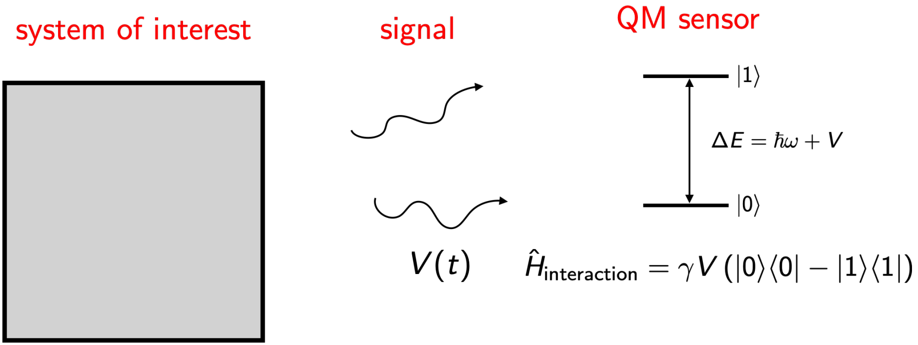

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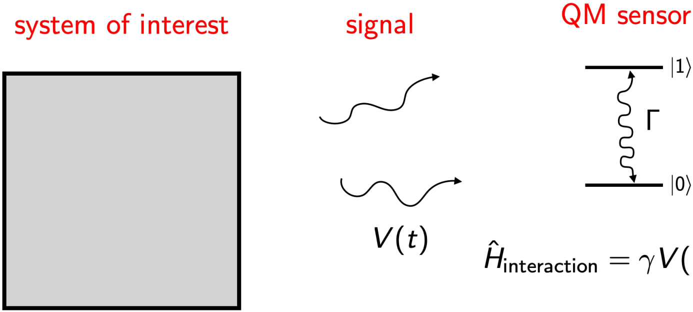

$$\hat{H}_{\text{interaction}} = \gamma V(t) \left(|1\rangle\langle 0| + |0\rangle\langle 1| \right)$$

TABLE I. Experimental implementations of quantum sensors.

Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency	Initalization	Readout	Type[a]
Neutral atoms						
Atomic vapor	Atomic spin	Magnetic field, rotation, time/frequency	dc-GHz	Optical	Optical	II, III
Cold clouds	Atomic spin	Magnetic field, acceleration, time/frequency	dc-GHz	Optical	Optical	II, III
Trapped ion(s)						
	Long-lived electronic state	Time/frequency	THz	Optical	Optical	II, III
		Rotation		Optical	Optical	II
	Vibrational mode	Electric field, force	MHz	Optical	Optical	II
Rydberg atoms						
	Rydberg states	Electric field	dc, GHz	Optical	Optical	II, III
Solid-state spins (ensembles)						
NMR sensors	Nuclear spins	Magnetic field	dc	Thermal	Pick-up coil	II
NV[b] center ensembles	Electron spins	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz	Optical	Optical	II
Solid-state spins (single spins)						
P donor in Si	Electron spin	Magnetic field	dc-GHz	Thermal	Electrical	II
Semiconductor quantum dots	Electron spin	Magnetic field, electric field	dc-GHz	Electrical, optical	Electrical, optical	I, II
Single *NV*[b] center	Electron spin	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz	Optical	Optical	II
Superconducting circuits						
SQUID[c]	Supercurrent	Magnetic field	dc-GHz	Thermal	Electrical	I, II
Flux qubit	Circulating currents	Magnetic field	dc-GHz	Thermal	Electrical	II
Charge qubit	Charge eigenstates	Electric field	dc-GHz	Thermal	Electrical	II
Elementary particles						
Muon	Muonic spin	Magnetic field	dc	Radioactive decay	Radioactive decay	II
Neutron	Nuclear spin	Magnetic field, phonon density, gravity	dc	Bragg scattering	Bragg scattering	II
Other sensors						
SET[d]	Charge eigenstates	Electric field	dc-MHz	Thermal	Electrical	I
Optomechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz	Thermal	Optical	I
Interferometer	Photons, (atoms, molecules)	Displacement, refractive index	...			II, III

Degen, Reinhard, Cappellaro, *Quantum sensing* (2017)

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Case study: particular quantum sensor and specific sensing application

QUANTUM ELECTRONICS

Probing Johnson noise and ballistic transport in normal metals with a single-spin qubit

S. Kolkowitz,[1*] A. Safira,[1*] A. A. High,[1,2] R. C. Devlin,[2] S. Choi,[1] Q. P. Unterreithmeier,[1] D. Patterson,[1] A. S. Zibrov,[1] V. E. Manucharyan,[3] H. Park,[1,2]† M. D. Lukin[1]†

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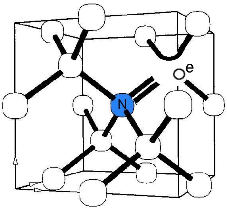
- Quantum sensor = nitrogen-vacancy (NV) center in diamond
- Signal = magnetic noise (random fluctuations of magnetic field)
- System = slab of silver (“normal metal”)

Nitrogen-vacancy (NV) centers

- NV center: point defect in diamond
- substitutional nitrogen + nearest neighbor vacancy
- NV^- has three low-energy states (spin $S = 1$):



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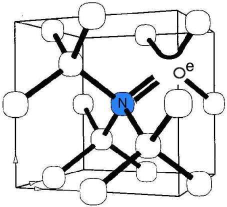

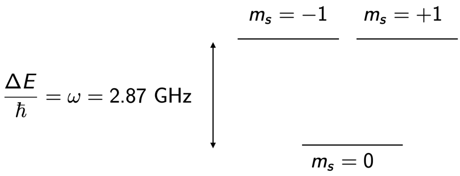

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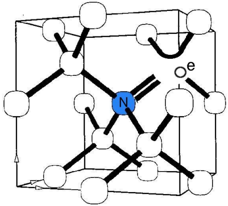

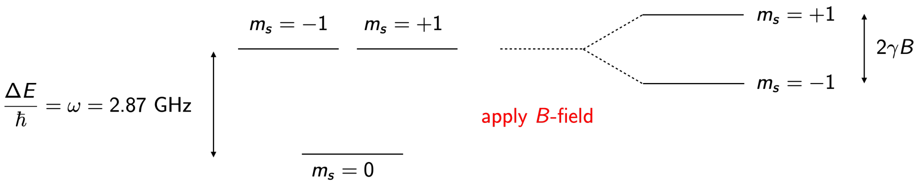

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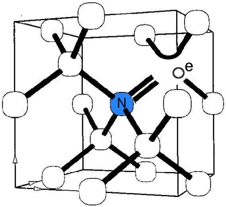
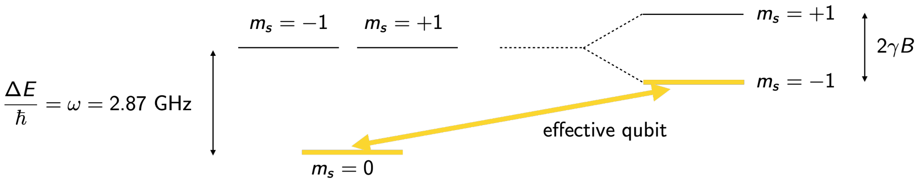
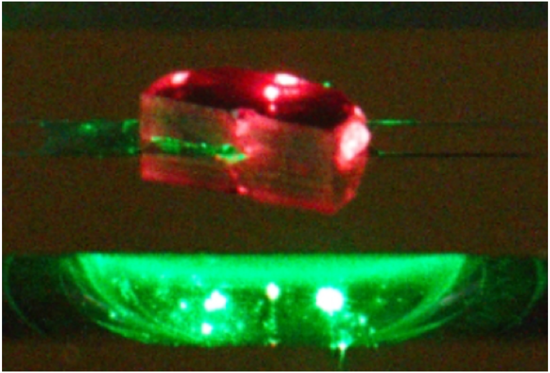




NV center ↔ single qubit nanoscale magnetometer

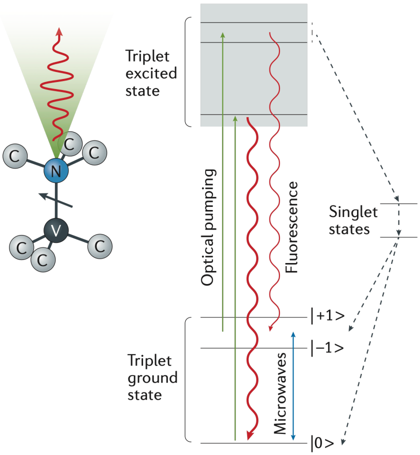
NV operation

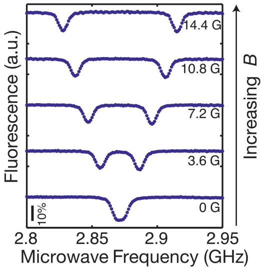
Shine green, record red

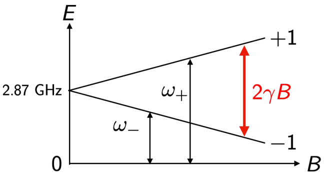


Hongkun Park lab, Harvard

NV operation

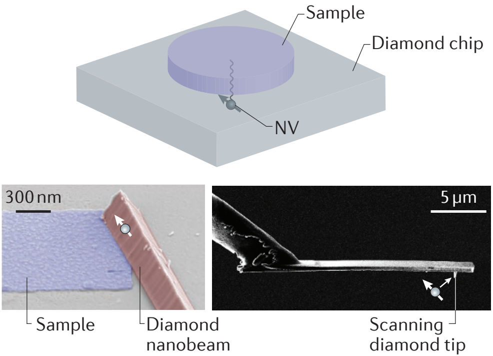






Hong, et. al., *Nanoscale magnetometry with NV centers in diamond* (2013)

NV measuring schemes



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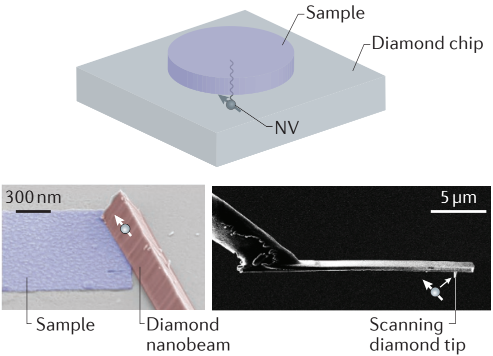

Applying fields (varying ΔE), varying temperature T, NV distance d, etc. yields information about sample of interest.

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Question: What do we see when we bring an NV center near the surface of an electrical conductor?

Electrical conductors

Conductors allow the flow of electrons (e.g, a copper wire):

$$I = V/R, \quad R = \text{resistance}$$

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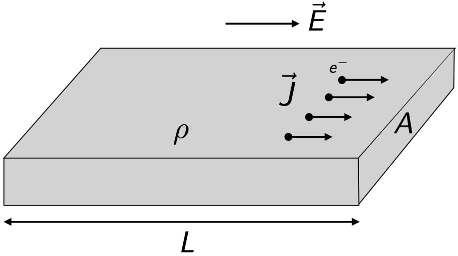

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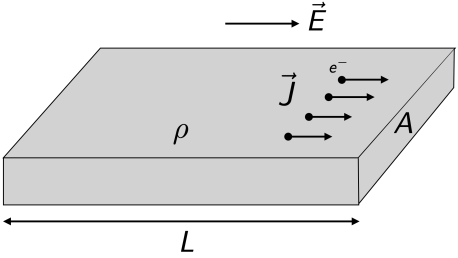
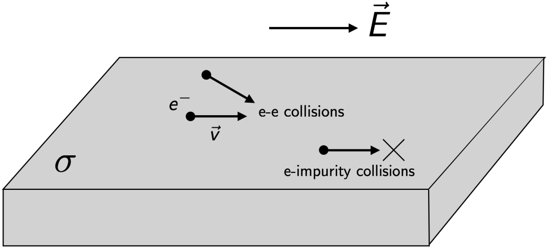


In the simplest situation, conductors obey the microscopic Ohm's law:

$$\vec{J}(x,t) = \sigma \vec{E}(x,t).$$

Conductivity – Drude model (1900)



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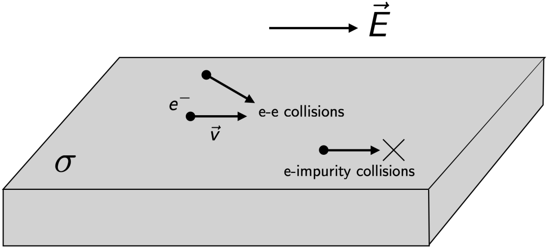

$$m\dot{\vec{v}} = -e\vec{E} - \frac{m}{\tau_D}\vec{v}$$

"Friction" determined by average time τ_D between e$^-$ scattering events.

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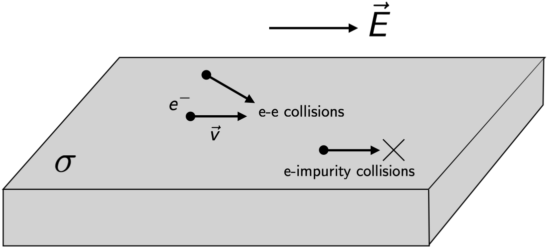

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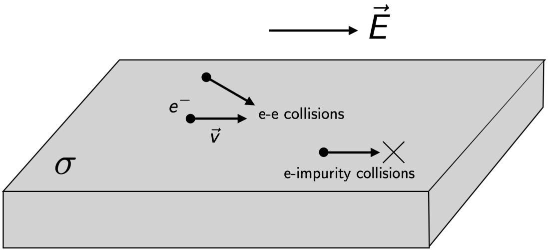

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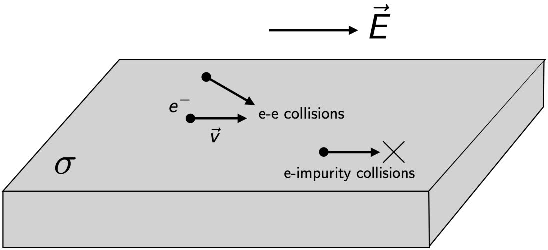

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mean free-path: $\ell = v_0\tau_D$, $\quad v_0$ = electron speed between collisions.

Johnson-Nyquist noise (1928)

Even in the *absence* of an applied field, thermal motion of e^- in a conductor leads to current fluctuations:

$$\frac{1}{2} m \langle v_{\mathrm{th}}^2 \rangle = \frac{3}{2} k_{\mathrm{B}} T \quad \text{(equipartition)}$$

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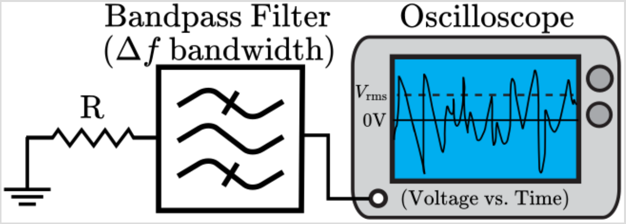

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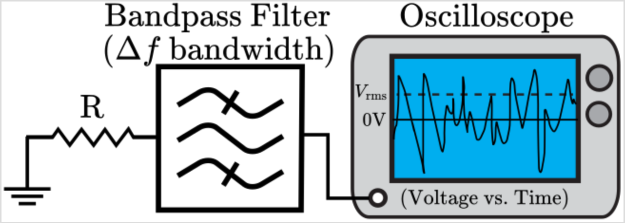

$$V_{\text{rms}}^2 = \overline{V^2} = 4 k_{\text{B}} T R \Delta f, \quad \overline{I^2} = \frac{4 k_{\text{B}} T \Delta f}{R}$$

Noise spectral density (more refined information)

- Consider electron velocity $v(t_0)$ and at a later time $v(t_0 + t)$. A useful quantity is:

$$C_v(t) = \int_{-\infty}^{\infty} \mathrm{d}t_0 \; v(t_0 + t) v(t_0)$$

  Measure of the correlation between the velocity at times t_0 and $t_0 + t$.

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- More relevant is the Fourier transform:

$$S_v(\omega) = \int_{-\infty}^{\infty} \mathrm{d}t \; e^{-i\omega t} C_v(t) \quad \text{(noise spectral density)}$$

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Measure of the correlation between the velocity at times t_0 and $t_0 + t$.

- More relevant is the Fourier transform:

$$S_v(\omega) = \int_{-\infty}^{\infty} \mathrm{d}t \; e^{-i\omega t} C_v(t) \quad \text{(noise spectral density)}$$

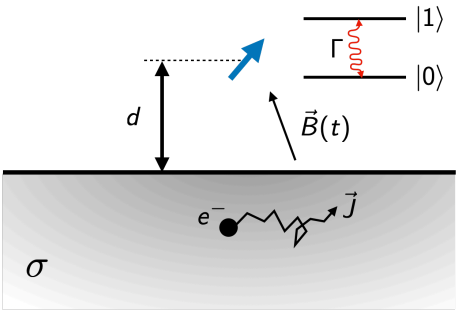
- A reasonable approximation:

$$C_v(t) = \overline{v^2} e^{-t/\tau_c}, \quad \tau_c = \text{noise correlation time}, \quad \overline{v^2} \sim k_\mathrm{B} T/m$$

$$\Rightarrow S_v(\omega) = 2\overline{v^2}\tau_c \frac{1}{1 + (\omega\tau_c)^2} \approx 2\overline{v^2}\tau_c$$

$$\text{Johnson noise: } S_I(\omega) = \frac{4k_\mathrm{B} T}{R}$$

Putting everything together: NV center near a conductor

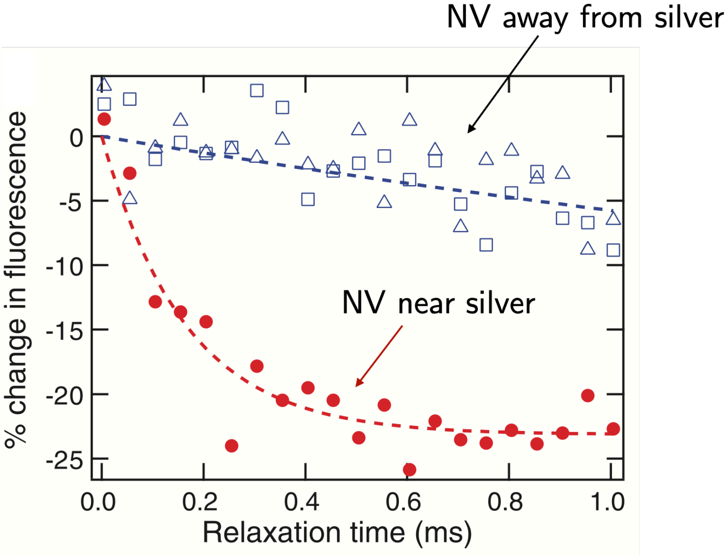


Current fluctuations ⇒ noisy magnetic fields B above the conductor

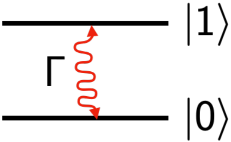
B-field at the position of the NV ⇒ transitions between levels with rate Γ

NV center near a conductor (experiment)

Decay of $|0\rangle$ state as a function of time



NV transition rate Γ



$$H_{\text{interaction}} = \gamma B(t)\left(|0\rangle\langle 1| + |1\rangle\langle 0|\right)$$

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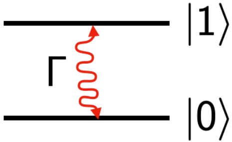

$$H_{\text{interaction}} = \gamma B(t)\left(|0\rangle\langle 1| + |1\rangle\langle 0|\right)$$

Transition rate is determined by “Fermi’s golden rule”

$$\Gamma = |\langle 1|H_{\text{interaction}}(\omega = \Delta E/\hbar)|0\rangle|^2$$

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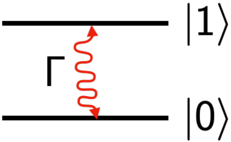

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$$\Gamma = \left|\langle 1|H_{\text{interaction}}(\omega = \Delta E/\hbar)|0\rangle\right|^2$$

$$\Gamma = \gamma^2 S_B(\omega = \Delta/\hbar) \approx \gamma^2 S_B(\omega = 0) = \gamma^2 \overline{B^2}\tau_c$$

Q: What are $\overline{B^2}$ and τ_c? How do they depend on d, T, etc...?

NV transition rate

$$\Gamma = \gamma^2 \overline{B^2} \tau_c$$

Magnetic field at heigh d from e^- moving in the conductor:

$$B = \frac{\mu_0 e v}{4\pi d^2} \quad \Rightarrow \overline{B^2} = \frac{\mu_0^2 e^2}{16\pi^2 d^4} \overline{v^2} \sim \frac{\mu_0^2 e^2}{d^4} \frac{k_B T}{m}$$

L. S. Langsjoen, A. Poudel, M. G. Vavilov, R. Joynt, *Qubit relaxation from evanescent-wave Johnson noise* (2012)

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Many electrons will contribute to the B-field noise: estimate $N \sim n d^3$, where n = electron density and the "sensing volume" $\sim d^3$.

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$$\Rightarrow \Gamma \sim \frac{\mu_0^2}{d} k_B T \frac{n e^2 \tau_c}{m}$$

L. S. Langsjoen, A. Poudel, M. G. Vavilov, R. Joynt, *Qubit relaxation from evanescent-wave Johnson noise* (2012)

NV transition rate (cont.)

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NV transition rate (cont.)

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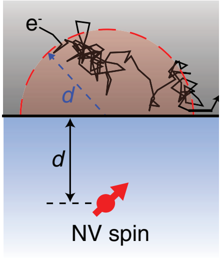
From the Drude model $\sigma = ne^2\tau_D/m$, with mean-free path $\ell = v_0\tau_D$. If $\ell < d$, then $\tau_c = \tau_D$.



NV transition rate (cont.)

$$\Gamma \sim \frac{\mu_0^2}{d} k_\mathrm{B} T \frac{ne^2 \tau_c}{m}$$

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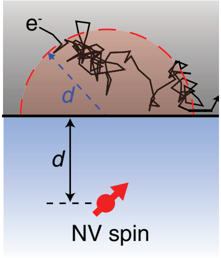
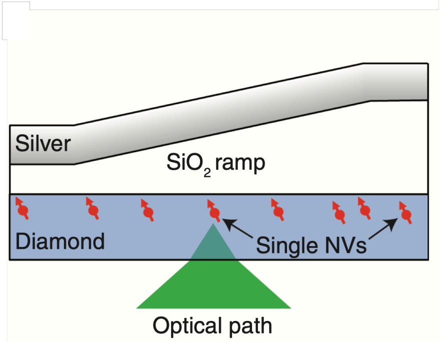
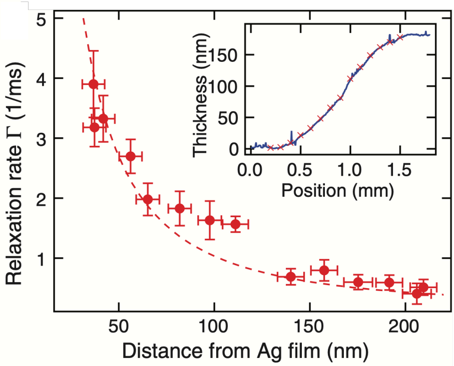


$$\Gamma \sim \frac{\mu_0^2}{d} k_\mathrm{B} T \sigma$$

NV transition rate (experiment)

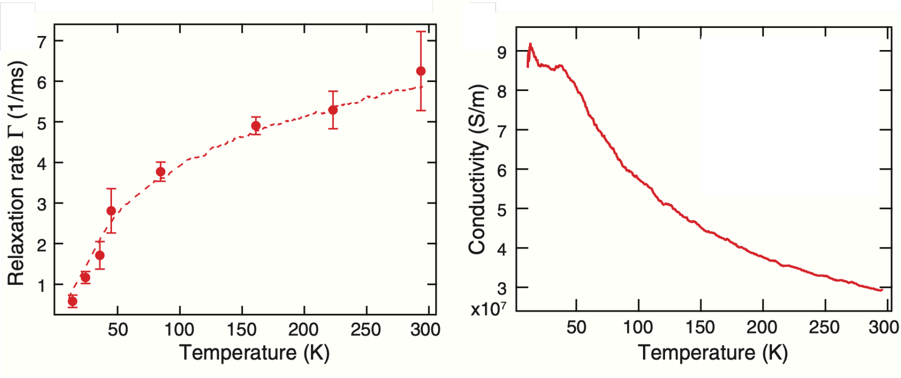
$$\Gamma \sim \frac{\mu_0^2}{d} k_B T \sigma$$





NV transition rate (experiment)

$$\Gamma \sim \frac{\mu_0^2}{d} k_B T\sigma(T)$$

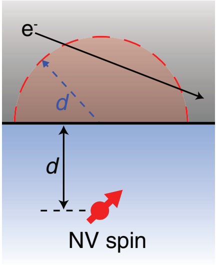


Noise for $d < \ell$

$$\Gamma \sim \frac{\mu_0^2}{d}\frac{ne^2}{m}k_B T \tau_c$$

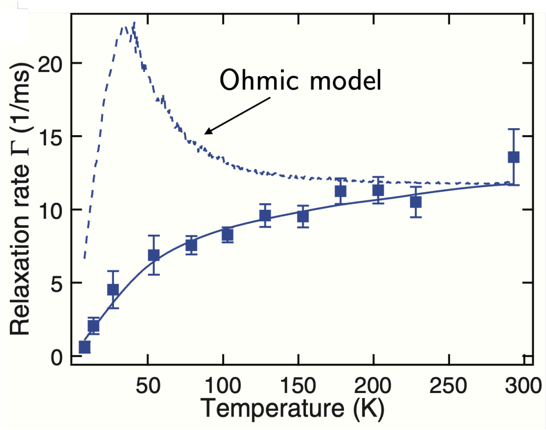
Q: What happens when the NV is at a distance $d < \ell$, the mean-free path?

Relaxation is *qualitatively changed* owing to ballistic motion of e^-.



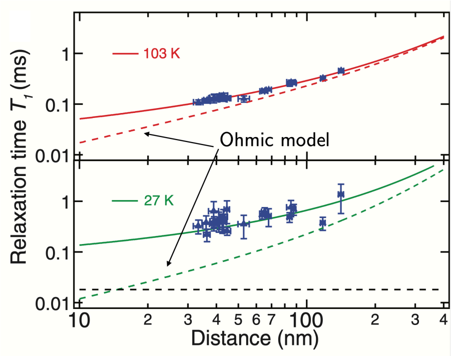
Roughly: $\tau_c \sim d/v_0$

Noise for $d < \ell$ (experiment)



Noise for $d < \ell$ (experiment)

$(T_1 = 1/\Gamma)$



Experiment shows saturation of $\Gamma \sim 1/d$ as $d \to 0$.

Ohmic conductivity predicts $\Gamma \sim d \to 0$ as $d \to 0$.

$$\tau_c \sim d/v_0 \quad \Rightarrow \quad \Gamma \sim \mu_0^2 \frac{ne^2 k_B T}{m v_0}$$

Noise for $d < \ell$

A proper understanding of this "ballistic" regime requires modification of Ohm's law in terms of "non-local conductivity":

$$J(x,t) = \int \mathrm{d}t'\mathrm{d}x'\sigma(x-x',t-t')E(x',t')$$

If we consider an oscillating field $E = E_0 e^{i(qx-\omega t)}$ the induced current is:

$$J(x,t) = \sigma(q,\omega)E_0 e^{i(qx-\omega t)}, \quad \sigma(q,\omega) = \text{F.T. of } \sigma(x,t)$$

In an NV experiment, we (roughly) probe $\sigma(q \sim 1/d, \omega = \Delta E/\hbar)$.

Noise probed by a quantum sensor yields information about nonlocal conductivity – useful for studying a variety of condensed matter systems.

PHYSICAL REVIEW B **95**, 155107 (2017)

Magnetic noise spectroscopy as a probe of local electronic correlations in two-dimensional systems

Kartiek Agarwal,[1,*] Richard Schmidt,[2] Bertrand Halperin,[1] Vadim Oganesyan,[3]
Gergely Zaránd,[4] Mikhail D. Lukin,[1] and Eugene Demler[1]

PHYSICAL REVIEW RESEARCH **4**, L012001 (2022)

Letter | Editors' Suggestion

Single-spin qubit magnetic spectroscopy of two-dimensional superconductivity

Shubhayu Chatterjee,[1,*] Pavel E. Dolgirev,[2,*] Ilya Esterlis,[2] Alexander A. Zibrov,[2] Mikhail D. Lukin,[2]
Norman Y. Yao,[1,3] and Eugene Demler[2,4]

PHYSICAL REVIEW LETTERS **132,** 246504 (2024)

Local Noise Spectroscopy of Wigner Crystals in Two-Dimensional Materials

Pavel E. Dolgirev,[1,*] Ilya Esterlis,[2,1,*] Alexander A. Zibrov,[1] Mikhail D. Lukin,[1]
Thierry Giamarchi,[3] and Eugene Demler[4]

PHYSICAL REVIEW B **98**, 195433 (2018)

Editors' Suggestion

Probing one-dimensional systems via noise magnetometry with single spin qubits

Joaquin F. Rodriguez-Nieva,[1] Kartiek Agarwal,[2] Thierry Giamarchi,[3] Bertrand I. Halperin,[1]
Mikhail D. Lukin,[1] and Eugene Demler[1]

Noise measurements with a quantum sensor can also (conceivably) be used to study magnetic insulators (e.g., spin liquids)

PHYSICAL REVIEW B **99**, 104425 (2019)

Editors' Suggestion

Diagnosing phases of magnetic insulators via noise magnetometry with spin qubits

Shubhayu Chatterjee,[1,2] Joaquin F. Rodriguez-Nieva,[1] and Eugene Demler[1]
[1]*Department of Physics, Harvard University, Cambridge Massachusetts 02138, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*

Quantum sensing

Studied noise magnetometry with NV-centers as example quantum sensor

What we did not discuss:

- NV-centers for sensing coherent (not fluctuating) static and time-varying B-fields[1]
- More broadly: Use of quantum coherence (superposition) to make measurements. Use of entanglement to improve sensitivity and precisions of measurements.[2]

[1] Casola, van der Sar, and Yacoby, *Probing condensed matter physics with magnetometry based on NV centers in diamond* (2018)
[2] Degen, Reinhard, Cappellaro, *Quantum sensing* (2017)

Thank you for your attention