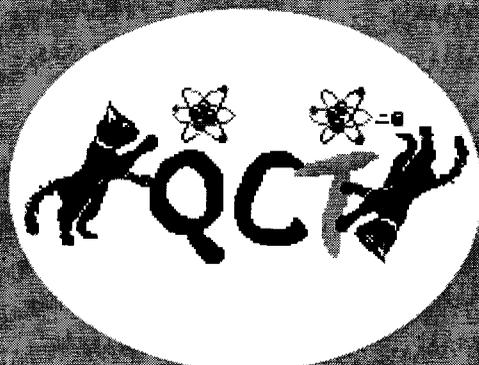




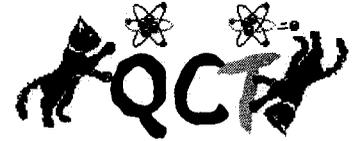
Schrödinger's Rainbow: The Renaissance in Quantum Optical Interferometry



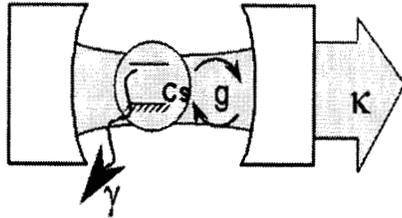
Jonathan P. Dowling

*Quantum Computing Technologies (QCT) Group
Explorations Systems Autonomy, Sec. 367*

<http://cs.jpl.nasa.gov/qct.html/qat.html>

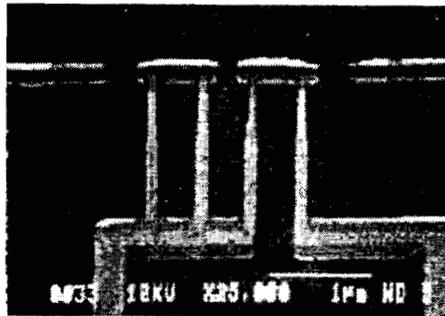
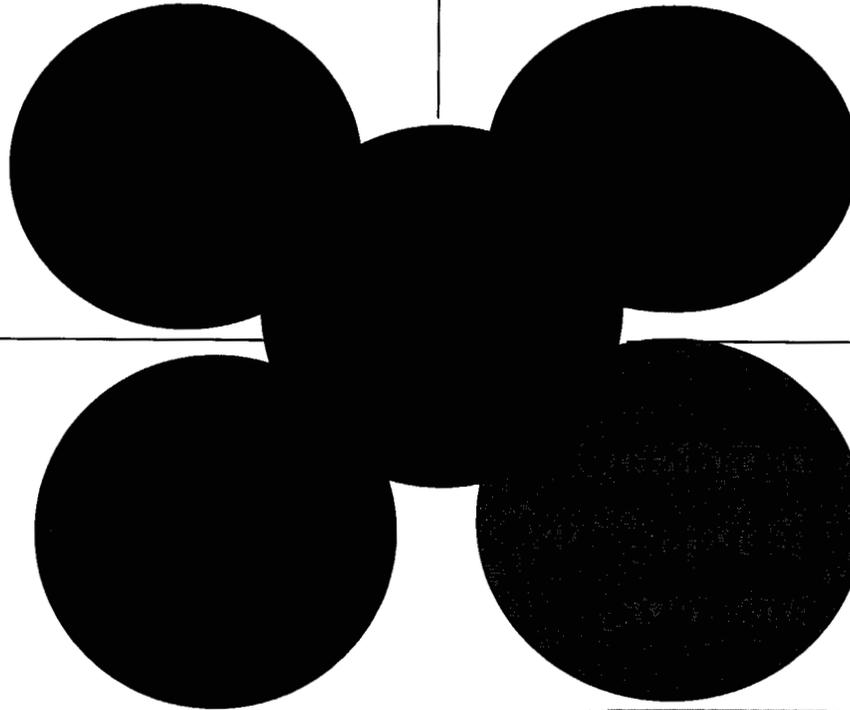


-
- **Quantum Technologies**
 - **Schrödinger's Cat and All That**
 - **Quantum Light—Over the Rainbow**
 - **Putting Entangled Light to Work**
 - **The Yellow-Brick Roadmap**



Ion Traps
Cavity QED
Linear Optics

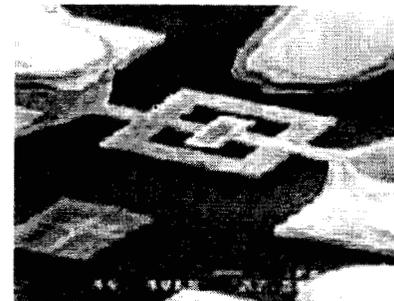
Bose-Einstein
Atomic Coherence
Ion Traps



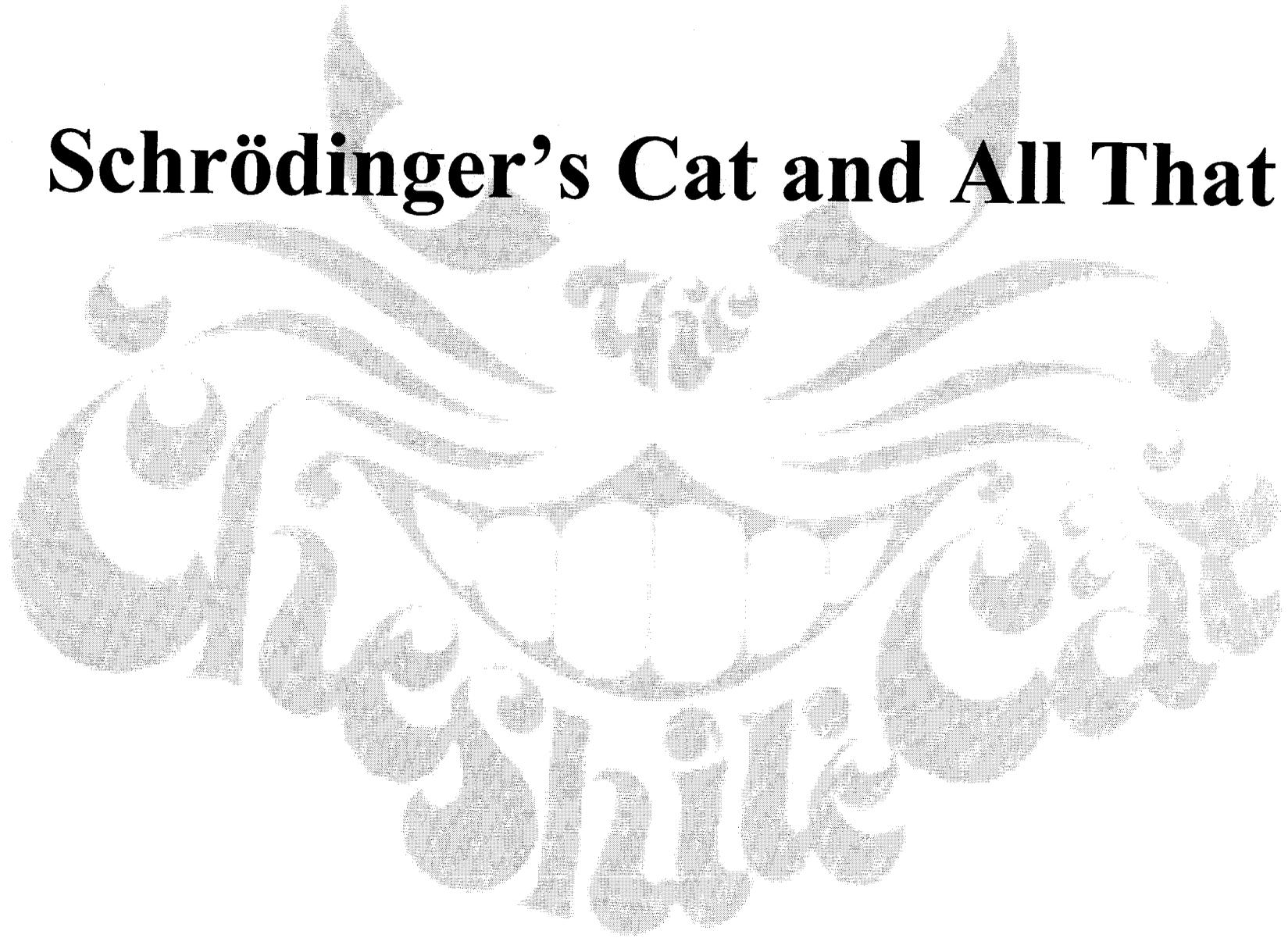
Superconductors
Excitons
Spintronics

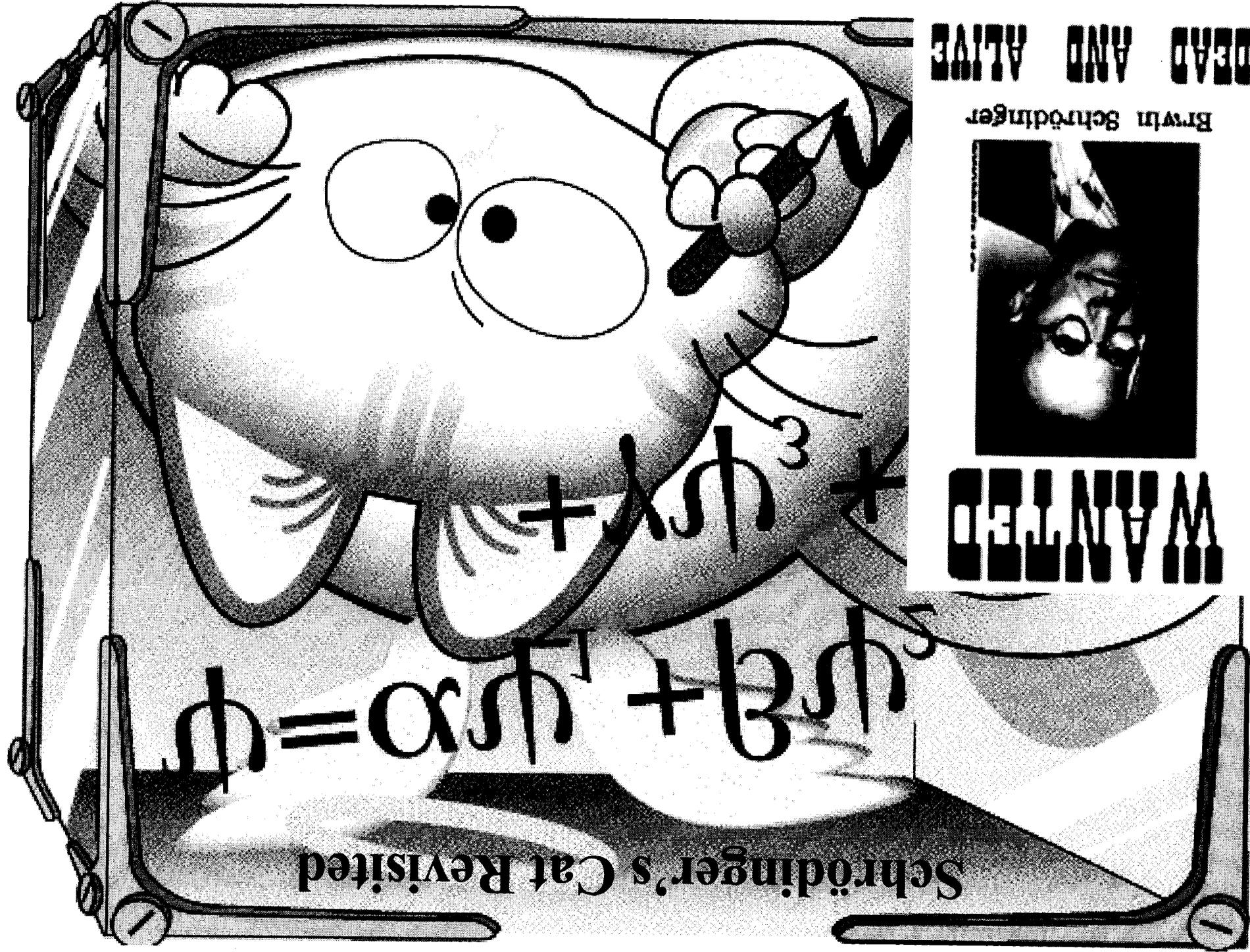


Pendulums
Cantilevers
Phonons



Schrödinger's Cat and All That





Schrödinger's Cat Revisited

$$\psi = \alpha\psi^1 + \beta\psi^2$$

$$\psi^3 + \psi^4 + \psi^5$$

DEAD AND ALIVE

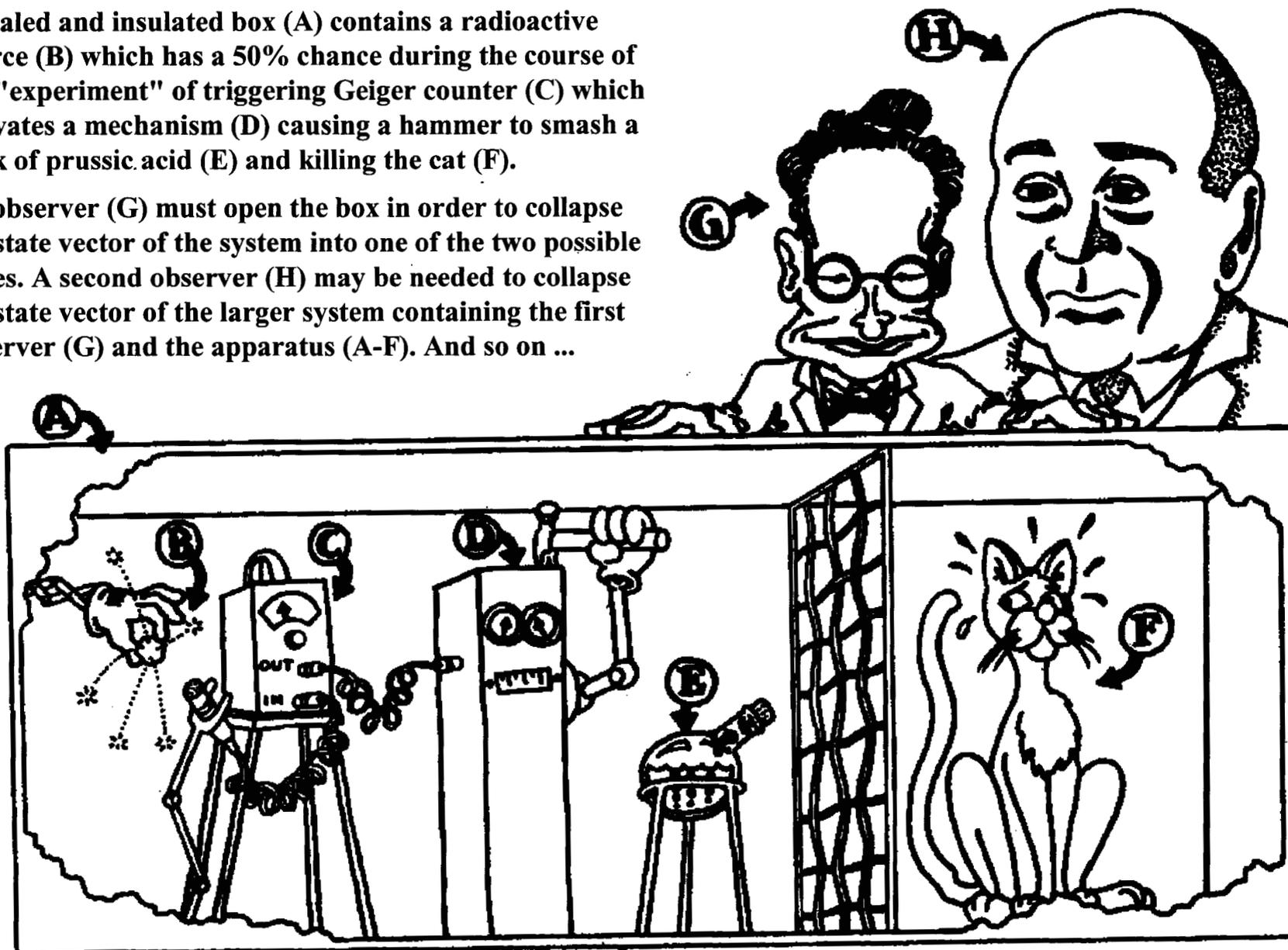
Brrin Schrödinger



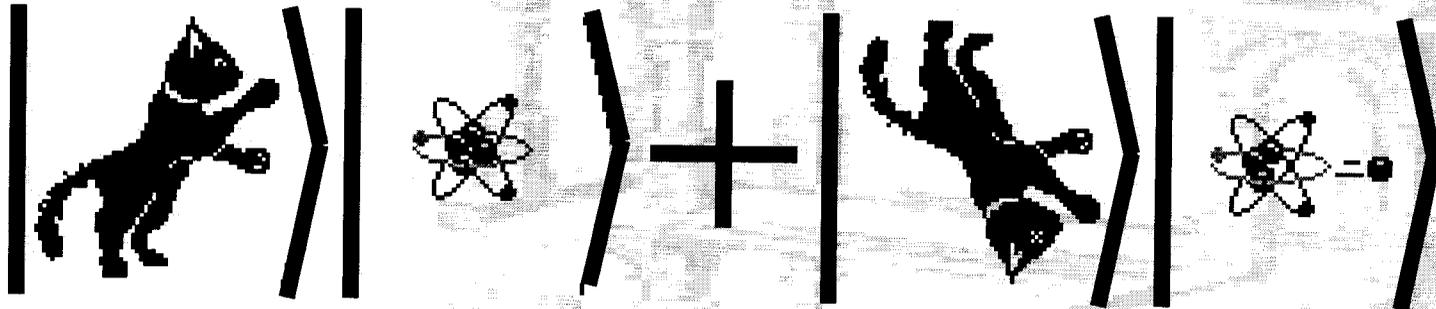
WANTED

A sealed and insulated box (A) contains a radioactive source (B) which has a 50% chance during the course of the "experiment" of triggering Geiger counter (C) which activates a mechanism (D) causing a hammer to smash a flask of prussic acid (E) and killing the cat (F).

An observer (G) must open the box in order to collapse the state vector of the system into one of the two possible states. A second observer (H) may be needed to collapse the state vector of the larger system containing the first observer (G) and the apparatus (A-F). And so on ...



Paradox? What Paradox!?



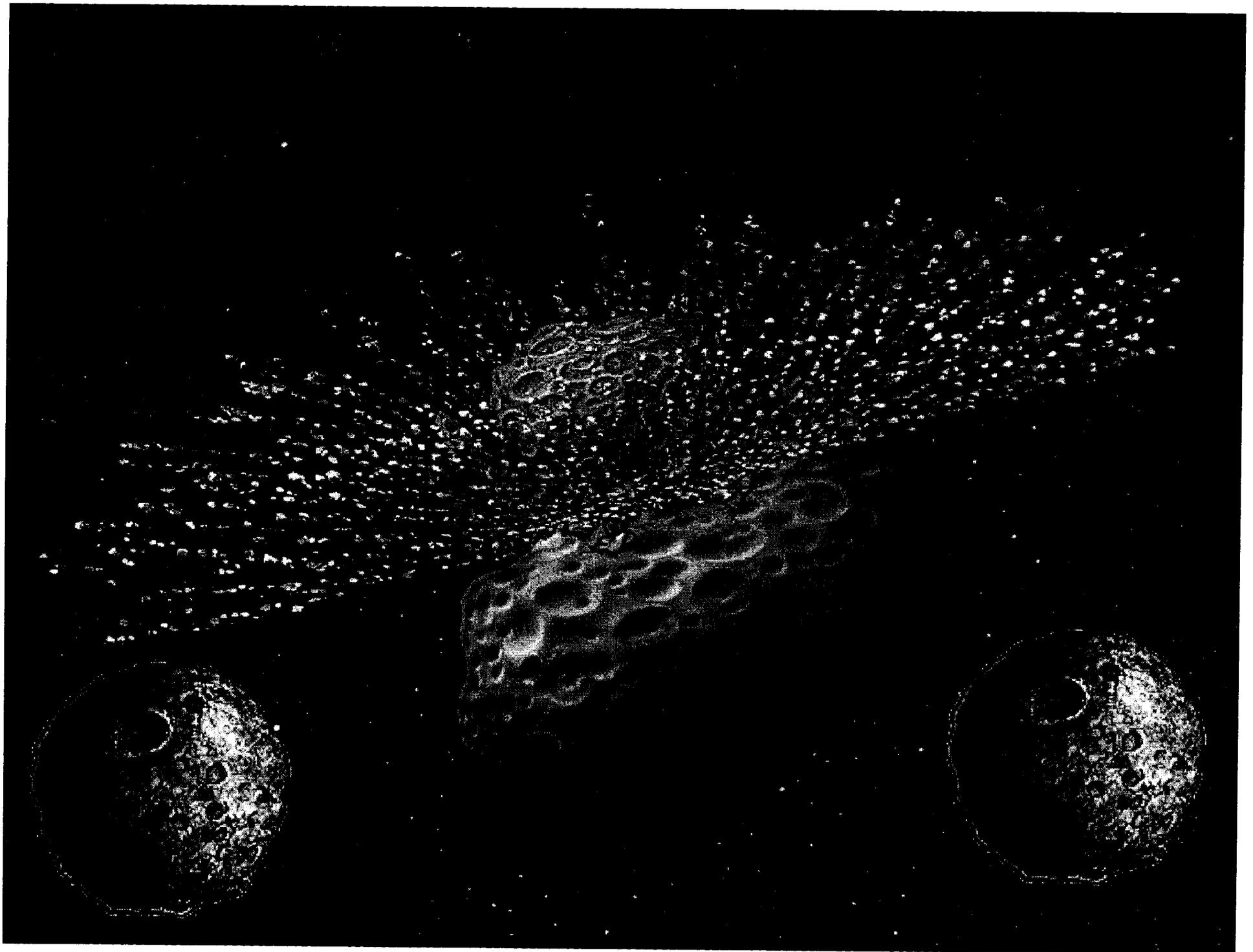
- (1.) The State of the Cat is “Entangled” with That of the Atom.
- (2.) The Cat is in a Simultaneous Superposition of Dead & Alive.
- (3.) Observers are Required to “Collapse” the Cat to Dead or Alive

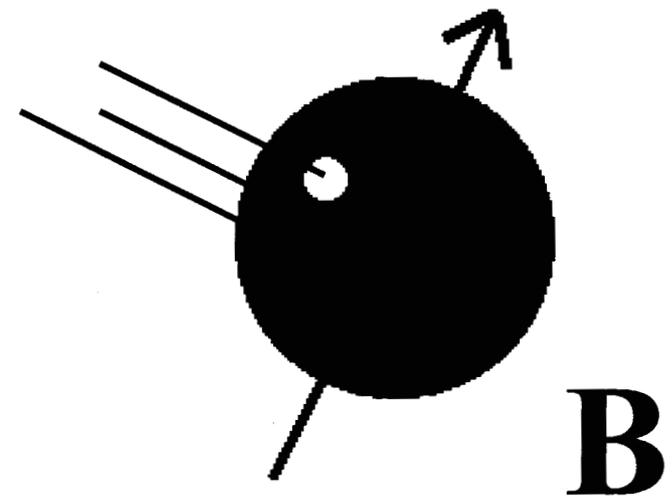
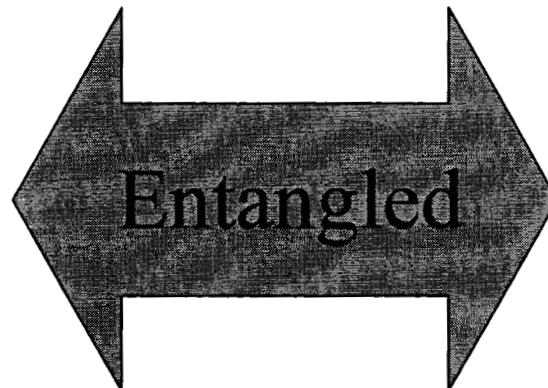
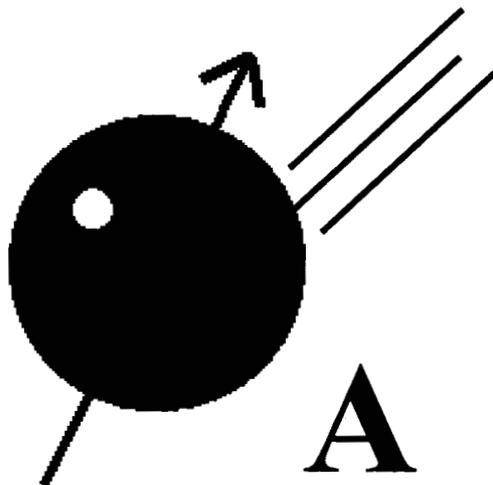
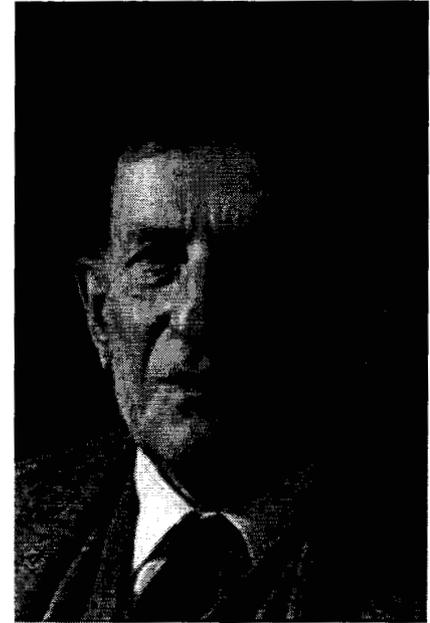
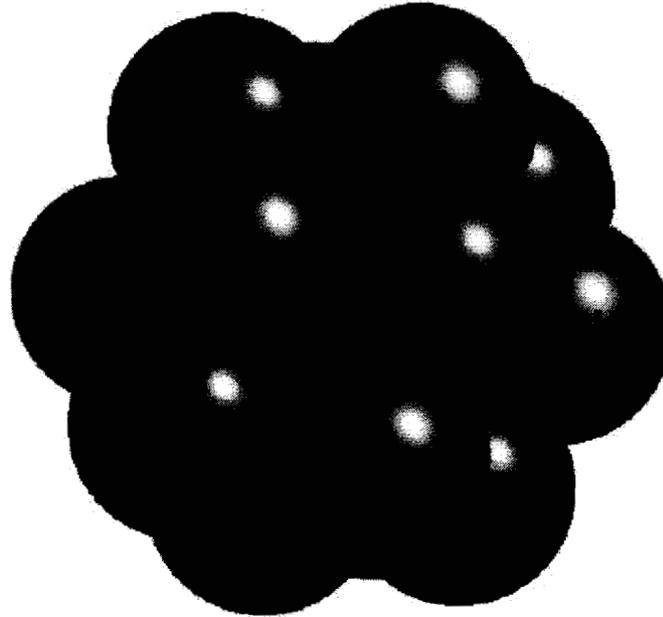
Quantum Entanglement

“Quantum entanglement is *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.”

— Erwin Schrödinger

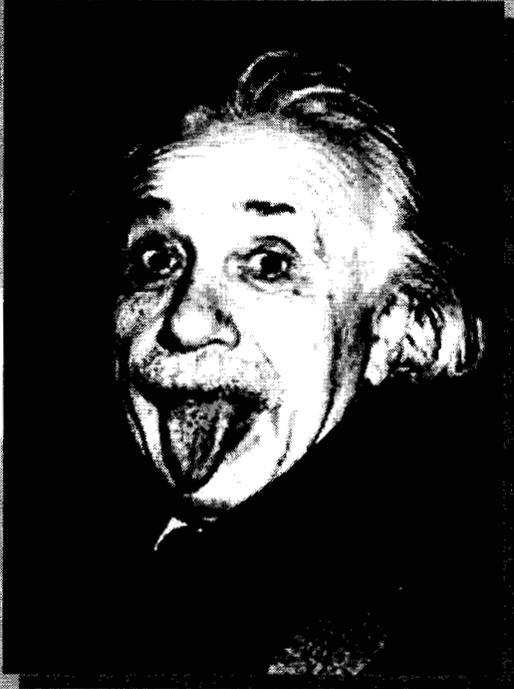




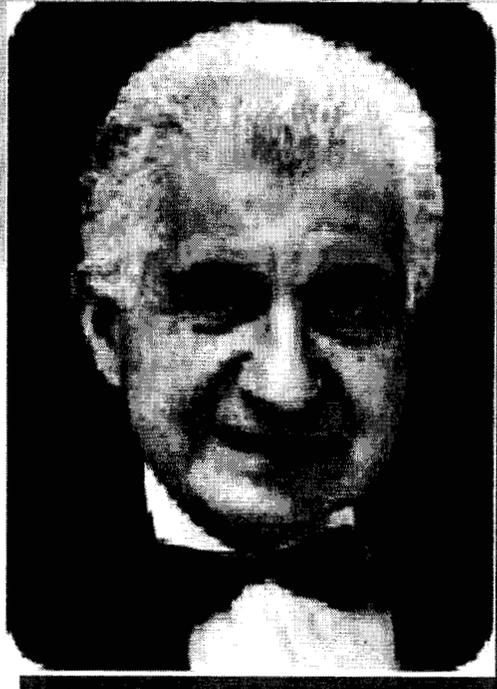


Einstein, Podolsky, Rosen (EPR) Paradox

Albert Einstein



Boris Podolsky

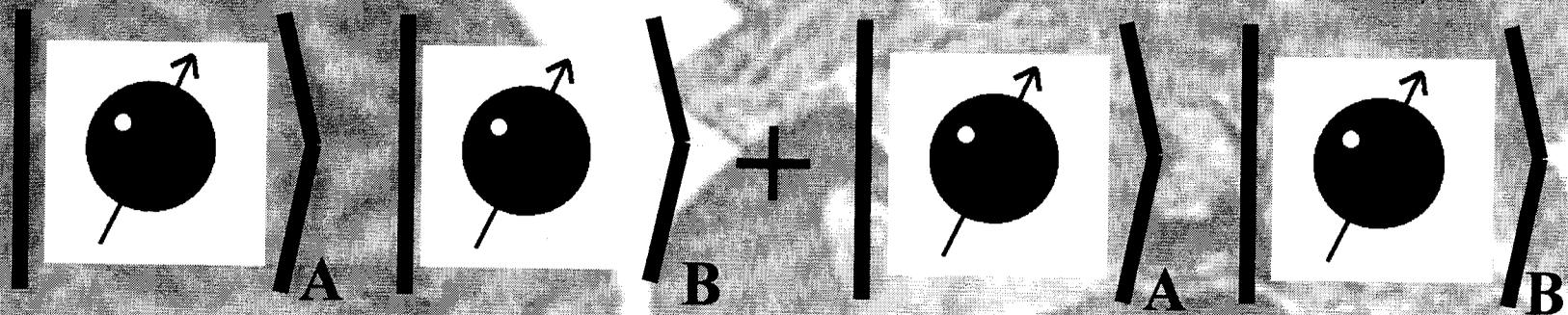


Nathan Rosen

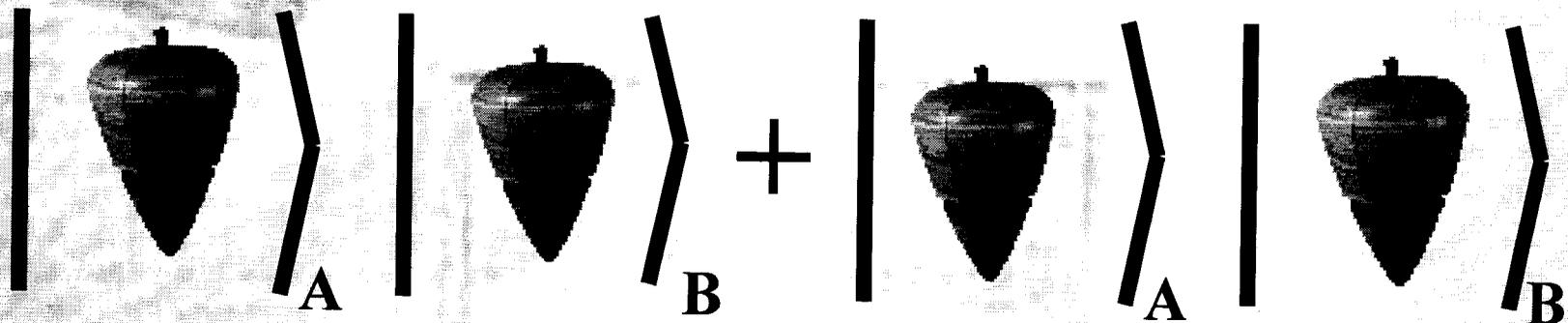


“If, without in any way disturbing a system, we can predict with certainty ... the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.”

Hidden Variable Theory



Can the Spooky, Action-at-a-distance Predictions
(Entanglement) of Quantum Mechanics...

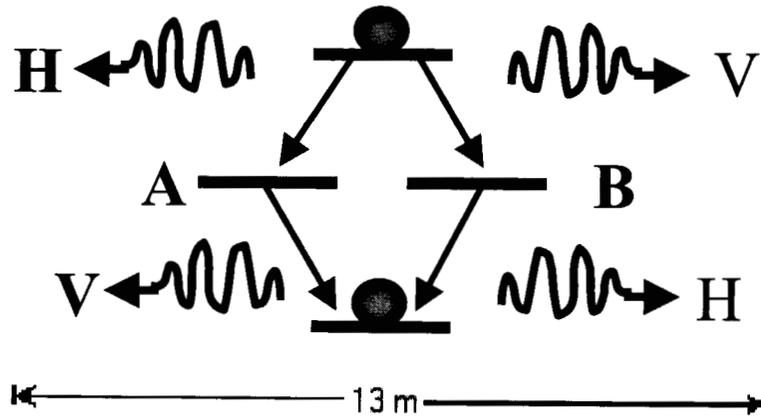


...Be Replaced by Some Sort of Local, Statistical,
Classical (Hidden Variable) Theory?

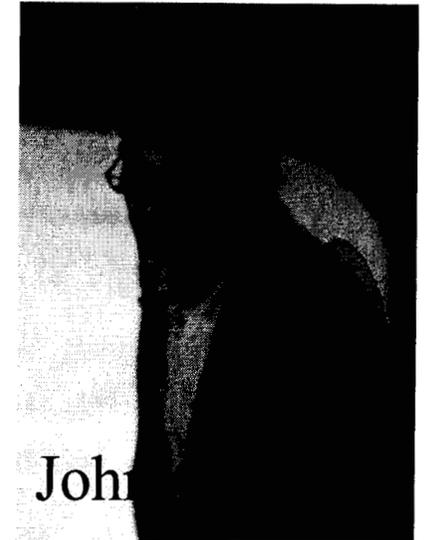
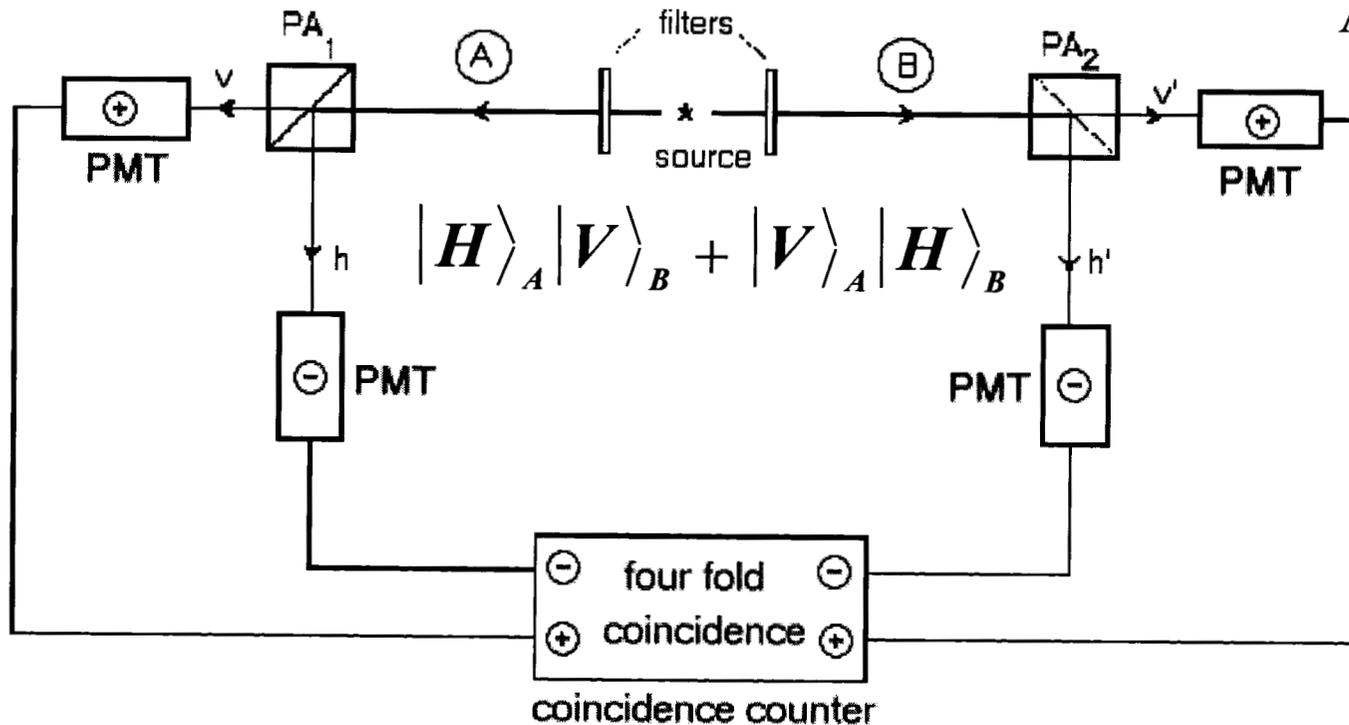


The physical predictions of quantum theory disagree with those of any local (classical) hidden-variable theory!

Two-Photon
Atomic
Decay



Alain Aspect



John Clauser

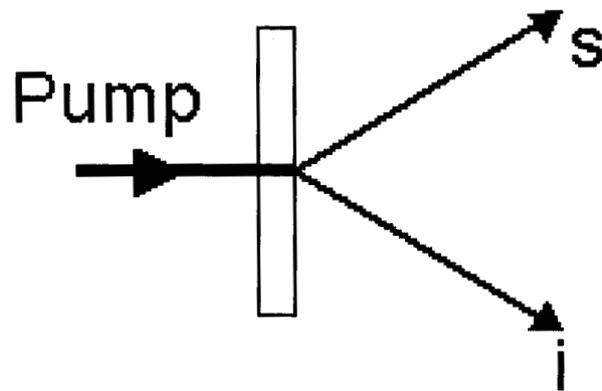
V = Vertical Polarization

H = Horizontal Polarization

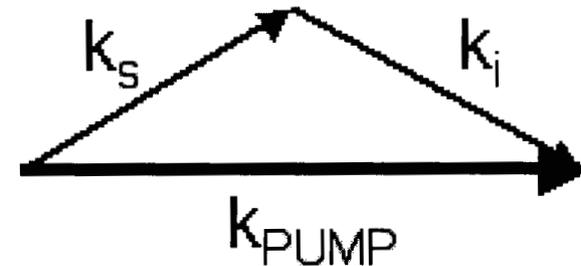


Quantum Light—Over the Rainbow

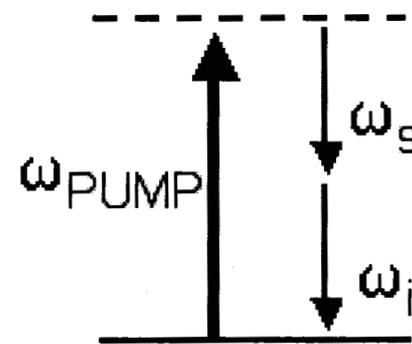
Downconversion



Momentum is conserved..

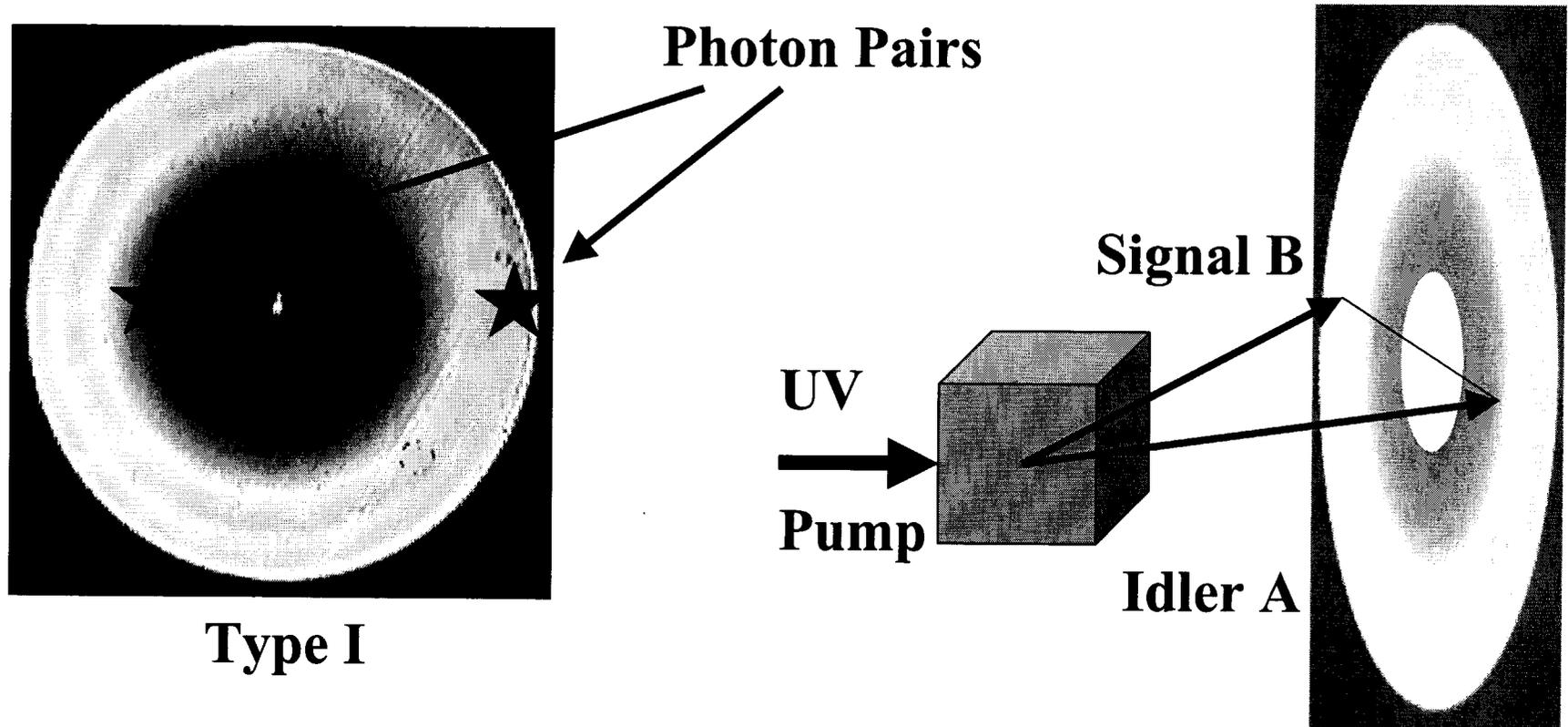


..as well as energy



$$\varphi_{PUMP} = \varphi_s + \varphi_i$$

- A pump photon is spontaneously converted into two lower frequency photons in a material with a nonzero $\chi^{(2)}$

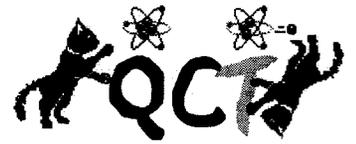


Degenerate (Entangled) Case: $\omega_s = \omega_i$

$$|\omega_s, \varphi_s, \mathbf{k}_s\rangle_A |\omega_i, \varphi_i, \mathbf{k}_s\rangle_B + |\omega_i, \varphi_i, \mathbf{k}_i\rangle_A |\omega_s, \varphi_s, \mathbf{k}_s\rangle_B$$

JPL

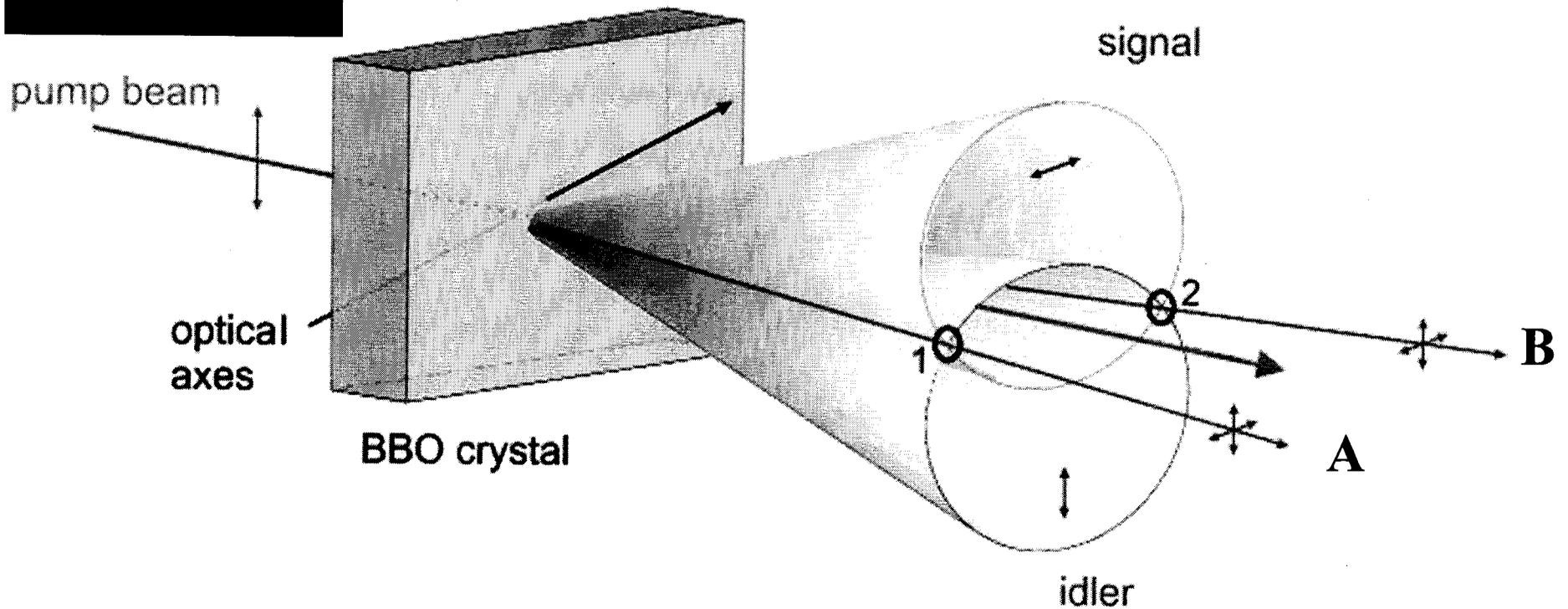
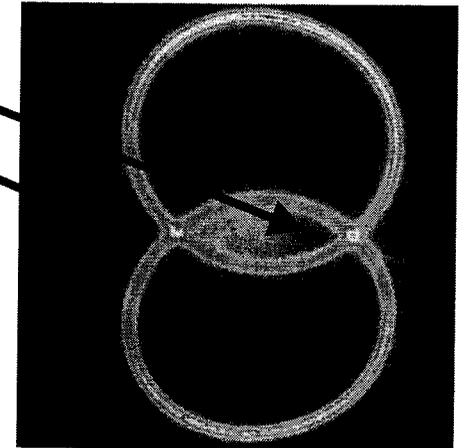
Parametric Downconversion: Type I



QuickTime™ and a Sorenson Video decompressor are needed to see this picture.

Degenerate (Entangled) Case: $\omega_s = \omega_i$

$$|H\rangle_A |V\rangle_B + |V\rangle_A |H\rangle_B$$

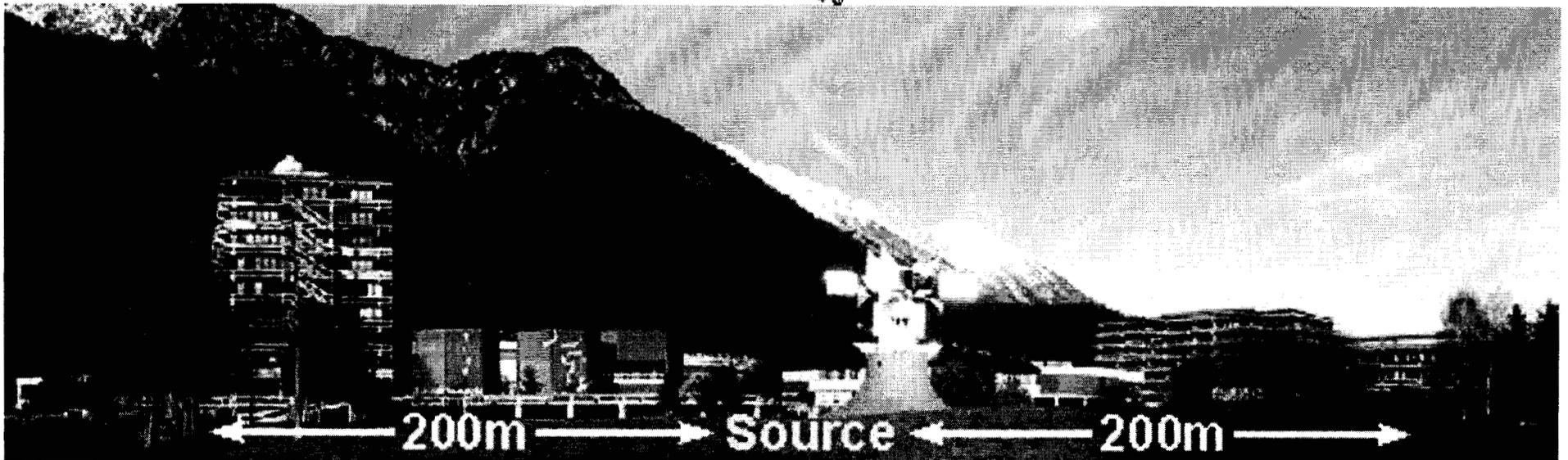
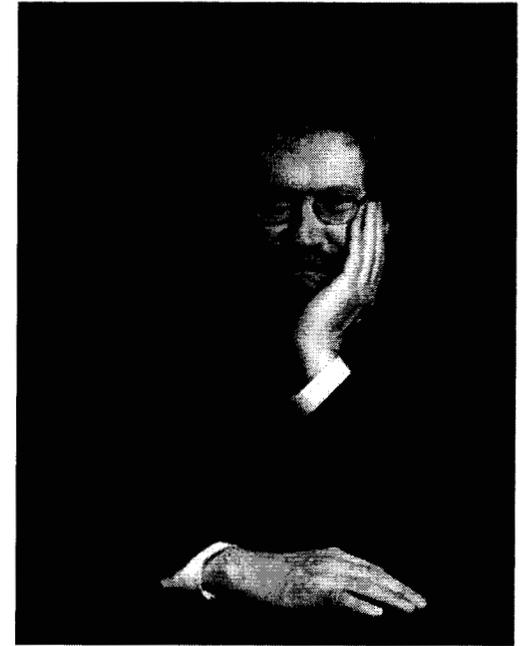
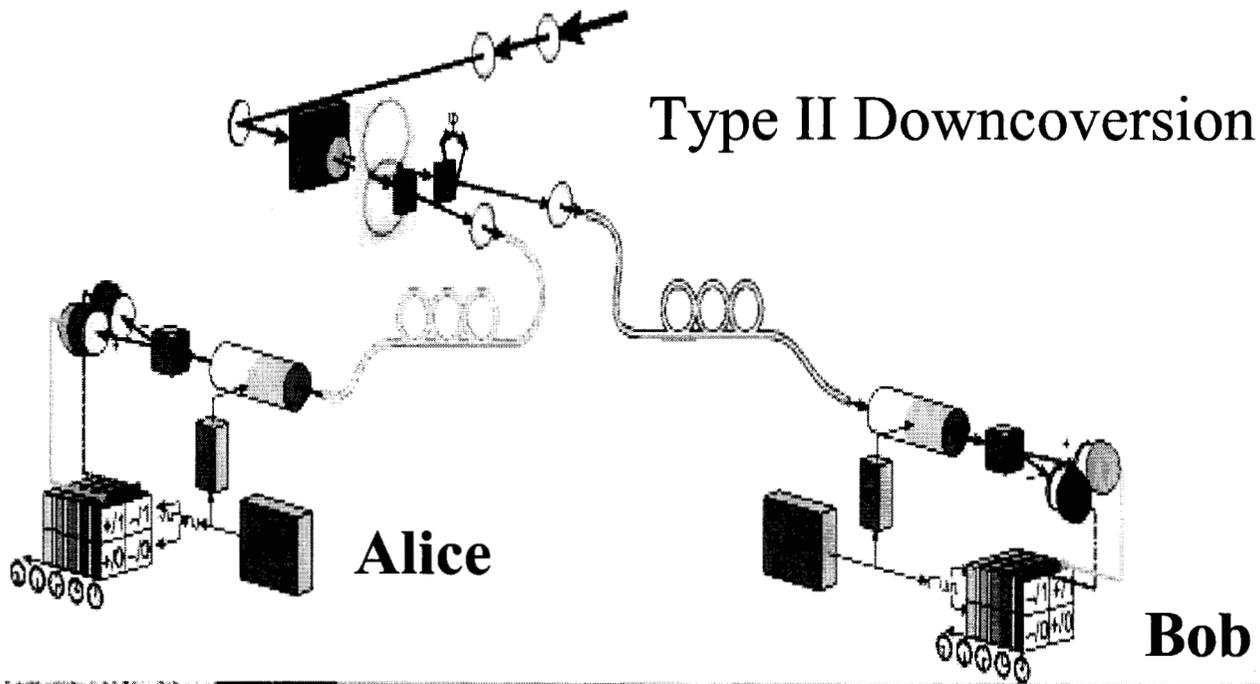


JPL



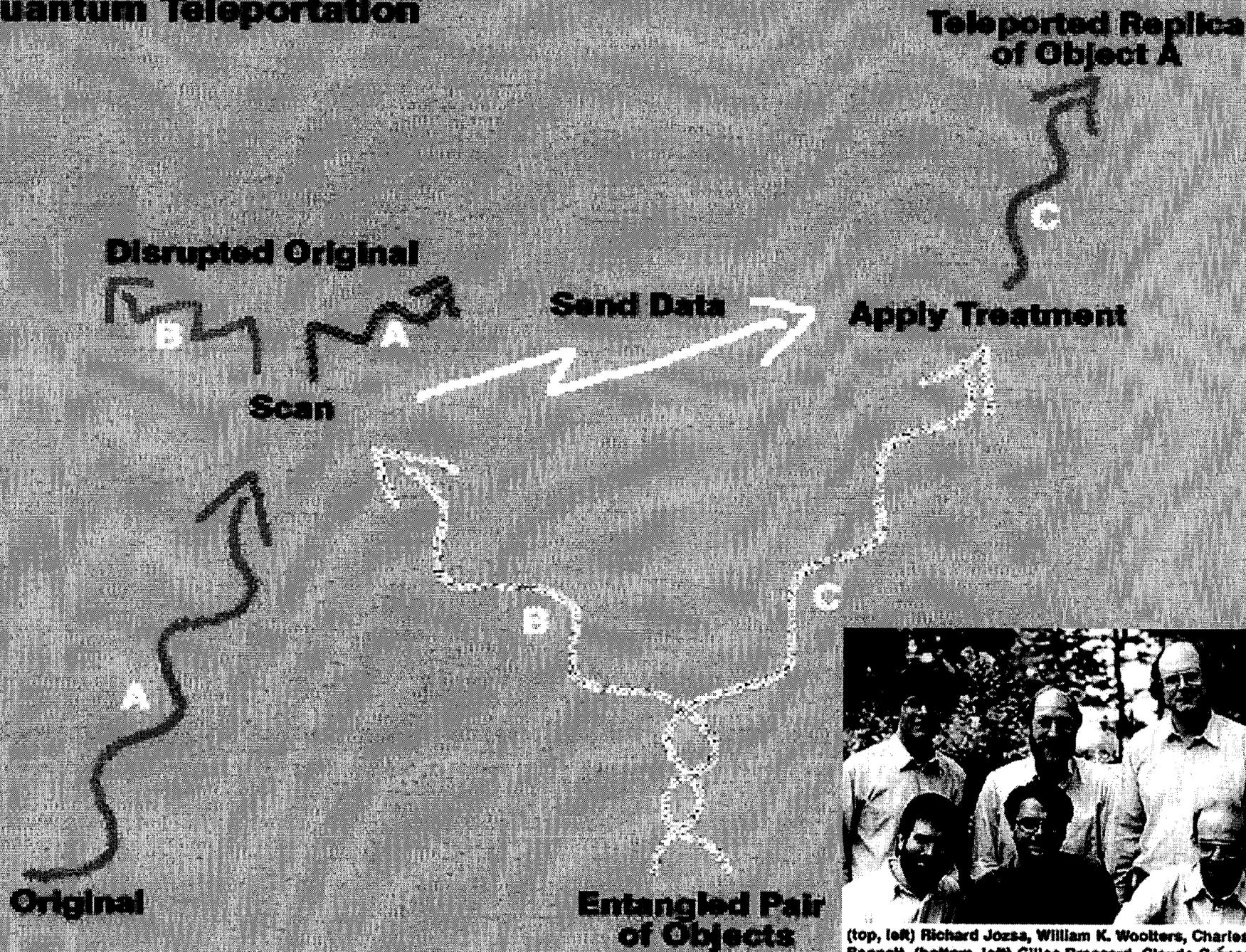
QuickTime™ and a Animation decompressor are needed to see this picture.



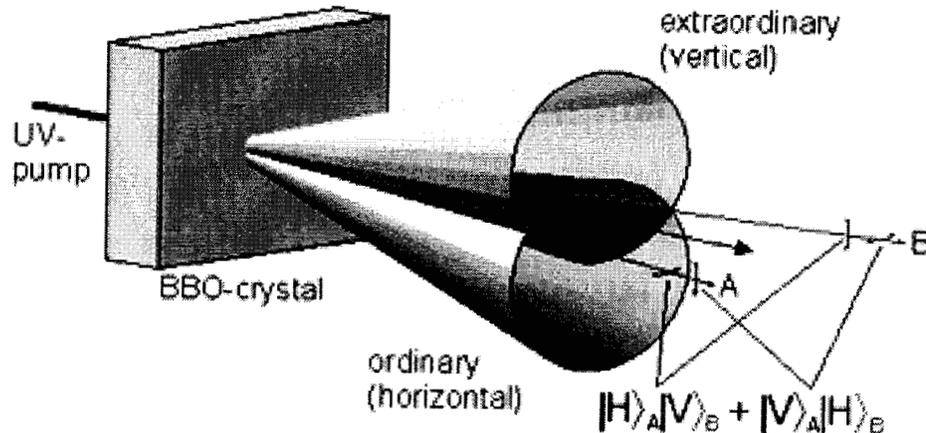




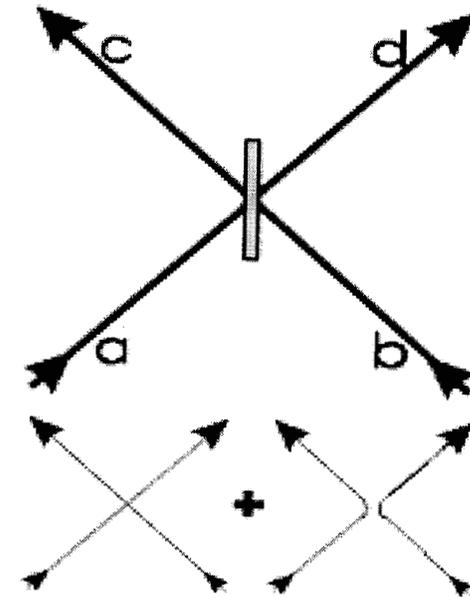
Quantum Teleportation



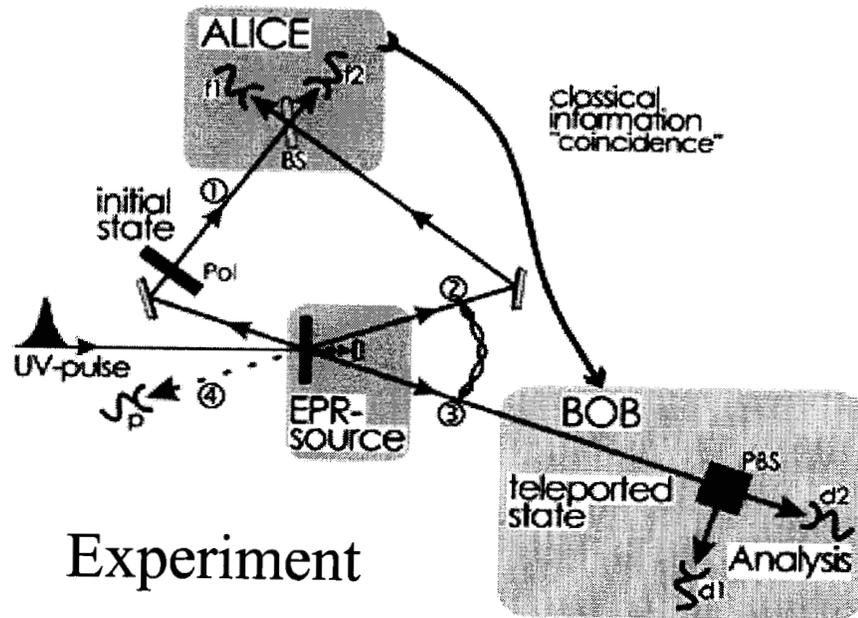
(top, left) Richard Jozsa, William K. Woollers, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.



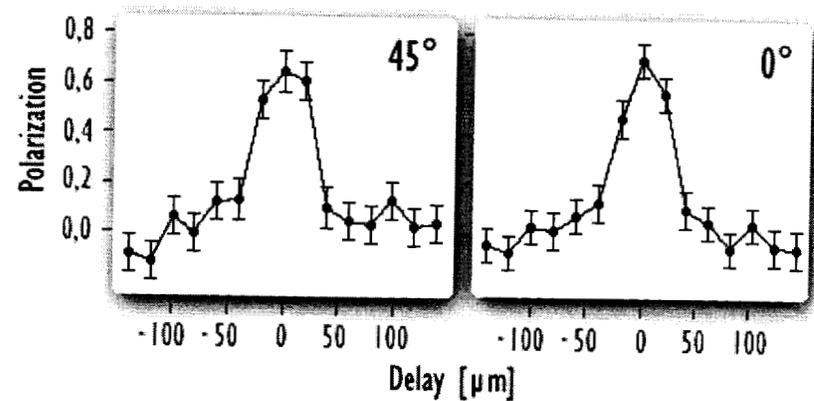
EPR Source

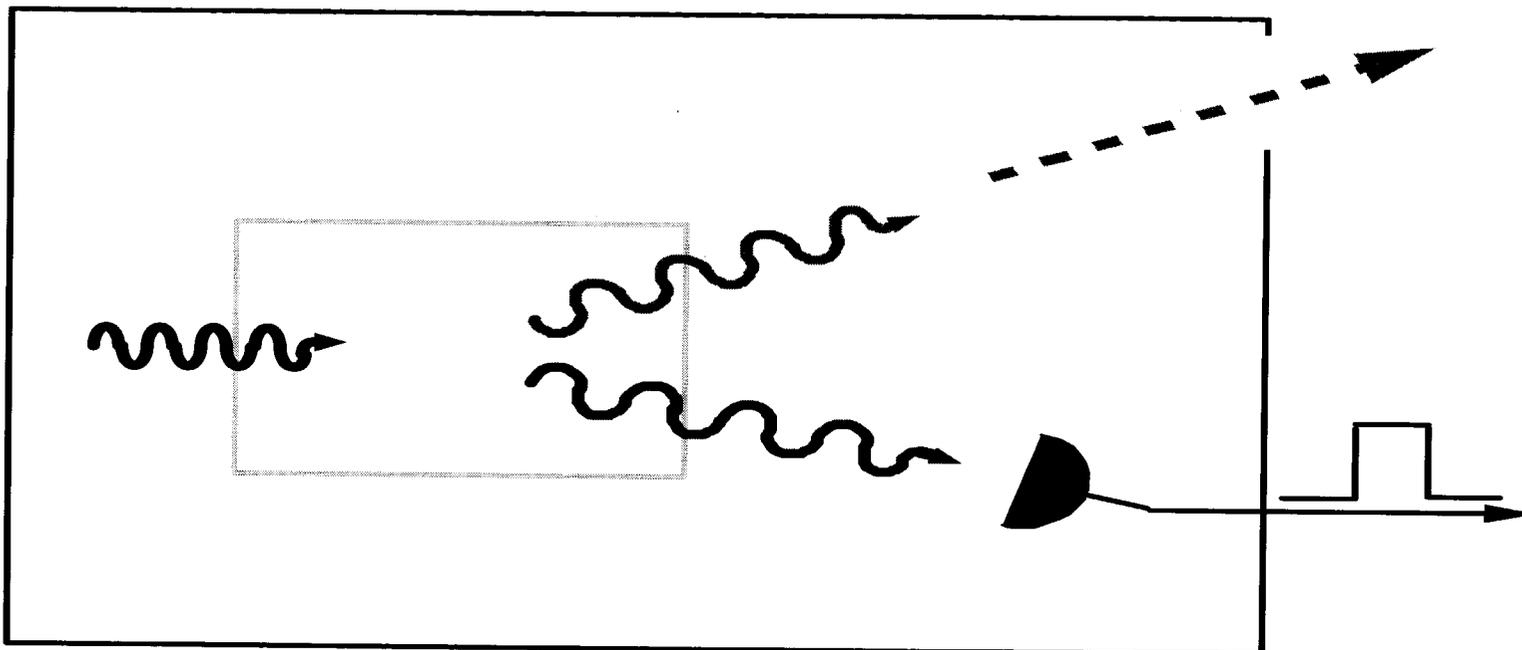


Bell State Analysis

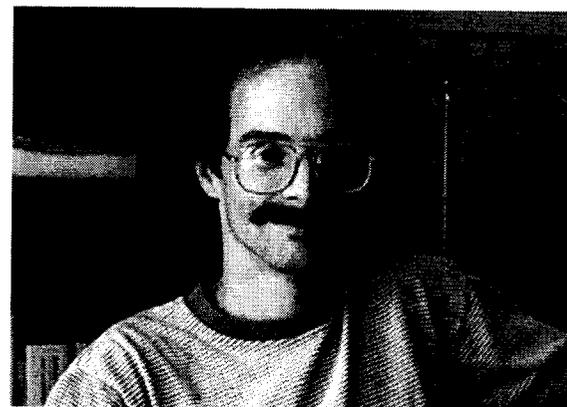


Experiment

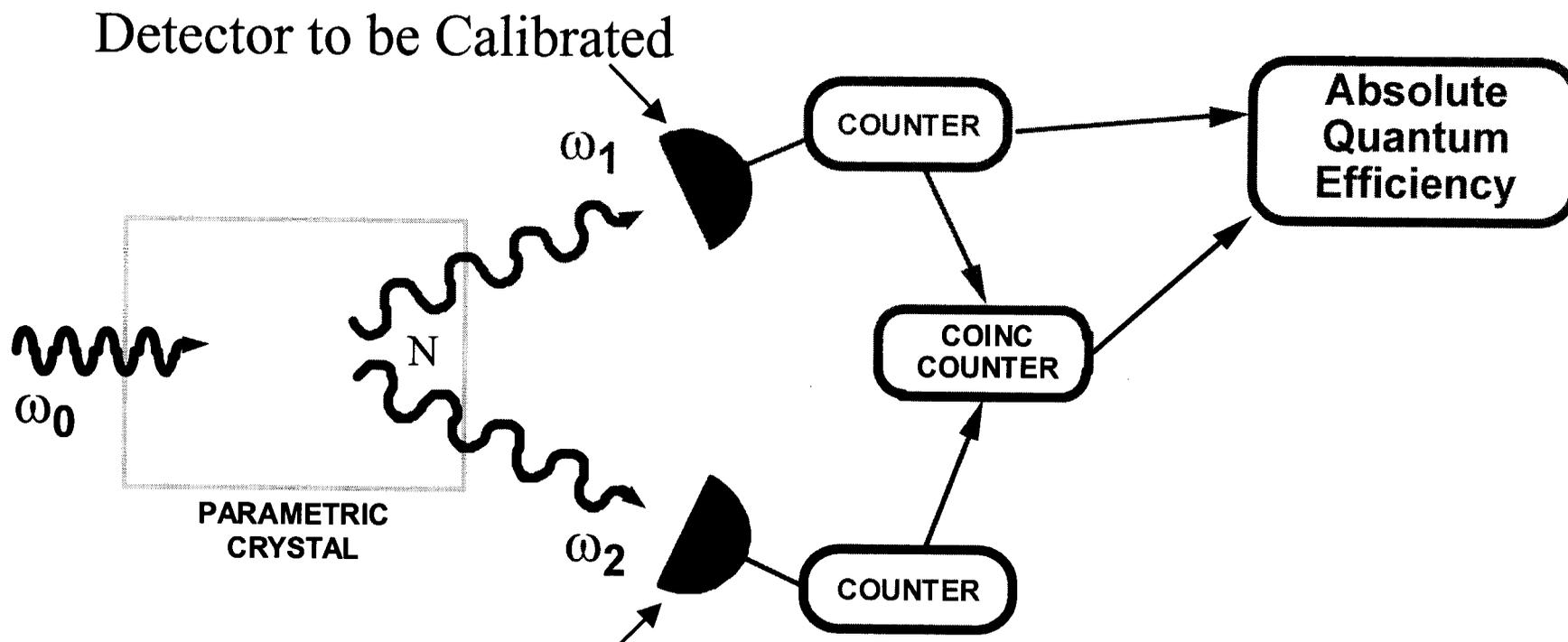


**Output characteristics :**

- photon #** → **known**
- photon timing** → **known**
- wavelength** → **known**
- direction** → **known**
- polarization** → **known**



Alan Migdall

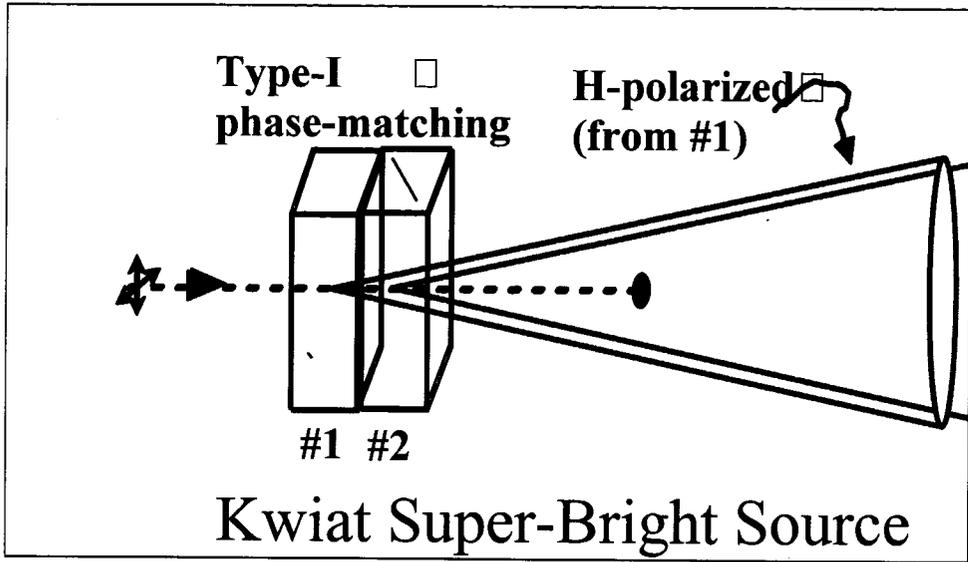


Trigger or "Herald" Detector

$$N_1 = \eta_1 N \quad N_2 = \eta_2 N \quad N_C = \eta_1 \eta_2 N$$

$$\eta_1 = N_C / N_2$$

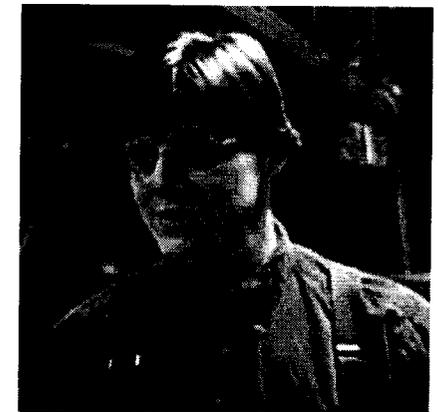
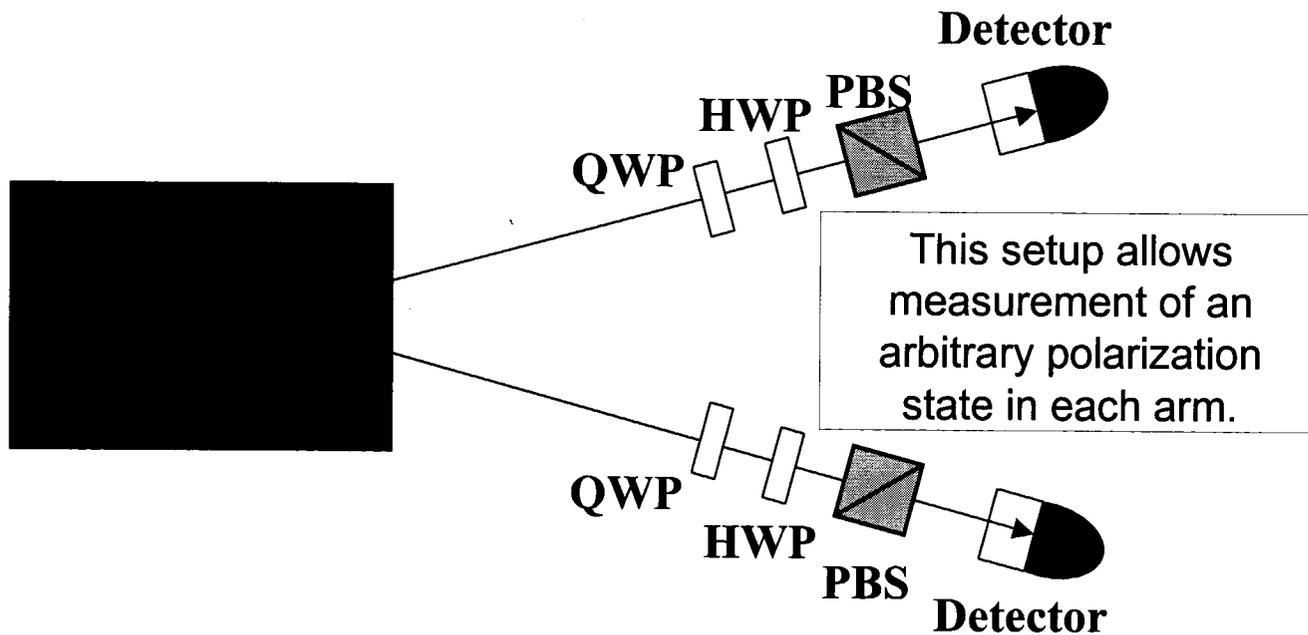
No External Standards Needed!



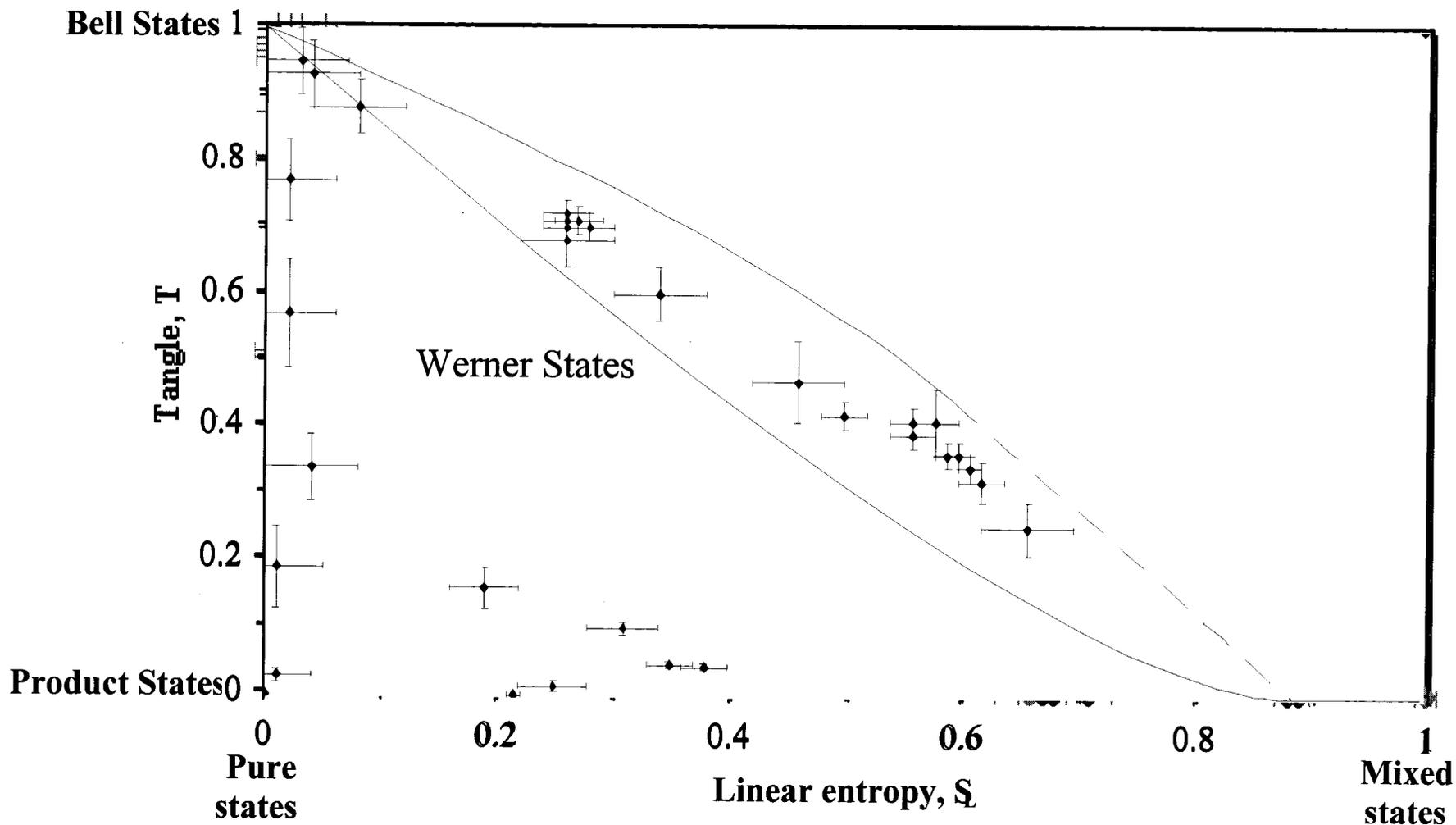
Any two-photon tomography requires 16 of these measurements.

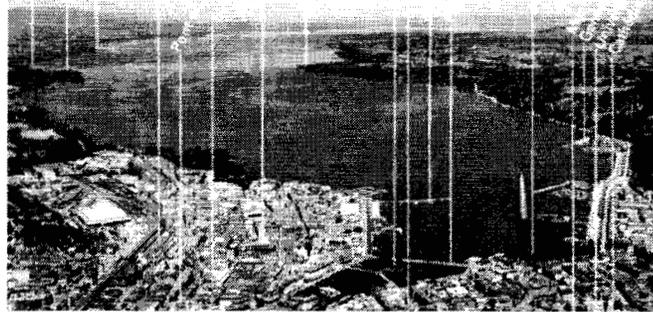
Examples

<u>Arm 1</u>	<u>Arm 2</u>
H	V
H	R
D	D

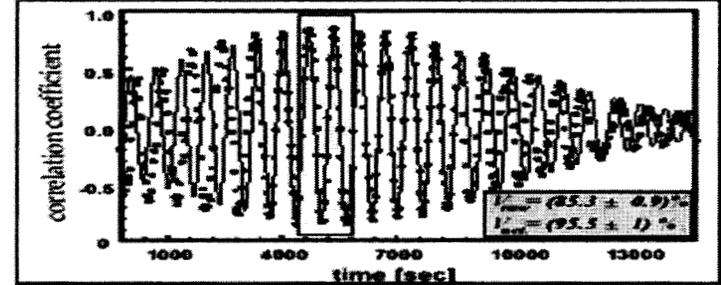
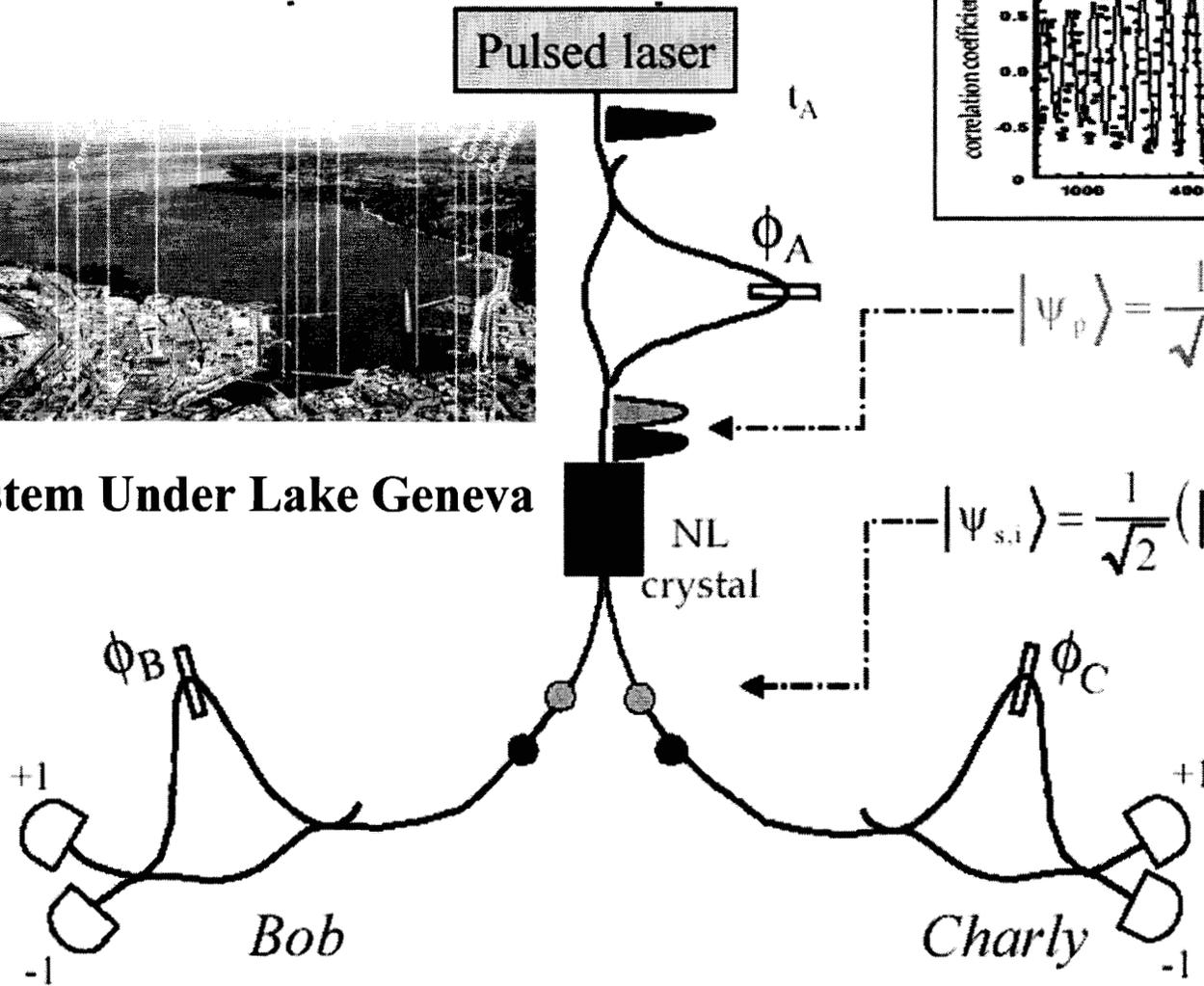


Paul Kwiat
U. Illinois





System Under Lake Geneva



$$|\psi_p\rangle = \frac{1}{\sqrt{2}} (|s\rangle_p + e^{i\theta} |l\rangle_p)$$

$$|\psi_{s,i}\rangle = \frac{1}{\sqrt{2}} (|s\rangle_s |s\rangle_i + e^{i\theta} |l\rangle_s |l\rangle_i)$$



Bob and "Charly" Share Random Crypto Key

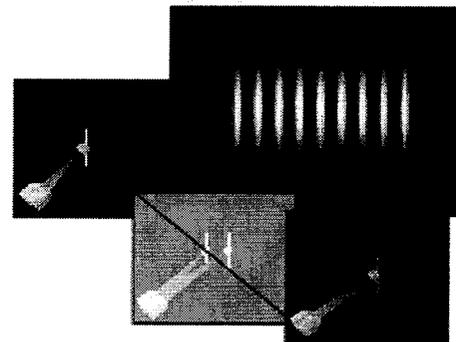
Nicolas Gisin

Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit

Agedi N. Boto,¹ Pieter Kok,² Daniel S. Abrams,¹ Samuel L. Braunstein,²
Colin P. Williams,¹ and Jonathan P. Dowling^{1,*}

WHAT'S NEXT *New York Times*
Quantum Leap May Transform Chips

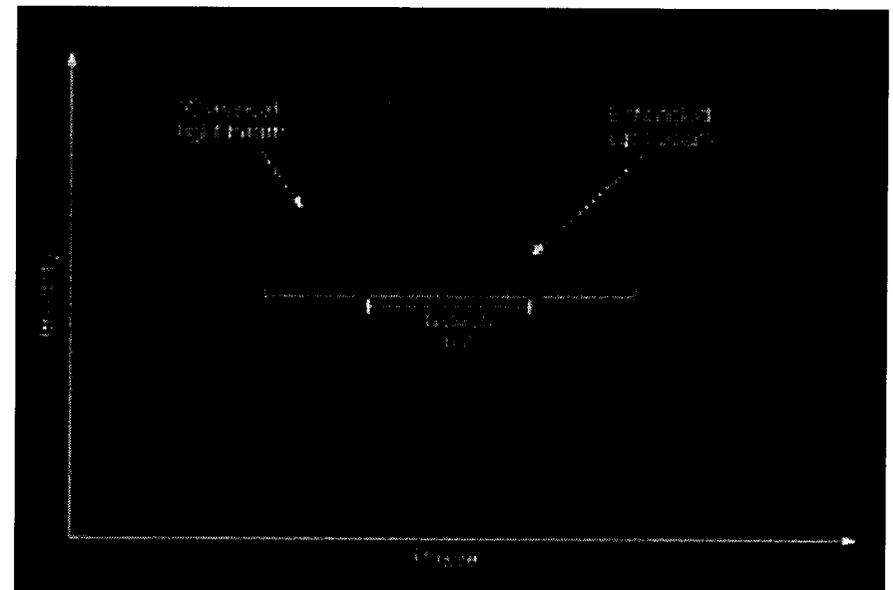
By IAN AUSTEN



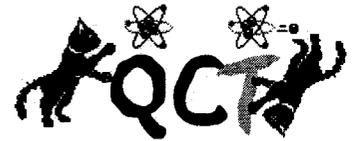
physics : Fine lines
PHILIP BALL *nature*

Science

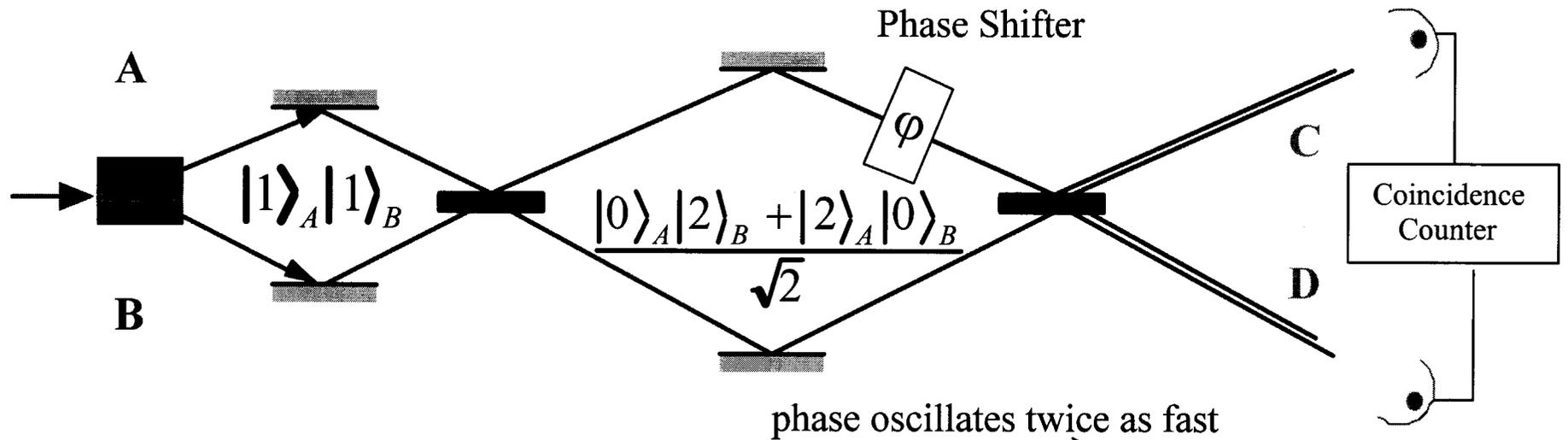
Yoked Photons Break a Light Barrier



The Hong-Ou-Mandel Effect



Parametric Downconversion



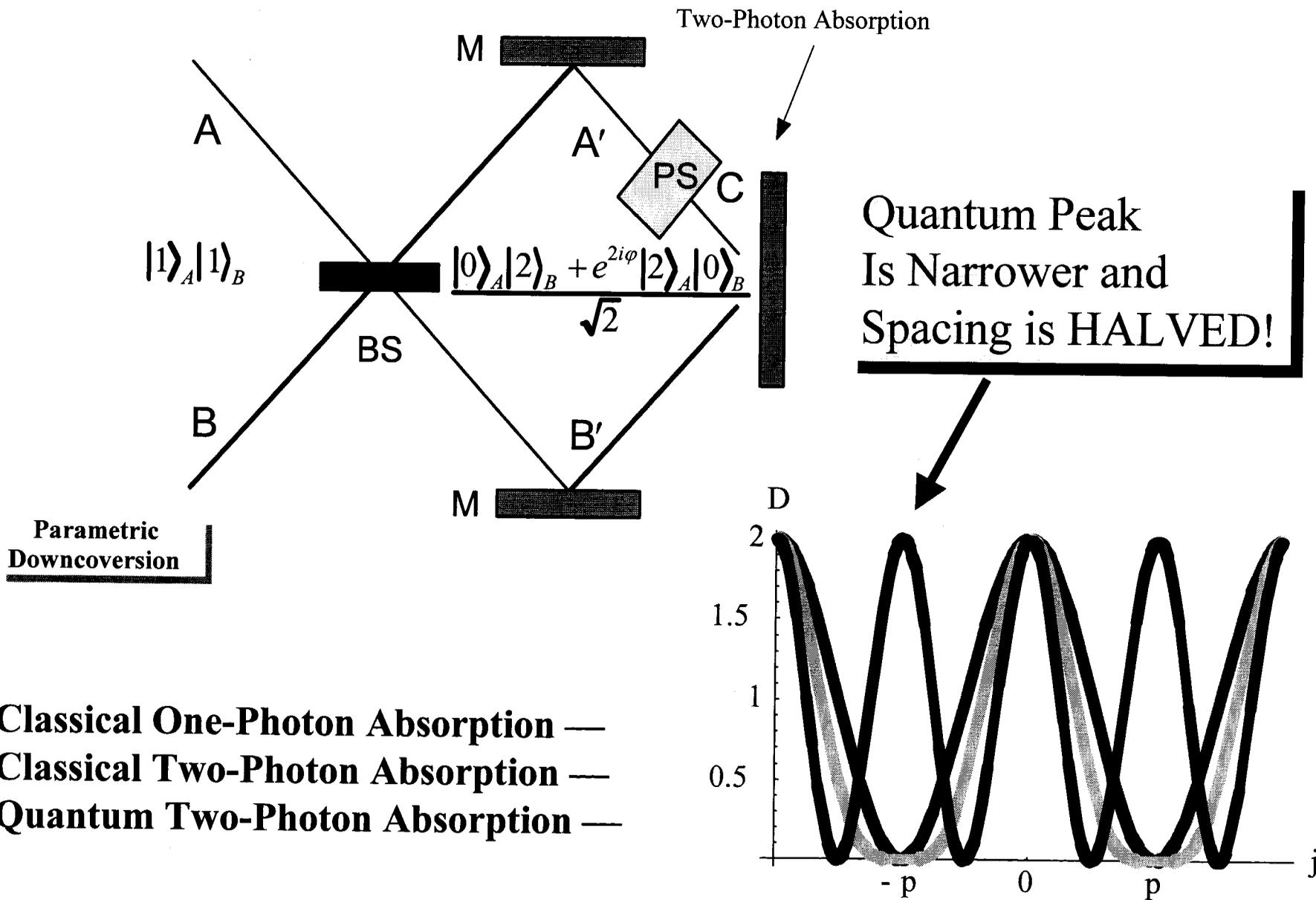
$$\frac{|0\rangle_A |2\rangle_B + |2\rangle_A |0\rangle_B}{\sqrt{2}}$$



$$\frac{|0\rangle_A |2\rangle_B + e^{2i\phi} |2\rangle_A |0\rangle_B}{\sqrt{2}}$$

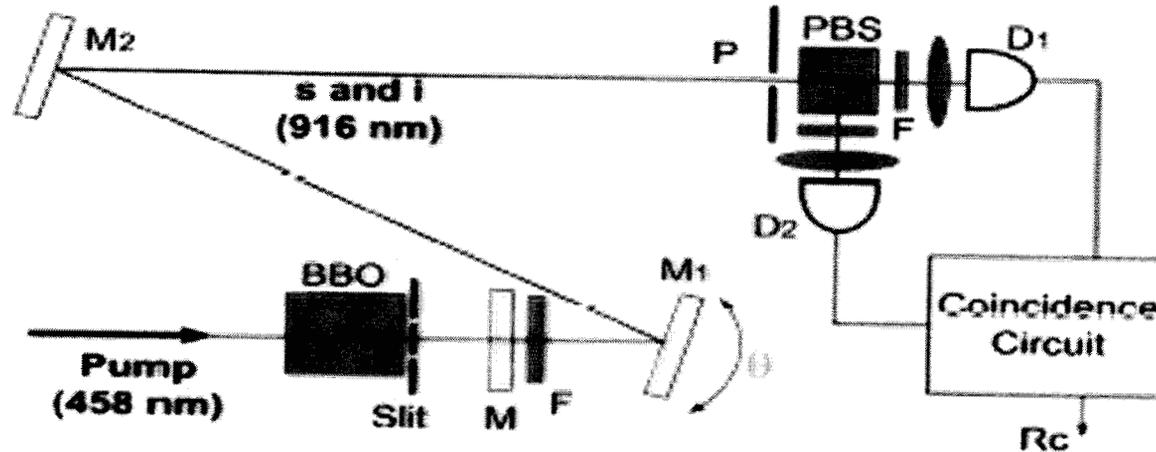


Leonard Mandel



Quantum lithography: setup

- Milena D'Angelo, Maria V. Chekhova, and Yanhua Shih, PRL 87, 013602 (2001)



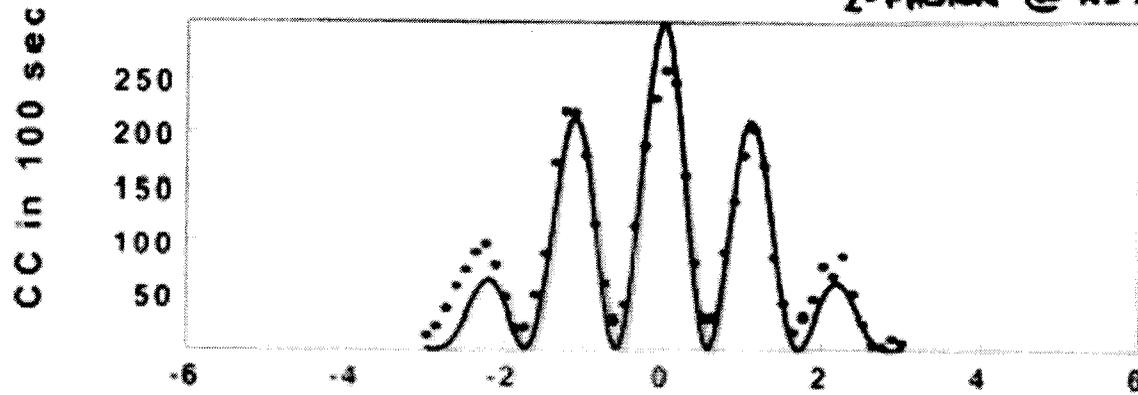
Two-photon source: Degenerate Collinear type-II SPDC

✓ Double-slit VERY close to the crystal $\Rightarrow \Delta\phi \ll b/D$
 $\rightarrow |\psi\rangle = \epsilon(a_s^\dagger a_i^\dagger + b_s^\dagger b_i^\dagger) |0\rangle$

$\Delta\phi$ —scattering angle inside the crystal; b —distance between slits; D —distance between input face of crystal and double slit

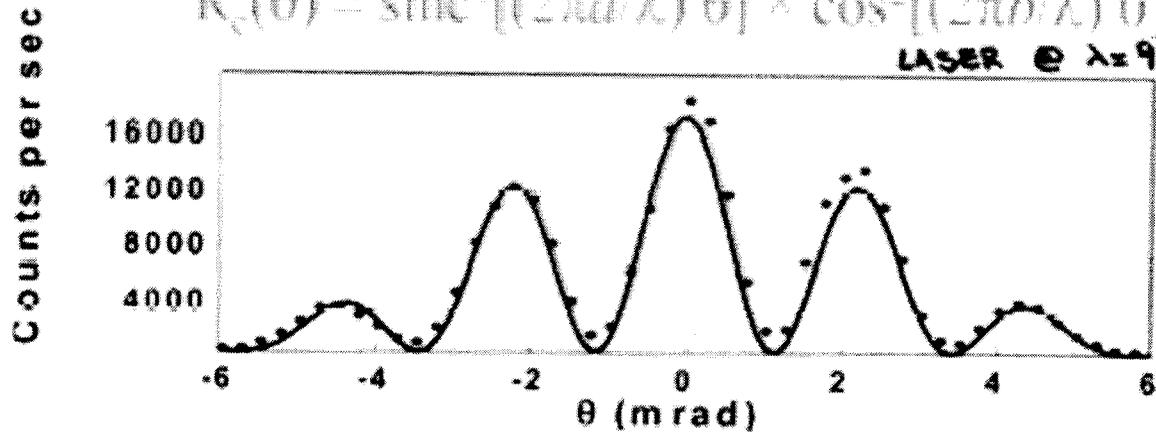
Results

2-PHOTON @ $\lambda = 916 \text{ nm}$

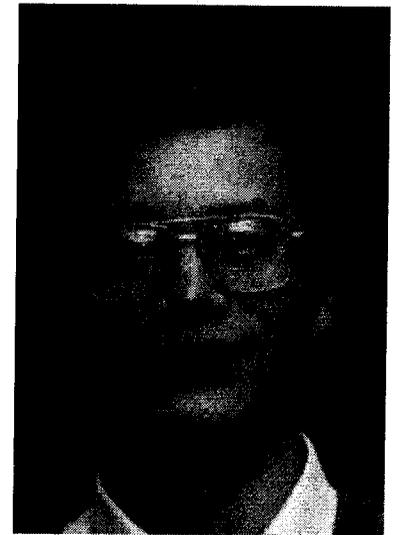


$$R_c(\theta) = \text{sinc}^2[(2\pi a/\lambda) \theta] \times \cos^2[(2\pi b/\lambda) \theta]$$

LASER @ $\lambda = 916 \text{ nm}$



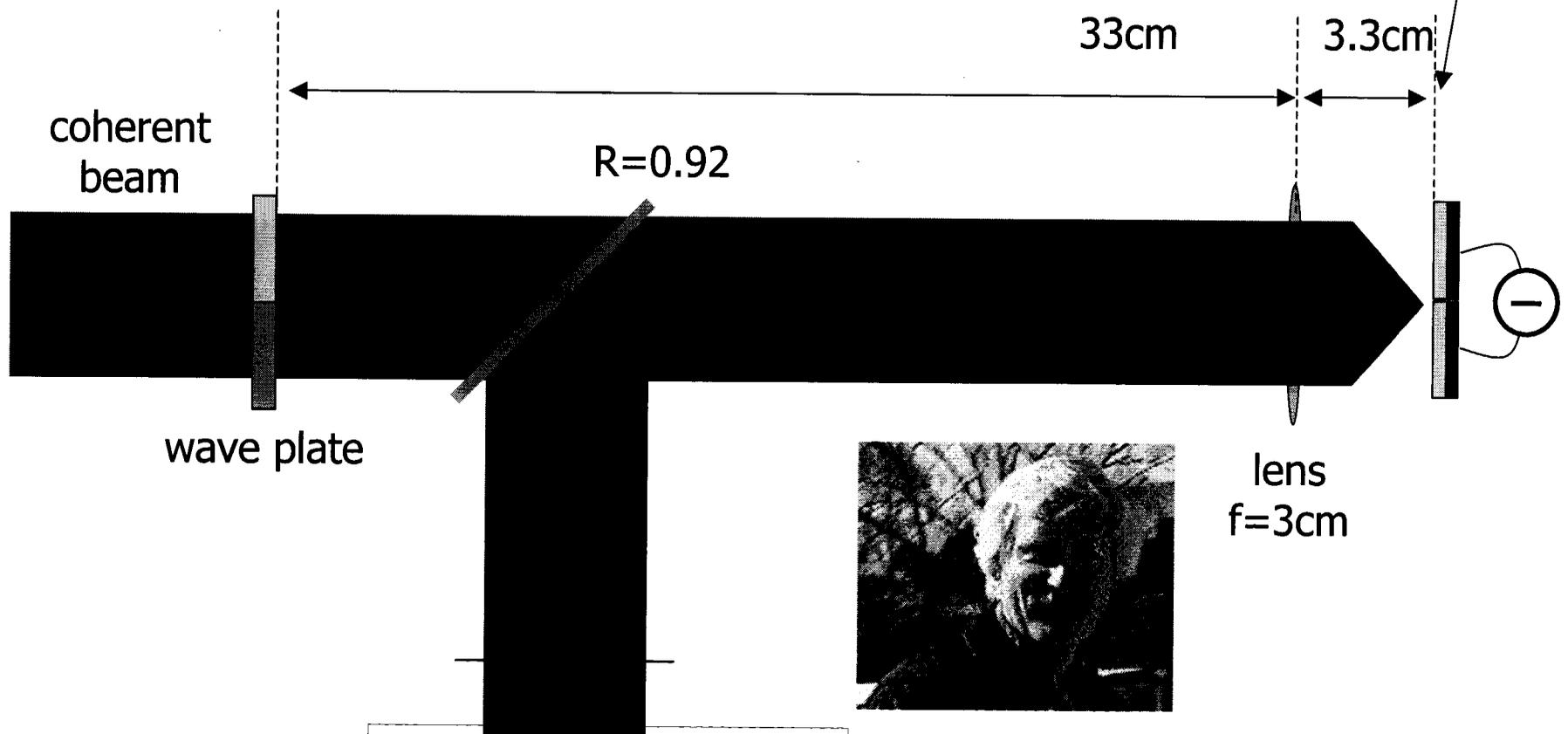
$$I(\theta) = \text{sinc}^2[(\pi a/\lambda) \theta] \times \cos^2[(\pi b/\lambda) \theta]$$



Yanhua
Shih

$$\Delta x_{classical} = \lambda, \quad \Delta x_{shotnoise} = \frac{\lambda}{\sqrt{N}}, \quad \Delta x_{Heisenberg} = \frac{\lambda}{N}$$

Image of the wave plate plane with waist=300μm

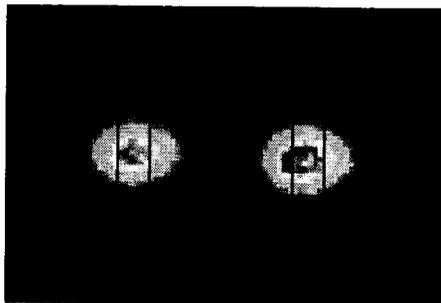
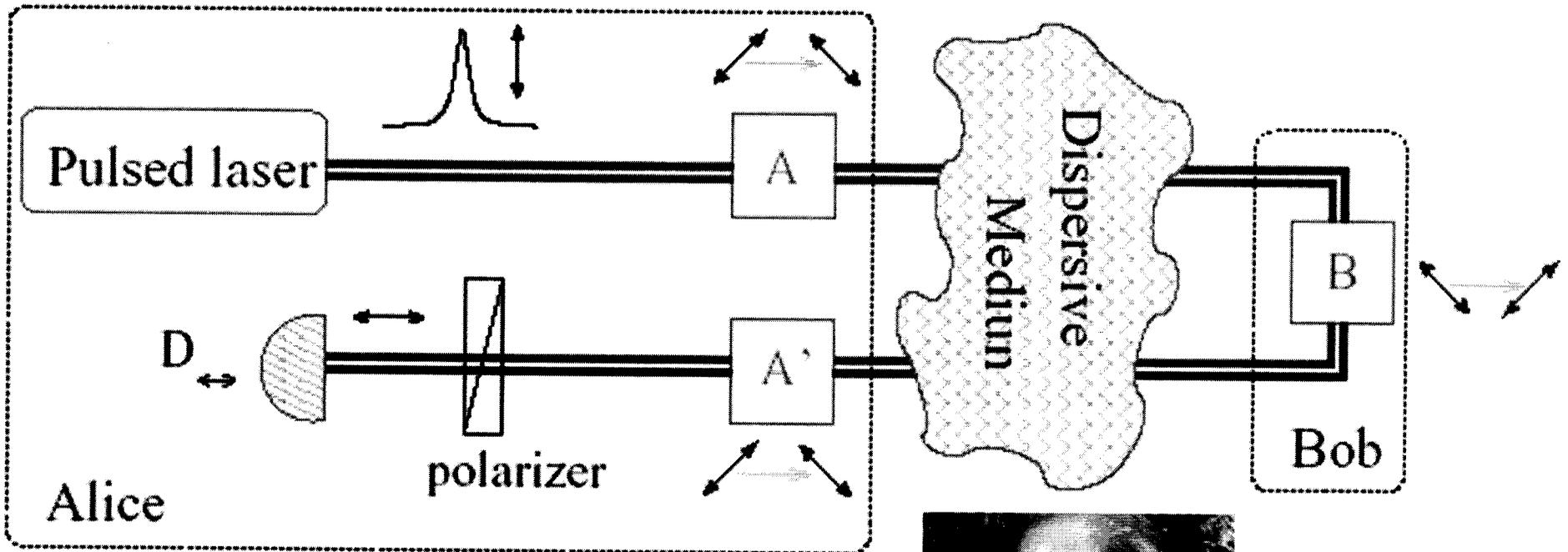


squeezed vacuum : OPA

Hans Bachor

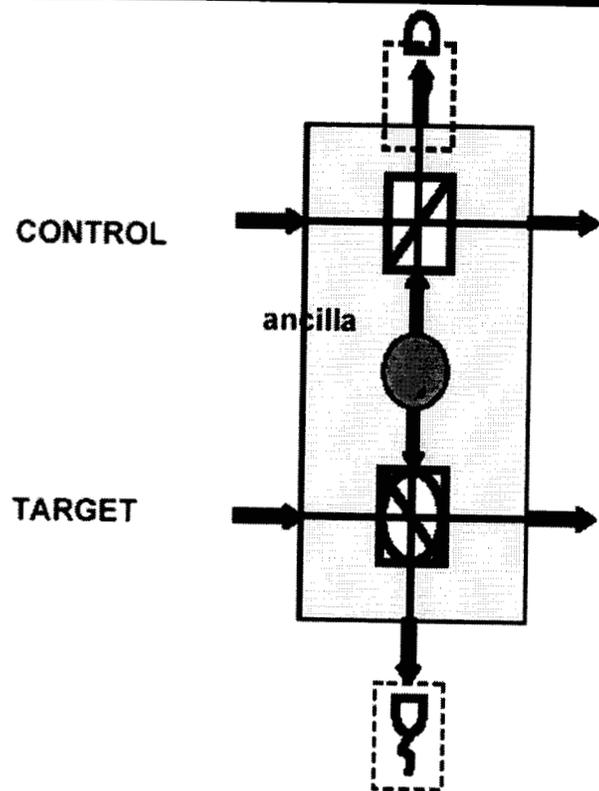
Australian National University

Entangled Photons Can Synchronize Past the Turbulent Atmosphere!



Seth Lloyd
MIT

Entangled Photons are a Resource for Scalable Quantum Computation!



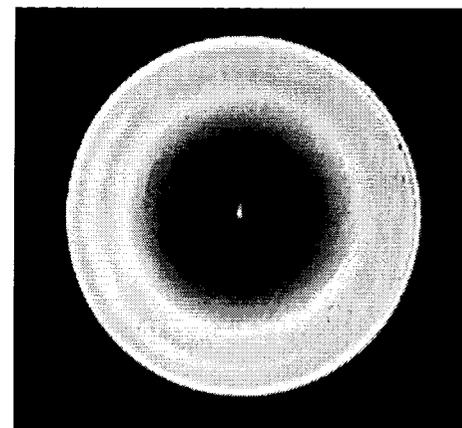
E. Knill, R. Laflamme and G. Milburn, Nature 409, 46, (2001)

Quantum Controlled-NOT Gate using an Entangled-Light Source, Beam Splitters, and Detectors.

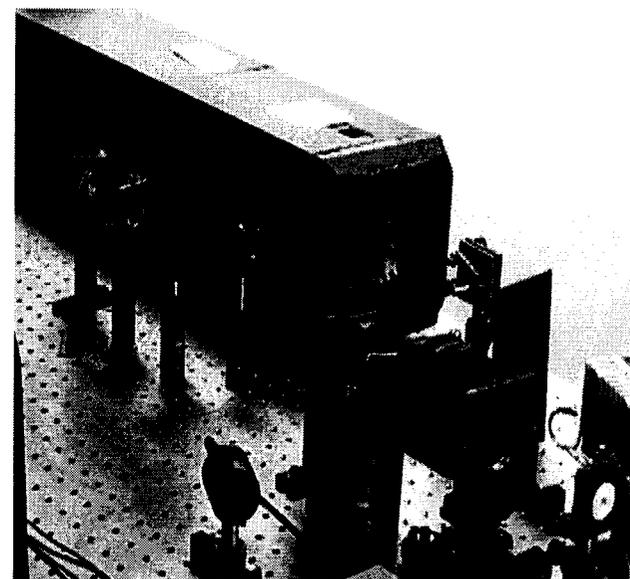
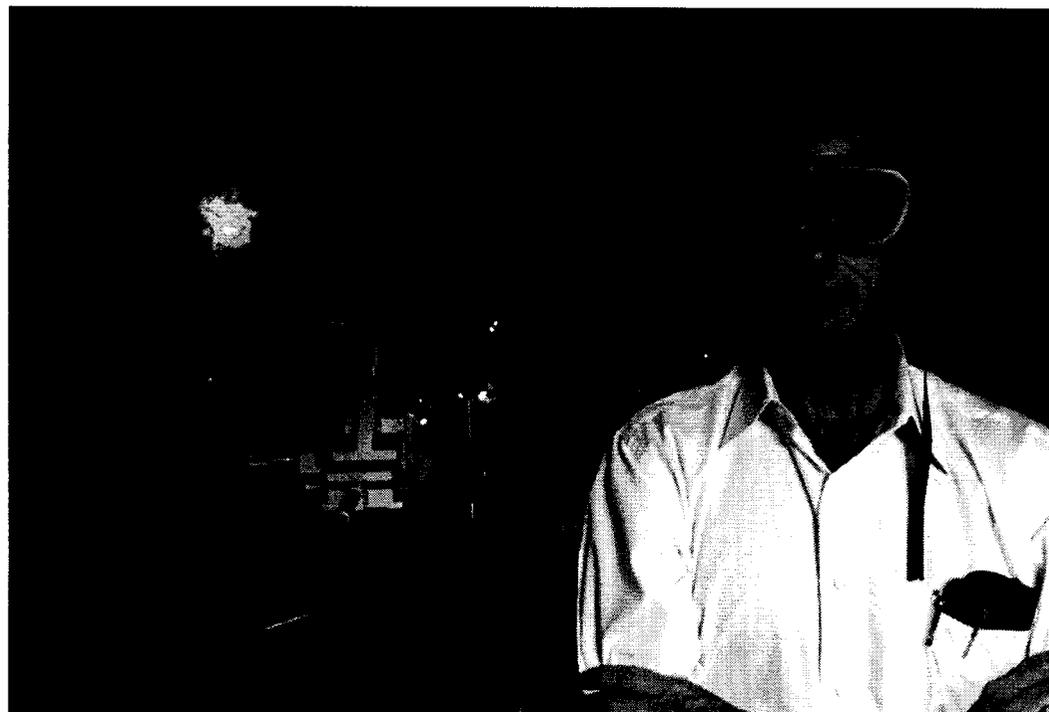


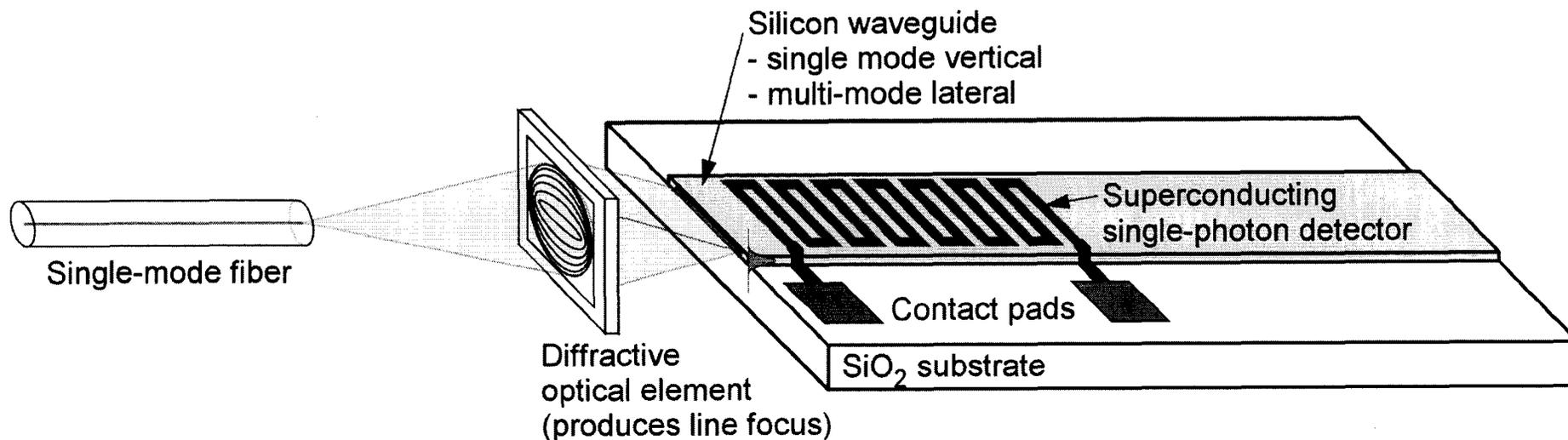
Gerard Milburn
University Of Queensland

- **QCT Group Quantum Optics Lab**
- **Single Photon Sources and Calibration**
- **Optical Imaging, Computing, and SATCOM**



Entangled Photons





- **We propose to develop a US Government single photon detector foundry at the Jet Propulsion Laboratory.**
- **This facility will provide a vertically integrated, completely in-house capability to develop, design, fabricate, test, and optically characterize ultra-fast, thin-film, superconducting, single-photon detectors.**
- **These detectors are targeted for use in wide-bandwidth, optical, quantum key distribution (QKD) for the DoD, as well as US intelligence, commercial, and academic applications.**

The Yellow-Brick Roadmap



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