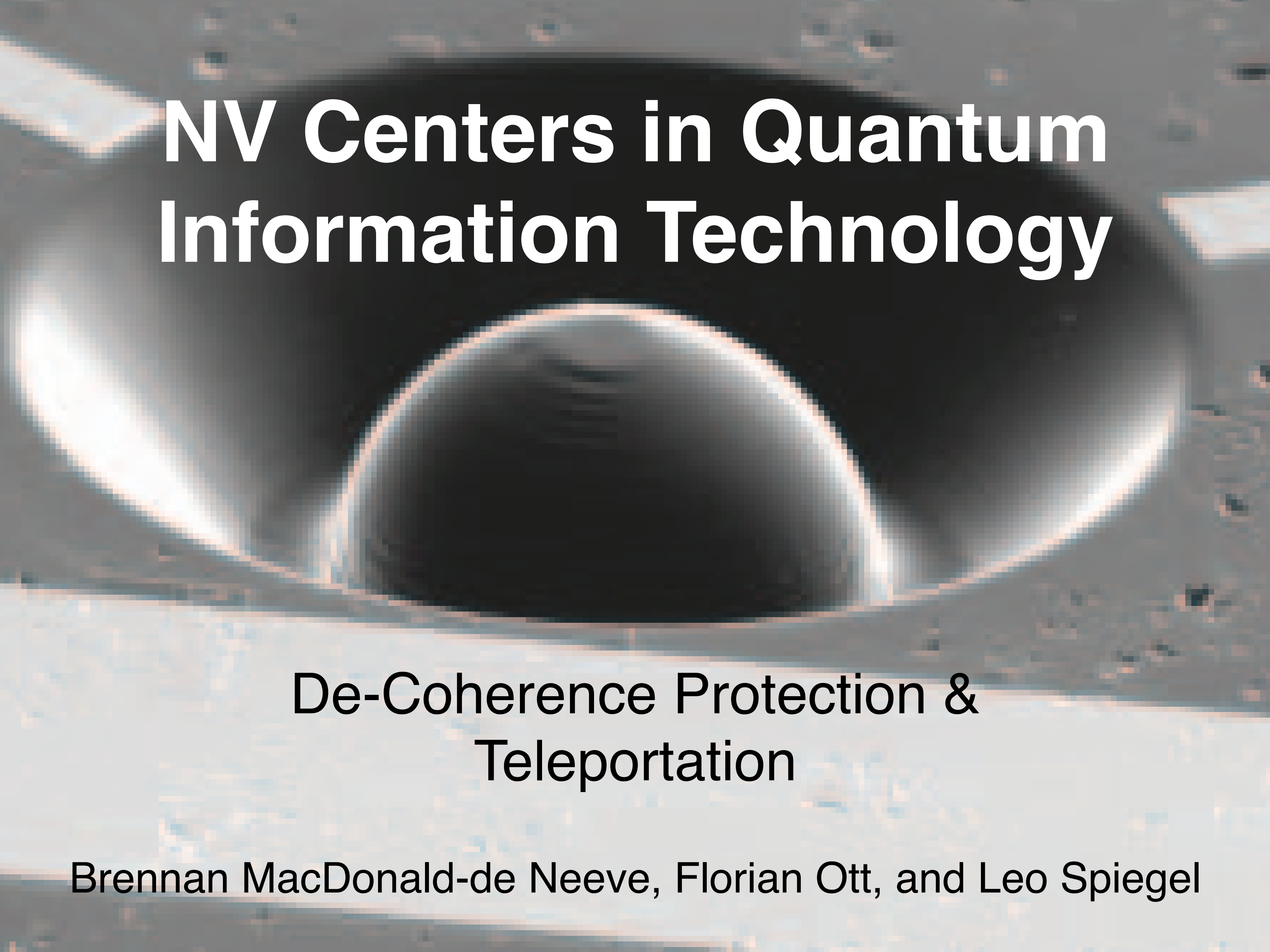


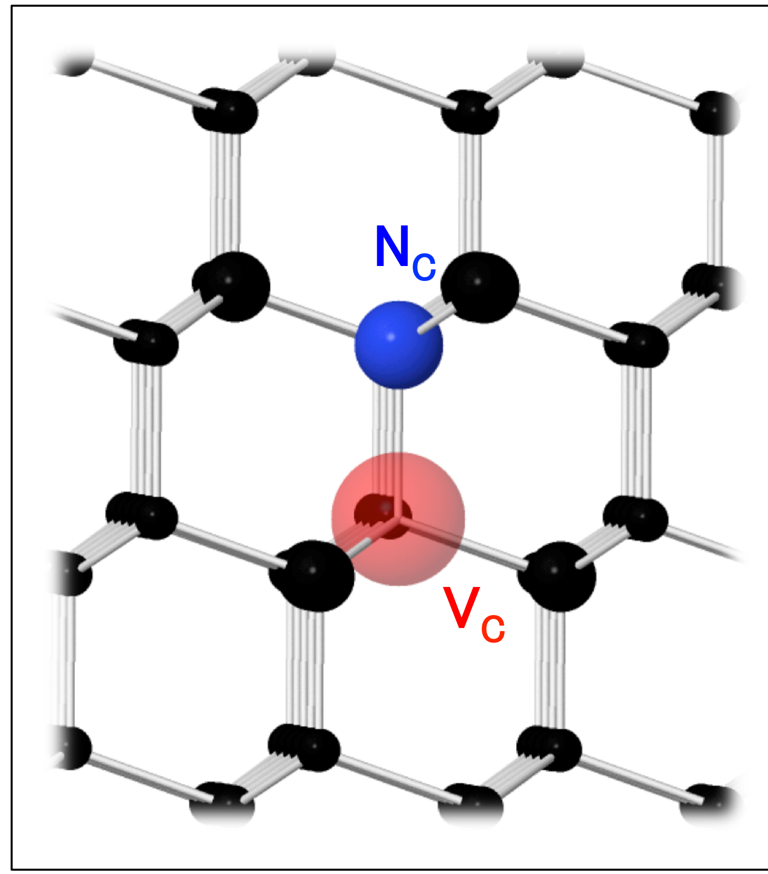
NV Centers in Quantum Information Technology

De-Coherence Protection & Teleportation

Brennan MacDonald-de Neeve, Florian Ott, and Leo Spiegel

The NV Center

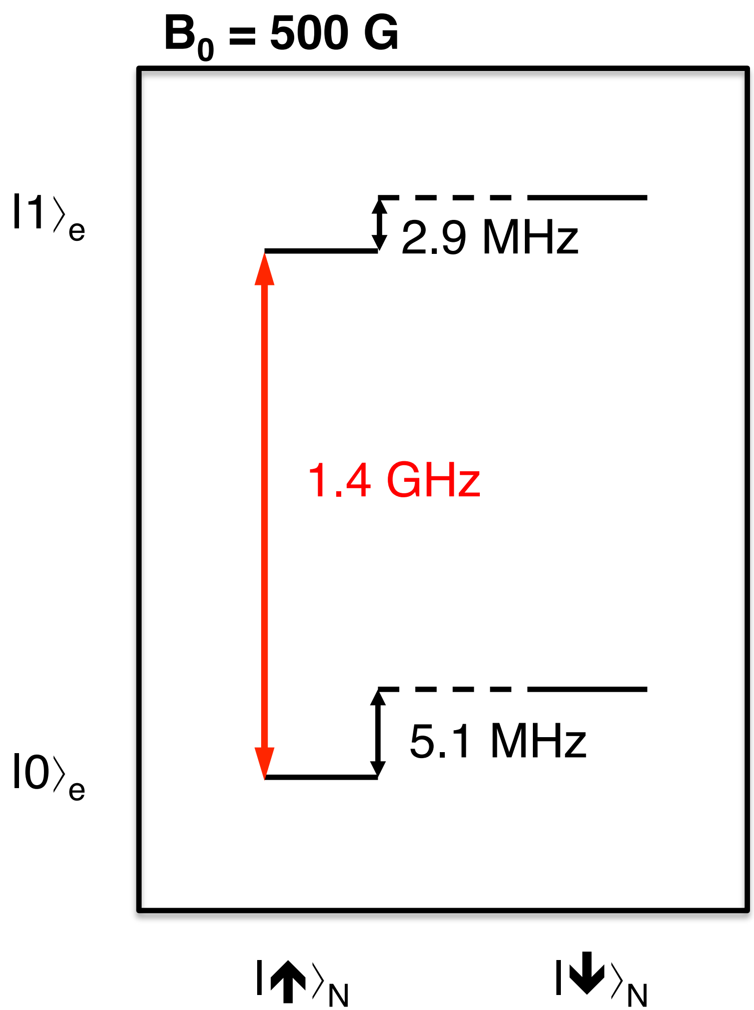
- Point Defect in Diamond
- Interesting Physics in negatively charged state NV^{-1}
- Total electron spin S=1
- ^{14}N Nuclear Spin I=1



Di Vincenzo Criteria

1. Well-defined qubits
2. Initialization
3. $t_{coherence} > t_{gate\ operation}$
4. Universal set of quantum gates
5. Qubit specific read-out
6. Convert from stationary to mobile qubit
7. Faithful transmission

Relevant Ground State Energy Structure



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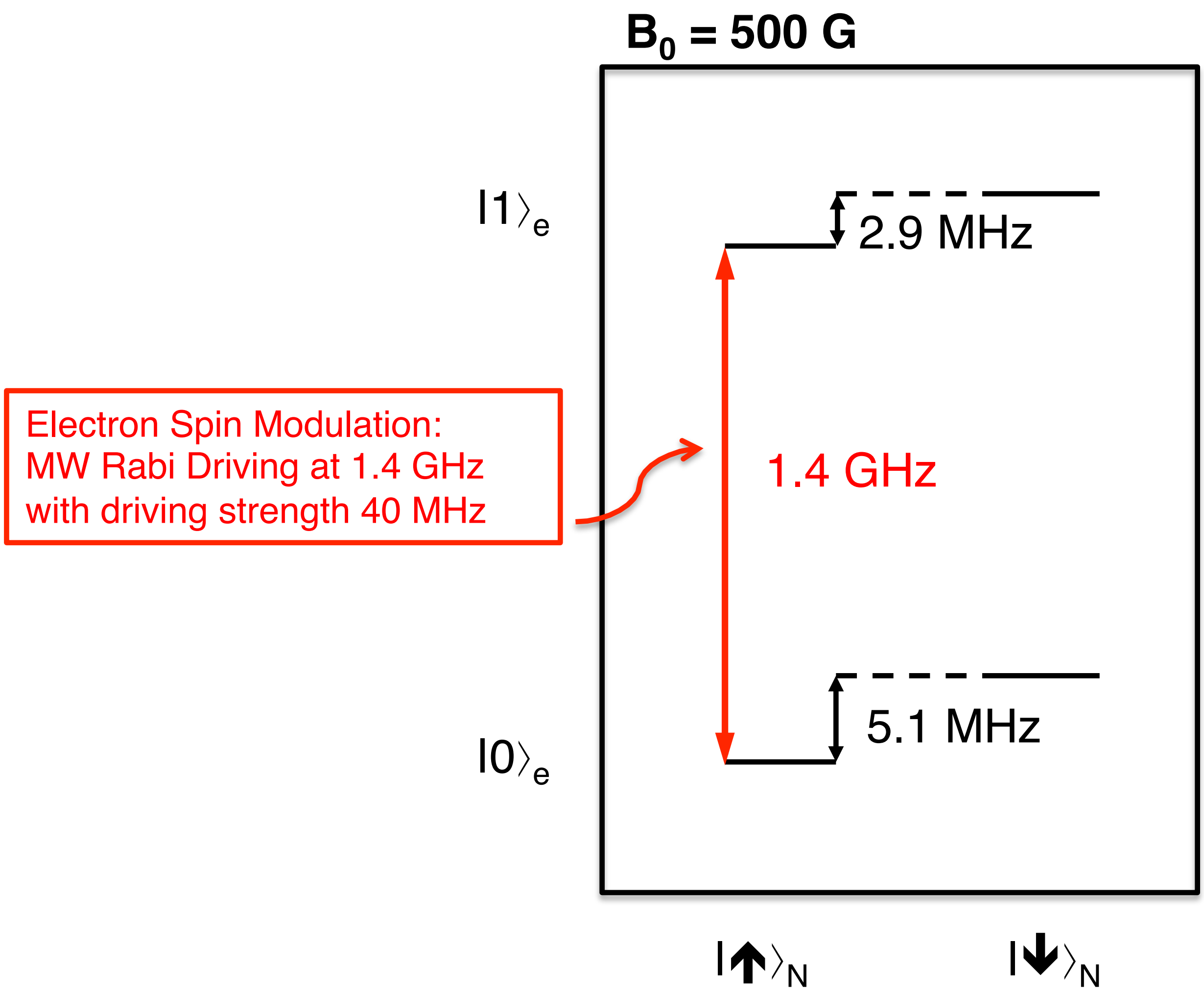
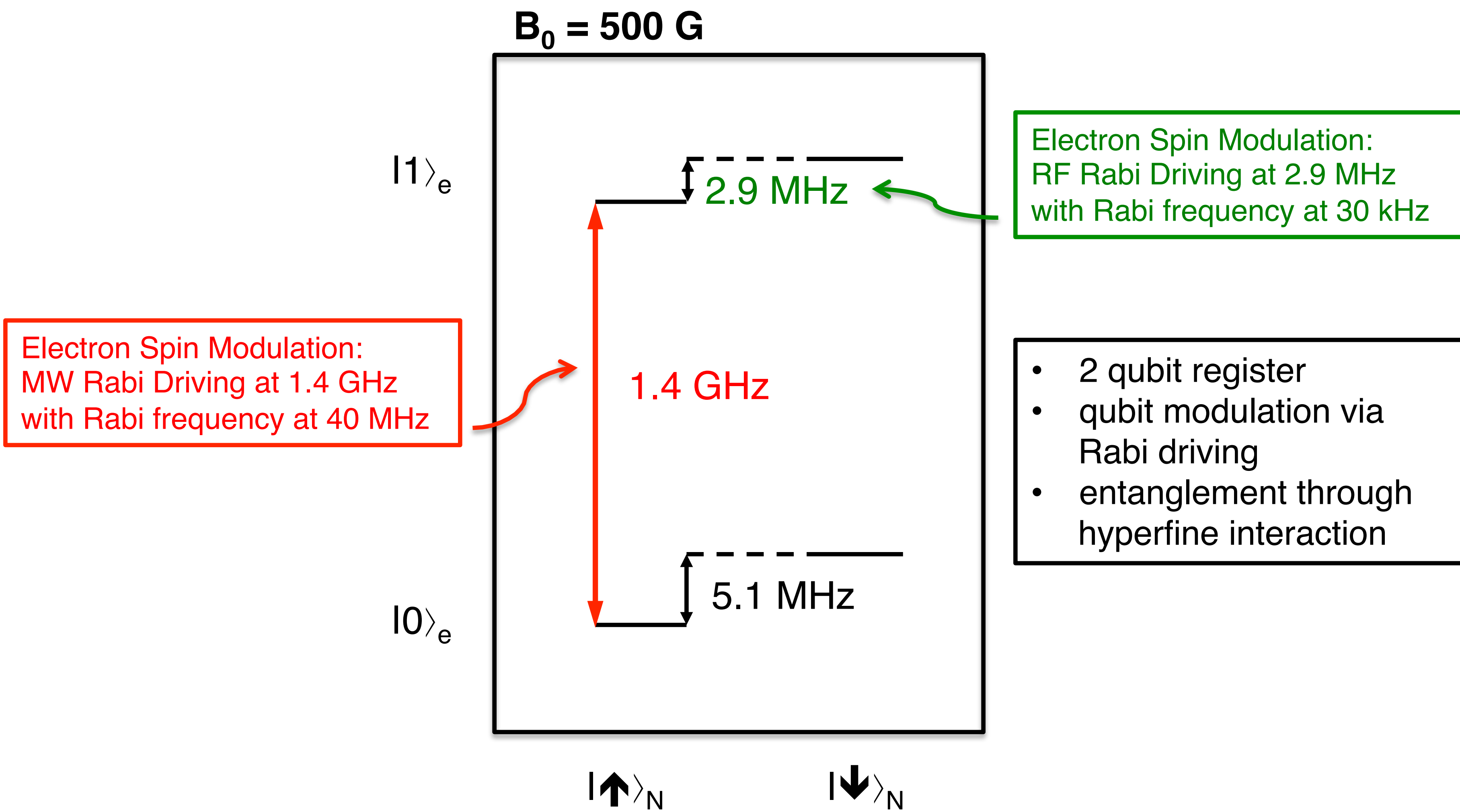


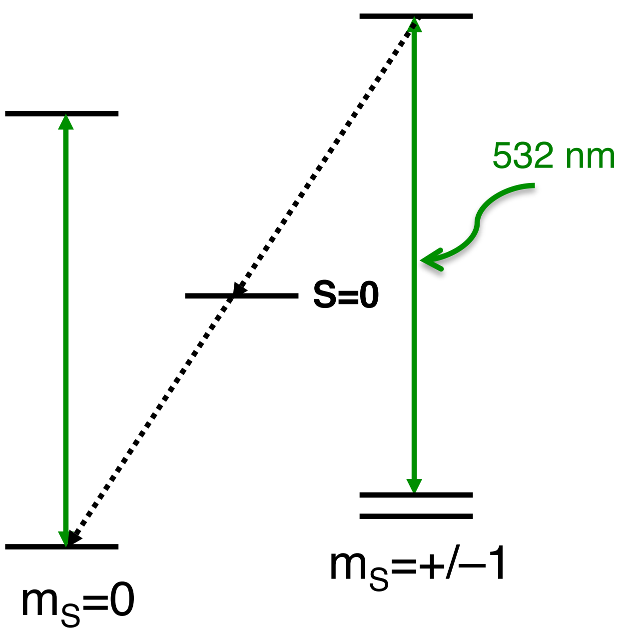
Relevant Ground State Energy Structure



- 2 qubit register
- qubit modulation via Rabi driving
- entanglement through hyperfine interaction

Spin Initialization from Excited State

1) Electron Spin using LASER pumping



N. B. Manson *et al*. Phys. Rev. B **47**, 104303 (2006).

Spin Initialization from Excited State

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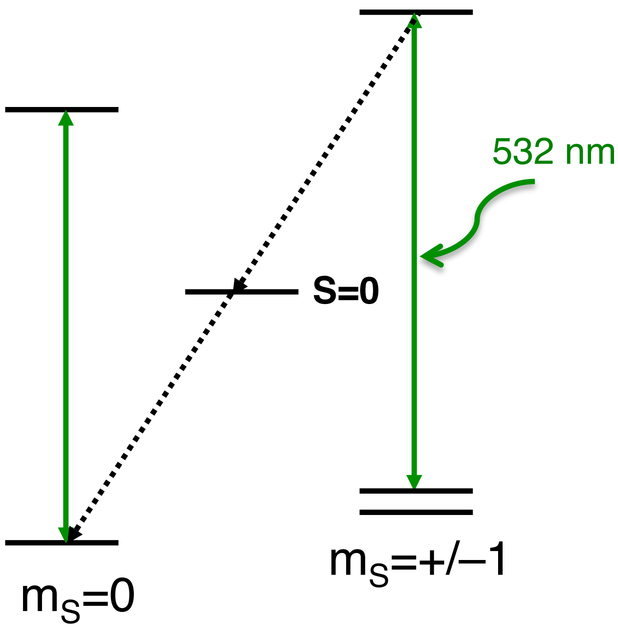
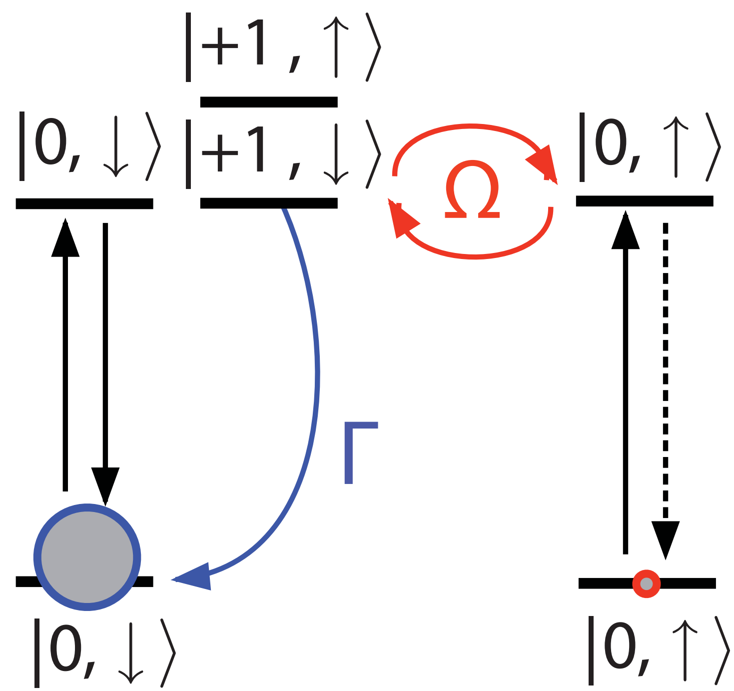


N. B. Manson *et al*. Phys. Rev. B **47**, 104303 (2006).

2) Nuclear Spin using LASER pumping at **B = 500 G**

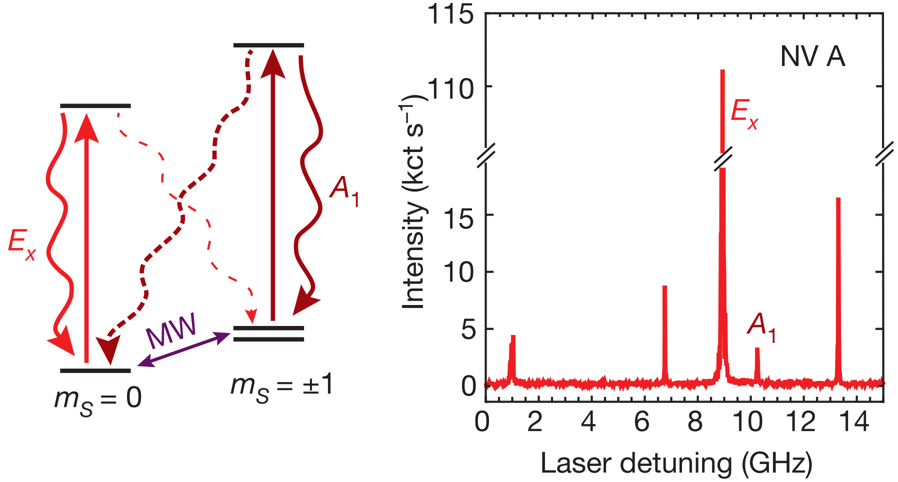


V. Jacques *et al*. Phys. Rev. Lett. **102**, 057403 (2011).

Read-Out

<u>PL Spectrum of optically excited NV Center:</u>

- m_S = 0 is bright (E_x)
- m_S = -1 is dark (A_1)



L. Robledo *et al*. Nature **477**, 574–578 (2011).

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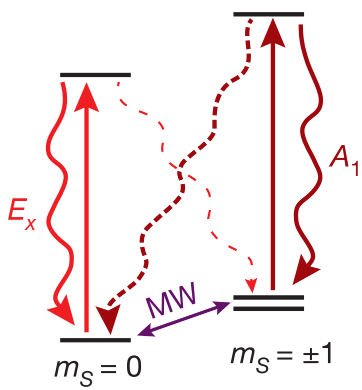
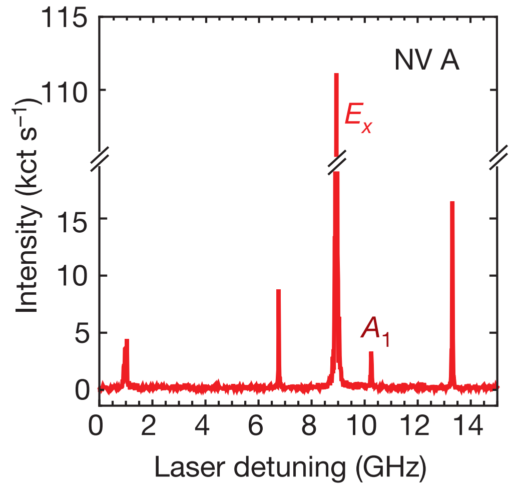
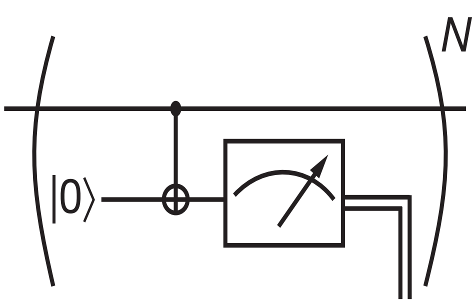




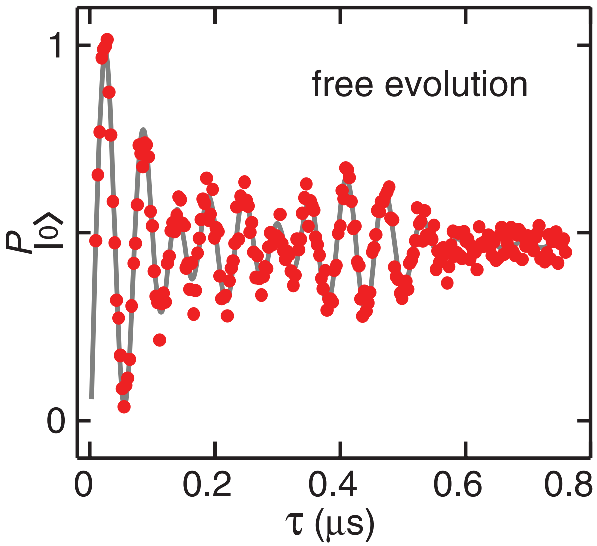
➢ Can also be used to read out m_I by using a CNOT gate:

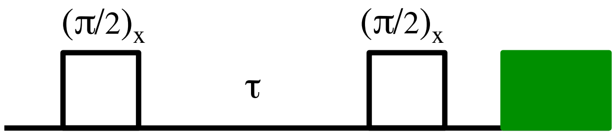


L. Robledo *et al*. Nature **477**, 574–578 (2011).

Decoherence

Decoherence is caused by all the undesired interactions of a quantum state with its environment which shortens its lifetime.





G. de Lange *et al*. Science **330**, 60–63 (2010).

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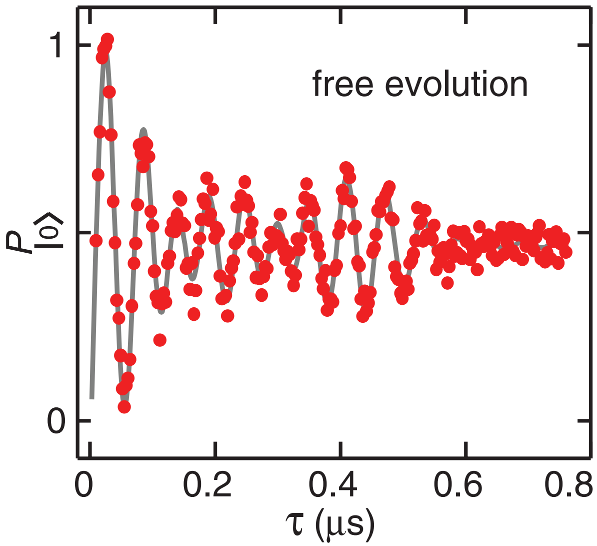
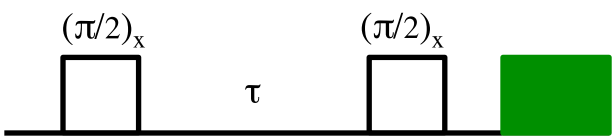


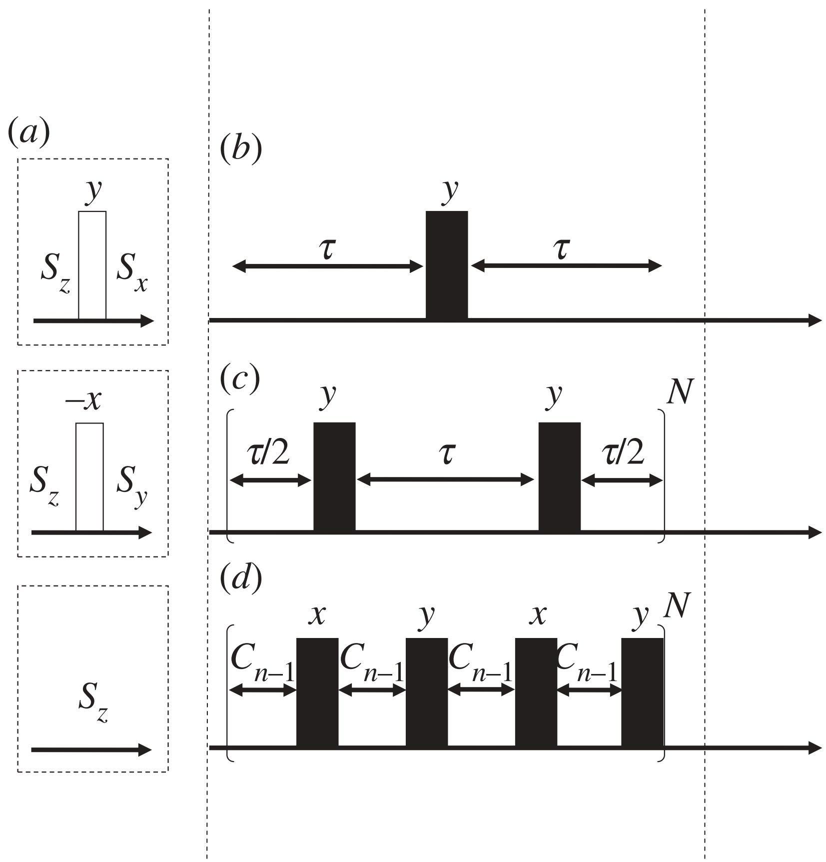


G. de Lange *et al*. Science **330**, 60–63 (2010).

- Dynamic decoupling: Periodic flipping of the qubit spin state to average out the interactions with the environment.

L. Viola *et al.* Phys. Rev A **58**, 2733 (1998).

Dynamical Decoupling



Hahn Echo

Carr–Purcell–Meiboom–Gill

XY-4

A. M. Souza *et al.* Phil. Trans. R. Soc. **370**, 4748–4769 (2012).

Decoherence in multi-qubit gates

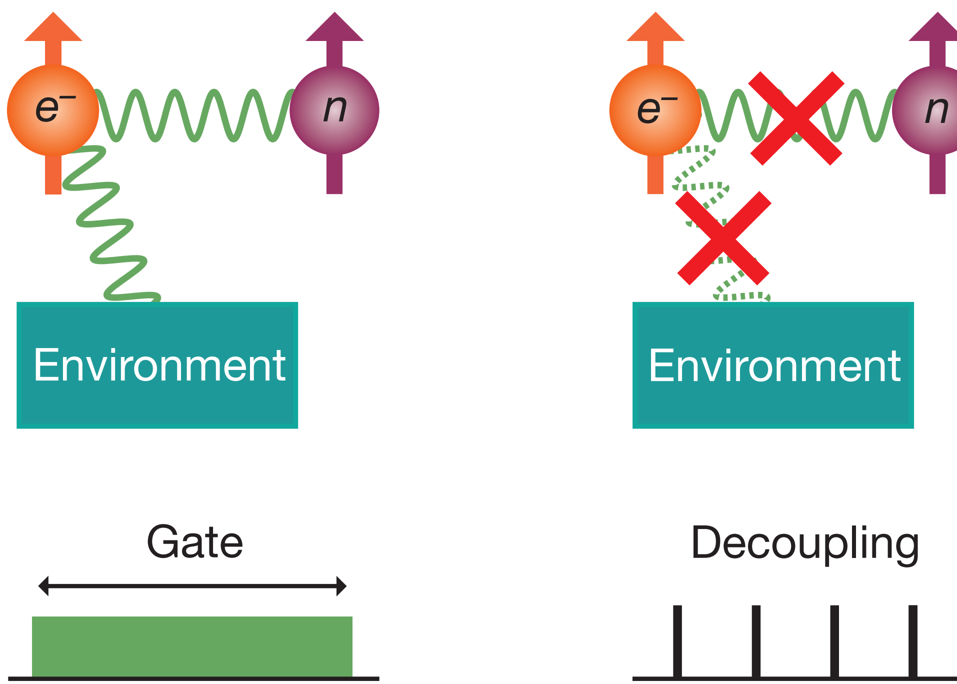
1) Qubits couple to each other but also to environment

N. van der Sar *et al*. Nature **484**, 82–86 (2012).

Decoherence in multi-qubit gates

1) Qubits couple to each other but also to environment

2) Qubits decoupled from each other and environment



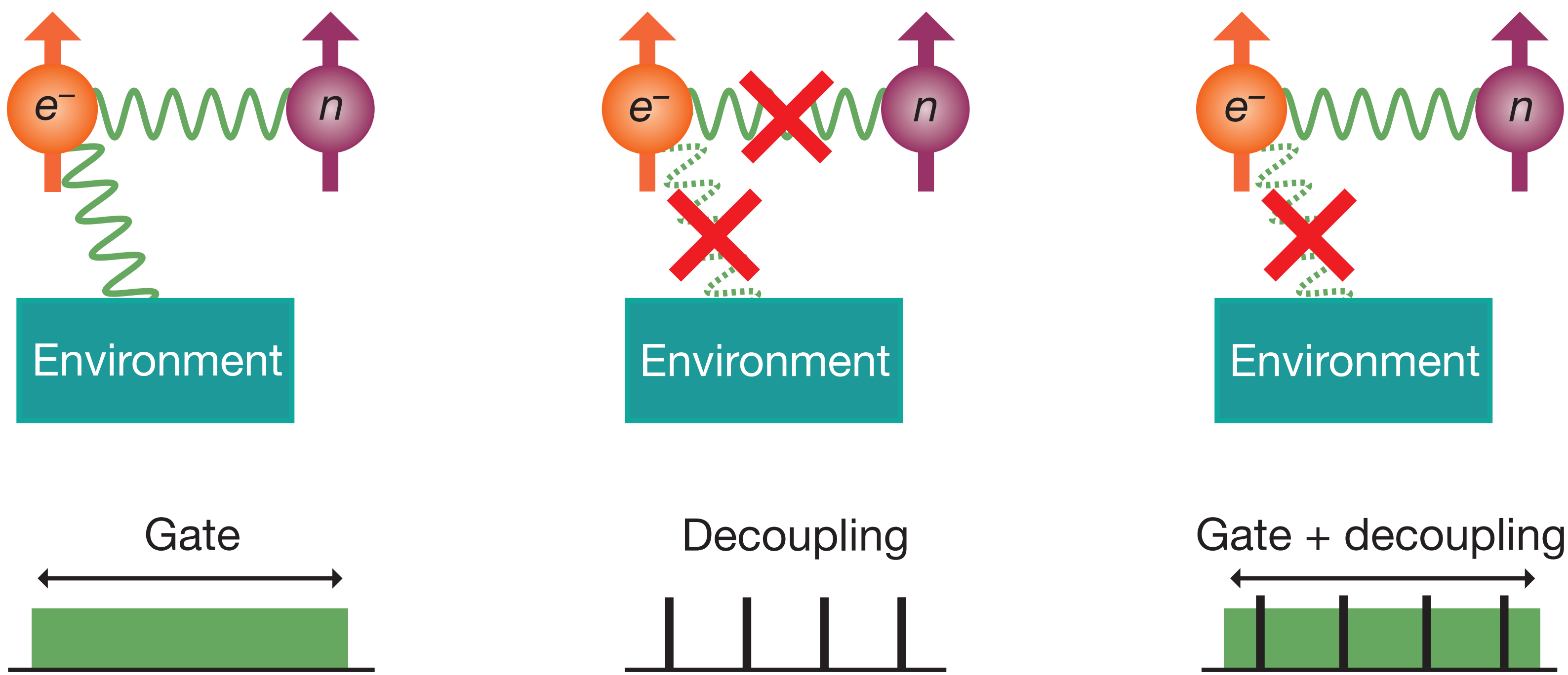
N. van der Sar *et al*. Nature **484**, 82–86 (2012).

Decoherence in multi-qubit gates

1) Qubits couple to each other but also to environment

2) Qubits decoupled from each other and environment

3) Qubits only decoupled from environment



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Qubit Coupling

Qubit Coupling

Generally desirable

Fast coupling for fast qubit manipulation

Qubit Coupling

Generally desirable

Fast coupling for fast qubit manipulation

But we pay a price

We also get faster coupling to the environment

"Fast" and "Slow" Qubits

Encode Physical Qubits in:

"Fast" and "Slow" Qubits

Encode Physical Qubits in:

- atomic states

"Fast" and "Slow" Qubits

Encode Physical Qubits in:

- atomic states
- superconducting circuits

"Fast" and "Slow" Qubits

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"Fast" and "Slow" Qubits

Encode Physical Qubits in:

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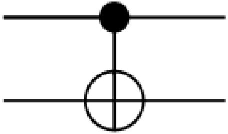
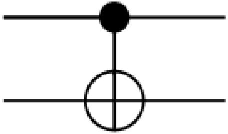
- NV centers

Two Qubit Gates



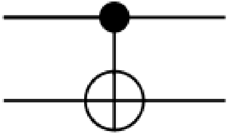
Two Qubit Gates



Difficult Scenario

Using "fast" qubit as the control bit

Two Qubit Gates



Difficult Scenario

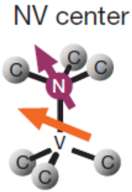
Using "fast" qubit as the control bit

Question

Can we use dynamical decoupling to make a gate using the "fast" qubit as our control bit?

"Fast" and "Slow" Qubits; NV Centers

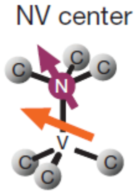
"Fast" qubit: electronic spin



"Fast" and "Slow" Qubits; NV Centers

"Fast" qubit: electronic spin

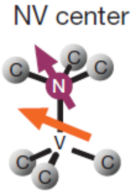
- GHz energy splitting



"Fast" and "Slow" Qubits; NV Centers

"Fast" qubit: electronic spin

- GHz energy splitting
- $T_2 = 3.5\mu s$; Rabi 2π pulse: $20ns$



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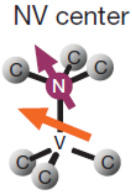

"Fast" and "Slow" Qubits; NV Centers

"Fast" qubit: electronic spin

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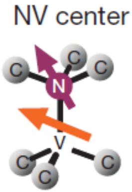
"Slow" qubit: nuclear spin

- MHz energy splitting



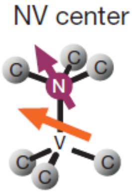
"Fast" and "Slow" Qubits; NV Centers

"Fast" qubit: electronic spin

- GHz energy splitting
- $T_2 = 3.5\mu s$; Rabi 2π pulse: $20ns$

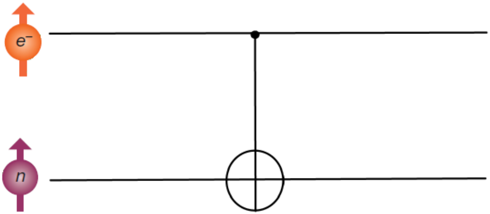
"Slow" qubit: nuclear spin

- MHz energy splitting
- $T_2 = 5.3ms$; Rabi 2π pulse: $30\mu s$



Two Qubit Gates

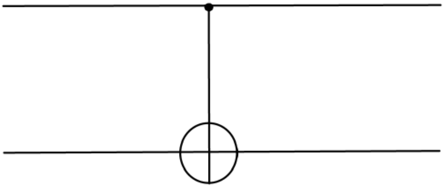
Imagine



Two Qubit Gates

Imagine

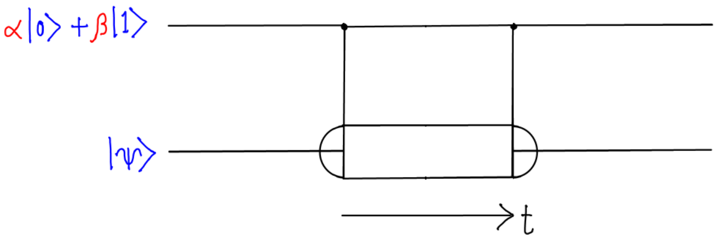
$\alpha|0\rangle + \beta|1\rangle$



$|\psi\rangle$

Two Qubit Gates

Imagine



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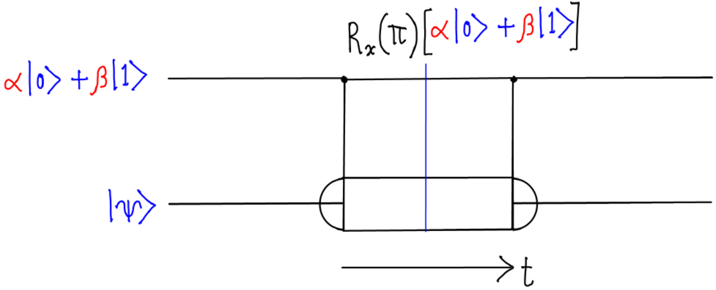

Two Qubit Gates

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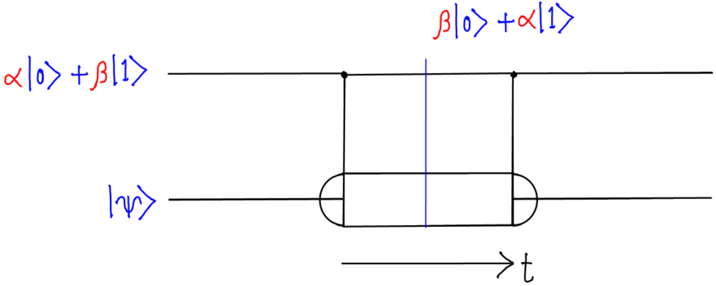

Two Qubit Gates

Not obvious whether this can work

Two Qubit Gates

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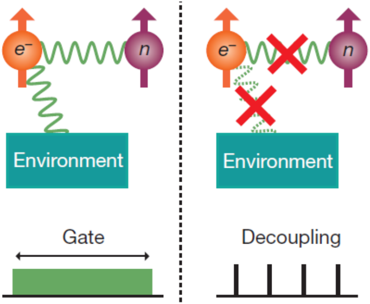
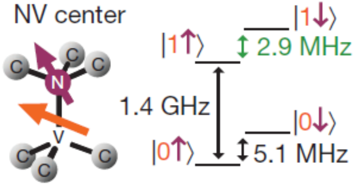


Building a 2-Qubit Gate



Electronic Spin

$m_S = 0 : |0\rangle$

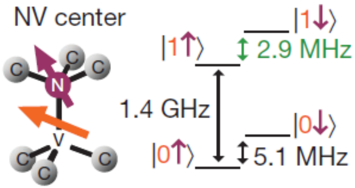
$m_S = -1 : |1\rangle$

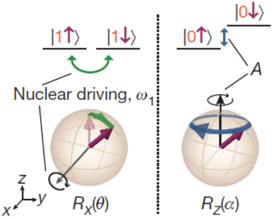
Nuclear Spin

$m_I = +1 : |\uparrow\rangle$

$m_I = 0 : |\downarrow\rangle$

Building a 2-Qubit Gate





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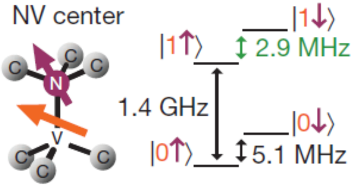

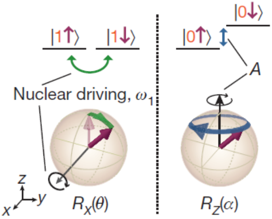

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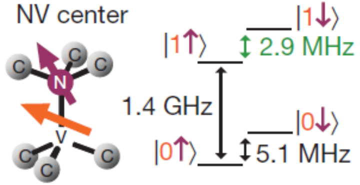
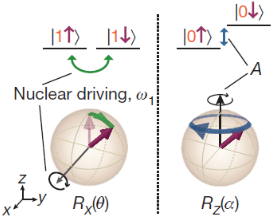
Timescales (μs)

3.5

$T_{2,e}$

Building a 2-Qubit Gate





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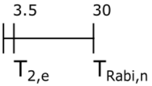
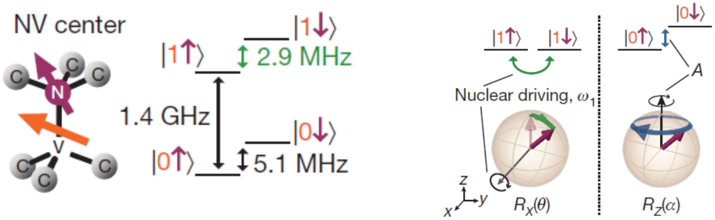
Timescales (μs)



Building a 2-Qubit Gate



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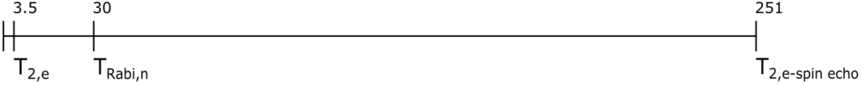
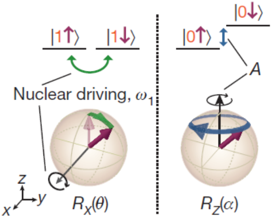


Building a 2-Qubit Gate

Decoupling Pulse Sequence

$\tau - X - 2\tau - Y - \tau$



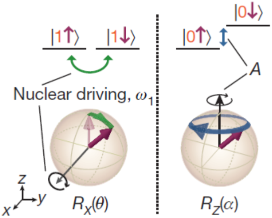
Building a 2-Qubit Gate

Decoupling Pulse Sequence

$\tau - X - 2\tau - Y - \tau$

Electronic Qubit in State $|0\rangle$

$exp(\frac{-i\sigma_z\theta_0}{\hbar})exp(\frac{-i\sigma_x 2\theta_1}{\hbar})exp(\frac{-i\sigma_z\theta_0}{\hbar})$



Building a 2-Qubit Gate

Decoupling Pulse Sequence

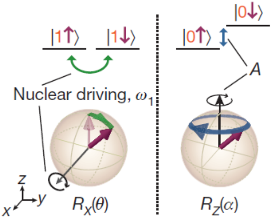
$\tau - X - 2\tau - Y - \tau$

Electronic Qubit in State $|0\rangle$

$$exp(\frac{-i\sigma_z\theta_0}{\hbar})exp(\frac{-i\sigma_x 2\theta_1}{\hbar})exp(\frac{-i\sigma_z\theta_0}{\hbar})$$

Electronic Qubit in State $|1\rangle$

$$exp(\frac{-i\sigma_x\theta_1}{\hbar})exp(\frac{-i\sigma_z 2\theta_0}{\hbar})exp(\frac{-i\sigma_x\theta_1}{\hbar})$$



Building a 2-Qubit Gate

Special case 1

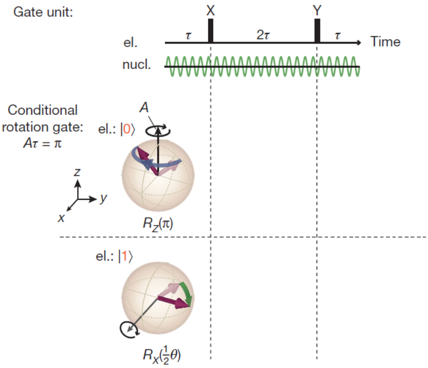
$\tau = (2n+1)\pi/A$

Building a 2-Qubit Gate

Special case 1

$\tau = (2n+1)\pi/A$

Example



Building a 2-Qubit Gate

Special case 1

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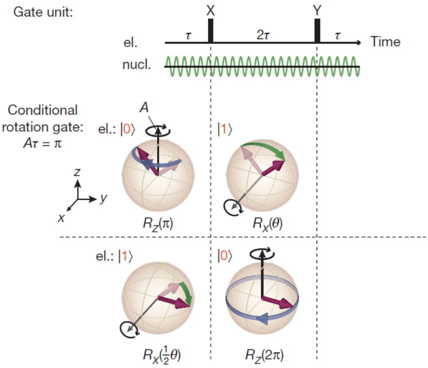
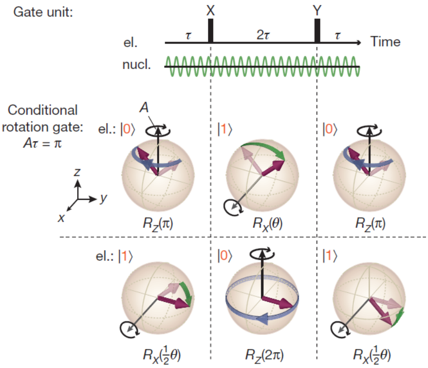


Building a 2-Qubit Gate

Special case 1

$\tau = (2n+1)\pi/A$

Example



Building a 2-Qubit Gate

Special case 2

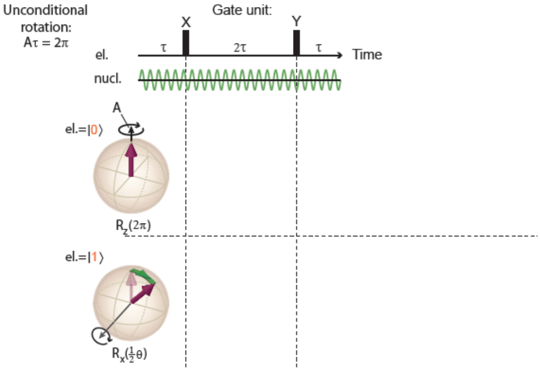
$\tau = 2n\pi/A$

Building a 2-Qubit Gate

Special case 2

$\tau = 2n\pi/A$

Example



Building a 2-Qubit Gate

Special case 2

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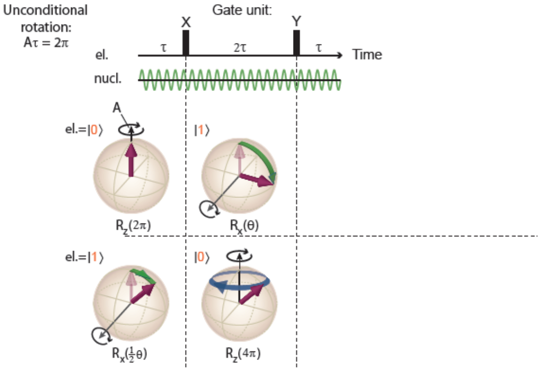
Example

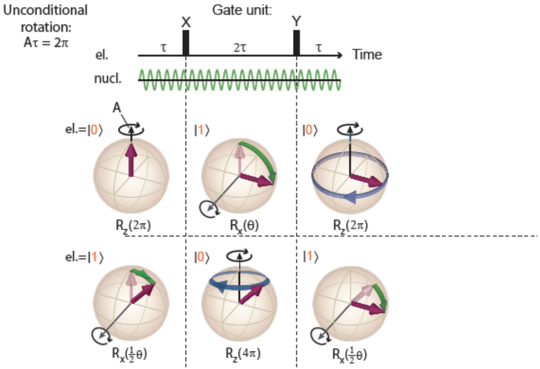


Building a 2-Qubit Gate

Special case 2

$\tau = 2n\pi/A$

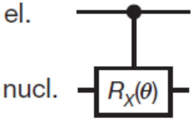
Example



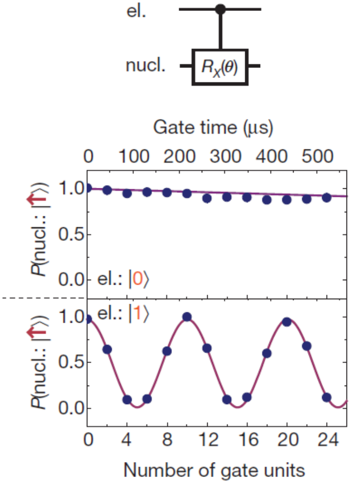
Building a 2-Qubit Gate

Combine special cases 1 and 2

obtain a conditional rotation gate



Experimental Results



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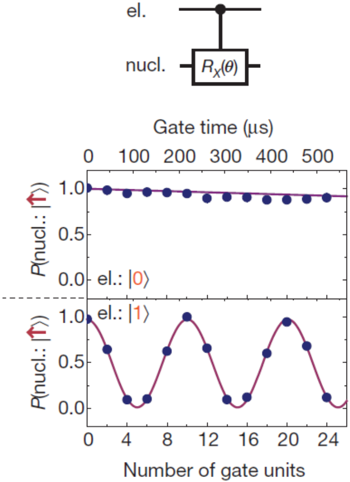

CNOT Gate ($\theta = \pi$)

Process fidelity:

$F_p = Tr(\chi_{ideal}\chi) = 83\%$

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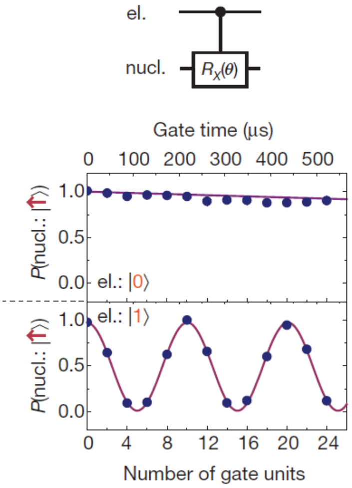

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For a State

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$\rho = |\psi\rangle\,\langle\psi|$

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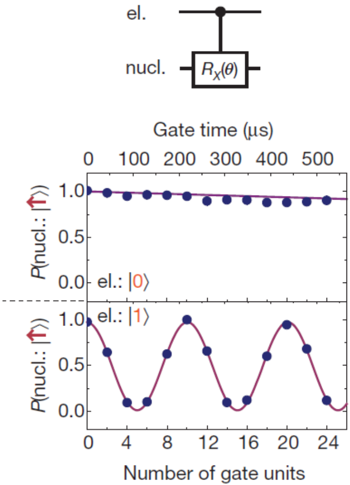

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$\rho = |\psi\rangle\,\langle\psi|$

For an Operator

$A = \alpha\mathbb{I} + \beta\sigma_x + \gamma\sigma_y + \delta\sigma_z$

$\varepsilon(\rho) = A\rho A^\dagger = \sum_{i,j}\chi_{ij}E_i\rho E_j{}^\dagger$

Testing Gate Robustness

Inject noise into the diamond

Reduce $T_{2,SE}$ from $251\mu s$ to $50\mu s$

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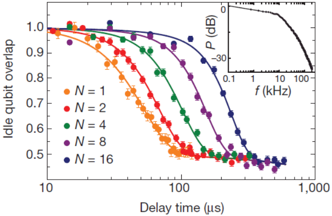
apply $(\tau - \pi - \tau)^N$



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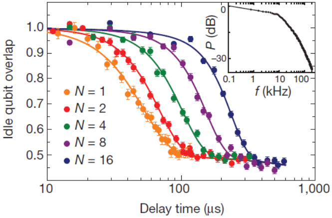


$$T_{2,N=16} = 234\mu s$$

Testing Gate Robustness

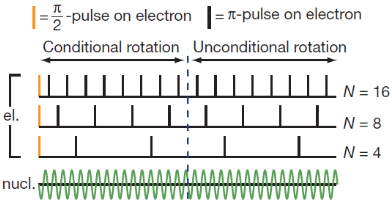
Apply CNOT

Input state

$(|0\rangle + i\,|1\rangle) \otimes |{\uparrow}\rangle$

Desired output state

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



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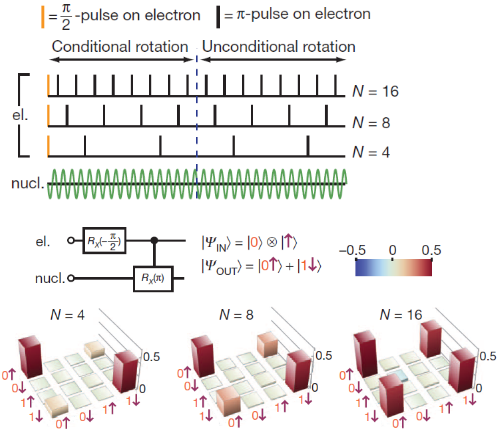

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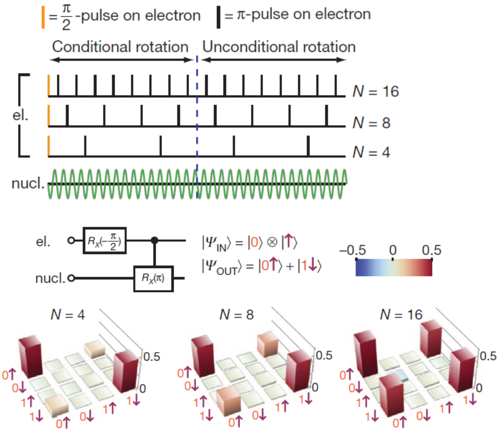
State Fidelity

$N = 16 : F = \sqrt{\langle\psi|\,\rho\,|\psi\rangle}$
reaches 96%



Running Grover's Algorithm

Recall: Search Algorithm

- Find entry in list of N elements
- Number of oracle calls scales as $\sqrt{N}$

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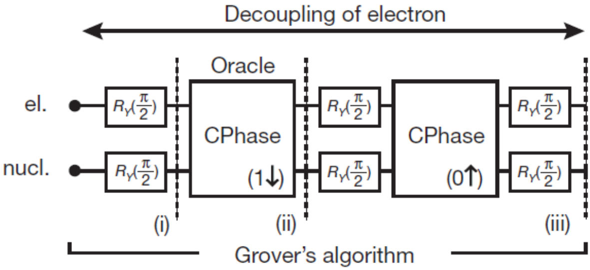

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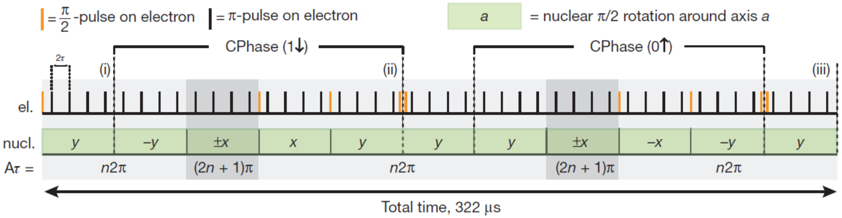

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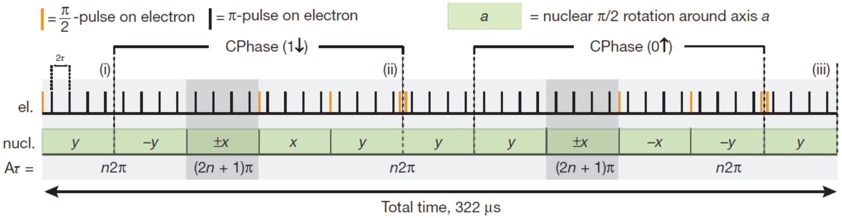

Final State Fidelity $> 90\%$

Summary

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- Can construct 2-qubit gate protected from decoherence

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- Can construct 2-qubit gate protected from decoherence
- Especially useful when control bit is "fast"
- Achieved process fidelities above 80%, and state fidelities above 90% using an NV center
- Ultimate goal: $< 10^{-4}$

Quantum Teleportation

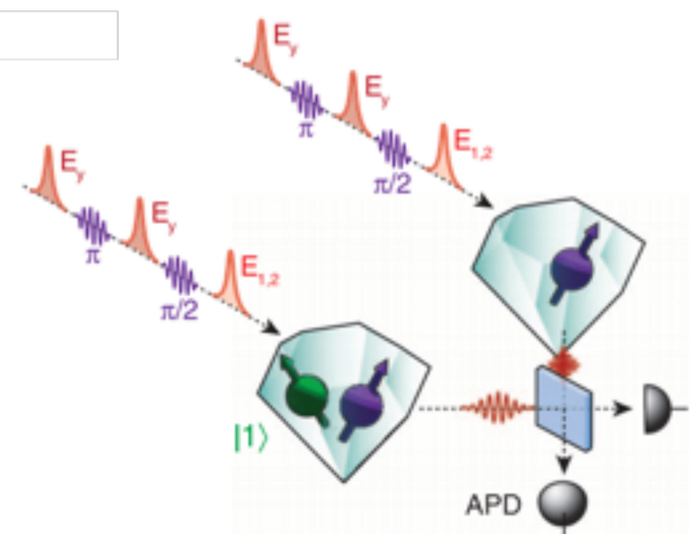
NV - Centers

Framework

- Unconditional teleportation
  - Any state can be transmitted
- Remoteness
  - Sender and reciever are reasonably separated *(3m)*

Entanglement

- Remote entanglement between NV electrons
  - Local entanglement: Spin rotation / Spin-selective excitation
    Electron-Photon
  - Local entanglement: Quantum interference photon detection
    Photon-Photon



Teleporter Setup

Configuration

- Alice NV-Center:
  Transmission Qubit (1) *Nuclear spin*
  Messenger Qubit (2) *Electron spin*

- Bob NV-Center:
  Reciever Qubit (3) *Electron spin*

- Qubits 2 & 3 entangled in $|\Psi^{-}\rangle_{23}$

Teleporter Setup

Initialization

- Transmission Qubit initialized in $|1\rangle_1$
  - Projective measurement of Messenger
  - Prior to entanglement
- Source State $|\psi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$
  - After entanglement to avoid Dephasing

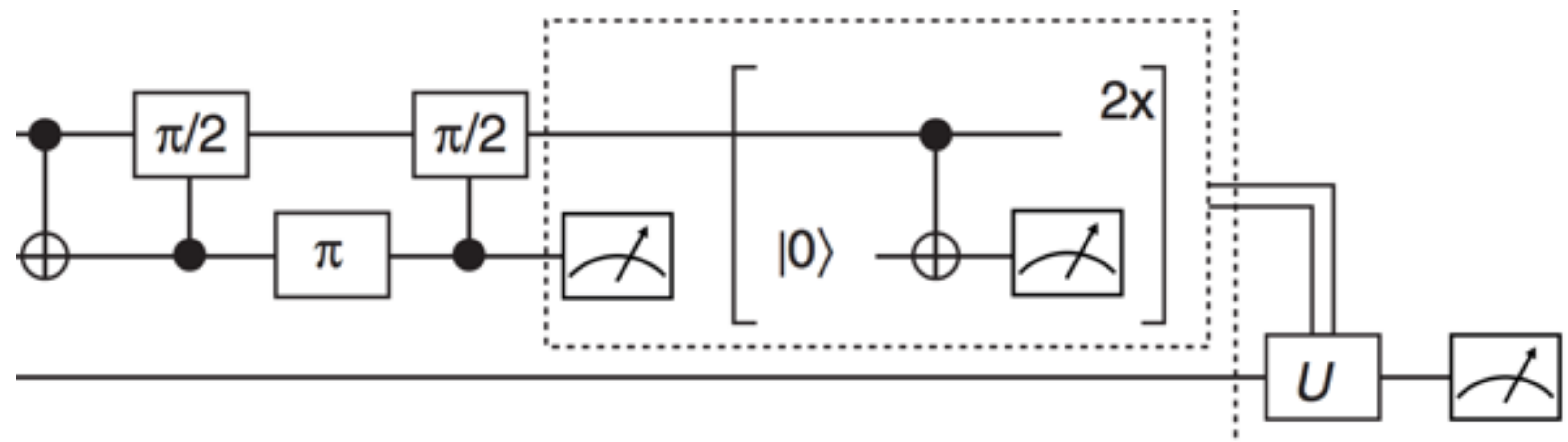
Teleporter Setup

Final State

- Final State in Bell basis:

$$
\begin{aligned}
|\psi\rangle_1 \otimes |\Psi^-\rangle_{23} = \frac{1}{2}[&|\Phi^+\rangle_{12}(\alpha|1\rangle_3 - \beta|0\rangle_3) \\
&+|\Phi^-\rangle_{12}(\alpha|1\rangle_3 + \beta|0\rangle_3) \\
&+|\Psi^+\rangle_{12}(-\alpha|0\rangle_3 + \beta|1\rangle_3) \\
&+|\Psi^-\rangle_{12}(-\alpha|0\rangle_3 - \beta|1\rangle_3)]
\end{aligned}
$$

Teleportation



- Interaction between Qubits 1 and 2
    - CNOT followed by $\pi/2$ Y-rotation of Transmitter
- Projective measurements
- Conditional Pauli-rotations

Teleportation

Interaction

- Nuclear rotations controlled by Electron excitation level:
  - Controlled $\pi/2$ Y-rotation (on 1 controlled by 2)
    π Y-rotation (unconditional on 2)
    Controlled $\pi/2$ Y-rotation (on 1 controlled by 2)

    Effectively: $\pi/2$ Y-rotation (unconditional on 1)

Teleportation

Interaction

- Overall state after interaction:

$$
\begin{aligned}
&R_{y1}(^{\pi}/_{2})U_{CNOT}(|\psi\rangle_1 \otimes |\Psi^-\rangle_{23}) = \\
&\frac{1}{2}[|11\rangle_{12}(\alpha|1\rangle_3 - \beta|0\rangle_3) \\
&+ |01\rangle_{12}(\alpha|1\rangle_3 + \beta|0\rangle_3) \\
&+ |10\rangle_{12}(\alpha|0\rangle_3 - \beta|1\rangle_3) \\
&+ |00\rangle_{12}(\alpha|0\rangle_3 + \beta|1\rangle_3)]
\end{aligned}
$$

Teleportation

Interaction

- Overall state after interaction:

$$R_{y1}({}^{\pi}/_{2})U_{CNOT}(|\psi\rangle_1 \otimes |\Psi^-\rangle_{23}) =$$
$$\frac{1}{2}[|11\rangle_{12}(\sigma_{xz}|\psi\rangle_3)$$
$$+ |01\rangle_{12}(\sigma_x|\psi\rangle_3)$$
$$+ |10\rangle_{12}(\sigma_z|\psi\rangle_3)$$
$$+ |00\rangle_{12}(\mathbb{1}|\psi\rangle_3)]$$

Teleportation

Measurement

- Direct measurement on messenger
- Projective measurement on transmitter
  - CNOT on $|0\rangle_2$ electron (on reinitialized messenger, controlled by transmitter)
    Direct measurement on messenger

Teleportation

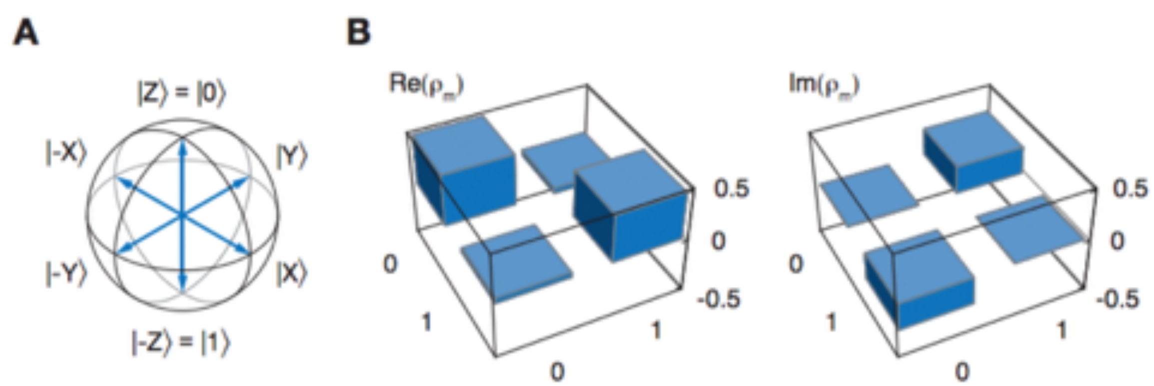
Pauli rotations

- Depending on measurement:

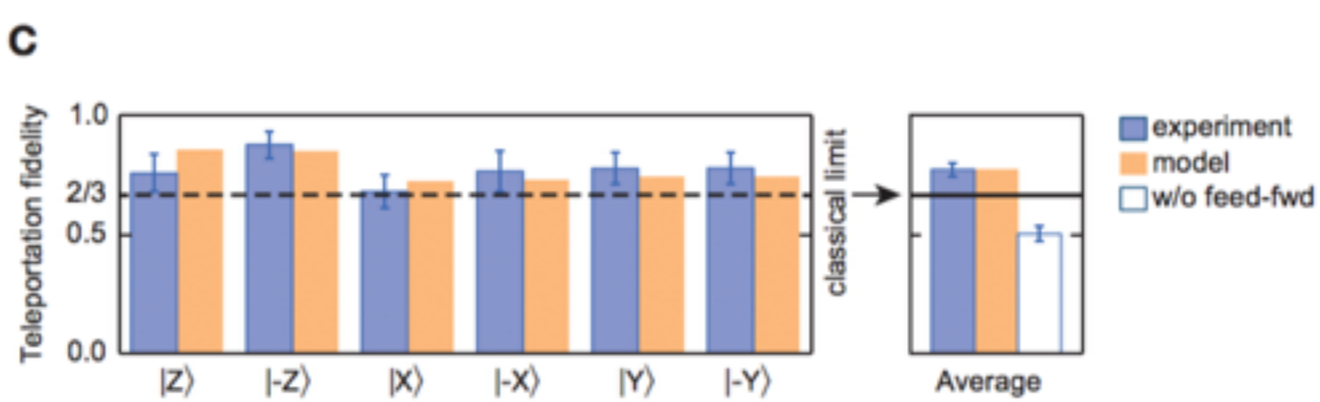
$$
\begin{aligned}
|00\rangle_{12} &\mapsto \mathbb{1} \\
|10\rangle_{12} &\mapsto \sigma_z \\
|01\rangle_{12} &\mapsto \sigma_x \\
|11\rangle_{12} &\mapsto \sigma_{xz}
\end{aligned}
$$

Results

- Tomography for Y on Bob's side to confirm alignment of reference frames



- 6 unbiased states transmitted. **Fidelity 0.77**



Outlook

- Remote Entanglement
  Mutliple Qubits per node:

  - NV Centers are a good candidate for Quantum networks

- Entanglement fidelity high enough to close detection loophole of Bell Inequality