Effects of dissipation on the superfluid-Mott-Insulator transition of photons

Physics Utrecht
EMMEΦ

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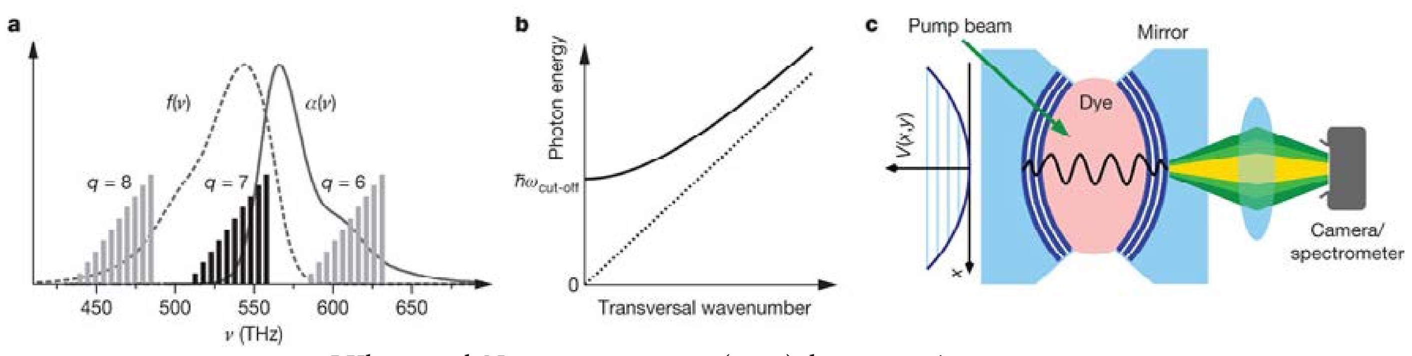
Experiment



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Photons are confined in a dye-filled optical microresonator [2]. Since the emission and absorption of photons with longitudional mode number q = 7 dominates over other emission processes, the number of photons in the cavity is conserved. The photon gas is formally equivalent to a two-dimensional harmonically trapped massive Bose gas ⟶ Bose-Einstein condensation of photons at non-zero temperature! By periodically changing the index of refraction of the dye inside the cavity a periodic potential for the photons can be induced.

Superfluid-Mott-Insulator transition

The Bose-Hubbard model describes a Bose gas in a periodic potential with a nearest-neighbour hopping parameter t and on-site interaction strength U.

$$S = \int_0^{\hbar\beta} d\tau \left\{ \sum_i a_i^*(\tau)\left(\hbar\frac{\partial}{\partial\tau} + \epsilon_i - \mu\right) a_i(\tau) - t\sum_{\langle i,j\rangle} a_i^*(\tau)a_j(\tau) + \frac{U}{2}\sum_i a_i^*(\tau)a_i^*(\tau)a_i(\tau)a_i(\tau) \right\}$$

t << U: Mott Insulator

- Hopping is energetically unfavorable.
- Equal and integer amount of particles per site.
- Particle number fluctuations are suppressed.

t >> U: Superfluid

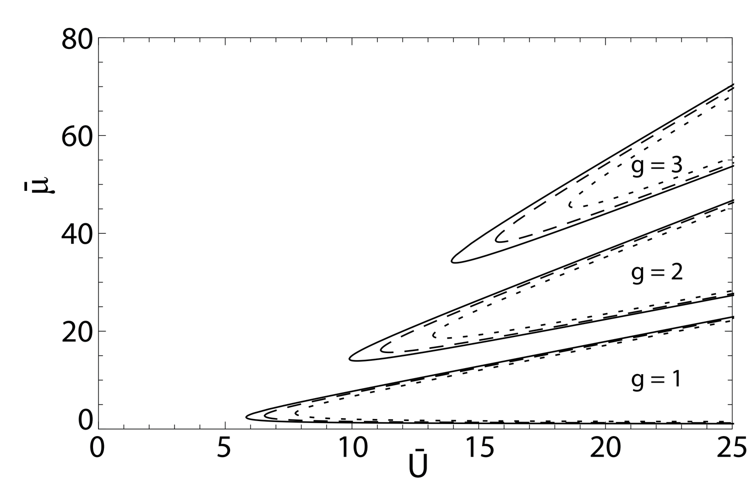
- Energy minimized by freely hopping around.
- Fluctuating number of particles per site.

Mean-Field theory

We investigate the effects of dissipation by treating the dye as an effective two level system that can absorp and emit photons.

$$S_{\mathrm{c}} = \frac{g_{\mathrm{m}}}{\sqrt{A}\sqrt{V}} \int_0^{\hbar\beta} d\tau \left\{ \sum_{i,\mathbf{p}} a_i^*(\tau) b_{\mathbf{p},\downarrow}^*(\tau) b_{\mathbf{p},\uparrow}(\tau) + a_i(\tau) b_{\mathbf{p},\uparrow}^*(\tau) b_{\mathbf{p},\downarrow}(\tau) \right\}$$

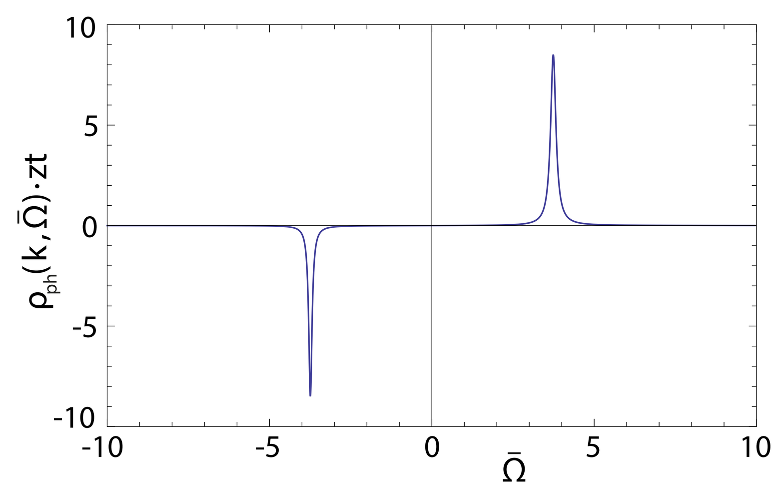
We construct a consistent mean-field theory for the superfluid order parameter $\langle a_i(\tau)\rangle$. Due to the coupling with the molecules a non-zero expectation value of $\langle a_i(\tau)\rangle$ will induce a non-zero expectation value of $\langle b_{\mathbf{p},\uparrow}^*(\tau) b_{\mathbf{p},\downarrow}(\tau)\rangle$. We solve the molecular problem exactly and perform second-order perturbation theory in the superfluid order parameter. We use the usual Landau procedure to determine the phase boundary between $\langle a_i(\tau)\rangle = 0$ and $\langle a_i(\tau)\rangle \neq 0$.



Phase diagram for the Bose-Hubbard model with the photon-molecule interaction parameter γ. From top to bottom the three contributions are for respectively 3,2 and 1 particle per site. The solid, dashed and dotted line are for $\gamma = 0$, $\gamma = 1/2$ and $\gamma = 1$.

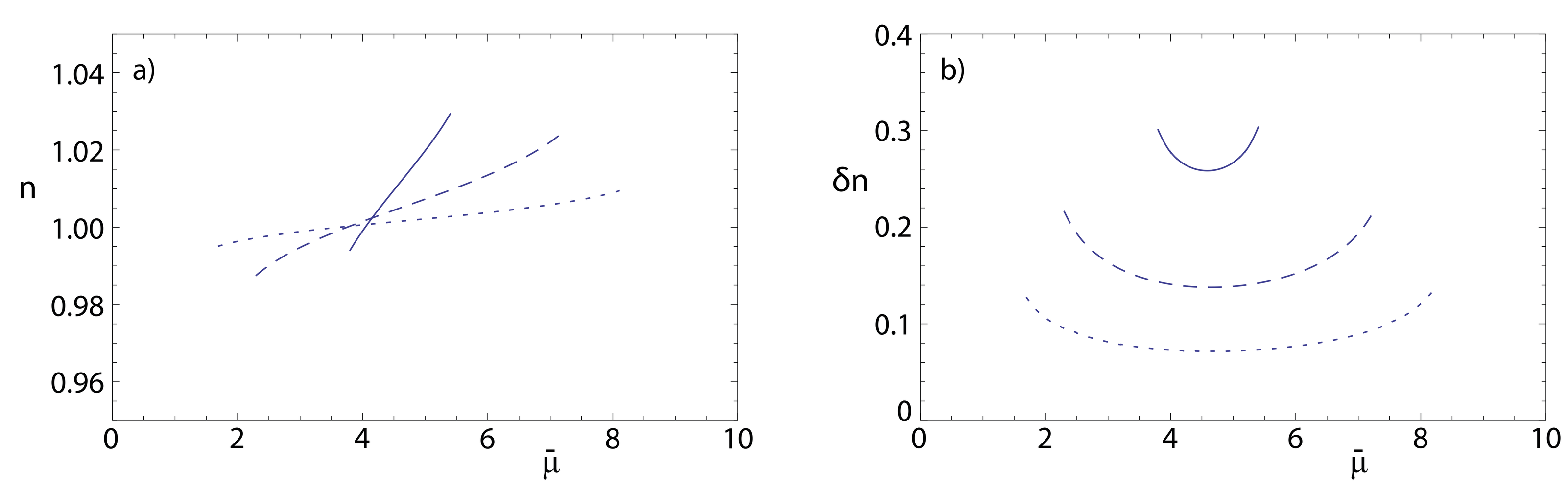
Beyond Mean-Field theory

We integrate out the molecules and perform second-order perturbation theory in the coupling constant g_{m} to consider Gaussian fluctuations of the photons inside the Mott lobes.



Inside the Mott lobes the excitations acquire a finite lifetime due to the coupling to the dye.

The number of photons varies inside the Mott lobes and the number fluctuations increase as the value of the damping parameter α increases.



Due to the photon-molecule coupling there are even number fluctuations are zero temperature ⟶ Mott Insulator does not exist!

Conclusions

- The photon-molecule coupling decreases the size of the Mott lobes.
- The excitations inside the Mott lobes acquire a finite lifetime.
- There are non-zero number fluctuations at zero temperature and therefore the true Mott Insulator is absent.

References

[1] A.-W. de Leeuw, O. Onishchenko, R.A. Duine, and H.T.C. Stoof, Phys. Rev. A. **91,** 033609 (2015).

[2] J.Klaers, J.Schmitt, F.Verwinger, and M.Weitz, Nature **468**, 545 (2010).

[3] D. van Oosten, P. van der Straten, and H.T.C. Stoof, Phys. Rev. A. **63,** 053601 (2001).

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