Title: Quantum control in foundational experiments: what can we say?

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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.

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

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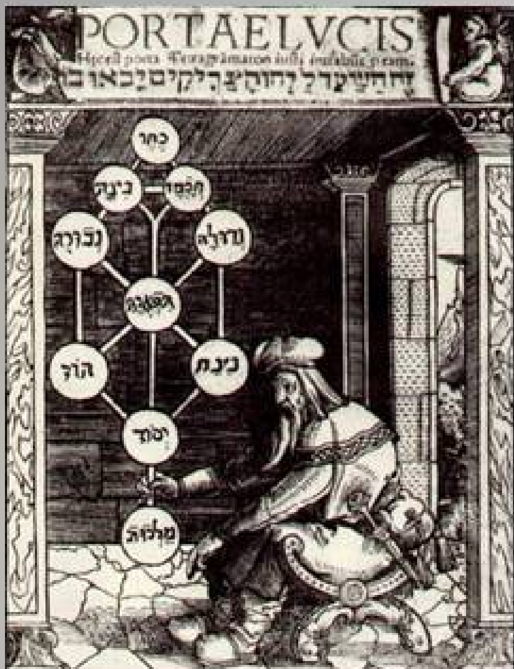
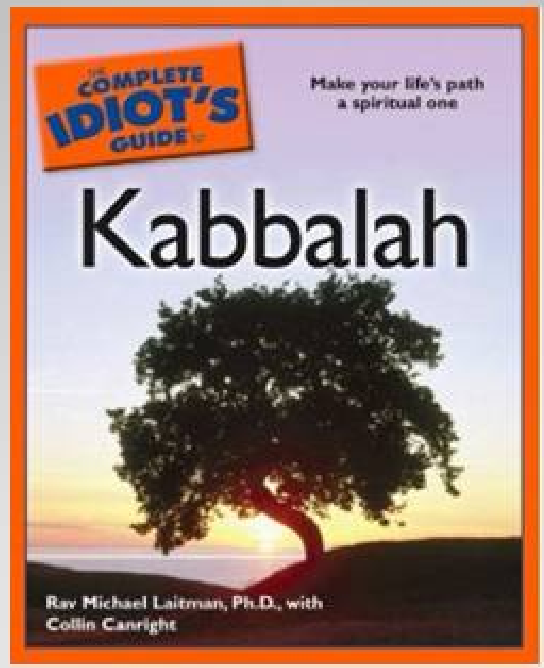
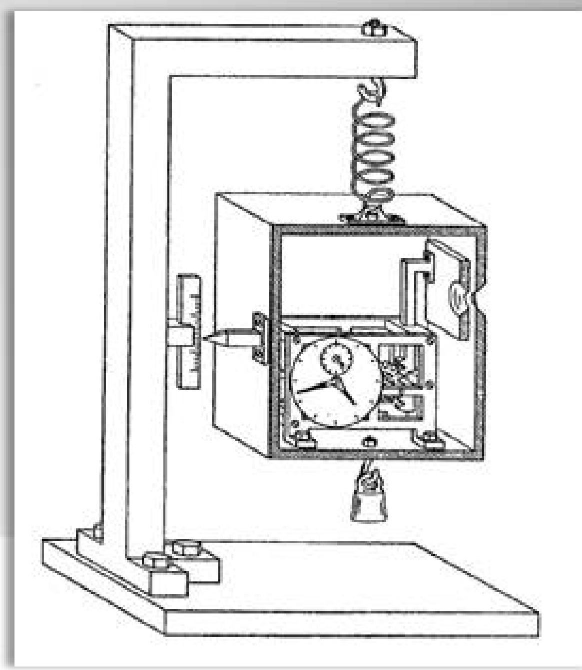
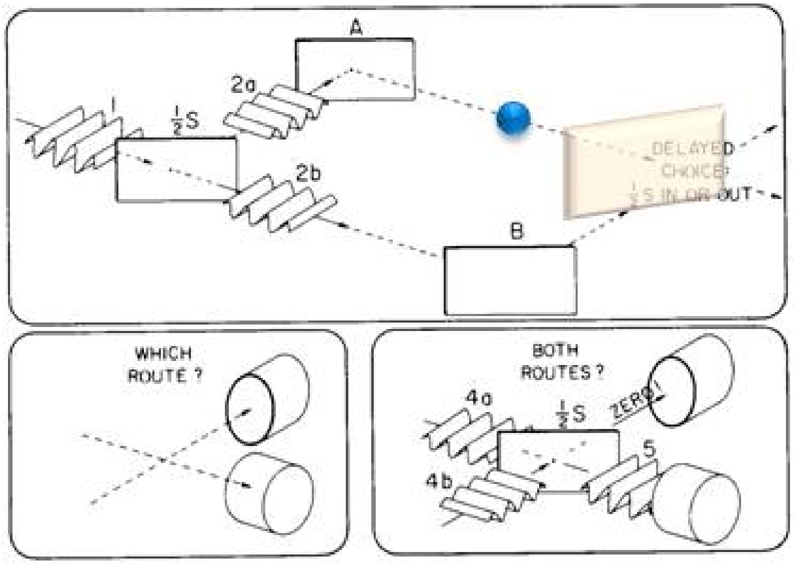




"Like with Kabbalah, you can start working on foundations of quantum mechanics only after forty"



Warning & Outline



Background

Wave-particle duality

Photons are particles / behave as particles

Photons are waves / 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

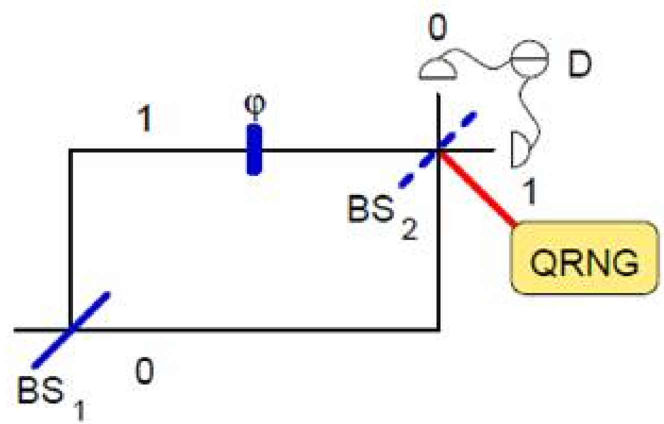
Complementarity *H. Stapp's summary*

... 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*.

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



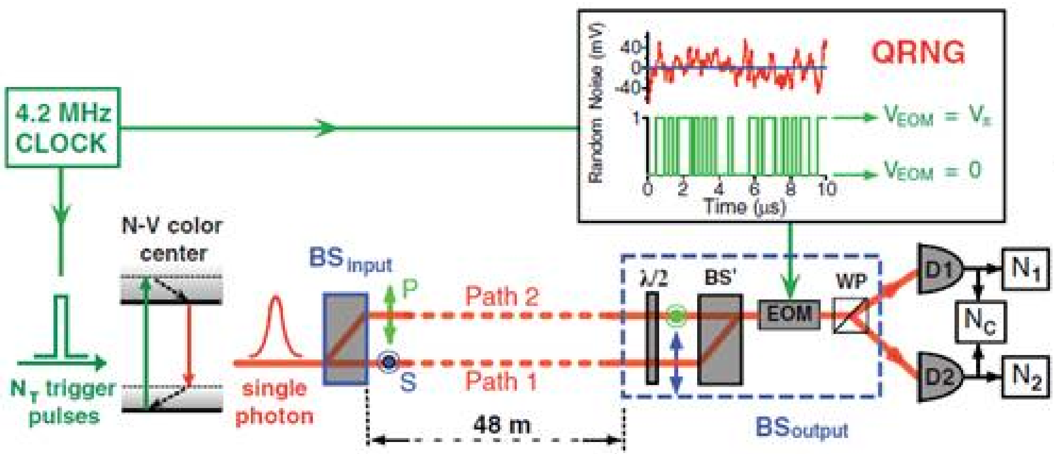
Open interferometer [particle]

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

Closed interferometer [wave]

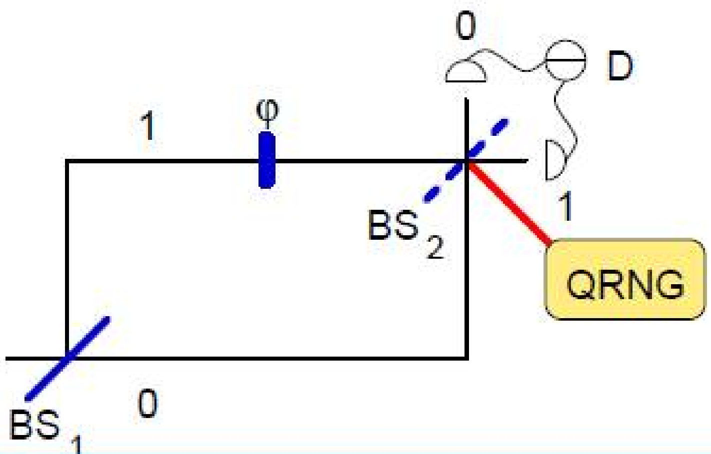
$$n(a) = (\cos^2 \tfrac{\varphi}{2}, \sin^2 \tfrac{\varphi}{2})$$

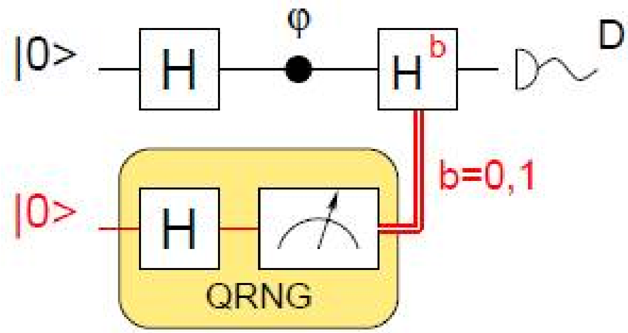
Spacelike separation between the source and the RNG



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

WDC circuits





State after the gates [before the detectors]

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

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

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

WDC QM

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Stats:

(Q)RNG/ancilla $\quad n(b) = (\cos^2\alpha, \sin^2\alpha)$

Total count

$$n(a,b) = \left(\tfrac{1}{2}\cos^2\alpha, \sin^2\alpha\cos^2\tfrac{\phi}{2}, \tfrac{1}{2}\cos^2\alpha, \sin^2\alpha\sin^2\tfrac{\phi}{2}\right)$$

00 01 10 11

WDC QM

State after the gates [before the detectors]

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

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Stats: [to be matched by conspirators]

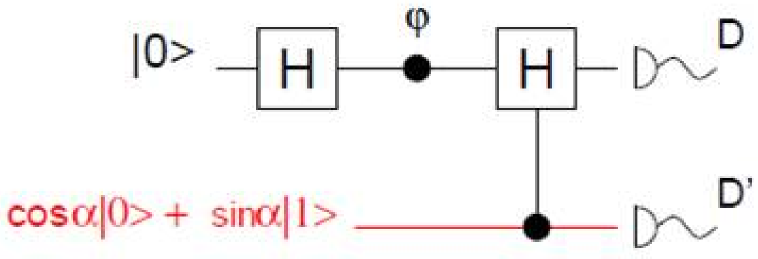
(Q)RNG/ancilla $\quad n(b) = (\cos^2\alpha, \sin^2\alpha)$

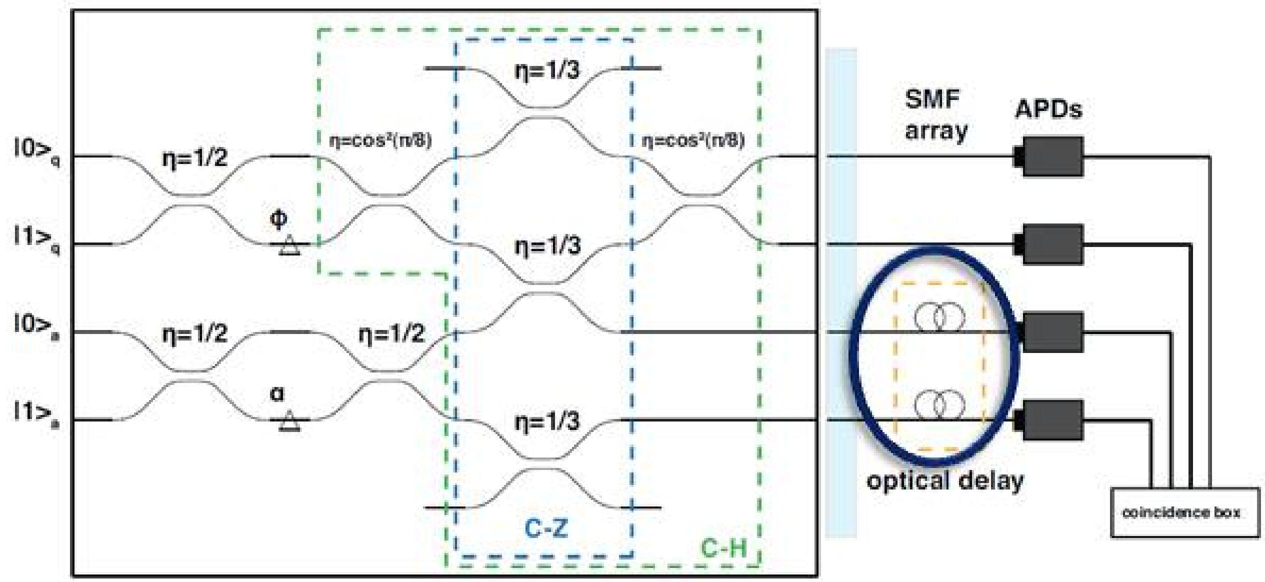
Total count

$$n(a,b) = (\tfrac{1}{2}\cos^2\alpha, \sin^2\alpha\cos^2\tfrac{\phi}{2}, \tfrac{1}{2}\cos^2\alpha, \sin^2\alpha\sin^2\tfrac{\phi}{2})$$

00 01 10 11

Experiment
at last





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 $\lambda = w$

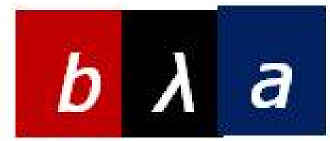
$$p(a \mid b=1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

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

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

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

WDC: classical control

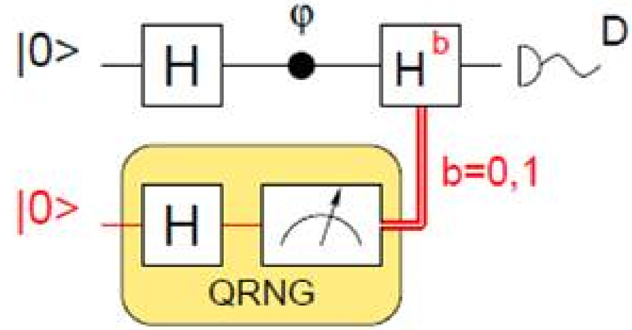


Logic

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

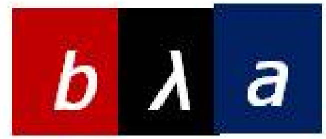
Causal:

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



This is the target of WDC experiments. Dismissed, unless "even more mind boggling" conspiracies are allowed

WDC: classical control



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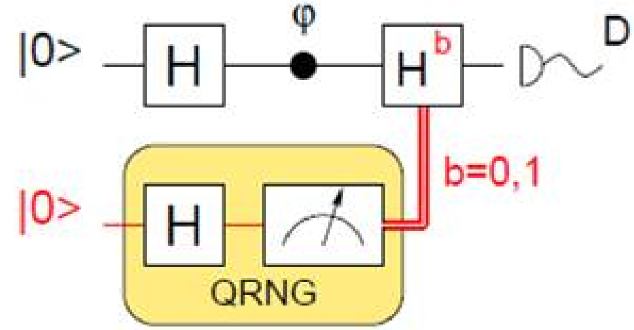

Causal:

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

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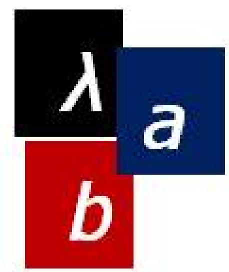
Stochastic:

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



Consistency requirements resurrect wave-particle duality:

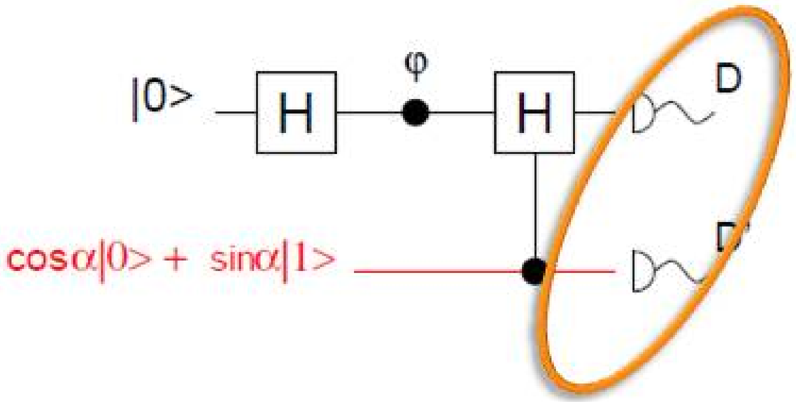
$$p(a\,|\,b,\lambda)=p(a\,|\,b)$$

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

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

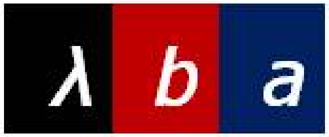
$$x=\tfrac{1}{2}, y=\cos^2\tfrac{\phi}{2}$$

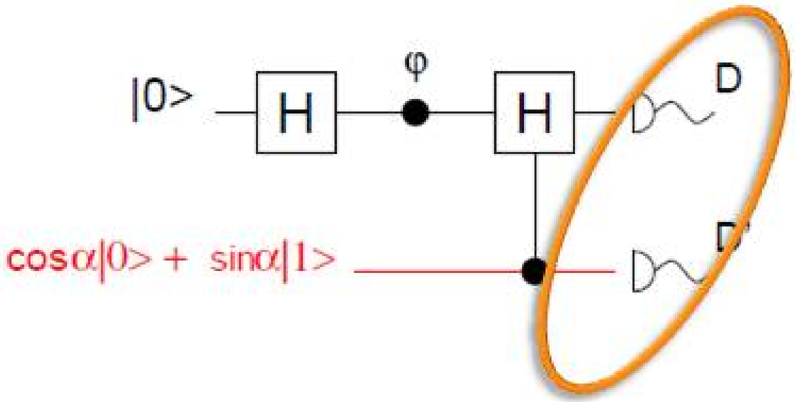
WDC: *Quantum control (1)*



Logic

WDC: *Quantum control (1)*





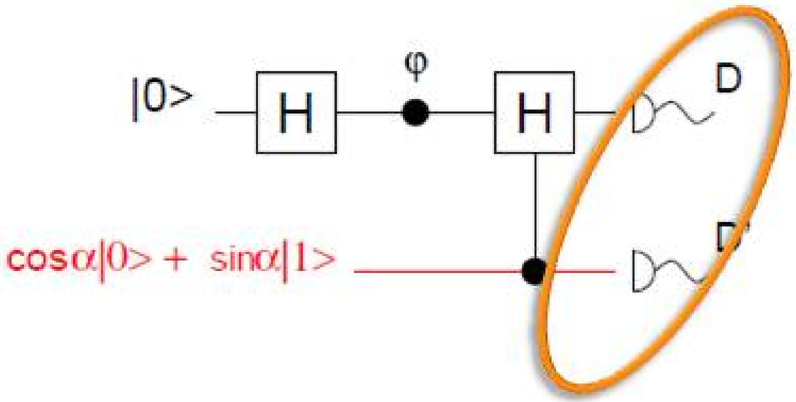
Logic

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

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

WDC: Quantum control (1)

λ b a



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

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

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

Causal:

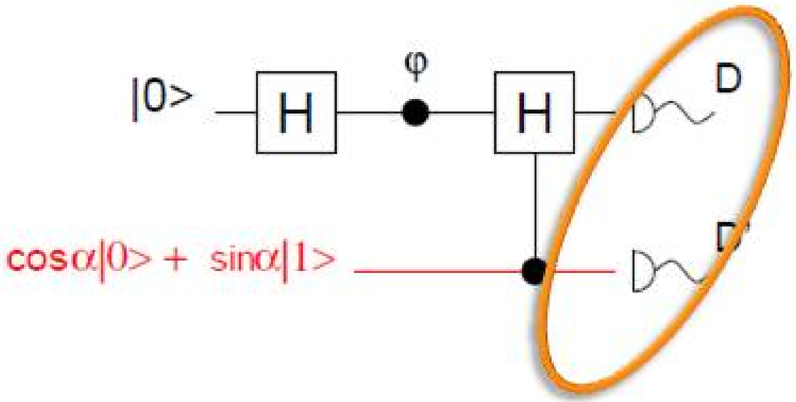
$$p(b\,|\,\lambda)=\delta_{\lambda p}\delta_{b0}+\delta_{\lambda w}\delta_{b1}$$

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 (1)

λ b a



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General: $p(b\,|\,\lambda) = ?$

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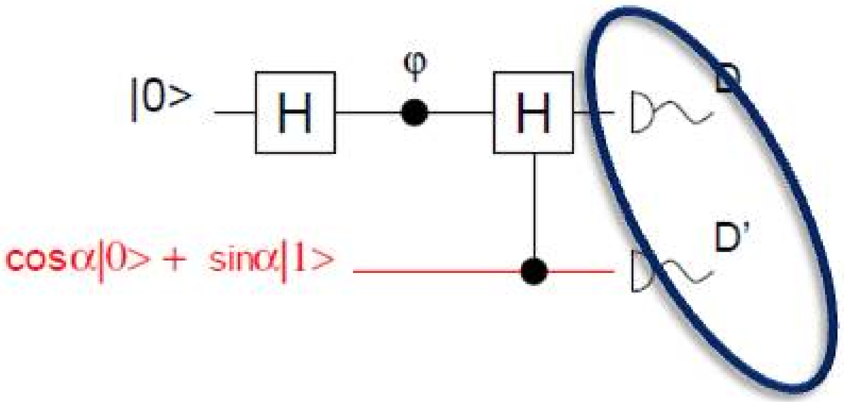
$$x = \tfrac{1}{2}, y = \cos^2 \tfrac{\phi}{2}$$

WDC: *Quantum control (2)*

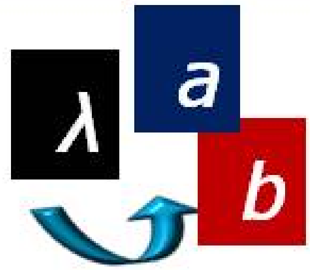


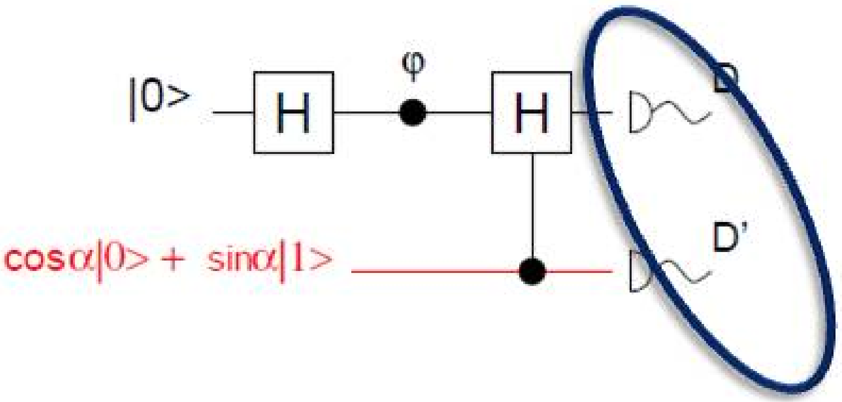
Logic

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

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

WDC: *Quantum control (2)*





Logic

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

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

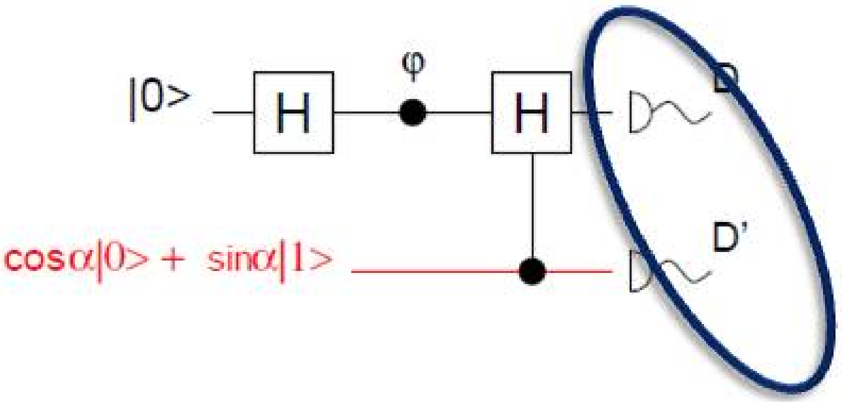
(super)Causal:

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

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)



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

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

Summary

- ❑ [Yet another] modification of complementarity
- ❑ Quantum controls allow more opportunities for the time ordering of classical interventions
- ❑ Spacelike separation is redundant
- ❑ Retrocausality is good?

Future

Quantum-controlled Bell/CHSH