Event-based Computer Simulation of Wheeler's Delayed-Choice Experiment with Photons

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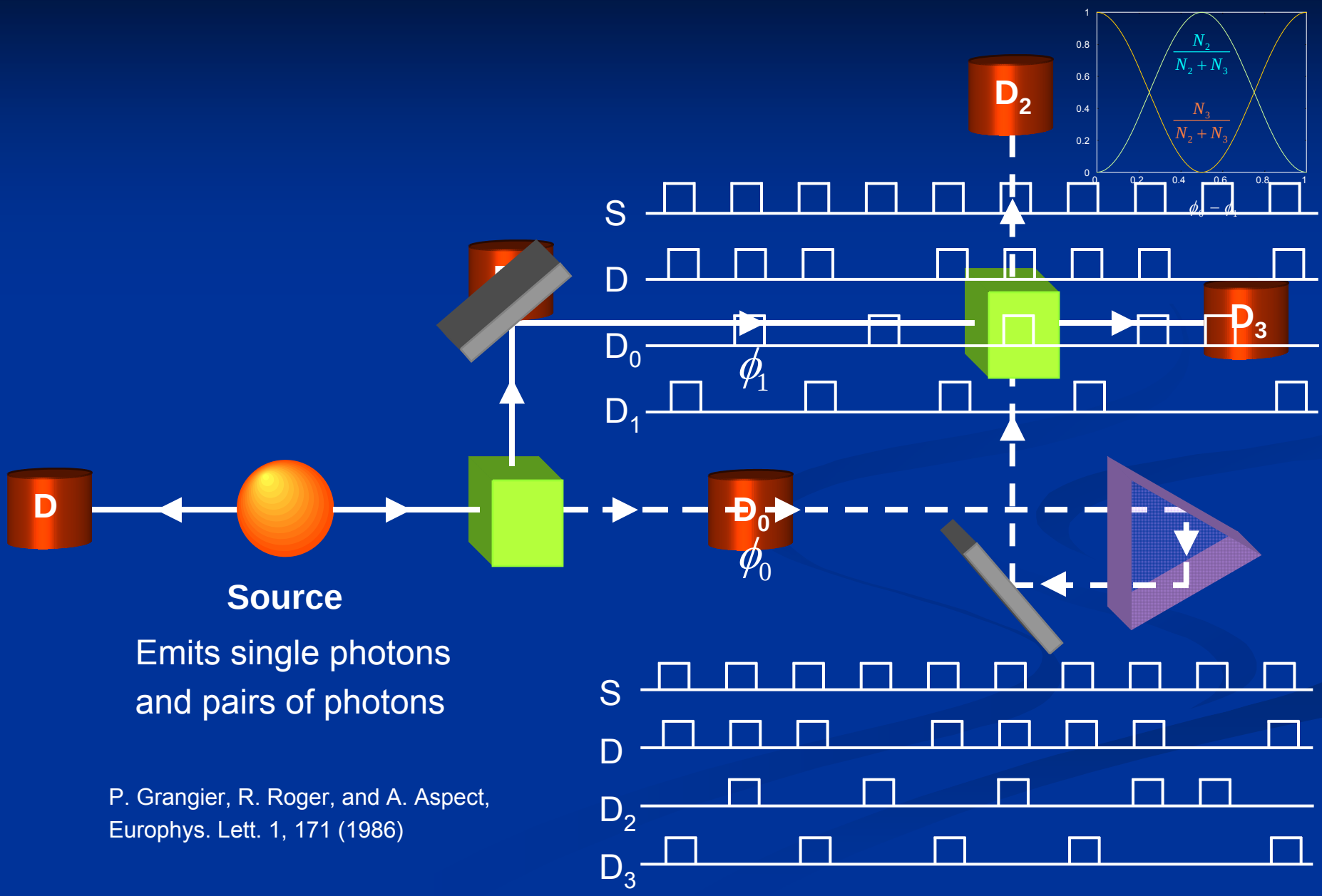
Wave-Particle Behavior: Mach-Zehnder Interferometer



P. Grangier, R. Roger, and A. Aspect, Europhys. Lett. 1, 171 (1986)

Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment

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Wave-particle duality is strikingly illustrated by Wheeler's delayed-choice gedanken experiment, where the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: Either the interferometer is closed (that is, the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that gedanken experiment with single photons allowing unambiguous which-way measurements. The choice between open and closed configurations, made by a quantum random number generator, is relativistically separated from the entry of the photon into the interferometer.

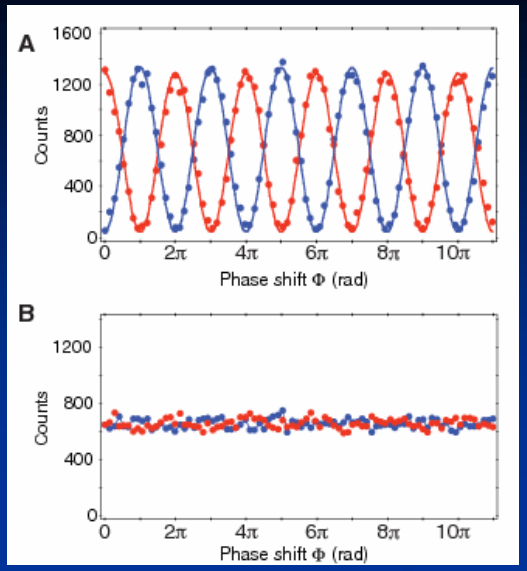
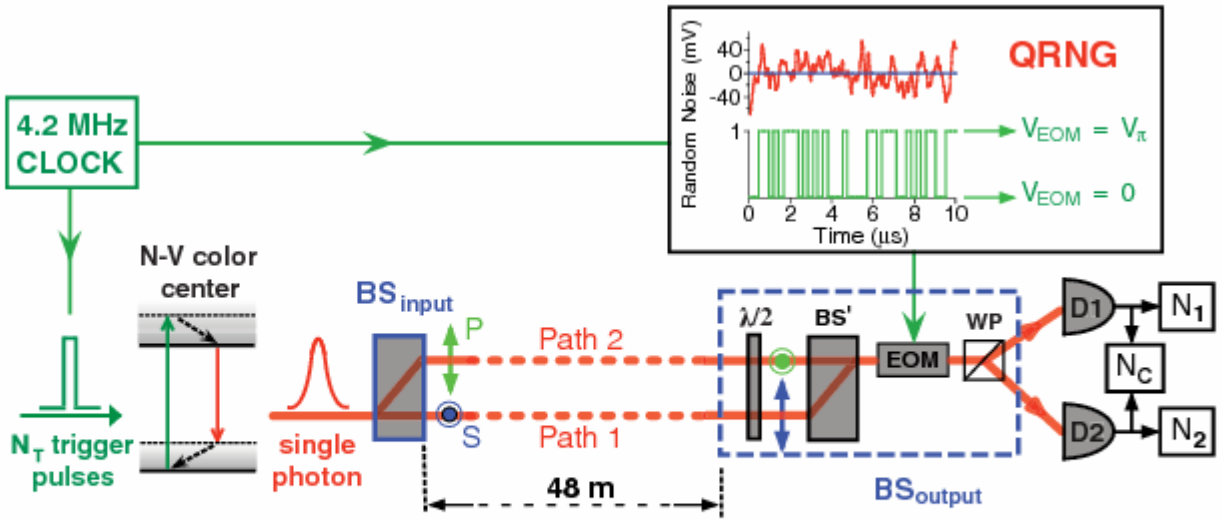


Fig. 2. Experimental realization of Wheeler's gedanken experiment. Single photons emitted by a single N-V color center are sent through a 48-m polarization interferometer, equivalent to a time of flight of about 160 ns. A binary random number 0 or 1, generated by the QRNG, drives the EOM voltage between $V = 0$ and $V = V_\pi$ within 40 ns, after an electronic delay of 80 ns. Two synchronized signals from the clock are used to trigger the single-photon emission and the QNRG. In the laboratory frame of reference, the random choice between the open and the closed configuration is made simultaneously with the entry of the photon into the interferometer. Taking advantage of the fact that the QNRG is located at the output of the interferometer, such timing ensures that the photon enters the future light cone of the random choice when it is at about the middle of the interferometer, long after passing BS_{input}.



Pictorial description: Concepts from QT applied to single events

- First beam splitter BS_{input} sends “photons” along path 1 (S-polarized) or path 2 (P-polarized), (or both 1 and 2 ?)
- BS_{output} collects photons from both paths
- If V=0, EOM does nothing: The third beam splitter (WP) sends P-photons to D1 and S-photons to D2 → Particle-like behavior
- If V≠0, EOM mixes P-photons and S-photons: WP sends P-photons to D1 and S-photons to D2 → Wave-like behavior (interference)

Pictorial description: Conclusion

- BUT: The decision to apply V≠0 can be made during the time that the photon travels from BS_{input} to BS_{output}
- To explain the experimental facts, that is particle-like results if V=0 and interference if V≠0, we have to accept that we can influence the nature (particle/wave) of the photon in its PAST
  - Sounds like a mystery or (bad) science fiction
- Task of science is to de-mystify our observations, not to cultivate mysteries

A way out ?

- Way out of this nonsensical conclusion: Quantum theory has nothing to say about individual events, it predicts averages only

- Einstein (1949): "The attempt to conceive the quantum mechanical description as the complete description of individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems"

A way out? Not really …

- “Way out” prevents us from making nonsensical statements
- Unfortunately, it does not give a single clue as how to explain the fact that individual events are observed and, when collected over a sufficiently long time, yield averages that agree with quantum theory.
  - Quantum measurement paradox

A common-sense solution

- What can we do if there is no “theory”?

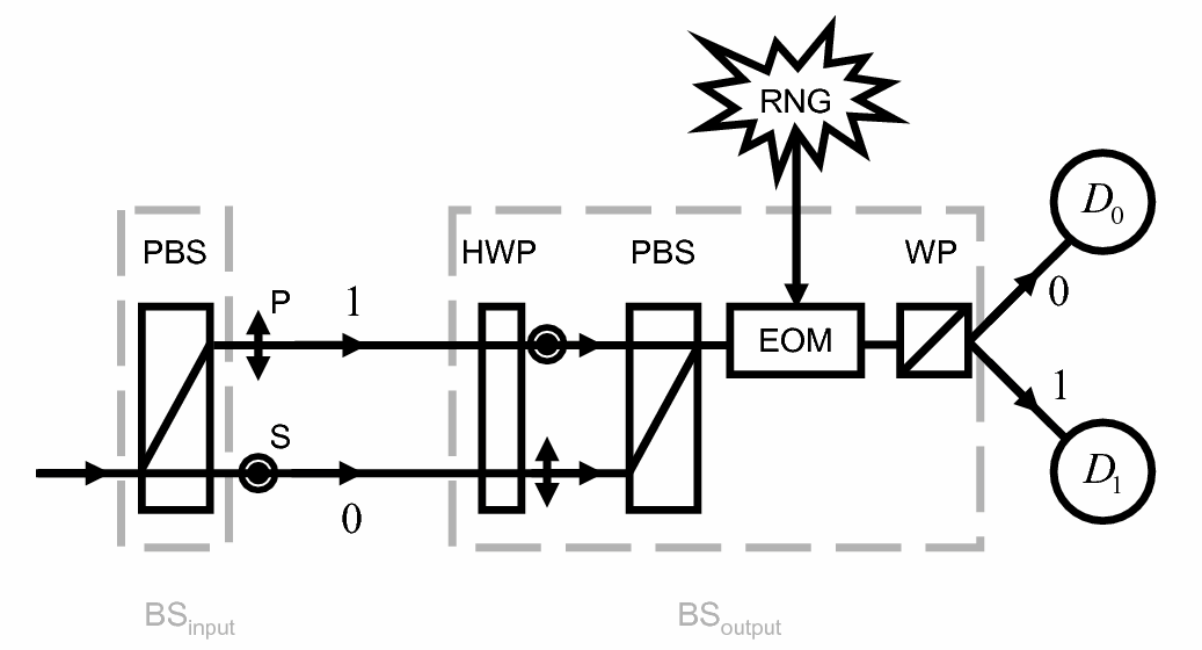
  - Maybe later, we can make a theory for the simulation models

Event-by-event simulation of quantum phenomena

- Basic idea: “Particles” are messengers that carry messages (relative time, polarization…).
- Optical components are “processors” that interpret and manipulate messages
- Interference appears as a result of processing
  - No direct communication between two messengers
  - Satisfies intuitive (= Einstein’s) notion of local causality

Basic idea

- Construct processors for each of the components in the experiment
  - Components should be “re-usable”



Example: Polarizing beam splitter

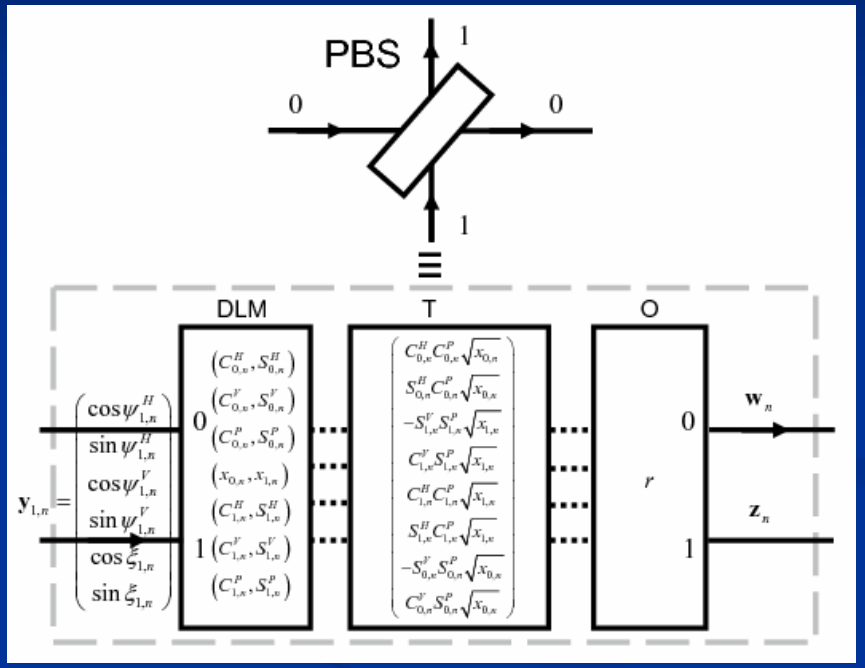
- Classical electrodynamics (Maxwell)

$$\mathbf{P}(k,\omega) = \chi(k,\omega)\mathbf{E}(k,\omega)$$

$$\mathbf{P}(k,t) = \int_0^t \chi(k,u)\mathbf{E}(k,t-u)du$$

- "Algorithm"
  - *n*th messenger arrives at input k_n

$$x_{i,n} = \alpha x_{i,n-1} + (1-\alpha)\delta_{i,k_n}$$

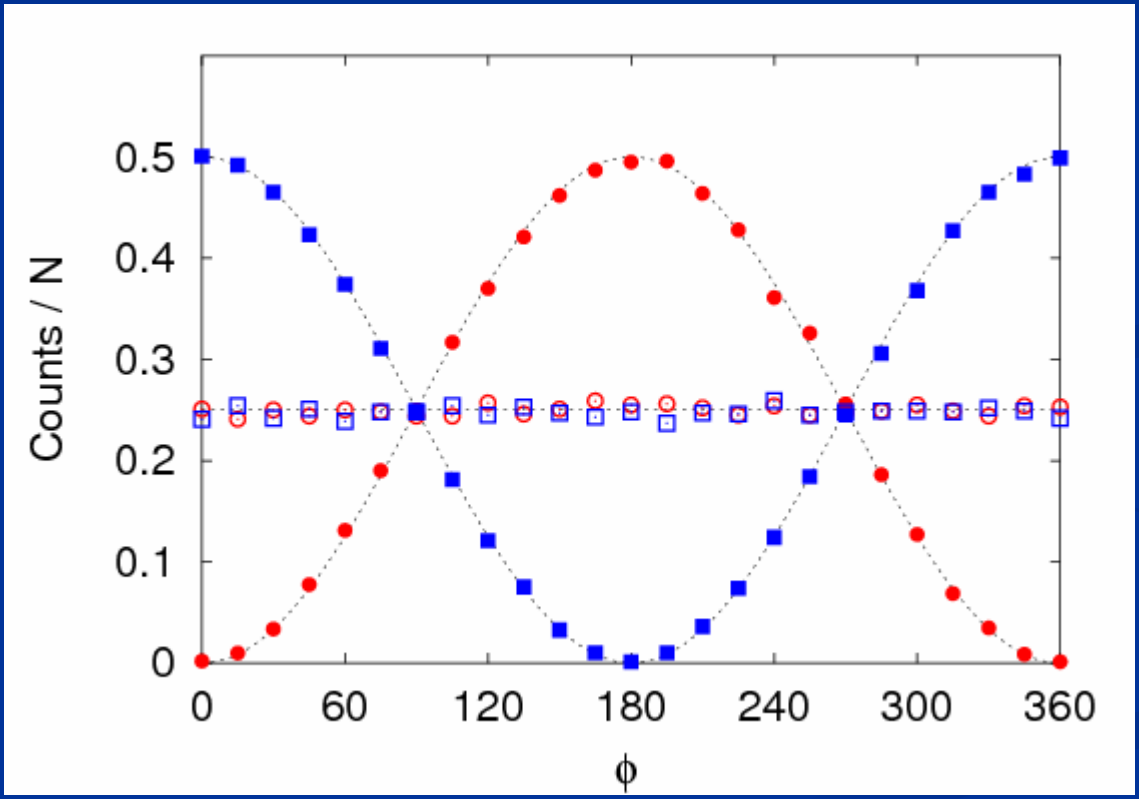


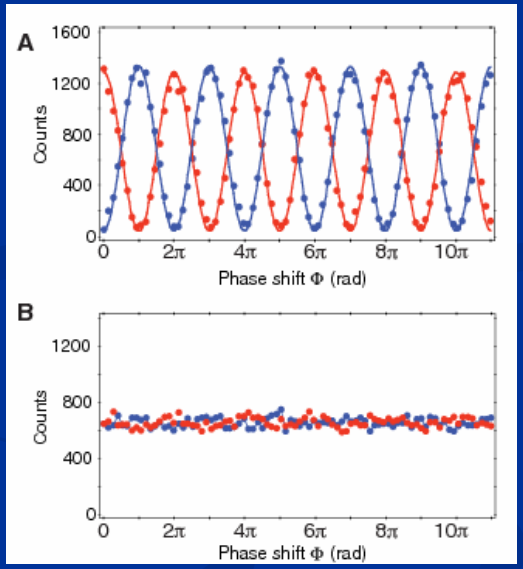
$$\mathbf{x}_n = \alpha^n \mathbf{x}_0 + (1-\alpha)\sum_{j=1}^{n-1} \alpha^{n-2-j}\mathbf{v}_j$$

$$\mathbf{v}_j = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Simulation results

- Excellent agreement with quantum theory!





Summary (1)

- We have proven that there exists a particle-only description of Wheeler's delayed-choice experiments that
  1. Reproduces the averages calculated from quantum theory
  2. Satisfies Einstein's criteria of realism and local causality
  3. Does not rely on any concept of quantum theory
  4. Is not in conflict with common sense

Summary (2)

- The same “components” have been used to simulate
  - Single-photon beam-splitter and Mach-Zehnder interferometer experiments
  - Quantum cryptography
  - Universal quantum computation
  - Wheeler’s delayed choice experiment
  - Quantum eraser, single-photon quantum optics in general
  - Einstein-Podolsky-Rosen-Bohm experiments with photons
  - Optical properties of layered materials,…
  - Single photon two-slit experiment

- Published papers, demo’s and additional information can be found on www.compphys.net/dlm