Atomic Hong-Ou-Mandel effect

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Outline

1. Quantum Optics with light
2. → HOM effect with photons
3. Quantum Optics with atoms
4. → HOM effect with metastable helium atoms
5. Conclusion and perspectives

Quantum Optics with light

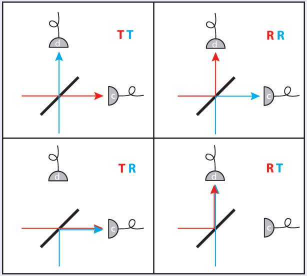
Quantum optics

- Effects involving at least two particles
- Hong-Ou-Mandel experiment (1987): milestone two-particle interference experiment
- HOM effect: a "last" step before entanglement criteria (e.g. Bell's inequality)
- HOM setup: building block for quantum information processing

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
- $P_{cd} = |A_{TT} + e^{i\pi} A_{RR}|^2 = 0!!$
  $|\Psi_{in}\rangle = |11\rangle, |\Psi_{out}\rangle = |20\rangle + |02\rangle$

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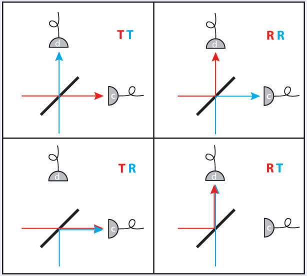

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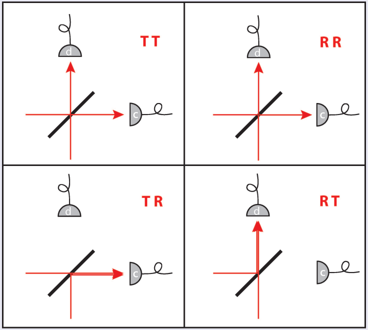

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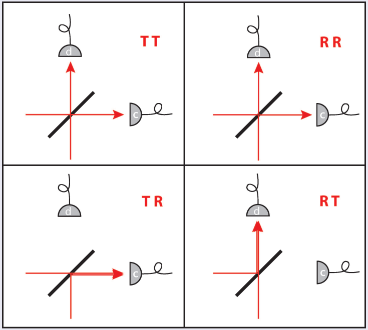

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Hong, Ou & Mandel, Phys. Rev. Lett. **59**, 2044 (1987)

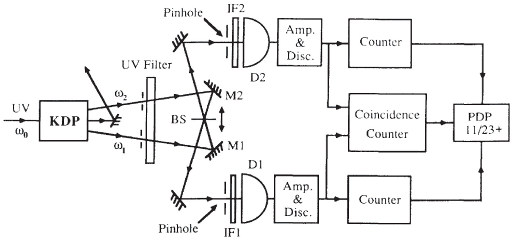
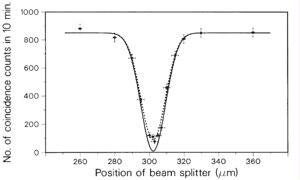


FIG. 1. Outline of the experimental setup.

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

Two-photon interference



The 'HOM dip' for indistinguisable 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...)

Atomic Hong-Ou-Mandel effect

What do we need for the atomic analogue?

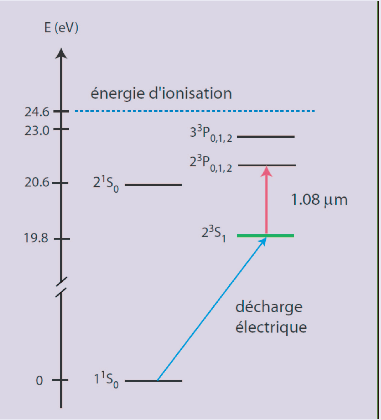
- An atom: metastable helium
- The ability to detect single particles: micro-channel plates
- An source of pairs: lattice-assisted collision
- Mirror, beam-splitter, pin-hole, interference filters: 2-photon Bragg diffraction + 3D capability of the detector

Let's go!

Quantum atom optics with metastable helium (He*)

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

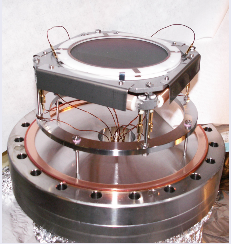
The detector

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

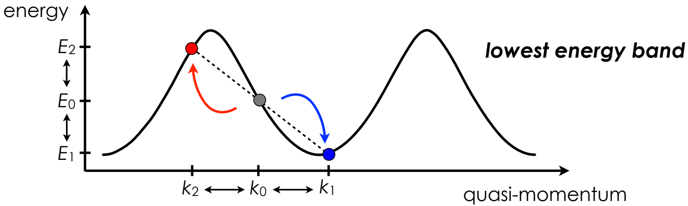
$g^{(2)} = \frac{G^{(2)}(\vec{\mathbf{v}}, \vec{\mathbf{v}'})}{\rho(\vec{\mathbf{v}})\rho(\vec{\mathbf{v}'})} \neq 1 \Leftrightarrow$ correlation



Pair production by lattice-assisted collision

Lattice-assisted collisions

Dynamical instability of a BEC in a moving optical lattice



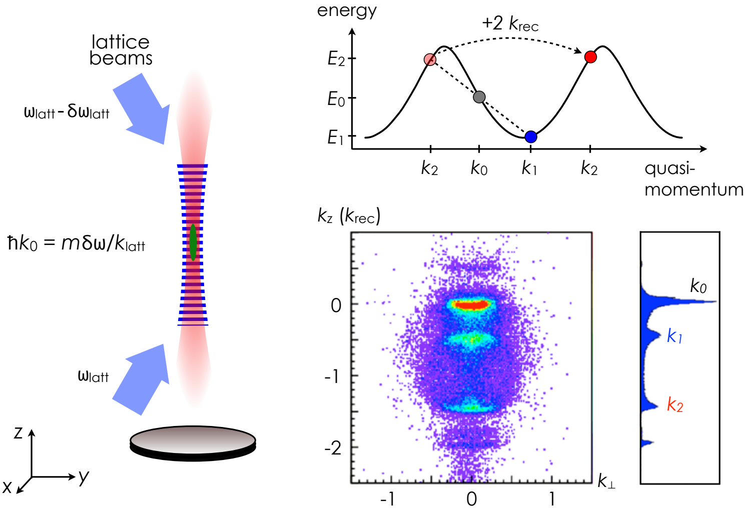
elastic collision between two atoms of the condensate:

$k_0 + k_0 \longrightarrow k_1 + k_2$

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

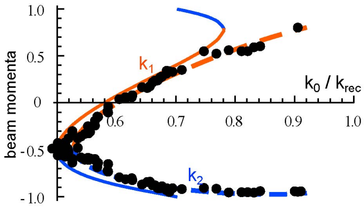
Lattice-assisted collision

Momentum distribution

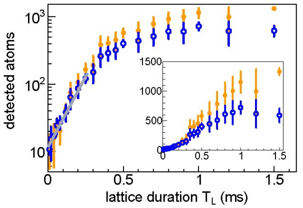


Tunability

Control over the output modes



Control over the population

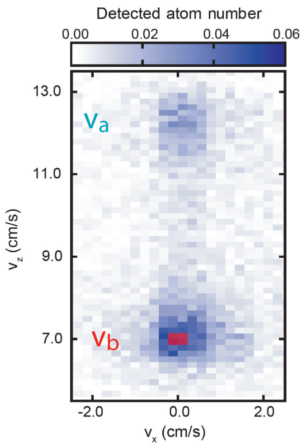


solid line: single-particle prediction

dashed line: mean field

Atom pairs

- Pairs of atoms ✓
- Detection → $G^{(2)}$ ✓
- +sub-Poissonian variance & violation of Cauchy-Schwarz inequality
- Beam-splitter (BS) ✓
  - 2 photon 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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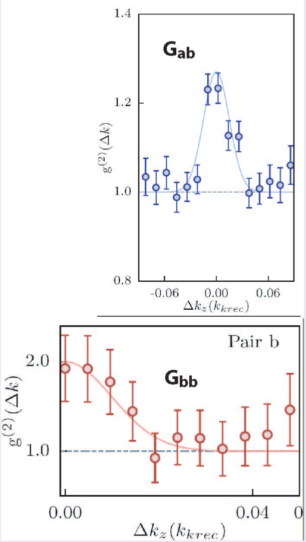

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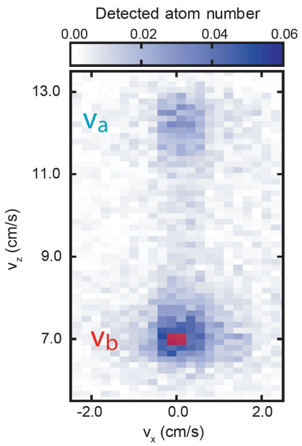

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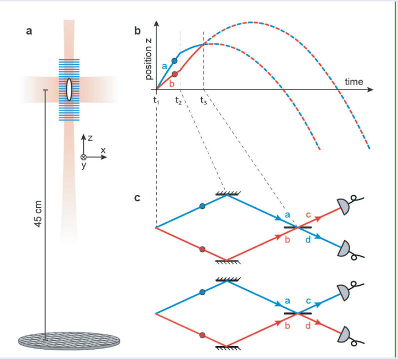
HOM experiment with He*

The experimental sequence

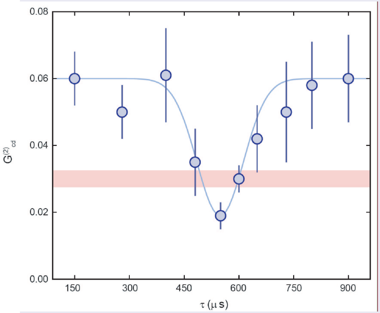


- t_0: Lattice switched on
- t_1: Trap switched off
- t_2: Bragg in mirror mode
- t_3: Bragg in BS mode ($t_3 - t_0 \sim 1$ ms) exact timing of t_3 control the overlap
- $t \sim 300$ ms: Detection by MCP

Mirror and beam-splitter by Bragg diffraction

HOM experiment with He*

The result: Cross-correlation G_{cd} in function of BS application time



- 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)
- ⇒ 2-atom interference

atomic Hong Ou Mandel effect!

→ Lopes *et al*, Nature **520**, 66 (2015)

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

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

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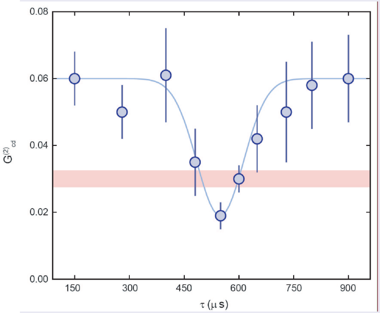

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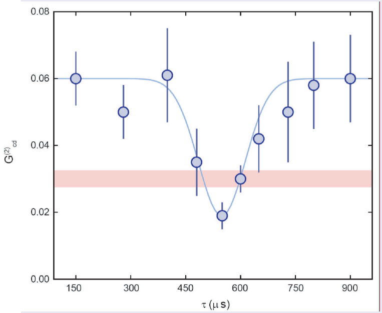

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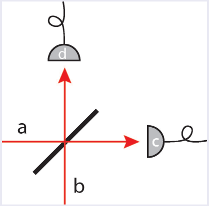
Non-zero dip

- atoms could be not totally indistinguishable
- $\rightarrow$ unlikely

  Indistinguishable particles $\rightarrow V_{\text{max}} = 1 - \frac{G_{aa}^{(2)} + G_{bb}^{(2)}}{G_{aa}^{(2)} + G_{bb}^{(2)} + 2G_{ab}^{(2)}}$

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

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



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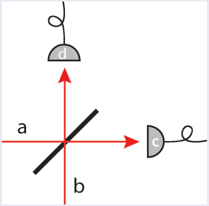

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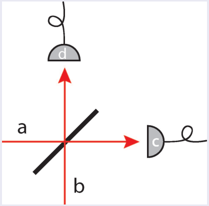

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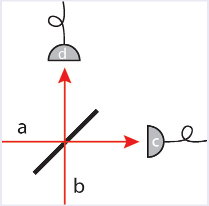

Conclusion and perspectives

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 $|\Psi\rangle = \int dk_1 dk_2 A(k_1, k_2)|k_1, k_2\rangle$
- The phase of $A(k_1, k_2)$ 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.