PhD project
Instituto de Física da Universidade de São Paulo

Autonomous quantum absorption refrigerators using ultra-cold atoms in an optical cavity

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Project summary

Ultra-cold atoms in optical lattices is currently one of the most rapidly advancing areas of research in physics and the main platform embodying the idea of *quantum simulation*. That is, the use of a controlled quantum system to simulate models or scenarios which could be of interest in other fields of physics, but which are out of reach using current experimental and/or computational methods. In this project we shall be interested in addressing whether ultra-cold atoms can be used for simulating an autonomous absorption refrigerator operating genuinely in the quantum regime, a task which is currently being pursued by several experimental research groups working in other controlled quantum platforms. To accomplish this the student will carry out a thorough theoretical study on the possible implementations of this type of device in a specific state-of-the-art experimental implementation developed in the group of Prof. Esslinger in ETH, Zürich, with whom Prof. Landi already has a recent collaboration. The platform consists of a Bose-Einstein condensate loaded in an optical lattice and also confined between two high-finesse optical cavities. The use of two cavities allow access to a broader range of excitations in the condensate, which are essential for constructing the absorption refrigerator. This research proposal should therefore help consolidate ultra-cold atoms as a robust platform for quantum thermodynamics experiments, with high potential scientific impact for the quantum physics community.

1 Introduction

The term *"ultra-cold atoms in optical lattices"* refers to the use of standing-wave lasers to create lattice-like potentials, in which atoms may interact in a controlled way. The seminal works on this field began with the group of Nobel laureate Theodore Hänsch [1, 2] and has since grown into one of the most important fields of research in physics. Shortly after these seminal papers, it became clear that this platform could be used to implement the idea of *quantum simulations* [3, 4]. That is, the use of a controlled platform to simulate models which are of relevance to the condensed matter and high energy communities [5], but which cannot be solved by standard analytical or computational methods. The original papers [1, 2] focused on the simulation of the so-called Bose-Hubbard model, which predicts a quantum phase transition from a Superfluid to a Mott insulating phase. This represents the bosonic analog of the Fermi-Hubbard model, which is believed to capture the main features behind the Cuprate high-temperature superconductors, of which much is still not understood. In cold-atom systems one is now able [6–10], with increasing sophistication, to simulate the Fermi-Hubbard model with experimental control over the model parameters, something which is seldom possible in an actual solid.

In the 16 years that have elapsed since the first contributions, the variety of models that have been simulated in ultra-cold atom platforms is quite remarkable. Examples include the Dicke and Roton-type models [11–15], supersolids [16, 17], many-body localization [18], topological models [19–24] and quantum spin chains [25–27]. In addition, ultra-cold atoms are also being employed in the study of fundamental properties of nature, such as the dynamics of quantum correlations [28–40], the role of entanglement in many-body thermalization [41–44], quantum thermodynamics [45], the physics of Higgs and Goldstone modes [46, 47], quantum tunneling and metastability [41, 48], quantum walks [49] and quantum transport [50–56]. Quite amusingly, ultra-cold atoms have also been used to simulate other quantum simulation platforms [57, 58], which is perhaps the ultimate goal of a quantum simulator.

In this project we shall be concerned more specifically with the use of ultra-cold atoms as simulators of a fully quantum autonomous absorption refrigerator. The typical scenario is depicted in Fig. 1: a quantum system is coupled to three reservoirs. One of the baths acts as a work reservoir and is engineered so as to reverse the heat flow in the other two, from cold to hot. The experimental implementation of heat engines operating genuinely at the quantum regime *and* in a completely autonomous way has become, in the past three years, one of the main goals from the quantum thermodynamics community [59–65] (see [66] for a very recent review). It should also be one of the main drives for progress in the field for the next years to come.

In this project we shall focus on the implementation of an absorption refrigerator at a specific experimental platform, consisting of a Bose-Einstein condensate of Rubidium atoms in an optical lattice, which also interact with two high-finesse optical cavities [17, 47, 67]. This platform is actually an upgrade from a previous version containing only one cavity. Prof. Landi was one of the co-authors in a recent paper [68] that used this single cavity setup to carry out the first experimental assessment of entropy production in quantum non-equilibrium steady states. Due to its novelty, this paper was chosen as an editor suggestion for *Phys. Rev. Lett.* and for the *Synopsis on physics* from the American Physical Society. In Brazil, it also featured in several outreach channels, including *Agência FAPESP*. It is also worth mentioning that the entire experiment was only made viable due to a theoretical framework first put forth by Prof. Landi and collaborators [69].

The present project is an extension of this work to the two-cavity setup, with the specific aim of implementing an absorption refrigerator. Our focus will be to carry out a detailed theoretical study on the viability and feasibility of this implementation, but also having a broader interest in mind, concerning other possible quantum thermodynamics applications. Central to this project will be a detailed investigation of the many-body physics behind the experimental setup, as well as the types of heat baths acting on the system. This project will therefore combine tools from many-body physics and open quantum systems. The technical details on how this will be accomplished will be detailed below in Secs. 2 and 3.

Scientific impact and academic contributions of this project

This PhD project is both timely and ambitious, focusing on a specific high impact physical problem. To aid in this task, the project will count with the collaboration of several researchers from Brazil and abroad. In particular, we mention Profs. John Goold (Trinity College Dublin),

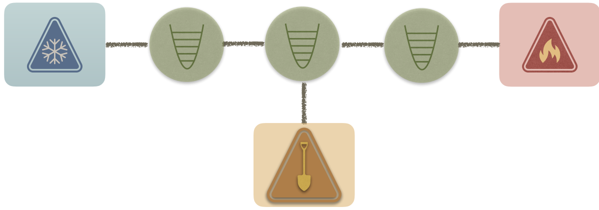

Figure 1: Basic setup of an absorption refrigerator. A quantum system (green) is coupled to three reservoirs. One of the reservoirs acts as a work bath (yellow), reversing the heat flow of the other two, from cold (blue) to hot (red).

Eric Lutz (University of Stuttgart), Tobias Donner (ETH Zürich), Mauro Paternostro (Queen's University in Belfast) and Gerardo Adesso (University of Nottingham), all of which are already active collaborators of Prof. Landi (the last two in the context of active FAPESP collaboration projects).

This project will also help to draw attention in Brazil to the important fields of ultra-cold atoms and quantum thermodynamics, which are among the fastest growing communities in physics. The State of São Paulo has been at the center of several successful experimental and theoretical initiatives in both fields. Examples include the Center for Optics and Photonics in São Carlos, which operates the only Bose-Einstein condensate in Latin America, and the *SPIN off QuBIT*[1] initiative of researchers working in quantum information and related fields, of which Prof. Landi is one of the co-founders. This project will serve to strengthen the collaboration between members of the SPIN off QuBIT community and thus help to maintain the reputation of the State of São Paulo as a leading hub for quantum science in Brazil and Latin America.

Ultra-cold atoms and quantum thermodynamics are also unique in how they mix a large variety of techniques borrowed from fields such as quantum optics, quantum information, quantum field theory and many-body physics. Operating at the boundaries of these different fields of research has always been a goal of Prof. Landi's research. This includes, for instance, the *Quantum Discussions* initiative at the University of São Paulo,[2] which aims to bring together researchers working in the tri-border between quantum information, condensed matter physics and high-energy physics. This integration is also a particular interest of Mr. Soldati, who worked with entanglement entropy in curved space-time during his masters at the Federal University of Minas Gerais. Hence, this project will have an important impact on Mr. Soldati's training as a researcher, placing him at the forefront of quantum physics research.

The progress of the project will be measured primarily by publications in high impact journals such as Physical Review Letters, Nature quantum information and Nature communications, Physical Review X, New Journal of Physics, Entropy, and Quantum. All papers will also be accessible on arXiv, and computational libraries will be made available in institutional repositories. The student will be encouraged to participate in international conferences and present talks, as well as to visit other universities to disseminate results of the project. We also recognize the importance of actively publicizing our research on blogs such as spinoffqubit.info and "quantum Rio", as well as social media pages such as "Quantum Information and Quantum Computer Scientists of the World Unite", "Quantum Correlations" and "Quantum Thermodynamics".

2 The double-cavity ultra-cold atom platforms

In this project we shall focus on the physics that can be simulated by the ultra-cold atom platform used in Refs. [17, 47, 67]. An illustration of the experimental setup is given in Fig. 2. It consists of an optical lattice supporting ultra-cold bosonic Rubidium atoms that can be arranged in either a 1- or 2-dimensional optical lattice (the drawing in Fig. 2 refers to a 1D lattice). In addition to the optical potential creating the lattice, the system is also confined inside two optical cavities which support an additional electromagnetic mode each. These optical cavities are made of semi-transparent mirrors, which serve to confine the radiation but also allow for photons to be injected and leak out. The injected photons serve to pump the cavity in different ways, which

[1] www.spinoffqubit.info

[2] http://quantumdiscussions.if.usp.br

can be used to generate dynamical protocols. The leaked photons, on the other hand, contain information about the system inside the cavity and are therefore the main quantities which are measured in the experiment.

We now discuss what types of models can be simulated with this system, by discussing separately the Hamiltonian (unitary) parts from the dissipative (reservoir) parts.

2.1 Hamiltonian modeling

The atomic rubidium gas is described by a matter-field operator $\Psi(\boldsymbol{r})$, whereas the optical cavities usually accept only one radiation mode, therefore providing two extra field operators a_1 and a_2, one for each cavity. The general Hamiltonian that describes this system and which was used as the starting point in Refs. [17, 47, 67], reads

$$H = \Delta_1 a_1^\dagger a_1 + \Delta_2 a_2^\dagger a_2 + \int \mathrm{d}x\,\mathrm{d}y\ \ \Psi^\dagger(x,y)\bigg\{ -\frac{\hbar^2}{2m}\nabla^2 + \hbar U_p \cos^2(\boldsymbol{k}_p\cdot\boldsymbol{r}) + \sum_{i=1,2} \hbar U_i a_i^\dagger a_i \cos^2(\boldsymbol{k}_i\cdot\boldsymbol{r}) + \hbar\eta_i (a_i + a_i^\dagger)\cos(\boldsymbol{k}_p\cdot\boldsymbol{r})\cos(\boldsymbol{k}_i\cdot\boldsymbol{r})\bigg\}\Psi(x,y). \tag{1}$$

Here Δ_i is the detuned frequency of each cavity and m is the mass of the Rubidium atoms. The suffix $i = 1,2$ refers to quantities pertaining to the two cavity modes a_1 and a_2, whereas the suffix p refers to the pump field which is the laser responsible for generating the optical lattice (the vertical field in Fig. 2). The pump field is assumed to be classical. The wave-vectors in Eq. (1) read $\boldsymbol{k}_p = k\hat{y}$ and $\boldsymbol{k}_i = k(\hat{x}\sin\theta + (-1)^i\hat{y}\cos\theta)$, where θ is the angle between each lattice and the $\hat{y}$ axis, $k = 2\pi/\lambda$ and λ is the pump wavelength. In Fig. 2, as well as in Refs. [17, 47, 67], the authors used $\theta = \pi/3$, as this entails a special symmetry to the system, as will be discussed below.

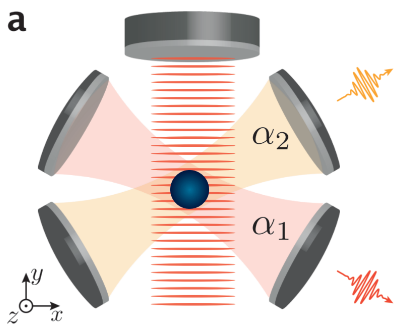

Figure 2: Illustration of the experimental setup that will be considered in this project. Taken from Ref. [17]. The system is composed of an optical lattice containing Rubidium atoms and confined inside two high-finesse optical cavities.

The Hamiltonian (1) is remarkably complex, so that in order to proceed it is customary to analyze the effective low energy excitations. To this end, the term proportional to $(a_i^\dagger + a_i)$ is particularly important. This term describes the creation and annihilation of cavity photons as they interact with the quantum gas. This effect actually originate from the interaction of the pump photons (which we treat classically) with the Rubidium atoms which generate the lattice. However, as a consequence of generating the lattice, some of the pump photons are scattered by the gas and converted into cavity photons.

In terms of the momentum basis $|\boldsymbol{k}\rangle = |k_x, k_y\rangle$ of the gas, the lowest energy processes of this model are therefore scattering events involving the Rubidium Bose-Einstein condensate (BEC) ground-state $|k_x, k_y\rangle = |0,0\rangle$ and eight excited states having momentum $\boldsymbol{k} = \pm\boldsymbol{k}_p \pm \boldsymbol{k}_1$ and $\boldsymbol{k} = \pm\boldsymbol{k}_p \pm \boldsymbol{k}_2$. One may show that these 8 excited states group into two excitation energies with values $\omega_+ = 2\omega_{\text{rec}}(1 + \cos\pi/3) = 3\omega_{\text{rec}}$ and $\omega_- = 2\omega_{\text{rec}}(1 - \cos\pi/3) = \omega_{\text{rec}}$, where $\omega_{\text{rec}} = 2\pi \times 3.7$ kHz is a reference frequency used by the experimentalists as the basic energy unit. Due to this factorization, one may single out the low-energy behavior from the Hamiltonian (1) by assuming an expansion of the field operator of the form

$$\Psi(\boldsymbol{r}) = \Psi_0 c_0 + \sum_{i=1,2}\sum_{\sigma=\pm 1} \Psi_{i,\sigma}(\boldsymbol{r}) c_{i,\sigma}, \tag{2}$$

where c_0 and $c_{i,\sigma}$ are bosonic operators describing the ground-state and the aforementioned excited states, whereas Ψ_0 and $\Psi_{i,\sigma}$ are the corresponding wave-functions, with $\Psi_0 = \sqrt{2/A}$ being the BEC zero momentum mode and $\Psi_{i,\pm} = \sqrt{\frac{2}{A}}\cos[(\boldsymbol{k}_p \pm \boldsymbol{k}_i)\cdot \boldsymbol{r}]$ (in these formulas A represents the area of the optical lattice potential). In Eq. (2) opposite momentum states have also been grouped into standing wave modes, hence reducing the expansion to a total of 5 modes.

Inserting Eq. (2) into Eq. (1) and carrying out the integration yields an effective Hamiltonian of the form

$$H_{\text{eff}} = \sum_{i=1,2}\Big\{\Delta_i a_i^\dagger a_i + \omega_+ c_{i+}^\dagger c_{i+} + \omega_- c_{i-}^\dagger c_{i-} + \frac{\lambda_i}{\sqrt{N}}(a_i + a_i^\dagger)(c_{i+}^\dagger c_0 + c_0^\dagger c_{i+} + c_{i-}^\dagger c_0 + c_0^\dagger c_{i-})\Big\}, \tag{3}$$

where N is the number of Rubidium atoms and $\lambda_i = \eta_i\sqrt{N}/(2\sqrt{2})$. This is the basic Hamiltonian which the authors have explored so far in Refs. [17, 47, 67].

Before we turn to the modeling of the reservoirs, we finish this subsection by discussing the concept of symmetry augmentation, which is one of the main reasons to consider two optical cavities instead of one. The Hamiltonian (3) has two Z_2 symmetries related to the transformations

$$(a_i, c_{i\sigma}) \to (-a_i, -c_{i\sigma}). \tag{4}$$

However, in the particular case where $\Delta_1 = \Delta_2$ and $\lambda_1 = \lambda_2$ these two symmetries can be combined into a stronger, $U(1)$ symmetry:

$$\begin{aligned} a_1 &\to a_1\cos\theta - a_2\sin\theta,\\ a_2 &\to -a_1\sin\theta + a_2\cos\theta,\\ c_{1\sigma} &\to c_{1\sigma}\cos\theta - c_{2\sigma}\sin\theta,\\ c_{2\sigma} &\to -c_{1\sigma}\sin\theta + c_{2\sigma}\cos\theta, \end{aligned} \tag{5}$$

parametrized by a continuous angle θ. The reason why this is important is because a $U(1)$ symmetry supports both a Higgs as well as a Goldstone (zero mass) excitation, whereas Z_2 symmetries support only Higgs modes.

2.2 Reservoir modeling

Next we turn to the possible reservoirs that can be modeled with this platform. The open-nature of this system means the dynamics of the global density matrix ρ will be described by a quantum master equation of the form

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -i[H,\rho] + \sum_\alpha \gamma_\alpha\Big[L_\alpha\rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\}\Big], \tag{6}$$

where L_α are the Lindblad jump operators and $\gamma_\alpha > 0$ are the corresponding dissipation rates. By far, the most relevant dissipative contributions are related to photon losses. Recall that the mirrors supporting the optical cavities (Fig. 2) are semi-transparent. Hence, photons in the cavities can leak out, which is described by jump operators $L = a_1$ and $L = a_2$.

For this reason, this type of model is usually referred to as a *driven-dissipative* system. The system is constantly being driven because the pump cavity is constantly providing energy in the form of the optical lattice. This energy is then scattered in the Rubidium atoms, converted into cavity photons and finally leaks out of the optical cavities. Driven-dissipative systems may present quantum phase transitions related to the competition between drive and dissipation. Examples include the Dicke model [11–15], optical bistability in exciton-polariton [70–74] systems.

In addition to the two leaky cavity dissipators, there may also be other loss channels related to incoherent processes of the Rubidium atoms. That is, scattering processes where the Rubidium atoms emit photons which are not converted into cavity photons and therefore leak out to the environment. Moreover, the Rubidium atoms are not actually at zero temperature, so there is the natural thermally induced agitation. Finally, in real experiments the optical lattice is not uniform, but rather has a parabolic shape. This induces what is usually referred to as the "wedding cake structure", which essentially means the density of Rubidium atoms goes down radially, being smaller near the border. This can described by a position-dependent chemical potential and effectively, it means that different "radial slices" will act as effective particle baths for other slices. These effects can also be captured with the Lindblad master equation (6).

3 Objectives and methodology

We now move on to describe the specific goals that will be pursued in this PhD project, together with the methodology with which they shall be approached. The objectives will be divided into two sections. The first (A) consists of bibliographical reviews that the student will have to learn in order to acquaint himself with the basic principles of ultra-cold atoms and quantum thermodynamics. The second (B) contains the main goal of the project, which is the theoretical study aimed at proposing experiments for an autonomous absorption refrigerator.

A. Bibliographical review and basic tools

A.1 **The physics of ultra-cold atoms:** The student will carry out a detailed bibliographic review of the physics of ultra-cold atoms, including how to implement the optical lattices and what kinds of Hamiltonians can be modeled. This part will benefit from the expertise in quantum field theory acquired by Mr. Soldati during his masters. This part of the project will be largely based on articles from the ETH group, as well as the PhD theses of former students in the group. It will also count with the assistance of Profs. Cecilia Cormick, from University of Cordoba.

A.2 **Quantum heat engines and absorption refrigerators:** in parallel, the student will also study the physics of quantum heat engines and absorption refrigerators. Useful reviews include [66, 75, 76]. A key aspect of absorption refrigerators is the need for a three-body non-Gaussian Hamiltonian, as will be discussed below in Sec. 3B (see also Ref. [77]). This part will count with the collaboration of Dr. Mark Mitchison, author of Refs. [66, 75] and a collaborator of Prof. Landi, who is planning to visit the University of São Paulo during the second semester of 2019, as a part of a ongoing collaboration with the group of Prof. John Goold, from Trinity College Dublin.

A.3 **Overview of experimental implementations of quantum heat engines:** Several experimental groups, in a variety of platforms, began pursuing implementations of quantum heat engines in the last few years [59–65]. Throughout his PhD, Mr. Soldati will be constantly studying the already published papers, as well as any other new ones that appear. This will help him to have a more global understanding of the challenges involved in implementing heat engines operating at the quantum regime.

Concerning all of the above topics, Mr. Soldati will also benefit from short-courses that will be held at IFUSP in 2019, given by specialists from the ultra-cold atoms community, which are currently being organized by Prof. Landi.

B. Execution of the main objectives of the project

B.1 **Hamiltonian features of an absorption refrigerator:** The double-cavity setup is a natural extension of the problem used in Ref [68] to simulate transport between two reservoirs. In that case, one of the reservoirs was the leaky cavity and the other were the incoherent losses in the Rubidium gas. Now, with the double-cavity, we can therefore have a total of 3 reservoirs (since we have 2 leaky cavities). This type of 3-bath model can be used to implement an absorption refrigerator. As discussed in Refs. [66, 75, 76], one of the defining features of an absorption refrigerator is the need to use a non-Gaussian Hamiltonian, of the form

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + \omega_c c^\dagger c + g(a^\dagger bc + ab^\dagger c^\dagger), \tag{7}$$

where a, b and c are bosonic modes. In this interaction the mode c serves to transfer excitations from a to b and vice-versa. The similarity in structure with Eq. (3) is evident. For this reason, the Hamiltonian in Eq. (3) offers a perfect opportunity for achieving this. As a first step in implementing the absorption refrigerator, Mr. Soldati will focus on these Hamiltonian aspects. First, he will strengthen further this connection between Eq. (7) and (3), including a detailed study on the magnitude of the free parameters in the Hamiltonian. Secondly, Mr. Soldati will investigate the role of the augmented symmetries of Eq. (3) in this thermodynamic scenario. Finally, he will return to the original many-body Hamiltonian (1) and investigate what other types of effective interactions could possibly be engineered, that could be of interest to the quantum thermodynamics community.

B.2 **Dissipative aspects of an absorption refrigerator:** As the second ingredient, the student will focus on understanding the dissipative ingredients necessary for implementing the absorption refrigerator. This part is, from a technical point of view, the most challenging. In addition to the two leaky-photon reservoirs from the cavities, there are also incoherent losses related to the different modes of the BEC. These losses will have different effective temperatures whenever the energies of the BEC modes are different. Hence, they will function as the hot and cold baths of the absorption refrigerator. On the other hand, the role of the work reservoir is not so trivial, and will be the main challenge in the development of this project. In the simplest configuration, the joint effect of the two cavities can be combined to lead to an effective driven-dissipative mechanism. Assessing whether this would suffice to induce the desired effect is not trivial and will be one of the questions to be addressed. Alternatively, one may also introduce additional ingredients into the cavity modes, such as periodic drives, thermal noise or radiation squeezing.

B.3 **Characterization of the absorption refrigerator:** Irrespective of the specifics of how the refrigerator will be implemented, Mr. Soldati will work to provide a full analytical/numerical characterization of the properties of the refrigerator, such as the coefficient of performance and the entropy production. This will benefit from the expertise of Prof. Landi in continuous time engines [78, 79], time-periodic cycles [80, 81], the characterization of irreversible entropy production [82, 83] and the use of quantum phase space to characterize entropy production [68, 69, 84, 85].

B.4 **Influence of the quantum phase transition in the operation of the refrigerator:** An important feature of the Hamiltonian (3) is the existence of a quantum phase transition to a supersolid phase [17]. The potential use of criticality as a resource for the operation of heat engines has been the subject of recurring investigations [86, 87]. In the present case this acquires an additional relevance in light of the notion of symmetry augmentation discussed in Eq. (5), which allows one to break both a discrete as well as a continuous symmetry. As a final part of this PhD project, Mr. Soldati will address the possible implications of this feature to the operation of the absorption refrigerator. This is a high scientific impact question which, if adequately addressed, could have a significant impact for the quantum thermodynamics community.

4 Summary and perspectives

To summarize, in this PhD research project we propose to investigate the implementation of a fully quantum absorption refrigerator using ultra-cold atoms in a double optical cavity. This research proposal is both timely and ambitious. It combines tools and concepts from the fields of ultra-cold atoms and quantum thermodynamics, two of the fast growing communities in physics. And, if well implemented, could lead to publications in high impact scientific journals. It may also eventually lead, in the future, to an actual experimental implementations using the experimental setup of Prof. Esslinger's group.

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