Second Semester Report

Alexandra Simonová (simonalxndra@student.elte.hu)
Statistical Physics, Biological Physics and Physics of Quantum Systems PhD Program
Supervisor: András Vukics
Thesis title:
Spin Models and Multistability in a Cold-Atom Cavity QED System

Introduction

The general background and motivation of this research were introduced in detail in the first-semester report. Briefly, the work is carried out in a cold-atom cavity quantum electrodynamics (cavity QED) platform, where ultracold atoms interact strongly with the field of a high-finesse optical cavity. The cavity mediates long-range interactions and introduces dissipation through photon loss, making the system a versatile platform for studying open quantum systems. Besides enabling the investigation of open-system dynamics, cavity QED systems can realize effective spin models that are difficult to access in conventional solid-state settings.

Research work carried out in the first semester

During the beginning of the semester, measurements were carried out to investigate the system response under different transverse pump powers, cavity detunings, and magnetic trapping conditions. In parallel with data acquisition, significant effort was devoted to optimizing the experimental setup. This included improving laser and cavity operation, implementing enhanced cooling schemes, and exploring different parameter settings to achieve lower atomic temperatures and higher atom numbers, thereby improving the overall performance of the cold-atom cavity QED system.

Several technical issues affecting laser frequency stabilization and cavity operation were identified and resolved, leading to improved reliability of the experiment. preparations were initiated for the future implementation of a homodyne detection scheme for the cavity output field. Homodyne detection will provide access to both the amplitude and phase quadratures of the cavity field with significantly improved sensitivity compared to direct intensity measurements. This will enable more precise characterization of atom–cavity interactions and facilitate the observation of collective phenomena such as self-organization, bistability, and other nonequilibrium dynamics that arise from the nonlinear feedback between the atomic ensemble and the cavity mode.

Towards the end of winter a series of diagnostic measurements was performed to optimize the preparation of the cold atomic ensemble and improve the overall stability of the experiment.

Following this work, the focus shifted to refining the MOT and cooling sequence. Beam powers, frequencies, polarizations, shutter timings, and geometrical alignment were systematically optimized. These efforts resulted in a somewhat colder atomic cloud, improved transfer into the magnetic trap, higher atom numbers, and increased trapping lifetimes. Subsequent work concentrated on improving the stability and reliability of the laser systems and other experimental subsystems through continued optimization of beam alignment, optical coupling, and atom-loading components.

In parallel with the optimization of the existing setup, planning for a future 2D MOT upgrade was initiated with the goal of improving atom loading. This involved designing the optical layout, allocating laser power for the new beam paths, and preparing the necessary vacuum and mechanical components.

Although the initial plan was only to prepare for a future 2D MOT upgrade, an unexpected failure of the electrical feedthrough supplying current to the rubidium dispensers in the main vacuum chamber made the upgrade immediately necessary. As a consequence, a significant part of the second half of the semester was dedicated to the implementation of the 2D MOT system. This involved extensive vacuum work, including the preparation and conditioning of the differential pumping section connecting the 2D MOT and the main chamber, as well as cleaning, assembly, and bake-out procedures required to achieve suitable vacuum conditions. In parallel, the optical infrastructure of the 2D MOT was designed and gradually implemented.

My primary contribution during this phase was the construction and alignment of the optical beam paths required for the 2D MOT, including the repump and push beams, the combination of the repump and cooling beams, and the integration of the corresponding AOMs and optical shutters.

As a result of these unforeseen maintenance and upgrade activities, experimental operation was largely suspended during the second half of the semester. Consequently, no substantial physics measurements were carried out that would warrant detailed discussion in this report. Nevertheless, the completed maintenance work and the implementation of the 2D MOT are expected to substantially improve the reliability, stability, and loading performance of the apparatus for future measurement campaigns.

Nevertheless, the completed maintenance work, the implementation of the 2D MOT are expected to substantially improve the reliability, stability, and loading performance of the apparatus for future measurement campaigns. Also the ongoing development of a homodyne detection system will provide sensitive access to the amplitude and phase quadratures of the cavity output field, enabling more precise studies of atom–cavity interactions and collective phenomena such as self-organization, multistability, and nonequilibrium dynamics.

Publications

List of all publications produced during the doctoral studies:

- [1] - published article in Physical Review Letters Applied `https://journals.aps.org/prapplied/abstract/10.1103/wclj-d912`
- [2] - submitted

Academic activities in the current Semester

ELTE courses I attended in this semester:

- Quantum information theory (FIZ/1,3/060E)
- Laser Cooling and Trapping of Neutral Atoms (FIZ/1,3/042E)

Summerschools:

- Participation in the **International Summer School on Driven-Dissipative Many-Body Systems, TU Dortmund University, Germany (June 2026).** Topics included open quantum systems, cavity QED, ultracold atoms, and nonequilibrium many-body physics. I also presented a poster based on our recently published article, *Cold-Atom Buoy: A Differential Magnetic Sensing Technique in Cold Quadrupole Traps*, during the poster session.

Conferences

- Accepted to participate in the 30th Central European Workshop on Quantum Optics (CEWQO 30), Erlangen, Germany (July 2026). During the poster session, I will also present the same poster based on our recently published article, *Cold-Atom Buoy: A Differential Magnetic Sensing Technique in Cold Quadrupole Traps*.

Teaching and Educational Activities in the Current Semester

- Mentored a B.Sc. student in a laboratory project focused on the first steps toward the implementation of a homodyne detection setup.

References

[1] Á. Kurkó, D. Nagy, A. Simon, T. W. Clark, A. Dombi, D. Varga, F. I. B. Williams, J. Fortágh, P. Domokos, and A. Vukics. "Cold-atom buoy: A differential magnetic sensing technique in cold quadrupole traps". In: *Phys. Rev. Appl.* 25 (5 May 2026), p. 054063. DOI: `10.1103/wclj-d912`. URL: `https://link.aps.org/doi/10.1103/wclj-d912`.

[2] Á. Kurkó, B. Gábor, D. Varga, A. Simon, T. Barmashova, A. Dombi, T. W. Clark, F. I. B. Williams, D. Nagy, A. Vukics, and P. Domokos. *Collective inhibition of light scattering from atoms into an optical cavity at a magic frequency*. 2026. arXiv: `2601.08978 [quant-ph]`. URL: `https://arxiv.org/abs/2601.08978`.