Dynamical Casimir emission from a polariton condensate

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Introduction

We study pair creation through the dynamical Casimir effect in a realisation of the weakly interacting Bose gas: an exciton-polariton quantum fluid.

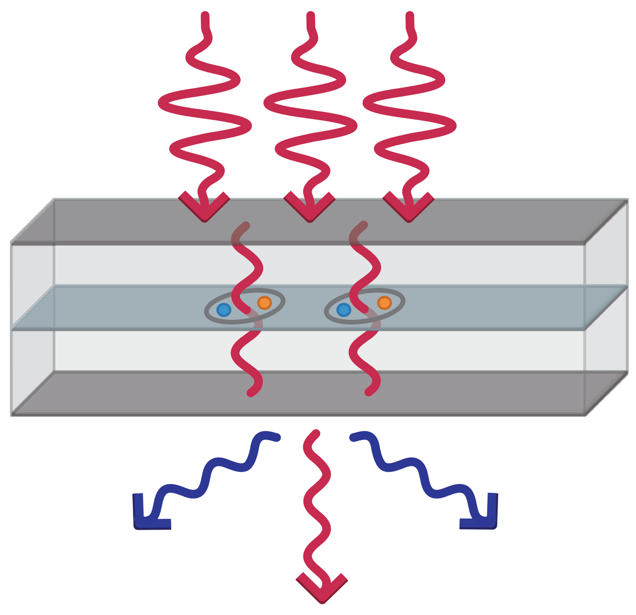
The dynamical Casimir effect describes the creation of particle pairs out of quantum fluctuations by changing the boundary conditions. It is an immediate implication of the rich ground-state structure of interacting systems.

Here, we study this effect in an exciton-polariton condensate. These quasiparticles are superpositions of two components:

- an exciton, i.e. a bound electron-hole pair. The Coulomb interactions between the electrons and holes govern the interactions between polaritons.
- a cavity photon. The photonic component of the polariton is directly related to the laser that pumps the system, which offers great flexibility in their creation.

The system

Photons inside the microcavity are dressed with matter excitations, thus forming exciton-polaritons.



1) Creation of the intial exciton-polariton condensate by a resonant laser pulse at normal incidence.

2) The evolution of the system is governed by interactions between the exciton-polaritons and losses due to imperfect mirrors.

3) The losses allow for experimental observation of the momentum distribution and the spatial coherence.

Calculations

From the Hamiltonian ...

Hamiltonian for the quantum fields

↓ Born approximation

Master equation for the reduced density matrix

↓ Truncated Wigner formulation

Gross-Piteavskii equation for the stochastic fields

↓ Bogoliubov approximation

- Solution for the condensate density:

$$n_c(t) = n_{(0)} e^{-\gamma t/\hbar}$$

- Linearised differential equation for the fluctuations:

$$\begin{pmatrix} d\phi(k,t) \\ d\phi^*(-k,t) \end{pmatrix} = B_k(t)\, dt \begin{pmatrix} \phi(k,t) \\ \phi^*(-k,t) \end{pmatrix} + \frac{\sqrt{\gamma}}{2} \begin{pmatrix} dW(k,t) \\ -dW^*(-k,t) \end{pmatrix}$$

... to the expectation values.

with the Bogoliubov matrix

$$B_k(t) = \begin{pmatrix} \epsilon(k) + gn_c(t) - i\gamma/2 & gn_c(t) \\ -gn_c(t) & -\epsilon(k) - gn_c(t) - i\gamma/2 \end{pmatrix}$$

The time evolution of the fluctuations is described by the Green's function

$$G_k(t,t') = \prod_{j=1}^{N} \exp[-i\Delta t B_k(t_j)]$$

The stochastic fields are related to the quantum field operators through

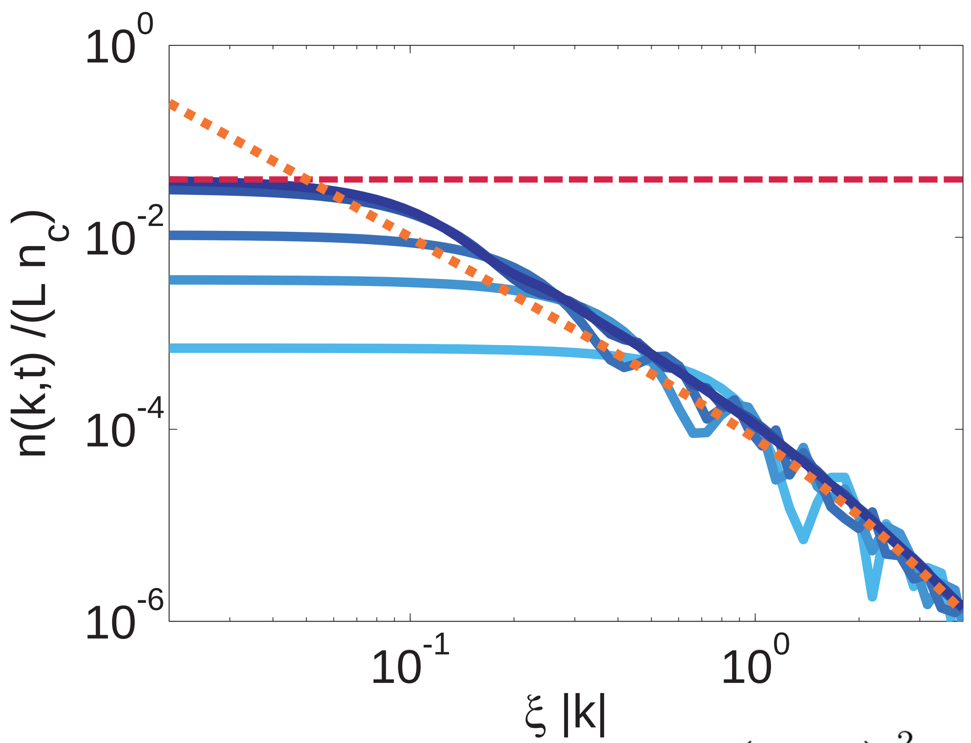
$$\langle \phi(k,t)\phi^*(k',t) \rangle_W = \langle \hat{\psi}(k,t)\hat{\psi}^\dagger(k',t) + \hat{\psi}^\dagger(k',t)\hat{\psi}(k,t) \rangle$$

This results in the solution for the momentum distribution n(k,t):

$$\langle \psi^\dagger(k,t)\psi(k,t) \rangle = \int dt' \left\{ |[G_k(t,t')]_{1,1}|^2 + |[G_k(t,t')]_{1,2}|^2 \right\} \frac{\delta(t')+1}{2} - \frac{1}{2}$$

Momentum distribution

For small momenta the distribution is constant; for large momenta it shows a power-law decay.



Numerical results for t=0.2, 0.5, 1, 3, 8

- Small momenta: Exact solution
$$n(k, t\to\infty) = 2\left(\frac{gn_{(0)}}{\gamma}\right)^2 e^{-\gamma t/\hbar}\left[1 - \left(1 + \frac{\gamma t}{\hbar}\right) e^{-\gamma t/\hbar}\right]$$

- Large momenta: Sudden jump approach from I. Carusotto *et al.* (2010)
$$n(k,t) = \frac{[gn_{(0)}]^2\, e^{-\gamma t/\hbar}}{2\,\epsilon(k)\,[\epsilon(k) + 2gn_{(0)}]}$$

- Cross-over around
$$k_*(t) = \frac{\gamma}{2\hbar}\sqrt{\frac{m}{gn_{(0)}}}\left[1 - e^{-\gamma t/\hbar}\left(\frac{\gamma t}{\hbar} + 1\right)\right]$$

Parameters

Interaction strength
$g = 0.01\,\mu\text{m MeV}$

Decay rate
$\gamma = 0.05$ MeV

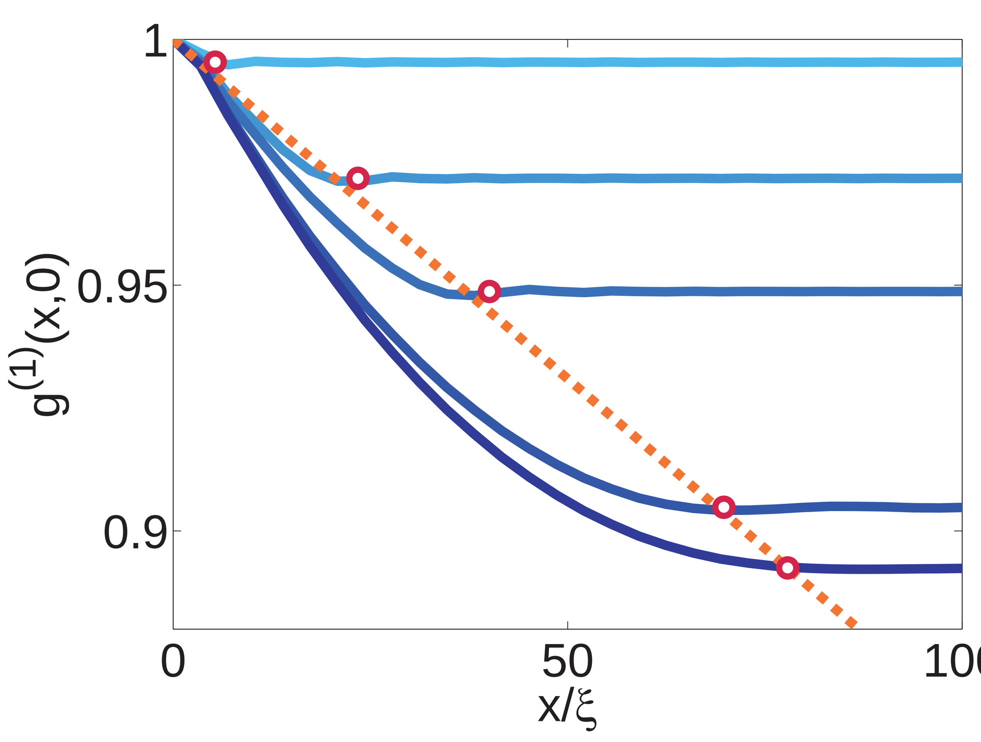
Initial condensate density
$n_{(0)} = 50\ \mu\text{m}^{-1}$

Length of the system
$L = 100\ \mu\text{m}$

Healing length
$\xi = \hbar\,(m\,g\,n_{(0)})^{-1/2}$

First order spatial coherence

There is a linear correlation between the coherence length and the quantum depletion.



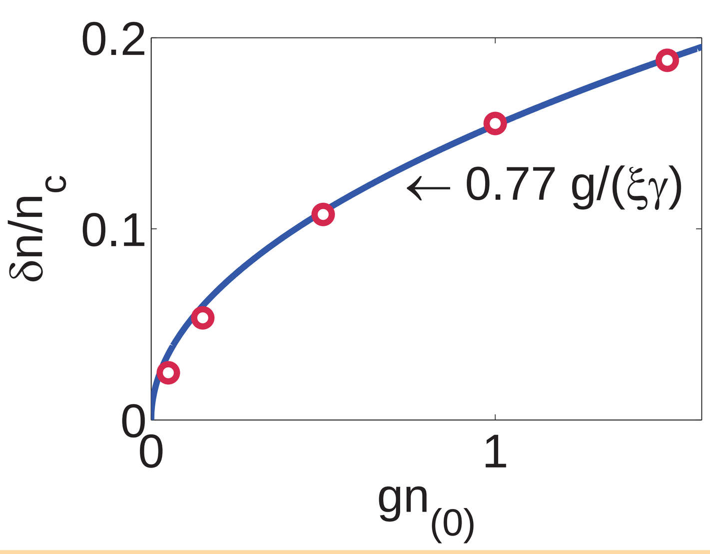
Numerical results for t=0.1, 0.5, 1, 3, 8

- A one-dimensional system shows the largest effect of quantum fluctuations.
- In Bogoliubov approximation:
$$g^{(1)}(x) = \frac{n_{(0)}(t) + \langle \psi^\dagger(x,t)\psi(0,t)\rangle - \langle \psi^\dagger(0,t)\psi(0,t)\rangle}{n_{(0)}(t)}$$
- Coherence length: $l_c(t) = \frac{3.9}{k_*(t)}$
- Quantum depletion: $\frac{\delta n(t)}{n_c(t)} = 0.38\frac{g\,m}{\hbar^2\, k_*(t)}$

Large times

As the off-diagonal elements of the Hamiltonian diminish, the momentum distribution and the spatial cohernece converge.

- The coherence length is proportional to the initial speed of sound times the lifetime of the polaritons:
$$l_c(t\to\infty) = 7.8\sqrt{gn_{(0)}/m}\;\hbar/\gamma$$
- The final quantum depletion is proportional to the 'blockade parameter' $g/(\xi\,\gamma)$.



Conclusions

For a suddenly created exciton-polariton condensate, dynamical Casimir emission is the first step towards equilibrium.

The sudden creation of a polariton condensate brings the system to the Bogoliubov vacuum, which is not the system's ground state. As a result, particles with higher momenta are created through the dynamical Casimir effect. When the density is reduced by the losses, interactions become less important. Consequently, both the momentum distribution and the spatial coherence converge. This is the first step towards thermal equilibrium. The second step will involve interactions between Bogoliubov excitations.

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References:
S. Koghee and M. Wouters, ArXiv: 1303.1027 (2013), submitted to PRL
I. Carusotto *et al.*, Eur. Phys. J. D. 56, 391-404 (2010)

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