Annual PhD report - 1st year

Giulia Gemme

XXXVIII cycle

Supervisor: Dr. Dario Ferraro

1 Research activity

During the first year of my PhD I worked in the field of quantum thermodynamics, focusing my study on quantum batteries (QB)s, namely miniaturized devices exploiting non-classical features to efficiently store, transfer and release energy on-demand. In this context, I mainly focused on characterizing the performances of these devices combining theoretical analysis, simulations and execution on real quantum machines accessible in cloud via the IBM Quantum Lab platform. In particular, I have investigated two possible kind of devices: collections of N two-level systems coupled to photons trapped in a resonant cavity [1] and three-level systems coupled to a classical external drive [2].

In the following I describe in further detail the two different lines of research.

- In my first work I have considered a Dicke QB. The Dicke model describes the interaction between light and matter: the light component, photons trapped in a resonant cavity, is described as a single quantum mode, while the matter is described as a set of two-level systems. I consider such model in the dispersive regime, where the photons trapped in the resonant cavity are much more energetic with respect to the two-level systems embedded into it. Under such off-resonant conditions, even an empty cavity can lead to the charging of the QB through a proper modulation of the matter-radiation coupling. This counter-intuitive behaviour has its roots in the effective interaction between two-level systems mediated by virtual photons emerging from the fluctuations of the quantum electromagnetic field. In order to properly characterize it, I studied relevant figures of merit such as the stored energy, the time required to reach the maximum charging, and the averaged charging power. Moreover I considered the scaling of stored energy and power as a function of the number N of two-level systems and for different values of the matter-radiation coupling, finding, in the strong coupling regime, performances in line with what is reported for the Dicke QB in the resonant regime.
- In my second work the QB is a superconducting circuit in the transmon regime and the charging is induced by a classical external drive. I compared two different charging protocols able to promote the transmon from the ground state to the second excited state, I therefore consider it as a three-level system. In the first case the complete charging is achieved through the application of two sequential pulses, while in the second the charging occurs in a unique step applying the two pulses simultaneously. Both protocols are analytically solvable leading to a complete control on the dynamics of the quantum system. According to this, it is possible to determine that the latter approach is characterized by a shorter charging time, and consequently by a greater charging power. I have then tested these protocols on IBM quantum devices that are based on superconducting circuits in the transmon regime.

Remaining in this field of research I'm currently investigating the possibility to efficiently simulate the thermalization steps of thermodynamics cycles using IBM quantum devices. This is an aspect still not largely investigated in literature which could lead to a better comprehension of the thermodynamics of miniaturized devices.

2 Courses and exams

I have attended the following courses:

- **Energetics in the quantum regime**, Dr. Dario Ferraro (PhD course)
  Exam given on 01/09/2023
- **Crash Course on Theoretical Condensed Matter Physics**, Dr. Niccolo Traverso Ziani (PhD course)
- **Machine learning**, Dr. Cesare Molinari, Prof. Lorenzo Rosasco, Prof. Silvia Villa (Master Degree course)

3 Publications

[1] G. Gemme et al. "Off-Resonant Dicke Quantum Battery: Charging by Virtual Photons". In: *Batteries* 9.4 (2023). ISSN: 2313-0105. DOI: `10.3390/batteries9040197`. URL: `https://www.mdpi.com/2313-0105/9/4/197`.

[2] G. Gemme et al. *Qutrit quantum battery: comparing different charging protocols*. Submitted to: *Quantum Science and Technology*. 2023. arXiv: `2306.14537 [quant-ph]`.

4 Schools and conferences

- **International Conference on Quantum Technologies for High-Energy Physics (QT4HEP22)**
  November 1-4, 2022, CERN, Geneve, Switzerland
  `https://indico.cern.ch/event/1190278`
  I presented a poster ("IBM Quantum Platforms: A Quantum Battery Perspective") in the poster session and it has been awarded as one of the best poster presented.
- **CERN QTI lecture series**
  May 17, 2023, Held online
  `https://indico.cern.ch/category/14582/`
  Talk "IBM Quantum Platforms: A Quantum Battery Perspective"
- **Quantum Matter International Conference – QUANTUMatter 2023**
  May 23-25, 2023, Madrid, Spain
  `https://www.quantumconf.eu/2023`
  I presented a poster ("Qutrit quantum battery: sequential vs simultaneous charging") in the poster session.
- **Summer School on Open Quantum Systems and Mesoscopic Physics**
  June 4- 9, 2023, 20 hours, Hyytiälä, Finland
  `https://instituteq.fi/oqs2023`
  I presented a poster ("Qutrit quantum battery: sequential vs simultaneous charging") in the poster session.

5 Other activity

- **Didactic tutor, project: A_SMFN_01**.
  Tutor for the course Fisica Generale 1 of the bachelor's degree in Physics.
- Referee for Physical Review E