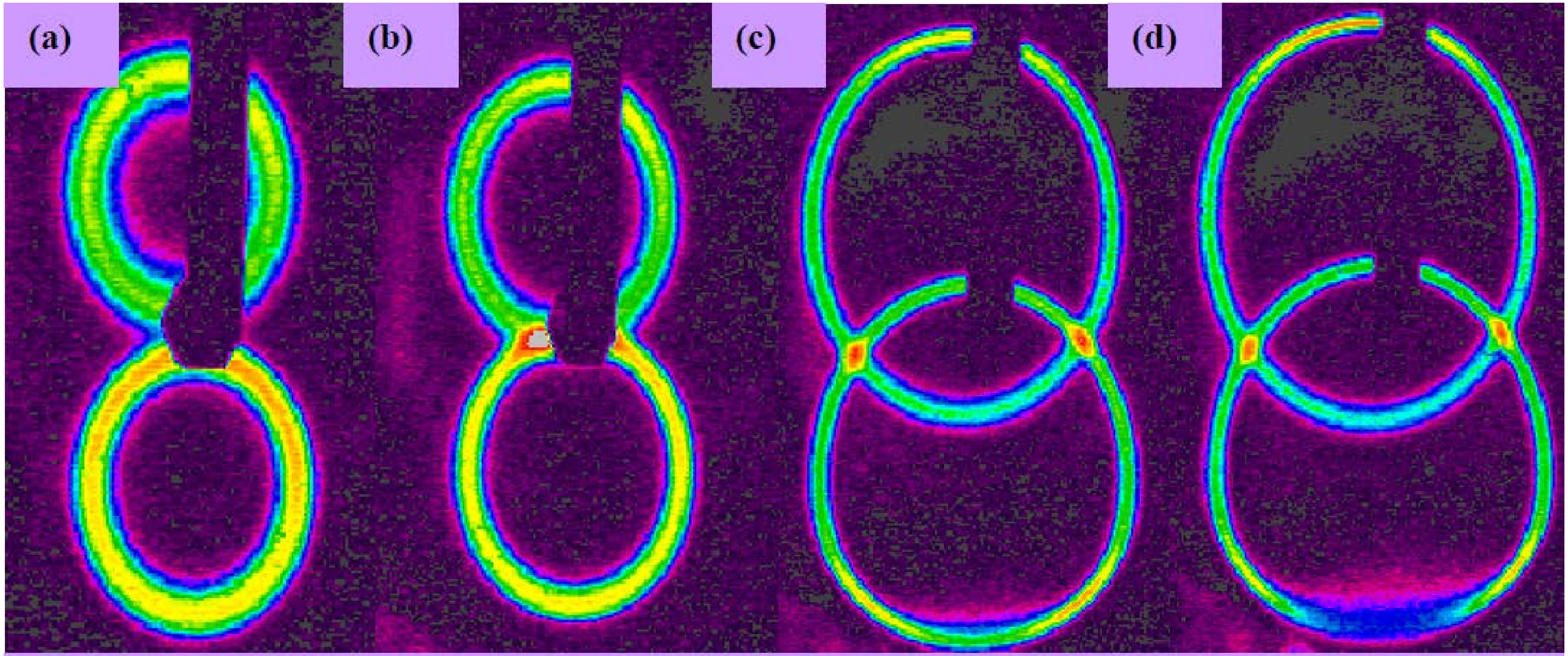
Quantum Physics in the lab?

Examples from quantum optics



Experimental source of polarization entangled photons: the down conversion cone

Who I am

Juan P. Torres
ICFO-Institut de Ciencies Fotoniques
Department of Signal Theory and Communications, UPC
juanp.torres@icfo.es, jperez@tsc.upc.edu

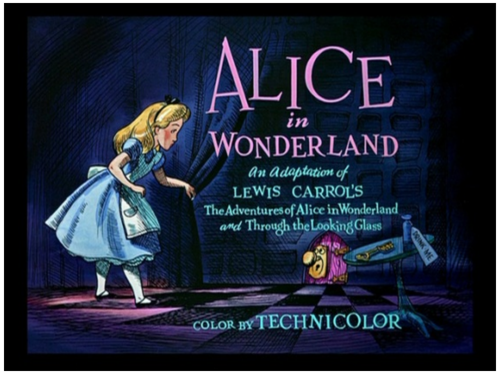
...Advancing the Frontiers of the Science of Light...

Quantum Engineering of light

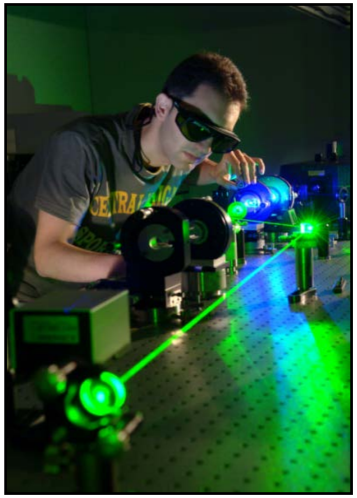
ICFO-Institute of Photonic Sciences
Quantum Engineering of light (QEL) group




Quantum



Engineering



Light

Goldfinger (1964)

My main aim in this talk is…

Quantum Information

Hilbert space

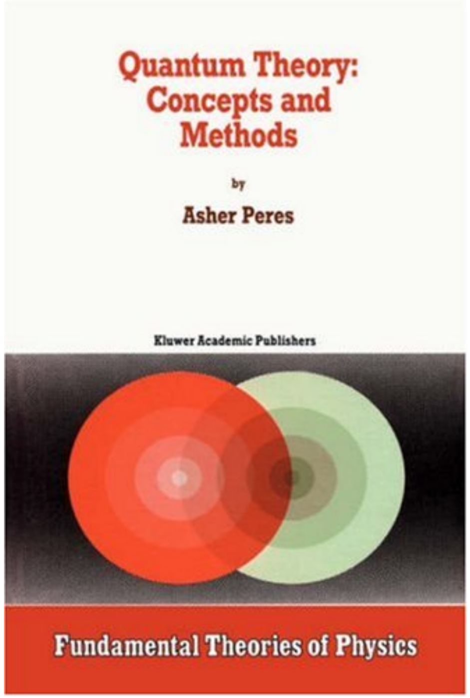
Entanglement

Superposition and Interference

Quantum Coherence

Quantum phenomena do not occur in a Hilbert space.
They occur in a laboratory

Quantum Theory: Concepts and Methods, Asher Peres
Kluwer Academic Publishers, p. 373, 1995



Quantum Theory:
Concepts and
Methods

by

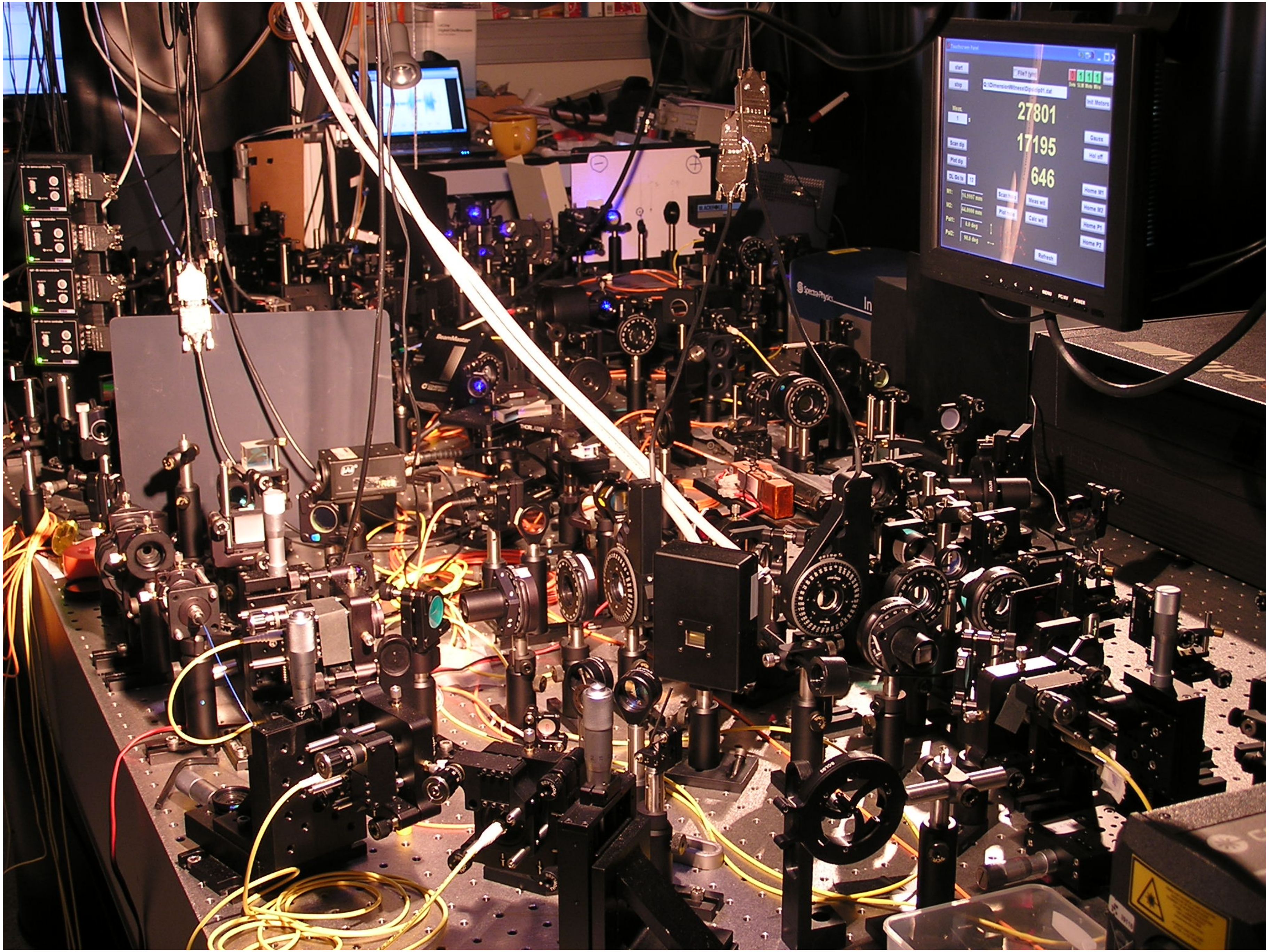
Asher Peres

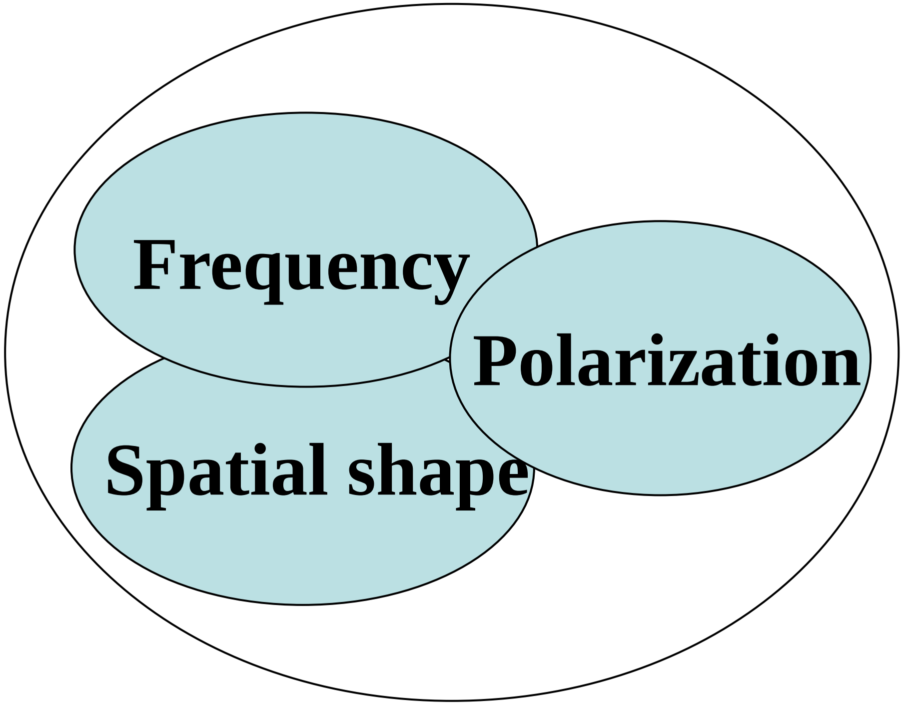
Kluwer Academic Publishers

Fundamental Theories of Physics

http://tx.technion.ac.il/~peres/

1934-2005
Technion, Israel Institute of Technology

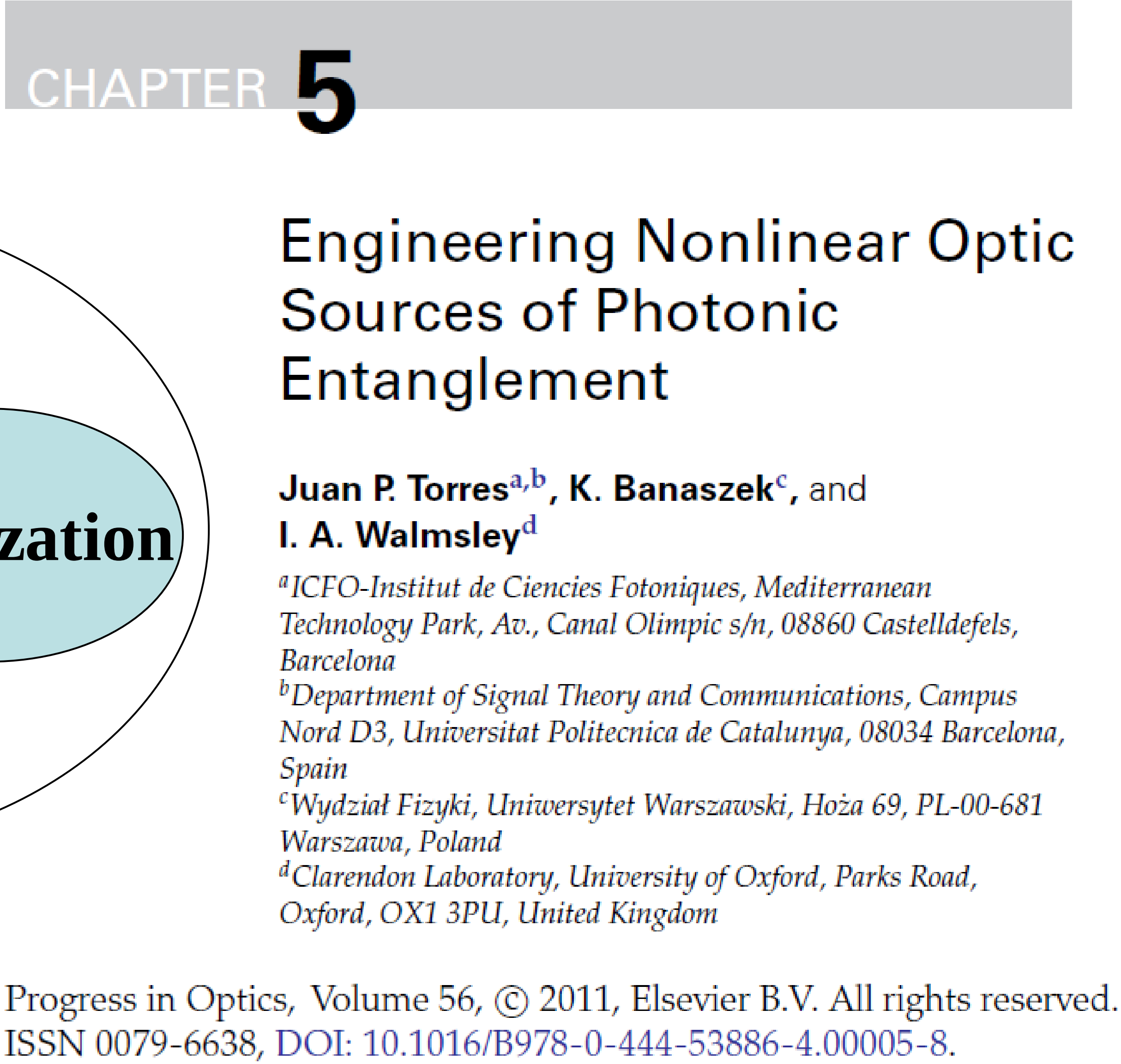

start
stop
File? (y/n)
Init Motors
Meas.
1
27801
17195
646
Scan dip
Plot dip
DL Go to
Gauss
Hol off
M1:
M2:
Pol1:
Pol2:
Meas wit
Calc wit
Home M1
Home M2
Home P1
Home P2
Refresh
MENU
PC/AV
POWER
BeamMaster
Spectra-Physics



Frequency

Polarization

Spatial shape



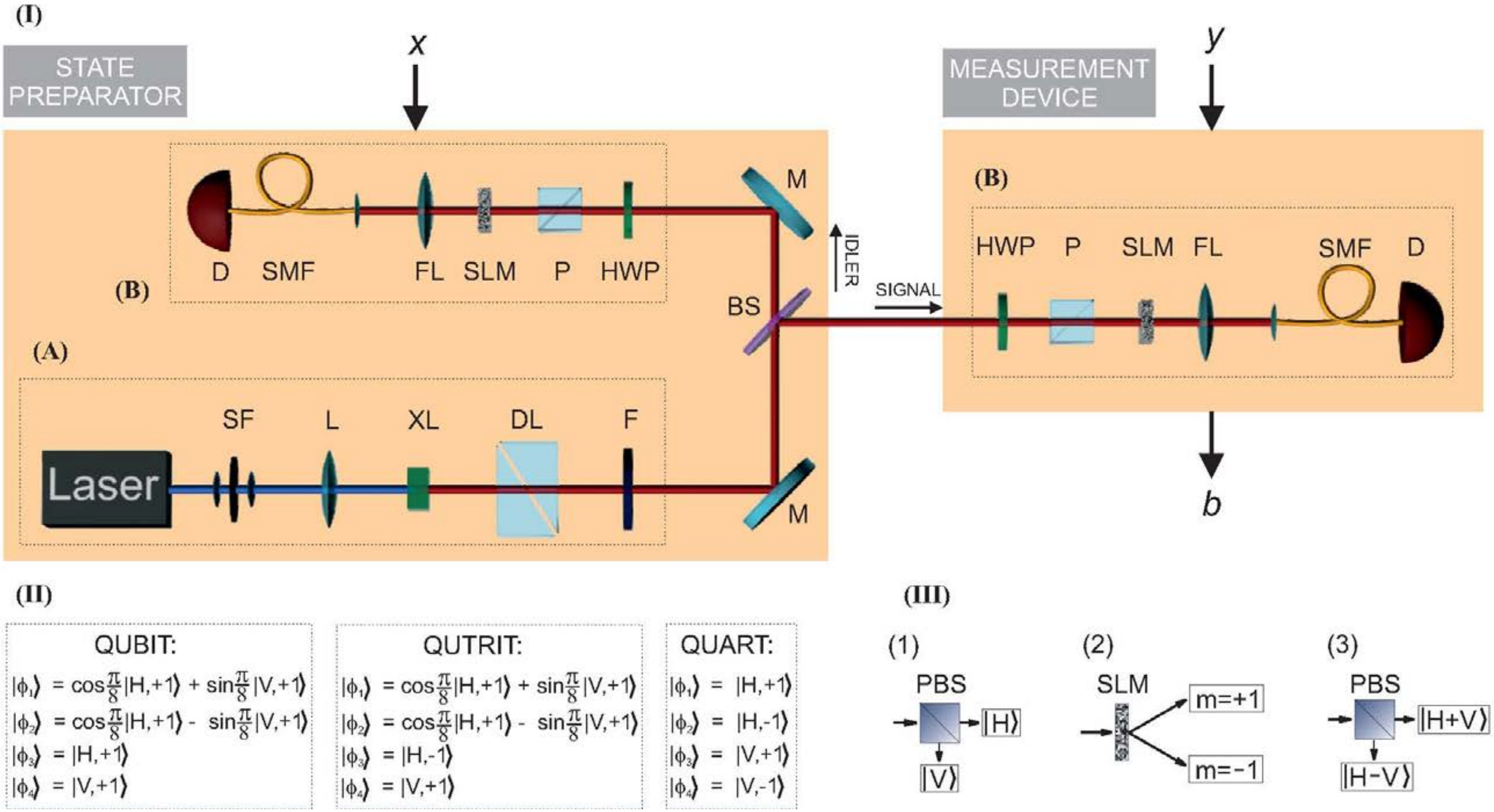
CHAPTER 5

Engineering Nonlinear Optic Sources of Photonic Entanglement

Juan P. Torres[a,b], **K. Banaszek**[c], and
I. A. Walmsley[d]

[a] *ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, Av., Canal Olimpic s/n, 08860 Castelldefels, Barcelona*
[b] *Department of Signal Theory and Communications, Campus Nord D3, Universitat Politecnica de Catalunya, 08034 Barcelona, Spain*
[c] *Wydział Fizyki, Uniwersytet Warszawski, Hoża 69, PL-00-681 Warszawa, Poland*
[d] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom*

Progress in Optics, Volume 56, © 2011, Elsevier B.V. All rights reserved.
ISSN 0079-6638, DOI: 10.1016/B978-0-444-53886-4.00005-8.



Hendrych, Gallego, Micuda, Acin and Torres, Nature Physics **8**, 588 (2012)

Quantum state engineering

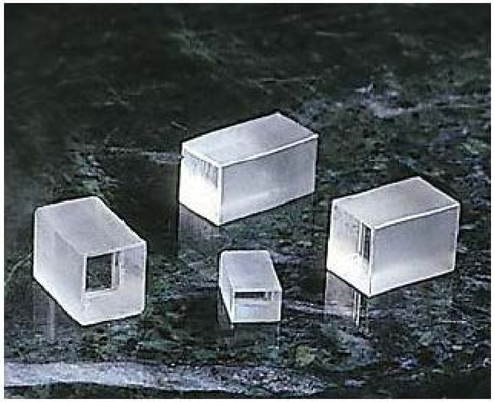
The photon gun

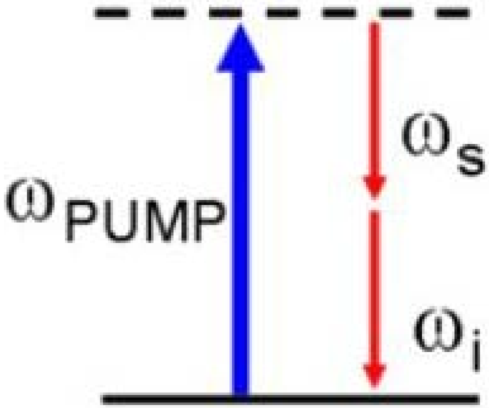
How to generate one-photon and two-photon states

Spontaneous Parametric Down Conversion (SPDC)

BETA BARIUM BORATE

BBO





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

$$k_p = k_s + k_i$$

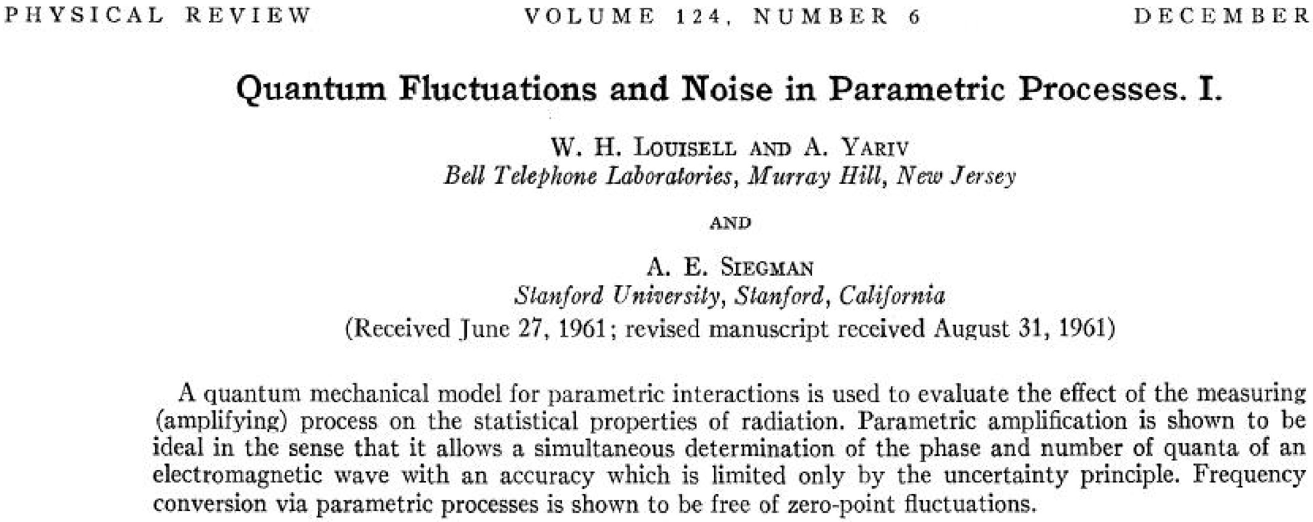
POTASSIUM TITANYL PHOSPHATE

KTP

EKSMA OPTICS OFFERS

- Crystal size up to 10×10×15 mm or 5×5×20 mm
- Singleband and dualband AR and BBAR coatings

$$H(t) = \varepsilon_0 \int d\vec{r}\, \chi^{(2)}(\vec{r}) E_p^{+}(\vec{r},t) E_s^{-}(\vec{r},t) E_i^{-}(\vec{r},t) + h.c.$$



PHYSICAL REVIEW VOLUME 124, NUMBER 6 DECEMBER 15, 1961

Quantum Fluctuations and Noise in Parametric Processes. I.

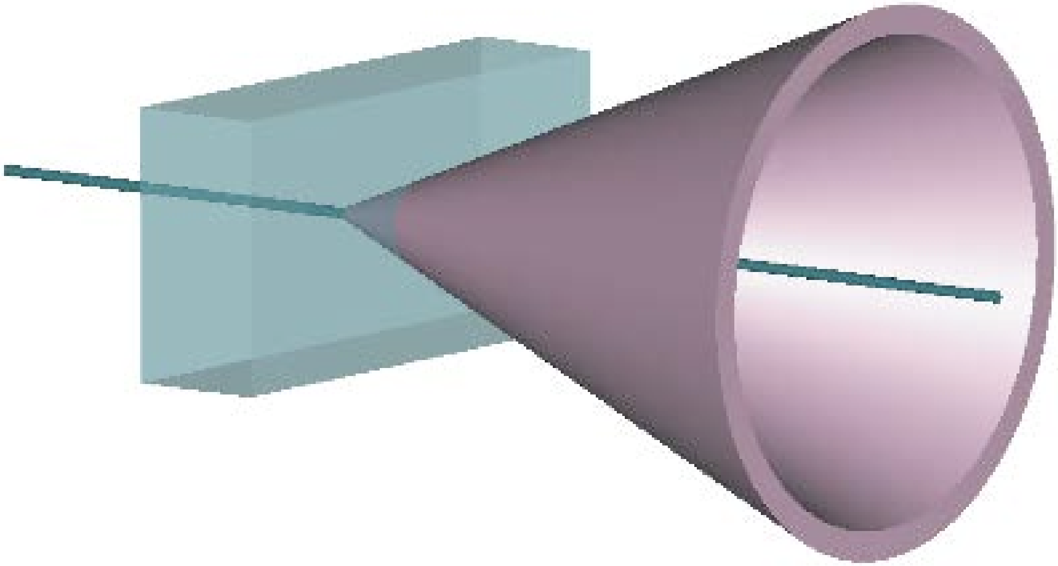
W. H. Louisell and A. Yariv
Bell Telephone Laboratories, Murray Hill, New Jersey

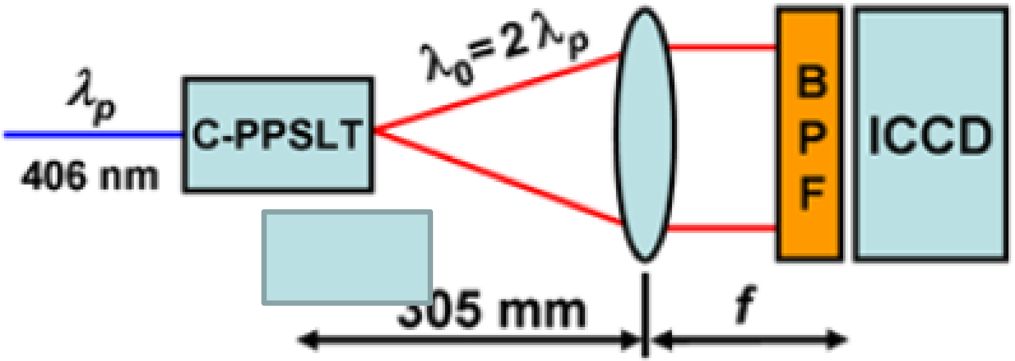
AND

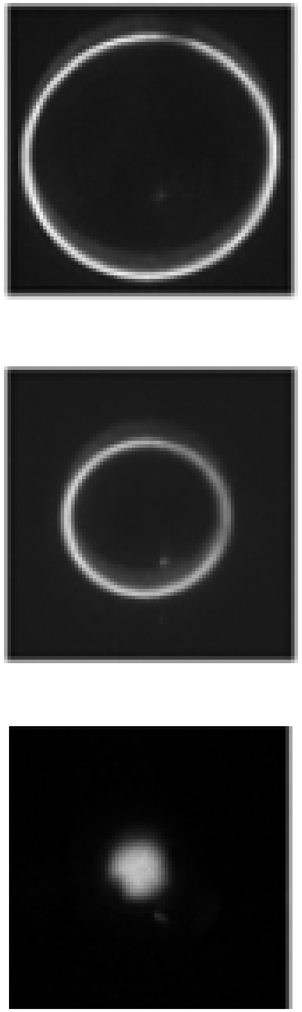
A. E. Siegman
Stanford University, Stanford, California

(Received June 27, 1961; revised manuscript received August 31, 1961)

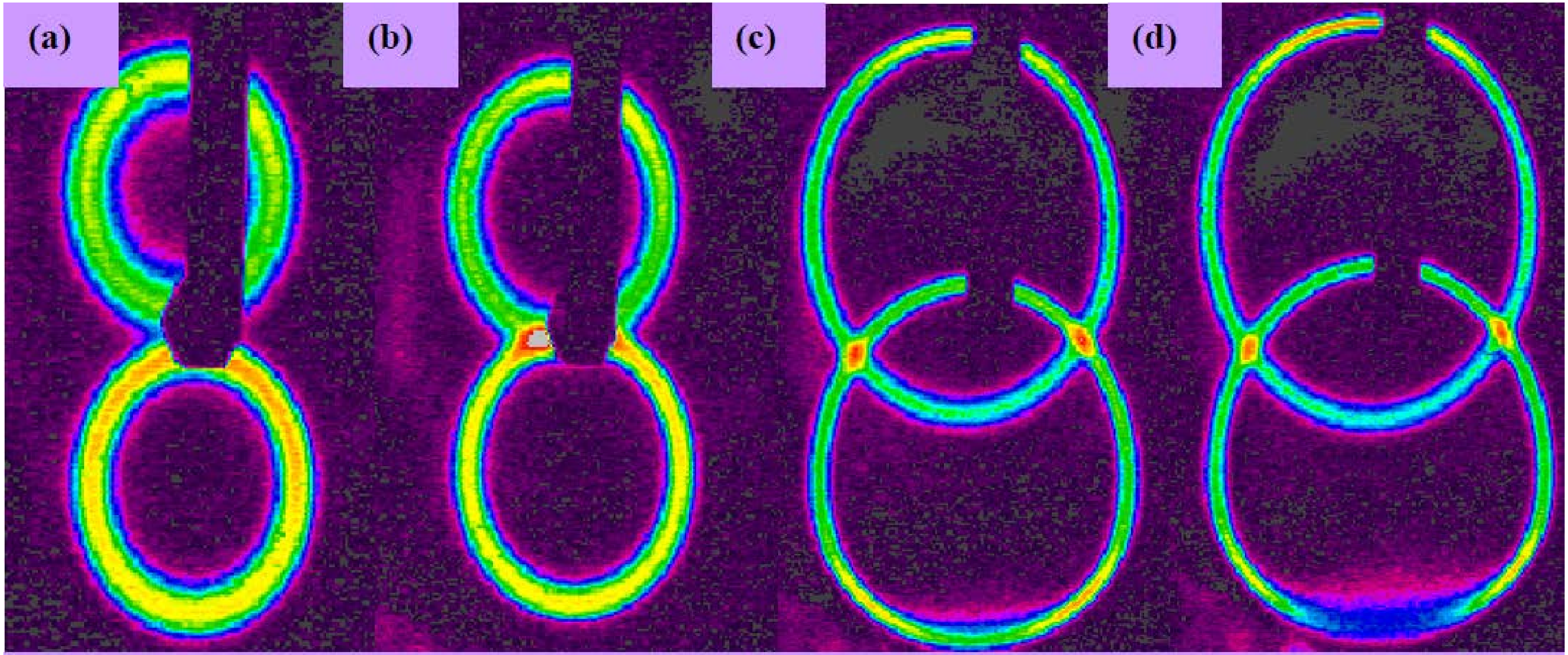
A quantum mechanical model for parametric interactions is used to evaluate the effect of the measuring (amplifying) process on the statistical properties of radiation. Parametric amplification is shown to be ideal in the sense that it allows a simultaneous determination of the phase and number of quanta of an electromagnetic wave with an accuracy which is limited only by the uncertainty principle. Frequency conversion via parametric processes is shown to be free of zero-point fluctuations.



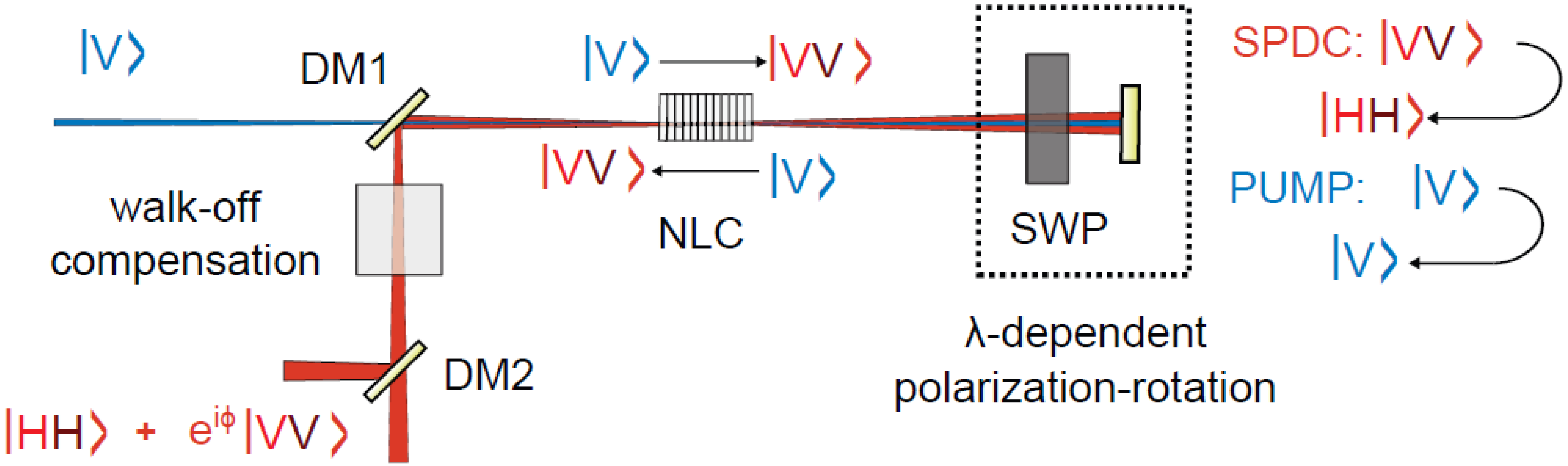




Nasr et al., Phys. Rev. Lett. 100, 183601 (2008)



Experimental source of polarization entangled photons: the down conversion cone



Fabian Steinlechner,[1,*] Sven Ramelow,[2,3] Marc Jofre,[1]
Marta Gilaberte,[1] Thomas Jennewein,[4] Juan. P. Torres,[1,5]
Morgan W. Mitchell,[1,6] and Valerio Pruneri[1,6]

Received 8 Feb 2013; revised 10 Apr 2013; accepted 12 Apr 2013; published 8 May 2013
20 May 2013 | Vol. 21, No. 10 | DOI:10.1364/OE.21.011943 | OPTICS EXPRESS 11943

Quantum state Tomography

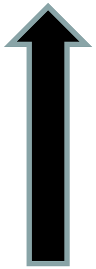
What is the quantum state?

$$\rho$$

Polarization of photons

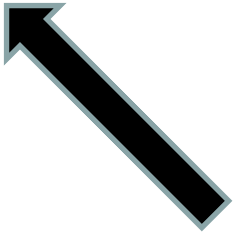
$|H\rangle$

$|V\rangle$



$|H\rangle + |V\rangle$

$|H\rangle - |V\rangle$

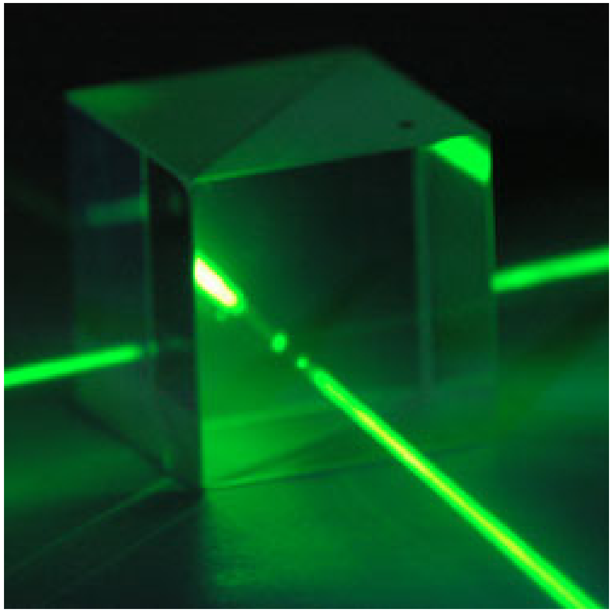


Polarization of a one-photon state

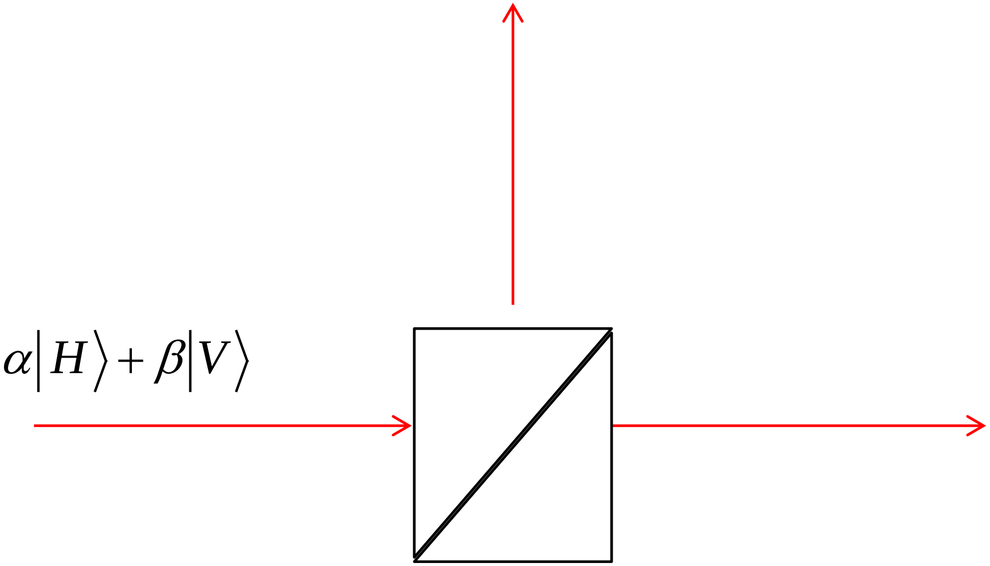
$$\rho = \begin{array}{cc} \begin{array}{cc} |H\rangle & |V\rangle \end{array} & \\ \begin{pmatrix} a & z \\ z^{*} & b \end{pmatrix} & \begin{array}{c} \langle H| \\ \langle V| \end{array} \end{array}$$

$$\begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix} \quad \begin{pmatrix} 1/2 & i/2 \\ -i/2 & 1/2 \end{pmatrix}$$

$$\begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix}$$



Polarization Beam splitter (PBS)

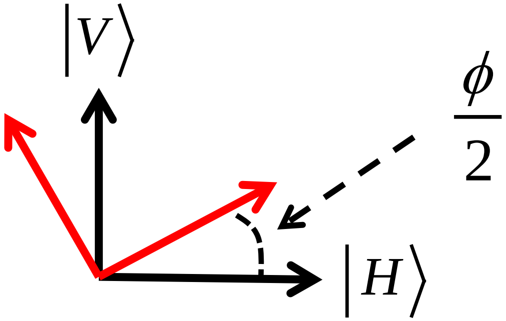


$$P_3 = |\alpha|^2$$

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

$$P_2 = |\beta|^2$$

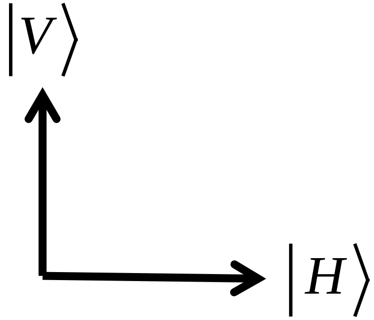
Half wave plate (HWP)



$$|H\rangle \Rightarrow \cos\phi|H\rangle + \sin\phi|V\rangle$$

$$|V\rangle \Rightarrow \sin\phi|H\rangle - \cos\phi|V\rangle$$

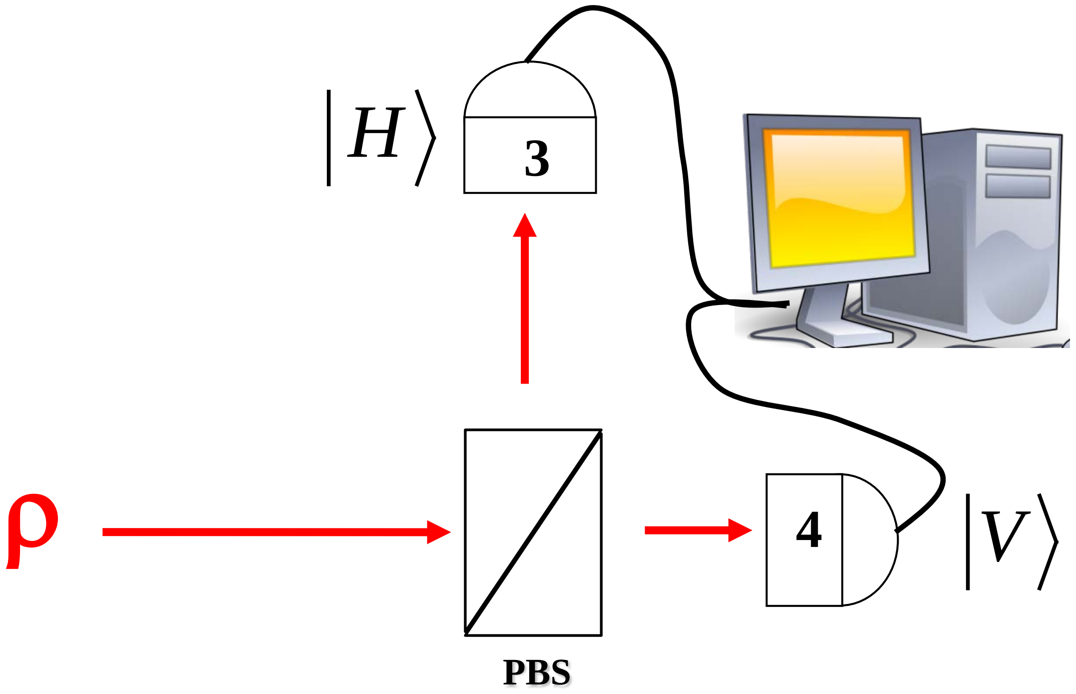
Quarter wave plate (QWP)



$$\frac{1}{\sqrt{2}}\left[|H\rangle + |V\rangle\right] \quad \Rightarrow \quad \frac{1}{\sqrt{2}}\left[|H\rangle + i|V\rangle\right]$$

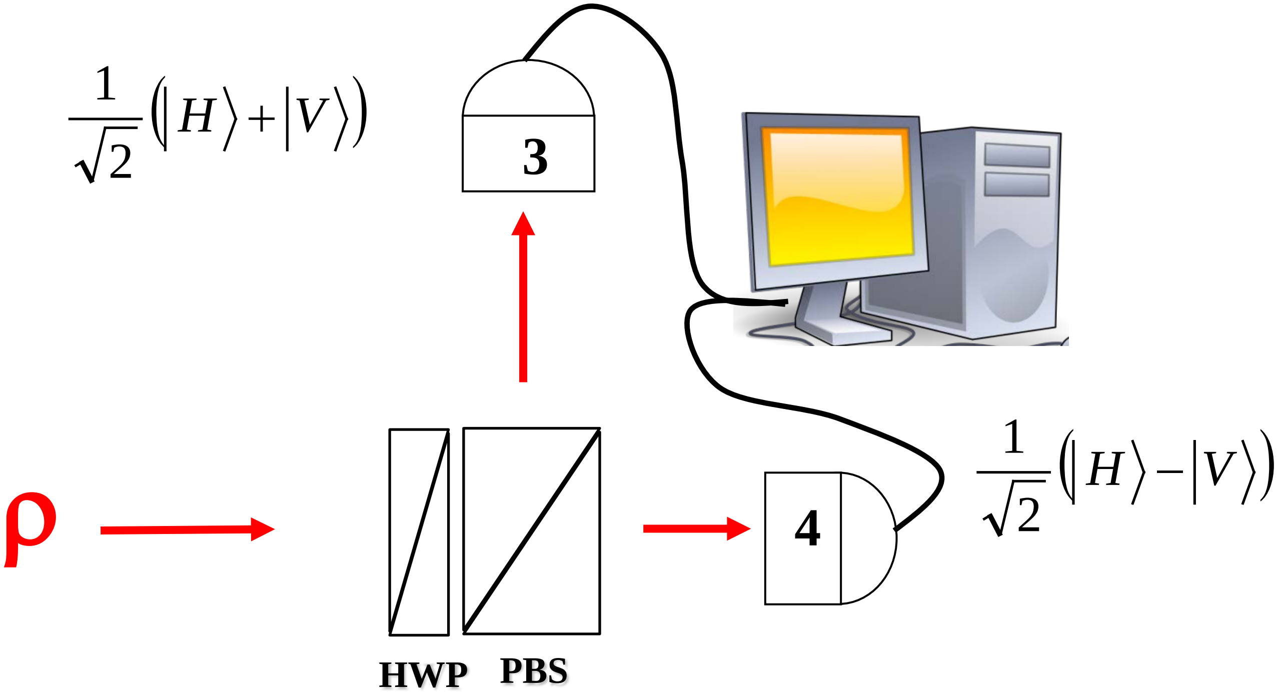
$$\frac{1}{\sqrt{2}}\left[|H\rangle - |V\rangle\right] \quad \Rightarrow \quad \frac{1}{\sqrt{2}}\left[|H\rangle - i|V\rangle\right]$$

Quantum state tomography



$$P_3 = a$$

$$P_4 = b \qquad a = \frac{N_3}{N_3 + N_4} \qquad b = \frac{N_4}{N_3 + N_4}$$



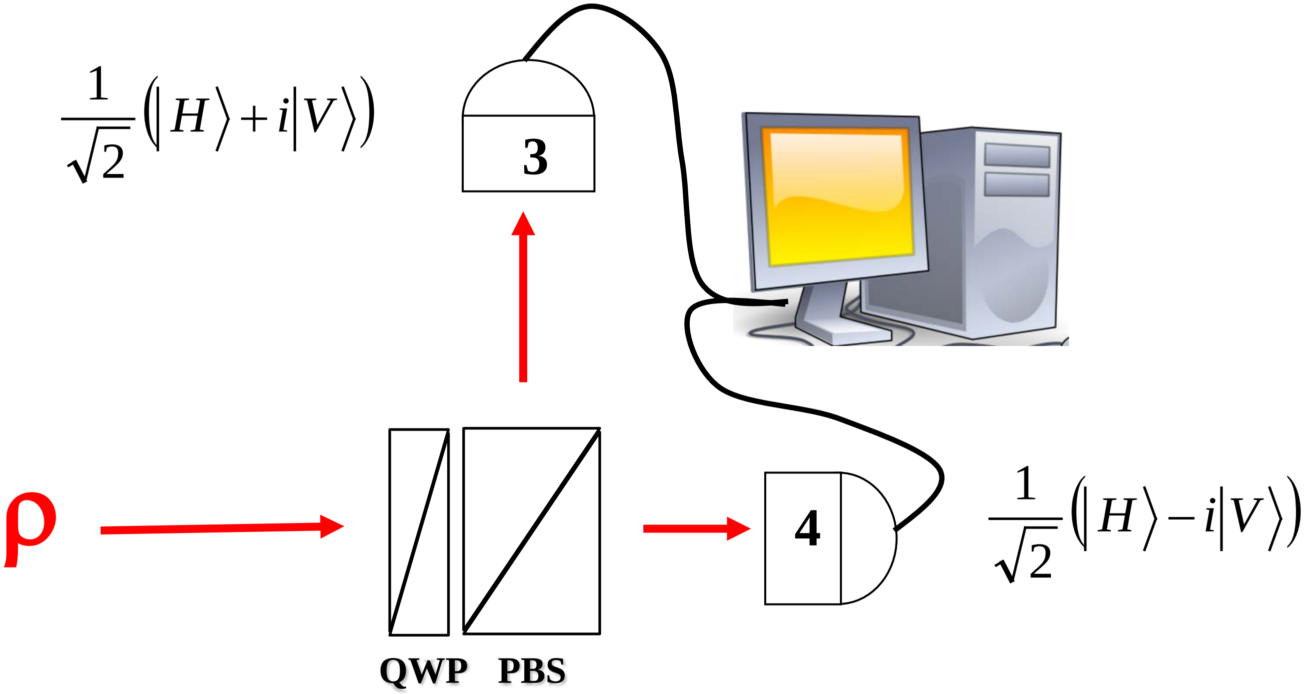
$$\frac{1}{\sqrt{2}}\left(|H\rangle+|V\rangle\right)$$

$$\frac{1}{\sqrt{2}}\left(|H\rangle-|V\rangle\right)$$

$$P_3 = \frac{1}{2} + \mathrm{Re}(z)$$

$$P_4 = \frac{1}{2} - \mathrm{Re}(z)$$

$$\mathrm{Re}(z) = \frac{1}{2}\frac{N_3 - N_4}{N_3 + N_4}$$



$$P_3 = \frac{1}{2} - \mathrm{Im}(z)$$

$$P_4 = \frac{1}{2} + \mathrm{Im}(z) \qquad \mathrm{Im}(z) = \frac{1}{2}\frac{N_4 - N_3}{N_3 + N_4}$$

Photons have a shape

or how to create a multidimensional Hilbert space

http://pulpypics.com/emoticons-for-facebook-and-skype/

One-photon state

Space representation:

$$\left|\Psi\right\rangle_A = \int dq F(q) \left|q\right\rangle_A$$

Momentum representation:

$$\left|\Psi\right\rangle_A = \int dp G(p) \left|p\right\rangle_A$$

Two-photon state

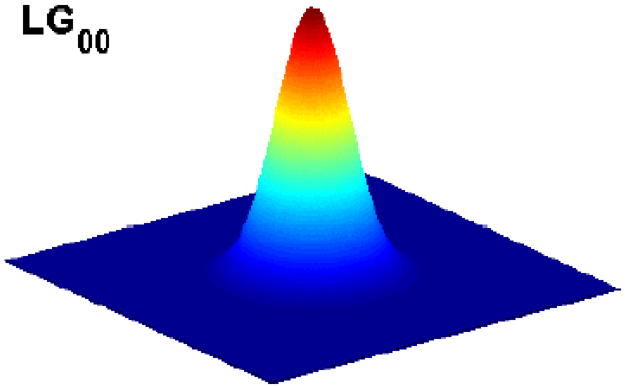
Space representation:

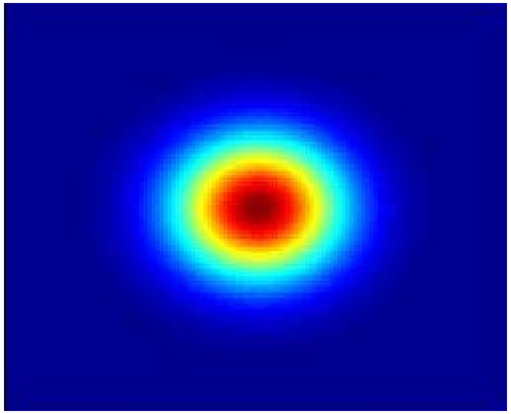
$$\left|\Psi\right\rangle_{AB} = \int dq_1 dq_2 F(q_1, q_2) \left|q_1\right\rangle_A \left|q_2\right\rangle_B$$

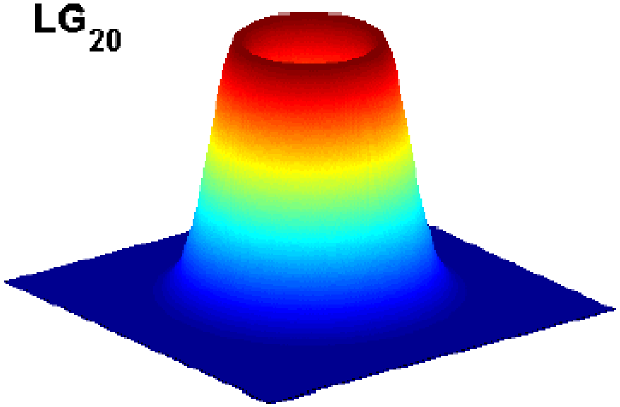
Momentum representation:

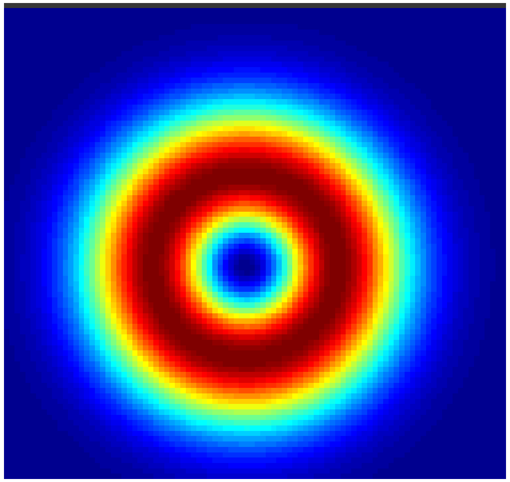
$$\left|\Psi\right\rangle_{AB} = \int dp_1 dp_2 G(p_1, p_2) \left|p_1\right\rangle_A \left|p_2\right\rangle_B$$

Photons with a Laguerre–Gauss shape

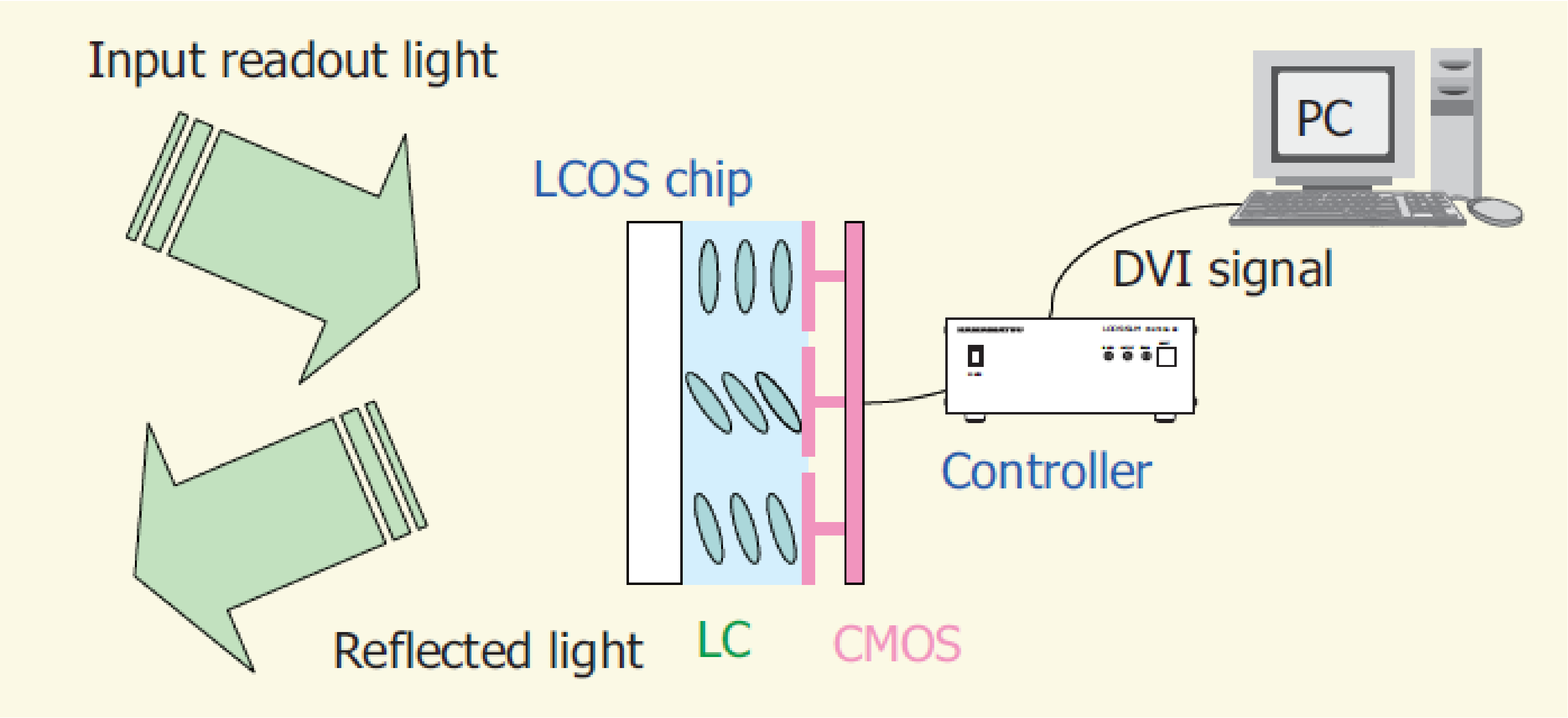




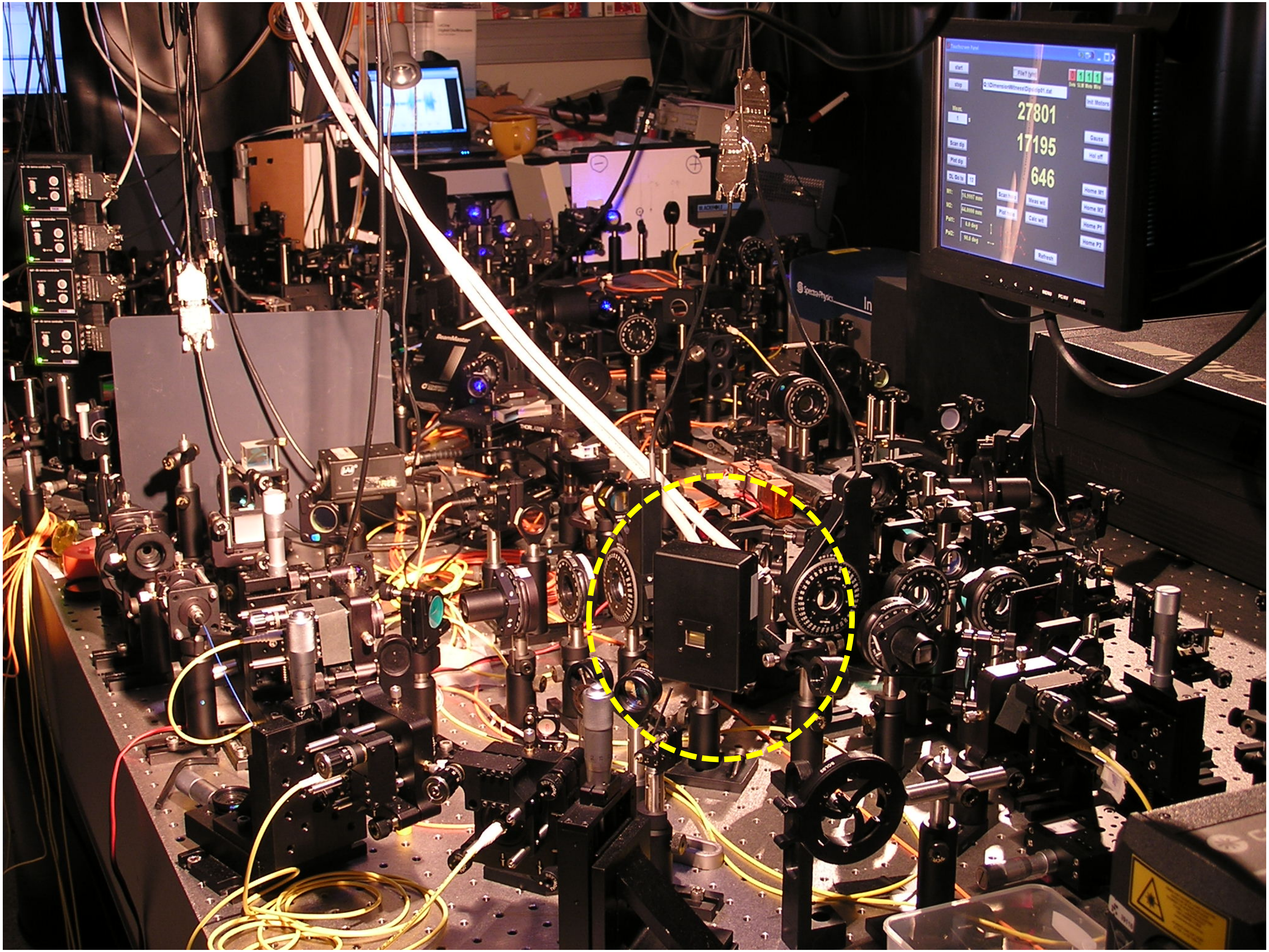


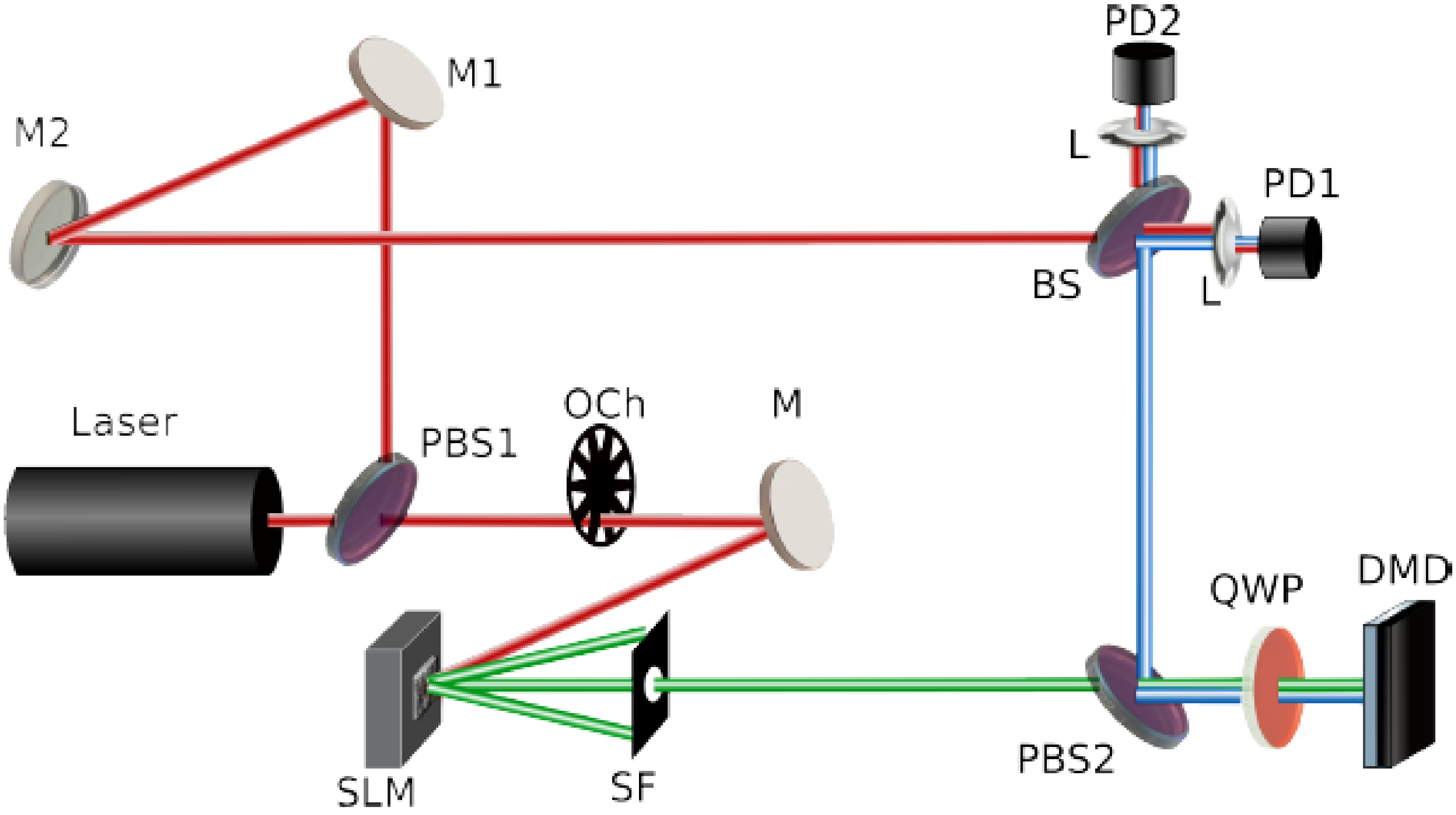


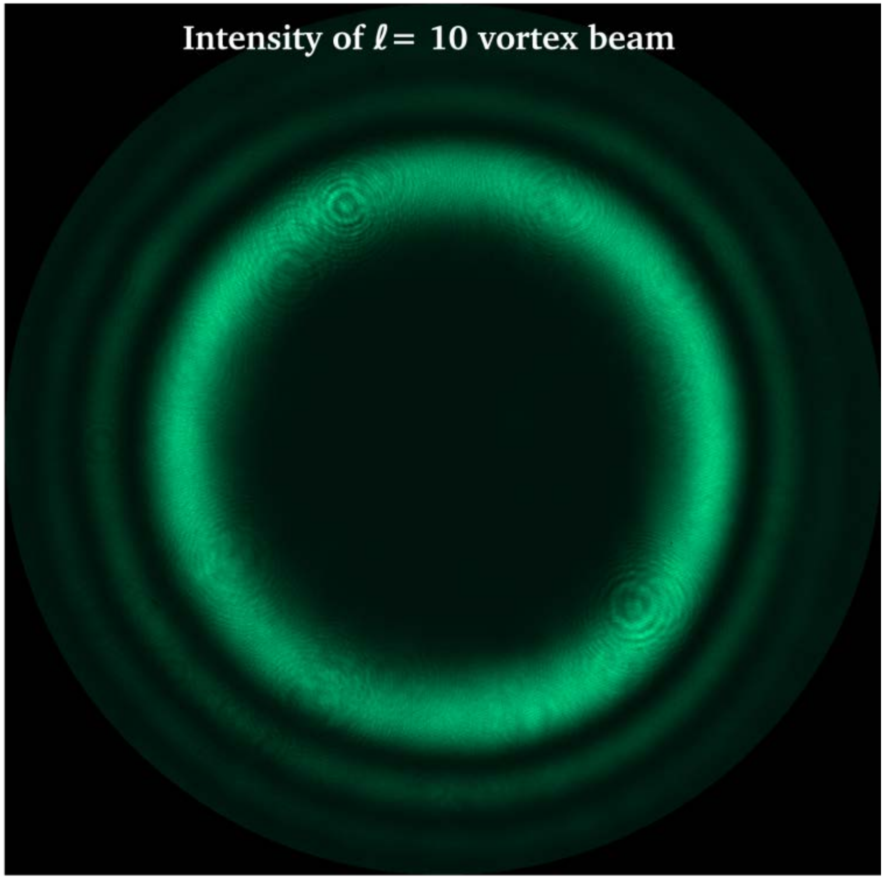
Spatial Light Modulators (SLM)



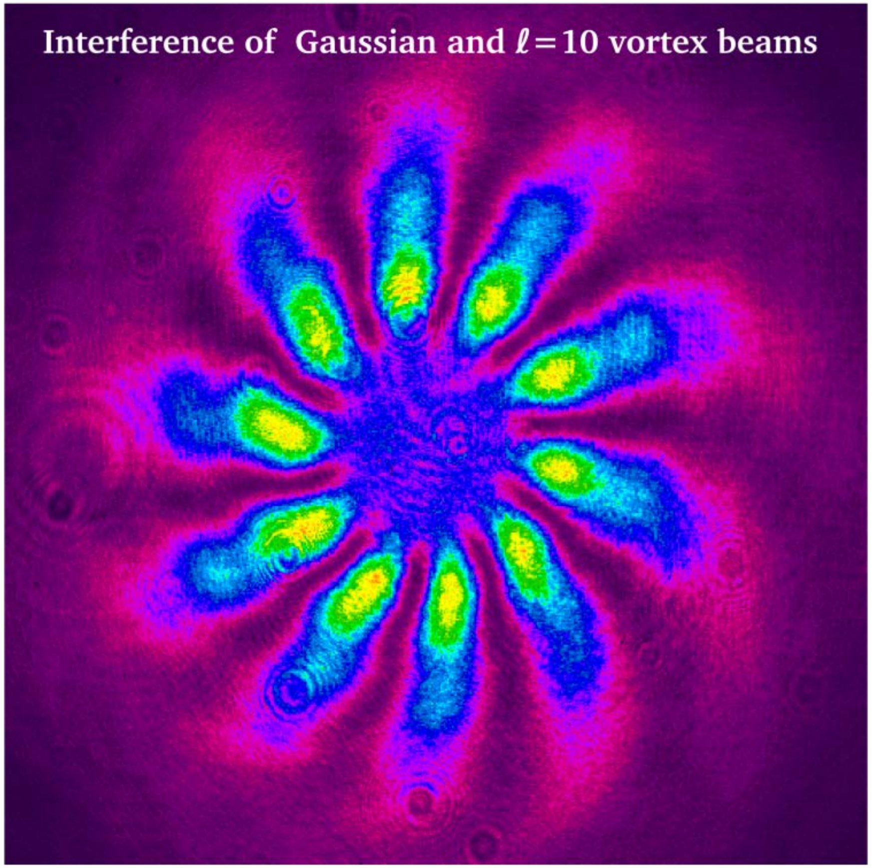
Spatial Light Modulator, Liquid Crystal on Silicon, Hamamatsu


27801
17195
646
Spectra-Physics

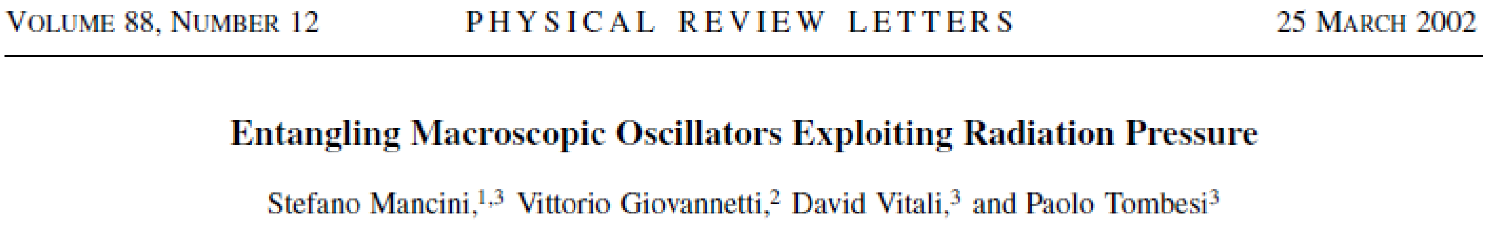

PD2
M1
M2
L
PD1
BS
L
Laser
OCh
M
PBS1
QWP
DMD
SLM
SF
PBS2



Intensity of $\ell =$ 10 vortex beam



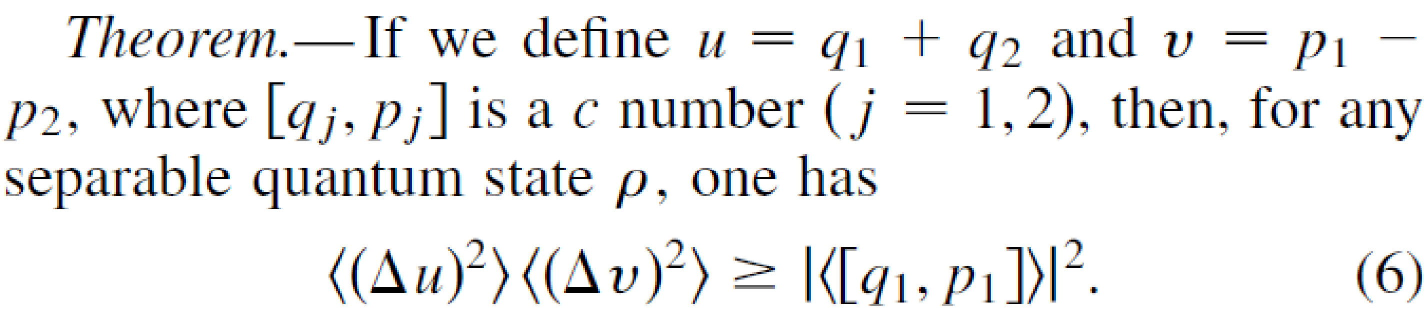
Interference of Gaussian and $\ell = 10$ vortex beams



VOLUME 88, NUMBER 12 PHYSICAL REVIEW LETTERS 25 MARCH 2002

Entangling Macroscopic Oscillators Exploiting Radiation Pressure

Stefano Mancini,[1,3] Vittorio Giovannetti,[2] David Vitali,[3] and Paolo Tombesi[3]



Theorem.—If we define $u = q_1 + q_2$ and $v = p_1 - p_2$, where $[q_j, p_j]$ is a c number ($j = 1, 2$), then, for any separable quantum state ρ, one has

$$\langle(\Delta u)^2\rangle\langle(\Delta v)^2\rangle \geq |\langle[q_1, p_1]\rangle|^2. \tag{6}$$

$$\left\langle q_1+q_2\right\rangle=\int dq_1dq_2\left(q_1+q_2\right)\left|F(q_1,q_2)\right|^2$$

$$\left\langle\left(q_1+q_2\right)^2\right\rangle=\int dq_1dq_2\left(q_1+q_2\right)^2\left|F(q_1,q_2)\right|^2$$

$$\left\langle\left(\Delta u\right)^2\right\rangle=\left\langle\left(q_1+q_2\right)^2\right\rangle-\left\langle q_1+q_2\right\rangle^2$$

$$\left\langle p_1+p_2\right\rangle=\int dp_1dp_2\left(p_1-p_2\right)\left|G(p_1,p_2)\right|^2$$

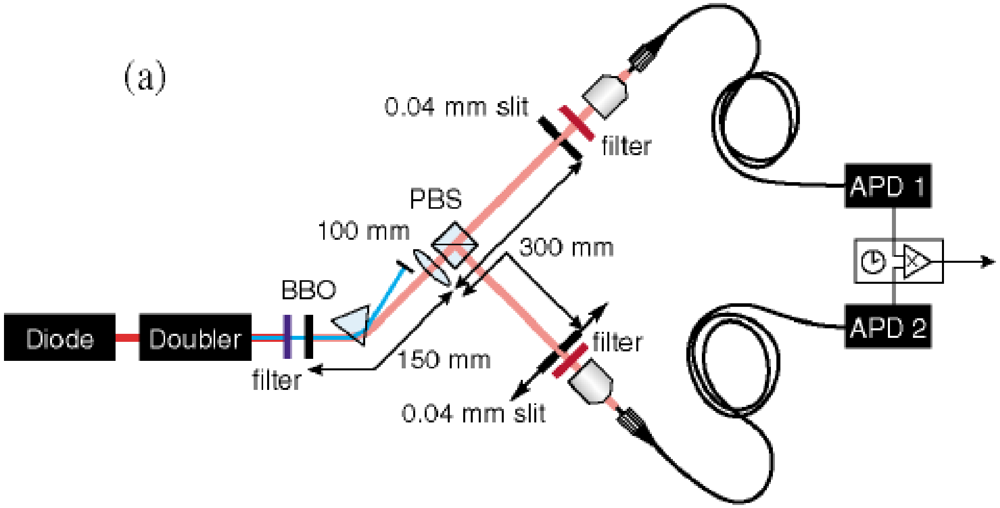
$$\left\langle\left(p_1+p_2\right)^2\right\rangle=\int dp_1dp_2\left(p_1-p_2\right)^2\left|G(p_1,p_2)\right|^2$$

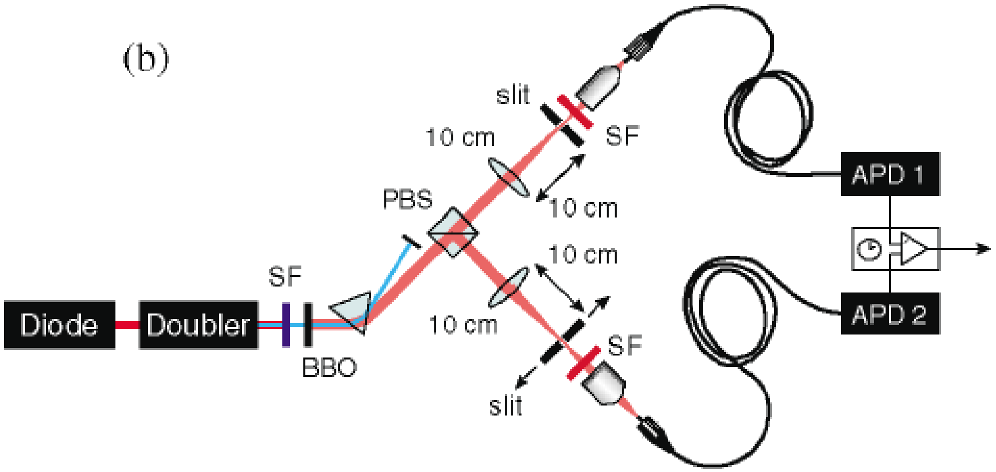
$$\left\langle\left(\Delta \mathrm{v}\right)^2\right\rangle=\left\langle\left(p_1-p_2\right)^2\right\rangle-\left\langle p_1-p_2\right\rangle^2$$

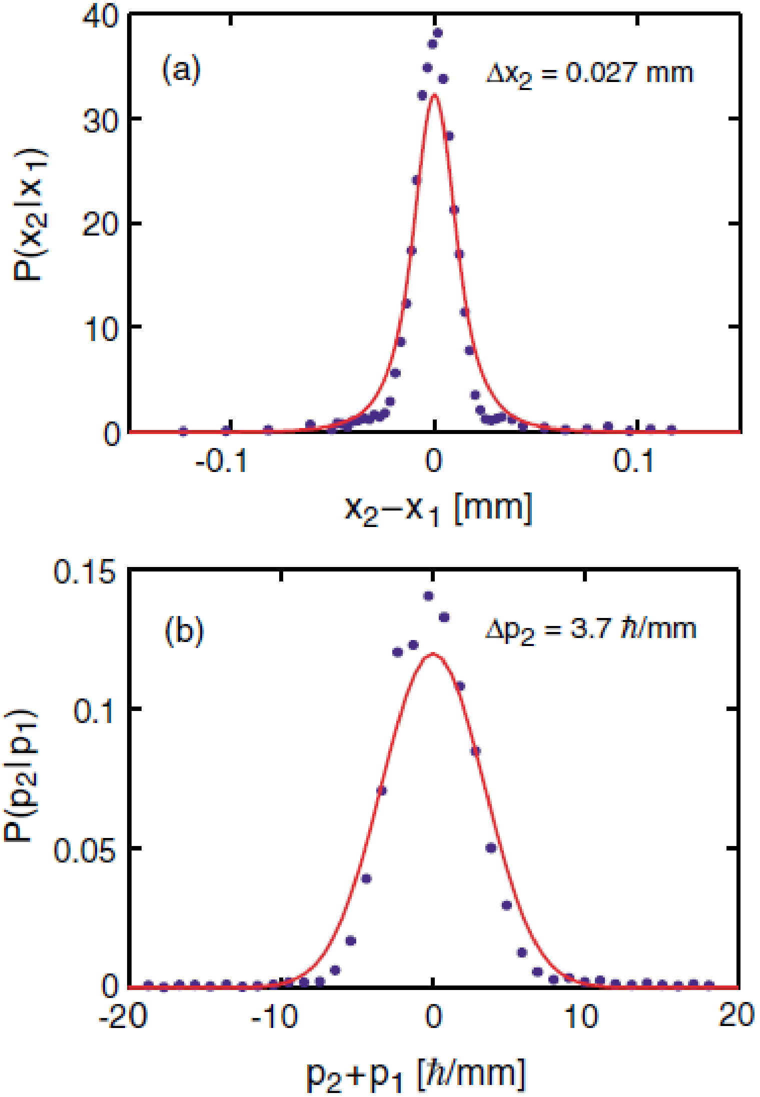
VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

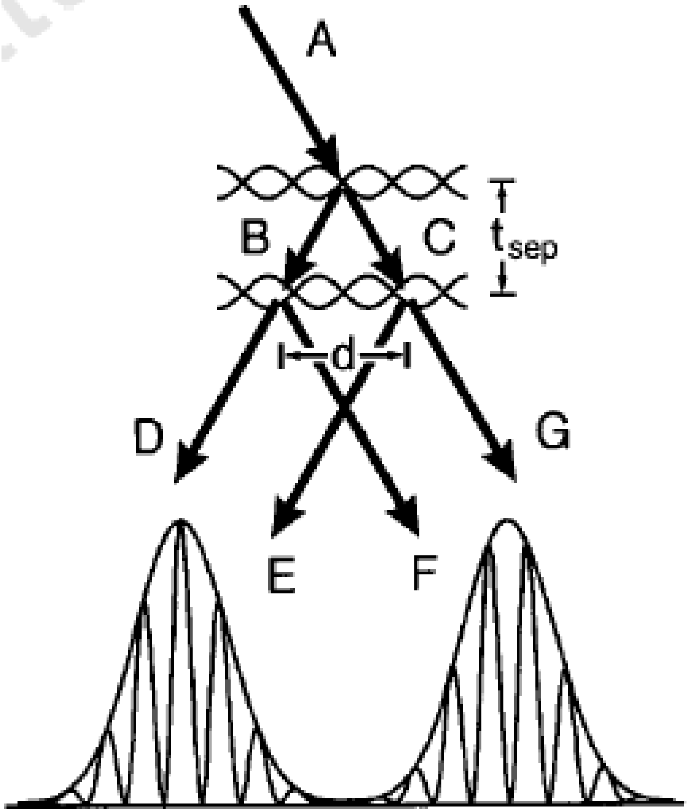
Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion

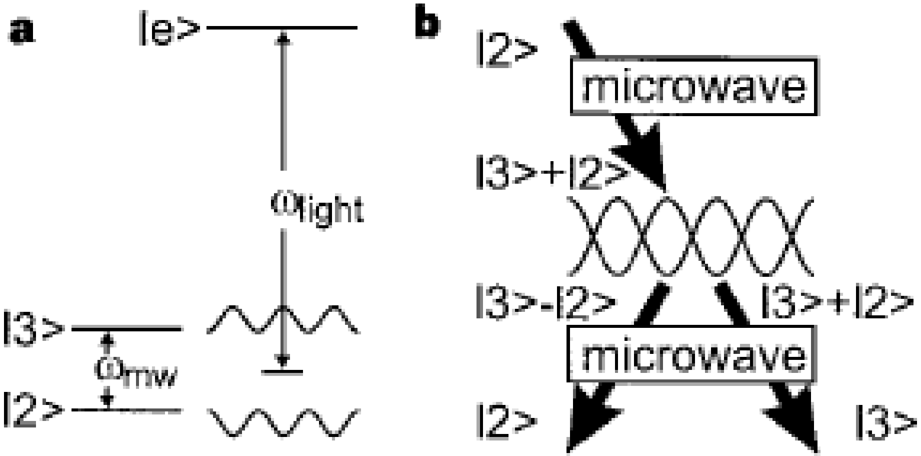
John C. Howell,[1] Ryan S. Bennink,[2] Sean J. Bentley,[2,*] and R.W. Boyd[2]



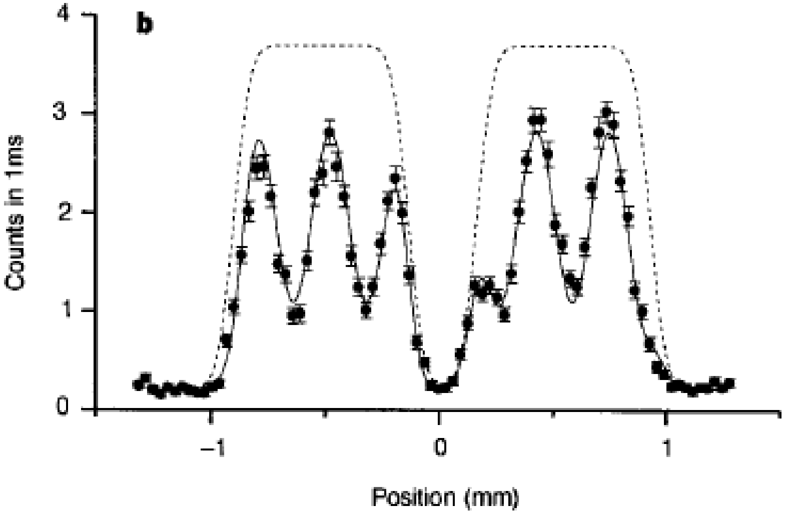


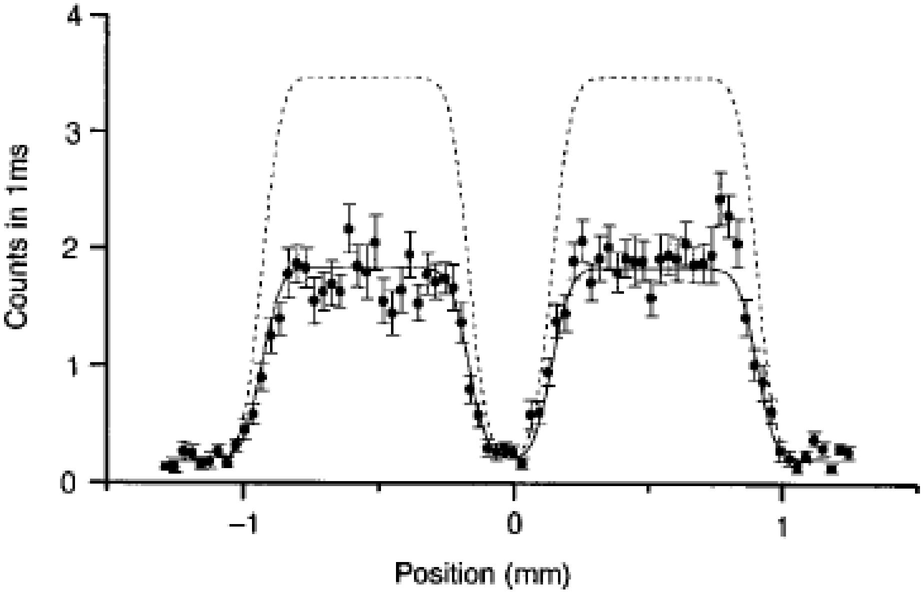

(a)
$\Delta x_2 = 0.027$ mm
$P(x_2|x_1)$
40
30
20
10
0
-0.1
0
0.1
$x_2 - x_1$ [mm]
(b)
$\Delta p_2 = 3.7\ \hbar$/mm
$P(p_2|p_1)$
0.15
0.1
0.05
0
-20
-10
0
10
20
$p_2 + p_1$ [$\hbar$/mm]



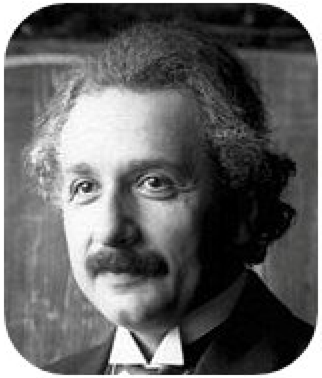


Durr, Nonn, Rempe, Nature **395**, 33 (1998)


b
4
3
2
1
0
Counts in 1ms
−1
0
1
Position (mm)

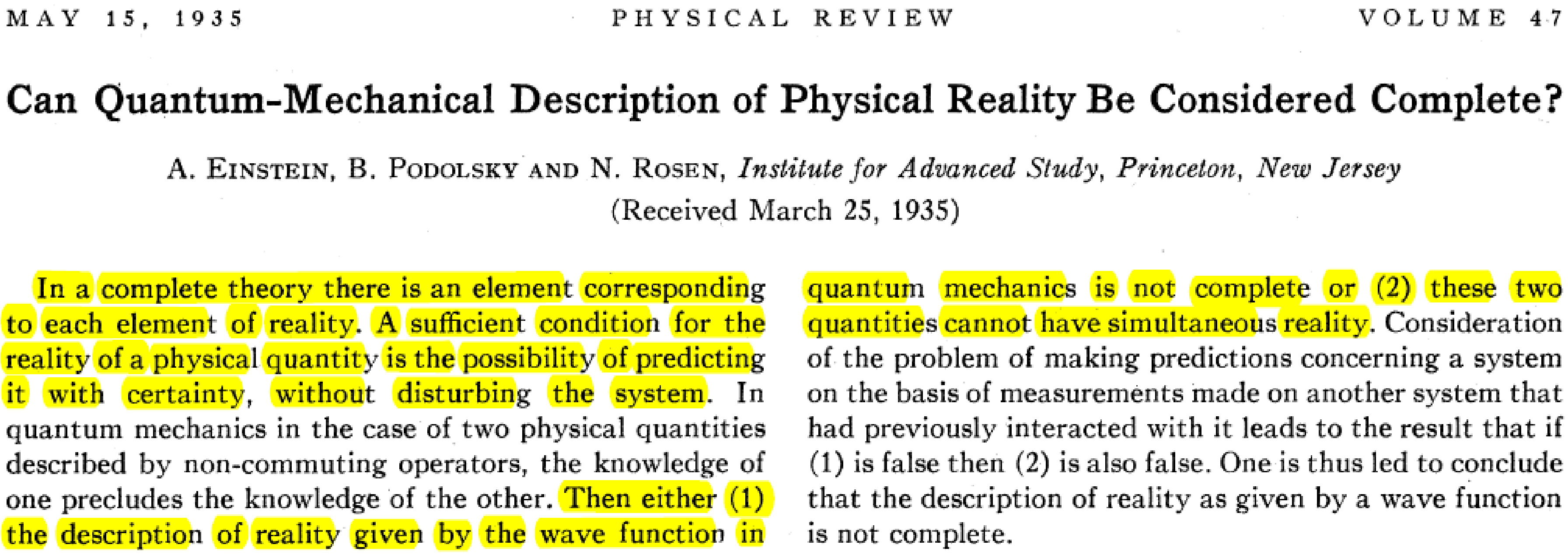

4
3
2
1
0
Counts in 1ms
−1
0
1
Position (mm)

Entanglement
and
Bell’s inequalities


A. Einstein


B. Podolsky


N. Rosen


MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

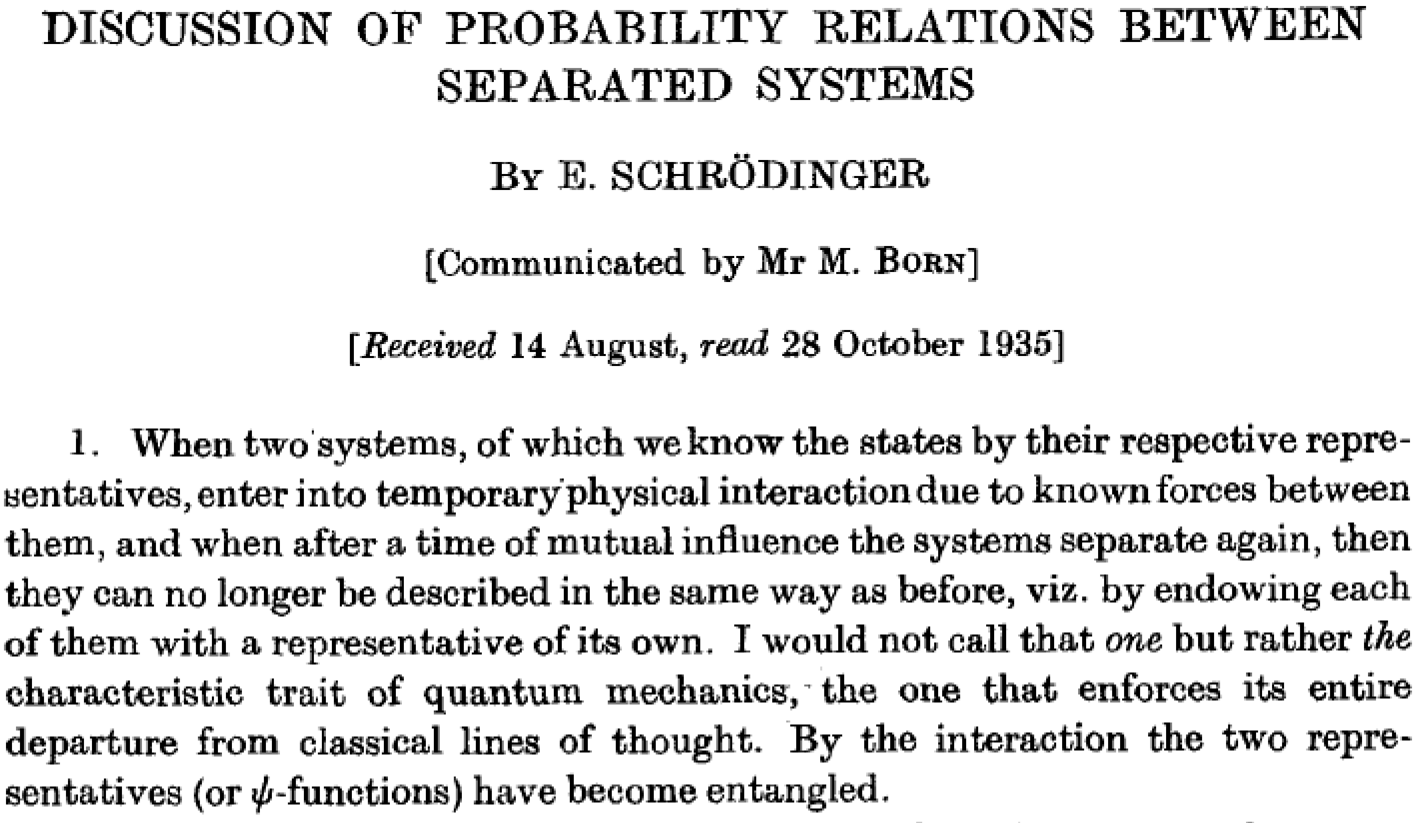
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

E. Schrodinger, 1933

Nobel prize in physics "for the discovery of new productive forms of atomic theory"



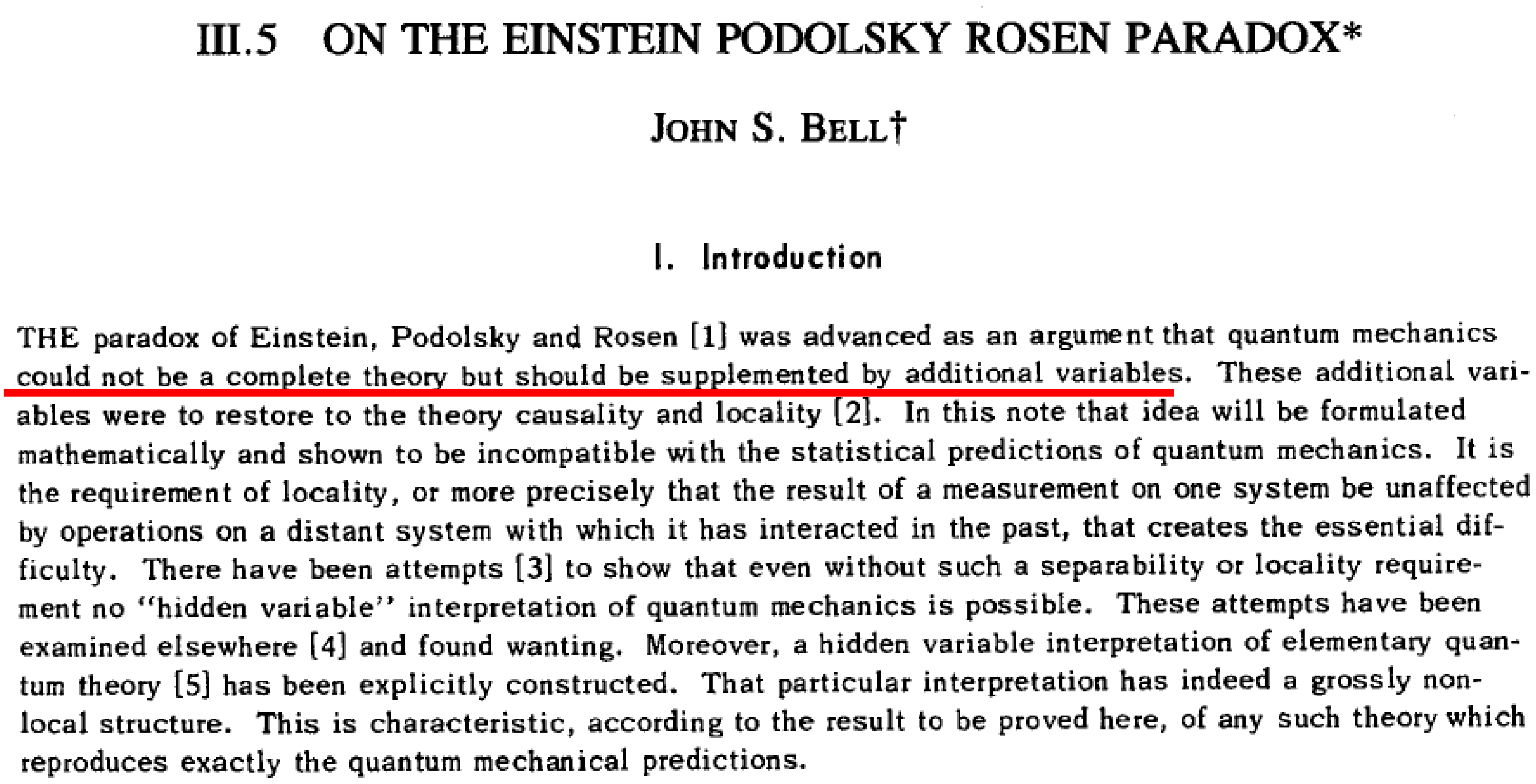
DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

1. When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled.



III.5 ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

JOHN S. BELL†

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly non-local structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.

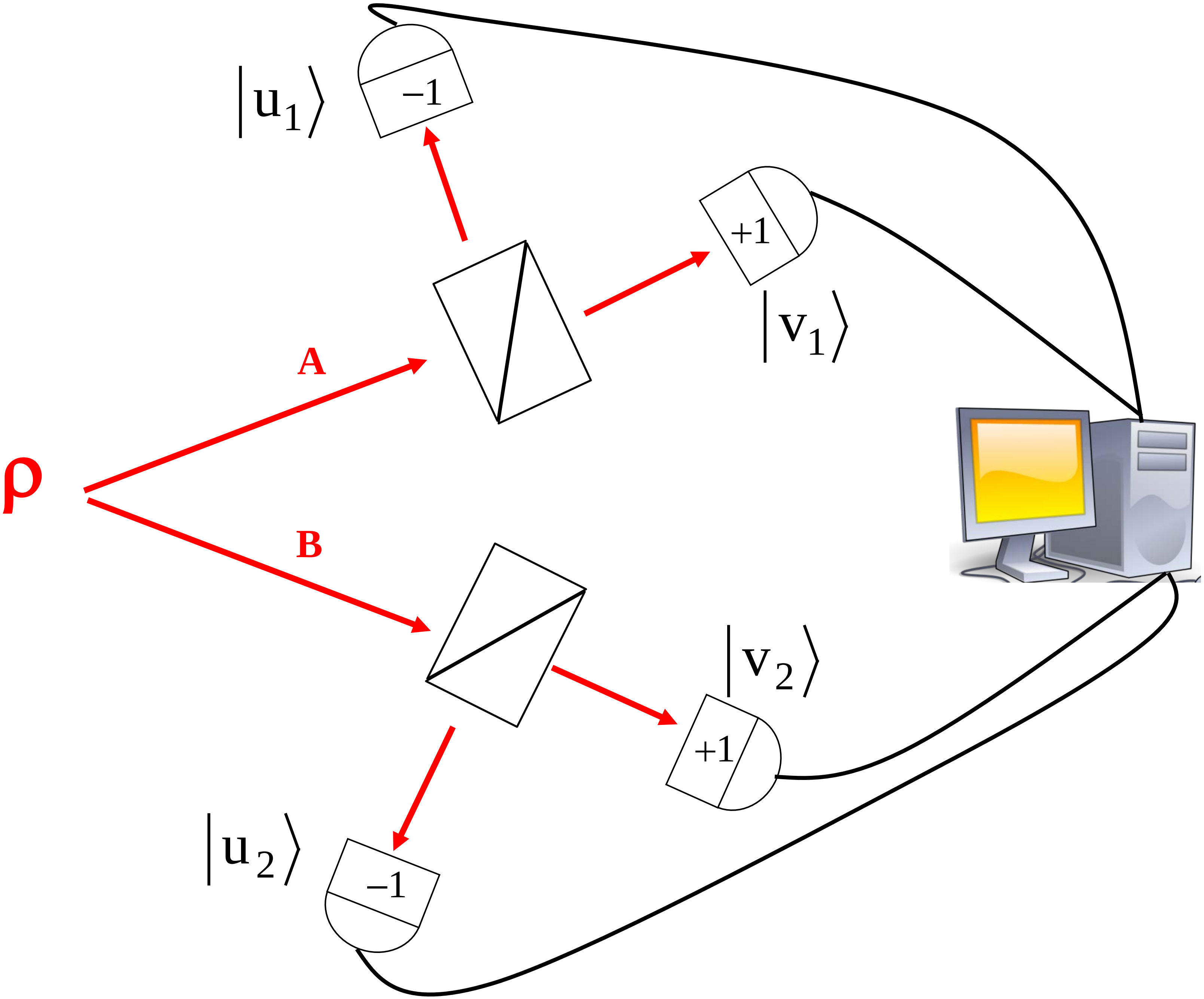
Originally published in *Physics*, *1*, 195-200 (1964).

Bell's states

$$\left|\Phi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|H\right\rangle_A \left|H\right\rangle_B \pm \left|V\right\rangle_A \left|V\right\rangle_B\right]$$

$$\left|\psi \pm\right\rangle = \frac{1}{\sqrt{2}}\left[\left|H\right\rangle_A \left|V\right\rangle_B \pm \left|V\right\rangle_A \left|H\right\rangle_B\right]$$


BELL`S THEOREM
CRESCENT


$|u_1\rangle$
−1
+1
$|v_1\rangle$
A
ρ
B
$|v_2\rangle$
+1
$|u_2\rangle$
−1

Bell’s inequalities (1964)
Clauser, Horne, Shimony, Holt (CHSH)(1969)

$$a_1 \quad A_1 = \pm 1 \qquad\qquad a_2 \quad A_2 = \pm 1$$

$$b_1 \quad B_1 = \pm 1 \qquad\qquad b_2 \quad B_2 = \pm 1$$

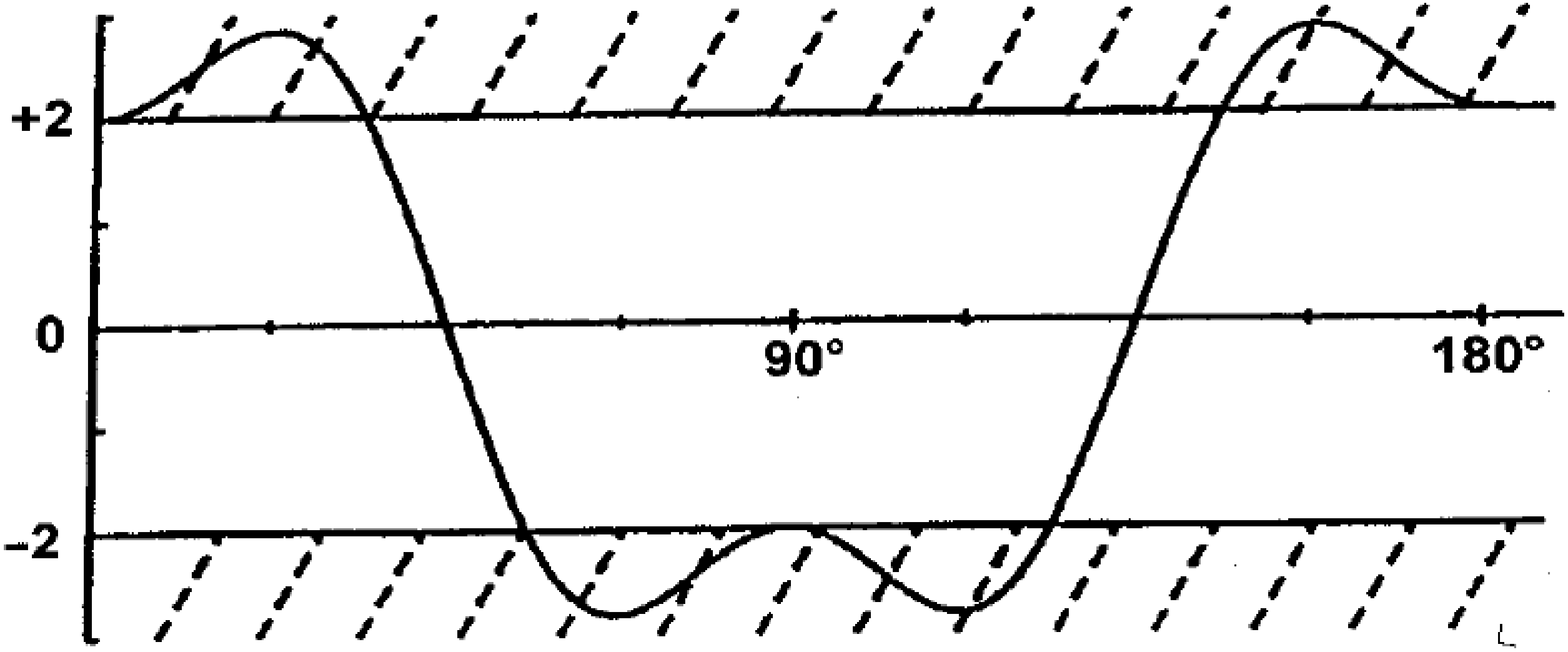
$$A_1(a_1, \lambda) \quad A_2(a_2, \lambda) \quad B_1(b_1, \lambda) \quad B_2(b_2, \lambda)$$

$$E(A_i \cdot B_j) = \int d\lambda \; \rho(\lambda) \, A_i(a_i, \lambda) B_j(b_j, \lambda)$$

$$\boxed{\begin{array}{l} S = E(A_1 \cdot B_1) + E(A_2 \cdot B_1) + E(A_2 \cdot B_2) - E(A_1 \cdot B_2) \\ -2 \le S \le 2 \end{array}}$$

BELL'S THEOREM : THE NAIVE VIEW OF AN EXPERIMENTALIST[†]

Alain Aspect



Generation of polarization-entangled photon pairs in a Bragg reflection waveguide

A. Vallés,[1,*] M. Hendrych,[1] J. Svozilík,[1,2] R. Machulka,[2] P. Abolghasem,[3] D. Kang,[3] B. J. Bijlani,[3] A. S. Helmy,[3] and J. P. Torres[1,4]

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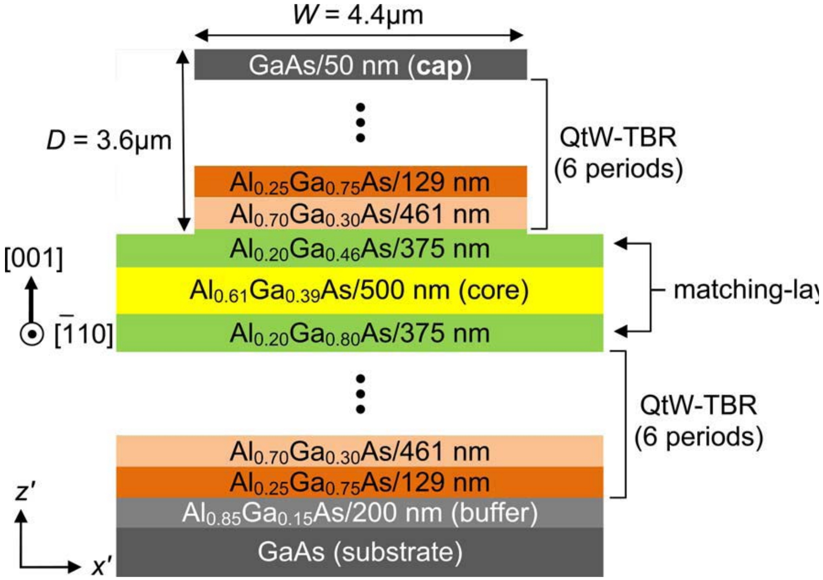
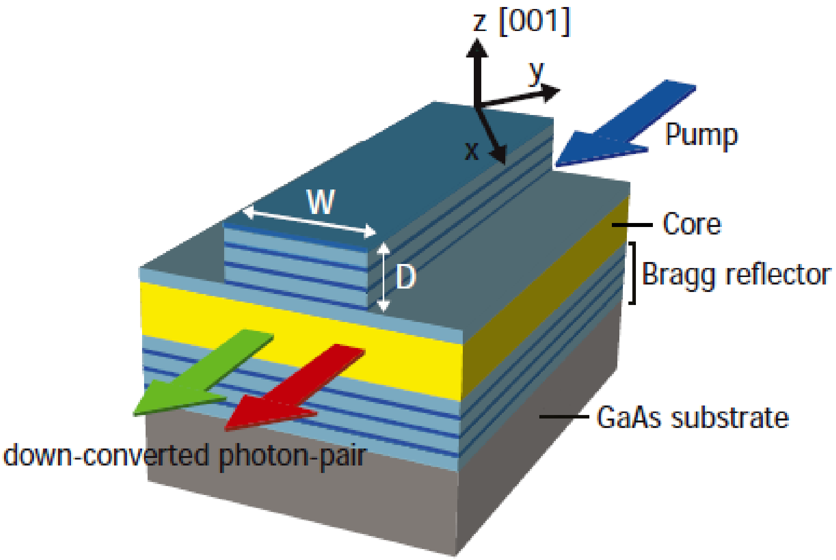
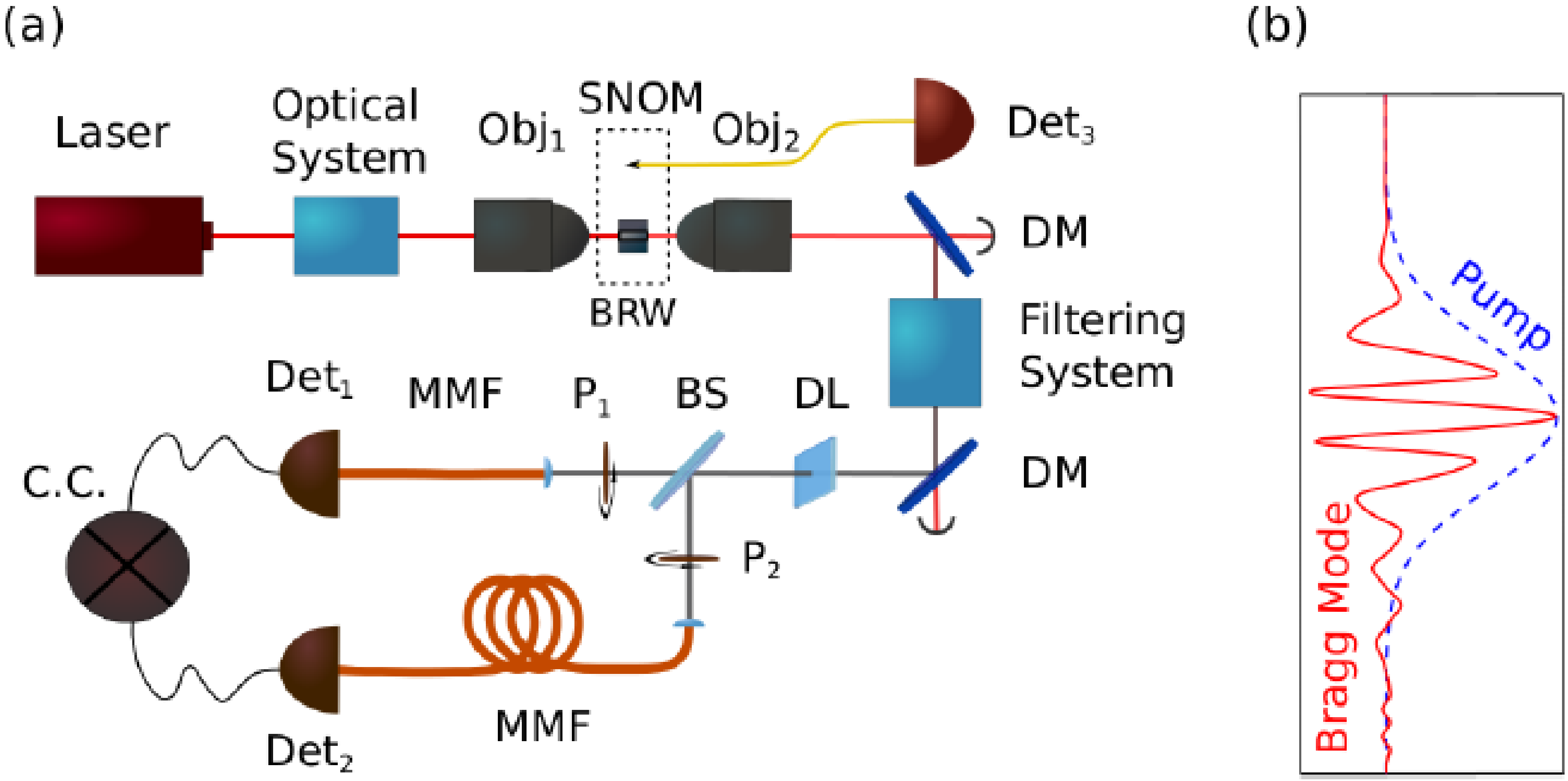
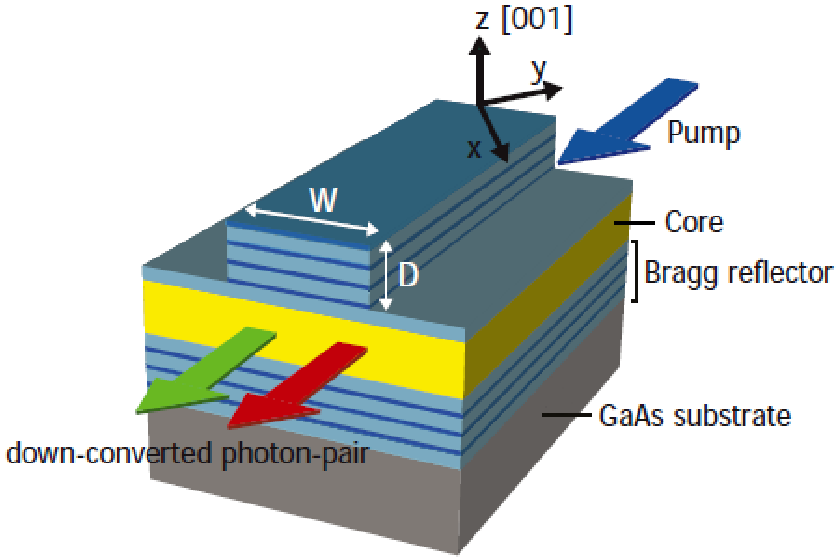
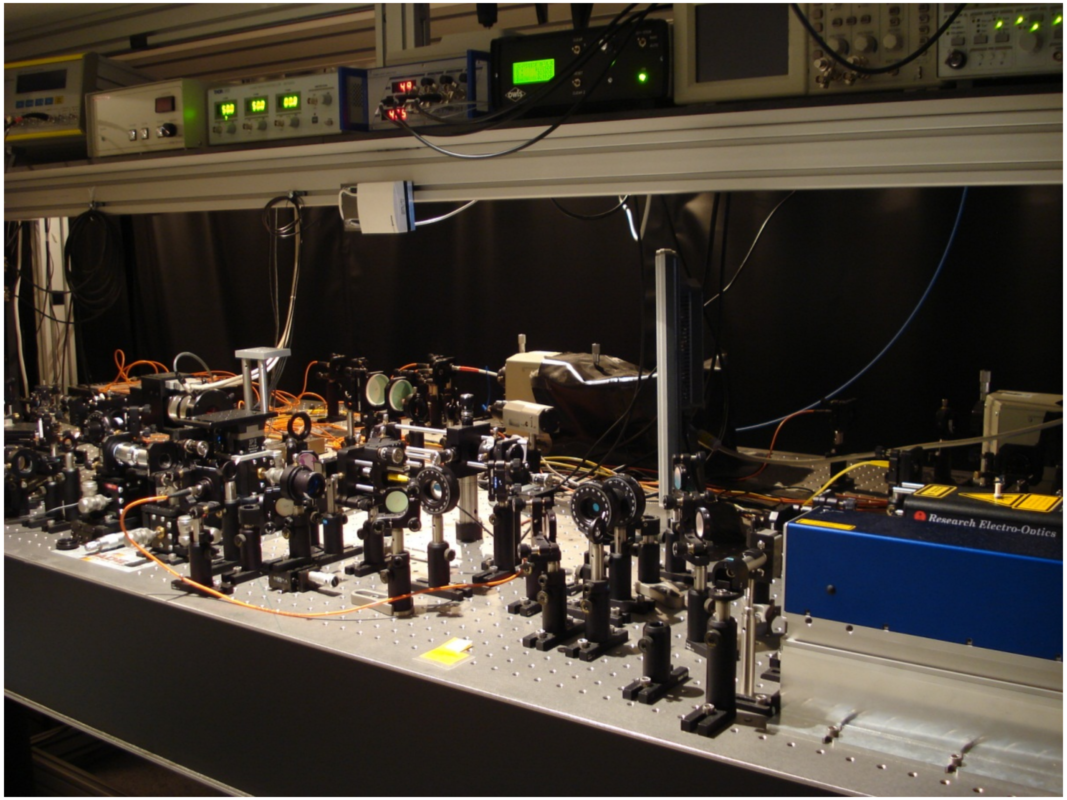
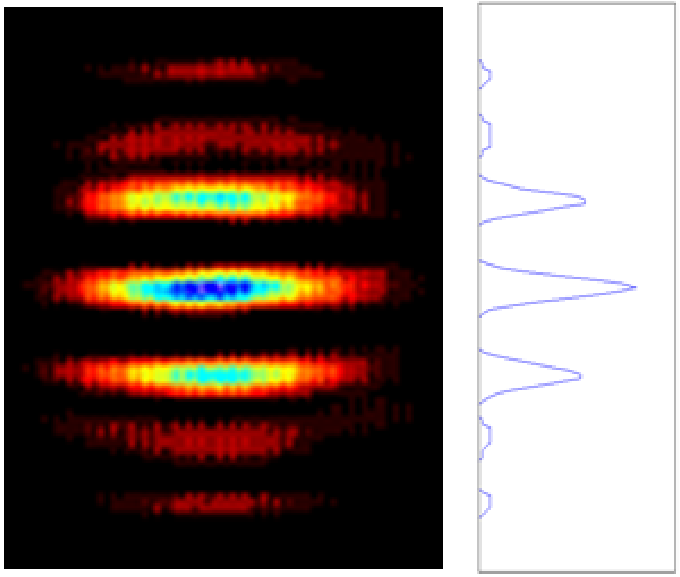




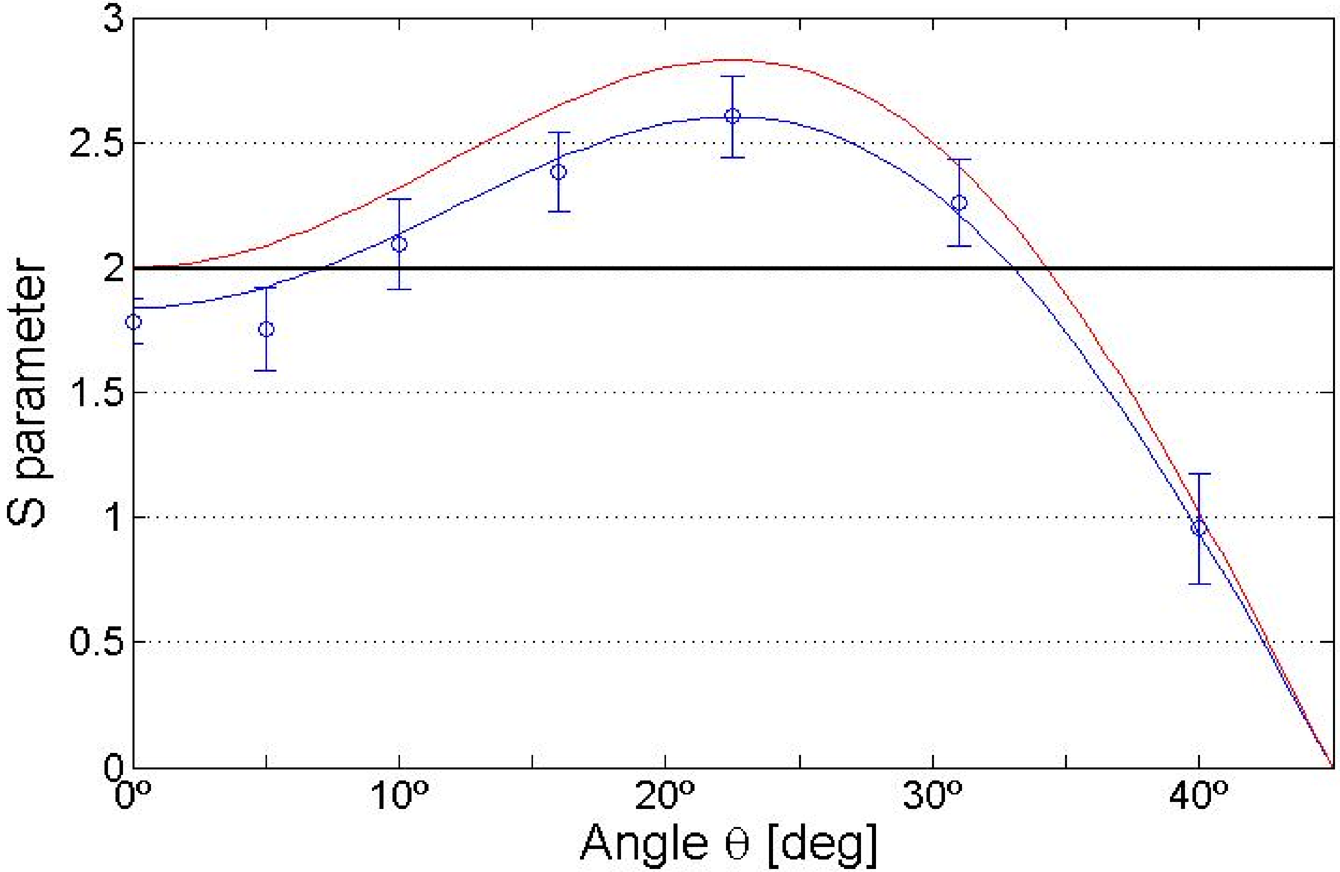

(a)
Laser
Optical System
Obj₁
SNOM
Obj₂
Det₃
DM
BRW
Filtering System
Det₁
MMF
P₁
BS
DL
DM
C.C.
P₂
MMF
Det₂
(b)
Pump
Bragg Mode


z [001]
y
x
Pump
W
D
Core
Bragg reflector
GaAs substrate
down-converted photon-pair


Research Electro-Optics



Bell’s inequality violation



Magic moments with John Bell

Reinhold A. Bertlmann

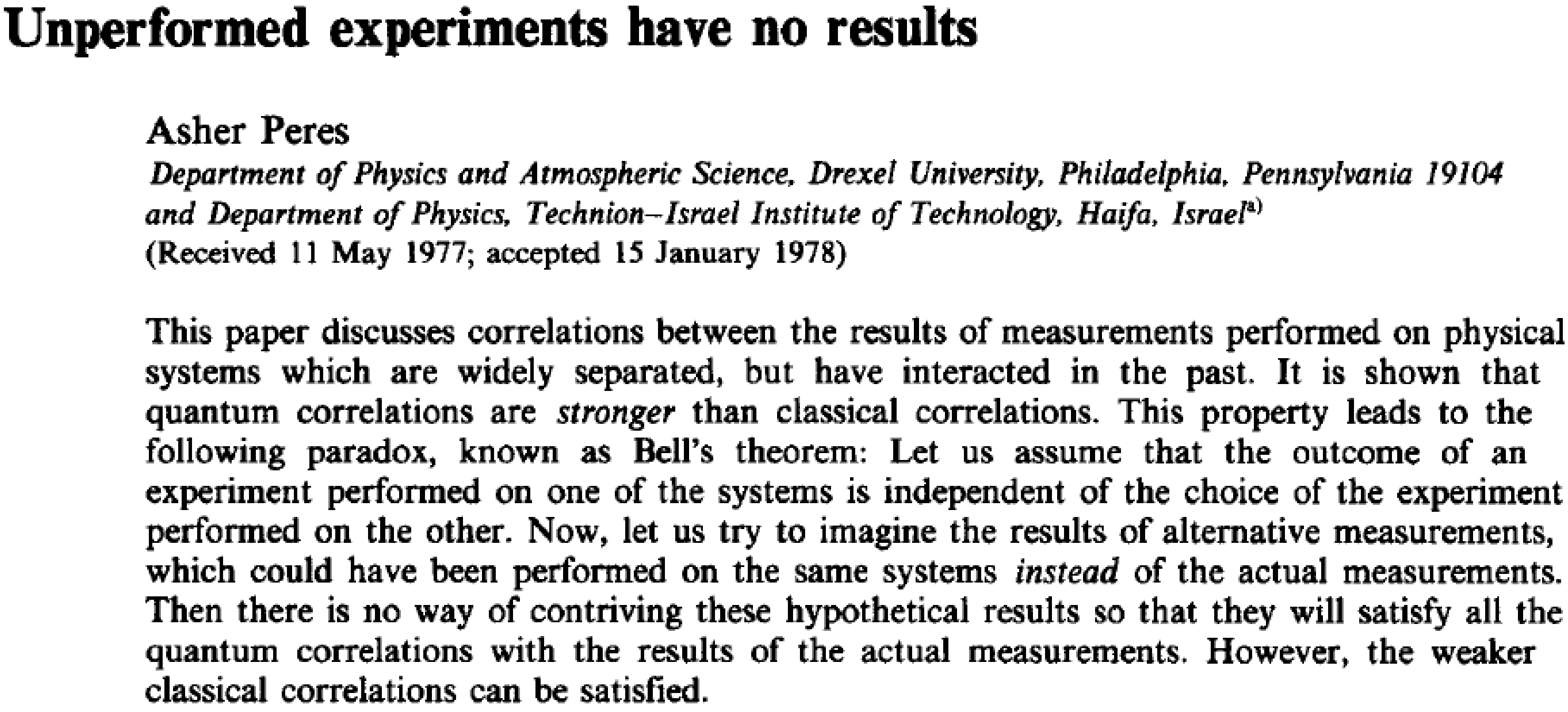
John Bell, with whom I had a fruitful collaboration and warm friendship, is best known for his seminal work on the foundations of quantum physics, but he also made outstanding contributions to particle physics and accelerator physics.

Physics Today

Magic moments with John Bell
Reinhold A. Bertlmann

Citation: Physics Today **68**(7), 40 (2015); doi: 10.1063/PT.3.2847

Asher Peres



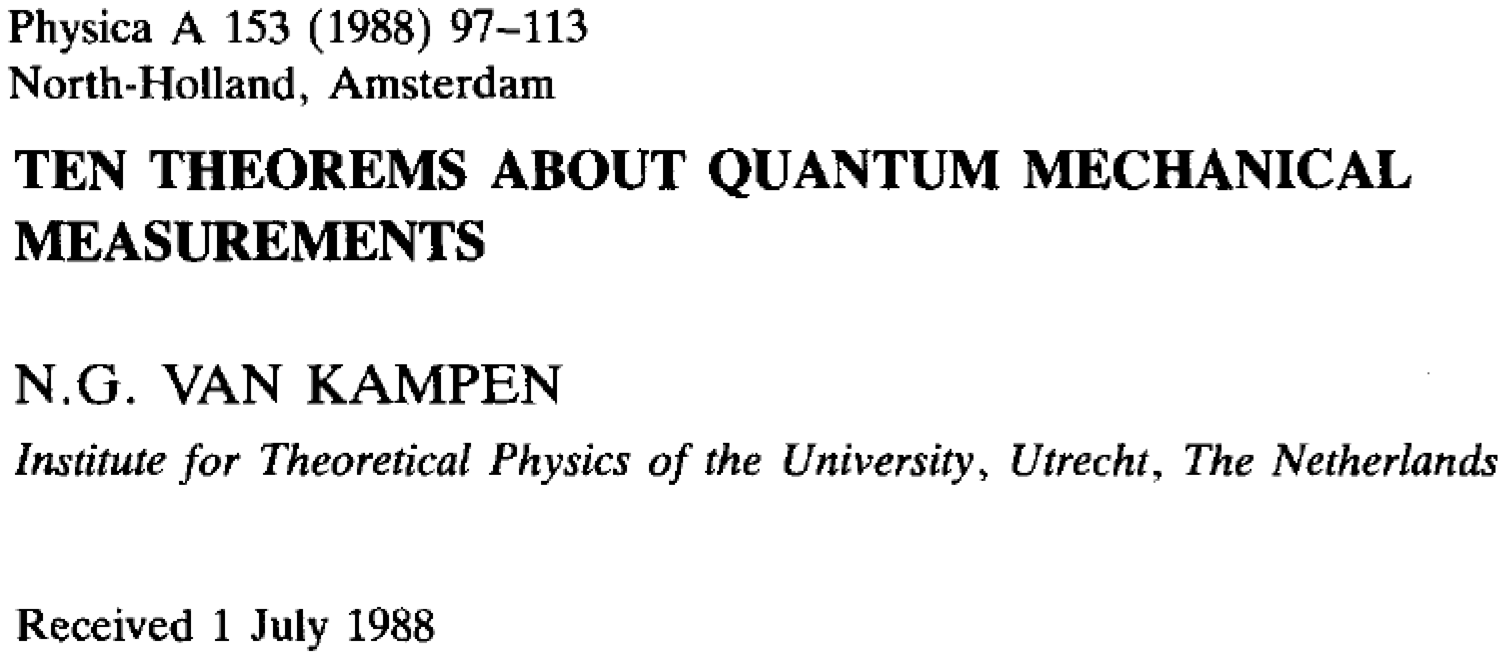
Unperformed experiments have no results

Asher Peres
Department of Physics and Atmospheric Science, Drexel University, Philadelphia, Pennsylvania 19104 and Department of Physics, Technion–Israel Institute of Technology, Haifa, Israel[a)]

(Received 11 May 1977; accepted 15 January 1978)

This paper discusses correlations between the results of measurements performed on physical systems which are widely separated, but have interacted in the past. It is shown that quantum correlations are *stronger* than classical correlations. This property leads to the following paradox, known as Bell's theorem: Let us assume that the outcome of an experiment performed on one of the systems is independent of the choice of the experiment performed on the other. Now, let us try to imagine the results of alternative measurements, which could have been performed on the same systems *instead* of the actual measurements. Then there is no way of contriving these hypothetical results so that they will satisfy all the quantum correlations with the results of the actual measurements. However, the weaker classical correlations can be satisfied.

Some conclusions and more



Physica A 153 (1988) 97–113
North-Holland, Amsterdam

TEN THEOREMS ABOUT QUANTUM MECHANICAL MEASUREMENTS

N.G. VAN KAMPEN

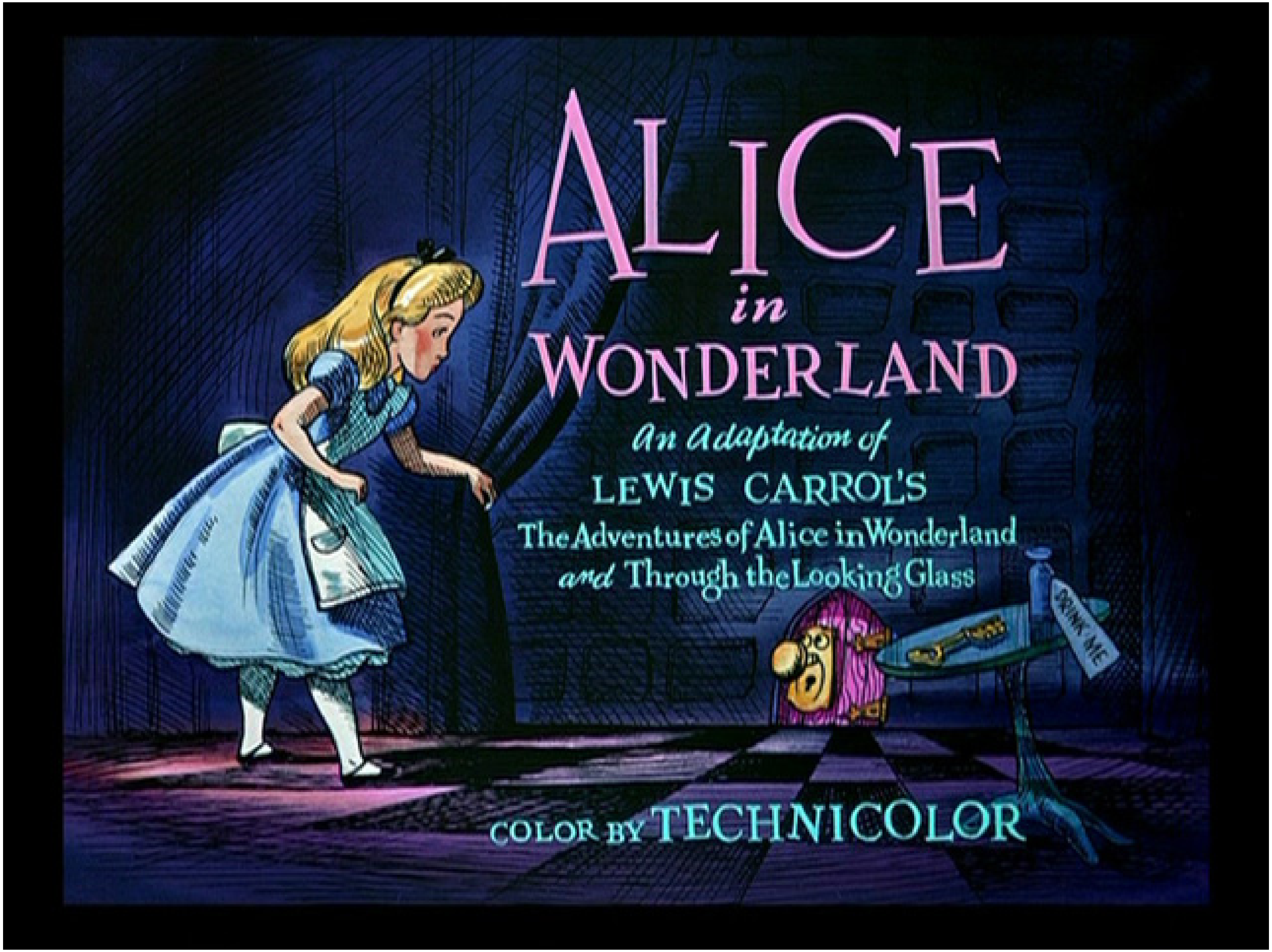
Institute for Theoretical Physics of the University, Utrecht, The Netherlands

Received 1 July 1988

Theorem I: Quantum mechanics works.

There can not be quantum measurement theory…there is only quantum mechanics. Either you use quantum mechanics to describe experimental facts or you use another theory. **A measurement is not a supernatural event**. It is a physical process, involving ordinary matter, and subject to ordinary physical laws.

Quantum Theory: concepts and methods, Asher Peres
Kuwer Academic Publishing, p. xiii,1993


ALICE
in
WONDERLAND
An Adaptation of
LEWIS CARROL'S
The Adventures of Alice in Wonderland
and Through the Looking Glass
DRINK ME
COLOR BY TECHNICOLOR

Alice laughed, "There is no use trying," she said, "one can't believe impossible things."

"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

--Lewis Carroll, Through the Looking Glass

http://thelifeofpsi.com/2013/09/01/the-measurement-problem/

her Peres

Impossible things usually don't happen

The Odd Quantum

Treiman

1999 Princeton University Press 272pp

£15.95/$24.95hb

Sam Treiman was a distinguished particle theorist. The famous Goldberger–Treiman relation was, at the time of its discovery in 1958, an amazing connection between the strong and weak interactions. Colleagues used to credit him with "Treiman's theorem" – impossible things usually don't happen.

Shortly before his untimely death late last year, Treiman wrote a book that, he said, was "aimed at a wide audience of the curious, scientists as well as non-scientists". The publishers advertise it as "a concise account of quantum mechanics written for general readers".

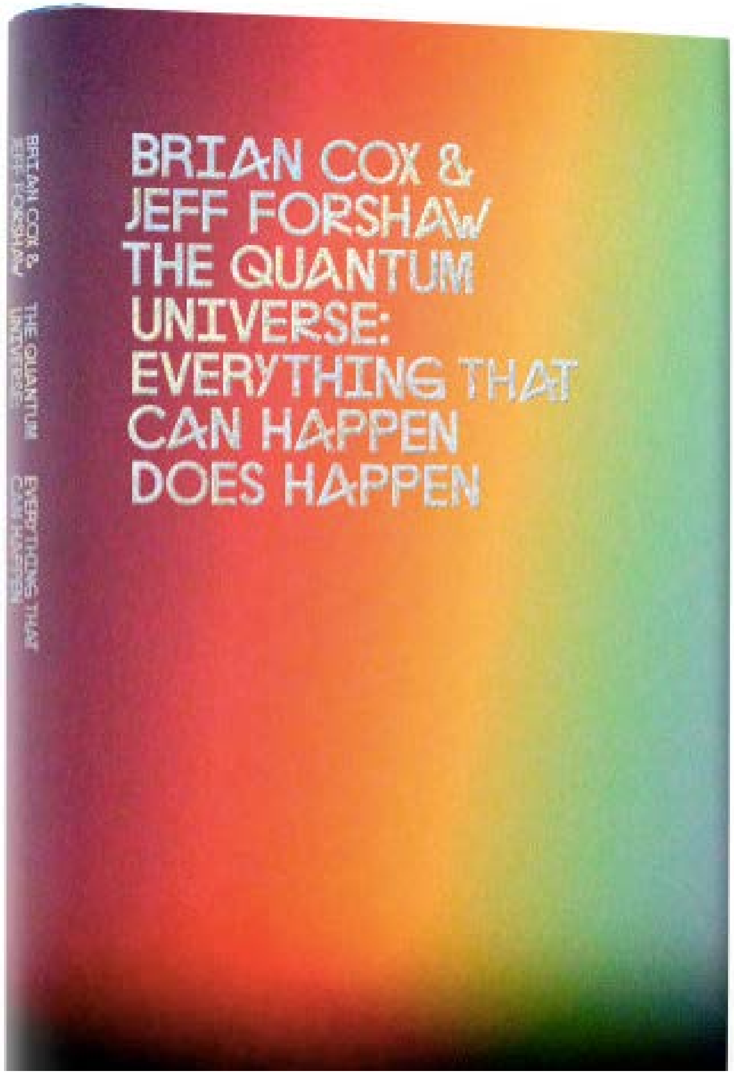
Writing a popular book on quantum mechanics is a perilous endeavour. When I was asked to review the book, my pred-

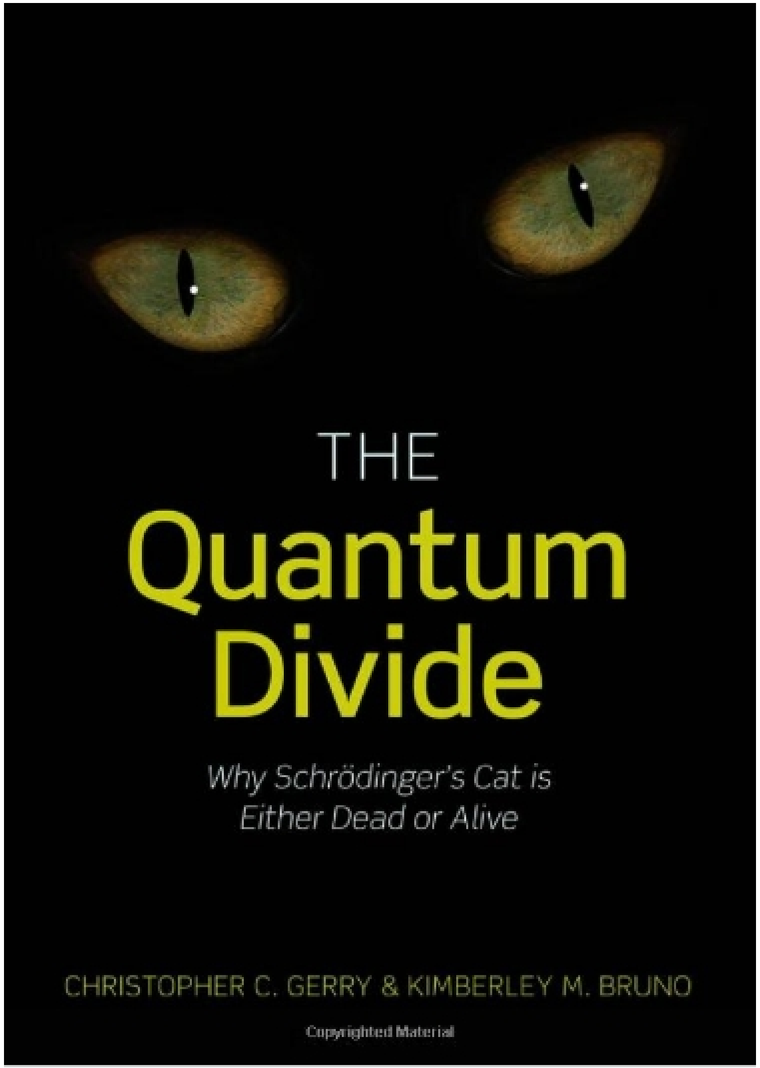
Law breaker – the strange effects of quantum theory

mostly misleading literature.

Indeed, some leading contemporary scientists have promoted wild speculations about the quantum measurement problem – for example, that human consciousness plays a role in it. Treiman, however, is faithful to his no-nonsense approach and is exceedingly careful. As he writes: "The quantum assertion is [that] the state of the system 'collapses' into the eigenstate that corresponds to the eigenvalue obtained in the measurement", and quickly adds, "for the present, let's stick with the naive proposition enunciated above."

There is the inevitable Schrödinger's cat parable, followed by a mundane explanation: "We are actually all of us, daily, in the position of Schrödinger's cat…To the *outside* observer, we are superpositions until the observation is made." One brief paragraph is devoted to Hugh Everett's many-worlds interpretation. "It is undoubtedly amusing to contemplate," says Treiman, "[but] it can neither be falsified





“Quantum mechanics is weird, but not that weird.”

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