High-fidelity transfer and storage of photon states in a single nuclear spin

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Snapshot

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High-fidelity transfer and storage of photon states in a single nuclear spin

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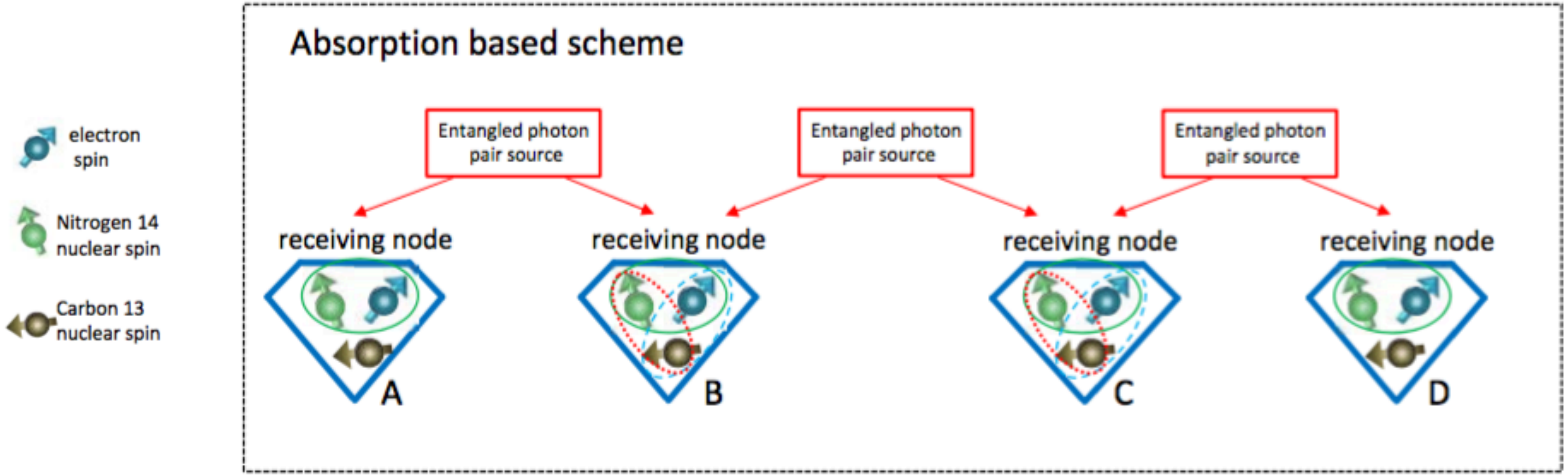
Long-distance quantum communication requires photons and quantum nodes that comprise qubits for interaction with light and good memory capabilities, as well as processing qubits for the storage and manipulation of photons. Owing to the unavoidable photon losses, robust quantum communication over lossy transmission channels requires quantum repeater networks[1,2]. A necessary and highly demanding prerequisite for these networks is the existence of quantum memories with long coherence times to reliably store the incident photon states. Here we demonstrate the high-fidelity (~98%) coherent transfer of a photon polarization state to a single solid-state nuclear spin that has a coherence time of over 10 s. The storage process is achieved by coherently transferring the polarization state of a photon to an entangled electron–nuclear spin state of a nitrogen-vacancy centre in diamond. The nuclear spin-based optical quantum memory demonstrated here paves the way towards an absorption-based quantum repeater network.

nuclear spins. Although its electron spin is used for interaction with photons[9], for fast[18] and high-fidelity control[19] and for readout of the spin state[20–22], its surrounding nuclear spins are well-isolated from their environment and yield very long coherence times. Thus nuclear spins make natural candidates for information storage and electron spins for spin photon interface. In addition, electron and nuclear spins form a multiqubit quantum register allowing for quantum information processing, for example high-fidelity quantum error correction[19] and quantum memory[23].

Although there has been much progress in photon transfer and storage onto ensembles of atoms/spins that have strong coupling to photons, a direct transfer of the photon state to a single qubit has only been demonstrated in single atoms[14,16]. Although the non-linear effects induced by strong light–matter coupling facilitated the transfer process, the low coherence times allowed storage for only few hundred microseconds. However, achieving such strong light–matter coupling for single solid-state qubits still remains a large technical challenge. In this work, we propose a new scheme that

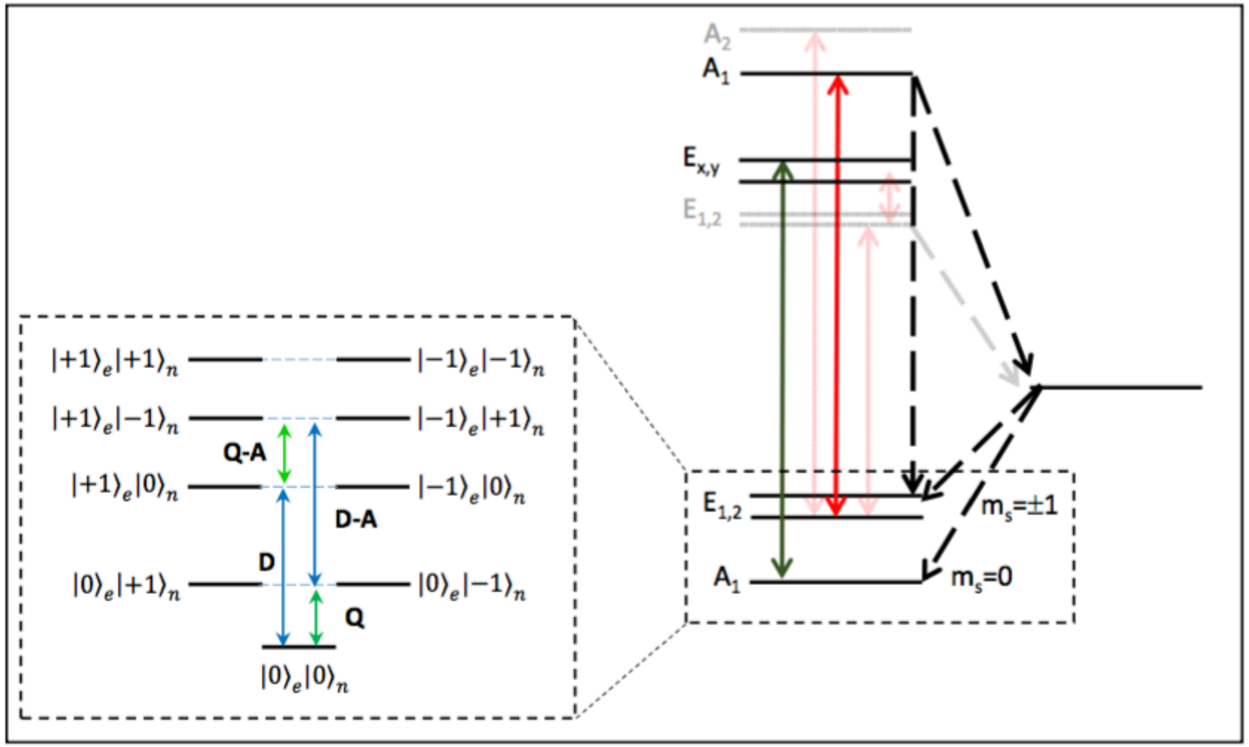
Motivation

- Quantum information transfer between photon and nuclear spin
  - Quantum Communication -> Quantum Repeater
  - Quantum Computation -> Node Connection $k2^n \rightarrow 2^{kn}$



Properties of NV System

- Optical ~ 100THz
  - Orbital of electron
- MW ~ GHz
  - Electron spin – zero field splitting
- RF ~ MHz
  - Nuclear spin - Nitrogen-14 quadruple spliitting/hyperfine interaction
- Magnetic field



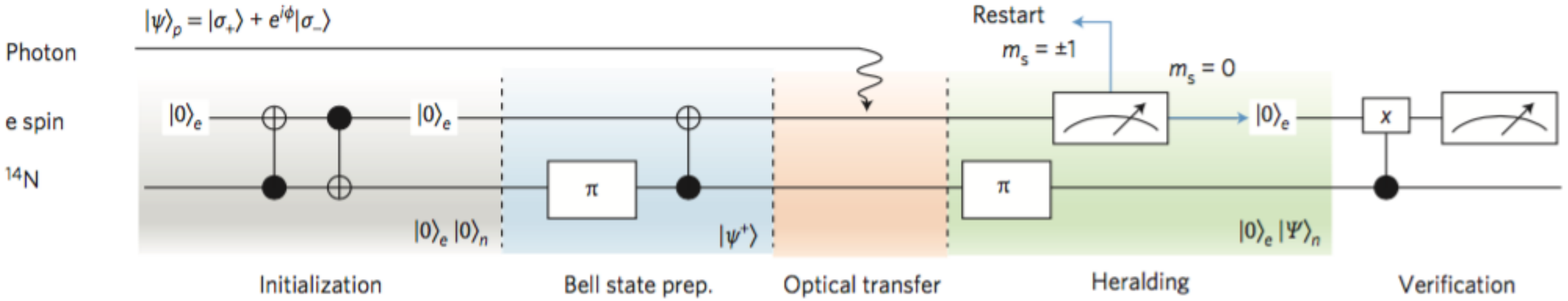
Level structure of NV. D = 2.877GHz is the electron spin zero field splitting; Q = 4.946MHz is the Nitrogen-14 nuclear spin quadruple; A = 2.2MHz is the hyperfine interaction.

Elements in the experiment

- Photon
- Electron spin in NV – interface of transfer
- Nuclear spin of nitrogen-14 in NV

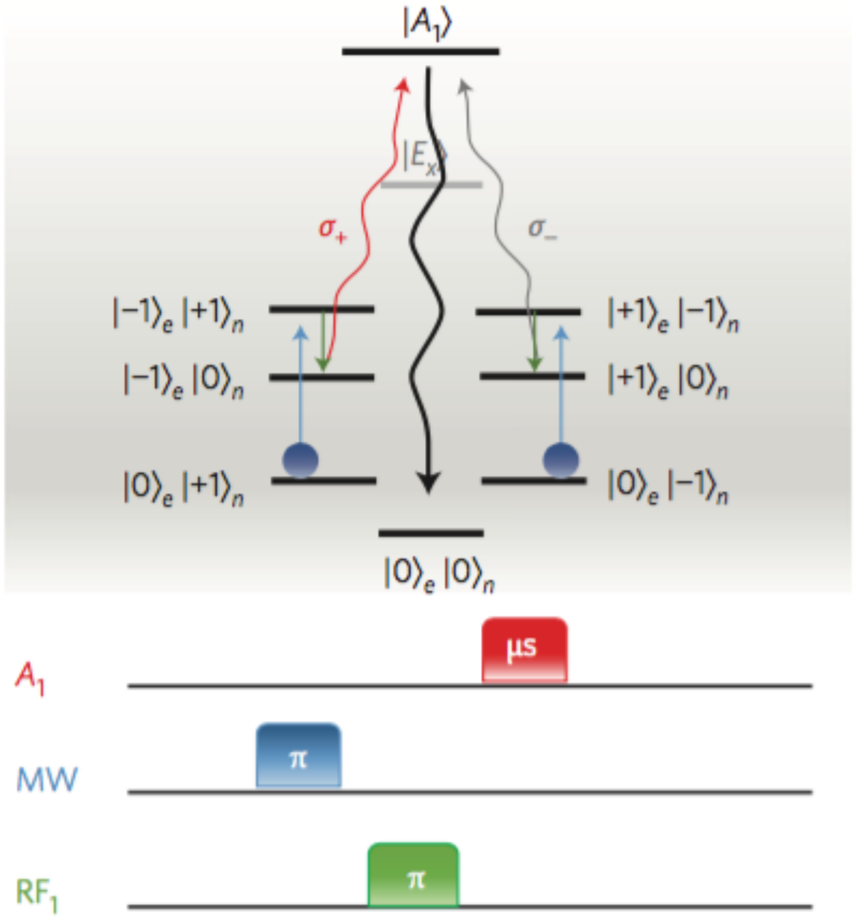
Scheme

- Initialization
- Bell state preparation of electron-nuclear spin system
- Optical transfer
- Heralding
- Verification



Scheme: Initialization

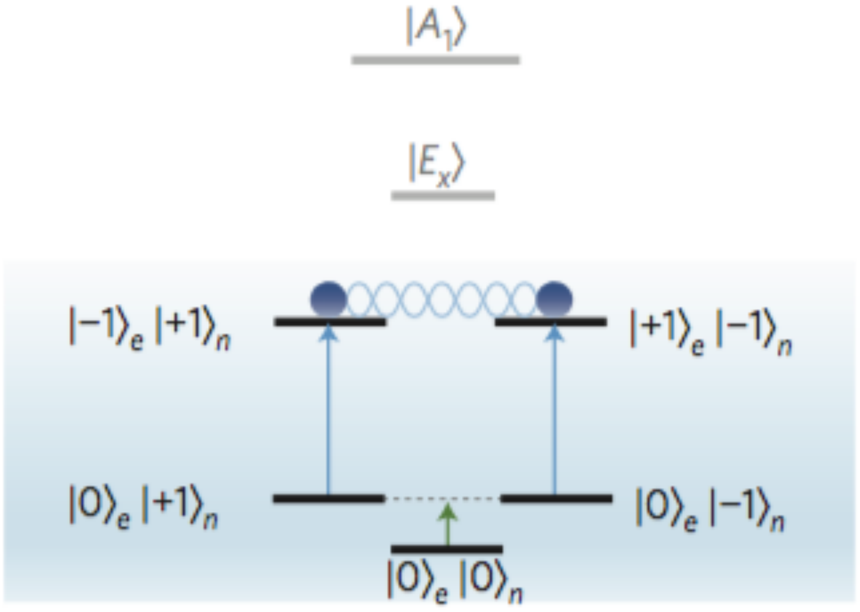
- A_1 Pumping (optical)
  - $|T\rangle_e \otimes |T\rangle_n \rightarrow |0\rangle_e \otimes |T\rangle_n$
- Electron CNOT
  - $|0\rangle_e |\pm1\rangle_n \rightarrow |\pm1\rangle_e |\pm1\rangle_n$
  - $|0\rangle_e |0\rangle_n \rightarrow |0\rangle_e |0\rangle_n$
- Nuclear CNOT (RF)
  - $|\pm1\rangle_e |\pm1\rangle_n \rightarrow |\pm1\rangle_e |0\rangle_n$
  - $|0\rangle_e |0\rangle_n \rightarrow |0\rangle_e |0\rangle_n$
- A_1 Pumping (optical)
  - $|\pm1/0\rangle_e |0\rangle_n \rightarrow |0\rangle_e |0\rangle_n$



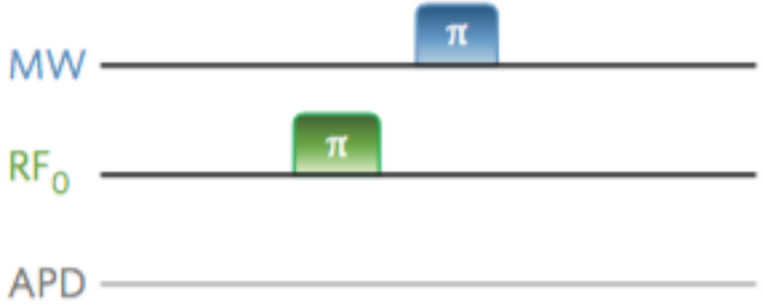
$|T\rangle$ represents thermal state

Scheme: Bell State Preparation

- Nuclear π Pulse (RF)
  - $|0\rangle_e|0\rangle_n \rightarrow |0\rangle_e|b\rangle_n$
- Electron CNOT (MW)
  - $|0\rangle_e|\pm1\rangle_n \rightarrow |\mp1\rangle_e|\pm1\rangle_n$



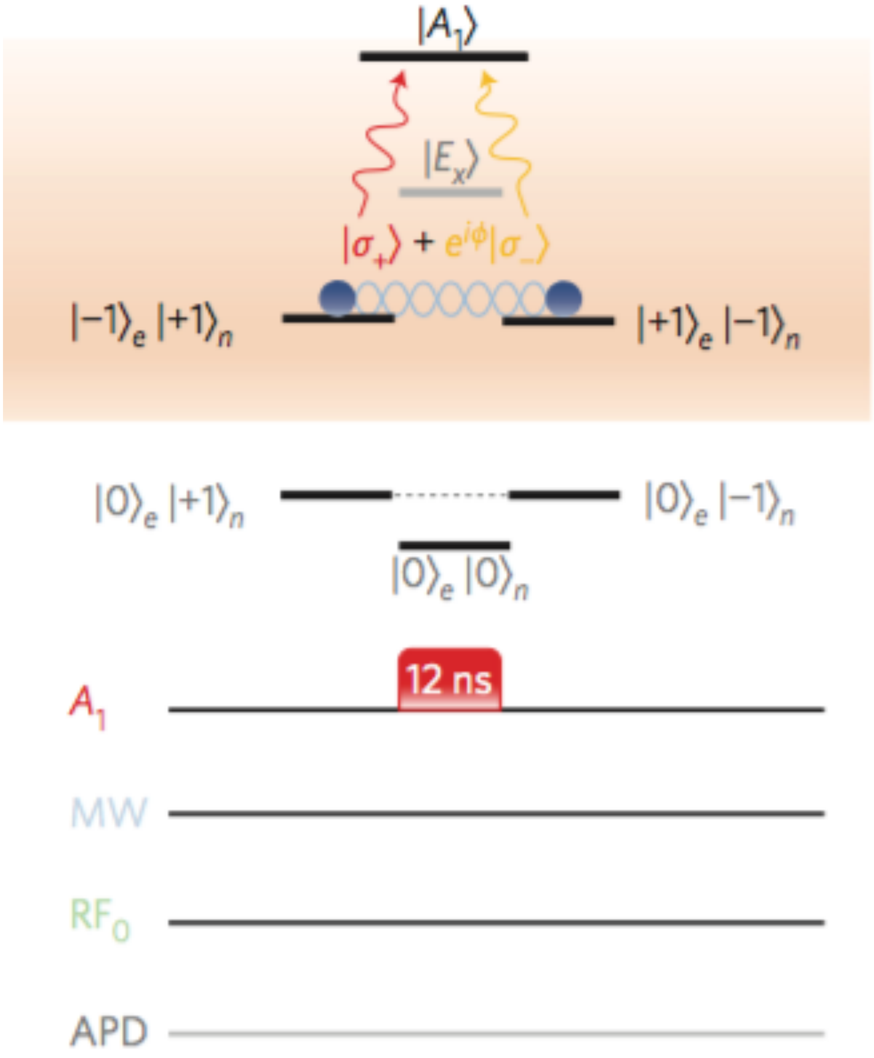
- Bell State
  - $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(\,|-1\rangle_e|+1\rangle_n + |+1\rangle_e|-1\rangle_n)$



Bright state: $|b\rangle = \frac{1}{\sqrt{2}}(\,|+1\rangle + |-1\rangle\,)$

Scheme: Optical Transfer

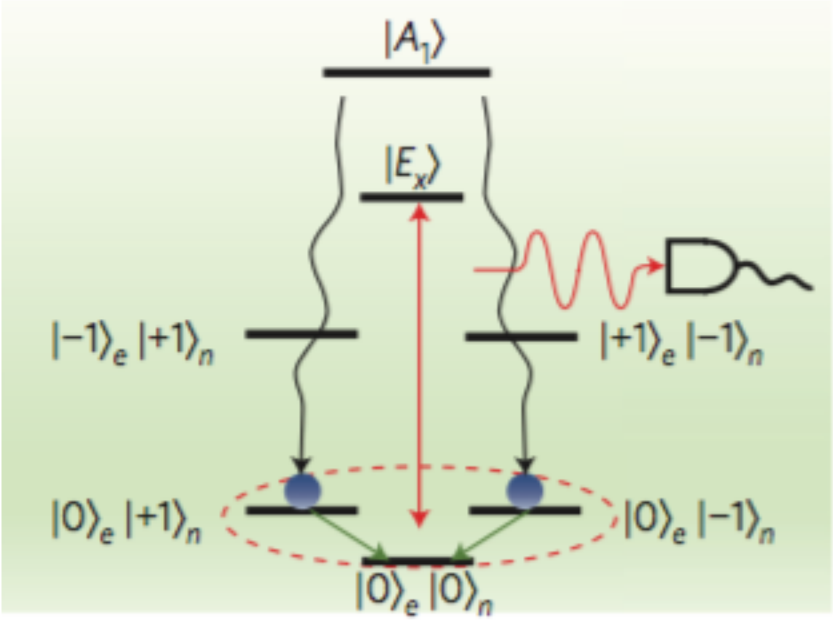
- Photon state $|\psi\rangle_p = \frac{1}{\sqrt{2}}(|\sigma_+\rangle - e^{i\phi}\,|\sigma_-\rangle)$ can only be deterministicaly absorbed by $|\psi\rangle_e = \frac{1}{\sqrt{2}}(|{+1}\rangle + e^{i\phi}\,|{-1}\rangle)$ whose orthogonal state, denoted as $|\psi^{\perp}\rangle_e$, can't be absorbed.
- Bell state $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(\,|\psi\rangle_e|\psi\rangle_n + |\psi^{\perp}\rangle_e|\psi^{\perp}\rangle_n)$
- 50% probability of photon absorption

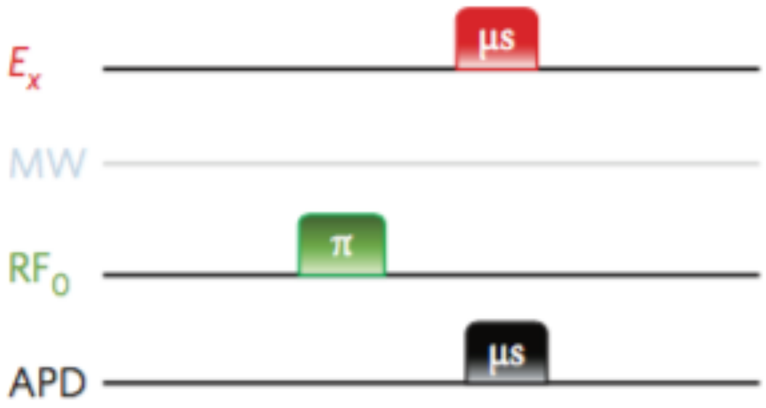


Scheme: Heralding

- $|A_1\rangle$ decays
  - Photon collection rate ~ 2% → too low
  - Back to $|0\rangle_e$ (with 40% probability) or $|\pm1\rangle_e$ (with 30% probability respectively)
- $|0\rangle_e \rightarrow |E_x\rangle_e$ transition
  - High-fidelity readout

- Efficiency = 50% × 40% = 20%





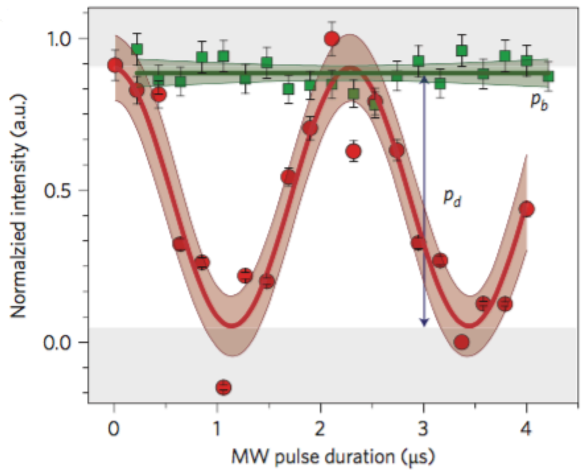
Scheme: Tomography for Verification

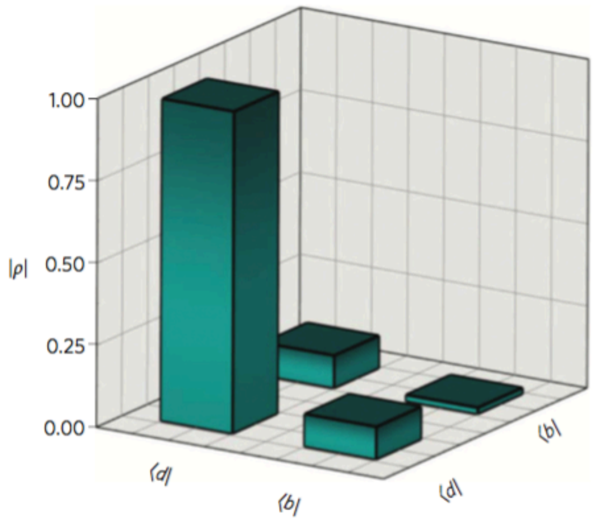
- $|\psi\rangle_p = \frac{1}{\sqrt{2}}\left(|\sigma_+\rangle + e^{i\phi_{photon}}|\sigma_-\rangle\right)$
- RF Pulse: $|\psi\rangle_n = \frac{1}{\sqrt{2}}\left(|+1\rangle_n + e^{i\phi_{nspin}}|-1\rangle_n\right) = \frac{1+e^{i\phi}}{2}|d\rangle_n - \frac{1-e^{i\phi}}{2}|b\rangle_n$

$$\rightarrow \frac{1+e^{i\phi}}{2}|d\rangle_n - \frac{1-e^{i\phi}}{2}|0\rangle_\mathrm{n}$$

- Measure $p_d = \left|\frac{1+e^{i\phi}}{2}\right|^2$ and $p_b = \left|\frac{1-e^{i\phi}}{2}\right|^2$ by Rabi Oscillation
- Reconstruct density matrix

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

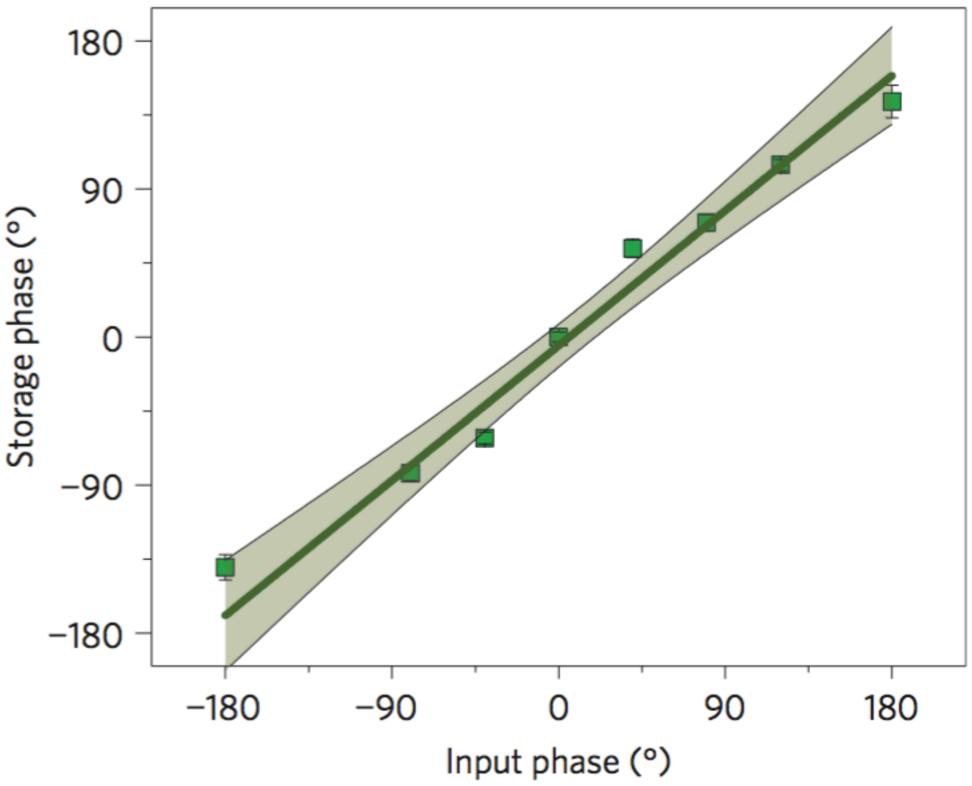




Rabi Oscillation and reconstructed desity matrix when $\phi_{photon} = 0$

Result: Fidelity

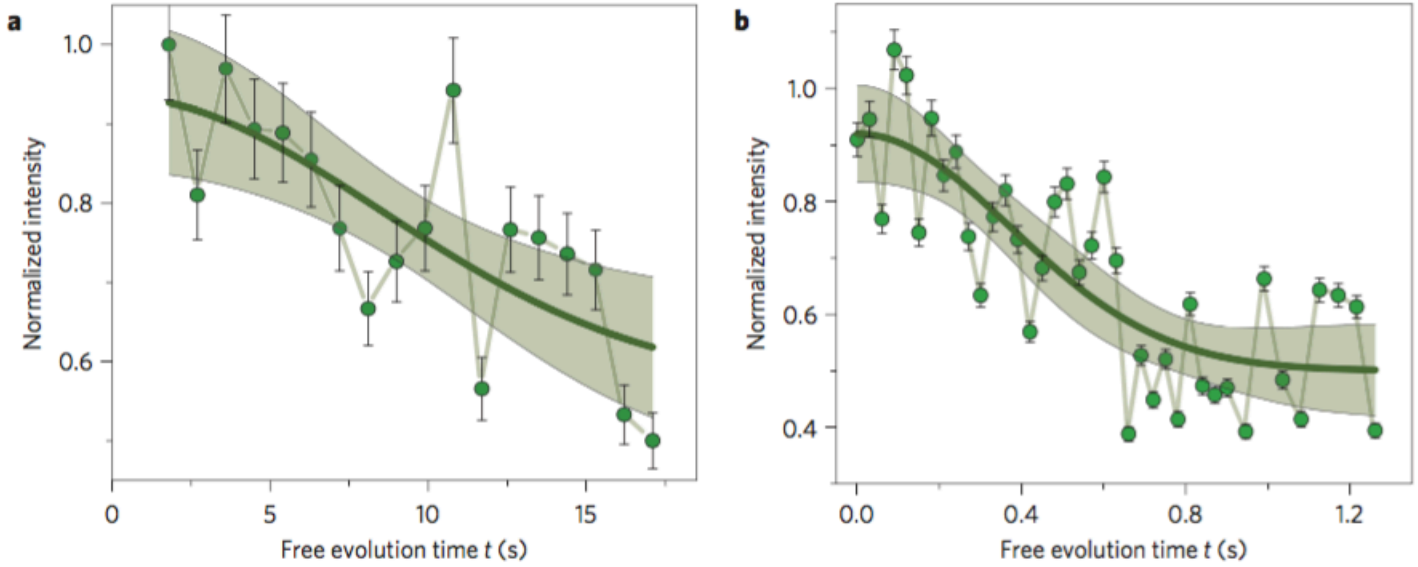
Average Fidelity : 98%



Comparison between the phase of the nuclear spin and the phase of optical photons. Shaded areas in the plots mark 95% confidence intervals. Error bars indicate the errors from fitting.

Result: Measurement of Coherent Time

Coherent Time T_2 exceeds 10s when $m_s = 0$



(a) Nuclear spin Hahn measurements for spin coherence between state $|e\rangle_e|+1\rangle_n$ and state $|0\rangle_e|-1\rangle_n$.
(b) Nuclear spin Hahn measurements for spin coherence between state $|\pm1\rangle_e|\mp1\rangle_n$ and state $|\pm1\rangle_e|0\rangle_n$.

Conclusion

- Realization of storage of a photon polarization state in a solid nuclear spin with high fidelity (~98%) and a long storage time (T_2>10s).

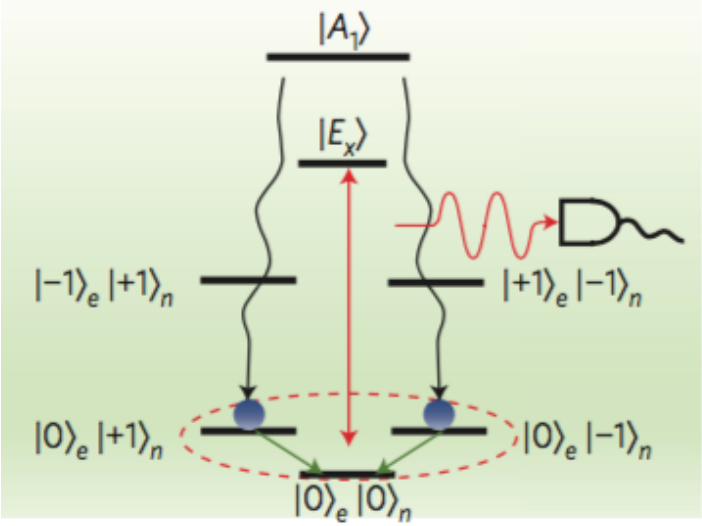
Thanks!

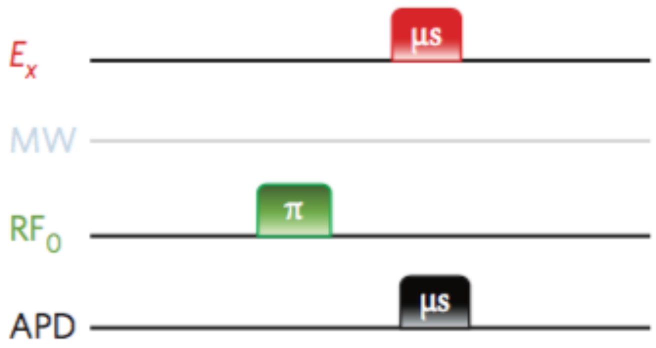
Question: Is NV excited by single photon?

- Due to the low efficiency of photon absorption, thousands of photon is exposed to NV in a pulse, but the NV is excited by a single photon at a time in a large probability (~97.5%).
- NV is excited by a 12ns laser pulse with a peak power of 20mW, containing a few thousands photons. Considering the absorption rate of approximately 0.1%, it can be regarded that only one photon is absorbed at a time. The absorption of absorbing more than one photon due to re-excitation is only about 0.025.

Question: Dose nuclear spin preserve coherence after heralding?

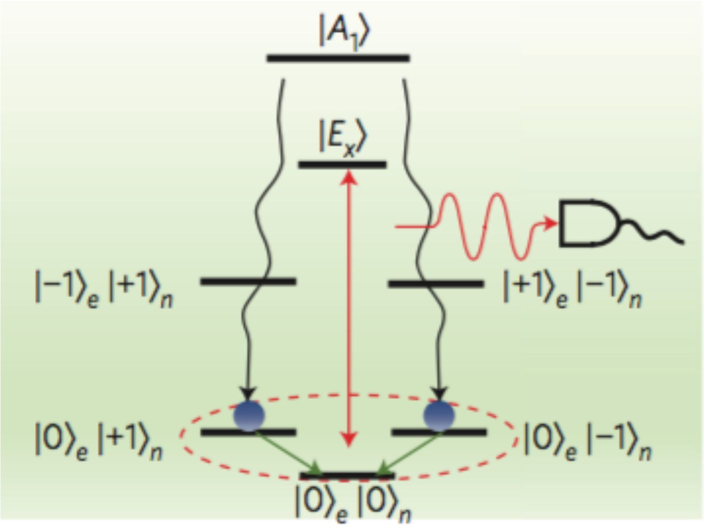
- When $|A_1\rangle_e \otimes [\frac{1}{\sqrt{2}}(|{+1}\rangle_n - e^{i\phi}|{-1}\rangle_n)]$ decays, it drops back to $|0\rangle_e \otimes \left[\frac{1}{\sqrt{2}}(|{+1}\rangle_n - e^{i\phi}|{-1}\rangle_n)\right] = |0\rangle_e \otimes \left[\cos\frac{\phi}{2}\ |b\rangle_n\ - i\sin\frac{\phi}{2}|d\rangle_n\right]$ with 40% probability. When RF pi pulse applied, it becomes $|0\rangle_e \otimes \left[\cos\frac{\phi}{2}\ |0\rangle_n\ - i\sin\frac{\phi}{2}|d\rangle_n\right]$.
- The red-line transition $|0\rangle_e \leftrightarrow |E_x\rangle_e$ is between all the three possible states in the red dashed circle and $|E_x\rangle_e$, but not only zero-zero state.

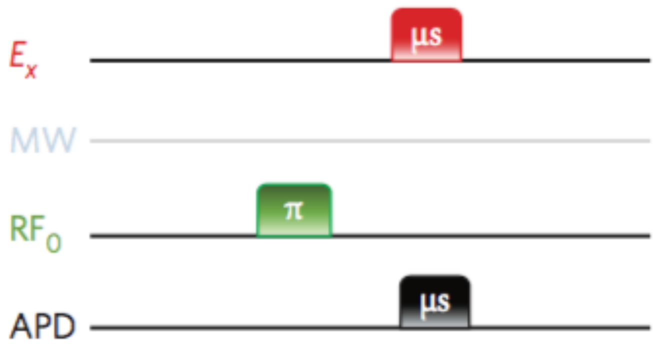




Question: Dose nuclear spin preserve coherence after heralding?

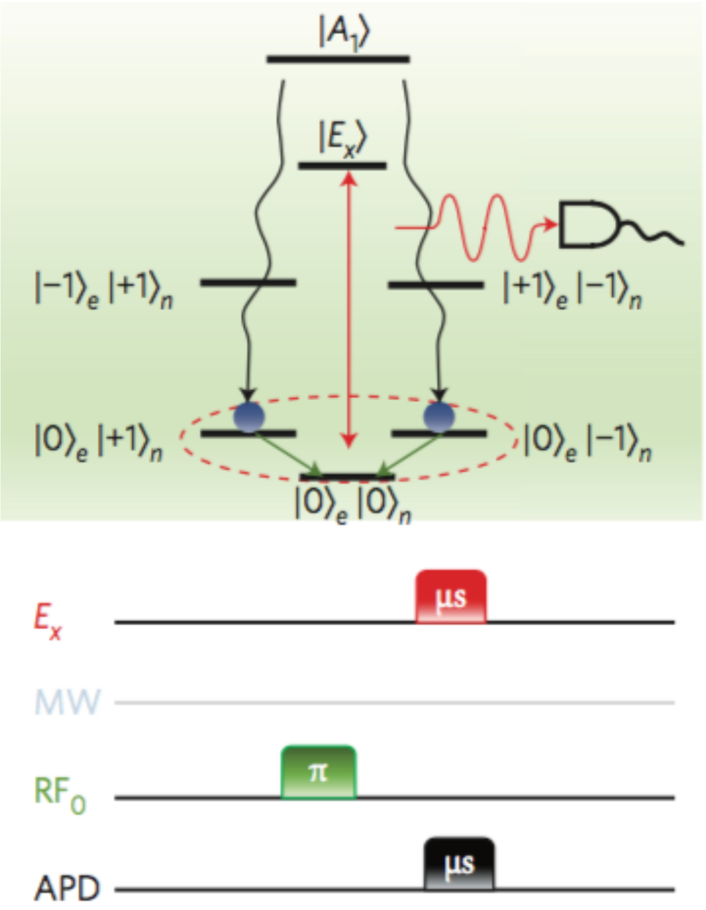
- Nuclear spin still preserve the information even it suffers from dephasing in the transition $|0\rangle_e \leftrightarrow |E_x\rangle_e$, since the information is transferred into the population of $|0\rangle_n$ from relative phase between $|+1\rangle_n$ and $|-1\rangle_n$.
- Nuclear spin state after heralding is the mixture of $|0\rangle_n$, $|+1\rangle_n$ and $|-1\rangle_n$, whose proportions of population are $\cos^2\frac{\phi}{2}$, $\frac{1}{2}\sin^2\frac{\phi}{2}$ and $\frac{1}{2}\sin^2\frac{\phi}{2}$, respectively.





Question: Dose nuclear spin preserve coherence after heralding?

- The state after heralding carries information of the original phase of photon polarization, but does not remain coherent. This state can be utilized for measurement for the relative phase of $|+1\rangle_n$ and $|-1\rangle_n$ before heralding by applying Rabi oscillation conditioned on the nuclear spin state $|0\rangle_n$ and $|\pm 1\rangle_n$.



Question: Why applying a pi pulse before heralding?

- Before applying a pi pulse, the information is stored in the relative phase between $|+1\rangle_n$ and $|-1\rangle_n$ (or, say between $|d\rangle_n$ and $|b\rangle_n$). There may be dephasing in the process of $|0\rangle_e \leftrightarrow |E_x\rangle_e$ transition.
- By applying a pi pulse, $\frac{1}{\sqrt{2}}(|+1\rangle_n - e^{i\phi}|-1\rangle_n)$ becomes $\cos\frac{\phi}{2}|0\rangle_n - i\sin\frac{\phi}{2}|d\rangle_n$, and the information is transferred from relative phase between $|+1\rangle_n$ and $|-1\rangle_n$ to the population of $|0\rangle_n$, thus increasing the fidelity.