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OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT

Nitrogen-Vacancy Centers in Diamond

- lecture 2 -

Alexander Huck

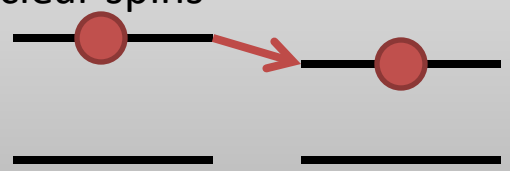
28 January 2014

QPIT
Quantum Physics and Information Technology
DTU Physics
DTU Physics
Department of Physics

Fields of Application

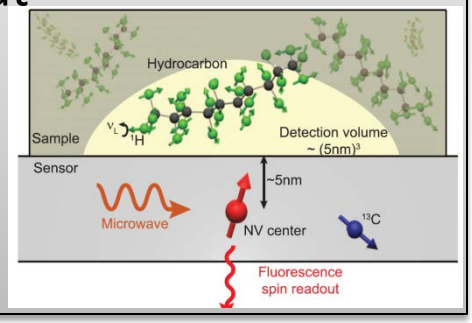
Quantum Information Processing

- solid-state qubit with long coherence time at room temperature
- transfer of coherence to adjacent nuclear spins



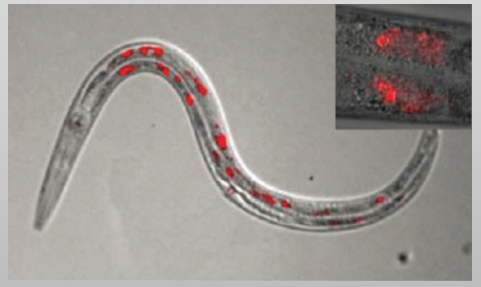
Magnetic Field Sensing Aplications

- coupling to B-fields
- optical readout
- nano-scale spatial resolution



Flourescence Marker

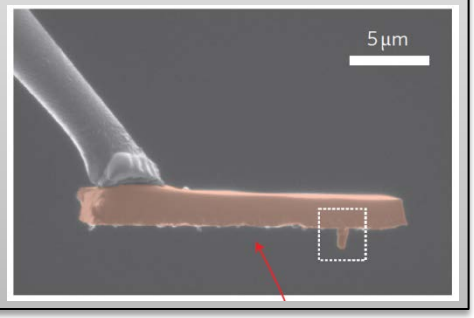
- non-toxic
- very stable fluorescence
- extremely high photo-stability



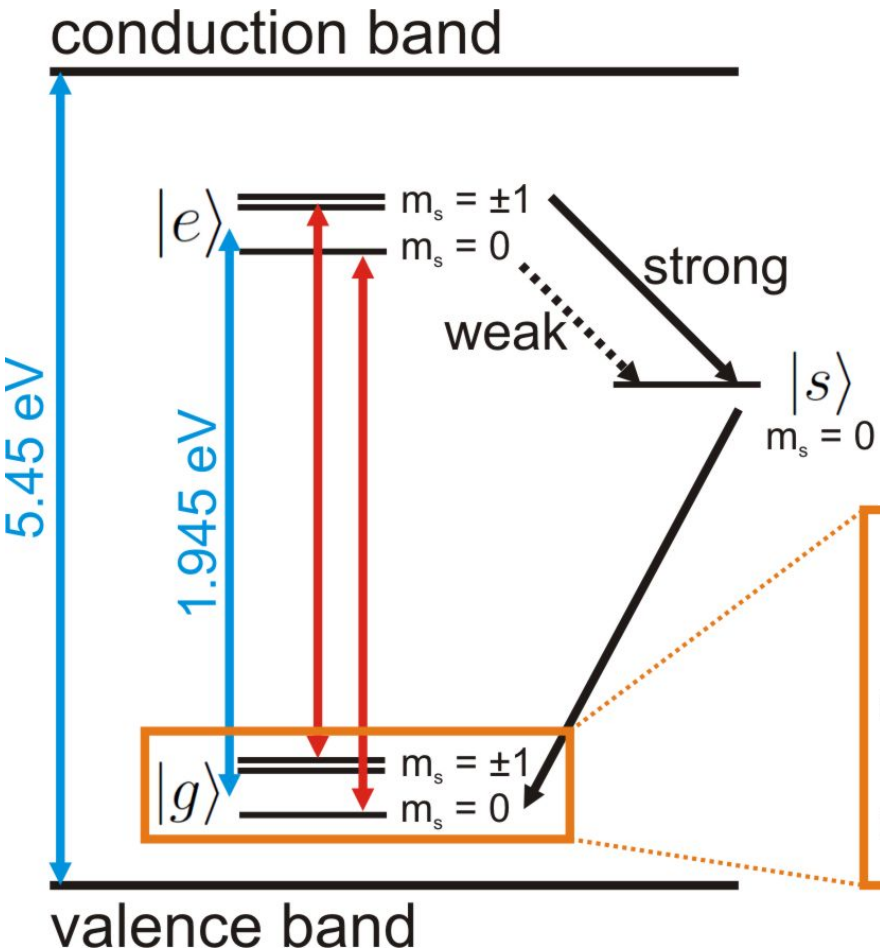
µ-organism fed with fluorescent nano-diamonds

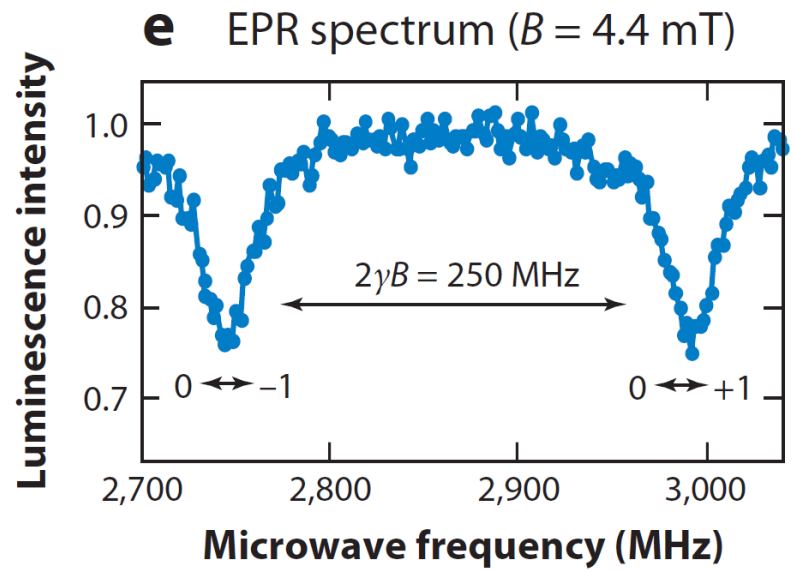
Robust Nano-Probe

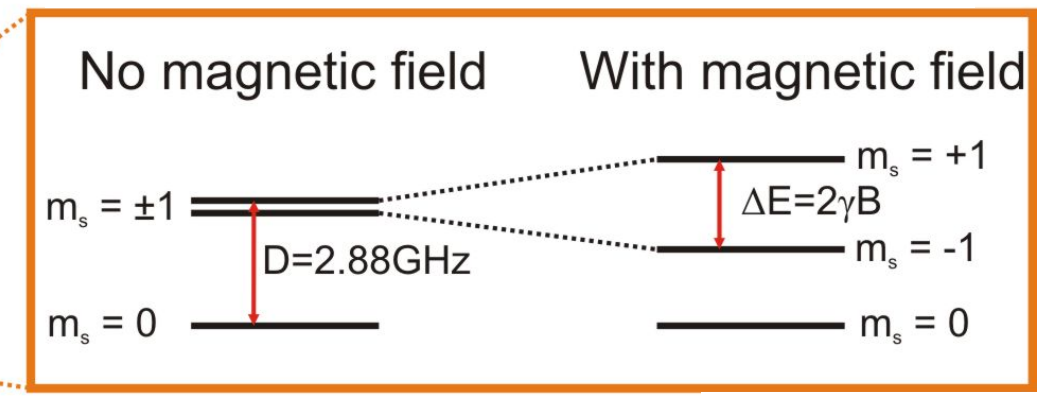
- photonic local-density of states
- reasonable lifetime



Continous wave excitation





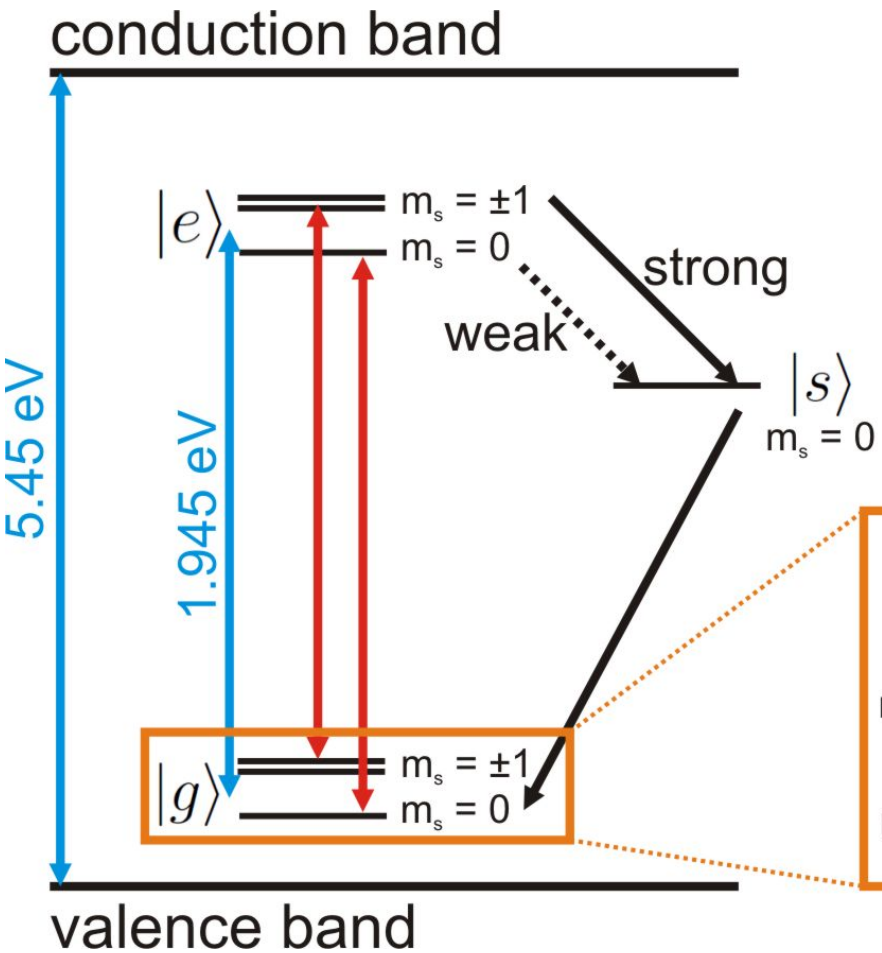


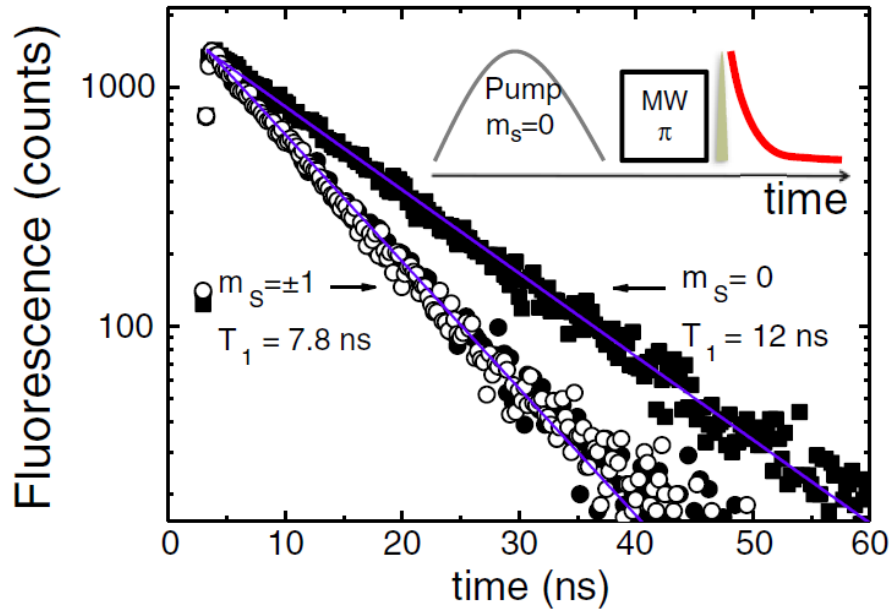
With: $\gamma = g\mu_B$

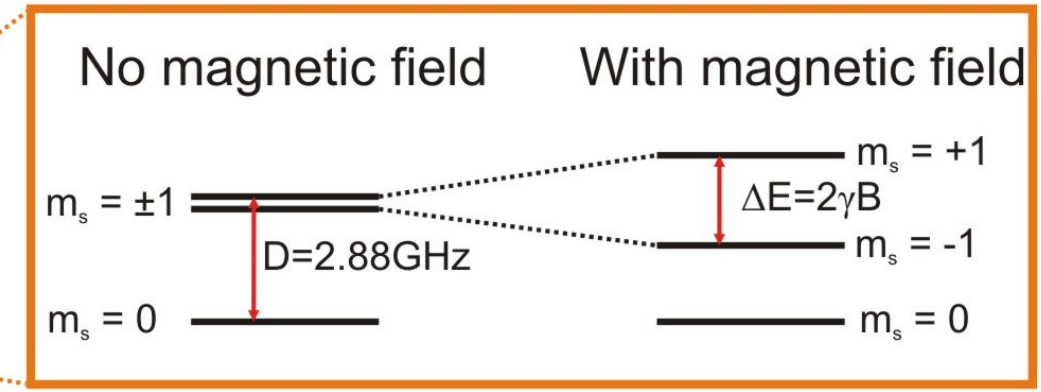
Electron spin hamiltonian:

$$H_{es} = DS_z^2 + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

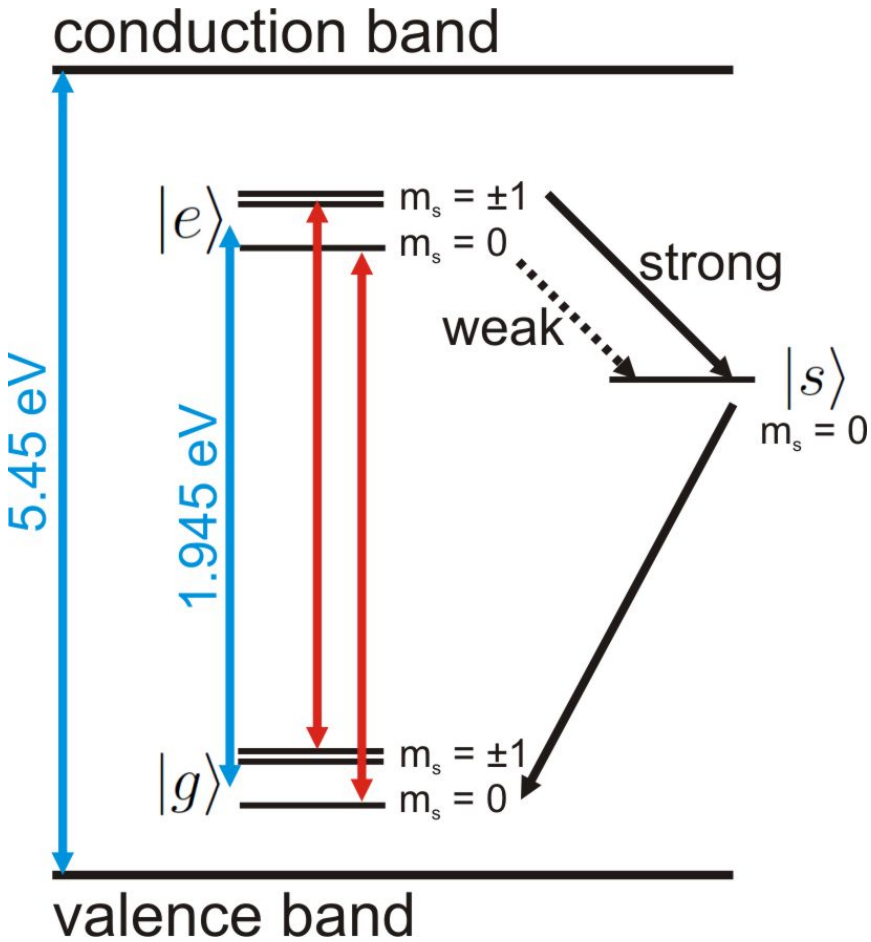
Continous wave excitation



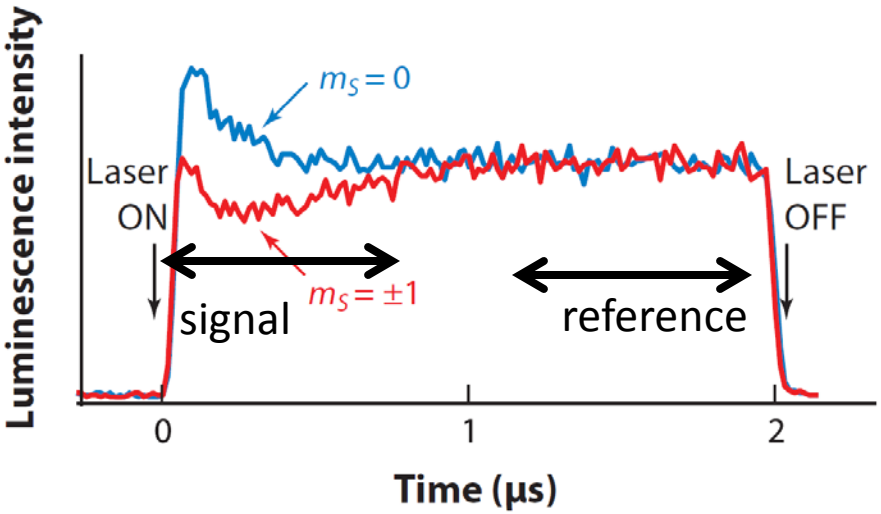




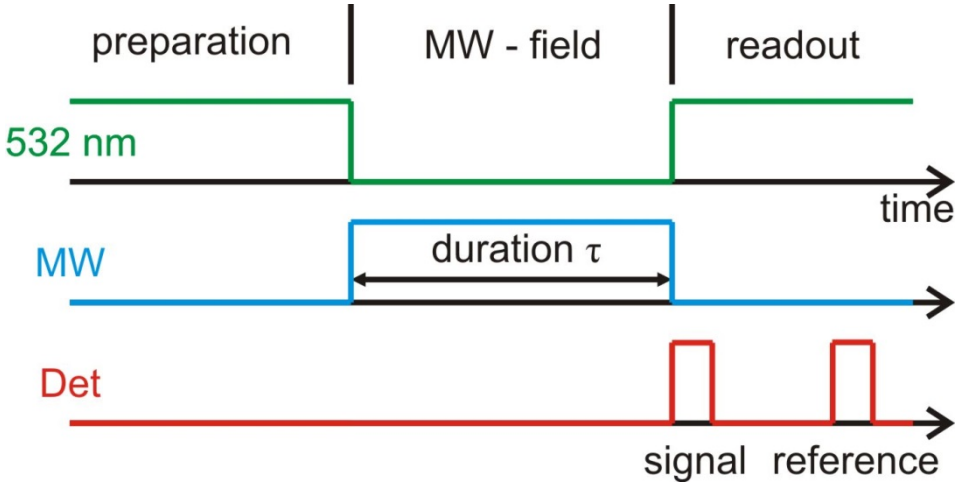
Pulsed detection



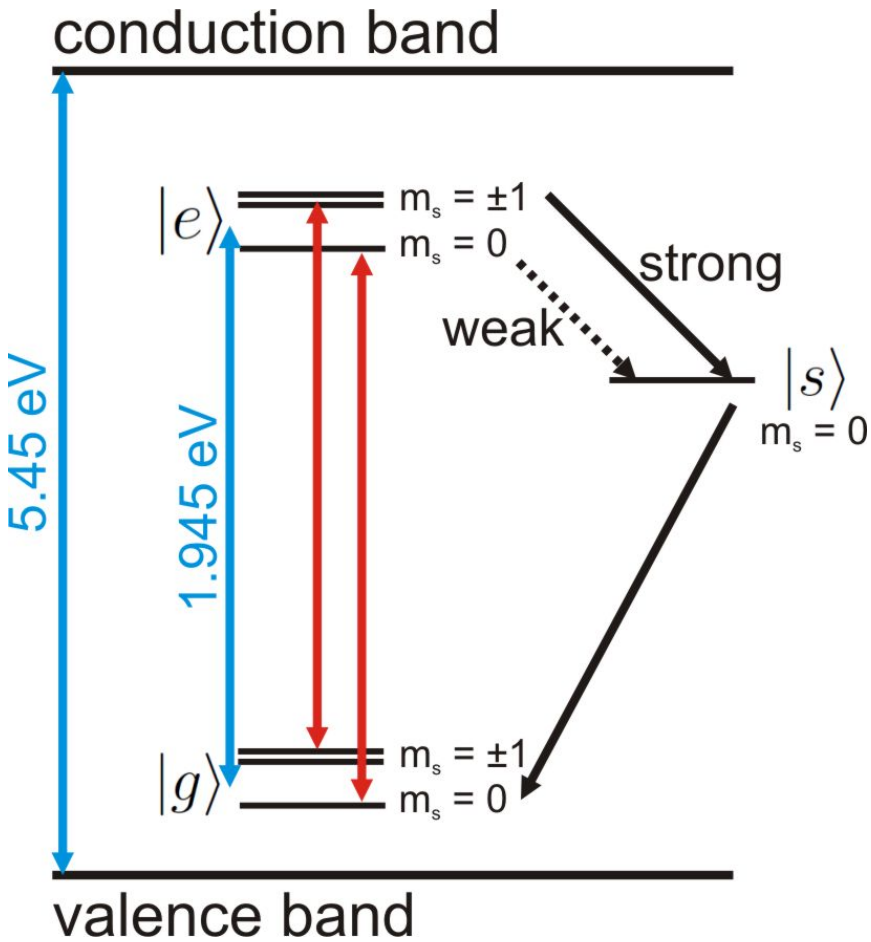
Typical readout signals:

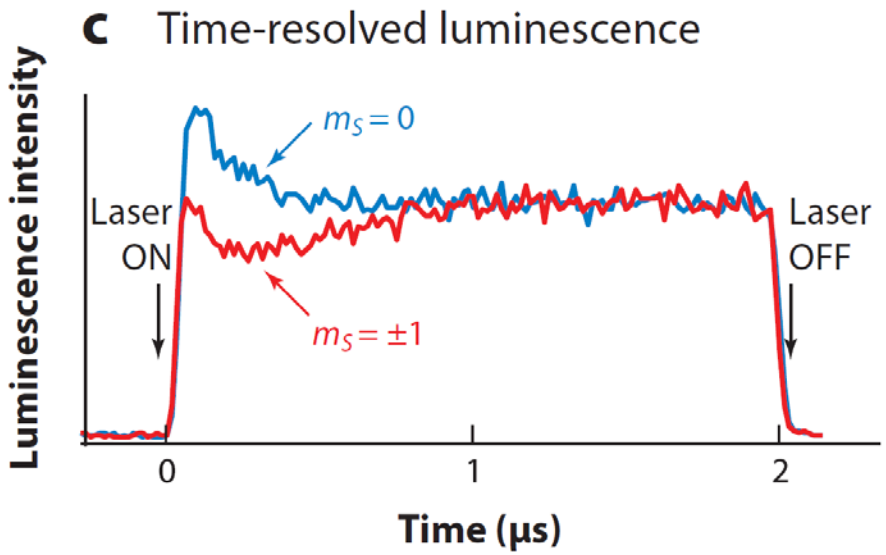


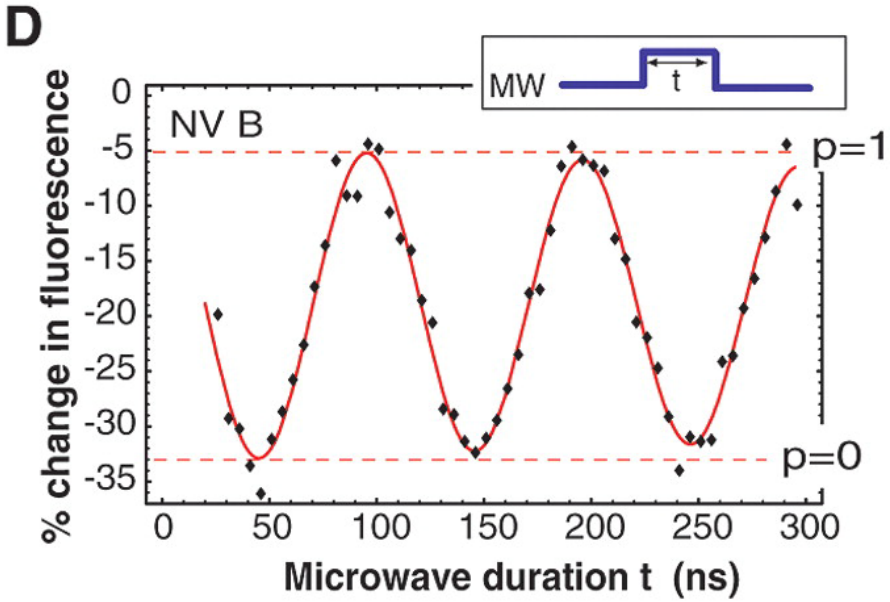
Typical test sequence:



Rabi nutation



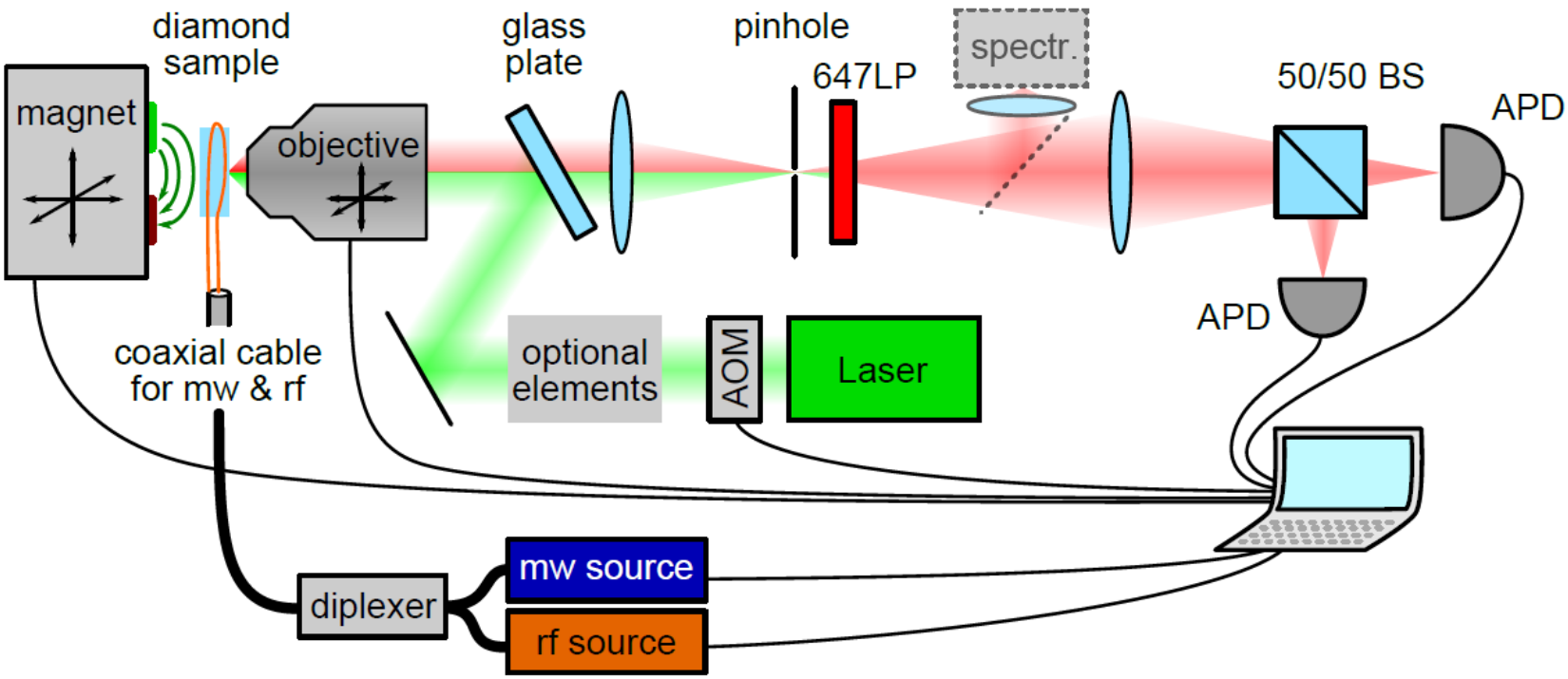




Rabi frequency:

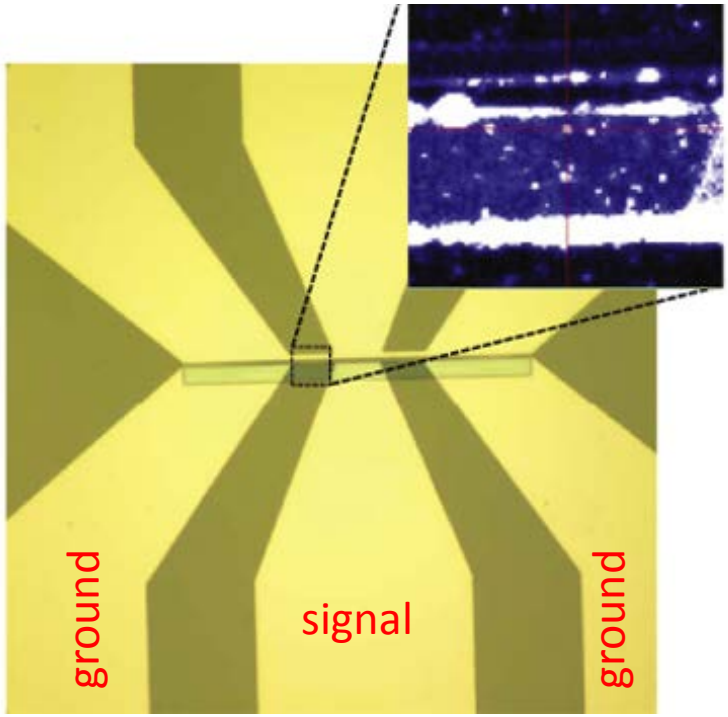
$$\Omega_R = g\mu_B B/h$$

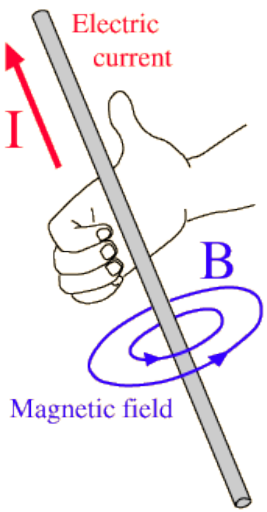
Experimental setup



Neumann, PhD thesis, U Stuttgart 2011

MW waveguides





<u>High microwave efficiency</u>

- Coplanar waveguides (impedence matched)
- Higher B-field
- Higher Rabi-frequency
- Eventually short terminated

<u>More simple solution:</u>

- Thin conductor with diameter d
- Wire impedance large
- High power needed

$$I_{ac} = \sqrt{\frac{P_{\mathrm{rf}}}{Z}} \qquad B_{\mathrm{ac}} = \frac{\mu_0 I_{ac}}{2\pi d}$$

Spectroscopy techniques - Ramsey

1) Create a superpositions (π/2 - pulse)

$$|\psi(0)\rangle = 1/\sqrt{2}\,(|0\rangle + |1\rangle)$$

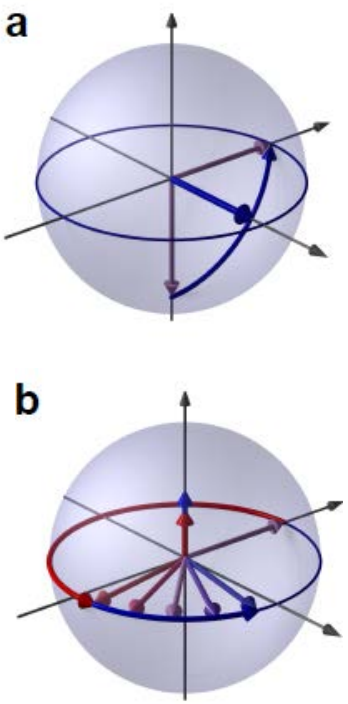
2) Free evolution – acquisition of a relative phase

$$|\psi(\tau)\rangle = 1/\sqrt{2}\,\left(|0\rangle + e^{i\phi}\,|1\rangle\right)$$

3) Final projection back on z-axis (π/2 - pulse) and measurement

$$|\psi(2\tau)\rangle = 1/\sqrt{2}\,\left((1+e^{i\phi})\,|0\rangle - (1-e^{i\phi})\,|1\rangle\right)$$

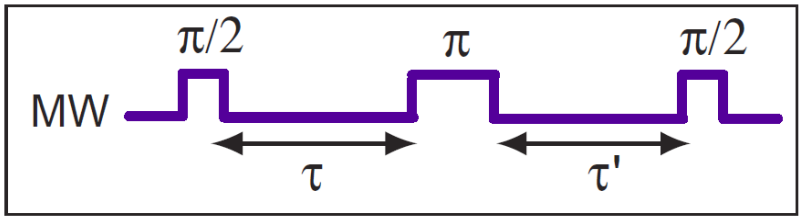
$$S = \frac{1}{2}\,|\langle 1|\,|\psi_{out}(\tau)\rangle|^2 = (1 - cos(\phi))$$

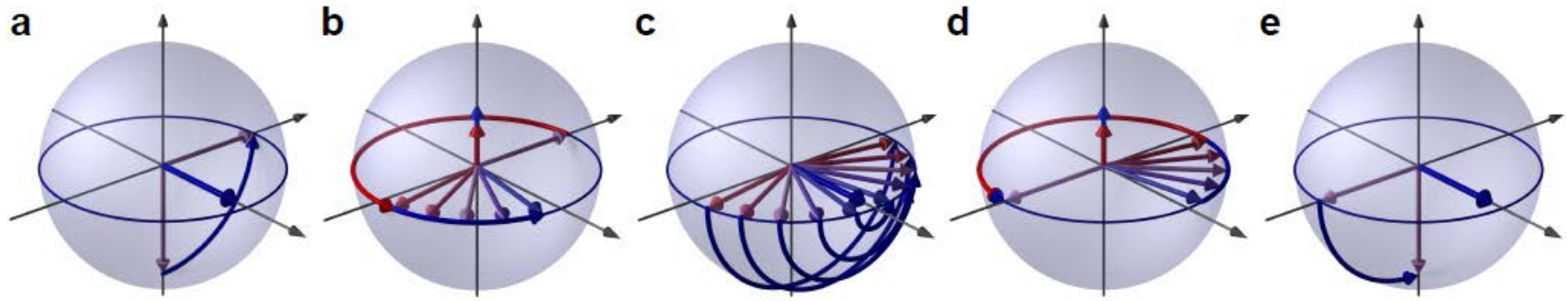


Spectroscopy techniques – Hahn echo

1) Create a superpositions (π/2 - pulse)
$$|\psi(0)\rangle = 1/\sqrt{2}\,(|0\rangle + |1\rangle)$$
2) Free evolution
$$|\psi(\tau)\rangle = 1/\sqrt{2}\,(|0\rangle + e^{i\phi}\,|1\rangle)$$
3) Flip the spin (π - pulse)
$$|\psi'(\tau)\rangle = 1/\sqrt{2}\,(|1\rangle + e^{i\phi}\,|0\rangle)$$
4) Free evolution
$$|\psi(2\tau)\rangle = 1/\sqrt{2}\,(e^{i\phi}\,|1\rangle + e^{i\phi}\,|0\rangle)$$
5) Final projection back on z-axis (π/2 - pulse)

$S \approx 1$ in case the environment didn't change





Spectroscopy techniques – CPMG

<u>effect:</u> - suppression of noise
- sensing of certain frequency components

1) Create a superpositions (π/2 - pulse)

…

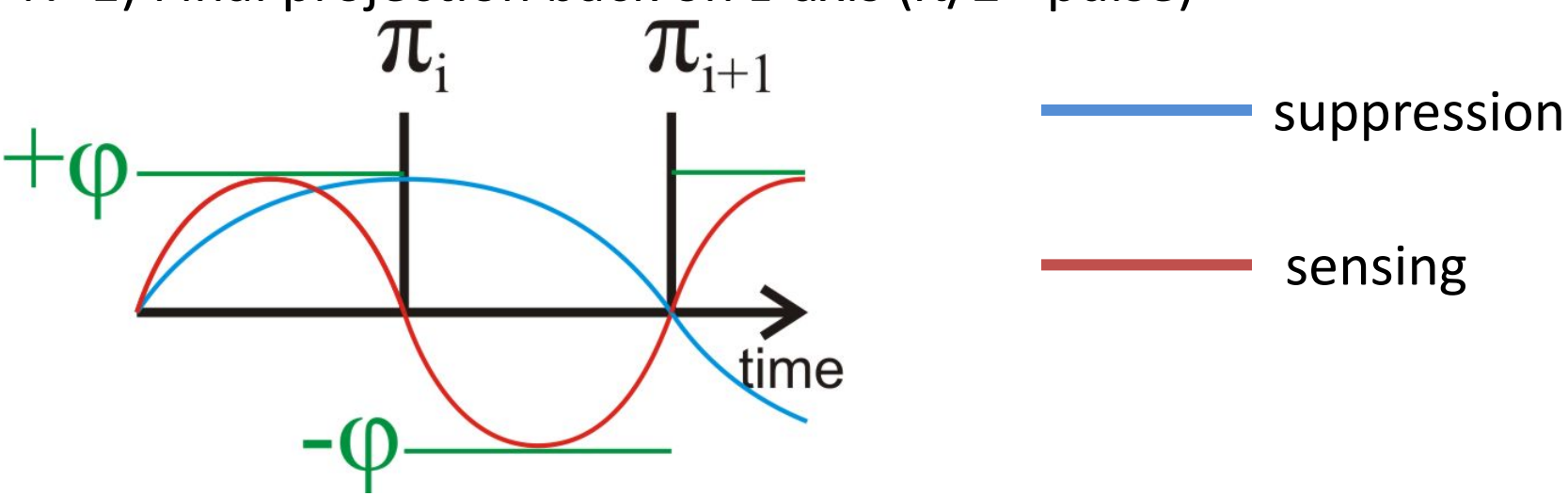
i) Flip the spin (π - pulse)

… Evolution

i+1) Flip the spin

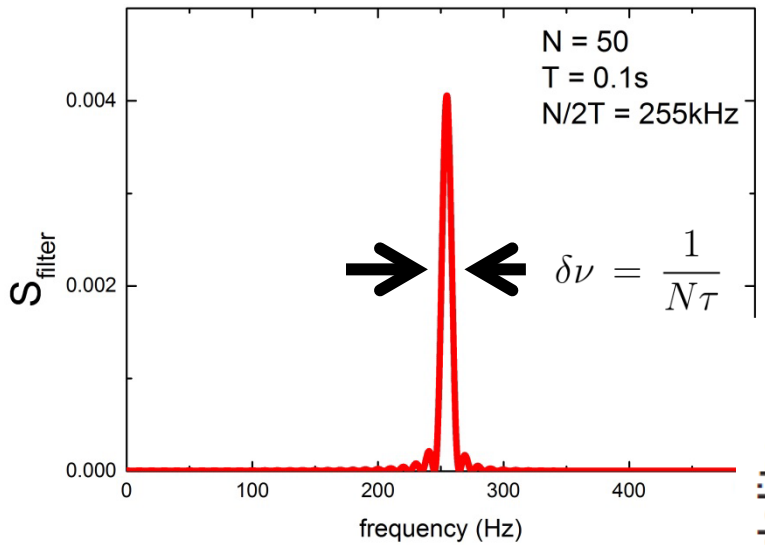
…

N+1) Final projection back on z-axis (π/2 - pulse)



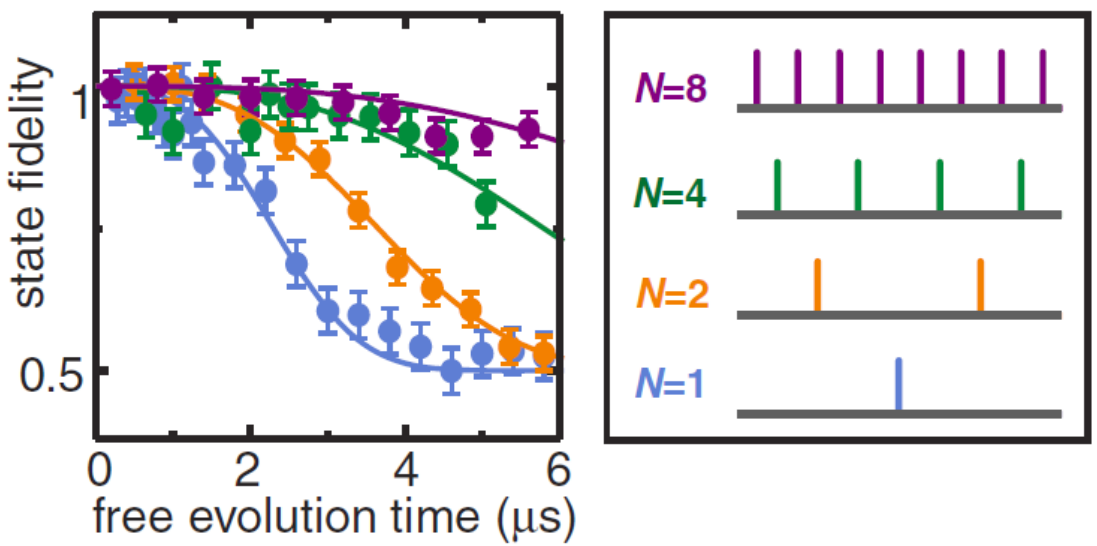
Spectroscopy techniques – CPMG

Filter function: $$F(\omega t) = \frac{1}{2}\left|\sum_{k=0}^{n}(-1)^k\left(e^{i\omega t_{k+1}} - e^{i\omega t_k}\right)\right|^2$$



Application:

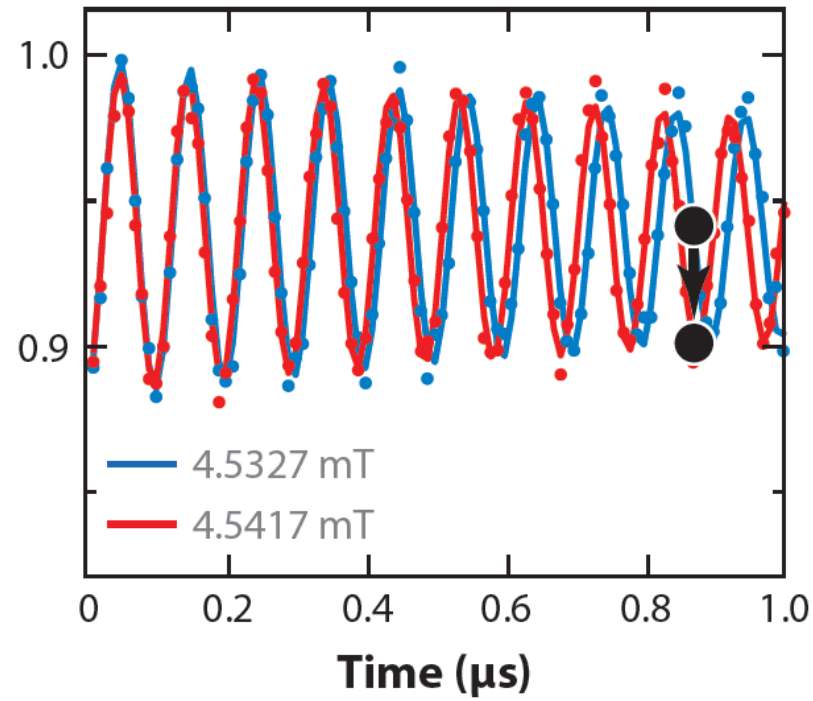
1) Extending the coherence time
2) Sensing



Ramsey DC - magnetometer

Accumulated phase difference:

$$\Delta\phi = \frac{g\mu_B}{\hbar}\int_0^\tau B(\tau)\,\mathrm{d}t$$



Sensitivity affacted by:

1) Slope of the Ramsey fringe

$$\approx g\mu_B\tau h$$

2) Optical detection (signal = shot noise limit)

$$\eta_{\mathrm{d.c.}} \approx \frac{\hbar}{g\mu_B C\sqrt{T_2^*}}$$

- C accounts for contrast and limited photon collection
- For T2* ≈ μs

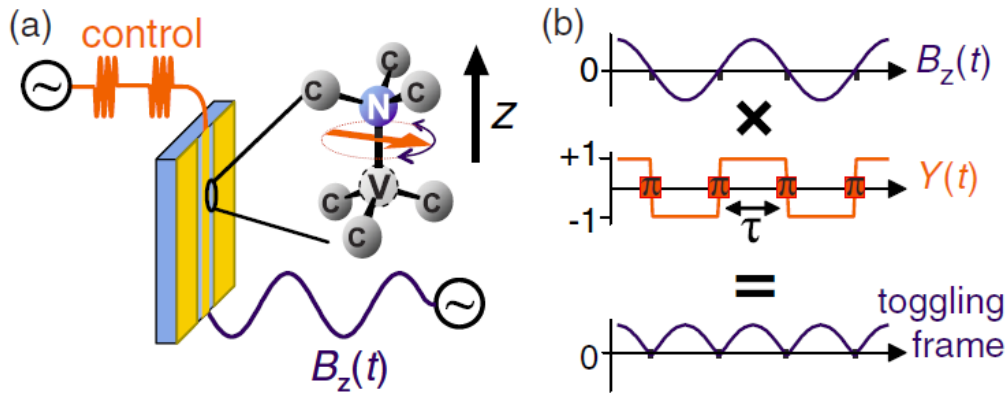
➢ $\eta_{\mathrm{d.c.}} \approx \mu\mathrm{T/(Hz)}^{-1/2}$

Balasubramanian et al., Nat. Mat. 2009, Taylor et al., Nat. Phys. 2008

AC - magnetometer

Field to be sensed: (phase locked)

$$B_z(t) = b_z \sin(2\pi f t + \phi)$$



Accumulation per half cycle:

$$\delta\Phi = \int_0^{1/2f} 2\pi\gamma B_z(t)dt = (2\gamma b_z/f)\cos\phi$$

Signal:

$$S_z(b_z) = \frac{1}{2}\sin\left(\frac{2N\gamma b_z}{f}\cos\phi\right)e^{-N/(2fT_2)^3}$$

$$b_{\min} = \sigma_{S_z}|db_z/dS_z| \approx \sigma_{S_z}\frac{f}{\gamma N}$$

Sensitivity:

$$\eta(f,N) = b_{\min}\sqrt{T} = \frac{1}{\gamma C}\sqrt{\frac{f}{2\varsigma N}}e^{N/(2fT_2)^3}$$

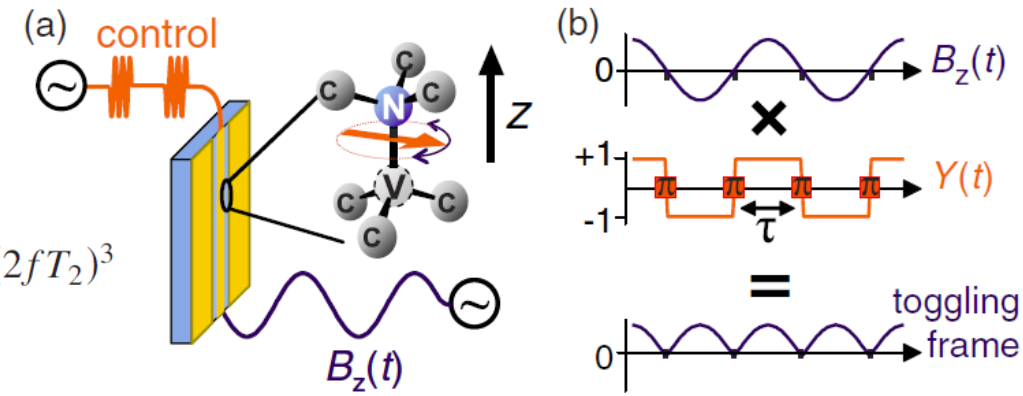
Noise per measurement

De Lange et al., Phys. Rev. Lett 2011

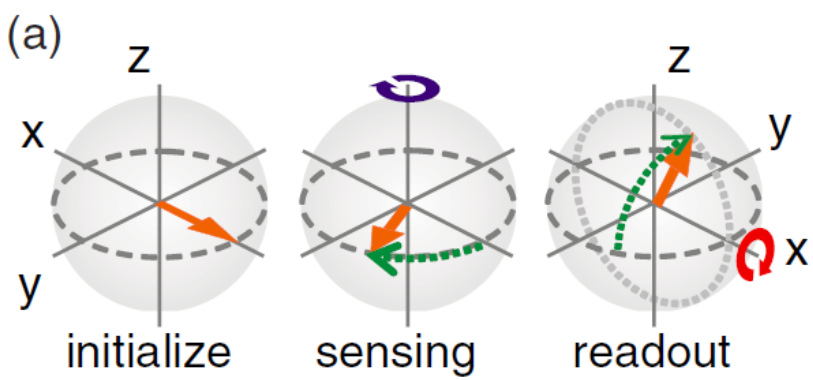
AC - magnetometer

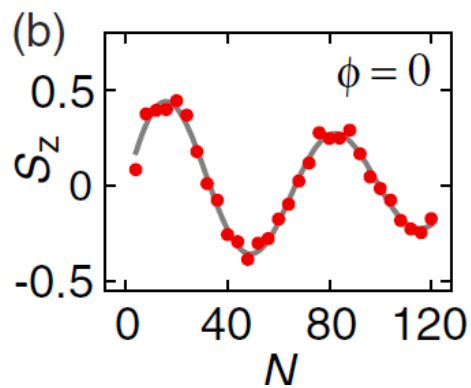
<u>Signal:</u>

$$S_z(b_z) = \frac{1}{2}\sin\left(\frac{2N\gamma b_z}{f}\cos\phi\right)e^{-N/(2fT_2)^3}$$



<u>Measuring a phase locked signal:</u>





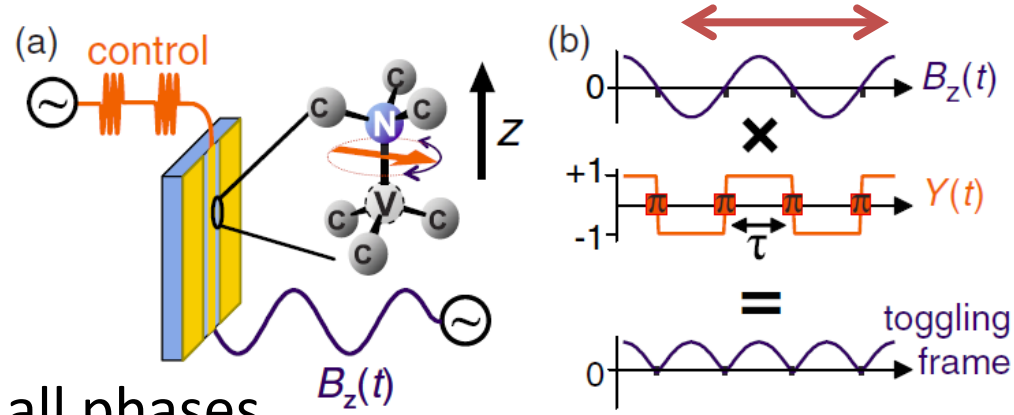
1 MHz signal

<u>Data fit:</u> b_z = 1.6μT

de Lange et al., Phys. Rev. Lett 2011

AC - magnetometer

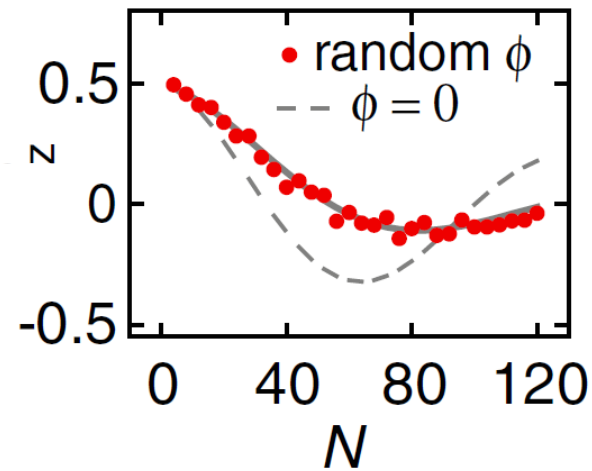
Phase ϕ randomly changing, but constant during one measurement run.

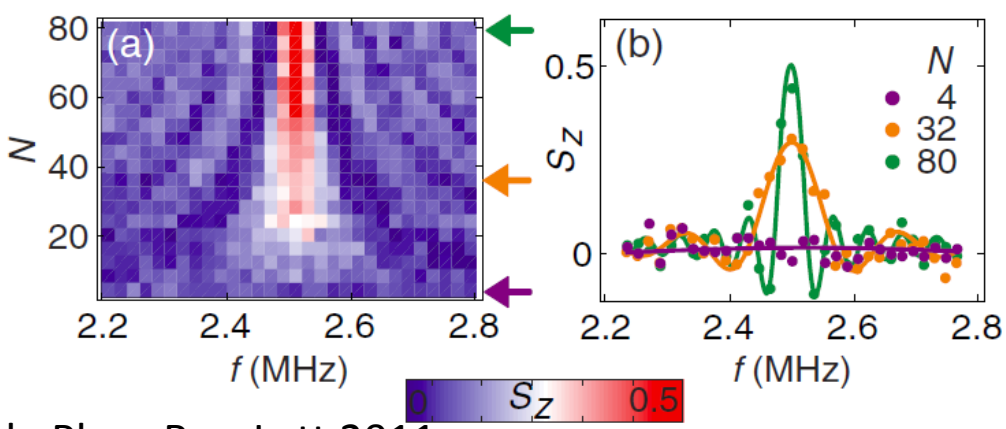


<u>Solution:</u> phase averaging over all phases

$$S_z(b_z) = \frac{1}{2}\left\langle \cos\left(\frac{2N\gamma b_z}{f}\cos\phi\right)\right\rangle_\phi e^{-N/(2fT_2)^3}$$

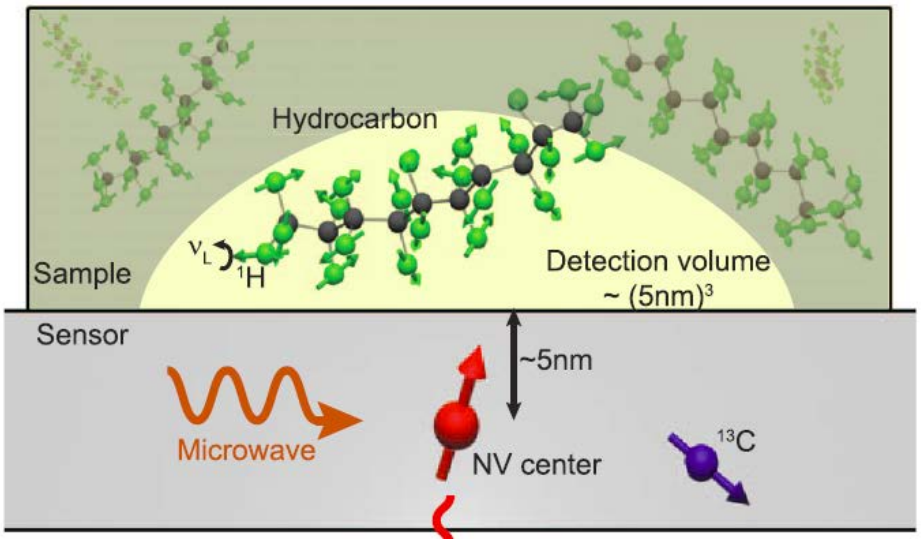
$$= \frac{1}{2} J_0\left(\frac{2N\gamma b_z}{f}\right) e^{-N/(2fT_2)^3},$$

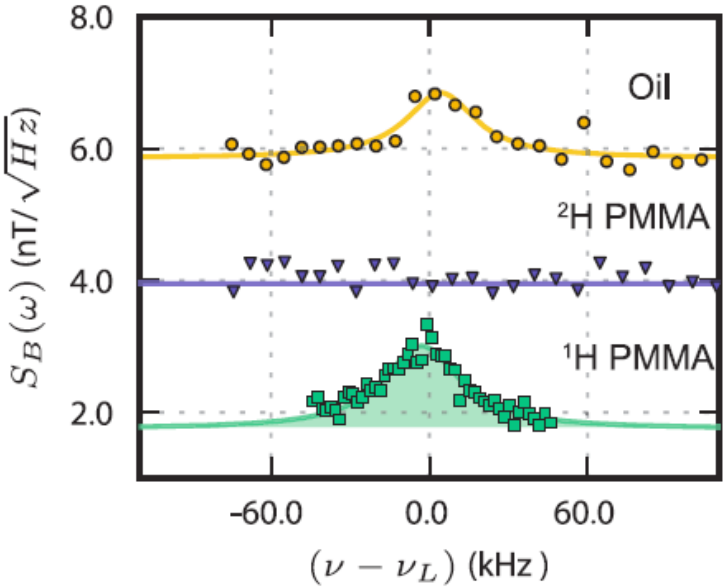




de Lange et al., Phys. Rev. Lett 2011

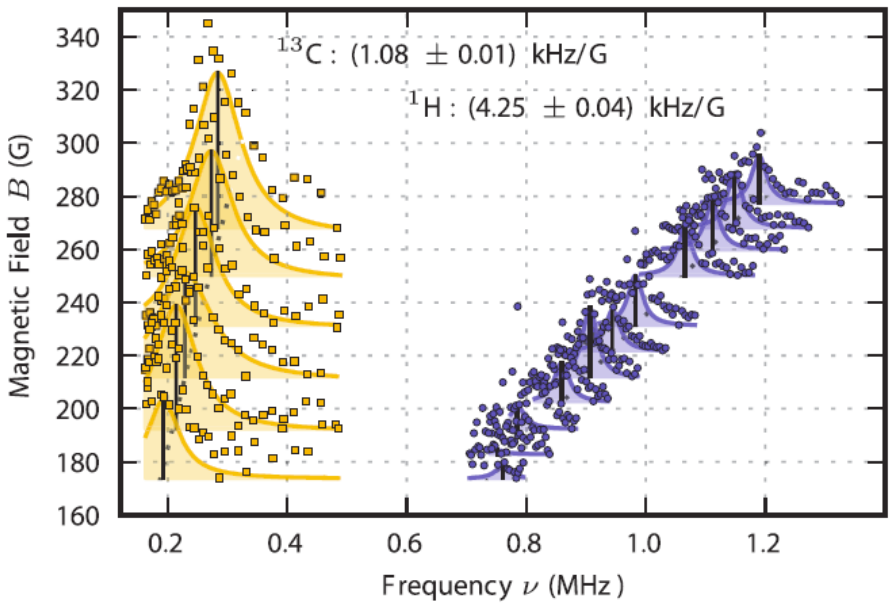
Nano-Scale Magnetic Field Sensing





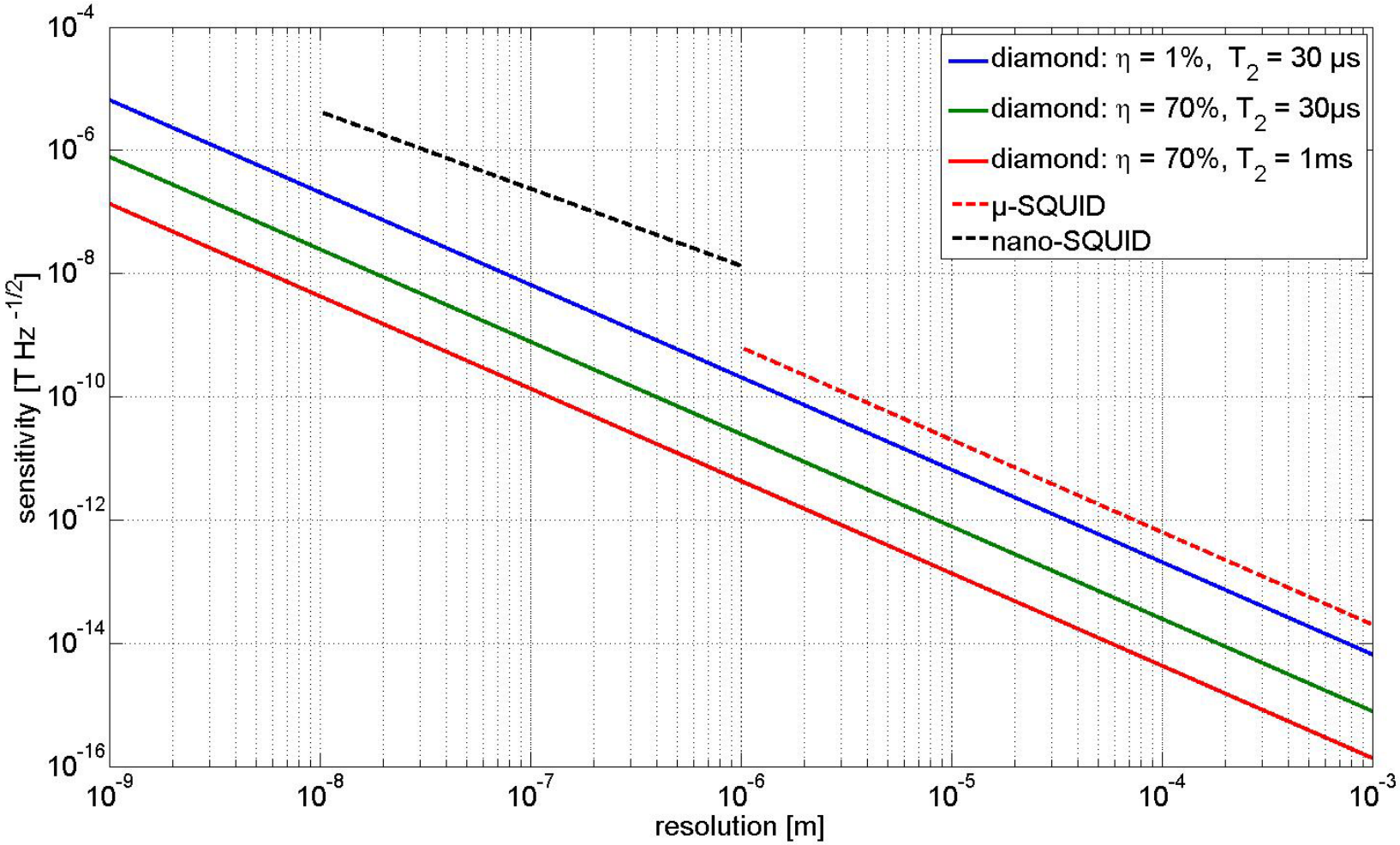
Staudacher et al., Science 339 (2013)

Experimental idea



Scaling with the Lamor frequency!

NV centers vs. SQUIDs

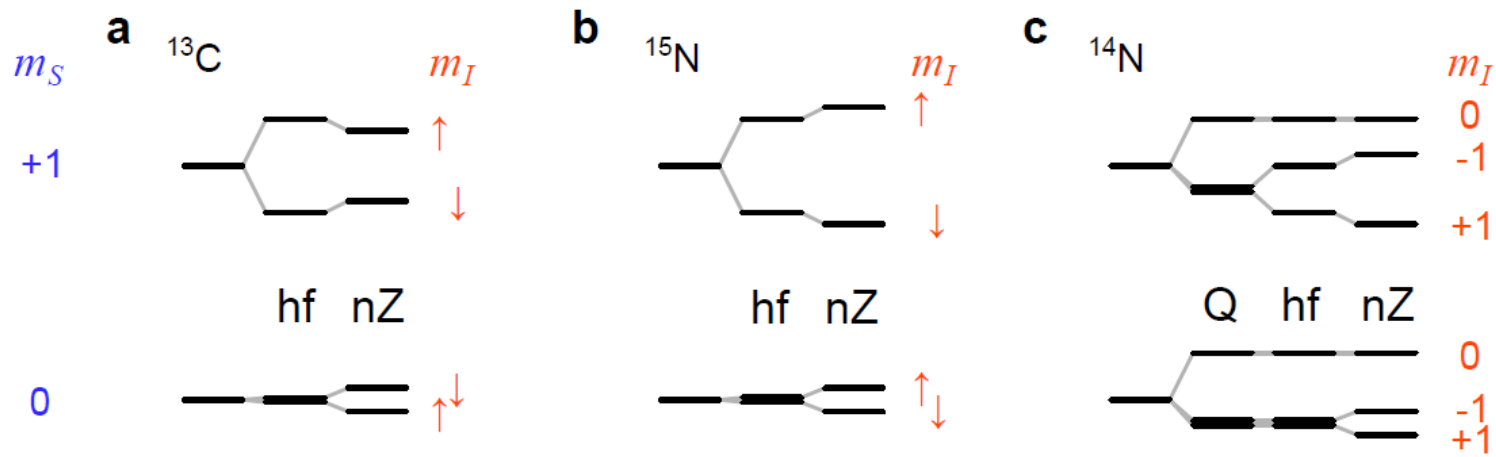


<u>NV sensitivity:</u> shot noise scaling ~$1/N^{(-1/2)}$

Nuclear spins in diamond

Most of diamond is made of ^{12}C with no nuclear spin.

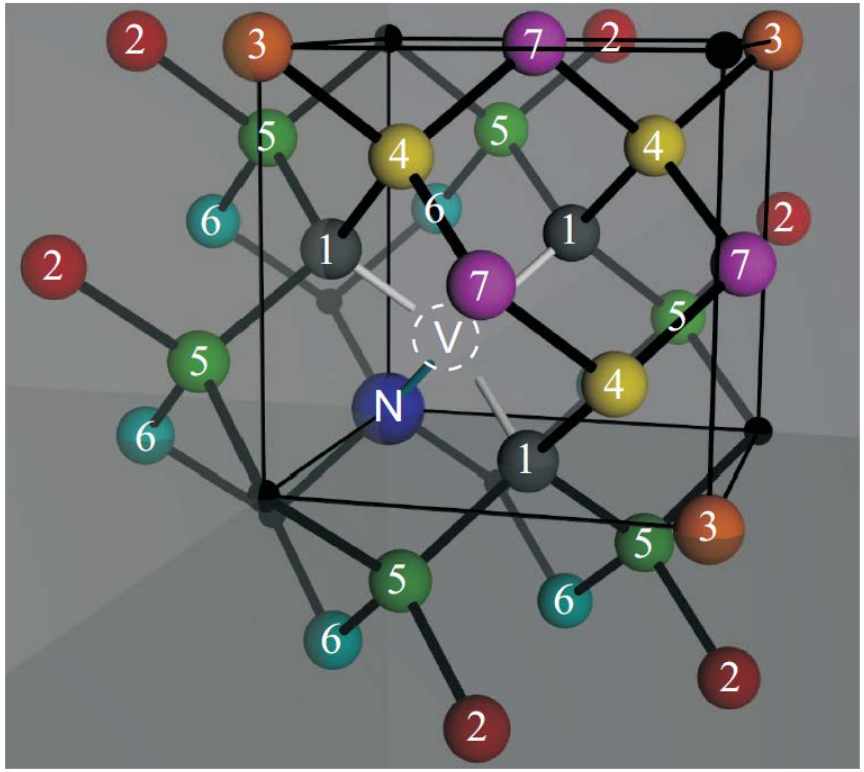
isotope	natural abundance (%)	nuclear spin I	g_n-factor and gyromagnetic ratio $\tilde{\gamma}_n$ (kHz/mT)	
^{13}C	1.1	½	1.40482	10.7051
^{14}N	99.63	1	0.4037607	3.0766
^{15}N	0.37	½	−0.566380	−4.3156



$$\hat{H}_n = \hat{H}_{hf} + \hat{H}_{nZ} + \hat{H}_Q$$

Neumann, PhD thesis, U Stuttgart 2011

Interaction with the environment



site #	A_{exp} [MHz]	distance [nm]	total # of sites
1	130	n.a.	3
2	13.72(3)	0.39	6
3	12.75(1)	0.39	3
4	-8.6(3)	0.25	3
5	-6.46(3)	0.25	6
6,7	4.15(3)	0.29	6,3

Schoenfeld, PhD thesis, FU Berlin 2011

Hyperfine interaction part:

$$\hat{H}_{hf} = \hat{H}_F + \hat{H}_{dd}$$

$$\hat{H}_F = -\frac{2\mu_0}{3}\tilde{\gamma}_e g_n \mu_n \left|\psi^e_{@n}\right|^2 \underline{\hat{S}} \cdot \underline{\hat{I}} = a_{iso}\underline{\hat{S}} \cdot \underline{\hat{I}}$$

$$\hat{H}_{dd} = \frac{\mu_0}{4\pi}\tilde{\gamma}_e g_n \mu_n \frac{\underline{\hat{S}} \cdot \underline{\hat{I}} - 3\left(\underline{\hat{S}} \cdot \underline{e}_r\right)\left(\underline{e}_r \cdot \underline{\hat{I}}\right)}{r^3}$$

Fermi contact term:

- Strongly site # dependent (density of electron)

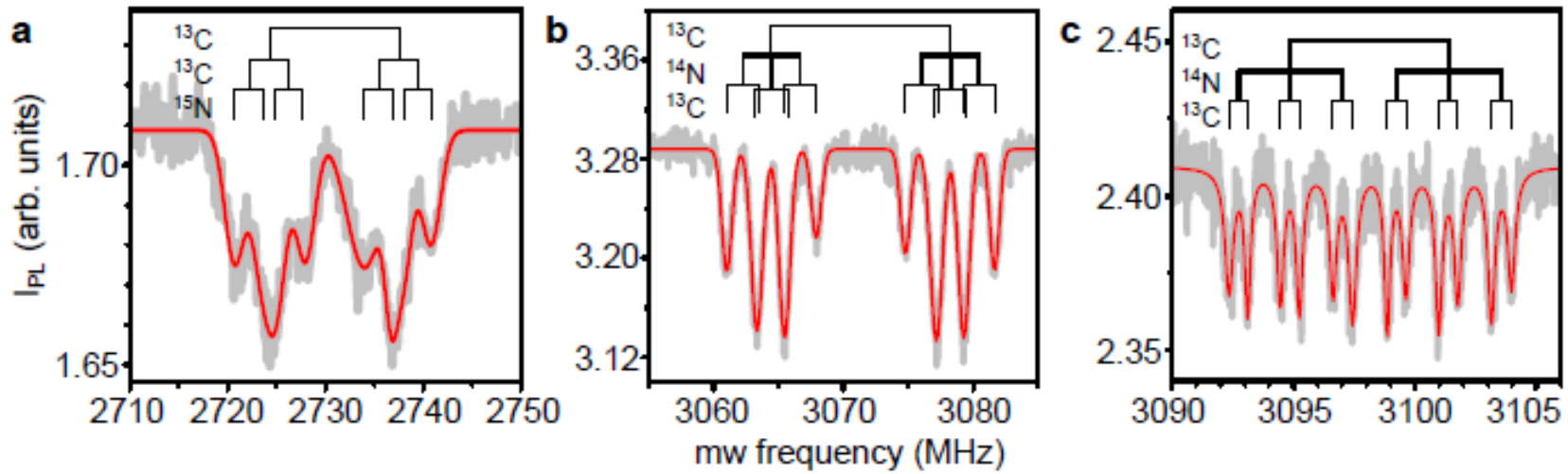
Dipole-dipole term:

- has "long" range, but $1/r^3$ dependent

Usually simplified as:

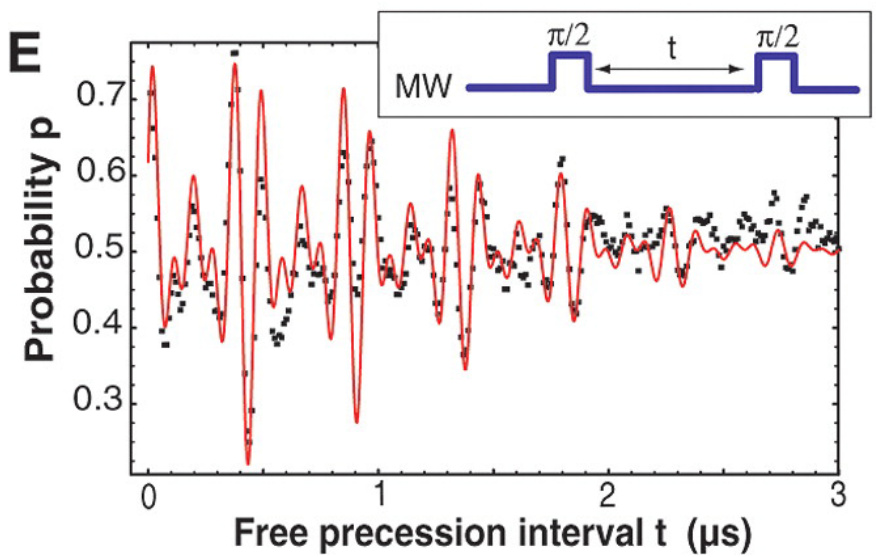
$$\hat{H}_{hf} = \underline{\hat{S}} \cdot \mathbf{A} \cdot \underline{\hat{I}}$$

Making HF interaction visible



Pulsed ODMR

<u>Ramsey sequence:</u> with 8MHz detuning



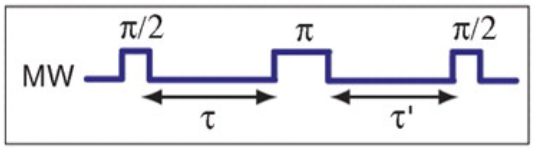
$$P = e^{-t/T_2^*} \sum_{i=1}^{3} cos(2\pi f_i t)$$

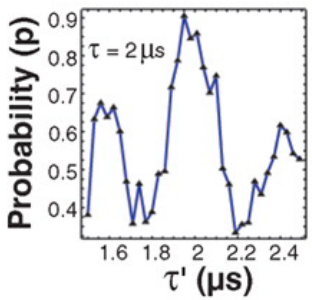
- Fast decay with $T_2^* = 1.7 \pm 0.2 \mu s$
- Signal caused by level shifts due to 14N nuclear spin.

Neumann, PhD thesis, U Stuttgart 2011

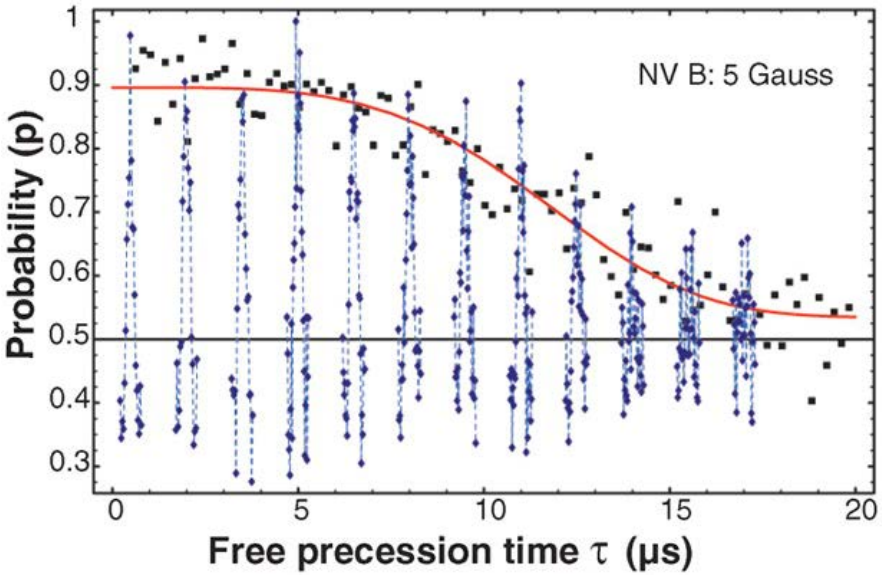
Spin – decoupling – Hahn echo

Hahn-echo sequence





- Decoupling of the spin from the slowly evolving environment.

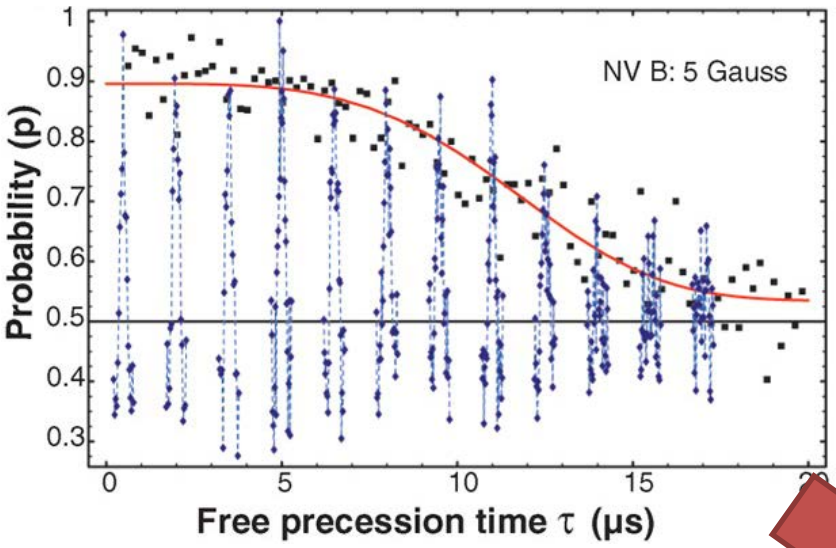


Decay with $T_2 = 13 \pm 0.5 \mu s >> T_2^*$

Childress et al., Science 2006

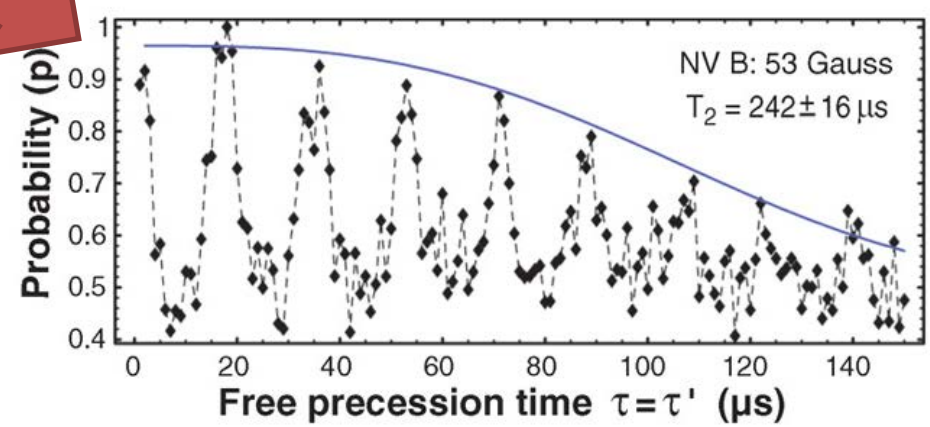
Spin – decoupling – Hahn echo

low field Hahn-echo sequence



Increase static B

high field Hahn-echo sequence

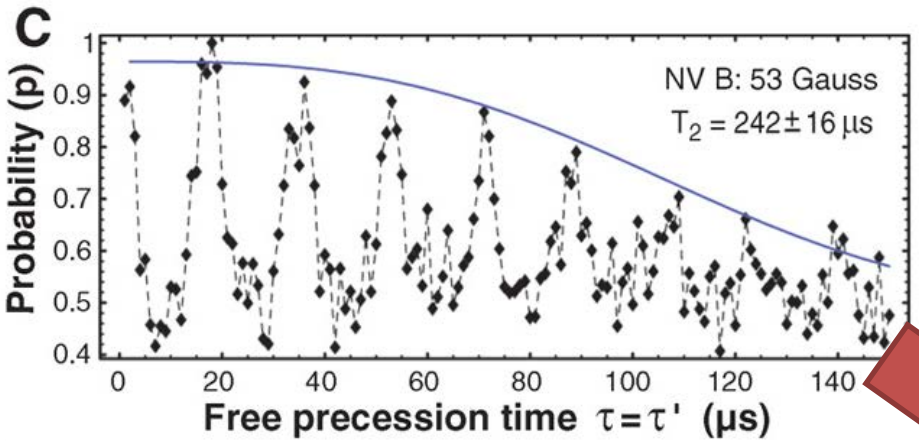


-> Extend dephasing time from **13μs** to **245μs**!

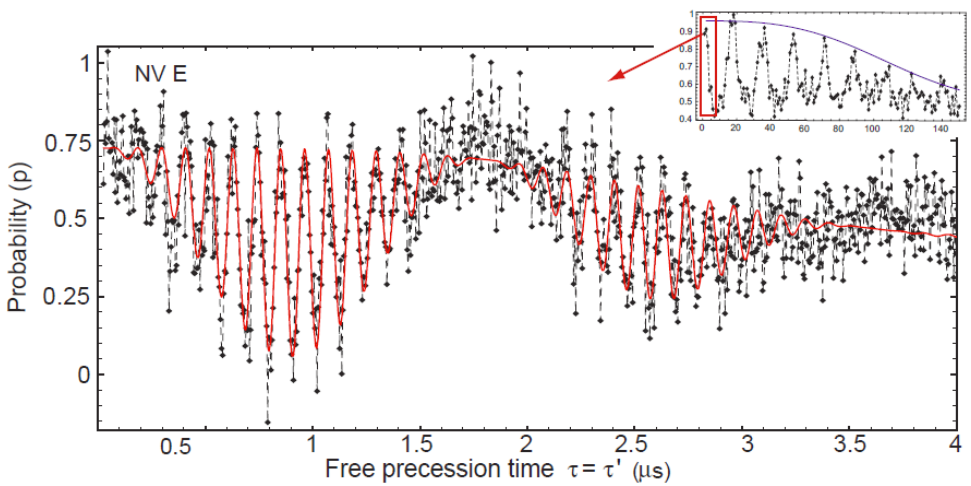
Childress et al., Science 2006

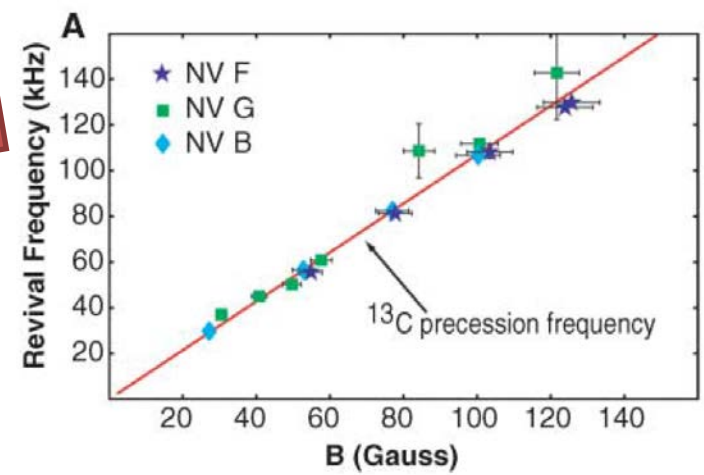
Spin – decoupling – Hahn echo

high field Hahn-echo sequence



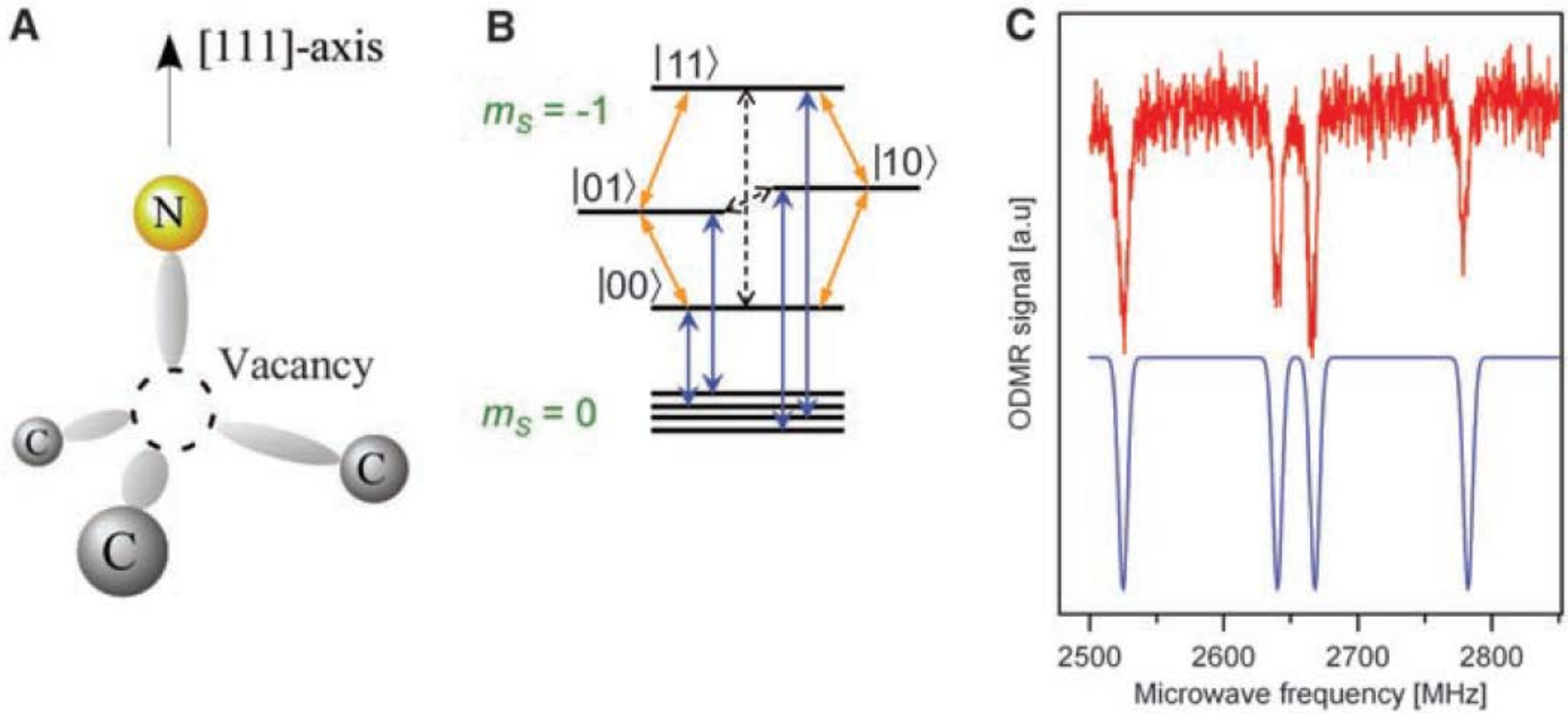
Period matches Lamor frequency of ^{13}C





Childress et al., Science 2006

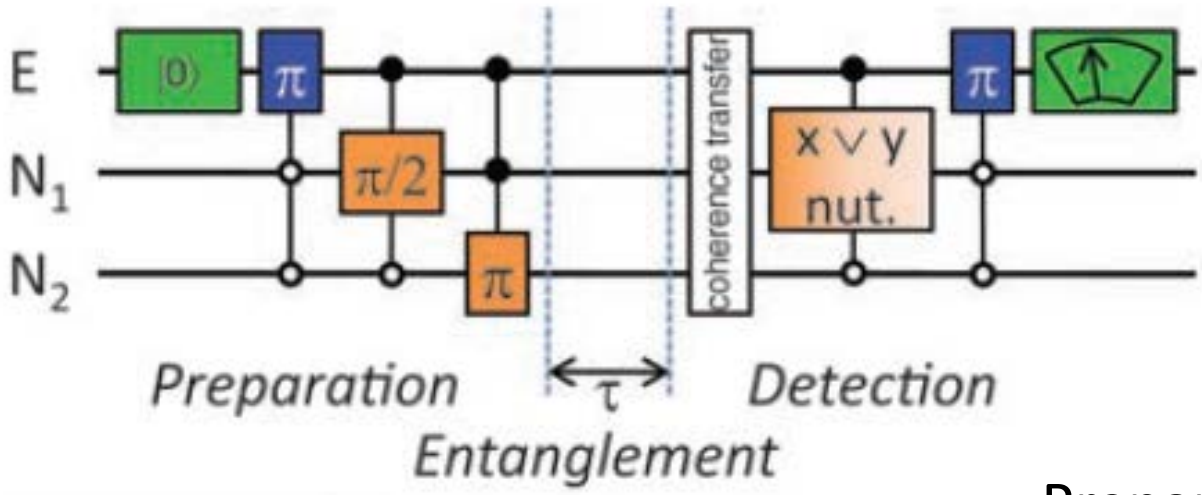
Multipartite Entanglement Among Spins

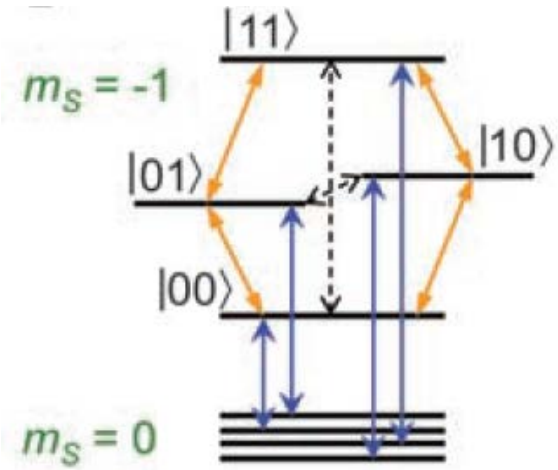


Two ^{13}C on lattice site # 1, coupling frequency A $\approx$ 130 MHz.

Neumann et al., Science 2008

Multipartite Entanglement Among Spins





Four Bell states: (-1/2 -> 0, +1/2 -> 1)

$$\Phi^{\pm} = {}^{1}\!/_{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

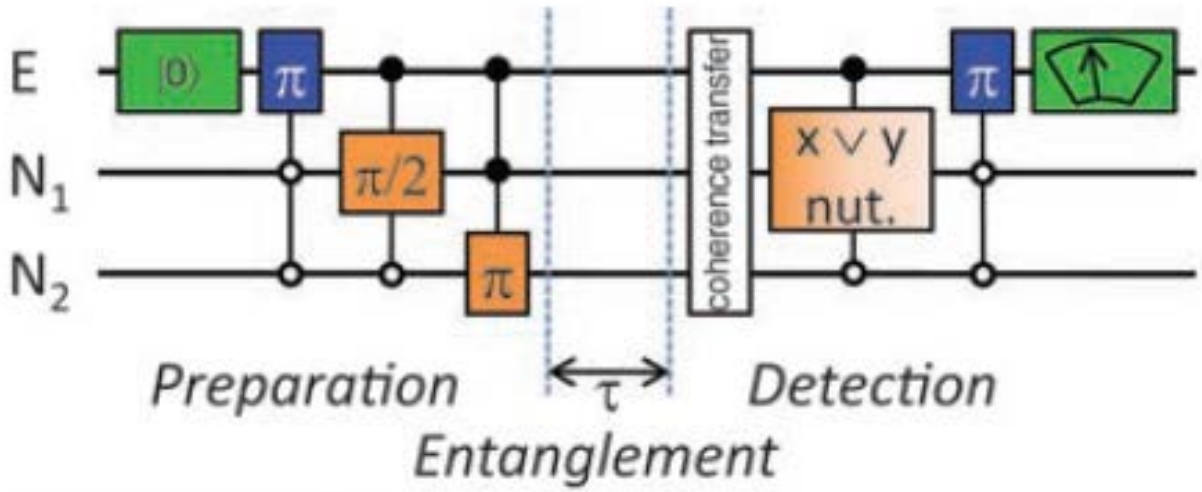
$$\Psi^{\pm} = {}^{1}\!/_{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

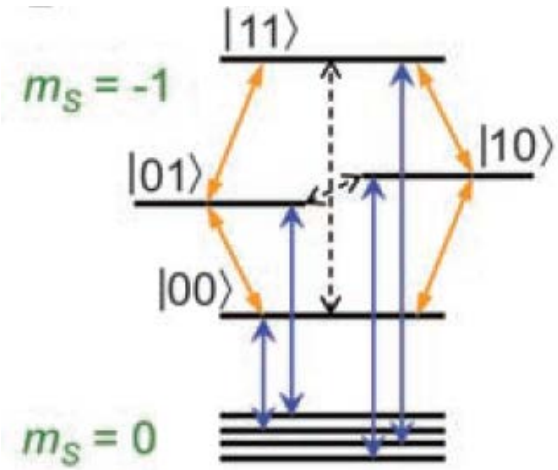
Preparation steps:

1) Initializatior $|000\rangle$
2) Preparation of $|100\rangle$
3) RF π/2-transition
$$\frac{1}{\sqrt{2}}(|00\rangle + |01\rangle)$$
4) RF π-trans. On $|01\rangle \Leftrightarrow |11\rangle$ yields Φ^{-}
… similar for other states

Neumann et al., Science 2008

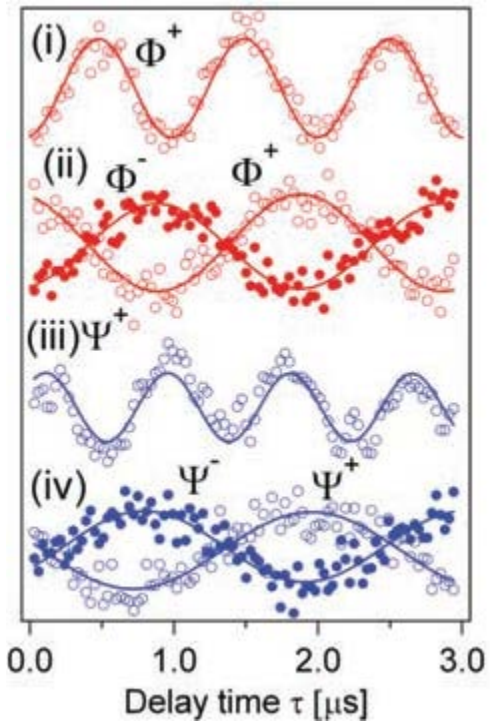
Multipartite Entanglement Among Spins





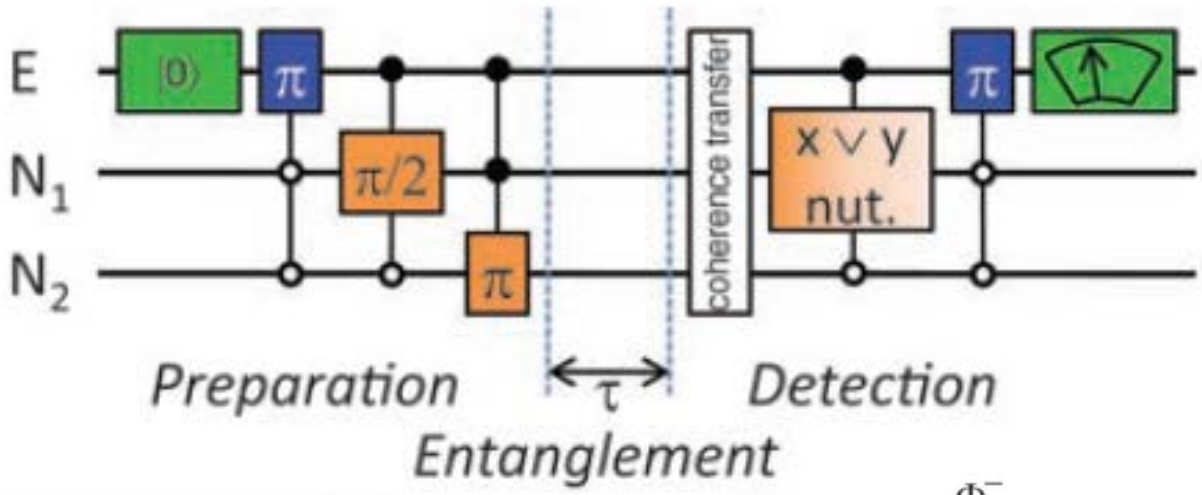
<u>Free evolution for time τ :</u>

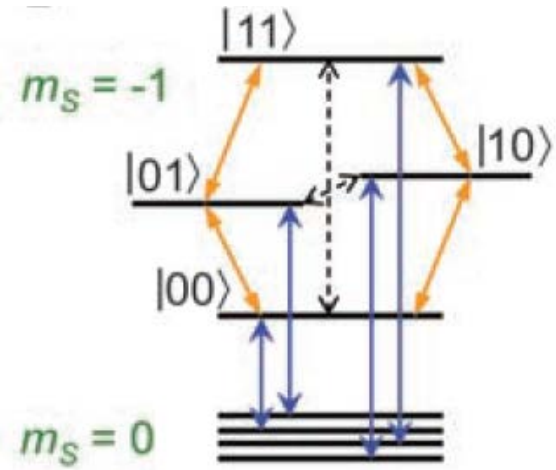
- acquisition of phase due to detuning
  $\Delta\omega_{\Phi,\Psi} = \Delta\omega_1 + \Delta\omega_2$ and $\Delta\omega_2 - \Delta\omega_1$
- ± distinguishable by phase

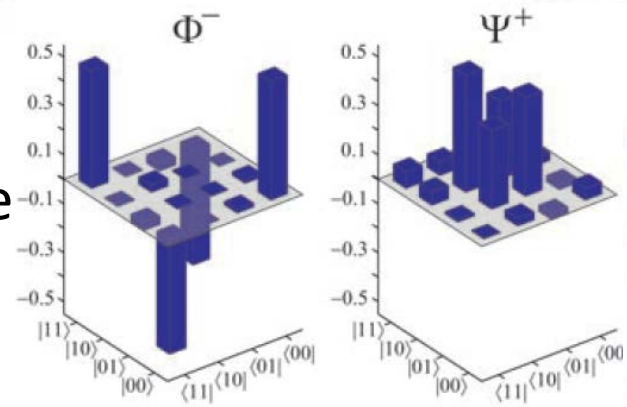


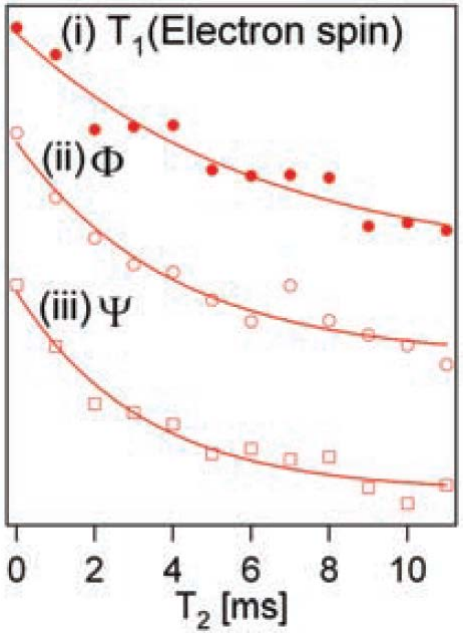
Neumann et al., Science 2008

Multipartite Entanglement Among Spins









<u>Tomographic reconstruction:</u>

- Projection of each Bell state back on $|100\rangle$
- Final π-trans. to $|000\rangle$ and optical readout

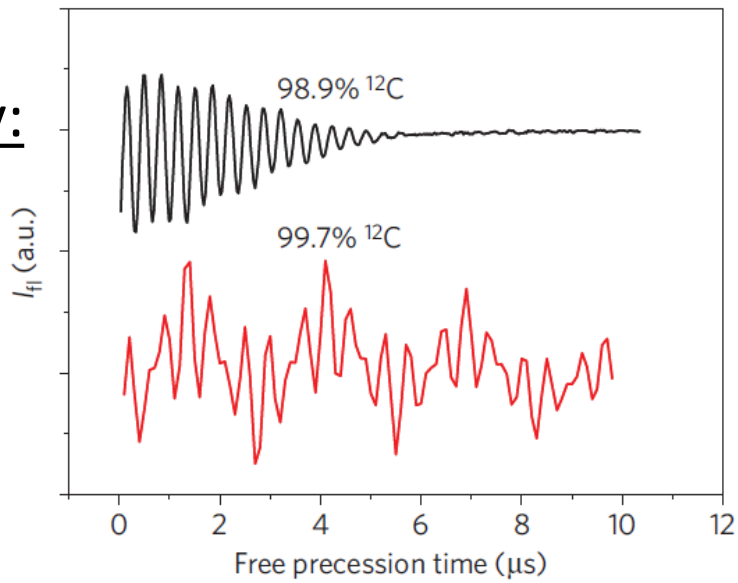
Coherence in ms range, comparable to T_1 of the electron.

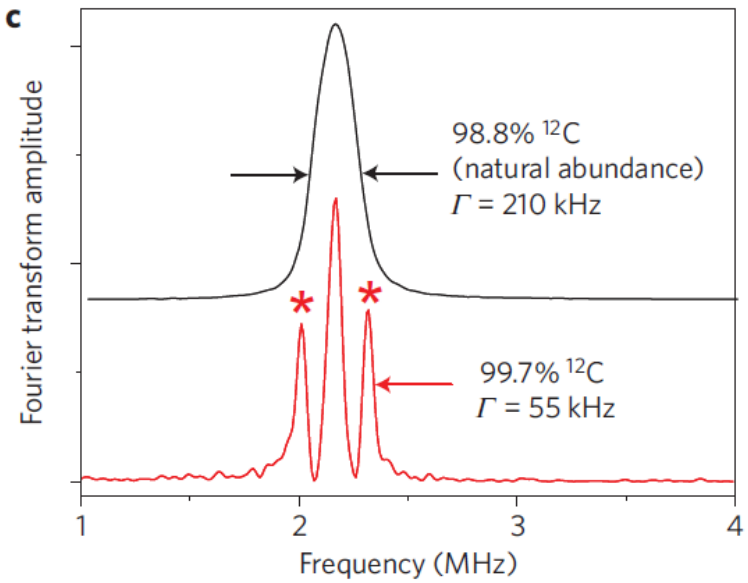
Neumann et al., Science 2008

Isotopically enriched ^{12}C diamond

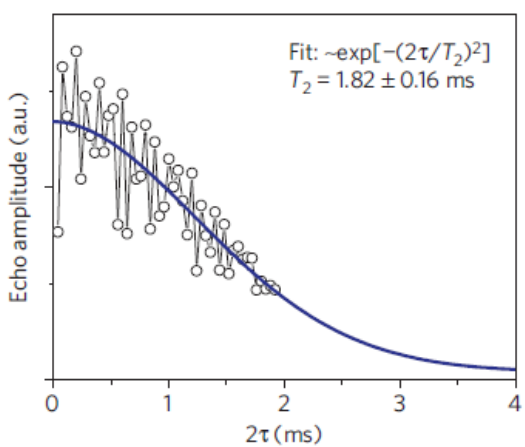
Isotopically enriched ^{12}C diamond

Ramsey spectroscopy:





Hahn echo sequence:



Electron dephasing time in the range of ms now!
(at room temperature)
Approaching the T_1

Balasubramanian et al., Nat. Mat. 2009

Exploiting Spin – Spin Entanglement

Dipole - dipole interaction:

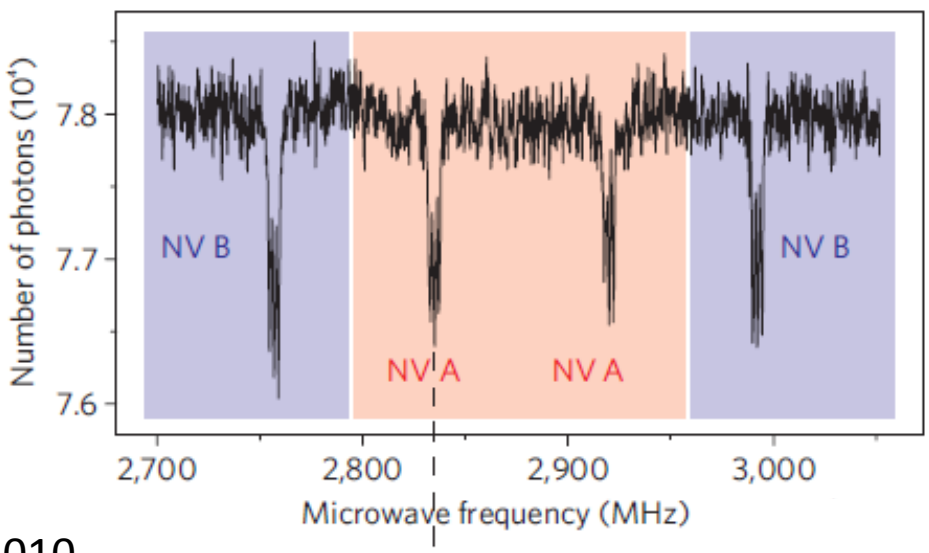
$$H_{\mathrm{dip}} = \frac{\mu_0 g^2 \mu_{\mathrm{B}}^2}{4\pi r^3}[\hat{S}_{\mathrm{NV\ A}} \cdot \hat{S}_{\mathrm{NV\ B}} - 3(\hat{S}_{\mathrm{NV\ A}} \cdot \mathbf{r})(\hat{S}_{\mathrm{NV\ B}} \cdot \mathbf{r})]$$

for r=10nm -> 70kHz

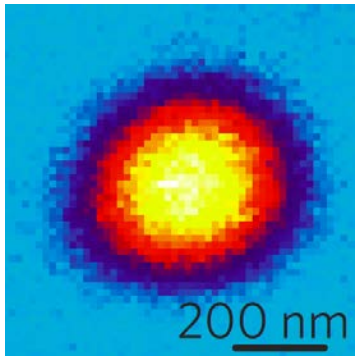
Full hamiltonian:

$$H = \Sigma_{i=\mathrm{NV\ A}}^{\mathrm{NV\ B}}(\hat{S}_i \underline{\underline{\mathbf{D}}}_i \hat{S}_i + \mu_{\mathrm{B}} g_e \underline{\mathbf{B}} \hat{S}_i) + H_{\mathrm{dip}}$$

^{12}C enriched diamond with long coherence time.

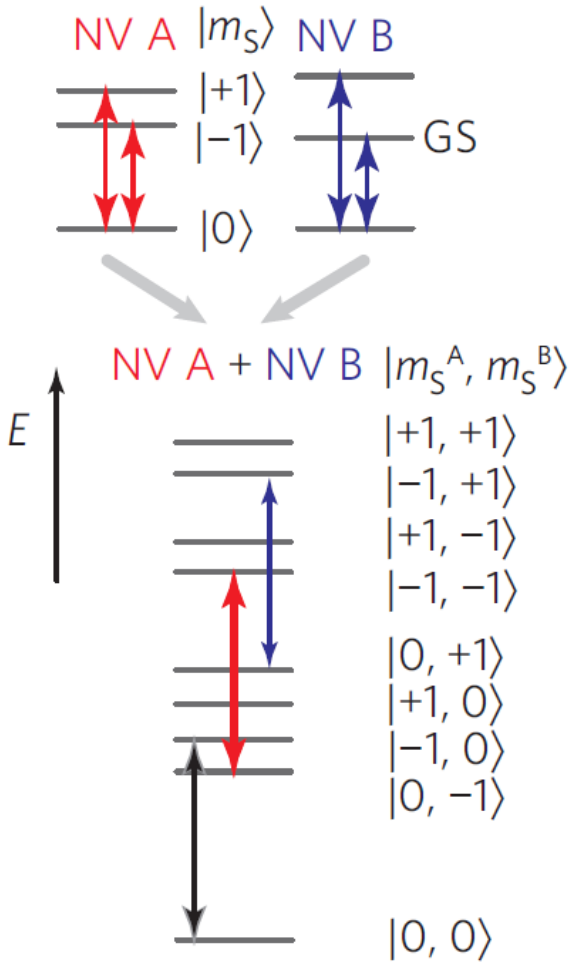


With external B-field || NVB



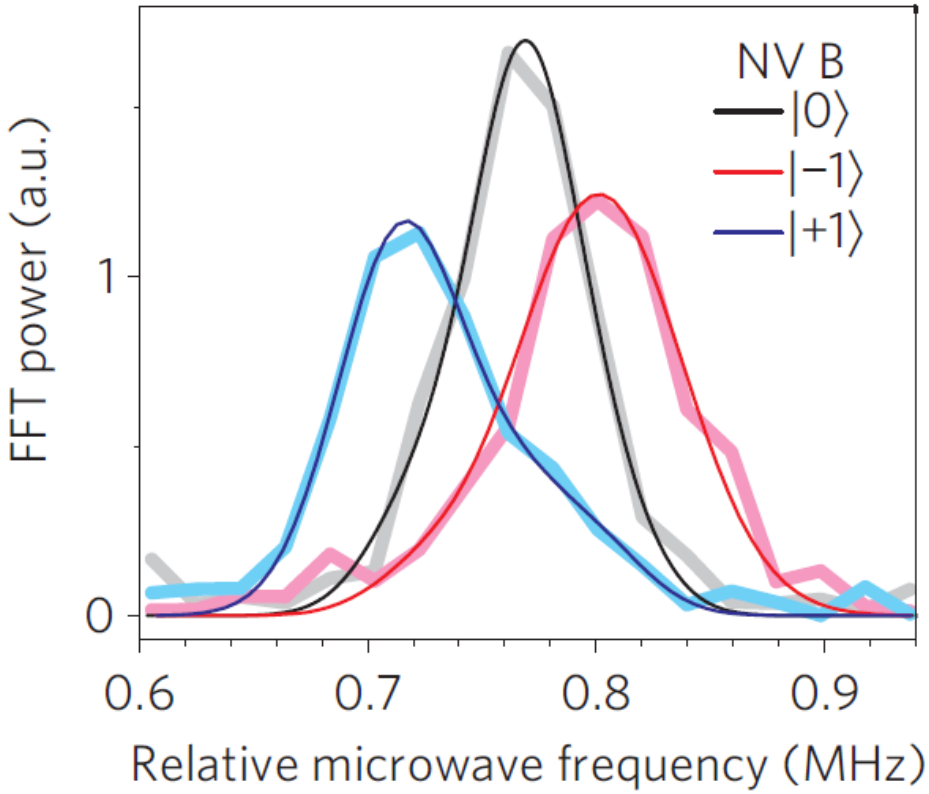
Neumann, Nature Phys. 2010

Spin – Spin entanglement



NVA conditionally prepared in $m_s = -1$

- Ramsey fringes measured
- Followed by fast Fourier transform

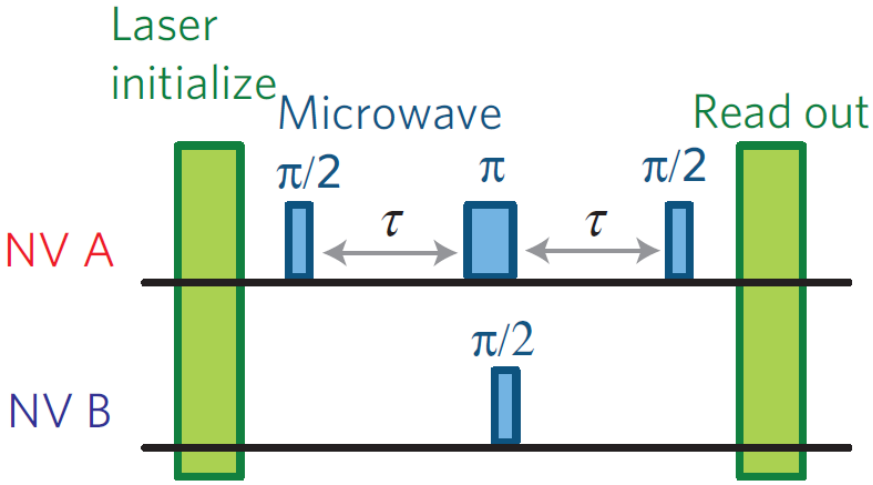


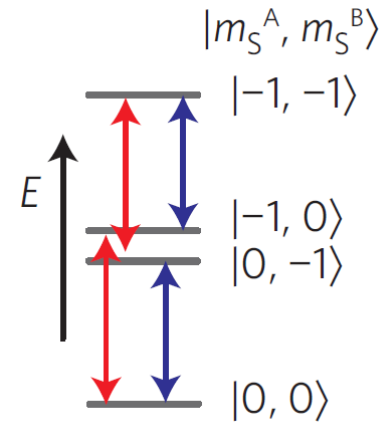
$\approx$ 40 kHz coupling strenght!

Neumann, Nature Phys. 2010

Spin – Spin entanglement

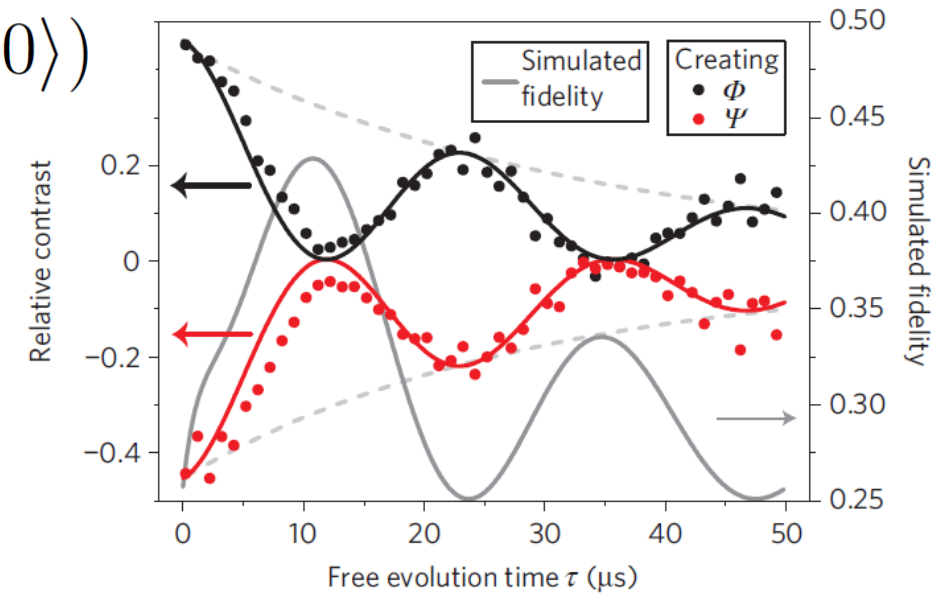
Protocol entangled state generation:





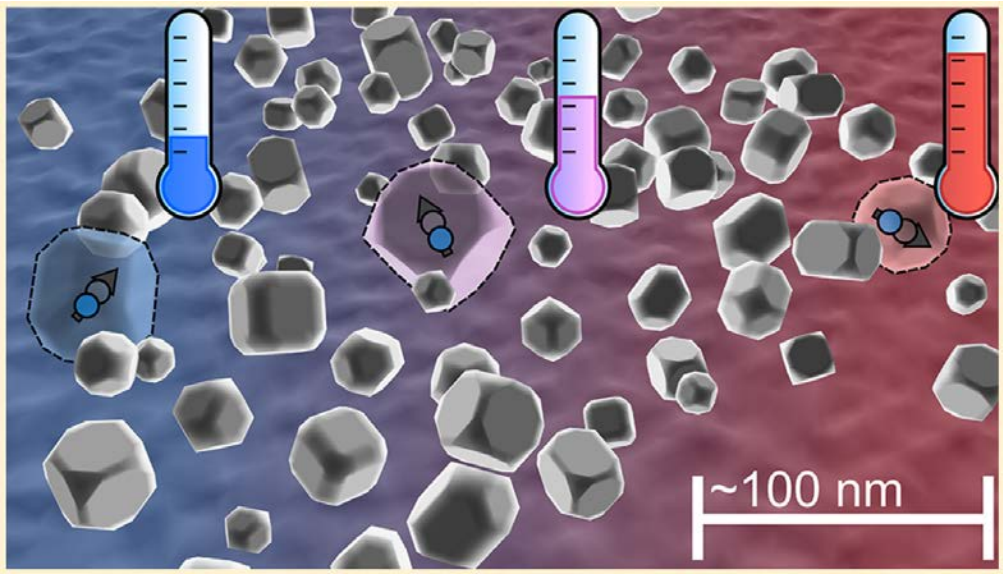
$$|\Phi\rangle = 1/\sqrt{2}\,(i\,|-1,-1\rangle - |0,0\rangle)$$

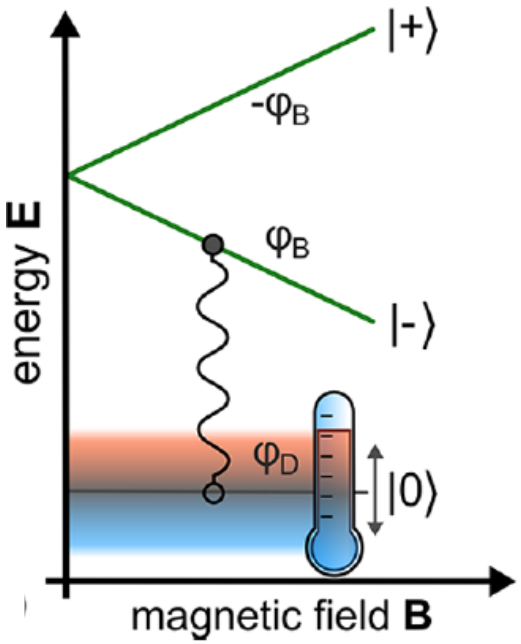
For $\tau = (1,3,5,\ldots)\pi/(\gamma \cdot \delta B)$



Neumann, Nature Phys. 2010

Nano-Scale Temperature Sensing





<u>Zero field splitting depends on:</u>

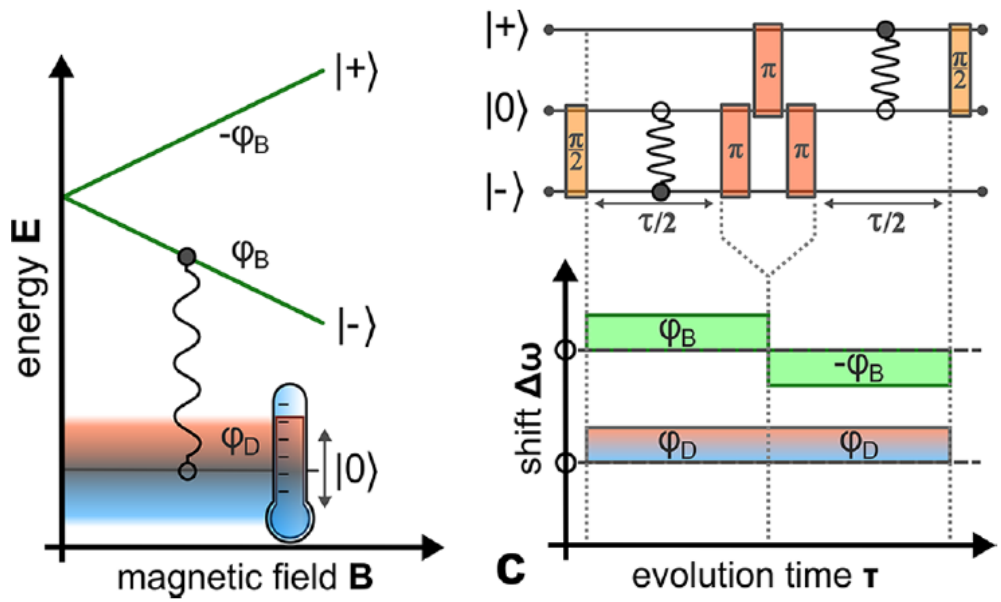
- Axial elctric field
- Temperature
- Strain

$$c_T = \mathrm{d}D/\mathrm{d}T = -74.2 \ \mathrm{kHz/K}$$

$$H = D(T)S_z^2 + \gamma_{\mathrm{NV}}(B_z S_z + B_x S_x + B_y S_y)$$

Neumann, Nano Lett. 2013

Nano-Scale Temperature Sensing



Sequence:

1)superposition $|0\rangle + |-\rangle$

2)Phase acquisition

$$\left(e^{-i\varphi_D}|0\rangle + e^{-i\varphi_B}|-\rangle\right)$$

3) Conversion to

$$e^{-i\varphi_D}|0\rangle - e^{-i\varphi_B}|+\rangle$$

4) Evolution

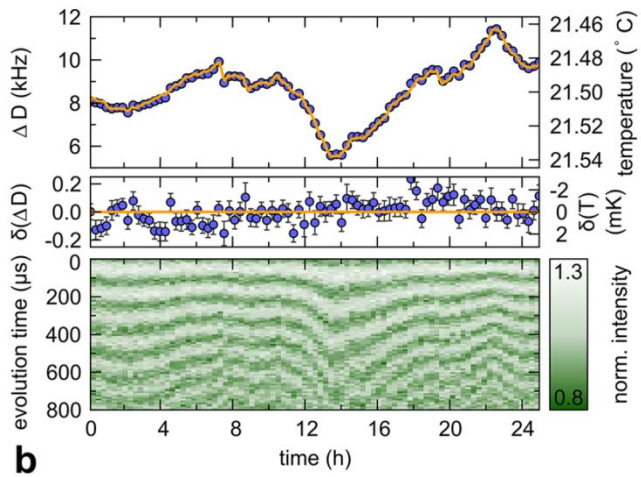
$$\left(e^{-i2\varphi_D}|0\rangle - |+\rangle\right)$$

5) Readout:

$$-2\varphi_D = \Delta D \cdot \tau$$

Sequence to suppress contribution from:

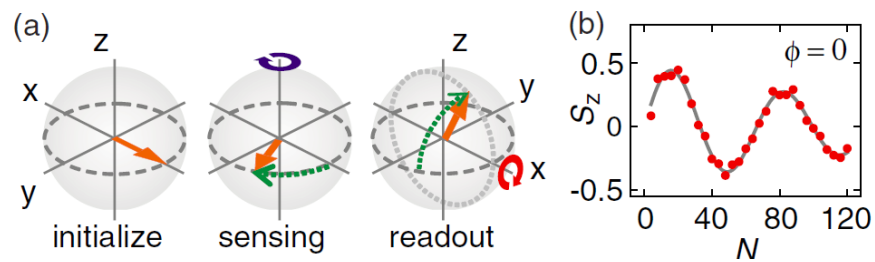
- Axial magnetic/electric fields
- Strain



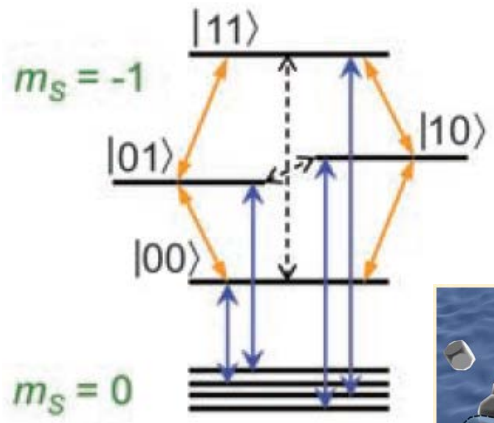
Neumann, Nano Lett. 2013

Summary

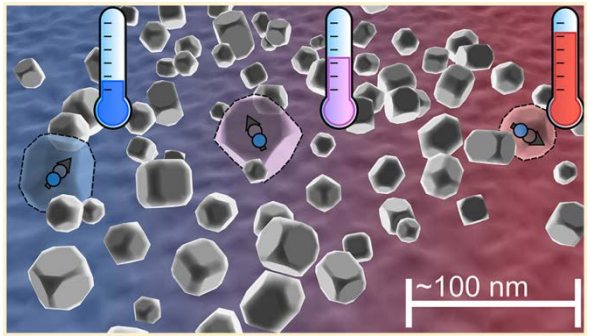
Magnetic field sensing



Coupling to nuclear spins



Entangled states of nuclear - and electron spins



Nano-scale temperature sensor

Comment: benifits of NV center are <u>long room temperature coherences</u> and <u>nano-scale implementations</u>!

Thank you and feel free to ask!