Title: Quantum Control in Foundational Experiments: What Can We Say?

Date: Sep 27, 2011 04:00 PM

URL: http://pirsa.org/11090124

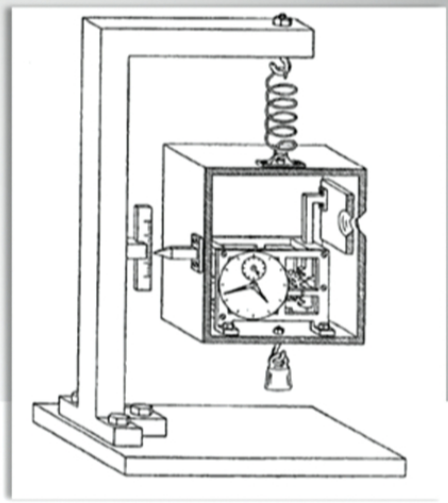
Abstract: Wheeler's delayed choice (WDC) is one of the "standard experiments in foundations". It aims at the puzzle of a photon simultaneously behaving as wave and particle. Bohr-Einstein debate on wave-particle duality prompted the introduction of Bohr's principle of complementarity, ---`.. the study of complementary phenomena demands mutually exclusive experimental arrangements" . In WDC experiment the mutually exclusive setups correspond to the presence or absence of a second beamsplitter in a Mach-Zehnder interferometer (MZI). A choice of the setup determines the observed behaviour. The delay ensures that the behaviour cannot be adapted before the photon enters MZI. Using WDC as an example, we show how replacement of classical selectors by quantum gates streamlines experiments and impacts on foundational questions. We demonstrate measurements of complementary phenomena with a single setup, where observed behaviour of the photon is chosen after it has been already detected. Spacelike separation of the setup components becomes redundant. The complementarity principle has to be reformulated --- instead of complementarity of experimental setups we now have complementarity of measurement results.
Finally we present a quantum-controlled scheme of Bell-type experiments.
To reach any of these conclusions in either classical or quantum setting a (simple) hidden variable model that represents the "reality" of "particle" and "wave" should be analyzed. The model is never fully exorcised but just pushed to have more and more conspiratorial set of assumptions.

Quantum controls in ex-Gedanken experiments: what can we say?

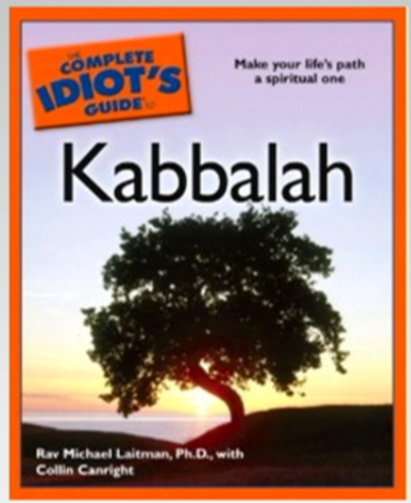
Radu Ionicioiu
Daniel Terno

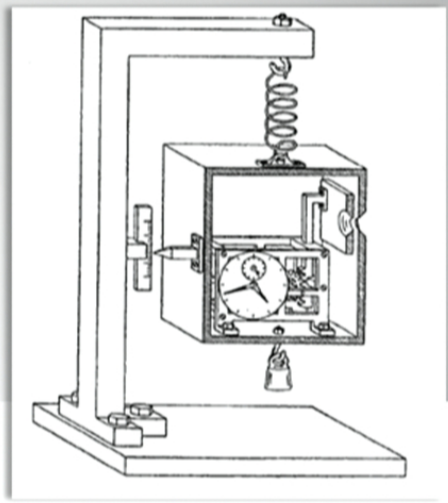
arXiv:1103.0117

"Like with Kabbalah, you can start working on foundations of quantum mechanics only after forty"



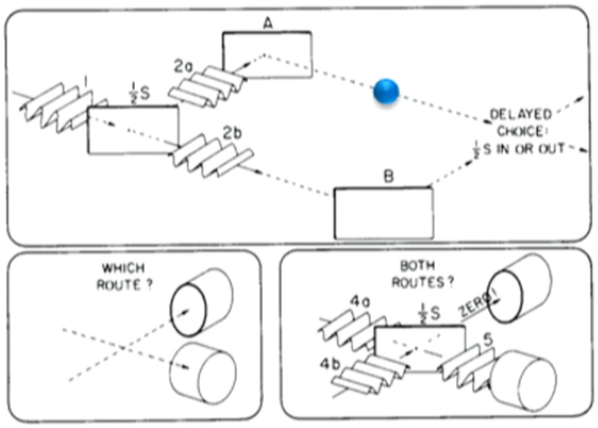
Warning & Outline



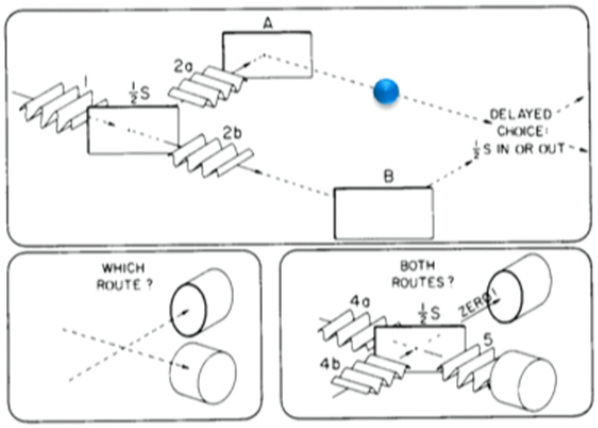


Warning & Outline

Background
Wave-particle duality



P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)

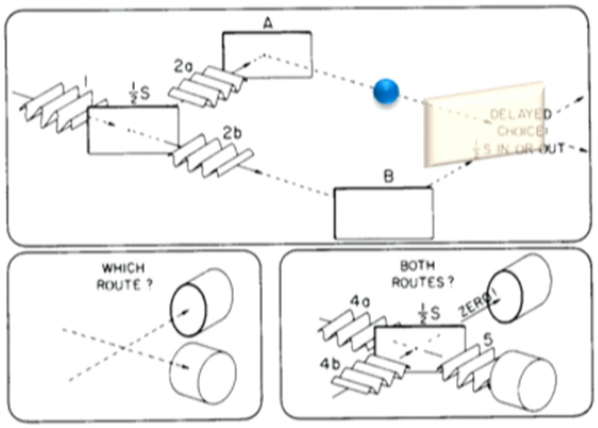


Background

Wave-particle duality

Photons are particles

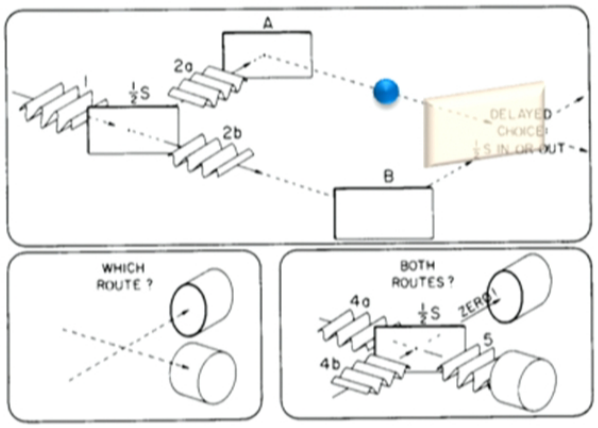
P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)



Background
Wave-particle duality

Photons are particles
Photons are waves

P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)



Background

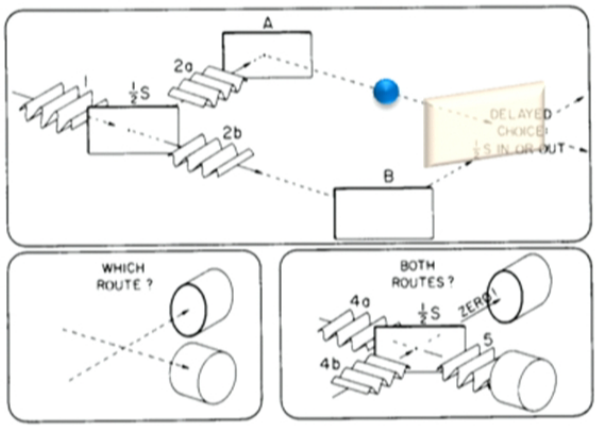
Wave-particle duality

Photons are particles
Photons are waves

P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)

Motivation

Background & complementarity conspiracy



Background

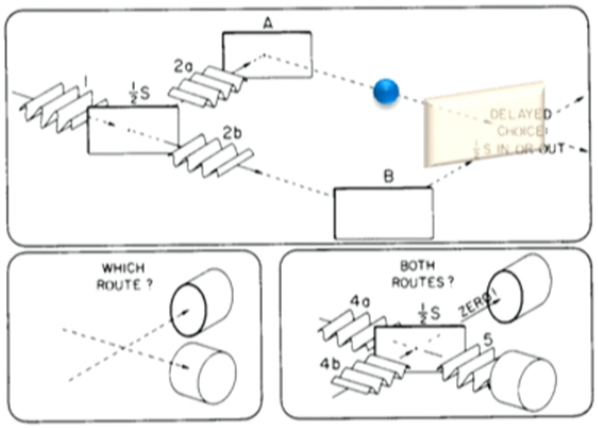
Wave-particle duality

Photons behave as particles
Photons behave as waves

P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)

Motivation

Background & complementarity conspiracy
Quantum switches
No word about altering the path/past…



Background
Wave-particle duality

Photons behave as particles
Photons behave as waves

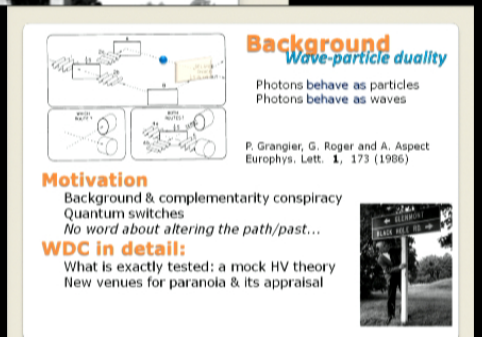
P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)

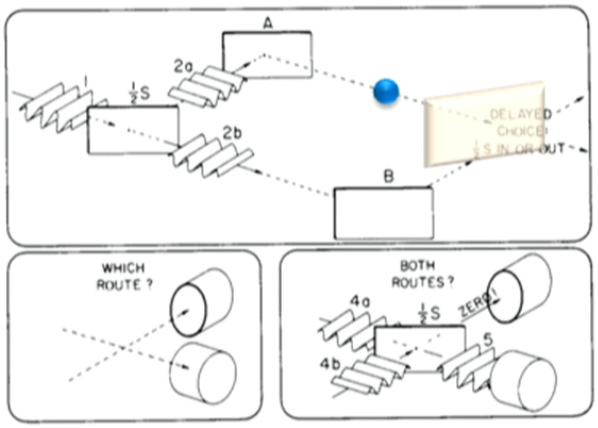
Motivation

Background & complementarity conspiracy
Quantum switches
No word about altering the path/past…

WDC in detail:

What is exactly tested: a mock HV theory
New venues for paranoia & its appraisal





Background

Wave-particle duality

Photons behave as particles
Photons behave as waves

P. Grangier, G. Roger and A. Aspect
Europhys. Lett. **1**, 173 (1986)

Motivation

Background & complementarity conspiracy
Quantum switches
No word about altering the path/past…

WDC in detail:

What is exactly tested: a mock HV theory
New venues for paranoia & its appraisal

Future

Complementarity

H. Stapp's summary

... the information provided by different experimental procedures that in principle cannot, because of the physical character of the needed apparatus, be performed simultaneously, cannot be represented by any mathematically allowed quantum state of the system. The elements of information obtainable from incompatible measurements are said to be *complementary*.

Complementarity

H. Stapp's summary

... the information provided by different experimental procedures that in principle cannot, because of the physical character of the needed apparatus, be performed simultaneously, cannot be represented by any mathematically allowed quantum state of the system. The elements of information obtainable from incompatible measurements are said to be *complementary*.

Conspiracy

The photon could know in advance of entering the apparatus whether the latter has been set up in the "wave" configuration with BS_2 in place or the "particle" one (BS_2 removed) and adjust accordingly.

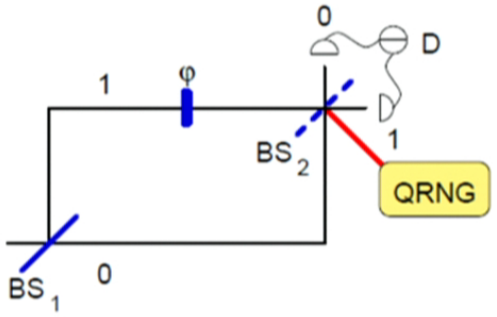
Wheeler's delayed choice

Open interferometer [particle]

$$n(a) = (\tfrac{1}{2}, \tfrac{1}{2})$$

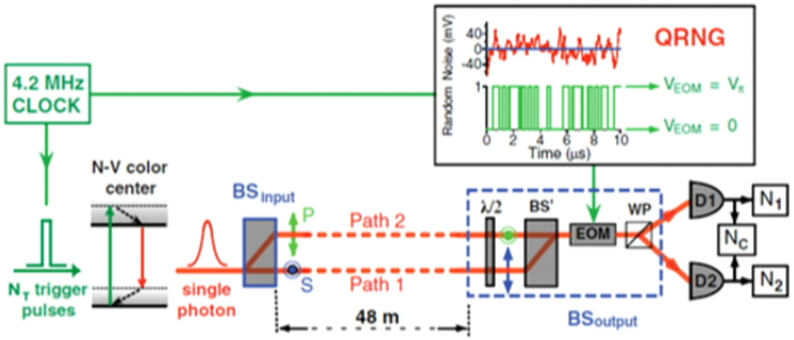
Closed interferometer [wave]

$$n(a) = (\cos^2 \tfrac{\varphi}{2}, \sin^2 \tfrac{\varphi}{2})$$



Spacelike separation between the source and the RNG

b



a

V Jacques, E Wu, F Grosshans, F Treussart, P Grangier, A Aspect, J-F Roch, Science **315**, 966 (2007)

WDC

Extensions & questions

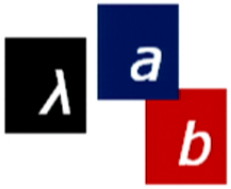
- What is the basis for assertion of wave-particle duality?
- Can we detect "it" first and decide what was it later?
- Is space-like separation necessary?
- What if the controlling devices are quantum?

WDC

Extensions & questions

- What is the basis for assertion of wave-particle duality?
- Can we detect "it" first and decide what was it later?
- Is space-like separation necessary?
- What if the controlling devices are quantum?

Conspiracy & counter-conspiracy



- A hidden variable λ=p,w set at production/before splitting
- Reproduction of the observed data for some $p(a,b,\lambda)$

$$n(a,b) = \sum_{\lambda=p,w} p(a,b,\lambda)$$

WDC
Analysis v1

Bias the generator $n(b) = (\cos^2 \alpha, \sin^2 \alpha)$ **b**

(Q)RNG/ancilla

Total counting statistics

$$n(a,b) = (\underset{00}{\tfrac{1}{2}\cos^2 \alpha}, \underset{01}{\sin^2 \alpha \cos^2 \tfrac{\phi}{2}}, \underset{10}{\tfrac{1}{2}\cos^2 \alpha}, \underset{11}{\sin^2 \alpha \sin^2 \tfrac{\phi}{2}})$$

Classical control

$$n(a,b) = \sum_{\lambda = p,w} p(a \mid b, \lambda) p(\lambda \mid b) n(b)$$ **λ**

The role of HV theory: supply of conditional probabilities

WDC
Analysis v1

Bias the generator $n(b) = (\cos^2 \alpha, \sin^2 \alpha)$ **b**

(Q)RNG/ancilla

Total counting statistics

$$n(a,b) = (\underset{00}{\tfrac{1}{2}\cos^2 \alpha}, \underset{01}{\sin^2 \alpha \cos^2 \tfrac{\phi}{2}}, \underset{10}{\tfrac{1}{2}\cos^2 \alpha}, \underset{11}{\sin^2 \alpha \sin^2 \tfrac{\phi}{2}})$$

Classical control

$$n(a,b) = \sum_{\lambda = p,w} p(a \mid b, \lambda) p(\lambda \mid b) n(b)$$ **λ**

The role of HV theory: supply of conditional probabilities

WDC *a la HV*

Photons are either particles $\lambda = p$ or waves $\lambda = w$

$$p(a \mid b = 1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

WDC *a la HV*

Photons are either particles $\lambda = p$ or waves $\lambda = w$

$$p(a \mid b = 1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

$$p(a \mid b = 0, \lambda = p) = (\tfrac{1}{2}, \tfrac{1}{2})$$

WDC *a la HV*

Photons are either particles $\lambda = p$ or waves $\lambda = w$

$$p(a \mid b = 1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

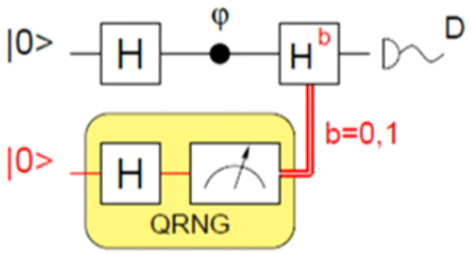
$$p(a \mid b = 0, \lambda = p) = (\tfrac{1}{2}, \tfrac{1}{2})$$

$$p(a \mid b = 0, \lambda = w) = (x, 1 - x)$$
$$p(a \mid b = 1, \lambda = p) = (y, 1 - y)$$

WDC: classical control

Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$



Causal:

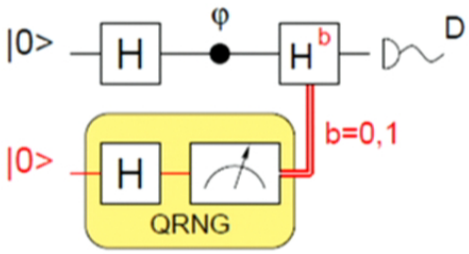
$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed [a correlation between HV of a photon & QRNG]

WDC: classical control

Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$



Causal:

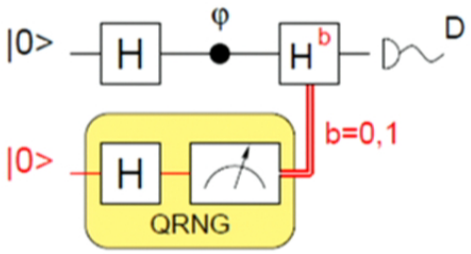
$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed [a correlation between HV of a photon & QRNG]

WDC: classical control

Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$



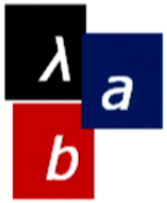
Causal:

$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed [a correlation between HV of a photon & QRNG]

Stochastic:

$$p(\lambda \mid b) = p(\lambda) = (\mathfrak{p}, 1-\mathfrak{p})$$



Consistency requirements resurrect wave-particle duality:

$$p(a \mid b,\lambda) = p(a \mid b)$$

$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

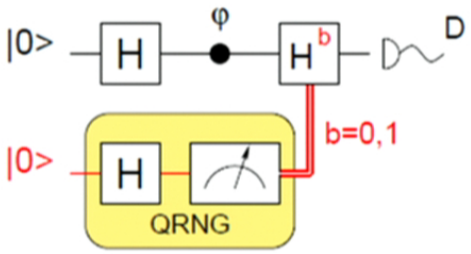
$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

WDC: classical control

Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$



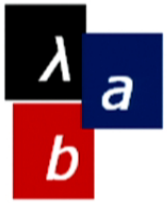
Causal:

$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed [a correlation between HV of a photon & QRNG]

Stochastic:

$$p(\lambda \mid b) = p(\lambda) = (\mathfrak{p}, 1-\mathfrak{p})$$



Consistency requirements resurrect wave-particle duality:

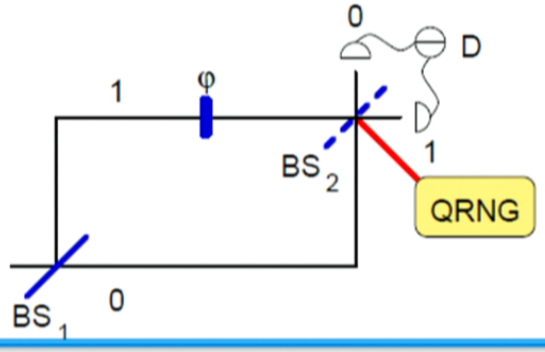
$$p(a \mid b,\lambda) = p(a \mid b)$$

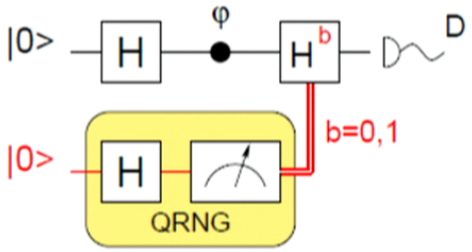
$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

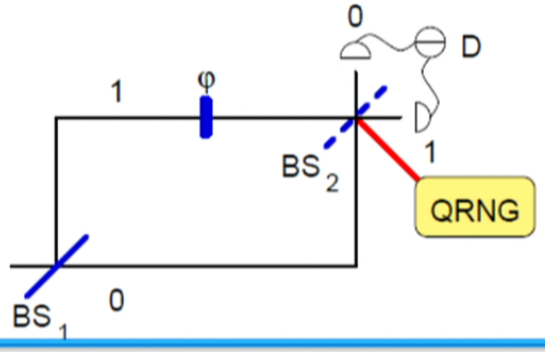
$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

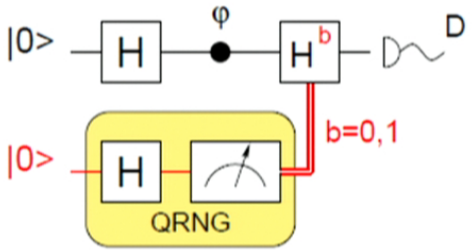
WDC circuits

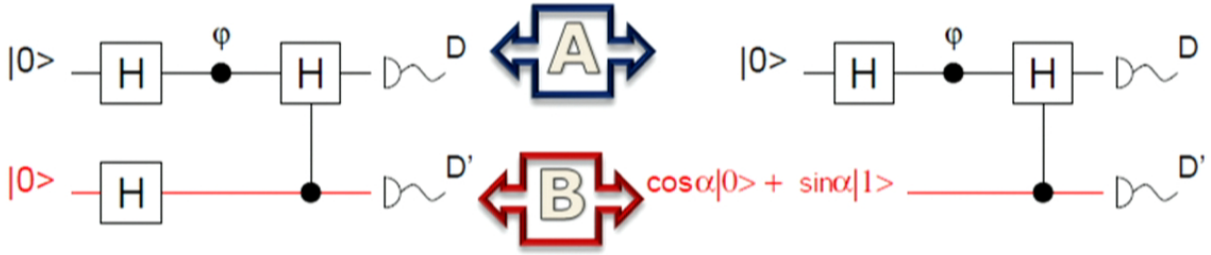




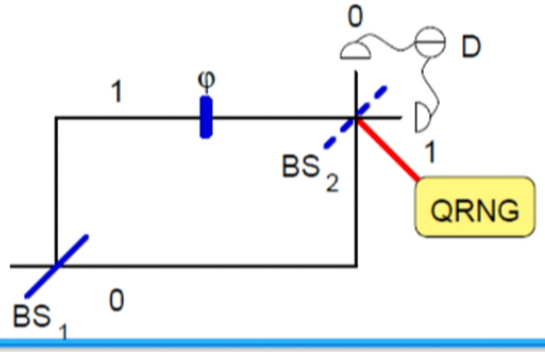
WDC circuits

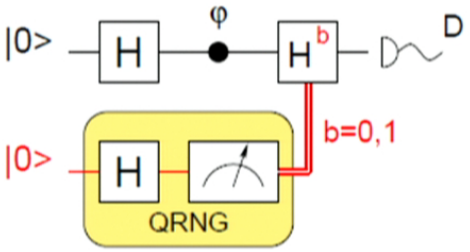


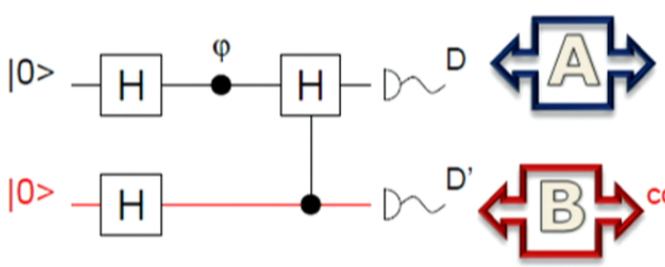




WDC circuits

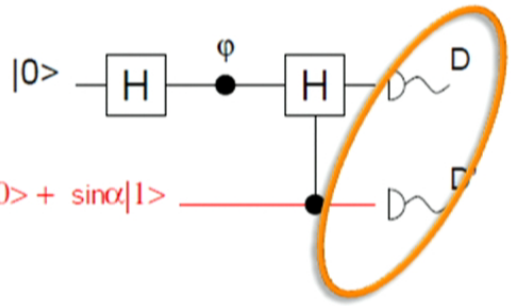




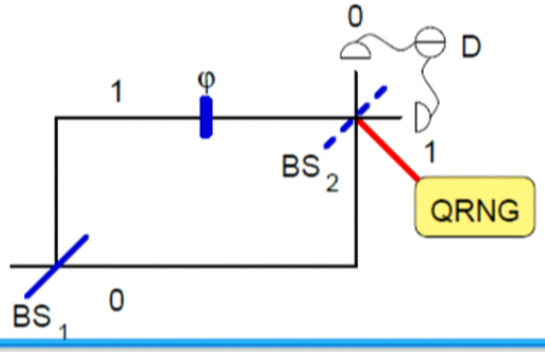


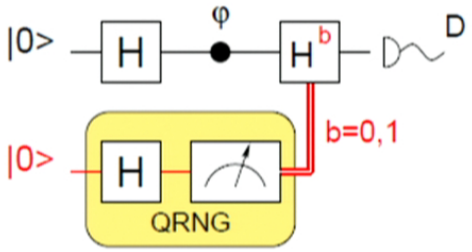
A

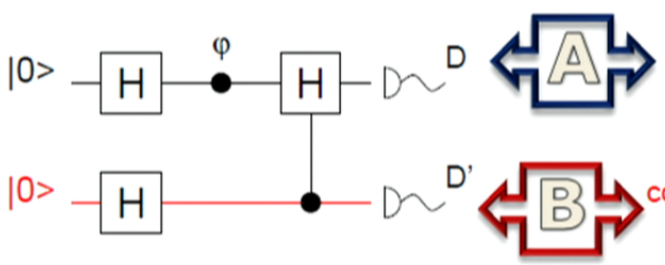
B

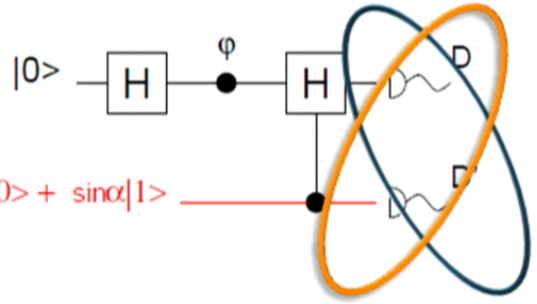


WDC circuits









WDC QM

State after the gates [before the detectors]

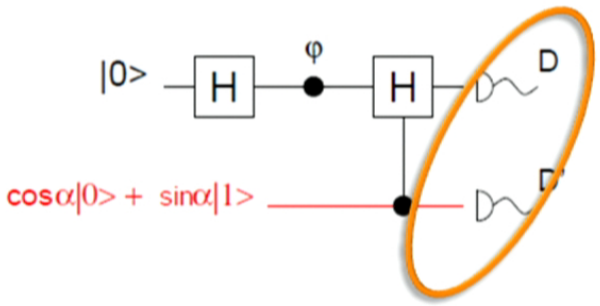
$$|\psi_f\rangle = \frac{1}{\sqrt{2}}\left(|\psi_p\rangle|0\rangle + |\psi_w\rangle|1\rangle\right)$$

$$|\psi_p\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\phi}|1\rangle\right)$$

$$|\psi_w\rangle = \frac{1}{\sqrt{2}} e^{i\phi/2}\left(\cos\tfrac{\phi}{2}|0\rangle - i\sin\tfrac{\phi}{2}|1\rangle\right)$$

- Can we detect "it" first and decide what it was later
- No space-like separation

WDC: Quantum control (1)



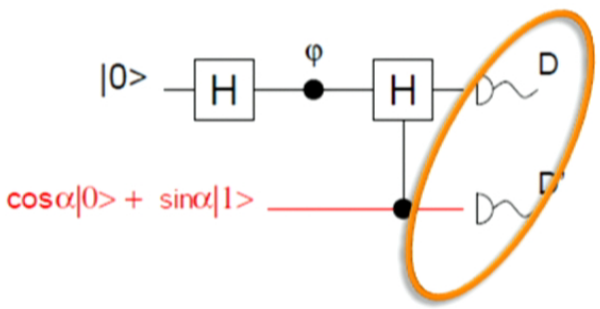
Logic

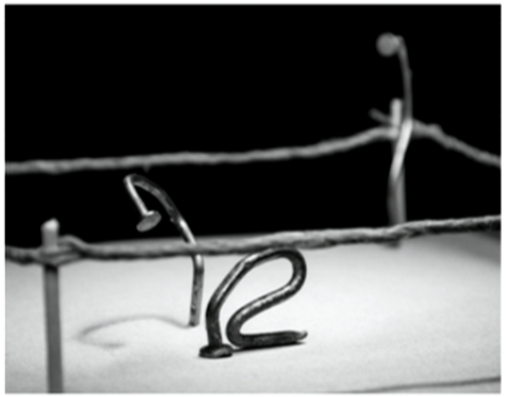
$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$

WDC: Quantum control (1)

λ b a

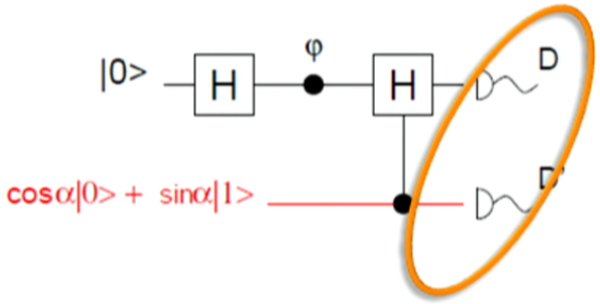
Logic

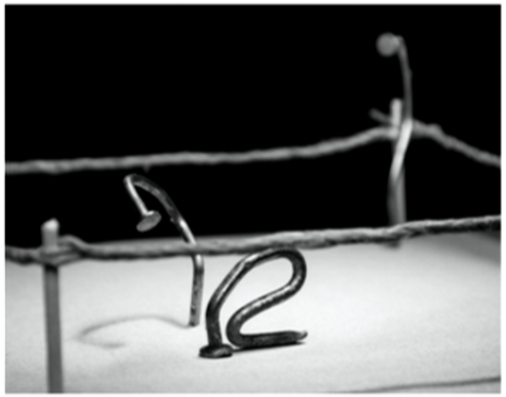




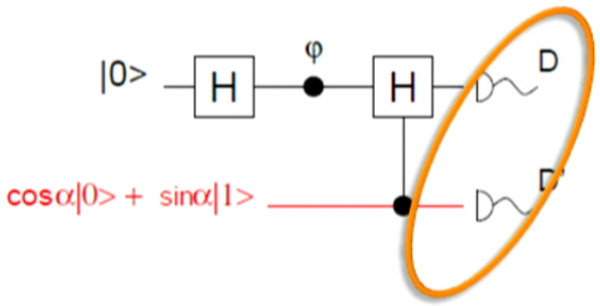
WDC: Quantum control (1)

Logic





WDC: Logic of quantum control

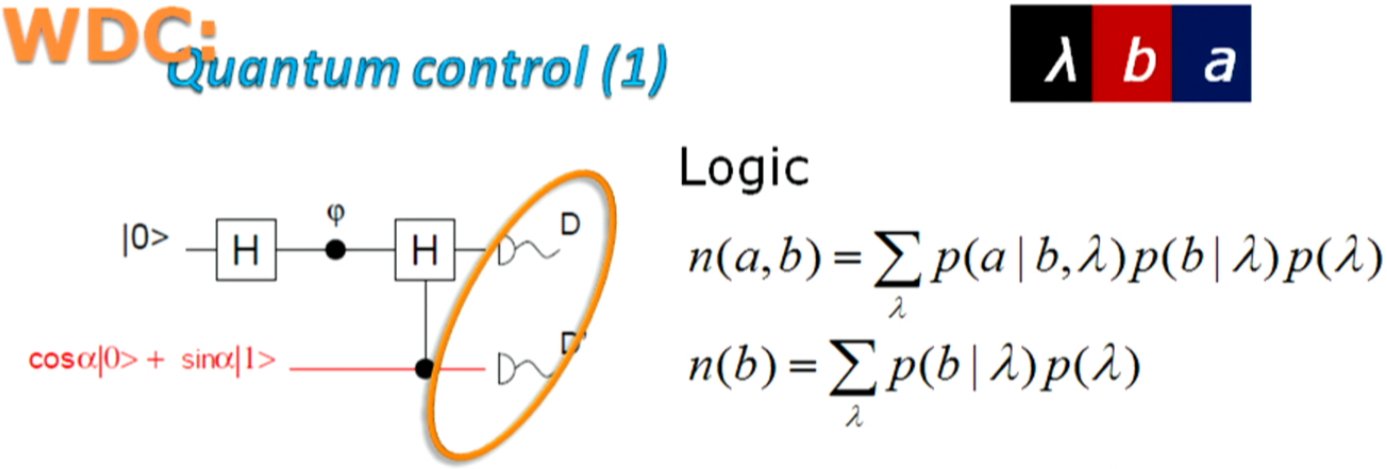


Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(b \mid \lambda)\, p(\lambda)$$

$$n(b) = \sum_{\lambda} p(b \mid \lambda)\, p(\lambda)$$

WDC: Quantum control (1)

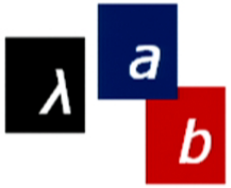


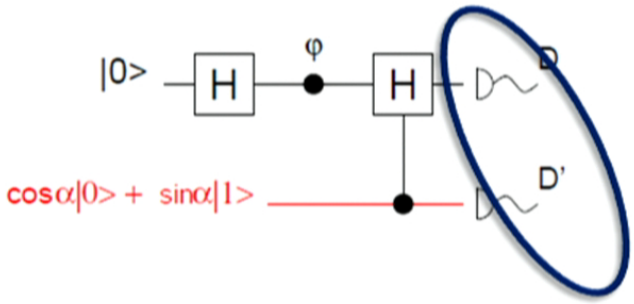
Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(b \mid \lambda)\, p(\lambda)$$

$$n(b) = \sum_{\lambda} p(b \mid \lambda)\, p(\lambda)$$

WDC: Quantum control (2)



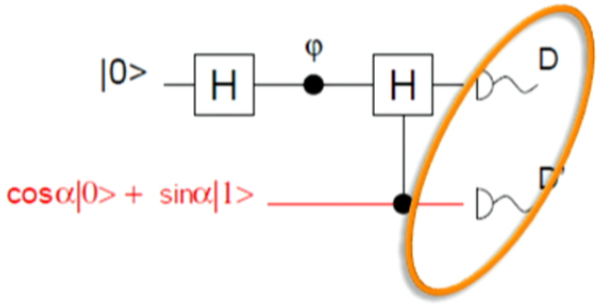


Logic

$$n(a,b) = \sum_{\lambda} p(b \mid a,\lambda)\, p(a \mid \lambda)\, p(\lambda)$$

Constraints: "wave" and "particle" defs still apply (Bayes theorem)

WDC: Quantum control (1)



Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(b \mid \lambda)\, p(\lambda)$$

$$n(b) = \sum_{\lambda} p(b \mid \lambda)\, p(\lambda)$$

Causal:

$$p(b \mid \lambda) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

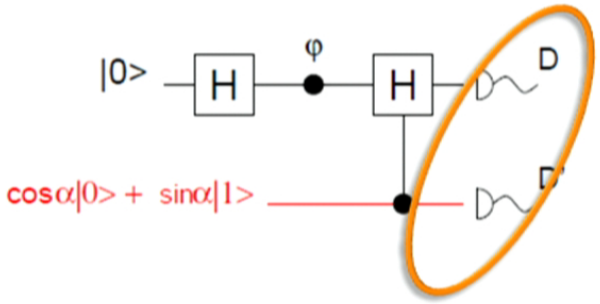
~~$p(a \mid b=0, \lambda = w) = (x, 1-x)$~~

~~$p(a \mid b=1, \lambda = p) = (y, 1-y)$~~

Can be maintained only with a higher-order conspiracy

$$p(\lambda) \equiv (\mathfrak{q}, 1-\mathfrak{q}) = (\cos^2\alpha, \sin^2\alpha)$$

WDC: Quantum control (1)



Consistency requirements resurrect wave-particle duality:

$$p(a \mid b,\lambda) = p(a \mid b)$$

General: $p(b \mid \lambda) = ?$

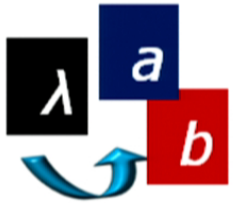
$$p(\lambda) \equiv (\mathfrak{q}, 1-\mathfrak{q})$$

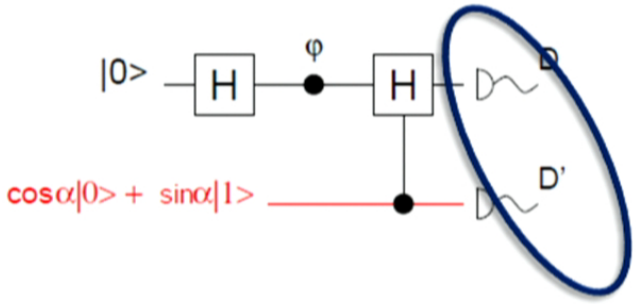
$$\mathfrak{q} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{q} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

WDC: Quantum control (2)





Logic

$$n(a,b) = \sum_{\lambda} p(b \mid a,\lambda)p(a \mid \lambda)p(\lambda)$$

Constraints: "wave" and "particle" defs still apply (Bayes' theorem)

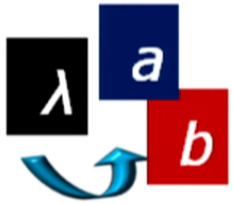
(super)Causal:

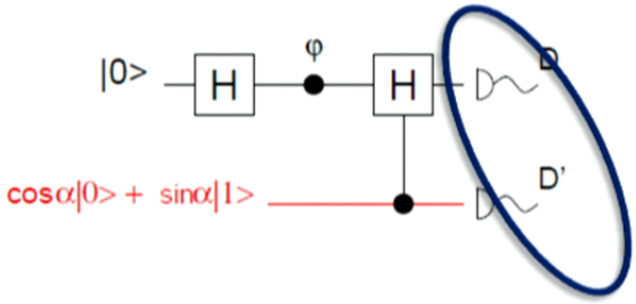
$$p(b \mid a,\lambda) = p(b \mid \lambda) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

Can be maintained only with a higher-order conspiracy

$$p(\lambda) \equiv (\mathfrak{q}, 1-\mathfrak{q}) = (\cos^2\alpha, \sin^2\alpha)$$

WDC: Quantum control (2)





Logic

$$n(a,b) = \sum_{\lambda} p(b \mid a,\lambda)p(a \mid \lambda)p(\lambda)$$

Constraints: "wave" and "particle" defs still apply (Bayes' theorem)

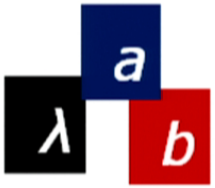
(super)Causal:

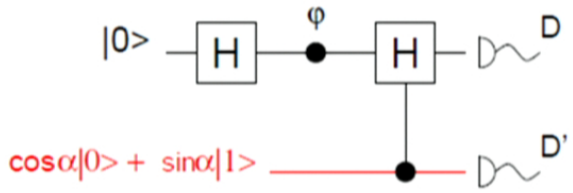
$$p(b \mid a,\lambda) = p(b \mid \lambda) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

Can be maintained only with a higher-order conspiracy

$$p(\lambda) \equiv (\mathfrak{q}, 1-\mathfrak{q}) = (\cos^2\alpha, \sin^2\alpha)$$

WDC: Quantum conclusions





- Can we detect "it" first and decide what was it later
- No space-like separation
- Duality restored OR HV pushed away (half-step)

Consistency requirements resurrect wave-particle duality:

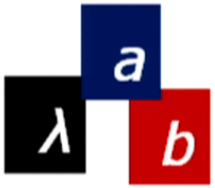
$$p(a \mid b,\lambda) = p(a \mid b)$$

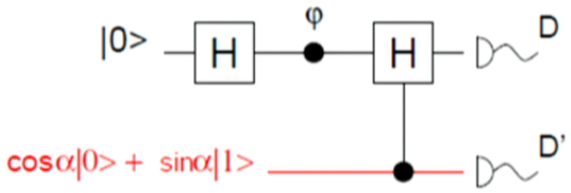
$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

WDC: Quantum conclusions





- Can we detect "it" first and decide what was it later
- No space-like separation
- Duality restored OR HV pushed away (half-step)

Consistency requirements resurrect wave-particle duality:

$$p(a \mid b,\lambda) = p(a \mid b)$$

$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

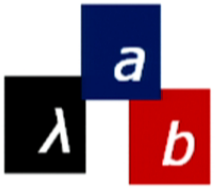
$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

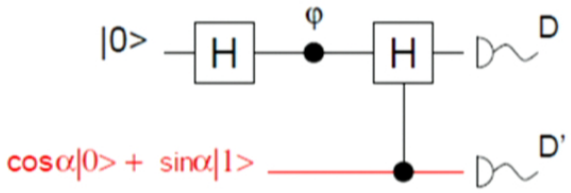
Or imply a higher level conspiracy

$$p(\lambda) = (\cos^2 \alpha, \sin^2 \alpha)$$

Small print:
- If you don't mind this weird causal interaction... but can get rid of it by more delays ... but
- HV only on a photon

WDC: Quantum conclusions





- Can we detect "it" first and decide what was it later
- No space-like separation
- Duality restored OR HV pushed away (half-step)

Consistency requirements resurrect wave-particle duality:

$$p(a \mid b,\lambda) = p(a \mid b)$$

$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

Or imply a higher level conspiracy

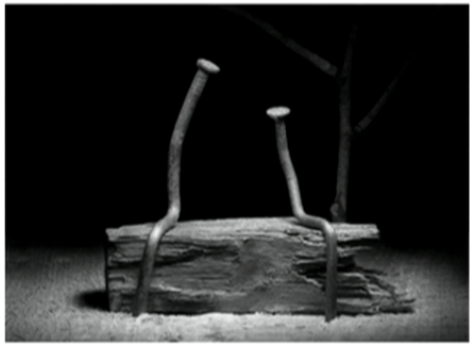
$$p(\lambda) = (\cos^2 \alpha, \sin^2 \alpha)$$

Small print:
- If you don't mind this weird causal interaction... but can get rid of it by more delays ... but
- HV only on a photon

Complementarity

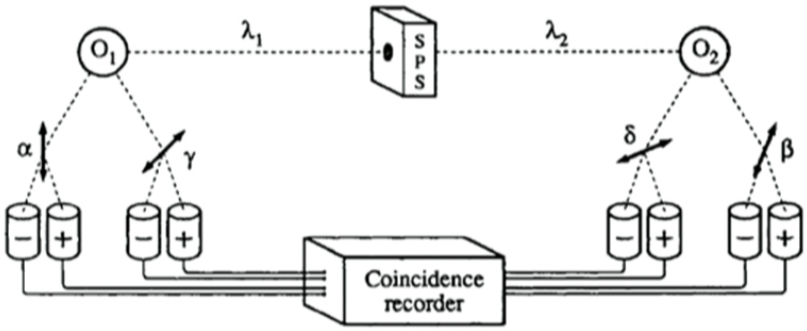
Complementary phenomena can be observed with a single experimental setup, provided that a component of the apparatus is a quantum device in a superposition state

Instead of complementarity of experimental setups (Bohr's view) we have complementarity of the experimental data



Future

CHSH



Angles for max violation:

$$0, \pi/8, \pi/4, 3\pi/8$$

Aspect, Dalibard, Roger,
PRL **49**, 1804 (1982)

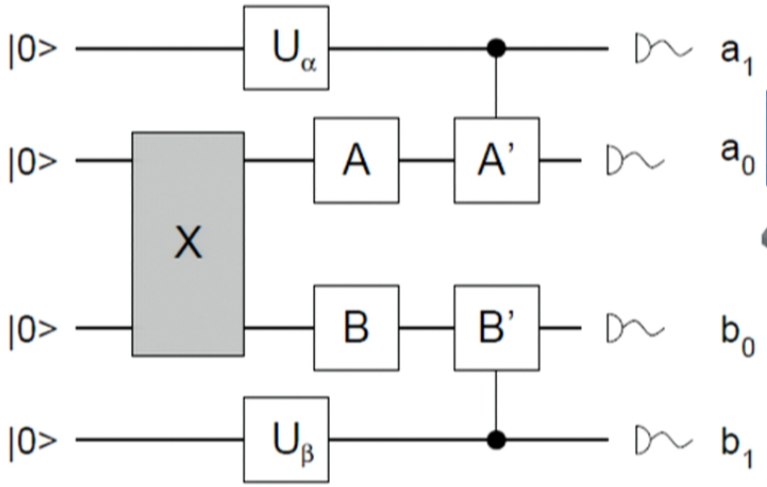
Quantum version

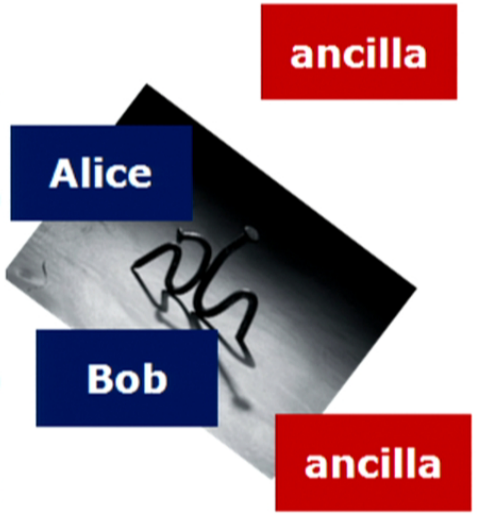
- Quantum controllers
- We detect "it" first and decide what it was later
- No space-like separation is possible

- Can we exorcise HV?

Future

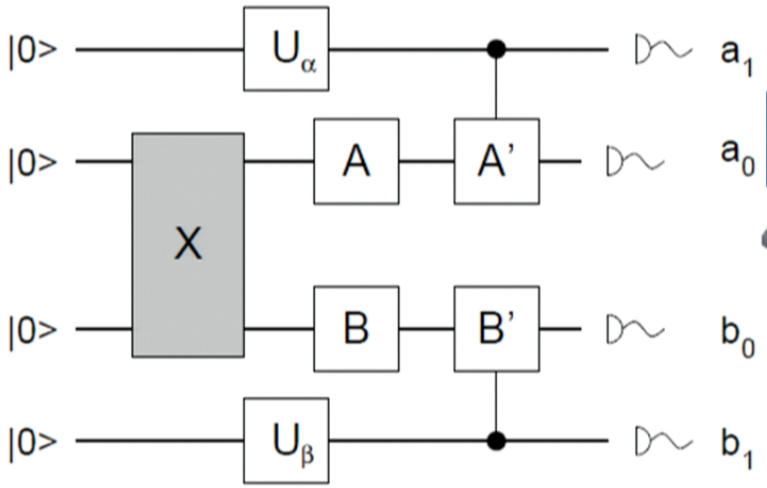
Quantum-controlled Bell/CHSH

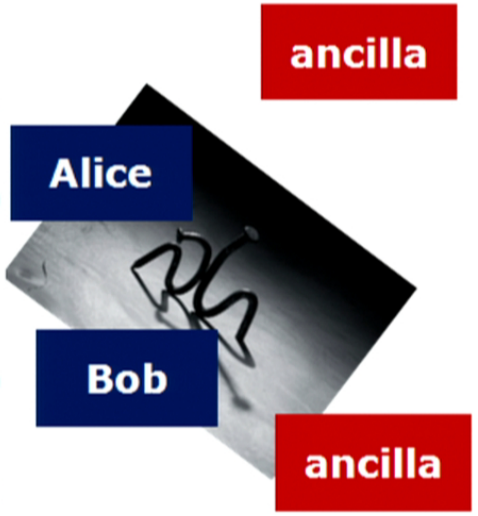




Future

Quantum-controlled Bell/CHSH





Problem: no reason why not to have HV for everybody

Summary

- ❑ Modification of complementarity
- ❑ Quantum controls allow more opportunities for the time ordering of classical interventions
- ❑ Space-like separation made redundant by quantum control?
- ❑ Retrocausality is good?

Summary

- ❑ Modification of complementarity
- ❑ Quantum controls allow more opportunities for the time ordering of classical interventions
- ❑ Space-like separation made redundant by quantum control?
- ❑ Retrocausality is good?
- ❑ What to do with CHSH?
  Or exo/endo HV

Summary

- Modification of complementarity
- Quantum controls allow more opportunities for the time ordering of classical interventions
- Space-like separation made redundant by quantum control?
- Retrocausality is good?
- What to do with CHSH?
  Or exo/endo HV

Summary

- ❑ Modification of complementarity
- ❑ Quantum controls allow more opportunities for the time ordering of classical interventions
- ❑ Space-like separation made redundant by quantum control?
- ❑ Retrocausality is good?
- ❑ What to do with CHSH?
  Or exo/endo HV

WDC *a la HV*

Photons are either particles $\lambda = p$ or waves $\lambda = w$

$$p(a \mid b = 1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

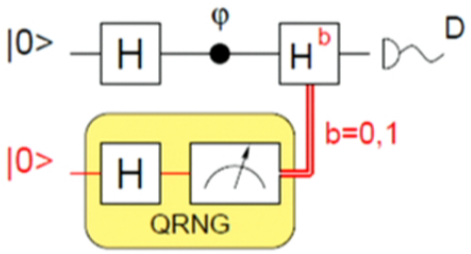
$$p(a \mid b = 0, \lambda = p) = (\tfrac{1}{2}, \tfrac{1}{2})$$

$$p(a \mid b = 0, \lambda = w) = (x, 1 - x)$$
$$p(a \mid b = 1, \lambda = p) = (y, 1 - y)$$

WDC: classical control

Logic

$$n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$



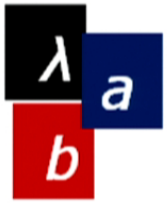
Causal:

$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed [a correlation between HV of a photon & QRNG]

Stochastic:

$$p(\lambda \mid b) = p(\lambda) = (\mathfrak{p}, 1-\mathfrak{p})$$



Consistency requirements resurrect wave-particle duality:

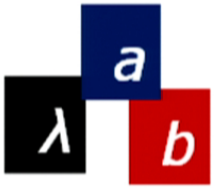
$$p(a \mid b,\lambda) = p(a \mid b)$$

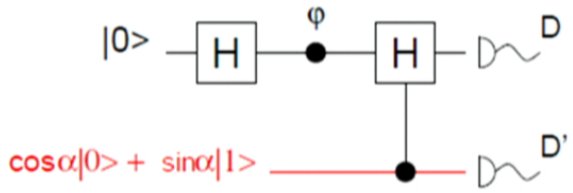
$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

WDC: Quantum conclusions





- Can we detect "it" first and decide what was it later
- No space-like separation
- Duality restored OR HV pushed away (half-step)

Consistency requirements resurrect wave-particle duality:

$$p(a \mid b,\lambda) = p(a \mid b)$$

$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2 \tfrac{\phi}{2}$$

$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

Or imply a higher level conspiracy

$$p(\lambda) = (\cos^2 \alpha, \sin^2 \alpha)$$