AMAZING POINT DEFECTS
OR
HÄMMÄSTYTTÄVIÄ PISTEVIRHEITÄ

Viktor Ivády[1,2]

[1]*Eötvös Loránd University, Budapest, Hungary*

[2] *MTA–ELTE Lendület "Momentum" NewQubit Research Group*

Outline

Part I.

- Q & A = 🤯

Part II.

Theory of the NV center

- Structure
- Electronic structure
- Spin
- Optical properties
- ODMR
- Coherence and spin manipulation

Part III.

- Interesting experiments and papers
- Perspectives and challenges in QC and QRC

PART I.

Q & A

What is the highest temperature at which coherent quantum control has been carried out?

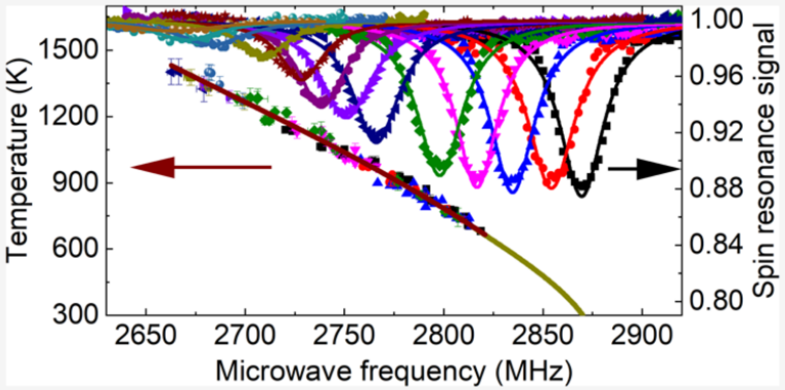
Quantum Coherence Control at Temperatures up to 1400 K

Jing-Wei Fan, Shuai-Wei Guo, Chao Lin, Ning Wang, Gang-Qin Liu, Quan Li,* and Ren-Bao Liu*

Cite This: https://doi.org/10.1021/acs.nanolett.4c04359 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Coherent quantum control at high temperatures is important for expanding the quantum world and is useful for applying quantum technologies to realistic environments. Quantum control of spins in diamond has been demonstrated near 1000 K, with the spins polarized and read out at room temperature and controlled at elevated temperatures by rapid heating and cooling. Further increase of the working temperature is challenging due to fast spin relaxation in comparison with the heating and cooling rates. Here we significantly improve the heating and cooling rates by using reduced graphene oxide as the laser absorber and heat drain and hence realize coherent quantum operation at up to 1400 K, which is higher than the Curie temperatures of all known materials. This work facilitates the use of diamond sensors to study



Is it possible to observe quantum jumps of a **single** nuclear spin?

Science

Current Issue First release papers Archive About Submit manuscript

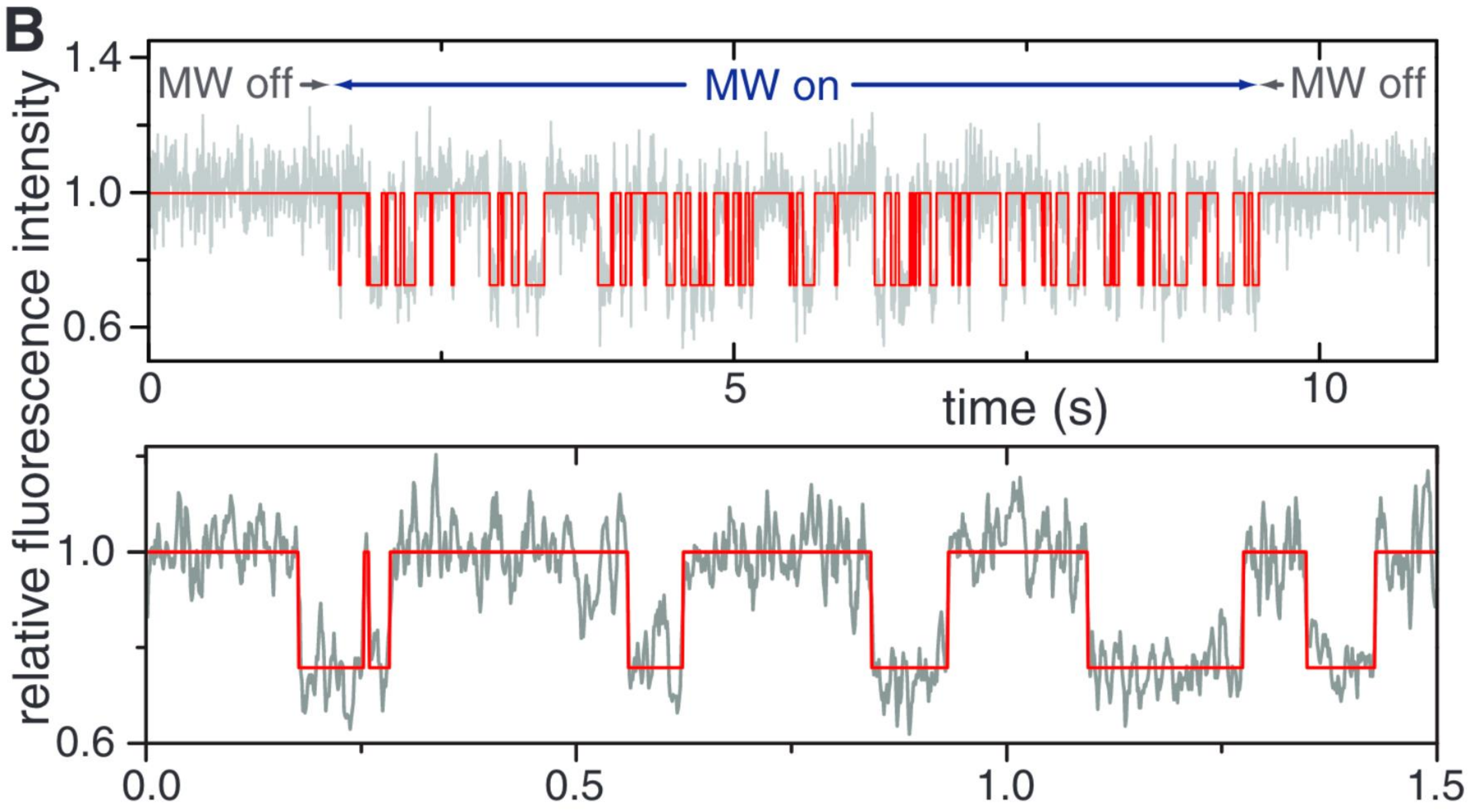
HOME > SCIENCE > VOL. 329, NO. 5991 > SINGLE-SHOT REA

REPORT

Single-Shot Readout o

PHILIPP NEUMANN, JOHANNES BECK, MATTHIAS STEINER, FLORIAN R

Affiliations



What is the longest quantum memory in solids at room temperature?

PHYSICAL REVIEW X **9,** 031045 (2019)

Featured in Physics

A Ten-Qubit Solid-State Spin Register with Quantum Memory up to One Minute

C. E. Bradley,[1,2,†] J. Randall,[1,2,†] M. H. Abobeih,[1,2] R. C. Berrevoets,[1,2] M. J. Degen,[1,2]
M. A. Bakker,[1,2] M. Markham,[3] D. J. Twitchen,[3] and T. H. Taminiau[1,2,*]

[1]*QuTech, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, Netherlands*
[2]*Kavli Institute of Nanoscience Delft, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, Netherlands*
[3]*Element Six, Fermi Avenue, Harwell Oxford, Didcot, Oxfordshire, OX11 0QR, United Kingdom*

(Received 9 May 2019; published 11 September 2019)

Is the collapse of the wavefunction of entangled particles limited by the speed of light?

LETTER

doi:10.1038/nature15759

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

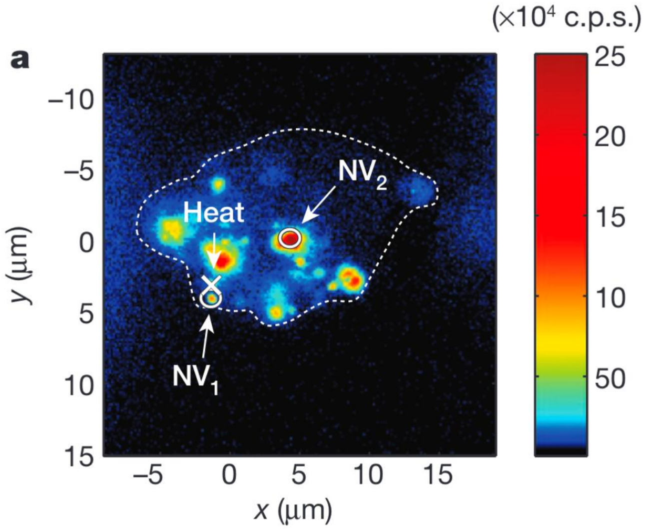
Can we measure temperature in living cells?

LETTER

doi:10.1038/nature12373

Nanometre-scale thermometry in a living cell

G. Kucsko[1]*, P. C. Maurer[1]*, N. Y. Yao[1], M. Kubo[2], H. J. Noh[3], P. K. Lo[4], H. Park[1,2,3] & M. D. Lukin[1]



What is the frequency resolution of nanoscale sensors?

REPORT

QUANTUM MEASUREMENT

Submillihertz magnetic spectroscopy performed with a nanoscale quantum sensor

Simon Schmitt,[1] Tuvia Gefen,[2] Felix M. Stürner,[1] Thomas Unden,[1] Gerhard Wolff,[1] Christoph Müller,[1] Jochen Scheuer,[1,3] Boris Naydenov,[1,3] Matthew Markham,[4] Sebastien Pezzagna,[5] Jan Meijer,[5] Ilai Schwarz,[3,6] Martin Plenio,[3,6] Alex Retzker,[2] Liam P. McGuinness,[1]* Fedor Jelezko[1,3]

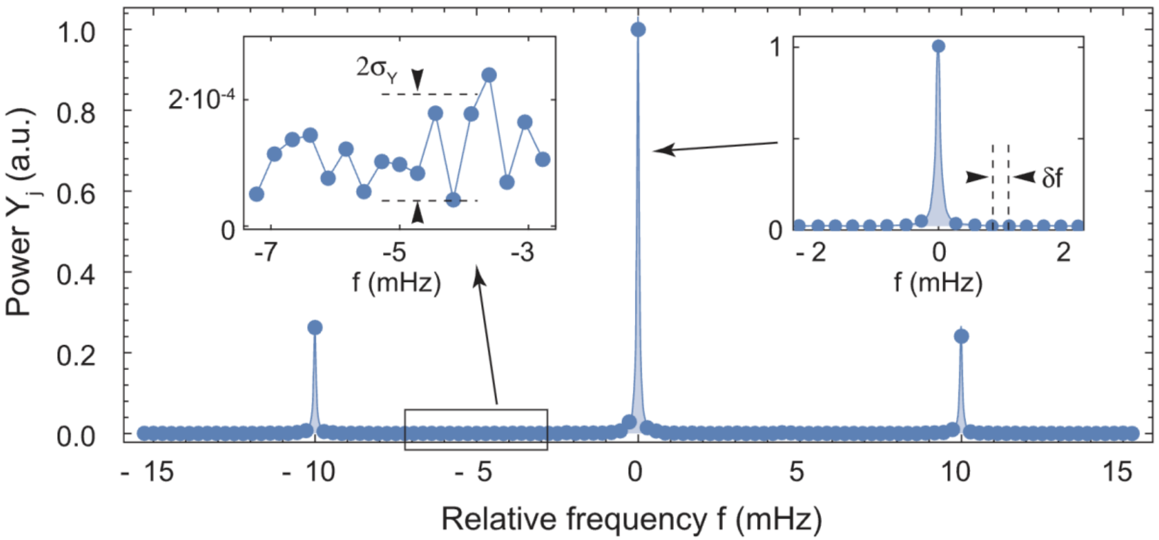
Science **356**, 832–837 (2017)

Science **356**, 837–840 (2017)

QUANTUM MEASUREMENT

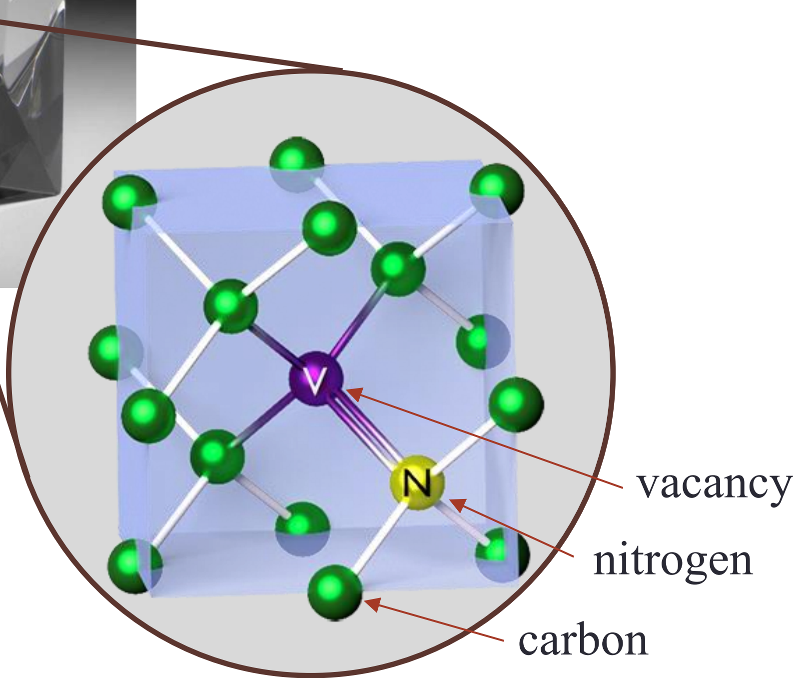
Quantum sensing with arbitrary frequency resolution

J. M. Boss,* K. S. Cujia,* J. Zopes, C. L. Degen†



What is this?

The **NV center** is the first prototypical example of point defect qubits in semiconductors

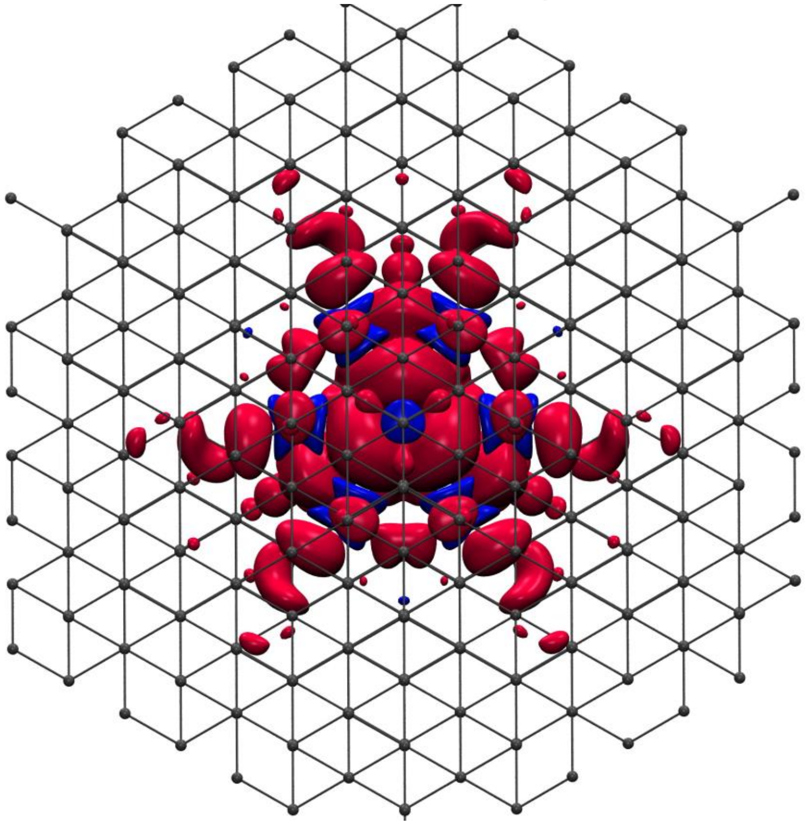


<u>NV center</u>: negatively charged nitrogen substitutional-carbon vacancy complex

<u>Qubit:</u> spin of the NV center

Spin density

$$\varrho_{\mathrm{spin}}(\mathbf{r}) = \sum_{i}^{N_{\mathrm{up}}} \left|\psi_i^{(\mathrm{up})}(\mathbf{r})\right|^2 - \sum_{j}^{N_{\mathrm{down}}} \left|\psi_j^{(\mathrm{down})}(\mathbf{r})\right|^2$$



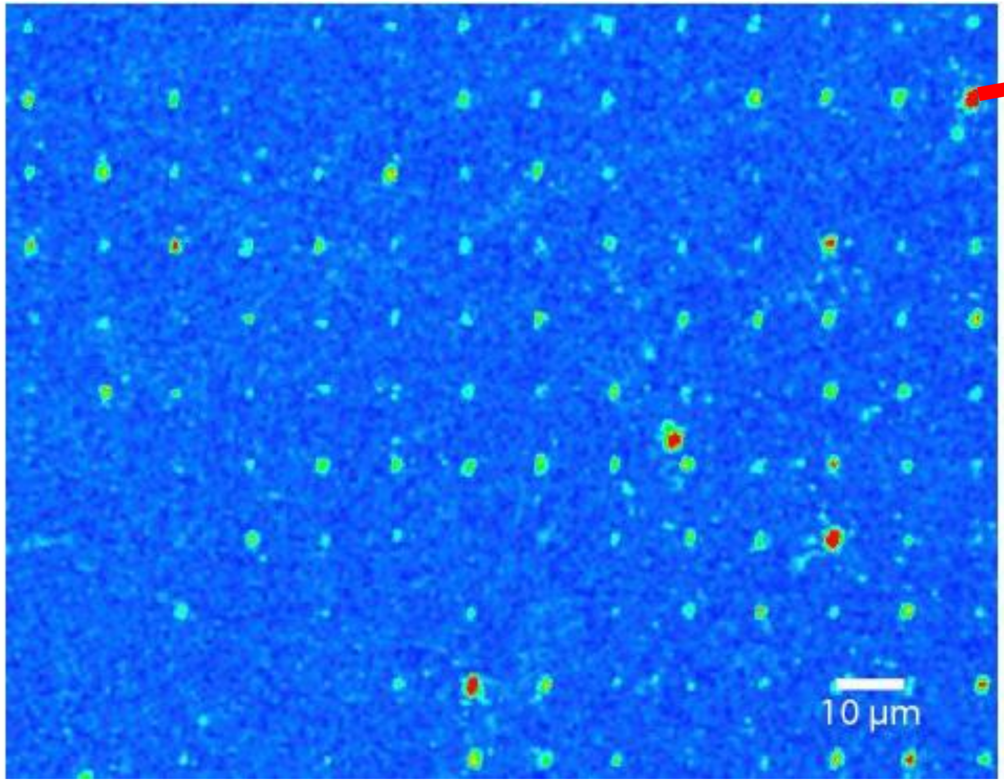
How to create NV centers?

Look for pink natural pink diamonds.

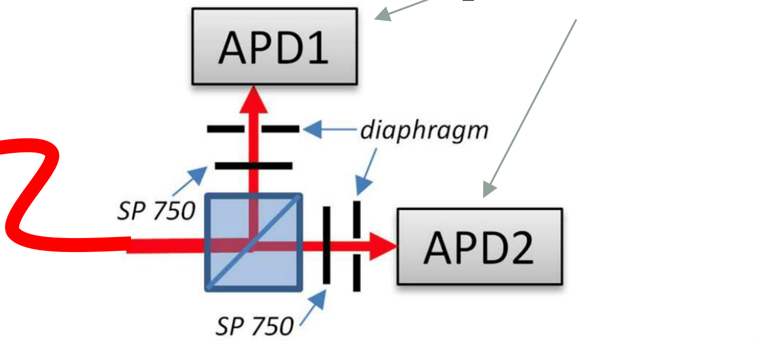
They may contain 100 000 000 000 000 000 NV centers.

Controlled fabrication

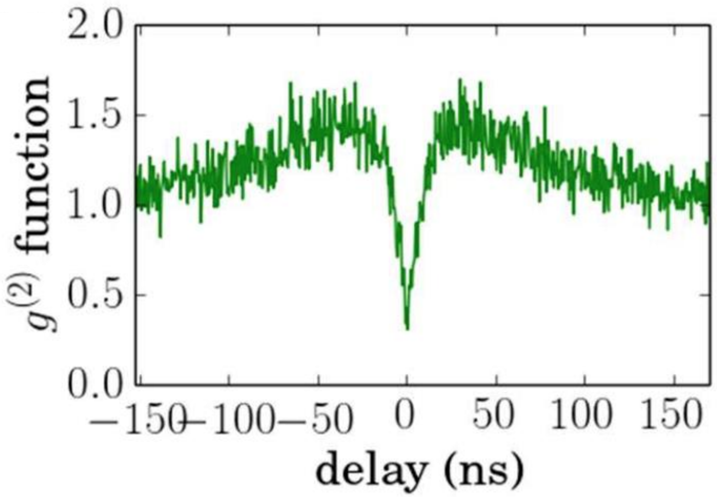
Nitrogen implanted diamond



False color image



$$g^{(2)}(\tau) = \frac{\langle : I(t+\tau)I(t) : \rangle}{(\langle I(t) \rangle)^2}$$



On demand creation of **single** NV centers

Phys. Rev. B **91**, 035308 (2015)

Quantum Computers - companies

Source: THE QUANTUM INSIDER

	Electron spins			Atoms		
	Superconducting	Silicon	NV Centers	Trapped Ion	Neutral Atoms	Photonics
Americas	rigetti, Google AI Quantum, IBM Q, intel, EeroQ (Electrons on Helium), D-Wave (Quantum Annealing), seeqc	intel, QUANTUM MOTION	QDTI, TURING	IONQ, Honeywell, QUANTUM FACTORY	ATOM COMPUTING, QuEra, Cold atom, ColdQuanta	PsiQuantum, XANADU, BardeenQ
EMEA	OQC, ALICE & BOB (Cat Qubits), IQM	equal1.labs, imec	XEED	UQ Universal Quantum, OXFORD IONICS, AQT	PASQAL	ORCA Computing, Quandela, LightOn, QuiX
APAC	Alibaba.com	Silicon Quantum Computing, NTT	QUANTUM BRILLIANCE	QUDOOR 启科量子		

Today	Day (after)^n tomorrow	Tomorrow

PART II.

Theory of the NV center

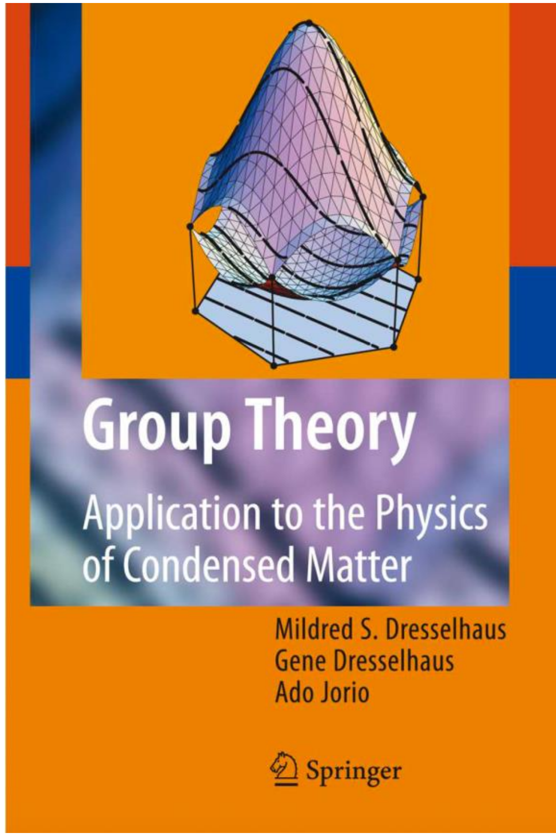
Basics of group theory

What define your systems are the **strucutre + number of electrons** ⟶ Symmetry is not everything but effects everything.

has a symmetry

1.1 Definition of a Group

Page 3 in



A collection of elements $A, B, C, \ldots$ form a group when the following four conditions are satisfied:

1. The product of any two elements of the group is itself an element of the group. For example, relations of the type $AB = C$ are valid for all members of the group.
2. The associative law is valid – i.e., $(AB)C = A(BC)$.
3. There exists a unit element E (also called the identity element) such that the product of E with any group element leaves that element unchanged $AE = EA = A$.
4. For every element A there exists an inverse element A^{-1} such that $A^{-1}A = AA^{-1} = E$.

Point groups

Multiplication table

	E	C_3^+	C_3^-	σ_v	σ_v'	σ_v''
E	E	C_3^+	C_3^-	σ_v	σ_v'	σ_v''
C_3^+	C_3^+	C_3^-	E	σ_v''	σ_v	σ_v'
C_3^-	C_3^-	E	C_3^+	σ_v'	σ_v''	σ_v
σ_v	σ_v	σ_v'	σ_v''	E	C_3^+	C_3^-
σ_v'	σ_v'	σ_v''	σ_v	C_3^-	E	C_3^+
σ_v''	σ_v''	σ_v	σ_v'	C_3^+	C_3^-	E

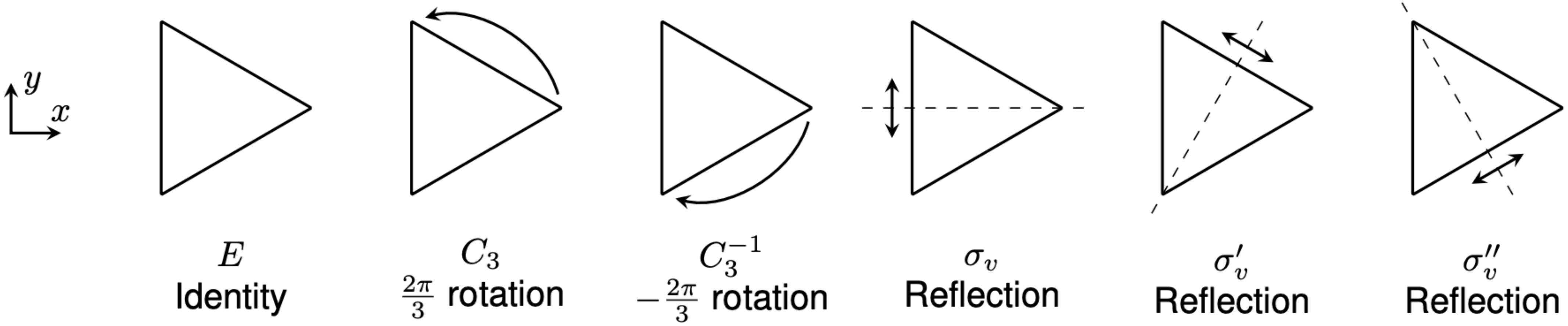
Symmetry operations of a structure form a group

- Group elements: symmetry operations
- Product: carry out symmetry operations in sequence

Point groups: all symmetry operations of point groups leave one point of space intact

- No translation symmetry, relevant for polygons, molecules, and **point defects**

Example: Triangle



Relevnt point groups

WebQC.org
CHEMICAL PORTAL

Point Group Symmetry Character Tables

- Chemistry tools
- Gas laws
- Unit converters
- Periodic table
- Chemical forum
- Constants
- Symmetry
- Contribute
- Contact us

Choose language

Deutsch
English
Español
Français
Italiano
Nederlands

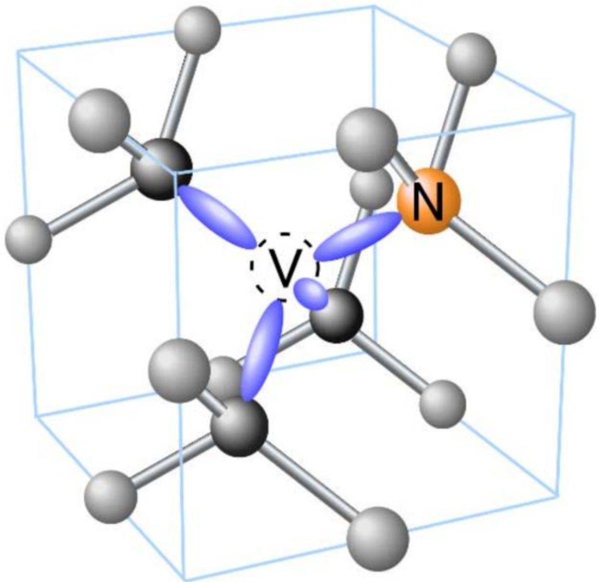
C_1	C_s	C_i		
C_2	C_3	C_4	C_5	C_6
C_{2v}	C_{3v}	C_{4v}	C_{5v}	C_{6v}
C_{2h}	C_{3h}	C_{4h}	C_{5h}	C_{6h}
D_2	D_3	D_4	D_5	D_6
D_{2h}	D_{3h}	D_{4h}	D_{5h}	D_{6h}
D_{2d}	D_{3d}	D_{4d}	D_{5d}	D_{6d}
S_4	S_6	S_8	S_{10}	
T_d	O_h	I_h		
$C_{\infty v}$	$D_{\infty h}$			

Representation

- Representations: Matrix forms (representations) of symmetry operators defined on a vector space that also form a group (isomorphic).
  - Elements: square matrices such that $D(\underbrace{A}_{\text{Symmetry operation}})$
  - Product: matrix product such that $D(AB) = D(A)\underbrace{\,}_{\text{Matrix product}}D(B)$
- Structure: 3×N dimensional vector:

$$\mathbf{R} = \{x_1, y_1, z_2, x_2, y_2, z_2, \ldots, x_N, y_N, z_N\}$$

$$D(A)\mathbf{R} = \mathbf{R}$$



Reducible representation

- Matrices of representations are usually sparse matrices.
  - GT says: They can be block diagonalized, i.e. **they are reducible**.

$$D(A) = \begin{pmatrix} 1.0 & 0 & 5.0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3.0 & 0 & 0 & 0 & 0 & 11.0 & 0 \\ 0 & 0 & 0 & 0 & 9.0 & 0 & 0 & 0 \\ 0 & 0 & 6.0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7.0 & 0 & 0 & 0 & 0 \\ 2.0 & 0 & 0 & 0 & 0 & 10.0 & 0 & 0 \\ 0 & 0 & 0 & 8.0 & 0 & 0 & 0 & 0 \\ 0 & 4.0 & 0 & 0 & 0 & 0 & 0 & 12.0 \end{pmatrix} \xrightarrow{U D(A) U^{-1}} \left(\begin{array}{c|c|c} \Gamma_1 & 0 & \mathcal{O} \\ \hline 0 & \Gamma_{1'} & \mathcal{O} \\ \hline \mathcal{O} & \mathcal{O} & \Gamma_2 \end{array}\right)$$

3N problem $\Longrightarrow$ K × smaller problems

Irreducible representations

$$\left(\begin{array}{c|c|c} \Gamma_1 & 0 & \mathcal{O} \\ \hline 0 & \Gamma_{1'} & \mathcal{O} \\ \hline \mathcal{O} & \mathcal{O} & \Gamma_2 \end{array}\right)$$

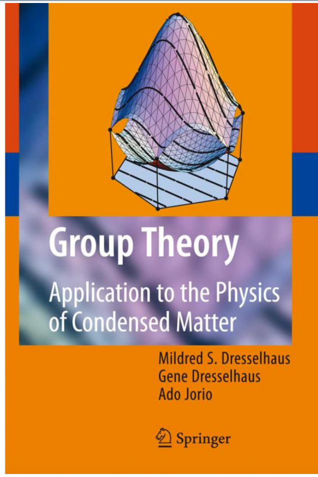
Irreducible representations

Reducible and irreducible representations can be characterized by the trace of the matrices, i.e., by the their characters

$$\chi^{(\Gamma_j)}(R) = \mathrm{trace}\, D^{(\Gamma_j)}(R)$$

Character table of the point group symmetry of the triangle

C_{3v} $h=6$	E	$2C_3$	$3\sigma_v$
A_1	1	1	1
A_2	1	1	–1
E	2	–1	0



Group theory and quantum mechanics

Structure **R** $\Longrightarrow$ Potential $V(\mathbf{r}) \Longrightarrow$ Hamiltonian H

Inherit the symmetry of the structure

Page 11 & 70

$$\mathcal{H}\psi_n = E_n\psi_n$$

$$\hat{P}_R\mathcal{H}\psi_n = \hat{P}_R E_n\psi_n = \mathcal{H}(\hat{P}_R\psi_n) = E_n(\hat{P}_R\psi_n)$$

Exists a group of operators that leave the Hamiltonian unchanged $\left[\mathcal{H}, \hat{P}_R\right] = 0$

Reducable / block diagonalizable matrix

$$\underbrace{\psi'_{n1}, \psi'_{n2}, \ldots, \psi'_{ns}}_{\text{subset 1}} \underbrace{\psi'_{n,s+1}, \ldots, \psi'_{nk}}_{\text{subset 2}},$$

ε_1, Γ_1 $\qquad$ ε_2, Γ_2

Degenerate subspaces that can be labelled by irreducible representations.

Within a degenerate subset:

$$\hat{P}_R\psi_{n\alpha} = \sum_j D^{(n)}(R)_{j\alpha}\psi_{nj}$$

Irreducible representation of G

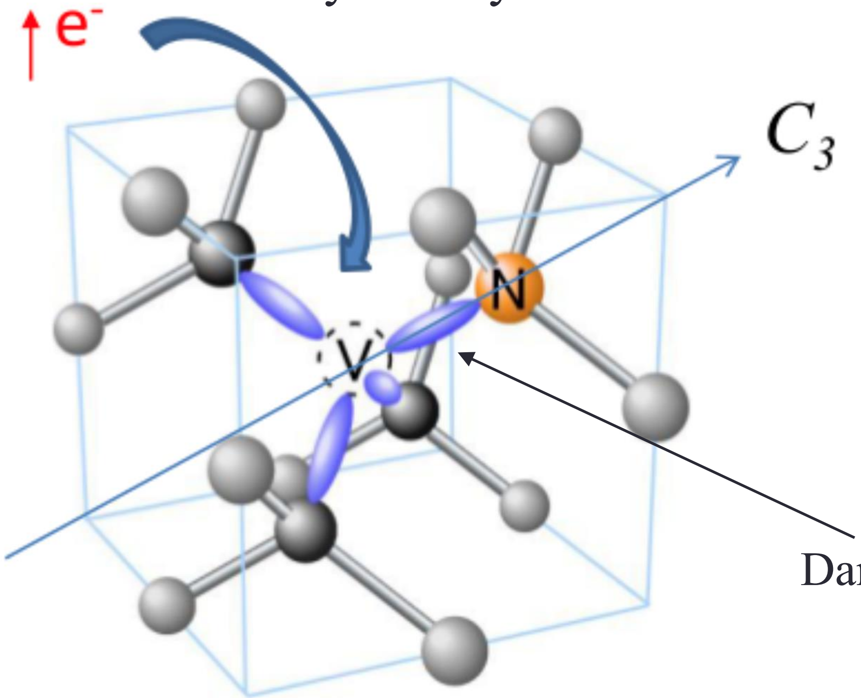
Splitting of spherical symmetric orbitals in C_{3v} symmetric potential

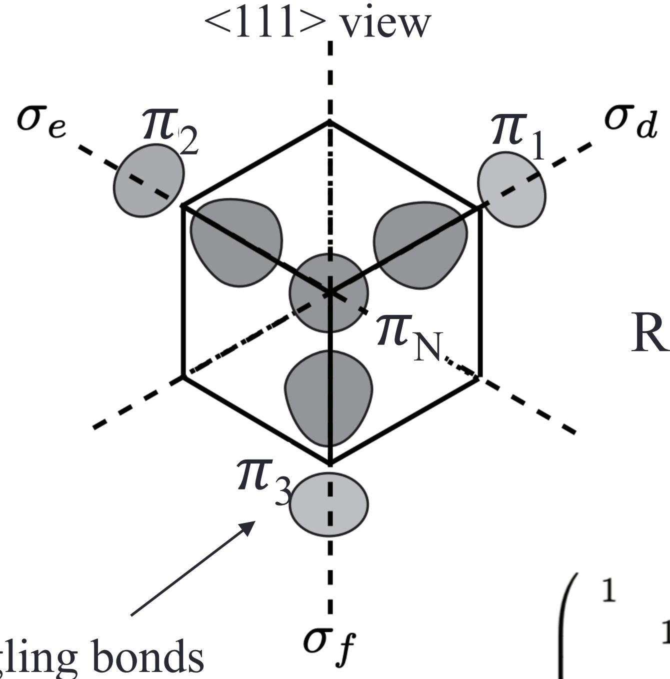
Symmetry of Spherical Harmonics (multipoles)

Angular momentum	Multipole order		Symmetry	permanent moment?	
S (ℓ=0)	1	(monopole)	$\mathbf{A_1}$		
P (ℓ=1)	2	(dipole)	$\mathbf{A_1 \oplus E}$	yes	▼
D (ℓ=2)	4	(quadrupole)	$\mathbf{A_1 \oplus 2\,E}$	yes	▼
F (ℓ=3)	8	(octupole)	$\mathbf{2\,A_1 \oplus A_2 \oplus 2\,E}$	yes	▼
G (ℓ=4)	16	(hexadecapole)	$\mathbf{2\,A_1 \oplus A_2 \oplus 3\,E}$	yes	▼
H (ℓ=5)	32	(dotriacontapole)	$\mathbf{2\,A_1 \oplus A_2 \oplus 4\,E}$	yes	▼
I (ℓ=6)	64	(tetrahexacontapole)	$\mathbf{3\,A_1 \oplus 2\,A_2 \oplus 4\,E}$	yes	▼
J (ℓ=7)	128	(octacosahectapole)	$\mathbf{3\,A_1 \oplus 2\,A_2 \oplus 5\,E}$	yes	▼
K (ℓ=8)	256		$\mathbf{3\,A_1 \oplus 2\,A_2 \oplus 6\,E}$	yes	▼
L (ℓ=9)	512		$\mathbf{4\,A_1 \oplus 3\,A_2 \oplus 6\,E}$	yes	▼
M (ℓ=10)	1024		$\mathbf{4\,A_1 \oplus 3\,A_2 \oplus 7\,E}$	yes	▼

Application to the NV center

NV center has C_{3v} point group symmetry



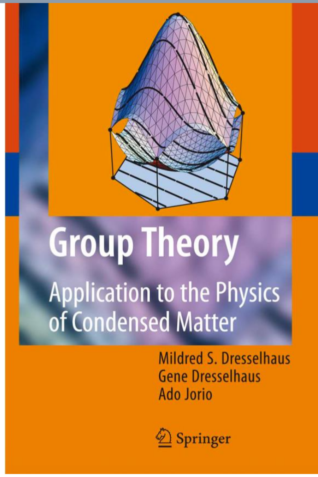


Dangling bonds

Reducible representation $\hat{P}_R$ defined on the basis of π_1, π_2, π_3, and π_N

$$
\begin{array}{ccc}
E & C_3^+ & C_3^- \\
\left(\begin{array}{ccc|c} 1 & & & \\ & 1 & & \\ & & 1 & \\ \hline & & & 1 \end{array}\right), &
\left(\begin{array}{ccc|c} & & 1 & \\ 1 & & & \\ & 1 & & \\ \hline & & & 1 \end{array}\right), &
\left(\begin{array}{ccc|c} & 1 & & \\ & & 1 & \\ 1 & & & \\ \hline & & & 1 \end{array}\right), \\
\sigma_d & \sigma_e & \sigma_f \\
\left(\begin{array}{ccc|c} 1 & & & \\ & & 1 & \\ & 1 & & \\ \hline & & & 1 \end{array}\right), &
\left(\begin{array}{ccc|c} & & 1 & \\ & 1 & & \\ 1 & & & \\ \hline & & & 1 \end{array}\right), &
\left(\begin{array}{ccc|c} & 1 & & \\ 1 & & & \\ & & 1 & \\ \hline & & & 1 \end{array}\right).
\end{array}
$$

Already partially block diagonal $\Longrightarrow$



Block diagonalization of the representation

- GT projector operators: provide symmetric basis functions from non-symmetric ones.

Page 11 & 70

$$\hat{P}^{(\Gamma_n)} = \frac{\ell_n}{h} \sum_R \chi^{(\Gamma_n)}(R)^* \hat{P}_R$$

Symmetry operator acts on the orbitals

Sum over all symmetry elements

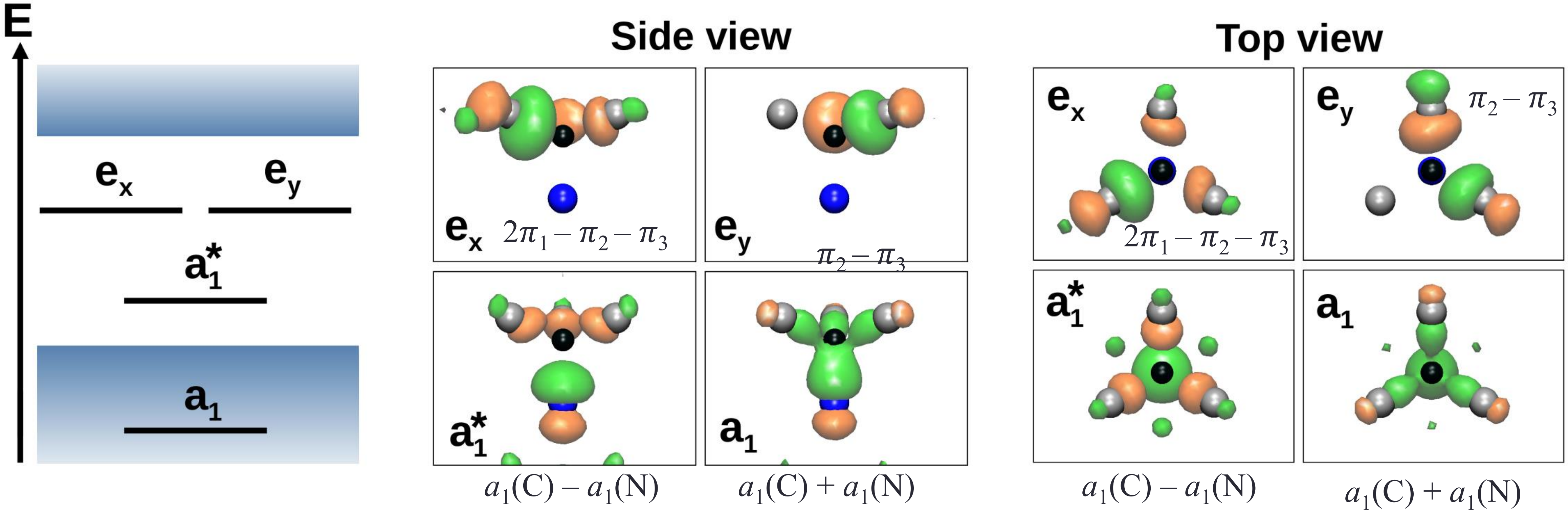
Character of representation Γ of symmetry element R.

C_{3v} $h=6$	E	$2C_3$	$3\sigma_v$
A_1	1	1	1
A_2	1	1	–1
E	2	–1	0

Irreducible basis:

- $a_1(\mathrm{N}) = \pi_\mathrm{N}$
- $a_1(\mathrm{C}) = (\pi_1 + \pi_2 + \pi_3)/\sqrt{3}$
- $e = \{(2\pi_1 - \pi_2 - \pi_3)/\sqrt{6}\,, (\pi_2 - \pi_3)/\sqrt{2}\ \}$

How does it look in the single-particle DFT method?

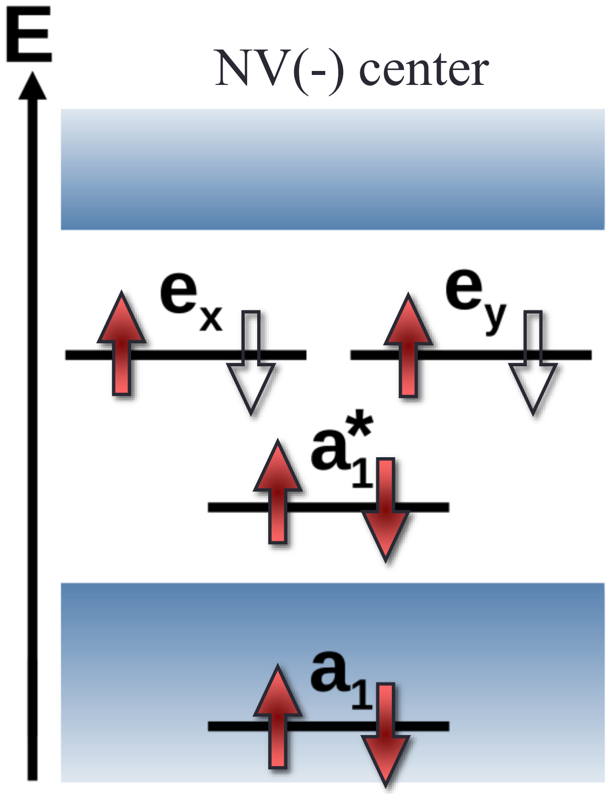


DFT knows group theory!
$V(\mathbf{r})$ is symmetric

Group theory does not tell you where these states are in the band structure of diamond.

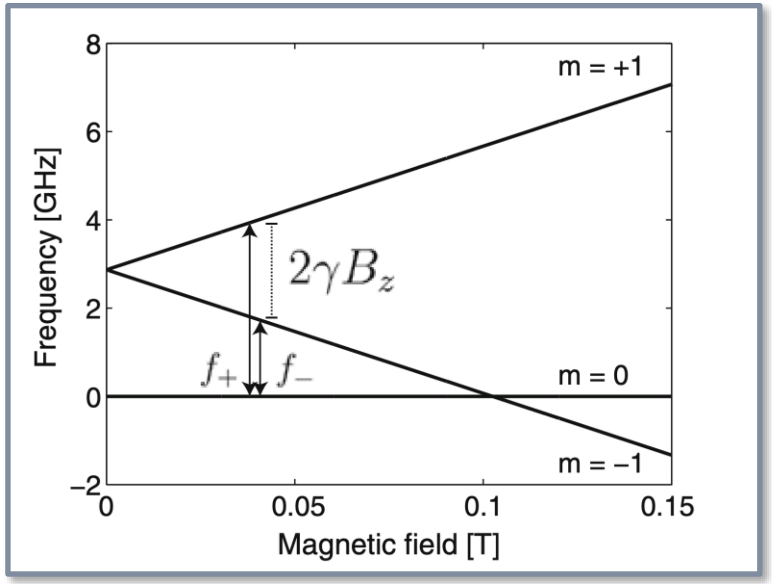
Let’s occupy the states with electrons

Number of electrons:
2 from N, 3 from 3 carbons, and 1 from the environment = 6



Triplet ground state

S = 1; $m_S = \{-1, 0, +1\}$



NV electron spin qubit:

- 2 states of the electron spin can form a qubit
- Coherent control via microwave irradiation
- Tuning with an external megnetic field
- **How can we read out and initialize?**

We need more group theory!

- Irreducible representation of the possible many-body WFs can be obtained by including all electrons and their spin:

$$\Gamma_{\Psi} = \prod_{n} (\Gamma_{hn} \otimes D_{1/2})$$

Irrep of the electron spin-1/2 in C_{3v}

Irrep of the spatial part (orbital)

Projectors can be used to obtain the symmetry-allowed states of the many-body system.

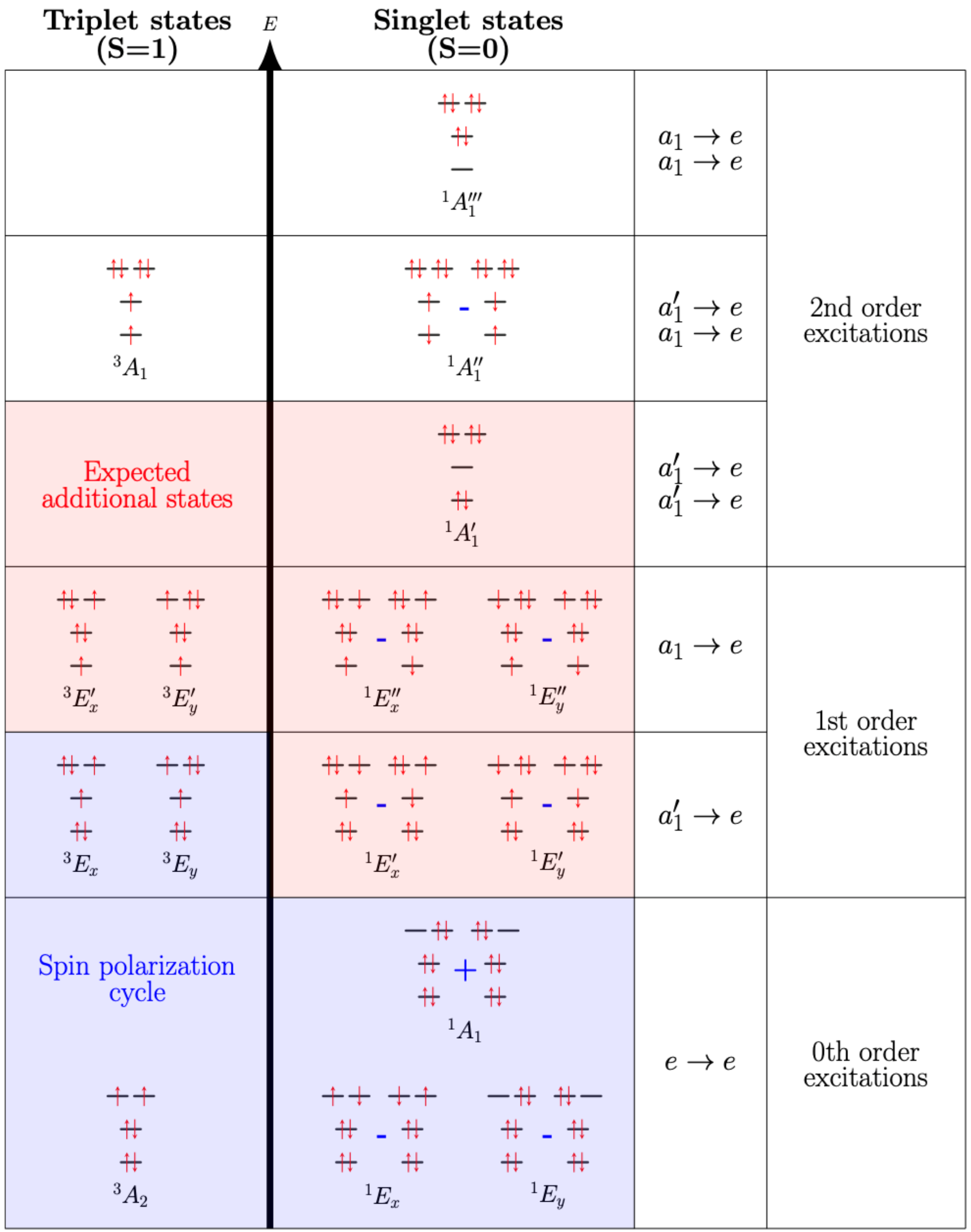
$$\Psi^{r} = P^{(r)} \varphi_1 \otimes \chi_1 \otimes \varphi_2 \otimes \chi_2 = \frac{l_r}{h} \sum_{e} \chi_e^{(r)*} R_e \varphi_1 \otimes U_e \chi_1 \otimes R_e \varphi_2 \otimes U_e \chi_2$$

Many-body spe

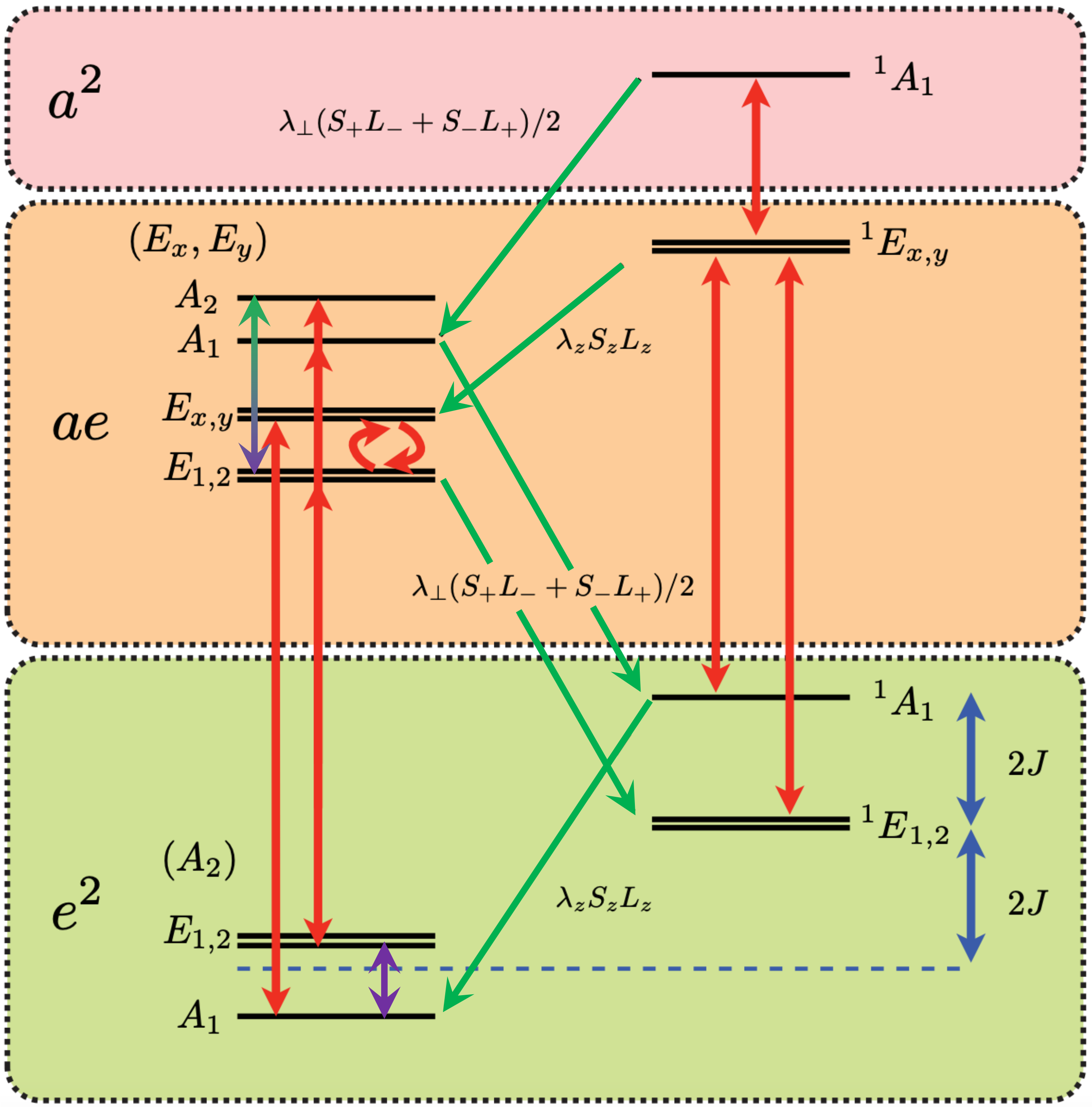
$$^3E$$

$$\overbrace{\begin{aligned}
A_1 &= |E_-\rangle \otimes |\alpha\alpha\rangle - |E_+\rangle \otimes |\beta\beta\rangle \\
A_2 &= |E_-\rangle \otimes |\alpha\alpha\rangle + |E_+\rangle \otimes |\beta\beta\rangle \\
E_1 &= |E_-\rangle \otimes |\beta\beta\rangle - |E_+\rangle \otimes |\alpha\alpha\rangle \\
E_2 &= |E_-\rangle \otimes |\beta\beta\rangle + |E_+\rangle \otimes |\alpha\alpha\rangle \\
E_y &= |Y\rangle \otimes |\alpha\beta + \beta\alpha\rangle \\
E_x &= |X\rangle \otimes |\alpha\beta + \beta\alpha\rangle
\end{aligned}}$$

$$\begin{aligned}
^3A_{2-} &= \\
^3A_{20} &= |e_x e_y - e_y e_x\rangle \otimes \\
^3A_{2+} &=
\end{aligned}
\left\{\begin{matrix} |\beta\beta\rangle \\ |\alpha\beta + |\beta\alpha\rangle \\ \alpha\alpha\rangle \end{matrix}\right.$$



$$\left.\begin{aligned}
^1E_1 &= |e_x e_x - e_y e_y\rangle \\
^1E_2 &= |e_x e_y + e_y e_x\rangle \\
^1A_1 &= |e_x e_x + e_y e_y\rangle
\end{aligned}\right\} \otimes |\alpha\beta - \beta\alpha\rangle$$



Many-body electronic structure and allowed transitions

Selection rules

Non-zeroness of matrix elements of the operators can be obtained from group theory.

- Optical transition (red arrows):

$$\mu_{fi} = \left\langle \Psi_f \middle| e\hat{\mathbf{r}} \middle| \Psi_i \right\rangle$$

$$\mu_{fi} \neq 0 \quad \text{only if} \quad A_1 \subset \Gamma_f \otimes \Gamma_{e\mathbf{r}} \otimes \Gamma_i$$

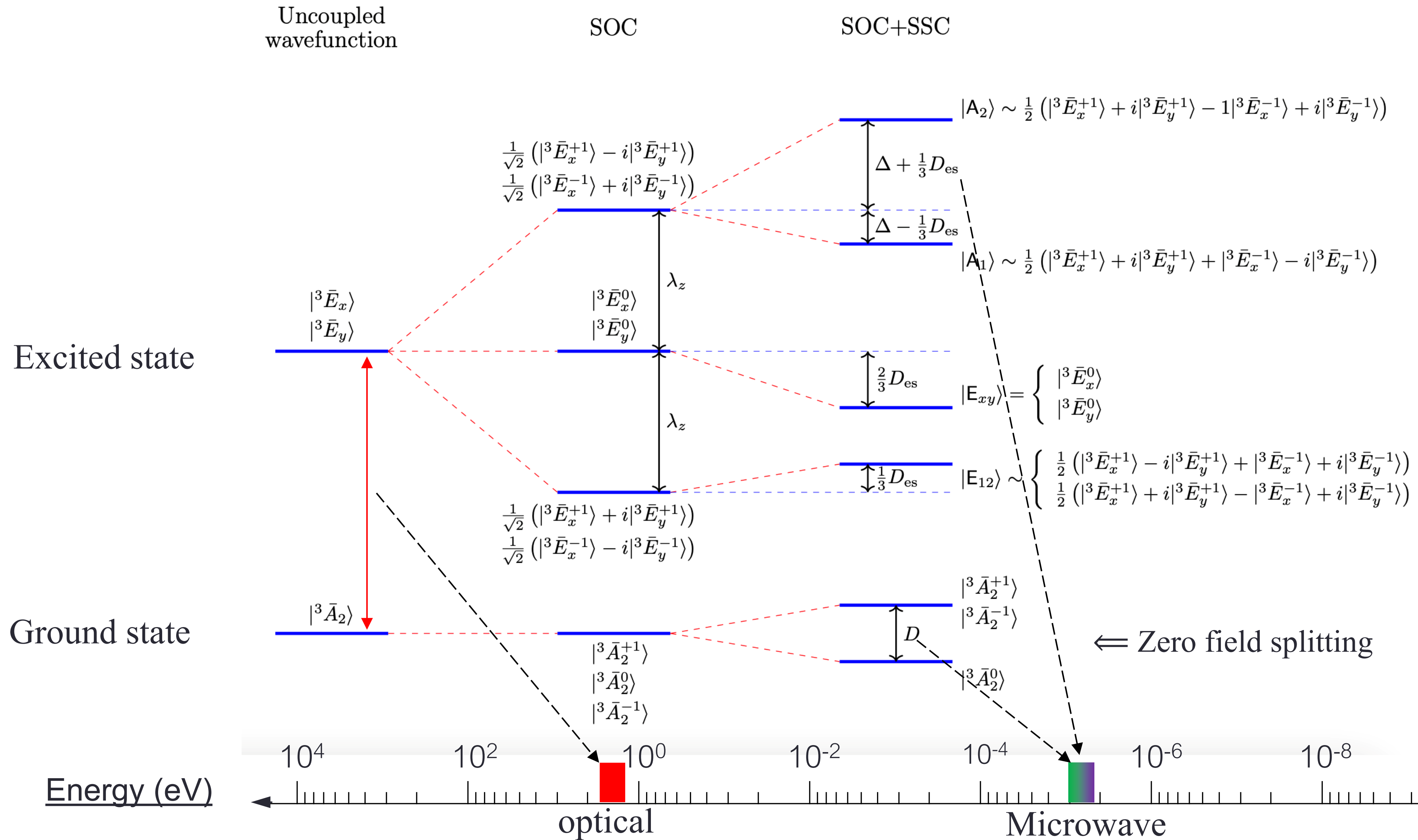
- Spin-spin interaction (purple arrows):

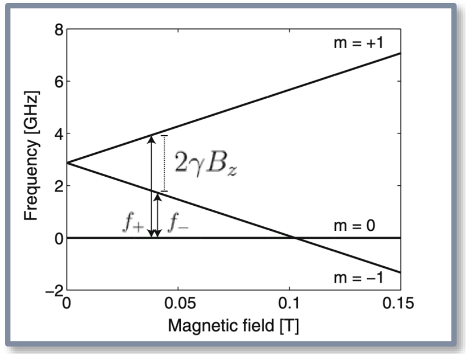
$$h_{ss} = -\frac{\mu_0}{4\pi}\frac{g^2\beta^2}{r^3}\left(3(\mathbf{s}_1 \cdot \hat{r})(\mathbf{s}_2 \cdot \hat{r}) - \mathbf{s}_1 \cdot \mathbf{s}_2\right)$$

- Spin-orbit interaction (green arrows):

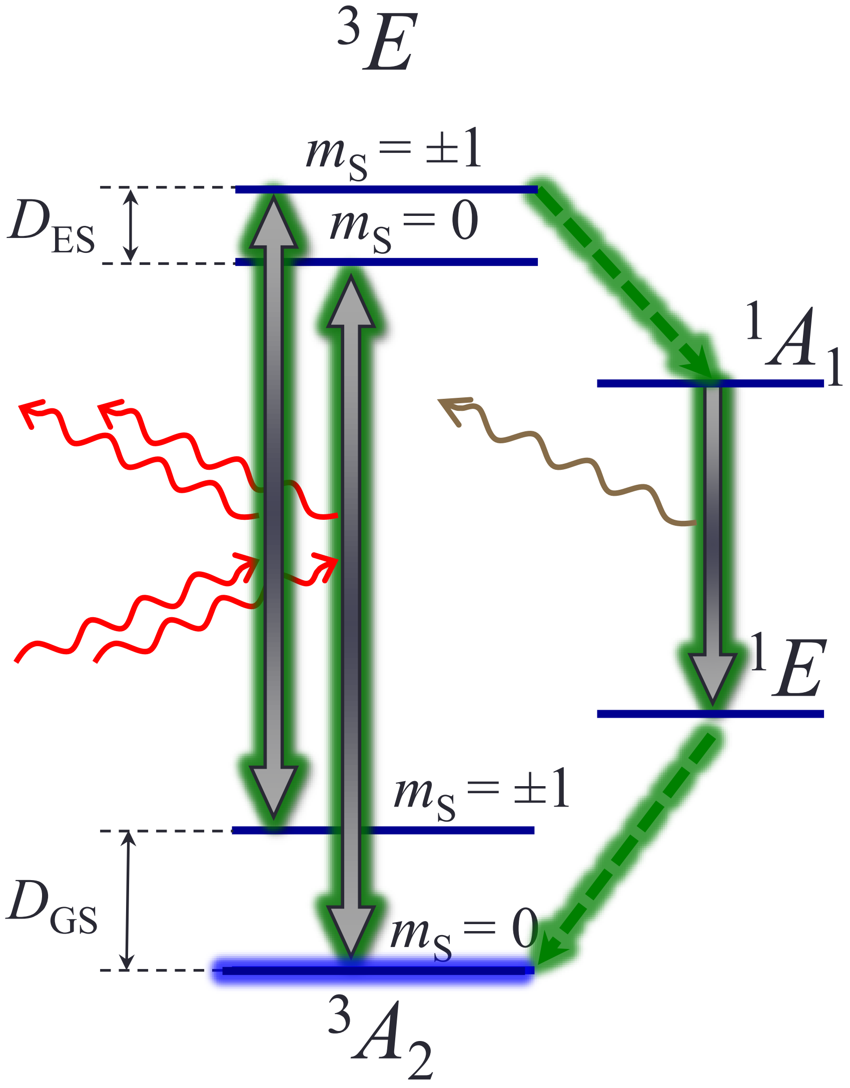
$$H_{SO} = \sum_k \frac{1}{2}\frac{\hbar}{c^2 m_e^2}(\nabla_k V \times \mathbf{p}_k) \cdot \left(\frac{\mathbf{s}_k}{\hbar}\right)$$

Ground and excited state fine structure





We can now understand how spin initialization and readout work.



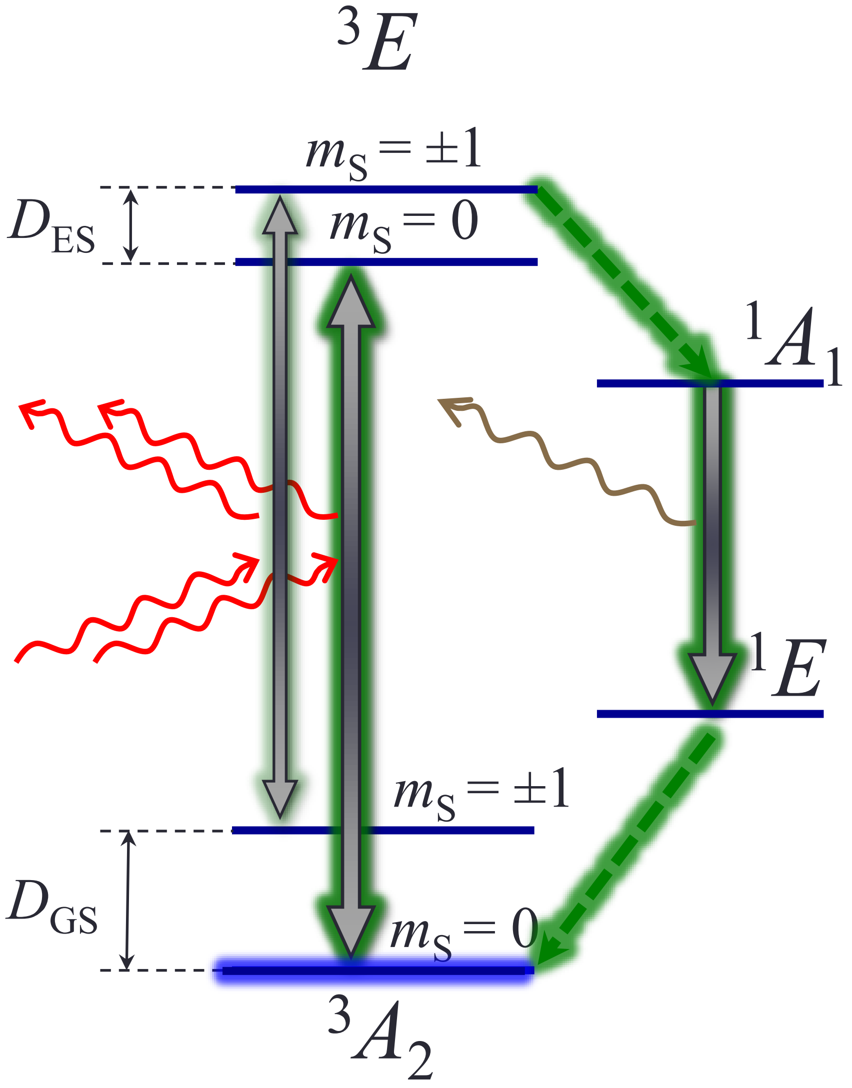
Initilzation with optical pumping:

State is in $m_S = 0 \implies$ stays there

State is in $m_S = \pm 1$ ⇗ stays there ⇘ decay to $m_S = 0$

The result of many optical cycling: Initialization with 95% probability in $m_S = 0$

We can now understand how spin initialization and readout work.



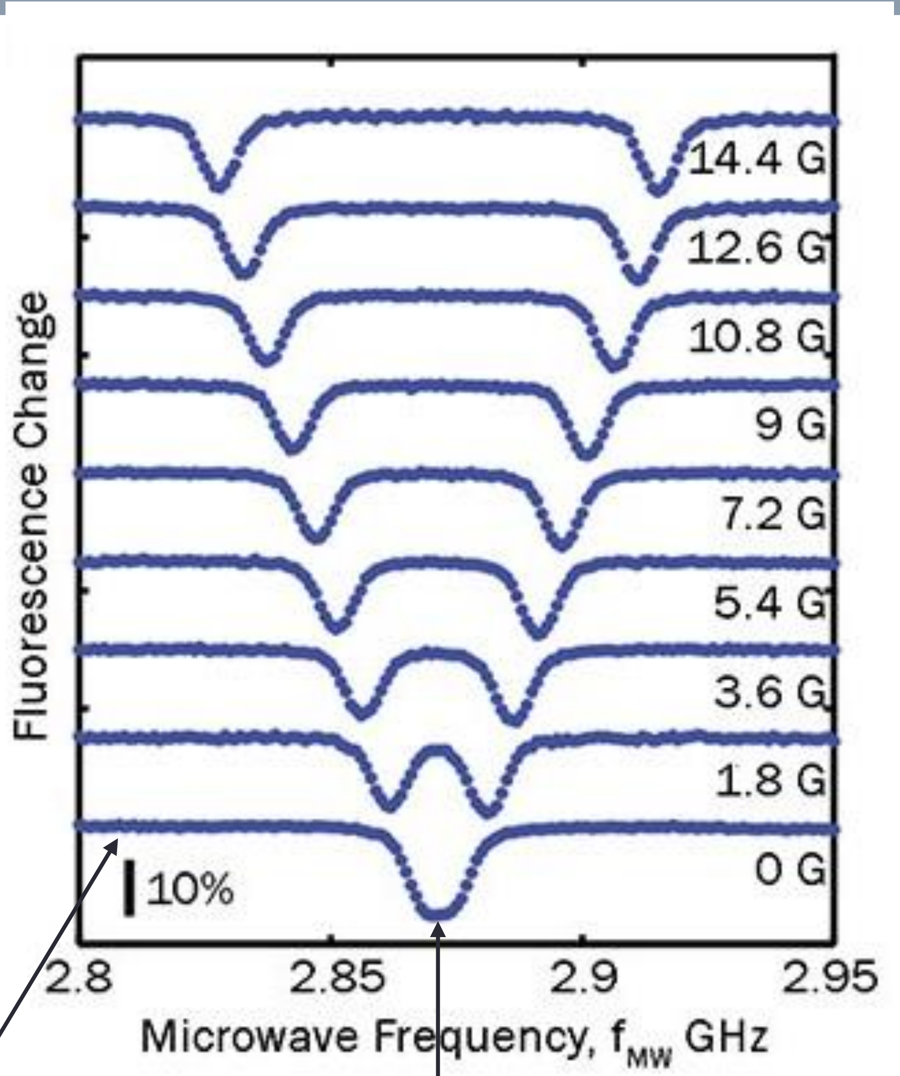
Principle of readout:

The NV in the $m_S = 0$ is brighter then in the $m_S = \pm 1$

Optically detected magnetic resonance

Continuous wave ODMR:

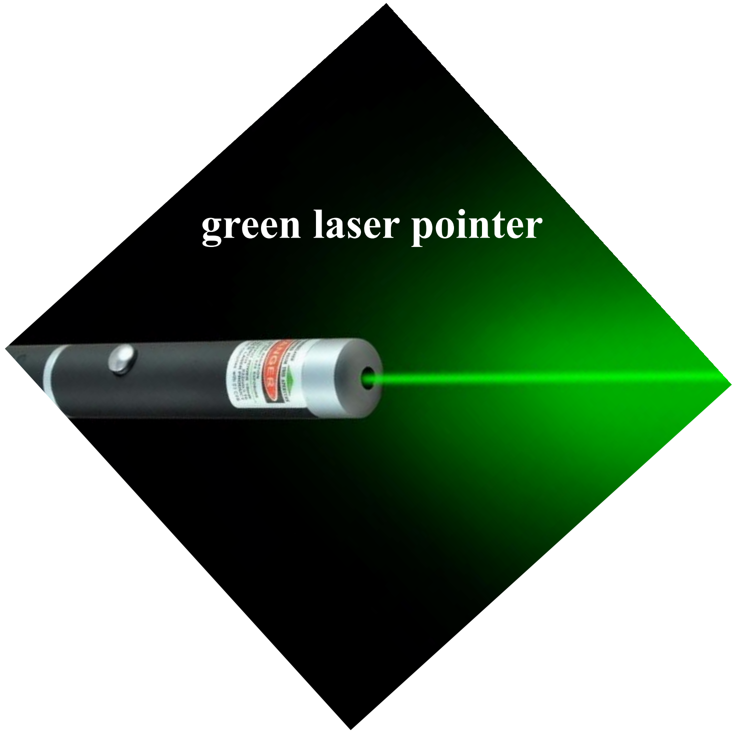
- Apply optical excitation
- Apply MW excitation
- Sweep the MW frequency
- (Sweep the magnetic field)

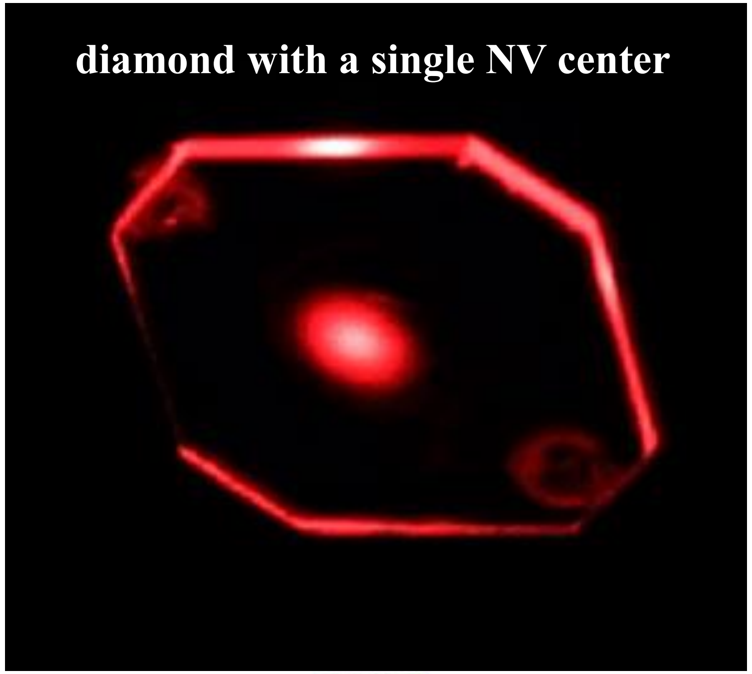


Off resonant MW: $m_S = 0$

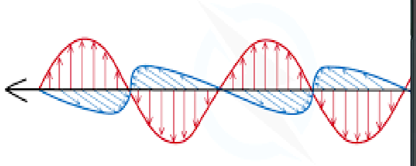
Resonant MW: 50% $m_S = 0$ + 50% $m_S = \pm 1$

DIY: room temperature quantum control

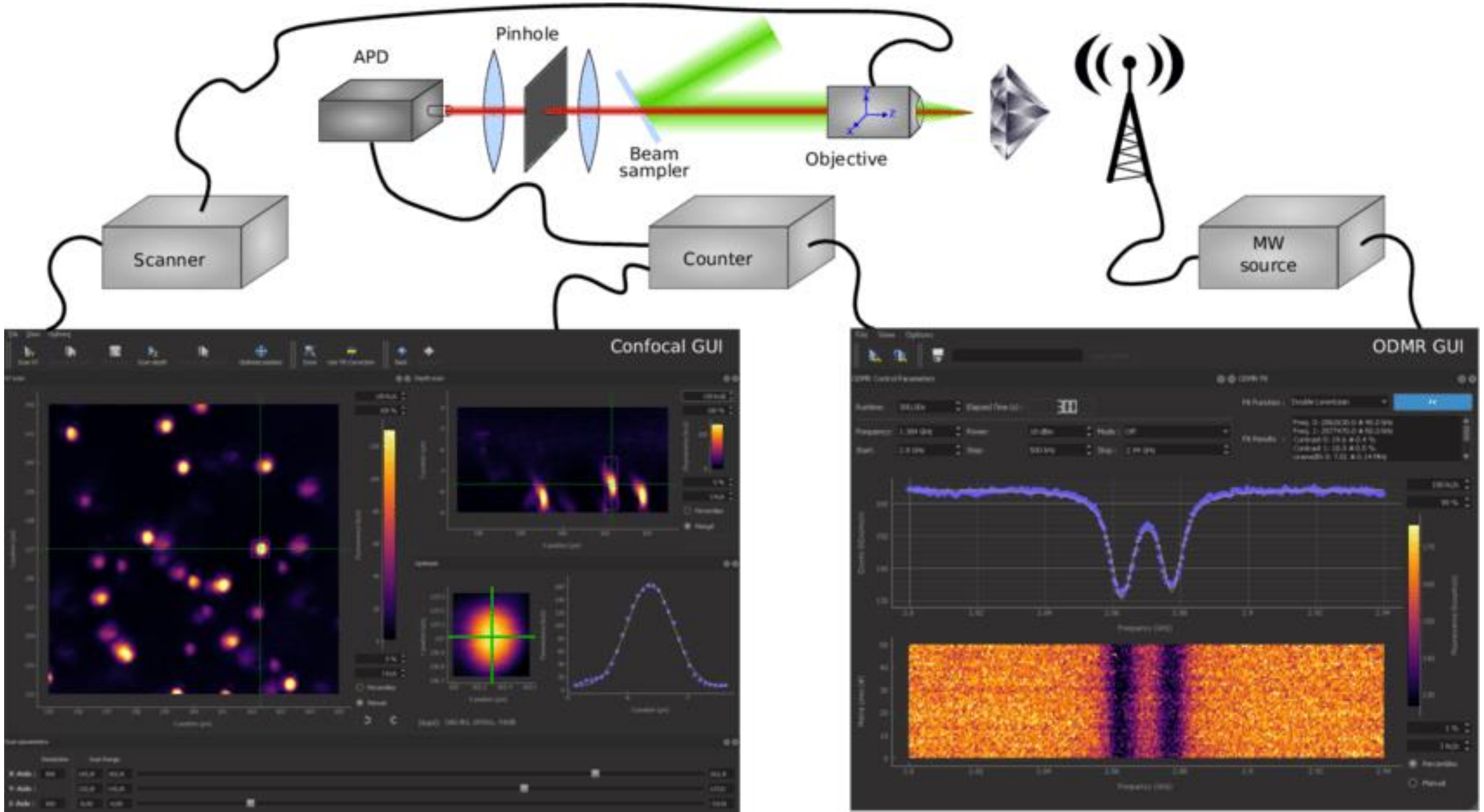




microwave source (1-2 GHz)



More professional way: confocal microscopy setup



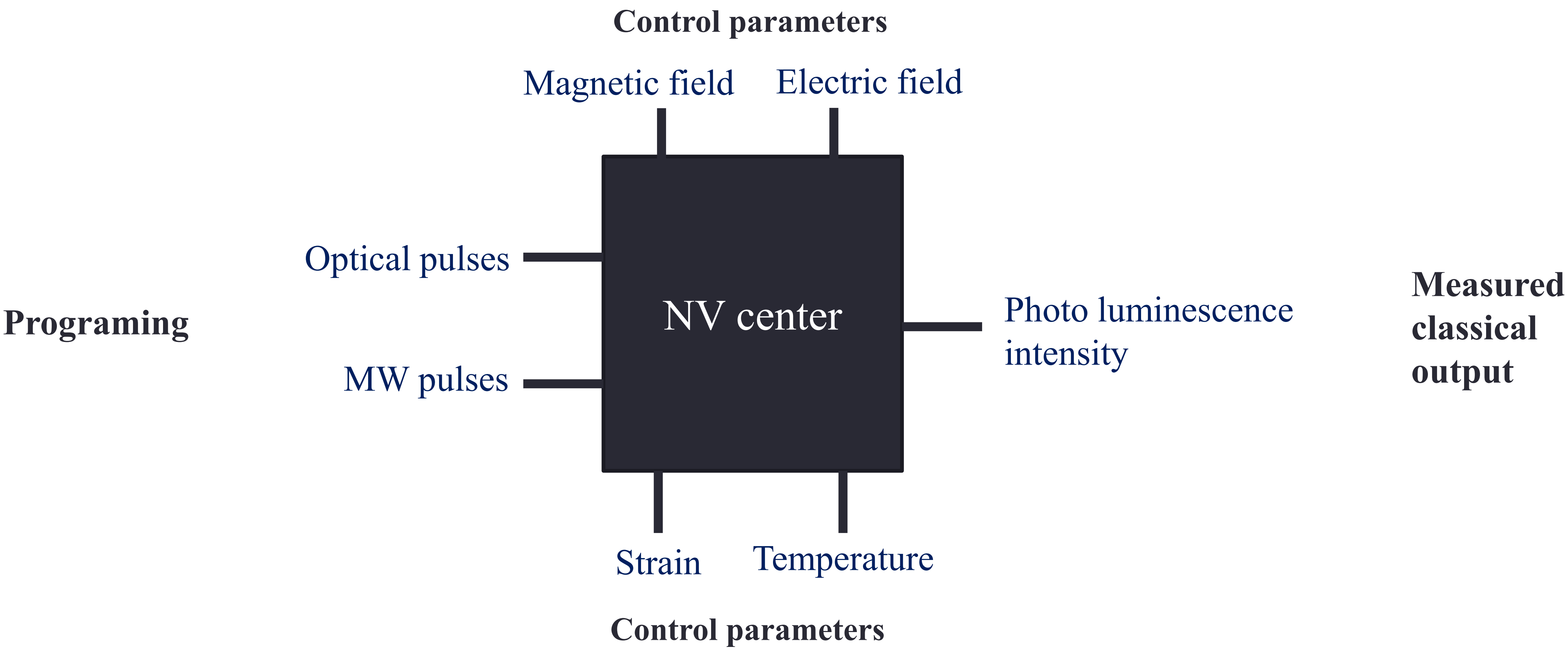
High temperature spin control?

How is it possible?
Short answer is: it is quantum mechanics!

- The localized defect states decouple from the bath of diamond electrons.
- Magnetic dipole interaction is much weaker than the electrostatic interaction
- No spin-orbit coupling in the ground state
- Low magnetic noise in diamond samples:
  - Low concentration of electron spins, i.e., high-quality diamond samples available.
  - Low concentration of nuclear spins, 1% ^{13}C spin-1/2 nuclear spin abundance.
- $\Longrightarrow$ spin states are preserved (even at 1400K)

- Read out works: demonstrates the rigour of selection rules.

Summary of control of the NV center



Instructions, standard NMR pulse sequences

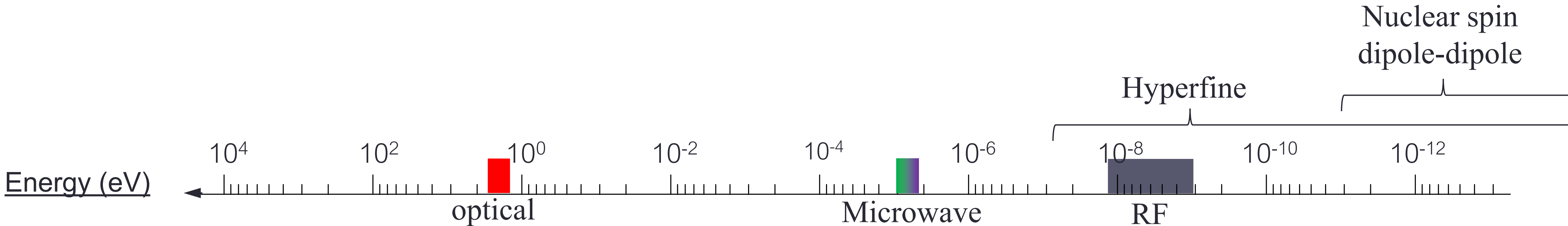
	CW ODMR	Pulsed ODMR	Ramsey	Hahn echo	Dynamical decoupling	Rabi	T1 relaxometry
Laser							
Microwave		π	π/2 π/2	π/2 π π/2	π/2 π π/2		π
Readout							
Bias field							
Sample field							
Swept parameter	Microwave frequency	Microwave frequency	Free precession time, τ	Spin evolution time, τ	Spin evolution time, τ	Microwave pulse duration, bias field	Laser pulse delay, bias field

Interaction with the environment

- Spin Hamiltonian:

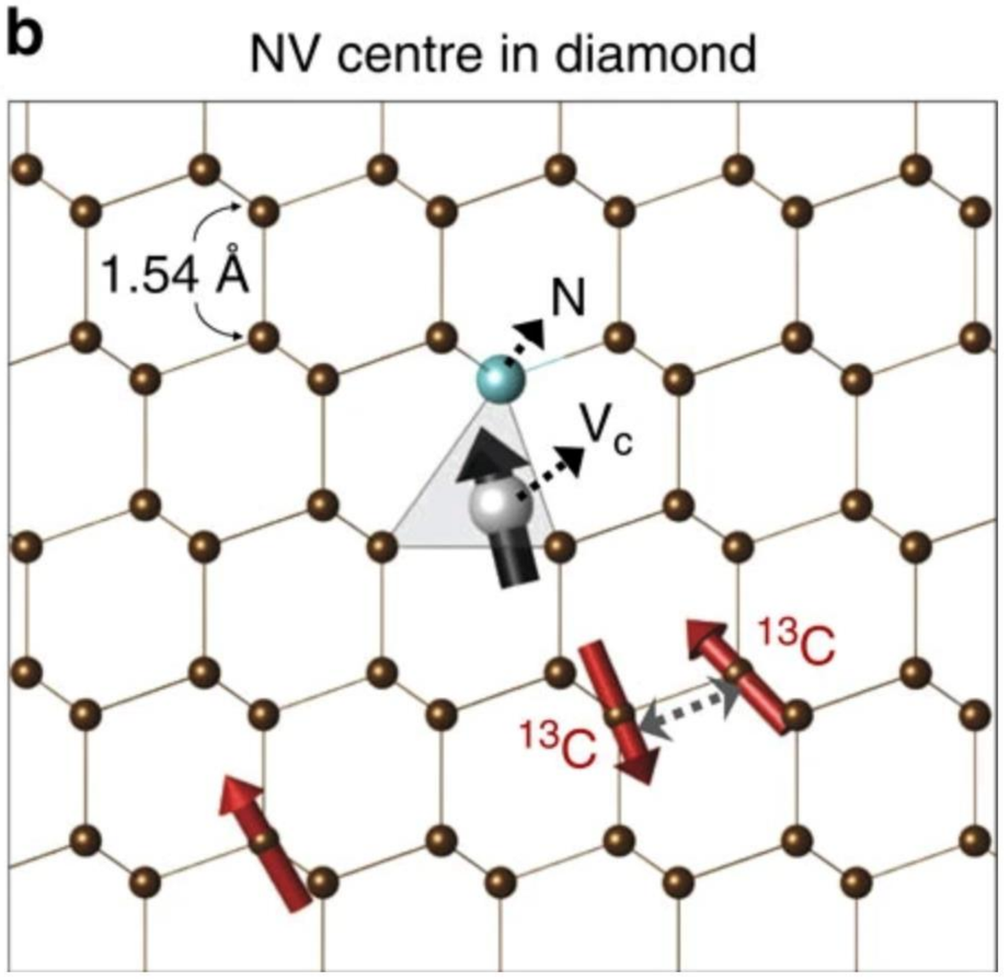
Strain and electric field dependent

$$\hat{H} = \hat{H}_e + \hat{H}_b + \hat{H}_{e-b} = D\left(\hat{S}_z^2 - S(S+1)/3\right) + \frac{E}{2}\left(\hat{S}_+^2 + \hat{S}_-^2\right) + g_e\mu_B\mathbf{B}^T\hat{\mathbf{S}} - \sum_i g_N^{(i)}\mu_N^{(i)}\mathbf{B}^T\hat{\mathbf{I}}^{(i)} + \sum_i \hat{\mathbf{I}}^{(i)}\mathbf{Q}^{(i)}\hat{\mathbf{I}}^{(i)} + \sum_{i<j}\hat{\mathbf{I}}^{T(i)}\mathbf{J}^{(ij)}\hat{\mathbf{I}}^{(j)} + \sum_i \hat{\mathbf{S}}^T\mathbf{A}^{(i)}\hat{\mathbf{I}}^{(i)},$$



Nuclear spins as sources of decoherence

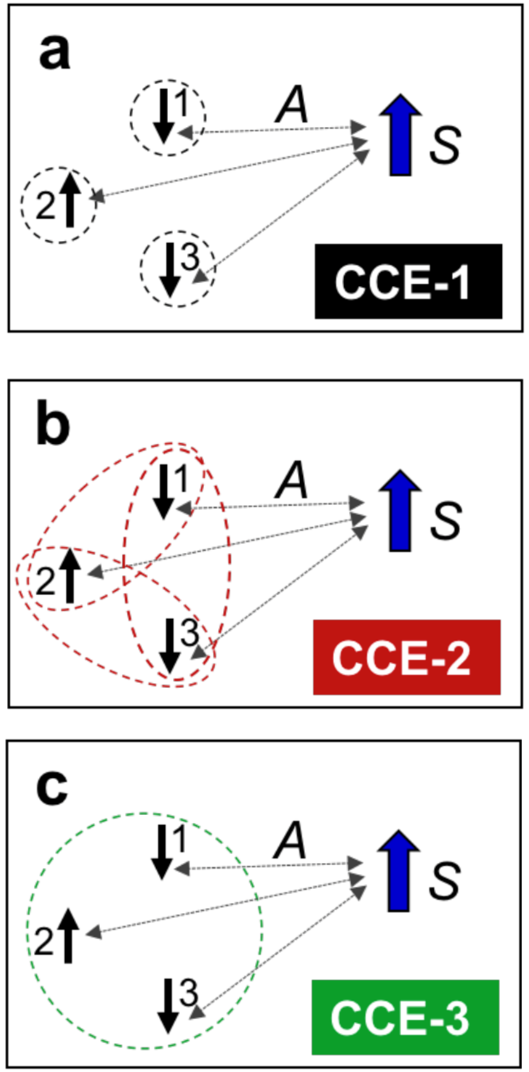
- Dipole-dipole interaction with ^{13}C nuclear spins is the major source of decoherence, $\Longrightarrow$ spinless ^{12}C isotope enrichment.
  - Open quantum system (?)
  - Electron spin is surrounded by a bath of quantum memories.
    - Nuclear spin coherence time can exceed seconds at room temperature in diamond
  - The cluster correlation expansion (CCE) method works very well in a parameter-free manner.



Introduction of the CCE method

Electron spin's density matrix: $\varrho_e(t) \;=\; \mathrm{Tr}_{\mathrm{bath}}\,\varrho(t)$

Coherence function: $L(t) = \mathrm{Tr}(\sigma_+ \varrho_e(t))$

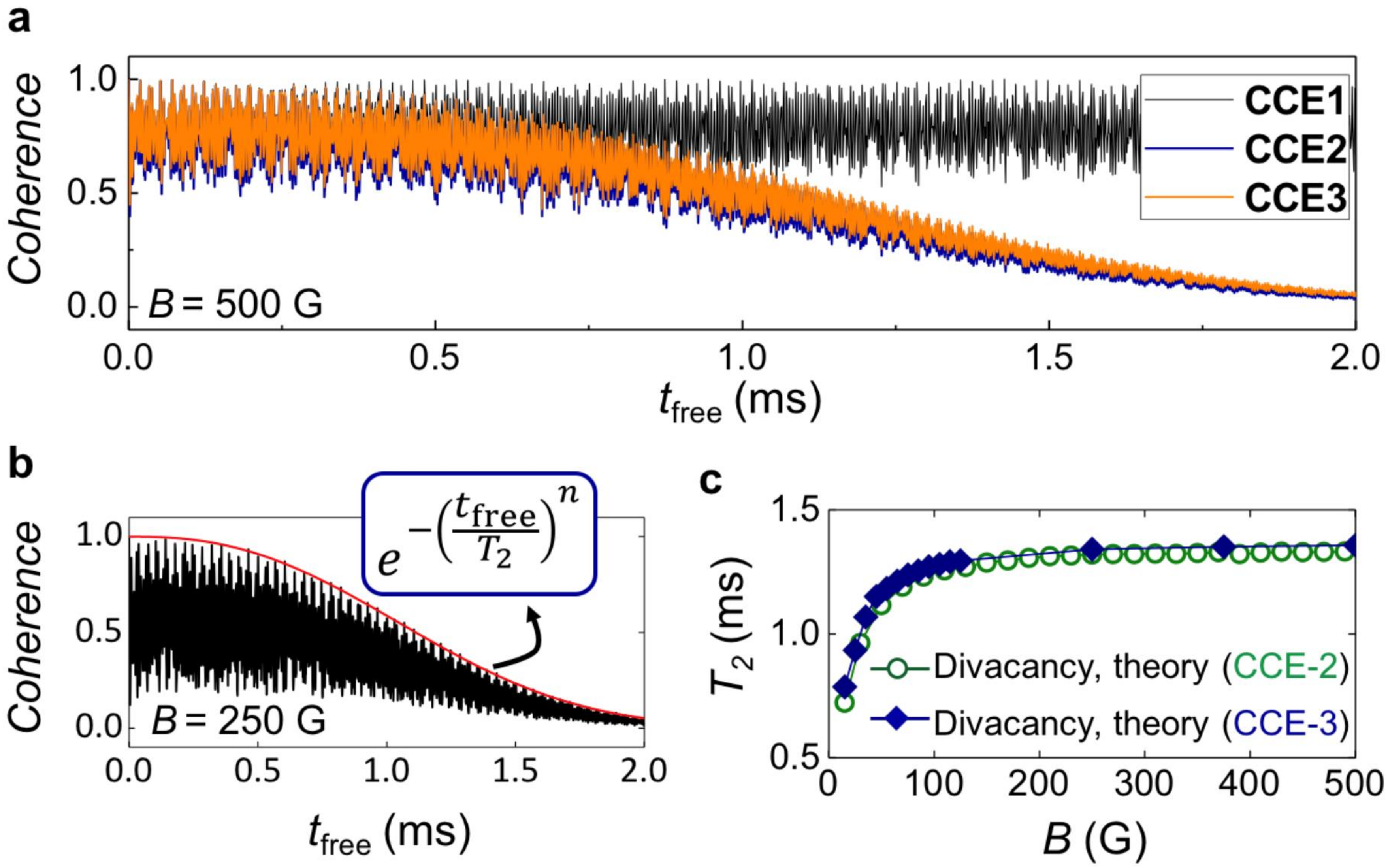


CCE ansatz:

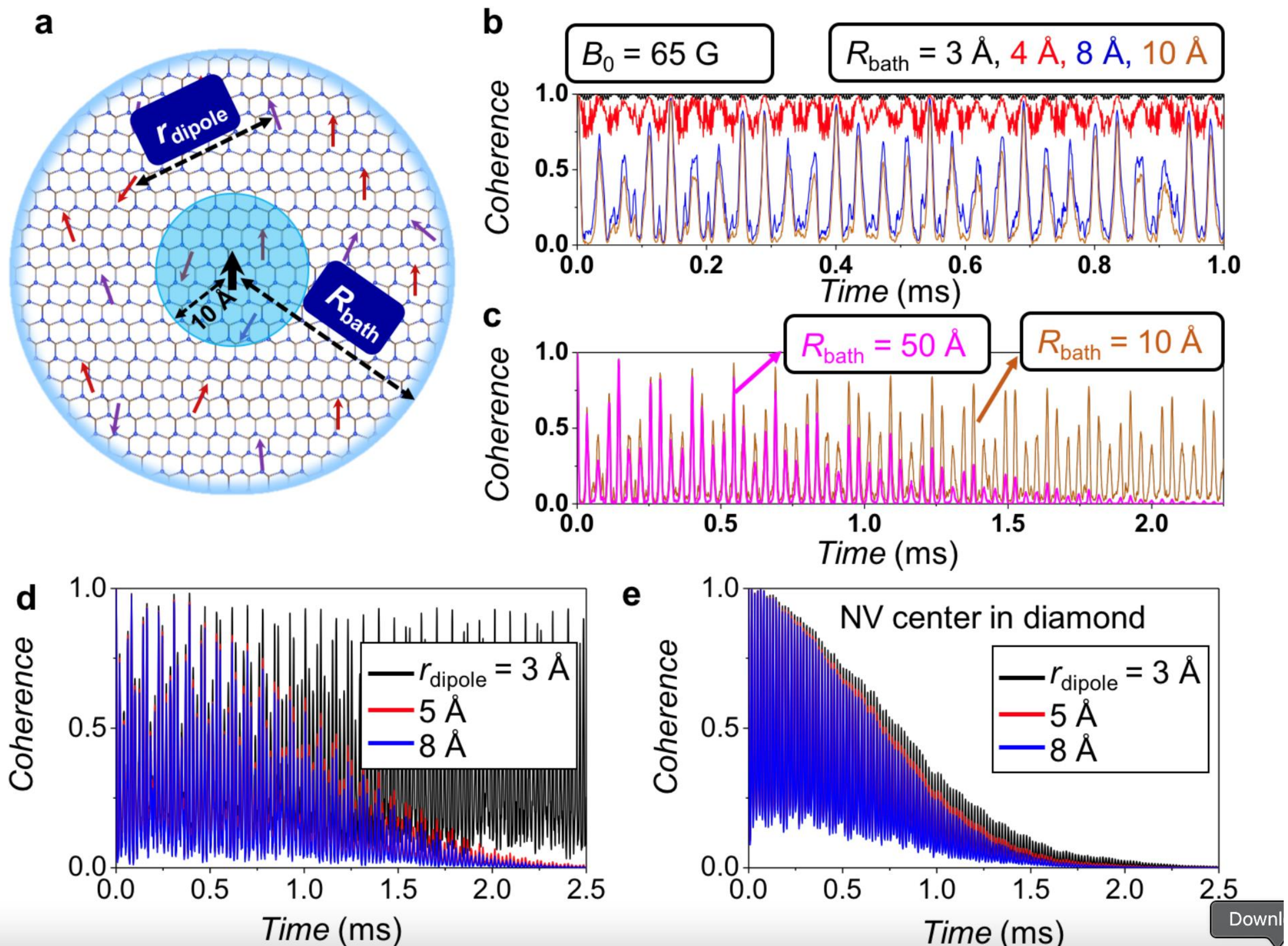
$$L(t) = \prod_n L_n(t) \qquad\qquad L_n(t) = \prod_{j\in C_n} \tilde{l}_j^{(n)}(t)$$

$$\tilde{l}_j^{(n)} = \frac{\mathrm{Tr}\left(\sigma_+ \mathrm{Tr}_{\mathrm{bath}}\left(\varrho_j^{(n)}\right)\right)}{l^{(0)} \prod_{p\in C_{1,j}} \tilde{l}_p^{(1)} \cdots \prod_{q\in C_{n-1,j}} \tilde{l}_q^{(n-1)}}$$

Introduction of the CCE method



Introduction of the CCE method

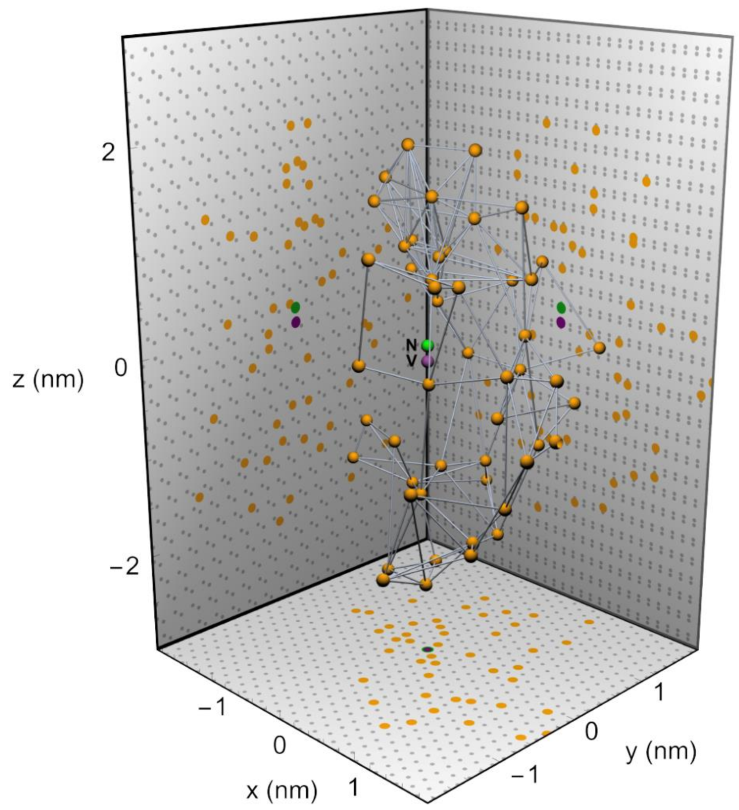


Nuclear spins as resources

- Adjacent nuclear spins can be addressed by the NV center
  - Additional spin qubits with long coherence time
  - Trend:
    - electron spin: means of nuclear spin initialization, control and read-out.
    - nuclear spins: multi-qubit quantum hardware.

Mapping a 50-spin-qubit network through correlated sensing

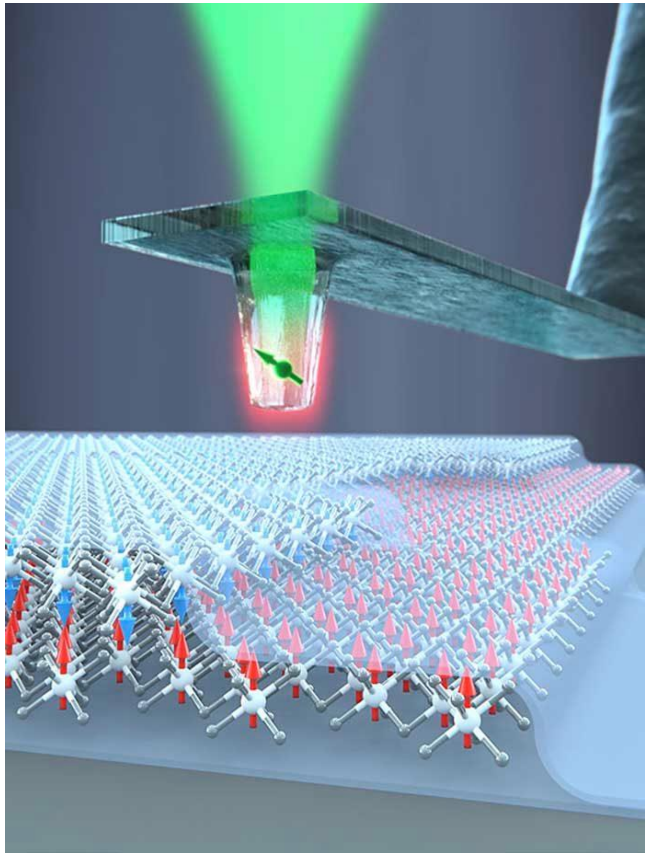
G.L. van de Stolpe[1,2], D. P. Kwiatkowski[1,2], C.E. Bradley[1,2], J. Randall[1,2], S. A. Breitweiser[3], L. C. Bassett[3], M. Markham[4], D.J. Twitchen[4], and T.H. Taminiau[1,2]
[1] *QuTech, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*
[2] *Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*
[3] *Quantum Engineering Laboratory, Department of Electrical and Systems Engineering, University of Pennsylvania, 200 South 33rd Street, Philadelphia, PA 19104, USA and*
[4] *Element Six Innovation, Fermi Avenue, Harwell Oxford, Didcot, Oxfordshire OX11 0QR, United Kingdom*



Part II.

Interesting experiments and papers

Quantum sensing with NV center



Single NV center
High spatial resolution

Nanoscale probe
Nature **455** 648 (2008)

Ensemble of NV centers

Very high precision, low spatial resolution

Sensitivity for AC magneometry

η (τ_{full}= 1 s) represents the smallest signal field that can be detected with SNR = 1 in 1 second of interrogation time.

$$\eta \approx \frac{\pi}{2} \frac{\hbar}{g_e \mu_B} \frac{1}{\sqrt{N \tau_{\mathrm{full}}}} \frac{1}{e^{-\tau_{\mathrm{full}}/(k^s T_2)^p}} \times \sqrt{1 + \frac{1}{C^2 n_{\mathrm{avg}}}} \sqrt{\frac{t_I + \tau_{\mathrm{full}} + t_R}{\tau_{\mathrm{full}}}}$$

Large $N \Longrightarrow$ sub femto tesla sensitivity

REPORT

QUANTUM MEASUREMENT

Submillihertz magnetic spectroscopy performed with a nanoscale quantum sensor

Simon Schmitt,[1] Tuvia Gefen,[2] Felix M. Stürner,[1] Thomas Unden,[1] Gerhard Wolff,[1] Christoph Müller,[1] Jochen Scheuer,[1,3] Boris Naydenov,[1,3] Matthew Markham,[4] Sebastien Pezzagna,[5] Jan Meijer,[5] Ilai Schwarz,[3,6] Martin Plenio,[3,6] Alex Retzker,[2] Liam P. McGuinness,[1*] Fedor Jelezko[1,3]

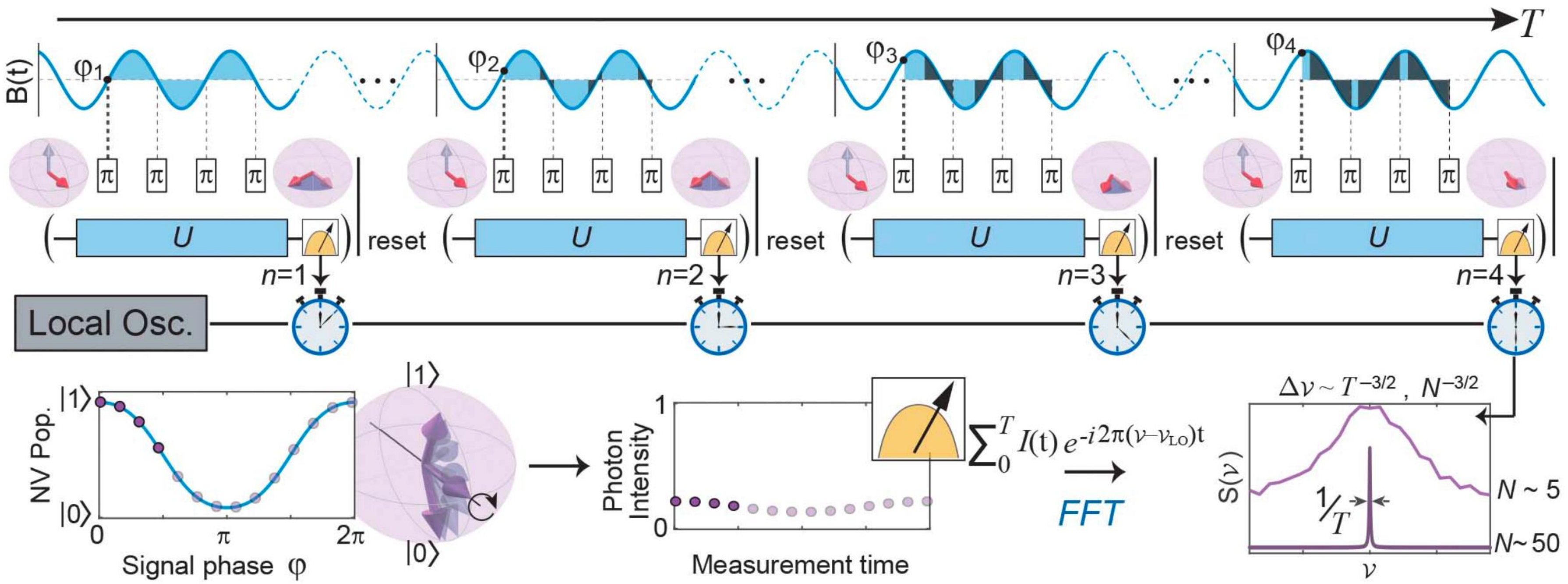
QUANTUM MEASUREMENT

Quantum sensing with arbitrary frequency resolution

J. M. Boss,* K. S. Cujia,* J. Zopes, C. L. Degen†

Science **356**, 832–837 (2017)

Science **356**, 837–840 (2017)

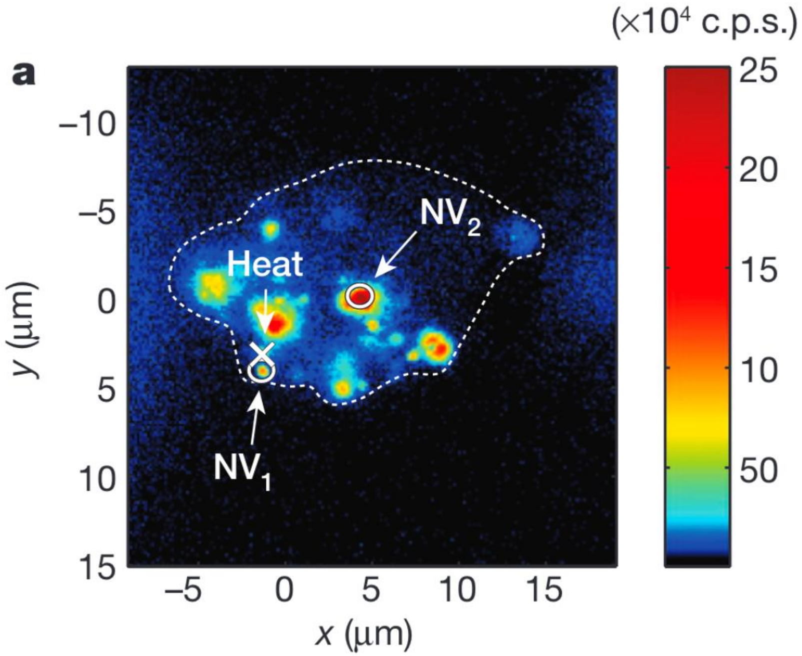


Can we measure temperature in living cells?

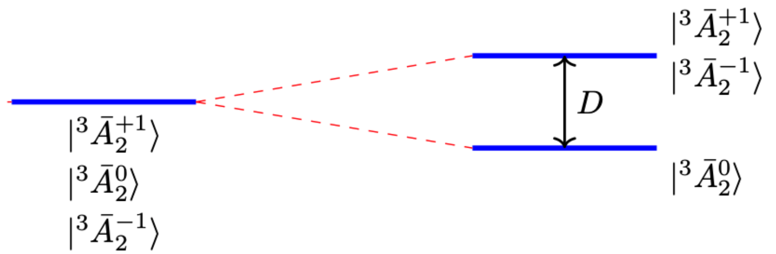
LETTER

Nanometre-scale thermometry in a

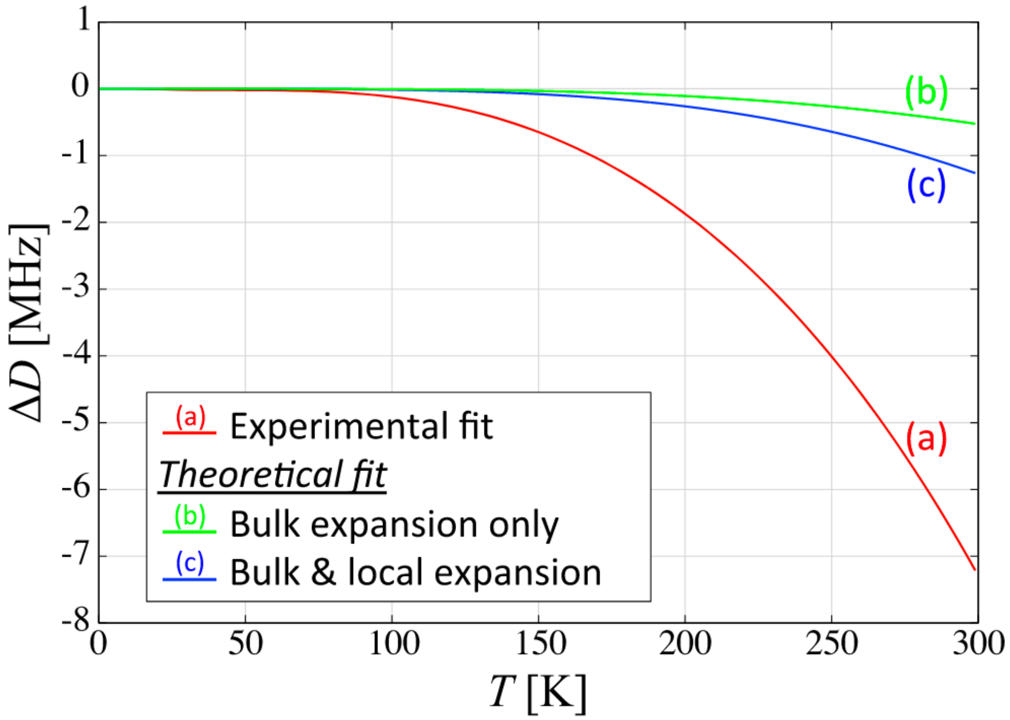
G. Kucsko[1]*, P. C. Maurer[1]*, N. Y. Yao[1], M. Kubo[2], H. J. Noh[3], P. K. Lo[4], H. Park[1,2,3] &



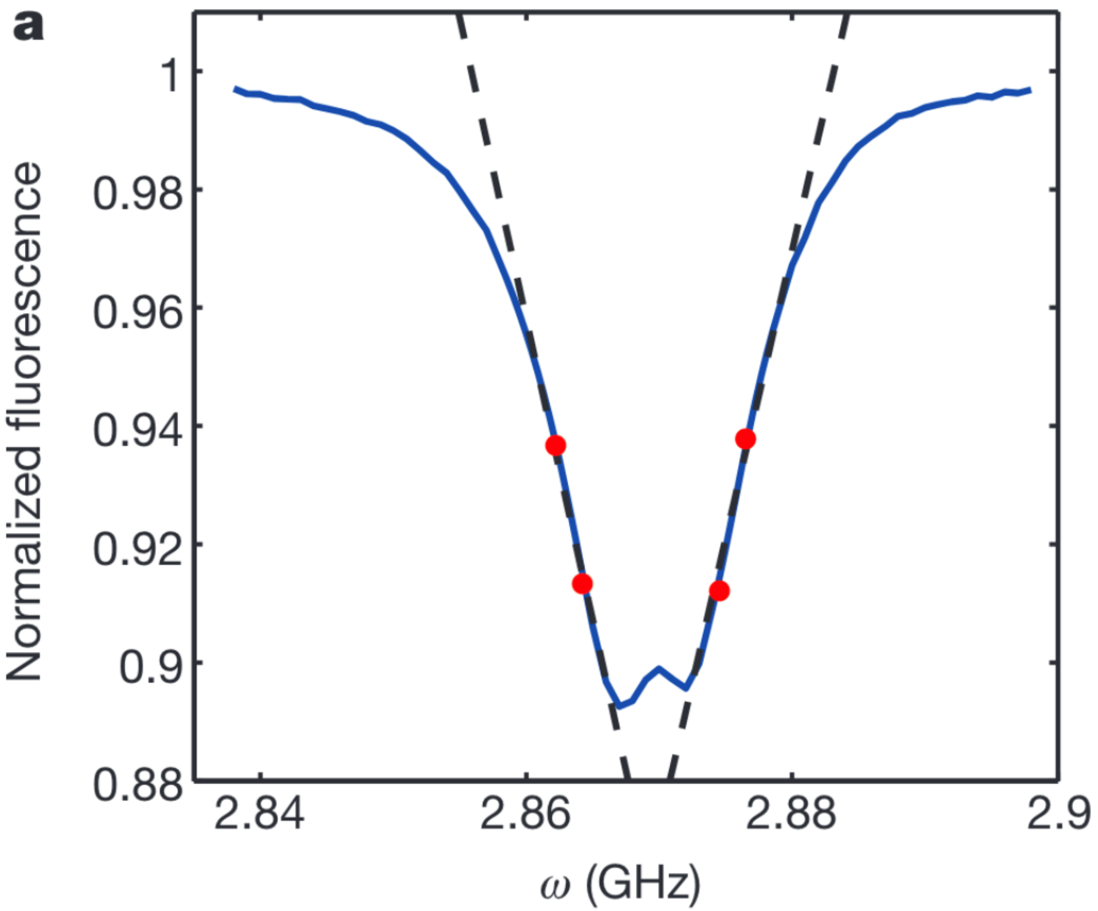
Temperature dependence of

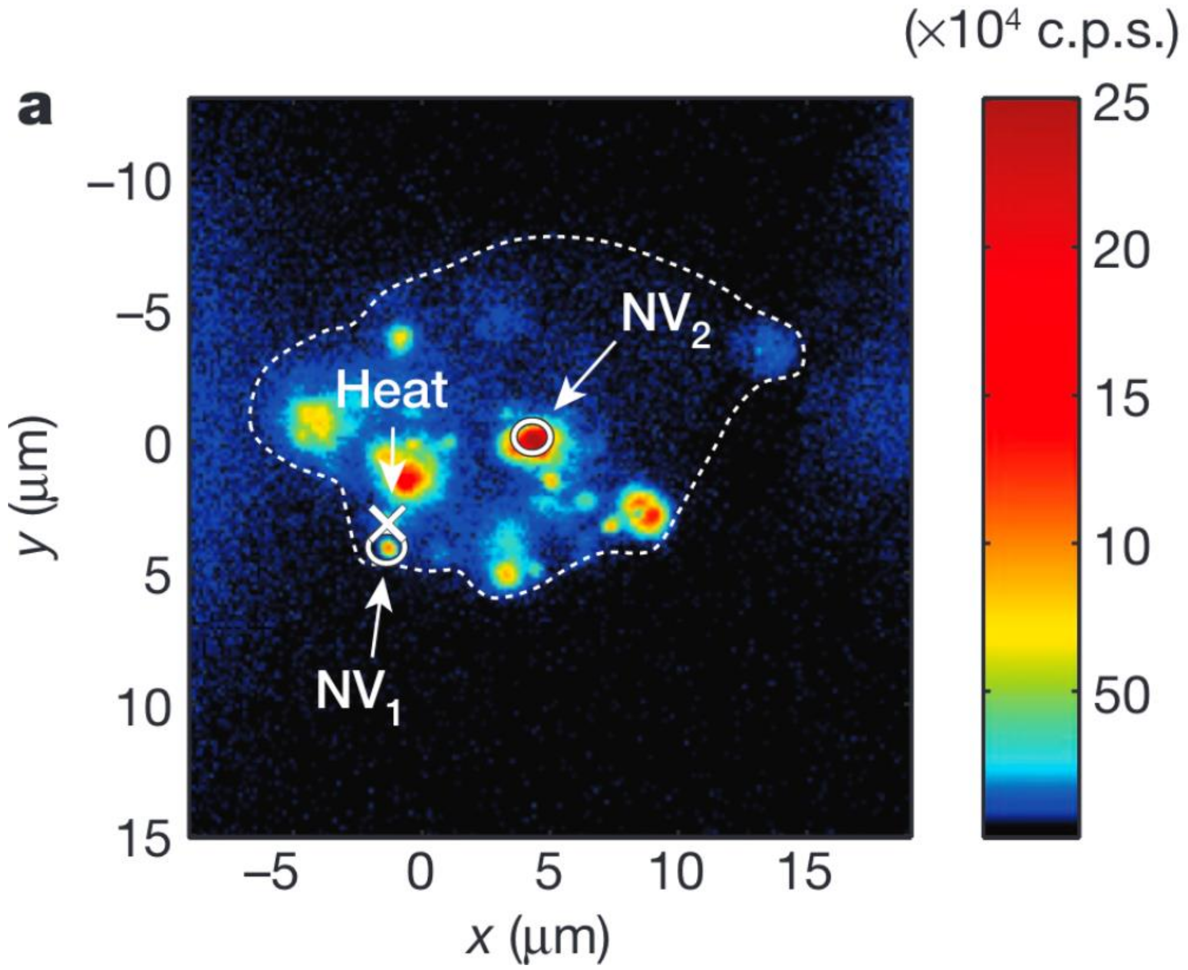


$$h_{ss} = -\frac{\mu_0}{4\pi}\frac{g^2\beta^2}{r^3}\left(3(\mathbf{s}_1\cdot\hat{r})(\mathbf{s}_2\cdot\hat{r}) - \mathbf{s}_1\cdot\mathbf{s}_2\right)$$

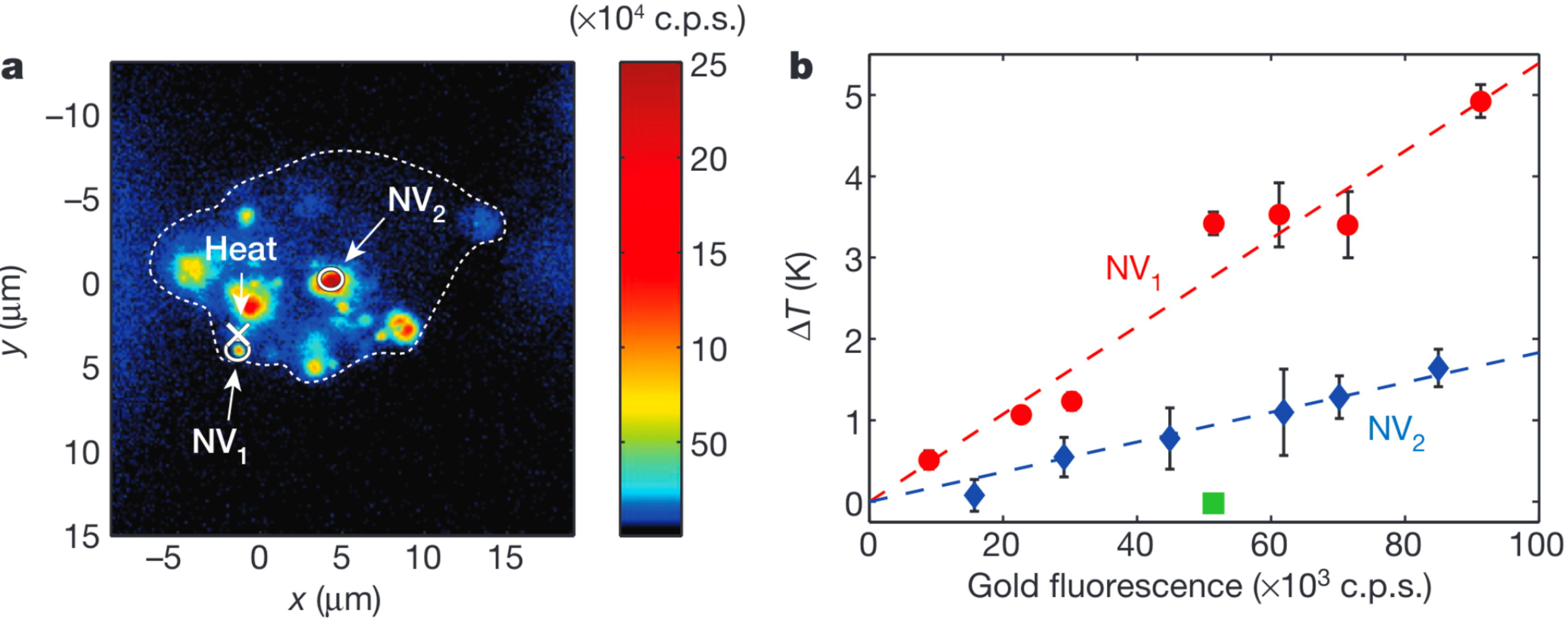


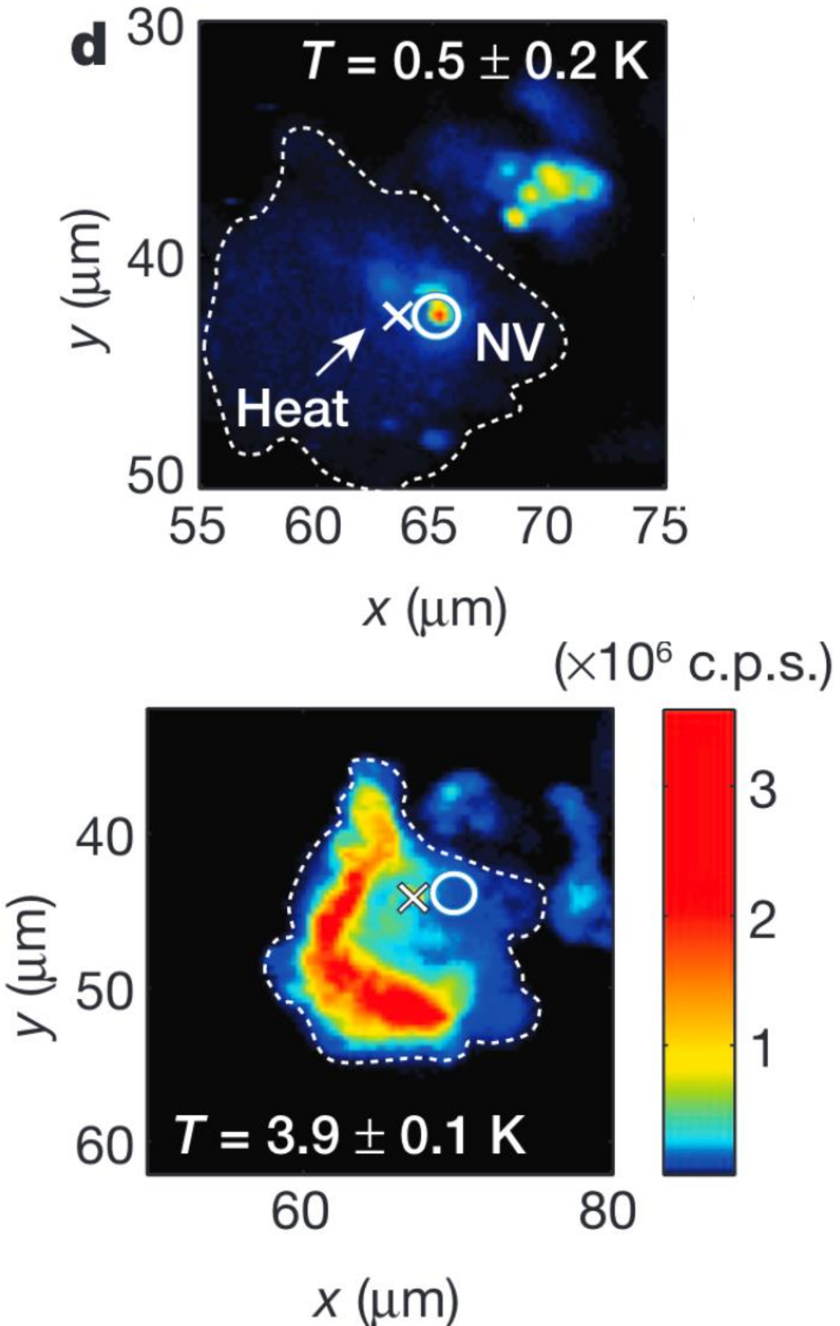
Use the PL intensity variation detect change of the temperature





Increased heating is detected in the cell untill it popped…





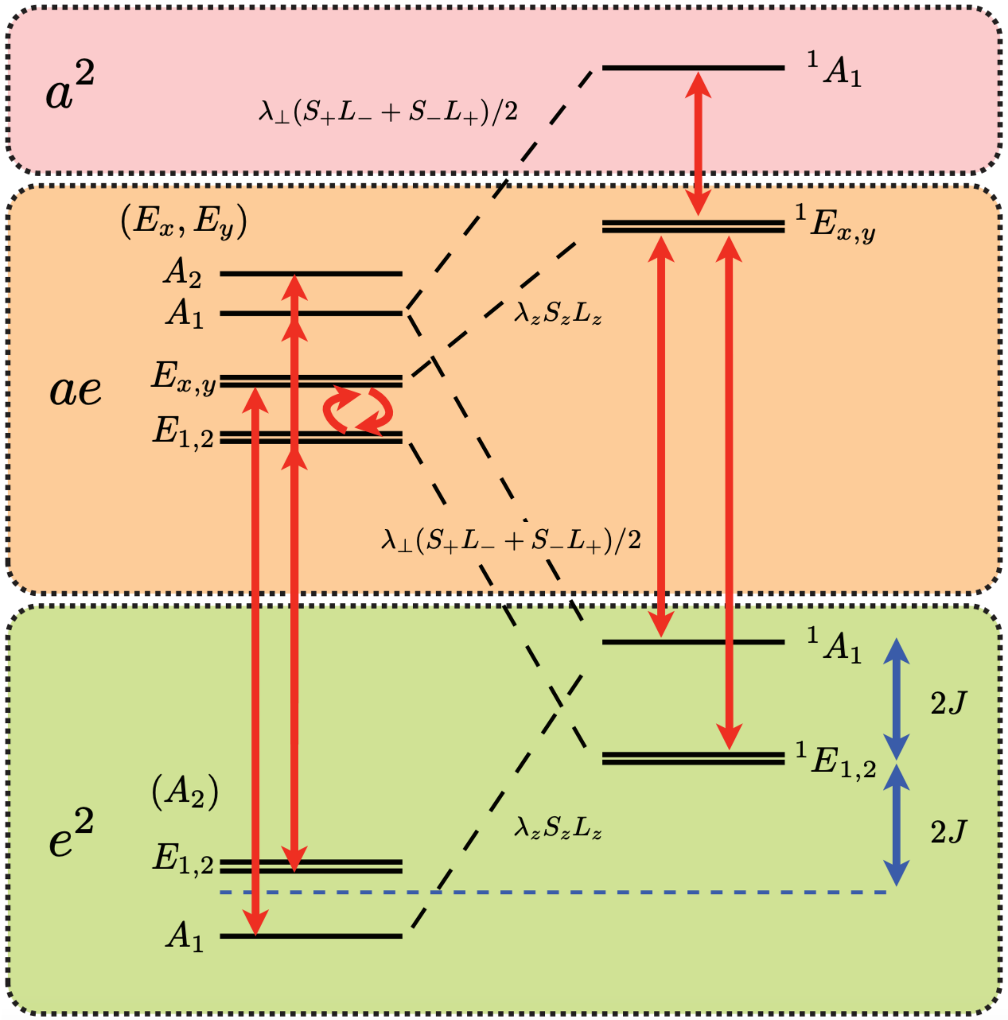
LETTER

doi:10.1038/nature15759

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

One way of creating spin-photon entangelement with the NV center



Optical selection rules can be derived from the many-body states.

$\hat{e}$	A_1	A_2	E_1	E_2	E_x	E_y
$^3A_{2-}$	$\hat{\sigma}_+$	$\hat{\sigma}_+$	$\hat{\sigma}_-$	$\hat{\sigma}_-$		
$^3A_{20}$					$\hat{y}$	$\hat{x}$
$^3A_{2+}$	$\hat{\sigma}_-$	$\hat{\sigma}_-$	$\hat{\sigma}_+$	$\hat{\sigma}_+$		

$\hat{e}$	^1E_x	^1E_y
$^1A_1$	$\hat{x}$	$\hat{y}$
$^1E_1$	$\hat{x}$	$\hat{y}$
$^1E_2$	$\hat{y}$	$\hat{x}$

$\hat{e}$	$^1A_1$
$^1E_1$	$\hat{x}$
$^1E_2$	$\hat{y}$

$\hat{\sigma}_\pm = \hat{x} \pm i\hat{y}$

[1] New Journal of Physics **13** 025025 (2011).

Linearly polarized photons

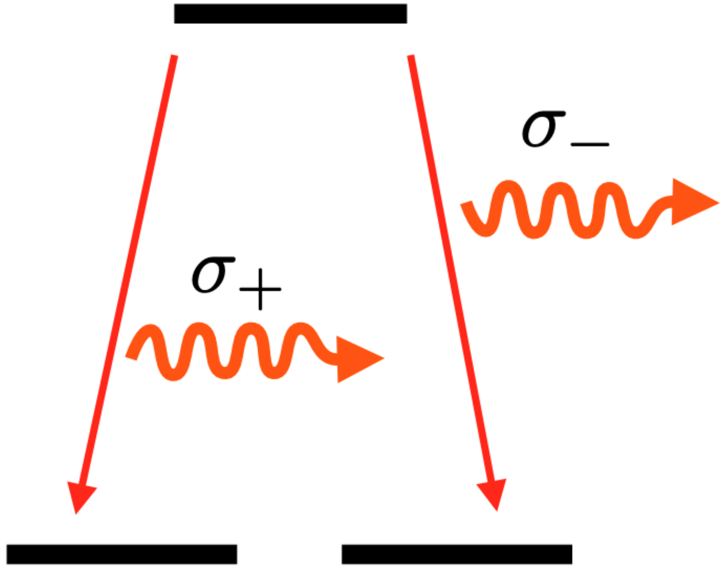
Circularly polarized photons

A_2: no non-radiative decay, selectively coupled with the ground state through circularly polarized photon emission.

Lambda sceme

Spin-photon entanglement generation

$$|A_2\rangle = |E_+\rangle \otimes |\beta\beta\rangle + |E_-\rangle \otimes |\alpha\alpha\rangle$$

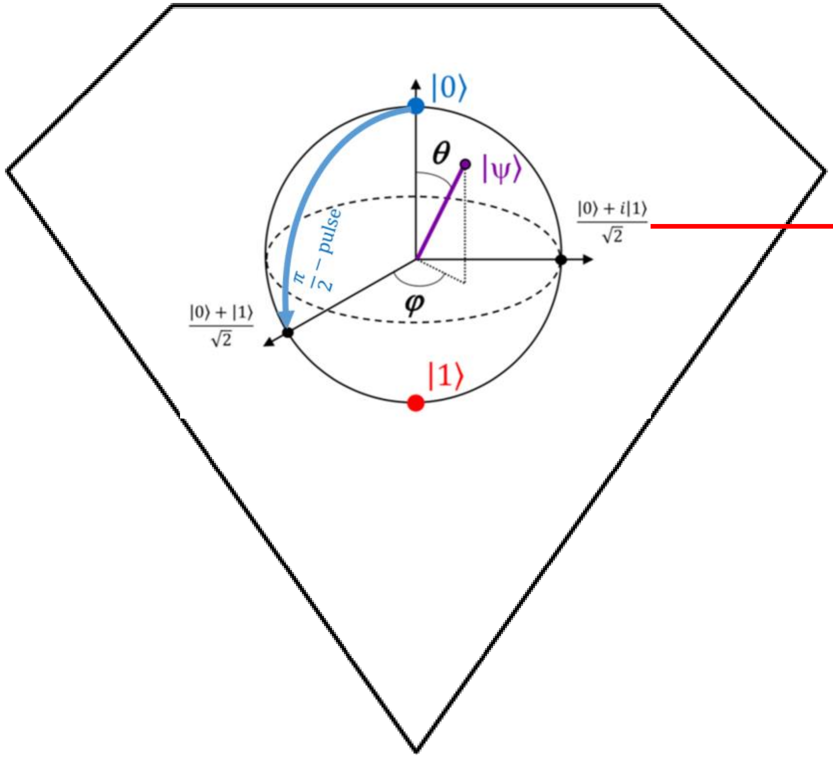


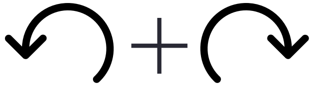
$$|^3A_{2-}\rangle = |E_0\rangle \otimes |\beta\beta\rangle \qquad |E_0\rangle \otimes |\alpha\alpha\rangle = |^3A_{2+}\rangle$$

$$\frac{1}{\sqrt{2}}(|+1\rangle \otimes |\sigma_-\rangle + |-1\rangle \otimes |\sigma_+\rangle)$$

Schrödinger's cat problem 2.0

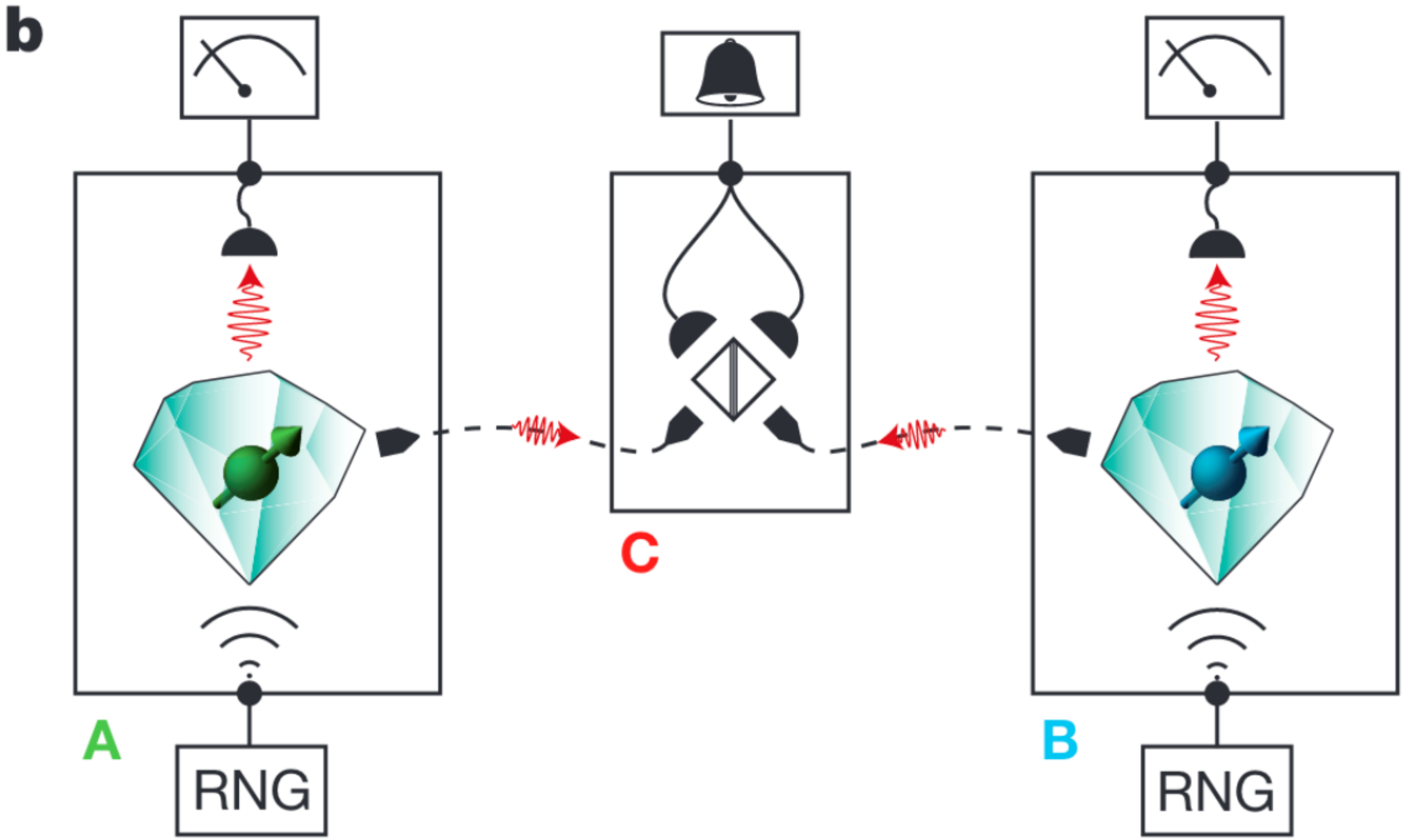
Low temperature NV emission





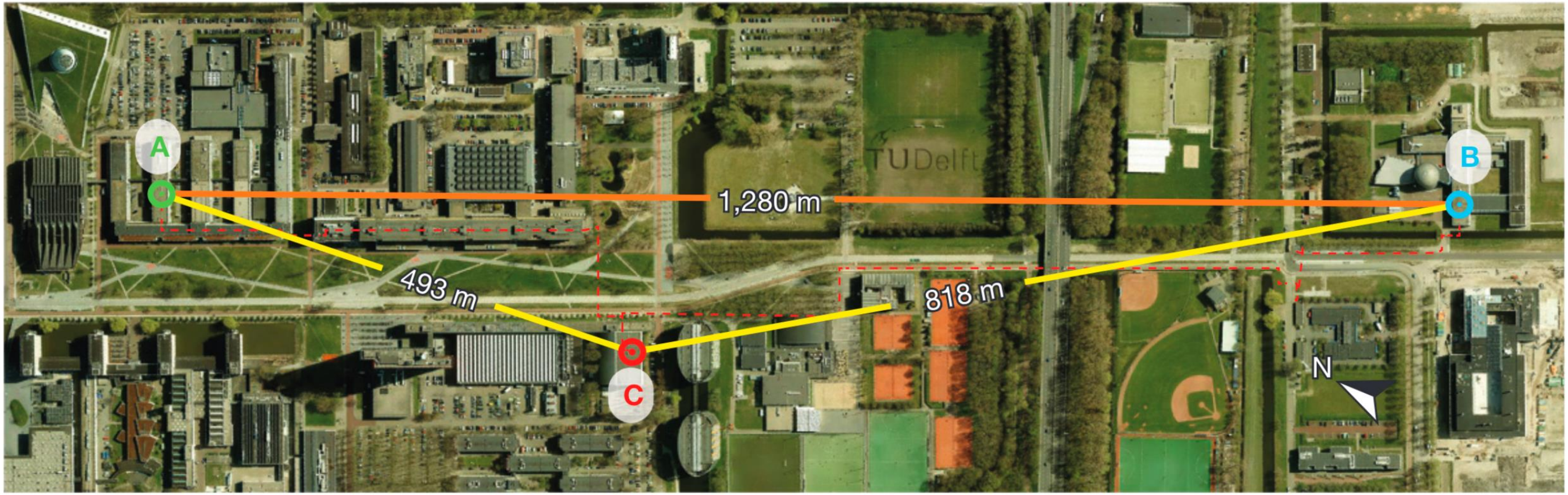
mantis crab

Entenglement swap via a beam splitter and photon detection



- Entangled photons are arrowing to C from A and B.
- Entangle through a beam splitter $\Longrightarrow$ four particle entanglement
- Photons are measured, which entangle the A and B.
- Bell inequality violation tested.

The tests are carried out faster than light could travel from A to B.



Science

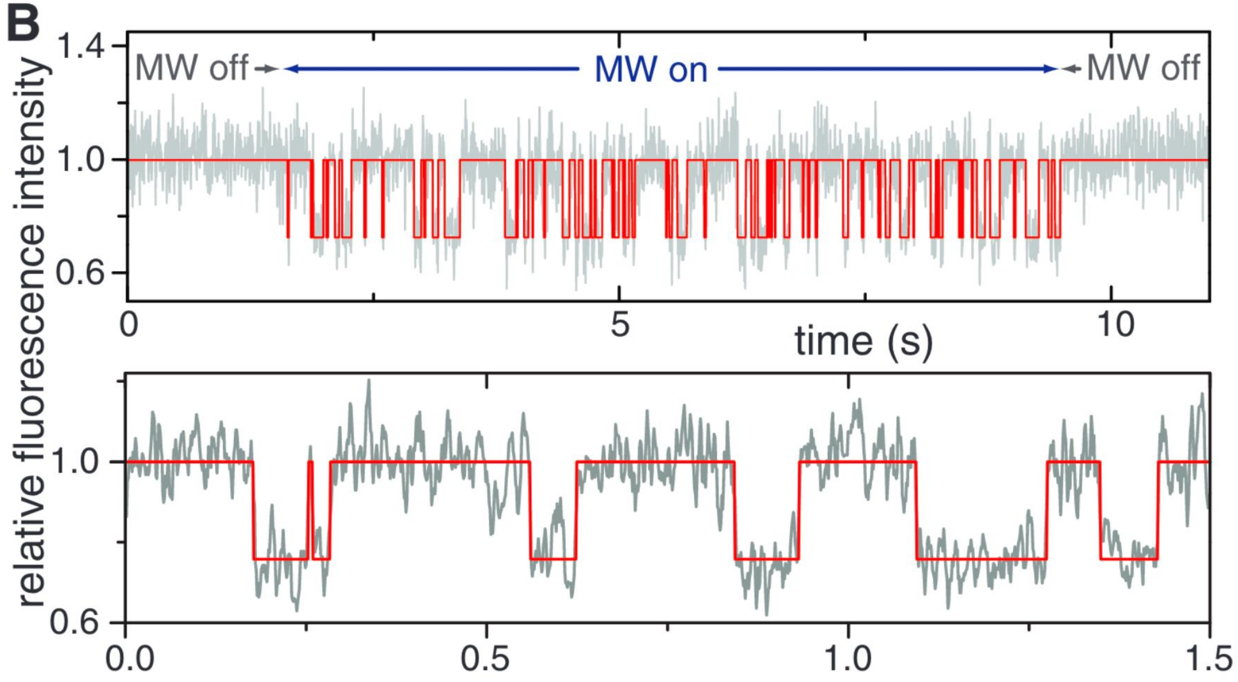
Current Issue First release papers Archive About Submit manuscript

HOME > SCIENCE > VOL. 329, NO. 5991 > SINGLE-SHOT READOUT OF A SINGLE NUCLEAR SPIN

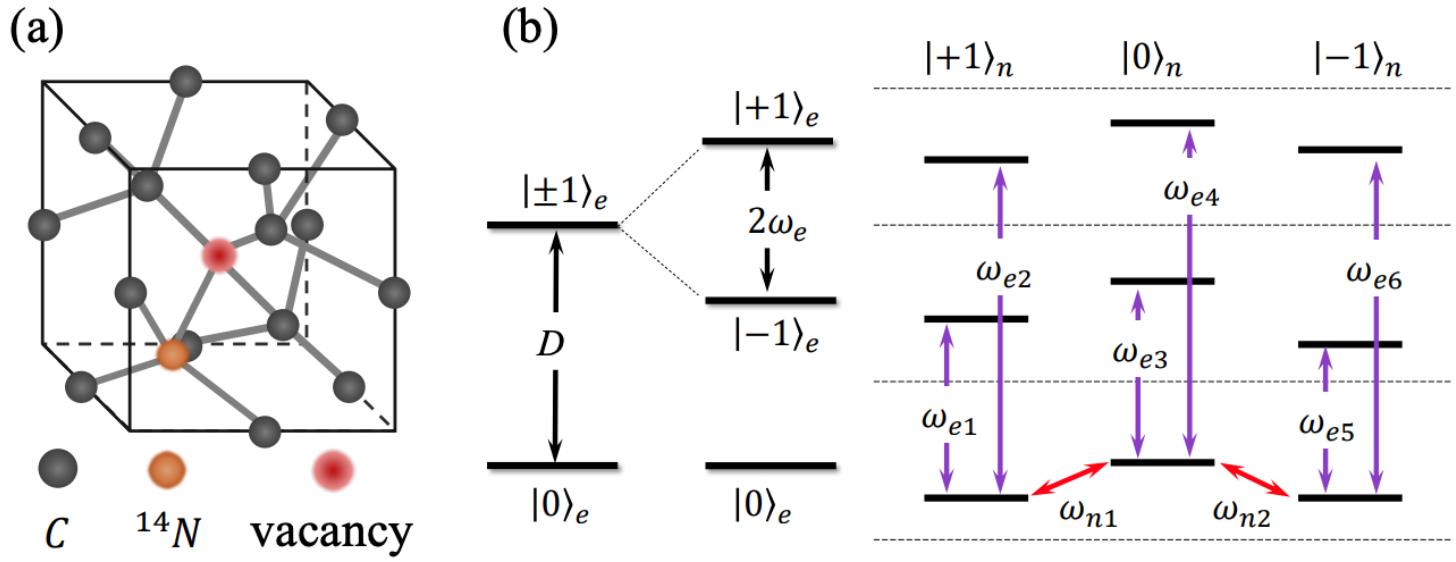
REPORT

Single-Shot Readout of a Single Nuclear Spin

PHILIPP NEUMANN, JOHANNES BECK, MATTHIAS STEINER, FLORIAN REMPP, HELMUT FEDDER, PHILIP R. HEMMER, JÖRG WRACHTRUP, AND FEDOR JELEZKO Authors Info & Affiliations



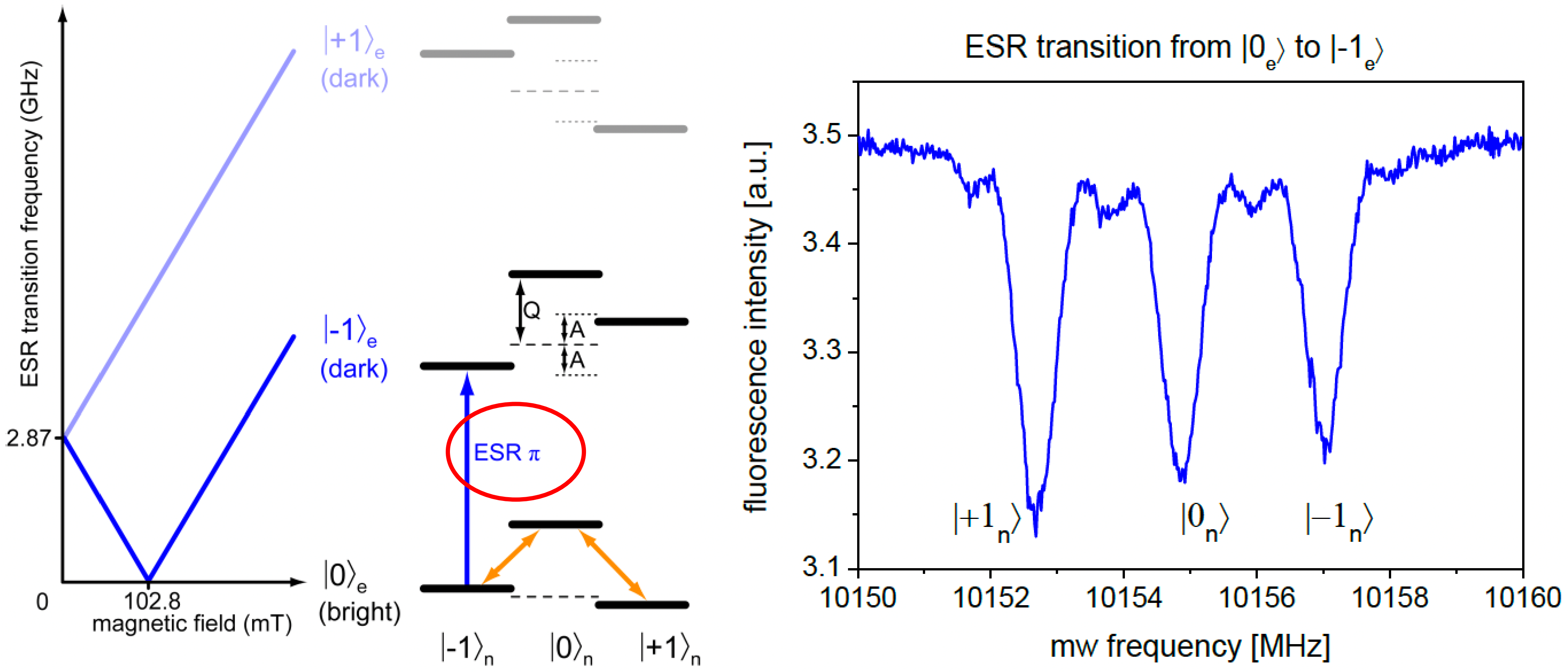
NV is it as two qutrit system



6 allowed transitions

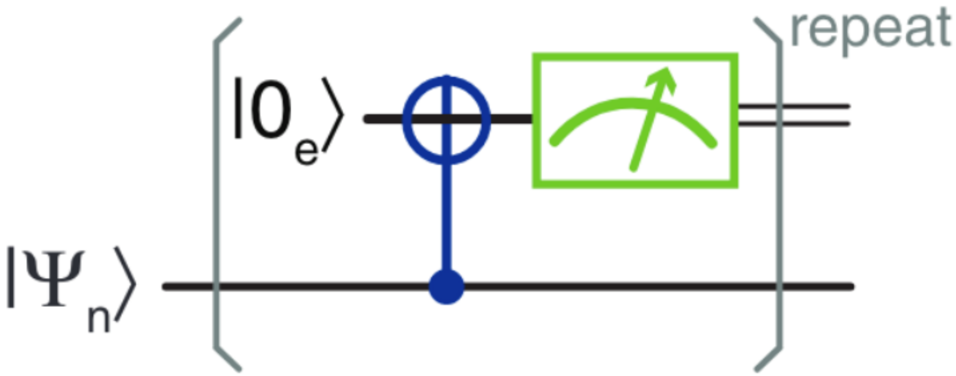
$$H = \underbrace{D\hat{S}_z^2 + g_e\mu_B B_z \hat{S}_z}_{H_e} + \underbrace{\underline{\hat{S}} \cdot \underline{\underline{A}} \cdot \underline{\hat{I}}}_{H_A} + \underbrace{Q\hat{I}_z^2 + g_n\mu_n B_z \hat{I}_z}_{H_n}$$

Nuclear spin resolved ODMR spectra

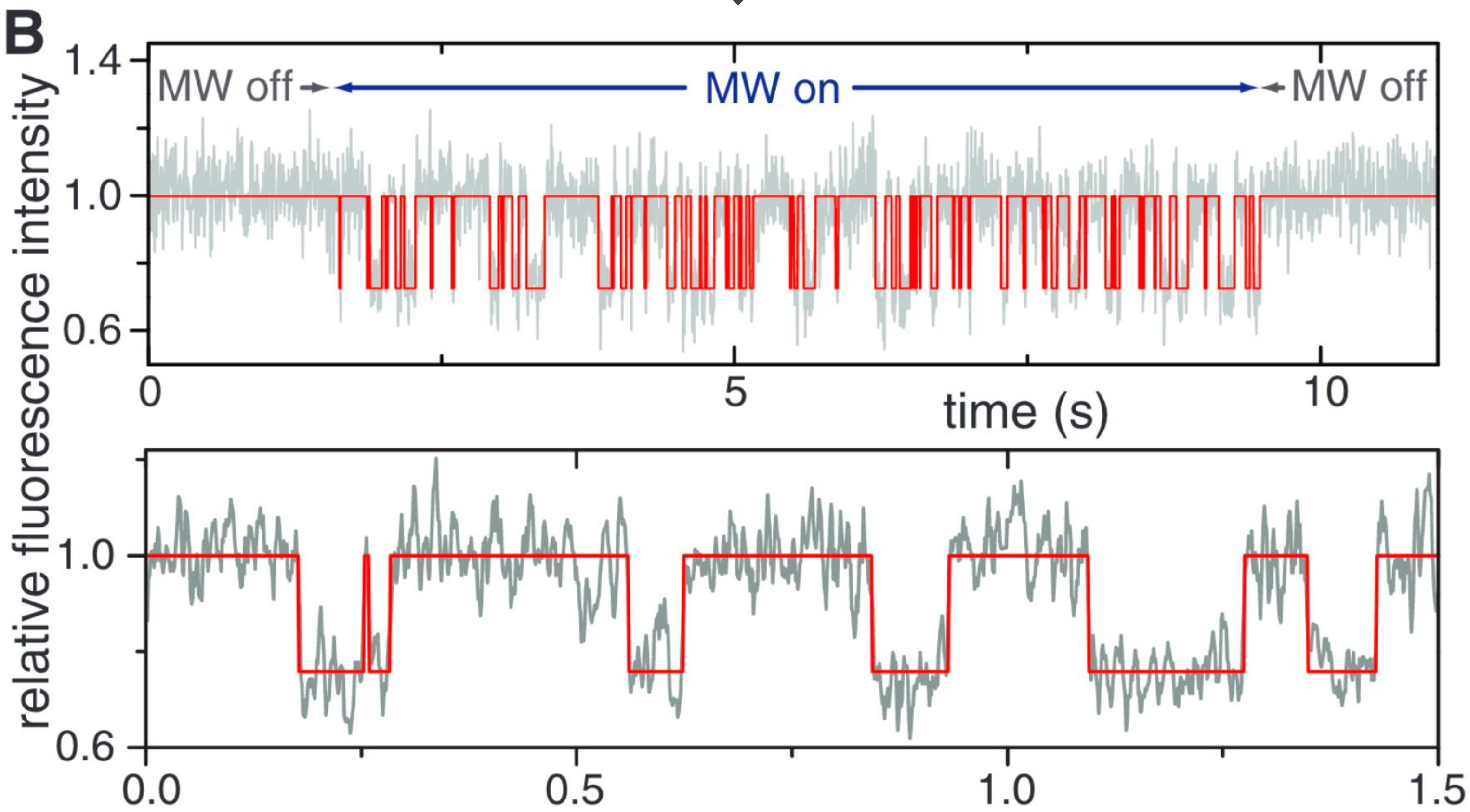


We can use these transitions to implement CNOT operation.

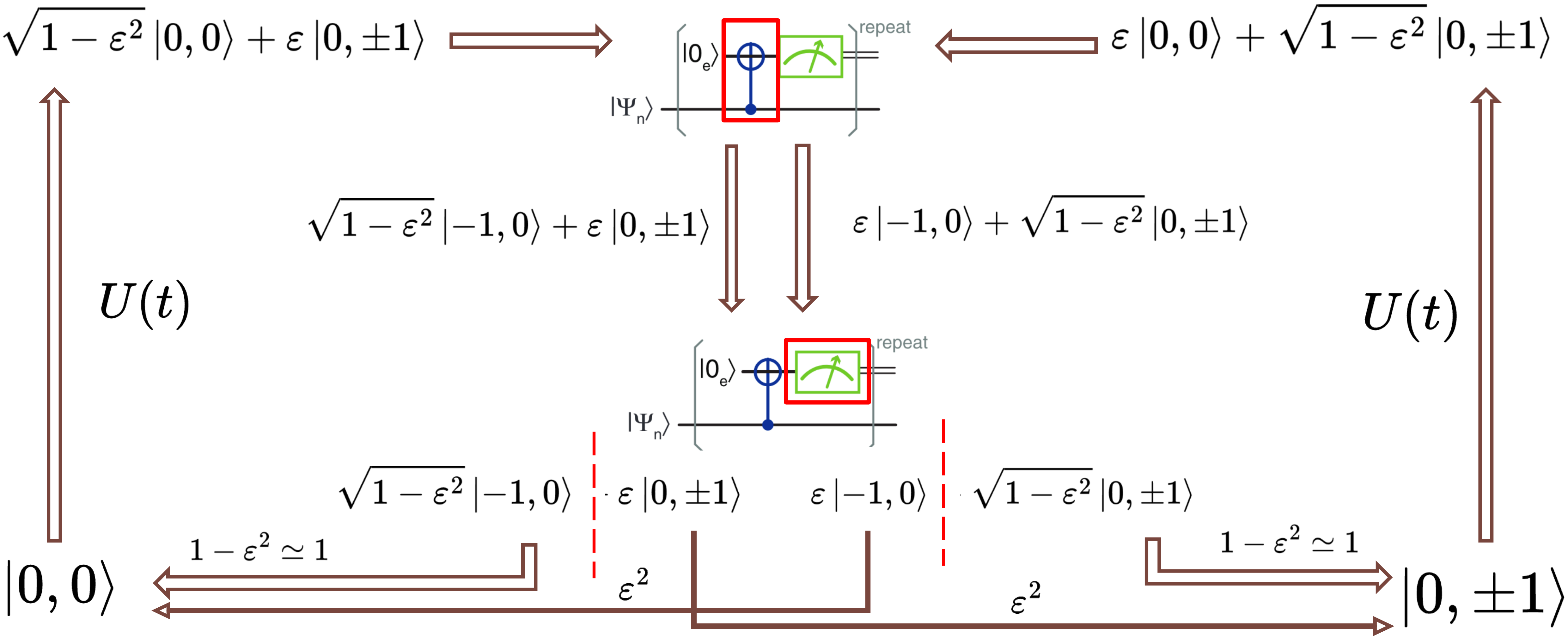
Implement “fast” indirect measurement of nuclear spin states



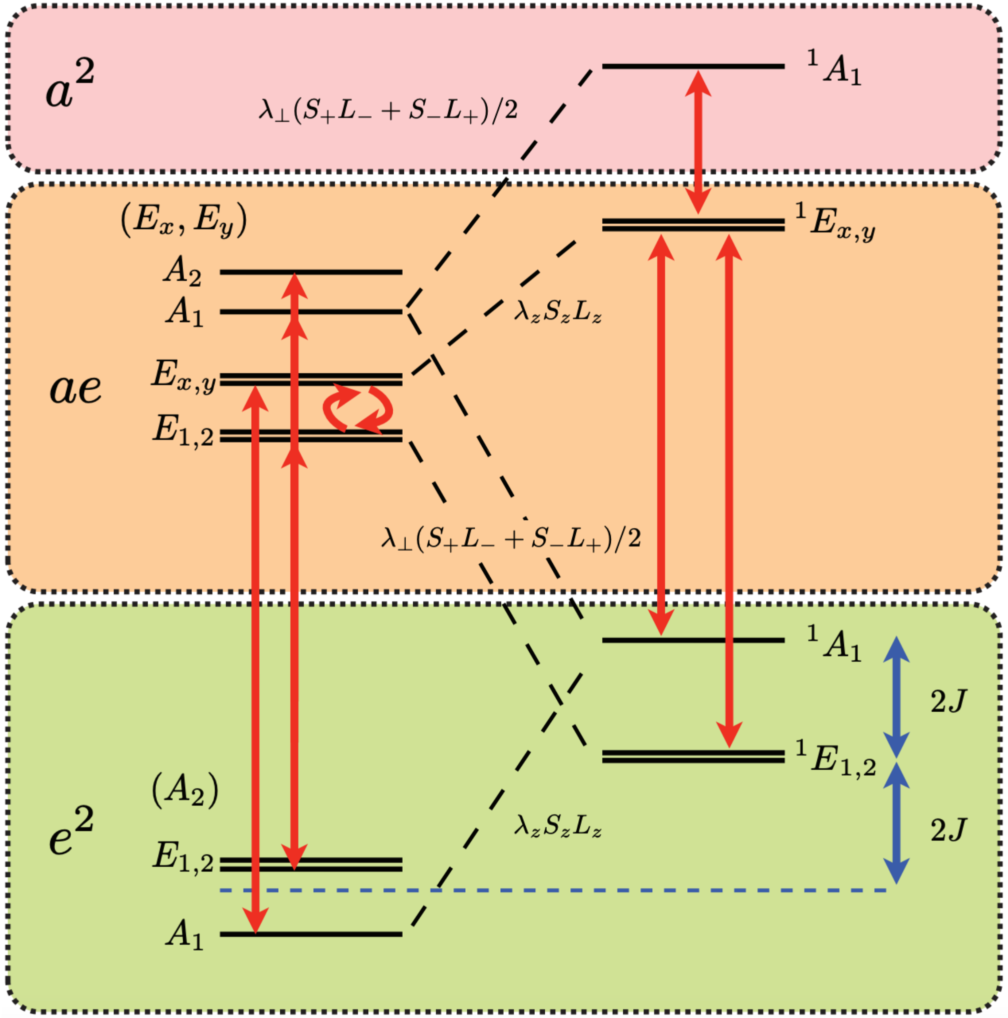
Approaching the quantum Zeno limit.



Two loops of time evolution



What we can learn from the optical cycle



$$\hat{M}_1 = |m_S = 0\rangle\langle m_S = 0|$$

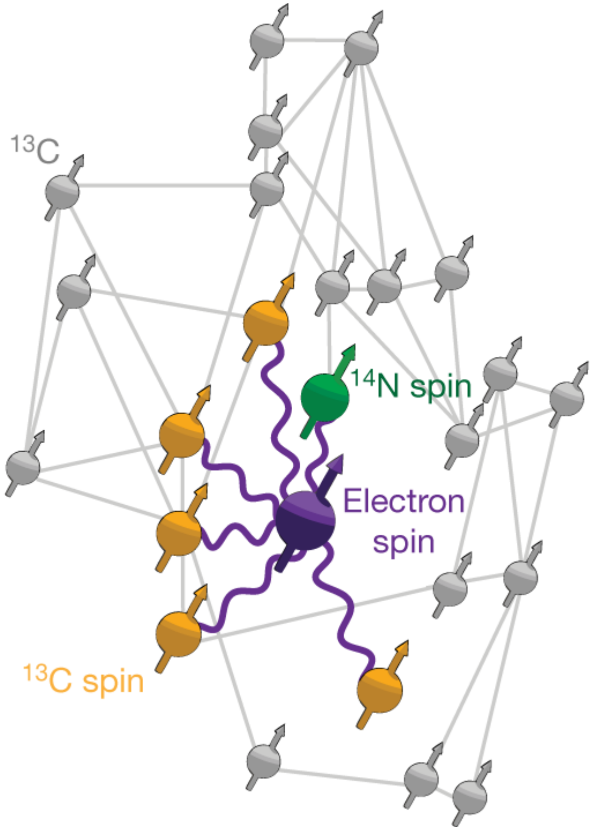
$$\hat{M}_2 = |m_S = 0\rangle\langle m_S = \pm 1|$$

Optical excitation coherent U(t)
Spontaneous emission projetive: M_1
Non-radiative decay projective: M_2

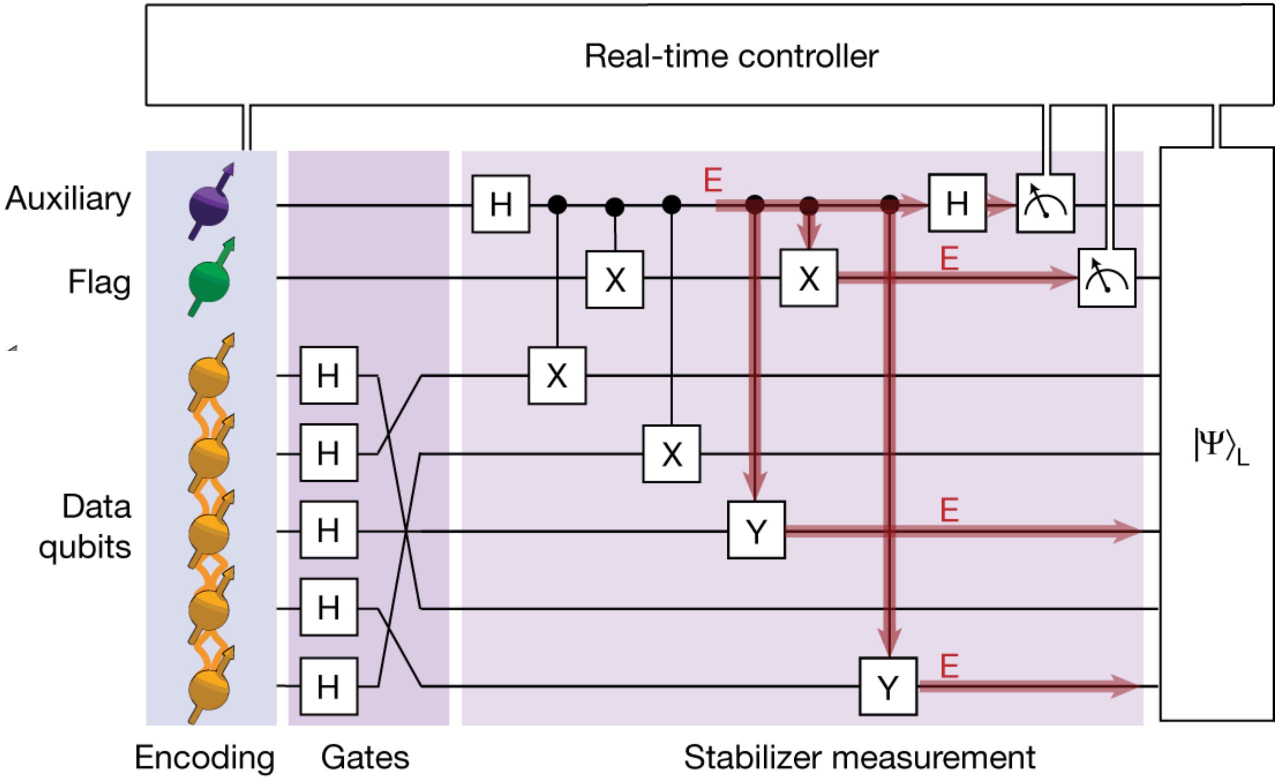
PART III.

Perspectives and challenges in QC and QRC

5-20 qubit quantum computer at room temperature



1 NV centrum + néhány magspin kubit

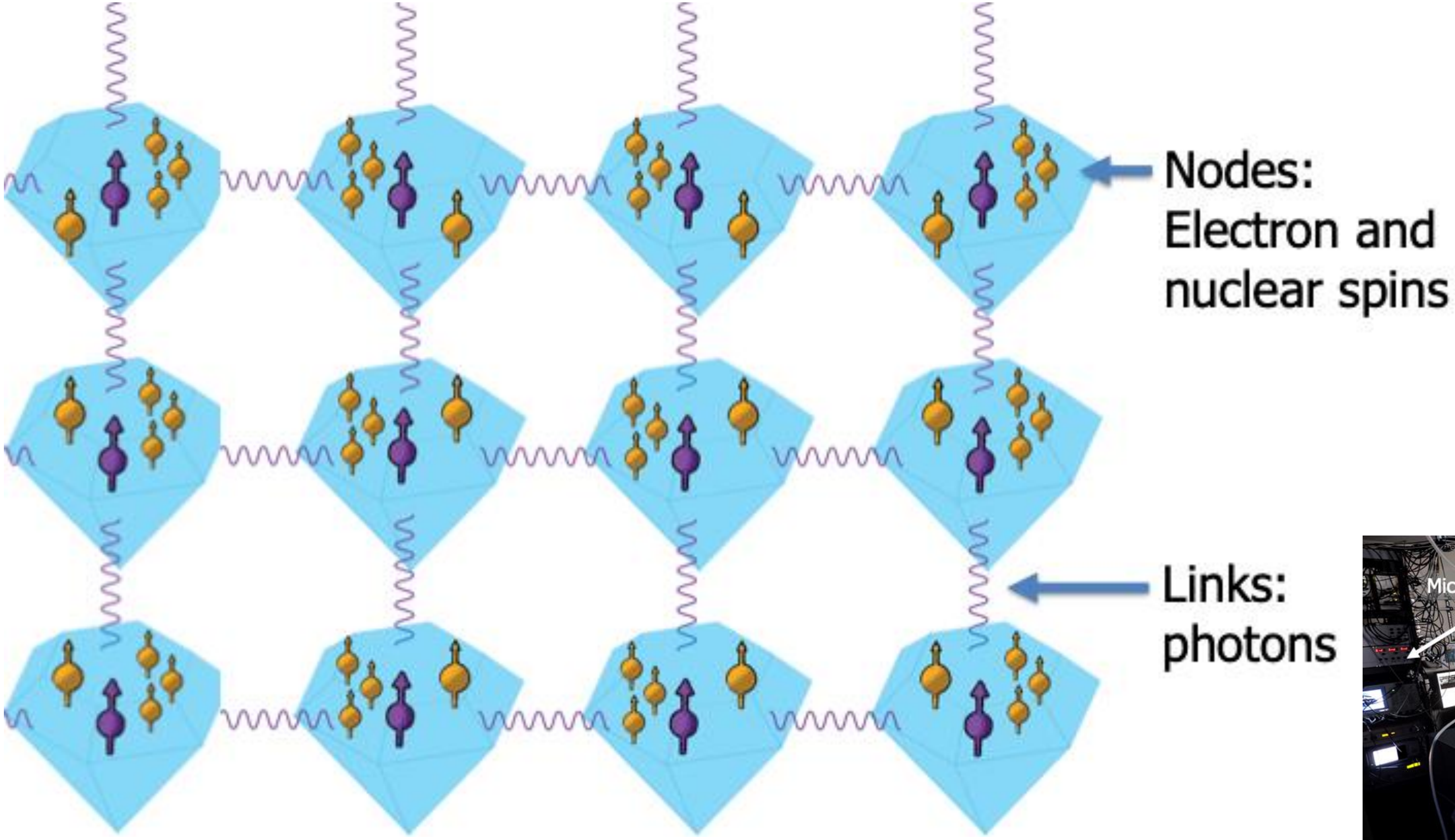


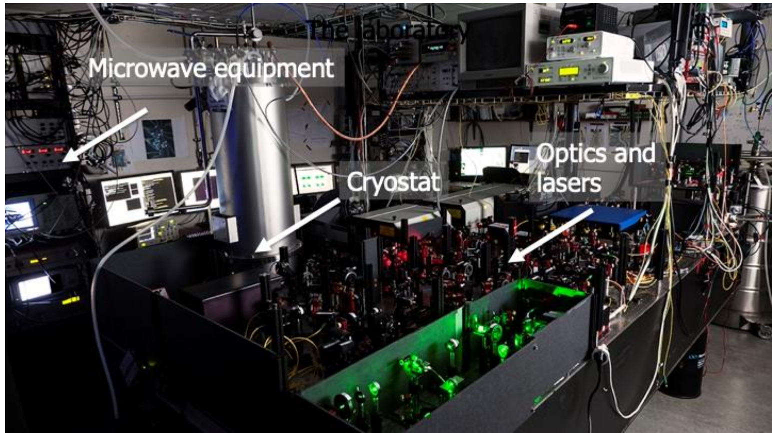
Fault-tolerant operation of a logical qubit in a diamond quantum processor

M. H. Abobeih, Y. Wang, J. Randall, S. J. H. Loenen, C. E. Bradley, M. Markham, D. J. Twitchen, B. M. Terhal & T. H. Taminiau

Nature **606**, 884–889 (2022) | Cite this article

Possibility of scaling?





Potential to Q(R)C

- Scalling is as hard as diamond.
    - Atomic-scale fabrication in hard materials is difficult.
- Flying qubits must be involved
    - Photon,
    - Phonons
    - Magnons
    - Electrons
- These will be / are the main sources of decoherence
- Noise-tolerant QC applications are required, such as QRC.