Many-body phenomena in ultra-cold Fermi gases in optical resonators

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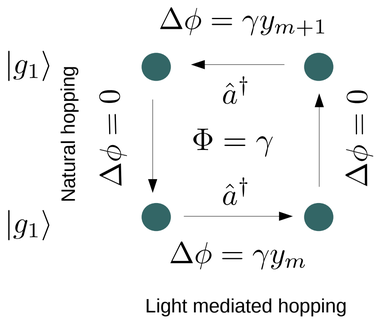
Dynamical light-matter coupling

In a cavity the back-action of the atoms on the light field becomes relevant. The system can dynamically stabilize exotic states, as supersolids, quasi-crystals, superconductivity and dynamical magnetic fields.

Cavity-induced dynamic Hofstadter butterfly



Objective: realization of **artificial gauge fields** in superradiant states of hybrid systems of light and neutral matter.

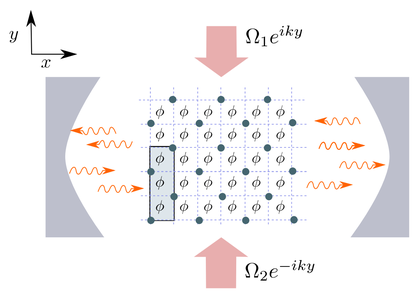
Physics in a nutshell:

1) A space dependent phase, similar to the one acquired by electrons in a magnetic field, is imprinted to the atomic wave-function by the exchange of photons between an external laser and a cavity mode.

2) The magnetic field piercing the unit cell is **statically** determined by the pumping geometry.

System

- *2D spinless Fermi gas* in a square lattice.
- *Single cavity mode* ($\hat{a}$) is pumped by two transversal running waves ($\Omega e^{\pm iky}$) and restores the hopping along the cavity axis.



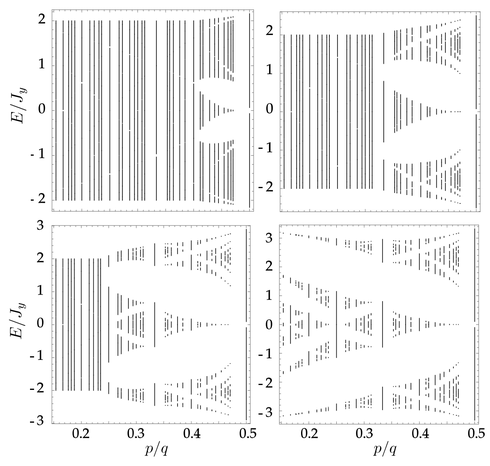
Harper-Hofstadter Hamiltonian

$$H = -J_y \sum_{l,m} (f^\dagger_{l,m+1} f_{l,m} + \text{H.c.}) - \hbar\eta(a + a^\dagger) \sum_{l,m} (e^{2i\pi m\gamma} f^\dagger_{l+1,m} f_{l,m} + \text{H.c.}) - \hbar\Delta_c a^\dagger a$$

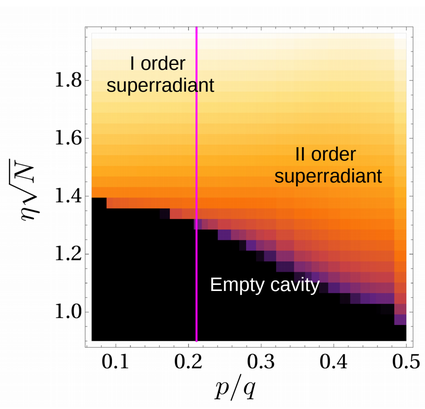
The ratio between the pump and the lattice wavelength sets the value of the magnetic flux piercing one plaquette.

$$\Phi = 2\pi k_L / k_l$$

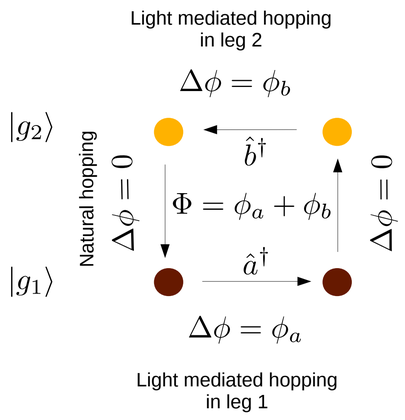
Properties



- *Superradiance:* the cavity mode is coherently populated by increasing the external pump strength.
- *Umklapp processes:* for weak magnetic field the phase transition becomes first order due to atom-photon scattering processes that bring particles outside the first Brillouin zone.
- *Fractal band structure:* the energy spectrum is distorted but preserves the topological nature of the static Hofstadter model.



Emerging photon-induced density-dependent gauge fields



Objective: realization of **density dependent dynamical artificial gauge fields**.

Physics in a nutshell:

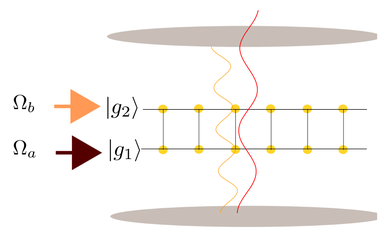
1) The phase acquired by electrons in a magnetic field is emulated in hybrid systems of coupled light and neutral matter.

2) The phase of the atomic wave-function is coupled to the phase of two independent cavity modes.

3) The magnetic flux piercing one plaquette is **dynamically** determined by the phase of the cavity fields and the atomic density configuration.

System

- *Ladder*: a degenerate quantum gas in two different internal states is confined in a 1D optical lattice.
- *Two cavity modes* (α and β) are pumped by two transversal constant pumping lasers (Ω_a and Ω_b) and respectively restore the hopping along the two legs ($|g_1\rangle$ and $|g_2\rangle$).



Dynamical ladder

$$H = -\eta \sum_i (\alpha^* a^\dagger_{i+1} a_i + \beta b^\dagger_{i+1} b_i + h.c) - K \sum_i (a^\dagger_i b_i + b^\dagger_i a_i) + U \sum_i n_{i,a(b)}(n_{i,a(b)} - 1) - \sum_i (\mu_\alpha a^\dagger_i a_i + \mu_\beta b^\dagger_i b_i) - \hbar\Delta_c(|\alpha|^2 + |\beta|^2)$$

$\mu_\alpha = \mu + U_0|\alpha|^2 \qquad \mu_\beta = \mu + U_0|\beta|^2$

$\hat{a}_i$ creates a particle at position i in the leg $|g_1\rangle$

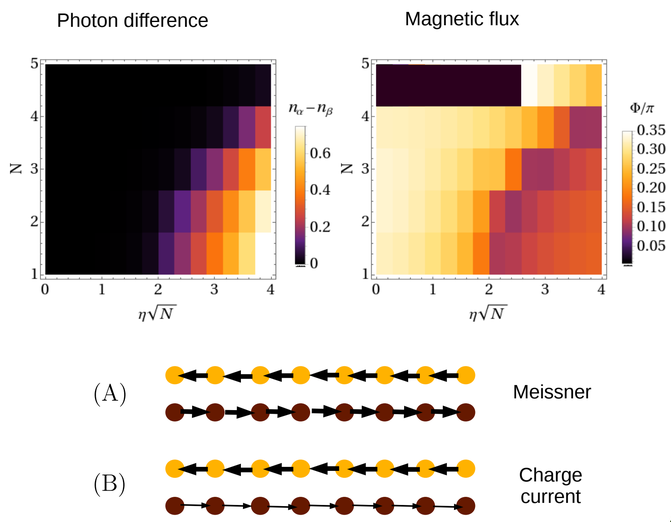
$\hat{b}_i$ creates a particle at position i in the leg $|g_2\rangle$

When a particle hops to an adjacent site, it acquires the phase of the cavity mode that is coupled to the respective leg. The total phase acquired in a closed loop sets the value of the magnetic flux in one plaquette:

$$\Phi = \phi_a + \phi_b$$

Properties

- *Superradiance*
- *Dynamical magnetic flux:* the redistribution of the particles in the two legs determines the value of the magnetic flux at each filling.
- *Phase transition:* the system shows a transition from an equally populated photon state (macroscopic chiral current A) to a photon imbalanced state (macroscopic charge current B).
- The photon number measures the current in the system.



Crystallization and pairing of a Fermi gas in a ring cavity

Objective: realization and measurement of Cooper pairs in Fermi gases coupled to a ring cavity.

Physics in a nutshell:

1) Photons are delocalized within the cavity and mediate infinite long-range interactions between atoms.

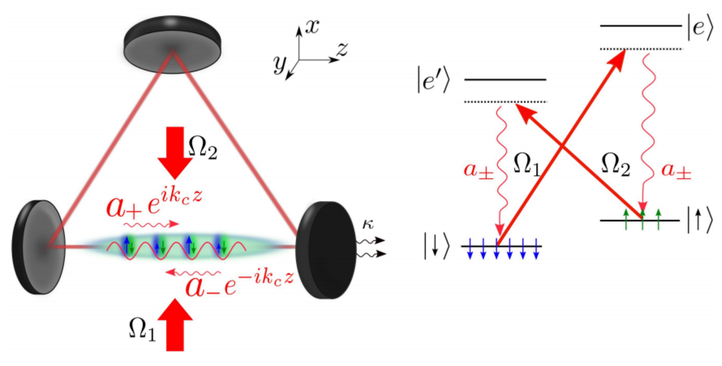
2) For attractive interactions two fermions near the Fermi surface can bound in a Cooper pair.

Project steps

- Study of the two-body momentum correlation in 1D and entanglement properties of few fermions coupled to two degenerate mode of a ring cavity.
- Study beyond mean field of the competing order between spin waves and superconductivity in a 2D Fermi gas coupled to the photon field of a ring cavity.

Method development

Numerical development of a Monte Carlo method for boson-fermion model with dissipation.



Hofstadter butterfly in a cavity-induced dynamic synthetic magnetic field, Elvia Colella, Farokh Mivehvar, Francesco Piazza, and Helmut Ritsch, Phys. Rev. B 100, 224306
Antiferromagnetic self-ordering of a Fermi gas in a ring cavity, Elvia Colella, Stefan Ostermann, Wolfang Niedenzu, Farokh Mivehvar and Helmut Ritsch, New Journal of Physics, Volume 21, April 2019

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