First 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

Quantum spin models play a central role in understanding magnetism at a fundamental level, they are important in the engineering of novel materials and the preservation of quantum information. They are also widely used as effective models for studying quantum phase transitions and nonequilibrium dynamics. However, many relevant spin models are difficult to realize and control in solid-state systems. For this reason, well-controlled quantum platforms for studying spin interactions are highly relevant. Cavity quantum electrodynamics (cavity QED) with cold atoms provides such a platform. In these systems, atoms are strongly coupled to the field of a high-finesse optical cavity. The cavity creates long-range interactions and dissipation through photon loss, which makes cavity QED an ideal platform for studying open quantum systems. The interaction between atoms and the cavity field leads to nonlinear feedback, which can give rise to self-organization, multistability, and collective dynamics far from equilibrium. Understanding such behavior is a major challenge in modern quantum simulation and nonequilibrium physics.

Research work carried out in the first semester

During the current semester, the experimental work focused on the preparation and optimization of our cold-atom cavity QED setup for the study of self-organization, quantum spin models, and multistability. The experiments are performed in a cold-atom setup using ultracold rubidium atoms coupled to a high-finesse optical cavity placed inside a vacuum chamber. The atomic sample is prepared and manipulated using laser cooling and optical pumping techniques. The sample is then magnetically transported into the cavity, where it is illuminated with laser light to induce scattering into the cavity. While in the cavity, the atoms sit in a dipole trap that is created by another laser, which is propagated along the direction of the cavity axis. The resulting cavity output is split into horizontal and vertical polarizations and detected by single-photon counters. The photon count rates of these two channels form the basis of the experimental data that is evaluated and used to identify the mentioned behaviors and phenomena.

There are still many parameters and small adjustments to test in the experiment to get closer to observing these phenomena in a more accurate and reliable way, for example optimizing the loading and tuning the dipole trap, testing different cavity detunings, and many more. Thus in order to enable precise and reliable measurements of the targeted phenomena, the setup underwent extensive optimization. Like the optimization of atom number during the relevant stages of the experimental sequence. In addition, several optical elements on the optical table were rearranged or replaced to reduce stray light entering the vacuum chamber during measurement periods, which is crucial for minimizing background signals and decoherence. These optimization tasks required a substantial portion of the semester. At the same time, additional calibration and verification measurements were performed to further improve the accuracy of the measueremnts. In particular, resonance verification was checked using Rabi splitting–based measurements to ensure that the relevant laser and cavity frequencies were precisely tuned.

Results

Rabi-Splitting–Based Resonance Verification

A weak cavity probe field was applied after switching off the magnetic trap, and the cavity resonance with the atomic $F = 2 \rightarrow F = 3$ transition was tested by sweeping the transverse drive laser frequency across the resonance within a ± 14 MHz range over 4 ms. By repeating this sweep for several frequency offsets, the symmetry of the observed Rabi splitting was used to determine exact resonance, where the laser frequency matches the resonance frequency. The results indicated (Figure 1) a frequency offset of several megahertz between the assumed reference and the true atomic resonance. This offset is likely linked to the mechanism of how the reference-laser crossover lock point is determined. The Rabi-splitting signal also indicated whether the final transport position is optimal, showing how well the atoms overlap with the cavity mode and the drive laser.

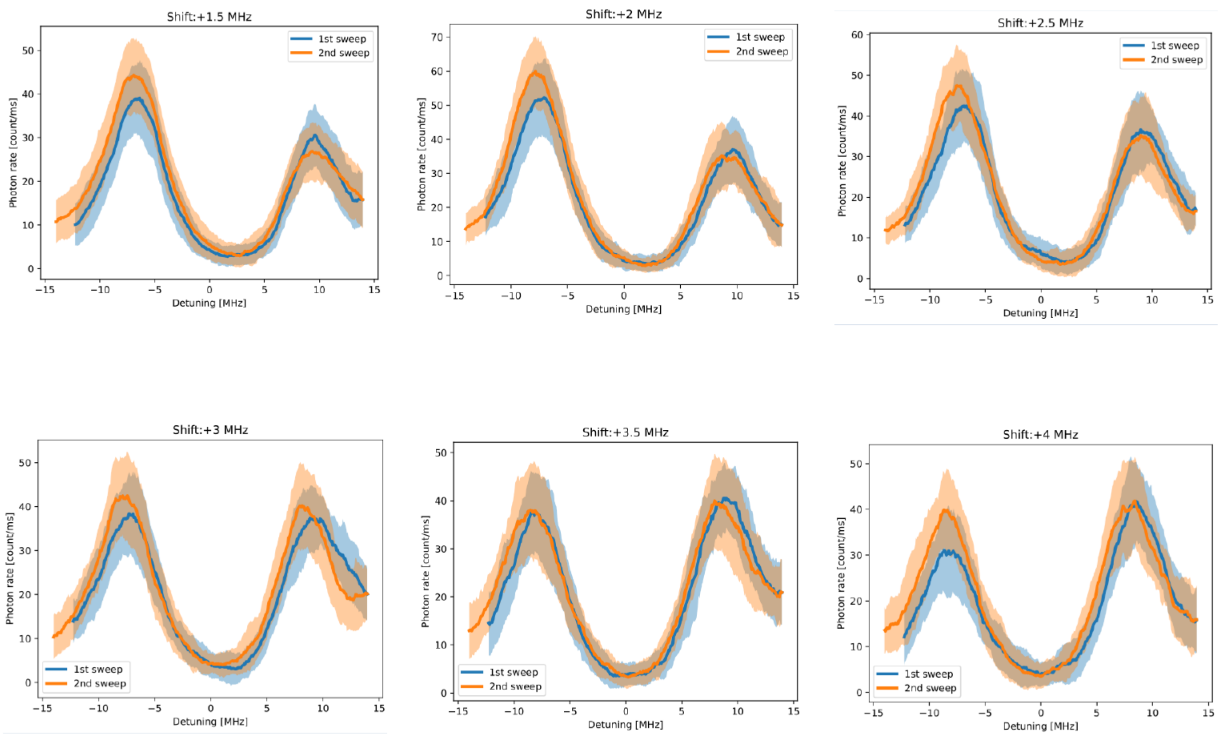

Figure 1: Cavity transmission spectra obtained after release from the magnetic trap, with each spectrum averaged over 25 repetitions.

Selforganization

We search for signatures of self-organization[1], in order to observe it we performed measurements under various experimental conditions. These include ramping or holding the transverse drive laser constant, switching the magnetic trap on or off during illumination, and either keeping the dipole trap depth fixed or varying it. For example (Fig. 2), one measurement under these experimental conditions was performed with the magnetic trap kept on, the dipole trap kept at its original (undecreased) power, an atomic detuning of $\Delta_A = 506$ MHz, and a cavity detuning of $\Delta_C = 0$ MHz.

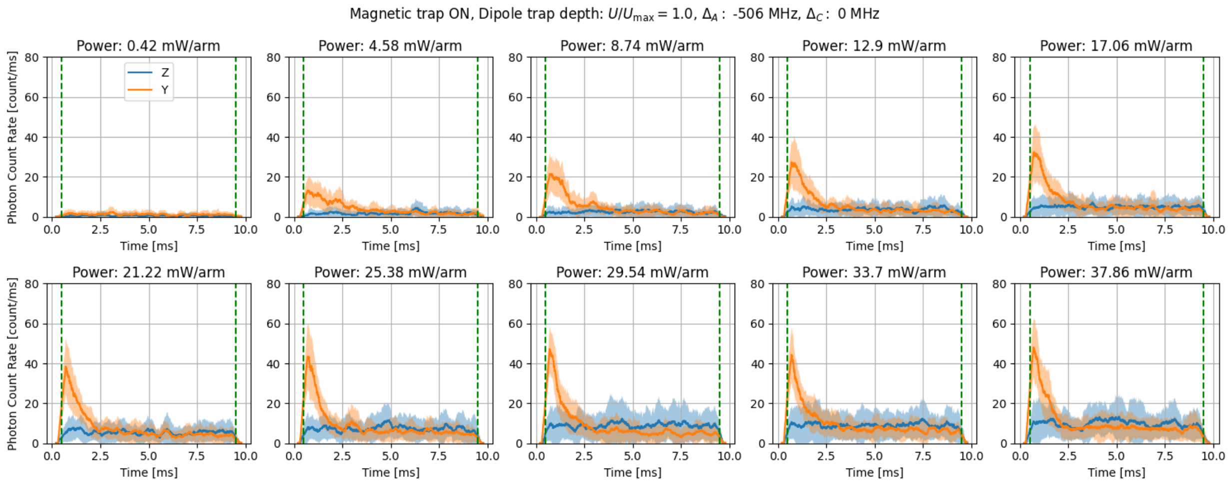

Figure 2: Averaged measurement results for ten equally spaced transverse drive powers. The atomic detuning is $\Delta_A = -506$ MHz, and the cavity is resonant with the drive field $\Delta_C = 0$ MHz for all measurements.

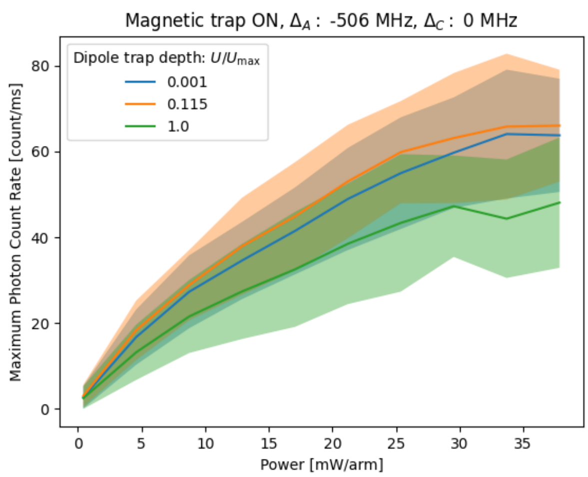

Figure 3: Maximum photon count rates or the peaks observed in Fig. 2.

When the magnetic trap was kept on, the dipole trap depth was first reduced by a factor of 10 and then by a factor of 1000. This reduction seems to increases the scattering rate by roughly a factor of 1.5 (Fig. 3). From here on, we will continue the measurements performed with the magnetic trap on and the reduced dipole trap depth.

Publications

List of publications associated with work carried out during the first semester:

- Árpád Kurkó, Dávid Nagy, Alexandra Simon, Thomas W. Clark, András Dombi, Dániel Varga, Francis B. Williams, József Fortágh, Peter Domokos, and András Vukics. Cold-Atom Buoy: A Differential Magnetic Sensing Technique in Cold Quadrupole Traps (https://arxiv.org/abs/2511.08797) - **submitted**
- 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 (https://arxiv.org/abs/2601.08978) - **submitted**

Academic activities in the current Semester

ELTE courses I attended in this semester:

- Classical and quantum optimization (FIZ/3/097)
- Cavity quantum electrodynamics (FIZ/3/070E)

References

[1] Peter Domokos and Helmut Ritsch. "Collective Cooling and Self-Organization of Atoms in a Cavity". In: *Phys. Rev. Lett.* 89 (25 Dec. 2002), p. 253003. DOI: 10.1103/PhysRevLett.89.253003. URL: https://link.aps.org/doi/10.1103/PhysRevLett.89.253003.