Hong-Ou-Mandel effect with matter waves

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Progresses in quantum information and quantum simulation, Lyon, November, 18th 2014

Outline

Quantum Optics with light

Some Quantum Optics milestones

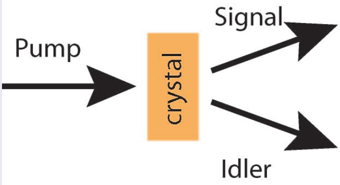
- 1935: Einstein, Podolski & Rosen – concept of entanglement
- 1956: Hanbury Brown & Twiss – bunching from chaotic source
- 1963: Bell's inequality – quantum *vs* local hidden variable theory
- 1970: Burnham & Weinberg – pairs of photon
- 1987: Hong, Ou & Mandel – 2-photon interference

Quantum optics

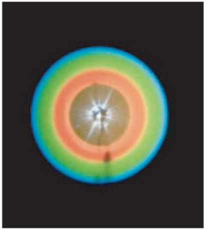
- Effects involving at least two particles
- This talk: pairs of particles

Pairs of photons

Parametric down-conversion



NIST



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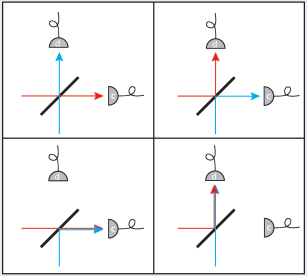
- Non-linear $\chi^{(2)}$ crystal
- Undepleted pump: $\hat{H} = i\hbar \int d\mathbf{k}_i d\mathbf{k}_s \kappa_{i,s} \left(\hat{a}_s^\dagger \hat{a}_i^\dagger - \hat{a}_s \hat{a}_i \right)$
- Phase-matching conditions : $\omega_p = \omega_i + \omega_s$ and $\mathbf{k}_p = \mathbf{k}_i + \mathbf{k}_s$
- Burnham & Weinberg: increased coincidence with detectors at phase matching

Hong Ou Mandel effect

2 photons + 1 beam-splitter: 4 possibilities

- 2 distinguishable photons



$$P_{cd} = \frac{1}{4} + \frac{1}{4} = \frac{1}{2}$$

- 2 indistinguishable photons
- $P_{cd} = |A_{TT} + e^{i\pi} A_{RR}|^2 = 0!!$

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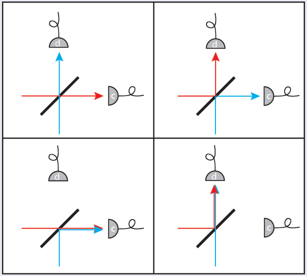

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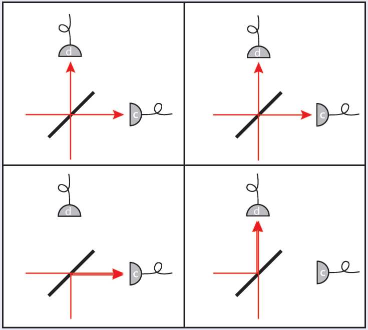

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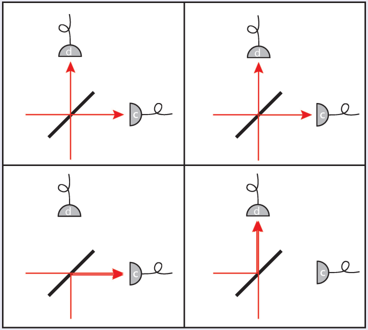

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Hong, Ou & Mandel, Phys. Rev. Lett. **59**, 2044 (1987)

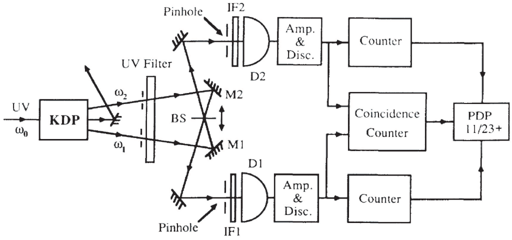
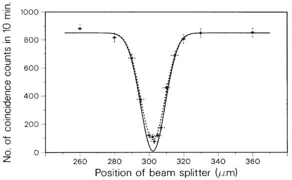


FIG. 1. Outline of the experimental setup.

Need *beam-splitter*, *pin-hole, spectral filters, photon-counter,* *coincidence counts*, *path delay*

Two-photon interference



The 'HOM dip' for indistinguishable photons works for 2 independent photons but experiment easier with pairs of photon

Hong Ou Mandel: striking 2-particle effect for input state of one particle per input beam

Quantum Optics with ultra-cold atoms

Pro-Cons

- ☺ Another platform for quantum information
- ☺ More degrees of freedom (internal state, boson/fermion)
- ☺ Controllable, tunable and strong non-linearity
- ☹ Purity of the state
- ☹ Manipulation (mirrors, beam-splitter, pin-hole, vacuum...)

- Entanglement by atom-light interaction (cavity), by atom-atom interaction
- Entanglement with internal or external degrees of freedom

Pairs of atoms

Mechanisms

- **Molecular dissociation**: $Mol.(p=0) \rightarrow At.(p) + At.(-p)$
  $\rightarrow$ M. Greiner *et al*, Phys. Rev. Lett. **94**, 110401 (2005)

- **Inelastic collision**: $2(m_F=0) \rightarrow (m_F=+1) + (m_F=-1)$
  $\rightarrow$ B. Lücke *et al*, Science **334**, 773 (2011), C. Gross *et al*, Nature **480**, 219 (2012), C. D. Hamley *et al*, Nat. Phys. **8**, 305 (2012)

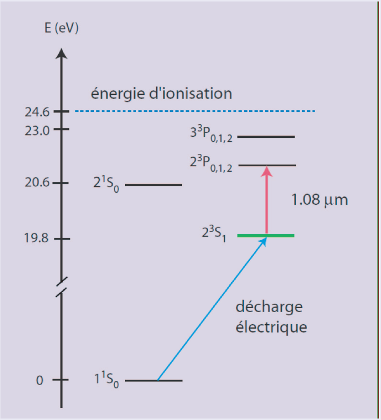
- **Decay from excited state by pairs**:
  $2(\nu_y=1, p=0) \rightarrow (\nu_y=0, p) + (\nu_y=0, -p)$
  $\rightarrow$ R. Bücker *et al*, Nat. Phys. **7**, 608 (2011)

- **Collision between 2 BEC**: $k_0 + (-k_0) \rightarrow k_1 + k_2$
  $\rightarrow$ A. Perrin *et al*, Phys. Rev. Lett. **99**, 150405 (2007)

- **Lattice-assisted collision**: $2k_0 \rightarrow k_1 + k_2$
  $\rightarrow$ M. Bonneau *et al*, Phys. Rev. A **87**, 061603(R) (2013)

Specificities of He*

2^3S_1 : metastable helium (life-time of $\sim$ 2 h): **He***



- Laser cooling at 1.08 μm
- 2001: Bose-Einstein Condensate of $\sim 10^5$ atoms
- High internal energy

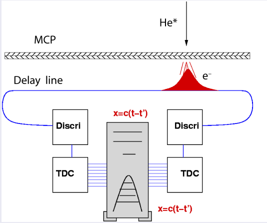
  $\Downarrow$
- **Electronic detection** by **micro-channel plates (MCP)**

Principle of the 3D detector

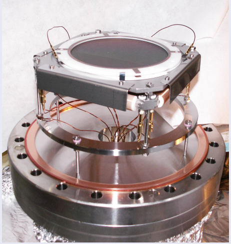
The detector

- Cloud released from the trap
  $\rightarrow$ atoms fall 50 cm to detector
  (300 ms fall time)
- MCP: low-noise electronic amplifier
  $\Rightarrow$ sensitive to single atom
  (quantum efficiency $\sim 25\%$)
- 3D detector: x, y and t
  (resolution 140 ns, 250 μm)

$\Rightarrow$ Measurement of $\vec{\mathbf{v}}$
$(x_0 + v_0 t \approx v_0 t)$



- Measurement of 2-body correlation $G^{(2)}(\vec{\mathbf{v}}, \vec{\mathbf{v}'})$



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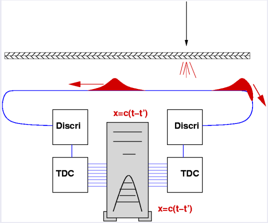

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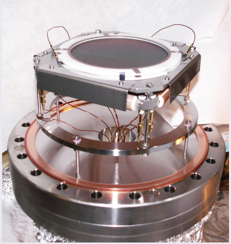

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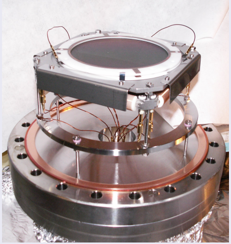
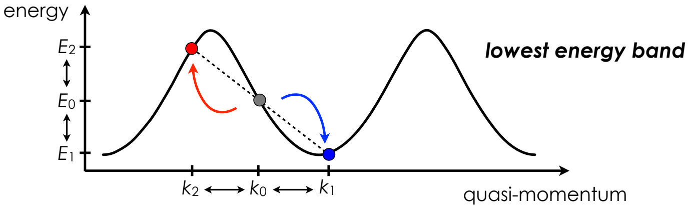


Lattice-assisted collisions

Dynamical instability of a BEC in a moving optical lattice



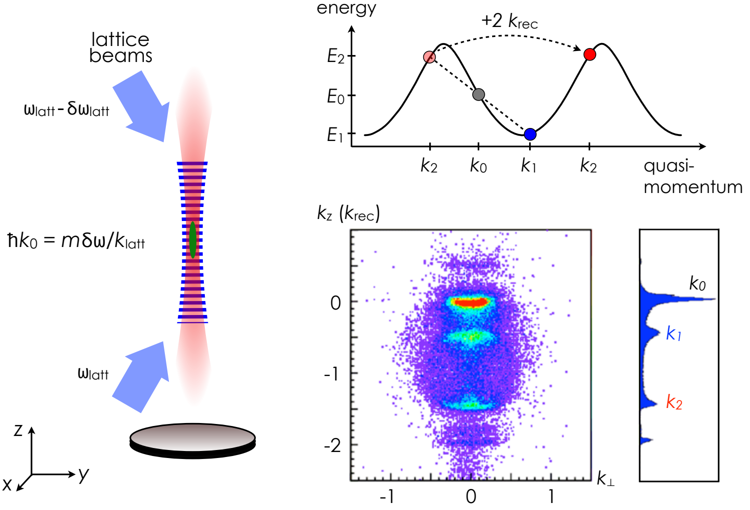
elastic collision between two atoms of the condensate:

$k_0 + k_0 \longrightarrow k_1 + k_2$

Hilligsøe & Mølmer, PRA **71**, 041602 (2005)
Campbell *et al.*, PRL **96**, 020406 (2006)

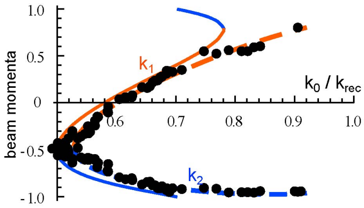
Lattice-assisted collision

Momentum distribution

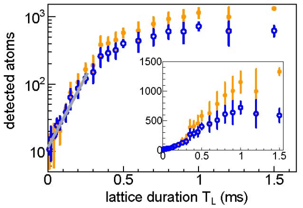


Tunability

Control over the output modes



Control over the population



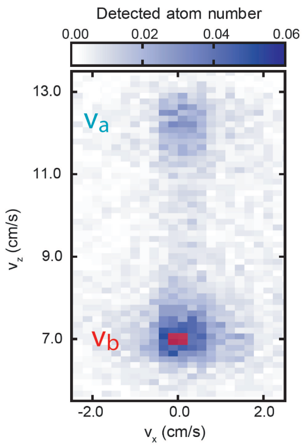
solid line: single-particle prediction

dashed line: mean field

Pairs of atoms

Atom pairs

- Pairs of atoms ✓
- Detection → $G^{(2)}$ ✓
- +sub-Poissonian variance & violation of Cauchy-Schwarz inequality
- Beam-splitter ✓
  - Bragg diffraction
  - 2 laser beams $(\Delta\mathbf{k}, \Delta\omega)$
  - Resonant for $\mathbf{p}_a = \mathbf{p}_b + \hbar\Delta\mathbf{k}$ and $\frac{p_a^2}{2m} = \frac{p_b^2}{2m} + \hbar\Delta\omega$.
  - Transmission coef. ↔ duration



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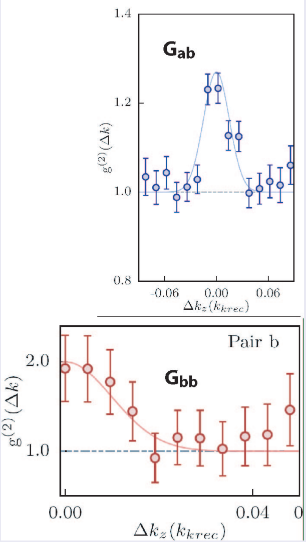

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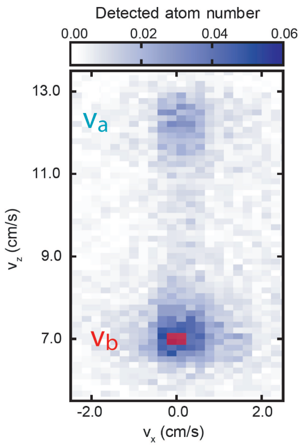

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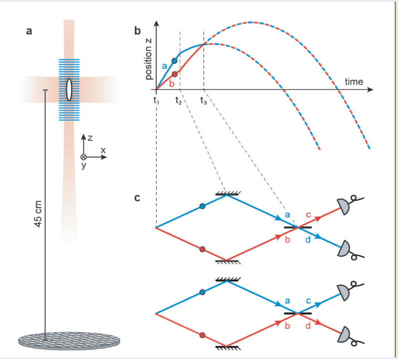
HOM experiment with He*

The experimental sequence

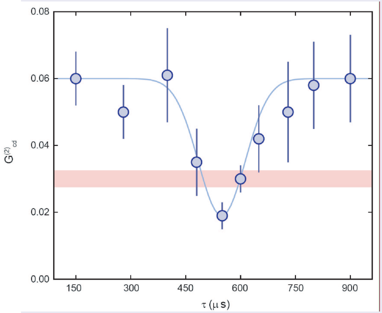


- t_0: Lattice switched on
- t_1: Trap switched off
- t_2: Atomic mirror
- t_3: Atomic beam-splitter ($t_3 - t_0 \sim 1$ ms) exact timing of t_3 control the overlap
- $t \sim 300$ ms: Detection by MCP

Mirror and beam-splitter by Bragg diffraction

HOM experiment with He*

The result



- DIP !!, with visibility of $V_{exp} = 0.65 \pm 0.07$
- Dip not allowed for classical particles
- but with (matter-)waves ?
- not either since visibility > 0.5 (red area)
- $\Rightarrow$ 2-atom interference

atomic Hong Ou Mandel effect!

$\tau = t_3 - t_2$: scan of the overlap

Visibility : $V = \frac{G^{(2)}_{max} - G^{(2)}_{min}}{G^{(2)}_{max}}$

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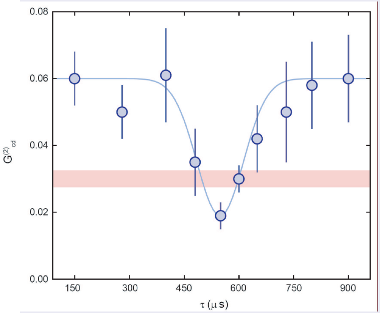

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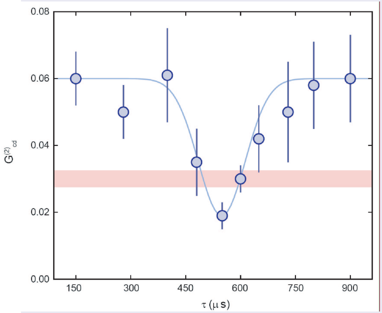

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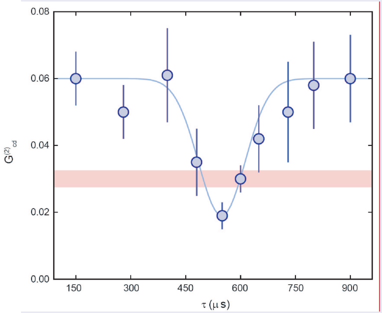

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HOM experiment with He*

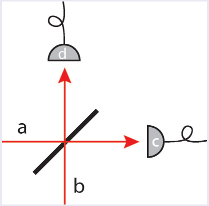
Non-zero dip

- atoms not totally indistinguishable
- → unlikely

  Indistinguishable particles → $V_{\max} = 1 - \frac{G^{(2)}_{aa} + G^{(2)}_{bb}}{G^{(2)}_{aa} + G^{(2)}_{bb} + 2G^{(2)}_{ab}}$

  Measurement of $V_{\max}$ with same sequence except mirror and beam-splitter non applied : $V_{\max} = 0.6 \pm 0.1$

  $V_{exp} \approx V_{max}$: atoms indistinguishable up to our signal to noise
- OR input state is not exactly one atom per beam
- → yes, mean atom number = 0.5 is not low enough



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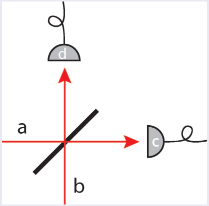

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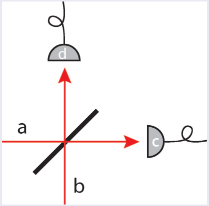

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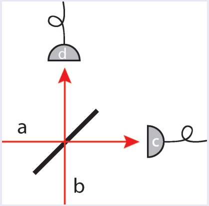

Conclusion and perspectives

Observation of the Hong-Ou-Mandel effect

- ☺ Benchmarks our ability to make 2-particle interference
- ☺ Benchmarks our source (modes with similar wave-functions)
- ☹ $\sim$ 10 hours integration time for each point in HOM plot...

see also Kaufman *et al*, Science **345**, 306 (2014)

Perspectives: EPR paradox and Bell's inequality

- State of our source $|\Psi\rangle = \int dp\, dp' A(p, p')|p, p'\rangle$
- The phase of $A(p, p')$ matters for EPR and Bell!
- **EPR**: A. J. Ferris, Phys. Rev. A **79**, 043634 (2009)
  $\rightarrow$ Homodyning the 2 atoms with condensate, measurement of atom number variance
- **Bell**: R. J. Lewis-Swan, K. V. Kheruntsyan, arXiv: 1411.019 (2014). $\rightarrow$ Need 4 modes, mixing 2 by 2 on beam-splitter, measurement of 2-body corr.