ETH
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DPHYS
Department of Physics

Photons: Experimental violation of Bell inequalities with photons

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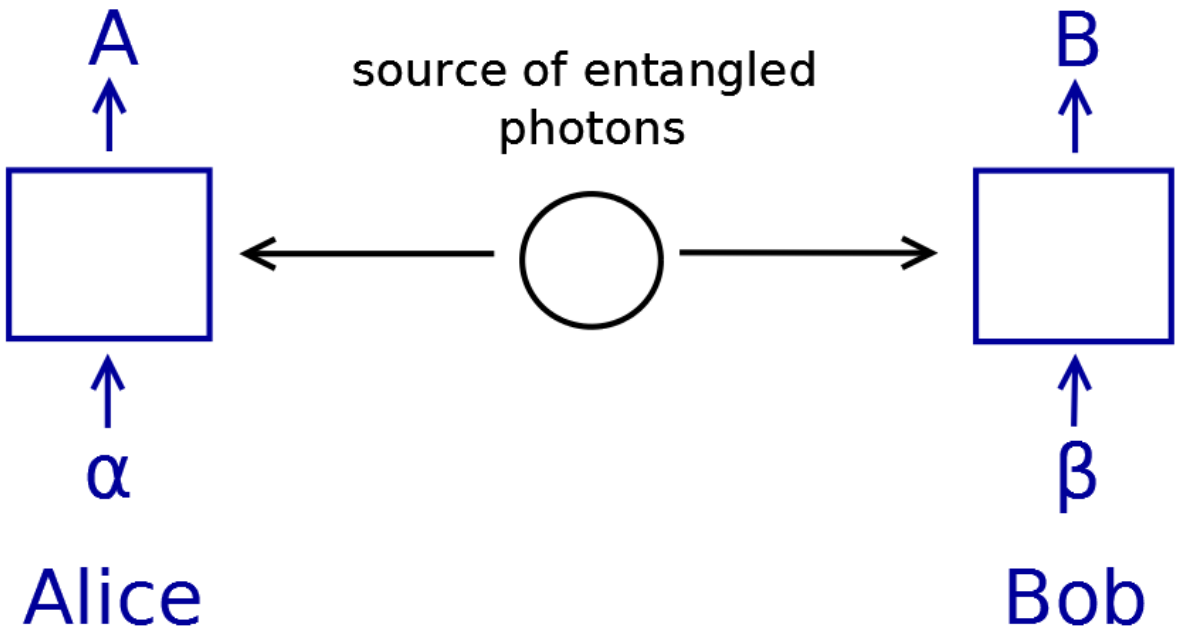
Content

- Theoretical Aspects
- Experimental Realization
  - 2 Experiments with Photon
  - Comparison with atomic and superconducting system

Background

- Einstein, Podolski and Rosen (1935):
  - quantum mechanics not complete
  - “hidden variables” needed
- Bell (1964):
  - “local realistic” theories not compatible with quantum mechanics

General Setup



α,β : detector settings, chosen by Alice and Bob respectively

A,B : outcomes ∈ {-1,1}

CHSH Inequality

- Alice and Bob can each choose between two detector settings (α,α' and β,β' respectivlely)
- Outcomes: $A(\alpha,\lambda),\ A'(\alpha',\lambda)$ & $B(\beta,\lambda),\ B'(\beta',\lambda) \in \{-1,+1\}$
- What values can $AB - AB' + A'B + A'B'$ take?

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- If one then takes the expectationvalue:

$$|E(AB) - E(AB') + E(A'B) + E(A'B')| \leq 2$$

Quantum mechanics Violation

- Consider an entangled state:

$$|\varphi\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

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- Choose the measurements:

$$A(\alpha) = \sigma_z, \qquad A'(\alpha') = \sigma_x$$

$$\mathrm{B}(\beta) = -\frac{1}{\sqrt{2}}(\sigma_z + \sigma_x), \quad \mathrm{B}'(\beta') = \frac{1}{\sqrt{2}}(\sigma_z - \sigma_x)$$

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- $E(AB) - E(AB') + E(A'B) + E(A'B') = 2\sqrt{2} > 2$

Loopholes

- Efficiency loophole
- Locality loophole

Experimental violation of Bell inequalities

- *Experimental Realization of EPR-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities.* Aspect, A. (1982)
- *Violation of Bell inequality under strict Einstein locality conditions.* Weihs, G. (1998)

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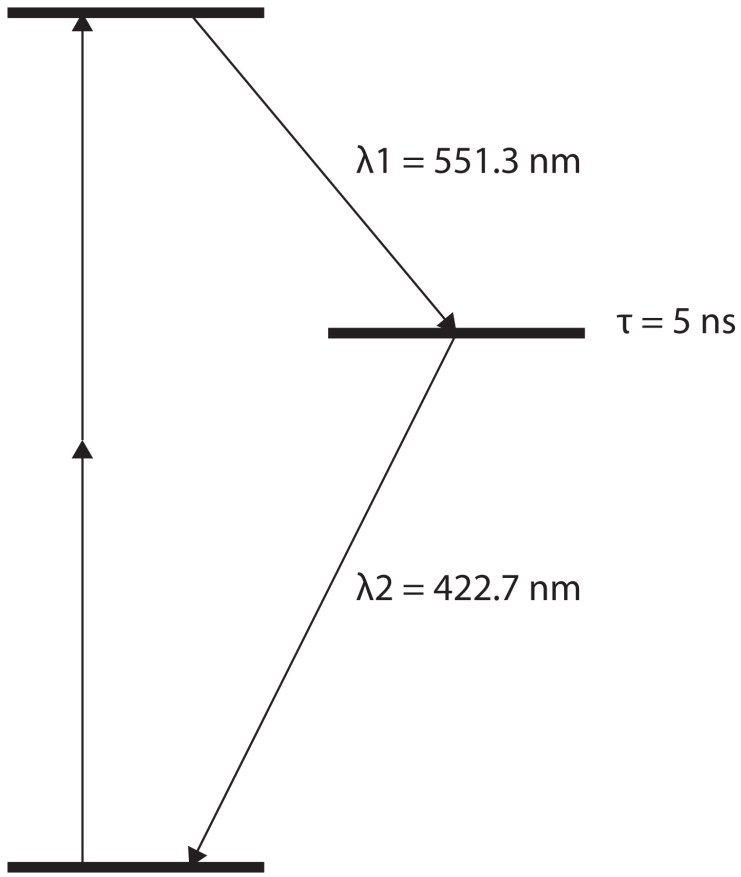
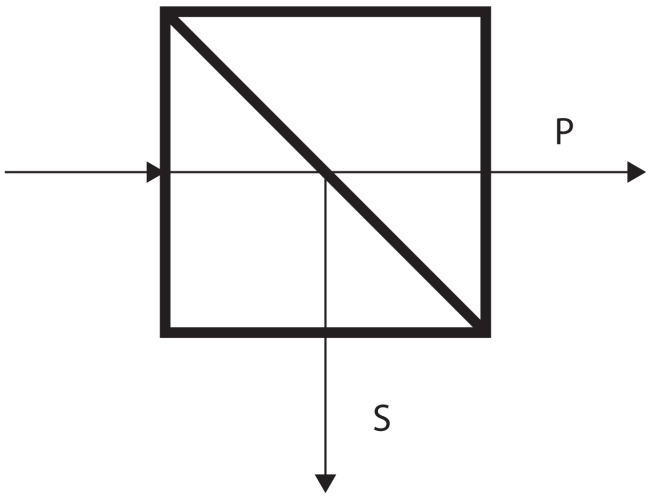
Aspect, A. (1982)

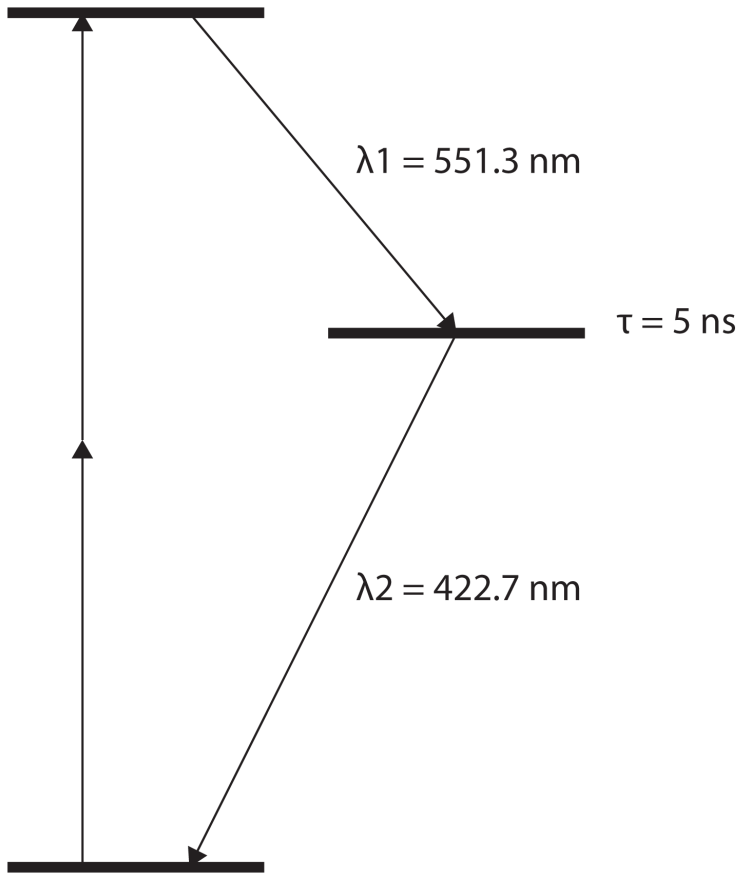
- Entangled photon pair
  - calcium-40 cascade
  - Rate: $5 \times 10^7\ s^{-1}$



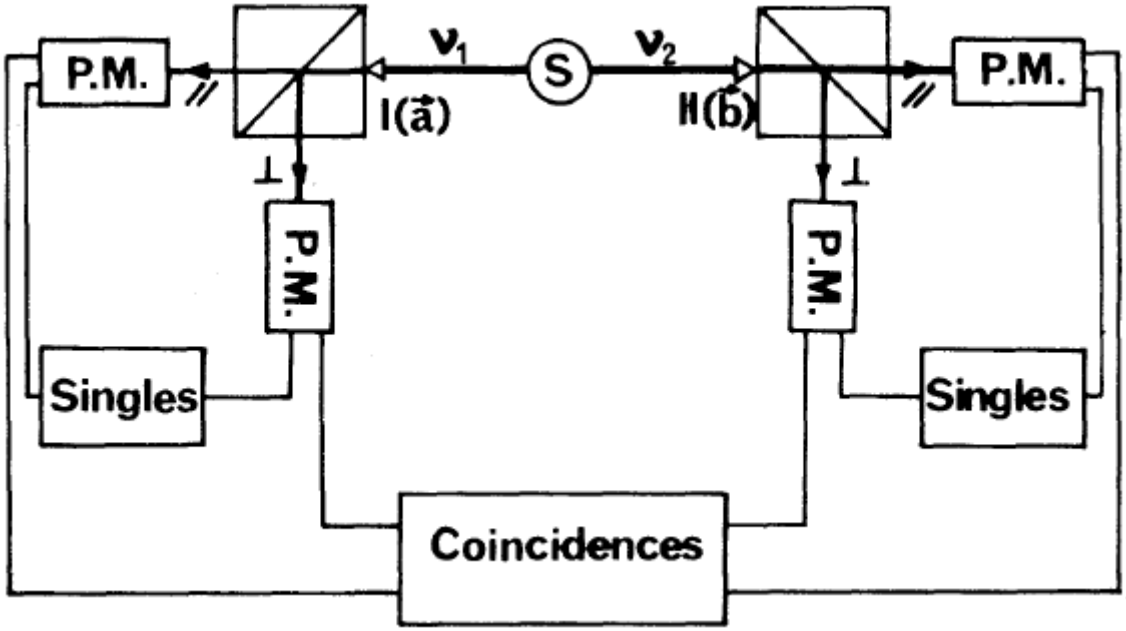
Aspect, A. (1982)

- Entangled photon pair
  - calcium-40 cascade
  - Rate: $5 \times 10^7\ s^{-1}$
- Two channel polarizer
  - $T^P = 0.950,\ R^P = 0.007$



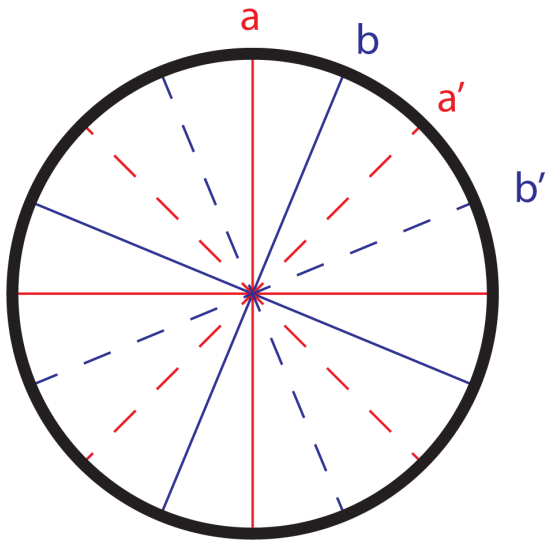


Aspect, A. (1982) - Experimental Setup



Aspect, A. (1982) - Bell Inequality

$$S(a,b) = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$



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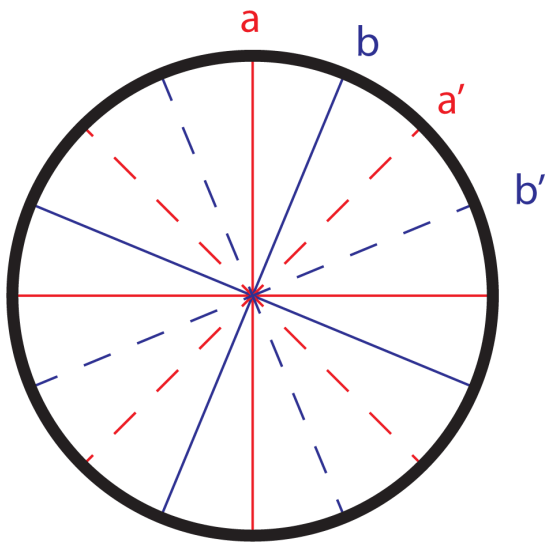

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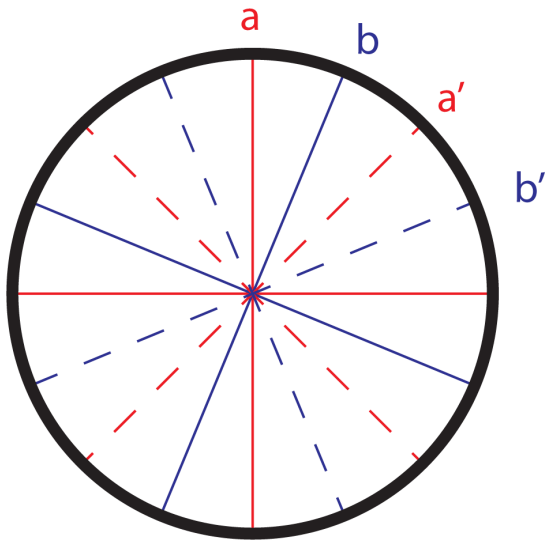
$$E(a,b) = \cos(2(a-b))$$



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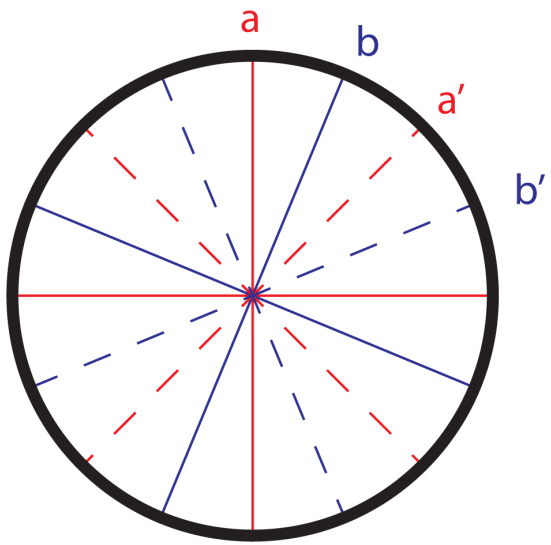
$$E(a,b) = F\,\frac{(T_1^P - T_1^S)(T_2^P - T_2^S)}{(T_1^P + T_1^S)(T_2^P + T_2^S)}\cos(2(a-b))$$



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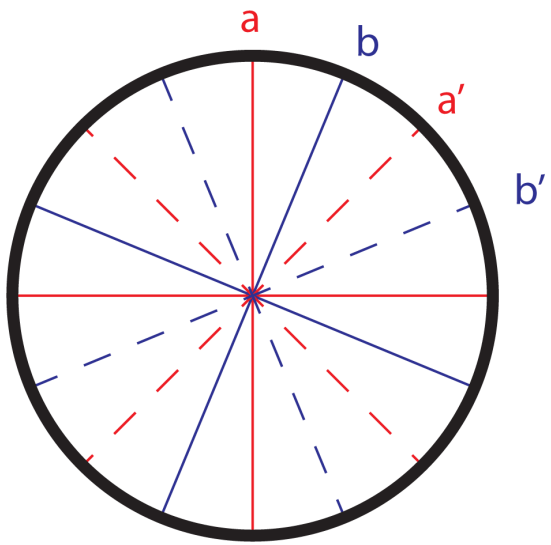
$$S_{exp} = 2.697 \pm 0.015$$

$$S_{QM} = 2.70 \pm 0.05$$



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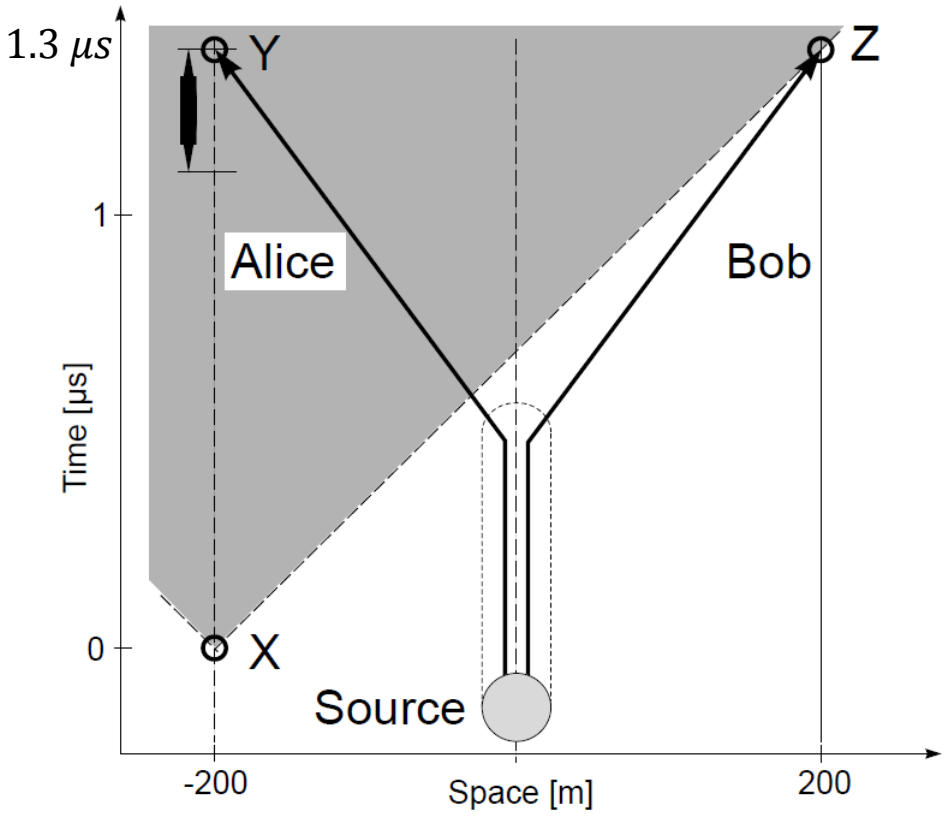
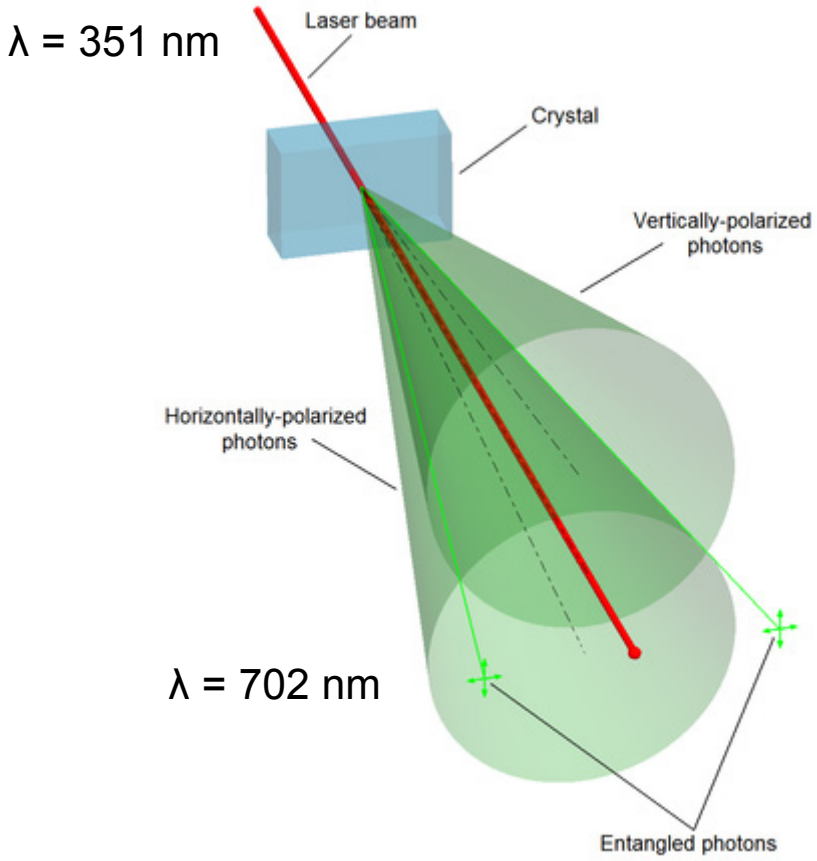
Weihs, G. (1998) - Locality

- Locality loophole
- Random choose of the measurement basis
- Spacelike separated



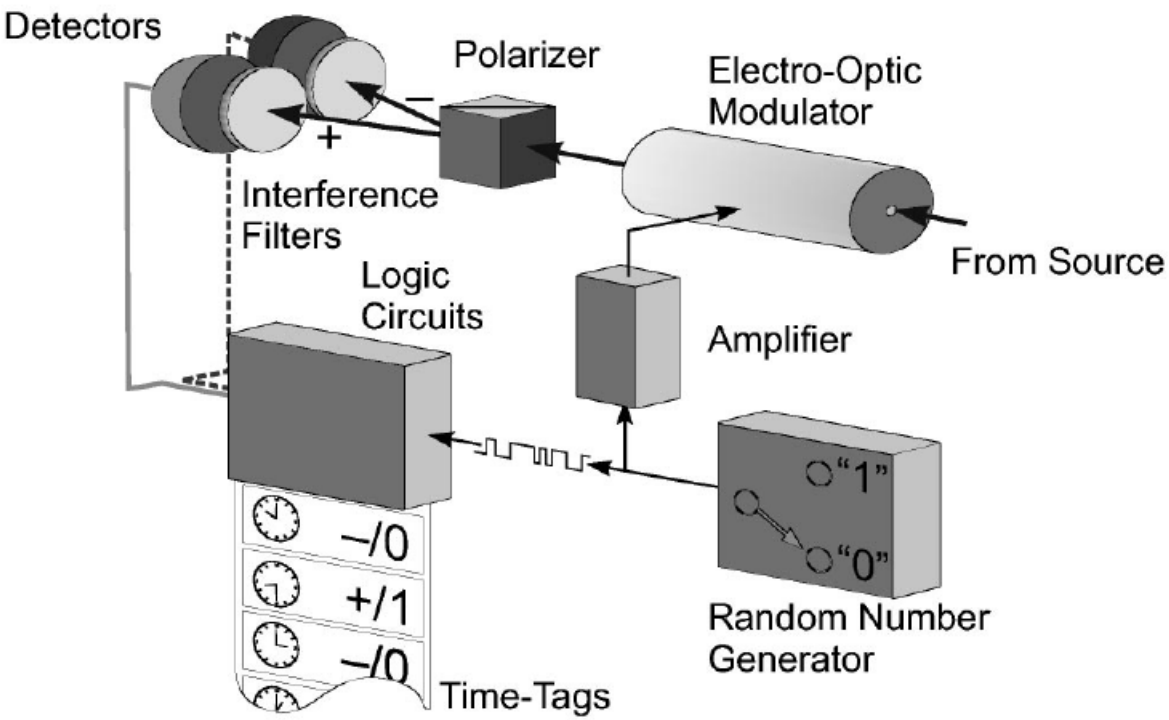
Weihs, G. (1998) - Source

- BBO Crystal
- degenerate type-II parametric down-conversion



Weihs, G. (1998) - Observer Station

- Physical random number generator
- Electro-optic modulator
- Pricise clock
  - Resolution: $75\ ps$

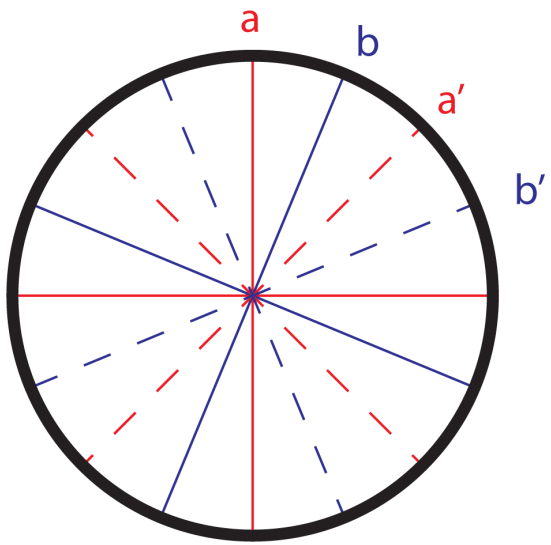


Weihs, G. (1998) - Bell Inequality

Reduced visibility : 97 %

$S_{exp} = 2.73 \pm 0.02$

$S_{QM} = 2.74$



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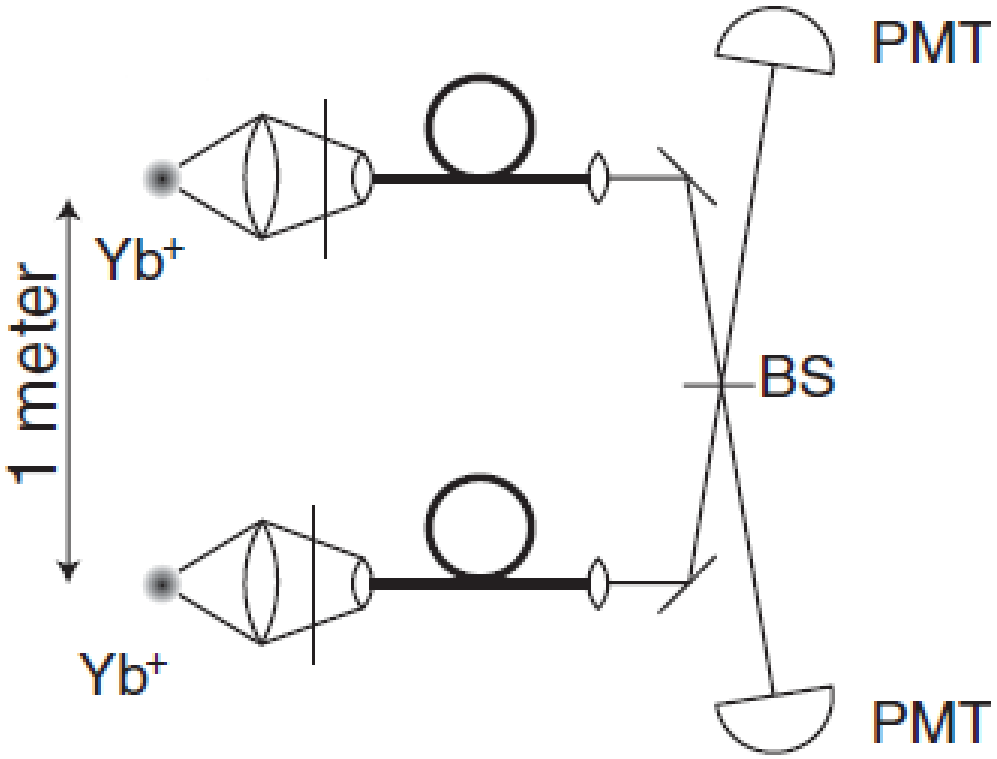
Matsukevich, D. N. (2008) - Experimental Setup



Matsukevich, D. N. (2008) - Bell Inequality

- Efficency loophole closed
- $S_{ip} = 2.54 \pm 0.02$

  $S_{ii} = 2.22 \pm 0.07$
- Locality loophole: $15\ km$ separation

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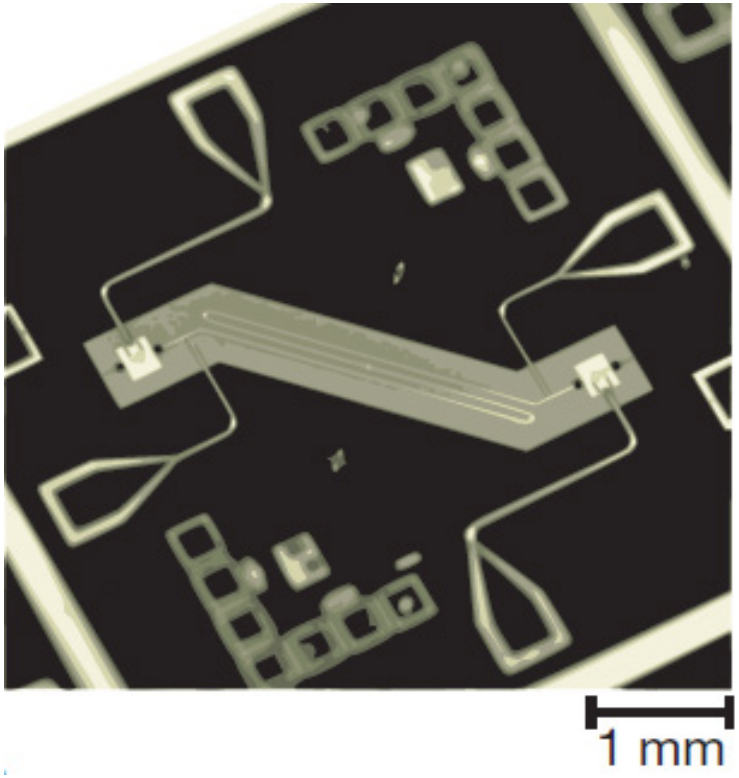
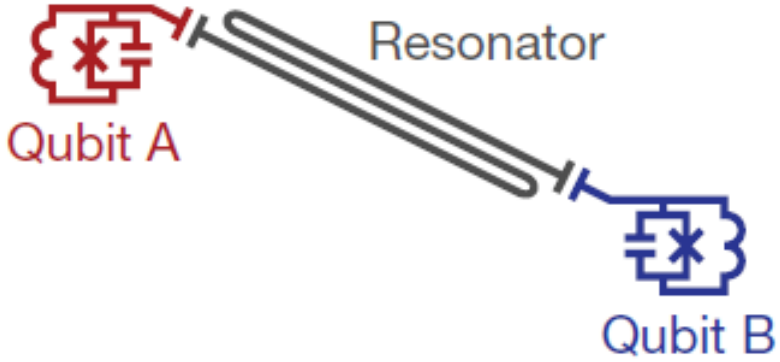
Ansmann, M. (2009) - Circuit Diagram





Ansmann, M. (2009) - Bell Inequality

- Measurement fidelities: $94.6\ \%$ and $93.4\ \%$
  → Efficiency loophole closed

$$S_{exp} = 2.0732 \pm 0.0003$$
$$S_{QM} = 2.064$$

Summary

- Aspect, A. (1982)
  - Two channel polarizer
- Weihs, G. (1998)
  - Locality loophole
- Matsukevich, D. N. (2008) & Ansmann, M. (2009)
  - Efficiency loophole
- No experiment closed both loopholes simoultaniously