Decoherence in analogue preheating experiment

Journées de la Matière Condensée 2021
Minicolloque 10 : Gravité Analogue

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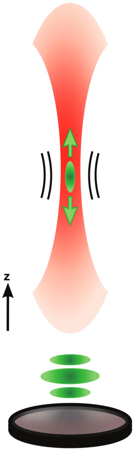
INTRODUCTION

OVERVIEW : GOAL AND LIMITATIONS



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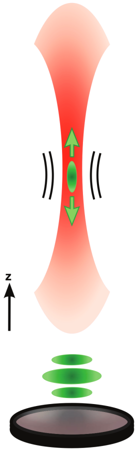

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→ Modulation of trapping size : **parametric creation of pairs of quasiparticles** of opposite momenta k_{res} and $-k_{\mathrm{res}}$ **out of the vacuum**.
Analogue of preheating !

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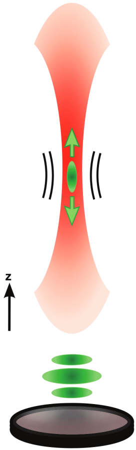

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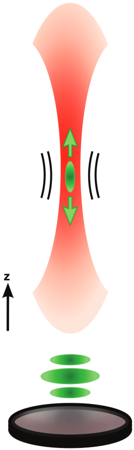

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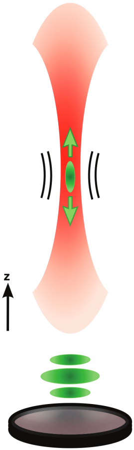

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→ *Experimental Goal :* Demonstrate creation out of the vacuum.

→ *Limitation :* Interactions between quasiparticles foster decoherence and might prevent observation.

MODEL FOR THE EXPERIMENT

→ Effectively 1D Bose gas modeled by :

$$\hat{H} = \int_{-\infty}^{+\infty} \left[\frac{\hbar^2}{2m} \frac{\partial \hat{\Psi}^\dagger}{\partial x} \frac{\partial \hat{\Psi}}{\partial x} + \frac{g_1(t)}{2} \hat{\Psi}^{\dagger\,2} \hat{\Psi}^2 \right] \mathrm{d}x \,,$$

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→ Quasicondensate approximation :

$$\hat{\Psi} = \sqrt{\bar{\rho} + \delta\hat{\rho}}\, e^{i\theta_0 + i\delta\hat{\theta}} \,,$$

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$$= \underbrace{H^{(0)} \left(\bar{\rho}, \theta_0; t\right)}_{\text{Background}} + \underbrace{\hat{H}^{(2)} \left(\delta\hat{\rho}, \delta\hat{\theta}; \bar{\rho}, \theta_0, t\right)}_{\text{Perturbations}} + \ldots \,.$$

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→ Diagonalizing $\hat{H}^{(2)}$ defines quasiparticles (phonons) c. and a. operators $\hat{b}_k$ / $\hat{b}_k^\dagger$:

$$\delta\hat{\rho}_k = \left(u_k + v_k\right)\left(\hat{b}_k + \hat{b}^\dagger_{-k}\right) ,$$

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→ Phonons evolve on a background controlled by $g_1(t)$. **Trap modulation** $\approx$ oscillating $g_1(t) \rightarrow$ **parametric amplification.**

PREVIOUS ANALYSIS AND EXPERIMENT

QUANTITIES OF INTEREST

→ $n_{\pm k} \equiv \left\langle \hat{b}^{\dagger}_{\pm k} \hat{b}_{\pm k} \right\rangle$ and $c_k \equiv \left\langle \hat{b}_k \hat{b}_{-k} \right\rangle$ number and correlation of phonons in the modes $\pm k$.

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- Normalized two-body correlation :

$$g^{(2)}_{(k,-k)} = \frac{\left\langle \hat{b}^{\dagger}_{k} \hat{b}^{\dagger}_{-k} \hat{b}_{k} \hat{b}_{-k} \right\rangle}{n_k n_{-k}}, \\ = 1 + \frac{\left|c_k\right|^2}{n_k^2},$$

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→ **How to demonstrate quantum origin of the phonons created during modulation using these quantities ?**

QUANTUMNESS CRITERION : NON-SEPARABILITY

→ A **bipartite state** $\hat{\rho}_{\pm k}$ of the phononic modes $\pm k$ is said to be **separable if** :

$$\hat{\rho}_{\pm k} = \Sigma_i \underbrace{p_i}_{p_i \geq 0\,,\,\Sigma_i p_i = 1} \overbrace{\hat{\rho}_k^i}^{\text{State of mode } k} \bigotimes \overbrace{\hat{\rho}_{-k}^i}^{\text{State of mode } -k} .$$

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→ **Goal :** Demonstrate non-separability of the bipartite state of the resonant phonon pairs $\hat{\rho}_{\pm k_{\mathrm{res}}}$.

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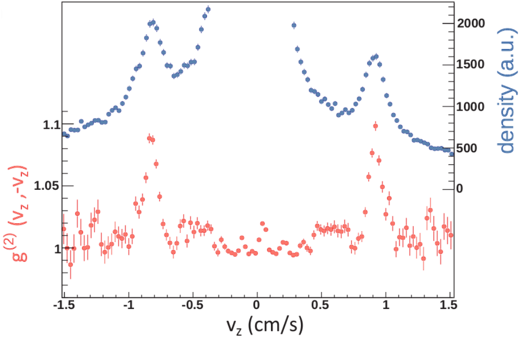
→ NB : Only creation out of the vacuum can explain such correlations [1].

1. [Busch et al., 2014]

2012'S RESULTS ANALYSIS

→ Experiment was performed by Chris Westbrook's team in Orsay [2].



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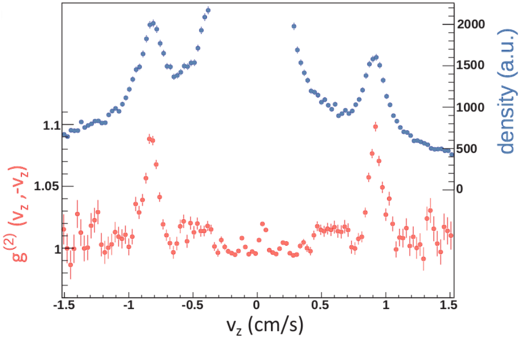

Did not witness non-separability !

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2012'S RESULTS ANALYSIS

- → Experiment was performed by Chris Westbrook's team in Orsay[2].
- → Posterior works[3] identified interactions, decay of n_k and c_k, as possible cause.
- → *Current work :* Analyze **intrinsic non-linearities** of the system to estimate **decay of phonon number n_k and of coherence c_k**.

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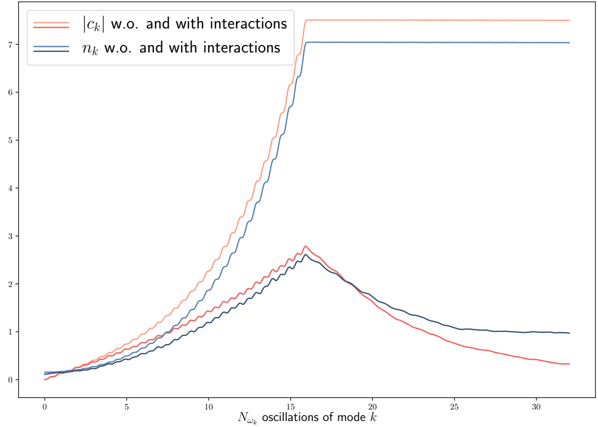
NON-LINEARITIES OF THE SYSTEM : NEW RESULTS

NUMERICAL OBSERVATION OF THE DECAY

→ **Simulations** of the **non-linear system** using the Truncated Wigner Approximations (TWA) allow to monitor directly n_k and c_k :



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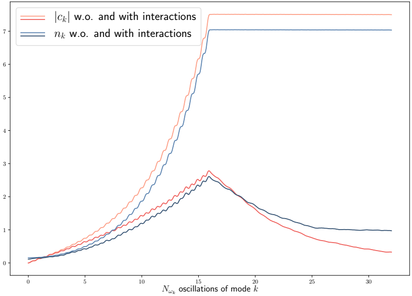


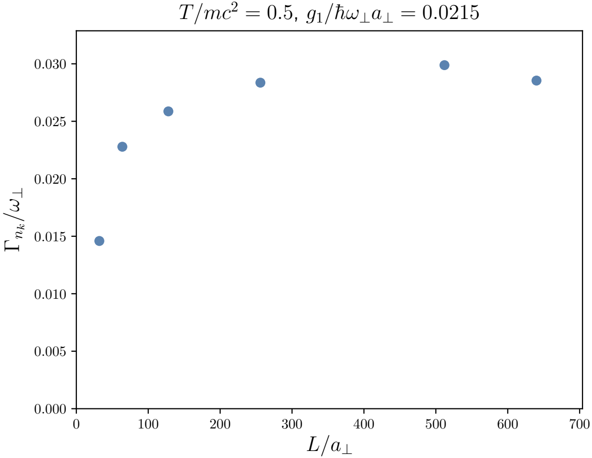
→ Observation of **loss of non-separability** in agreement with [4].

4. [Pylak and Zin, 2018]

STUDY OF Γ_{n_k}

- → Until now we have been focusing on n_k. Extracted decay rate Γ_{n_k} of for various values of : L **size of the system**, T the **temperature** and g_1 **effective interaction constant**.

STUDY OF Γ_{n_k}



Γ_{n_k} does not depend on L for L large enough.

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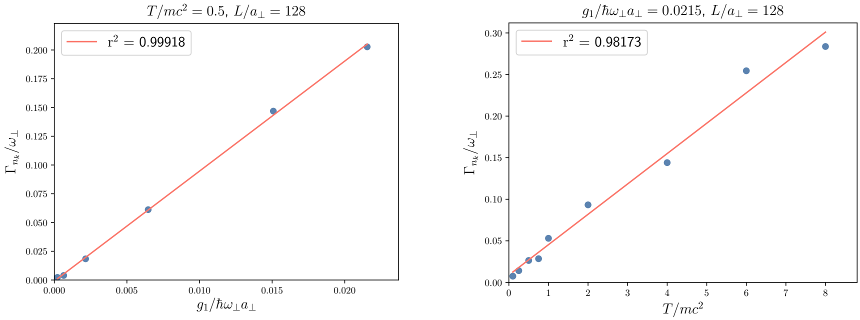

$$\Gamma_{n_k} \propto g_1 T\,.$$

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→ **(To be done)** Finally, tune the experimental parameters in order to optimize the visibility of non-separability in a future experiment.

Thank you for your attention !

Busch, X., Parentani, R., and Robertson, S. (2014).
Quantum entanglement due to a modulated dynamical casimir effect.
Phys. Rev. A, 89:063606.

Jaskula, J.-C., Partridge, G. B., Bonneau, M., Lopes, R., Ruaudel, J., Boiron, D., and Westbrook, C. I. (2012).
Acoustic analog to the dynamical casimir effect in a bose-einstein condensate.
Phys. Rev. Lett., 109:220401.

Pylak, M. and Zin, P. (2018).
Influence of the interaction between quasiparticles on parametric resonance in bose-einstein quasicondensates.
Phys. Rev. A, 98:043603.

Robertson, S., Michel, F., and Parentani, R. (2017a).
Assessing degrees of entanglement of phonon states in atomic bose gases through the measurement of commuting observables.
Physical Review D, 96(4).

Robertson, S., Michel, F., and Parentani, R. (2017b).
Controlling and observing nonseparability of phonons created in time-dependent 1d atomic bose condensates.
Physical Review D, 95(6).

Robertson, S., Michel, F., and Parentani, R. (2018).
Nonlinearities induced by parametric resonance in effectively 1d atomic bose condensates.
Phys. Rev. D, 98:056003.

QUANTITIES OF INTEREST

→ Normalized density-density correlation :

$$G^{(2)}_{k,-k} \equiv \frac{\langle \delta\hat{\rho}_k \delta\hat{\rho}_{-k} \rangle}{\bar{\rho}} = (u_k + v_k)^2 \left[1 + 2n_k + 2\mathrm{Re}\,(c_k)\right] \, .$$

→ A **sufficient criterion** for the state to be **non-separable** is simply $n_k < |c_k|$...

→ which is experimentally testable via :

$$G^{(2)}_{k,-k} - G^{(2)\,\mathrm{vac}}_{k,-k} = 2\,(u_k + v_k)^2 \left[n_k - \mathrm{Re}\,(c_k)\right] < 0 \, .$$

→ ***In-situ*** criterion vs. after expansion for $g^{(2)}$

SIMULATED $G_K^{(2)}$