The Quantum Eraser as a “Delayed-Choice Experiment”

Hendrik van Hees

Goethe-Universität Frankfurt and FIAS

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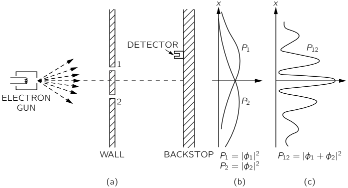
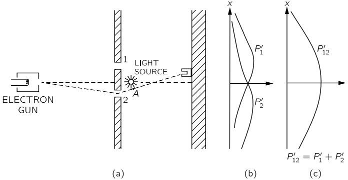
Wave-Particle Dualism

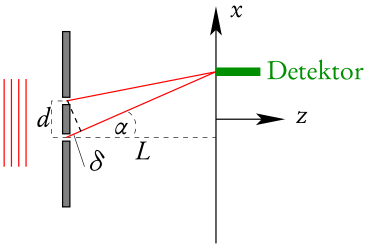
- Schrödinger (1926): Wave mechanics for particles
- Born (1926): position-probability distribution $|\psi(t,\vec{x})|^2$
- Heisenberg (1927): Uncertainty Relation $\Delta x \Delta p_x \geq \hbar/2$
- Bohr (1927) Complementarity:
  experimental setup $\Leftrightarrow$ particle or wave aspects
- double-slit epxeriment with electrons
  Feynman, Leighton, Sands, The Feynman Lectures on Physics III





  - no which-way information $\Rightarrow$ interference (wave phenomenon)
  - get which-way information (particle property) $\Rightarrow$ no interference
- Wheeler (1978): choice between particle or wave properties **after** "particles" are registered $\Rightarrow$ "delayed choice"
- here experiment with photons
  S. P. Walborn, M. O. Terra Cunha, S. Pádua, and C. H. Monken, PRA **65** 033818 (2002)

Double-slit experiment with photons



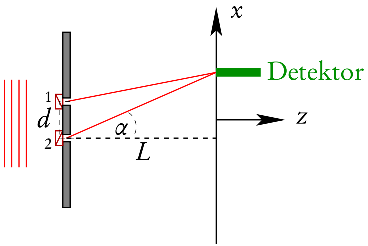
- $|\hat{x}\rangle$: in x direction linearly polarized photon
- $|\psi\rangle = |\psi_1\rangle + |\psi_2\rangle = N_0/\sqrt{2}\left\{1+\exp[\mathrm{i}\varphi(x)]\right\}|\hat{x}\rangle$
- $P(x) = \left\langle \psi \middle| \psi \right\rangle = N_0\left(1+\cos[\varphi(x)]\right)$

- $\varphi(x) = \frac{2\pi}{\lambda}\delta = k\delta = \frac{kxd}{L}$
- taking into account the finite width of the slits

$$\text{counting rate:} \quad P(x) = N_0 \frac{\sin^2\left(\frac{kxb}{2L}\right)}{\left(\frac{kxb}{2L}\right)^2}\left(1+\cos[\varphi(x)]\right) = N_{\mathrm{ES}}(x)\left(1+\cos[\varphi(x)]\right)$$

- no which-way information
- amplitudes for the photon going through either slit add
  $\Leftrightarrow$ interference (wave phenomenon)
- single photon $\Rightarrow$ single spot on photo plate (particle property)
  detection position for each photon random
- many equally prepared photons $\Rightarrow$ interference pattern (wave property)

Gaining which-way information



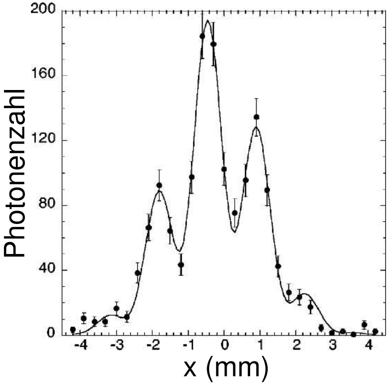
- $\lambda/4$ plate at slit 1
  $(+\pi/4)$ orientation
- $\lambda/4$ plate at slit 2 in
  $(-\pi/4)$ orientation
- $\left|\psi_1\right\rangle = \hat{Q}_+ |\hat{x}\rangle = \frac{1}{\sqrt{2}}(|\hat{x}\rangle + \mathrm{i}\left|\hat{y}\right\rangle) = |L\rangle$
  $\left|\psi_2\right\rangle = \hat{Q}_- |\hat{x}\rangle = \frac{1}{\sqrt{2}}(|\hat{x}\rangle - \mathrm{i}\left|\hat{y}\right\rangle) = |R\rangle$
- $\left\langle\psi_1\middle|\psi_2\right\rangle = 0$!

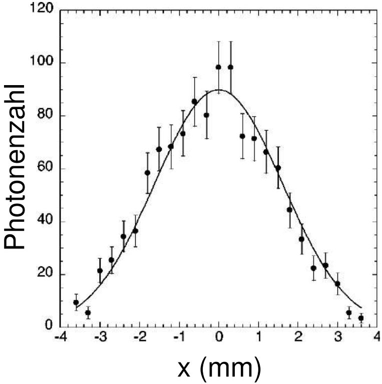
$$\text{counting rate}: \quad P(x) = N_{\text{ES}}(x)$$

- which-way information:
  stored in the polarization state of the photons
- no double-slit interference
  probability distributions add (particle property)
- particle property excludes wave property (complementarity)
- NB: $\hat{Q}_+ \left|\hat{y}\right\rangle = \mathrm{i}|R\rangle, \quad \hat{Q}_- \left|\hat{y}\right\rangle = -\mathrm{i}|L\rangle$

Experimental confirmation

S. P. Walborn, M. O. Terra Cunha, S. Pádua, and C. H. Monken, PRA **65** 033818 (2002)



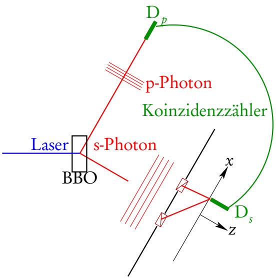


no $\lambda/4$ plates
(no which-way information)
$\Rightarrow$ interference (wave properties)

with $\lambda/4$ plates
(which-way information)
$\Rightarrow$ no interference (particle property)

- experimental setup $\Leftrightarrow$ photon's wave **or** particle properties
- complementarity: **either** particle **or** wave properties

Polarization-entangled photons



- before slits:
  polarization-entangled photon pairs

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\hat{x}\rangle \otimes |\hat{y}\rangle + |\hat{y}\rangle \otimes |\hat{x}\rangle\right)$$

- behind slits: which-way marked s-photons

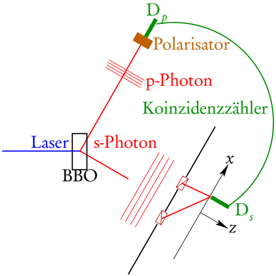
$$|\Psi_1'\rangle = (\hat{Q}_+ \otimes \mathbb{1})|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|L\rangle \otimes |\hat{y}\rangle + \mathrm{i}|R\rangle \otimes |\hat{x}\rangle\right],$$

$$|\Psi_2'\rangle = (\hat{Q}_- \otimes \mathbb{1})|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|R\rangle \otimes |\hat{y}\rangle - \mathrm{i}|L\rangle \otimes |\hat{x}\rangle\right],$$

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}\left\{|\Psi_1'\rangle + \exp[\mathrm{i}\varphi(x)]|\Psi_2'\rangle\right\}$$

- $\langle \Psi_1' | \Psi_2' \rangle = 0 \Rightarrow$ no interference, which-way information

Erasing which-way information without touching γ_s



- before slits:
  polarization-entangled photon pairs

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\hat{x}\rangle \otimes \left|\hat{y}\right\rangle + \left|\hat{y}\right\rangle \otimes |\hat{x}\rangle\right)$$

- mark WWI for γ_s with $\lambda/4$ plates

$$\left|\Psi_1'\right\rangle = (\hat{Q}_+ \otimes \mathbb{1})|\Psi\rangle, \quad \left|\Psi_2'\right\rangle = (\hat{Q}_- \otimes \mathbb{1})|\Psi\rangle,$$

- polarization filter in $\pm\pi/4$ orientations for γ_p
  register only γ_s, if γ_p is registered

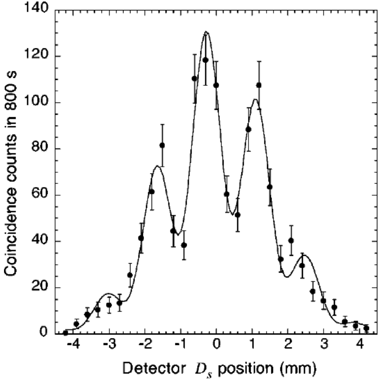
$$\left|\Psi_{1\pm}''\right\rangle = (\mathbb{1} \otimes \hat{P}_\pm)\left|\Psi_1'\right\rangle = \frac{1}{2}(\pm|L\rangle + \mathrm{i}|R\rangle) \otimes \left|\widehat{\pm\pi/4}\right\rangle$$

$$\left|\Psi_{2\pm}''\right\rangle = (\mathbb{1} \otimes \hat{P}_\pm)\left|\Psi_2'\right\rangle = \frac{1}{2}[\pm|R\rangle - \mathrm{i}|L\rangle] \otimes \left|\widehat{\pm\pi/4}\right\rangle = \mp\mathrm{i}\left|\Psi_{1\pm}''\right\rangle,$$

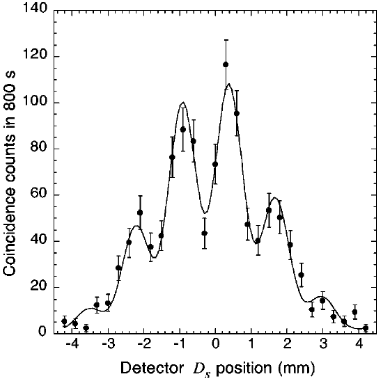
$$\left|\Psi_\pm''\right\rangle = \left\{1 \mp \mathrm{i}\exp[\mathrm{i}\varphi(x)]\right\}\left|\Psi_{1\pm}''\right\rangle$$

- $\left\langle\Psi_\pm''\middle|\Psi_\pm''\right\rangle = \frac{1}{2}\left\{1 \pm \sin[\varphi(x)]\right\}$
  $\Rightarrow$ double-slit interference, which-way information erased!

Restoration of interference pattern



γ_p polarized $(+\pi/4)$ direction



γ_p polarized in $(-\pi/4)$ direction

- interference pattern restored (though shifted)
- which-way information erased
- can place polarization filter for γ_p at arbitrary distance!
  $\Rightarrow$ WWI erased **long after** γ_s was registered
  $\Rightarrow$ Delayed-Choice Experiment a la Wheeler
- "erasure" can take place before or after registering γ_s!

Discussion

- experimental verification of the possibility of Delayed-Choice experiments/postselection
- quantum entanglement allows for choice whether wave or particle properties are realized after measurement established
- retrocausality?
  cf. QED no!
  $\Rightarrow$ registration of γ_s and polarization filtering of γ_p cannot influence each other due to locality and microcausality
- reason for possibility of delayed choice/postselection is correlation due to entanglement of γ_s and γ_p
  $\Rightarrow$ i.e., because of preparation of the entangled state **before** registration/measurement and choice what's measured