Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres[1]

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[1]Hensen, B., *et al.* (2015) Nature, 526 (7575), pp. 682-686.

EPR (Einstein-Podolsky-Rosen) Paradox

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B)$$

- Outcome of the measurement on qubit A could determine the outcome of the measurement on qubit B even if the two measurement events are space like

- Contradict with special relativity?

Physical review, 47(10), 777 (1935)

Two Explanations of the Paradox

- Non-locality:

Influence could travel faster than c in Quantum Mechanics

Does not allow for faster-than-light communication

- Hidden variables:

Outcome of measurement is determined by some hidden variables λ

Two qubits get same hidden variables λ when they are entangled

Measurement of A provides information about λ which is local to B

Physical review, 47(10), 777 (1935)

Test the two explanations experimentally

For hidden variables case:

CHSH (Clauser-Horne-Shimony-Holt) Inequality

- Outcome of the measurement on qubit A,B along direction $\hat{a}$, $\hat{b}$ respectively with the same hidden variables λ : $A(\hat{a}, \lambda) \in \{-1, 1\}$ $B(\hat{b}, \lambda) \in \{-1, 1\}$
- Denote correlation between two measurement $\int d\lambda \rho(\lambda) A(\hat{a}, \lambda) B(\hat{b}, \lambda)$ as $P(\hat{a}, \hat{b})$, where $\rho(\lambda)$ is probability distribution with respect to λ

Correlation of measurements on four directions is constrained:

$$|P(\hat{a}, \hat{b}) - P(\hat{a}, \hat{c}) + P(\hat{d}, \hat{c}) + P(\hat{d}, \hat{b})| \leq 2$$

Physical review letters, 23(15), 880. (1969)

Violation of CHSH Inequality in Quantum Mechanics

In quantum mechanics:

- The correlation between measurement is not constrained as strong as in hidden variables theory
- $P(\hat{a}, \hat{b}) = \langle \psi_{AB} | (\hat{\sigma}_A \cdot \hat{a})(\hat{\sigma}_B \cdot \hat{b}) | \psi_{AB} \rangle = -\cos\theta_{ab}$
- Construct the measurement in four directions as shown in the figure

$$\theta_{ab} = \pi/4,\ \theta_{ac} = 3\pi/4,\ \theta_{dc} = \pi/4,\ \theta_{db} = \pi/4$$
$$|P(\hat{a}, \hat{b}) - P(\hat{a}, \hat{c}) + P(\hat{d}, \hat{c}) + P(\hat{d}, \hat{b})| = 2\sqrt{2} > 2$$

- CHSH inequality is violated!
- Quantum mechanics is non-local

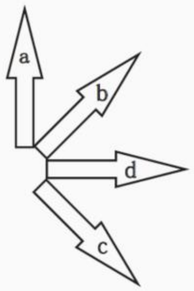

Figure 1: Directions of measurement

Previous Bell Test Experiment Loopholes

- Previous tests of Bell's inequality have loopholes
  - None have simultaneously closed detection and locality
  - Detection: detection efficiency is not 100%
    - Subsample may violate Bell inequality when the whole data set does not
  - Locality: timelike separation between measurement sites allows communication

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- Loophole-free Bell test would fundamentally test QM
- Test security of QM security protocols
  - Use Bell tests to detect interception

Closing Detection and Locality Loopholes

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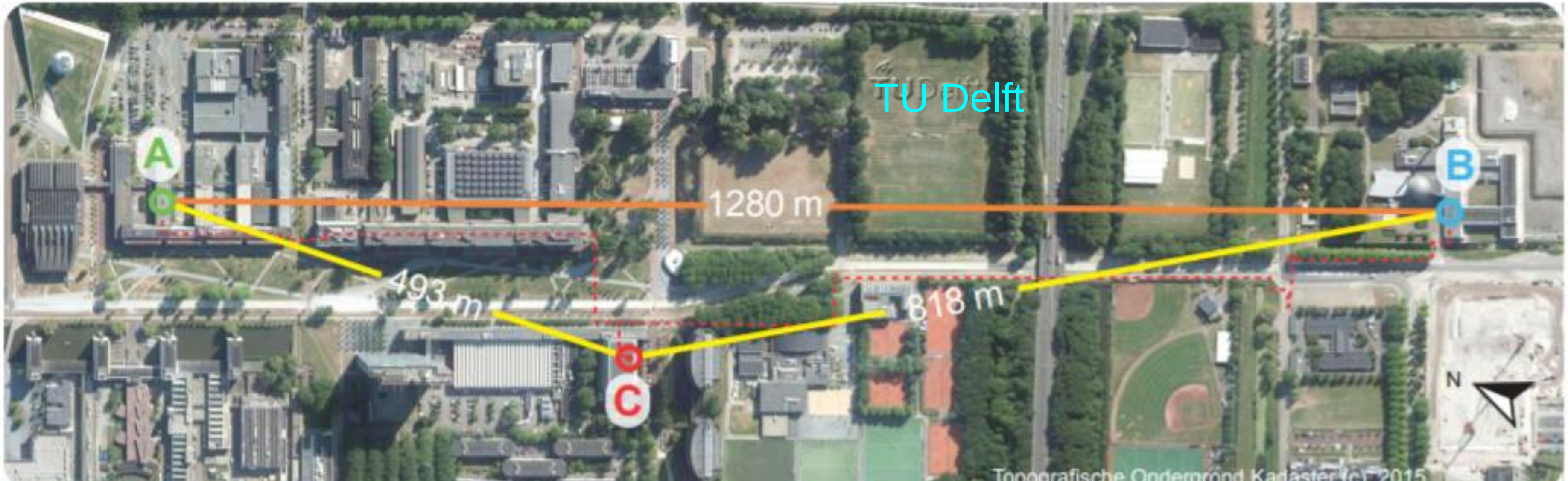
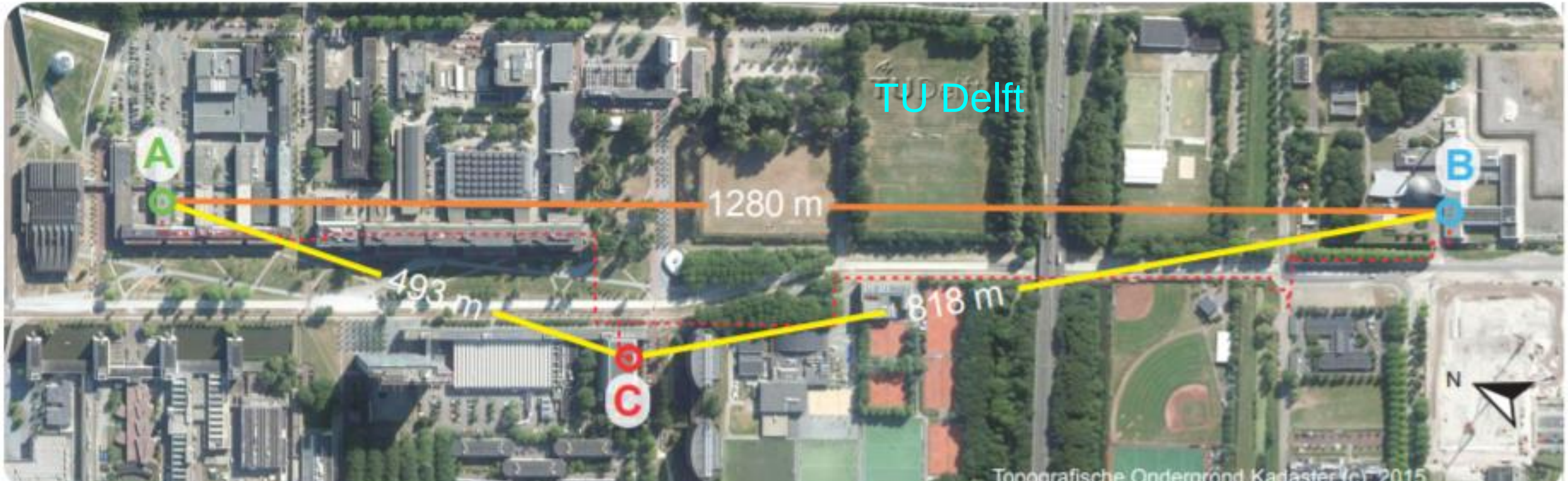


Closing Detection and Locality Loopholes

- Goal: close all measurement loopholes
- Photons with uncorrelated spins emitted from A and B, measured at C
- Additional signal to close detection loophole
  - Determines whether both photons arrived simultaneously

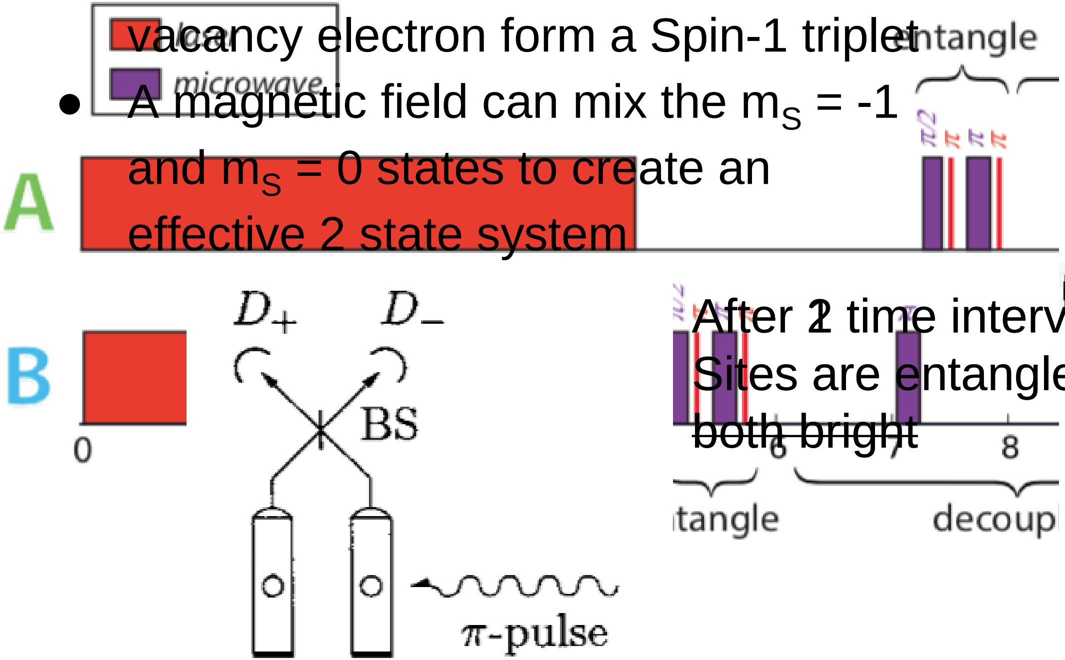


Creating and Entangling Electron Spins

- Unpaired Nitrogen electron and vacancy electron form a Spin-1 triplet
- A magnetic field can mix the m_S = -1 and m_S = 0 states to create an effective 2 state system

- The spins of the two separate sites are entangled by the Barrett-Kok scheme

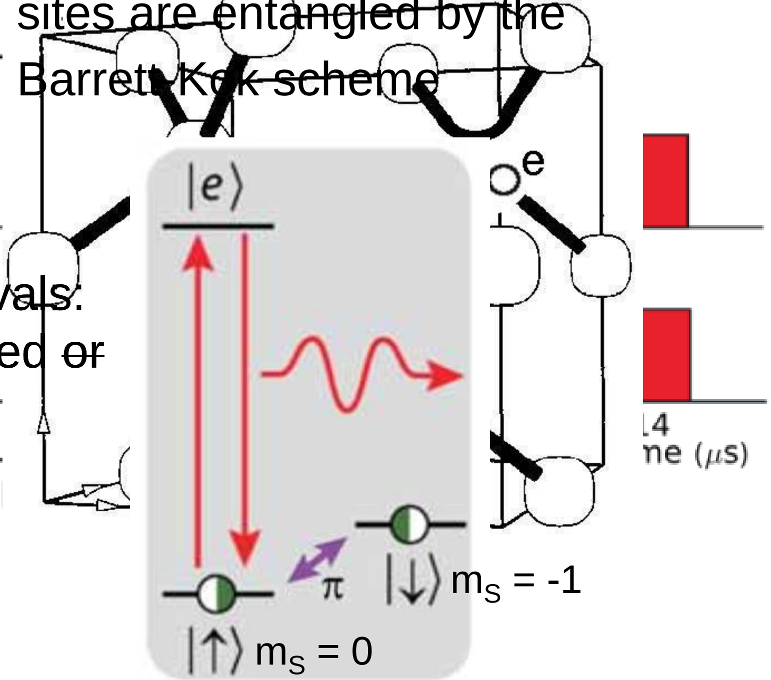
NV Center



After 2 time intervals:

Sites are entangled ~~or both bright~~

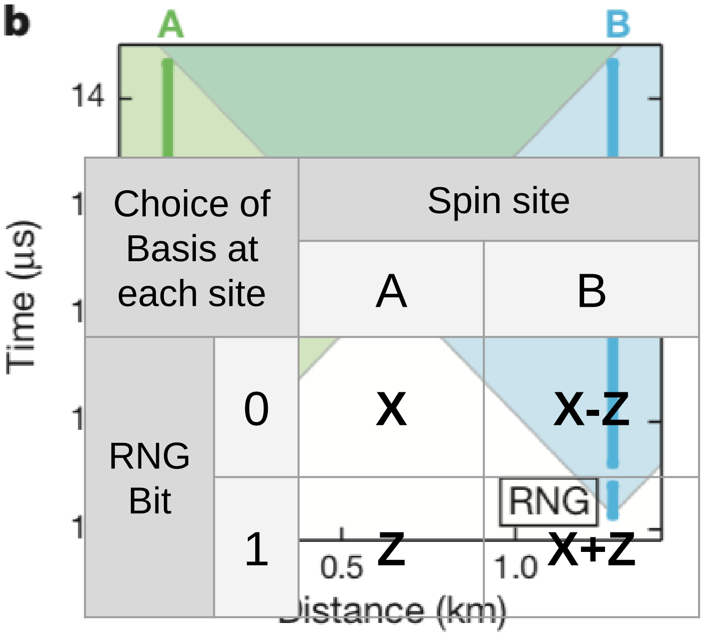
After 1 time interval:



Physical review A, 71(6), 060310 (2005)

Reading Out the Entangled Spins

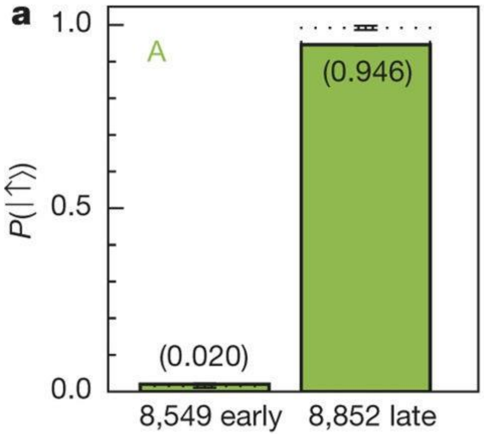
- The group uses two binary RNGs to choose between two measurement bases to evaluate A and B on
- After evaluation, but before entanglement is confirmed, the group rotates to the required basis and reads out the signal.
- Rotation and readout takes <4.27μs (the amount of time it would take for sites A and B to communicate).

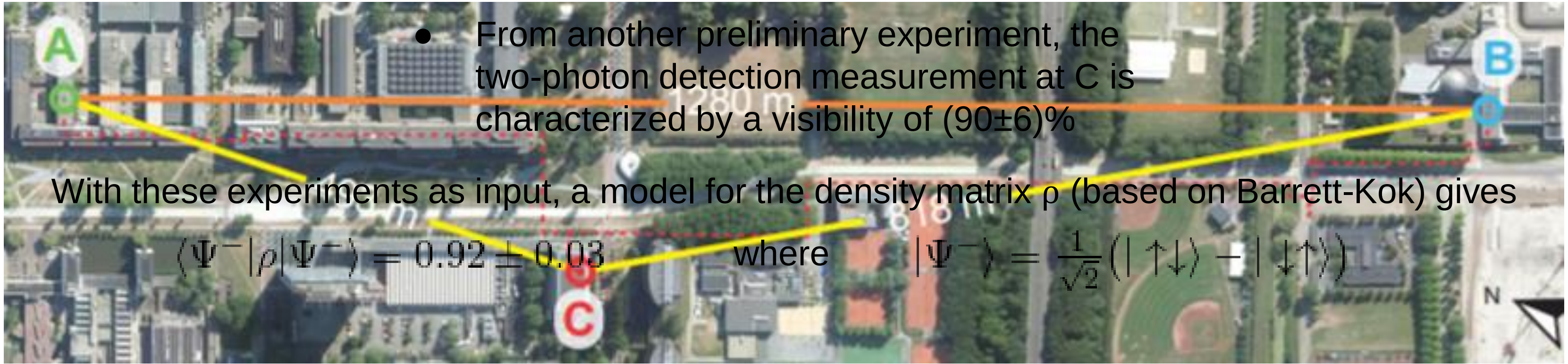


Choice of Basis at each site		Spin site	
		A	B
RNG Bit	0	X	X-Z
	1	Z	X+Z

Preliminary experiments predict strong entanglement

- Ignored site B, and generated spin-photon entanglement at A
- Measured spin at A and photon arrival time at C
- Spin is entangled with photon arrival time



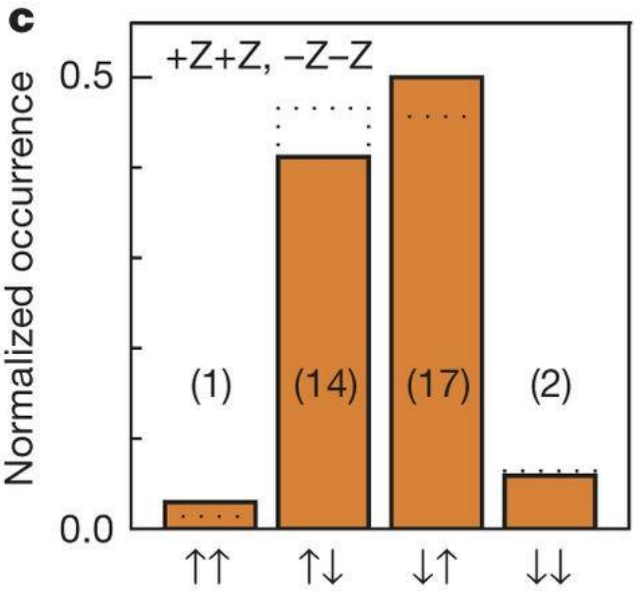


- From another preliminary experiment, the two-photon detection measurement at C is characterized by a visibility of (90±6)%

With these experiments as input, a model for the density matrix ρ (based on Barrett-Kok) gives

$$\langle\Psi^-|\rho|\Psi^-\rangle = 0.92 \pm 0.03 \quad \text{where} \quad |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Generated spin states are highly entangled

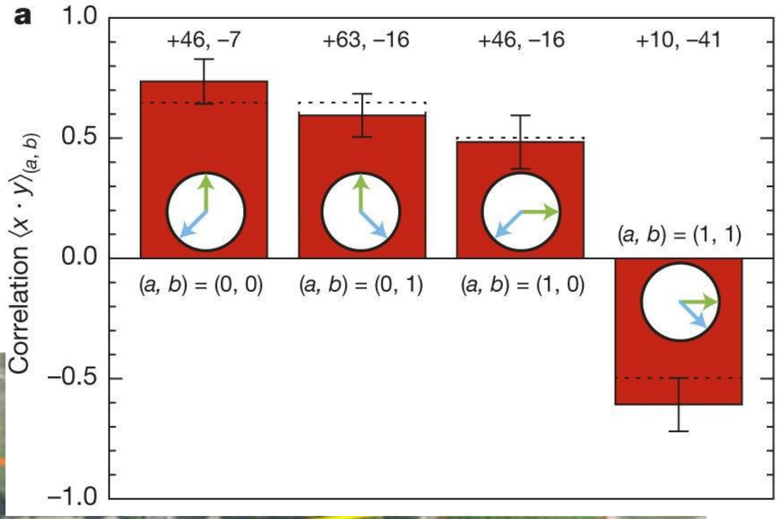


Measurement outcomes for successful entanglement attempts (dotted: prediction based on model ρ)

- Ran experiment with fixed collinear measurement bases
- Data indicates entanglement
- Gives a lower bound $\langle \Psi^- | \rho | \Psi^- \rangle > 0.83 \pm 0.05$
- Numerically optimized angles of measurement bases for maximal correlations

CHSH-Bell inequality is violated with p-value 0.039

- Experiment was iterated 1 billion times per hour
  - Spin-photon entanglement at A and B
  - Two-photon measurement and event-ready signal at C
  - Measure spins along random bases



- 245 successful entanglements during 220 hours of data collection

- Iterations with successful entanglements were used to find S.

- Found S= 2.42 ± 0.20, violating S≤2

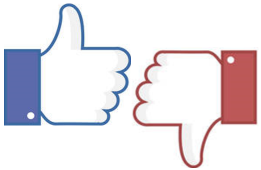
Conclusions

- Reports the **first** Loophole-free Bell inequality violation detection using electrons. They found **$S = 2.42 \pm 0.20$**

  as compared to **$S \leq 2$**

- It successfully closes the **detection** loophole and the **locality** loophole.
- Uses an event-ready scheme to generate entanglement between electrons separated by 1.28 km.
- Statistically significant result with a P value of 0.039.

Critiques



- A concise and well-written abstract, which answers all the questions expected of it.
- For every ‘field-specific term’ that is used, a nice review paper/ publication (that first introduced the concept) has been cited. This makes the paper an ideal-read for a general Physics audience.
- Explains the footing of their experiment in the light of several past failures in the field.
- Covers all the bases- provides a detailed characterization of the experimental setup and explicitly shows how both the loopholes are taken care of.
- The paper is self-sufficient. But whatever little has been left out, is covered by the Supplementary Information.

Citation Report

- This paper was published on 29 October 2015
- It has been cited 314 times. (Scopus, 12 December 2017)
  - Facebook - Shares, likes and comments - 1379
  - Twitter - 200 Tweets
- A really important scientific paper in the field of quantum information.
- The follow up work, by a different group. Cited 149 times. It does a Loophole-free test of the Bell's inequality with entangled photons.

Selected for a Viewpoint in *Physics*
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Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons

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