Journal Club:
Heralded entanglement between solid-state qubits separated by three metres

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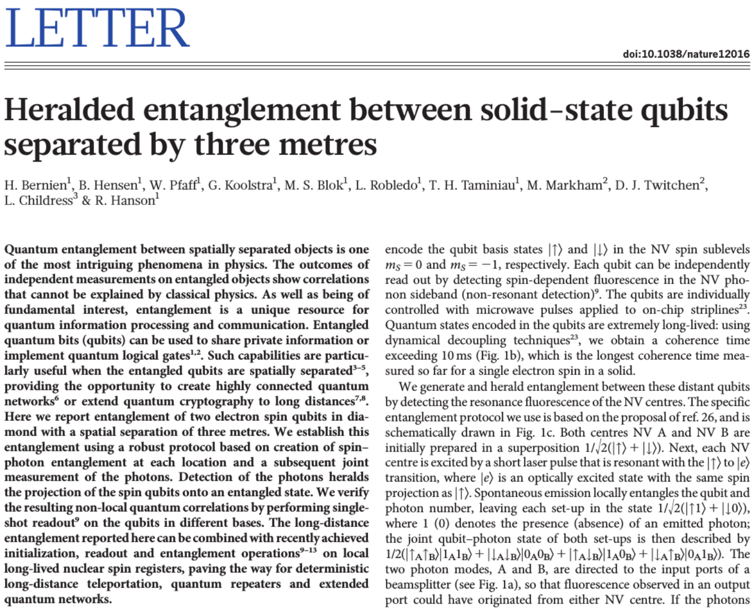

LETTER

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Heralded entanglement between solid-state qubits separated by three metres

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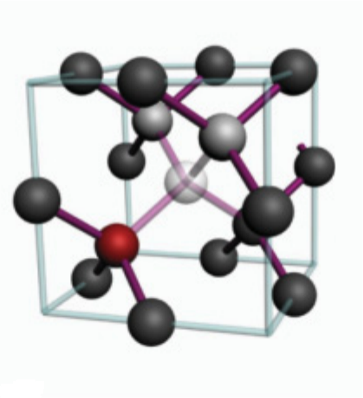
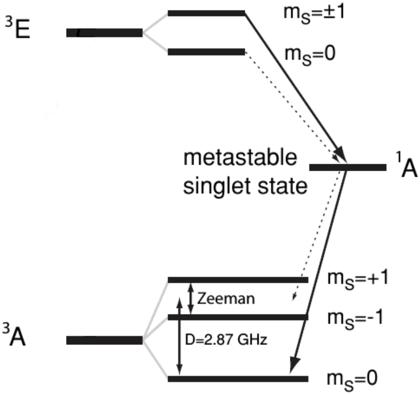
Quantum entanglement between spatially separated objects is one of the most intriguing phenomena in physics. The outcomes of independent measurements on entangled objects show correlations that cannot be explained by classical physics. As well as being of fundamental interest, entanglement is a unique resource for quantum information processing and communication. Entangled quantum bits (qubits) can be used to share private information or implement quantum logical gates[1,2]. Such capabilities are particularly useful when the entangled qubits are spatially separated[3–5], providing the opportunity to create highly connected quantum networks[6] or extend quantum cryptography to long distances[7,8]. Here we report entanglement of two electron spin qubits in diamond with a spatial separation of three metres. We establish this entanglement using a robust protocol based on creation of spin–photon entanglement at each location and a subsequent joint measurement of the photons. Detection of the photons heralds the projection of the spin qubits onto an entangled state. We verify the resulting non-local quantum correlations by performing single-shot readout[9] on the qubits in different bases. The long-distance entanglement reported here can be combined with recently achieved initialization, readout and entanglement operations[9–13] on local long-lived nuclear spin registers, paving the way for deterministic long-distance teleportation, quantum repeaters and extended quantum networks.

encode the qubit basis states $|\uparrow\rangle$ and $|\downarrow\rangle$ in the NV spin sublevels $m_S = 0$ and $m_S = -1$, respectively. Each qubit can be independently read out by detecting spin-dependent fluorescence in the NV phonon sideband (non-resonant detection)[9]. The qubits are individually controlled with microwave pulses applied to on-chip striplines[23]. Quantum states encoded in the qubits are extremely long-lived: using dynamical decoupling techniques[23], we obtain a coherence time exceeding 10 ms (Fig. 1b), which is the longest coherence time measured so far for a single electron spin in a solid.

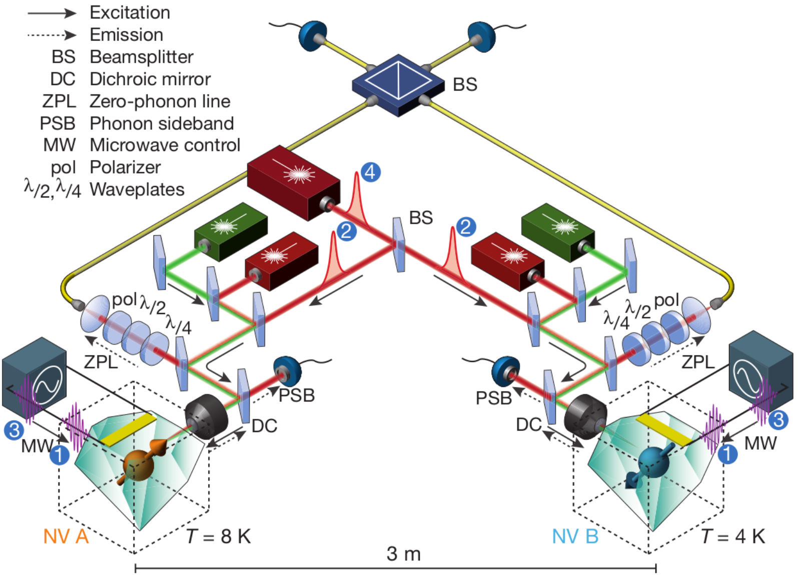
We generate and herald entanglement between these distant qubits by detecting the resonance fluorescence of the NV centres. The specific entanglement protocol we use is based on the proposal of ref. 26, and is schematically drawn in Fig. 1c. Both centres NV A and NV B are initially prepared in a superposition $1/\sqrt{2}(|\uparrow\rangle + |\downarrow\rangle)$. Next, each NV centre is excited by a short laser pulse that is resonant with the $|\uparrow\rangle$ to $|e\rangle$ transition, where $|e\rangle$ is an optically excited state with the same spin projection as $|\uparrow\rangle$. Spontaneous emission locally entangles the qubit and photon number, leaving each set-up in the state $1/\sqrt{2}(|\uparrow 1\rangle + |\downarrow 0\rangle)$, where 1 (0) denotes the presence (absence) of an emitted photon; the joint qubit–photon state of both set-ups is then described by $1/2(|\uparrow_A\uparrow_B\rangle|1_A 1_B\rangle + |\downarrow_A\downarrow_B\rangle|0_A 0_B\rangle + |\uparrow_A\downarrow_B\rangle|1_A 0_B\rangle + |\downarrow_A\uparrow_B\rangle|0_A 1_B\rangle)$. The two photon modes, A and B, are directed to the input ports of a beamsplitter (see Fig. 1a), so that fluorescence observed in an output port could have originated from either NV centre. If the photons

Nitrogen-vacancy defect center in diamond

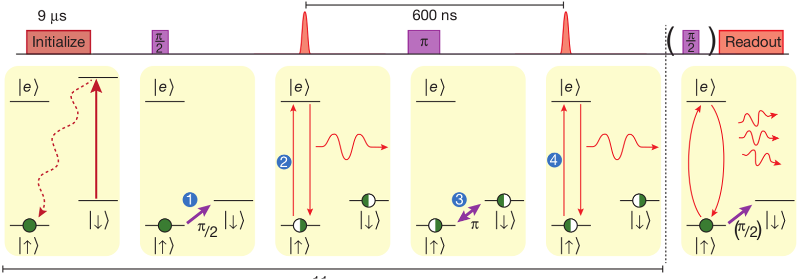




Experimental setup

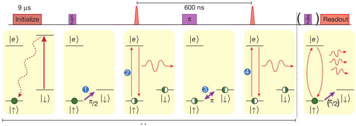


Entanglement protocol



Entanglement protocol

1. Both centres NV A and NV B are initially prepared in a superposition
$$\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$$
2. Next, each NV centre is excited by a short laser pulse that is resonant with the $|\uparrow\rangle$ to $|e\rangle$ transition, where $|e\rangle$ is an optically excited state with the same spin projection as $|\uparrow\rangle$.
3. Spontaneous emission locally entangles the qubit and photon number, leaving each set-up in the state
$$\frac{1}{\sqrt{2}}(|\uparrow 1\rangle + |\downarrow 0\rangle)$$



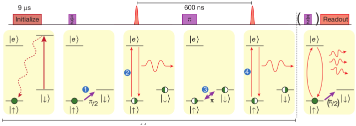
Entanglement protocol

4. The joint qubit-photon state of both setups is then described by

$$\frac{1}{2}(|\uparrow_\mathrm{A}\uparrow_\mathrm{B}\rangle|1_\mathrm{A}1_\mathrm{B}\rangle + |\downarrow_\mathrm{A}\downarrow_\mathrm{B}\rangle|0_\mathrm{A}0_\mathrm{B}\rangle + |\uparrow_\mathrm{A}\downarrow_\mathrm{B}\rangle|1_\mathrm{A}0_\mathrm{B}\rangle + |\downarrow_\mathrm{A}\uparrow_\mathrm{B}\rangle|0_\mathrm{A}1_\mathrm{B}\rangle)$$

5. The two photon modes, A and B, are directed to the input ports of a beamsplitter
6. Detection of precisely one photon on an output port would correspond to measuring the photon state

$$\frac{1}{\sqrt{2}}(|1_\mathrm{A}0_\mathrm{B}\rangle \pm \mathrm{e}^{-\mathrm{i}\varphi}|0_\mathrm{A}1_\mathrm{B}\rangle)$$

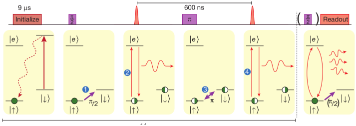


Entanglement protocol

7. Such a detection event would thereby project the qubits onto the maximally entangled state

$$\frac{1}{\sqrt{2}}(|\uparrow_\mathrm{A}\downarrow_\mathrm{B}\rangle \pm e^{-i\varphi}|\downarrow_\mathrm{A}\uparrow_\mathrm{B}\rangle)$$

8. Imperfect detector efficiency is thus also consistent with creation of the state $|\uparrow\uparrow\rangle$
   To eliminate this possibility, both qubits are flipped and optically excited for a second time. Because $|\uparrow\uparrow\rangle$ is flipped to $|\downarrow\downarrow\rangle$, no photons are emitted in the second round for this state.

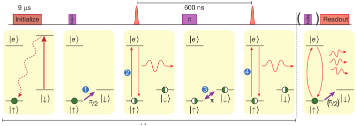


Entanglement protocol

8. The final state is one of two Bell states

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|\uparrow_{\mathrm{A}}\downarrow_{\mathrm{B}}\rangle \pm |\downarrow_{\mathrm{A}}\uparrow_{\mathrm{B}}\rangle)\,,$$

with the sign depending on whether the same detector (+) or different detectors (-) clicked in the two rounds.



Full procedure

1. Both NV centres are independently prepared into the correct charge state and brought into optical resonance
2. The entangling protocol is applied using a $600\,\mathrm{ns}$ delay between the two optical excitation rounds.
3. The protocol is repeated 300 times before returning to step 1.
4. When entanglement is obtained, the states of each qubit are measured.

- The success probability of the protocol $P \approx 10^{-7}$
- The entanglement attempt rate is about $20\,\mathrm{kHz}$ yielding one entanglement event per $10\,\mathrm{min}$.

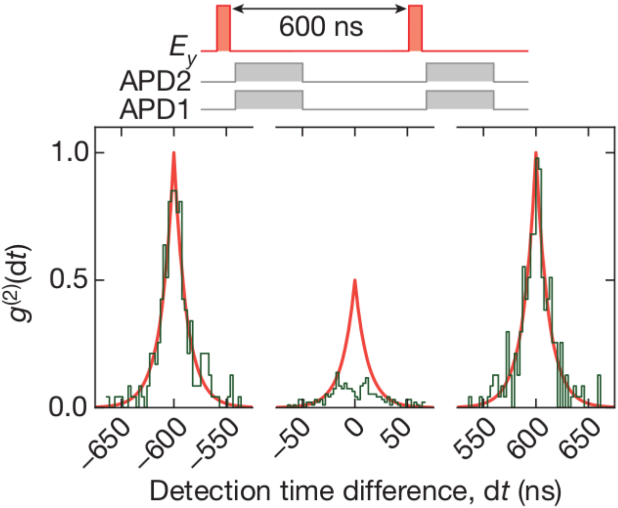
Complications

- A key challenge for generating remote entanglement with solid-state qubits is obtaining a large flux of indistinguishable photons, in part because local strain in the host lattice can induce large variations in photon frequency.
- Owing to different strain in the two diamonds, the frequencies of the E_y transitions differ by 3.5 GHz
- The optical transition frequency of one centre (NV B) is tuned through the d.c. Stark effect by applying a voltage to an on-chip electrode.

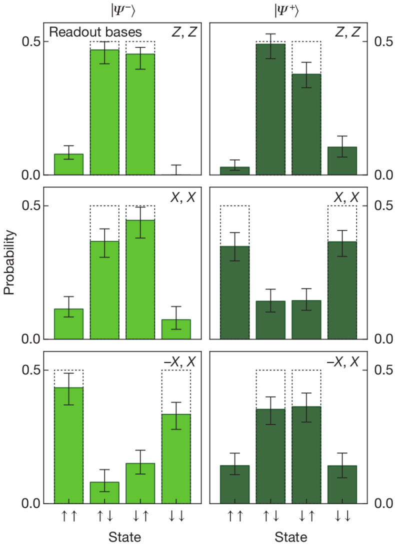
Complications

- To counteract photo-ionization, a green laser pulse is regularly applied to repump the NV centre into the desired charge state.
- For NV centres only about 3% of emission is in the zero-phonon line and useful for the protocol.
- To minimize detection of laser photons, a cross-polarized excitation-detection scheme together with a detection time filter are used. The time filter exploits the difference between the length of the laser pulse ($2\,\mathrm{ns}$) and the NV centre's excited-state lifetime ($12\,\mathrm{ns}$).

Second-order autocorrelation function g^2



Spin-spin correlations



Summary

Creation of entanglement between distant spin qubits in diamond, as reported here, opens the door to extending the remarkable properties of NV-based quantum registers towards applications in quantum information science. By transferring entanglement to nuclear spins near each NV centre, a non-local state might be preserved for seconds or longer, facilitating the construction of cluster states or quantum repeaters. At the same time, the auxiliary nuclear spin qubits also provide an excellent resource for processing and error correction. When combined with future advances in nanofabricated integrated optics and electronics, the use of electrons and photons as quantum links and nuclear spins for quantum processing and memory offers a compelling route towards realization of solid-state quantum networks.

Thank you for your attention!