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Bell test using NV-centers

Local Realism

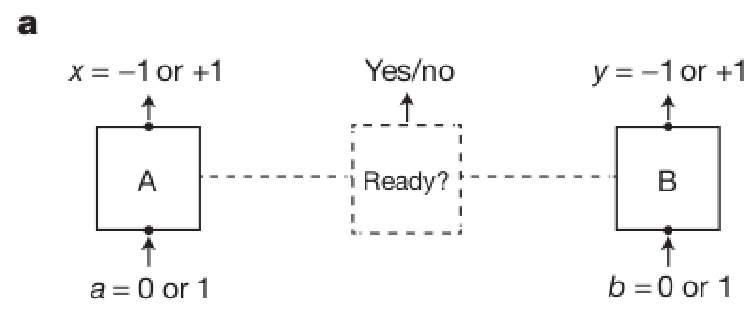
- **Local**

  Physical influences can't propagate faster than light
- **Realism**

  Physical properties are defined before and independent of measurement
- **CHSH Bell test**

  Gives us an inequality $S \leq 2$ that holds under local realism
  - Inequality violated in many experiments → our world is QM!

Basic experiment



- **For each trial**
  - Entangle Spins in Box A and B
  - Measure Spins
    - a=0 → Z measurement in Box A
      a=1 → X measurement in Box A
    - b=0 → $(-Z + X)/\sqrt{2}$ measurement in Box B
      b=1 → $(-Z - X)/\sqrt{2}$ measurement in Box B
- **Evaluate CHSH inequality**
  - $\boldsymbol{S = \left|\langle x \cdot y\rangle_{(0,0)} + \langle x \cdot y\rangle_{(0,1)} + \langle x \cdot y\rangle_{(1,0)} - \langle x \cdot y\rangle_{(1,1)}\right|}$
    → $\langle x \cdot y\rangle_{(a,b)}$ expectation value for input bits a and b
  - QM predicts $S = 2\sqrt{2}$
  - Problem: Loopholes! → Need Event-Ready signal

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Locality Loophole

Locality condition:

- signals travel with $v \leq c$
- two boxes A and B are separated s.t. a signal from A cannot arrive at B before the output value of B has been recorded

Problem:

- possible communication between the two boxes

→ this leads to locality loophole

Solution:

- spatial separation of 1.3 km between the boxes
- distance between pair of photons long enough to address locality loophole using fast setting changes

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Detection Loophole

Problem:

- We need to exclude errorneous output bits x and y for assuming «fair sampling»

Solution:

- Check that entanglement was successful and record Event-Ready signal
- Spin read-out is measured very efficiently

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Simultaneously closing both loopholes

- Spatial separation of 1280 m between the qubits at locations A, B
- Record Event-Ready signal at location C

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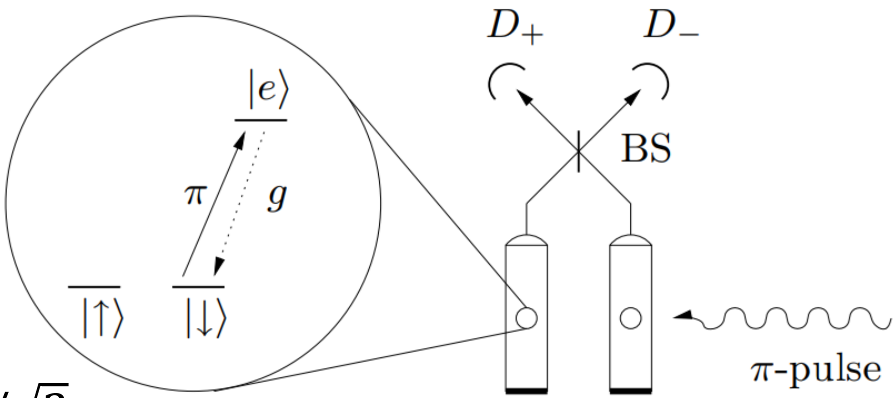
Entangling distant NV centers



- Optical π-Pulse induces transition (selection rule)
  - $|\downarrow\rangle \rightarrow |e\rangle$
  - $|\uparrow\rangle \rightarrow |\uparrow\rangle$
- Scheme
  1) Initialize both qubits to $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$
  2) To both apply a π-Pulse
  3) Wait for some time t for an event at $D_\pm$ ($|e\rangle \rightarrow |\downarrow\rangle$ emits photon)
  4) Apply SWAP operation to both qubits
  5) Repeat steps 2-4
- If we detect exactly one photon each round
  → get max. entangled state $(|\downarrow\uparrow\rangle \pm |\uparrow\downarrow\rangle)/\sqrt{2}$
  → Event ready signal
- Beam splitter erases which-path information

Don't confuse:
This is not the π-Pulse on the Bloch-Sphere!

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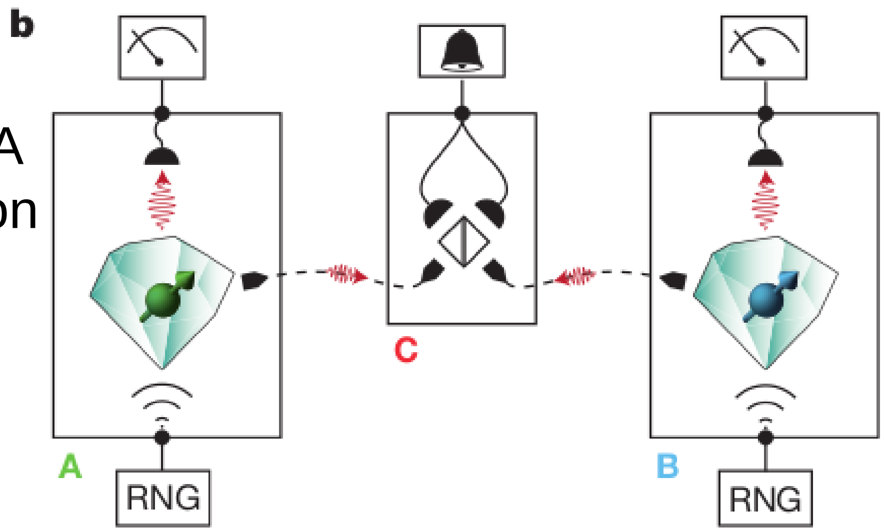
Experimental setup



- Entangle NV centers at locations A and B and send photons to location C → Record event ready signal

- RNG generates the input bit a (or b) to choose random basis → rotate spins accordingly

- Optical readout (Z measurement)
  $m_s = 0 \equiv |\uparrow\rangle \rightarrow x, y = +1$
  $m_s = \pm 1 \equiv |\downarrow\rangle \rightarrow x, y = -1$

  As before only $m_s = 0$ state is excited → dark & bright state

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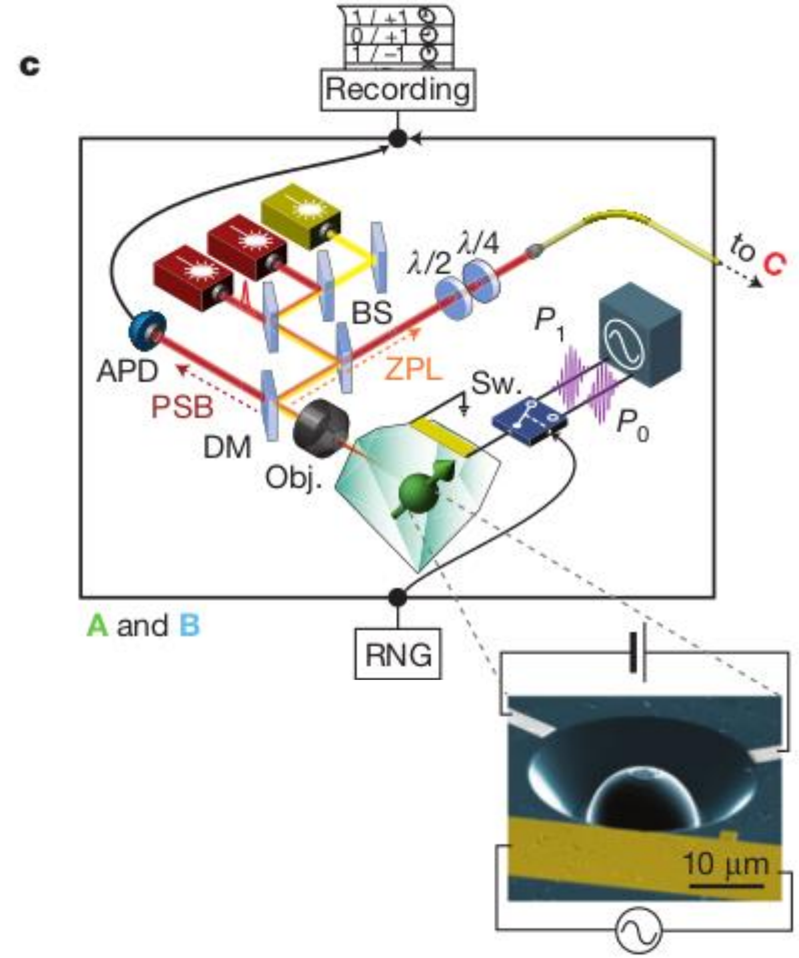
Detailed Setup at locations A,B

- DM: Dichroic mirror allows separation into a off-resonant part (ZPL) and a resonant part (PSB)
- Sw: Selects predefined MW-pulses P0, P1 for basis selection
- APD: Single-photon counter

→ confocal microscope



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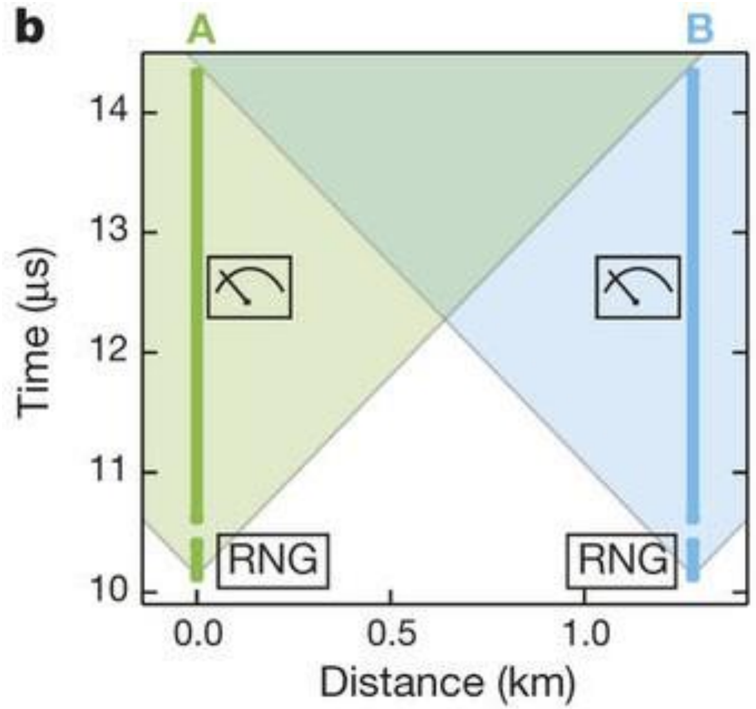
Space-time analysis

- spin separation: 1'280 km

$\rightarrow \mathbf{4.27}\ \mu\boldsymbol{s}$ separation between local events at A and B

- random basis choice: **160 ns**
- read-out duration: $\mathbf{3.7}\ \mu\boldsymbol{s}$
- uncertainity in distance between the laboratories: **90 ns**
- initalisation and single-shot read-out fidelity:
  - for A: **97.1%**
  - for B: **96.3%**
- fidelity of ideal state Y: **92%**



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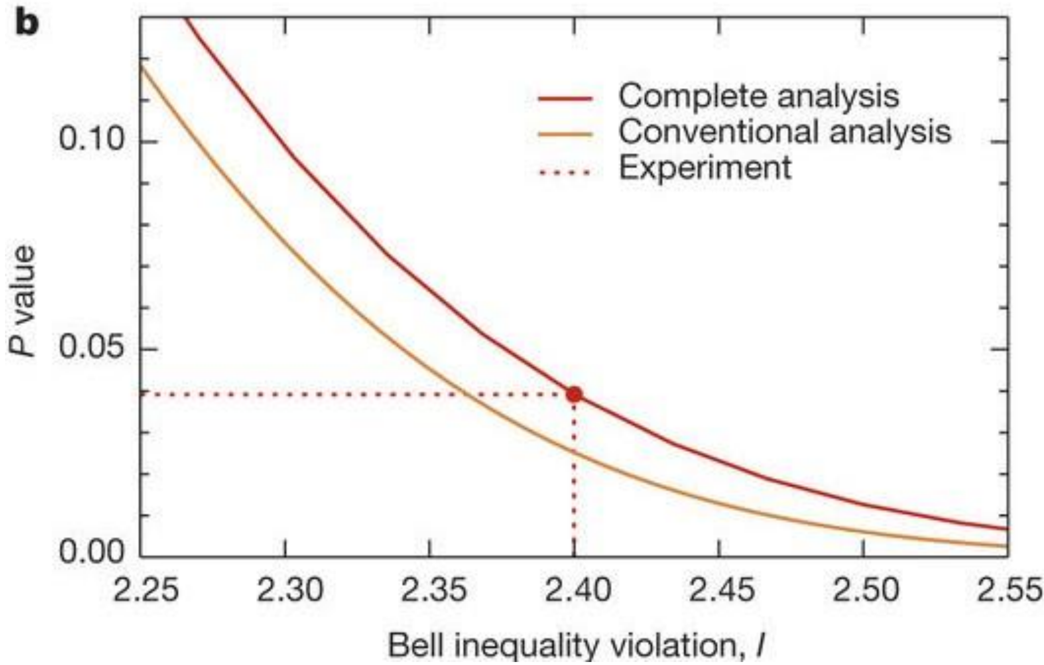
Results

- Entanglement success probability: 6.4×10^{-9}
  →1 event-ready signal per hour
- 245 trials were performed over 220 hours
- expected value:
  $\boldsymbol{S = 2.30 \pm 0.07}$
- theoretically maximum value: $\boldsymbol{S = 2\sqrt{2} \approx 2.83}$
- found value:
  $\boldsymbol{S = 2.45}$



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“Conventional” Analysis

Assumptions:

- Bell trials are independent of each other
- random input have zero predictability
- outcome follows Gaussian distribution

→ standard deviation of **0.20** for S

→ **P = 0.019**

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“Complete” Analysis

Assumption:

- random input have partial predictability

→ **P = 0.039**

Lookout:

- for 700 trials and S = 2.4 one could get P = 0.001

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Final Comments

- The experiment violates the CHSH inequality
  → reject local-realist theories
- It was the first test that simultaneously closed the detection AND the locality loophole
- Central idea: Entangle distant NV centers with photons by using an Event-Ready scheme