Color Centers in Diamond

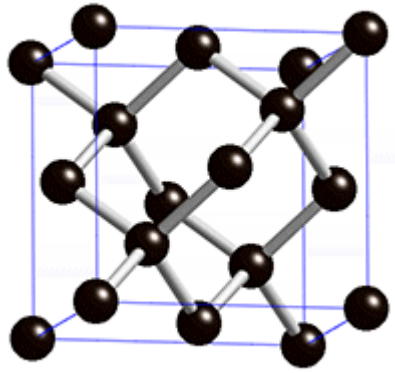
Slides and material courtesy of: Joerg Wrachtrup, Ronald Hanson, Lilly Childress, and Christian Degen as indicated

Reading: Papers, Reviews, Other Material

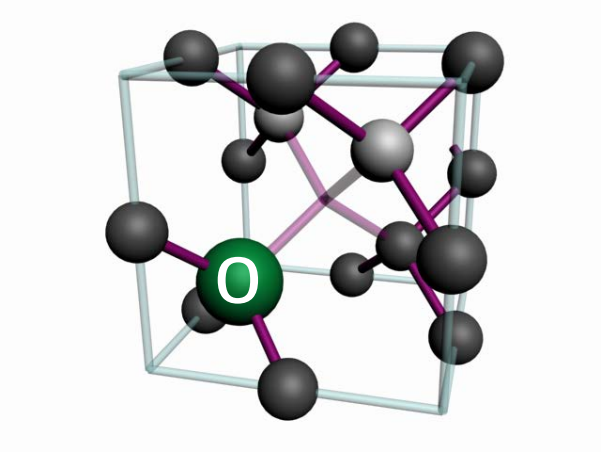
Reviews:

- **NV centers (long):** M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. Hollenberg, The nitrogen-vacancy colour centre in diamond, *Physics Reports* **528**, 1-45 (2013). (http://www.sciencedirect.com/science/article/pii/S0370157313000562)
- **NV centers (less long):** F. Jelezko, and J. Wrachtrup, Single defect centres in diamond: A review, *Phys. Stat. Sol. (a)* **203**, 3207 (2006). (http://dx.doi.org/10.1002/pssa.200671403)
- **Quantum sensing:** C. L. Degen, F. Reinhard, and P. Cappellaro, Quantum sensing, *arXiv:1611.02427* (2016). (https://arxiv.org/abs/1611.02427)

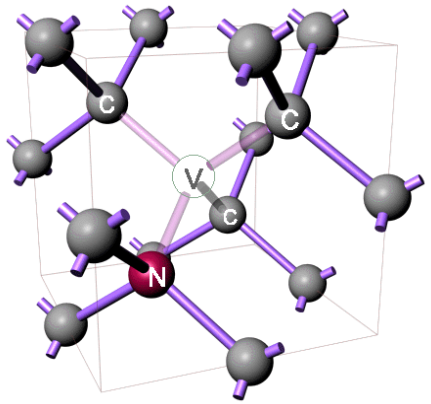
The Dopants



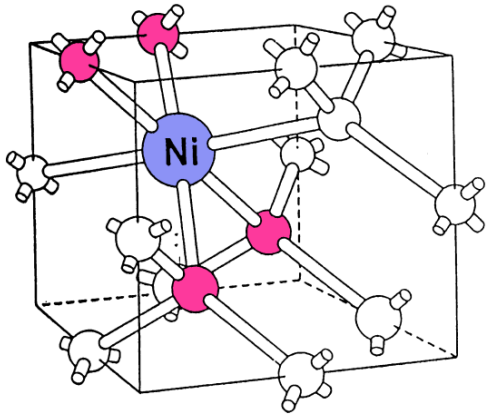
standard diamond lattice



TR12 (interstitial Carbon)
PRB 72, 035214 2005



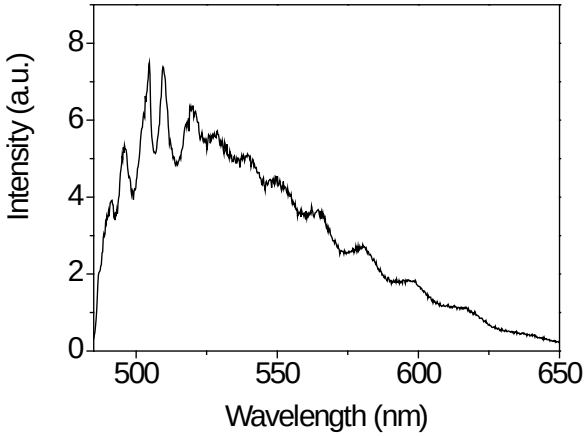
NV (Nitrogen, Vacancy)
Science 276, 2012-2014 (1997)

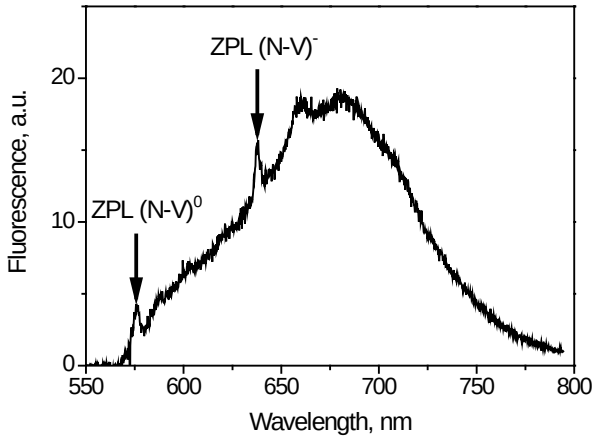


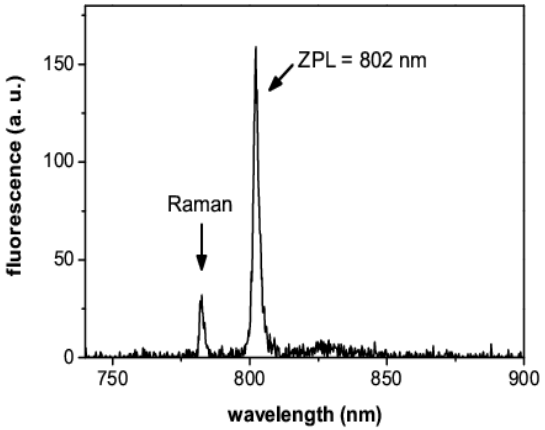
NE8b (Nickel, Nitrogen)
Phys. Rev. Lett. **94**, 180602 (2005)

$_6C$
- Carbon
- 4 valence electrons
- sp^3 hybridization

$_7N$
- Nitrogen
- 5 valence electrons

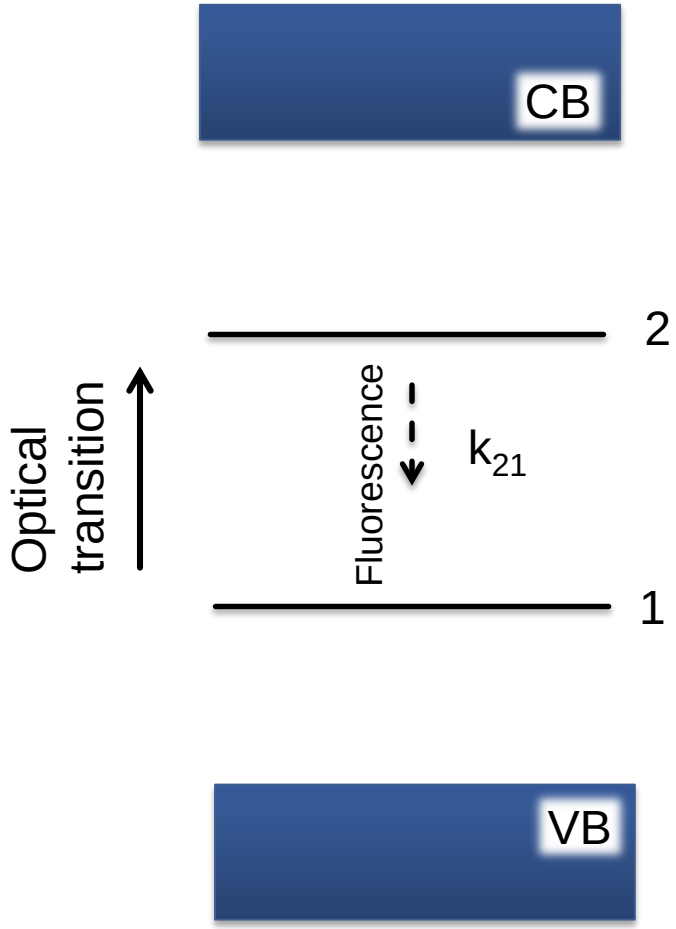






Slide material: Joerg Wrachtrup, Stuttgart

Level Scheme of Color Centers

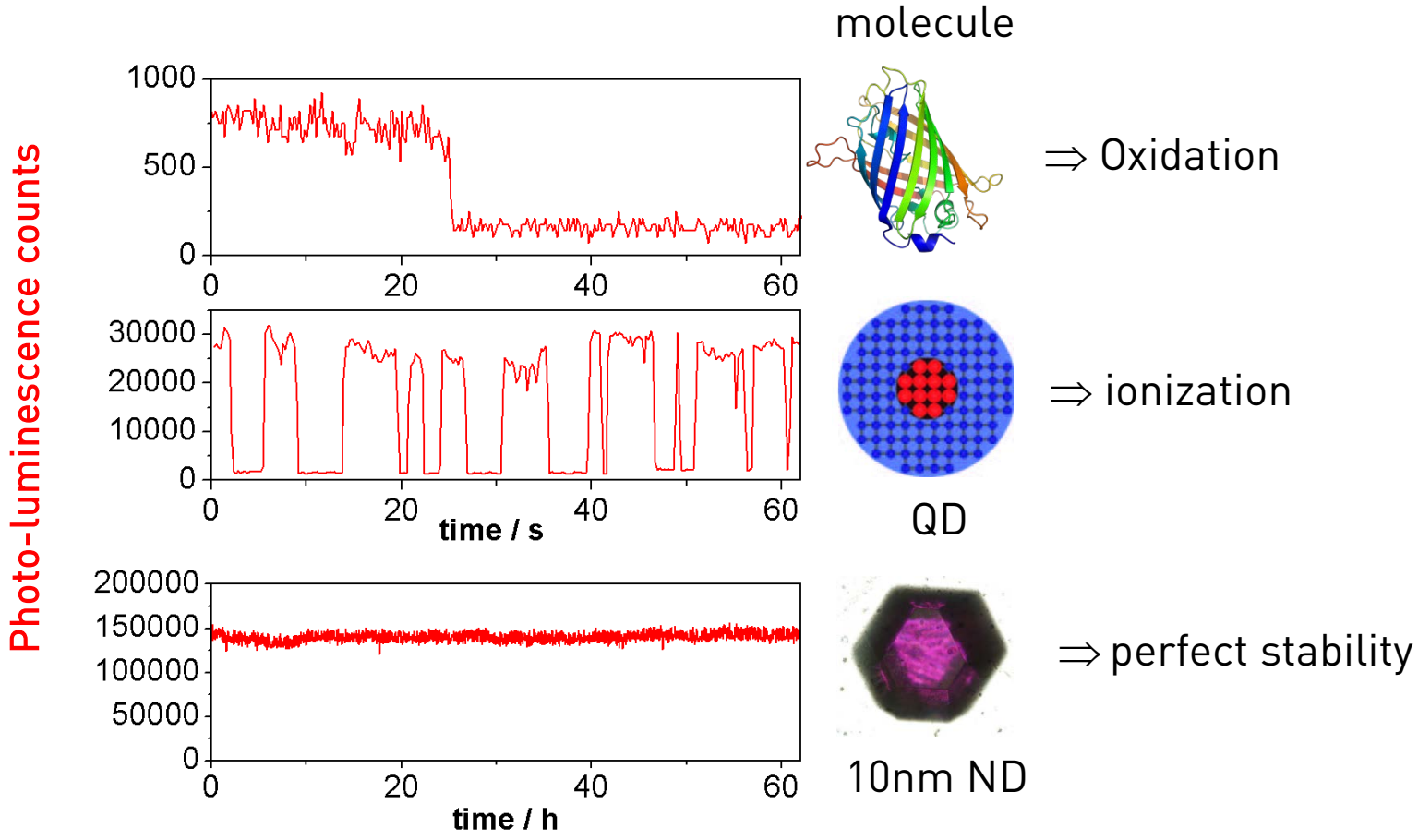


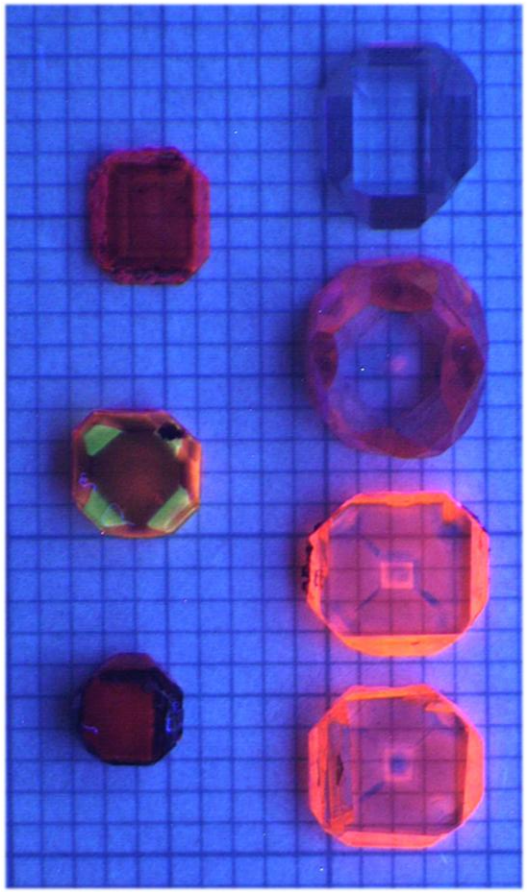
Properties:

- Large band gap E_g = 5.4 eV
- Defects form inter-gap states

Slide material: Joerg Wrachtrup, Stuttgart

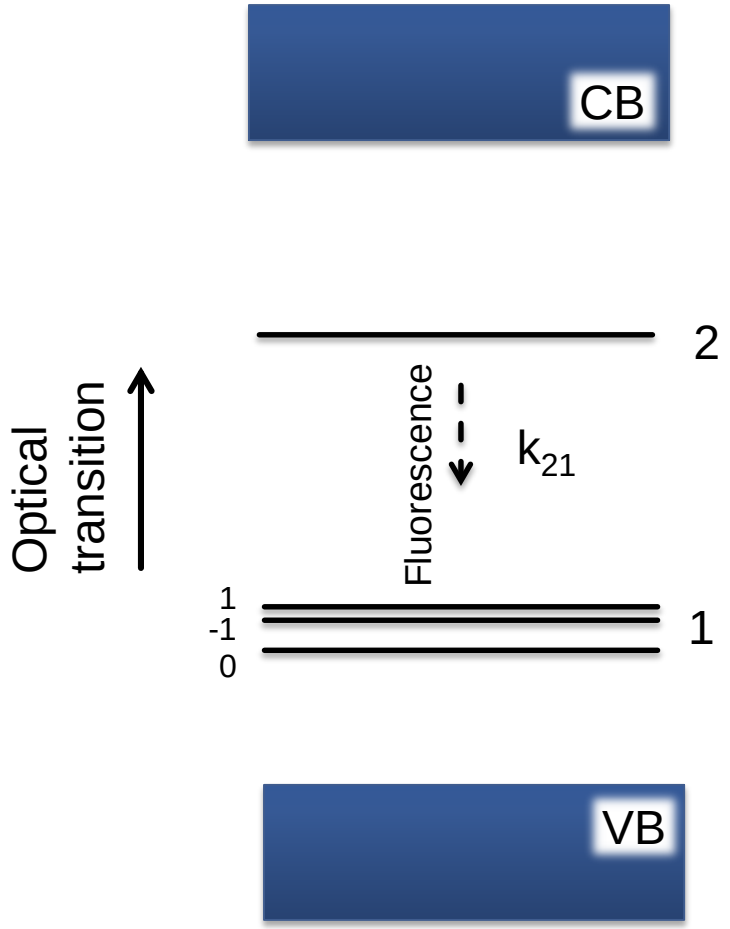
Shielding by the Diamond Lattice Provides Photostability





Slide material: Joerg Wrachtrup, Stuttgart

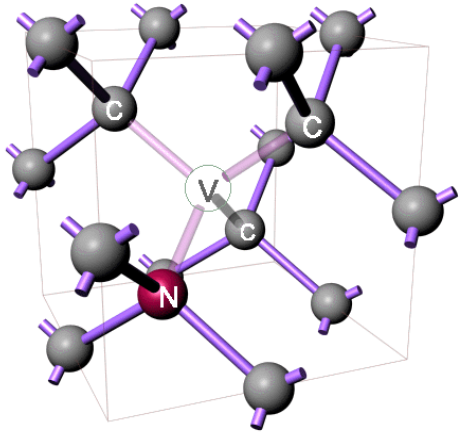
Level Structure of Color Centers

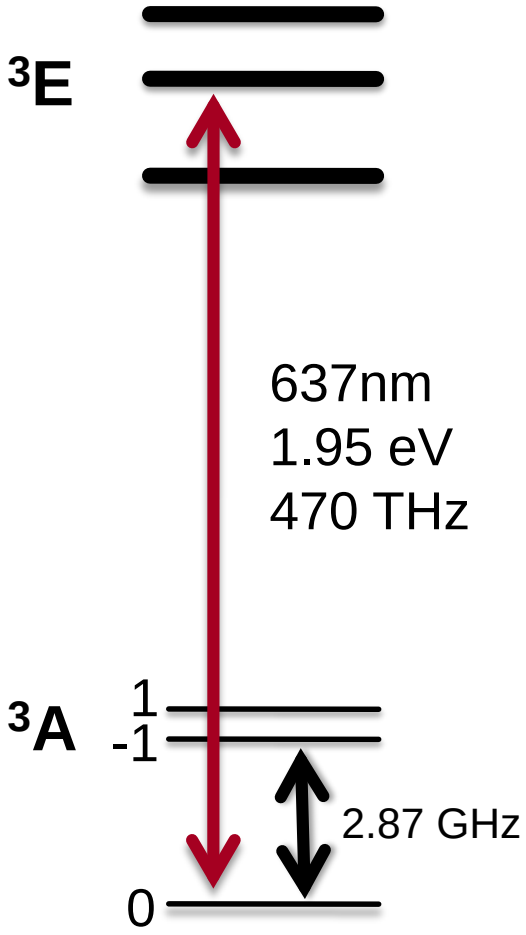


- Electron spin states are spectroscopically resolvable
- Defect behaves as a single atom, trapped in the diamond lattice
- Level structure similar to trapped ions or atoms
  - ⇒ Diamond provides a solid state ion trap
  - ⇒ Experimental power similar to trapped particles, but much easier to transform into certain applications, e.g. sensing and quantum networks

Slide material: Joerg Wrachtrup, Stuttgart

The NV Center





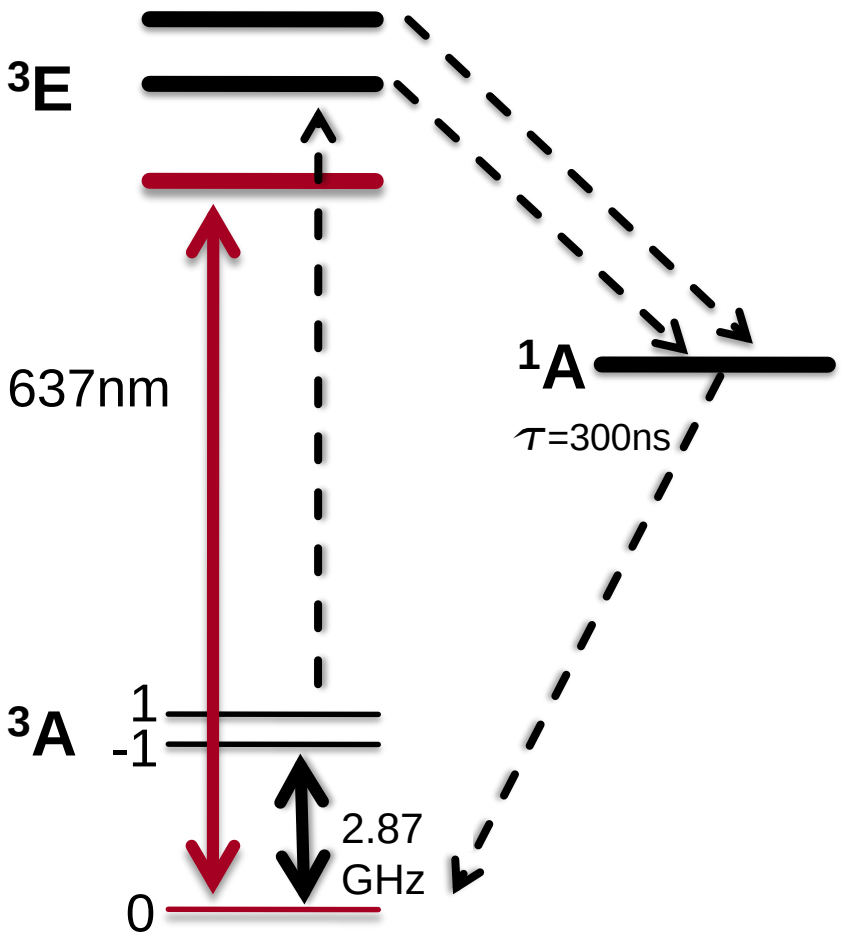
- Joint defect consisting of
  - Vacancy
  - Neighboring substitutional N
- Negatively charged (NV^-)
- Six electron (= two hole) system

Slide material: Joerg Wrachtrup, Stuttgart

The NV Center

Features:

- **Initialization:**
  Optical spin polarization of the ground state (« Laser cooling »)
- **Coherence:**
  Narrow lines, $T_2 = 1$ ms, linewidth of ground state levels 1 kHz.
- **Readout:**
  Optical detection of the spin state



Slide material: Joerg Wrachtrup, Stuttgart

The NV Center

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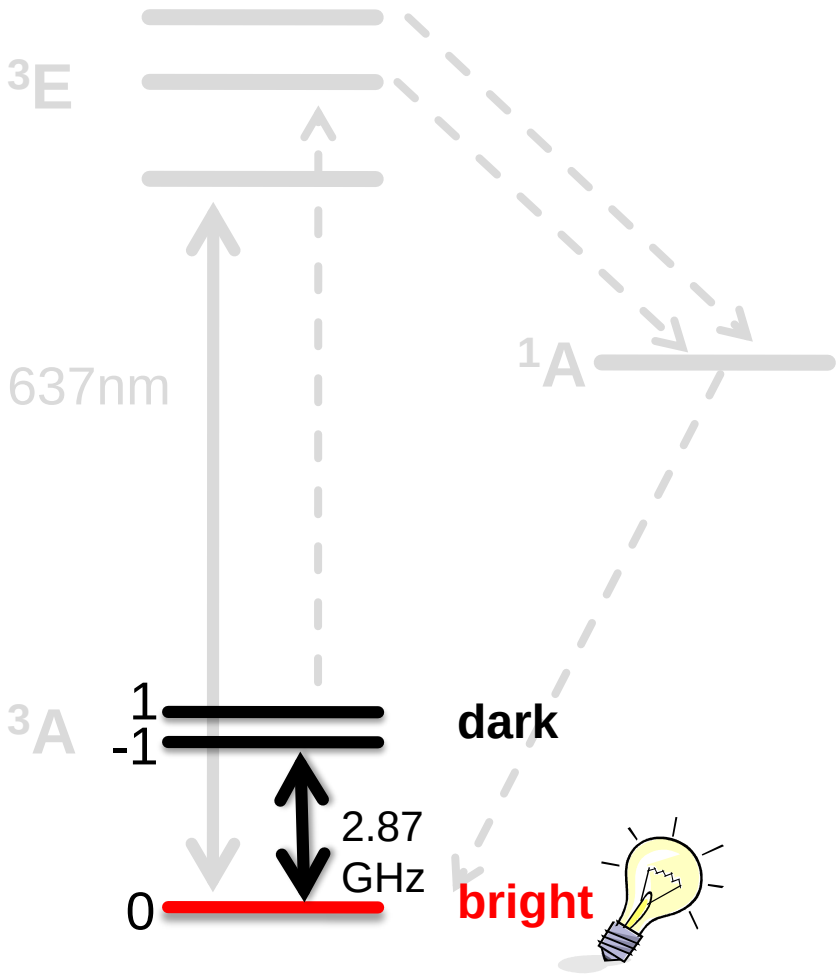


Slide material: Joerg Wrachtrup, Stuttgart

Experimental Setup for Optical Spin Readout

Confocal microscope
with microwave access

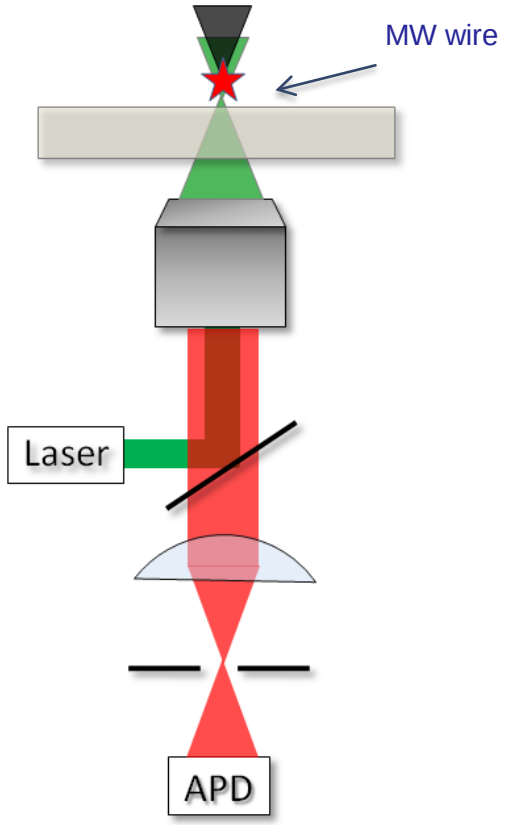
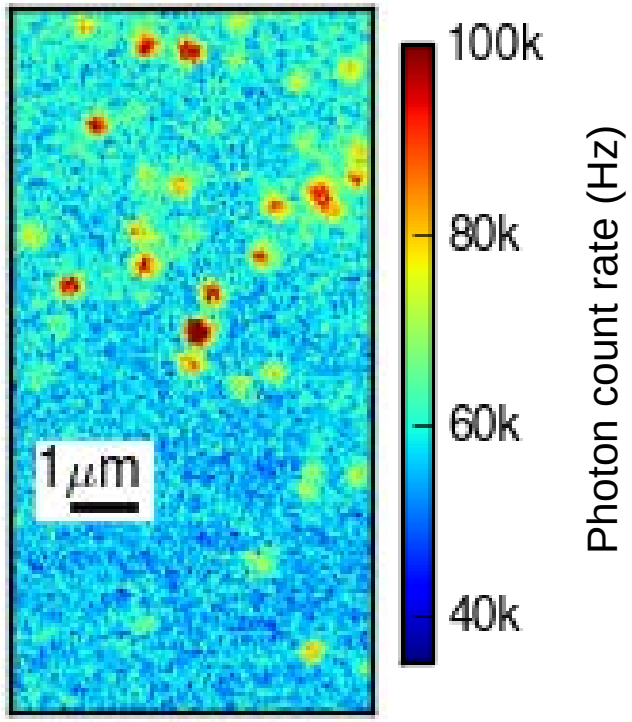
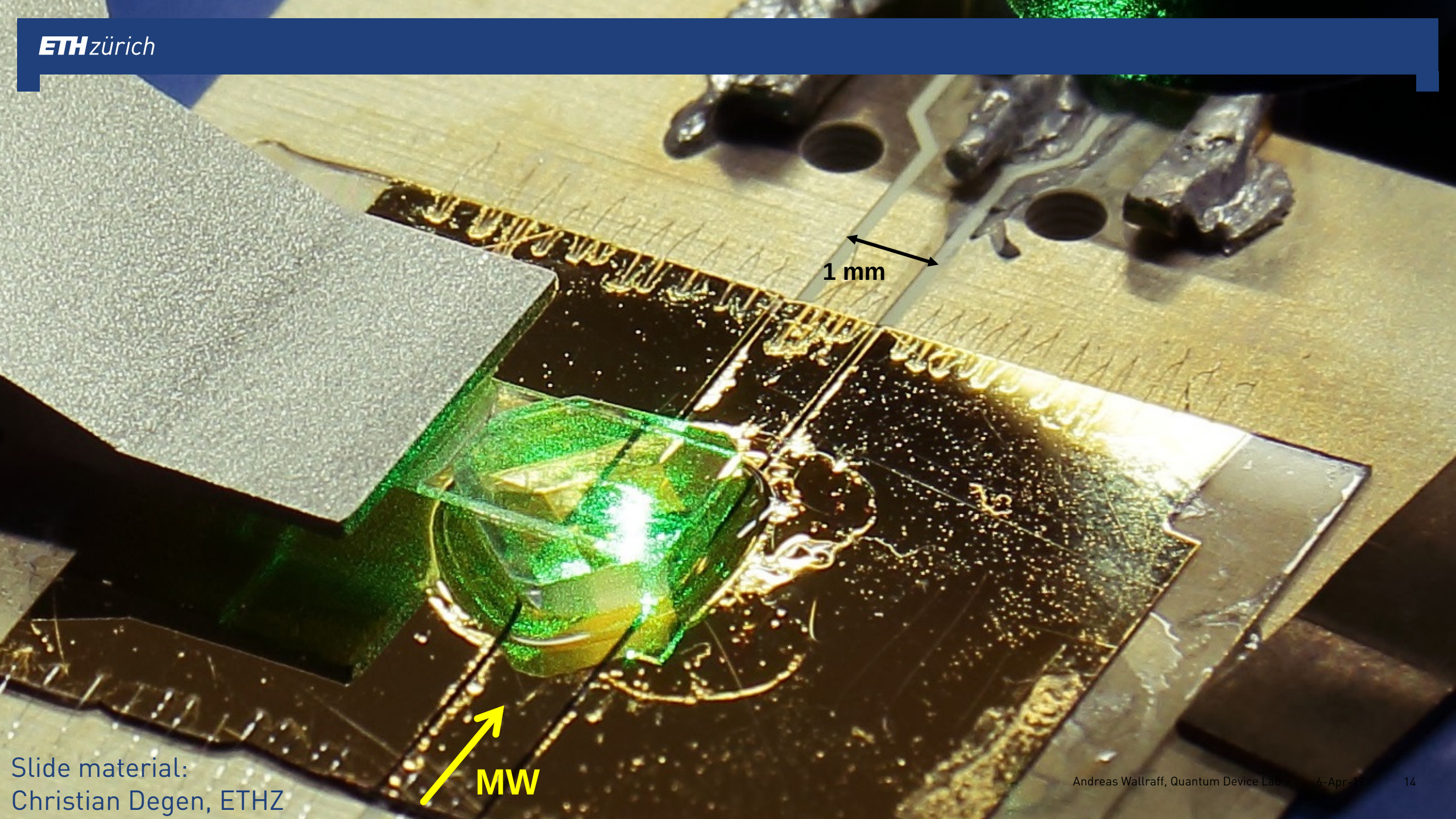


Image of implanted diamond



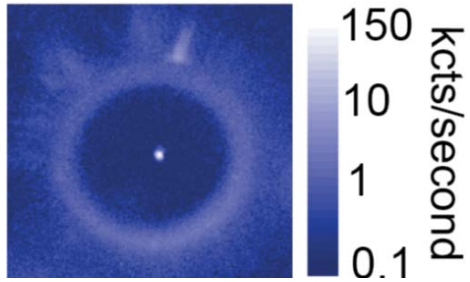
Slide material: Joerg Wrachtrup, Stuttgart

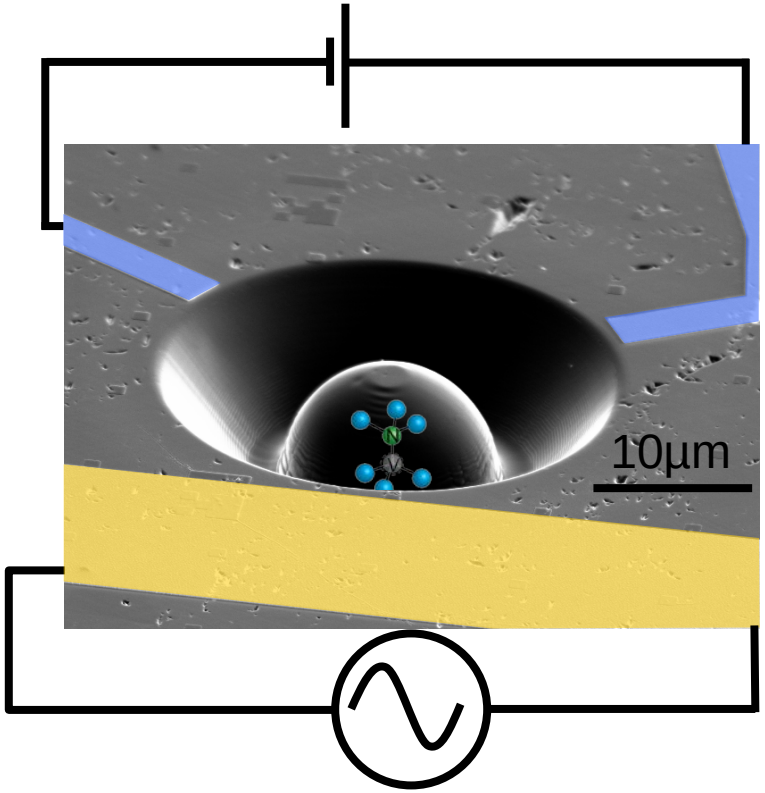


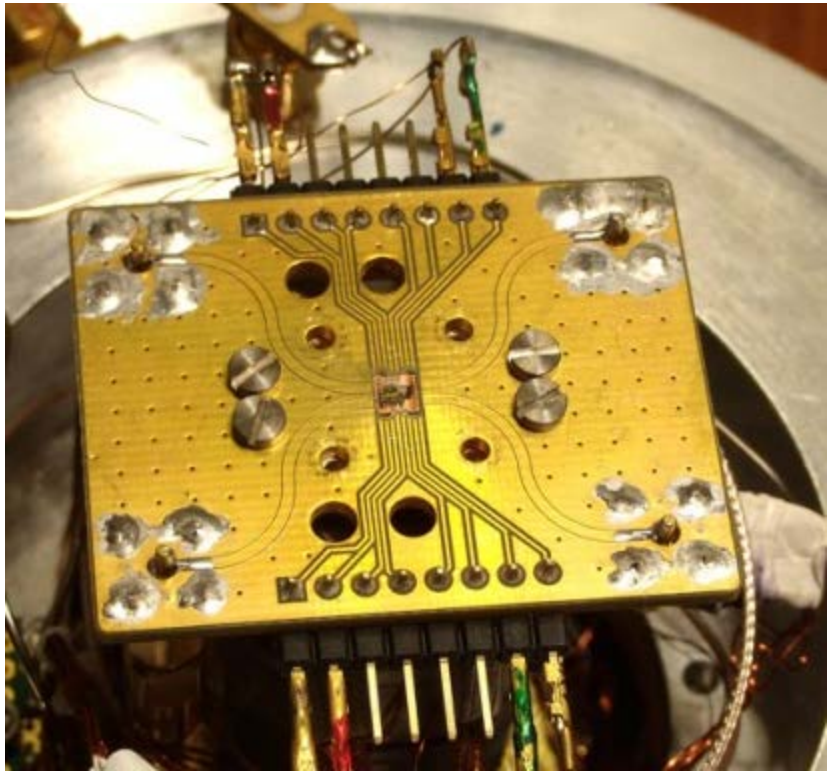
Slide material:
Christian Degen, ETHZ

Wiring up NV Centers

CVD diamonds grown by Element6

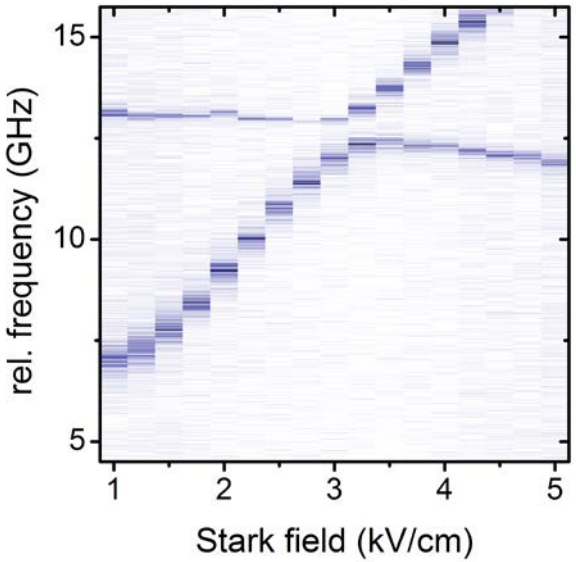




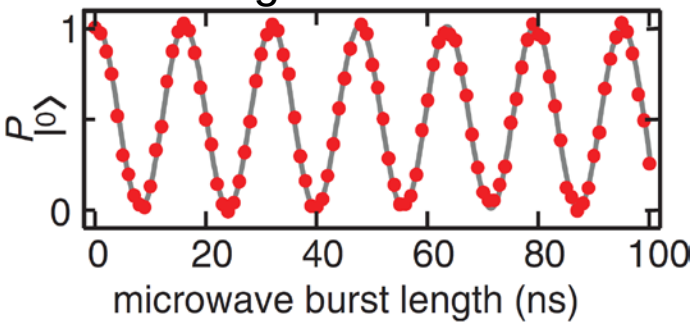


deterministically placed silicon immersion lens (SIL)

dc Stark tuning:

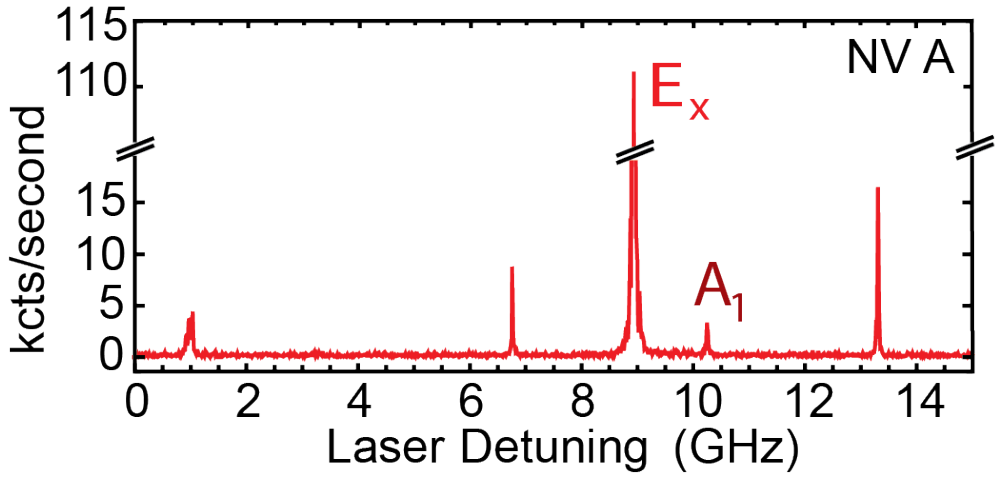


high-fidelity spin control via magnetic resonance

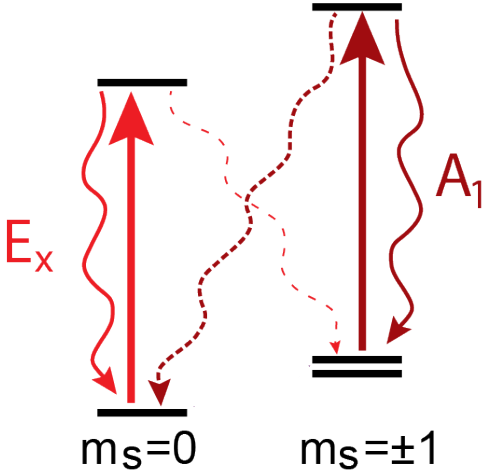


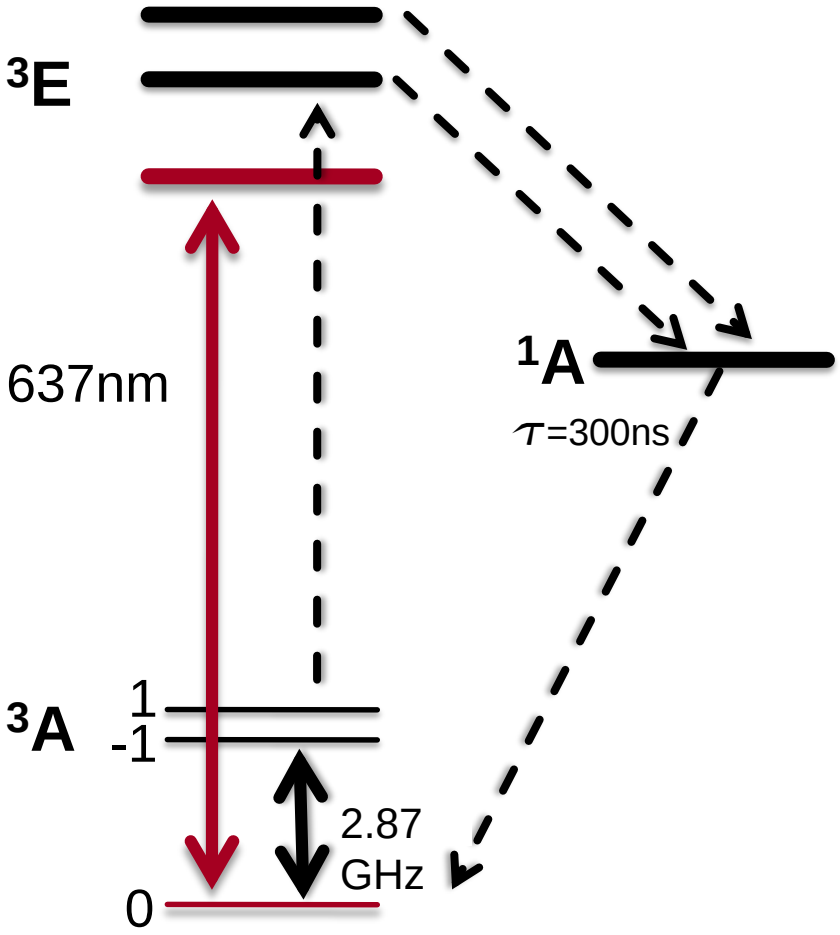
Slide material: Ronald Hanson, TU Delft

Spin-Resolved Optical Excitation (T < 10K)



from 470 THz transition



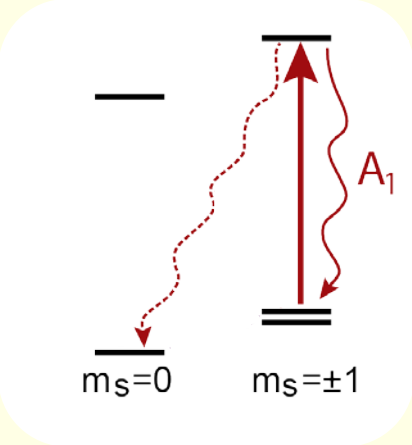


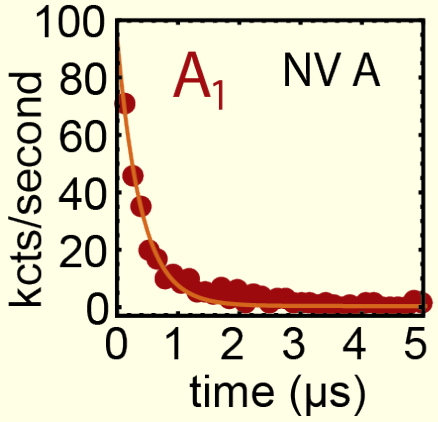
Early work by Stuttgart, Harvard, HP Labs

Slide material: Ronald Hanson, TU Delft

Initialization and Readout by Resonant Excitation

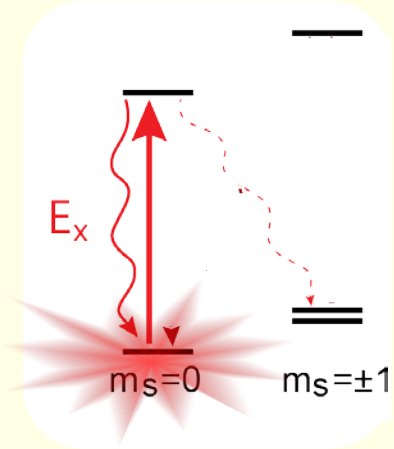
Initialization



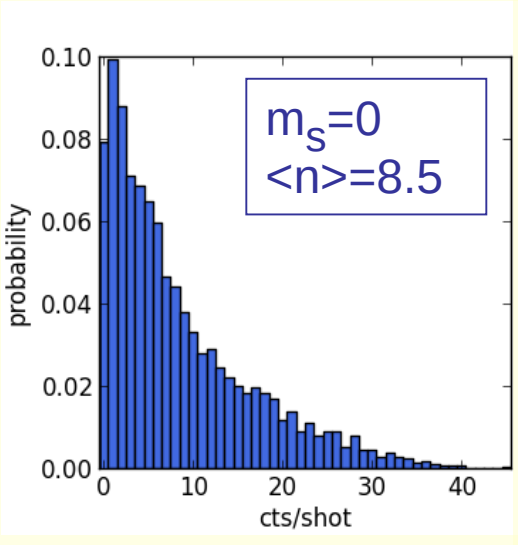


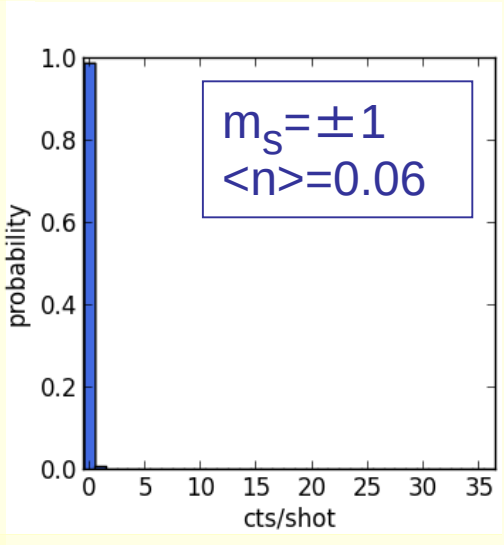
fidelity > 99.7%

Single-Shot Readout



at the time at TU Delft: best fidelity F ≈ 98%





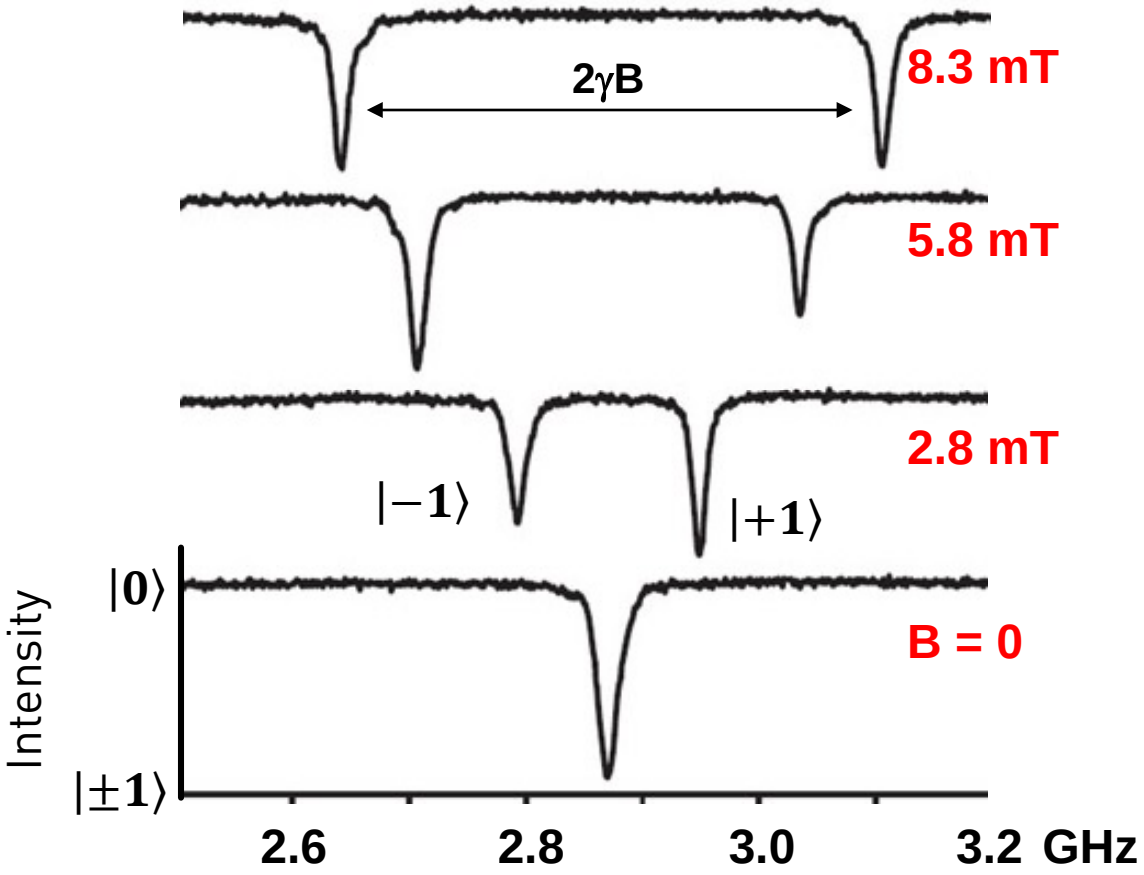
Nature **477**, 574 (2011)

Slide material: Ronald Hanson, TU Delft

Optically Detected Magnetic Resonance

Experimental Sequence:

- Set magnetic field
- Initialize optically
- Apply microwave with controlled frequency and amplitude
- Read out optically

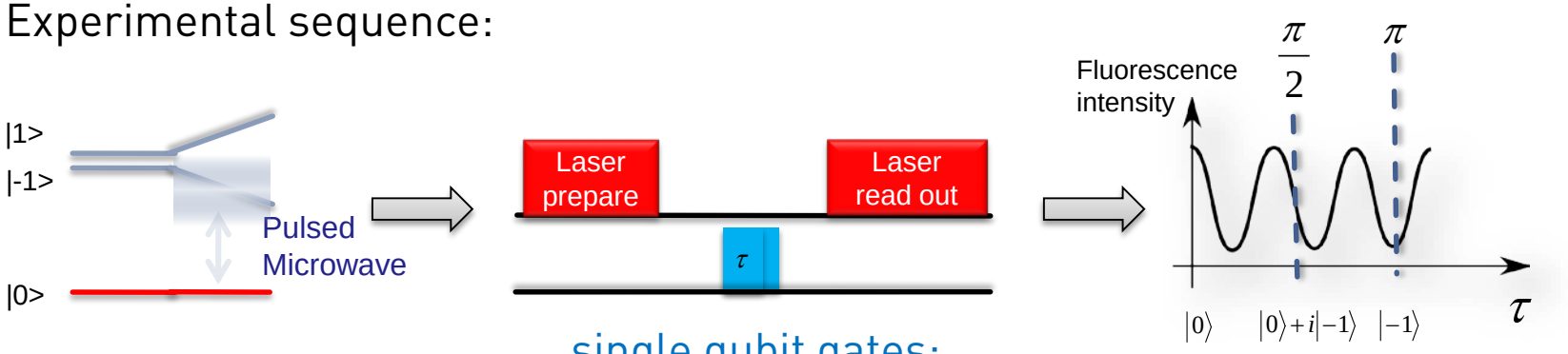


γ = 28 GHz/T

Gruber et al, *Science* (1997)
Balasubramanian et al, *Nature* (2008)
Schirhagl et al, *ARPC* (2014)
Slide material: Christian Degen, ETHZ

Manipulating a Single Spin

Experimental sequence:



single qubit gates:
microwave pulses

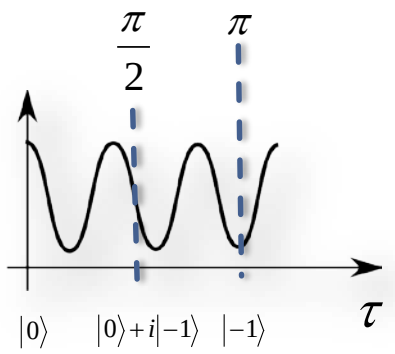
- Pulsed sequence consisting of laser cooling, spin manipulation by pulsed microwaves and detection
- Signal is <1photon/repetition => many repetitions
- Similar to ion trap, but experimentally easier

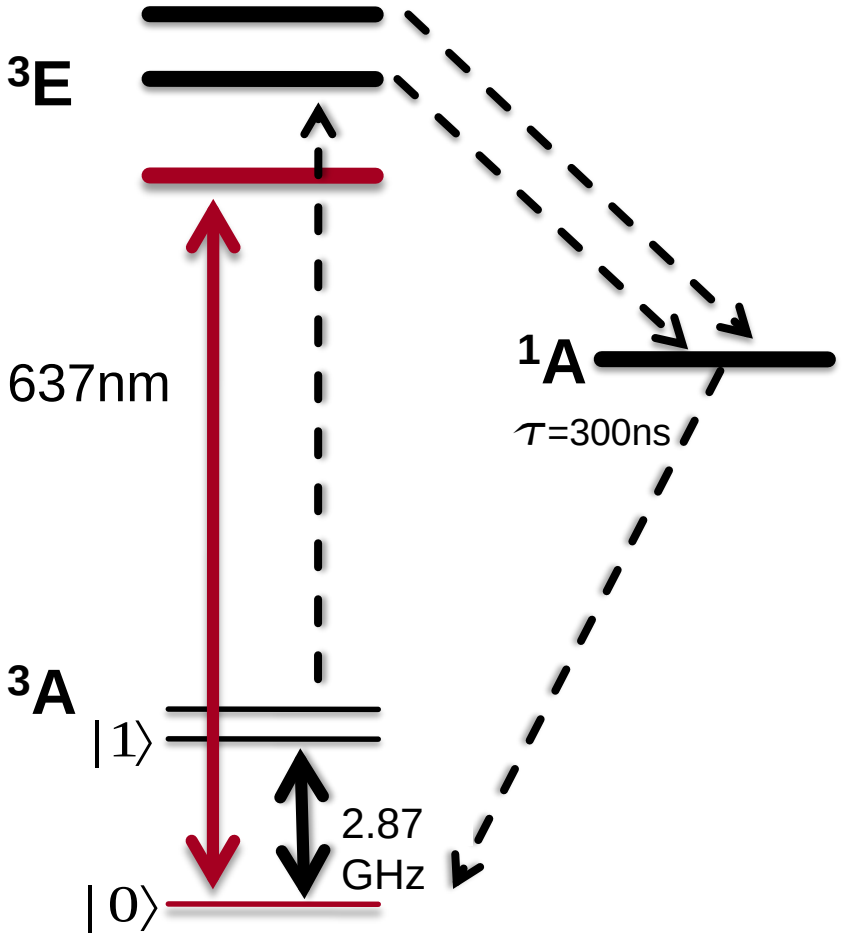
Slide material: Joerg Wrachtrup, Stuttgart

NV Center: Intermediate Summary

Features:

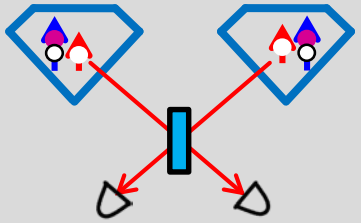
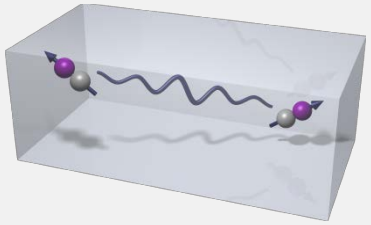
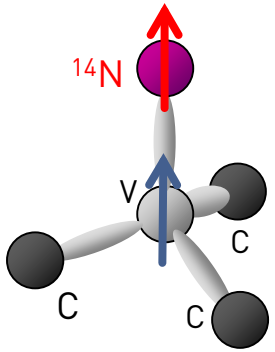
- **Initialization:**
  Optical spin polarization of the ground state (« Laser cooling »)
- **Coherence:**
  Narrow lines, $T_2 = 1$ ms, linewidth of ground state levels 1 kHz.
- **Readout:**
  Optical detection of the spin state
- **Single qubit gates:**
  Microwave pulses





Slide material: Joerg Wrachtrup, Stuttgart

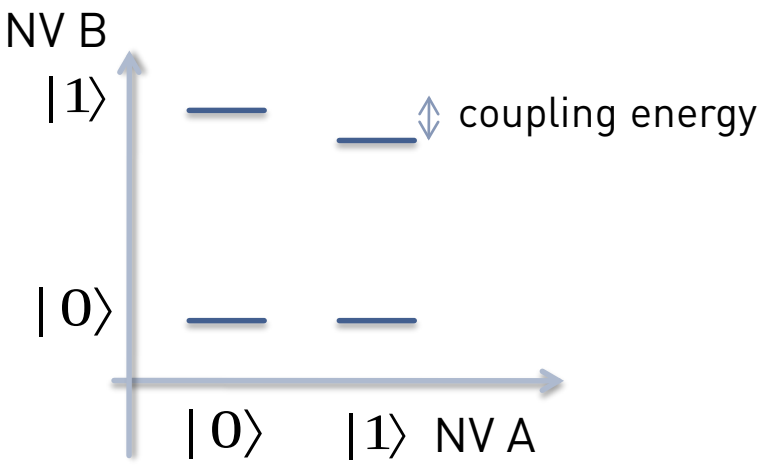
Three Approaches to Coupling NV Centers

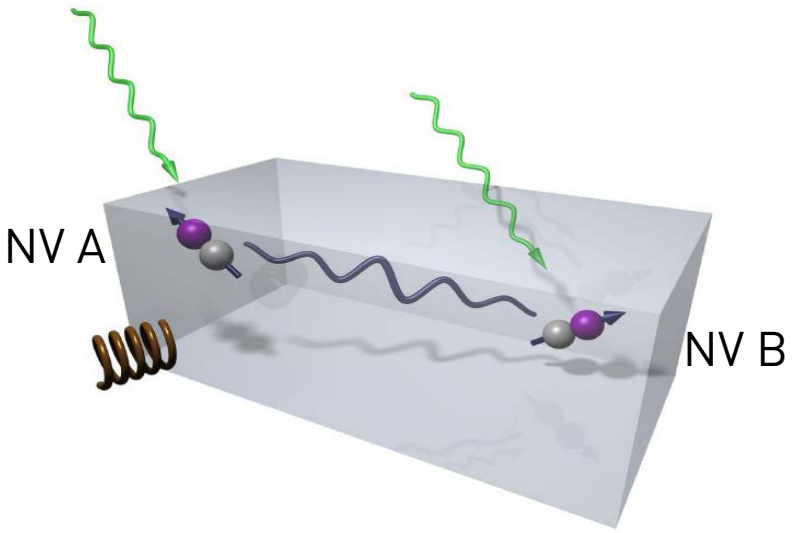
Photons	Magnetic dipolar coupling	Use nuclear spin qubits
 Cirac, Zoller, Lukin `06 • Proper levels and transitions Manson, Hemmer, Santori • Transfer limited photons: Batalov et al. PRL 08 • But: bad coupling efficiency	 • Magnetic dipoles $d_{coherent} \propto \sqrt[3]{T_2}$	 • Couple NV to surrounding nuclei • Couple nuclei via NV • Read out single nuclei

Slide material: Joerg Wrachtrup, Stuttgart

Coupling by Dipolar Interaction

ground state energy levels:





Idea:

- NV B interacts with the magnetic dipole of the electron spin of NV A
- Depending on the state NV A, NV B has another resonance frequency

Slide material: Joerg Wrachtrup, Stuttgart

Spin Hamiltonian: Coupled Spins

Ising coupling term

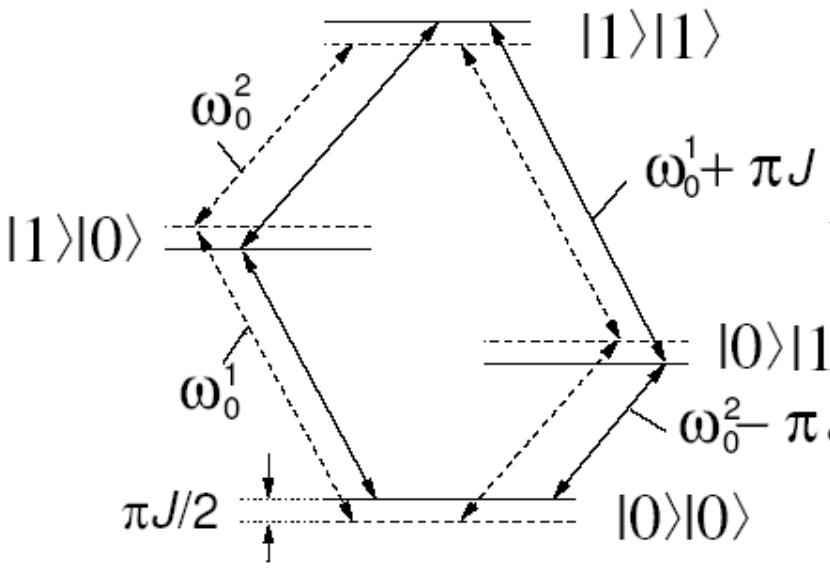
$$\mathcal{H}_J = \hbar \sum_{i<j}^{n} 2\pi J_{ij} I_z^i I_z^j$$

$J > 0$: antiferro mag.

$J < 0$: ferro-mag.

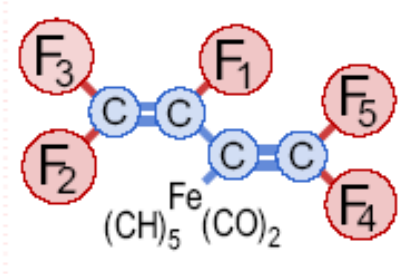
Typical values for *J depending on distance between spins*

- from kHz up to few 10 MHz for electron spins
- up to few 100 Hz for nuclear spins

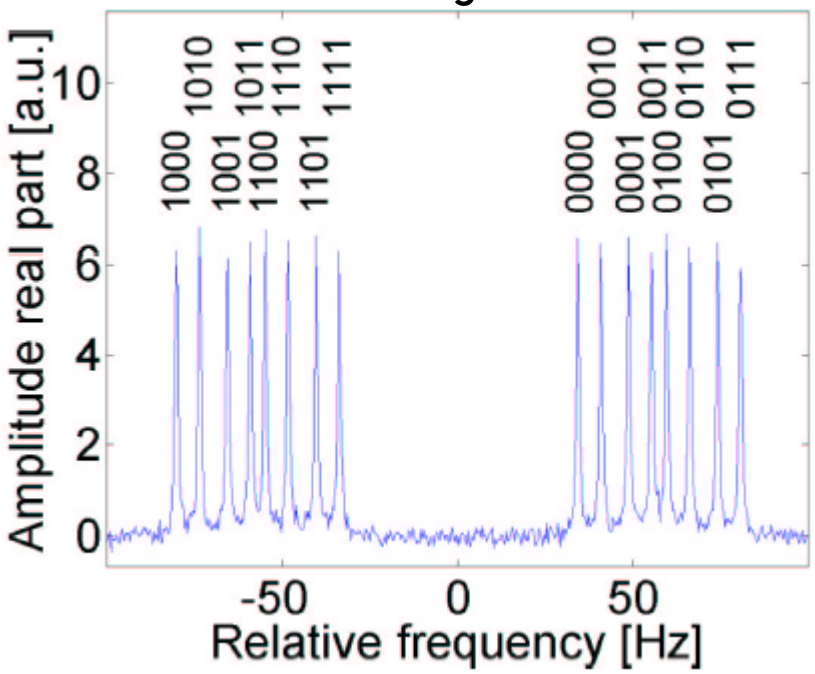


solid (dashed) lines are (un)coupled levels

Example with 5 nuclear spins:

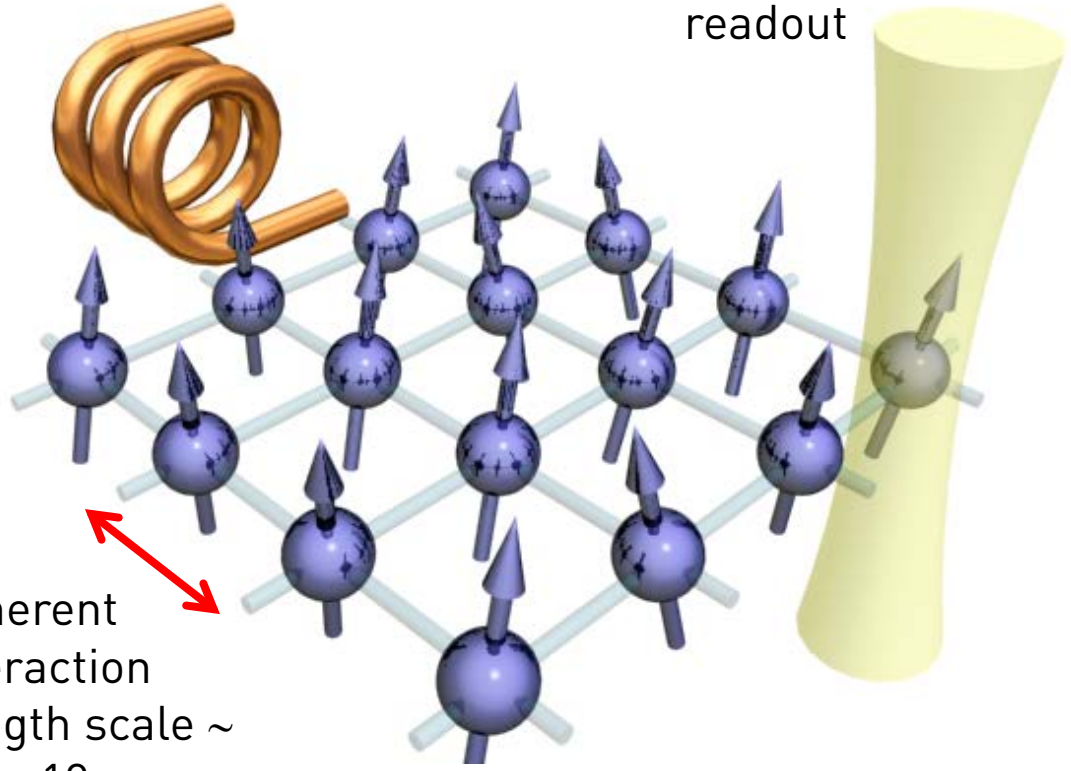


16 configurations



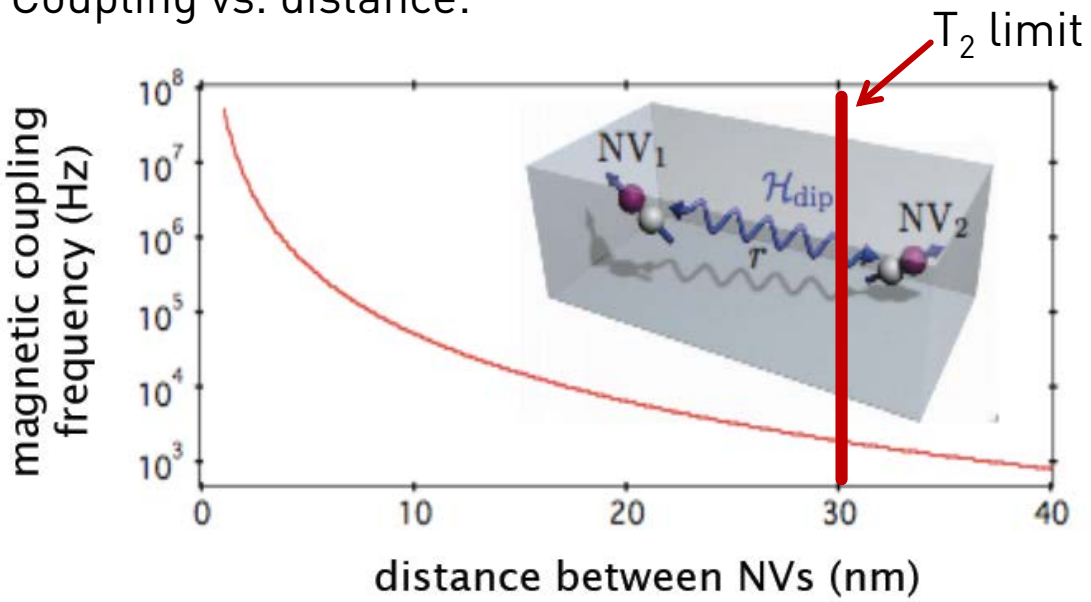
Slide material: Lieven vanderSypen, TU Delft

Magnetic Dipole Coupled Spin Arrays



Coherent
interaction
Length scale ~
some10 nm,

Coupling vs. distance:



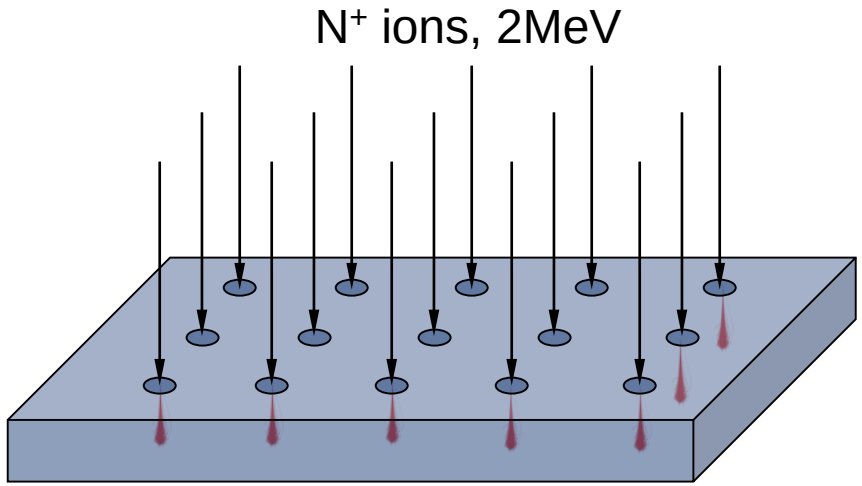
- Distance dependence of dipole coupling scales as d^{-3}

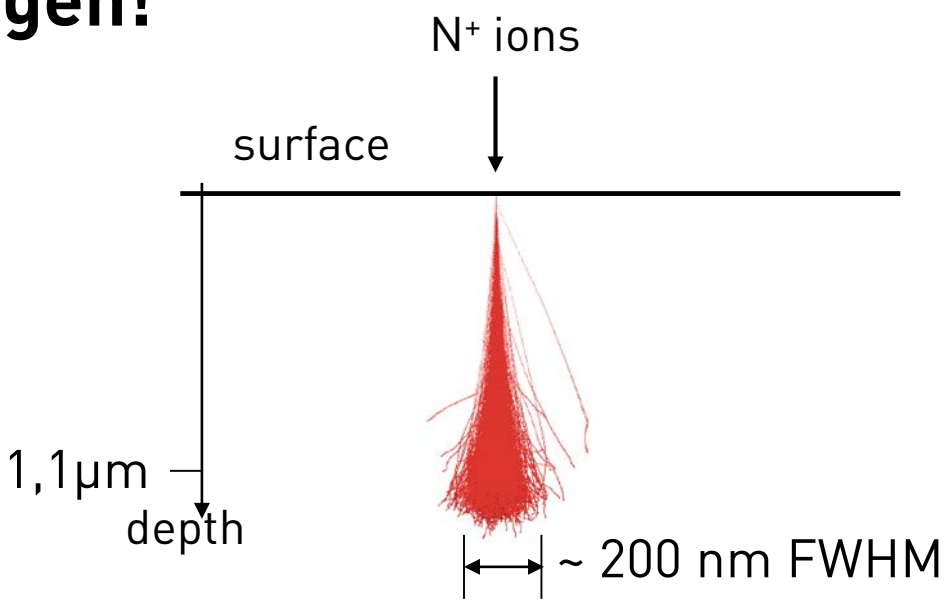
STED on NV: 10nm resolution: Hell *et al., Nat. Phot.* (2009)

Slide material: Joerg Wrachtrup, Stuttgart

Take Pure (CVD) Diamond and Implant Nitrogen!

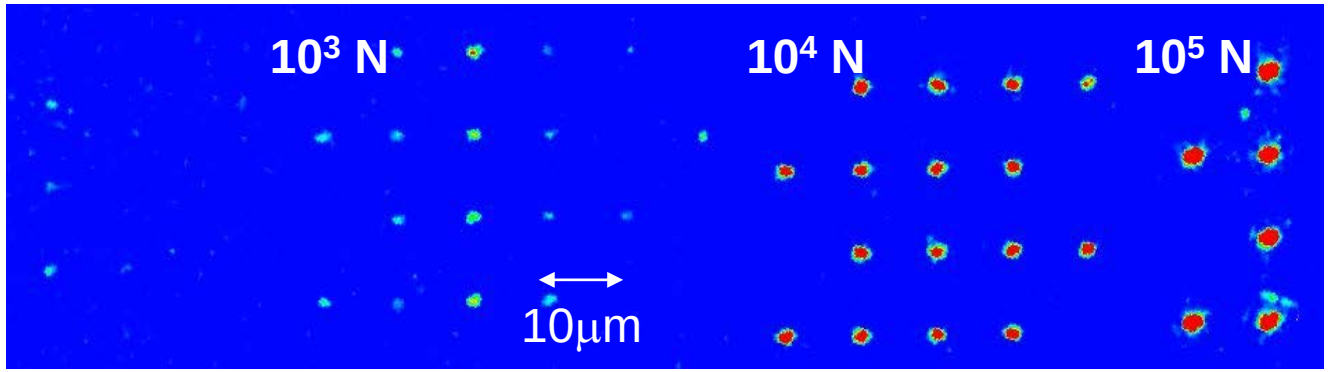
*Element Six Ltd., UK





Annealing at 900° C

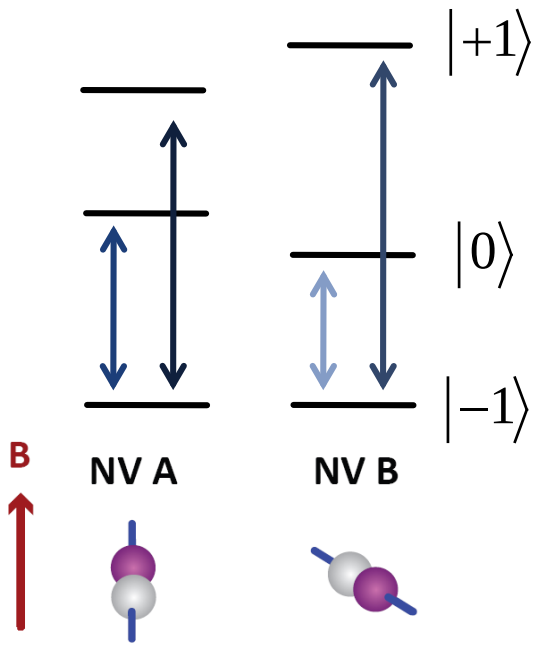
Success chance 1% to have two coherently interacting dimers

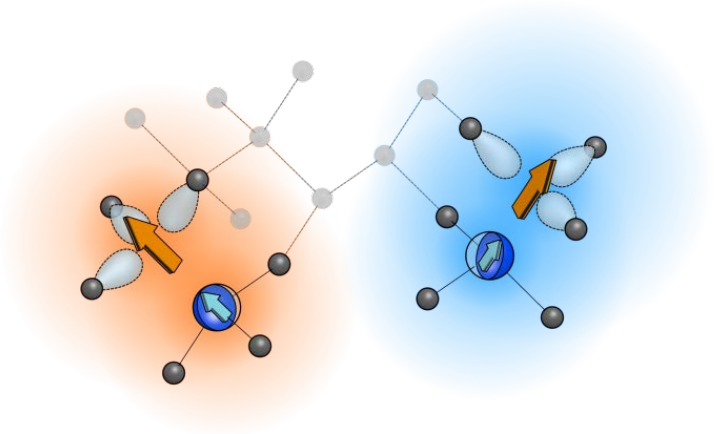


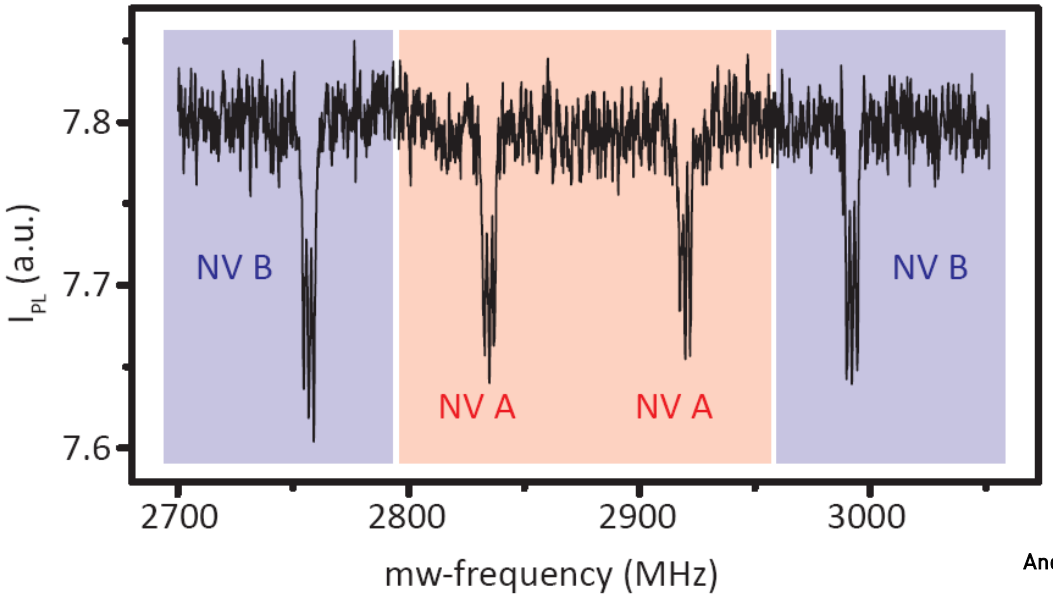
Slide material: Joerg Wrachtrup, Stuttgart

Two Defect Centers

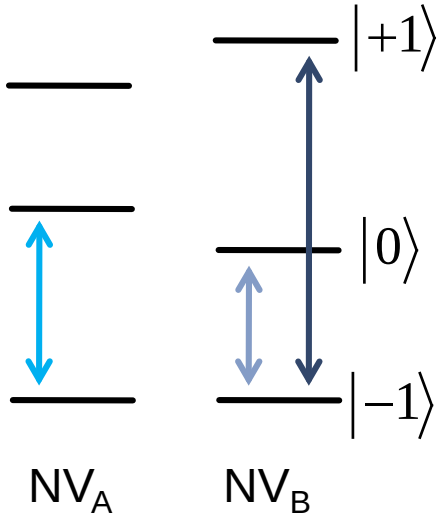
Electron spin ground state:

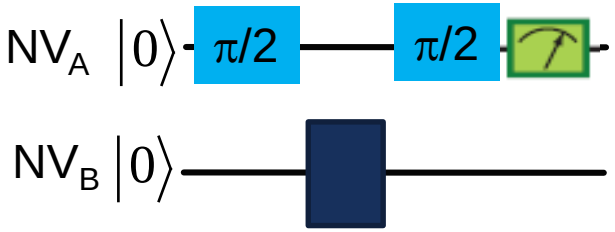




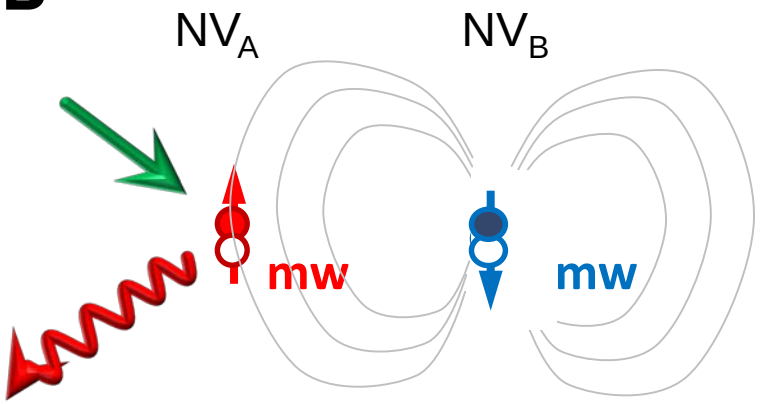


Dipolar Coupling: Switching of Spin B

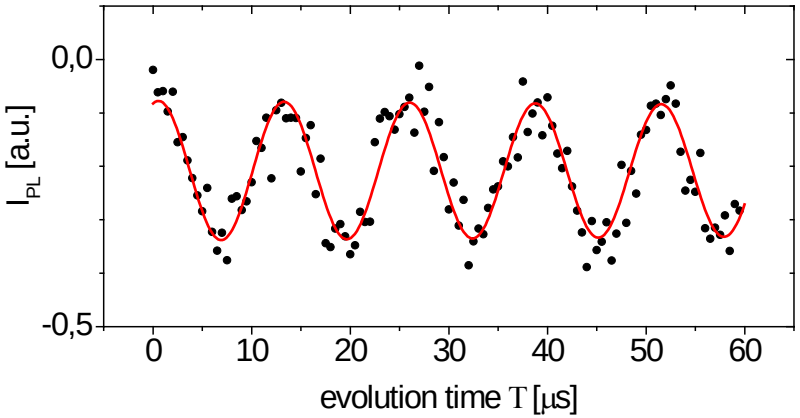




Initial state F≥85%

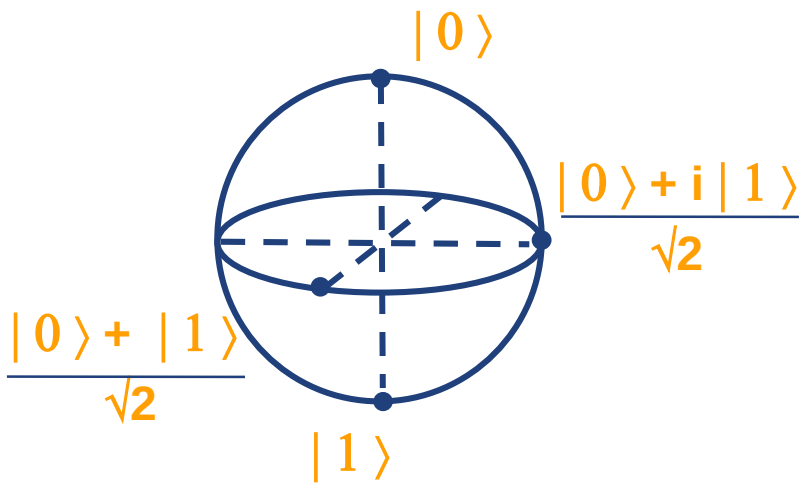


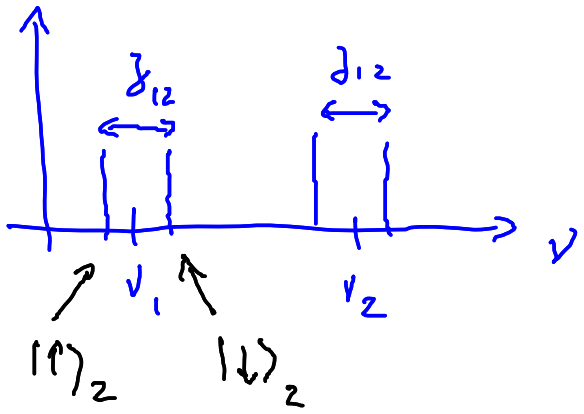
Ramsey fringe on NV_A

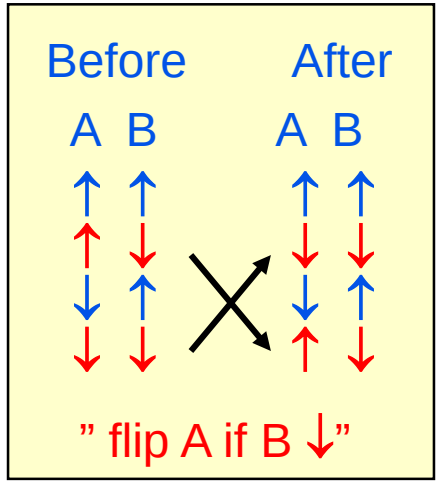


Switchable interaction! Coupling between defect: 0,5,10,20 kHz

Controlled-NOT for Spin-Spin Coupling







A target bit
B control bit

wait

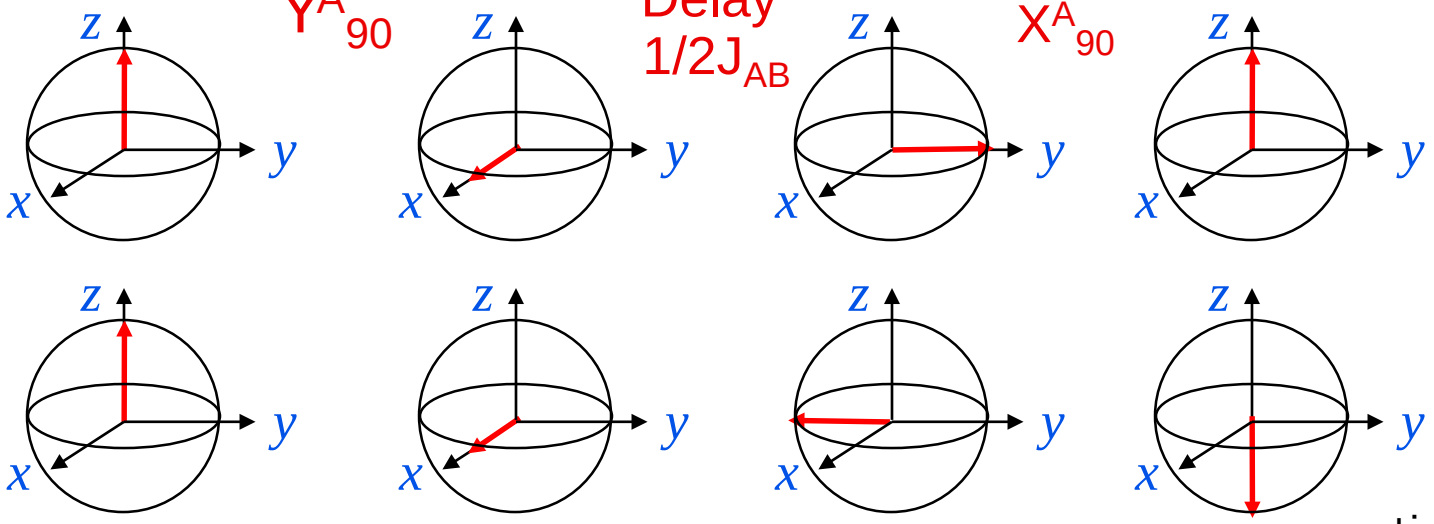
Y^A_{90}

Delay $1/2J_{AB}$

X^A_{90}

if spin B is ↑

if spin B is ↓

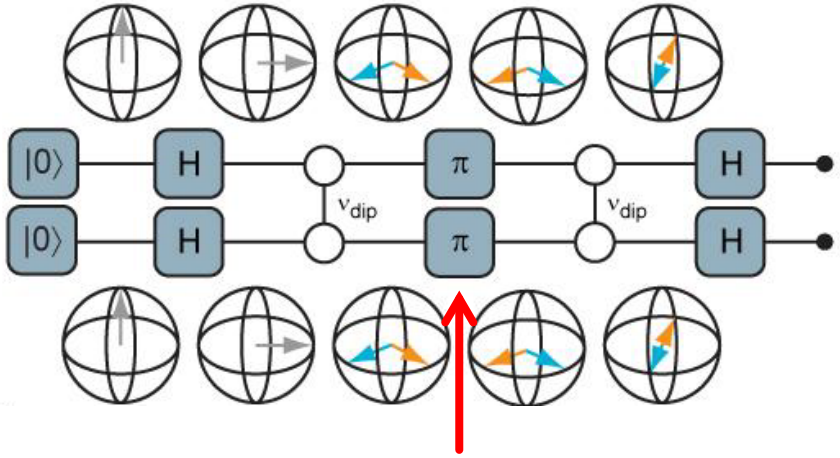


different rotation direction depending on control bit

time

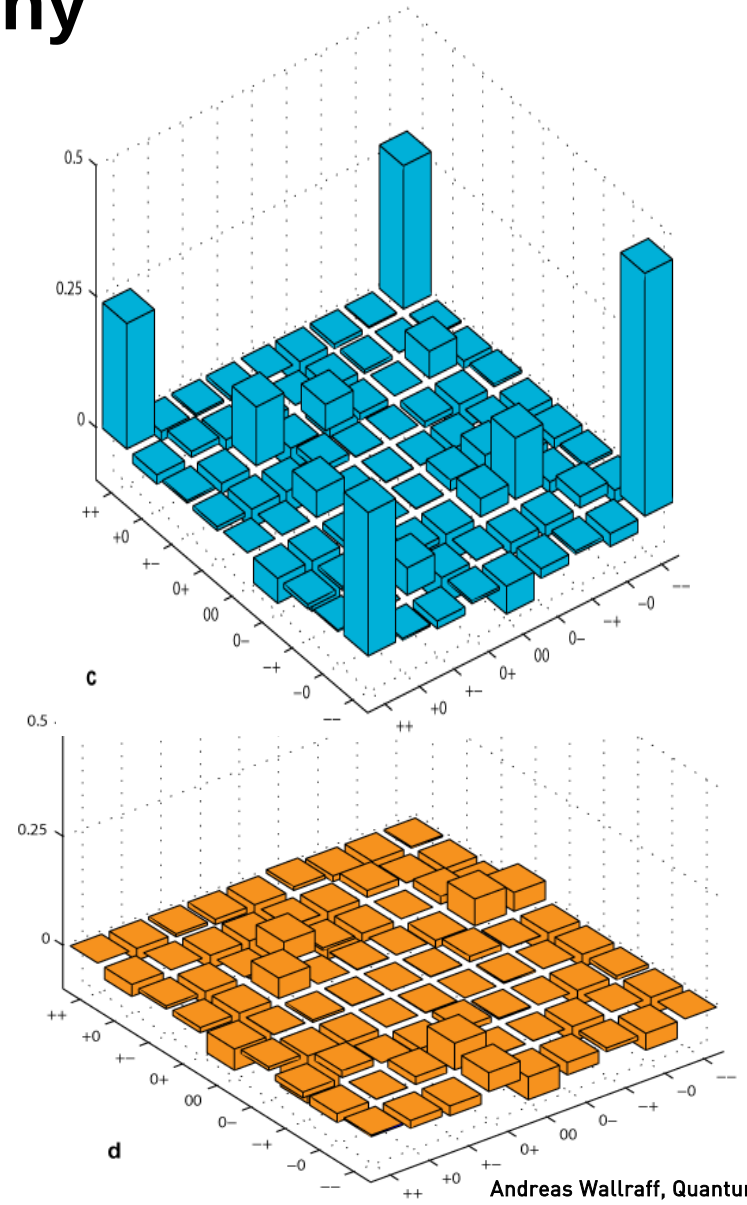
Bell State: Density Matrix Tomography

$$\Phi_+ = \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle)$$

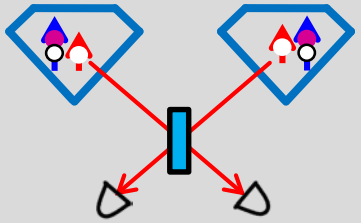
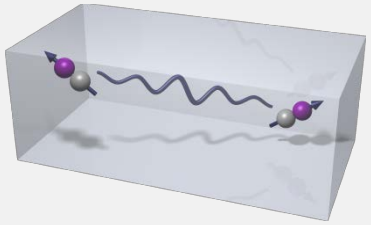
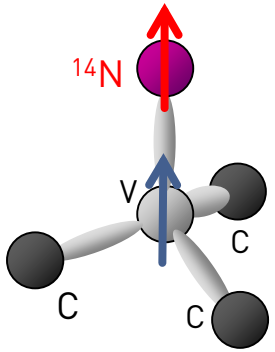


decoupling

Fidelity Φ+: 0.67
(theoretically: 0.9)

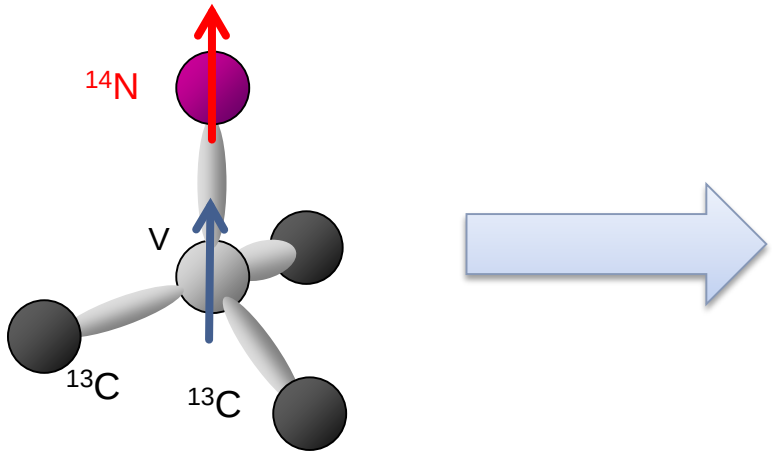


Three Approaches to Coupling NV Centers

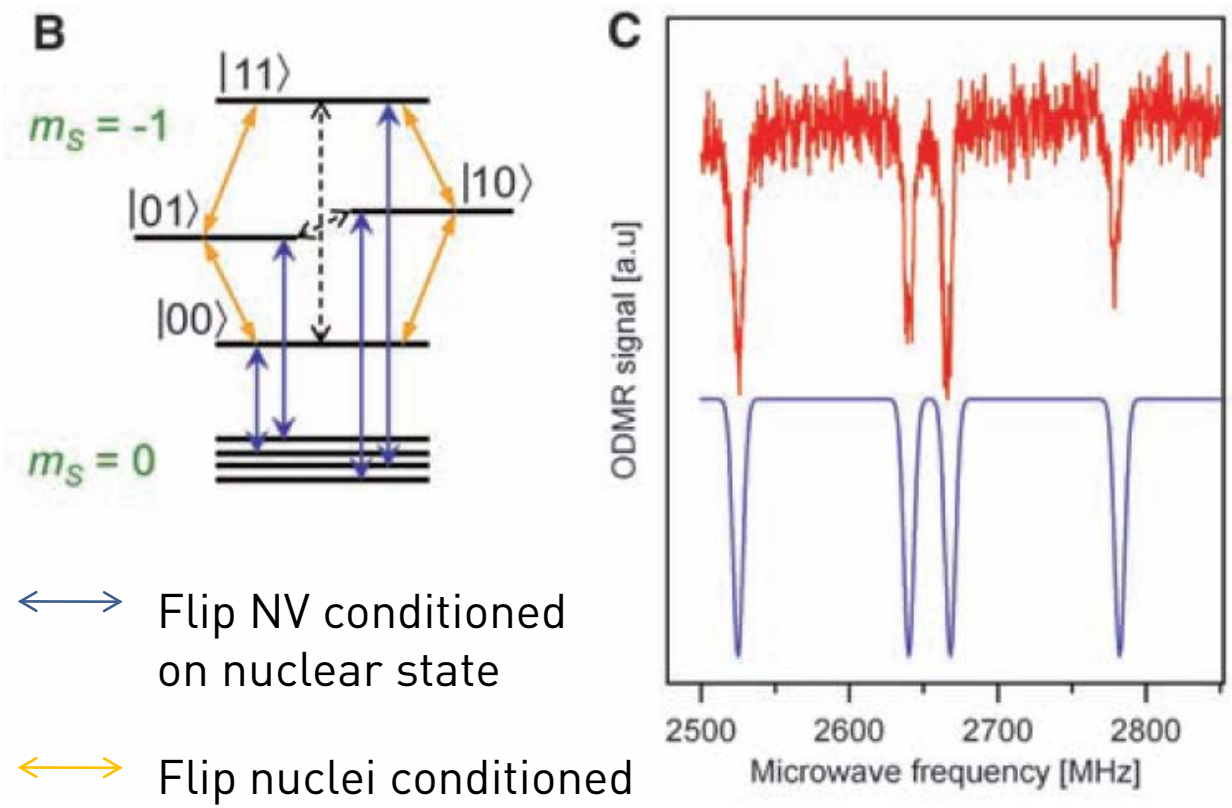
Photons	Magnetic dipolar coupling	Use nuclear spin qubits
 Cirac, Zoller, Lukin `06 • Proper levels and transitions Manson, Hemmer, Santori • Transfer limited photons: Batalov et al. PRL 08 • But: bad coupling efficiency	 • Magnetic dipoles $d_{coherent} \propto \sqrt[3]{T_2}$	 • Couple NV to surrounding nuclei • Couple nuclei via NV • Read out single nuclei

Slide material: Joerg Wrachtrup, Stuttgart

Coupling Nearby ^{13}C Nuclei



Splitting of electron spin spectrum:



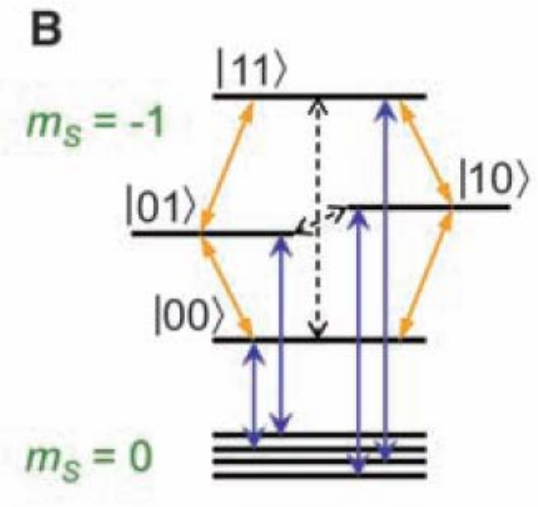
- ^{12}C has no nuclear spin ($I = 0$) and magnetic moment
- ^{13}C nuclear spins ($I = ½$, 1.1 % abundance) create magnetic field at NV
- CNOT gate is implemented by selective microwave transition (flip nucleus if other nucleus is in |0>)

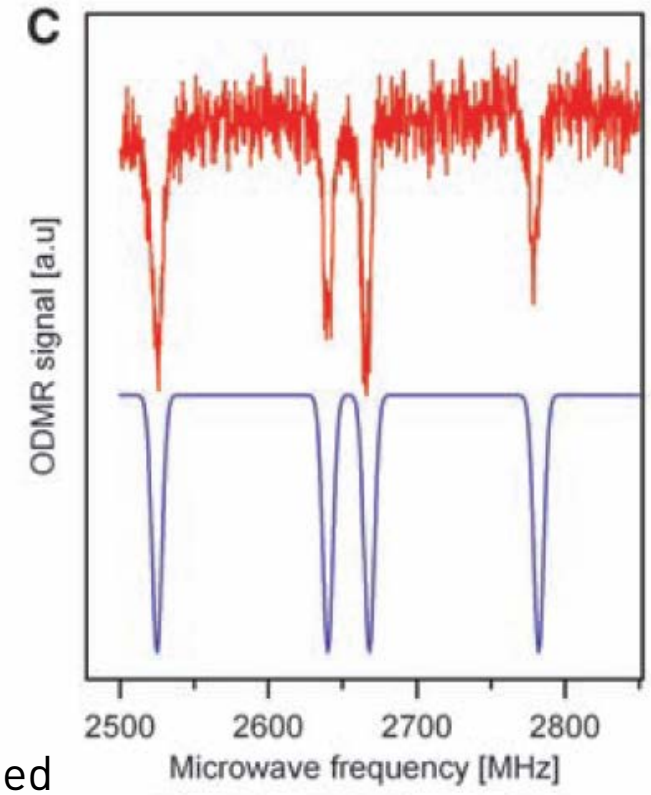
⟷ Flip NV conditioned on nuclear state

⟷ Flip nuclei conditioned on NV and nuclear state

Slide material: Joerg Wrachtrup, Stuttgart

Creation of Entangled States





⟷ Flip NV conditioned on nuclear state

⟷ Flip nuclei conditioned on NV and nuclear state

- Creation of entangled states possible

  $$|00\rangle \mp |11\rangle$$

  P. Neumann et.al., Science **320**, 1326 (2008)
- Scaling up to four nuclear spins straightforward
- Combination of electron and nuclear spin states for quantum register
- Scaling to 10-20 spins presumably possible

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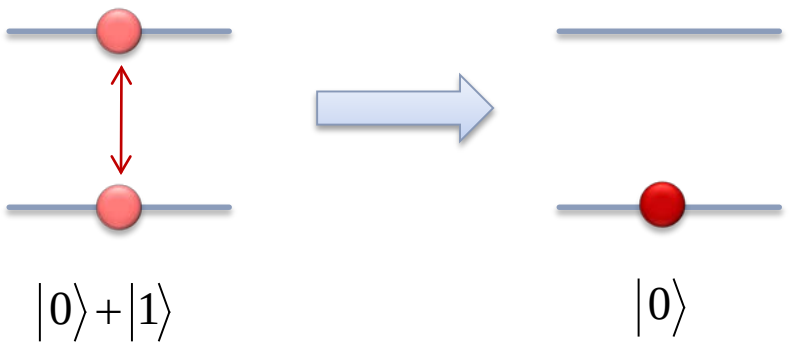
Different development: QND readout of nuclear spins

Readout of single quantum systems

- Standard readout
  - <1 photon per run limited by photon shot noise (at best)
  - Example: fluorescence detection of single NV
- Single shot readout
  - determine spin state in a single run but destroy the system or its quantum state
  - requires >1 photon per run limited by quantum shot noise
  - Example: Photon detection in Photomultiplier
- Quantum non demolition (QND) readout
  - >1 photon per run and preservation of the system and its spin state
  - Projective measurement
  - Example: Microwave photons in circuit QED



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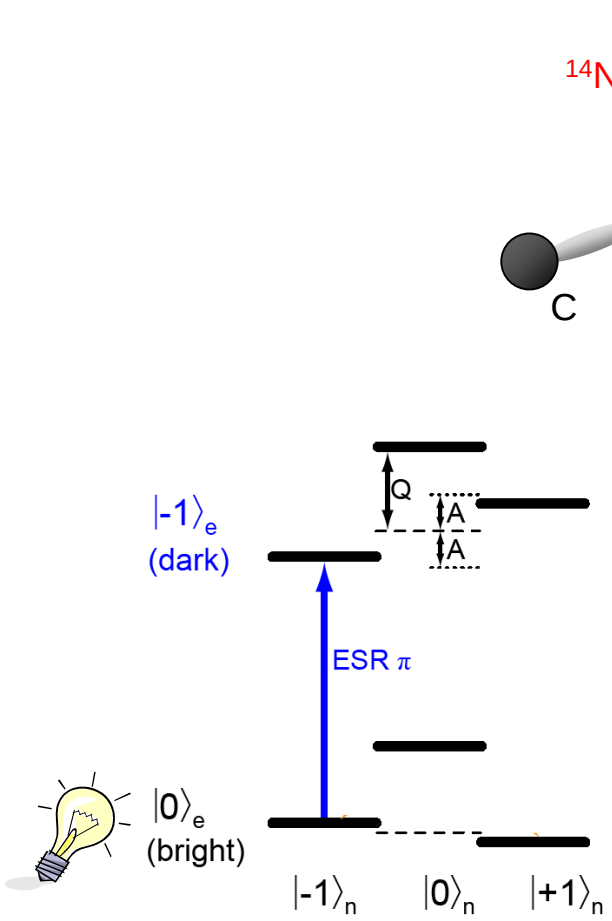
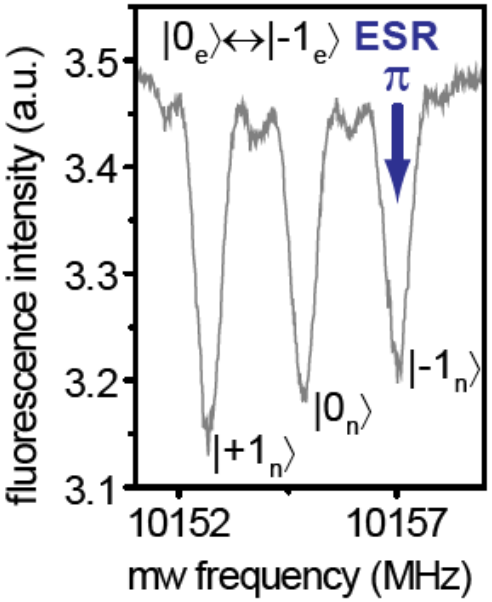
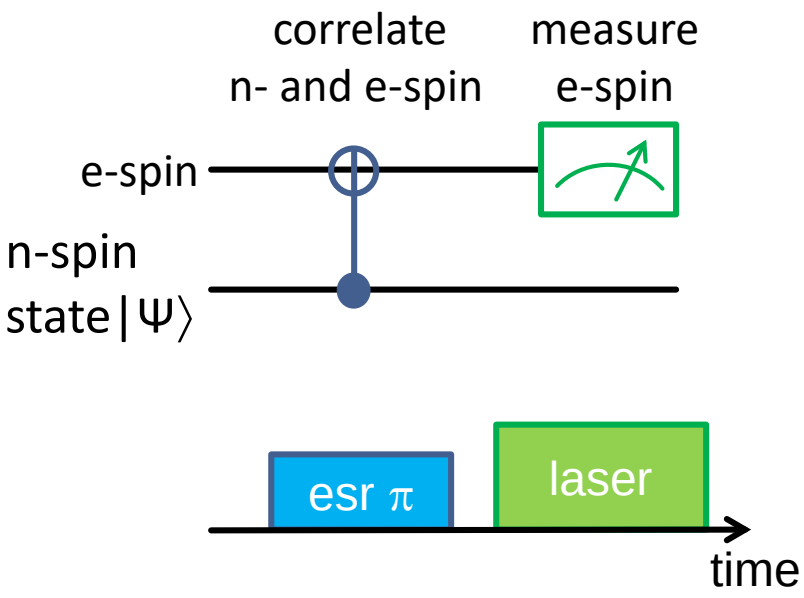
QND Readout of a Single Nuclear Spin







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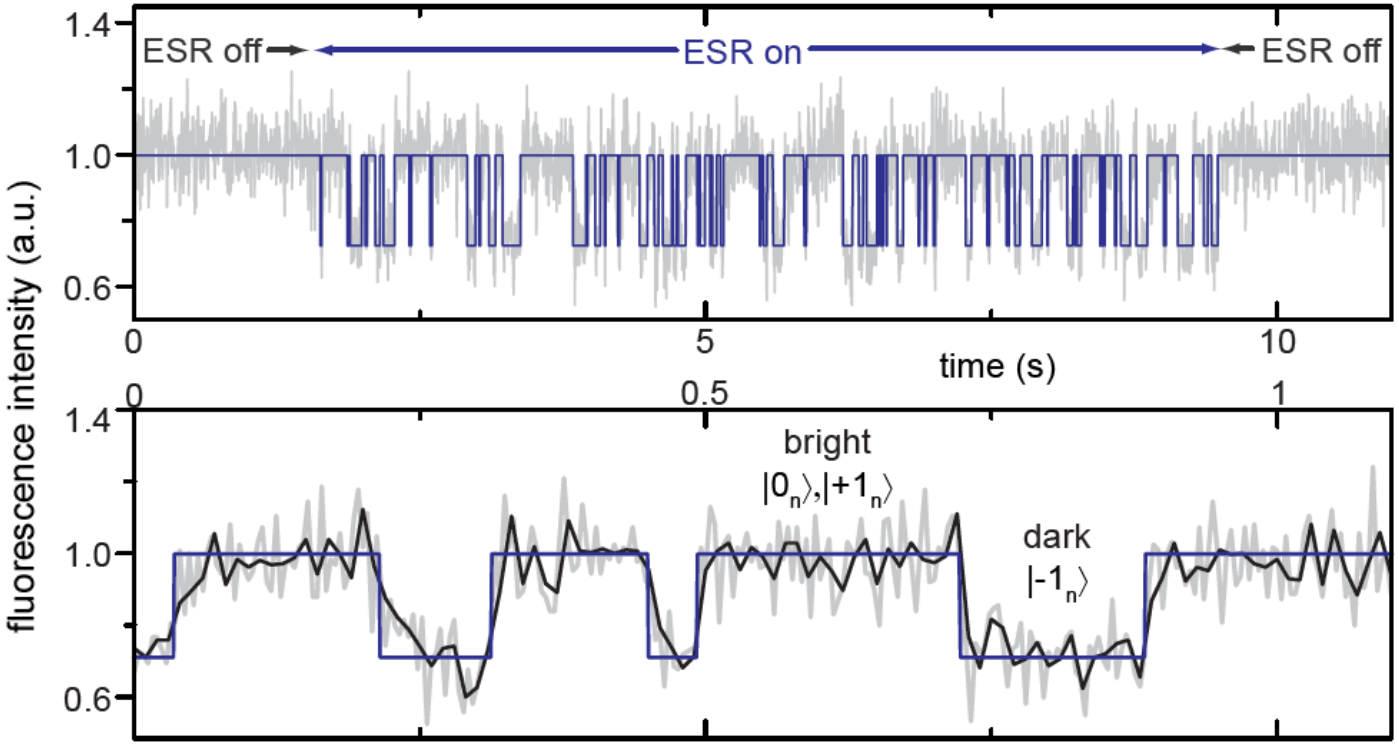
Observing Flips of a Single Nuclear Spin

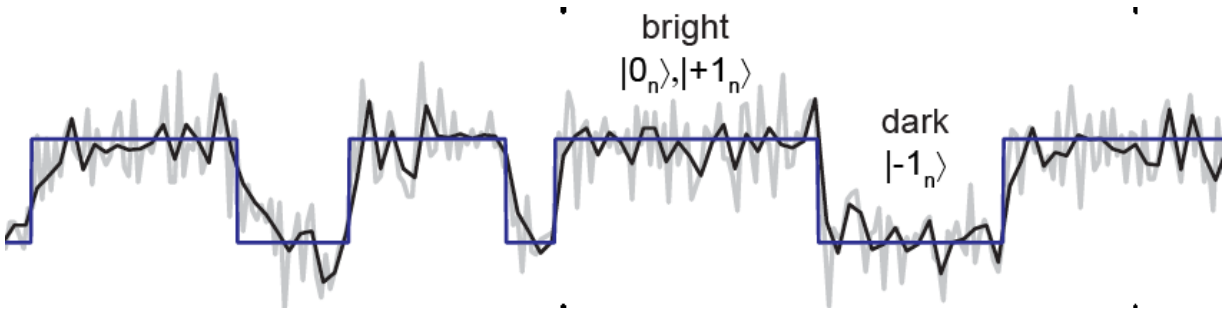
Repetitive QND measurements reveal quantum jumps of a single nuclear spin (in diamond at room temperature)

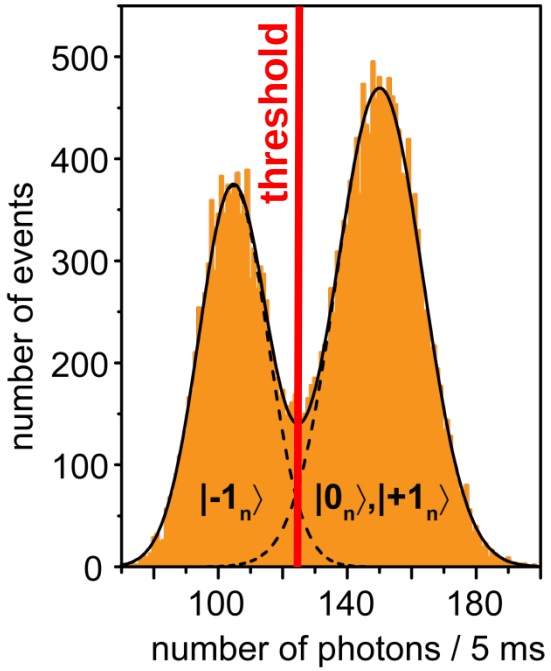


P.Neumann et.al., *Science* **329**, p.542 (2010)

Fidelity of Spin State Detection

Photon counting histogram of time trace





- Two almost perfect Poissonians
- Threshold for state discrimination
  - Fidelity from overlap 99%
  - Fidelity to detect given state 92%

Slide material: Joerg Wrachtrup, Stuttgart

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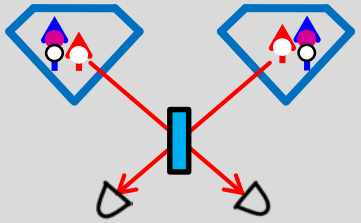
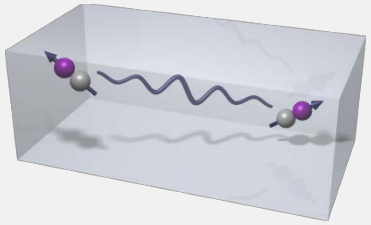
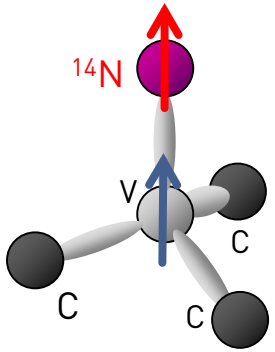
 Cirac, Zoller, Lukin `06 • Proper levels and transitions Manson, Hemmer, Santori • Transfer limited photons: Batalov et al. PRL 08 • But: bad coupling efficiency	 • Magnetic dipoles $d_{coherent} \propto \sqrt[3]{T_2}$	 • Couple NV to surrounding nuclei • Couple nuclei via NV • Read out single nuclei

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