

The Quantum Eraser as a “Delayed-Choice Experiment”

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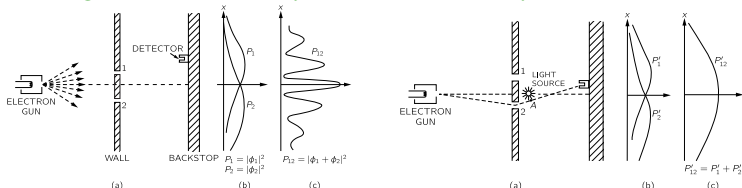
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Wave-Particle Dualism

- 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 experiment with electrons

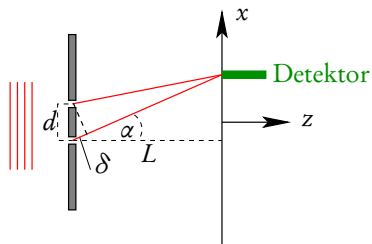
Feynman, Leighton, Sands, *The Feynman Lectures on Physics III*



- 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



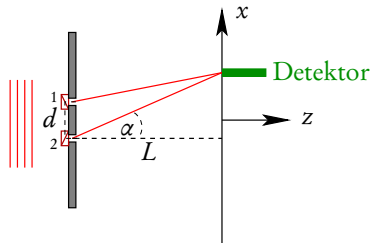
- $|\hat{x}\rangle$: in x direction linearly polarized photon
- $|\psi\rangle = |\psi_1\rangle + |\psi_2\rangle = N_0/\sqrt{2} \{1 + \exp[i\varphi(x)]\} |\hat{x}\rangle$
- $P(x) = \langle \psi | \psi \rangle = N_0 (1 + \cos[\varphi(x)])$

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

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

- 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



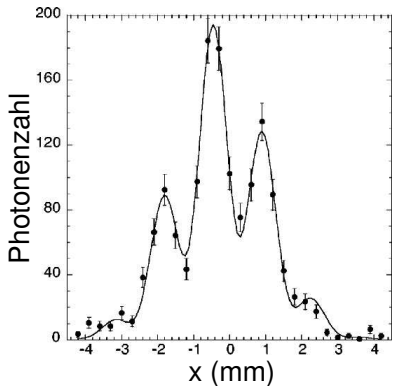
- $\lambda/4$ plate at slit 1
($+\pi/4$) orientation
- $\lambda/4$ plate at slit 2 in
($-\pi/4$) orientation
- $|\psi_1\rangle = \hat{Q}_+|\hat{x}\rangle = \frac{1}{\sqrt{2}}(|\hat{x}\rangle + i|\hat{y}\rangle) = |L\rangle$
- $|\psi_2\rangle = \hat{Q}_-|\hat{x}\rangle = \frac{1}{\sqrt{2}}(|\hat{x}\rangle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

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

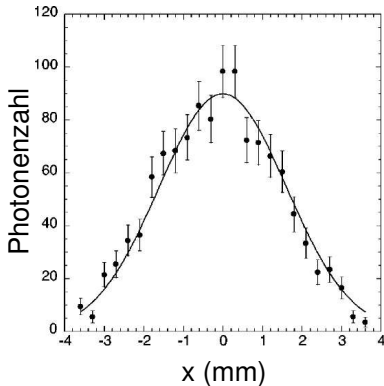
- **which-way information:**
stored in the polarization state of the photons
- no double-slit interference
probability distributions add (**particle property**)
- **particle property** excludes wave property (**complementarity**)
- NB: $\hat{Q}_+|\hat{y}\rangle = i|R\rangle$, $\hat{Q}_-|\hat{y}\rangle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

Experimental confirmation

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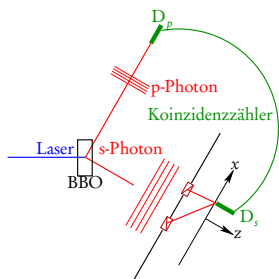
no $\lambda/4$ plates
(no which-way information)
⇒ interference (**wave properties**)



with $\lambda/4$ plates
(which-way information)
⇒ 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

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

- behind slits: which-way marked s-photons

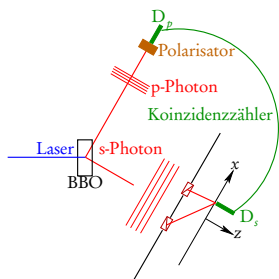
$$|\Psi'_1\rangle = (\hat{Q}_+ \otimes \mathbb{1})|\Psi\rangle = \frac{1}{\sqrt{2}} [|L\rangle \otimes |\hat{y}\rangle + i |R\rangle \otimes |\hat{x}\rangle],$$

$$|\Psi'_2\rangle = (\hat{Q}_- \otimes \mathbb{1})|\Psi\rangle = \frac{1}{\sqrt{2}} [|R\rangle \otimes |\hat{y}\rangle - i |L\rangle \otimes |\hat{x}\rangle],$$

$$|\Psi'\rangle = \frac{1}{\sqrt{2}} \{ |\Psi'_1\rangle + \exp[i\varphi(x)] |\Psi'_2\rangle \}$$

- $\langle \Psi'_1 | \Psi'_2 \rangle = 0 \Rightarrow$ no interference, which-way information

Erasing which-way information without touching γ_s



- before slits:
polarization-entangled photon pairs

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

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

$$|\Psi'_1\rangle = (\hat{Q}_+ \otimes \mathbb{1})|\Psi\rangle, \quad |\Psi'_2\rangle = (\hat{Q}_- \otimes \mathbb{1})|\Psi\rangle,$$

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

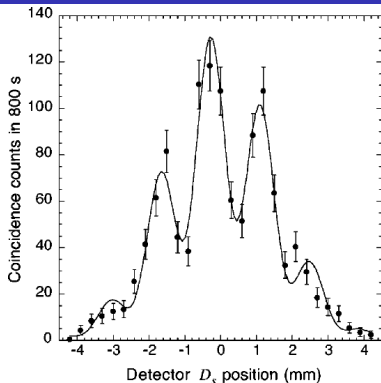
$$|\Psi''_{1\pm}\rangle = (\mathbb{1} \otimes \hat{P}_{\pm})|\Psi'_1\rangle = \frac{1}{2} (\pm|L\rangle + i|R\rangle) \otimes |\pm\pi/4\rangle$$

$$|\Psi''_{2\pm}\rangle = (\mathbb{1} \otimes \hat{P}_{\pm})|\Psi'_2\rangle = \frac{1}{2} [\pm|R\rangle - i|L\rangle] \otimes |\pm\pi/4\rangle = \mp i |\Psi''_{1\pm}\rangle,$$

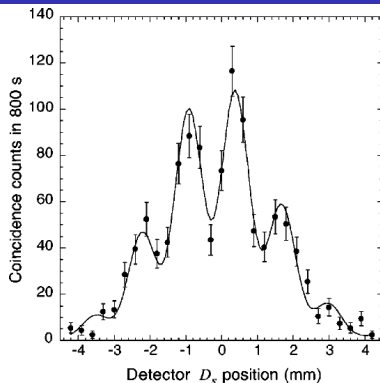
$$|\Psi''_{\pm}\rangle = \{1 \mp i \exp[i\varphi(x)]\} |\Psi''_{1\pm}\rangle$$

- $\langle \Psi''_{\pm} | \Psi''_{\pm} \rangle = \frac{1}{2} \{1 \pm \sin[\varphi(x)]\}$
 \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!
⇒ WWI erased **long after** γ_s was registered
⇒ **Delayed-Choice Experiment** a la Wheeler
- “erasure” can take place **before or after** registering γ_s !

- experimental verification of the possibility of 0 **Delayed-Choice experiments/postselection**
- quantum entanglement allows for choice whether **wave or particle properties** are realized **after** measurement established
- retrocausality?
cf. QED **no!**
⇒ 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
⇒ i.e., because of preparation of the entangled state **before** registration/measurement and choice what's measured