Entanglement of quasiparticles in a modulated Bose-Einstein condensate

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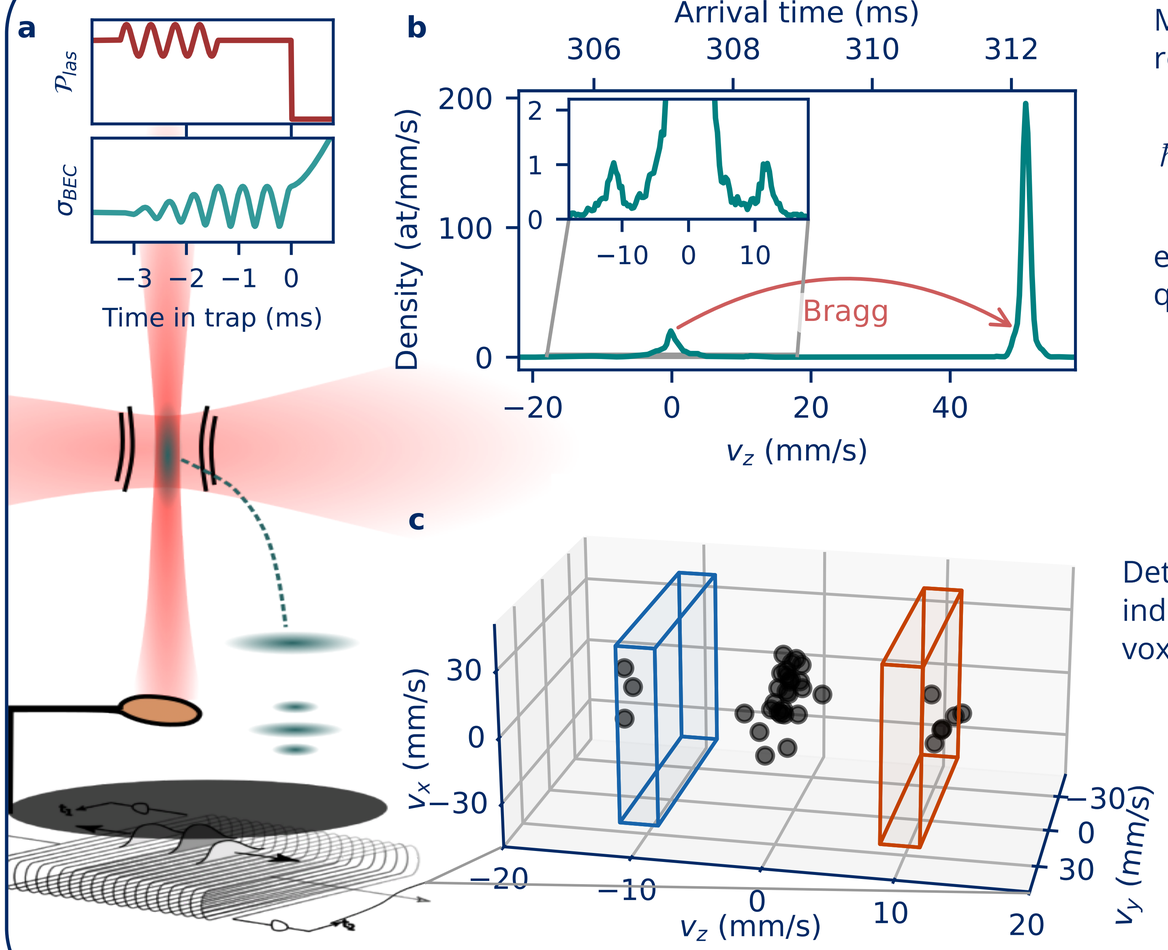
Parametric excitation of quasiparticles

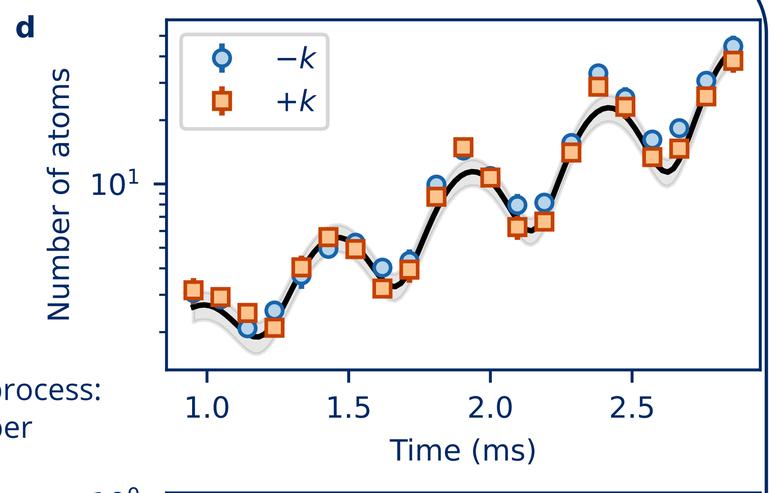


Modulate the dispersion relation at frequency Ω

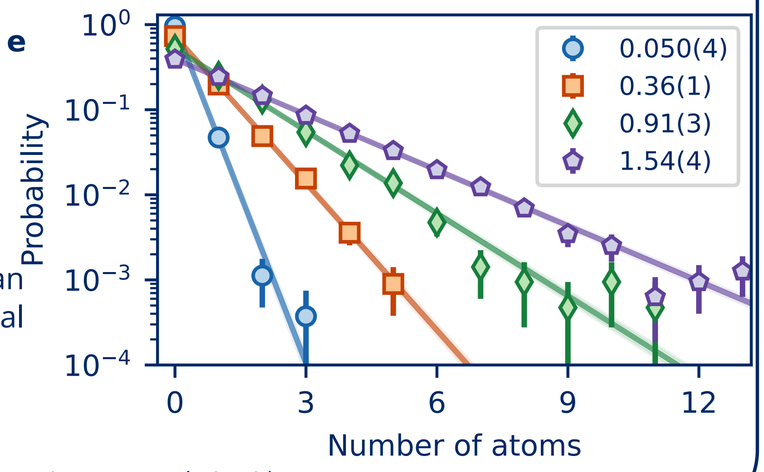
$$\hbar\omega_k = \sqrt{2g_1 n_1 \frac{\hbar^2 k^2}{2m} + \left(\frac{\hbar^2 k^2}{2m}\right)^2}$$

excites opposite momentum quasiparticles by pairs at $\omega_k = \Omega/2$.

Detect 3D velocity of individual atoms: define 3D voxel with a size of a mode.



Parametric excitation process: the quasiparticle number grows exponentially.



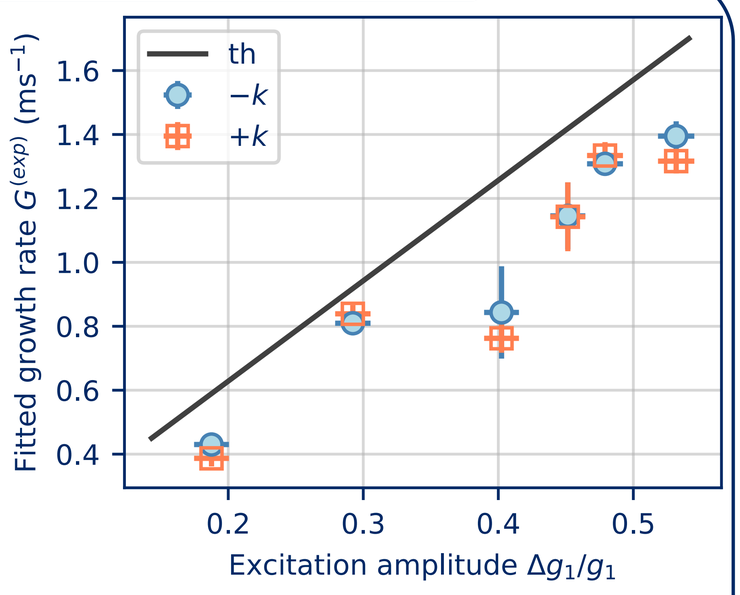
If a mode of a Gaussian state exhibits a thermal statistics, it is [1]:
- centered
- unsequeezed

[1] A. Avagyan, E. Knill, and S. Glancy, Multi-mode Gaussian state analysis with total-photon counting, J. Phys. B: At. Mol. Opt. Phys. 56, 145501 (2023).

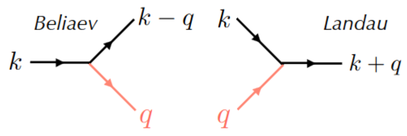
Studying the growth of quasiparticles

The amplitude of the breathing gives the amplitude of the excitation strenght Δg_1 which yields the theoretical Bogoliubov growth rate of the particle number [2].

The measured growth rate is smaller than the Bogoliubov theoretical one *because of the interaction between quasiparticles*. as recently predicted by Micheli & Robertson [3].



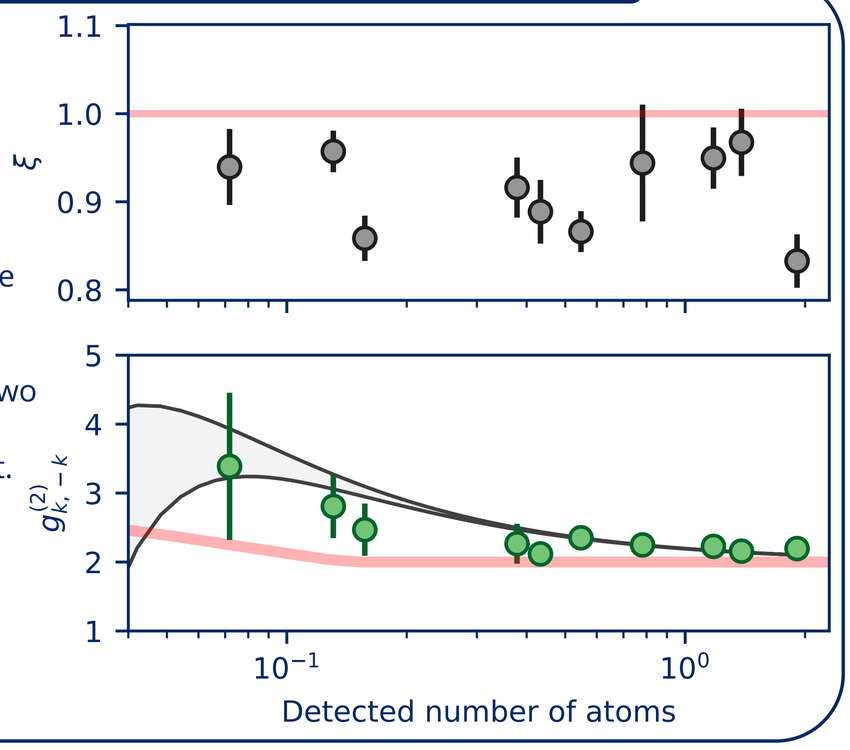
The reduction of the growth rate (a decay rate) can be computed from third order terms in the contact Hamiltonian. Our measurement are compatible with the prediction.



[2] X. Busch, R. Parentani, and S. Robertson, Quantum entanglement due to a modulated dynamical Casimir effect, Phys. Rev. A 89, 063606 (2014).
[3] A. Micheli and S. Robertson, Phonon decay in 1D atomic Bose quasicondensates via Beliaev-Landau damping, Phys. Rev. B 106, 214528 (2022).

Observing entanglement between quasiparticles

Varying the amplitude of the excitation process, we observe:
- relative number squeezing between the two modes,
- $g^{(2)}>2$ i.e. entanglement.



Outlooks

Higher order peaks appear: they are correlated with the primary peaks. Where do they come from ? See Denis's talk!

Linking entanglement and number correlation function

We only measure *number* correlation function while entanglement criterion are often based on *field* correlation functions.

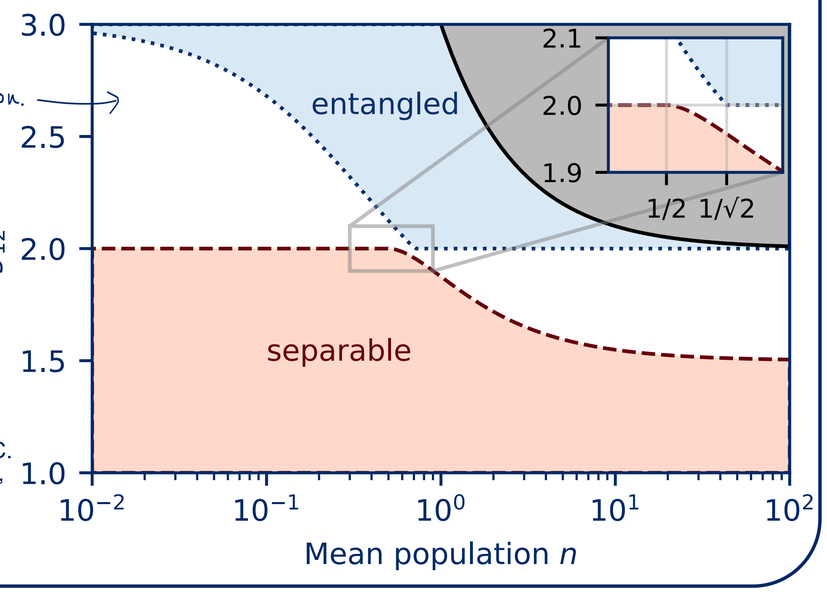
BUT when the state is Gaussian, they can be linked:

$$g^{(2)}_{12} := \frac{\langle \hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_1 \hat{a}_2 \rangle}{n_1 n_2} = 1 + \frac{|\langle \hat{a}_1 \hat{a}_2 \rangle|^2}{n_1 n_2} + \frac{|\langle \hat{a}_1 \hat{a}_2^\dagger \rangle|^2}{n_1 n_2}$$

Entanglement criterion — the two-mode entanglement of a gaussian state whose each mode exhibits a thermal statistics is quantified from the measurement of the populations and the two- and four-body correlation function [4].

We need $g^{(4)}$ to assess entanglement in this region.

Entanglement witness: only the measurement of the two-body correlation function yields an entanglement witness [4].

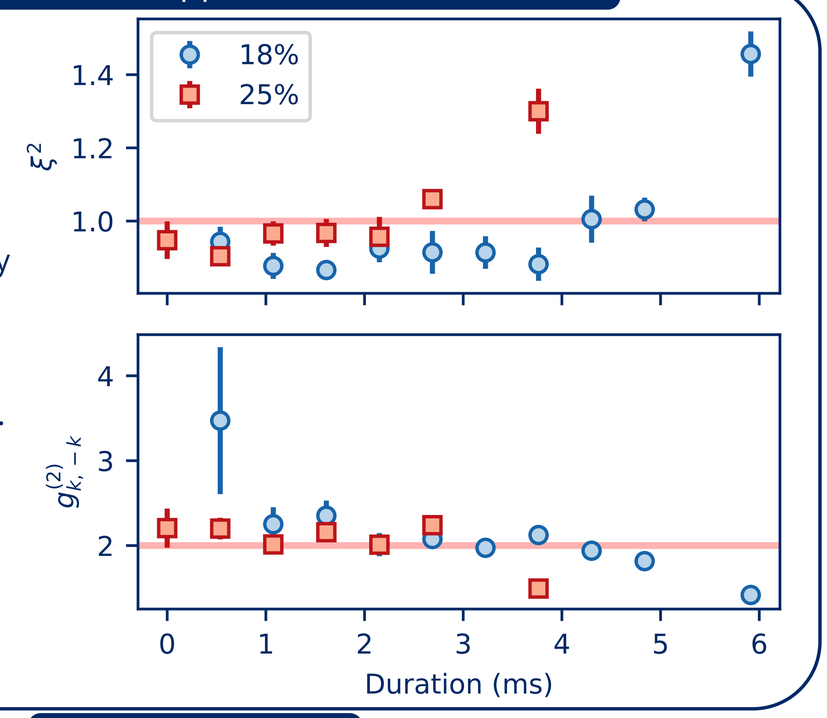


[4] V. Gondret, C. Lamirault, R. Dias, C. Leprince, C. I. Westbrook, D. Clément, and D. Boiron, Quantifying Two-Mode Entanglement of Bosonic Gaussian States from Their Full Counting Statistics, arXiv 2503.09555.

Appearance and disappearance of correlation

Keeping the amplitude of excitation constant, we vary its duration.

The correlation decreases... but are the mode disantangled? The state might not be Gaussian anymore (TBC).



Fundings