Report - 1st PhD year

Alba Crescente (XXXV cycle) Supervisor: Prof. Maura Sassetti

Research activity:

During the first year of my PhD I focussed my research activity on the topic of quantum batteries (QBs), namely elementary quantum systems that allows to store, transfer and release energy with better performances compared to their classical counterpart. In this context I considered the theoretical description of different possible realistic implementation based on qubit coupled to classical or quantum external drives. Using these models I also adrassed important open problems such as quantum energy fluctuations and dissipation due to an external environment.

In the following I describe in more details the different lines of research:

- **Quantum batteries coupled to a classical time dependent external drive (charger)**

  Here the battery is modeled as a collection of N independent two-level systems (TLSs), namely quantum systems made of two distinguishable states usually labeled ground state (lower energy) and excited state (higher energy). Our aim is to completely charge the battery, namely reach the excited stated starting form an arbitrary initial state (representing the initial preparation of the QB). For various possible technological applications it is important to achieve this charging in the shortest time enhancing the charging power, i.e. the energy stored in a given time interval. Moreover it is also important to consider quantum fluctuations of the energy. These are usually neglected in the literature, but they can have detrimental effects on the charging of the QB. In this framework I have analyzed the above figures of merit (stored energy, charging power and fluctuations) comparing the effects of three different shapes of external drive, namely a static drive (the most used in literature), a monochromatic source and a train of peaked rectangular pulses. As a first consideration it is possible to observe that, tuning the parameters, a train of rectangular pulses leads to a faster charging compared to the harmonic source and the static one. Furthermore, a complete charging of the QB can be achieved even at small driving amplitude in the case of the time dependent drives while it is not possibile for the static one. Moreover I focussed my attention on the role of different initial states. The main result obtained from this analysis is that an optimal charging is achieved when the battery is initialized in its empty state (ground state of the TLS), leading to complete absence of energy fluctuations. Other initial pure states lead either to longer charging times or considerable energy fluctuations, which can be explained by means of the path followed by the state evolution on the surface of the Bloch sphere. These results have been published in [1].

- **Quantum batteries coupled to an external environment**

  Most of the literature about QBs considers them as closed systems and justifies this statement by assuming that the evolution of the system is investigated for times shorter than the relaxation and dephasing times of the TLSs. It is however important to see how a battery coupled to an external environment is affected by dissipation both in its charging and discharging processes. In my study I have considered N independent TLSs charged by means of an external classical static drive, coupled to a thermal reservoir to analyze how dissipation affects stored energy and charging power of the QB. Taking into account the limit of weak coupling with the environment I found that, tuning the parameters, better performances concerning both these figures of merit can be reached compared to the case without dissipation. Another important result is that after "switching-off" the charger the amount of energy stored in the battery remains quite stable. These considerations lead to the possibility of engineering QBs in solid state devices where the presence of an external environment is unavoidable. These results have been published in [2].

- **Quantum batteries coupled to a single cavity**

  Here the battery is represented by N TLSs embedded in a cavity with a single photonic mode. The radiation of the cavity coupled with the TLSs acts as the charger in this system. In this context it is important to analyze what is called collective advantage, namely the capability of reaching better performances in terms of charging times and charging power compared to the results obtained in the independent case, where each of the N TLSs is coupled to a separate photonic cavity. In literature it was observed a $\sqrt{N}$ speed-up using a single-photon interaction (related to the conventional dipole coupling between the TLSs and the cavity). In my study I have considered an exotic coupling with the cavity given by the two-photon interaction, which is usually negligible compared to the single-photon one but that in some recent experimental proposal, based on superconducting qubits, has been enhanced and made dominant. Indeed I found a regime of parameters where this unconventional interaction dominates the dynamics, leading to important improvements of the QB performances. Here considering different interaction strengths I found that for large number of TLSs a N advantage compared to the independent system is achieved. Moreover I also showed that the two-photon coupling leads to better performances compared to the single-photon one both in the charging times and in the charging power. These results have been recently submitted [3].

A natural consequence of these studies will be the analysis of dissipative effects in the case of N TLSs collectively coupled to a single cavity and also coupled to an external environment.

Publications:

[1] A. Crescente, M. Carrega, M. Sassetti, D. Ferraro, *Charging and energy fluctuations of a driven quantum battery*, New J. Phys. **22**, 063057 (2020).

[2] M. Carrega, A. Crescente, D. Ferraro, M. Sassetti, *Dissipative dynamics of an open quantum battery*, New. J. Phys. **22**, 083085 (2020).

[3] A. Crescente, M. Carrega, M. Sassetti, D. Ferraro, *Ultrafast charging in a two-photon Dicke quantum battery*, submitted to Phys. Rev. B., *arXiv:2009.09791.*

Courses and Exams:

I have attended and passed the exams of the following courses:

- **Quantum Optics** (PhD course)
- **Introduction to Quantum Technology** (Second half of the Master course)
- **Hand-on Crash Course on Theoretical Condensed Matter Physics** (PhD course)
- **Introduction to the Foundations of Quantum Mechanics and Applications** (PhD course)