The Abdus Salam International Centre for Theoretical Physics

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Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

4 - 15 February 2013

Laser Sources for Quantum Optics (entangled photons sources)

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Laser Sources for Quantum Optics
(entangled photon sources)

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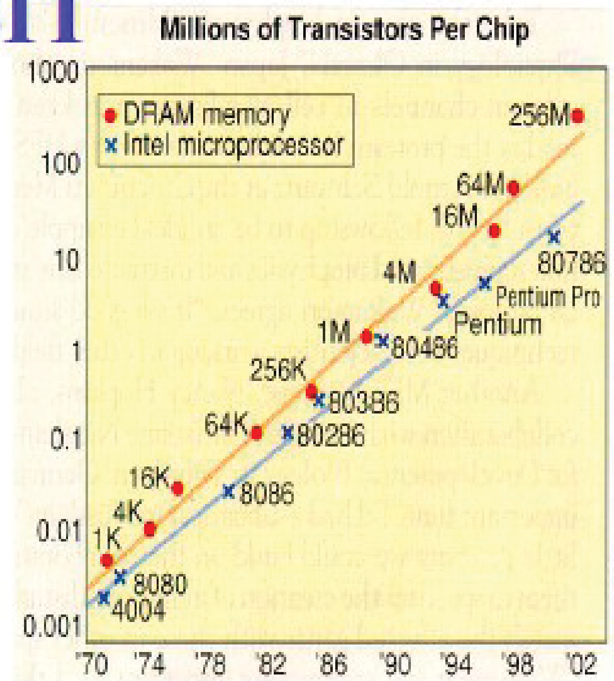
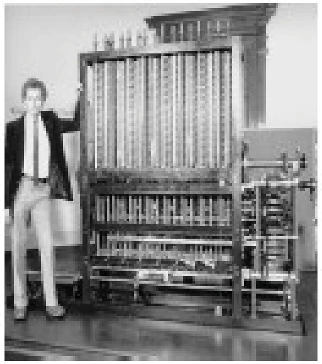
ICTP-Trieste
February 7, 2013

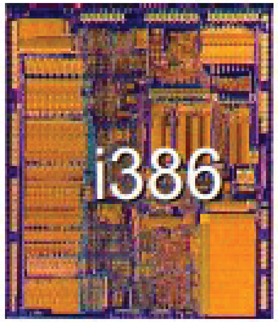
BIT



1879

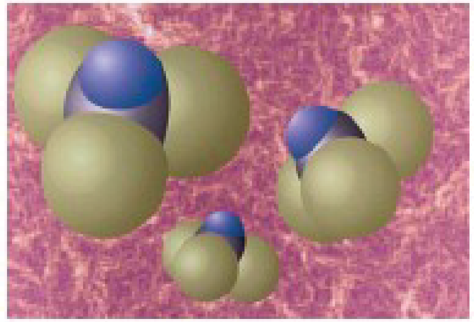


1986



1 micron

2020



1 nanometer

Qubit: variable defined into H_2 generated into the basis $\{|0\rangle, |1\rangle\}$

By 2015 a single electron could be confined in a transistor

Factorizing a 1024-digit number:

- Classical computer takes a period > universe lifetime
- Quantum computer <u>could</u> find the answer in 1s….
(P.V.Shor 1994)

news & views

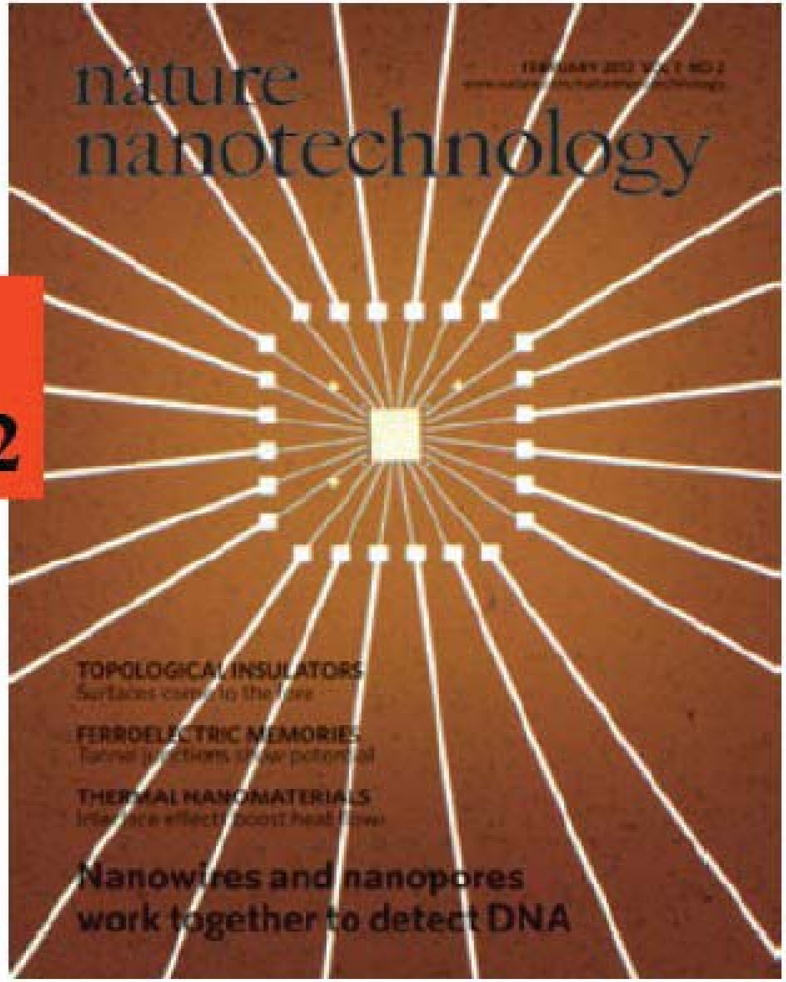
NANOELECTRONICS

Transistors arrive at the atomic limit

A single-atom transistor has been made by positioning a phosphorus atom between metallic electrodes, also made of phosphorus, on a silicon surface.

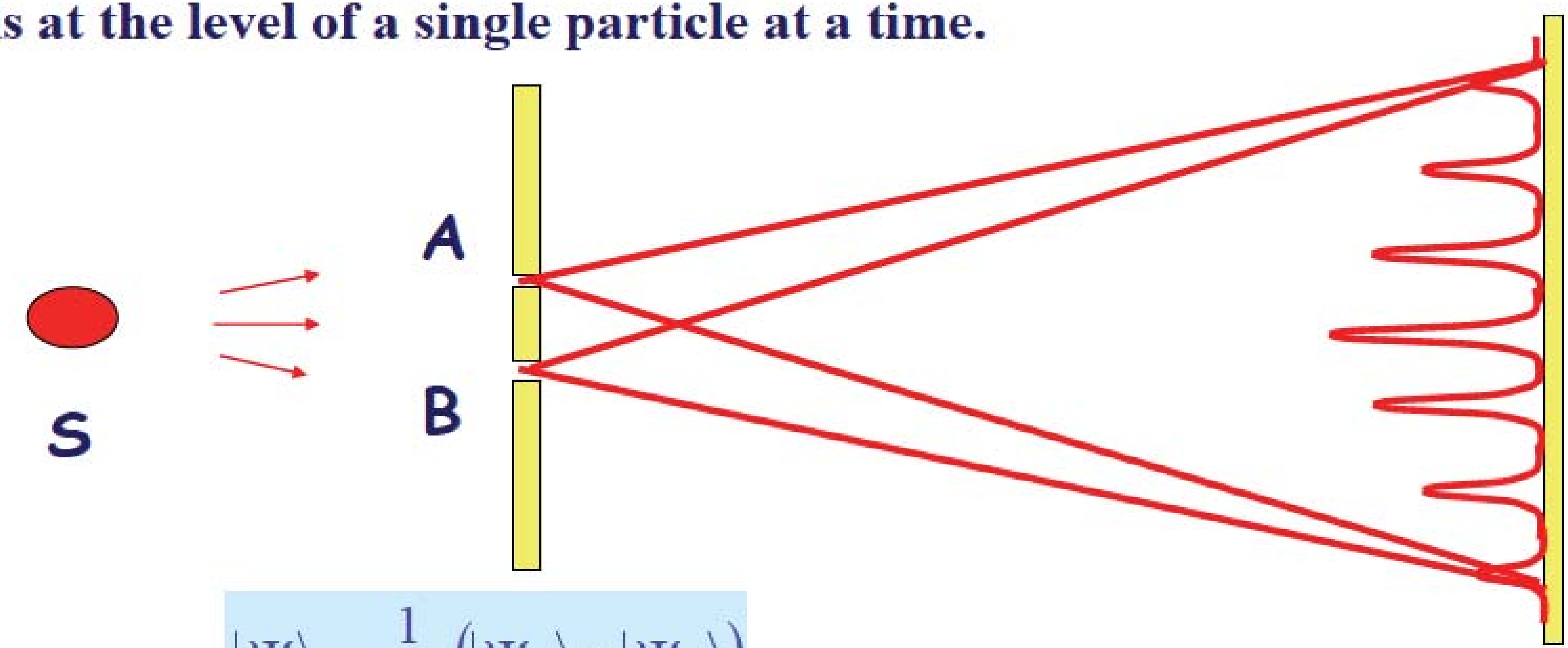
Gabriel P. Lansbergen

Breaking news!
February 19, 2012



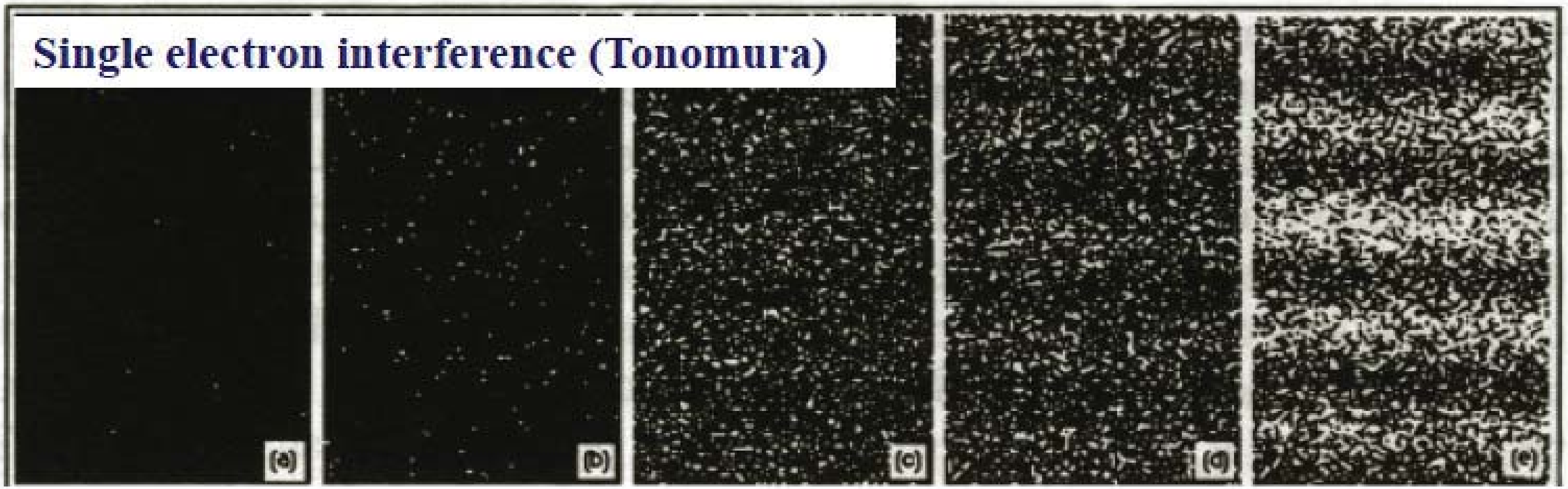
Basic Concepts

Quantum Superposition: In a double-slit experiment the interference pattern is observed even if the intensity of the source is at the level of a single particle at a time.



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\Psi_A\rangle + |\Psi_B\rangle\right)$$

Photon passes through both slits!



N = 10 N = 100 N = 3000 N = 20000 N = 70000

"We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by explaining how it works..."

R. Feynman

$$|\,\textit{photon in } A\rangle + |\,\textit{photon in } B\rangle$$

Superposition of two orthogonal states

From Bit to Qubit

Bit: two-state system, prepared in one of two distinguishable states representing the two logical values 0 or 1

Classical computer:

charged capacitor ≡ 1

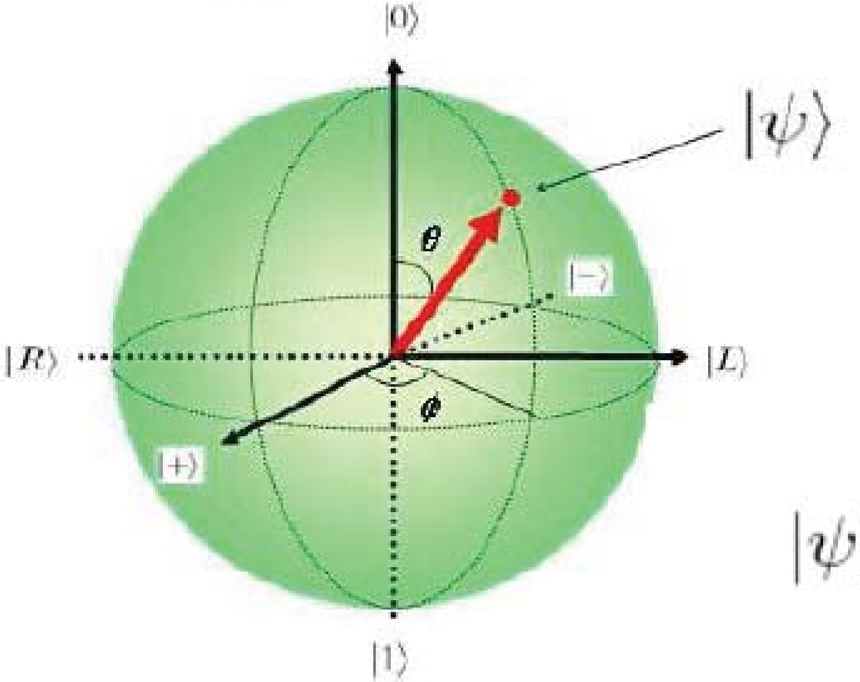
no charged capacitor ≡ 0

- A qubit (quantum-bit) is represented by any two-level quantum system
- The two basis states are labelled as $|0\rangle$ and $|1\rangle$
- A generic qubit is in a quantum state given by

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle\,, \qquad |\alpha|^2 + |\beta|^2 = 1$$

System	Qubit States	Decoherence Mechanism
Atoms/Lattices	Electron energy	Collisions/spontaneous emission
Ions	**Electron energy**	**Trap fields**
Doped solids	Impurity nuclei spin	Local fields
Quantum dots	Electron energy	Local fields
Quantum dots	Spin	Off-resonant Raman spin flip/ Spin-orbit coupling
Superconductors	**Trapped flux**	**Local flux or current fluctuations**
Superconductors	**Charge**	**Local charg or voltage fluctuations**
Atoms/CQED	**Electron energy/ Presence or absence of photons**	**Spontaneous emission/ Photon scattering**
Photons	**Polarization,linear momentum, time, OAM...**	**Coupling to other degrees of freedom or scattering to other modes**

Bloch sphere



$$|+(-)\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle \pm |1\rangle\big)$$

$$|L(R)\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle \pm i|1\rangle\big)$$

$$|\psi\rangle = e^{i\gamma}\Big(\cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle\Big),$$

Impossible to extract the complete information from a single qubit

Impossible to perform perfect copies of the same qubit (no-cloning theorem)

But we can make unperfect copies of the original qubit

Fidelity <1

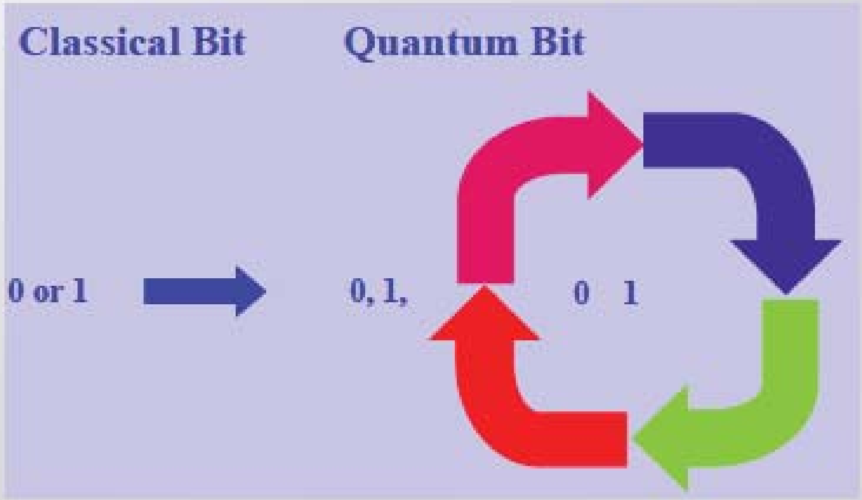
$$F = \langle\psi|\rho|\psi\rangle$$

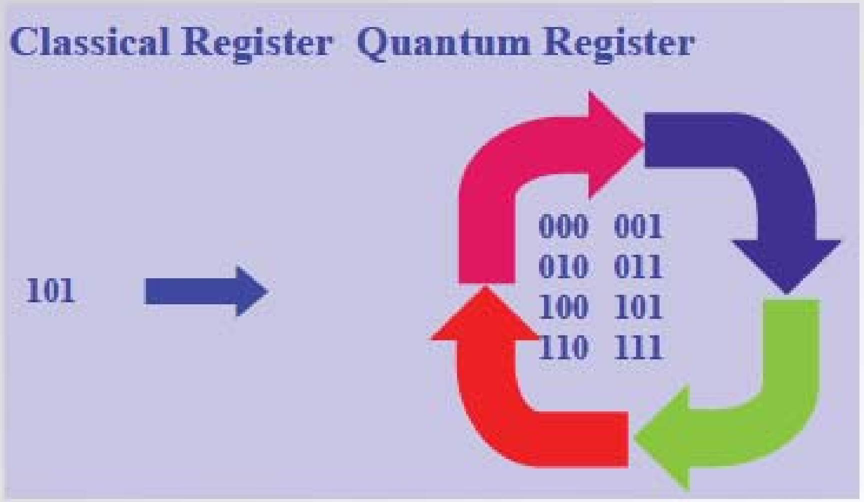
$$\rho(\theta,\phi) = |\psi\rangle\langle\psi| = \frac{1}{2}(\mathbb{1} + \vec{r}\cdot\vec{\sigma})$$

3-bit Register

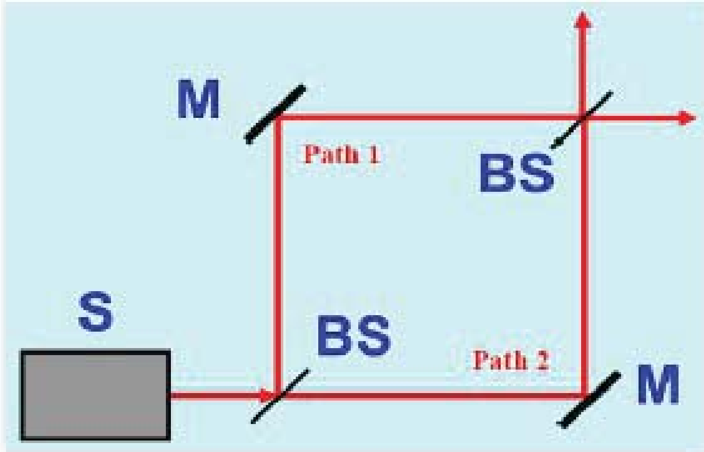
Classical: can store exactly one of the eight different numbers, 000, 001, 010, ….., 111

Quantum: can store up to eight numbers in a quantum superposition $\rightarrow$ N qubits: up to 2^N numbers at once





Makes possible the factorization of large digit numbers, otherwise impossible with a classical computer (Shor's quantum algorithm)

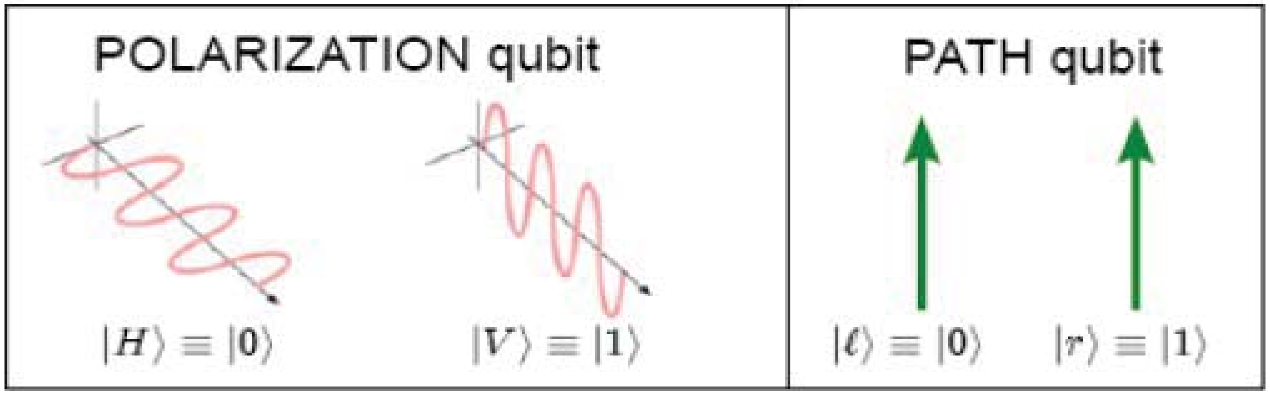


Qubit (examples):

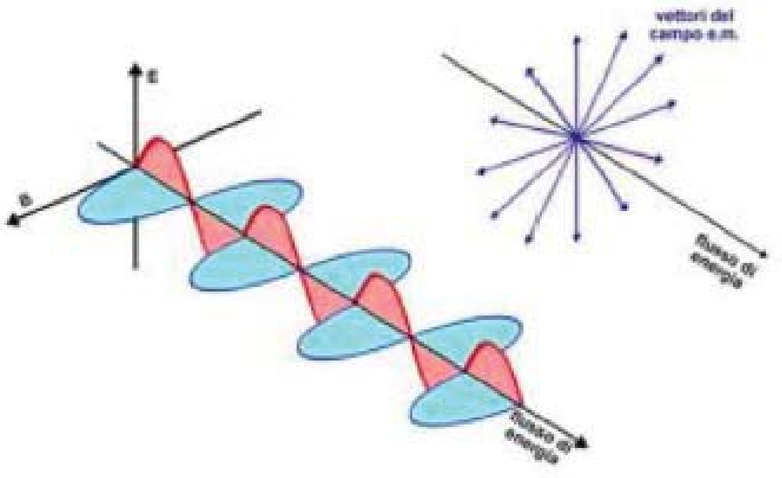
- photon passing through a Mach-Zehnder interferometer is the carrier of information

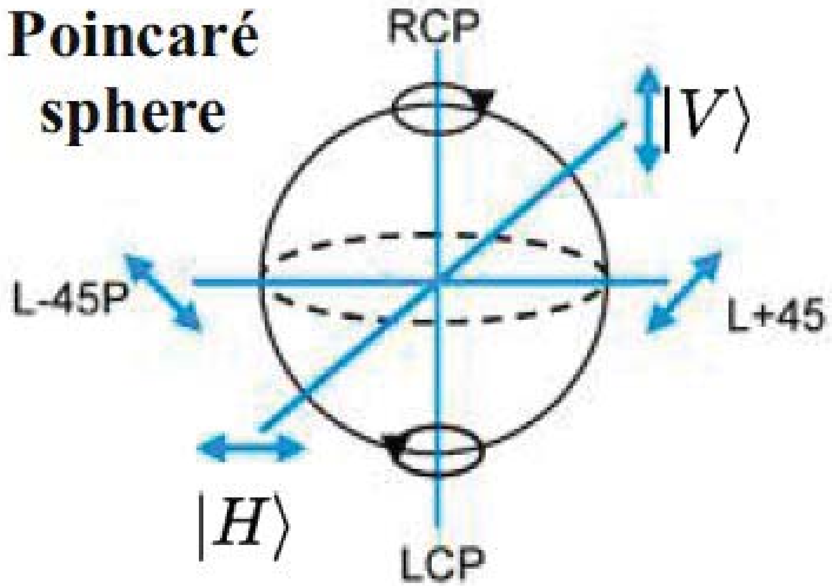
-coherent superposition state of horizontal (H) and vertical (V) polarization of a photon:Q = a|H> + b|V>

Qubit realization with photons



Polarization of light





Qubit

$$\alpha|0\rangle + \beta|1\rangle$$

Polarization of a single photon

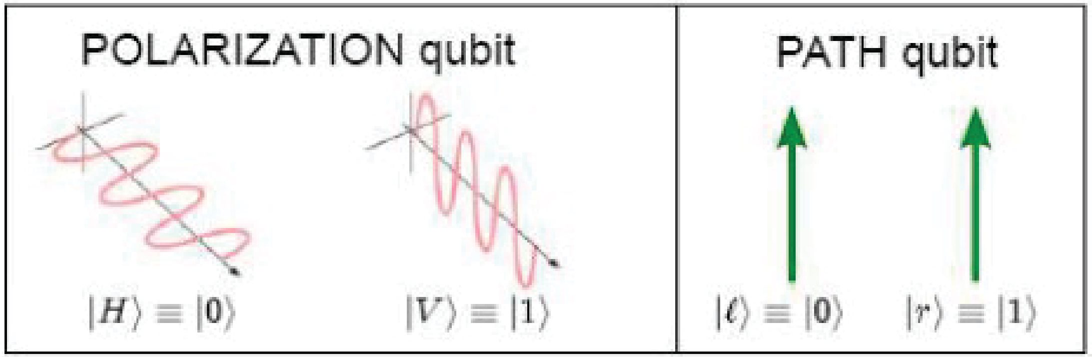
$$\alpha|H\rangle + \beta|V\rangle$$

H: horizontal

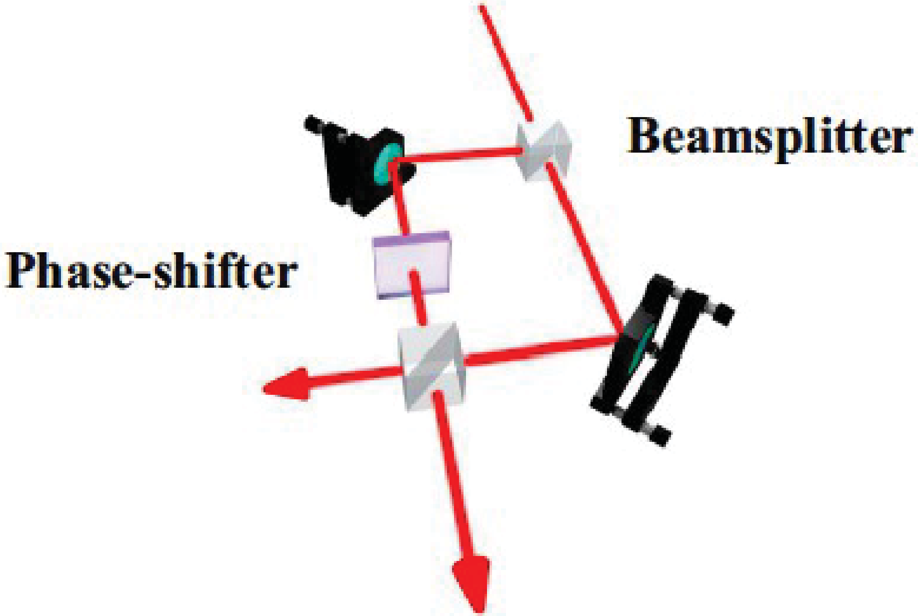
V: vertical

Implementation via path encoding

Qubit realization with photons



Manipulation: beamsplitters and phase-shifters

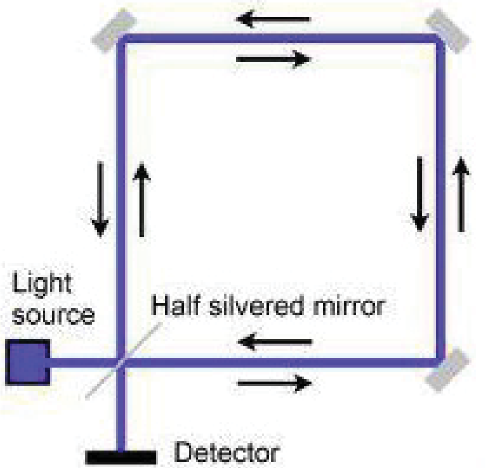


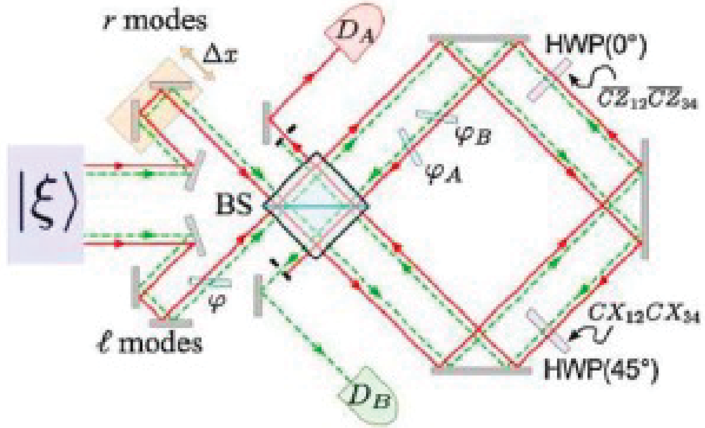
Problem!

...Phase-stability of the interferometer...

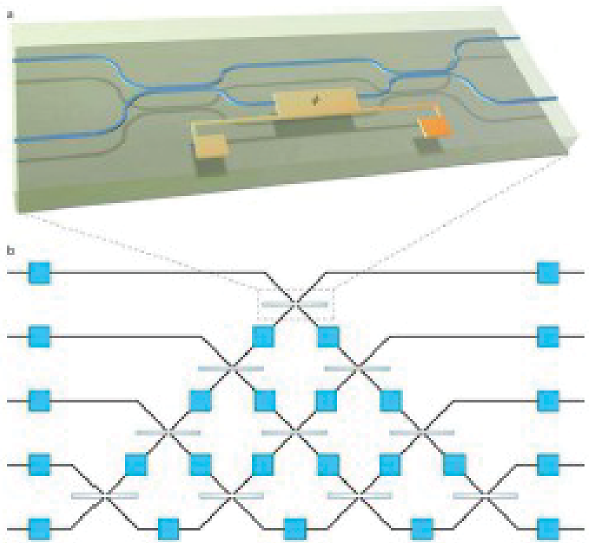
Manipulation via complex interferometers

Inherently stable bulk interferometer (Sagnac...)

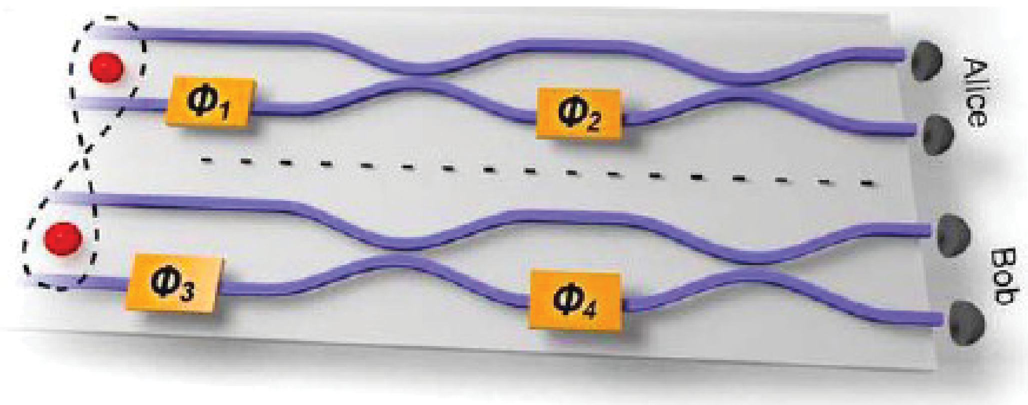




Interferometer on a chip



(tomorrow talk..)



Entanglement

"…the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." (E. Schroedinger)

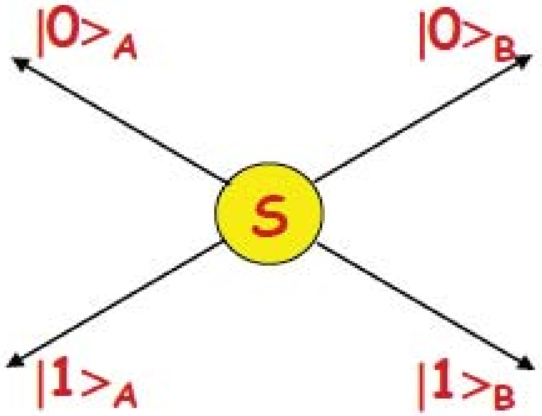
Valuable resource for quantum information, enables computational and cryptographic tasks and protocols that would be otherwise impossible with classical technology.

Two systems A and B are **entangled** if the (pure) state of the total system $|\psi\rangle_{AB}$ is not **separable**, i.e. if it cannot be written as a product of two states belonging to A and B:

$$|\psi\rangle_{AB} \neq |\chi\rangle_A \otimes |\varphi\rangle_B \tag{1}$$

In case of mixed states ρ_{AB} of the composite system $A \otimes B$, the previous relation generalizes to $\rho_{AB} \neq \sum_k p_k \rho_k^A \otimes \rho_k^B$, where p_k are probabilities and ρ_k^A's (ρ_k^B's) are generic density matrix of the system A (B).

Entanglement and Quantum Indistinguishability



Left: particle A carries the information "0", or vice versa.

Right: particle B carries the information "1", or vice versa.

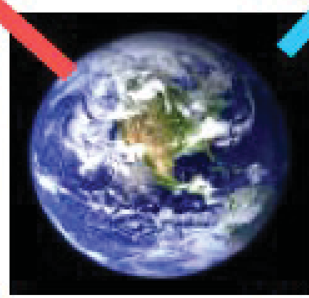
$$\Rightarrow \quad |\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|0\rangle_A |1\rangle_B + e^{i\phi}|1\rangle_A |0\rangle_B\right)$$

Neither of the two qubits carries a definite value: as soon as one qubit is measured randomly, the other one will immediately be found to carry the opposite value, *independently of the relative distance* (A. Einstein: "**spooky action at a distance**")

Quantum nonlocality

2 photons in the state

$$|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B$$

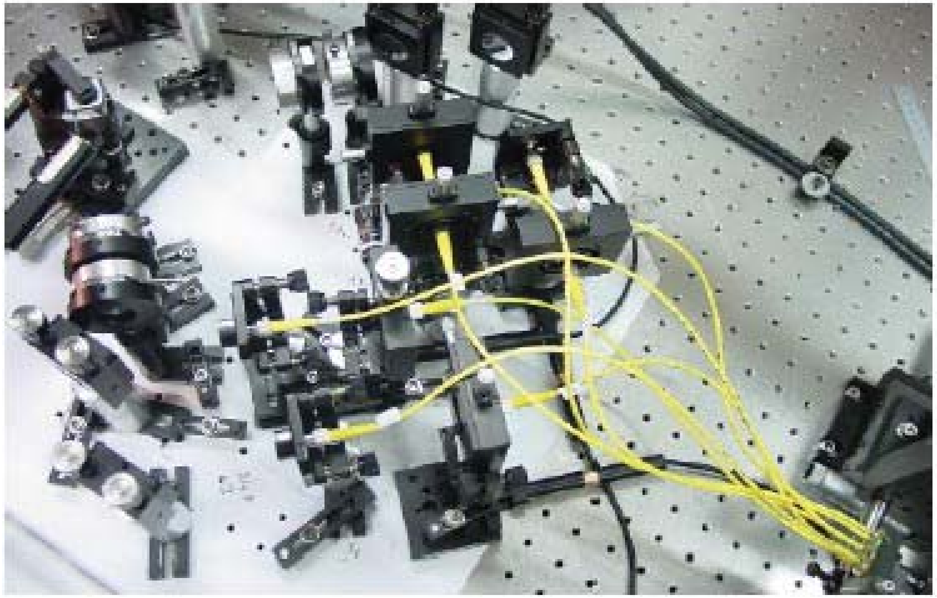


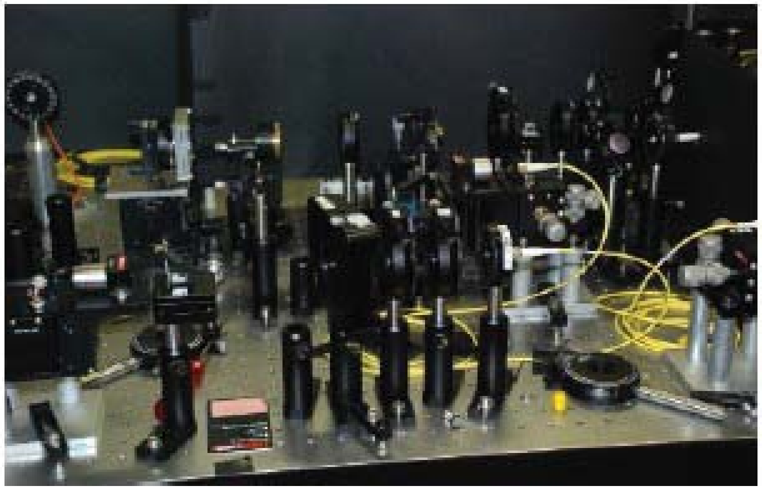
Alice measures photon A with 50% probability to detect:

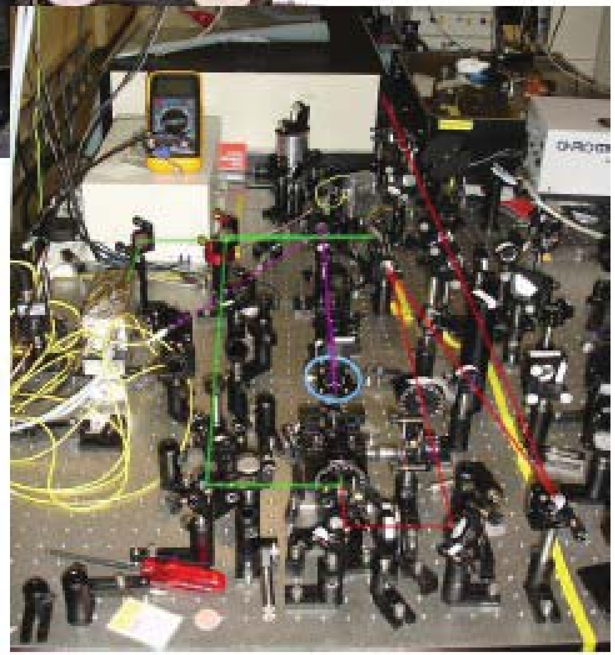
- H or V (|0> or |1>): ↔, ↕
- 45° or -45° (|+> or |->): ⤢, ⤡
- R or L:

Nonlocality verified by Bell's inequality and many other tests

Quantum nonlocality test inside the lab...







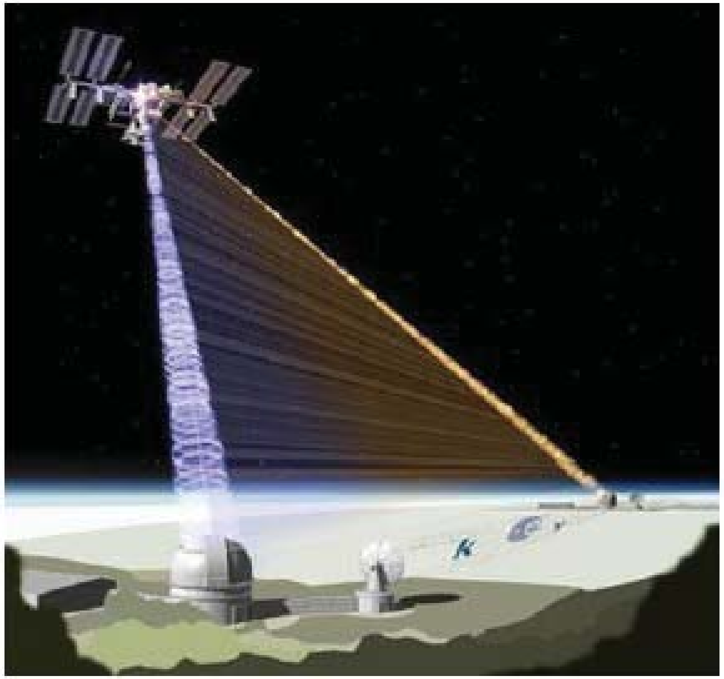
...or outside the lab

Violation of local realism with freedom of choice

Thomas Scheidl[a], Rupert Ursin[a], Johannes Kofler[a,b,1], Sven Ramelow[a,b], Xiao-Song Ma[a,b], Thomas Herbst[b], Lothar Ratschbacher[a,2], Alessandro Fedrizzi[a,3], Nathan K. Langford[a,4], Thomas Jennewein[a,5], and Anton Zeilinger[a,b,1]

[a]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria; and [b]Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria

Quantum satellite communication



Quantum Computation

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

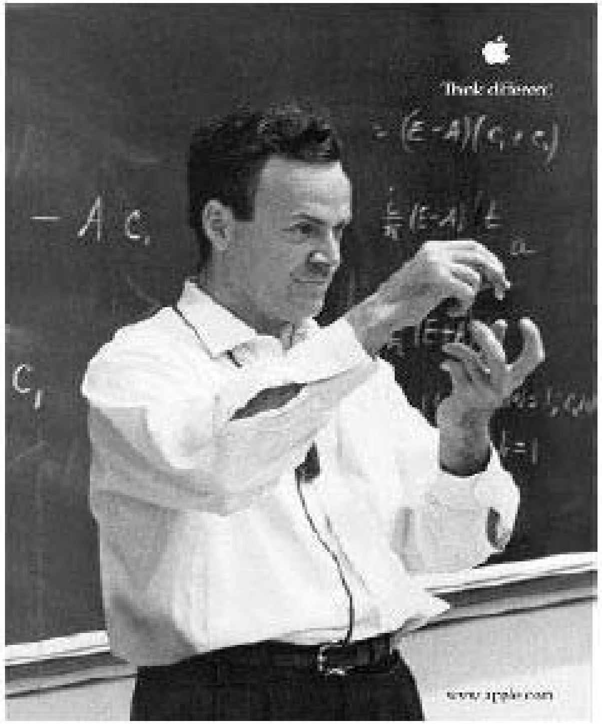
Received May 7, 1981

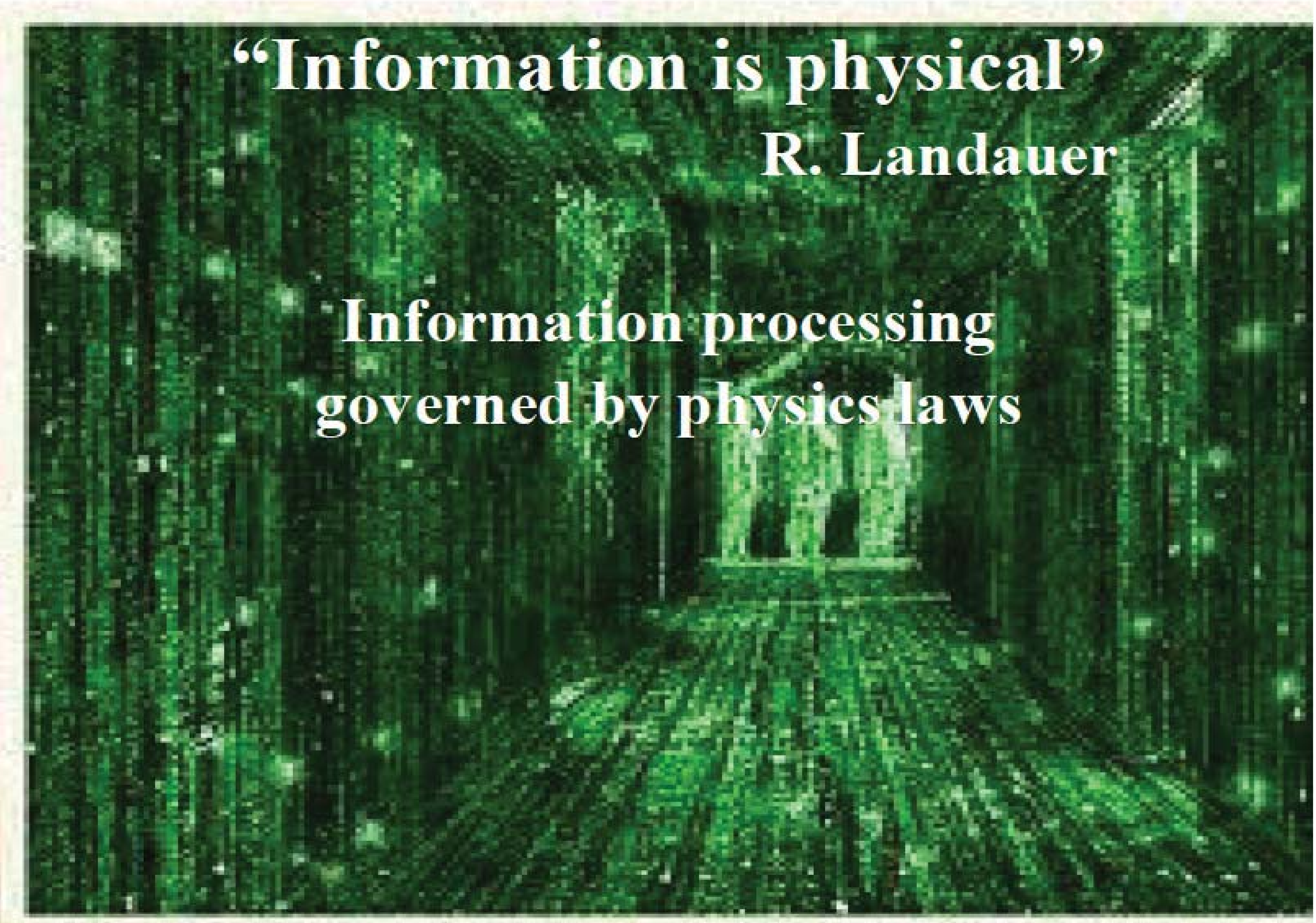
1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally intercon-*

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982




"Information is physical"
R. Landauer
Information processing
governed by physics laws

Quantum information: building blocks

Classical computation

IDENTITY

0	$\longrightarrow$	0
1	$\longrightarrow$	1

NOT

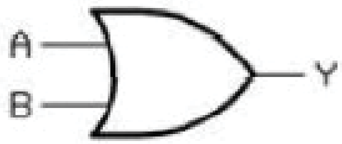
0 $\longrightarrow$ 1

1 $\longrightarrow$ 0

AND

A,B $\longrightarrow$ A x B

OR



Quantum computation

Single qubit gates

IDENTITY

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$|0\rangle \rightarrow |0\rangle$$
$$|1\rangle \rightarrow |1\rangle$$

HADAMARD

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$|0\rangle \rightarrow \tfrac{1}{\sqrt{2}}\left[|0\rangle + |1\rangle\right]$$

$$|1\rangle \rightarrow \tfrac{1}{\sqrt{2}}\left[|0\rangle - |1\rangle\right]$$

Two qubit gate

Controlled-NOT

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$|00\rangle \rightarrow |00\rangle$$
$$|01\rangle \rightarrow |01\rangle$$
$$|10\rangle \rightarrow |11\rangle$$
$$|11\rangle \rightarrow |10\rangle$$

Quantum logic gates with photons

- Ingredients:

- CW and pulsed (10^{-13} fsec) laser
- Qubits encoded in polarization, linear and transverse momentum, orbital angular momentum, time-energy
- Qubit unitary transformations allowed by quarter and half waveplates, rotation quartz plates, glass phase shifters
- Qubit measurements performed by beam splitters (BS), polarizing beam splitters (PBS)
- Free-space or single mode optical fiber transmission
- Single photon detectors

Quantum Optics for Quantum Information Processing

- Qubit state $\alpha|0\rangle + \beta|1\rangle \longleftrightarrow \alpha|H\rangle + \beta|V\rangle$

  Polarization of a single photon:

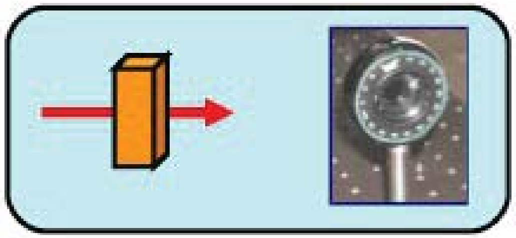
  H: horizontal polarization

  V: vertical polarization

  Mode of the electromagnetic field (k,wavelength)

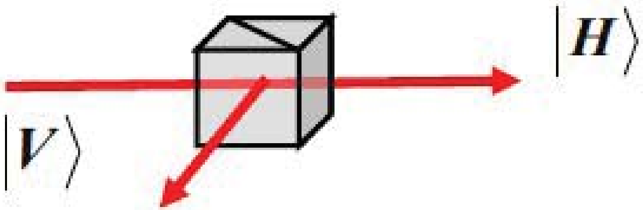
- Logic gate acting on a single qubit

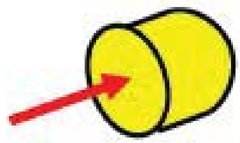
  Rotation of the polarization: waveplates

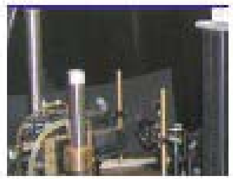


- Measurement of the qubit:

  polarizing beam splitter | Single photon detectors







Single photon sources

Necessary for quantum cryptography, based on
the adoption of the single photon state |n=1>

Single photon states approximated by the following
techniques :

- Faint laser pulses
- Photon pairs generated by parametric down conversion

Faint laser pulses
(strongly attenuated laser pulses)

$$|\alpha\rangle = \exp(-|\alpha|^2/2)\cdot\sum[\alpha^n/(n!)^{1/2}|n\rangle \overset{\alpha<0.1}{\cong}$$
$$1/(1 - |\alpha|^2/2)\cdot(|0\rangle + \alpha|1\rangle + \alpha^2/2\ |2\rangle)$$

$\Rightarrow$

$$p(1) = |\alpha|^2$$

$$p(2) = |\alpha|^4/2$$

$$p(2)/p(1) = |\alpha|^2/2$$

for $p(2)/p(1) = .01$, $p(1) = .02$

The field contains zero photons most of the time and one photon is obtained only *a posteriori* (can know that one photon has been generated only after its detection)

Faint laser pulses
(strongly attenuated laser pulses)

$$|\alpha\rangle = \exp(-|\alpha|^2/2)\cdot\Sigma[\alpha^n/(n!)^{1/2}|n\rangle \overset{\alpha<0.1}{\cong} 1/(1 - |\alpha|^2/2)\cdot(|0\rangle + \alpha|1\rangle + \alpha^2/2\ |2\rangle)$$

$$\Rightarrow \quad p(1) = |\alpha|^2$$

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for $p(2)/p(1) = .01$, $p(1) = .02$

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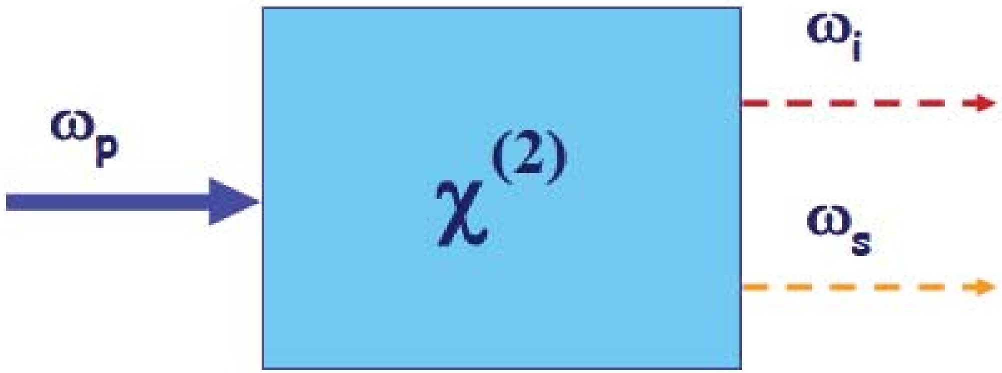
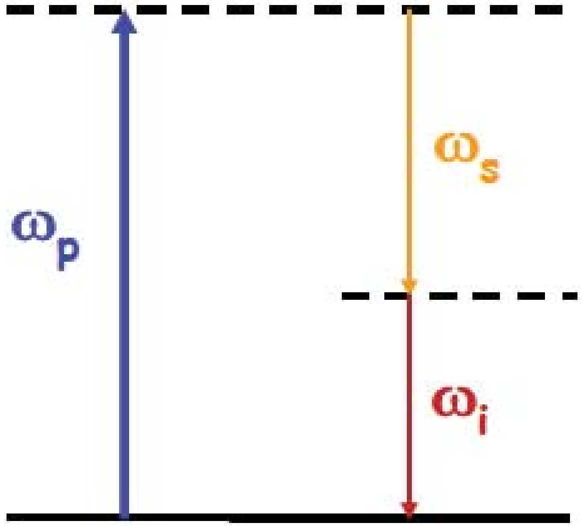
Spontaneous Parametric Down Conversion: 2-photon state





$\approx 10^{10}$ photon pairs/sec generated over the entire emission cone by 100 mW UV in few mm of NL crystal

Process probability is maximized if the following conditions are satisfied: →

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

$$K_p = K_s + K_i$$

Degenerate parametric fluorescence, $\omega = \omega_p/2$

Phase matching: $\vec{K}_p - \vec{K}_s - \vec{K}_i = 0$

Momentum conservation: implies different phase matching conditions

	Positive uniaxial ($n_e > n_o$)	Negative uniaxial ($n_e < n_o$)
Type I	$o \to e + e$	$e \to o + o$
Type II	$o \to o + e$	$e \to e + o$

⇓

Positive uniaxial	Negative uniaxial
$H \to V + V$	$V \to H + H$
$H \to V + H$	$V \to H + V$

Entangled "Bell States":

$$|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$
$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

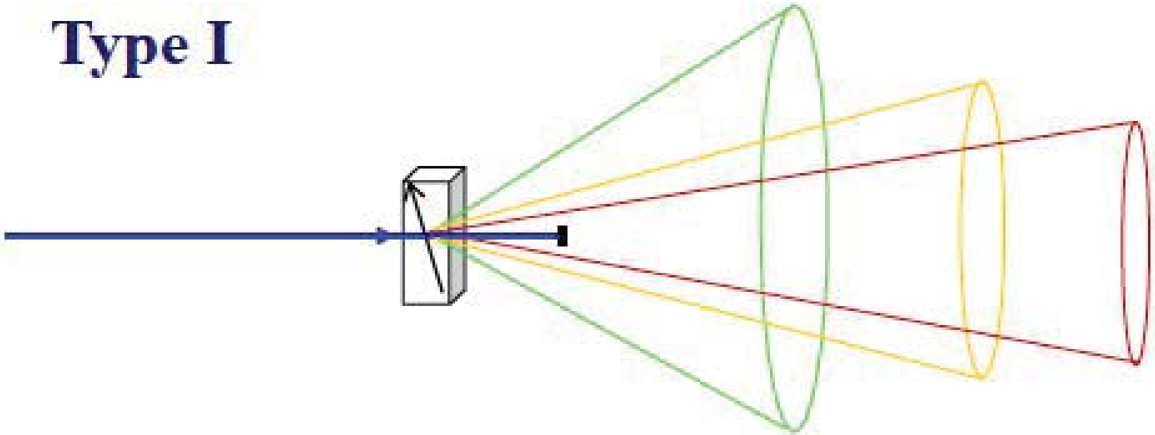
$$|\Phi^{\pm}> = 1/\sqrt{2}\,[\,|H>_A|H>_B \pm |V>_A|V>_B\,]$$

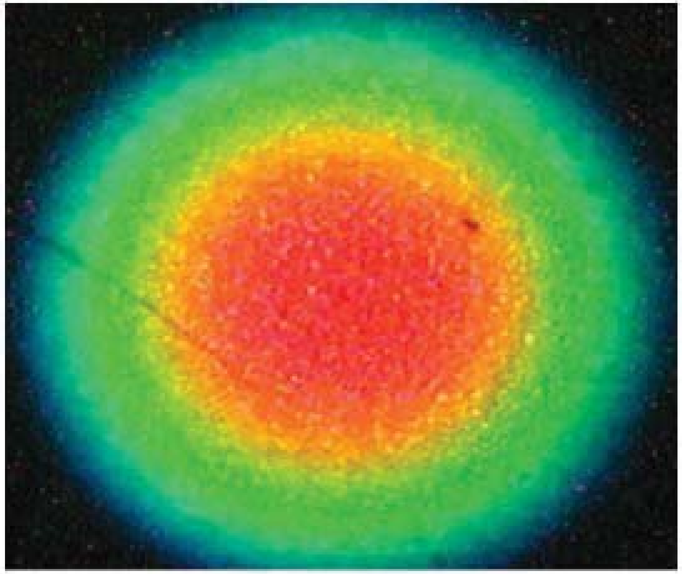
$$|\Psi^{\pm}> = 1/\sqrt{2}\,[\,|H>_A|V>_B \pm |V>_A|H>_B]$$

analogous to the decay of a spin-0 particle into two spin 1/2 particles:

$$|\Psi>_{AB} = 1/\sqrt{2}(|\uparrow>_A|\downarrow>_B - |\downarrow>_A|\uparrow>_B)$$

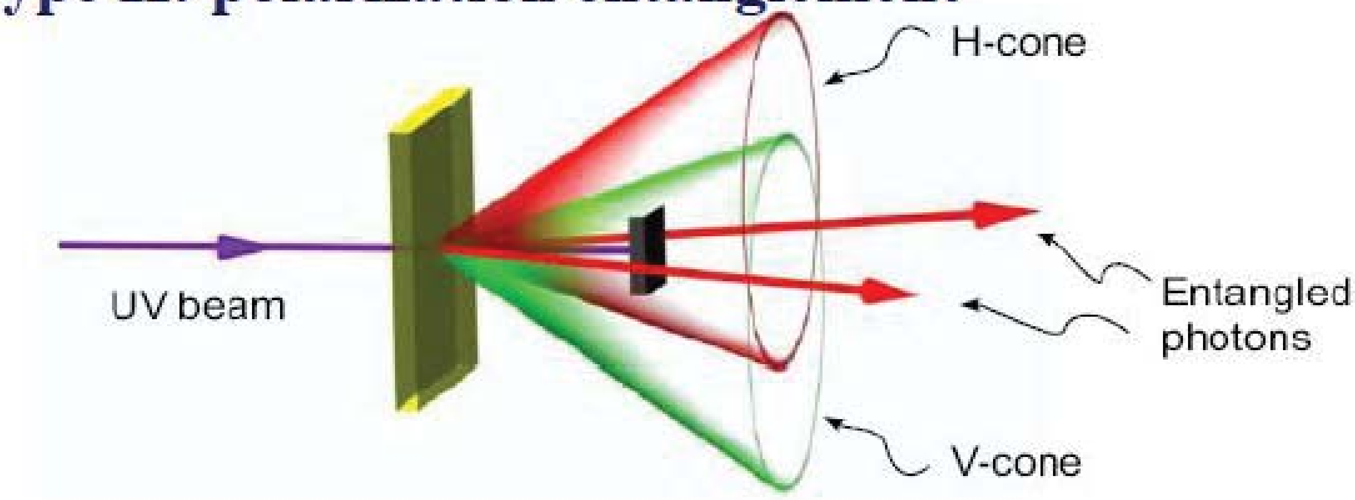
Type I

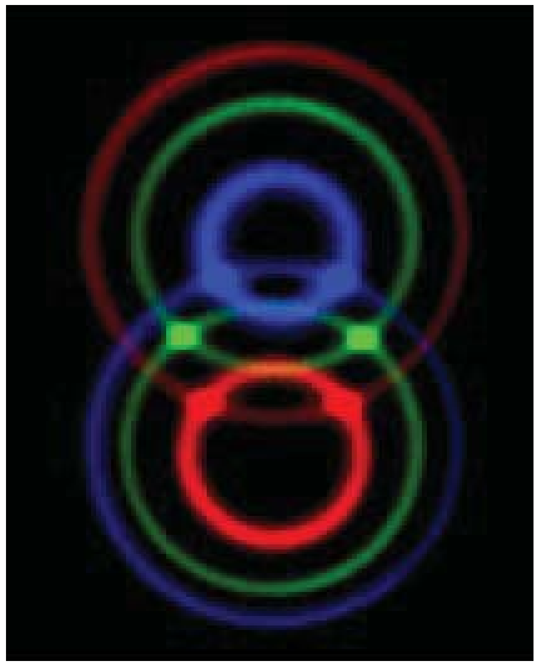




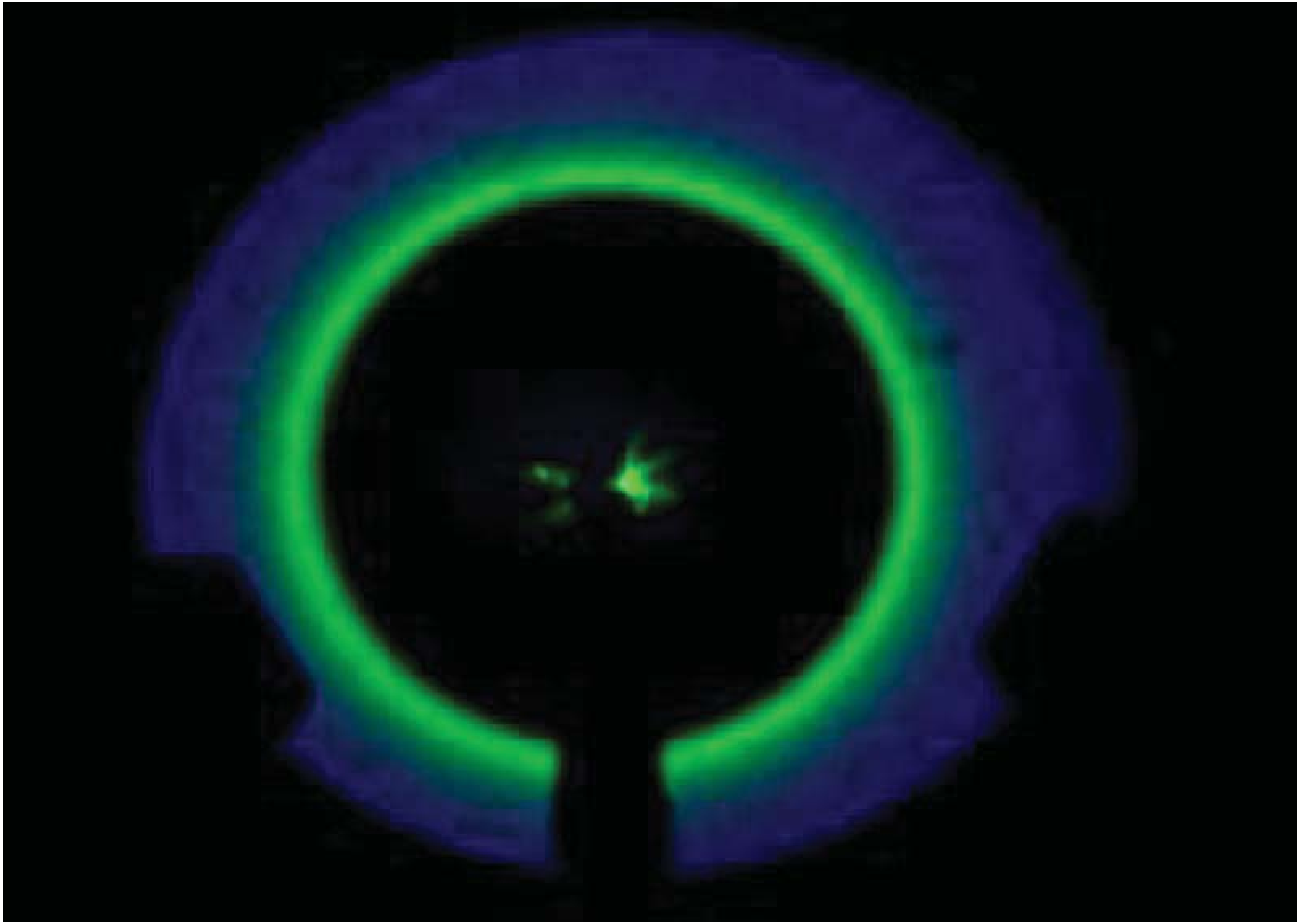
P. G. Kwiat *et al.* Phys. Rev. Lett. ('95)

Type II: polarization entanglement

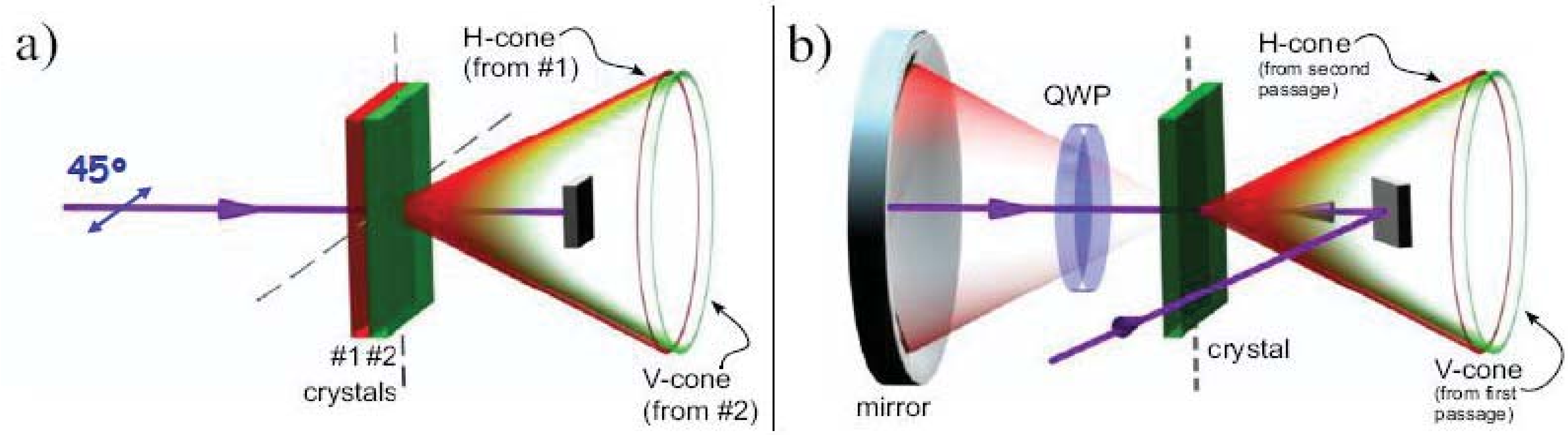




$$|\Psi\rangle = 1/\sqrt{2}\,|H\rangle_A\,|V\rangle_B + e^{i\phi}\,|V\rangle_A\,|H\rangle_B$$



Type I: polarization entanglement



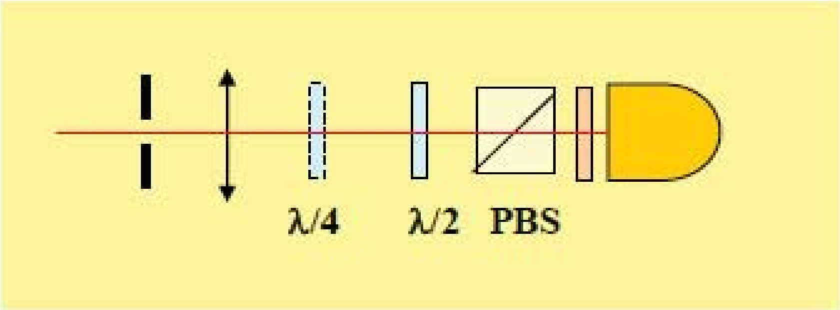
$$|\Phi\rangle = 1/\sqrt{2}\, |H\rangle_A |H\rangle_B + e^{i\phi} |V\rangle_A |V\rangle_B$$

P. G. Kwiat *et al.* Phys. Rev. A ('99) M. Barbieri *et al.* Phys. Rev. Lett. (04)

Characterizing polarization entanglement

v	Alice	Bob
1	H	H
2	H	V
3	V	V
4	V	H
5	R	H
6	R	V
7	D	V
8	D	H
9	D	R
10	D	D
11	R	D
12	H	D
13	V	D
14	V	L
15	H	L
16	R	L

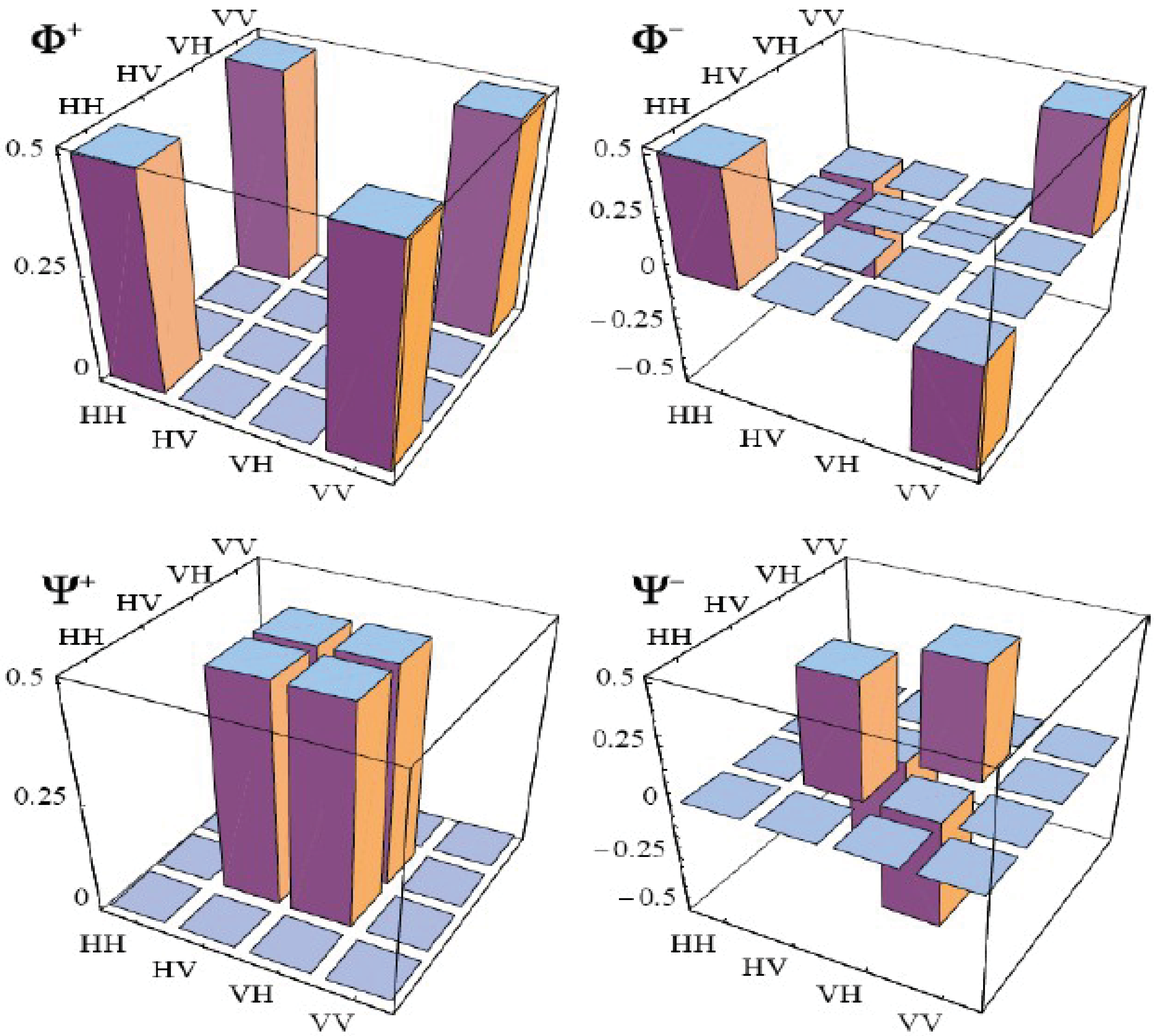
Density matrix of the state reconstructed by Quantum State Tomography



$$|D\rangle \equiv (|H\rangle + |V\rangle)/\sqrt{2}$$

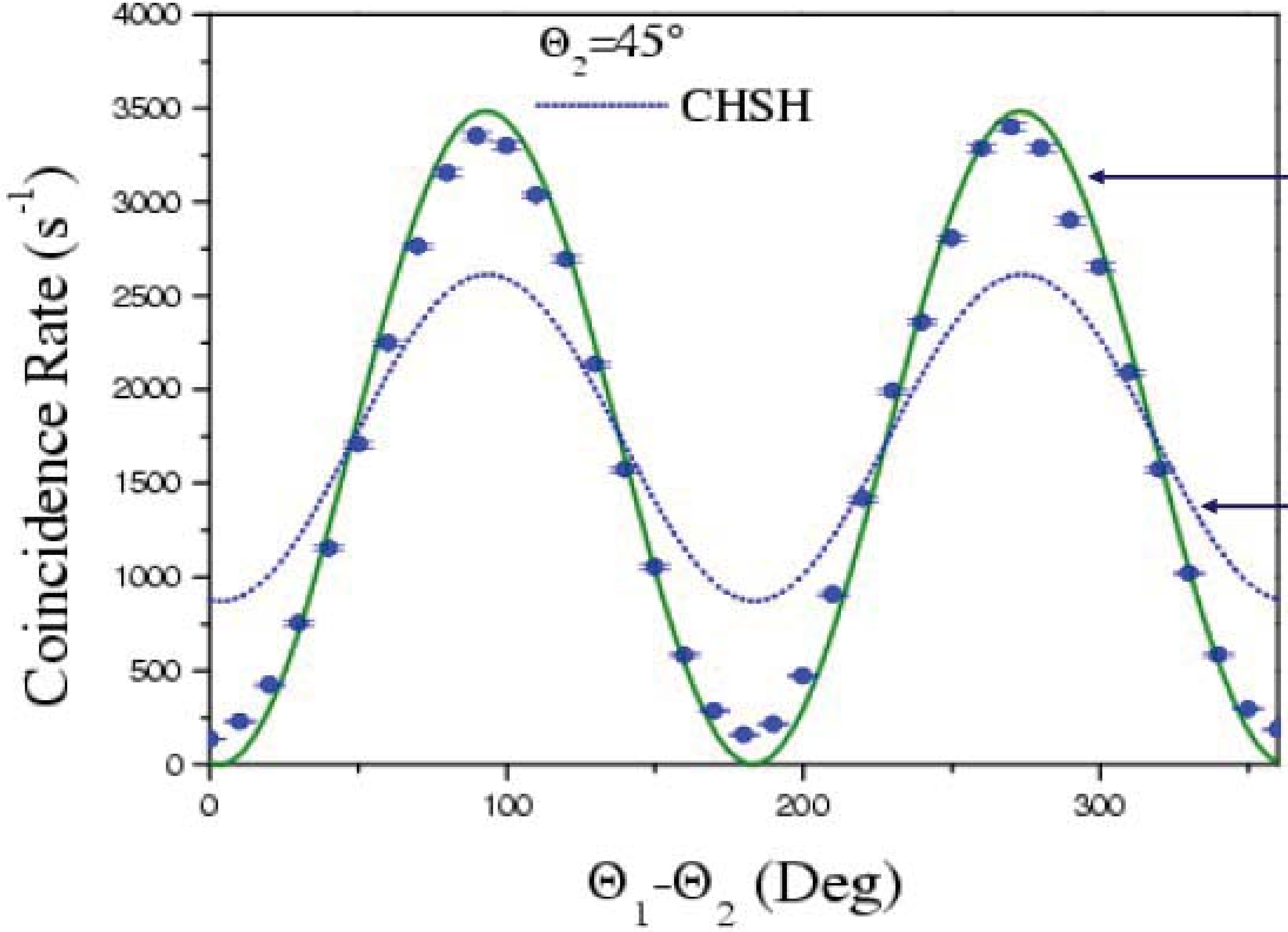
$$|L\rangle \equiv (|H\rangle + i|V\rangle)/\sqrt{2}$$

$$|R\rangle \equiv (|H\rangle - i|V\rangle)/\sqrt{2}$$



Φ⁺
Φ⁻
Ψ⁺
Ψ⁻
HH
HV
VH
VV
0.5
0.25
0
−0.25
−0.5

Polarization entanglement



Quantum limit

Classical limit

C. Cinelli *et al.* Phys. Rev. A ('04)

Photon entanglement based on other degrees of freedom

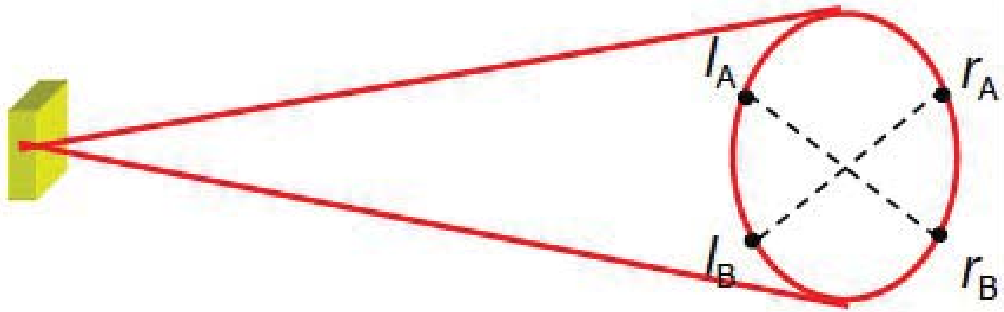
- Momentum (path) entanglement: use different k-vectors (different paths) for photons. Use interferometric setup for measurement

- Energy-time entanglement. Measure with interferometers

- Orbital angular momentum (OAM) entanglement. Measure with LCD, spiral phase plate, q-plate…

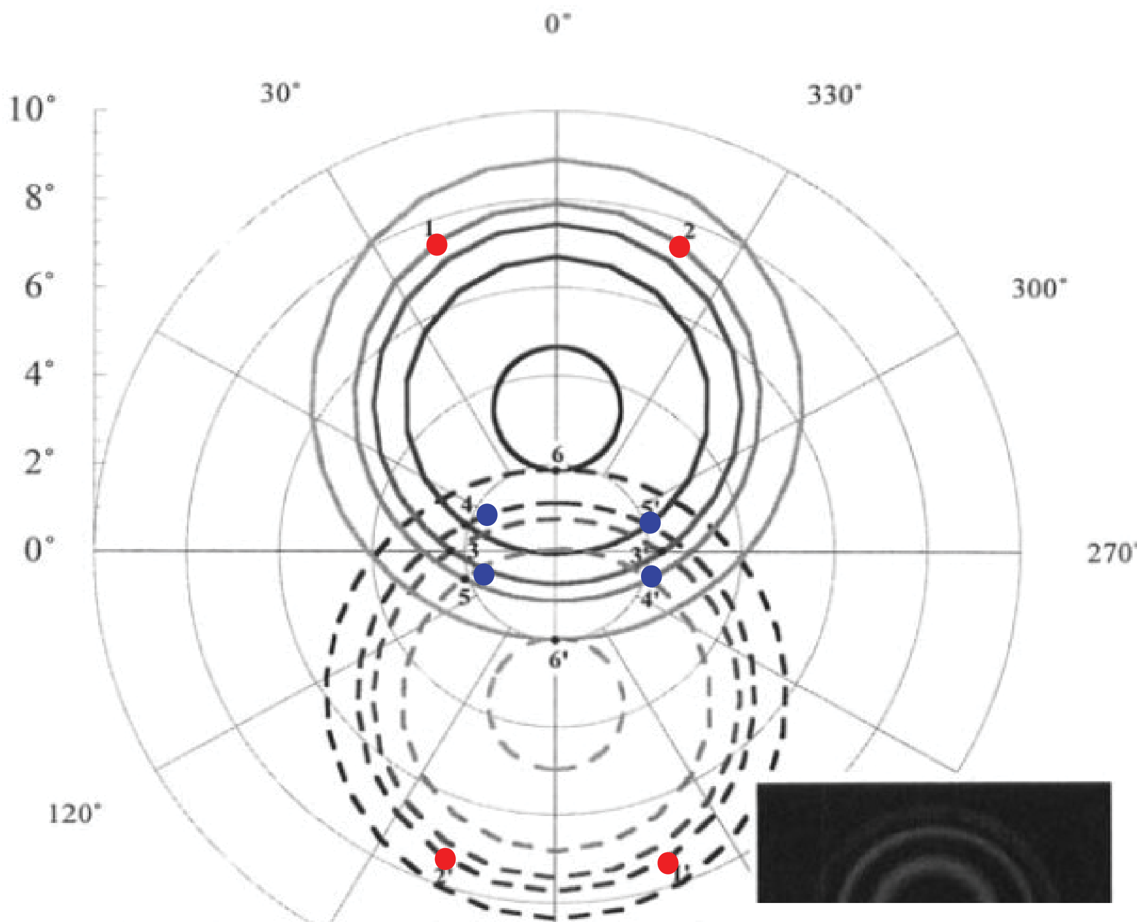
Path entanglement. Photons emitted through opposite directions belonging to the SPDC cone surface

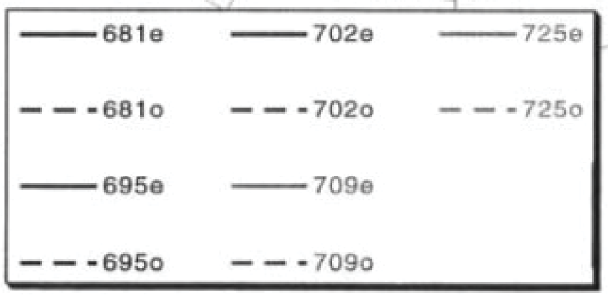
$$|\phi\rangle = 1/\sqrt{2}\, |l\rangle_A |r\rangle_B + |r\rangle_A |l\rangle_B$$



C. Cinelli *et al.*, PRL ‘05

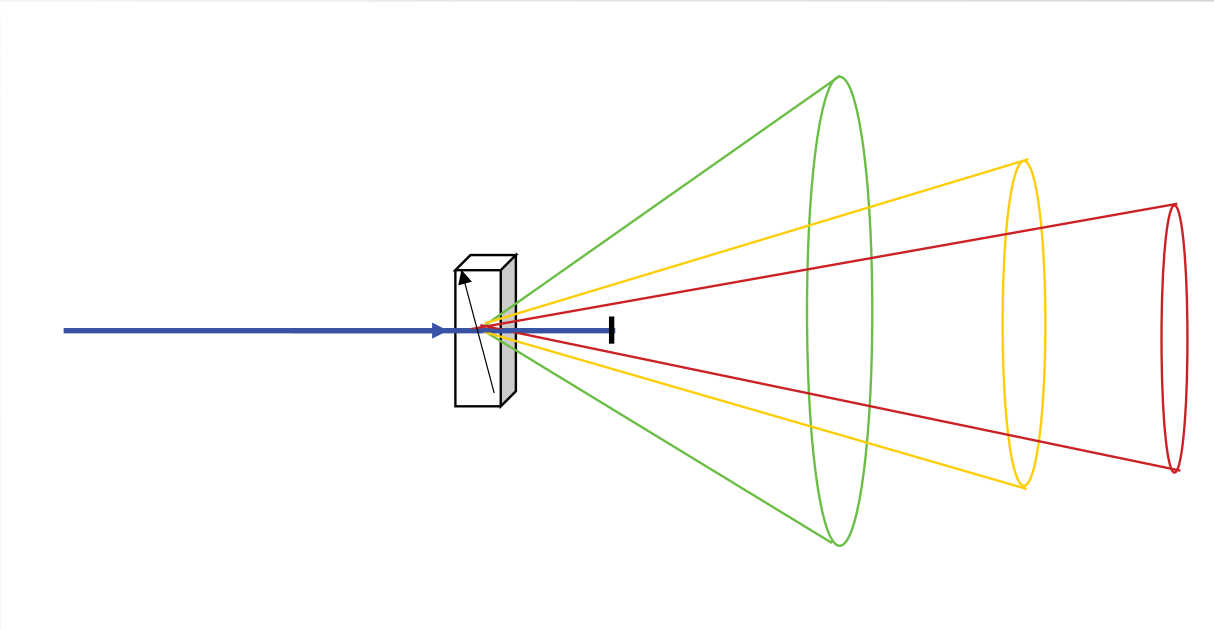
Path entanglement: Type II crystal (P.G. Kwiat, J.Mod. Opt. '97)

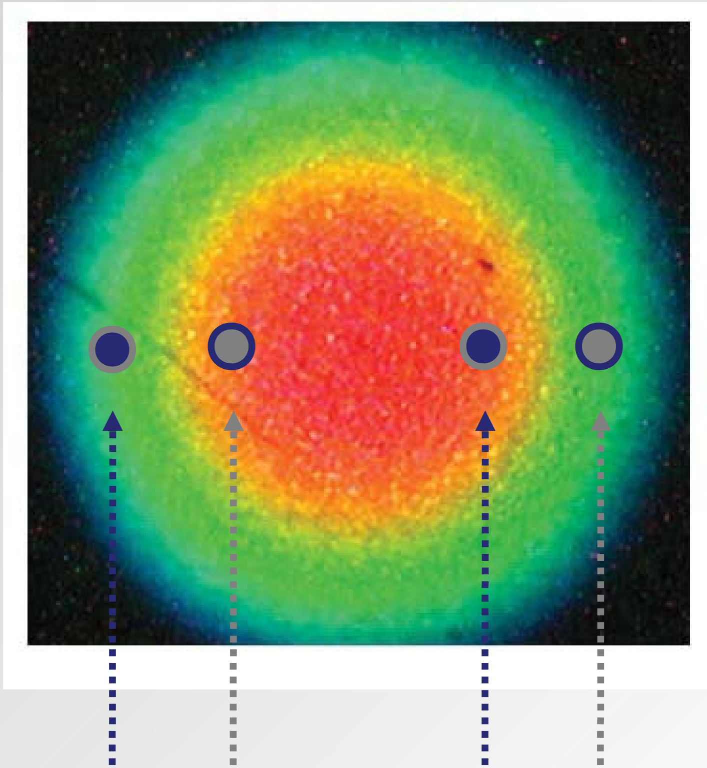




Conjugate points from figure 1	Energy–time entangled	Momentum-entangled	Polarization-entangled	Non-maximally entangled
1-1′	✓			
1-1′–2-2′	✓	✓		
3-3′	✓		✓	
4-4′–5-5′	✓	✓	✓	
6-6′	✓		✓	✓

Frequency entanglement

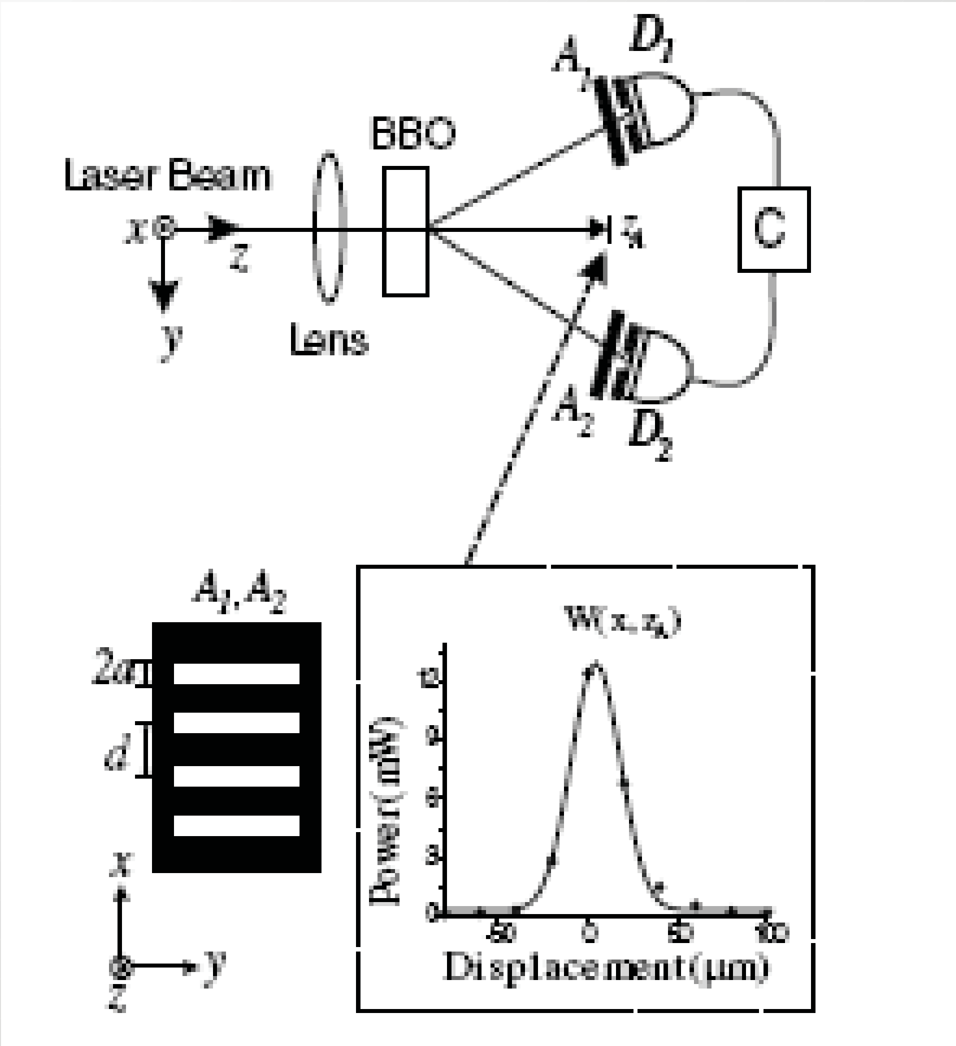


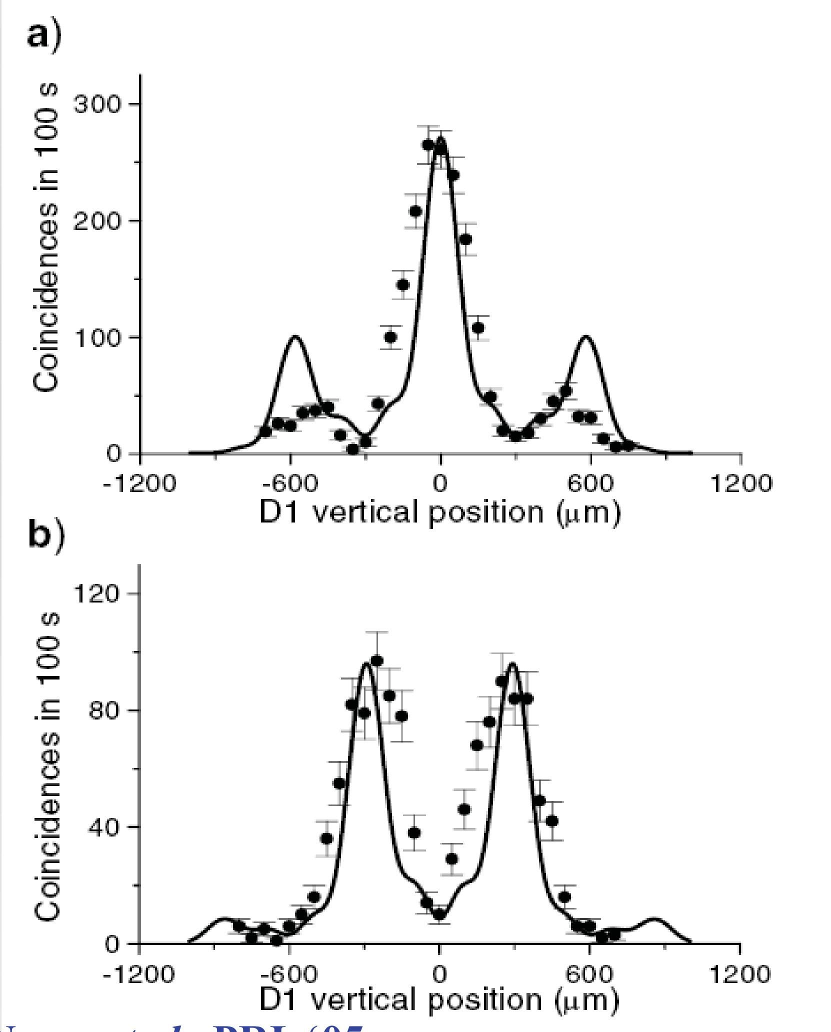


$$\Psi = [|\omega_1\rangle + |\omega_2\rangle] + [|\omega_2\rangle + |\omega_1\rangle]$$

- Different approach: each photon is forced to pass through two slits corresponding to two orthogonal states. Transverse spatial correlations controlled by manipulating the pump laser beam.

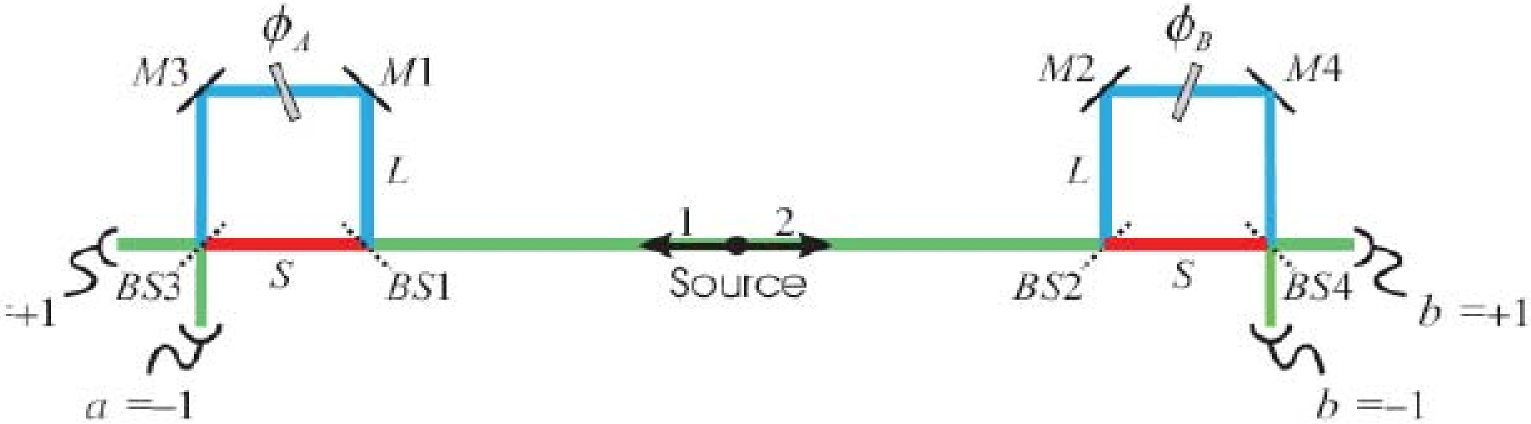
Allows to create d-level (d>2) entangled states: qudits.





Neves *et al.*, PRL '05

Energy-time entanglement



$$|\phi\rangle = 1/\sqrt{2}\ [|L\rangle_A |L\rangle_B + |S\rangle_A |S\rangle_B]$$

Energy anticorrelations and emission time correlations observed

Temporal post selection needed to discard the events $|LS\rangle$ and $|SL\rangle$. Coincidences counted within a precise temporal window.

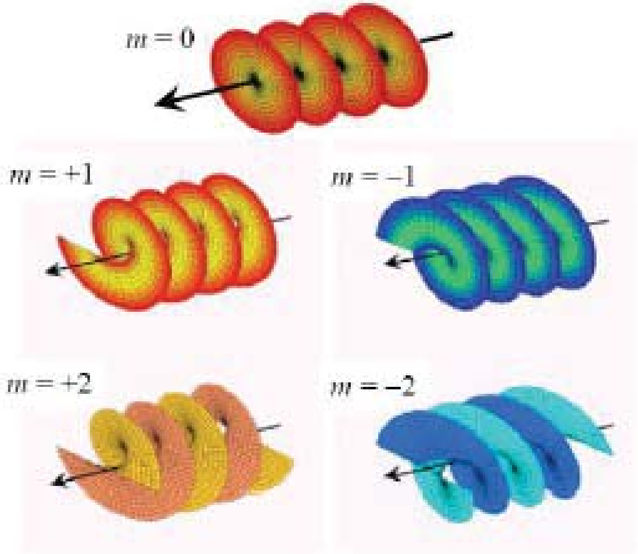
J. Franson, PRL '89

Orbital angular momentum (OAM)

Paraxial approximation: photons described by a mode function expressed by a Laguerre-Gaussian mode |*m, p*>.
Eigenstates of the OAM operator with eigenvalues:

$$m(h/2\pi) \qquad (m = 0, \pm 1, \pm 2, \ldots)$$

p **related to the radial profile of the beam**
m **, topological winding number. Describes the helical function of the wavefront around a wavefront singularity.**



OAM manipulated by computer generated holograms, Dove's prisms, cylindrical lenses, spiral phase plates, q-plates

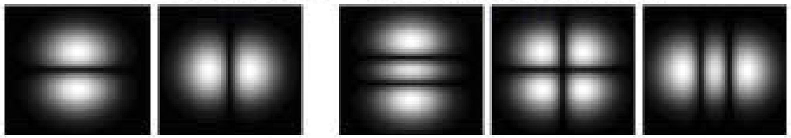
The orbital angular momentum of light

The dynamics of a light beam propagating along the z direction is described by the Helmoltz's equation in the paraxial approximation:

$$\boxed{\frac{\partial^2 A(\vec{r})}{\partial x^2} + \frac{\partial^2 A(\vec{r})}{\partial y^2} = 2ik\,\frac{\partial A(\vec{r})}{\partial z}}$$

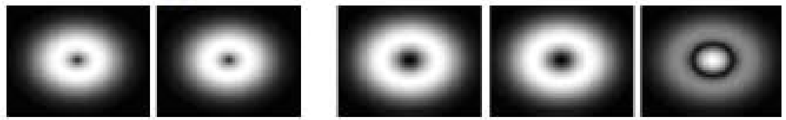
Cartesian coordinates

Hermite – Gauss modes



Cylindrical coordinates

Laguerre – Gauss modes

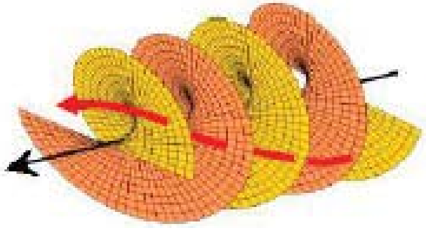


Laguerre-Gauss :

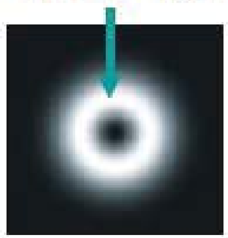
$$u_{p,l}(r,\varphi,z) \propto u(r,z)\,e^{-il\varphi}$$

Helicoidal phase front

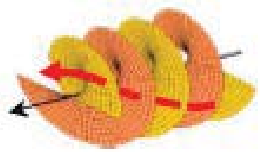
$l = 0\ ,\ \pm 1\ ,\ \pm 2\ ,\ \ldots$



Phase Singularity



➡ Each photon carries OAM equal to $l\hbar$

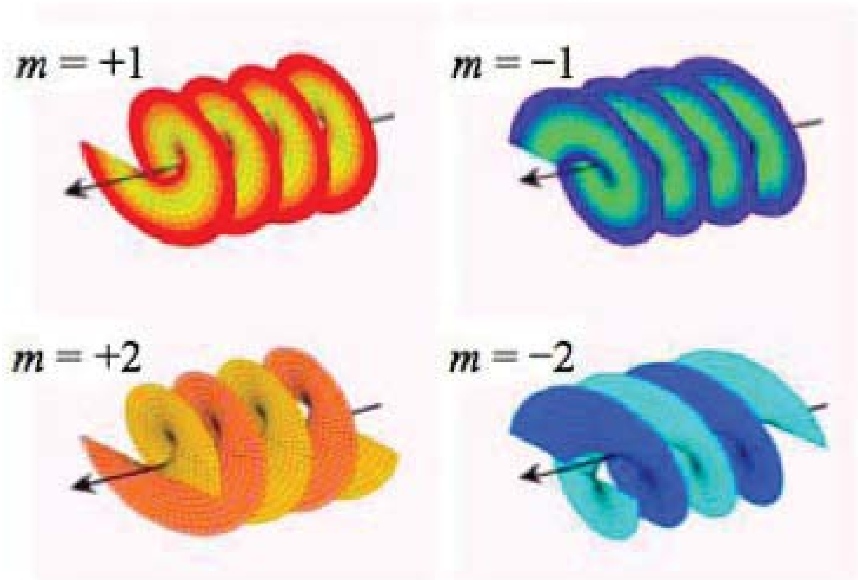


Spin and orbital angular momentum of light (SAM & OAM)

Laguerre-Gauss modes

Helical modes:
(using cylindrical coordinates r, φ, z)

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0(r,z)e^{im\varphi}e^{i(kz-\omega t)}$$



helical phase factor:

$$e^{im\varphi}$$

$m = 0, \pm 1, \pm 2, \pm 3 \ldots$

Angular momentum:

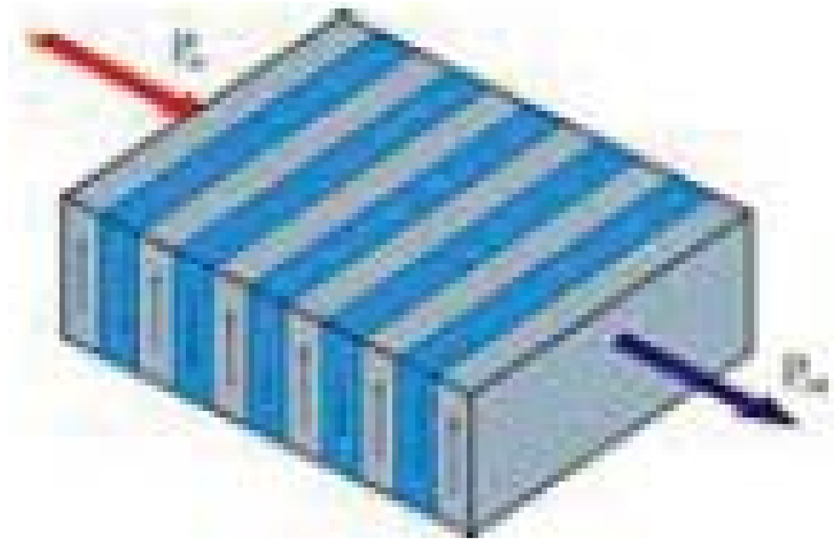
OAM: $L_z = m\hbar$ per photon + SAM: $S_z = \pm\hbar$ per photon

[L. Allen, M.W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, *Phys. Rev. A* **45**, 8185 (1992)]

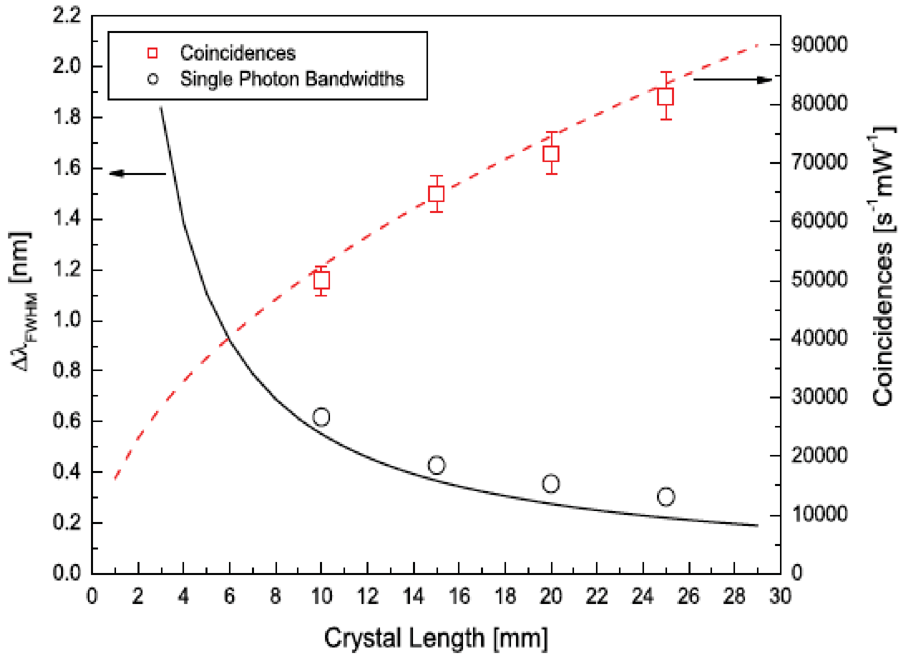
Alternative solution: Periodically Poled Crystals

Allows to fully exploit the nonlinear properties of certain materials while relaxing phase the matching conditions

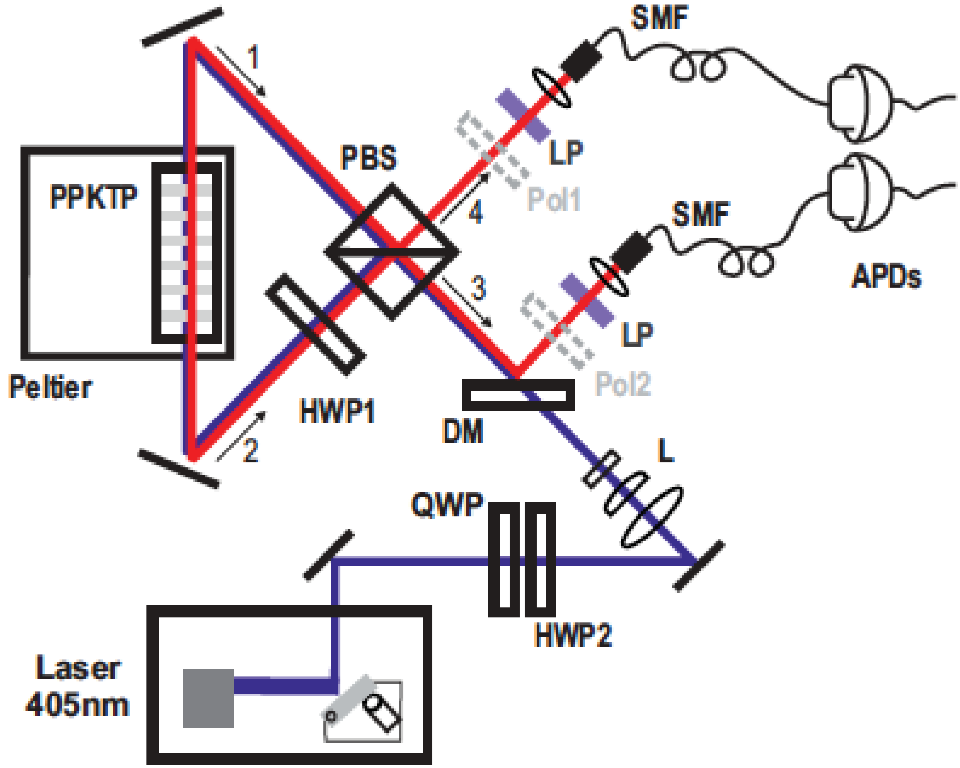
$$\mathbf{k}_p(\lambda_p, n_p(\lambda_p, T)) = \mathbf{k}_s(\lambda_s, n_s(\lambda_s, T)) + \mathbf{k}_i(\lambda_i, n_i(\lambda_i, T)) + \frac{2\pi}{\Lambda(T)}$$



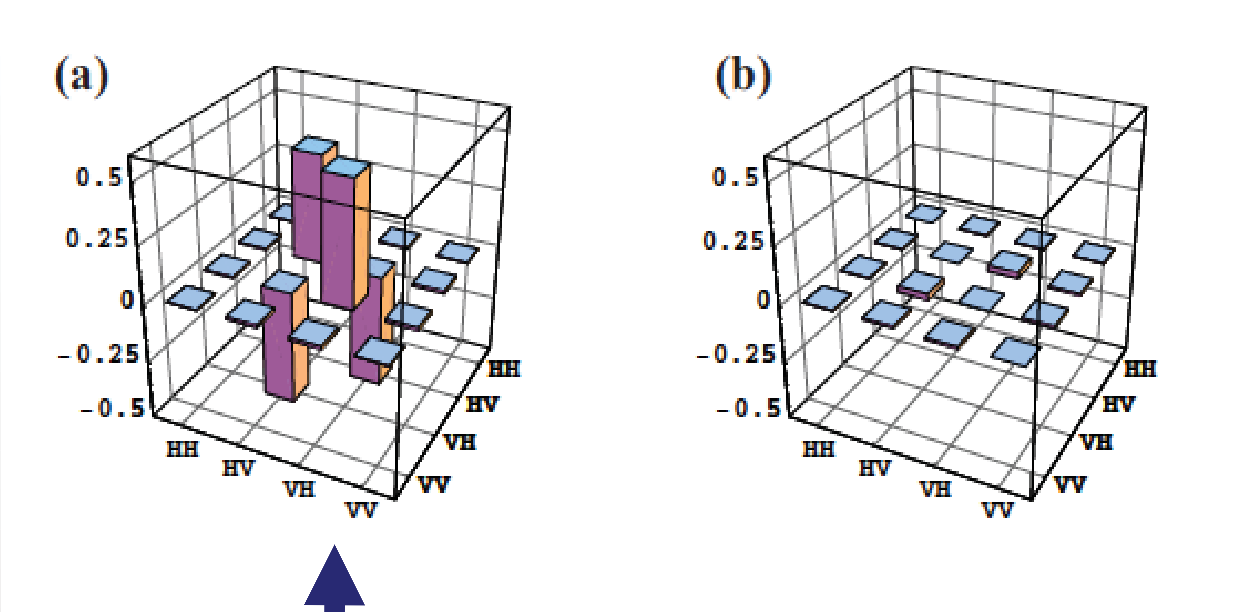
Best employed in collinear configuration where a much bigger fraction of the created photons can be entangled than in the conelike geometry.
Enable achievement of much higher spectral brightness.
Need to spatially separate the collinear downconversion modes.



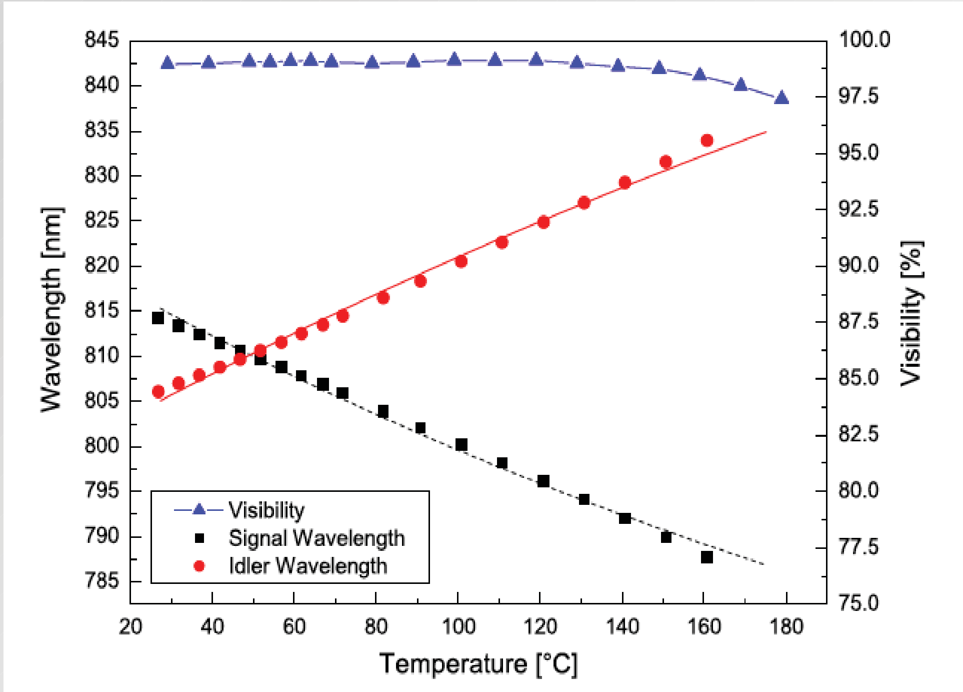
$$|\Psi^{\pm}\rangle = 1/\sqrt{2}\,[\,|H\rangle_A|V\rangle_B \pm |V\rangle_A|H\rangle_B]$$



A. Fedrizzi *et al.* Opt. Expr. (2007)



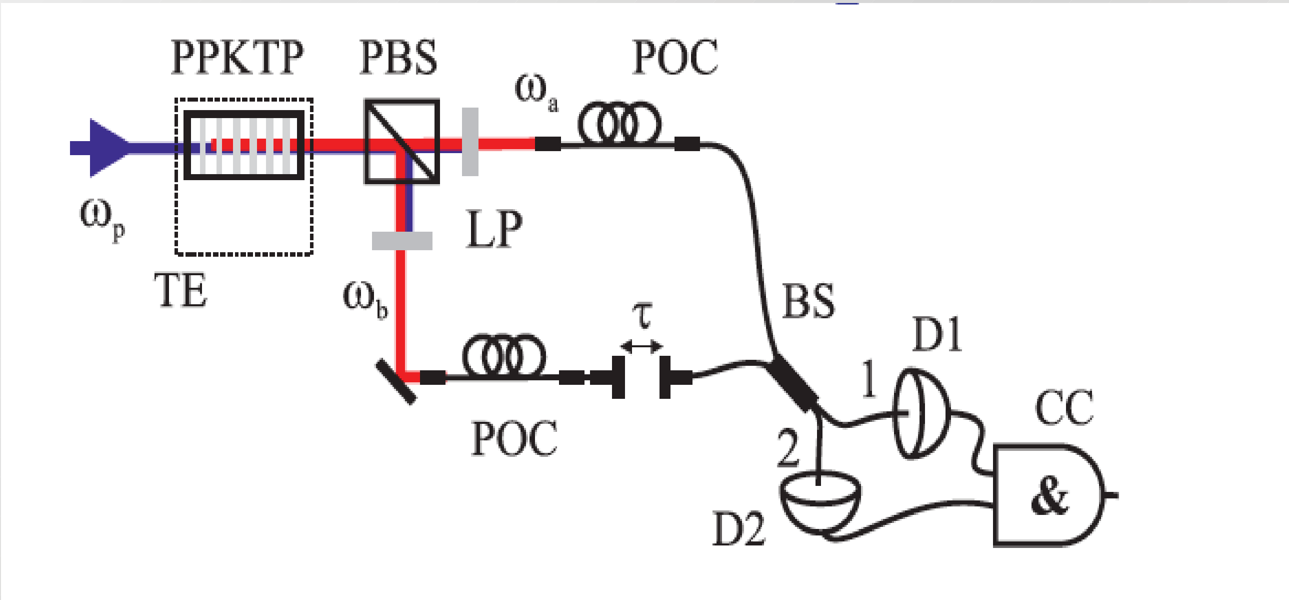
Singlet entangled state $|\Psi^{-}\rangle$



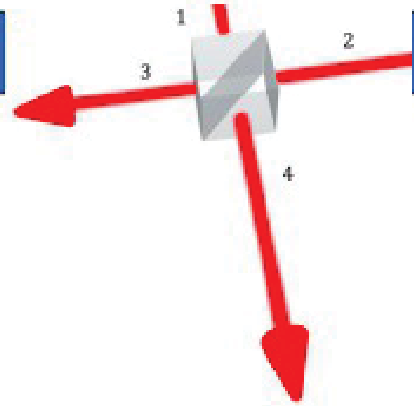
Photon undistinguishability needed for many interference effects.

Check for 2-photon coalescence on a beam splitter (BS).

Hong-Ou-Mandel (HOM) effect.



Beam splitter



E1 e E2: input fields
E3 e E4: output fields

Transmission and Reflection coefficients

$$\mathcal{T} = t e^{\imath\phi_t} \qquad \mathcal{R} = r e^{\imath\phi_r}$$

Classical picture

$$E_3 = \mathcal{R}_{31} E_1 + \mathcal{T}_{32} E_2$$

$$E_4 = \mathcal{T}_{41} E_1 + \mathcal{R}_{42} E_2$$

Quantum picture

$$\hat{a}_3 = \mathcal{R}\hat{a}_1 + \mathcal{T}\hat{a}_2$$

$$\hat{a}_4 = \mathcal{T}\hat{a}_1 + \mathcal{R}\hat{a}_2$$

Energy conservation

$$|E_3|^2 + |E_4|^2 = |E_1|^2 + |E_2|^2$$

Commutation relations:

$$\left[\hat{a}_i, \hat{a}_j^{+}\right] = \delta_{ij}$$

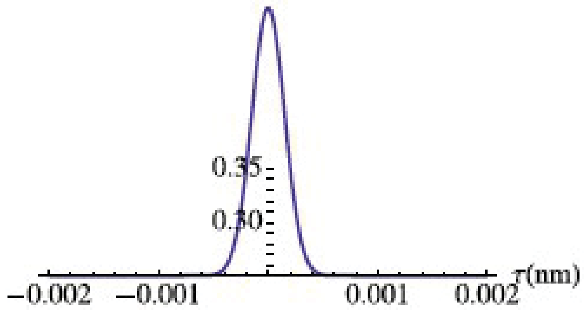
$$\boxed{\begin{array}{c} |\mathcal{R}|^2 + |\mathcal{T}|^2 = 1 \\ \phi_r - \phi_t = \pm\dfrac{\pi}{2} \end{array}}$$

Hong-Ou-Mandel effect

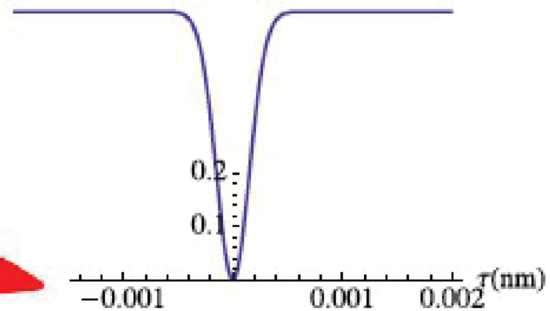
$R^2 = 1/2$

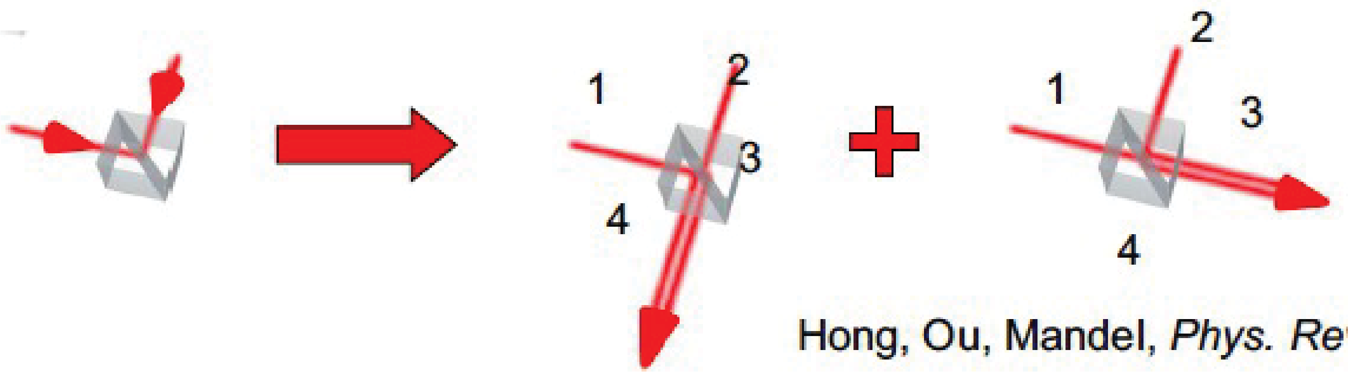
$$
\begin{aligned}
|1_1, 1_2\rangle &= a_1^\dagger a_2^\dagger |0\rangle \\
&= \left(\mathcal{R} a_3^\dagger + \mathcal{T} a_4^\dagger\right)\left(\mathcal{T} a_3^\dagger + \mathcal{R} a_4^\dagger\right)|0\rangle \\
&= \mathcal{R}\mathcal{T}\left[(a_3^\dagger)^2 + (a_3^\dagger)^2\right] + (\mathcal{R}^2 \cancel{-\mathcal{T}^2}) a_3^\dagger a_4^\dagger \\
&= \frac{|2_3, 0_4\rangle + |0_3, 2_4\rangle}{\sqrt{2}}
\end{aligned}
$$

Coincidences on the same output mode



Coincidences on different modes



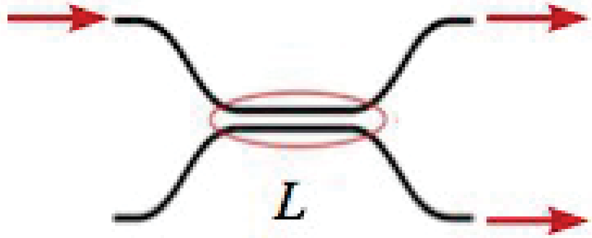


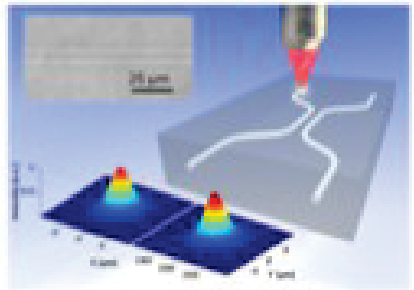
Hong, Ou, Mandel, *Phys. Rev. Lett.* **59**, 2044 (1987)

Beam splitter: Hong-Ou-Mandel effect

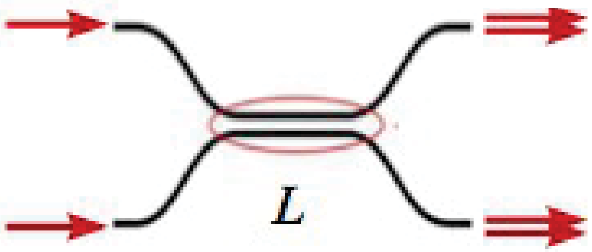
$$\boxed{\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}}$$

Single photons





Indistinguishable photons

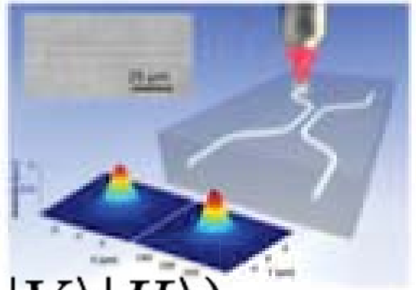


Hong-Ou-Mandel effect: Bosonic coalescence

Two-photon always emerge from the same output port

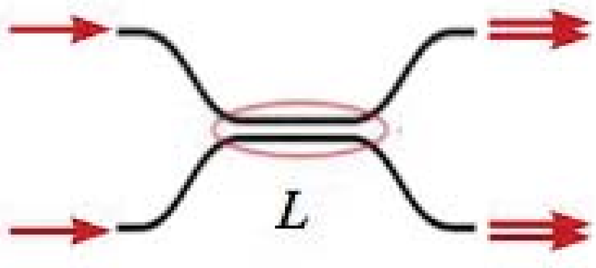
Beam splitter: polarization entangled states

Two photons entangled in the polarization DOF

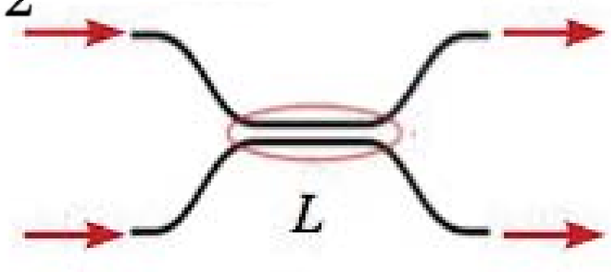


$$\{|\Psi^+\rangle, |\Phi^-\rangle, |\Phi^+\rangle\}$$

$$|\psi^-\rangle = \frac{2}{\sqrt{2}} (|H\rangle|V\rangle - |V\rangle|H\rangle)$$



Symmetric states: Triplet



Antisymmetric state: Singlet

Monolithic semiconductor parametric sources

PRL **108,** 153605 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

Monolithic Source of Photon Pairs

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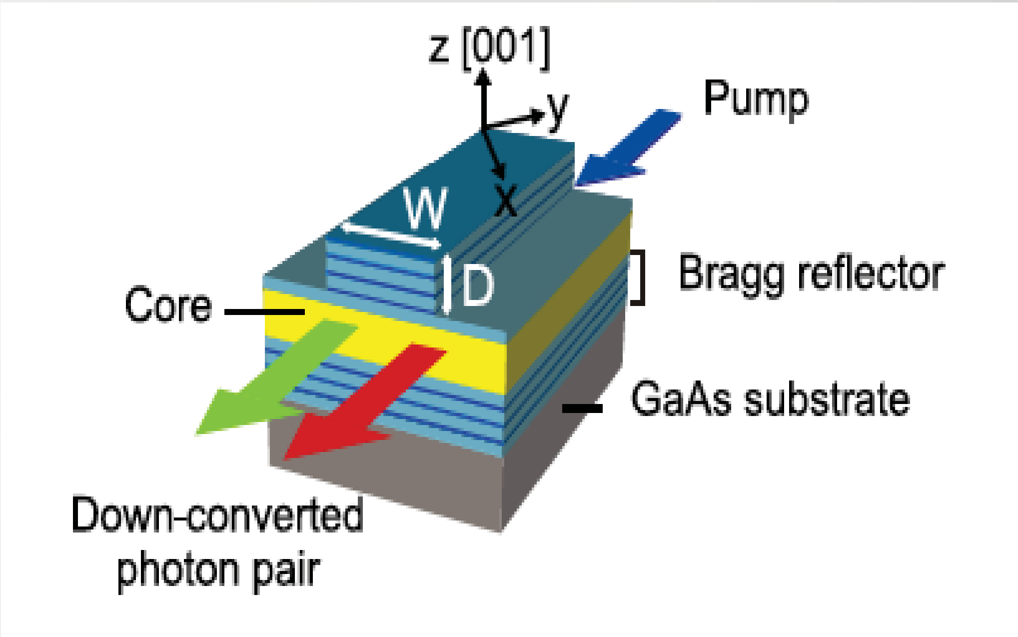
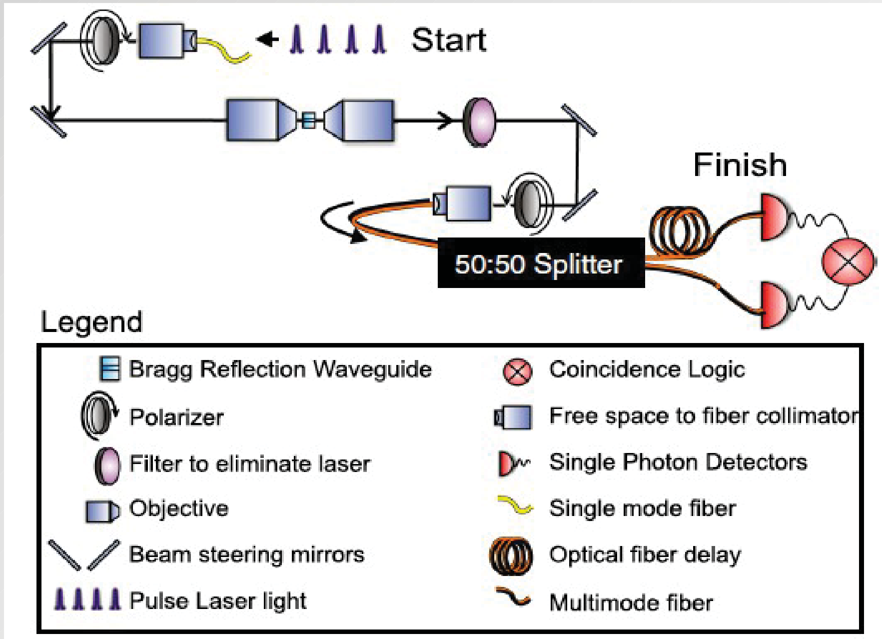
[1]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue W, Waterloo, Ontario, N2L 3G1, Canada*
[2]*The Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, Ontario M5S 3G4, Canada*
[3]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria*





Semiconductor Waveguide Source of Counterpropagating Twin Photons

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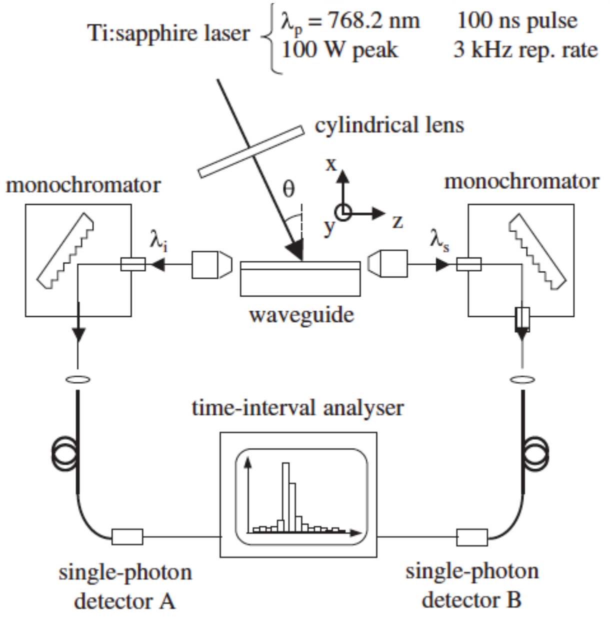
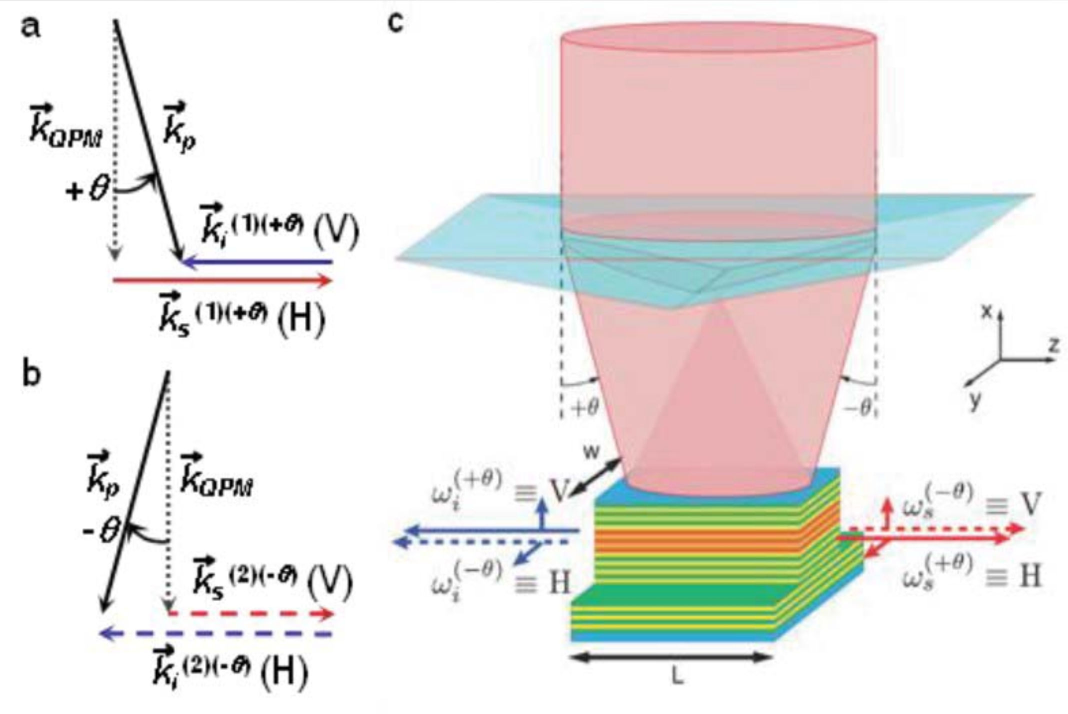
(Received 10 July 2006; published 23 October 2006)

We experimentally demonstrate an integrated semiconductor source of counterpropagating twin photons in the telecom range. A pump beam impinging on top of an AlGaAs waveguide generates parametrically two counterpropagating, orthogonally polarized signal/idler guided modes. A 2 mm long waveguide emits at room temperature one average photon pair per pump pulse, with a spectral linewidth of 0.15 nm. The twin character of the emitted photons is ascertained through a time-correlation measurement. This work opens a route towards new guided-wave semiconductor quantum devices.



A. Orieux *et al.* arXiv:1301.1764



Thank you!