Correlated Atoms in 3 Dimensions

Chris Westbrook
Laboratoire Charles Fabry, Palaiseau

IQO, Hannover
5 June 2014
Correlated photons in Quantum optics
Production of correlated atoms
Are our atom correlations good enough for “quantum atom optics”?
Inspirations from quantum optics

“... time intervals between two photons by interference”, Hong, Ou, Mandel PRL 1987

|2,0⟩ + |0,2⟩

“... Bell’s inequality based on phase and momentum”, Rarity and Tapster PRL 1990

|k₁,k₂⟩ + |q₁,q₂⟩
Hong Ou Mandel effect

Start with 1 photon in each input $\rightarrow$ 4 QM amplitudes:

- Both transmitted
- Both reflected

1st two amplitudes cancel, leaving: $|2,0\rangle + |0,2\rangle$
Beating the standard q-limit with 4 entangled photons


Input state is $|2,2\rangle$
Photon pairs

parametric downconversion:

\[ H \sim b \ a_1^\dagger a_2^\dagger + \ h.c. \]

4 wave mixing:

\[ H \sim b \ b \ a_1^\dagger a_2^\dagger + \ h.c. \]

These processes have led to Bell’s inequality violations, squeezing, improvements in interferometry ...
### Atom pairs

#### Bell state

- coupling to cavities

- interaction blockade
  - Isenhower *et al.*, *ibid.*, 010503 (2010)

- ions

#### Two-mode squeezed state

- coupling to cavities
  - Chen *et al.*, PRL **106**, 133601 (2011)

- spin changing interactions
  - Bookjans *et al.*, PRL **107**, 210406 (2011)

*previous work performed (almost) exclusively in the spin sector*
We want to work in position space rather than in spin space.

Why?

1. Inertial sensors (gyro, accelerometer ...) require spatial separation. Maybe we can do “quantum inertial sensing”.

2. Bell’s inequalities with spatially separated massive particles. What if a gravitational effect affects QM?

3. We have to. With He*, using the spin sector looks very difficult.

4. ...
The team

New people:
Almaz Imanaliev
Marc Cheneau

Guthrie Partridge

C IW
Denis Boiron
Rafael Lopes

Josselin Ruaudel
Marie Bonneau

Jean-Christophe Jaskula
Metastable Helium, He*

Lifetimes:
2³S₁: 8000 s
2³P_J: 100 ns

Collisions:
• elastic scattering length 7.5 nm
• inelastic rate collision rate
  He* + He* → He + He⁺ + e⁻
  polarized 2 × 10⁻¹⁴ cm³/s
  unpolarized 2 × 10⁻¹⁰ cm³/s

• excitation in discharge
• deexcitation enables electronic detection: He* → He + e⁻
hole separation: 24 µm
spatial resolution ~250 µm
$5 \times 10^4$ detectors in //
q.e. for He* ~ 25%

must be careful about saturation

time differences give the position on MCP
digitizing step: 275 ps
“Time of flight” observation

typically $10^5$ atoms
time of flight $\sim 300$ ms
width of TOF $\sim 10$ ms
We record $x,y,t$ for every detected atom.
Get velocity distribution and correlation function.

there is also a laser trap
4 wave mixing, seen in 3D
Four wave mixing

a.k.a. “a collision”

\[ H = \chi \hat{a}_1 \hat{a}_2 \hat{a}_3 \hat{a}_4^\dagger + h.c. \]

energy and momentum conservation:

\[ k_1 + k_2 = k_3 + k_4 \]
\[ E_1 + E_2 = E_3 + E_4 \]

restricts atoms to a spherical shell

Correlated atom pairs

Correlation function for back to back pairs

\[ g^{(2)}(p, -p + \Delta p) \]

normalised variance:

\[ V_{ij} = \frac{\Delta(N_i - N_j)}{\langle N_i + N_j \rangle} \]

Jaskula et al. PRL 2010
Other methods

why look for alternatives?
small occupation per mode (0.1 - 0.01)
not easily controlled

relaxation of transverse excitations in BEC

modulation of speed of sound
parametric downconversion of phonons (DCE)
Jaskula et al. PRL (2012)
4 wave mixing in a (moving) lattice

Energy and quasi-momentum conservation

\[ 2k_0 = k_1 + k_2 \]
\[ 2E_0 = E_1 + E_2 \]

Interactions produce a dynamical instability for large \( k_0 \)

Hillingsoe and Molmer, PRA 2005
Campbell et al. PRL 2006
Momentum distribution

\[ \hbar k_0 = m \delta \omega / k_{\text{latt}} \]

\[ \omega_{\text{latt}} - \delta \omega_{\text{latt}} \]

\[ \text{lattice beams} \]

energy

\[ k_2 \quad k_0 \quad k_1 \quad k_2 \]

quasi-momentum

\[ k_z (k_{\text{rec}}) \]

\[ -2 \quad -1 \quad 0 \quad 1 \]

\[ k_0 \quad k_1 \quad k_2 \]
A few characteristics

Final momenta can be chosen with \( k_0 \)

Turning lattice off stops interaction \( \rightarrow \) atom number can be controlled

Bonneau et al. PRA 2013
Variance in the number difference

\[ V = \frac{\langle (N_1 - N_2)^2 \rangle - \langle N_1 - N_2 \rangle^2}{\langle N_1 + N_2 \rangle} \]

\( N_1, N_2 \sim 100 \)

\( V_{\text{min}} \sim 0.75 \)
A multiparticle Hong Ou Mandel expt

2 Bragg pulses ($\pi, \pi/2$)

Interference?
Hong Ou Mandel effect

Start with 1 photon in each input $\rightarrow$ 4 QM amplitudes:

\[
\begin{align*}
|2,0\rangle + |0,2\rangle
\end{align*}
\]

1st two amplitudes cancel, leaving:

average number in one output port $\langle N \rangle = 1$

variance $\nu = \langle N^2 \rangle - \langle N \rangle^2 = 1$

\[
\nu = 1/2 \text{ without interference}
\]

normalized variance $V = \nu/\nu = 2$
Multiparticle interference with spins

In the spin sector


Photonic version, Spasibko et al. NJ Phys 2014
What ought to happen?

counts in a single detector

$\eta = 1$

$\eta = 0.15$

twin Fock states, $n = 30$

blue distinguishable

orange indistinguishable
Can they interfere?

Preliminary
Dual Fock state $|N, N\rangle$ with *indistinguishable* particles and quantum efficiency $\eta$:

- **no beam splitter**
  - $V = 1 - \eta$
  - $= 0.75$

- **with beam splitter**
  - $V = 1 + \eta N$
  - $= 20$?

Dual Fock state $|N, N\rangle$ with *distinguishable* particles and quantum efficiency $\eta$:

- **no beam splitter**
  - $V = 1$

- **with beam splitter**
  - $V = 1$
Longitudinal overlap

Vary delay in the 2nd Bragg pulse

Preliminary
Test of the Bragg pulses

Replace 50/50 beamplitter ($\pi/2$ pulse) by a mirror ($\pi$ pulse). We recover the sub-Poissonian variance.
What’s wrong?

Are we single mode?

- Transverse structure due to mean field repulsion of BEC
  - use lower densities?
  - other collisional effects
- Velocity spread of BEC
  - pairwise correlated modes: $|n,n\rangle |m,m\rangle$
- Imperfect phase matching
  - one mode correlated with several others: $|n_1,n_2,n_3,n_4\rangle$

Can the Bragg pulses be used as filters?
Questions

- Use lower density?
- Can Bragg beams be used as spatial or spectral filters?
- What can we say about multiparticle entanglement given our contrast?
- Fewer particles to approach a HOM or Bell’s inequality situation?

\[ \text{does not require different spins} \]
\[ \text{maybe we can do this} \]
Thanks
Laser trap and detector

position at detector gives initial velocity