MURI: Quantum imaging- kickoff meeting

University of Rochester June 9, 2005

Spontaneous Parametric Down Conversion

and

The Biphoton

Quantum Optics Group
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History 1960's

Laser made possible the study of non-linear optics

Improved materials

Importance of phase matching

First observation of SPDC

Summarized in

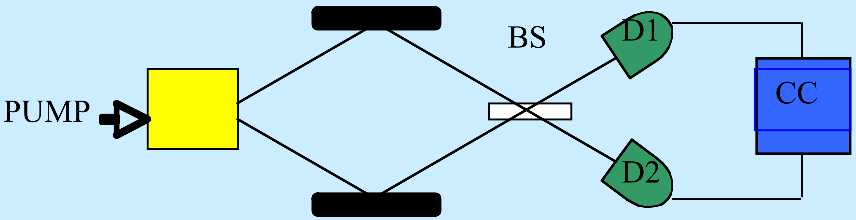
D. N. Klyshko, *Photons and Nonlinear Optics*

(Russian edition 1980, Revised and Enlarged English edition 1988)

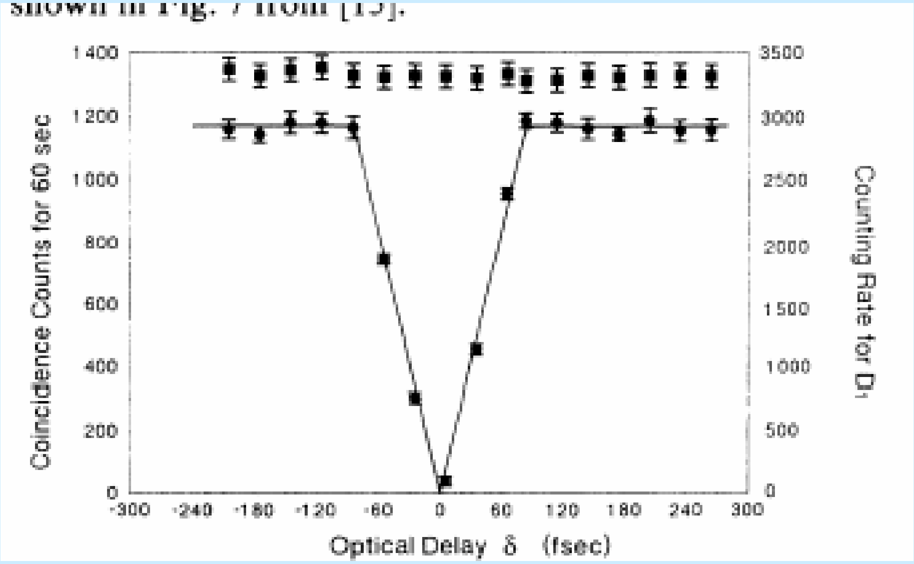
1986-89: Two photon interference and entanglement

HOM and SA interferometer and Franson interferometer

Study of temporal properties of biphoton.

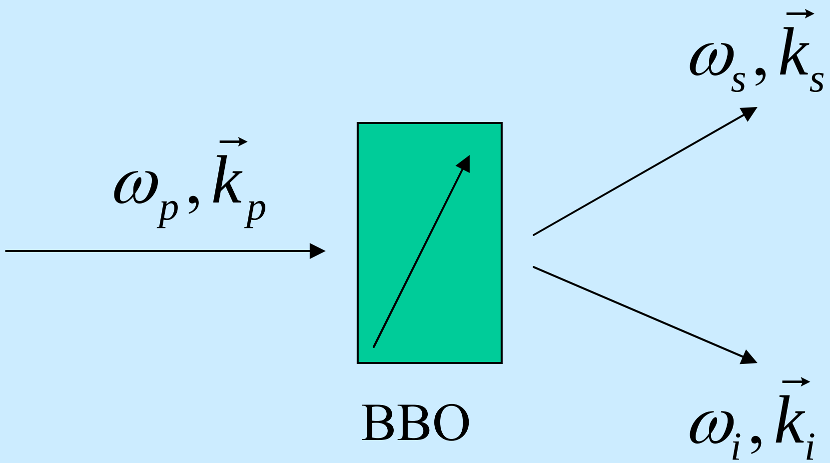


HOM Interferometer



Review: Yanhua Shih, IEEE J. Sel. Topics in Quant. Elect. Vol 9, no. 6, (2003).

Spontaneous Parametric Down Conversion



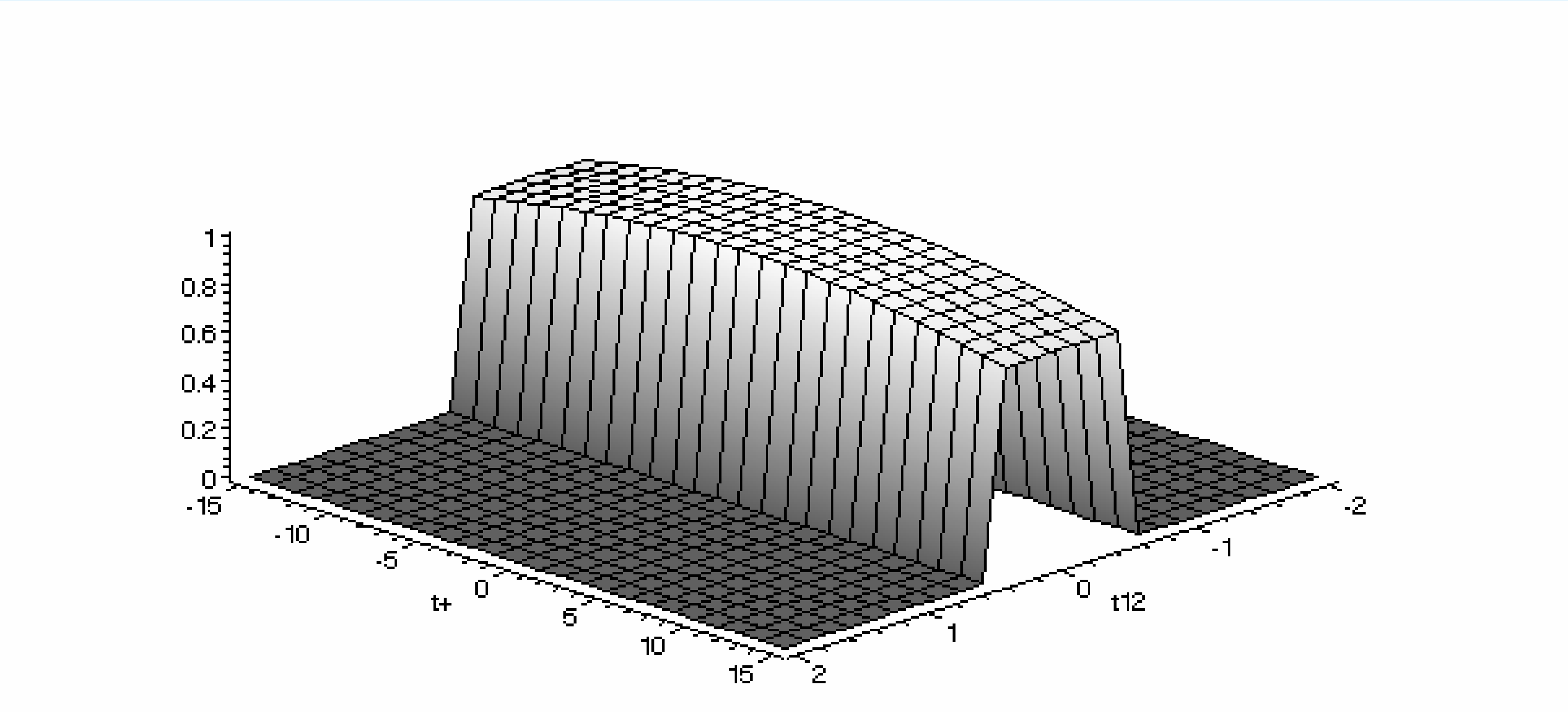
Phase matching condition

$$\omega_p = \omega_s + \omega_i$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

Entangled in **energy** and **momentum**.

Biphoton

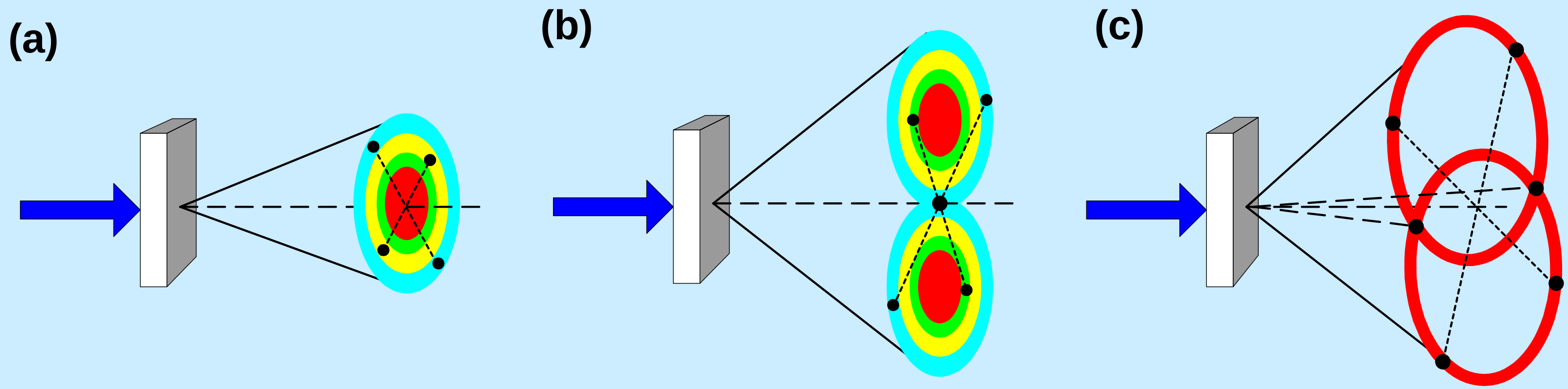


polarization entangled states

Type-I SPDC

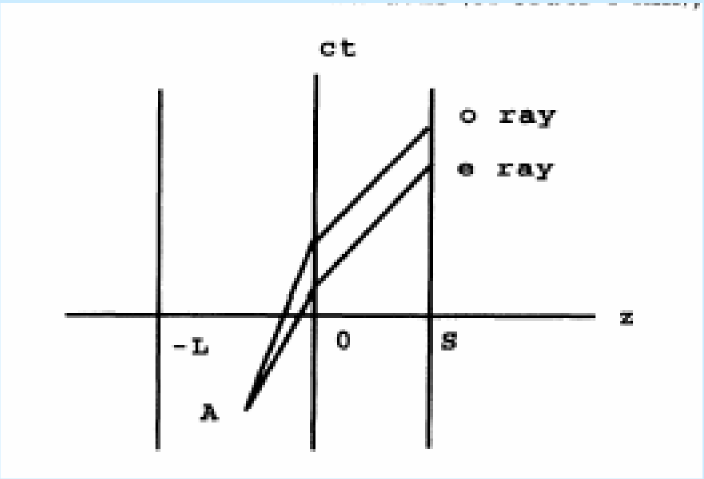
Collinear type-II SPDC

Non-collinear type-II SPDC



In type-II the biphoton is not entangled in

polarization.

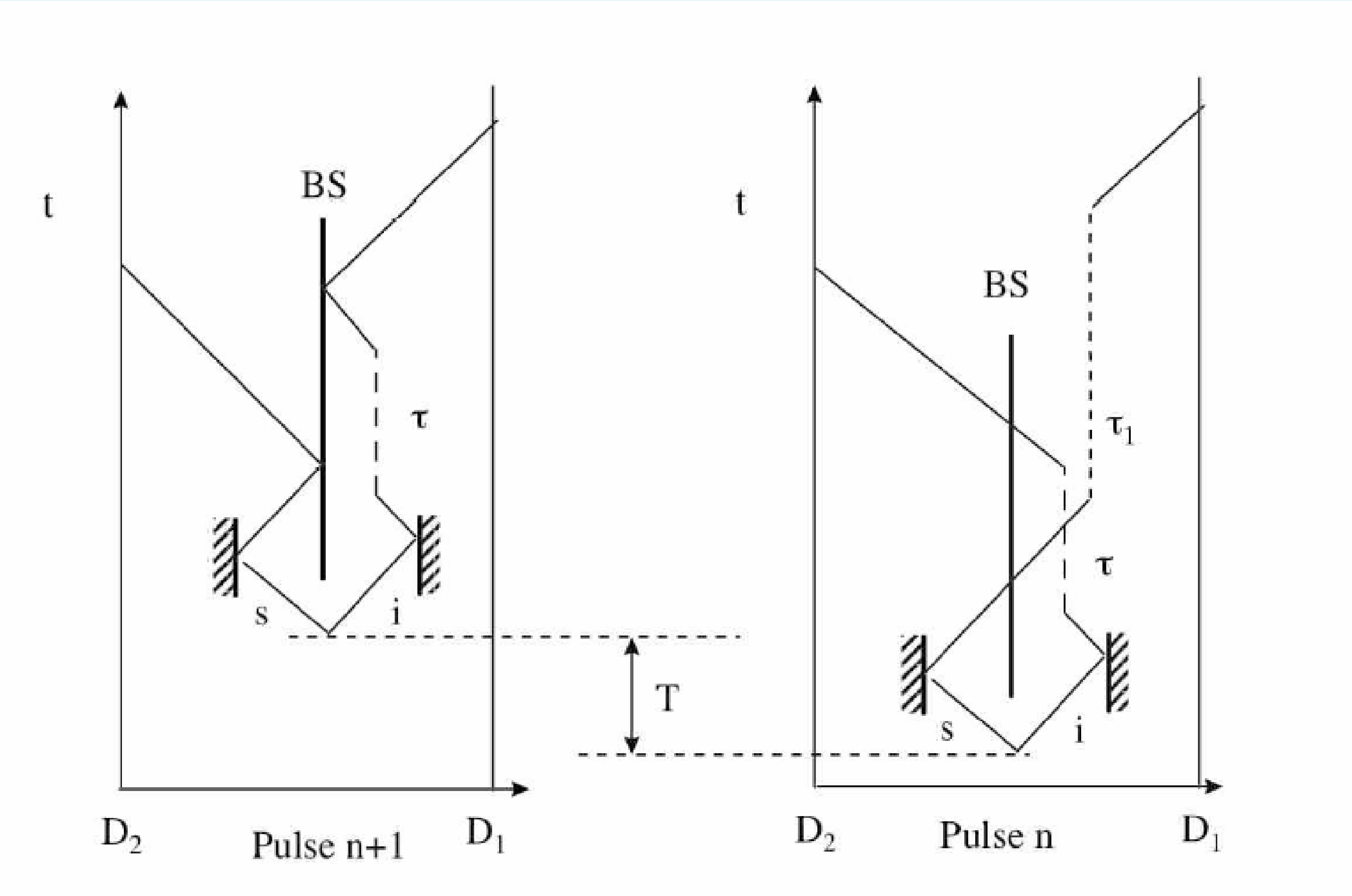


Use of a compensator to entangle polarization led to “double entanglement” :

Shih and Sergienko, Phys. Lett. A 186 (1994) 29.

Example of quantum erasure.

Interference from different pump pulses



Keller, Rubin, Shih, Phys. Lett. A 244 (1998) 507.

Temporal correlation:

Bell inequality violation

EPR state

Interference from separate pump pulses

Induced coherence

Dispersion cancellation and dispersion in fibers

Quantum Metrology

Quantum cryptography

Teleportation of a quantum state

1994-96: Transverse Correlations

:

Grayson and Barbosa, Phys. Rev. A 49 (1994) 2948

Joobeur, Saleh, and Teich, Phys. Rev A 50 (1994) 3349

Pittman, Shih, Strekalov and Sergienko, Phys. Rev. A 52 (1995) 3429

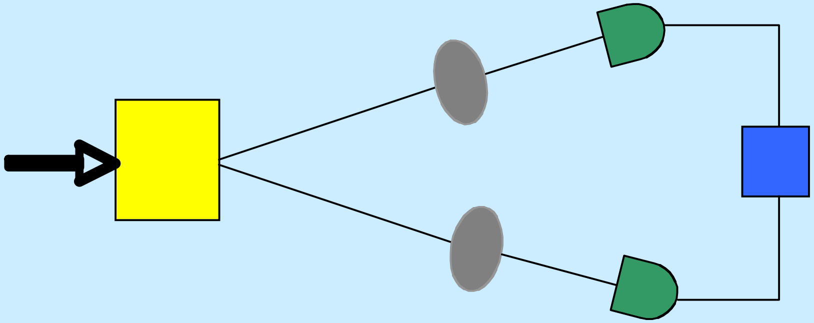
Quantum imaging experiment

Strekalov, Sergienko, Klyshko, and Shih, Phys. Rev. Lett 74 (1995) 3600

Ghost interference experiment

Pittman, Strekalov, Klyshko, Rubin, Sergienko, and Shih, Phys. Rev. A 53 (1996) 2804

Rubin, Phys. Rev. A 54 (1996) 5349.



$$|\Psi>=|0>+\sum_{\mathbf{k},\mathbf{k}'} F(\mathbf{k}\beta,\mathbf{k}'\beta')a^{\dagger}_{\mathbf{k}\beta}a^{\dagger}_{\mathbf{k}'\beta'}|0>$$

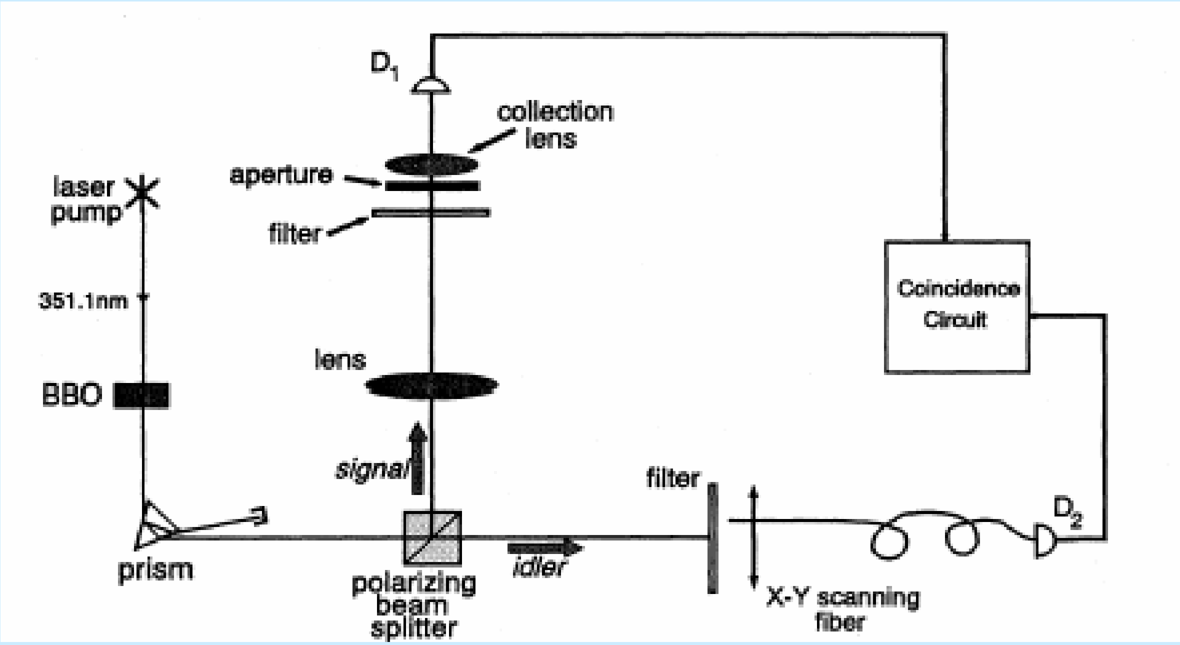
$$<\Psi|E_1^{(-)}E_2^{(-)}E_2^{(+)}E_1^{(+)}|\Psi>=|A_{12}|^2,$$

$$A_{12}=<0|E_2^{(+)}E_1^{(+)}|\Psi>$$

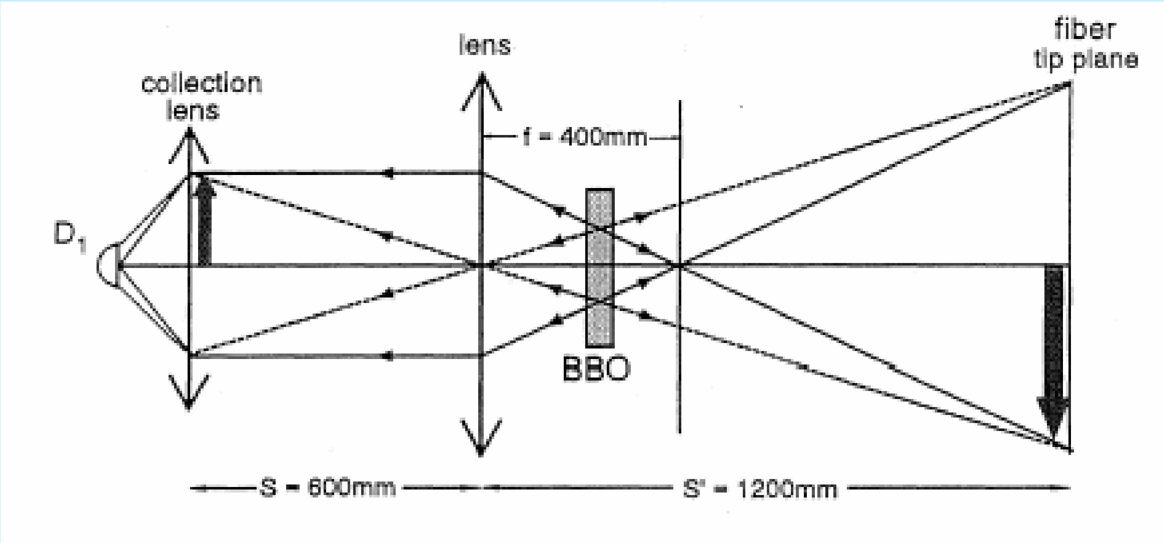
$$E_1=\sum_{\mathbf{k}\beta} G_{1,\mathbf{k}\beta}E_{\mathbf{k}\beta}$$

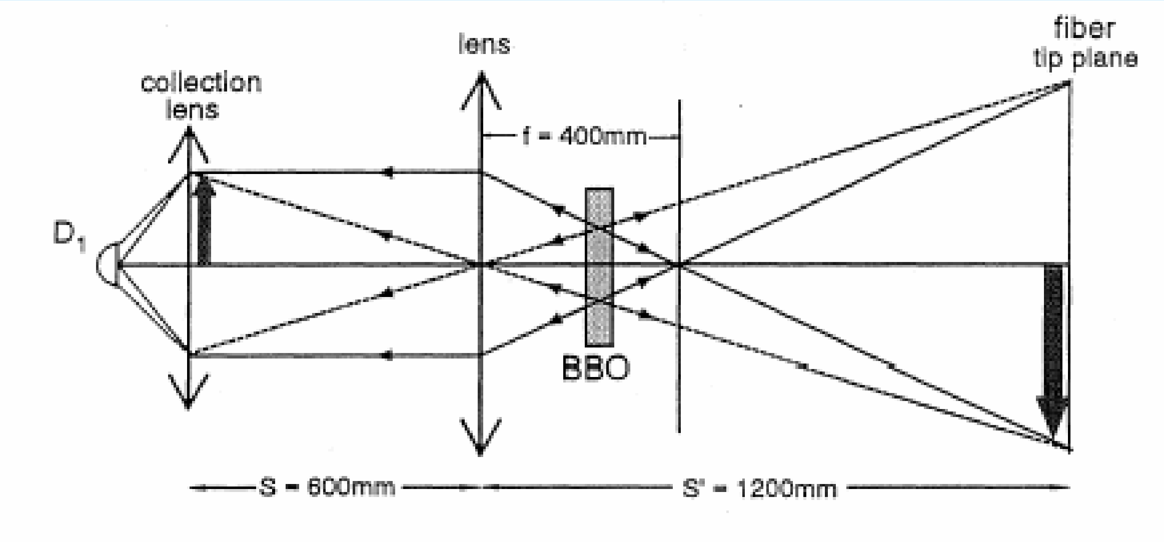
$$A_{12}=\sum_{\mathbf{k}\beta,\mathbf{k}'\beta'} G_{1,\mathbf{k}\beta}G_{2,\mathbf{k}'\beta'}A_{\mathbf{k}\beta,\mathbf{k}'\beta'}$$

$$F=\sum_a c_a U_a^{(s)} V_a^{(i)}$$



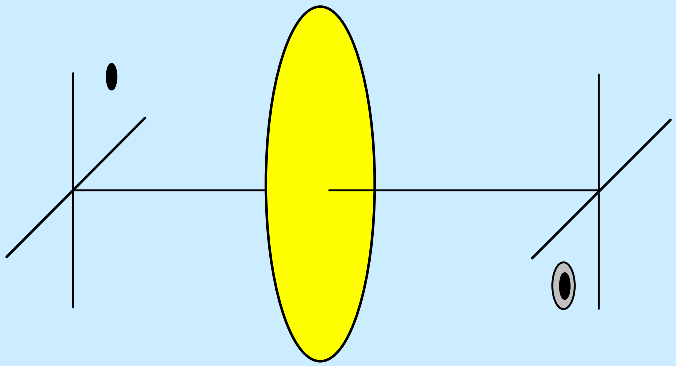
Klyshko picture



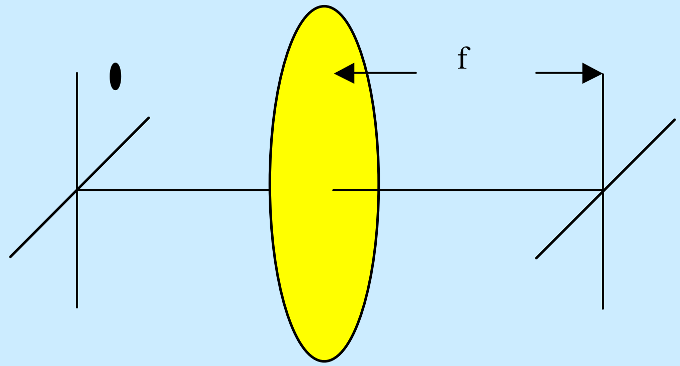


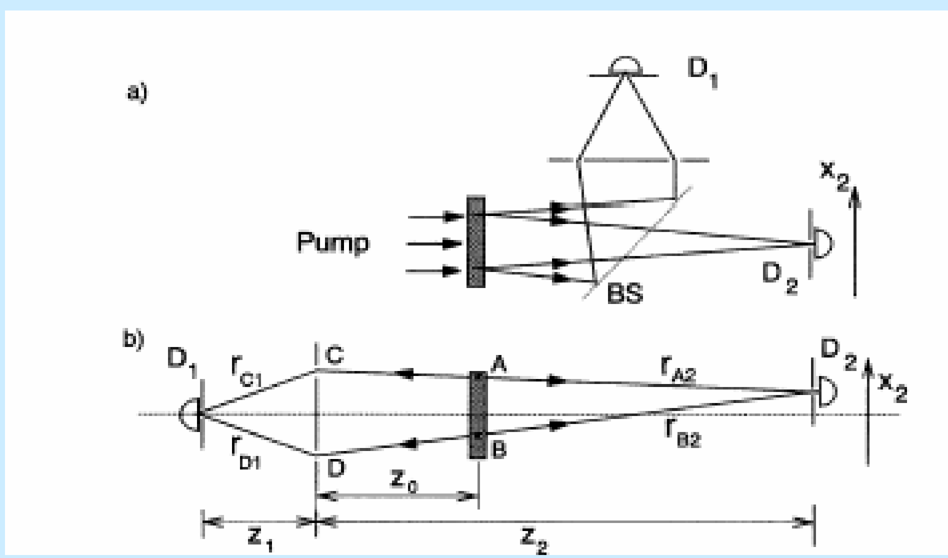
$$1/S + 1/S' = 1/f.$$

What do we mean by a real image?

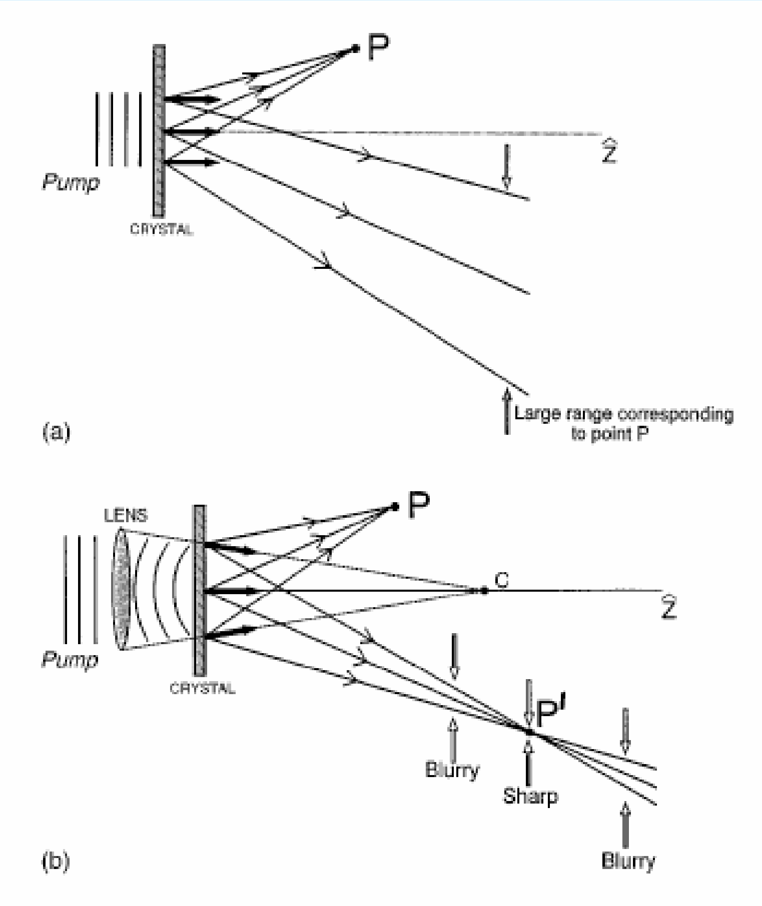


For a coherent image the focal plane gives the two-dimensional Fourier Transform of the object.





Effect of the transverse modes of the pump



$$\frac{1}{Z_1\left[\frac{\lambda_1}{2\lambda_p}\right]}+\frac{1}{Z_2\left[\frac{\lambda_2}{2\lambda_p}\right]}=\frac{2}{R},$$

Entanglement and classically correlation

Classically correlated state

$$\sigma_{AB} = \sum_u p_u \sigma_A^{(u)} \otimes \sigma_B^{(u)}$$

If a bipartite system AB is in an entangled state, it is always possible to reproduce the measurement of a operator $O_{AB}=O_A \otimes O_B$ by using a classically correlated state:

$$\Psi = \sum_{j,k} c_{jk} \phi_j \otimes \chi_k \qquad \text{where } O_A \phi_j = \lambda_j \phi_j$$

$$tr\left(O_{AB} |\Psi\rangle\langle\Psi|\right) = \sum_{jk} \lambda_j c_{jk} c_{jk'}^* \langle \chi_{k'} | O_B | \chi_k \rangle = tr\left(O_{AB}\sigma\right)$$

$$\sigma = \sum_j |\phi_j\rangle\langle\phi_j| \otimes |\omega_j\rangle\langle\omega_j| \qquad |\omega_j\rangle = \sum_k c_{jk} |\chi_k\rangle$$

Rubin, quant-ph/0303188

Uncertainty principle for imaging

There have been a number of discussions of the uncertainty principle for entangle states. I want to briefly outline a discussion for maximally entangled states two-photon states.

Let p_1 and p_2 be transverse momentum components and x_1 and x_2 be their respective Fourier position components, then $P_+=p_1+p_2$ and $X_-=x_1-x_2$ are independent variables, and consequently $\Delta P_+ \Delta X_-$ □0.

For a maximally entangled state each particle is described separately by a projection operator

$$\Psi = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \phi_j \otimes \chi_j$$

$$tr_2\left(\left|\Psi\right\rangle\left\langle\Psi\right|\right) = \frac{1}{N} \sum_{j=1}^{N} \left|\phi_j\right\rangle\left\langle\phi_j\right| = \mathrm{Pr}_1$$

If we consider a classically correlated state with independent particles then

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

$$\Delta(x_1 \pm x_2) = \sqrt{\Delta x_1^2 + \Delta x_2^2},$$

implies

$$\Delta(p_1 + p_2)\Delta(x_1 - x_2) \geqslant \hbar,$$

Milena D'Angelo,* Alejandra Valencia, Morton H. Rubin, and Yanhua Shih — PHYSICAL REVIEW A 71, 1 (2005)

Reid, quant-ph/0112038

SPDC has proved to be a source of entangled photons that can be exploited for a number of applications. Our current research has turned toward increasing the intensity of SPDC photons sources and examining the use of incoherent sources to repeat some of the imaging experiments by exploiting the Hanbury-Brown and Twiss effect.

CW-pumped SPDC:

Entangled photon pairs are created randomly within the coherence time (30 ns) of the pump laser beam.

Femtosecond-pulse pumped type-II SPDC

Time of creation of entangle photon pairs is known within 100 femtoseconds.

The pump intensity can be chosen so that there is one pair at a time of entangled photons in the system.

For the CW case, if the crystal is placed in a cavity, the number of pairs can be increased substantially.

Entanglement

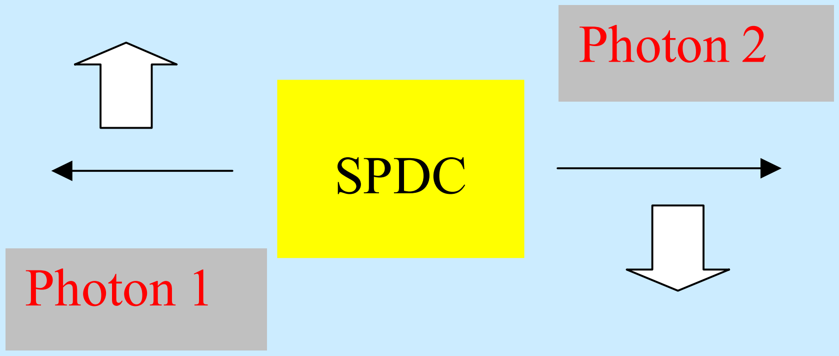
Quantum Entanglement leads to correlations which are stronger than local classical correlations.

Classical: $$|\langle a(b+b') + a'(b-b')\rangle| \leq c$$

Quantum: $$|\langle a(b+b') + a'(b-b')\rangle| \leq q$$

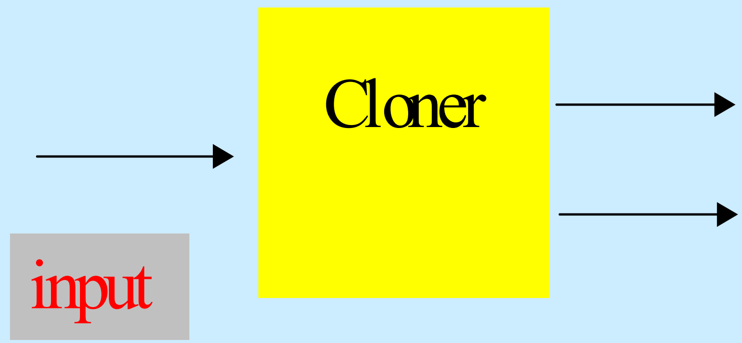
$$c \leq q$$

Entanglement is non-local



Perfect anti-correlation for all measurement axes.

No Cloning of Arbitrary Quantum States



Classical cloner

Arbitrary input cloned perfectly.

Quantum cloner

Only orthogonal states cloned perfectly.

Quantum Cryptography

No cloning theorem implies that it is impossible to measure the quantum state of a given system.

Must repeat measurement on identically prepared systems.

Consequently it is possible to use entangled states to produce random cryptographic keys non-locally.

Conclusions

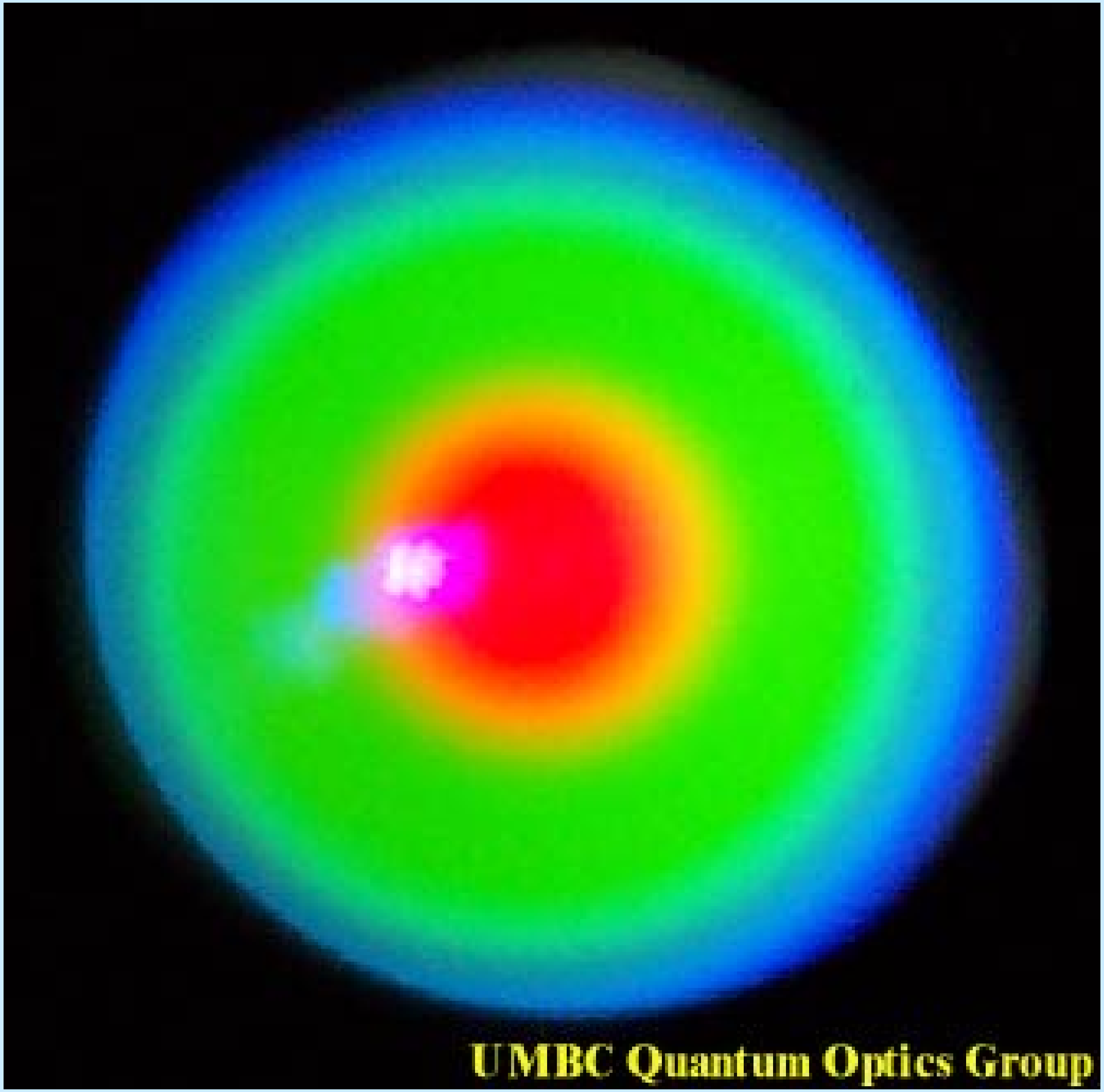
Entanglement is a new resource for communication, computing, and interferometric applications.

Entangled states are fragile.

At present only a few particles (3-6) have been entangled in a way that allows them to be controlled and addressed.

Quantum cryptography using photons is already at a stage where it can be used.

A general quantum computer is many years away, but a dedicated application quantum computer may be only 5-10 years away.


UMBC Quantum Optics Group

Research Areas

1. Quantum States of Light

a. Production and Properties of Two-Photon Entangled States

Applications: Quantum measurement, quantum cryptography, quantum communication, clock synchronization, metrology

b. Production of Multi-Photon Entangled States

Applications: Quantum image transfer and lithography, quantum computing

Multi-Photon entangled photons are necessary for quantum communication applications and will be required to transfer information in quantum computers