Hanbury-Brown and Twiss bunching of phonons and of the quantum depletion in a strongly-interacting Bose gas

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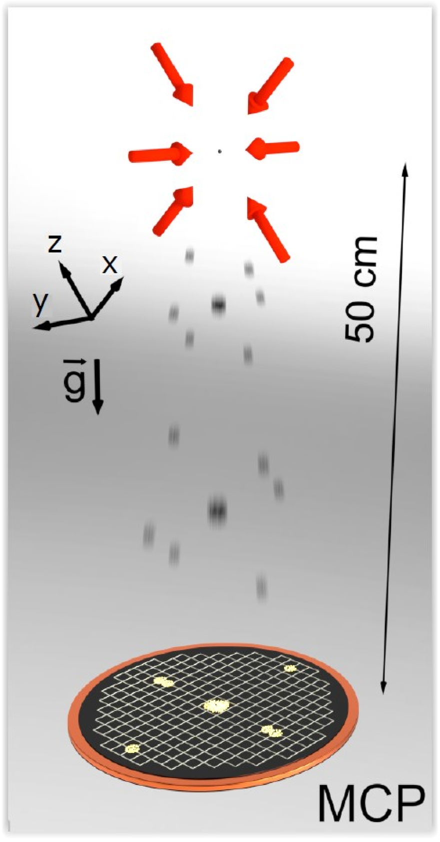
Measuring 3D (far-field) momentum distributions of individual atoms

Bose-Einstein condensates of metastable Helium atoms $^4He^*$

3D optical lattice (λ=1550 nm)

He^* detector (micro-channel plates and delay lines):

1. Reconstruction of **3D positions of individual atoms**
2. **Large dynamic range** in densities (no background)
3. **Excellent resolution**
4. **Saturation** at high flux

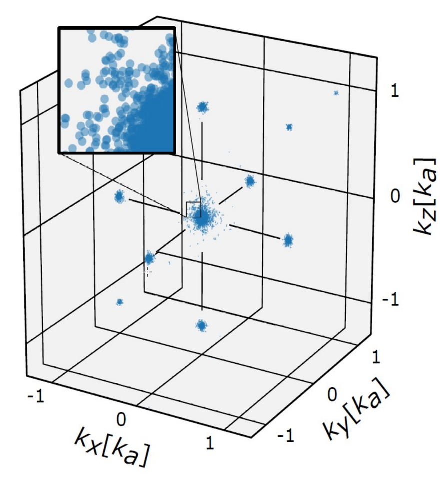


Single-atom-resolved 3D distribution in far-field

- Detection in far-field regime of expansion [1]:

$$t_{\mathrm{tof}} \simeq 300\ \mathrm{ms} > t_{\mathrm{FF}} = \frac{mL^2}{2\hbar} \simeq 60\ \mathrm{ms}$$

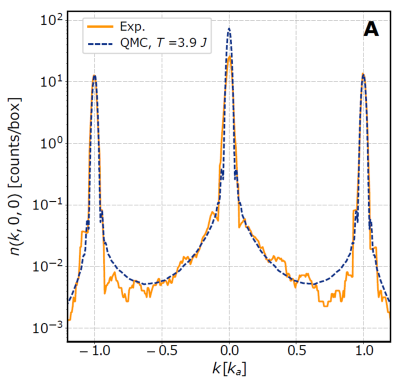
- Ballistic expansion:
  - mean-field effect negligible ($\hbar\omega_{\mathrm{site}} \gg \mu$)
  - two-body collisions negligible



A. Tenart et al., Phys. Rev. Research 2, 013017 (2020)

Benchmarking the experiment with ab-initio Quantum Monte-Carlo (QMC)

Excellent match between measured TOF densities and QMC calculations of the in-trap momentum distributions by G. Carleo (Flatiron Institute) [2,3]



H. Cayla et al., Phys. Rev. A 97, 061609(R) (2018)

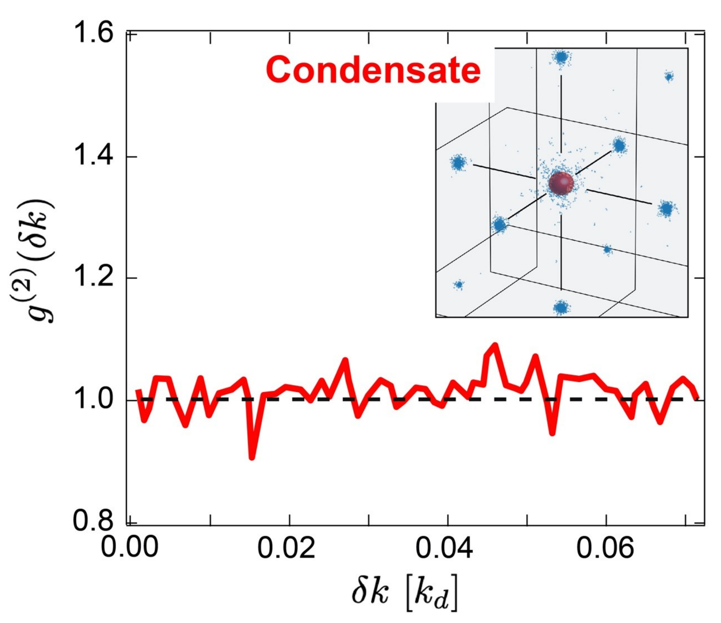
Second order correlation function in the depletion

Goal: Measure two-particles HBT like correlations with interacting particles.

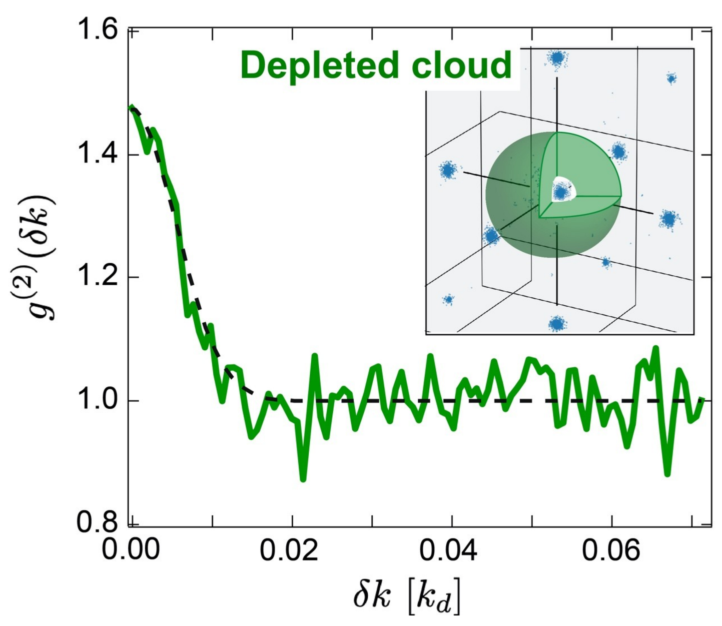
Measuring 3D atom distributions allows us to separate the contribution of the condensate from that of the depletion (thermal+quantum):

$$g^{(2)}_{\Omega_{\mathbf{k}}}(\delta\mathbf{k}) = \frac{\int_{\Omega_{\mathbf{k}}} \langle a^\dagger(\mathbf{k})a^\dagger(\mathbf{k}+\delta\mathbf{k})a(\mathbf{k})a(\mathbf{k}+\delta\mathbf{k})\rangle\, \mathrm{d}\mathbf{k}}{\int_{\Omega_{\mathbf{k}}} \langle n(\mathbf{k})\rangle \langle n(\mathbf{k}+\delta\mathbf{k})\rangle\, \mathrm{d}\mathbf{k}}$$

→ Volume over which we compute the correlation function



Coherent, no correlations



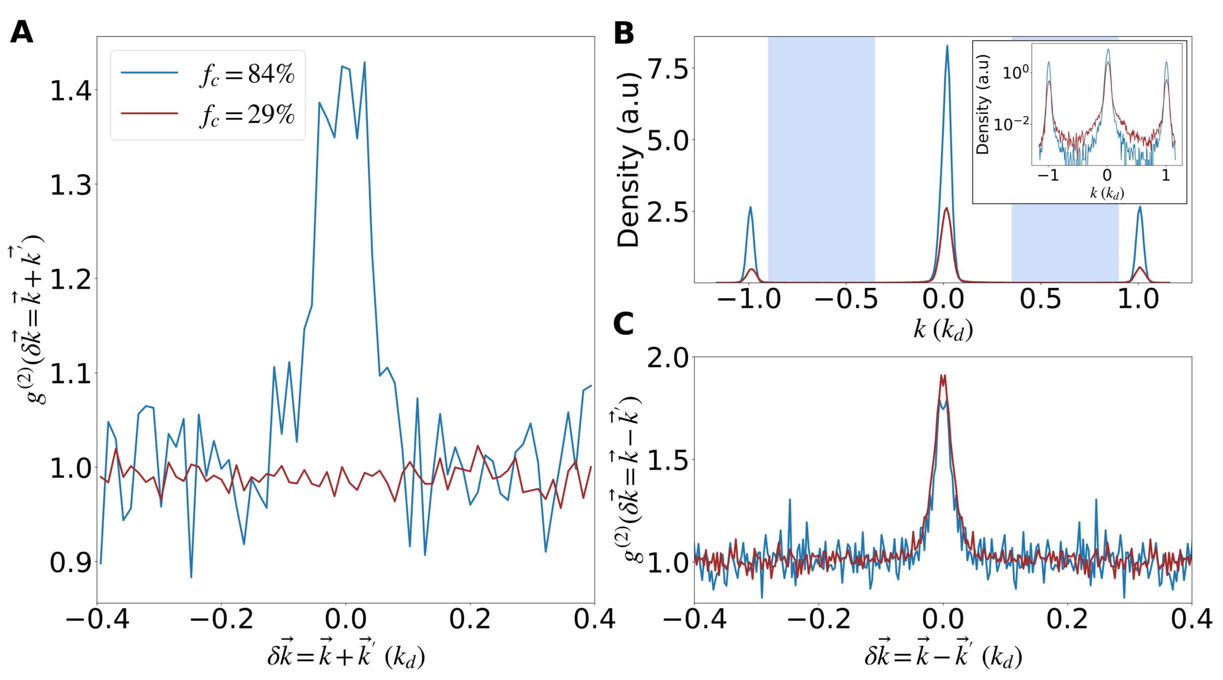
Chaotic statistics, bosonic bunching

Advantages of using a 3D optical lattice:

1. Ballistic expansion → no interaction induced expansion of the BEC → the BEC is not covering up the depleted atoms.
2. Access the strongly interacting regime: $\mu = n_0 U > k_B T$

New results: k/-k correlations in the quantum depletion

Quantum depletion = pairs of opposite momenta



k/-k peak!

→ Broader than local correlations

→ Signal lost when temperature increases since only quantum depletion show k/-k corelations

Amplitude and width of the correlation peak

Analysis of the amplitude

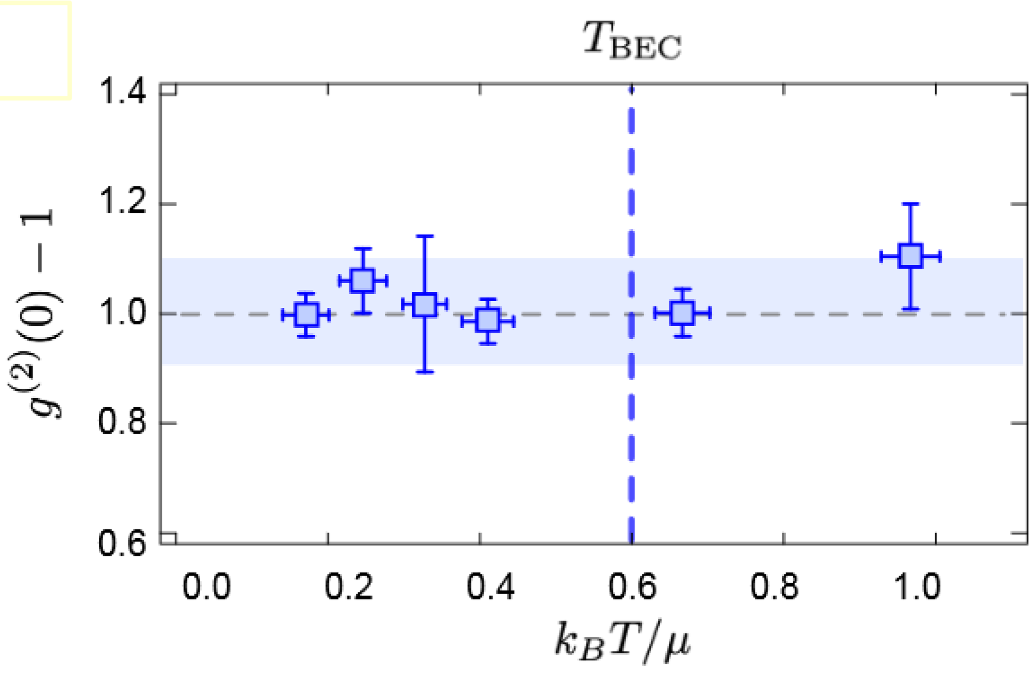
Bogoliubov transformation:
Interacting Bose gas = many-body ground state + non-interacting quasi-particles excitations of phononic nature at low k.

Non-interacting quasi-particles: Population set by temperature → Thermal Depletion → Same as the ideal Bose gas → Gaussian/Chaotic statistics → $g^{(2)}(0) = 2$

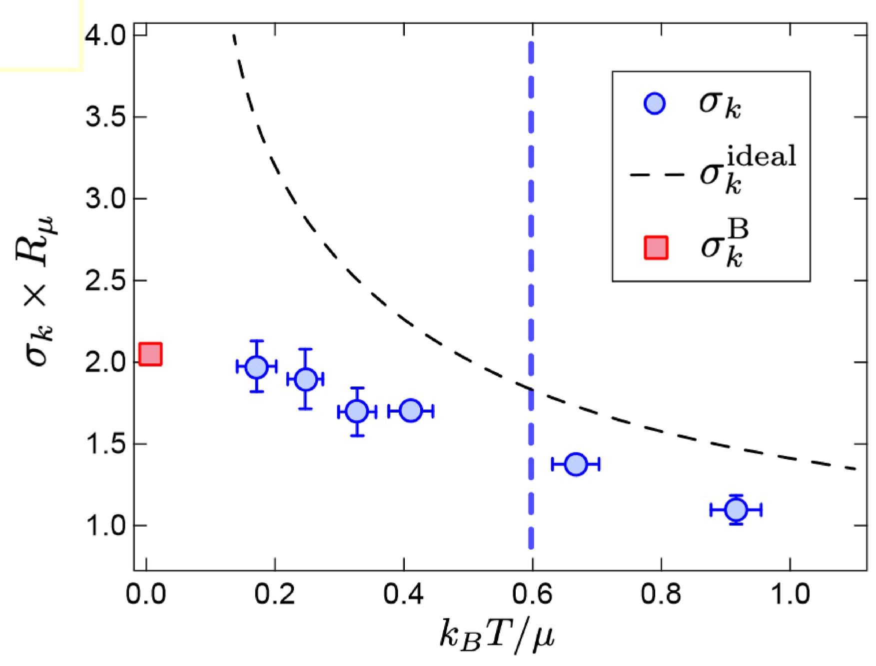
Many-body ground state : BEC + Quantum Depletion
→ Pair-correlated atoms with opposite momenta → Pure quantum state (analogy with two-mode squeezed vacuum) → No bunching?

IN FACT: we measure local correlations between atoms belonging to two different pairs.
→ The density matrix is obtained by tracing over the second partner which is ignored
→ Chaotic character → Bunching! → $g^{(2)}(0) = 2$

Both thermal and quantum depletion show perfect bosonic bunching → no effect of temperature on the amplitude.



Analysis of the width



T=0 → only quantum depletion whose spatial size is limited to the BEC
→ Peak width is the inverse of the BEC width

At low temperature, low-lying phononic excitations appear, spatial size is very close to the BEC size → Peak width close to T=0 width AND signficantly different from the ideal case.

When T increases, Bogoliubov excitations progressively extends out of the condensate
→ Spatial size increases → Peak width diminishes

In general, the correlation peak width is smaller than that of ideal bosons in the same trap at same temperature, as the in-trap size is broadened by interactions → Stronger difference at low temperature where interactions play a prominent role.

Work recently published, H. Cayla et al., *Phys. Rev. Letters*, 125(16), 165301.

Bibliography

1. F. Gerbier *et al. Phys. Rev. Lett.* 101, 155303 (2008).
2. Y. Kato *et al. Nature Physics* 4, 617 - 621 (2008) ; R. Ushnish & D.M. Ceperley, *Phys. Rev. A* 87, 051603 (2013).
3. S. Trotzky *et al. Nat Phys* 6, 998–1004 (2010).