Title: The Physics of 2 != 1+1

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Abstract: Feynman was probably correct to say that the only mystery of quantum mechanics is the principle of superposition. Although we may never know which slit a photon has been passing in a YoungÂ's double-slit experiment, we do have a corresponding classical concept in classical electromagnetic theory: the superposition of electromagnetic fields at a local space-time point is a solution of the Maxwell equations. In the case of joint photo-detection measurement of two photons, however, the superposition involves the addition of two-photon amplitudes, different yet indistinguishable alternatives resulting in a click-click joint photo-detection event. There is no counterpart of such concept in classical electromagnetic theory and the superposition may happen at distance. It is the two-photon superposition responsible for the mysteries of EPR by means of reality and causality. This talk will analyze the physics of based on several recent experiments.

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The physics of $2 \neq 1+1$

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Can quantum mechanical physical reality be considered complete?

Einstein, Poldosky, Rosen, Phys. Rev. **47**, 777 (1935).

(1) Proposed the entangled two-particle state according to the principle of quantum superposition:

$$\Psi(x_1,x_2) = \int dp\, \psi_p(x_2) u_p(x_1) \Rightarrow \delta(x_1 - x_2 + x_0)$$

$$\overline{\Psi}(p_1,p_2) = \int dx\, \varphi_x(x_2) v_x(x_1) \Rightarrow \delta(p_1 + p_2)$$

(2) Pointed out a surprising phenomenon: the momentum (position) for neither subsystem is determinate; however, if one particle is measured to have a certain momentum (position), the momentum (position) of its "twin" is determined with certainty, *despite the distance between them!*

EPR δ-function:

-- perfect entangled system

$$\Delta(x_1 - x_2) = 0, \quad \Delta(p_1 + p_2) = 0.$$

Although: $\Delta x_1 \approx \infty,\ \Delta x_2 \approx \infty,\ \Delta p_1 \approx \infty,\ \Delta p_2 \approx \infty.$

A Cartoon: Schrodinger Cats

A pair of interaction-free cats "propagate" to distant locations:

(1) each of the cats are in the state of alive and dead, simultaneously;

(2) the two has to be observed both alive or both dead, despite the distance between the two.

There would be probably no surprise if our observation is based on a large number of alive-alive or dead-dead twin cats. But, here we are talking about:

(1) A pair has to be observed both alive or both dead whenever we look at them;

(2) Each cat of the pair is alive and dead simultaneously;

Are we sure we are talking about a pair to be alive and dead, simultaneously (pure state), but not an ensemble of pairs in which 50% are alive, 50% are dead (mixed state)?

Yes. EPR state is a pure state.

$$\Psi(x_1,x_2) = \sum_{p_1,p_2} \delta(p_1 + p_2)\left|p_1\right\rangle\left|p_2\right\rangle \Rightarrow \delta(x_1 - x_2 + x_0)$$

$$\overline{\Psi}(p_1,p_2) = \sum_{x_1,x_2} \delta(x_1 - x_2 + x_0)\left|x_1\right\rangle\left|x_2\right\rangle \Rightarrow \delta(p_1 + p_2)$$

EPR state is characterized by two δ-functions, simultaneously. A statistical mixed state may hold one of them, but never both.

EPR state is the result of QM superposition:

$$\Psi(x_1,x_2) = \frac{1}{2\pi\hbar}\int dp_1 dp_2 \delta(p_1+p_2)\left|p_1\right\rangle\left|p_2\right\rangle$$
$$= F_{x_1,x_2}\left\{f(p_1,p_2)\right\}$$
$$= \delta(x_1 - x_2 + x_0)$$

$$\overline{\Psi}(p_1,p_2) = \frac{1}{2\pi\hbar}\int dx_1 dx_2 \delta(x_1 - x_2 + x_0)\left|x_1\right\rangle\left|x_2\right\rangle$$
$$= F_{p_1,p_2}\left\{f(x_1,x_2)\right\}$$
$$= \delta(p_1 + p_2)$$

It is a two-particle superposition !

A statistical mixture works differently:

$$\hat{\rho} = \sum_{p_1, p_2} \delta(p_1 + p_2) \left| p_1 \right\rangle \left| p_2 \right\rangle \left\langle p_2 \right| \left\langle p_1 \right| \neq \delta(x_1 - x_2 + x_0)$$

$$\hat{\rho} = \sum_{x_1, x_2} \delta(x_1 - x_2 + x_0) \left| x_1 \right\rangle \left| x_2 \right\rangle \left\langle x_2 \right| \left\langle x_1 \right| \neq \delta(p_1 + p_2)$$

One can never obtain two δ-functions in space and in momentum simultaneously.

Pure State vs. Statistical Mixture:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{alive}\rangle + |\text{dead}\rangle)$$

100 cats, all and each of them are simultaneously alive and dead (in the same superposition state: pure).

$$\hat{\rho} = \frac{1}{2}(|\text{alive}\rangle\langle\text{alive}| + |\text{dead}\rangle\langle\text{dead}|)$$

100 cats, 50 are alive, 50 are dead (50 in the state of alive, 50 in the state of dead: mixture).

Two-particle Pure State vs. Statistical Mixture:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{alive}_1, \text{alive}_2\rangle + |\text{dead}_1, \text{dead}_2\rangle)$$

100 cat-pairs, all and each of the pair are in the same superposition state of alive-alive and dead-dead.

$$\hat{\rho} = \frac{1}{2}(|\text{alive}_1, \text{alive}_2\rangle\langle\text{alive}_2, \text{alive}_1| + |\text{dead}_1, \text{dead}_2\rangle\langle\text{dead}_1, \text{dead}_1|)$$

100 cat-pairs, 50 are alive-alive, 50 are dead-dead.

EPR δ-function:

$$\delta(x_1 - x_2 + x_0) \Rightarrow \Delta(x_1 - x_2) = 0$$
$$\delta(p_1 + p_2) \quad \Rightarrow \Delta(p_1 + p_2) = 0$$

Although: $\Delta x_1 \approx \infty,\ \Delta x_2 \approx \infty,\ \Delta p_1 \approx \infty,\ \Delta p_2 \approx \infty.$

EPR Inequality:

-- non-perfect entangled system

$$\Delta(x_1 - x_2) < \min(\Delta x_1, \Delta x_2)$$
$$\Delta(p_1 + p_2) < \min(\Delta p_1, \Delta p_2)$$

Statistical mixed state may satisfy one of them, but never both!

Quite a surprise !

* $H = H_1 + H_2; \quad H_{\text{interaction}} = 0$
* Space-like separated measurement events.

(1) No interaction between two distant quanta;

(2) No action-at-a-distance between individual measurements.

To EPR: the two quanta are independent as well as the measurements, so that

$$\Delta(x_1 - x_2) = \sqrt{(\Delta x_1)^2 + (\Delta x_2)^2} > Max(\Delta x_1, \Delta x_2)$$

$$\Delta(p_1 + p_2) = \sqrt{(\Delta p_1)^2 + (\Delta p_2)^2} > Max(\Delta p_1, \Delta p_2)$$

The apparent contradiction deeply troubled Einstein.

While one sees the measurement on (p_1+p_2) and (x_1-x_2) of two individual particles satisfy the EPR δ-function and believes the classical inequality, one might easily be trapped into considering either there is a violation of the uncertainty principle or there exists action-at-a-distance.

Feynman: "… the only mystery of quantum mechanics is the superposition principle …"

It is a superposition between two-particle states, which has brought us more mysteries.

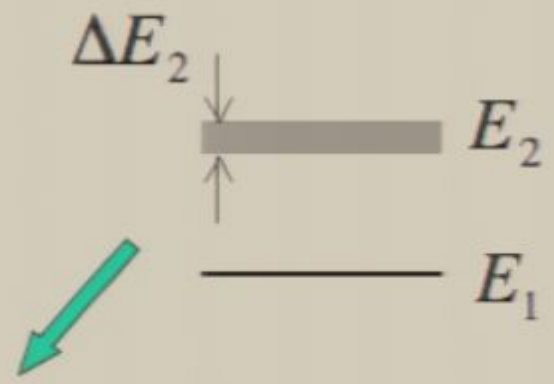
$$\Psi(x_1,x_2) = \frac{1}{2\pi\hbar}\int dp_1 dp_2 \delta(p_1+p_2)\left|p_1\right\rangle\left|p_2\right\rangle$$
$$= F_{x_1,x_2}\left\{f(p_1,p_2)\right\}$$
$$= \delta(x_1 - x_2 + x_0)$$

$$\overline{\Psi}(p_1,p_2) = \frac{1}{2\pi\hbar}\int dx_1 dx_2 \delta(x_1 - x_2 + x_0)\left|x_1\right\rangle\left|x_2\right\rangle$$
$$= F_{p_1,p_2}\left\{f(x_1,x_2)\right\}$$
$$= \delta(p_1 + p_2)$$

Photon, a good concept for the physics of superposition.

A good example about the state and the measurement.

A photon:



from $|\hbar\omega\rangle$

to $$|\Psi\rangle = \sum_{\omega} f(\omega)\,|\hbar\omega\rangle = \sum_{\omega} f(\omega)\,\hat{a}^{+}(\omega)\,|0\rangle$$

Result of superposition:
A wavepacket
in operational approach.

Glauber Theory

$$G^{(1)}(x,t) = \langle \Psi | \hat{E}^{(-)} \hat{E}^{(+)} | \Psi \rangle = \left| \langle 0 | \hat{E}^{(+)}(x,t) | \Psi \rangle \right|^2$$

Probability to produce a photo-electron event at (x,t).

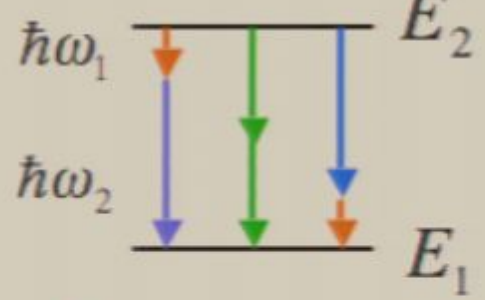
$$\begin{aligned}
\Psi(x,t) &\equiv \langle 0 | \hat{E}^{(+)}(x,t) | \Psi \rangle \\
&= \int_0^\infty d\omega \, f(\omega) \, e^{-i[\omega t - k(\omega) x]} \\
&= e^{-i[\omega_0 t - k(\omega_0) x]} \int_{-\infty}^{\infty} d\Omega \, f(\Omega) \, e^{-i\Omega t} \\
&= e^{-i[\omega_0 t - k(\omega_0) x]} \, F_\tau \{ f(\Omega) \}
\end{aligned}$$

Operational approach

$$\omega \equiv \omega_0 + \Omega \qquad \tau \equiv t - x / u(\omega_0) \qquad u(\omega_0) = \frac{1}{dk/d\omega}$$

A "wavepacket" is the result of coherent superposition. Quantum mechanically, the measurement cannot precisely locate a light quantum within the "uncertainty" of the wavepacket.

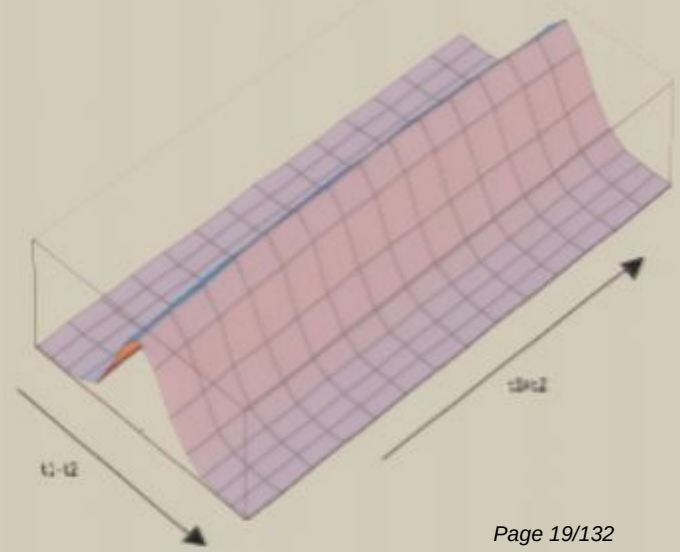
A biphoton:



$$|\Psi\rangle = \sum_{\omega} \delta(\omega_1 + \omega_2 - \omega_0)\, |\omega_1, \omega_2\rangle$$

$$= \sum_{\omega} \delta(\omega_1 + \omega_2 - \omega_0)\, \hat{a}^{+}(\omega_1)\, \hat{a}^{+}(\omega_2)\, |0\rangle$$

Result of 2-photon superposition:
A 2-D wavepacket



$$G^{(2)}(x_1,t_1;x_2,t_2) = \langle \Psi | \hat{E}_1^{(-)} \hat{E}_2^{(-)} \hat{E}_2^{(+)} \hat{E}_1^{(+)} | \Psi \rangle = \left| \langle 0 | \hat{E}^{(+)}(x_2,t_2) \hat{E}^{(+)}(x_1,t_1) | \Psi \rangle \right|^2$$

Probability to produce a joint-detection event at $(x_1,t_1;x_2,t_2)$.

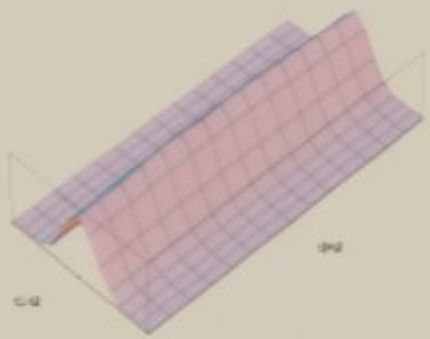
$$\Psi(x_1,t_1;x_2,t_2) \equiv \langle 0 | \hat{E}^{(+)}(x_1,t_1) \hat{E}^{(+)}(x_2,t_2) | \Psi \rangle$$

$$\cong e^{-i\omega_0(\tau_1+\tau_2)} \int_{-\infty}^{\infty} d\Omega \, f(\Omega) \, e^{-i\Omega(\tau_1-\tau_2)}$$

$$= e^{-i[\omega_0 t - k(\omega_0)x]} F_{\tau_1-\tau_2}\{f(\Omega)\}$$

Operational approach

$$\omega \equiv \omega_0 + \Omega \qquad \tau \equiv t - x/u(\omega_0) \qquad u(\omega_0) = \frac{1}{dk/d\omega}$$



A "biphoton" is the result of superposition of 2-photon state. Quantum mechanically, the measurement on $t_1 - t_2$ can achieve resolution even beyond classical limit of $\Delta(t_1 - t_2) \geq Max(\Delta t_1, \Delta t_2)$.

The two-photon superposition is nonlocal !

$$\Psi(x,t) \equiv \langle 0 | \hat{E}^{(+)}(x,t) | \Psi \rangle$$
$$= e^{-i[\omega_0 t - k(\omega_0)x]} \int_{-\infty}^{\infty} d\Omega \, f(\Omega) \, e^{-i\Omega t}$$
$$= e^{-i[\omega_0 t - k(\omega_0)x]} \, F_\tau \{ f(\Omega) \}$$

The superposition happens at a space-time point. We do have a classical concept for this.

$$\Psi(x_1,t_1;x_2,t_2) \equiv \langle 0 | \hat{E}^{(+)}(x_1,t_1) \hat{E}^{(+)}(x_2,t_2) | \Psi \rangle$$
$$\cong e^{-i\omega_0(\tau_1+\tau_2)} \int_{-\infty}^{\infty} d\Omega \, f(\Omega) \, e^{-i\Omega(\tau_1-\tau_2)}$$
$$= e^{-i[\omega_0 t - k(\omega_0)x]} \, F_{\tau_1-\tau_2} \{ f(\Omega) \}$$

The superposition happens between different yet equivalent two-photon amplitudes that lead to a joint detection event of two photo-detectors at distant space-time points $(x_1,t_1;x_2,t_2)$. This represents a quite troubling concept in classical physics, because there is no counterpart of such concept in classical electromagnetic theory.

The uncertainties for entangled EPR photon pair:

$$\Delta(t_1 - t_2) = 0$$
$$\Delta(\omega_1 + \omega_2) = 0$$

Simultaneously !

Although $\left\{ \begin{array}{ll} \Delta t_1 = \infty, & \Delta t_2 = \infty \\ \Delta\omega_1 = \infty, & \Delta\omega_2 = \infty \end{array} \right\}$

Violation of the uncertainty principle ?

$$\Delta(p_1 + p_2) = 0 \quad \Delta(x_1 - x_2) = 0$$

Simultaneously !

(p_1+p_2) and (x_1-x_2) are not conjugate variables !!!!

$$\Psi(x_1,x_2) = \frac{1}{2\pi\hbar}\int dp_1 dp_2 \delta(p_1+p_2) e^{ip_1x_1/\hbar} e^{ip_2(x_2-x_0)/\hbar}$$

$$= \frac{1}{2\pi\hbar}\int d(p_1+p_2)\delta(p_1+p_2) e^{i(p_1+p_2)(x_1+x_2')/2\hbar}$$

$$\times \int d(p_1-p_2)/2\, e^{i(p_1-p_2)(x_1-x_2')/2\hbar}$$

$$= 1 \times \delta(x_1 - x_2 + x_0)$$

$$\overline{\Psi}(p_1,p_2) = \frac{1}{2\pi\hbar}\int dx_1 dx_2 \delta(x_1 - x_2 + x_0) e^{-ip_1x_1/\hbar} e^{-ip_2(x_2-x_0)/\hbar}$$

$$= \frac{1}{2\pi\hbar}\int d(x_1+x_2')\, e^{-i(p_1+p_2)(x_1+x_2')/2\hbar}$$

$$\times \int d(x_1-x_2')/2\, \delta(x_1-x_2') e^{-i(p_1-p_2)(x_1-x_2')/2\hbar}$$

$$= \delta(p_1+p_2) \times 1$$

Conjugate Variables:

$$(x_1 + x_2) \Leftrightarrow (p_1 + p_2)$$
$$(x_1 - x_2) \Leftrightarrow (p_1 - p_2)$$

$$\Downarrow$$

$$\Delta(x_1 + x_2) = \infty \quad \Leftrightarrow \quad \Delta(p_1 + p_2) = 0$$
$$\Delta(x_1 - x_2) = 0 \quad \Leftrightarrow \quad \Delta(p_1 - p_2) = \infty$$

Observation:

$$\Delta(x_1 - x_2) = 0, \quad \Delta(p_1 + p_2) = 0$$

Believing:

$$\Delta(x_1 - x_2) > Max(\Delta x_1, \Delta x_2)$$
$$\Delta(p_1 + p_2) > Max(\Delta p_1, \Delta p_2)$$

Conclusion:

$$\Delta x_1 = 0, \quad \Delta p_1 = 0$$
$$\Delta x_2 = 0, \quad \Delta p_2 = 0$$

(Violation of the …)

EPR δ-function:

$$\Delta(x_1 - x_2) = 0, \quad \Delta(p_1 + p_2) = 0.$$

with: $\Delta x_1 \approx \infty, \Delta x_2 \approx \infty, \Delta p_1 \approx \infty, \Delta p_2 \approx \infty.$

Although it is not the violation of the uncertainty principle, it is truly a violation of the classical inequalities: $\Delta(x_1 - x_2) > Max(\Delta x_1, \Delta x_2)$

$$\Delta(p_1 + p_2) > Max(\Delta p_1, \Delta p_2)$$

How much we know a subsystem in the EPR system ?

Pure state for the system of two:

$$|\Psi\rangle = \sum_{\omega} \delta(\omega_1 + \omega_2 - \omega_0)\, \hat{a}^+(\omega_1)\, \hat{a}^+(\omega_2)\, |0\rangle$$

Statistical mixed state for a subsystem:

$$\hat{\rho}_1 = Tr_2\, |\Psi\rangle\langle\Psi| = \sum_{\omega} \hat{a}^+(\omega_1)\, |0\rangle\langle 0|\hat{a}^+(\omega_1)$$

Negative entropy ? (Von Neuman entropy)

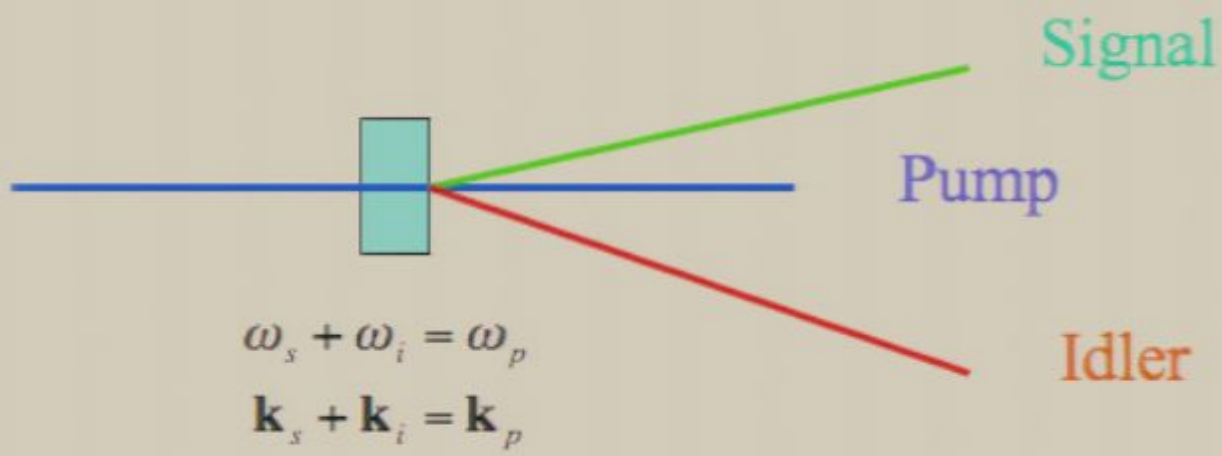
$$S = -tr(\hat{\rho}\log\hat{\rho}) \qquad S_{EPR} = 0; \quad S_{1,2} > 0 \quad \longrightarrow \quad S_1 + S_{1|2} = 0$$

"…given the result of a measurement over one particle, the result of the measurement over the other must yield negative information."

Does nature allow entangled states ?

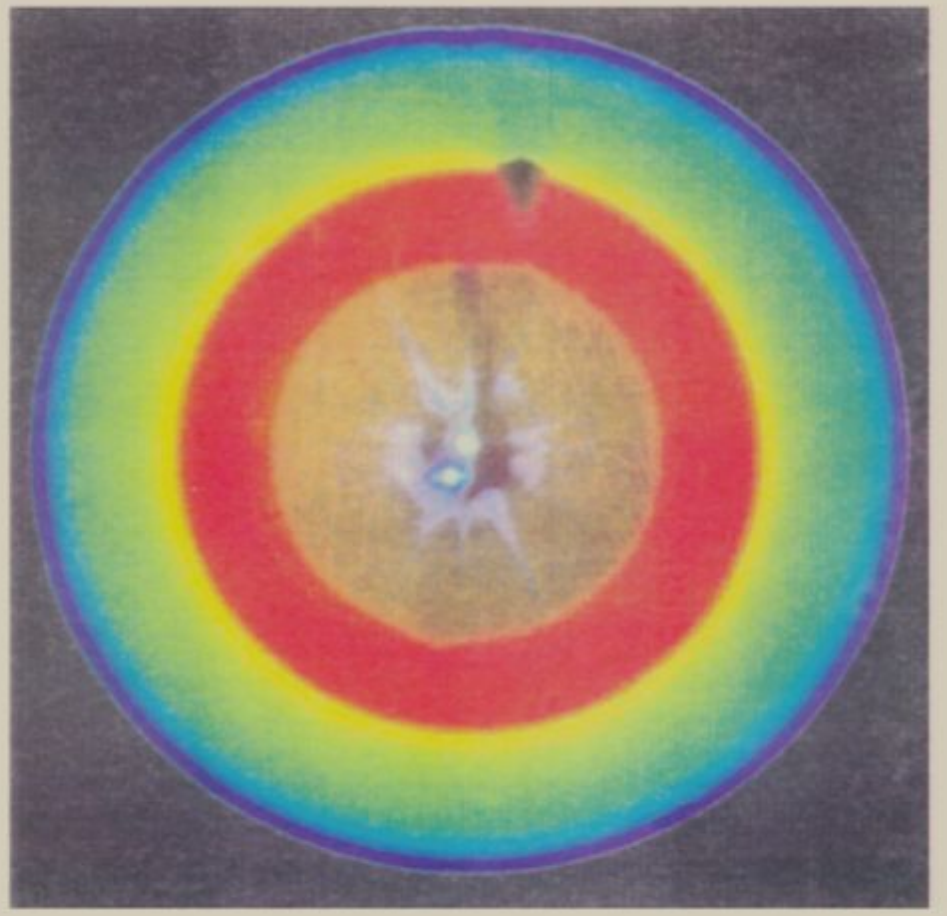
Spontaneous Parametric Down Conversion

A nonlinear optical process in which a laser beam incident on a nonlinear material leads to the emission of a pair of photons: signal-idler.



$$H^I = \int d^3r\, \chi^{(2)} E_p^{(+)} E_s^{(-)} E_i^{(-)} + H.C.$$

Biphoton State: Spontaneous Parametric Down Conversion



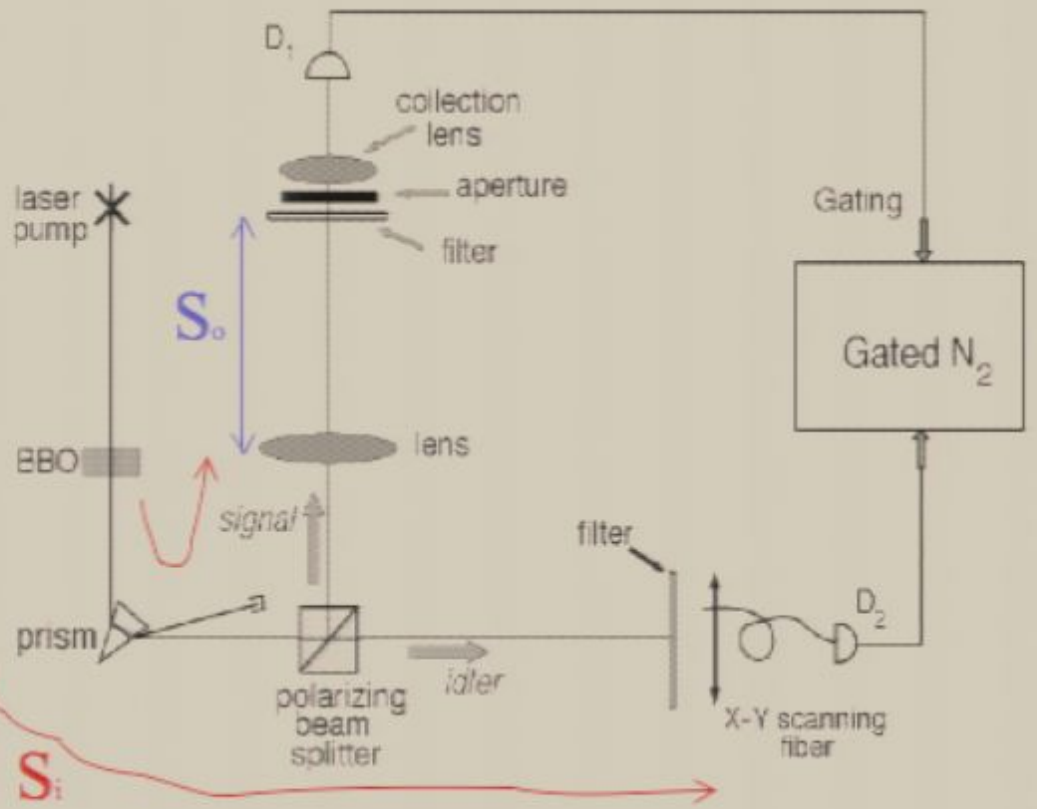
Two-photon Pure State

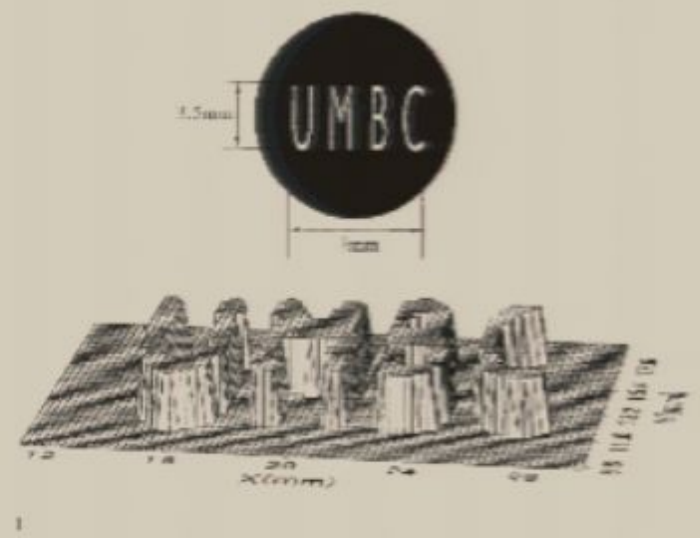
The signal (idler) photon can have any energy (momentum), however, if one of the photons is measured at certain energy (momentum) its twin must be at a certain energy (momentum).

$$|\Psi\rangle = \sum_{s,i} \delta(\omega_s + \omega_i - \omega_p)\,\delta(\mathbf{k}_s + \mathbf{k}_i - \mathbf{k}_p)\,\hat{a}_s^+ \hat{a}_i^+ |0\rangle$$

“Ghost” Imaging

-- Experimental demonstration of EPR δ-functions in transverse momentum and position



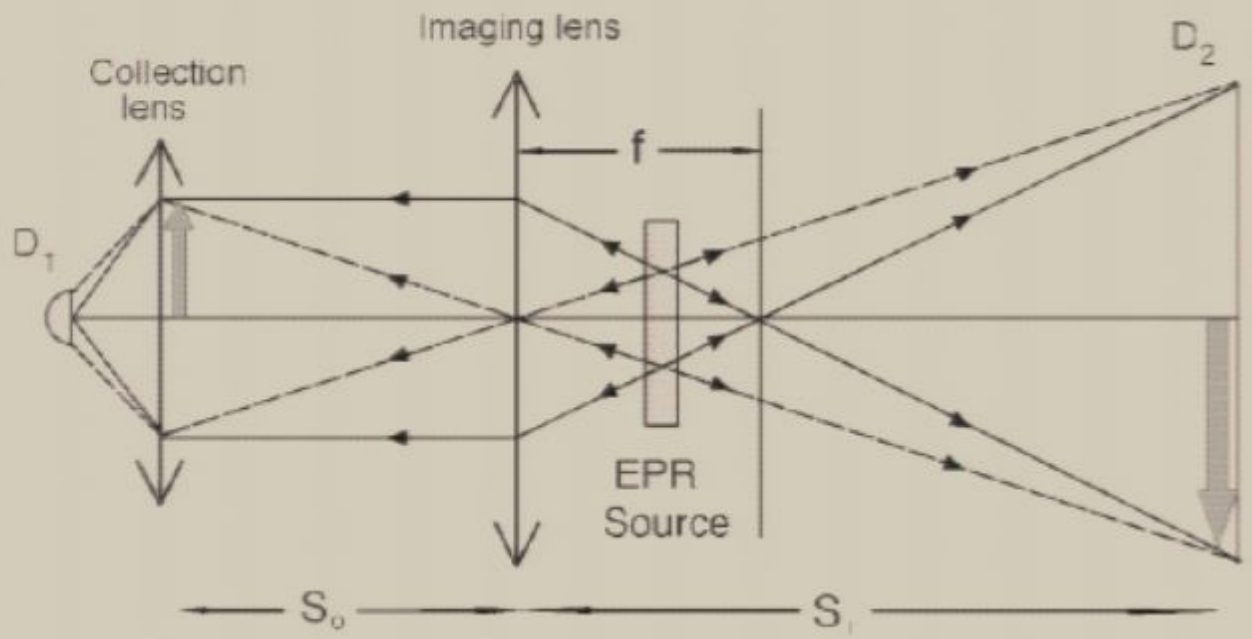


$$\frac{1}{S_0} + \frac{1}{S_i} = \frac{1}{f}$$

"Ghost" Image and "Ghost" Interference
EPR Experiment in momentum-position

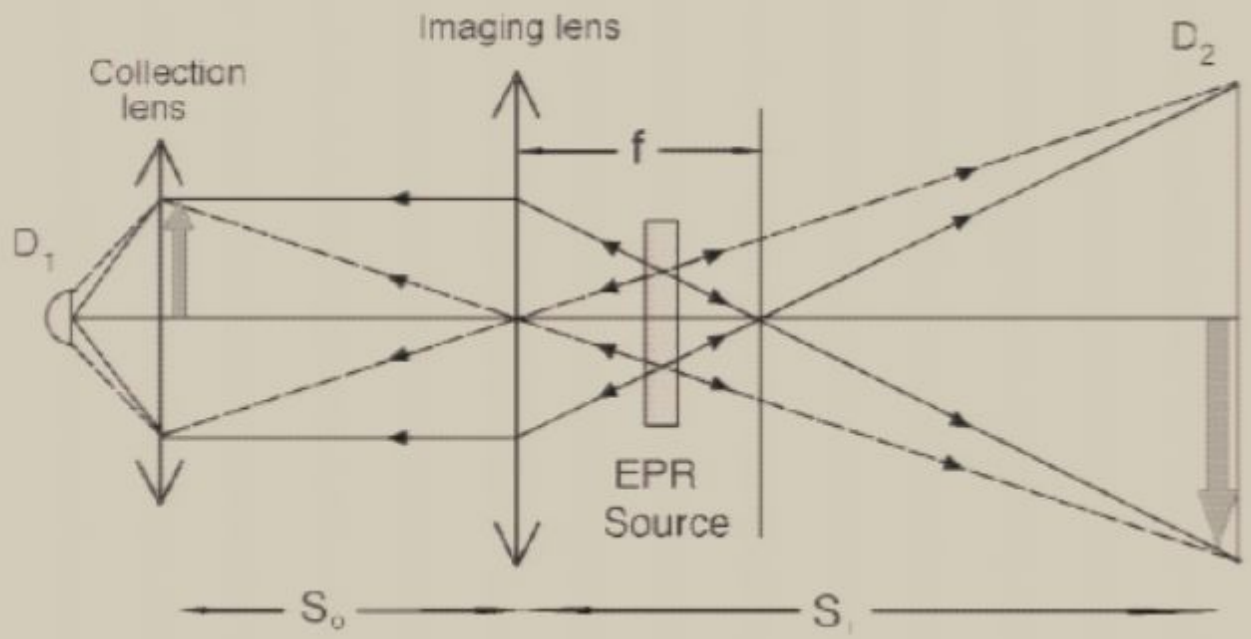
PRL, 74, 3600 (1995); PRA, 52, R3429 (1995).

"Ghost" Imaging



Photon #1 stop at a point on object plane $\Rightarrow$ Photon #2 stop at a point on image plane ??

"Ghost" Imaging



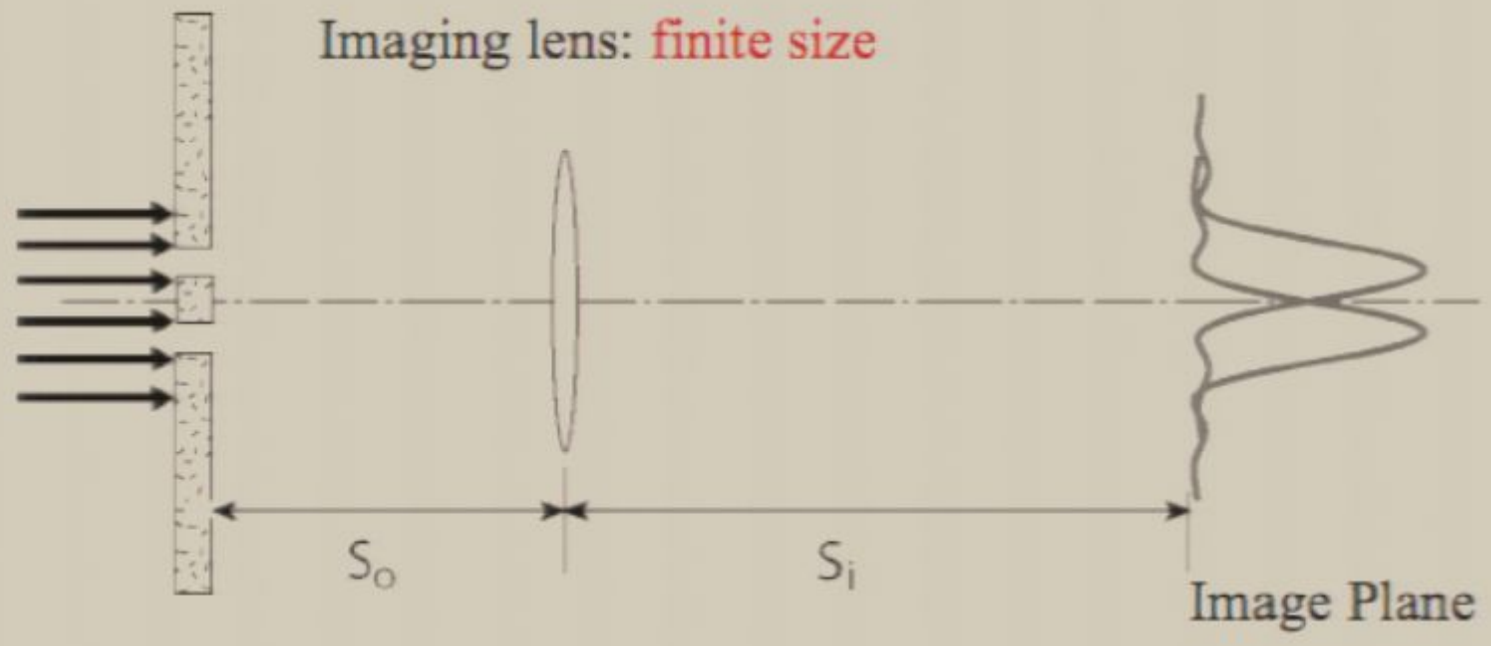
A typical EPR experiment:

$$\vec{k}_1 + \vec{k}_2 = 0 \qquad \Delta\vec{k}_1 = \infty \qquad \Delta\vec{k}_2 = \infty$$

$$\vec{x}_1 - \vec{x}_2 = 0 \qquad \Delta\vec{x}_1 = \infty \qquad \Delta\vec{x}_2 = \infty$$

Although questions regarding fundamental issues of quantum theory still exist, quantum entanglement has indeed led to novel technological concepts, some of which are already being used in practical applications.

Spatial Resolution



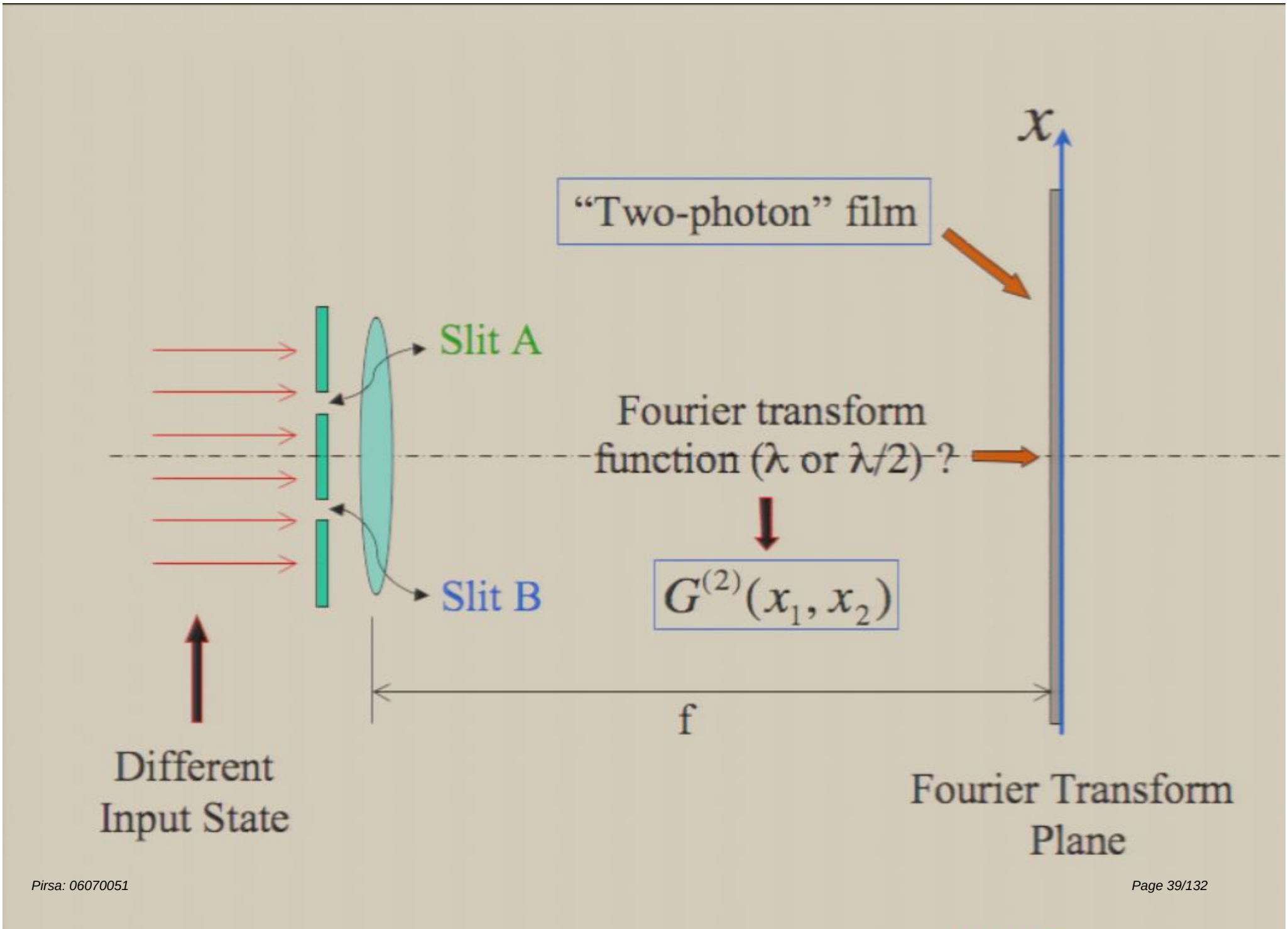
Point (object plane) $\Longrightarrow$ Spot (image plane)

δ–function $\Longrightarrow$ *somb*-function

$$\Delta(x_1 - x_2) \Rightarrow comb(\xi) = \frac{2J_1(\pi\xi)}{\pi\xi}$$

Quantum lithography

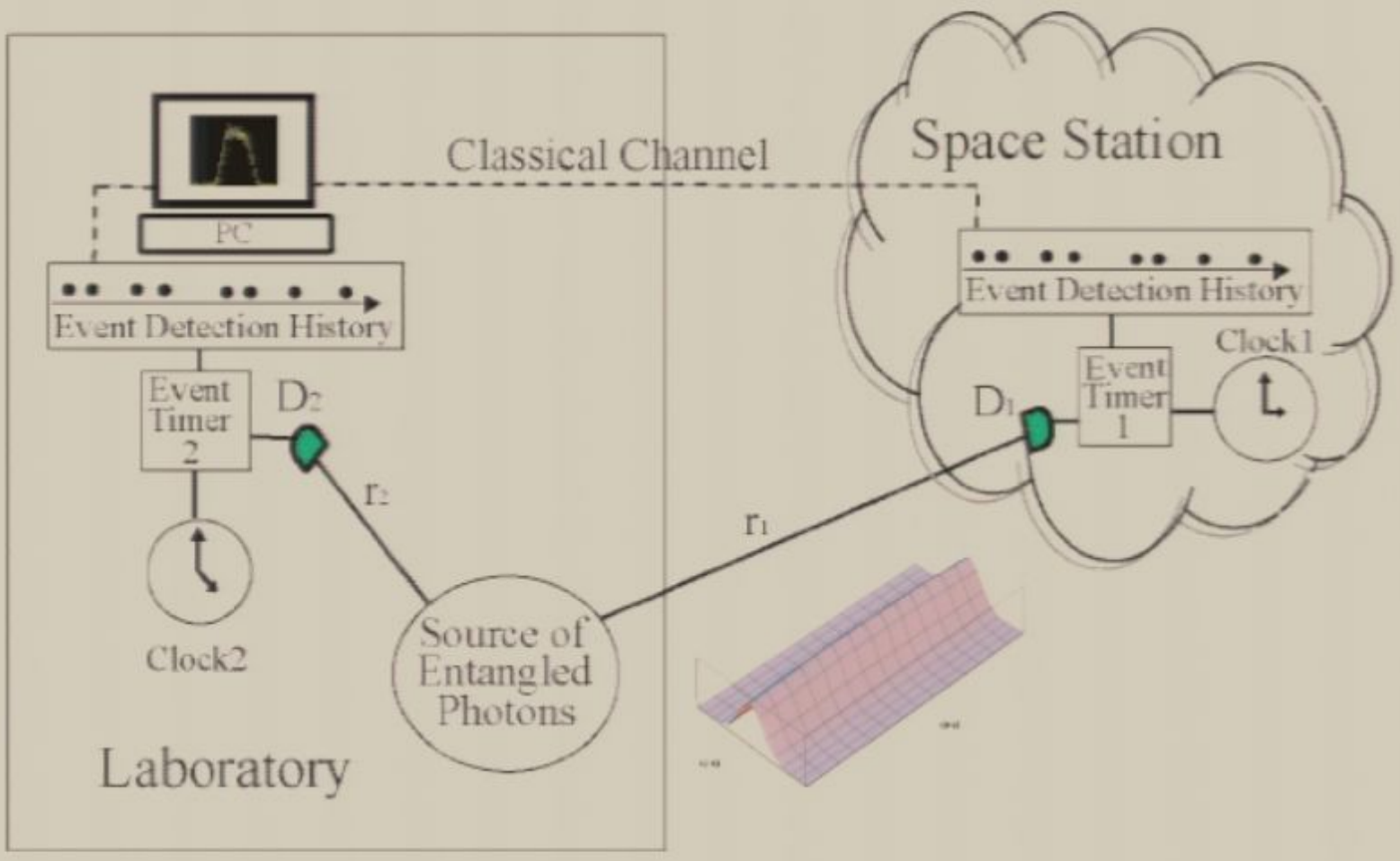
(Spatial-resolution: beyond classical limit)

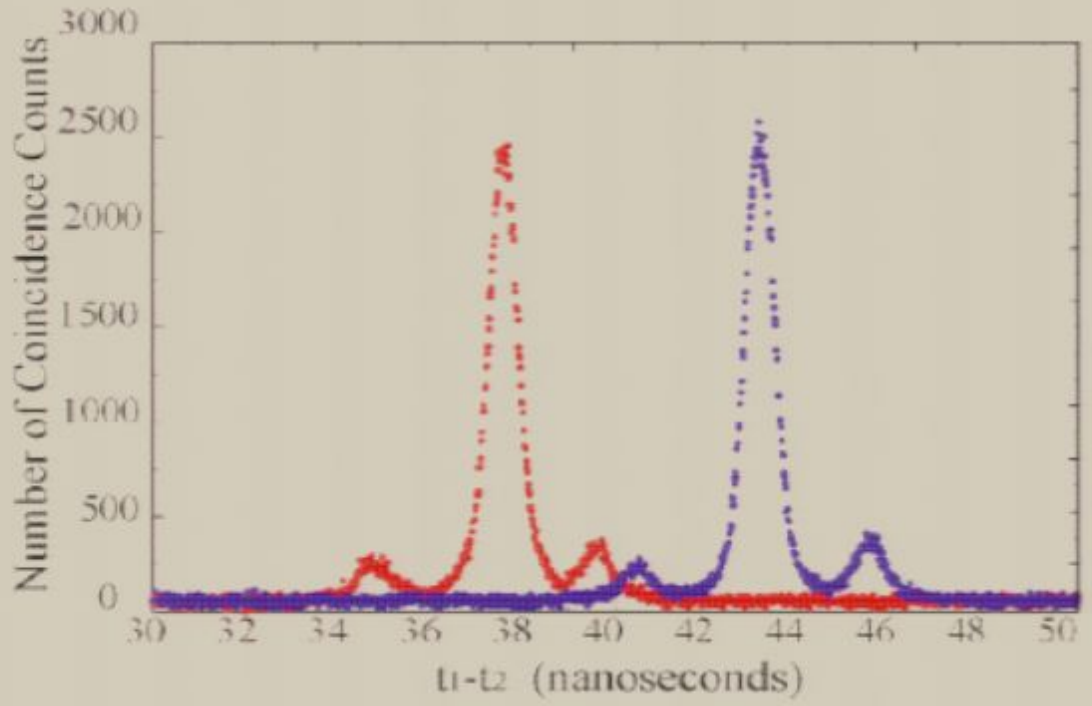

x
"Two-photon" film
Slit A
Fourier transform
function (λ or λ/2) ?
Slit B
$G^{(2)}(x_1, x_2)$
f
Different
Input State
Fourier Transform
Plane

Synchronization of distant clocks

-- an application of nonlocal timing and positioning

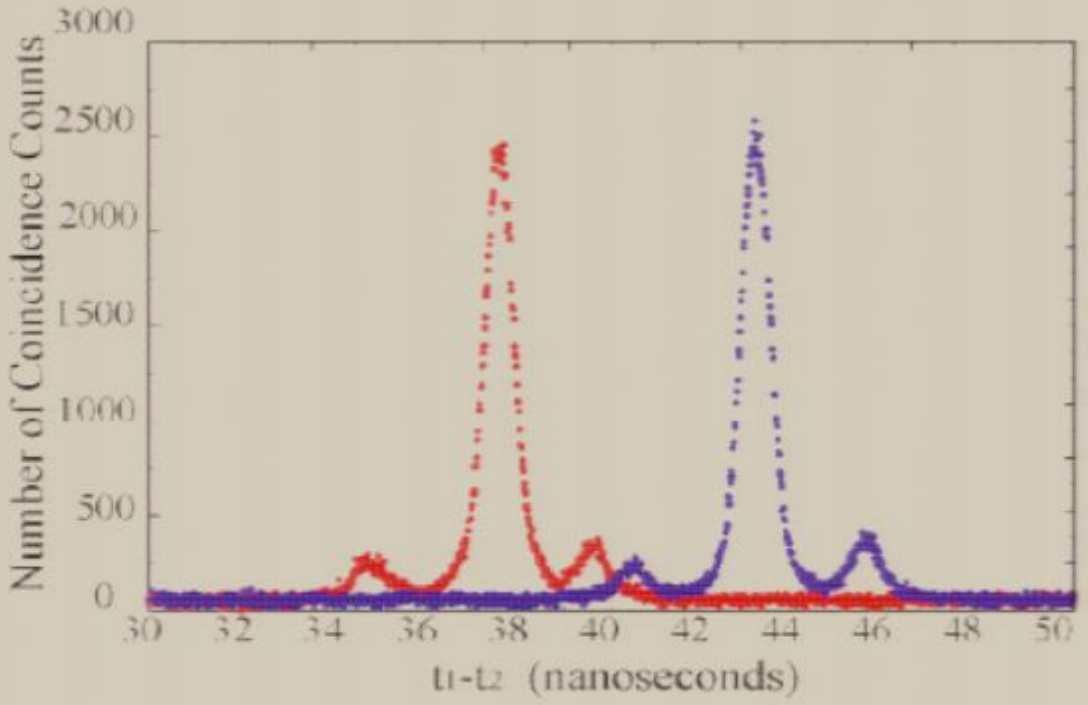
Synchronization of Distant Clocks





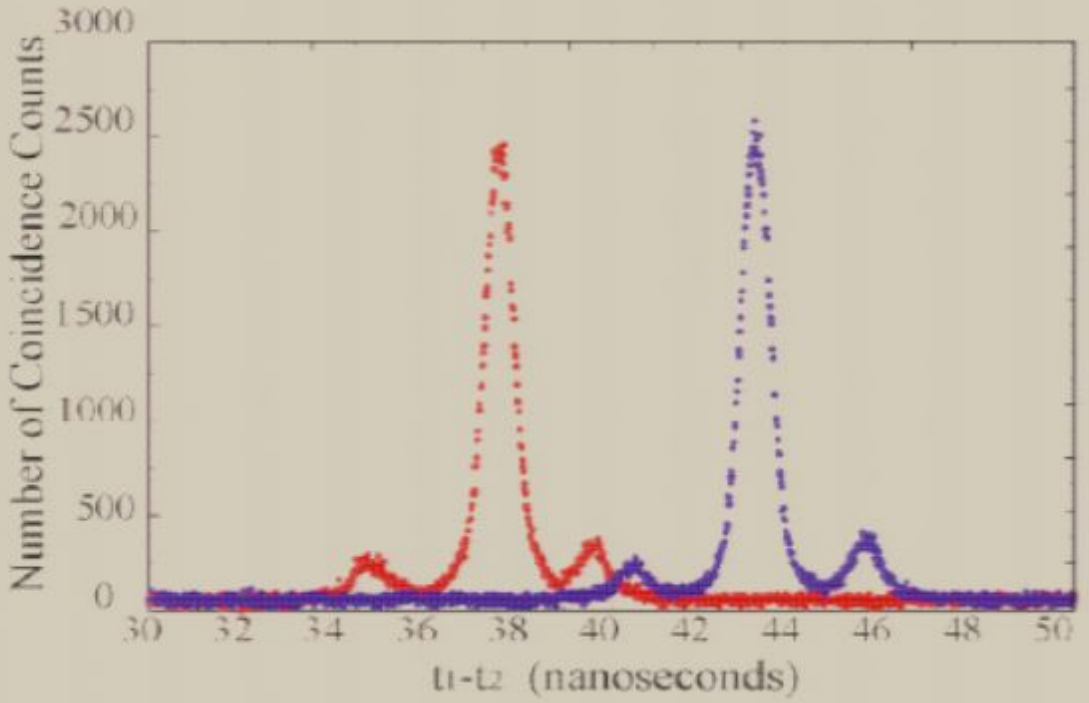
Experimentally measured time offset:

Applied Physics Letter, **85**, 2655 (2004).



Experimentally measured time offset: $t_0 = 40{,}369 \pm 1ps$

Applied Physics Letter, **85**, 2655 (2004).



Experimentally measured time offset: $t_0 = 40{,}369 \pm 1ps$

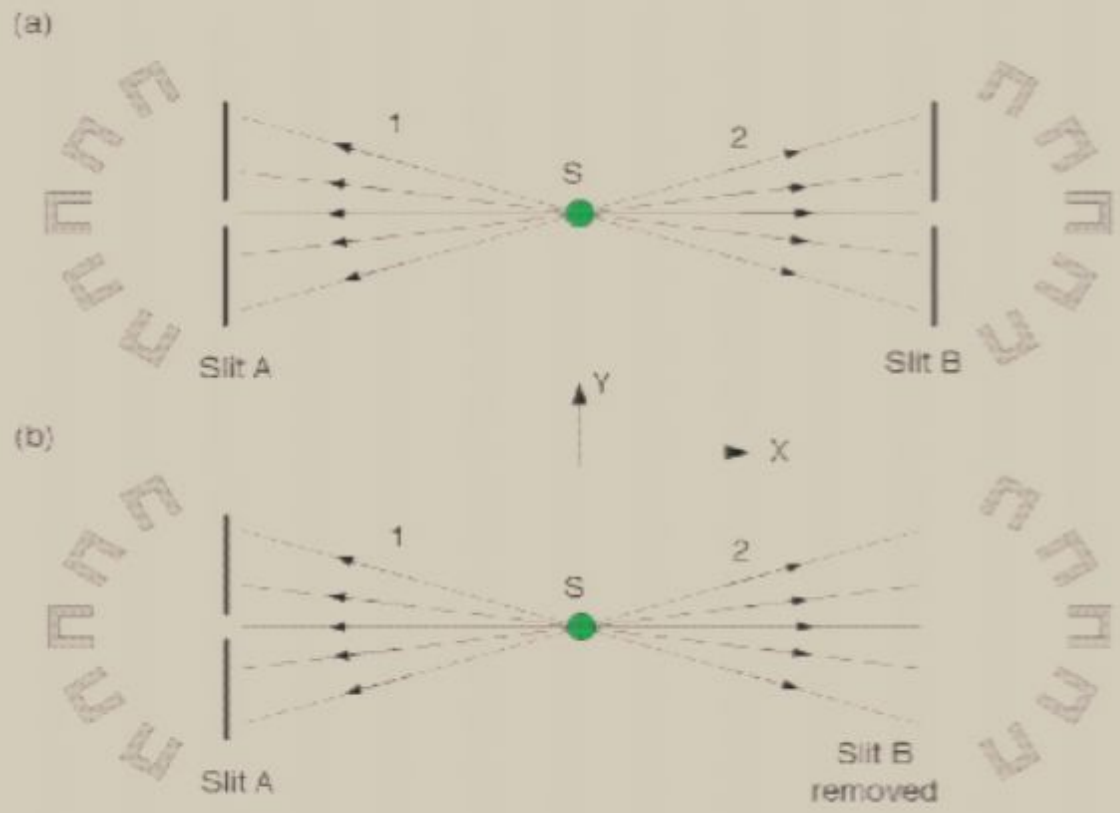
Optical distance 3,000 meters.

Applied Physics Letter, **85**, 2655 (2004).

Popper's Experiment

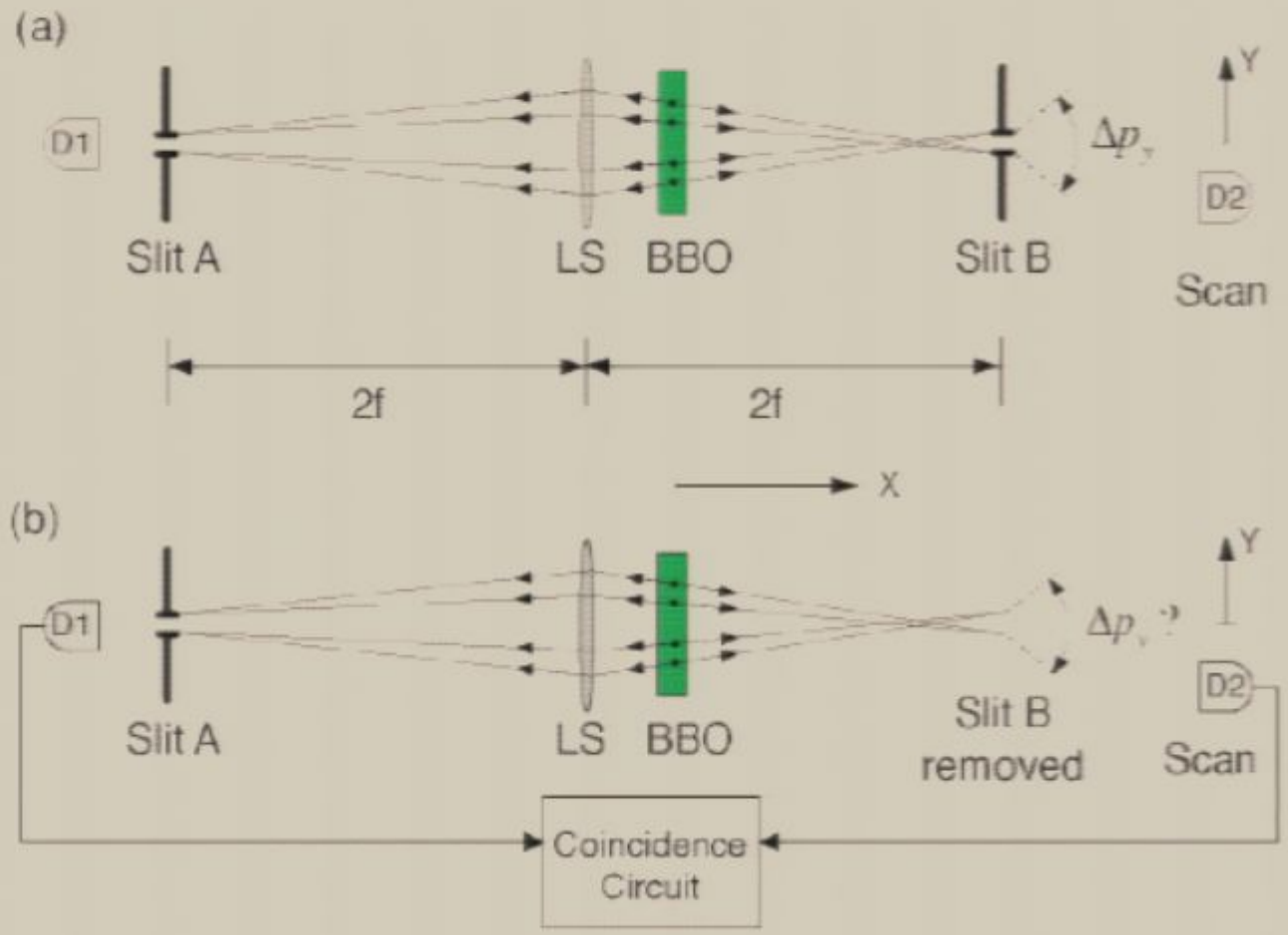
Karl Popper, being a metaphysical realist" took a realistic view point of quantum formalism: a particle must have precise position and momentum, independent of any observation. In this regard, he invented a thought experiment in 1934 aimed to support his realistic interpretation of quantum mechanics.

A modified Popper's experiment, after he learned EPR's *gedankenexperiment* of 1935.

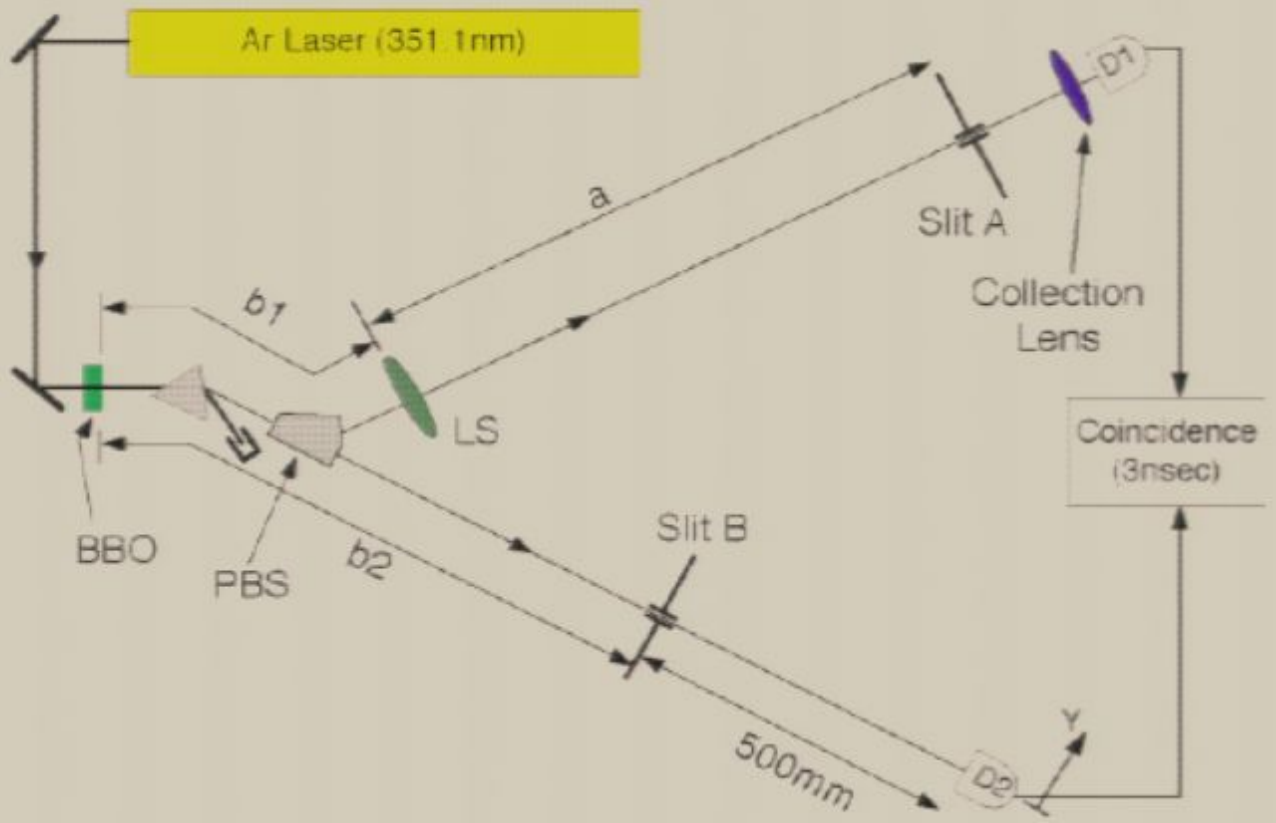


An entangled pair of particles are emitted from a point source with momentum conservation. A narrow slit on screen A is placed in the path of particle 1 to provide the precise knowledge of its position on the y-axis and this also determines the precise y-position of its twin, particle 2, on screen B. (a) Slits A and B are both adjusted very narrowly. (b) Slit A is kept very narrow and slit B is left wide open. In the absence of an actual slit, does particle 2 experience a greater uncertainty due to the precise knowledge of its position?

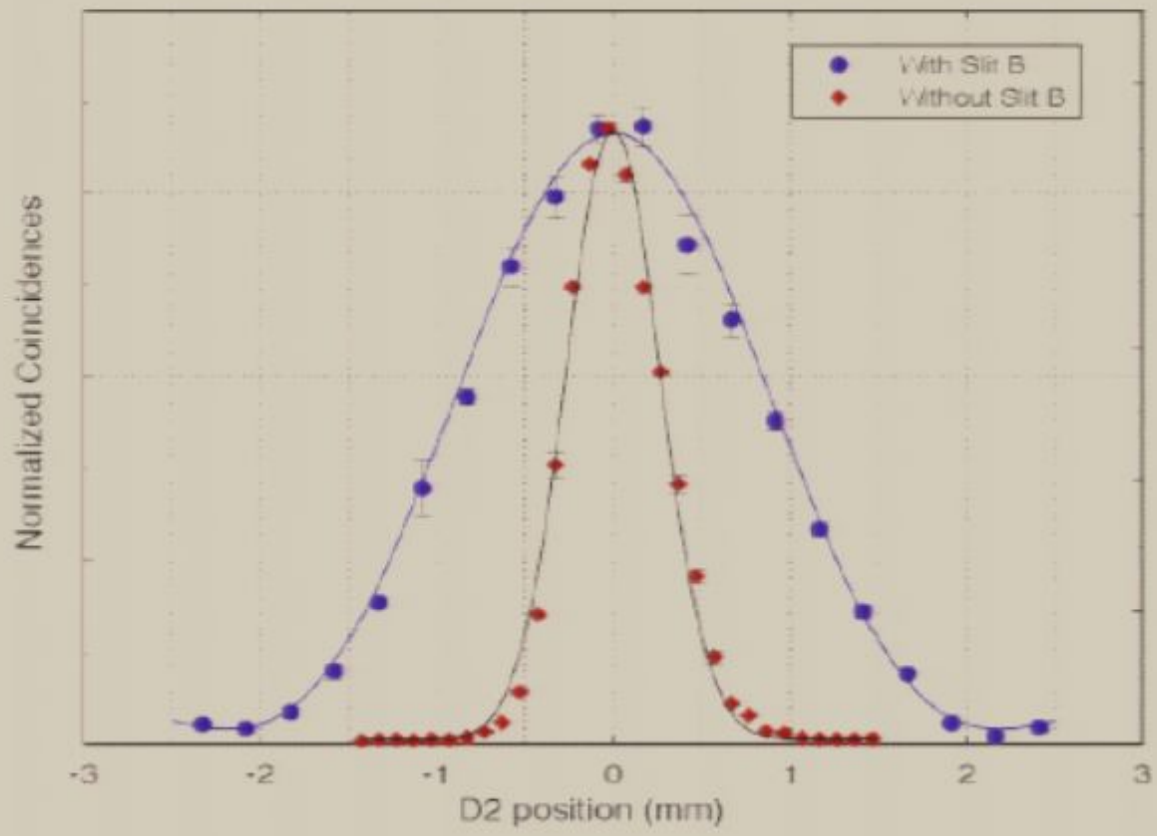
Modified Popper's experiment: Y.H. Kim et al, 1998.



An entangled photon pair is generated by SPDC. A lens and a narrow slit A are placed in the path of photon 1 to provide the precise knowledge of its position on the y-axis and also to determine the precise y-position of its twin, photon 2, on screen B by means of two-photon "ghost" imaging. Photon counting detectors D_1 and D_2 are used to scan in y-axes for joint detections. (a) Slits A and B are both adjusted very narrowly. (b) Slit A is kept very narrow and slit B is left wide open.



Schematic experimental setup: A pair of signal-idler photon is generated in the BBO crystal by nonlinear SPDC. A "ghost" image of slit A is formed on screen B, where slit B is located. In the setup, we chose $s_o = s_i = 2f$, thus produce an equal size image of slit A.



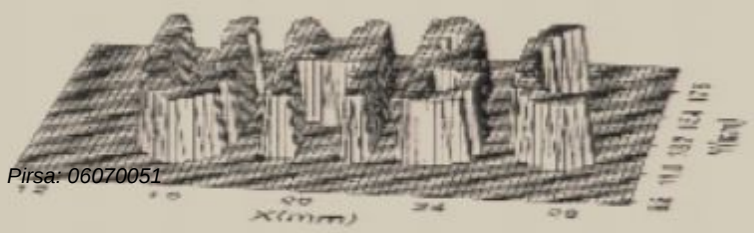
The observed coincidence patterns. The y-coordinate of D_1 was chosen to be 0 (center) while D_1 was scanning along its y-axis. Circled dot points: Slit A = Slit B = 0.16mm. Diamond dot points: Slit A = 0.16mm, Slit B wide open. The width of the sinc function curve fitted by the circled dot points is a measure of the minimum Δp_y determined by a 0.16mm slit.

Conclusions

* $2 \neq 1 + 1$

** The mysteries: two-particle superposition.

www.physics.umbc.edu/research/quantum



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