Kioloa, February 11, 2006

Talk dedicated to François Bardou

Atomic Hanbury Brown and Twiss effect with He*: a step in quantum atom optics

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QUDEDIS

ESF/PESC Programme

Atomic Hanbury Brown and Twiss effect with He*: a step in quantum atom optics

- The H. B. & T. experiment with light: a landmark in quantum (photon) optics
- The HB&T effect with atoms
- Ultra cold He* with a space and time resolved detector: a new tool in quantum atom optics

The HB&T experiment

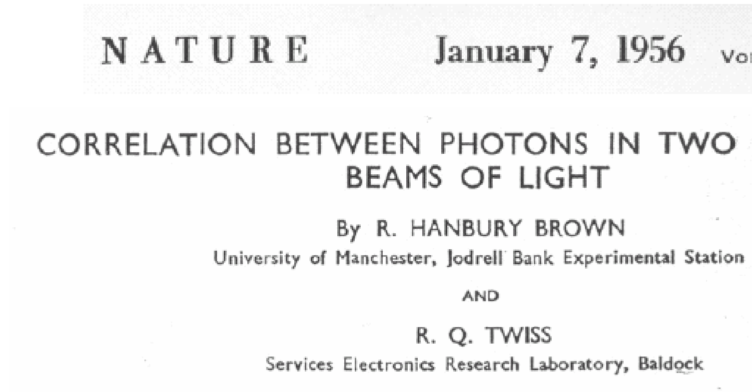
Measurement of the correlation function of the photocurrents at two different points and times

$$g^{(2)}(\mathrm{r}_1,\mathrm{r}_2;\tau)=\frac{\langle i(\mathrm{r}_1,t)\,i(\mathrm{r}_2,t+\tau)\rangle}{\langle i(\mathrm{r}_1,t)\rangle\langle i(\mathrm{r}_2,t)\rangle}$$

Semi-classical model of the photodetection (classical em field, quantized detector):

Measure of the correlation function of the light intensity:

$$i(\mathrm{r},t)\ \propto\ I(\mathrm{r},t)=\left|\mathrm{E}(\mathrm{r},t)\right|^2$$


NATURE January 7, 1956 Vol. 177

CORRELATION BETWEEN PHOTONS IN TWO COHERENT BEAMS OF LIGHT

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AND

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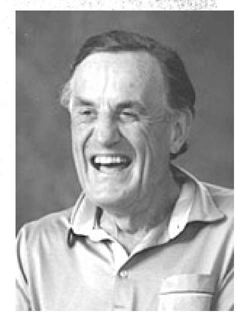
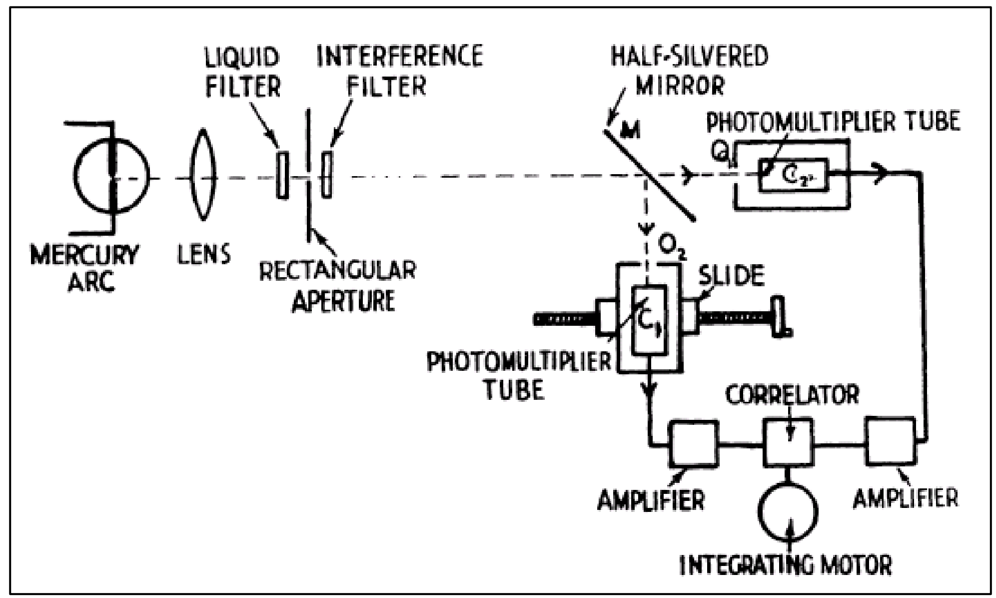
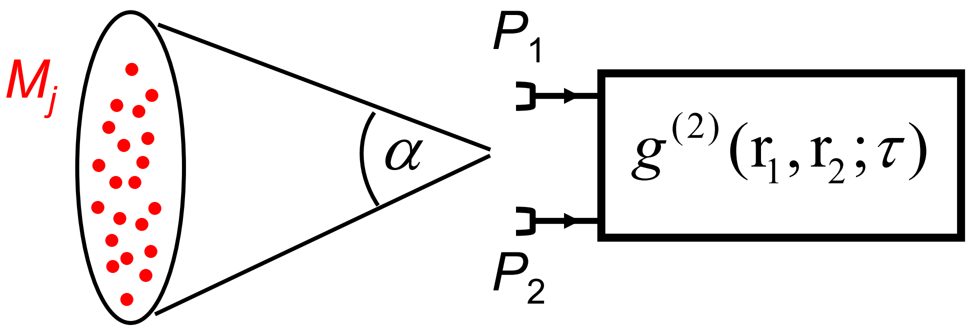


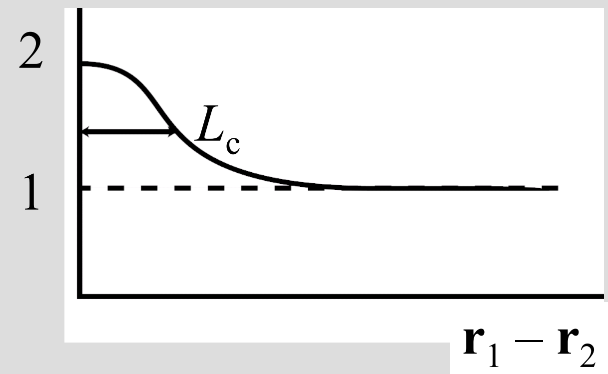


The HB&T effect

Light from incoherent source: time and space correlations



$g^{(2)}(\mathrm{r}_2 - \mathrm{r}_1; \tau = 0) > 1$



$$g^{(2)}(\mathrm{r}_1 = \mathrm{r}_2; \tau = 0) = 2$$

$$g^{(2)}(\mathrm{r}_1 - \mathrm{r}_2 \gg L_c; \tau \gg \tau_c) = 1$$

A measurement of $g^{(2)} - 1$ *vs.* τ and $\mathbf{r}_1 - \mathbf{r}_2$ yields the coherence volume

- time coherence

$$\tau_c \approx 1/\Delta\omega$$

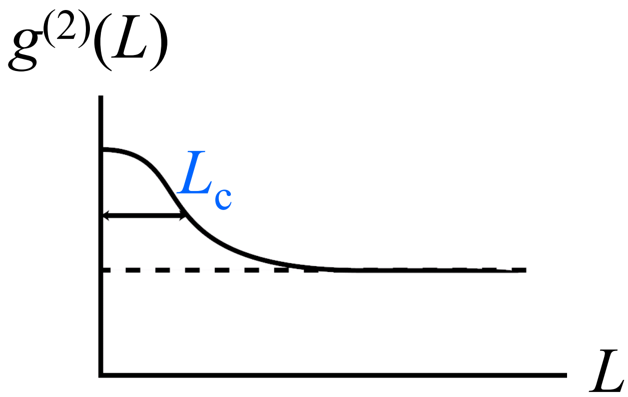
- space coherence

$$L_c \approx \lambda/\alpha$$

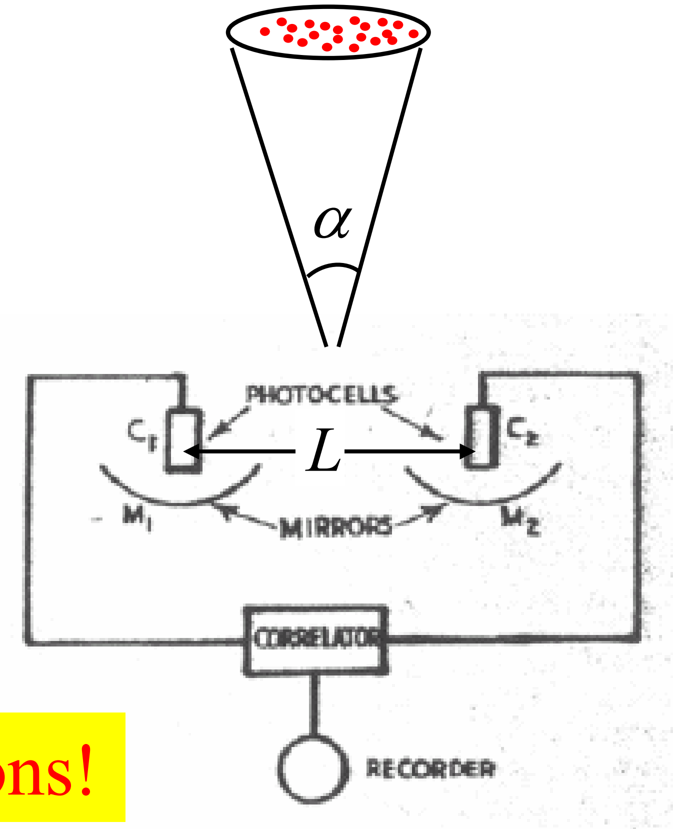
The HB&T stellar interferometer

Measure of the coherence area

$\Rightarrow$ angular diameter of a star



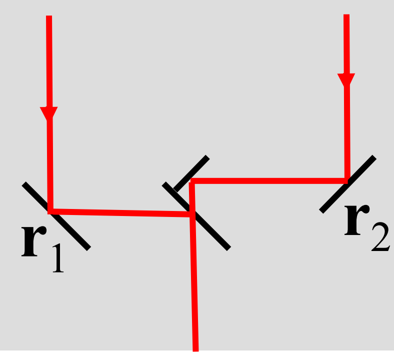
$$\alpha = \frac{\lambda}{L_C}$$



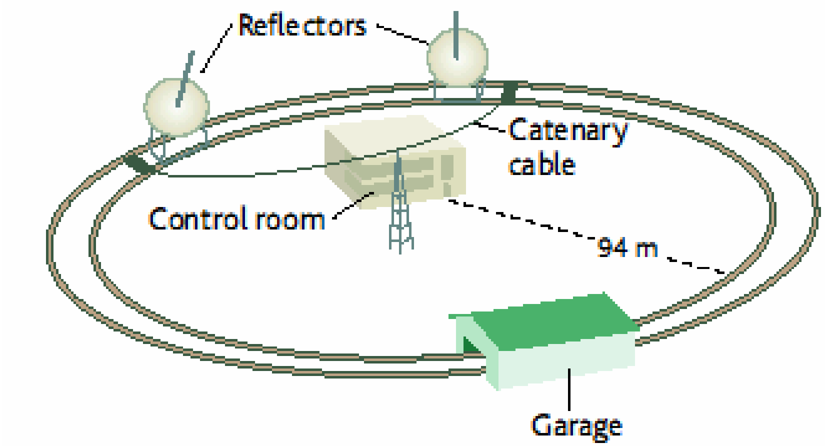
HB&T insensitive to atmospheric fluctuations!

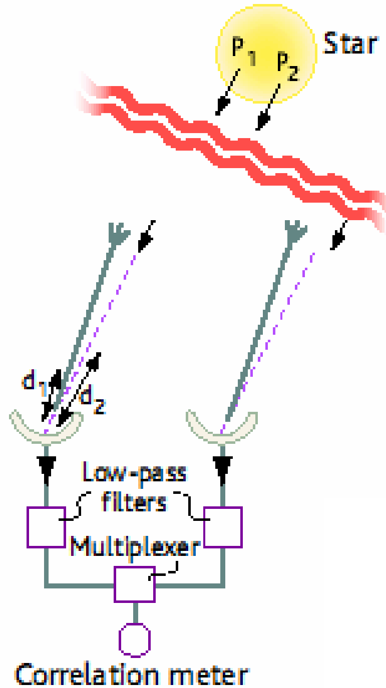
Equivalent to the Michelson stellar interferometer ?

Visibility of fringes $\Rightarrow$ $\left|g^{(1)}(\mathrm{r}_1,\mathrm{r}_2;\tau)\right|$ $\Rightarrow L_C$



The HB&T stellar interferometer





NATURE November 10, 1956

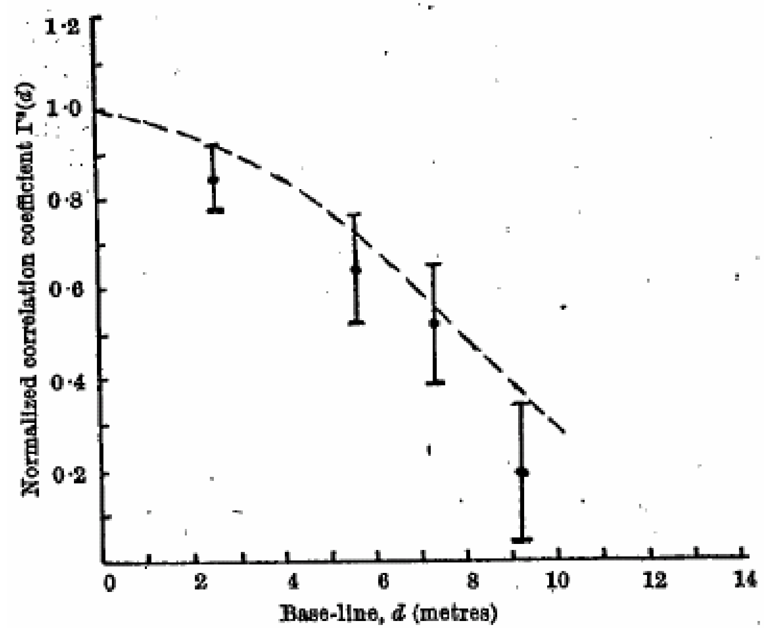


Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN
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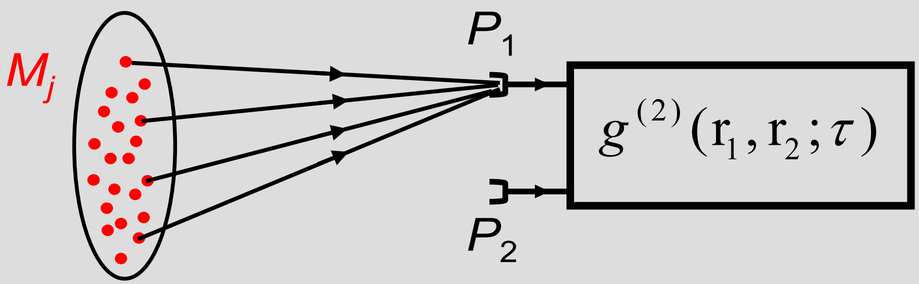
AND
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock

Classical wave explanation for HB&T correlations (1)



Many independent random emitters: complex electric field = sum of many independent random processes

$$E(P,t) = \sum_j a_j \exp\left\{\phi_j + \frac{\omega_j}{c} M_j P - \omega_j t\right\}$$

Gaussian random process $\Rightarrow$ $g^{(2)}(r_1, r_2; \tau) = 1 + \left|g^{(1)}(r_1, r_2; \tau)\right|^2$

$$g^{(2)}(r_1, r_2; \tau) = \frac{\langle i(r_1,t)\, i(r_2, t+\tau)\rangle}{\langle i(r_1,t)\rangle \langle i(r_2,t)\rangle} = \frac{\langle E^*(r_1,t) E(r_1,t) E^*(r_2,t+\tau) E(r_2,t+\tau)\rangle}{\langle |E(r_1,t)|^2 \rangle \langle |E(r_2,t+\tau)|^2 \rangle}$$

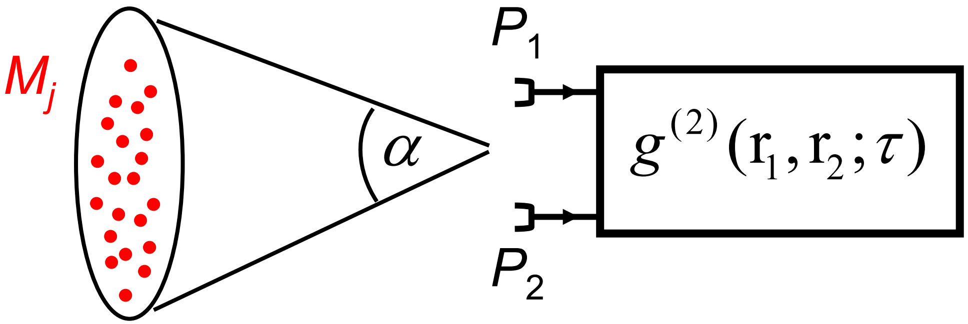
$$g^{(1)}(r_1, r_2; \tau) = \frac{\langle E^*(r_1,t) E(r_2,t+\tau)\rangle}{\langle |E(r_1,t)|^2 \rangle^{1/2} \langle |E(r_2,t+t)|^2 \rangle^{1/2}}$$

Stochastic process

$\langle\rangle$ = statistical (ensemble) average

(= time average if stationary and ergodic)

Classical wave explanation for HB&T correlations (1')



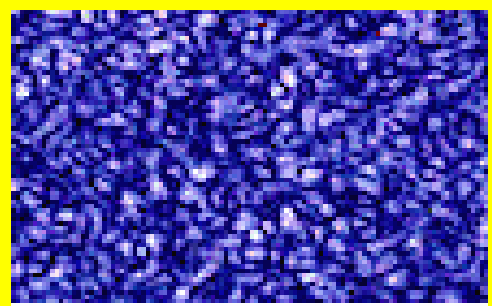
Many independent random emitters: complex electric field = sum of many independent random processes

$$\mathrm{E}(P,t) = \sum_j a_j \exp\left\{\phi_j + \frac{\omega_j}{c} M_j P - \omega_j t\right\}$$

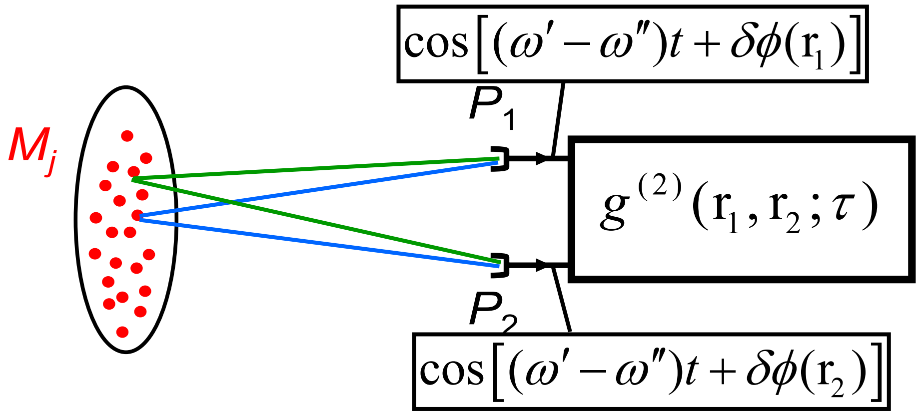
Gaussian random process $\Rightarrow$ $g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = 1 + \left| g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau) \right|^2$

Speckle in the observation plane:

- Correlation radius $L_c \approx \lambda / \alpha$
- Changes after $\tau_c \approx 1 / \Delta\omega$



Classical wave explanation for HB&T correlations (2)



Many independent random emitters: complex electric field = sum of many independent random processes

$$E(P,t)=\sum_j a_j \exp\left\{\phi_j+\frac{\omega_j}{c}M_jP-\omega_j t\right\}$$

Noise excess, due to beat notes between various spectral components from various emitters, is correlated in coherence volume $|\delta\phi(r_1)-\delta\phi(r_2)|<\pi/2$

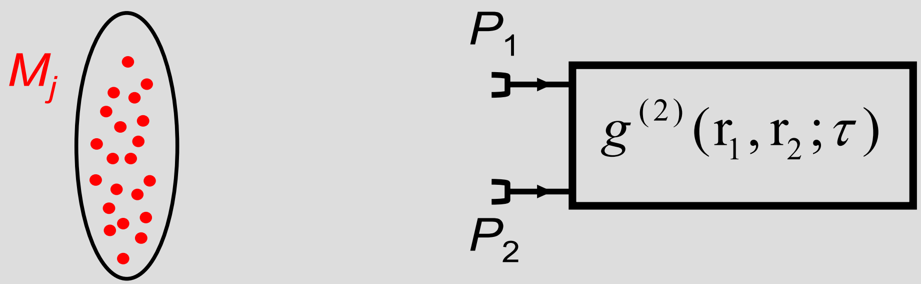
Simple explanation for insensitivity to atmospheric turbulence:

- path fluctuations small compared to "effective wavelength" $\lambda = c/(\omega'-\omega'')$ of beat note
- but large at the scale of optical wavelength: Michelson fringes move

The HB&T effect with photons: a hot debate

Strong negative reactions to the HB&T proposal (1955)

In term of photons



joint detection probability

$$g^{(2)}(r_1, r_2; \tau) = \frac{\langle \pi(r_1, r_2, t) \rangle}{\langle \pi(r_1, t) \rangle \langle \pi(r_2, t) \rangle}$$

single detection probabilities

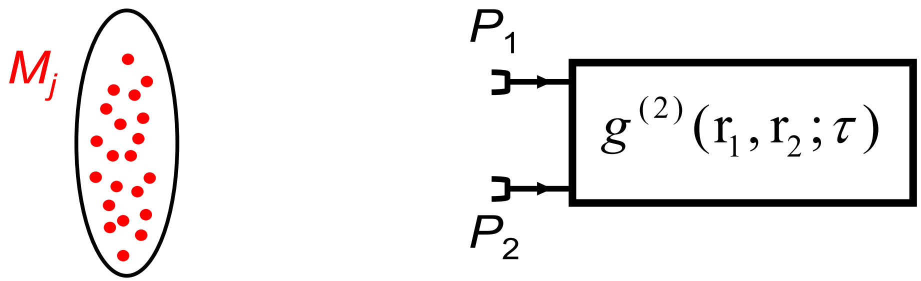
For independent detection events $g^{(2)} = 1$

$g^{(2)}(0) = 2 \Rightarrow$ probability to find two photons at the same place larger than the product of simple probabilities: bunching

How might independent particles be bunched ?

The HB&T effect with photons: a hot debate

Strong negative reactions to the HB&T proposal (1955)



How might photons emitted from distant points in an incoherent source (possibly a star) not be statistically independent ?

HB&T answer

- Experimental demonstration!
- Light is both wave and particles.

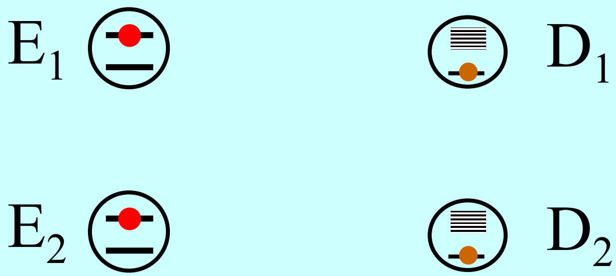
$$g^{(2)}(r_1, r_2; \tau) = 1 + \left| g^{(1)}(r_1, r_2; \tau) \right|^2$$

  - Uncorrelated detections easily understood as independent particles (shot noise)
  - Correlations (excess noise) due to beat notes of random waves

cf. Einstein's discussion of wave particle duality in Salzburg (1909), about black body radiation fluctuations

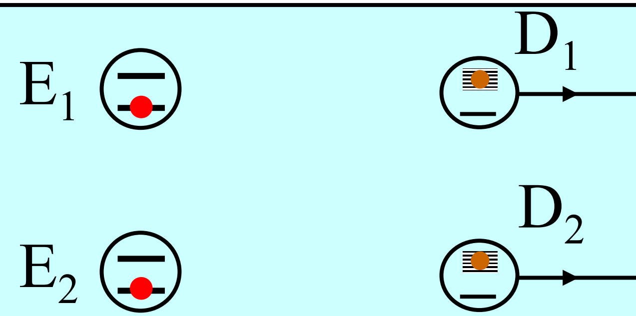
The HB&T effect with photons: Fano-Glauber interpretation

Two photon emitters, two detectors



Initial state:

- Emitters excited
- Detectors in ground state



Final state:

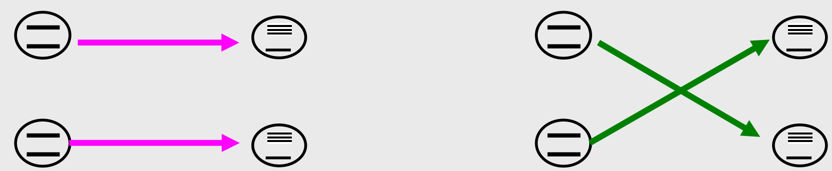
- Emitters in ground state
- Detectors ionized

Two paths to go from THE initial state to THE final state

Amplitudes of the two process interfere ⇒ factor 2

The HB&T effect with particles: a non trivial quantum effect

Two paths to go from one initial state to one final state: quantum interference



Two photon interference effect: quantum weirdness

- happens in configuration space, not in real space
- A precursor of entanglement, HOM, etc…

Lack of statistical independence (bunching) although no “real” interaction

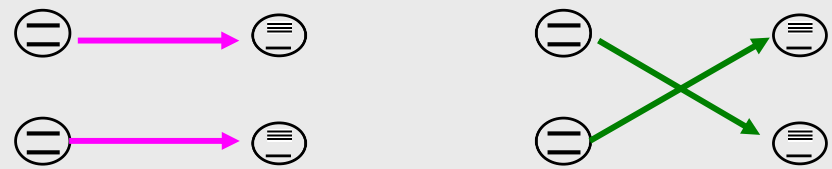
cf Bose-Einstein Condensation (letter from Einstein to Schrödinger, 1924)

… but a trivial effect for a radio (waves) engineer or a physicist working in classical optics (speckle)

$$\langle I(t)^2 \rangle \geq \langle I(t) \rangle^2$$

The HB&T effect with fermions: a fully quantum effect

Two paths to go from one initial state to one final state: quantum interference



Amplitudes added with opposite signs: antibunching

Two particles interference effect: quantum weirdness

- happens in configuration space, not in real space
- A precursor of entanglement etc…

Lack of statistical independence although no “real” interaction

… no classical interpretation

$$\left\langle n(t)^2 \right\rangle < \left\langle n(t) \right\rangle^2$$

Impossible for classical densities

Intensity correlation with laser light:

1960: inv

•1961: M

to obser

•1963: G

→ quant

•1965: A

laser: no

below th

•1966: A

Simple classi

$E = E_0 \exp\{-i$ ... $\}$ ... n ... 0

ntical by

eam.

use of Glauber coherent states

Phys Rev Lett 1963

PHOTON CORRELATIONS*

Roy J. Glauber

Lyman Laboratory, Harvard University, Cambridge, Massachusetts

(Received 27 December 1962)

In 1 ... that th ... tral w ... pairs ... ted ... e-

tons ... t ... that ... row- ... ing t ... ction[2] ... of la ... the ... bear ... e ... that ... s ... from an inappropriate model ...

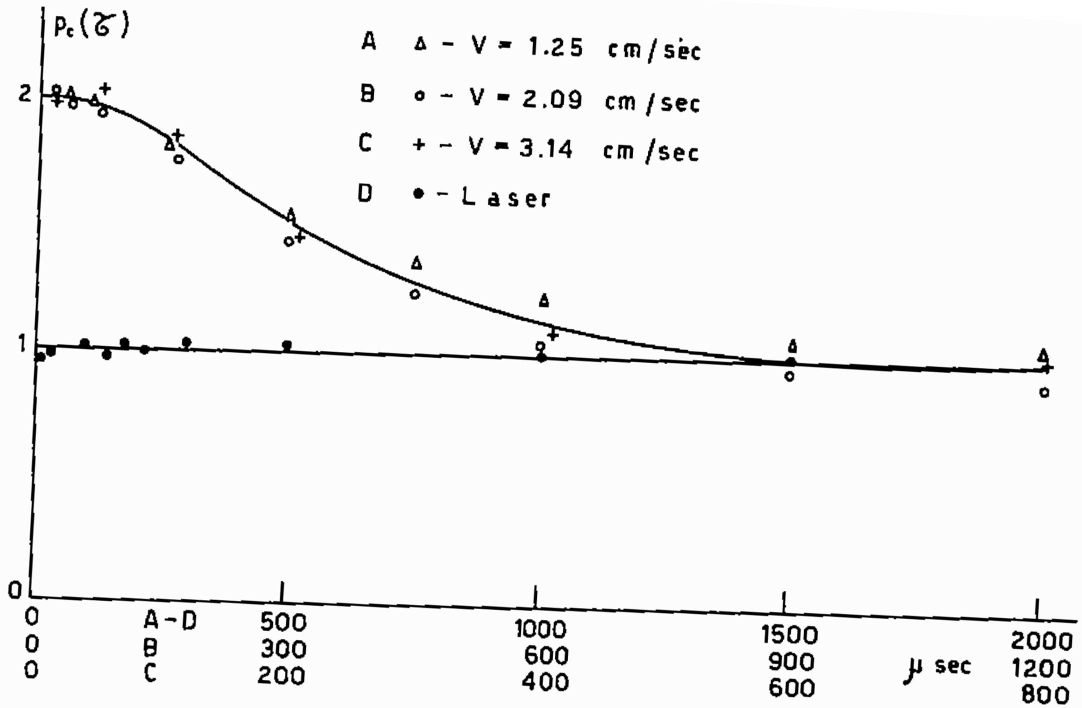


Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

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An atomic Hanbury Brown and Twiss experiment with He*

- The H. B. & T. experiment with light: a landmark in quantum (photon) optics
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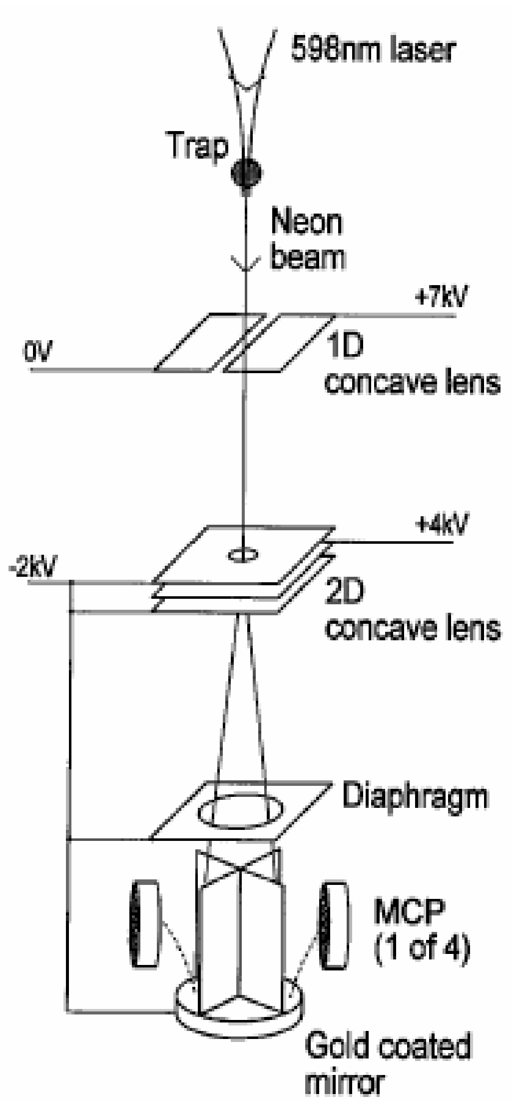
- Ultra cold He* with a space and time resolved detector: a new tool in quantum atom optics

The HB&T effect with atoms: Yasuda and Shimizu, 1996

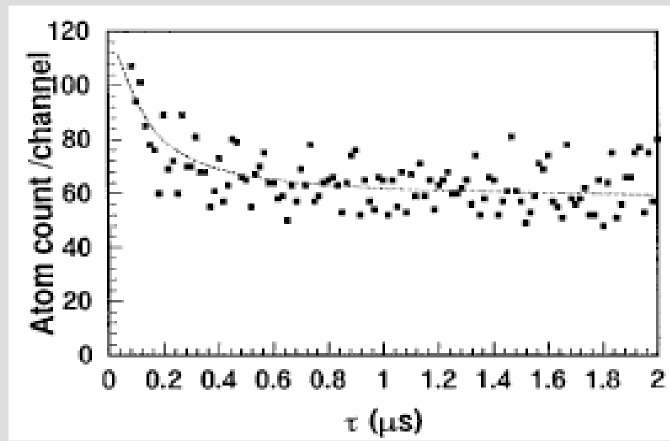


- Cold neon atoms in a MOT (100 μK) continuously pumped into a non trapped (falling) metastable
  - ➢Single atom detection (metastable atom)
  - ➢Narrow source (<100μm): coherence volume as large as detector viewed through diverging lens: no reduction of the visibility of the bump

Effect clearly seen

•Bump disappears when detector size $>> L_C$

•Coherence time as predicted: $\hbar / \Delta E \approx 0.2\ \mu s$



Completely analogous to HB&T: continuous; longitudinal ≠ transverse

HB&T type effects with particles

Atomic density correlations

- $g^{(3)}(0) = 3!$ (JILA, 1997): 3 body collisions in a thermal cloud, in contrast to a BEC (Kagan, Svistunov, Shlyapnikov, JETP lett 1985)
- $g^{(2)}(0) = 2$ (MIT, 1997): Interaction energy of a thermal gas
- Correlations in a quasicondensate (Hannover 2003)
- Correlations in the atom density fluctuations in cold atomic samples
  - Atoms released from a Mott phase (Mainz, 2005)
  - Molecules dissociation (D Jin et al., Boulder, 2005)
  - Atomic density fluctuations on an atom chip (Orsay, 2005)

Also observed in nuclear and particle physics

G. Baym, Acta Phys. Pol. B 29, 1839 (1998).

Fermionic antibunching observed with electrons

M. Henny et al., (1999); W. D. Oliver et al.(1999); H. Kiesel et al. (2002).

An atomic Hanbury Brown and Twiss experiment with He*

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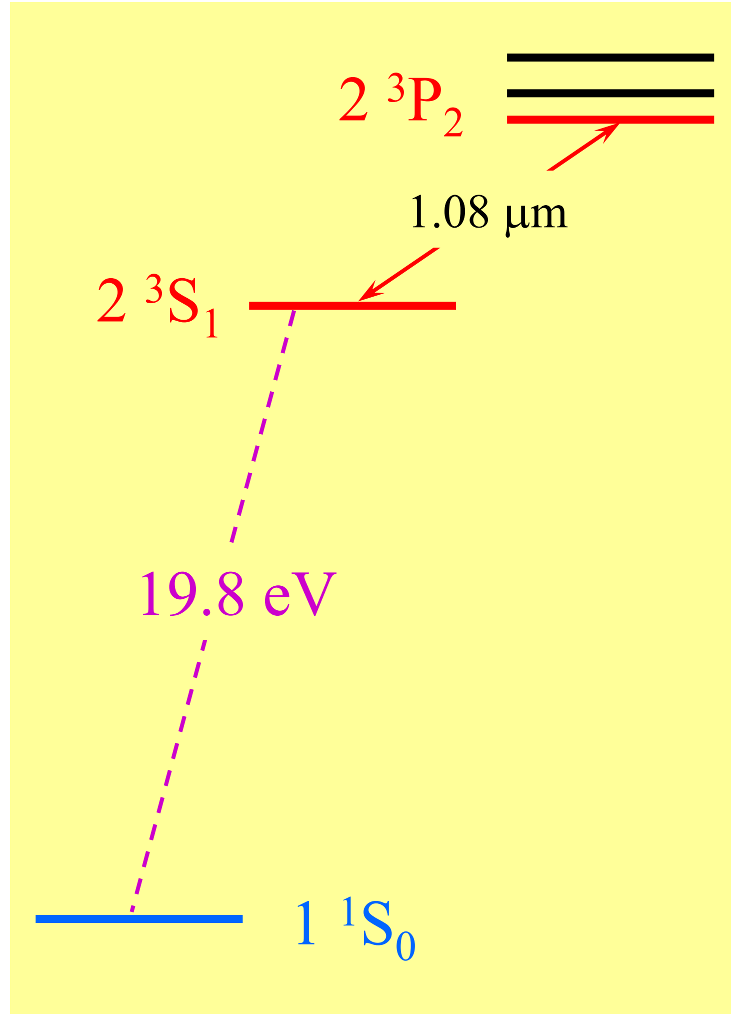
Metastable Helium $2\,^3S_1$

- Triplet (↑↑) $2\,^3S_1$ cannot *radiatively* decay to singlet (↑↓) $1\,^1S_0$ (lifetime 9000 s)
- Laser manipulation on closed transition $2\,^3S_1 \rightarrow 2\,^3P_2$ at 1.08 μm (lifetime 100 ns)

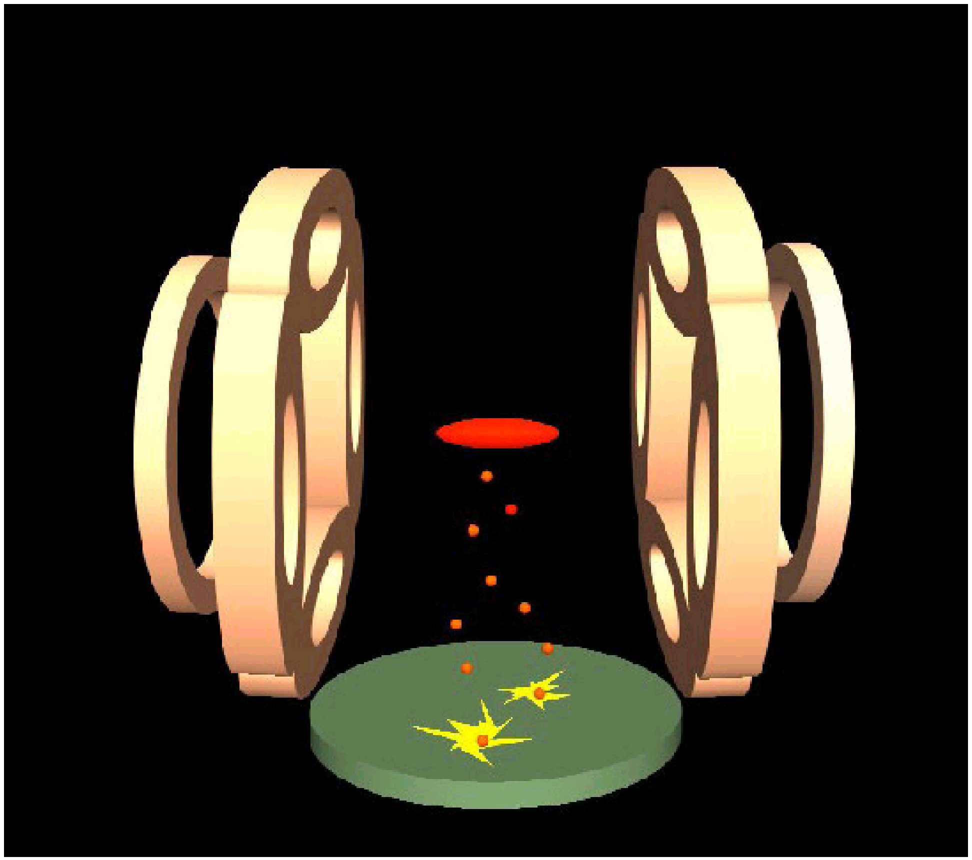
- Large electronic energy stored in He*

  ⇒ ionization of colliding atoms or molecules

  ⇒ extraction of electron from metal: single atom detection with Micro Channel Plate detector



He* trap and MCP detection



Clover leaf trap

@ 240 A : B_0 : 0.3 to 200 G ;

B' = 90 G / cm ; B''= 200 G / cm^2

$\omega_z / 2\pi = 50$ Hz ; $\omega_\perp / 2\pi = 1800$ Hz

(1200 Hz)

He* on the Micro Channel Plate detector:

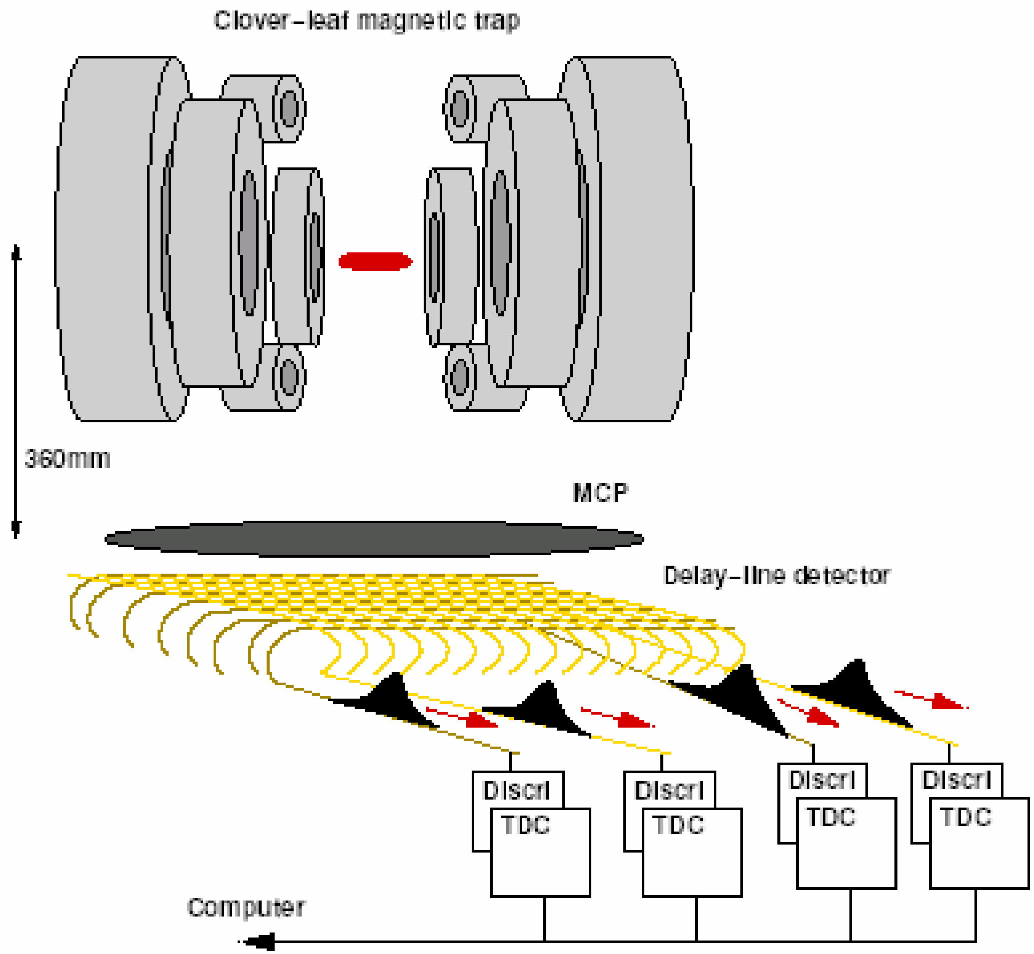
⇒ an electron is extracted

⇒ multiplication

⇒ observable pulse

Single atom detection of He*

A position and time resolved detector



Delay lines + Time to digital converters: detection events localized in time and position

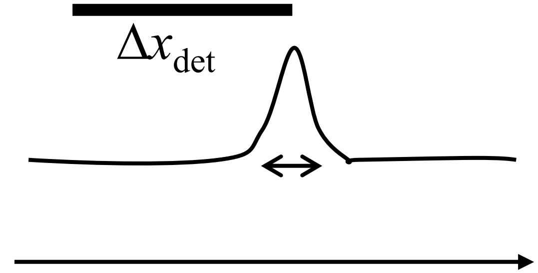
- Time resolution better than 1 ns ☺
- Dead time : 30 ns ☺
- Local flux limited by MCP saturation ☹
- Position resolution (limited by TDC): 200 µm ☹

10^4 detectors working in parallel ! ☺ ☺ ☺ ☺ ☺ ☺

The detector resolution issue

If the detector size Δx_{det} is larger than the HBT bump width L_{cx}

$$L_{\mathrm{cx}} \sim \frac{\hbar}{2M\,\Delta x_{\mathrm{source}}}\, t_{\mathrm{fall}}$$

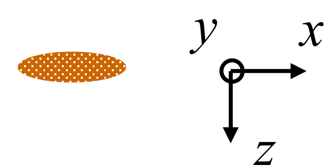


then the height of the HB&T bump is reduced:

$$g^{(2)} - 1 \sim \frac{L_{\mathrm{C}}}{\Delta x_{\mathrm{det}}} < 1$$

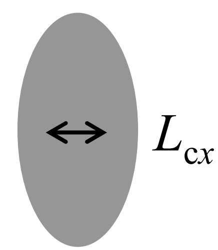
At 1 μK,

- $\Delta y_{\mathrm{source}} \approx 4\ \mu\mathrm{m}$ (1800 Hz) ☺
- $\Delta x_{\mathrm{source}} \approx 150\ \mu\mathrm{m}$ (50 Hz) ☹



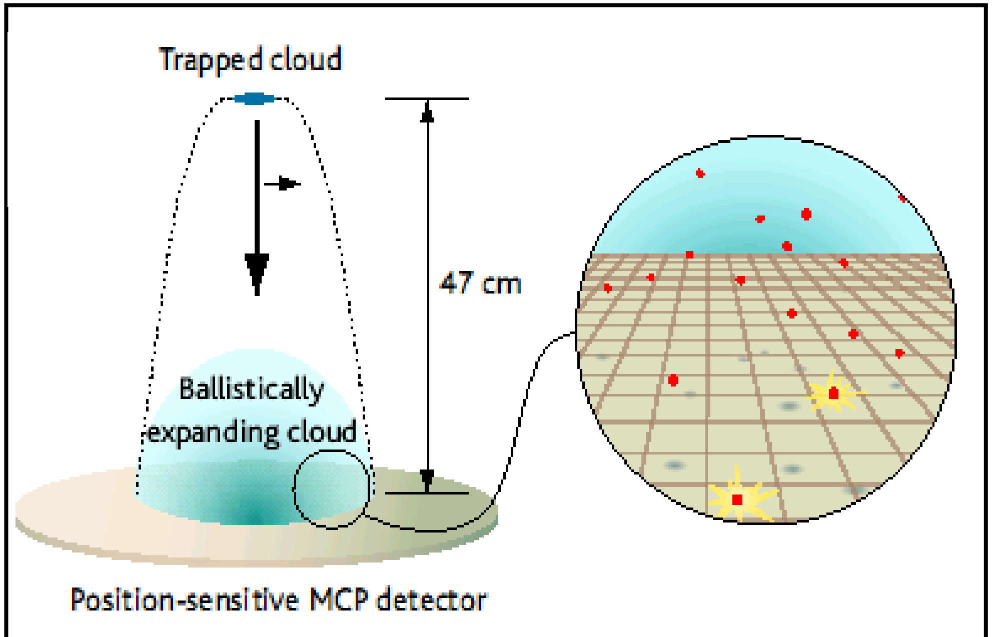
Resolution sufficient along y (200 μm compared to 500 μm) but insufficient along x.

Expected reduction factor of 15



NB: vertical resolution is more than sufficient: $\Delta z_{\mathrm{det}} \approx V\,\Delta t \approx 1$ nm ☺

Experimental procedure



$$(i_1,t_1),\ldots(i_n,t_n),\ldots$$

- Cool the trapped sample to a chosen temperature (above BEC transition)
- Release onto the detector
- Monitor and record each detection event n:
  - ✓Pixel number i_n (coordinates x, y)
  - ✓Time of detection t_n (coordinate z)

$$\{(i_1,t_1),\ldots(i_n,t_n),\ldots\} = \text{a record}$$

Related to a single cold atom sample

Repeat many times (accumulate records) at same temperature

Pulsed experiment: 3 dimensions are equivalent $\neq$ CW experiment

z axis (time) correlation function: thermal sample above T_c

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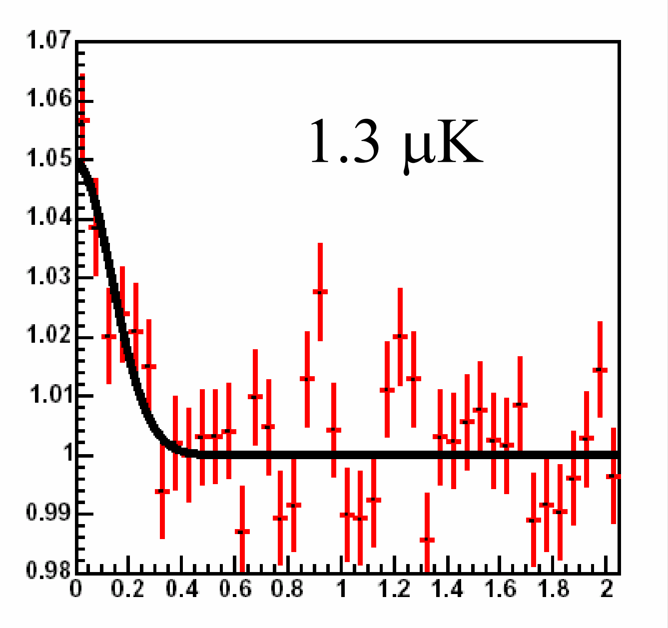
- For a given record (ensemble of detection events for a given released sample), evaluate two-time joint detections probability separately for each pixel j

  $$\rightarrow [\pi^{(2)}(\tau)]_i$$

- Average over all pixels of the same record and over all records (at same temperature)
- Normalize by the autocorrelation of average (over all pixels and all records) time of flight

$$\rightarrow \quad g^{(2)}(\Delta x = \Delta y = 0; \tau)$$

$$g^{(2)}(\Delta x = \Delta y = 0; \tau)$$



Bump visibility = 5 x 10^{-2}

Agreement with prediction (resolution)

x,y correlation function (thermal sample)

For a given record (ensemble of detections for a given released sample), look for time correlation of each pixel j with neighbours k

$\rightarrow [\pi^{(2)}(\tau)]_{jk}$

Process

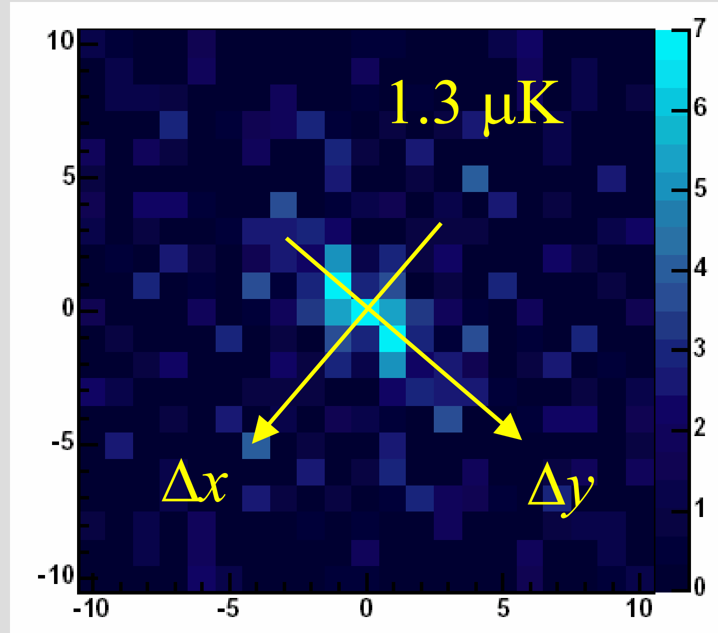
- Average over all pixel pairs with same separation, and over all records at same temperature
- Normalize

$\rightarrow \quad g^{(2)}(\Delta x; \Delta y; 0)$

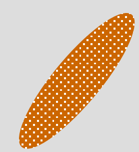
Hanbury Brown Twiss Effect for Ultracold Quantum Gases

M. Schellekens,[1] R. Hoppeler,[1] A. Perrin,[1] J. Viana Gomes,[1,2] D. Boiron,[1] A. Aspect,[1] C. I. Westbrook[1]*

$g^{(2)}(\Delta x; \Delta y; 0)$



Extends along y (narrow dimension of the source)



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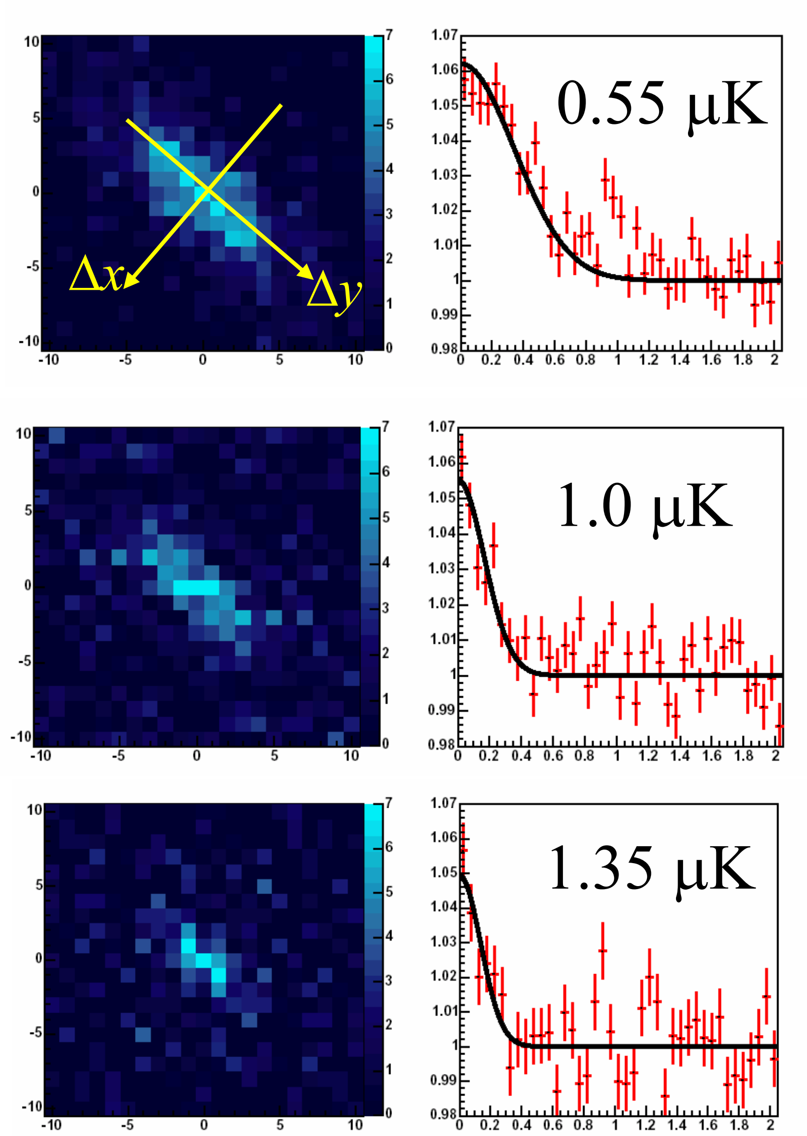
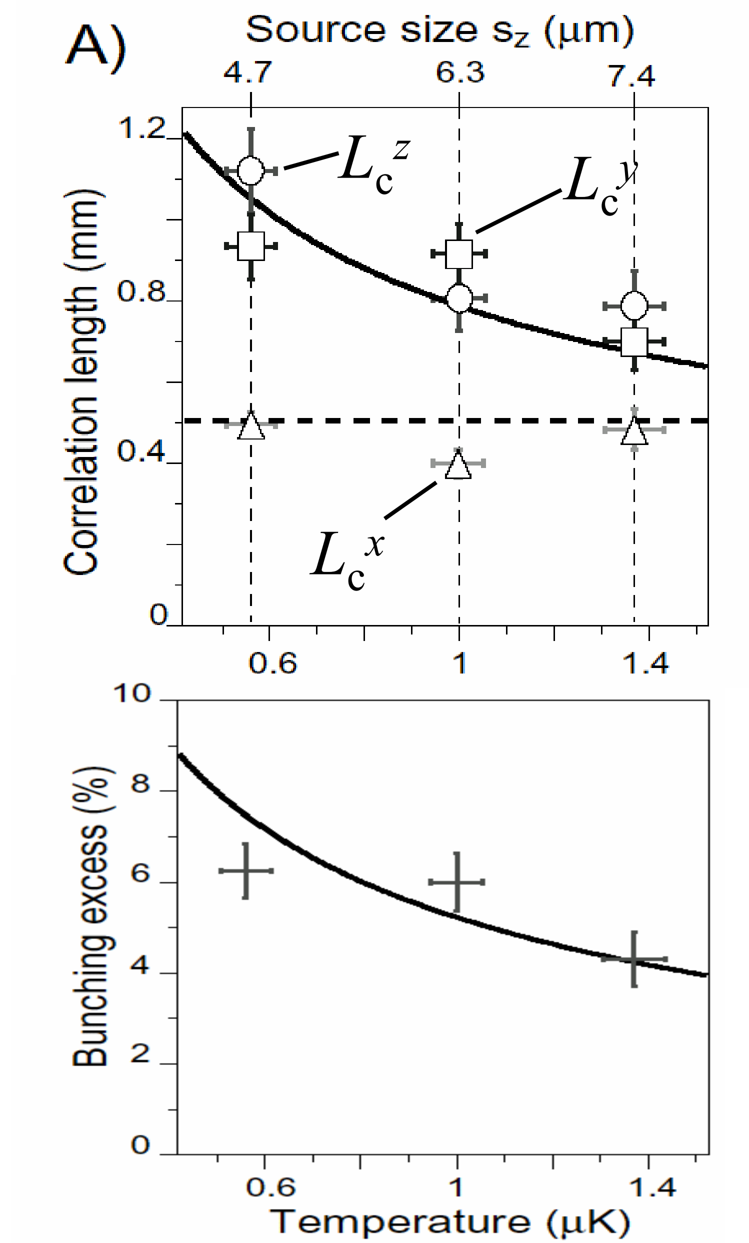
More results (thermal sample)

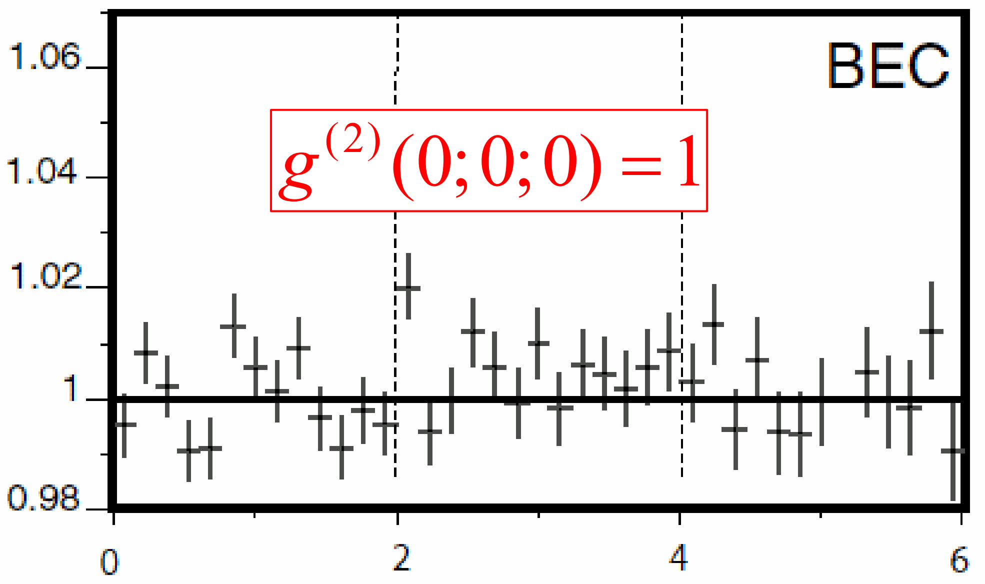




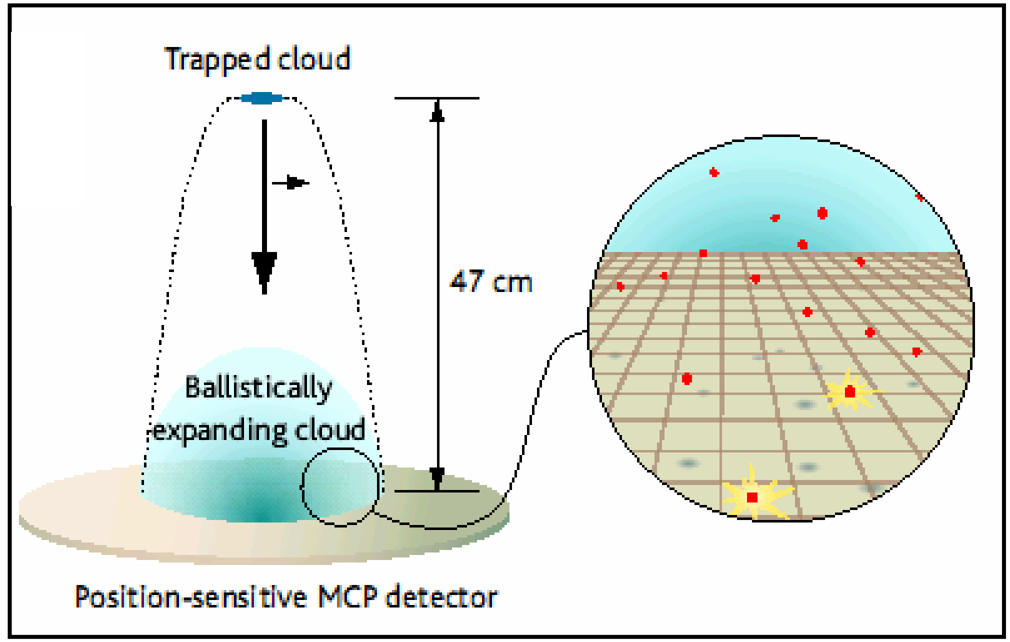
Temperature controls the size of the source (harmonic trap)

z axis correlation function: case of a BEC ($T < T_c$)

Experiment more difficult: atoms fall on a small area on the detector
$\Rightarrow$ problems of saturation



$$g^{(2)}(0;0;0)=1$$

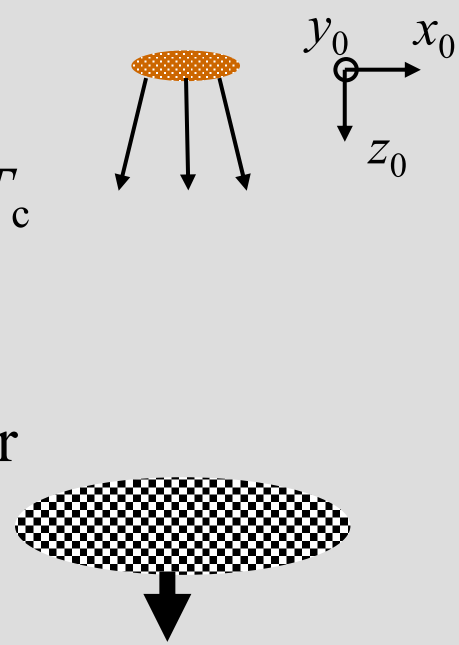


No bunching: analogous to laser light

(see also Öttl et *al.*; PRL 95,090404)

What is the HB&T signal? (thermal sample above T_c)

Cold sample above T_c



Detector

$g^{(2)}(\Delta r)$

Analogy to optics

- Thermal sample above T_c
- Sample size >> Λ_T (coherence length of the sample)

  ⇒Many independent sources
- Propagation to detector

  ⇒Gaussian field: $g^{(2)}(\Delta r) = 1 + \left|g^{(1)}(\Delta r)\right|^2$

$g^{(1)}(\Delta r)$ = Fourier Transf. of the momentum distribution on detector $\rho(P)$

In the far field regime, $\rho(P)$ maps the density $n(r_0)$ of the source.

$\Rightarrow g^{(2)}(\Delta r) - 1 = \left|FT\{n(r_0)\}\right|^2$ Does not depend on the coherence length in the source

What next?

Take more data around the BEC transition, and compare to theory (when available)

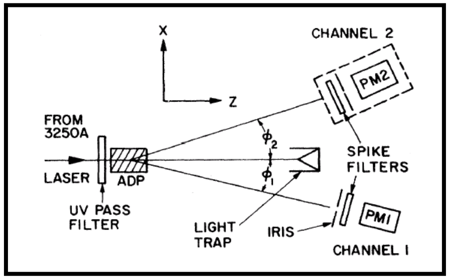
- Case of an ideal gas (without interaction)
- Case of an interacting gas (expansion an issue)
- Critical fluctuations?

Improve the detector

- Spatial resolution (depends on the TDC time resolution); make full use of high resolution along vertical direction
- Saturation of MCP at high flux
- Install a better (more homogeneous) MCP

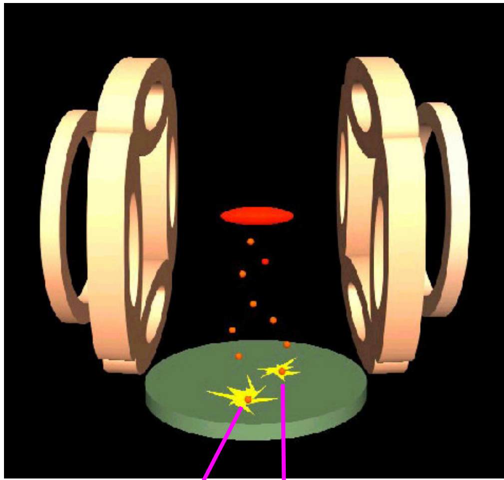
Single atom detection resolved in space and time: fascinating possibilities in quantum atom optics

Photon counting (1950-): start of modern quantum optics $g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2)$

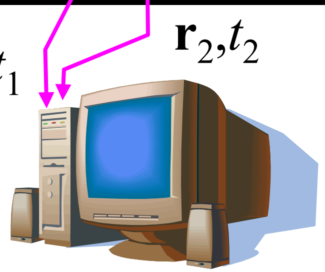


Single atom detection, resolved in time and space (2005-)

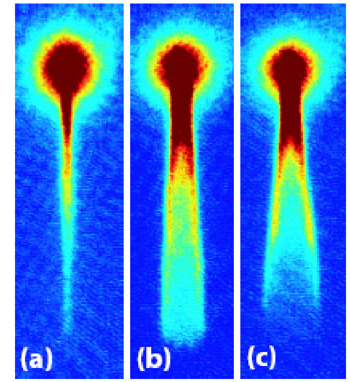
- Study of any correlation function of atomic field
  - Hanburry-Brown & Twiss type experiments
  - Fluctuations of atom laser around BEC transition
  - Detection of correlated atom pairs in 4-wave mixing
  - Entangled atomic pairs? Bell's inequalities violation? A ressource for quantum information?



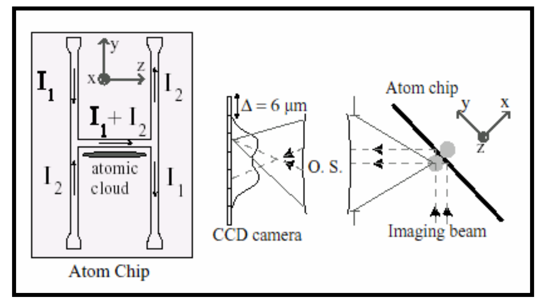
$\mathbf{r}_1, t_1$ $\mathbf{r}_2, t_2$



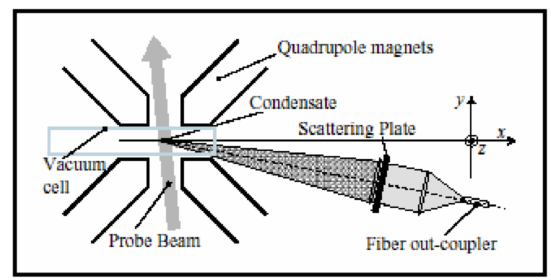
More atom lasers, atom-atom correlations, and BEC studies at LCFIO: a sampling



- Beam quality (M^2 factor) of a non ideal atom laser
  J.-F. Riou, W. Guerin, Y. Le Coq, M. Fauquembergue, V. Josse, P. Bouyer, AA, PRL 2006



- In situ observation of bunching in a quasi 1D cold sample (atom chip):
  J.Estève, J.-B. Trebbia, T. Schumm, A. A., C. I. Westbrook, and I. Bouchoule, PRL 2006



- Suppression of transport of an interacting BEC in a random potential:
  D. Clément, A.F. Varon, M. Hugbart, J.A. Retter, P. Bouyer, L. Sanchez-Palencia, D.M. Gangardt, G.V. Shlyapnikov, AA, PRL 2005

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Nathalie Wesbrook

***ATOM CHIP BEC* (x2)**

Torsten Schumm
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Yannick Pohon
Ron Cornelussen

1D BEC

Andres Varon
David Clément
Pierre Lugan
Jocelyn Retter

He* BEC

M. Schellekens
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V Krachmalnicoff
Hong Chang

ATOM LASER

Jean Felix Riou
William Guérin

FERMIONS BOSONS MIXTURES

Gaël Varoquaux
Jean-François Clément
Rob Nyman

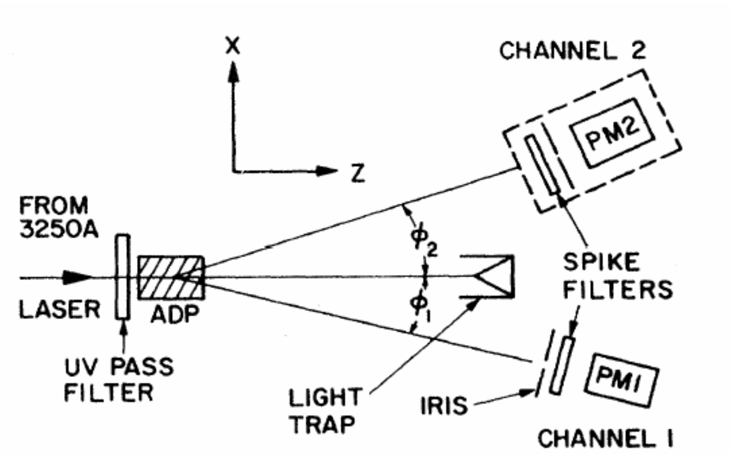
BIOPHOTONICS

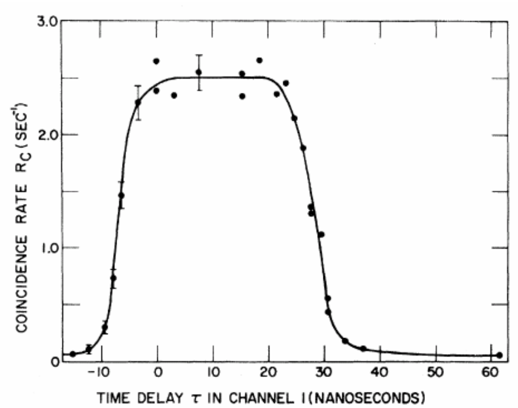
Karen Perronet

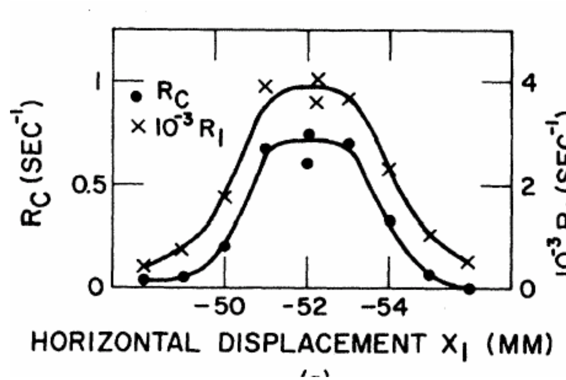
Single He* detection: breakthrough in quantum atom optics

Photon counting (1950-): start of modern quantum optics

Correlation function resolved in space and time $g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2)$







OBSERVATION OF SIMULTANEITY IN PARAMETRIC PRODUCTION OF OPTICAL PHOTON PAIRS

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(Received 12 May 1970)

PRL 25, 84 (1970)

TIME DISTRIBUTION OF PHOTONS FROM COHERENT AND GAUSSIAN SOURCES *

F. T. ARECCHI **, E. GATTI *** and A. SONA
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Received 28 December 1965

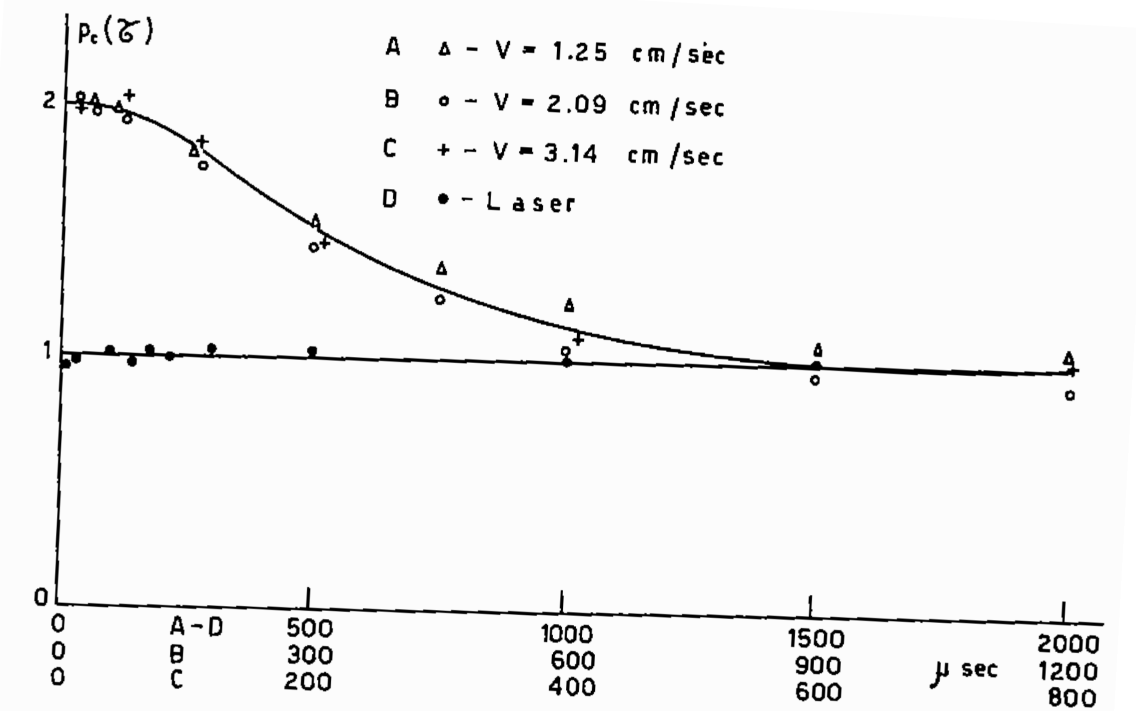

Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.