Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

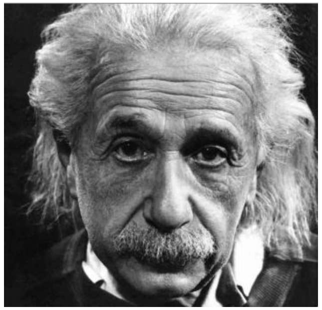
Experimental Violations of Bell's Inequalities

Julia Cramer, Christian Schütte-Nütgen

Is the moon there when nobody looks?

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete

- 1935 – EPR ‘gedankenexperiment’

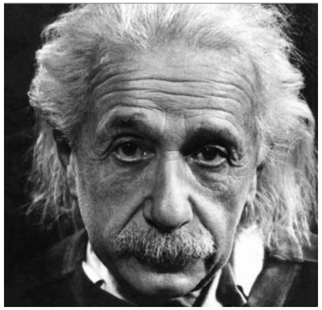


- Simultaneous reality?
  - *“every element of the physical reality must have a counterpart in the physical theory”*

- Entanglement – locality problem

- Bell’s inequality theorem
  - Violation shows “completeness” of quantum mechanics
  - No hidden variables

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete



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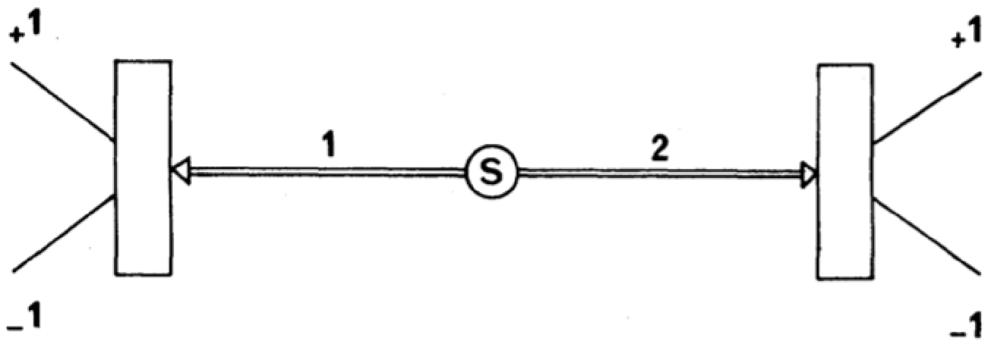
→ **non-realistic, non-local**

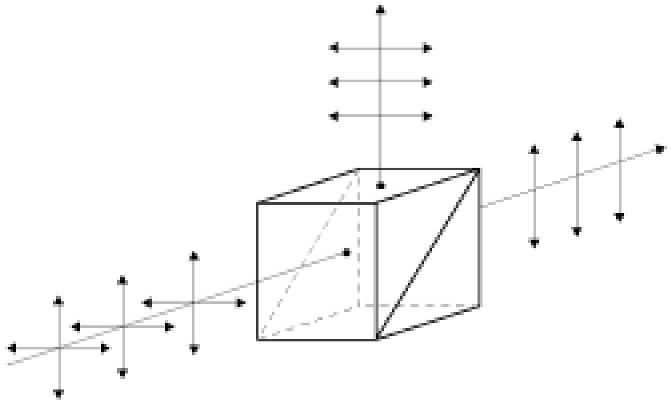
Outline

- Bell‘s Inequality – CHSH form
- Connection to QC
- Experimental challenges: Loopholes
- Experiments
  - Aspect
  - Weihs
  - Matsukevich
  - Ansmann
- Conclusion

Bell's Inequality – CHSH form



Bell's Inequality – CHSH form

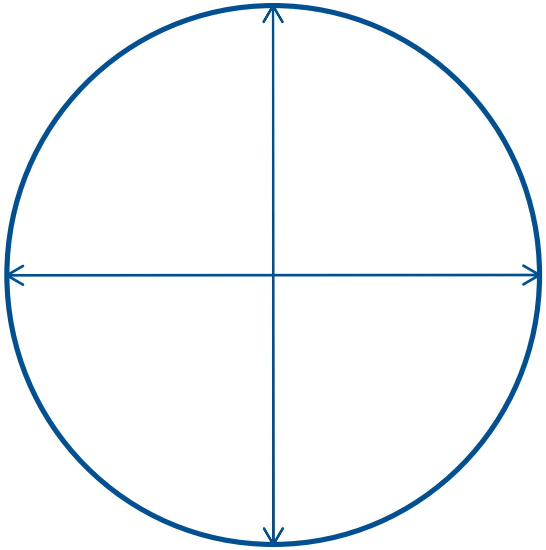


Alice's basis	outcome		Bob's basis	outcome	
A_1	H1	+1	B_1	H1	+1
	V1	-1		V1	-1
A_2	H2	+1	B_2	H2	+1
	V2	-1		V2	-1

- $|B_1(A_1+A_2)+B_2(A_1-A_2)| \leq 2$
- $|B_1A_1+B_1A_2+B_2A_1-B_2A_2| \leq 2$
- $S=|E(B_1,A_1)+E(B_1,A_2)+E(B_2,A_1)-E(B_2,A_2)| \leq 2$

Bell's Inequality – CHSH form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|HV\rangle + |VH\rangle\right]$$



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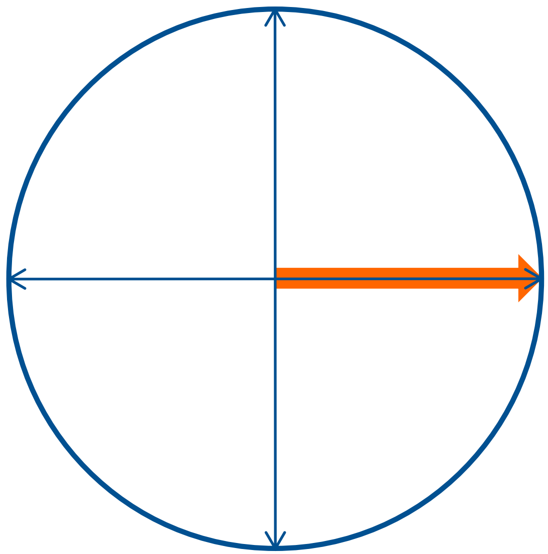

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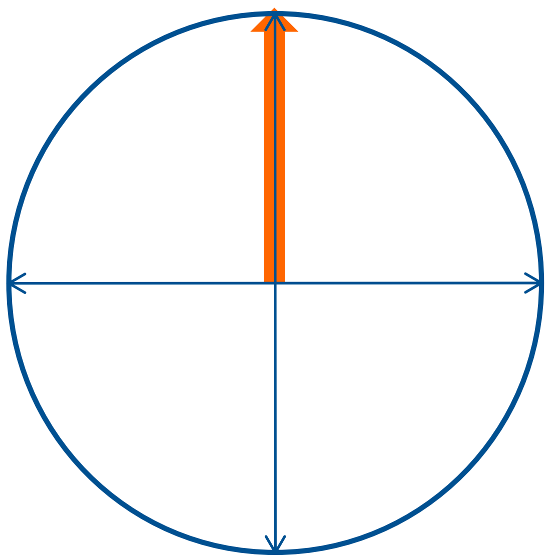

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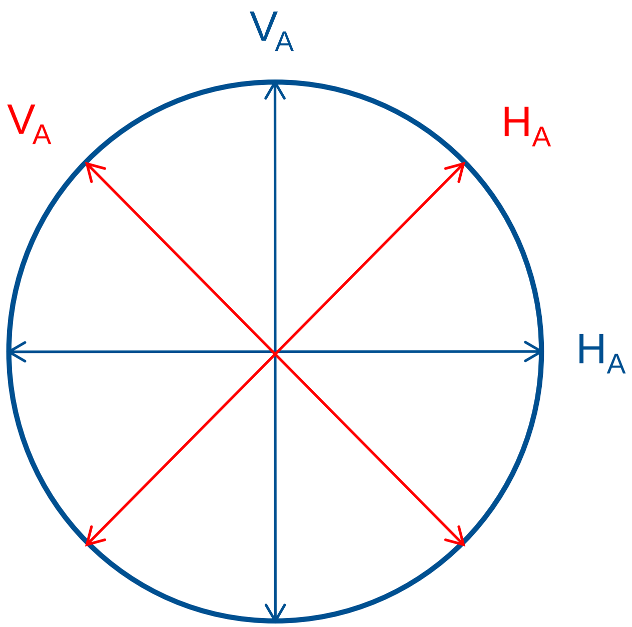
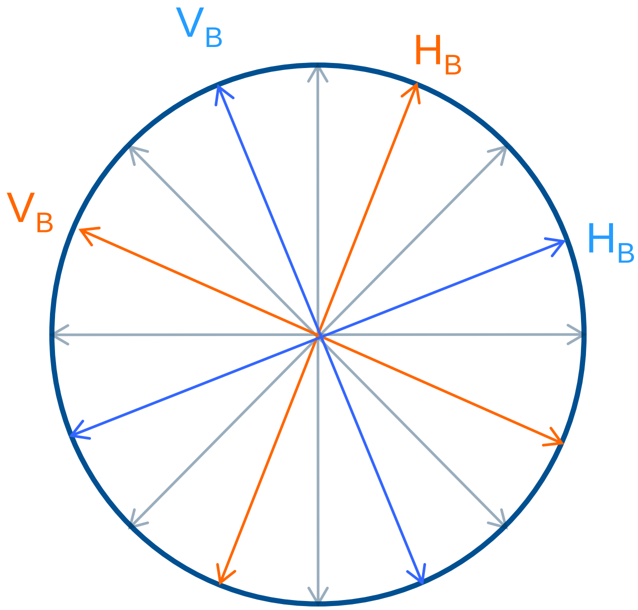


Bell's Inequality – CHSH form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|HV\rangle + |VH\rangle\right]$$

$$B_1 = \frac{1}{\sqrt{2}}\left[A_1 + A_2\right]$$

$$B_2 = \frac{1}{\sqrt{2}}\left[A_1 - A_2\right]$$



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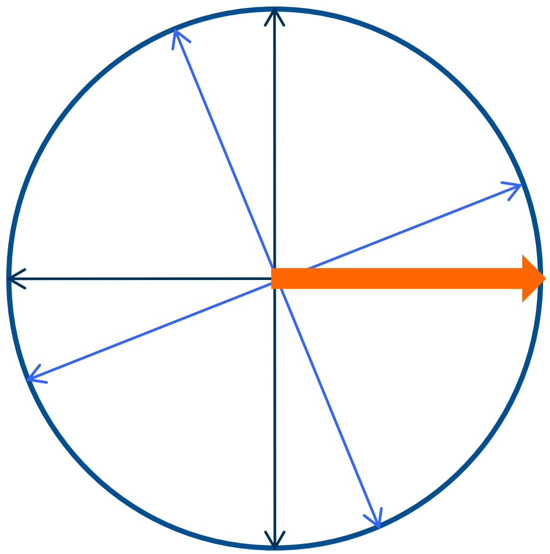

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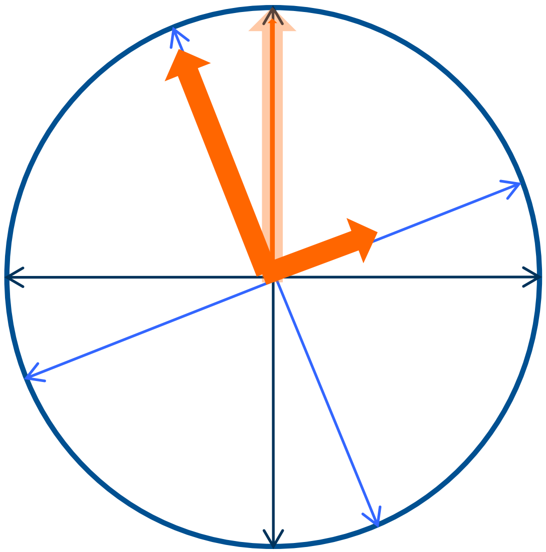

$$E = P('right') - P('wrong')$$

$$E(A_1, B_1) = 1 \cdot \frac{1}{\sqrt{2}}$$

Bell's Inequality – CHSH form

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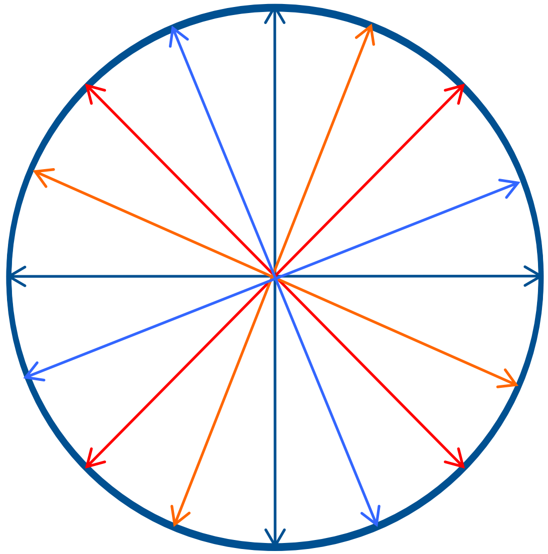


$$E(A_1,B_1) = 1\cdot\frac{1}{\sqrt{2}}$$

$$E(A_1,B_2) = 1\cdot\frac{1}{\sqrt{2}}$$

$$E(A_2,B_1) = 1\cdot\frac{1}{\sqrt{2}}$$

$$E(A_2,B_2) = 1\cdot -\frac{1}{\sqrt{2}}$$

$S=|E(B_1,A_1)+E(B_1,A_2)+E(B_2,A_1)-E(B_2,A_2)|$ = $\mathbf{2\sqrt{2}}$

Connection to QC

- Proposal: Violation of Bell's Inequality as a single number benchmark for any quantum computation implementation
- Violation of Bell's Inequality is a totally non-classical phenomenon → quantum behavior of a system
- Successfully measuring violation requires simultaneous optimization of several qubit performance benchmarks
- → DiVincenzo criteria

Experimental Challenges - Loopholes

- Mainly two loopholes in experiments that allow to keep up a classical local-realistic view
- 1. Detection loophole
- 2. Locality loophole
- Ambition: close both loopholes

Detection Loophole

- Detection efficiency < 100%
- → measure only a subset of all emitted pairs
- → could introduce classical correlation

- For measurement of whole set Bell's Inequalities may still hold

- "Fair sampling assumption": sample of detected pairs is representative of all emitted pairs

- problem in optical experiments:
- Photon detectors only measure a fraction of all photons

Locality Loophole

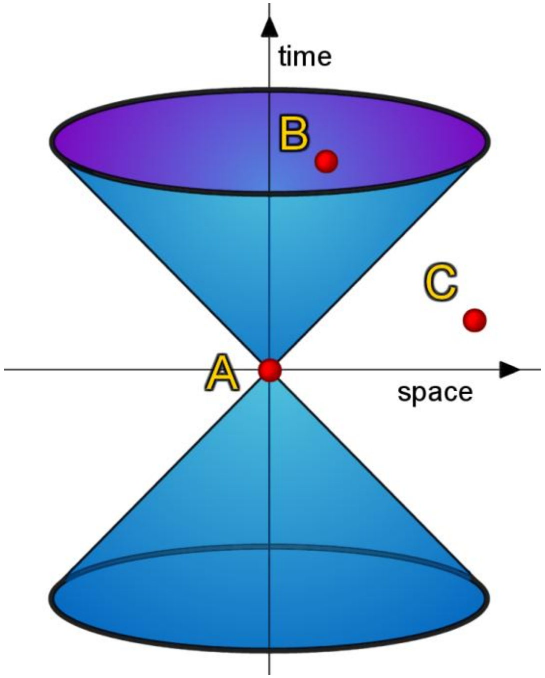
- Bell's Inequality requires absence of "communication" between measurement sites

- Can be ensured: $d \geq c\, t_{mea}$

  d: distance of the sites

  c: speed of light

  t_{mea}: measurement duration (choice of basis + detection)



Experiments

- Aspect et al. 1982
- Weihs et al. 1998

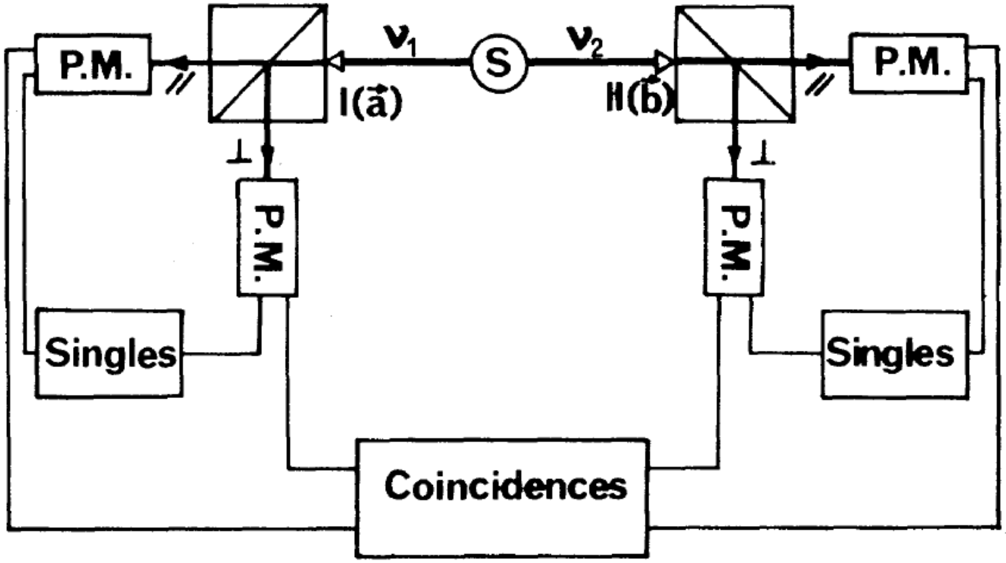
Close locality loophole

- Matsukevich et al. 2008
- Ansmann et al 2009

Close detection loophole

Experimental Realization of EPR Gedankenexperiment: A new Violation of Bell's Inequality

A. Aspect, P. Grangier, G. Roger, 1982



- Source emits entangled pairs of photons (radiative cascade of Ca)
- Polarizer orientations changed manually
- Infer accidental coincidence rates from single rates

Experimental Realization of EPR Gedankenexperiment: A new Violation of Bell's Inequality

A. Aspect, P. Grangier, G. Roger, 1982

- Low detection efficiency of photon detectors

  → fair sampling assumption

- Previous experiments with one-channel polarizers:

  problem: if no count at one site: photon blocked by polarizer or missed by detector?

  → here: two-channel polarizers

- Choice of orientations of polarizers optimal for maximal violation $|S| = 2\sqrt{2}$

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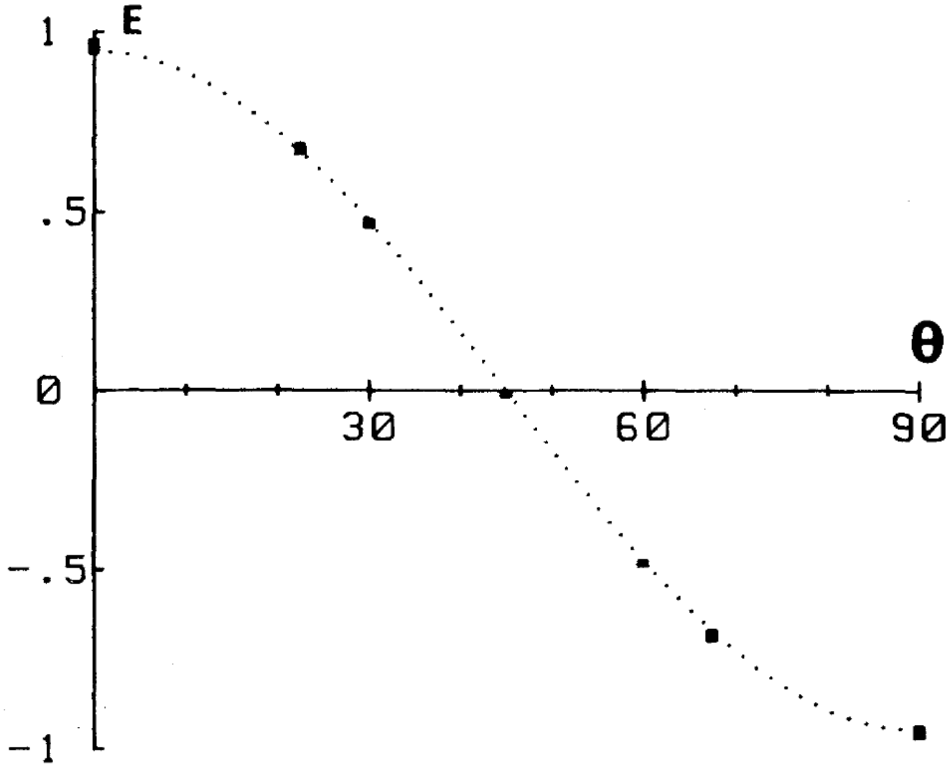


- S = 2.697 ± 0.015
- (83 % of maximum violation)

$$E(\vec{a},\vec{b}) = \frac{R_{++}(\vec{a},\vec{b}) + R_{--}(\vec{a},\vec{b}) - R_{+-}(\vec{a},\vec{b}) - R_{-+}(\vec{a},\vec{b})}{R_{++}(\vec{a},\vec{b}) + R_{--}(\vec{a},\vec{b}) + R_{+-}(\vec{a},\vec{b}) + R_{-+}(\vec{a},\vec{b})}$$

Experimental Realization of EPR Gedankenexperiment: A new Violation of Bell's Inequality

A. Aspect, P. Grangier, G. Roger, 1982

- Static experiment (no dynamic, random choice of polarizers)

  → locality loophole

- Low detection efficiency

  → detection loophole

- Improvements: Weihs et al. 1998

Violation of Bell's Inequality under Strict Einstein Locality Conditions

C. Weihs, T. Jennewein, C. Simon, H. Weinfurter, A. Zeilinger, 1998

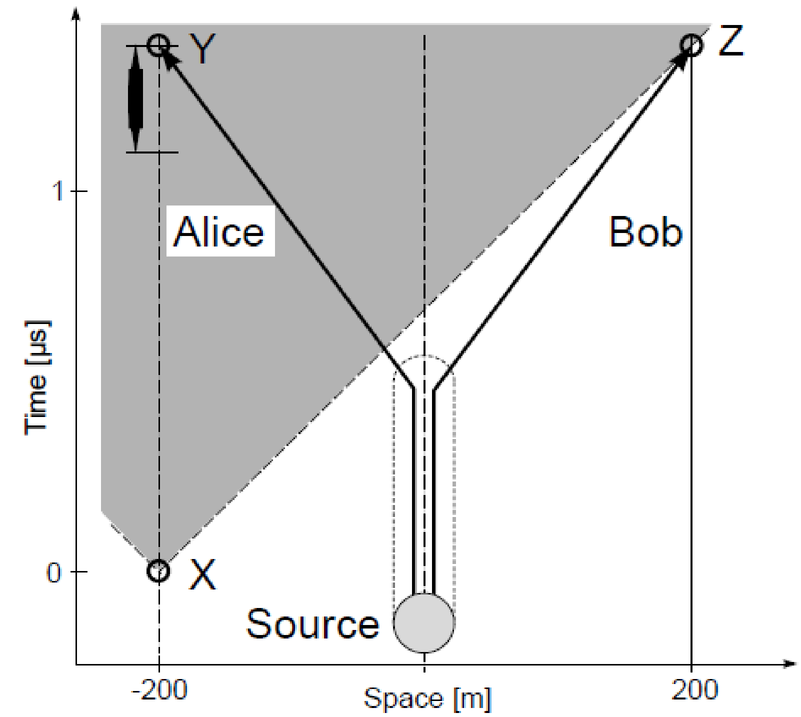
- Basis: experiment by Aspect et al.
- Locality loophole closed by:
  - Necessary spacelike separation of the two measurement sites
  - Ultrafast and random setting analyzers
  - Completely independent data registration

Violation of Bell's Inequality under Strict Einstein Locality Conditions

C. Weihs, T. Jennewein, C. Simon, H. Weinfurter, A. Zeilinger, 1998

- Spacelike separation

- Def. measurement duration: first point in time which can influence choice of analyzer setting until registration of photon



- Here: spatial separation 400m (photons sent through optical fibers) → $t_{mea} < 1.33$ μs
  $t_{mea} = 100$ ns

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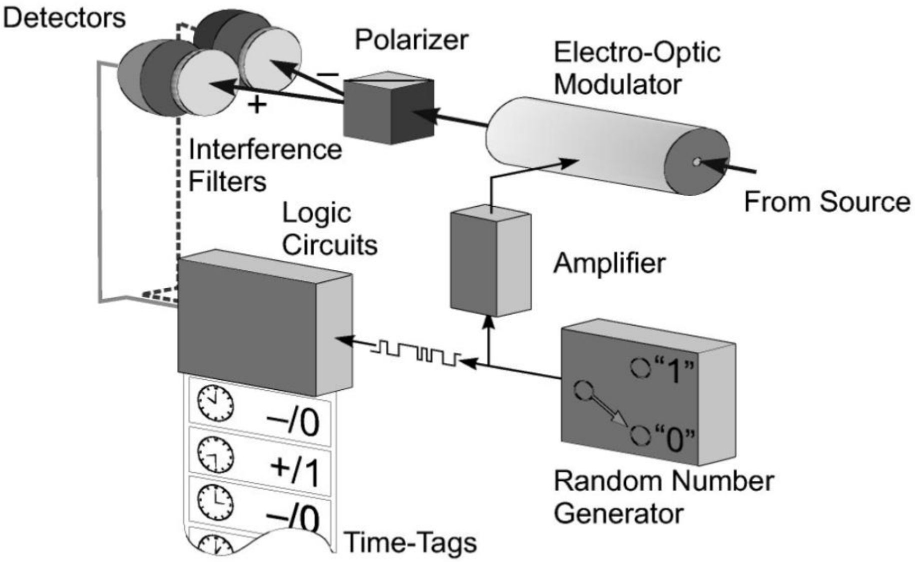

- Ultrafast and random setting analyzers

- Selection has to be unpredictable:
  → high speed physical random number generators (beamsplitters) and
  fast electro optic modulators to choose measurement polarization

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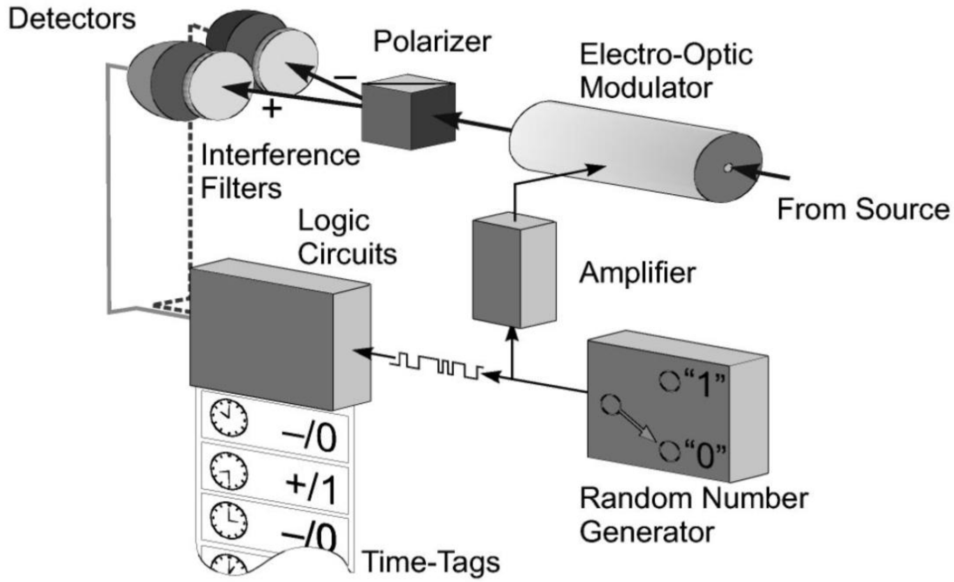


- Completely independent data registration

- Comparison of results **after** measurements are finished
  → avoid conventional registration of coincidences:
  each observer has his own time interval analyzer and atomic clock for synchronization

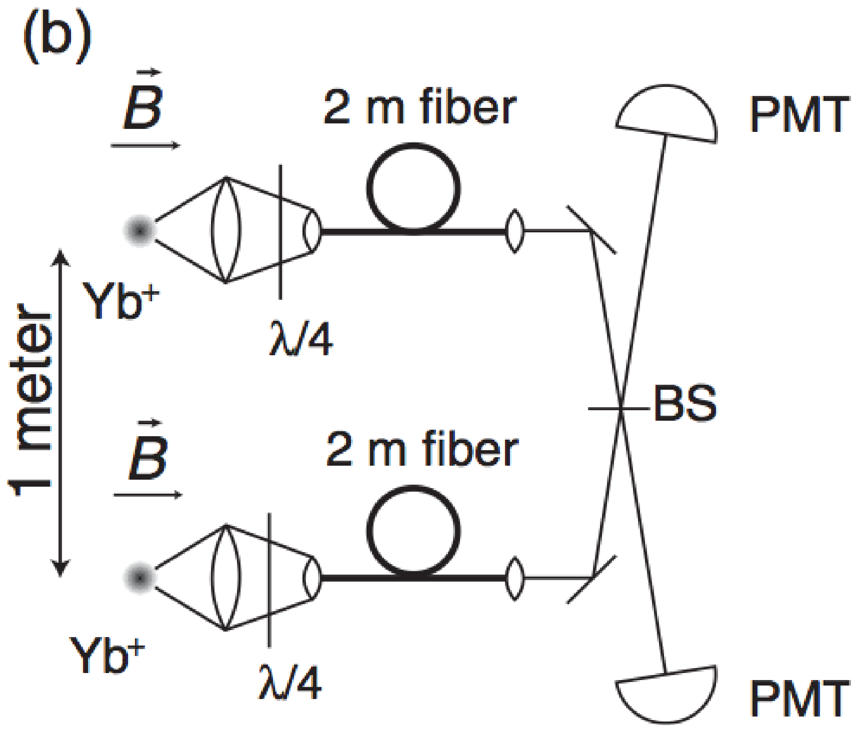
Violation of Bell's Inequality under Strict Einstein Locality Conditions

C. Weihs, T. Jennewein, C. Simon, H. Weinfurter, A. Zeilinger, 1998

- Outcome: $S = 2.73 \pm 0.02$
- Locality loophole closed
- BUT: detection loophole due to low detection efficiency of photon detectors

Bell Inequality Violation with two Remote Atomic Qubits

D.N. Matsukevich, P. Maunz, D.L. Moehring, S. Olmschenk, C.Monroe (Maryland)

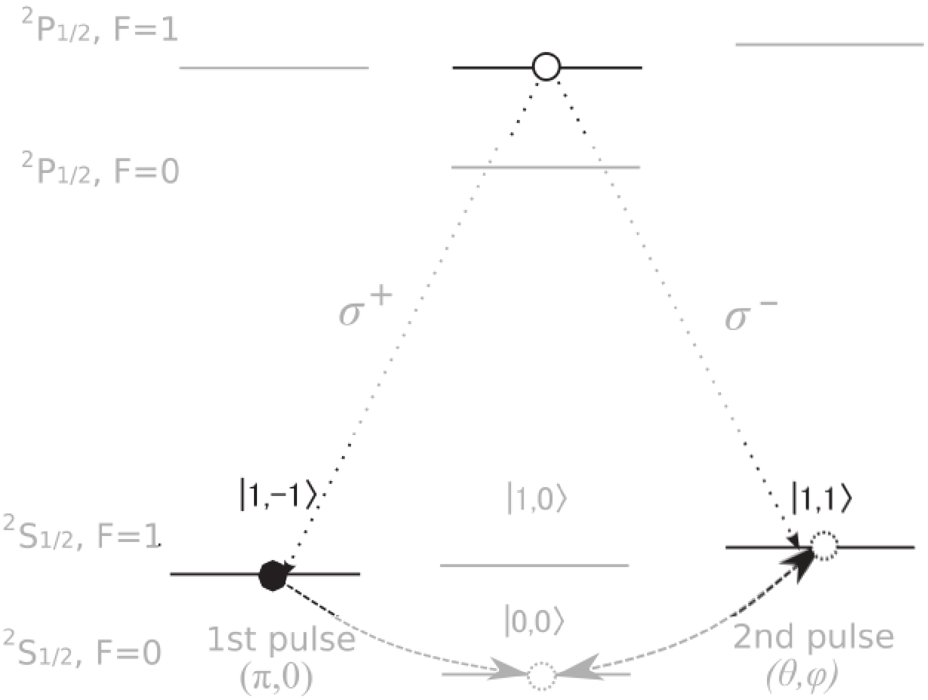


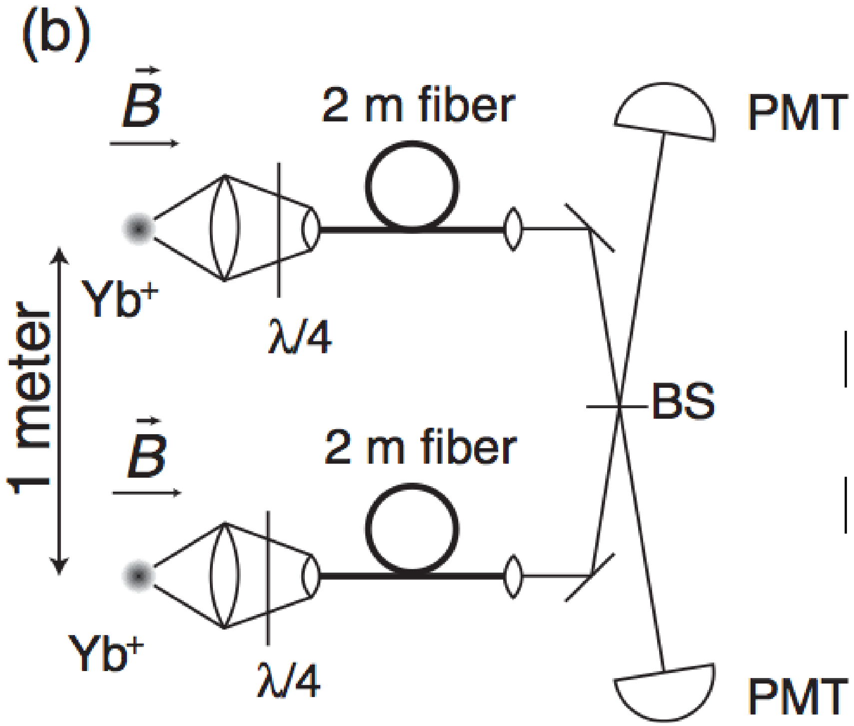
Bell Inequality Violation with two Remote Atomic Qubits

D.N. Matsukevich, P. Maunz, D.L. Moehring, S. Olmschenk, C.Monroe (Maryland)

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|1,1\rangle|\sigma^-\rangle - |1,-1\rangle|\sigma^+\rangle\right]$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|1,1\rangle|V\rangle - i|1,-1\rangle|H\rangle\right]$$





$$|\Psi\rangle_{ph} = \frac{1}{\sqrt{2}}\left[|H\rangle|V\rangle - |V\rangle|H\rangle\right]$$

$$|\Psi\rangle_{ion} = \frac{1}{\sqrt{2}}\left[|1,1\rangle_a|1,-1\rangle_b - |1,-1\rangle_a|1,1\rangle_b\right]$$

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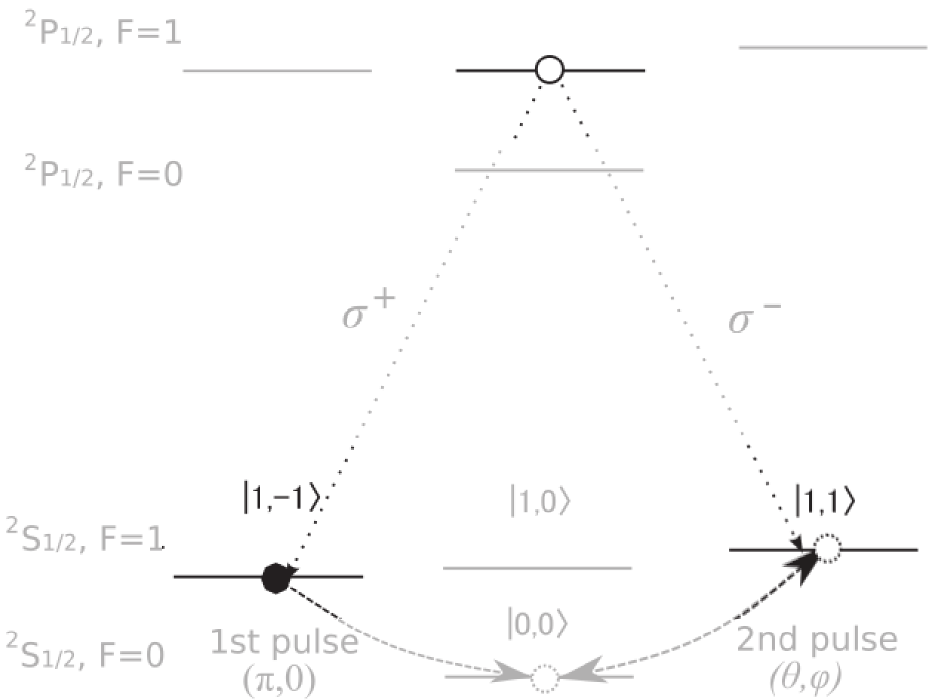


$$\cos(\theta_i/2)|1,1\rangle + \sin(\theta_i/2)e^{i\phi}|1,-1\rangle \longrightarrow |1,1\rangle$$

$$-\sin(\theta_i/2)e^{-i\phi}|1,1\rangle + \cos(\theta_i/2)|1,-1\rangle \longrightarrow |0,0\rangle$$

$$\left|\Psi\right\rangle_{ion,a} = \cos(\theta_a/2)\left|1,1\right\rangle + \sin(\theta_a/2)\left|1,-1\right\rangle$$

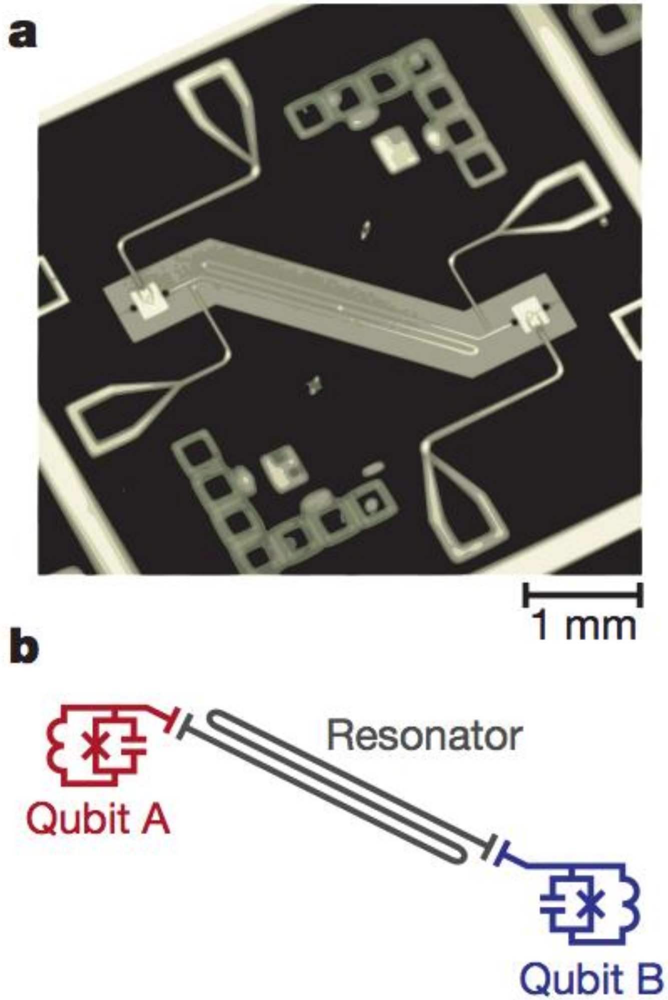
$$S = |E(\theta_a, \theta_b) + E(\theta'_a, \theta_b)| + |E(\theta_a, \theta'_b) - E(\theta'_a, \theta'_b)| \leq 2.$$

- $S = 2.22 \pm 0.07$
- Entanglement-fidelity 81%
- Detection efficiency 98%

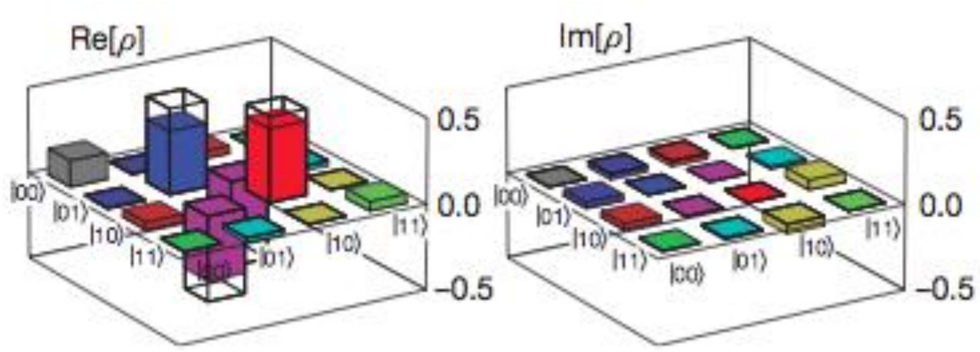
Violation of Bell's inequality in Josephson phase qubits

M. Ansnamm, H. Wang, R.C. Bialczak, M. Hofheinz, E. Lucerno, M. Neeley, A.D. O'Connel, D. Sank, M. Weides, J. Wenner, A.N. Cleveland, J.M. Martinis (Santa Barbara)

- 2 qubits act as phase-1/2 particles
- Qubits are rotated with microwave pulses
- Resonater entangled with qubit A
- Resonater entanglement swapped to qubit B



b



- S = 2.0732 ± 0.0003
- Entanglement of formation 0.378
- Measurement fidelities 94.6% and 93.4%

Conclusion

- Violation of Bell's Inequality is a totally non-classical i.e. qm phenomenon:

  → non-realistic

  → non-local
- hence it can be a single number benchmark for quantum computation implementation

- Experimental challenge: close loopholes
  - Locality loophole closed in photon experiments
  - Detection loophole closed in solid state experiments
- Ultimate goal: close both loopholes in one experiment