ETH zürich

# "Demonstration of entanglement-by-measurement of solid-state qubits" Pfaff et al., Nature Physics (2013)

Maximilian Holst, Joshua Maas

# Entanglement by measurement

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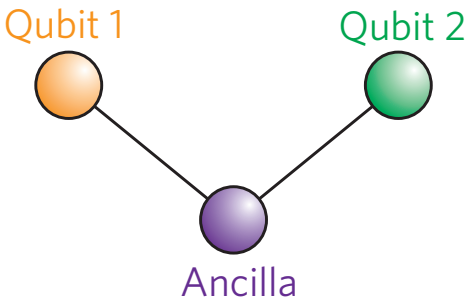


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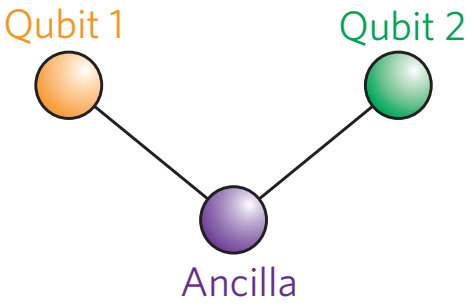


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Separable state:

$$|\psi\rangle = |00\rangle + |01\rangle + |10\rangle + |11\rangle$$

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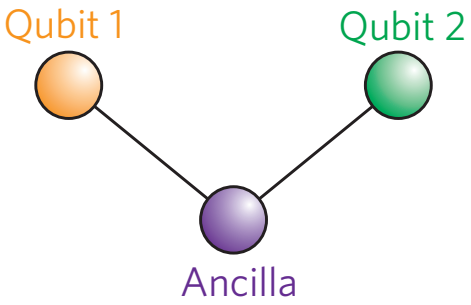


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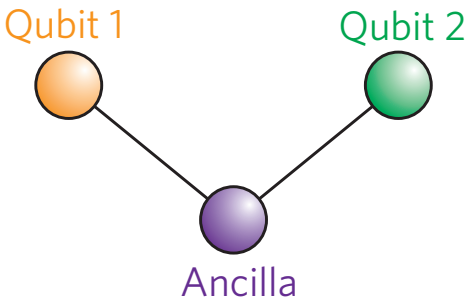


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Measurement:

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Maximally entangled state:

$$\hat{P}\,|\psi\rangle = |00\rangle + |11\rangle = \left|\Phi^{+}\right\rangle$$

# Overview

- Part 1 - Physical system
- Part 2 - Entanglement by measurement
- Part 3 - Results

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- **Part 1 - Physical system**
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# NV centre

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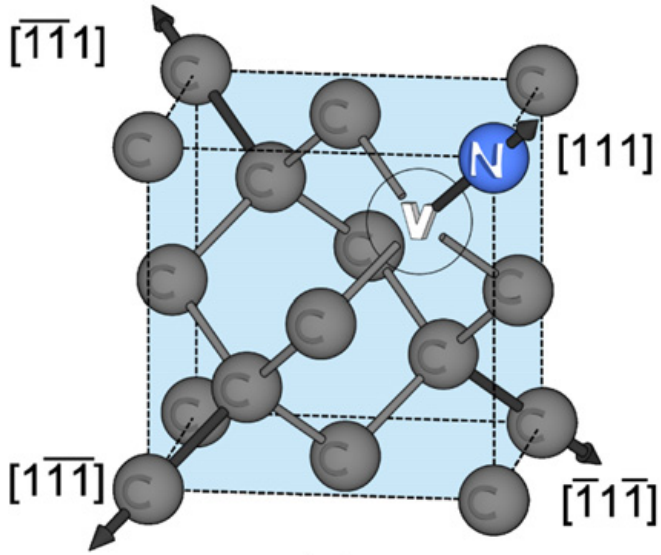
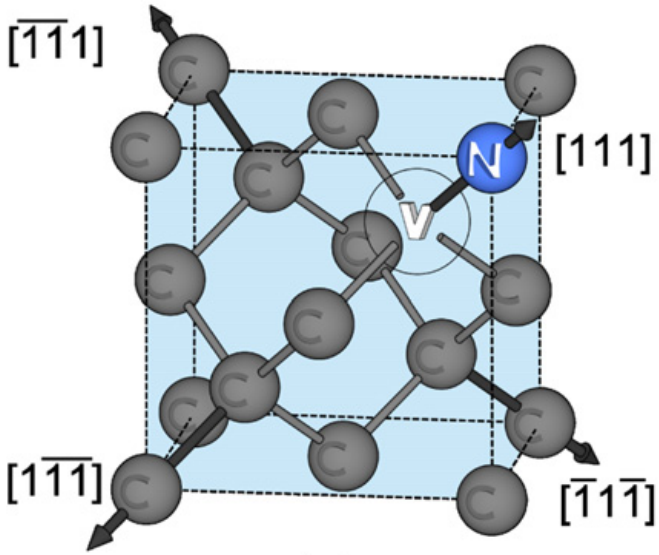



Doherty et al., Measuring the defect structure orientation of a single NV centre in diamond, New Journal of Physics, Vol. 16, 063067

# NV centre

- NV = nitrogen vacancy
- Point defect in $^{13}C$ diamond
  - One $^{13}C$ is missing
  - One $^{13}C$ is replaced by $^{14}N$

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# Electronic ground state configuration

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- 6 electrons in the NV centre
- 4 dangling bonds $\sigma_1, \sigma_2, \sigma_3, \sigma_N$ result in the orbitals $a_1', a_1$
- 2 electrons occupy the orbitals $e_x, e_y$ and form a spin triplet state
  - interpret them as 1 effective “ancilla” electron with spin $S = 1$

# Energy level splitting

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- Zero-field splitting

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- Zeeman splitting
  - Magnetic field: $B = 5 \cdot 10^{-4}\ \mathrm{T}$

# Energy level splitting

- Zero-field splitting
- Zeeman splitting
  - Magnetic field: $B = 5 \cdot 10^{-4}\ \mathrm{T}$
- Hyperfine splitting
  - Nuclear spin of carbon: $I_C = 1/2$
  - Nuclear spin of nitrogen: $I_N = 1$

# Qubits

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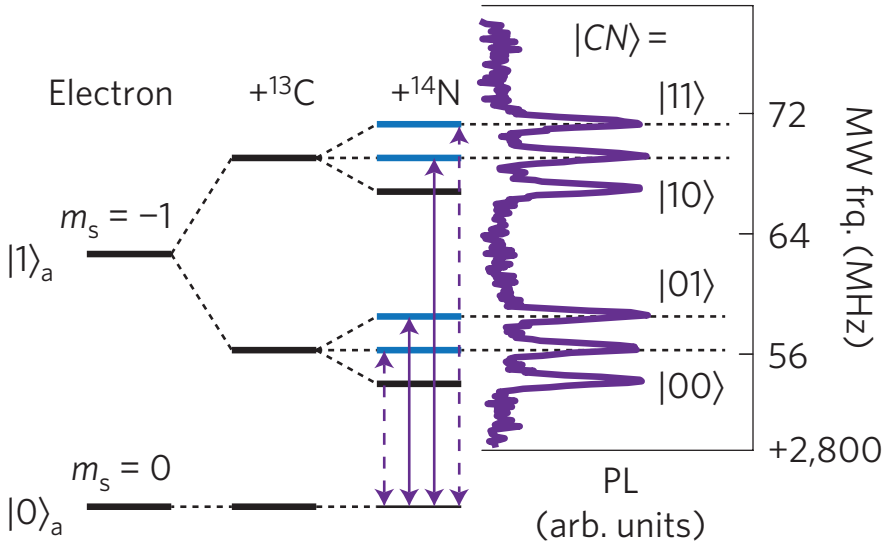


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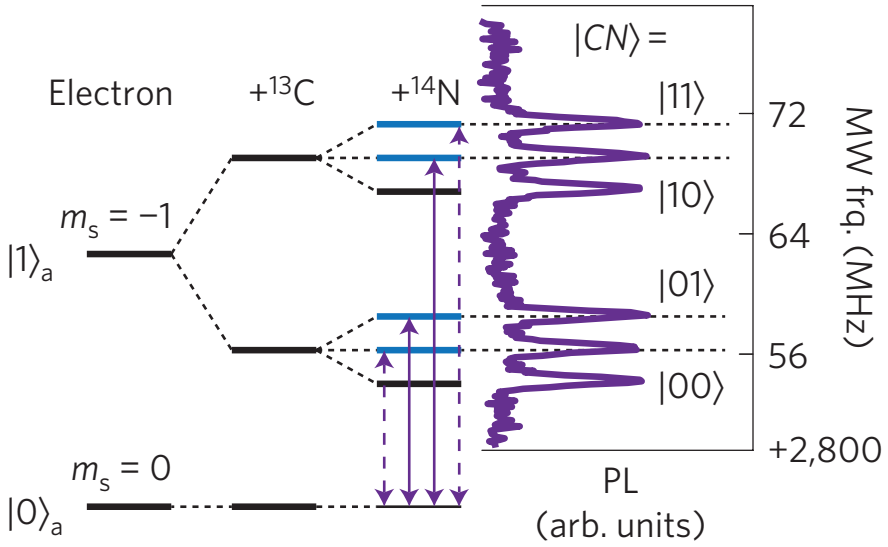


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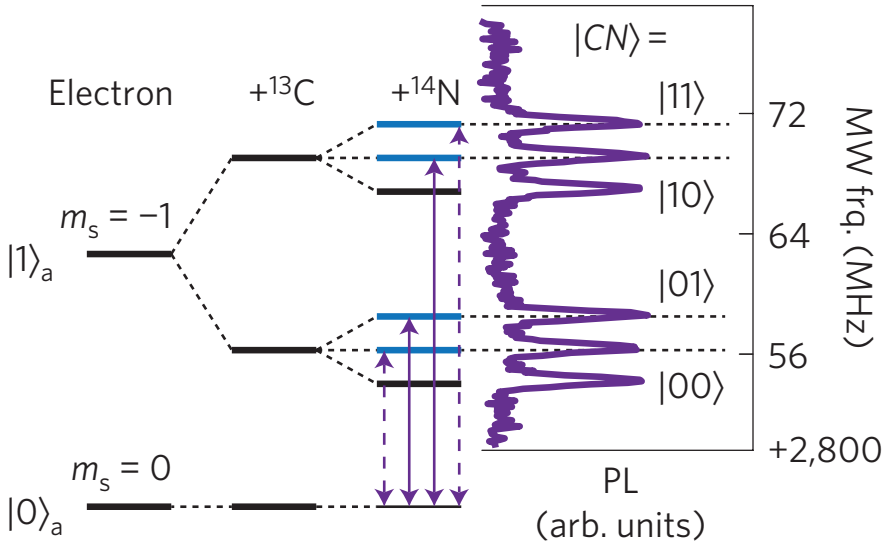


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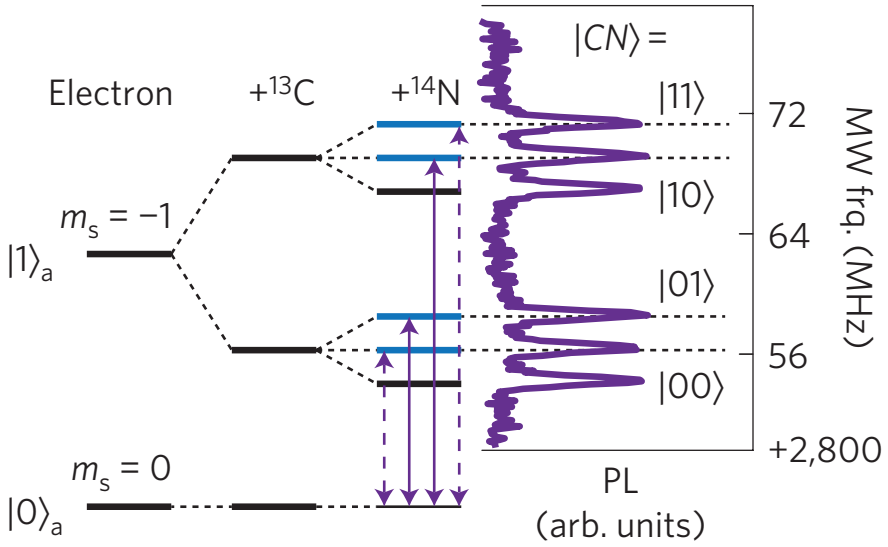


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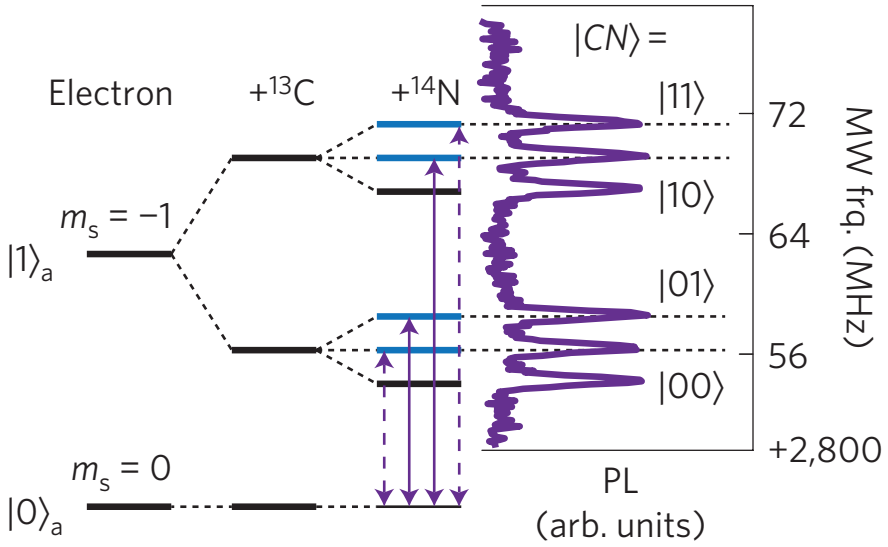


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- Qubits: $|CN\rangle = (m_{I_C}, m_{I_N})$

  $|11\rangle = (-1/2, 1)$
  $|10\rangle = (-1/2, 0)$
  $|01\rangle = (1/2, 1)$
  $|00\rangle = (1/2, 0)$

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# Entanglement by measurement

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**mixed state**

$$\left|\Phi^{+}\right\rangle_{CN} = |00\rangle_{CN} + |11\rangle_{CN}$$

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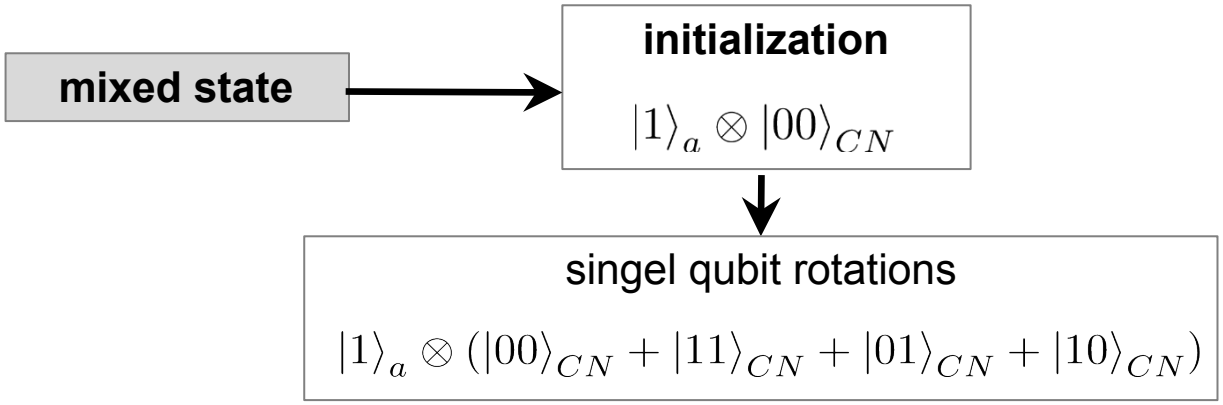


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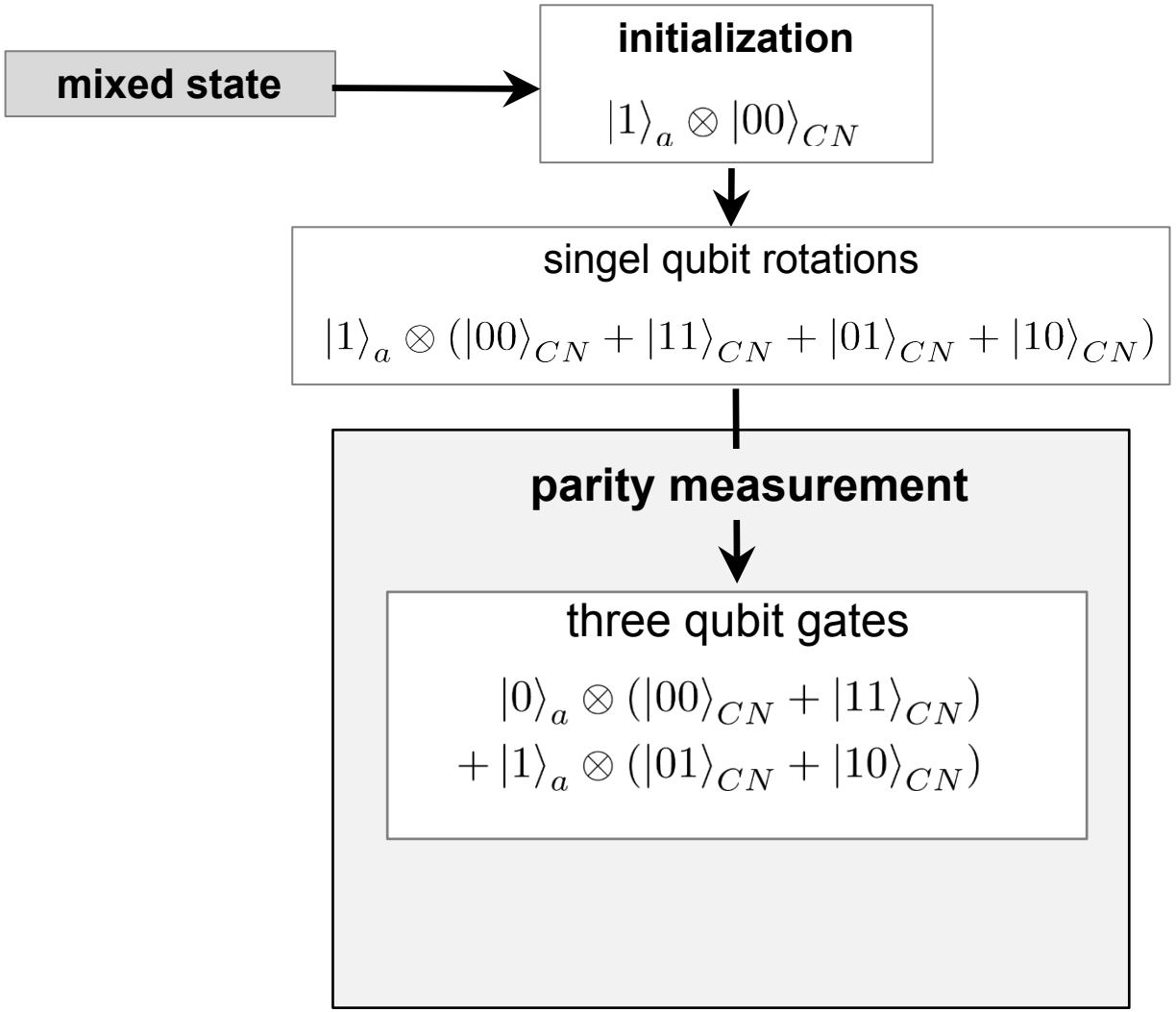


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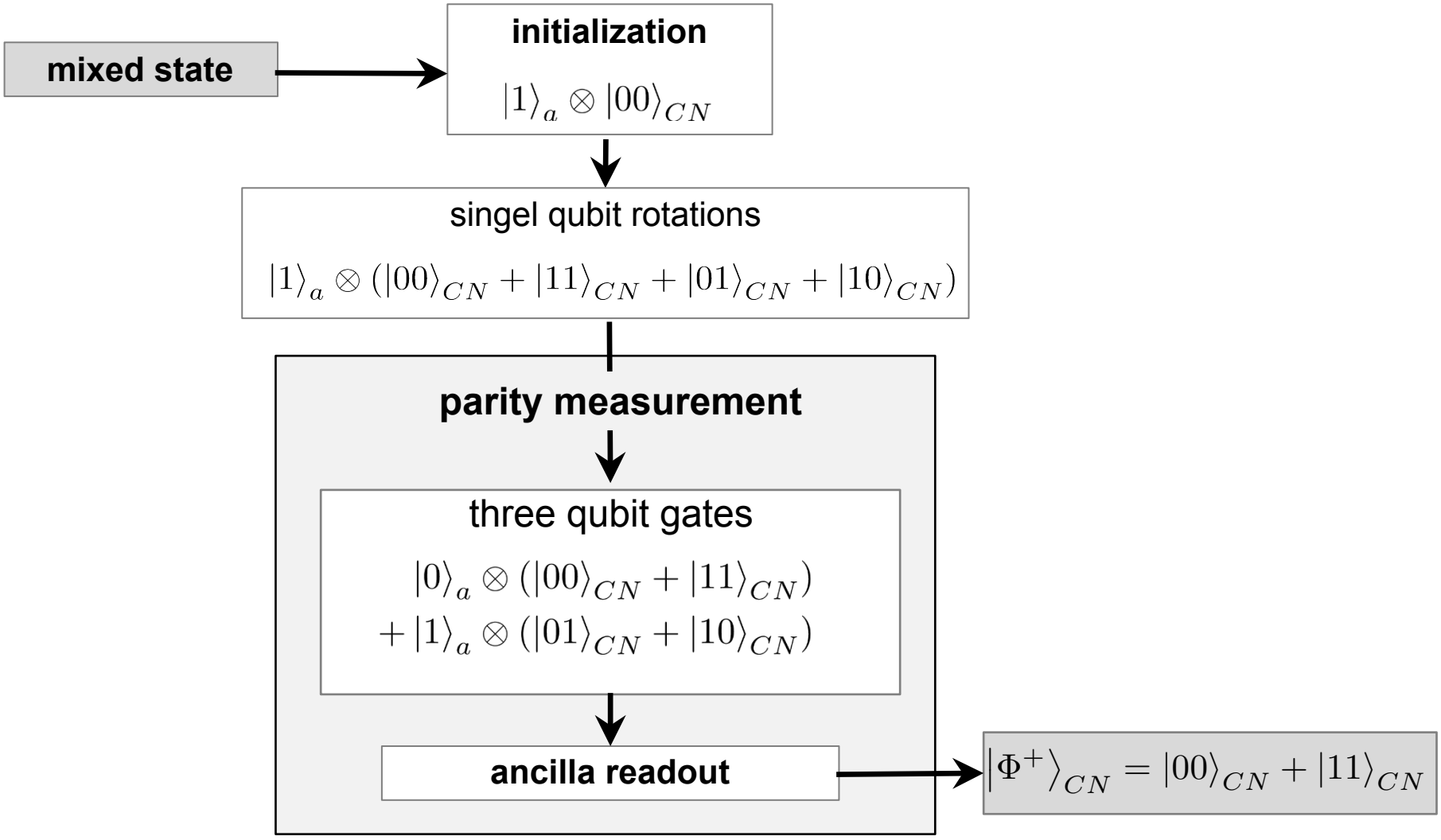

# Ancilla readout

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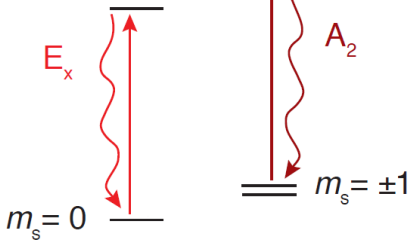
## NV-levelscheme

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—— radiative, spin-conserving transition

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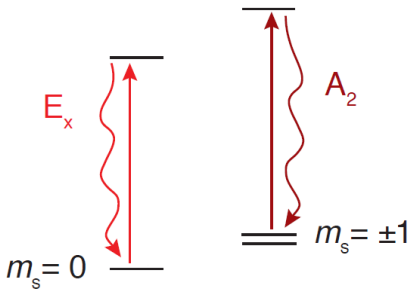


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measure flourescence:
Observed a photon?!

yes

no

$m_s = 0$

$abort$

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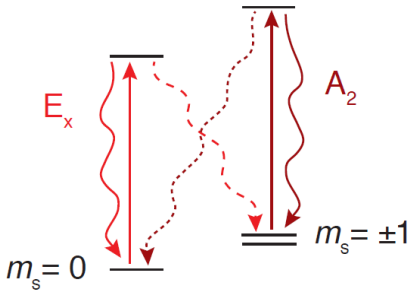


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~~~ non-radiative transition

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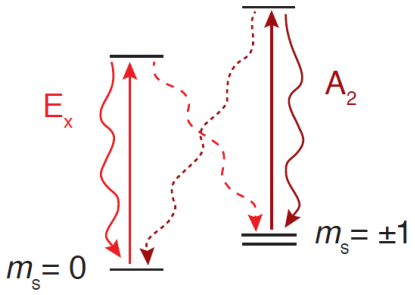


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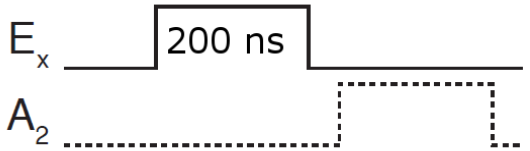
## Non-destructive readout sequence

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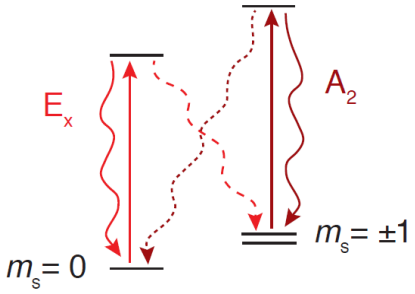


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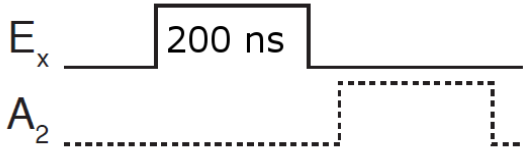


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measure flourescence:
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- post-readout state fidelity $(99 \pm 1)\%$
- successrate $6\%$
~~~

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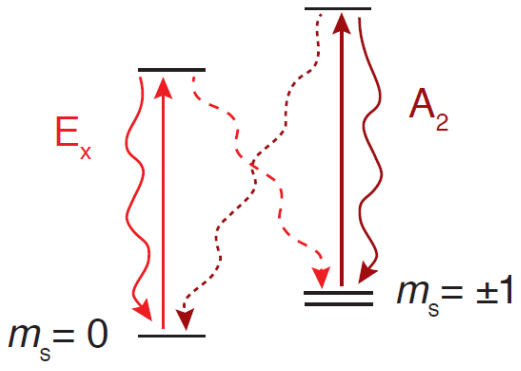


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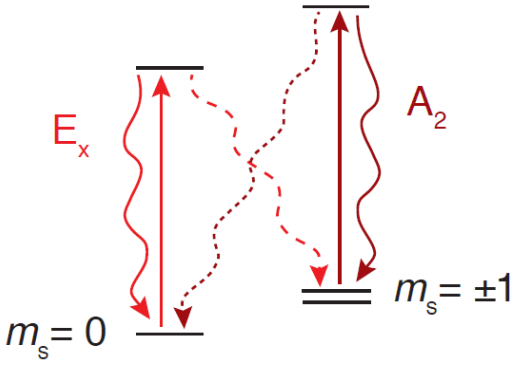


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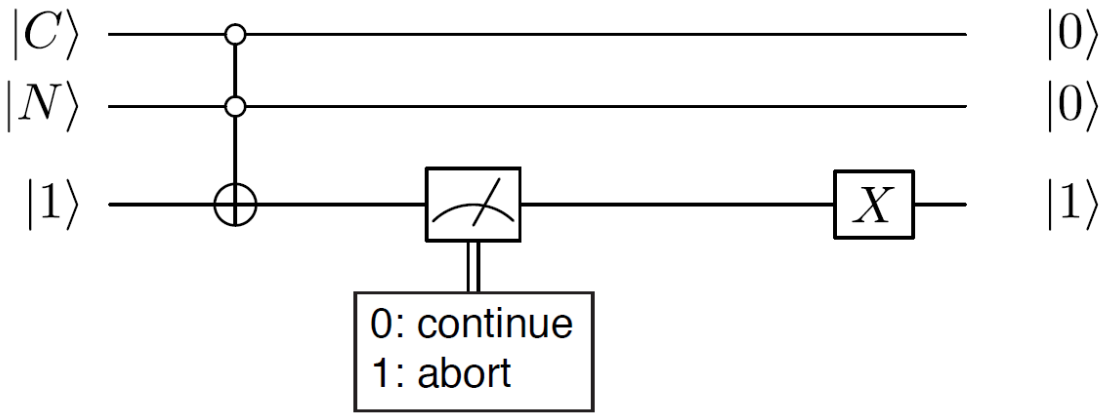


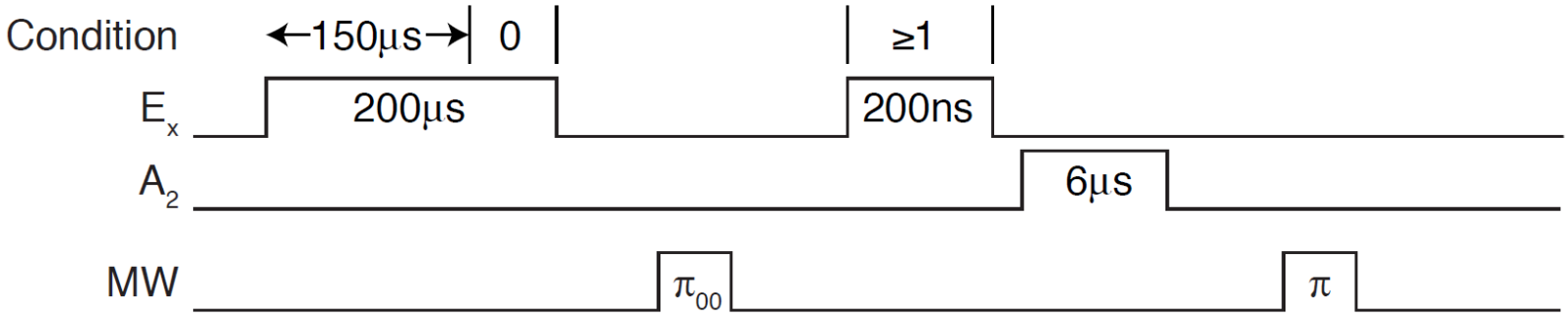

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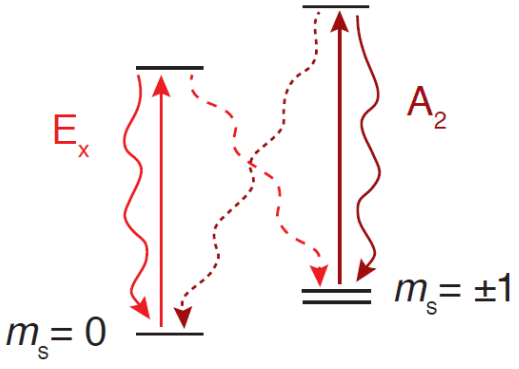


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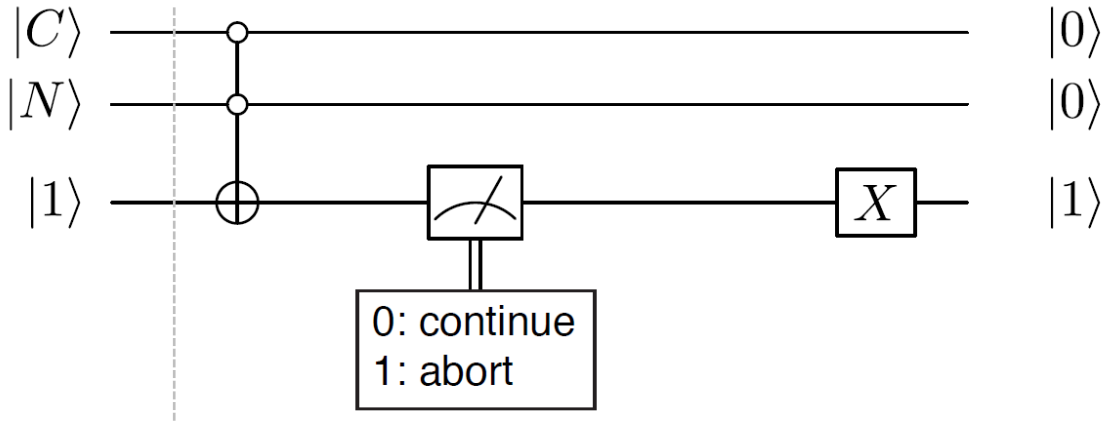


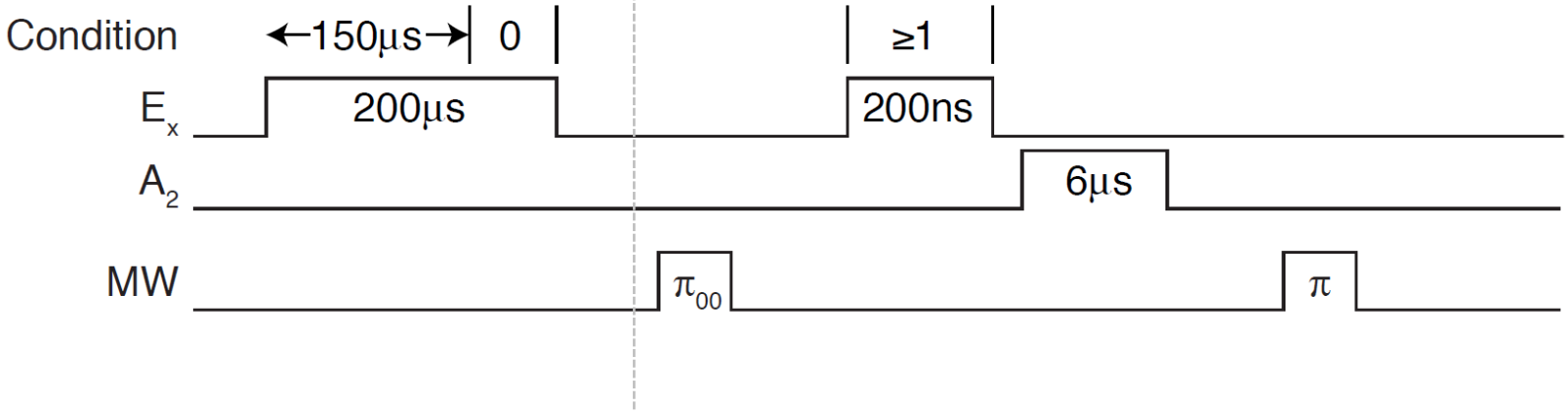

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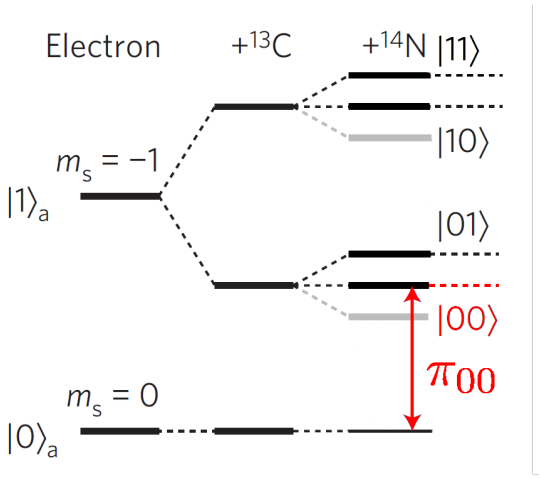


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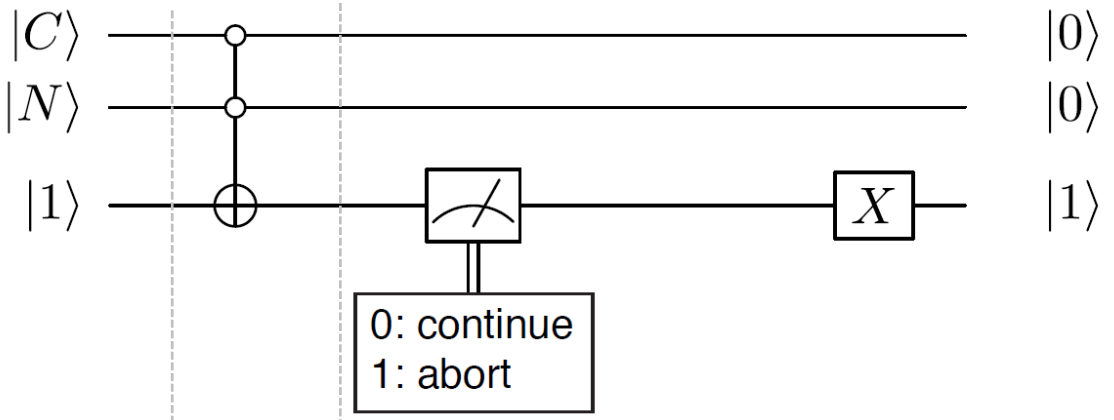


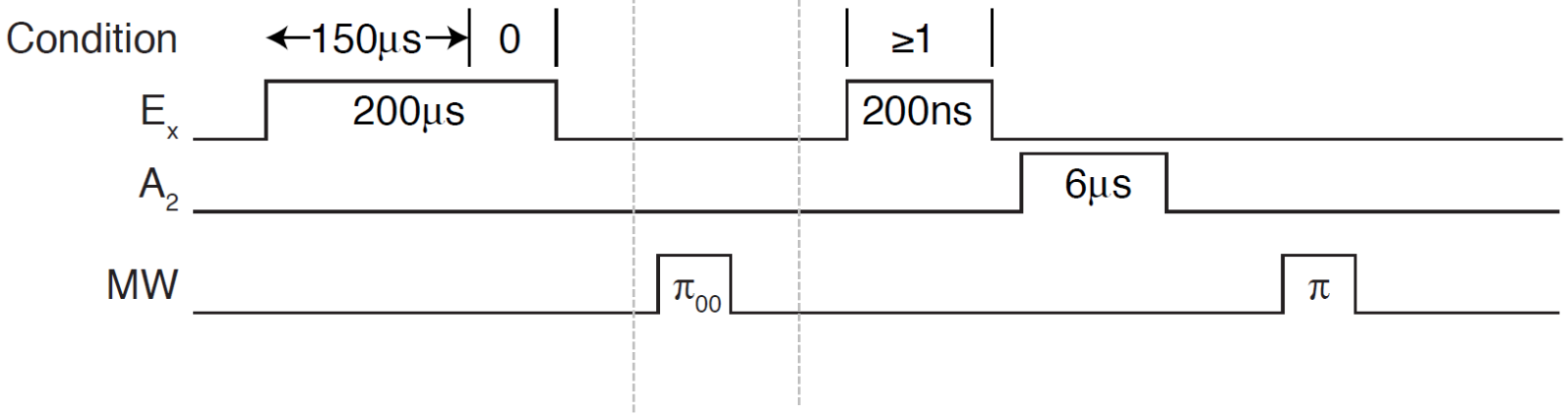

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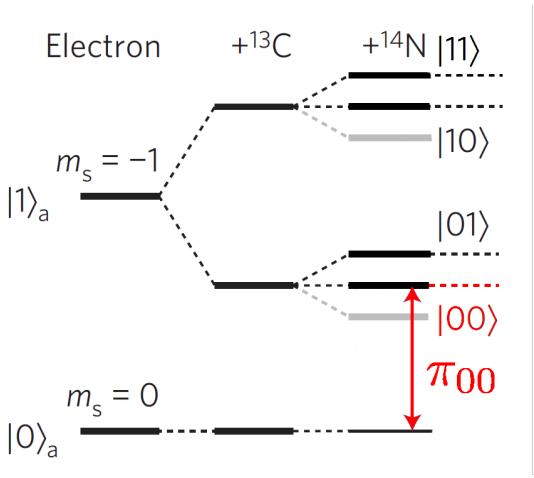


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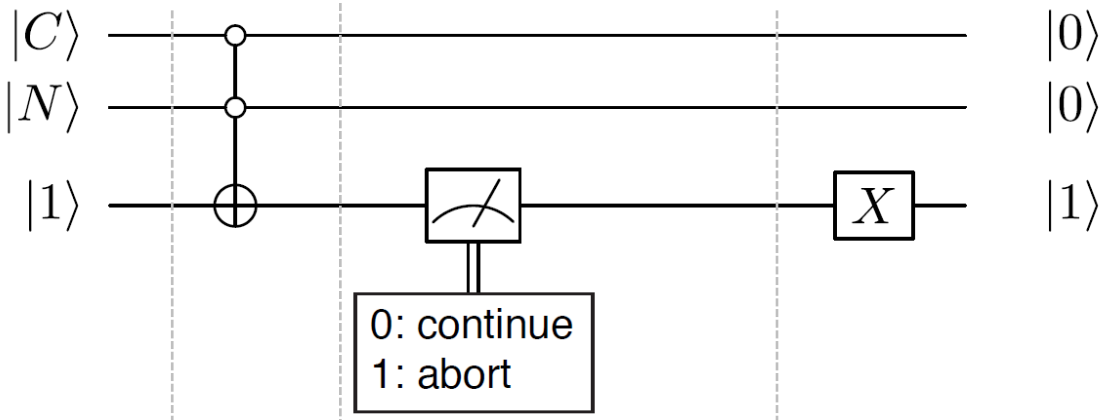
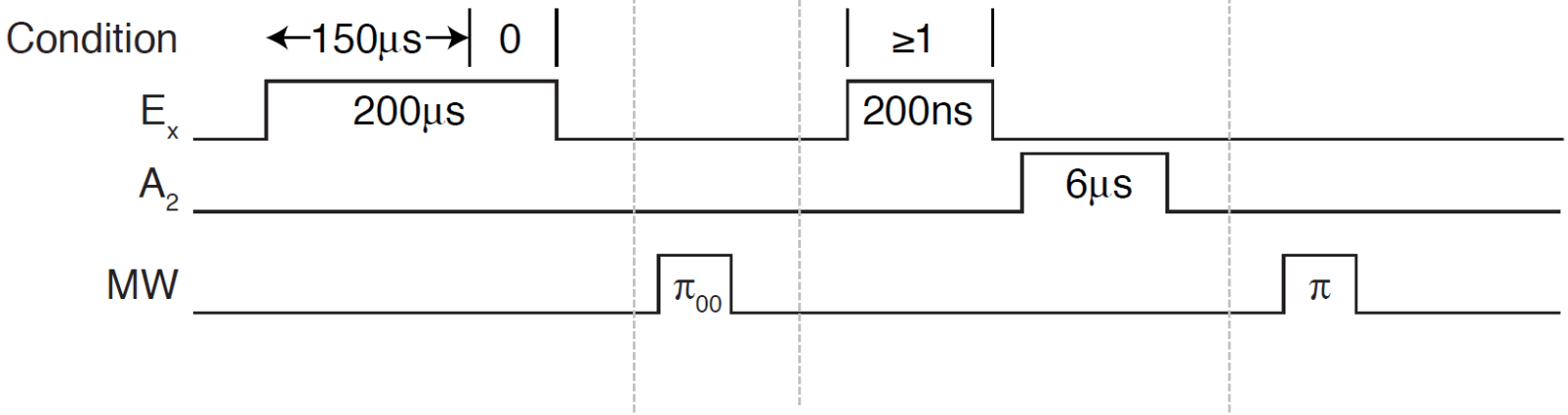
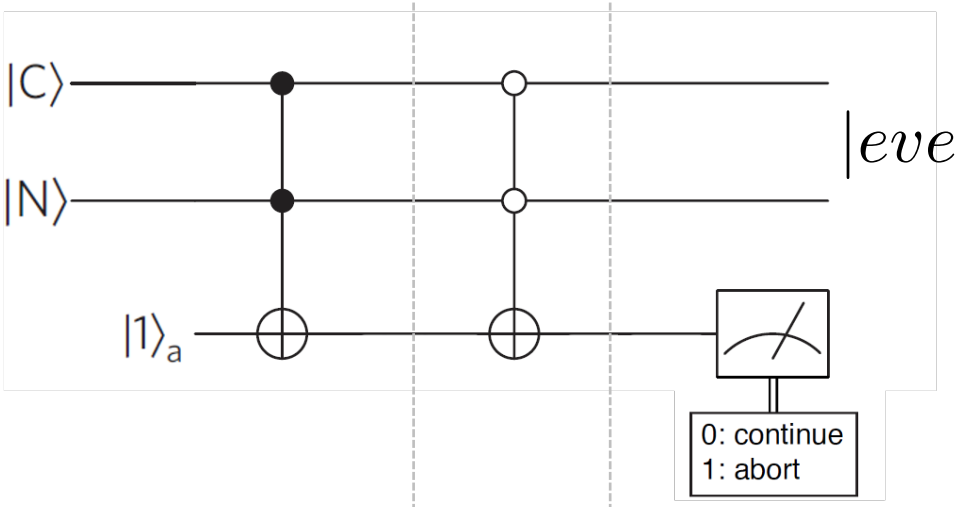


# Parity measurement




$$|even\rangle_{CN}$$

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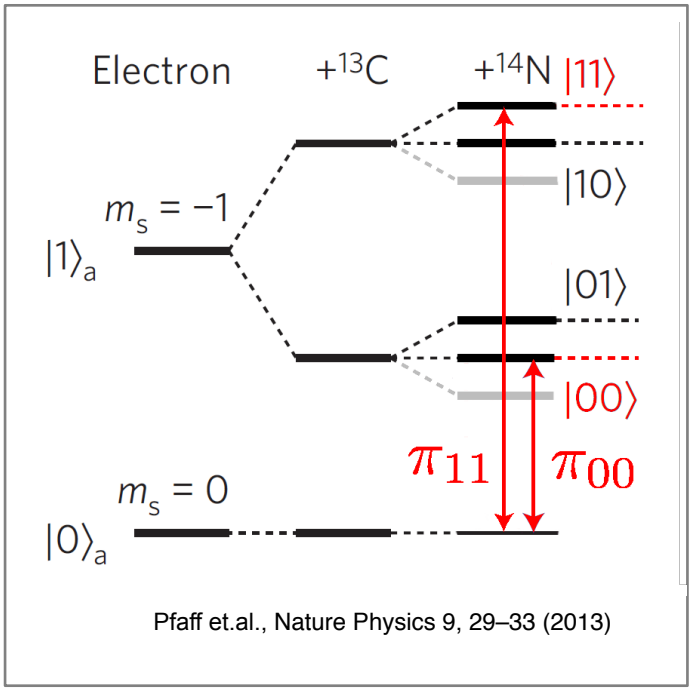


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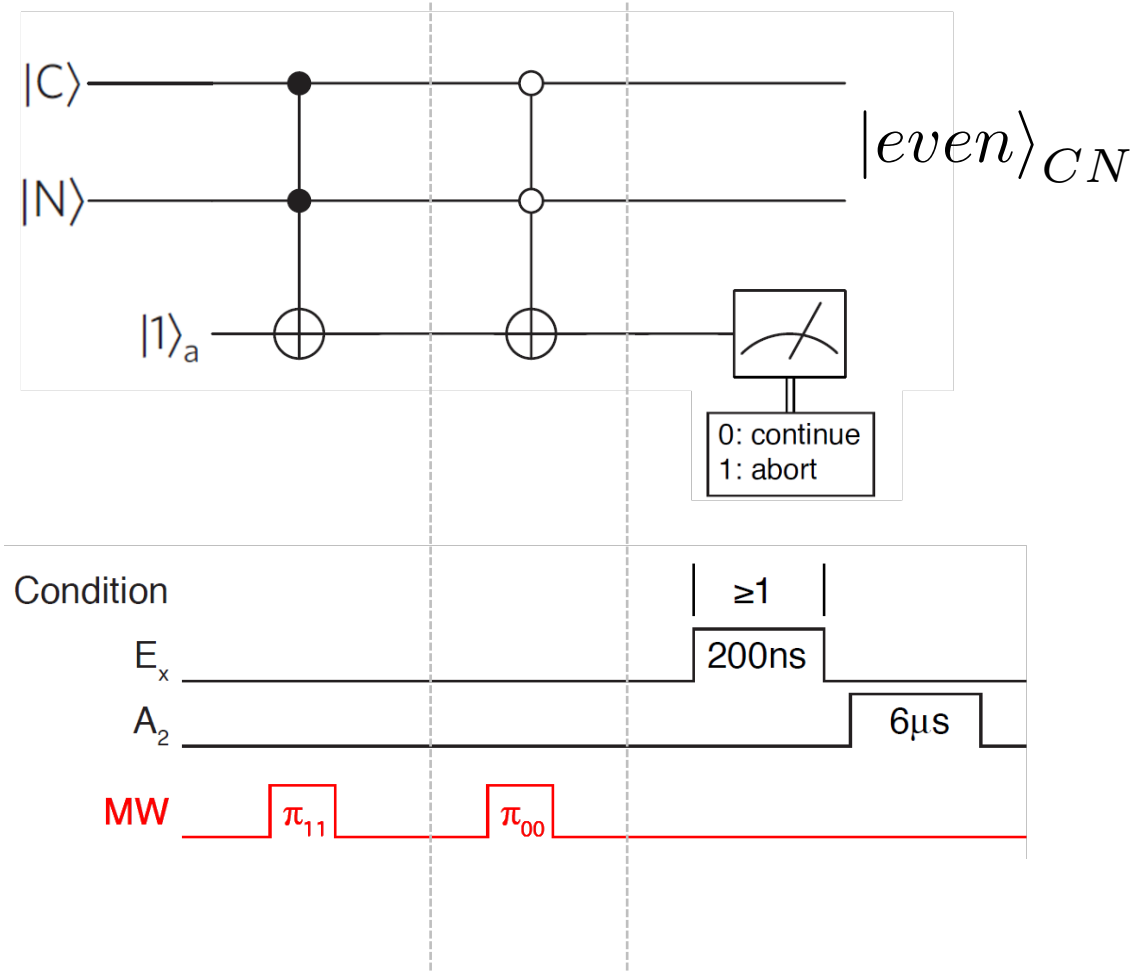

# Bell state preparation

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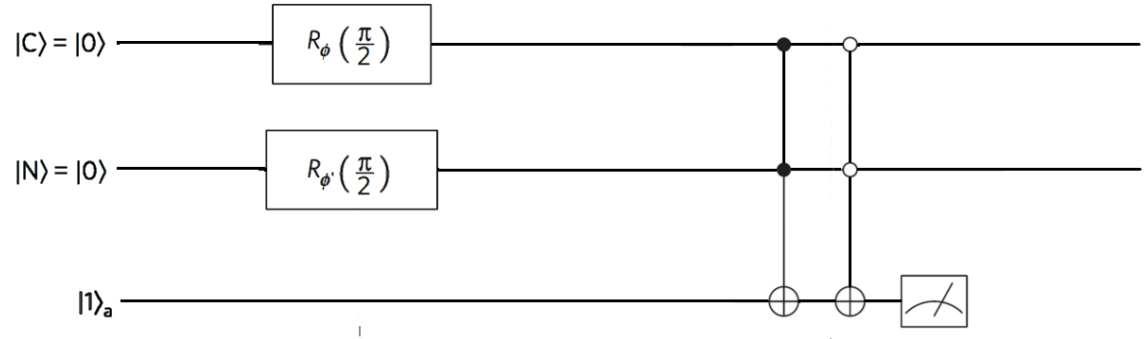
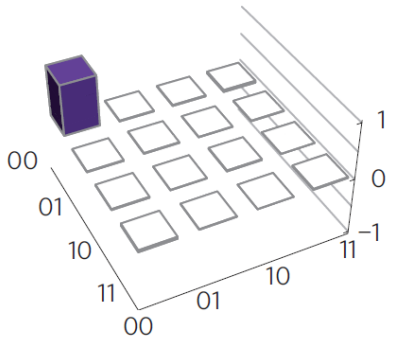
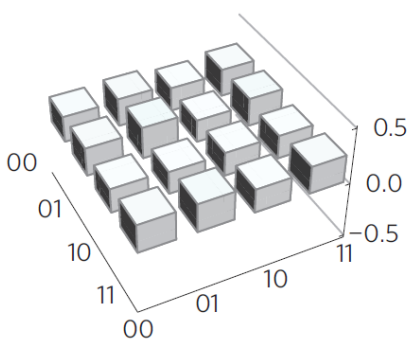
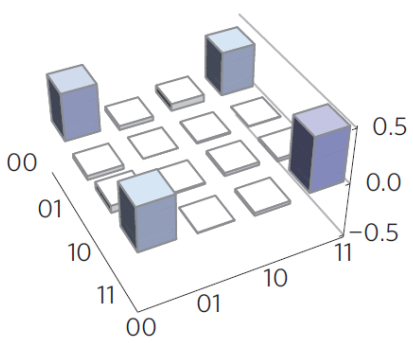
*circuit*

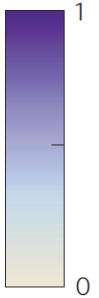



$Re(\rho_{exp})$




*state (ideal)*

$|00\rangle$

$(|00\rangle + |01\rangle + |10\rangle + |11\rangle)/2$

$|\Phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$

Pfaff et al., Nature Physics 9, 29–33 (2013)

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# Part 3 - Results

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- State tomography

$$F = \left\langle \Phi^+ \middle| \rho_m \middle| \Phi^+ \right\rangle = (90 \pm 3)\%$$

# Part 3 - Results

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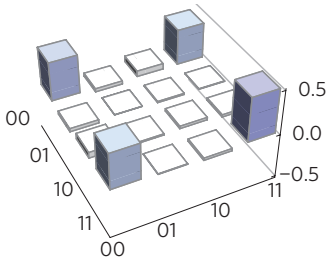


Pfaff et al., Nature Physics 9, 29–33 (2013)

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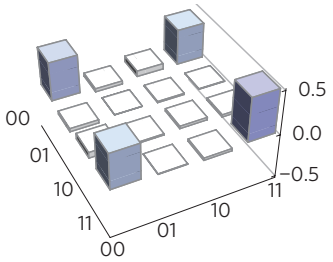


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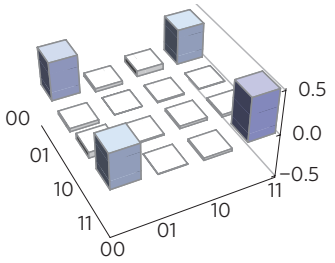


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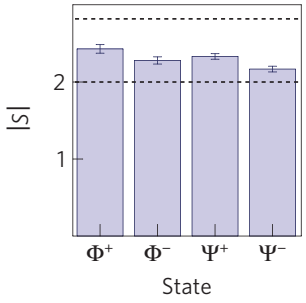


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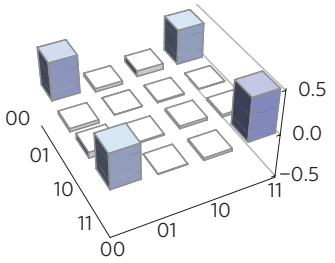


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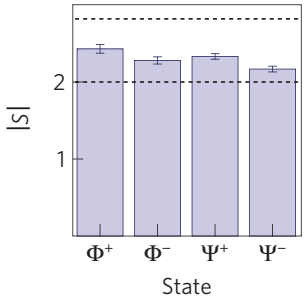


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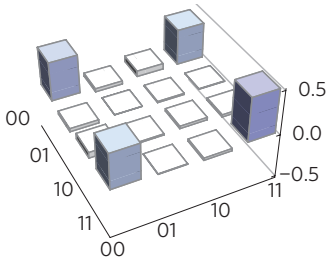


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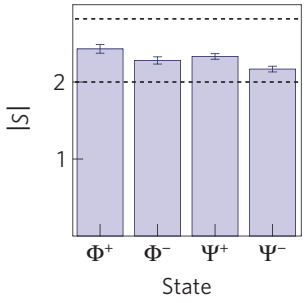


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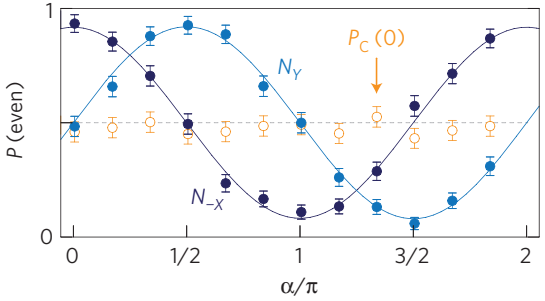


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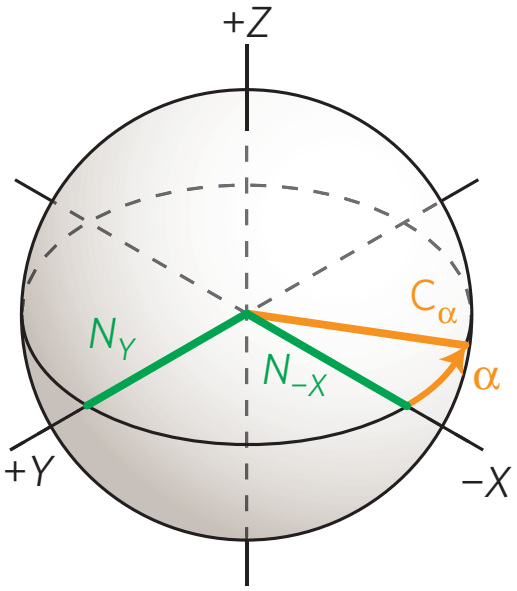


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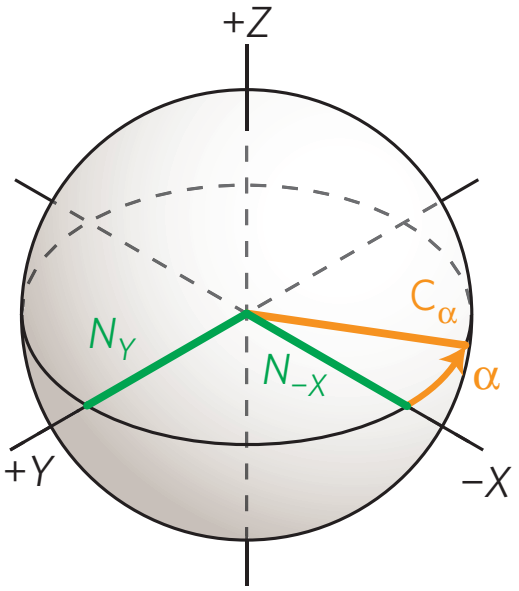


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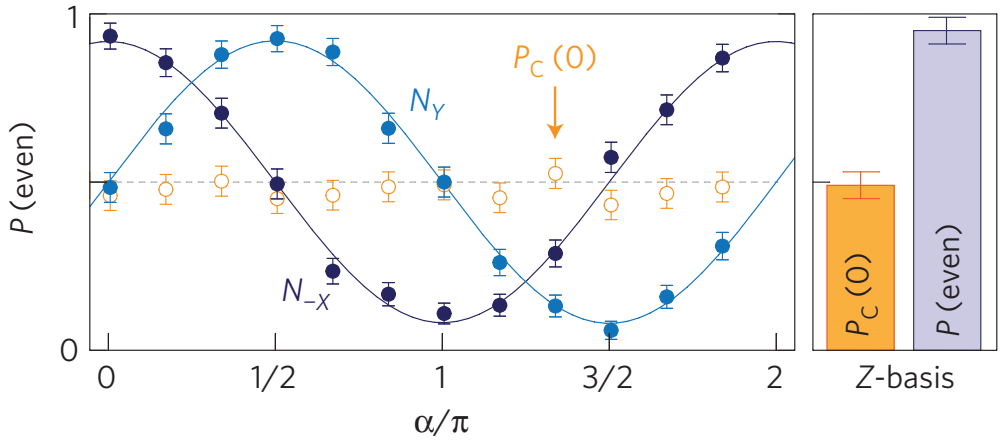


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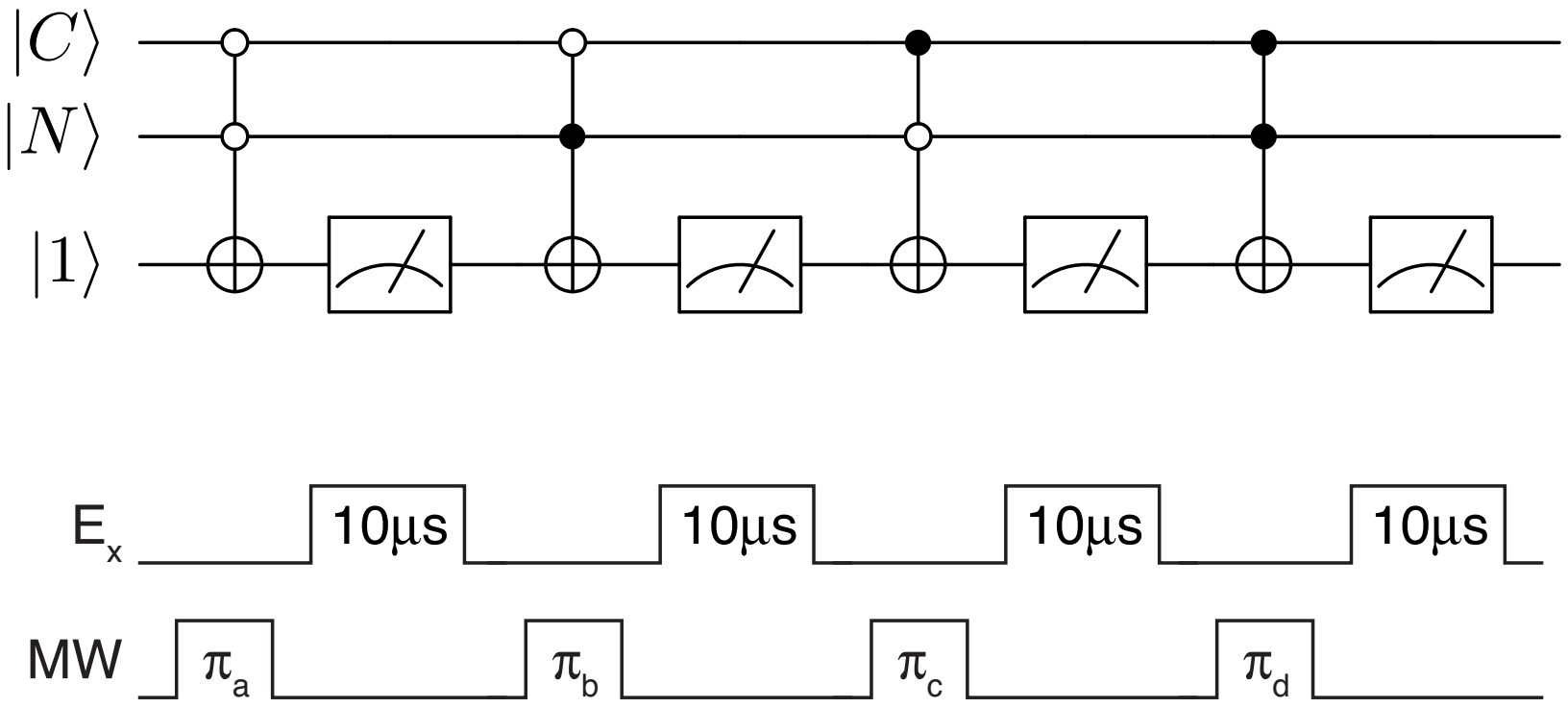


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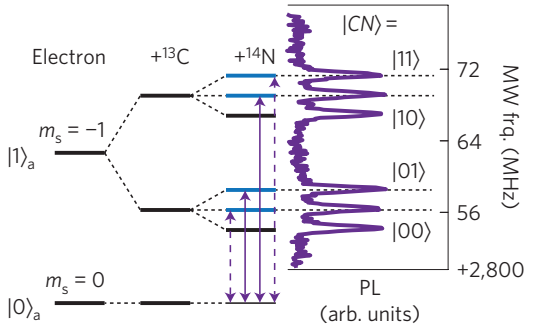


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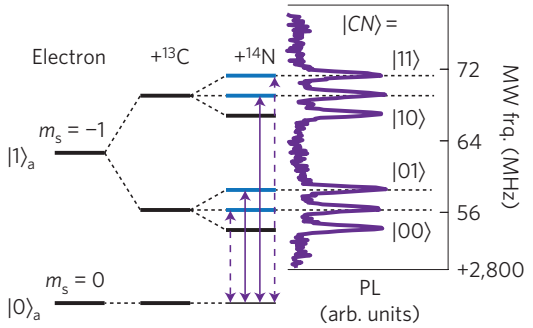


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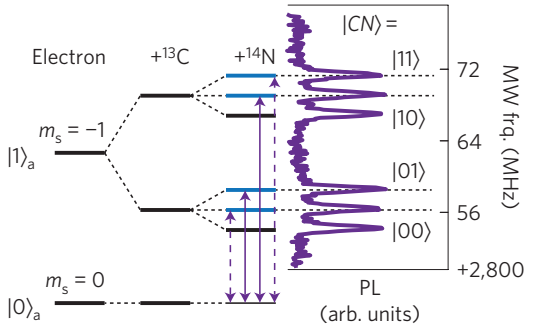


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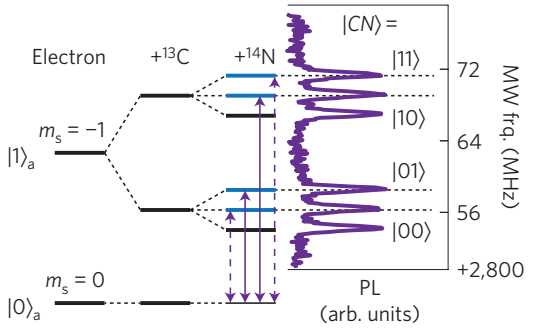


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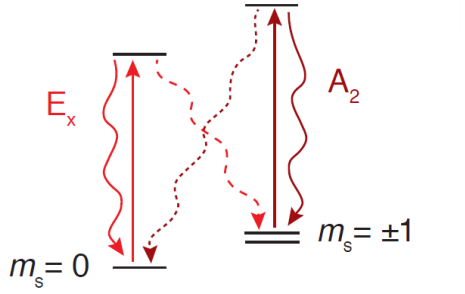


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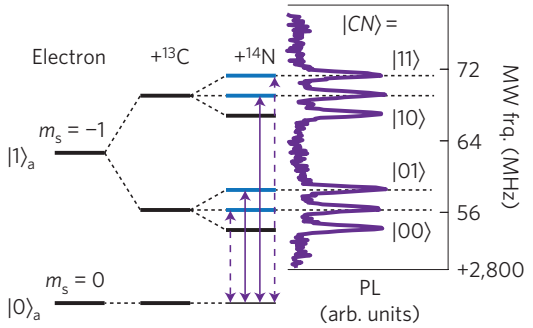


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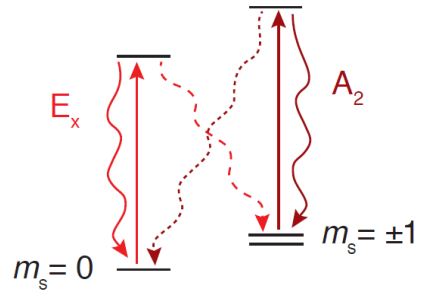


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$\Rightarrow$ Entanglement of nuclear spins in NV centres