Analogue of dynamical Casimir effect with matter waves

He* Experiment

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05/04/2013
Different well known effects due to vacuum fluctuations

Quantum optics and classical optics are quite different when the number of photons are decreasing. But when we reduce the number of photons to zero, then the classical point of view is no longer valid.

Static Casimir effect:

Boundaries conditions impose a quantization of the vacuum. Less modes inside the cavity can induce a “pressure force”.

Spontaneous emission
Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect DCE

The boundary conditions are modified at a velocity close to the speed of light. In this conditions the ground state of the system at a given time \( t \) becomes an excited state at time \( t + dt \).

This excited state can be written as pairs of photons satisfying:

\[
\omega = \omega_1 + \omega_2
\]


System:

Bose-Einstein condensate

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Bose-Einstein condensate
System:

Bose-Einstein condensate and Bogoliubov excitations

All atoms in the same state $\rightarrow$ The vacuum of Bogoliubov excitations.

At $t=0$

$$H = \sum_k \hbar \omega_k b_K^\dagger b_k$$

with,

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

$\mu = mc^2$

Speed of sound in the condensate
System:

Bose-Einstein condensate and Bogoliubov excitations

Chemical potential modulation $\rightarrow$ Analogy to the modulation of an optical index of refraction in a cavity

\[ \mu(t) = \mu_0 + \delta \mu(t) \]

\[ H = H_0 + \frac{\delta \mu(t)}{2} \sum (u_k + v_k)^2 \times (b_k^\dagger + b_{-k})(b_k + b_{-k}^\dagger) \]

Production of pairs of phonons

Realization of the experiment:

How do we change $\mu$?

\[
\mu(t) = \frac{4\pi \hbar^2 a}{m} n(t)
\]

By changing the density of our cloud we can change $\mu$

A change in the power of the optical dipole trap (ODP), can change the density

- Sudden re-compression of the trap
- Modulation of the trap
Experimental Setup

Red detuned light → Attractive force to the maximum of intensity → Increase of the density

Evaporative cooling → We lose atoms with higher energy

Dipole Trap
1550nm
1700 Hz, 10 Hz

\(^4\text{He}^*\) quasi-BEC
10^6 atoms / 100nK
\(\lambda = 1083\text{nm}\)

45cm
308 ms ToF

MCP
Experimental Setup:
The detection & Micro Channel Plate (MCP)

\[ ^4\text{He}^* \rightarrow \text{internal energy of } 20 \text{ eV} \]

Single particle detection:
Low noise
Quantum efficiency \(\sim 12\%\)

3D reconstruction:
300 \(\mu\text{m}\) resolution on horizontal plane
20 ns \((\sim 60 \text{ nm})\) resolution on the vertical axis.
Realization of the experiment: Modulation of the trap

Modulation of the laser intensity of about 15 % for ~ 20 ms.

\[ \omega_{mod} \approx 2\pi \times 0.9 - 5 \text{ kHz} \]

In our process, momentum must be conserved -> \( k_2 = -k_1 \).

Realization of the experiment:

Modulation of the trap

Example of data after TOF for $\omega_{\text{mod}} = 2.5$ kHz

Averaged over $\sim$2000 shots

Realization of the experiment:

Modulation of the trap
two-body correlation function

\[ g^{(2)}(v, v') = \frac{\langle n_v n_{v'} \rangle}{\langle n_v \rangle \langle n_{v'} \rangle} \]
Realization of the experiment:
Modulation of the trap
two-body correlation function

Conclusions

- We demonstrated creation of pairs of phonon but not really from vacuum, since \(T>0K\);

- Next step: Sub-Poissonian distribution for the difference atomic population between the two peaks will prove the quantum nature of the process. We modified the experiment and expect to have new results soon.
Thank you for your attention

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J-C Jaskula
Realization of the experiment:

Modulation of the trap
Experimental Setup:
The detection & Micro Channel Plate (MCP)

This detection gives us nice images but also the possibility to study second order correlations

$$g^{(2)}(v,v') = \frac{\langle n_v n_{v'} \rangle}{\langle n_v \rangle \langle n_{v'} \rangle}$$

Analogy to DCE with matter waves:
Theory in this context, Bogoliubov excitations

To take into account quantum fluctuations about the state in which all the atoms are condensed in a single quantum state one can write:

\[ \hat{\psi}(\vec{r}) = \psi(\vec{r}) + \delta \]

\[ \psi(\vec{r}) = \sqrt{N_0} V^{-1/2} \]

The Hamiltonian can then be written in terms of single particle operators

\[ \mu = \frac{4\pi \hbar^2 a}{m} n(\vec{r} = 0) \]

Describe the ground state of the system and treated as a classical field

Chemical potential
General idea of the experimental realization

Shake shake shake
Realization of the experiment:

Sudden re-compression

Sudden increase (factor 2) of the power of the ODP in ~ 30 µs and hold for ~30 ms

Laser intensity (W)

Time (ms)
Realization of the experiment:
Sudden re-compression
Realization of the experiment:
Sudden re-compression
2\textsuperscript{nd} order correlation function

Hambury Brown and Twiss effect


M. Schellekens et al., Science 310 (2005)
Realization of the experiment:
Modulation of the trap
Bragg spectroscopy

Realization of the experiment:

Modulation of the trap

Bragg spectroscopy

\[ \omega_k = \sqrt{\frac{\hbar k^2}{2m} \left( \frac{\hbar k^2}{2m} + 2mc^2 \right)} \]

Value obtained by Bragg spectroscopy
Realization of the experiment:
Modulation of the trap
Dispersion relation

For a different density we obtain by Bragg spectroscopy $c=0.75$ cm/s and $\alpha = 2.02 \pm 0.1$

New way to determine the sound velocity of a condensate
Perspectives

Hawking radiation

Near the horizon of a black hole:

The particle of negative energy “falls” in the black hole. For an external observer the black hole seems to radiate particles, photons.

P. Nation & al. Rev. Mod. Phys. 84, 1 (2012)

Perspectives
Hawking radiation
An analog model: dumb hole

Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect

Drive: $\omega = 2\pi \times 10$ GHz

Output analysed at

$\omega_1 = \omega + \Delta$

$\omega_2 = \omega - \Delta$

2 Josephson junctions at 50 mK

Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect DCE

a) For $\omega_2 = \omega - \Delta$

b) For $\omega_1 = \omega + \Delta$
Realization of the experiment:

Modulation of the trap

Dispersion relation

\[ \omega_k + \alpha \sqrt{\frac{\hbar k^2}{2m} \left( \frac{\hbar k^2}{2m} + 2mc^2 \right) - \alpha \frac{\hbar k^2}{2m}} \]
Realization of the experiment:

Modulation of the trap

Dispersion relation
Realization of the experiment:
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Realization of the experiment:

Modulation of the trap

Dispersion relation
Realization of the experiment:
Modulation of the trap
Dispersion relation
Squeezing for $k_1 = 0.85 \, v_{\text{rec}}$