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Summer School on Novel Quantum Phases and Non-Equilibrium Phenomena in Cold Atomic Gases

27 August - 7 September, 2007

Atom-atom correlation measurements: a fundamental tool for quantum atom optics

Alan Aspect
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ICTP Summer School on Novel Quantum Phases and Non-equilibrium Phenomena in Cold Atomic Gases, Trieste, August 28, 2007

Atom-atom correlation measurements: a fundamental tool for quantum atom optics

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QUDEDIS
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Atom-atom correlation measurements: a fundamental tool for quantum atom optics

- The Hanbury Brown and Twiss photon-photon correlation experiment: a landmark in quantum optics
- Elementary notions on production of ultra cold atomic gases and Bose-Einstein Condensates
- Atom-atom correlations in ultra cold quantum gases
- Detection of atom pairs in spontaneous non linear mixing of 4 de Broglie waves

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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:

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

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CORRELATION BETWEEN PHOTONS IN TWO COHERENT BEAMS OF LIGHT

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AND
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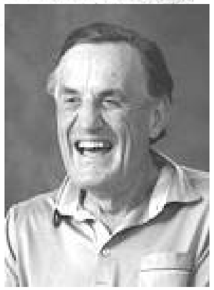
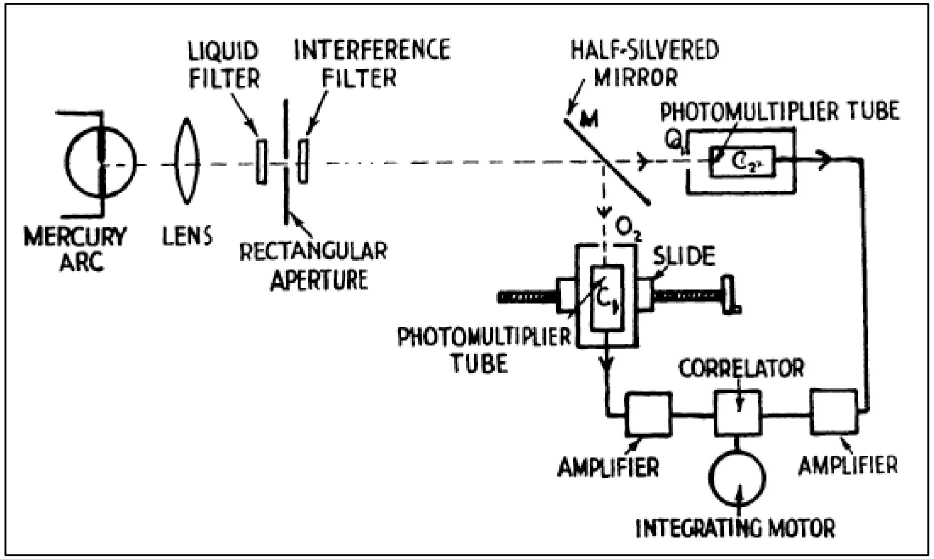
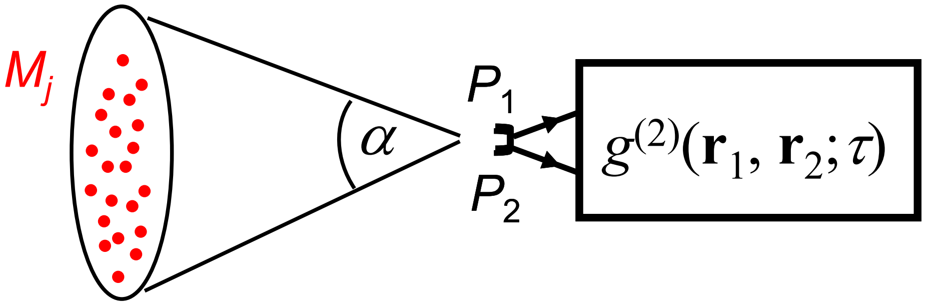
Services Electronics Research Laboratory, Baldock



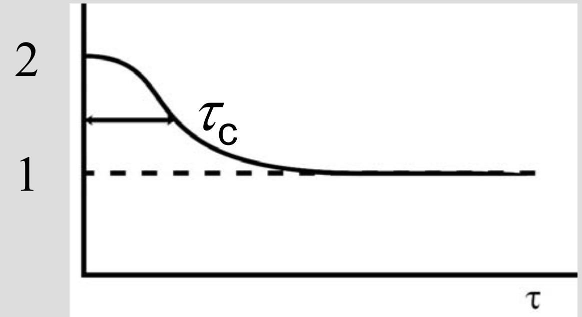


The HB&T effect

Light from incoherent source: time and space correlations



$$g^{(2)}(r_1 = r_2; \tau) > 1$$



$$g^{(2)}(r_1 = r_2; \tau = 0) = 2$$

$$g^{(2)}(r_1 - r_2 \gg L_c; \tau \gg \tau_c) = 1$$

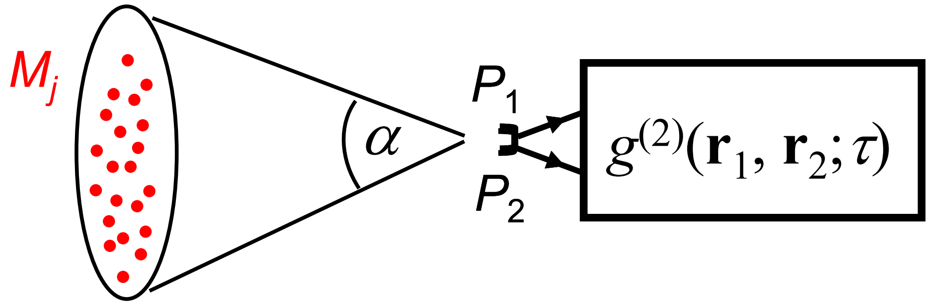
A measurement of $g^{(2)} - 1$ *vs.* τ and $\mathbf{r}_1 - \mathbf{r}_2$ yields the coherence volume

- time coherence

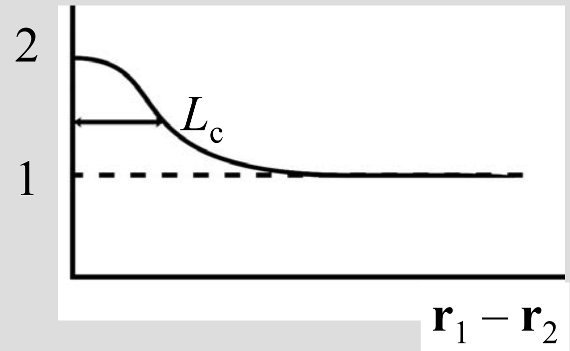
$$\tau_c \approx 1/\Delta\omega$$

The HB&T effect

Light from incoherent source: time and space correlations



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



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

- time coherence

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

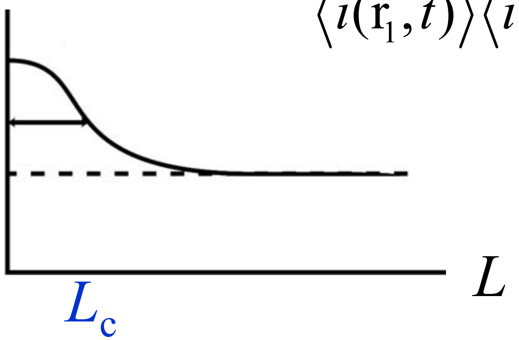
- space coherence

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

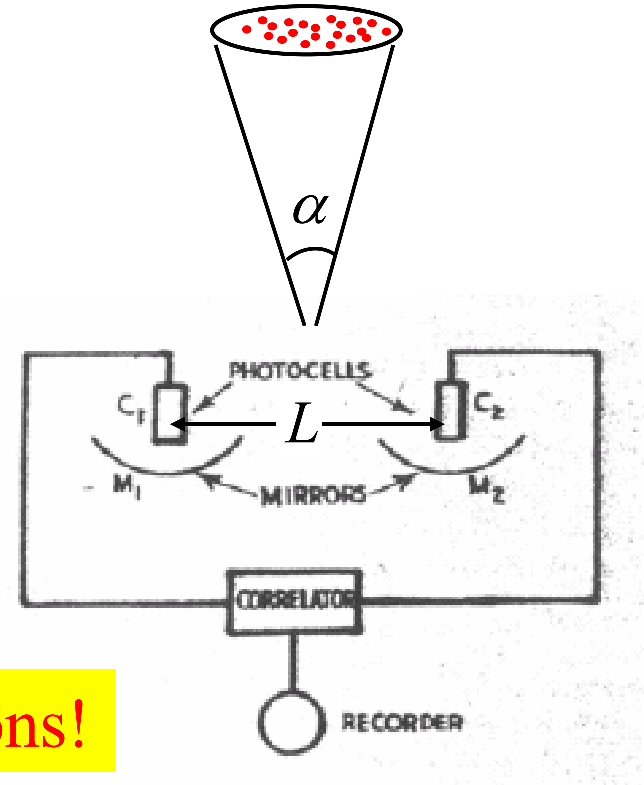
The HB&T stellar interferometer

Measure of the coherence area
$\Rightarrow$ angular diameter of a star

$$g^{(2)}(L;0) = \frac{\langle i(r_1,t)\, i(r_1 + L, t+\tau)\rangle}{\langle i(r_1,t)\rangle \langle i(r_2,t)\rangle} \quad \Rightarrow L_C$$



$$\Rightarrow \quad \boxed{\alpha = \frac{\lambda}{L_C}}$$

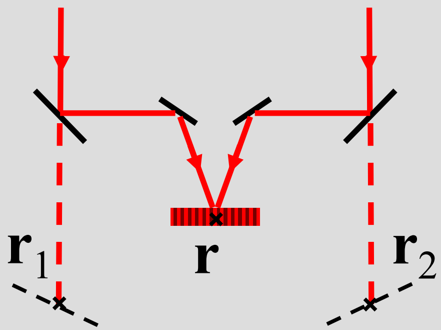


HB&T insensitive to atmospheric fluctuations!

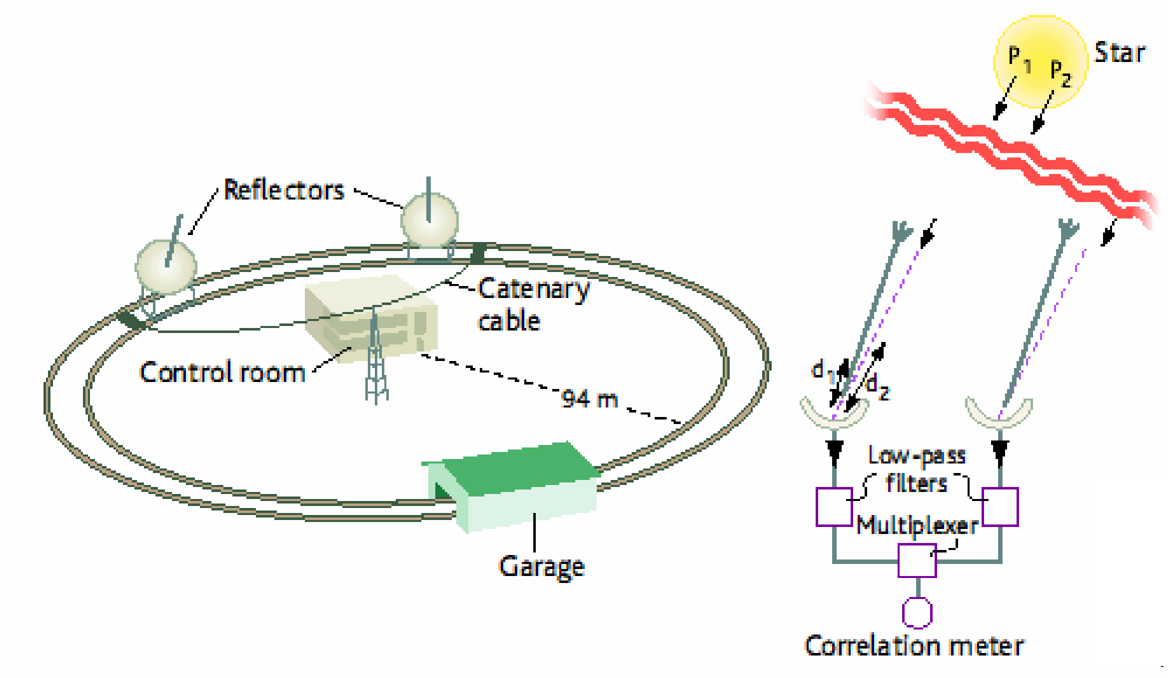
Equivalent to the Michelson stellar interferometer ?

Visibility of fringes

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



The HB&T stellar interferometer



NATURE November 10, 1956

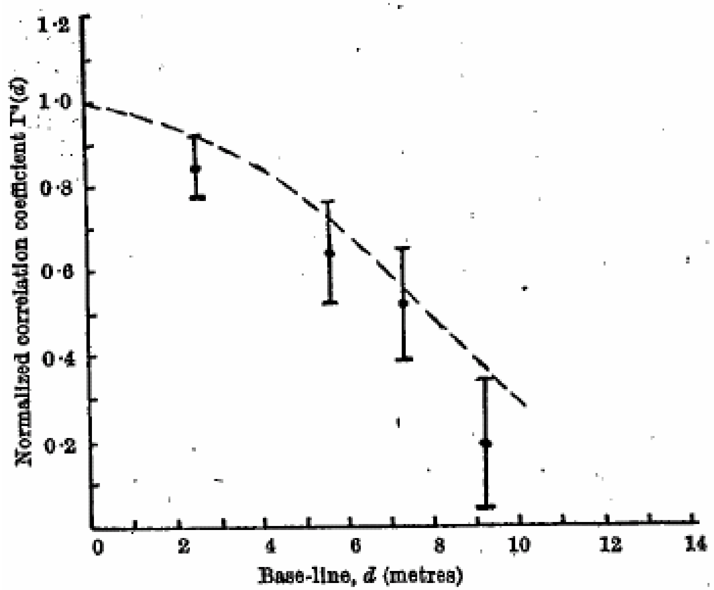


Fig. 2. Comparison between the values of the normalized correlation coefficient Γ²(d) observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

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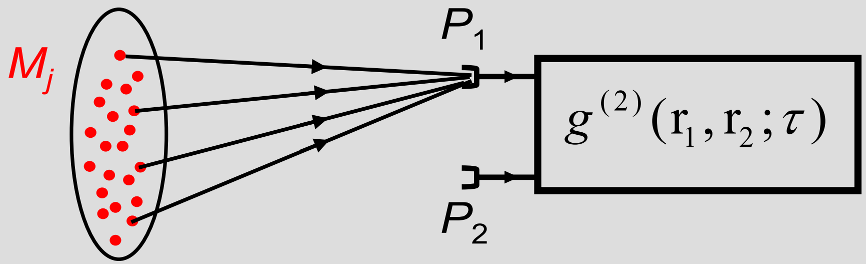
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock

Classical wave explanation for HB&T correlations (1)



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

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

Central limit theorem
$\Rightarrow$ Gaussian random process

⟹

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

$$g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = \frac{\langle i(\mathrm{r}_1, t)\, i(\mathrm{r}_2, t+\tau) \rangle}{\langle i(\mathrm{r}_1, t) \rangle \langle i(\mathrm{r}_2, t) \rangle} = \frac{\langle \mathcal{E}^*(\mathrm{r}_1, t)\, \mathcal{E}(\mathrm{r}_1, t) \mathcal{E}^*(\mathrm{r}_2, t+\tau)\, \mathcal{E}(\mathrm{r}_2, t+\tau) \rangle}{\left\langle |\mathcal{E}(\mathrm{r}_1, t)|^2 \right\rangle \left\langle |\mathcal{E}(\mathrm{r}_2, t+\tau)|^2 \right\rangle}$$

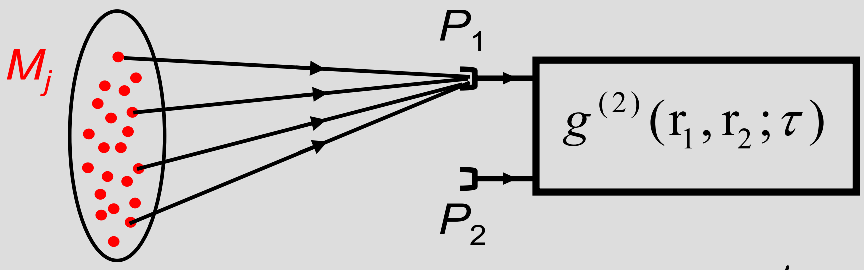
$$g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = \frac{\langle \mathcal{E}^*(\mathrm{r}_1, t)\, \mathcal{E}(\mathrm{r}_2, t+\tau) \rangle}{\left\langle |\mathcal{E}(\mathrm{r}_1, t)|^2 \right\rangle^{1/2} \left\langle |\mathcal{E}(\mathrm{r}_2, t+t)|^2 \right\rangle^{1/2}}$$

Random 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 fluctuates
$\Rightarrow$ intensity fluctuates

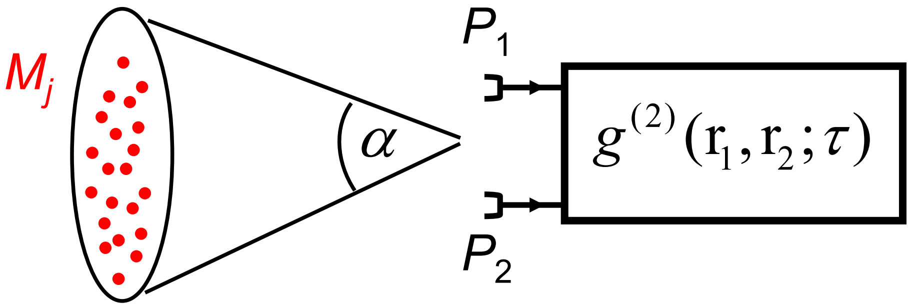
$$\left\langle I(t)^2 \right\rangle \geq \left\langle I(t) \right\rangle^2 \Leftrightarrow g^{(2)}(\mathbf{r}_1, \mathbf{r}_1; 0) \geq 1$$

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

Width of intensity correlation function = Width of field correlation function

Measure of coherence volume $\Rightarrow$ source size

Classical wave explanation for HB&T correlations: optical speckle in light from an incoherent source



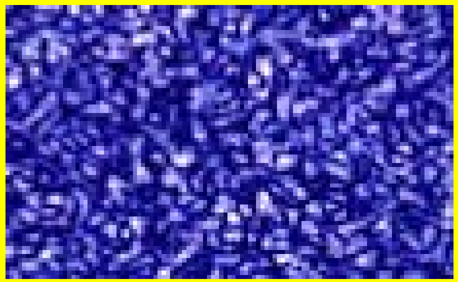
Many independent random emitters: complex electric field = sum of many independent random processes

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

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

Speckle in the observation plane:

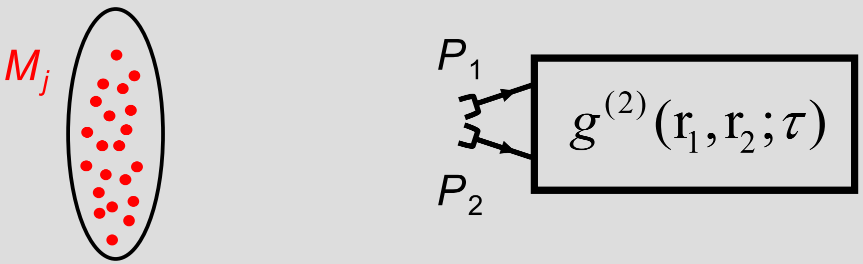
- Correlation radius $L_c \approx \lambda / \alpha$
- Changes after $\tau_c \approx 1 / \Delta\omega$



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

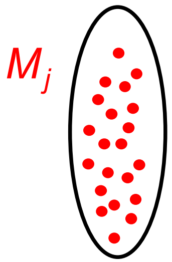
For independent detection events $g^{(2)} = 1$

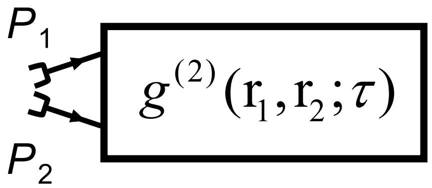
$g^{(2)}(0) = 2 \Rightarrow$ probability to find two photons at the same place larger than the product of simple probabilities: bunching

How might independent particles be bunched ?

The HB&T effect with photons: a hot debate

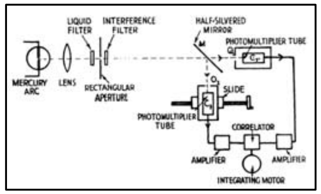
Strong negative reactions to the HB&T proposal (1955)





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.

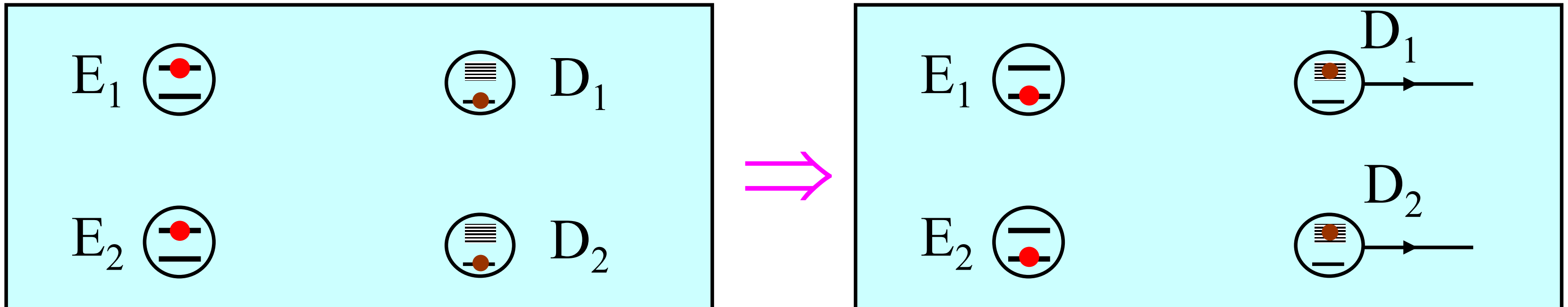
$$g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = 1 + \left| g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau) \right|^2$$

- 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:

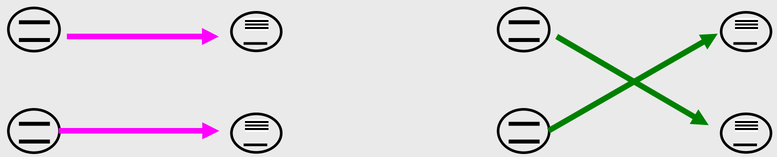
- Emitters in ground state
- Detectors ionized

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)

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

Intensity correlation with laser light: more confusion

1960: invention of the laser (Maiman, Ruby laser)

•1961: Mandel & Wolf: HB&T bunching effect should be easy to observe with a laser: many photons per mode

•1963: Glauber: laser light should NOT be bunched:
$\rightarrow$ quantum theory of coherence

•1965: Armstrong: experiment with single mode AsGa laser: no bunching well above threshold; bunching below threshold

•1966: Arecchi: similar with He Ne laser: plot of $g^{(2)}(\tau)$, almost

Simple classical model for laser light:

$$\mathcal{E} = E_0 \exp\{-i\omega t + \phi_0\} + e_n \qquad |e_n| \ll |E_0|$$

Quantum description identical by use of Glauber-Sudarshan P representation (coherent states)

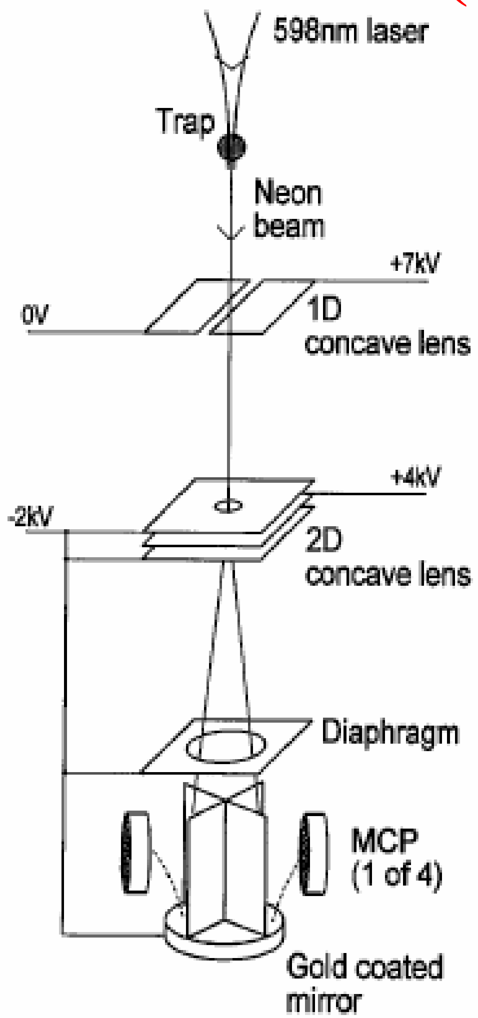
The Hanbury Brown and Twiss light intensity correlation experiment: a landmark in quantum optics

- Easy to understand if light described as an electromagnetic wave
- Subtle quantum effect if one describes light as made of photons

Intriguing quantum effect for particles

Hanbury Brown and Twiss effect with atoms?

The HB&T effect with atoms: first evidence (Yasuda and Shimizu, 1996)

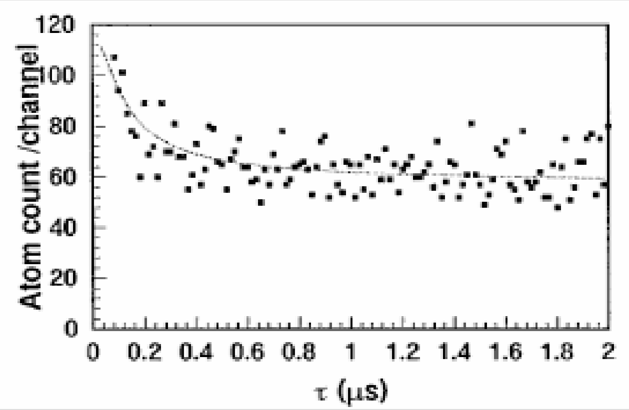


- Cold neon atoms in a MOT (100 μK) continuously pumped into a non trapped (falling) metastable state
  - ➢Single atom detection (metastable atom)
  - ➢Narrow source (<100μm): coherence volume as large as detector viewed through diverging lens: no reduction of the visibility of the bump

Effect clearly seen

•Bump disappears when detector size $>> L_C$

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



Other atom-atom correlations with ultra-cold quantum gases

Atom-atom correlation measurements: a fundamental tool for quantum atom optics

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Recipe for BEC with a dilute atomic sample

$n\Lambda_T^3 \geq 1 \quad \Rightarrow$ decrease temperature and/or increase density (moderately)

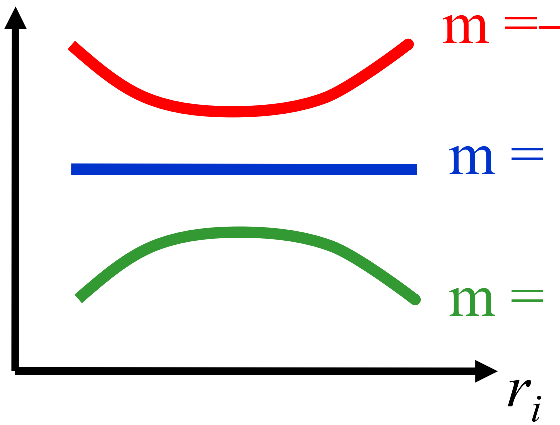
- Laser cooling and trapping $\Rightarrow \quad n\Lambda_T^3 \leq 10^{-6}$ (start from 10^{-15})

- Turn off lasers (avoid rescattering, light induced inelastic collisions..)

- Turn on a magnetic trap, with a non nul (bias) minimum magnetic field (avoid Majorana non adiabatic losses)

  $n\Lambda_T^3 < 10^{-6}$

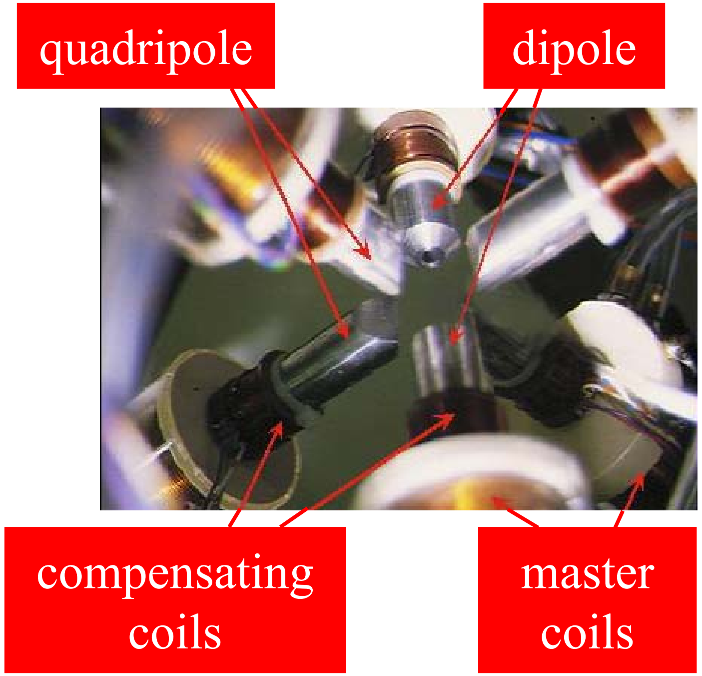
$U = g\, m\, \mu_B |\mathbf{B}|$

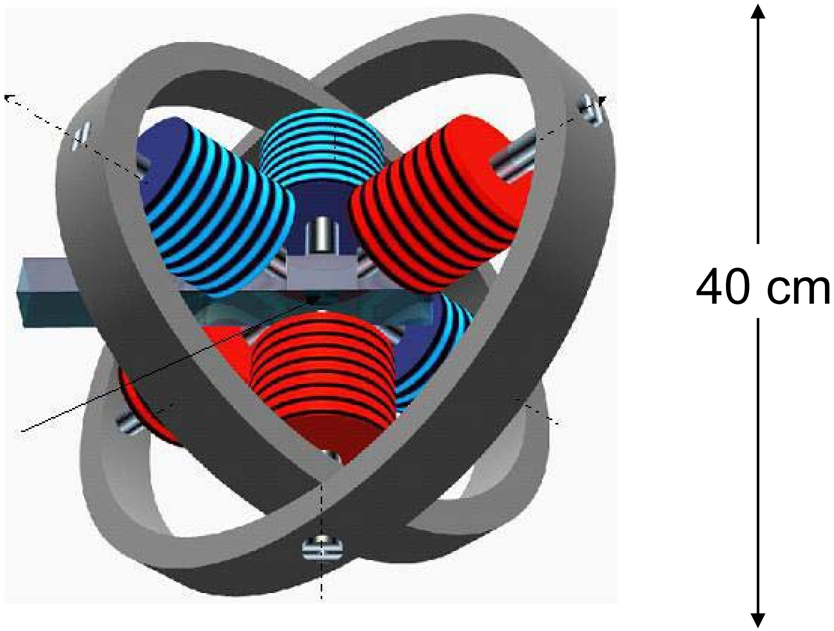


Low field seekers ($g\, m > 0$)
trapped at minimum of $|\mathbf{B}|$
Demands large gradients

A magnetic trap for Rb atoms in an iron core electromagnet

- Low electric power (80 W)
- Strong gradient
- Shielding of the ambient magnetic field





- Car battery operated BEC (mobile BEC…)
- Low dimensionality possible
- Stability good enough to allow for quasi CW atom laser

Recipe for BEC with a dilute atomic sample

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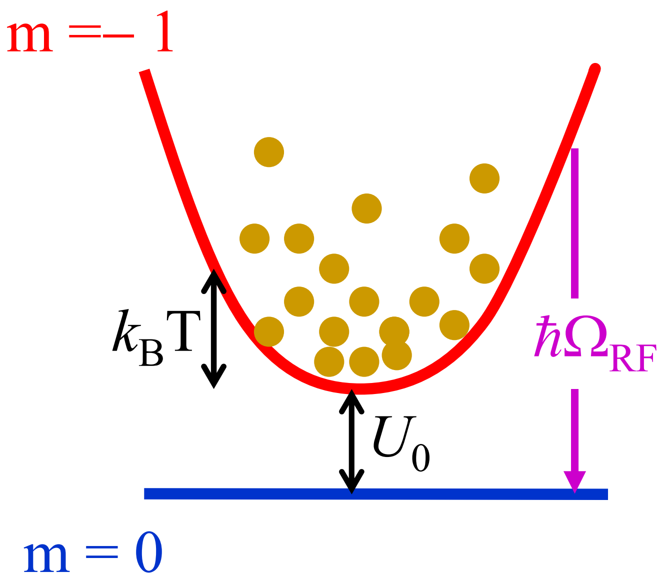
- Laser cooling and trapping $\Rightarrow$ $n \Lambda_T^3 \approx 10^{-6}$ (start from 10^{-15})
- Turn off lasers (avoid rescattering, light induced inelastic collisions..)
- Turn on a magnetic trap, with a non nul (bias) minimum magnetic field minimizing entropy increase (match potential) $n \Lambda_T^3 < 10^{-6}$

- Forced (RF transition) evaporative cooling

$\Rightarrow$ T decreases and $n \Lambda_T^3$ increases to 2.6…

Forced evaporative cooling



RF eliminates atoms with energy > $\eta\, k_B\, T$ (typically $\eta \approx 6$)

After rethermalization (elastic collisions)

- T ↘ $\Rightarrow$ Λ_T ↗
- n ↗ (although N ↘, because T ↘)

$\Rightarrow$ $n\,\Lambda_T{}^3$ ↗

Ω_{RF} ramped down to BEC

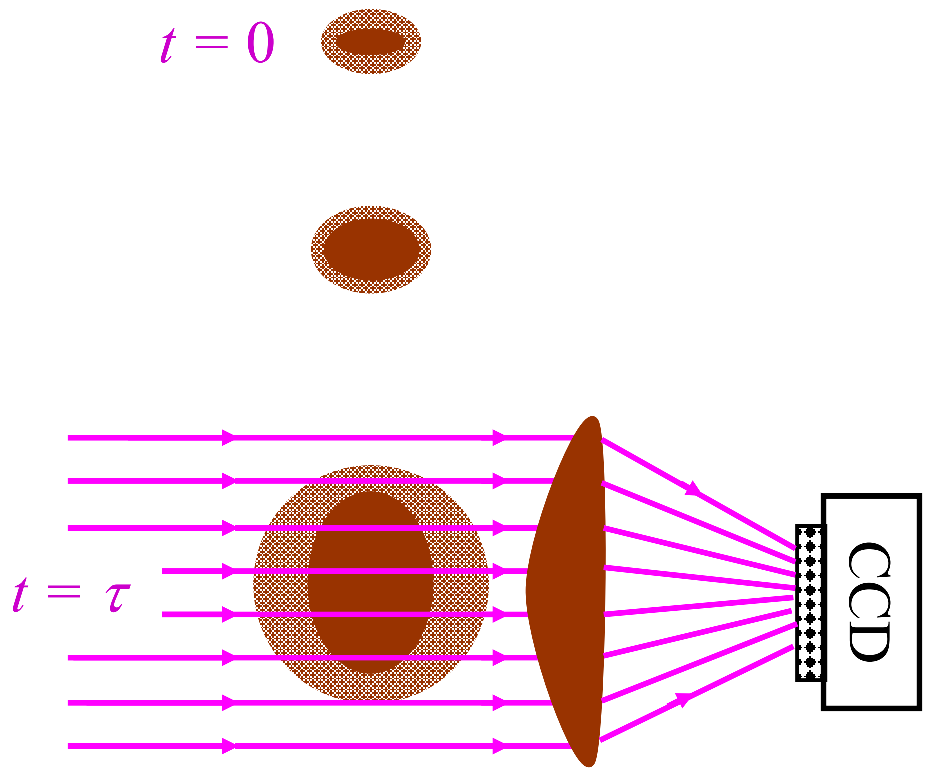
$\boldsymbol{n\,\Lambda_T{}^3 > 2.612}$

Strong demands

- large elastic cross section
- small losses (< 1/300 el.)
  - background pressure ultra low
  - no inelastic processes

Optical observation of Rb condensation

- Turn off the trap at $t = 0$
- Ballistic expansion, duration τ
- Absorption imaging
  - ∗Thermal component (Bose function, Gaussian wings): mostly velocity
  - ∗Condensate (Thomas Fermi profile, inverted parabola): mostly interaction energy



Measurement difficult for less than 10^4 atoms

Optical observation of Rb condensation

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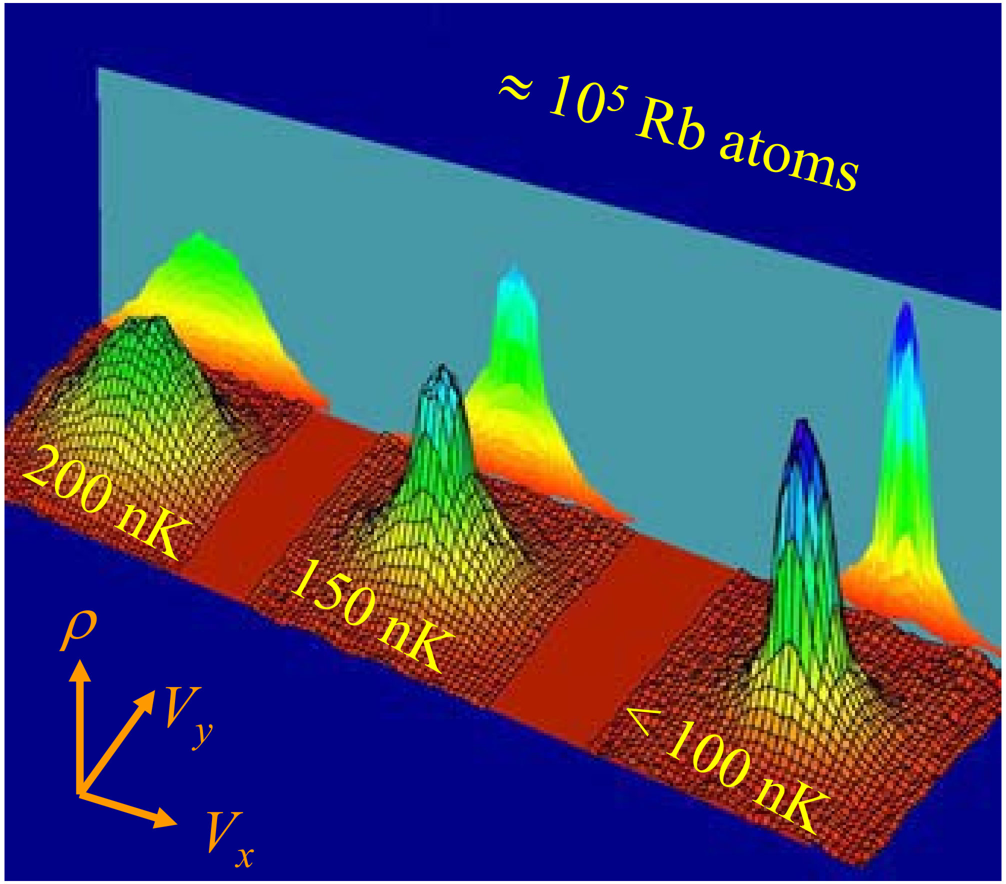

Measurement difficult for less than 10^4 atoms

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Atomic density correlation effects

3 atoms collision rate enhancement in a thermal gas, compared to a BEC

- Factor of 6 ($\langle n^3(\mathrm{r})\rangle = 3!\langle n(\mathrm{r})\rangle^3$) observed (JILA, 1997) as predicted by Kagan, Svistunov, Shlyapnikov, JETP lett (1985)

Interaction energy of a sample of cold atoms

- $\langle n^2(\mathrm{r})\rangle = 2\langle n(\mathrm{r})\rangle^2$ for a thermal gas (MIT, 1997)
- $\langle n^2(\mathrm{r})\rangle = \langle n(\mathrm{r})\rangle^2$ for a quasicondensate (Institut d'Optique, 2003)

Density correlation in absorption images of a sample of cold atoms (as proposed by Altmann, Demler and Lukin, 2004)

- Correlations in a quasicondensate (Hannover 2003)
- Correlations in the atom density fluctuations of 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 (Institut d'Optique, 2005)

What about individual atoms correlation function measurements?

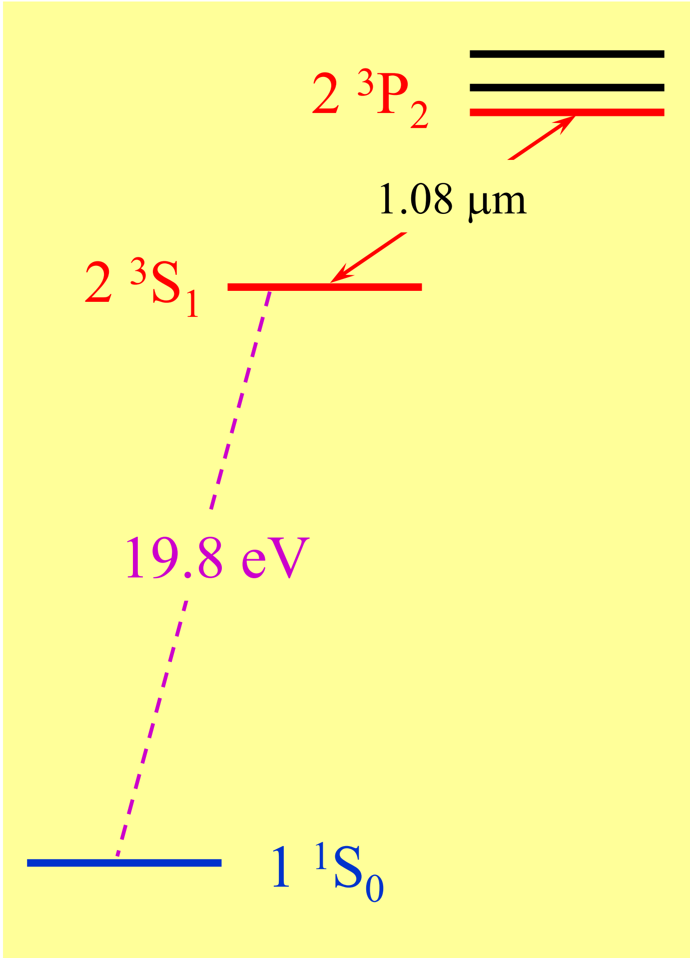
Metastable Helium $2\ ^3S_1$

- 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)

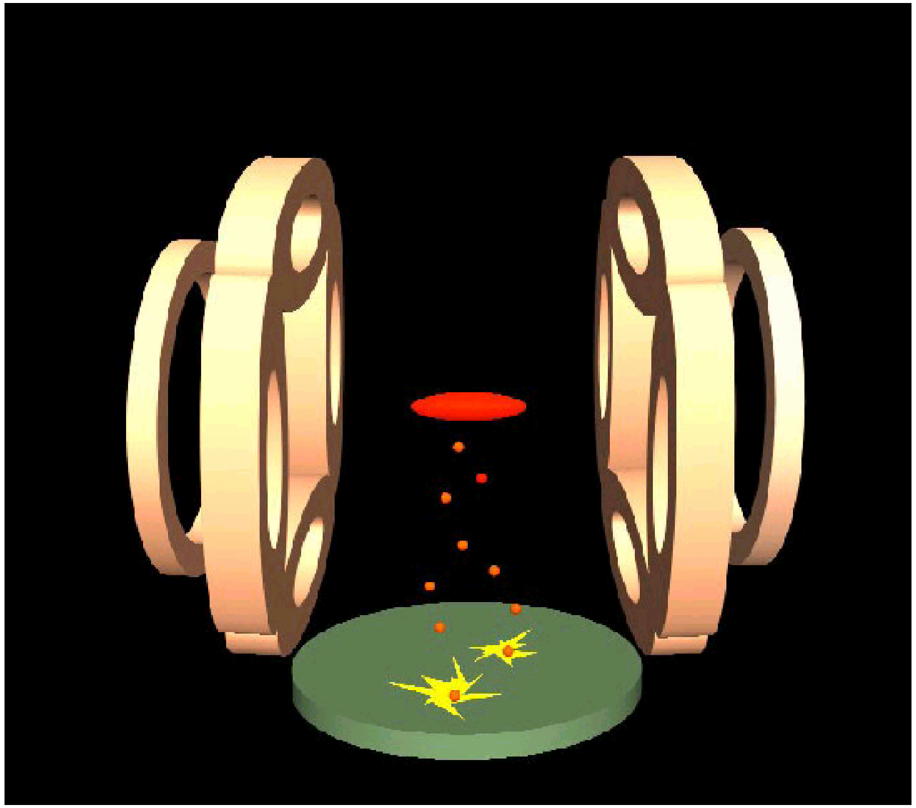
- Large electronic energy stored in He*

  ⇒ 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*

The route to ultra-cold He* and BEC: not an easy way

Pros:

- Strong magnetic trap (2 Bohr magnetons)
- Ultrasensitive detection scheme
- Very rapid release scheme

⇒ Excellent TOF diagnostic

Cons:

- Source of cold He* not as simple as alkalis'; vacuum challenges
- Elastic cross section *a priori* unknown at low temperature

  Direct measurement of rethermalization of the energy distribution after RF knife disturbance (A. Browaeys et al., PRA…): *a large enough* (≈ 10-20 nm), as predicted by Shlyapnikov 95, Venturi …

- Penning ionization

Penning ionization of He*

$$He^{*} + He^{*} \rightarrow He(1\,^{1}S_{0}) + He^{+} + e^{-}$$

Reaction constant ≈ 5 x 10^{-10} $cm^3.s^{-1}$ @ 1 mK

Impossible to obtain a sample dense enough for fast thermalization?

Solution (theory, Shlyapnikov et al., 1994; Leo el al.):

Penning ionization strongly suppressed (10^{-5} predicted!) in spin polarized He* because of spin conservation:

$$m = 1 \; + \; m = 1 \;\not\rightarrow\; s = 0 \; + \; s = 1/2 \; + \; s = 1/2$$

Magnetically trapped He* ***is*** spin polarized

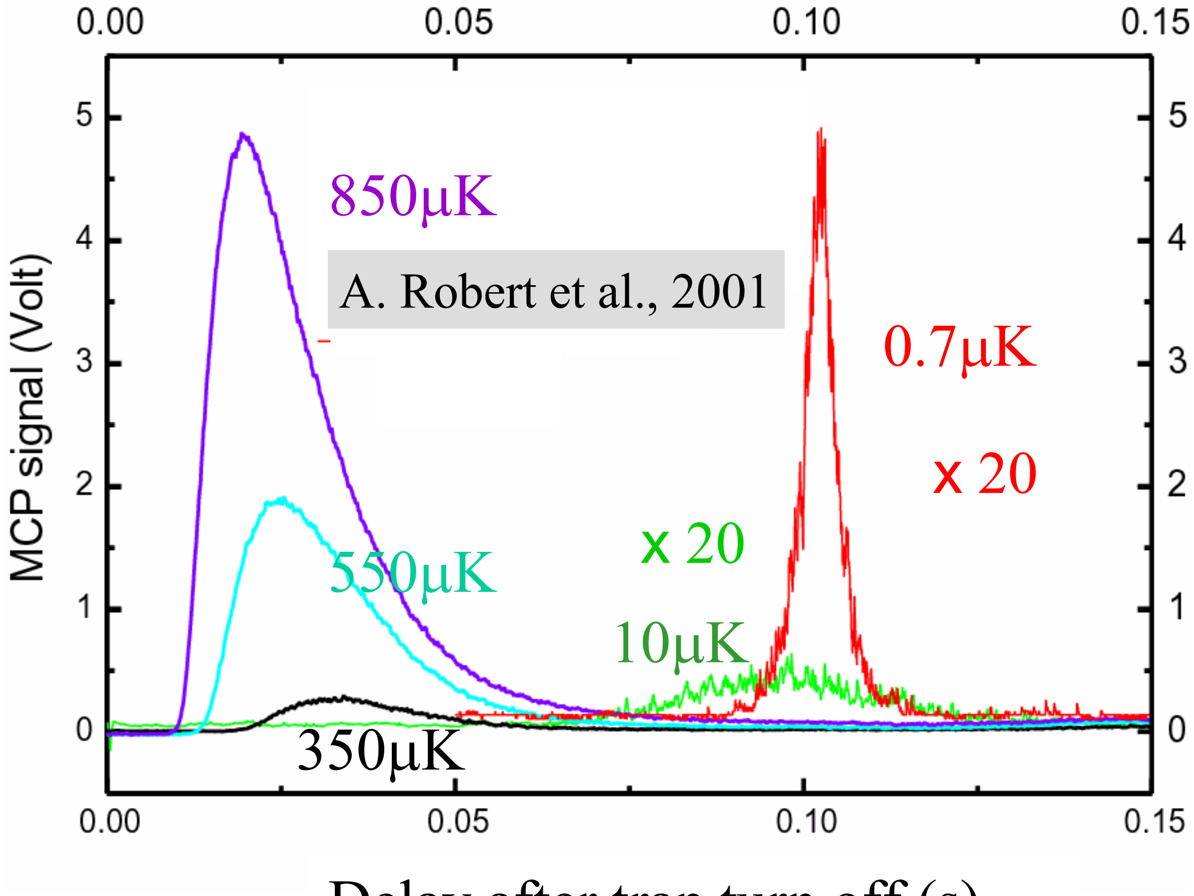
Preliminary experimental evidence (Amsterdam, Orsay, 1999): suppr. < 10^{-2}

Definitive evidence of supression (~ 10^{-4}) :
BEC of He* observed (Orsay, Paris, 2001)

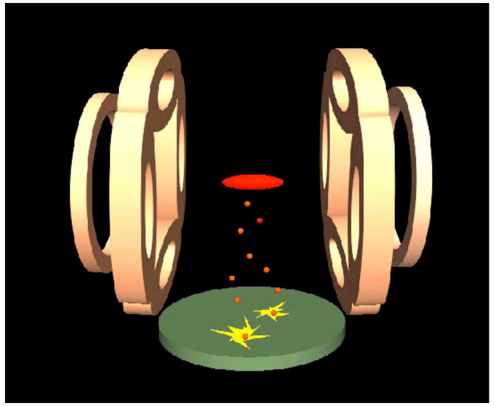
$a \approx 10 \pm 10$ nm

Clear signature of He* BEC

Time of flight on the MCP



Delay after trap turn off (s)

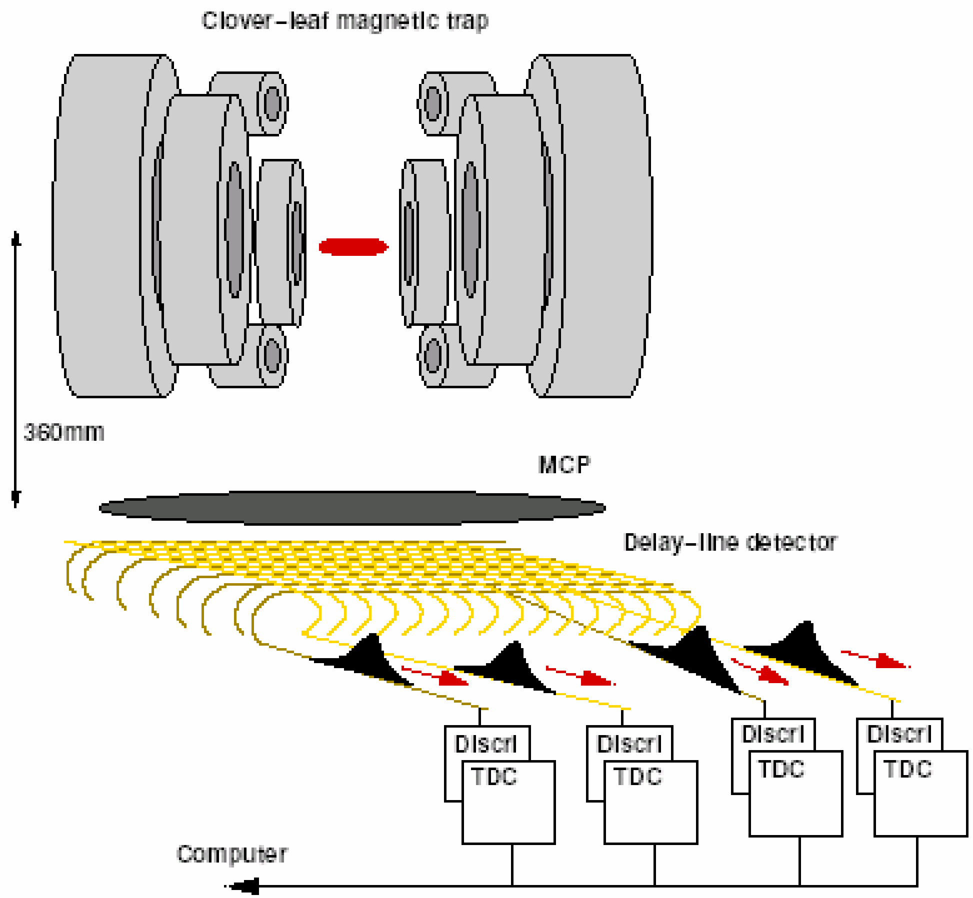


- RF ramped down from 130 MHz to ~ 1 MHz in 70 s (exponential 17 s)

  ⇒ less atoms, colder

- Small enough temp. (about 2µK): all atoms fall on the detector, better detectivity
- At 0.7µK: narrow peak, BEC

A position and time resolved detector

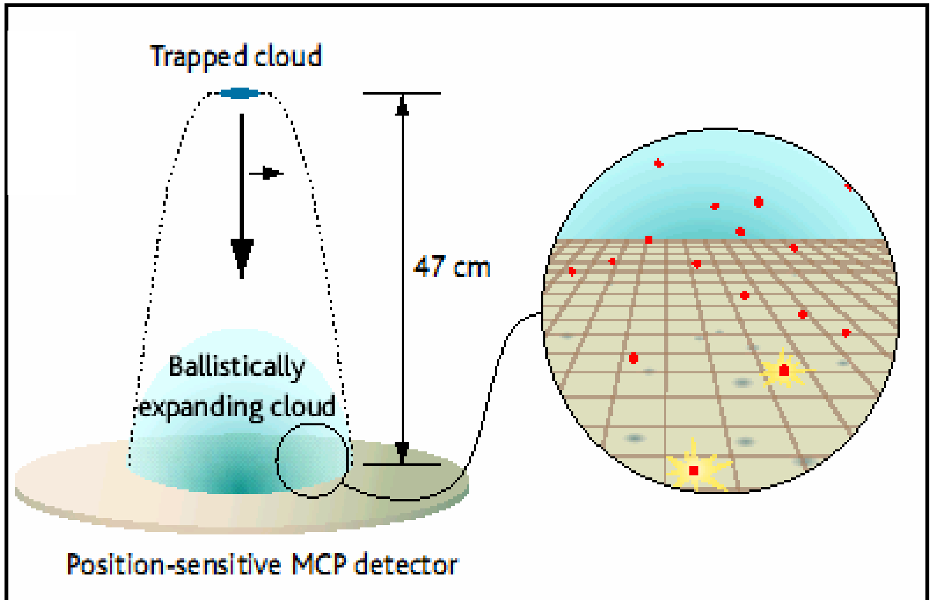


Delay lines + Time to digital converters: detection events localized in time and position

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

10^5 single atom detectors working in parallel ! ☺ ☺ ☺ ☺ ☺ ☺

Experimental procedure



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

- 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)

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

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: ^{4}He* thermal sample (above T_{BEC})

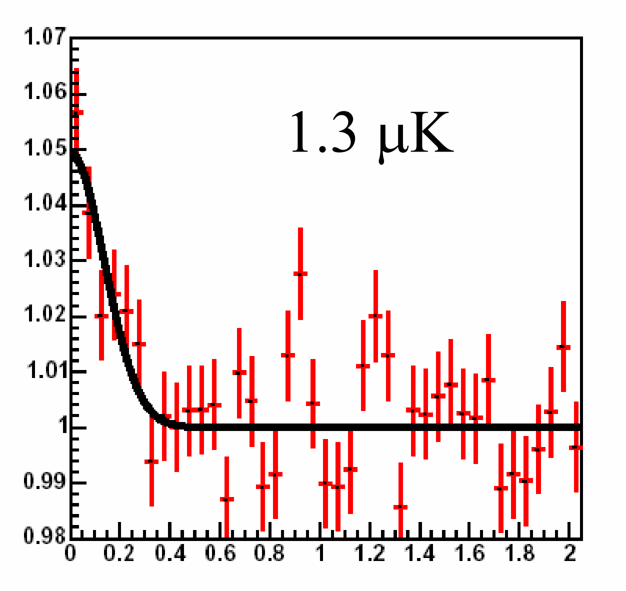
- For a given record (ensemble of detection events for a given released sample), evaluate two-time joint detections probability separately for each pixel j

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

- 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 ^{4}He*)

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

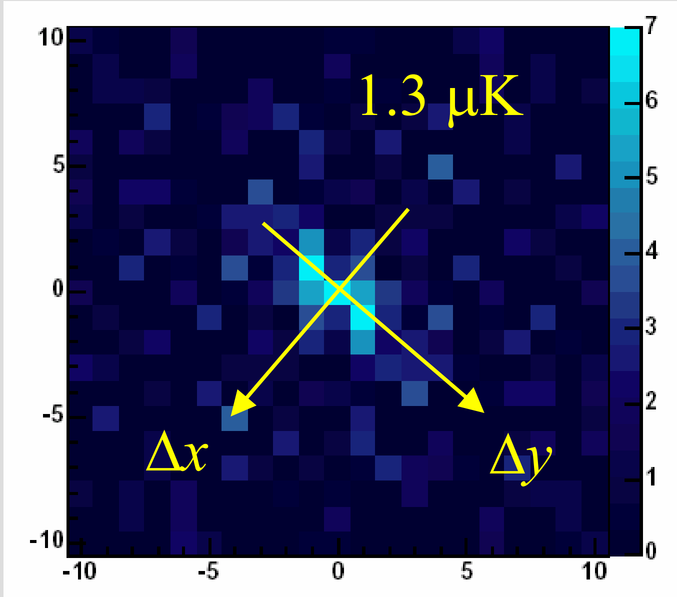
- Average over all pixel pairs with same separation, and over all records at same temperature
- Normalize

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

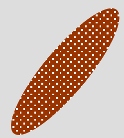
Hanbury Brown Twiss Effect for Ultracold Quantum Gases

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

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



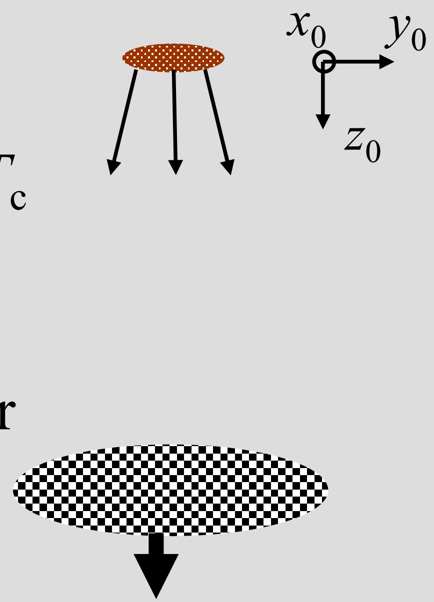
Extends along y (narrow dimension of the source)



SCIENCE VOL 310 28 OCTOBER 2005

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)

  $\Rightarrow$ Many independent sources
- Propagation to detector

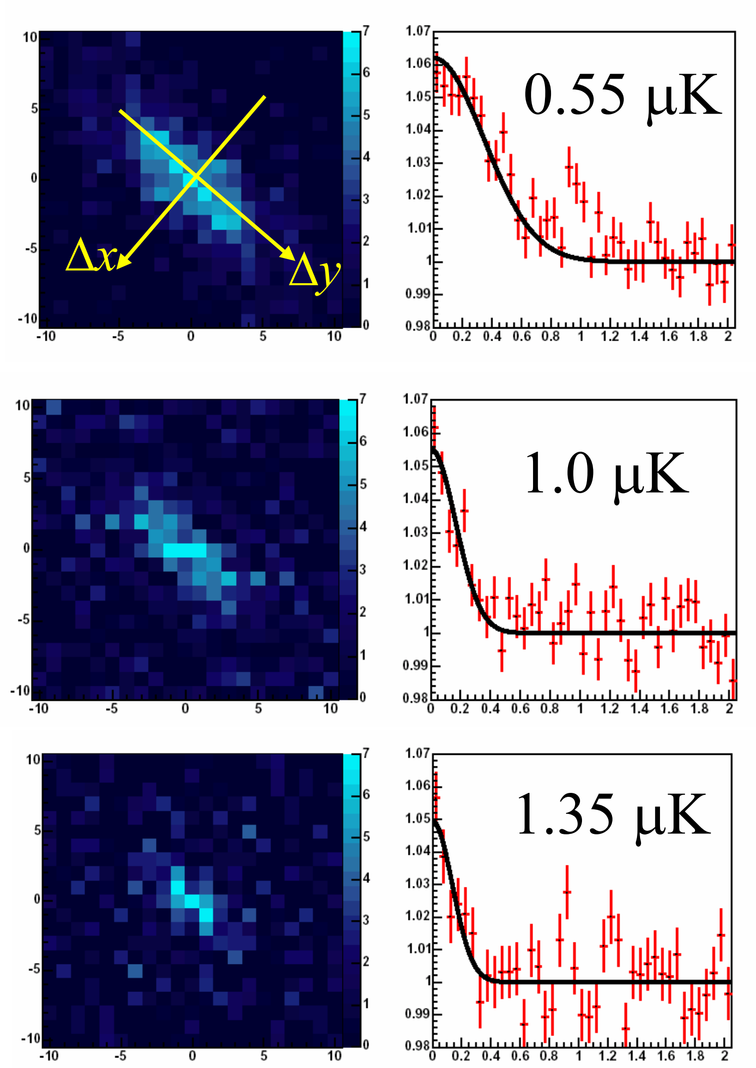
  $\Rightarrow$ Gaussian field: $g^{(2)}(\Delta r) = 1 + \left|g^{(1)}(\Delta r)\right|^2$

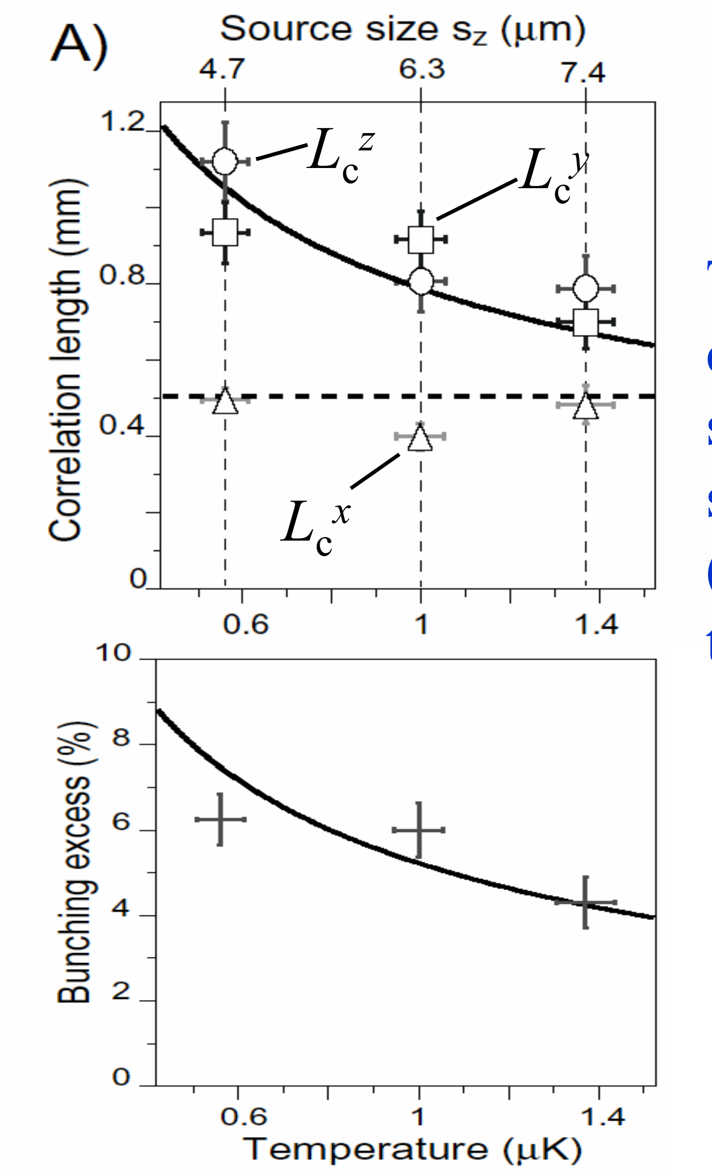
$g^{(1)}(\Delta r)$ = Fourier Transf. of the momentum distribution on detector $\rho(P)$

After time of flight t_0 , $\rho(P)$ maps the density $n(r_0)$ of the source.

$\Rightarrow g^{(2)}(\Delta r) - 1 = \left|FT\{n(r_0)\}\right|^2$ Depends only on the size of the source

Role of source size (^{4}He* thermal sample)

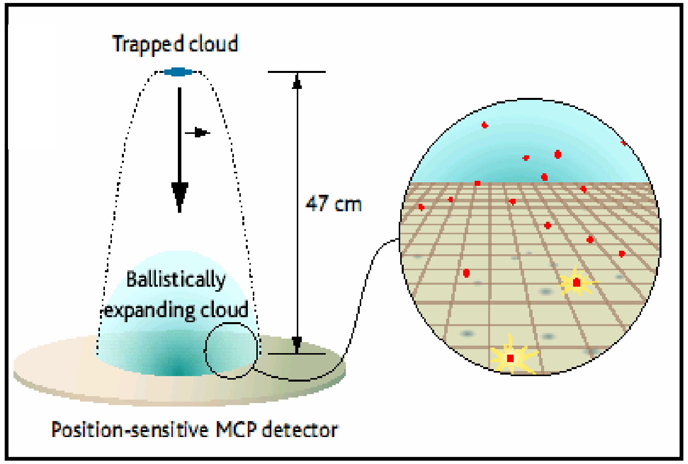


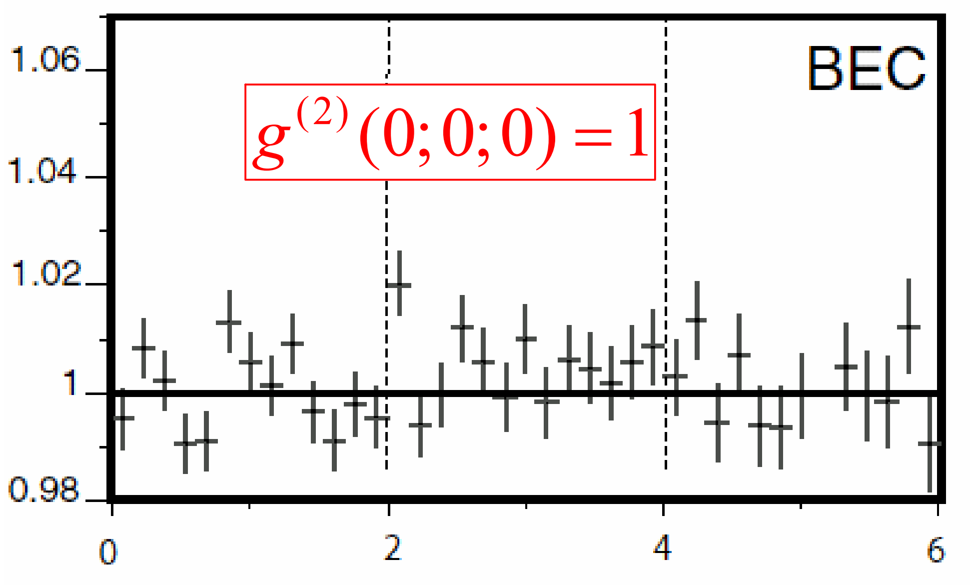


Temperature controls the size of the source (harmonic trap)

$g^{(2)}$ correlation function: case of a ^{4}He* BEC ($T < T_c$)

Experiment more difficult: atoms fall on a small area on the detector
⇒ problems of saturation





No bunching: analogous to laser light

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

Atoms are as fun as photons?

They can be more!

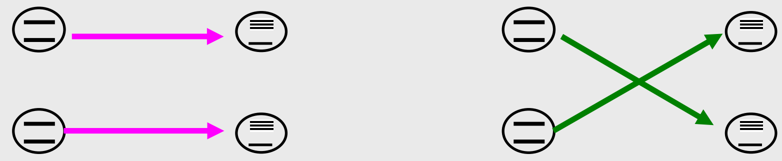
In contrast to photons, atoms can come not only as bosons (most frequently), but also as fermions, *e.g.* ^3He, ^6Li, ^{40}K...

Possibility to look for pure effects of quantum statistics

- No perturbation by a strong "ordinary" interaction (Coulomb repulsion of electrons)
- Comparison of two isotopes of the same element (^3He *vs* ^4He).

The HB&T effect with fermions: antibunching

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, lack of statistical independence although no real interaction

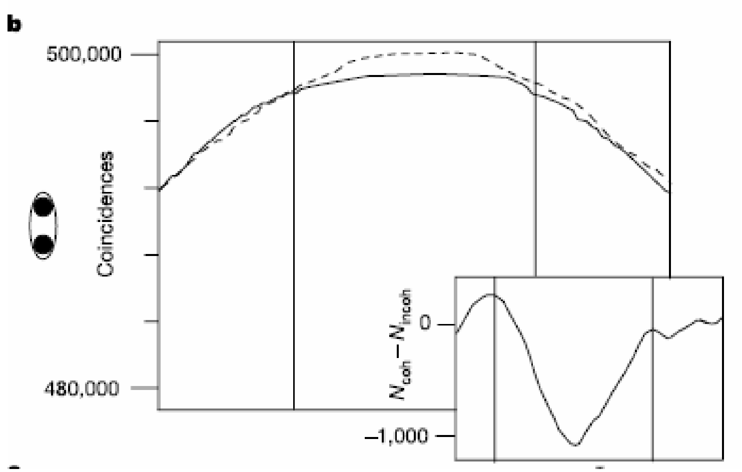
… no classical interpretation

$$\left\langle n(t)^2 \right\rangle < \left\langle n(t) \right\rangle^2$$ impossible for classical densities

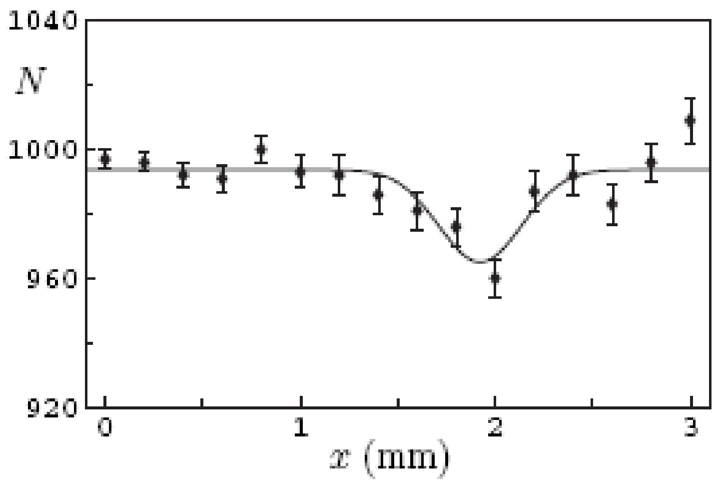
Not to be confused with antibunching for a single particle (boson or fermion): a single particle cannot be detected simultaneously at two places

Evidence of fermionic HB&T antibunching

Electrons in solids or in a beam:
M. Henny et al., (1999); W. D. Oliver et al.(1999);
H. Kiesel et al. (2002).

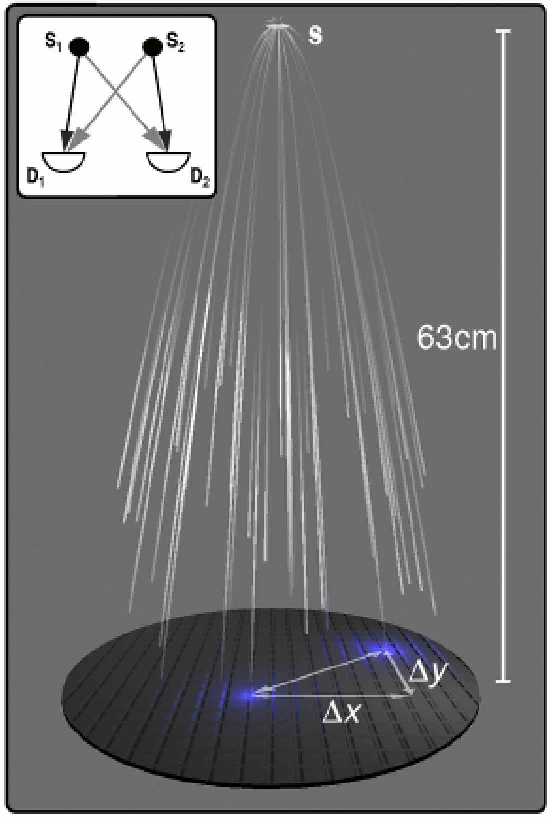


Neutrons in a beam:
Iannuzi et al. (2006)



Heroic experiments, tiny signals !

HB&T with $^3He^*$ and $^4He^*$ an almost ideal fermion vs boson comparison



Neutral atoms: interactions negligible

Samples of $^3He^*$ and $^4He^*$ at same temperature (0.5 μK, sympathetic cooling) in the trap :

⇒ same size (same trapping potential)

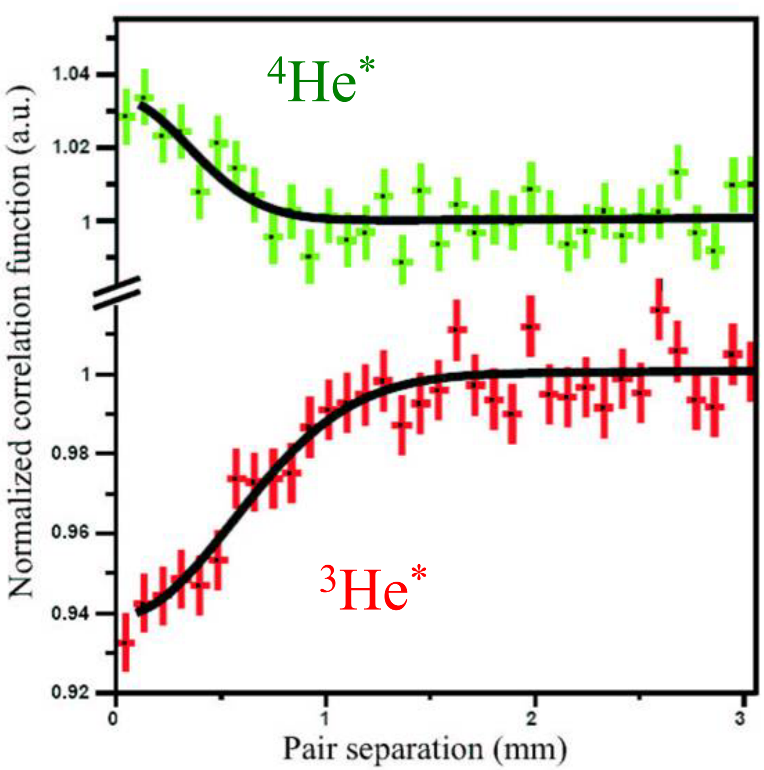
⇒ Coherence volume scales as the atomic masses (de Broglie wavelengths)

⇒ ratio of 4 / 3 expected for the HB&T widths

Collaboration with VU Amsterdam (W Vassen et al.)

HB&T with $^3He^*$ and $^4He^*$ fermion versus bosons

Jeltes et al. Nature 445, 402–405 (2007) (Institut d'Optique-VU)



Direct comparison:

- same apparatus
- same temperature

Ratio of about 4 / 3 found for HB&T signals widths and contrasts (mass ratio, ie de Broglie wavelengths ratio)

Pure quantum statistics effect

Collaboration with VU Amsterdam (W Vassen et al.)

See also Rom, T. et al. Nature 444, 733–736 (2006) (Mainz)

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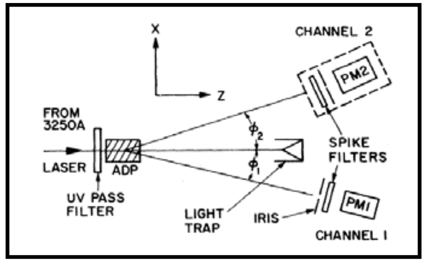
Atom-atom correlation measurements: a fundamental tool for quantum atom optics

- The Hanbury Brown and Twiss photon-photon correlation experiment: a landmark in quantum optics
- Elementary notions on production of ultra cold atomic gases and Bose-Einstein Condensates
- Atom-atom correlations in ultra cold quantum gases
- Detection of atom pairs in spontaneous non linear mixing of 4 de Broglie waves

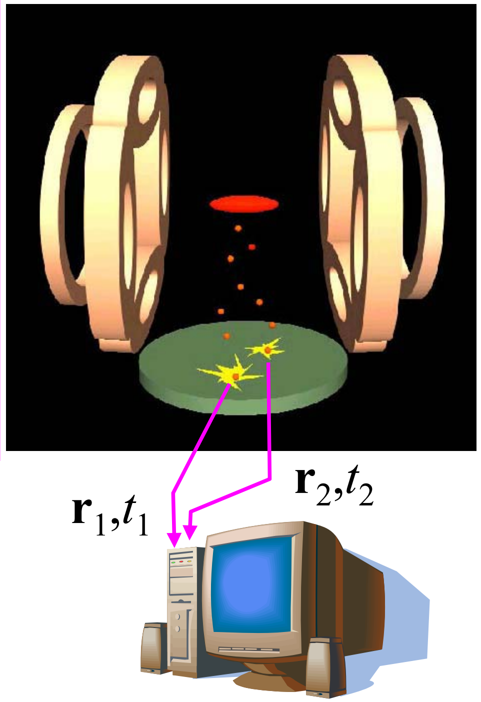
Single atom detection resolved in space and time: fascinating possibilities in quantum atom optics

1970: evidence of photons created in pairs in parametric down conversion (1987: entanglement)



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

- Study of any correlation function of atomic field
  - Hanburry-Brown & Twiss type experiments
    fermions and bosons: beyond photon quantum optics



2007: Detection of correlated atom pairs produced in non linear atom optics? Entanglement?

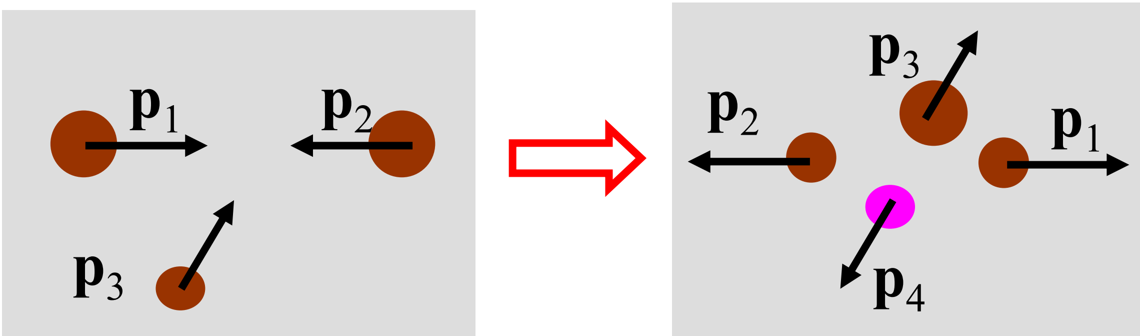
Non linear mixing of 4 matter waves

Stimulated process (NIST, MIT)

3 colliding BEC's

$\mathbf{p}_2 = -\mathbf{p}_1$

$p_3 = p_1 = p_2$



Appearance of a daughter BEC

$\mathbf{p}_4 = -\mathbf{p}_3$

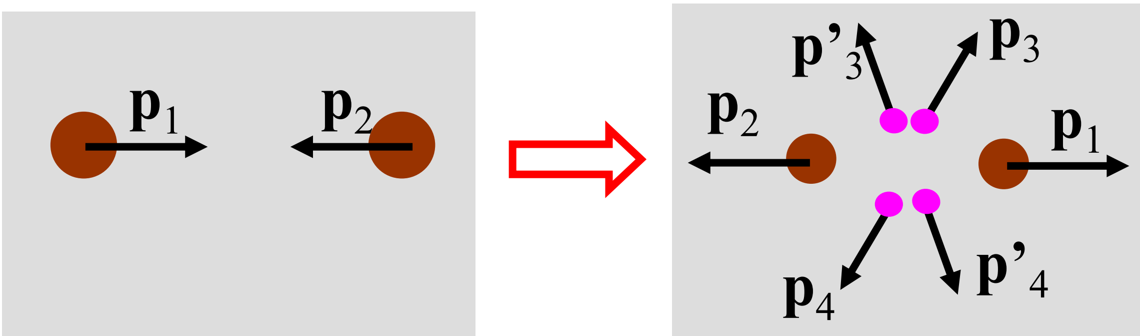
Amplification of 3

Spontaneous process

2 colliding BEC's

$\mathbf{p}_2 = -\mathbf{p}_1$

$p_1 = p_2$



Appearance of atom pairs

$\mathbf{p}_4 = -\mathbf{p}_3$

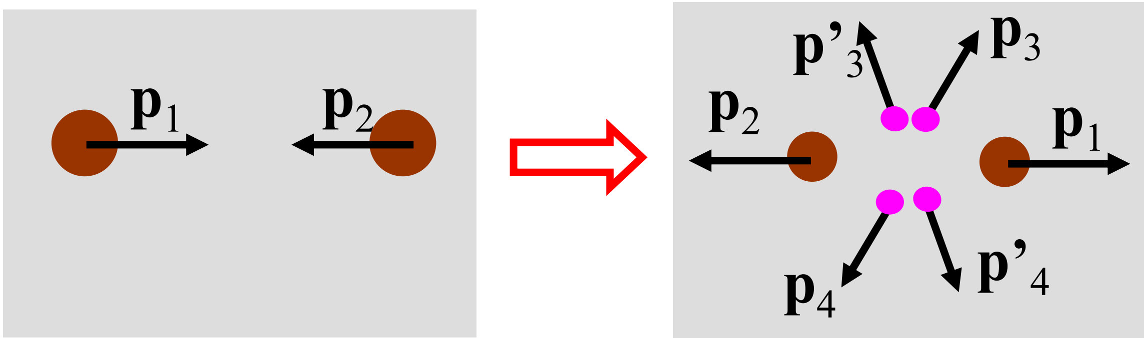
$p_4 = p_3 = p_1 = p_2$

Spontaneous non linear mixing of 4 matter waves

2 colliding BEC's

$\mathrm{p}_2 = -\mathrm{p}_1$

$p_1 = p_2$



Appearance of atom pairs

$\mathrm{p}_4 = -\mathrm{p}_3$

$p_4 = p_3 = p_1 = p_2$

Observed?

- scattered atoms with $p = p_1 = p_2$

Yes: s-wave (or higher order partial wave) collision halo (MIT, Penn state, Amsterdam)

- atom pairs?

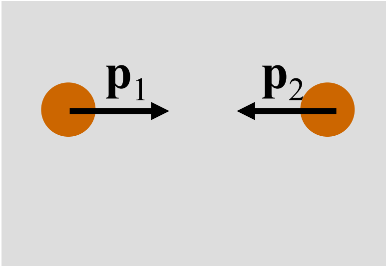
Recently observed at Institut d'Optique: metastable helium correlation function (Perrin et al., PRL 2007)

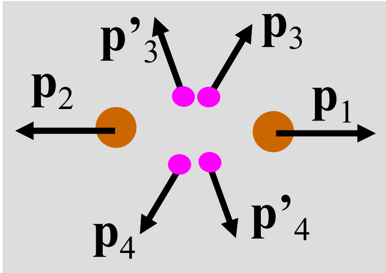
Velocity distribution of scattered atoms in the collision of two ^{4}He* BEC's

2 colliding BEC's

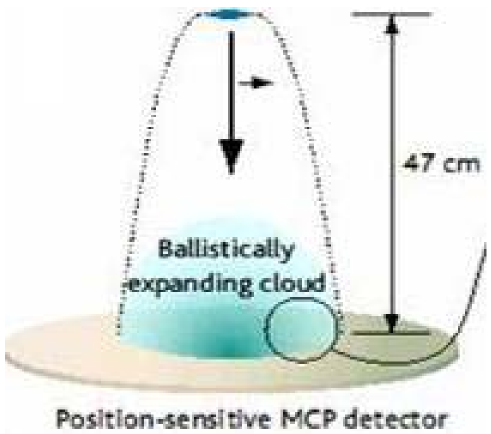
$\mathbf{p}_2 = -\mathbf{p}_1$

$p_1 = p_2$



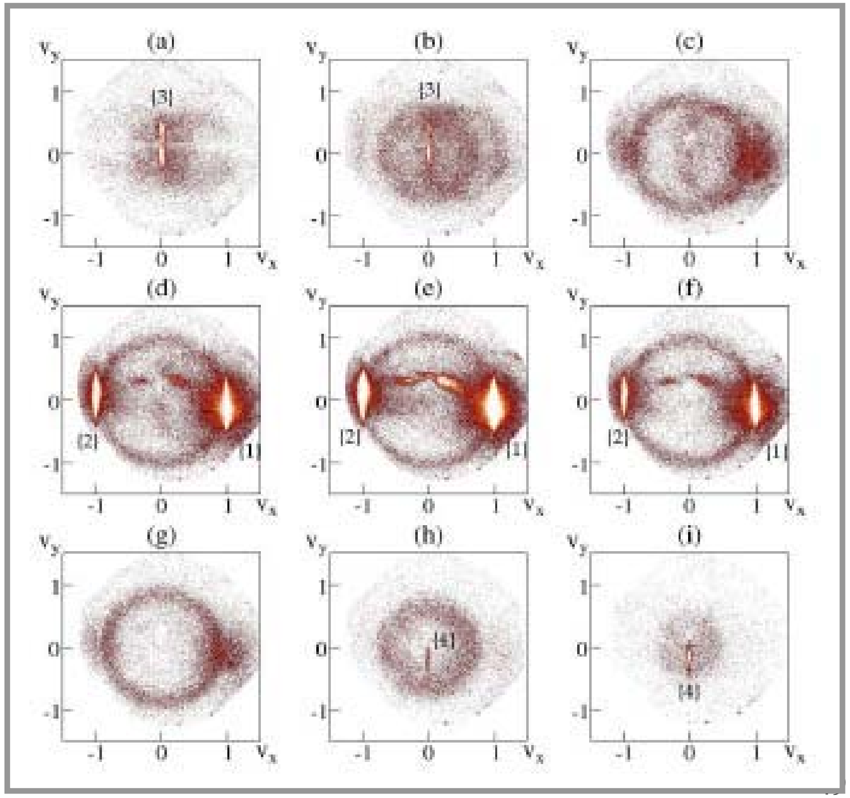


$$p_4 = p_3 = p_1 = p_2$$

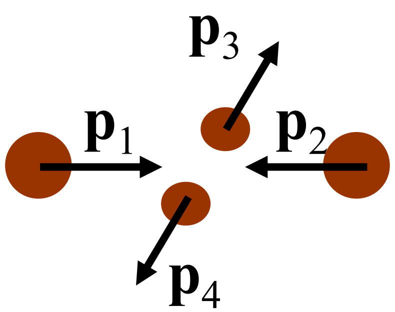


p reconstruction by elementary kinematics (free fall)

Observation of the full s-wave scattering spherical shell

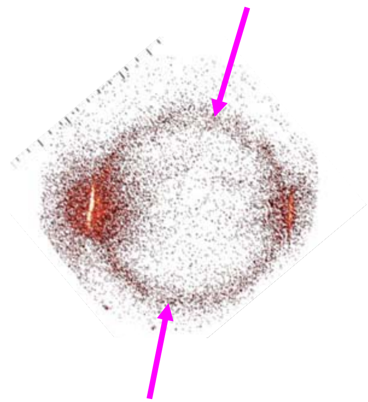


Observation of correlated ^{4}He* pairs



Colliding BEC's $\quad p_2 = -p_1$

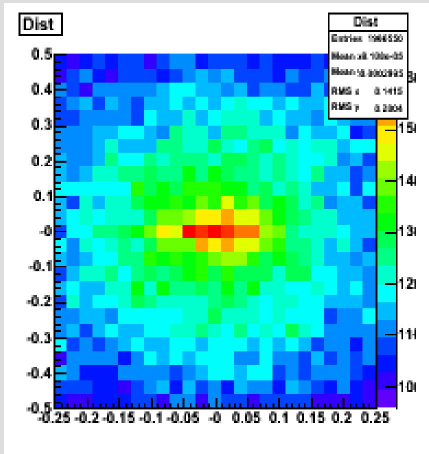
$$p_4 = -p_3$$
$$|p_3| = |p_4| = \text{const}$$

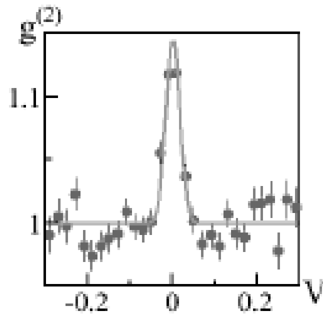


Momentum correlation in scattered atoms

Correlation of antipodes on momentum sphere

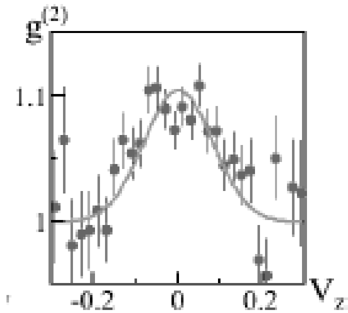
Atoms in pairs of opposite momenta





$g^{(2)}(V_{1\parallel} + V_{2\parallel})$

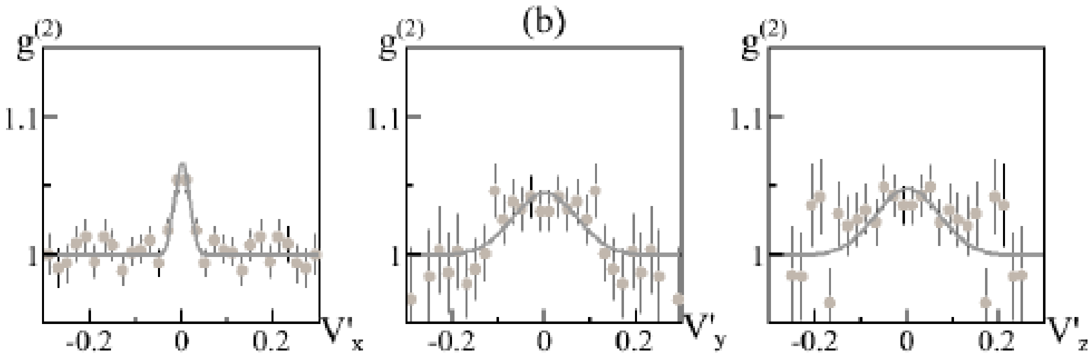
$g^{(2)}(V_{1\perp} + V_{2\perp})$



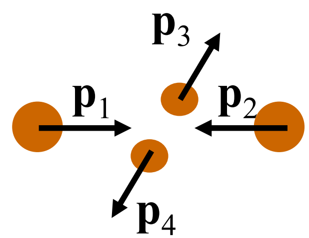
How to render an account of the width of $g^{(2)}(\mathbf{V}_1 + \mathbf{V}_1)$? Depends on the width of velocity distributions of colliding BEC's

How to measure the velocity distribution width of scattered atoms?

HBT correlations for (almost) collinear atoms!



$$g^{(2)}(\mathbf{V}_1 - \mathbf{V}_1)$$



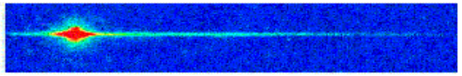
Results consistent with:

- back to back (pairs) correlation function widths
- thickness of the s-wave scattering spherical shell (individual atoms)
- estimated properties of the colliding BEC's

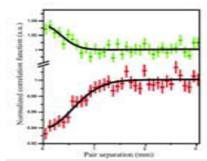
Pair production process reasonably understood

Summary: progress in quantum atom optics

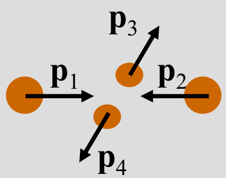
Atom lasers and atomic cavity: in progress

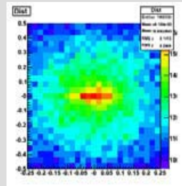


HB&T observed with bosons and fermions



Observation of pairs of atoms obtained in a spontaneous non-linear atom optics process





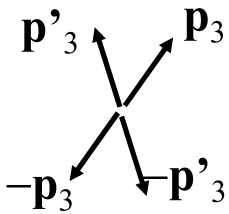
Fully quantum process:

- back to back correlations = particle image;
- HBT = 2 particle quantum amplitudes (classical waves)

Do we have entangled atom pairs?

Simplified model, in analogy to quantum photon optics: yes!

Entanglement in momentum state: $|\psi\rangle = |p_3, -p_3\rangle + |p_3', -p_3'\rangle + \ldots$



Experiments are going to be hard, but an experimental test of Bell's inequalities seems possible… hopefully before 2024!

Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes[1], J. M. McNamara[1], W. Hogervorst[1], W. Vassen[1], V. Krachmalnicoff[2], M. Schellekens[2], A. Perrin[2], H. Chang[2], D. Boiron[2], A. Aspect[2] & C. I. Westbrook[2]

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William Guérin
Chris Vo
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Fermions Bosons mixtures
Thomas Bourdel
Gaël Varoquaux
Jean-François Clément
Thierry Botter
J.-P. Brantut
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He* BEC
Denis Boiron
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V Krachmalnicoff
Hong Chang
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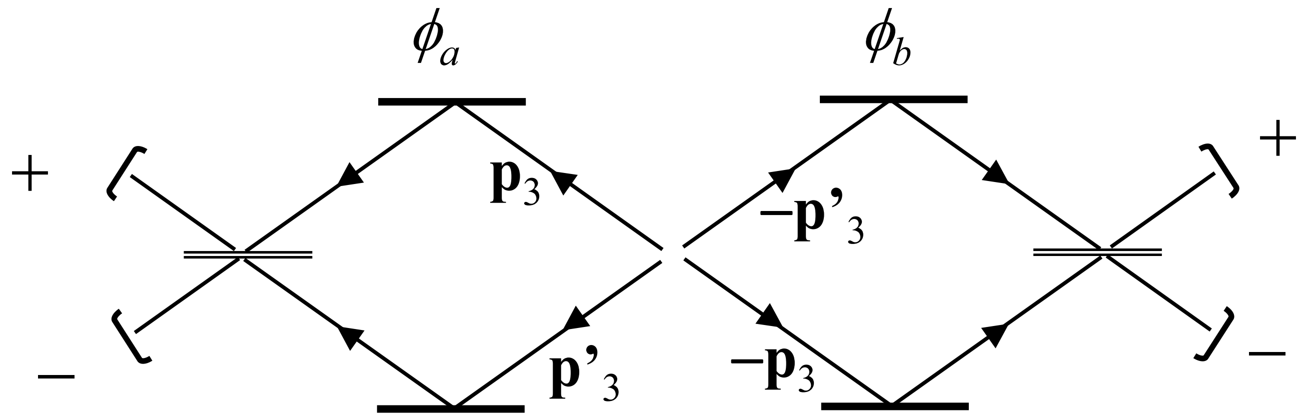
Pairs entangled in momentum?

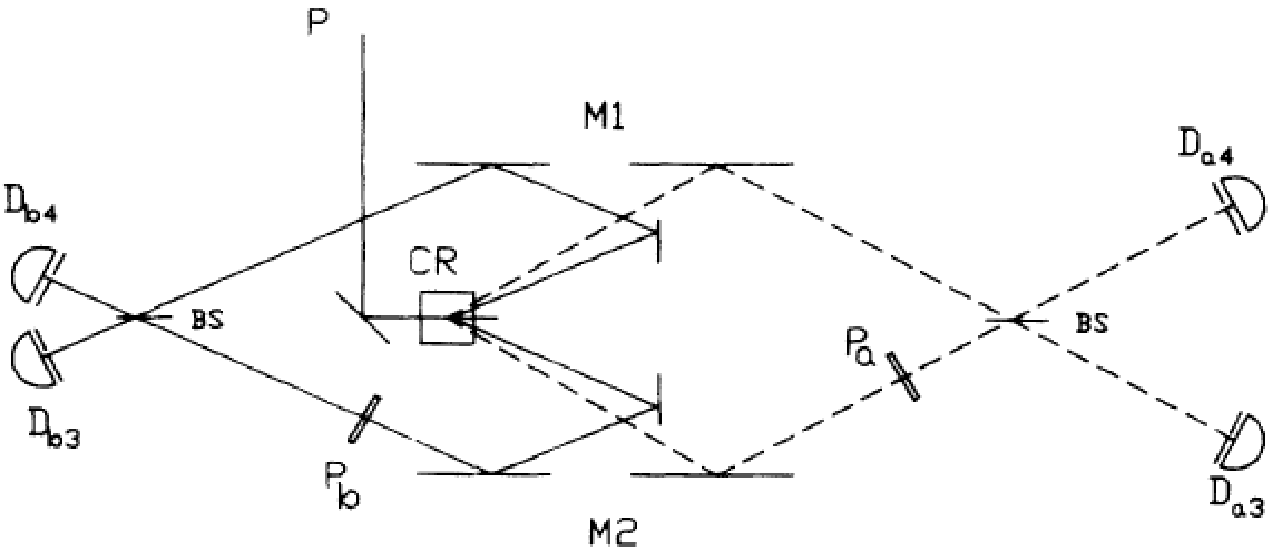


Single pair $$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|p_3, -p_3\rangle + |p'_3, -p'_3\rangle\right)$$

How to show entanglement? Measure coincidence rates N_{++} , N_{+-}, N_{-+} , N_{--},versus $\phi_a - \phi_b$, and test Bell's inequalities

Analogous to Rarity and Tapster / Horne-Shimony-Zeilinger

Momentum entanglement



Rarity and Tapster (1990)