Report - 3$^{\text{RD}}$ PhD year

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

Research activity:

During the third year of my PhD I have investigated the topic of energy transfer between quantum devices. In particular I studied the energy transport from a full charger to an empty quantum battery (QB), both modeled as two-level systems (TLSs). In this context I considered as full the TLS in the excited state and as empty the TLS in the ground state. Moreover I identified as ideal an energy transfer process that leads to a charger in the ground state and a QB in the excited state. The case of direct energy transfer between two quantum devices was already studied in literature and presented several flaws. In particular it is characterized by a short interaction between the two TLSs ($\sim \mu$m) and more importantly it allows to achieve a complete energy transfer only in the case of two TLSs on resonance, i.e. TLS with the same energy separation. These two problems strongly affect the implementation of this setup. In fact experimentally it is really difficult to realize identical TLSs and it would be also relevant to coherently transfer energy over a longer range ($\sim$ mm). In this direction I studied how to overcome these issues by adding, between the charger and the QB, a mediator of the energy transfer, namely a third TLS or a photonic cavity. In addition, I also studied the effects of adding more than one TLS as a madiator and I compared the theoretical results with the one obtained working on the IBM quantum machines.

In the following I describe in more details the effects of the different mediators.

- **TLS-mediated energy transfer**

  The first idea is to add a third TLS as the mediator between the charger and the QB. We can consider the mediating TLS both as empty or full, obtaining different results. In the first case, where the additional TLS is in the ground state, a complete energy transfer can be achieved when the system is on resonance. However the process is slower compared to the direct case since firstly the charger transfers energy to the mediator and only later it can be transferred to the QB. Different is the situation in which the mediator is initially in the excited state. When the system is on resonance the QB reaches a complete charging with times similar to the direct case. This is possible because here the energy is provided directly to the QB by the mediator. Off resonance, i.e. when the TLSs have different energy separations, we don't observe better performances compared to the direct case and only $\sim 20\%$ of the total energy can be transferred. In general the only advantage of this model is the possibility of longer range interaction due to the presence of the mediator.

- **Cavity-mediated energy transfer**

  The addition of a cavity presents several advantages. Firstly, it has been shown experimentally, that energy transfer between two quantum devices mediated by a photonic cavity allows for a long range and stable interaction. Also, in this model we have the possibility of exploiting the additional degree of freedom offered by the number of photons n to improve the performance of the energy transfer in the system. In fact, by considering as example $n = 8$, we observe that on resonance the complete energy transfer is achieved 3 times faster compared to the other two cases. Moreover, when off resonance, the addition of the photons in the cavity allows to achieve a better energy transfer ($\sim 60\%$ of the total energy). Moreover by further increasing the number of photons in the cavity it is possible to restore an almost complete energy transfer. These considerations allows to state that the cavity as a mediator of the energy transfer process is desirable and shows important implications for experimental implementations, where identical TLSs are difficult to realize.

These results are in publication on Physical Review Research [2].

- **Coherent energy transfer in IBM quantum machines**

  Another point I have addressed is the possibility of adding more than one TLS as a mediator for the energy transfer. This has been done both by studying the theoretical model, where the system consists of a total of N TLSs, where $N-2$ of them are acting as the mediator, and by implementing it on the IBM quantum machines. Here the TLSs are transmon qubits coupled capacitively, which well describe the system above. In this set up we want to compare the passive energy transfer with an active one where we control the interaction between TLSs in such a way that it is possible to decide when the energy can be transferred between them and when not. This should improve the performance of the energy transfer in the TLS-mediated scenario and also introduce a possibility on how to implement it experimentally.

These results are in preparation and will be soon submitted [3].

Publications, time period 15/09/2021-15/09/2022:

[1] A. Crescente, *Advantages of two-photon processes in quantum batteries*, Il Nuovo Cimento 45 C **6**, 165 (2022).

[2] A. Crescente, D. Ferraro, M. Carrega, M. Sassetti, *Enhancing coherent energy transfer between quantum devices via a mediator*, in publication on Physical Review Research.

[3] A. Crescente, G. Gemme, D. Ferraro, M. Grossi, S. Vallecorsa, M. Sassetti, *Passive vs active energy transfer in IBM quantum machines*, in preparation.

Online Courses, time period 15/09/2021-15/09/2022:

I have attended the online **Course on Energetics in the quantum regime** (02-05 May 2022), Università degli Studi dell'Insubria.

Conferences and Schools, time period 15/09/2021-15/09/2022:

I have attended the following online conferences and schools:

[1] **Openness as a resource: Accessing new quantum states with dissipation** (31 January- 04 February 2022).

[2] **Conference on quantum thermodynamics** (27 June-01 July 2022).

[3] **SQMS/GGI Summer School on Quantum Simulation of Field Theories** (25-29 July 2022).

[4] **SIF National Congress** (12-16 September 2022). Oral Talk: *Enhancing coherent energy transfer between quantum batteries via a mediator*.

Achievements, time period 15/09/2021-15/09/2022:

- Winner of the "Assegno di ricerca" with title "Studio teorico di batterie quantistiche e dispositivi per il trasferimento coerente di energia", scientific-disciplinary sector FIS/03 Fisica della Materia, at the Physics Department, Università di Genova, (01 September 2022-31 August 2023).
- Winner of a publication on the Nuovo Cimento journal for the talk "Advantages of two-photon processes in quantum batteries" at the "Congresso Nazionale SIF" 2021.

Other activities, time period 15/09/2021-15/09/2022:

- **Didactic Tutor, project: A_ING_12**
  Tutor for the course *Fisica Generale* of the bachelor's degree in *Ingegneria Navale*. 30 hours (01 October 2021 - 30 June 2022).
- **Referee for international journals**: New Journal of Physics, Physical Review A, Physical Review E, Physical Review Letters, Journal of Physics A: Mathematical and Theoretical.
- **Assistant Guest Editor** for the "New trend in quantum batteries and energetics in the quantum regime" special issue for Entropy journal.

I spent the last two months of this PhD year writing my PhD thesis with the aim of defend it in early 2023.