Quantum atom optics with metastable helium

Atom interferometry and correlated phonon pairs generation

Quentin Marolleau

17 August 2026

Coherence and Quantum Technology group
Eindhoven University of Technology

Introduction

Atom pair generation and interferometry

Correlated phonon generation

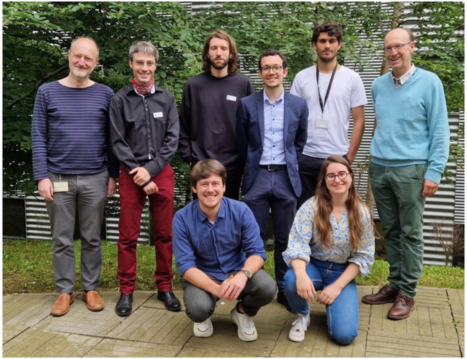
Conclusion and outlook

Quantum gases at Laboratoire Charles Fabry

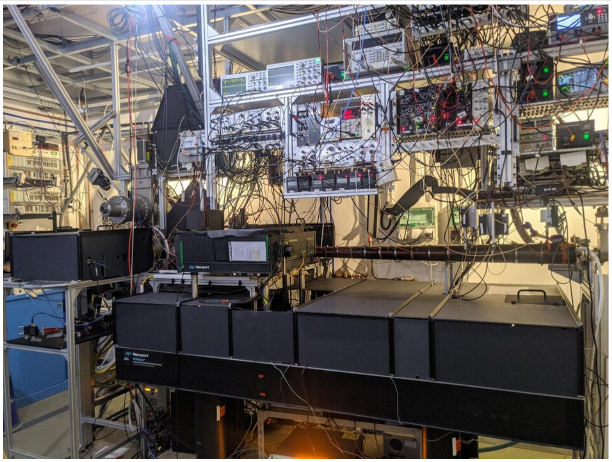
8 permanent researchers

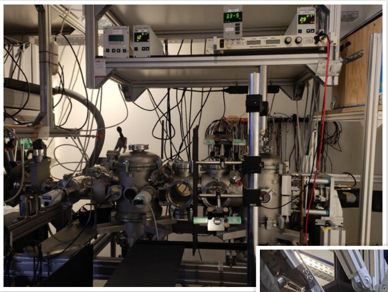
6 experiments, from 1D to 3D

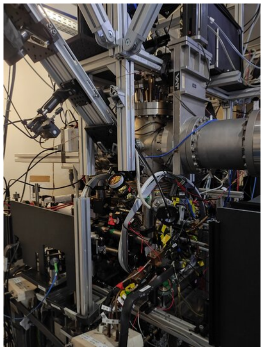
37	38	19	2
Rb	Sr	K	He
Rubidium	Strontium	Potassium	Helium
84.468	87.62	39.098	4.003



The ^{4}He*1 team: 2 PIs and ~ 5 PhD / PD.







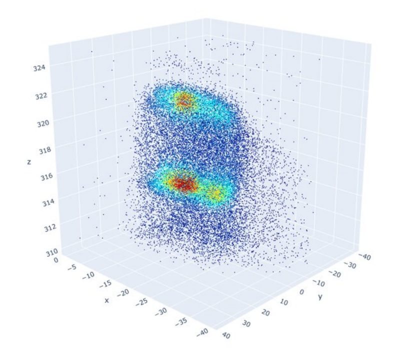
The metastable helium machine “^{4}He*1”

Laboratoire Charles Fabry, Institut d’Optique.

Introduction

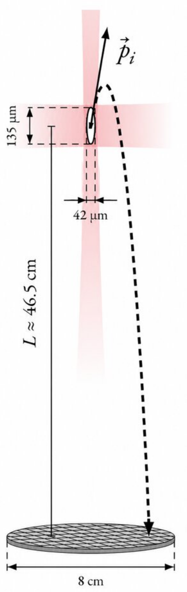
Notable features

- No hyperfine structure (no nuclear spin)
- 💔 Small saturation intensity 0.165 mW/cm²
- 💖 High energy (20 eV) and long-lived (2h) first excited state

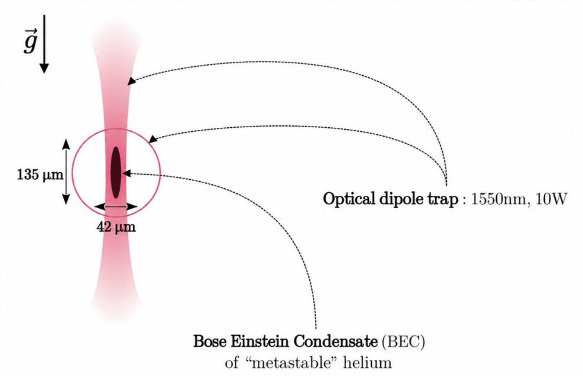


MCP detector

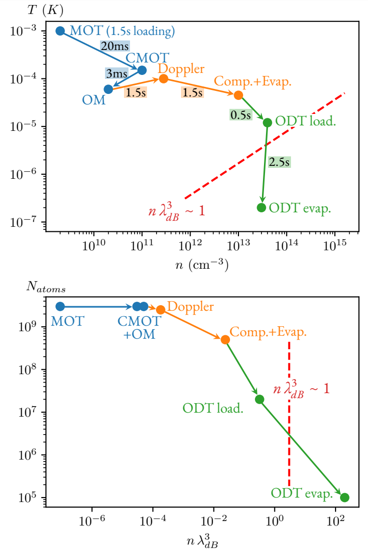
- Single atom resolved
- 3D in momentum space
- ~25% quantum efficiency



BEC preparation



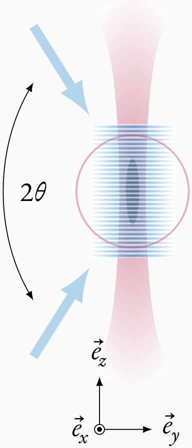
Duty cycle	~ 10 s
Number of atoms	~ 10^5

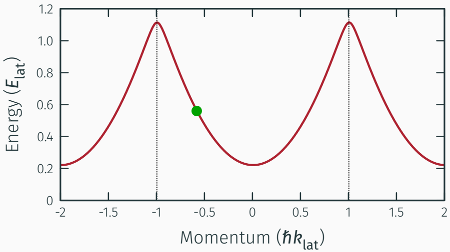


Atom pair generation and interferometry

Pair creation lattice

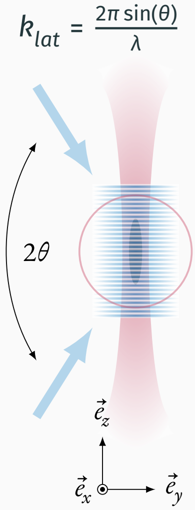
$$k_{lat} = \frac{2\pi \sin(\theta)}{\lambda}$$

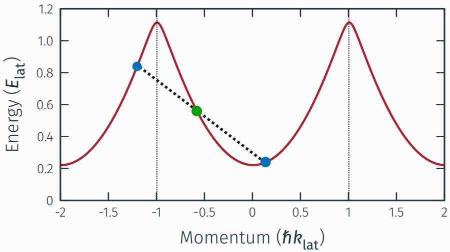




In the lattice frame of reference

Pair creation lattice





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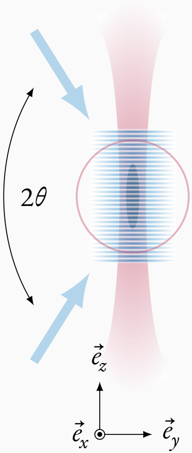

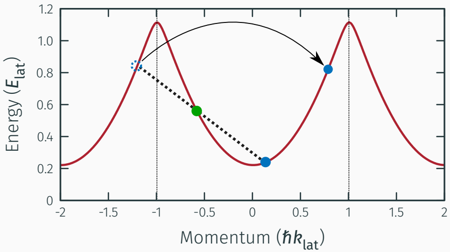

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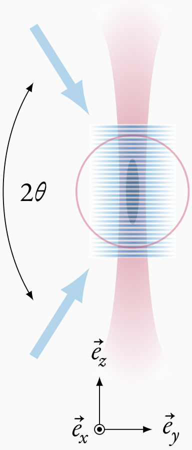
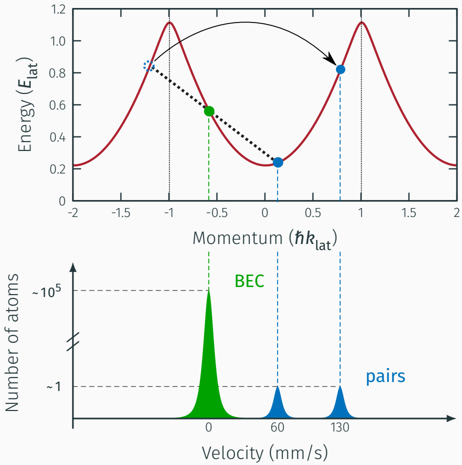
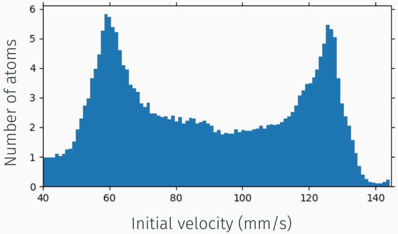




In the lattice frame of reference

In the lab's frame of reference

Second-order correlations of particle numbers



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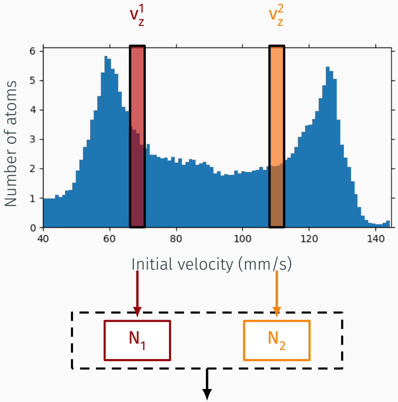
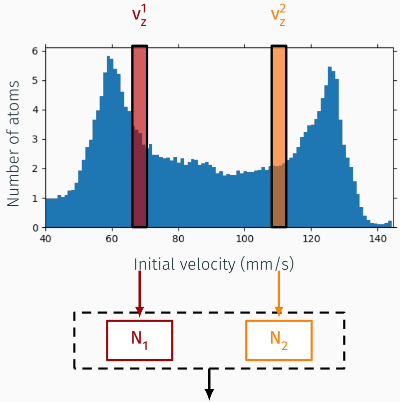


$$g^{(2)}(v_z^1, v_z^2) = \frac{\langle : N_1 N_2 : \rangle}{\langle N_1 \rangle \langle N_2 \rangle}$$



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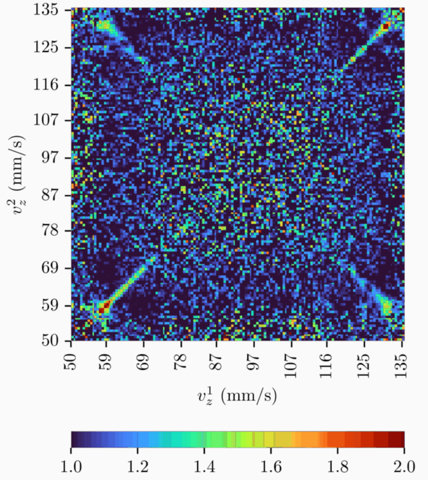
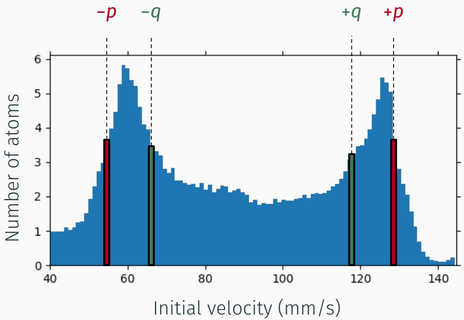


Model for the generated state

Two-mode squeezed vacuum state

$$|TMS\rangle_p = \sqrt{1 - |\alpha|^2} \sum_n \alpha^n |n\rangle_p |n\rangle_{-p}$$



Generated state

$$|\Psi\rangle = |TMS\rangle_p \otimes |TMS\rangle_q \otimes \cdots$$

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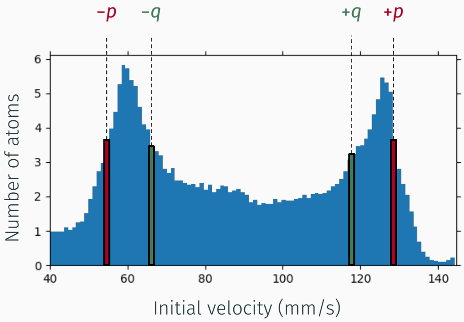

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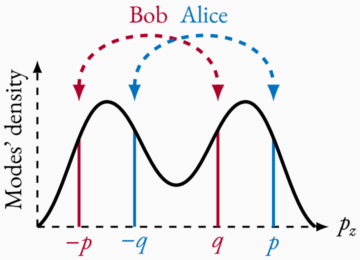
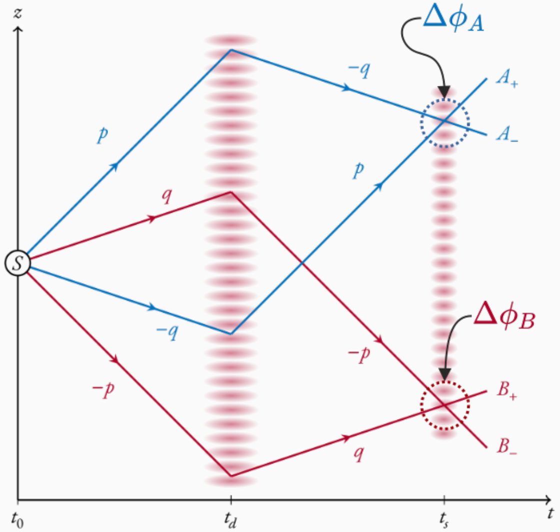


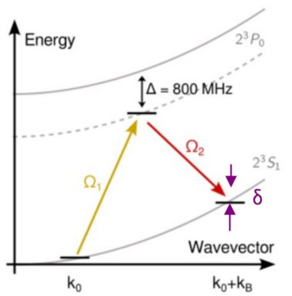
Towards a Bell test: Rarity–Tapster topology

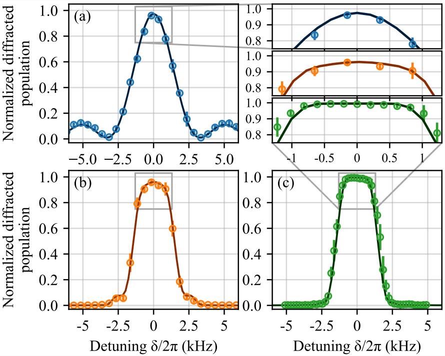


Requirements

- Mirrors and beamsplitter
- Selectivity and phase control
- Defining a correlator

Two-photon Bragg transitions: $\Omega_{2ph} = \frac{\Omega_1 \Omega_2^*}{2\Delta}$





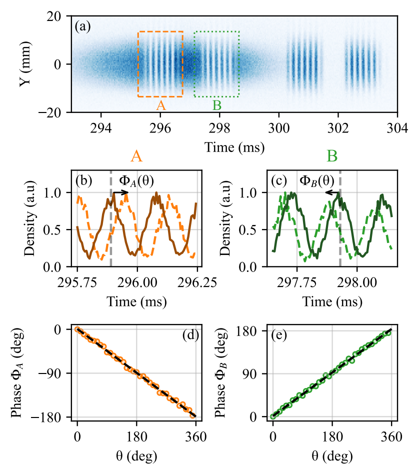
1

C. Leprince et al. **"Coherent coupling of momentum states: Selectivity and phase control".** In: *Phys. Rev. A* 111 (6 June 2025), p. 063304. DOI: `10.1103/PhysRevA.111.063304`

Bragg phase control verification

$$\Omega_{2ph}(t) = \Omega_M \,\mathrm{sinc}\left[\Omega_S (t - T/2)\right] \cos\left[\left(\Omega_D t + \theta\right)/2\right]$$

- Ω_M: controls the pulse duration ($T \sim 1.5$ ms)
- $\hbar\Omega_M < \hbar k^2/m$ (two-photon recoil) to cancel higher-order diffraction.
- $\Omega_S = \Omega_M$ for a mirror. $\Omega_S = 2\Omega_M$ for a beamsplitter.
- Ω_D controls the separation between the two selected doublets. θ controls the relative phase applied to it.



Correlated phonon generation

A minute of theory

$$\hat{H} = \sum_k \frac{\hbar^2 k^2}{2m} \hat{a}^\dagger_k \hat{a}_k + \frac{gn}{2} \sum_{k_1,k_2,q} \hat{a}^\dagger_{k_1+q} \hat{a}^\dagger_{k_2-q} \hat{a}_{k_1} \hat{a}_{k_2}$$

Bogoliubov theory

- Classical treatment of the BEC (coherent state) & quantized treatment of the excitations ⇒ effective quadratic Hamiltonian $\hat{H}_{eff}$.
- Introduction of the quasiparticles $\hat{b}_k$ diagonalizing $\hat{H}_{eff}$.
- $\hat{a}_k = u_k \hat{b}_k + v_k \hat{b}^\dagger_{-k}$
- $\omega_k = \sqrt{\frac{gn}{m} k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$ (dispersion relation)
- $\partial_t \hat{b}_k = -i\omega_k \hat{b}_k + \frac{\dot{\omega}_k}{2\omega_k} \hat{b}^\dagger_{-k}$ (dynamic evolution driven by ω_k)

Theoretical cheatsheet

If **non-zero temperature**, both **thermal** and **vacuum** fluctuations are amplified

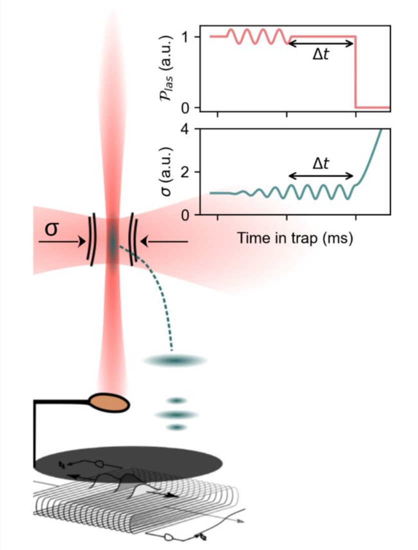
Amplification of **vacuum fluctuation** is witnessed by **two-mode entanglement**.

Large temperature prevent the appearance of entanglement.

Beyond Bogoliubov numerics: quasiparticle interactions further destroy entanglement.

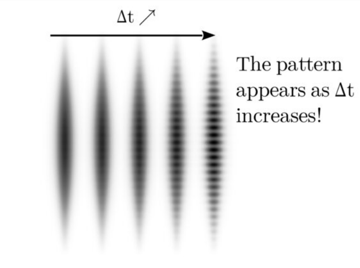
Busch *et al.* Phys. Rev. A **89** (2014),
Robertson *et al.*, Phys. Rev. D **95**, 065020 (2017),
Robertson *et al.*, Phys. Rev. D **98**, 056003 (2018).
Micheli & Robertson.Comptes Rendus. Phys., (2024),

What do we do in practice?

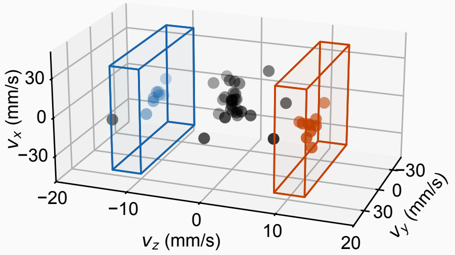


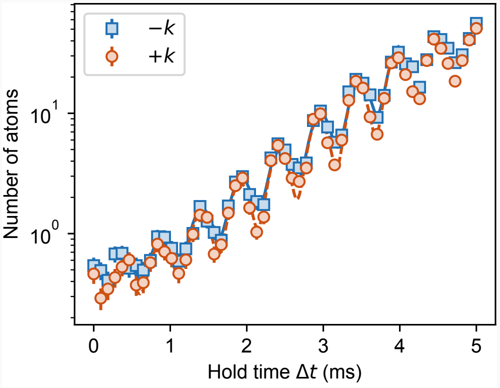
Method:

1. Excitation of the transverse breathing mode at $\Omega = 2\omega_\perp = 2\omega_k$
2. Let the BEC breathe for $\boldsymbol{\Delta t}$: exponential growth of collective excitations
3. Adiabatic release of the trap $\Rightarrow$ *phonon evaporation* (i.e. *quasi*particles are remapped onto individual atoms in free space)



Collective excitation growth





$$n_k(\Delta t) = n_0 + \Delta n e^{G_k \Delta t} \times \left[1 + A_k \cos(2\omega_k \Delta t + \phi_k)\right]$$

2

V. Gondret et al. **"Parametric pair production of collective excitations in a Bose–Einstein condensate".** In: *Comptes Rendus Physique* (Dec. 2025)

Is it entangled?

Entanglement definition

A two-mode state is entangled iff it cannot be written as:

$$\hat{\rho} = \sum_i \rho_{i,k} \otimes \rho_{i,-k}$$

Werner, *Phys. Rev. A* **40**, 4277–4281 (1989)

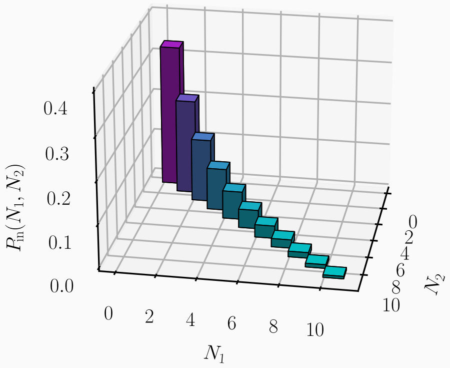
The full counting statistics is in general not enough for proving entanglement.

e.g.:

$$\hat{\rho}_{TMS} \propto \sum_{i,j} \kappa^{i+j} |i\rangle\langle i|_k \otimes |j\rangle\langle j|_{-k}$$

$$\hat{\rho}_{sep} \propto \sum_i \kappa^i |i\rangle\langle i|_k \otimes |i\rangle\langle i|_{-k}$$

have the same counting statistics...



Is it entangled?

$$g^{(2)}_{k,-k} = \frac{\langle \hat{a}^\dagger_k \hat{a}^\dagger_{-k} \hat{a}_k \hat{a}_{-k} \rangle}{n_k n_{-k}}$$

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For zero-mean ($\langle \hat{a}_k \rangle = 0$) Gaussian states:

$$g^{(2)}_{k,-k} = 1 + \underbrace{\frac{\left|\langle \hat{a}_k \hat{a}_{-k} \rangle\right|^2}{n_k n_{-k}}}_{>1 \,\Rightarrow\, \text{entangled}} + \frac{\left|\langle \hat{a}_k \hat{a}^\dagger_{-k} \rangle\right|^2}{n_k n_{-k}}$$

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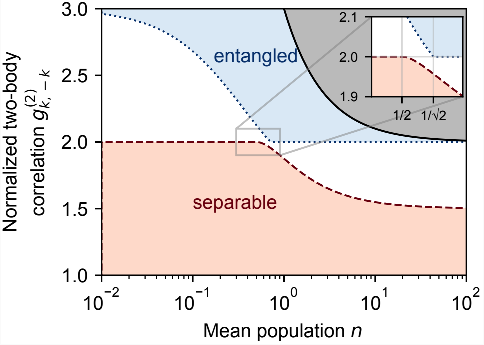
If $\langle \hat{a}_k \rangle = \langle \hat{a}_k^2 \rangle = 0$, then we also have:

$$\frac{|\langle \hat{a}_k \hat{a}^\dagger_{-k} \rangle|^2}{n_k n_{-k}} < f(n_k, n_{-k})$$



Gondret et al., *Phys. Rev. Lett.* **135**, 100201 (2025)

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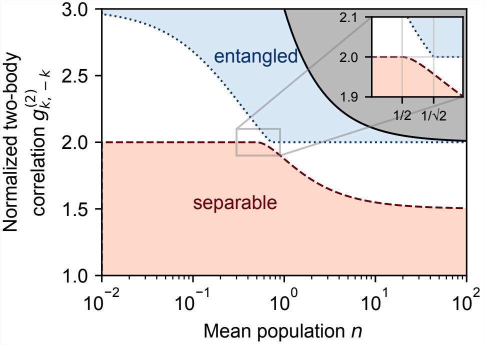
$$\underbrace{\text{Gaussian + thermal statistics}}_{\text{expected for TMS}} \Rightarrow \langle \hat{a}_k \rangle = \langle \hat{a}_k^2 \rangle = 0$$



Gondret et al., *Phys. Rev. Lett.* **135**, 100201 (2025)

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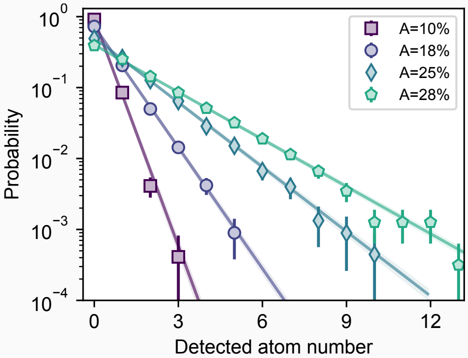
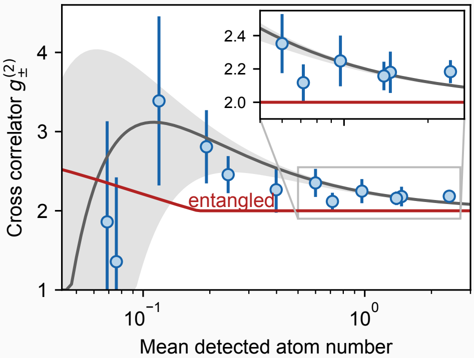




3

V. Gondret et al. **“Observation of Entanglement in a Cold Atom Analog of Cosmological Preheating”.** In: *Phys. Rev. Lett.* 135 (24 Dec. 2025), p. 240603. DOI: 10.1103/h7ws-g9z2

Conclusion and outlook

What have we achieved & where this goes next

What we have done

- Two different processes of parametric amplification shown
- The use of an optical lattice enables the generation of quasiparticles at large momenta
- The modulation of ***gn*** stimulates the creation of excitations closer to the phononic regime
- Quantum correlations can be probed in both cases

Future investigations

- Complete the Bell interferometer experiment. (Similar experiment achieved by Truscott et al., Canberra, Australia)[4]
- Thermalization in the interaction-dominated regime & backreaction from the produced quasiparticles shall be studied.

Athreya et al., *"Bell correlations between momentum-entangled pairs of ^{4}He* atoms"*, Nat. Commun. **17** (2026).

Thank you

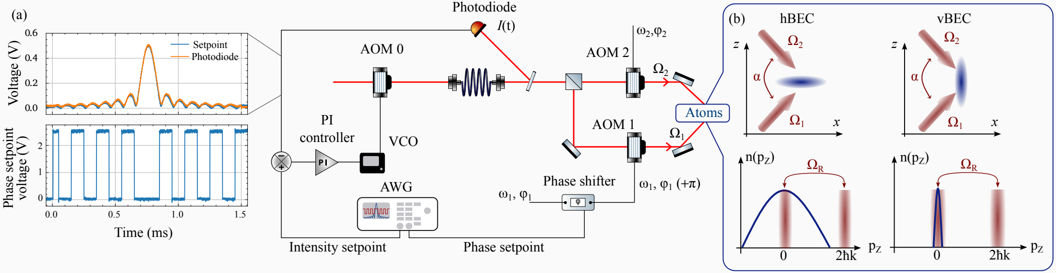
labmon — a side project of mine

Whatever you'd like to monitor in your lab — temperature, chamber pressure, laser power — recorded into a time-series database and put on a live dashboard, with calibrations and physical units checked on the way in.

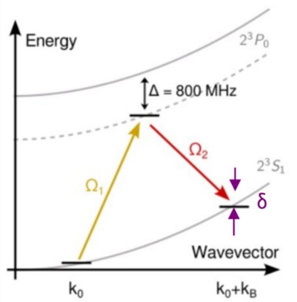
`github.com/quentinmarolleau/labmon`

Backup

Bragg setup



(a)
Photodiode
I(t)
AOM 0
AOM 2
AOM 1
ω_2, φ_2
Ω_2
Ω_1
Atoms
PI controller
VCO
AWG
Phase shifter
ω_1, φ_1
$\omega_1, \varphi_1\ (+\pi)$
Intensity setpoint
Phase setpoint
Setpoint
Photodiode
Voltage (V)
Phase setpoint voltage (V)
Time (ms)
(b)
hBEC
vBEC
$n(p_Z)$
Ω_R
p_Z
0
$2\hbar k$



Energy
2^3P_0
Δ = 800 MHz
Ω_2
Ω_1
2^3S_1
δ
Wavevector
k_0
k_0+k_B

Bragg phase control verification

$$\Omega_{2ph}(t) = \Omega_M \,\mathrm{sinc}\left[\Omega_S\,(t - T/2)\right] \cos\left[\left(\Omega_D t + \theta\right)/2\right]$$

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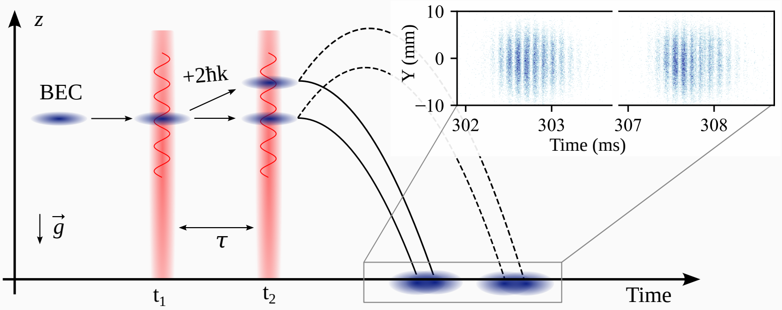
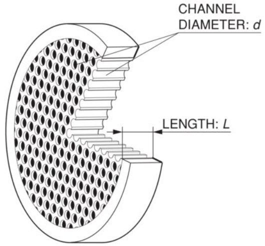
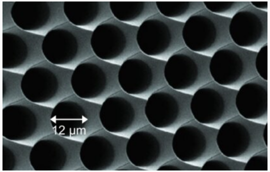
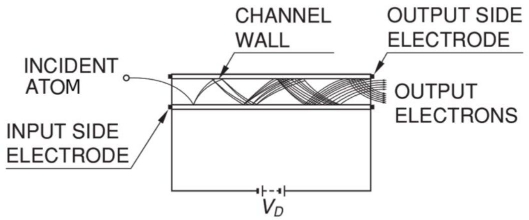


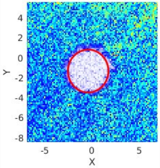
MCP

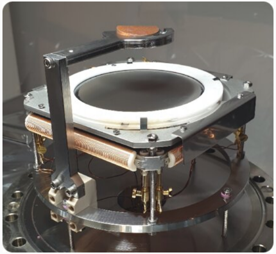

CHANNEL
DIAMETER: d
LENGTH: L

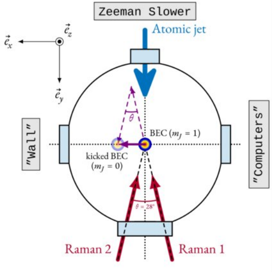

12 µm


CHANNEL
WALL
OUTPUT SIDE
ELECTRODE
INCIDENT
ATOM
OUTPUT
ELECTRONS
INPUT SIDE
ELECTRODE
V_D

MCP hole and Raman transfer push







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