Collective Effects of Laser-Driven Cold Atoms in an Optical Cavity

PhD theses

Supervisor: Peter Domokos
research professor

Doctoral School of Physics
Department of Theoretical Physics
University of Szeged

Bence Gábor

2025

Theses of the PhD thesis

Collective Effects of Laser-Driven Cold Atoms in an Optical Cavity

Bence Gábor

Supervisor: Peter Domokos, PhD, research professor

Doctoral School of Physics

Department of Theoretical Physics

Faculty of Science and Informatics

University of Szeged

Quantum Optics "Momentum" Group

Department of Quantum Optics and Quantum Information

Institute for Solid State Physics and Optics

HUN–REN Wigner Research Centre for Physics

Szeged, 2025

1 Introduction

Among the research fields of modern quantum physics, cavity quantum electrodynamics (CQED), arising from the application of optical cavities, reveals a genuinely distinct regime of light-matter interactions. Cavity QED schemes typically involve few degrees of freedom that are relevant to the atom-light interaction. The field is composed of a single or only a few modes, and the interacting atoms can be represented by a small set of electronic states. These systems become particularly interesting when the characteristic frequency of the coupling strength exceeds the dissipative rates. Aiming for this so-called *strong coupling regime*, CQED, as a research field, is devoted to explore the ultimate limits of non-linear atom-light interaction at the single atom, single photon level, with the prospect of a variety of applications in quantum information processing.

Within this general perspective of strongly-coupled, interacting atom-light system, CQED is an outstanding platform to study phase transitions in driven-dissipative open quantum systems [1–3]. In its natural setting, a CQED system (see a generic scheme in Fig. 1) is driven by external coherent sources, e.g. by laser or microwave radiation, meanwhile the energy is dissipated through a number of channels leading to a steady state resulting from a dynamical equilibrium between driving and loss [4]. One of the dissipation channels is the coupling of the cavity field to external, freely propagating, spatially well-defined modes, which can be efficiently collected for detection. The outcoupled field then affords an indirect observable of the intracavity steady state [5], in the sense of continuous weak quantum measurement. Although the intracavity system size is small, the continuously measured outcoupled field is a macroscopic observable, and it can be considered an *order parameter* of the system and the steady states can be referred to as *phases*. Transitions between phases can be affected by changing drive parameters (*control parameters*) and monitored as a macroscopic change in the recorded signal. Such driven-dissipative phase transitions have been discussed and experimentally studied recently in CQED [6–13].

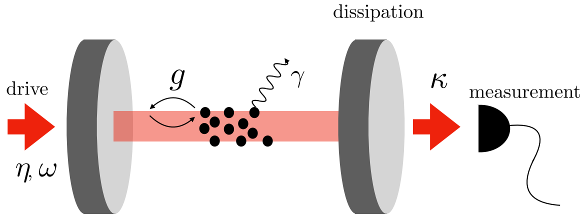

Figure 1: *A scheme of a generic CQED system. Atoms with natural linewidth γ are positioned between the mirrors of an optical resonator, coupled to its mode with coupling strength g. The cavity is driven coherently with angular frequency ω and drive amplitude η. The cavity mode decays through one of the mirrors with rate κ towards a detector. The evolution of the atom-cavity system takes place under the effect of the measurement back action.*

In 2016, the Quantum Optics Group of the HUN-REN Wigner Research Centre for Physics started to build a CQED laboratory [14]. The aim was to realize quantum technological applications based on atoms and photons. Today, the laboratory, called *Atom-photon interface*, hosts experiments which are based on complex procedures of routinely trapping and cooling rubidium atoms, coupling them to a single mode of a high-finesse optical resonator and observing feeble light signals by single photon counters as well as by avalanche photodiodes. By the time I joined in 2021, the group had already published experimental results [15, 16]. In the spirit of *learning by doing*, I started to use, maintain and develop the system with my colleagues. Now, I have the honour of being the first in the group to write a PhD thesis out of measurements performed in the Atom-photon interface. As a pioneering work in this sense, the present thesis (beyond its natural aim of summarizing my scientific results) also provides a detailed description of the setup, the experimental methods and the underlying principles, serving as a useful reference for both current and future members of the group.

2 Methods

2.1 Interaction of atoms with a single optical mode

For modelling the experiments and deriving the main theoretical results presented in this thesis, a semi-classical mean-field model is invoked. N identical atoms are considered with one relevant dipole transition at angular frequency $\omega_{\rm A}$, placed at the positions $x^{(i)}$, $(i = 1, \ldots, N)$ along the axis of a high-finesse linear optical resonator with resonance at angular frequency $\omega_{\rm C}$. The cavity is driven by a laser field with amplitude $\tilde{\eta}$, and angular frequency ω. The atoms are considered to be pointlike objects with a dipole moment

$$\mathbf{d}^{(i)} = \mathbf{d}_{eg}\left(\sigma^{(i)} + \sigma^{(i)\dagger}\right), \tag{1}$$

where $\sigma^{(i)} \equiv \left|g^{(i)}\right\rangle\left\langle e^{(i)}\right|$ is the lowering operator, and the matrix element of the dipole moment $\mathbf{d}_{eg}$ is chosen to be real.

The total Hamiltonian of the interacting system takes the form in a frame rotating at the drive lasser frequency and in the rotating wave approximation:

$$H/\hbar = -\Delta_{\rm C} a^\dagger a - \Delta_{\rm A}\sum_{i=1}^{N}\sigma^{(i)\dagger}\sigma^{(i)} + i\sum_{i=1}^{N}\tilde{g}^{(i)}\left(a^\dagger\sigma^{(i)} - a\sigma^{(i)\dagger}\right) + i\tilde{\eta}\left(a^\dagger - a\right), \tag{2}$$

where $\Delta_{\rm C} \equiv \omega - \omega_{\rm C}$, $\Delta_{\rm A} \equiv \omega - \omega_{\rm A}$ are detunings of the laser from the cavity and from the atoms, respectively, $\tilde{g}^{(i)} = \sqrt{\frac{\omega_{\rm C}}{2\epsilon_0\hbar\mathcal{V}}}d_{eg}\cos\left(kx^{(i)}\right)$ is the coupling coefficient between the i-th atom and the cavity mode (with $\mathcal{V}$ being the volume of the cavity mode, d_{eg} the projection of the matrix element of the dipole moment to the field polarization, and $k = \omega_{\rm C}/c$ the wavenumber of the cavity mode).

Assuming homogeneous coupling, that is $\tilde{g}^{(i)} \equiv \tilde{g}$ for all i, the coupling coefficient can be factored out, and a closed set of equations can be obtained for the collective atomic operators $\Sigma = \sum_{i=1}^{N}\sigma^{(i)}$ and $N_e = \sum_{i=1}^{N} n_e^{(i)}$, $N_g = \sum_{i=1}^{N} n_g^{(i)}$, given as:

$$
\begin{aligned}
\dot{a} &= (i\Delta_{\rm C} - \kappa)\, a + \tilde{g}\,\Sigma + \tilde{\eta} + \tilde{\xi}, \\
\dot{\Sigma} &= (i\Delta_{\rm A} - \gamma)\,\Sigma + \tilde{g}\,\left(N_e - N_g\right)\, a + N\,\Xi, \\
\dot{N}_e &= -2\gamma N_e - \tilde{g}\left(\Sigma^\dagger a + a^\dagger \Sigma\right) + N\,\Theta_e, \\
\dot{N}_g &= 2\gamma N_e + \tilde{g}\left(\Sigma^\dagger a + a^\dagger \Sigma\right) + N\,\Theta_g,
\end{aligned} \tag{3}
$$

where the last term in each equation represents the noise of the corresponding operator.

The use of collective atomic operators is a crucial assumption to close the set of equations, which is exact e.g. for atoms in the antinodes of the mode, in an optical dipole lattice. This approximation is the starting point for a mean-field description of a randomly distributed ensemble of atoms when their collective behaviour is considered, such as in the experiment discussed in Ch. 3. By contrast, spatially dependent coupling coefficients must be maintained when the different positions of the individual atoms play a significant role in the dynamics, like in the case studied in Ch. 5.

The operator products in the above equations (e.g. the product $\Sigma^\dagger a$ in the evolution equation for the population N_e) make this problem analytically intractable. We resort therefore to the standard mean field approach, linearizing the above operator equations around the mean values. For later convenience, let us introduce scaled variables in the form of a sum of the scaled mean-field and scaled fluctuation variables, i.e., $a = \sqrt{N}(\alpha + \delta a)$, $\Sigma = N(m + \delta\Sigma)$, $N_e = N\left(n_e + \delta N_e\right)$ and $N_g = N\left(n_g + \delta N_g\right)$. With a suitable scaling of the parameters $g = \sqrt{N}\tilde{g}$ and $\eta = \tilde{\eta}/\sqrt{N}$, the mean field variables obey the Maxwell–Bloch equations

$$
\begin{aligned}
\dot{\alpha} &= (i\Delta_{\rm C} - \kappa)\,\alpha + g\,m + \eta, \\
\dot{m} &= (i\Delta_{\rm A} - \gamma)\,m + g\,\left(n_e - n_g\right)\,\alpha, \\
\dot{n}_e &= -2\gamma n_e - g\left(m^*\alpha + \alpha^* m\right), \\
\dot{n}_g &= 2\gamma n_e + g\left(m^*\alpha + \alpha^* m\right).
\end{aligned} \tag{4}
$$

The model above can be straightforwardly extended with other atomic levels, drives and cavity modes. Such extensions are used throughout the thesis. In Ch. 3, another ground state $|f\rangle$ and an effective drive, λ from $|g\rangle$ to $|f\rangle$ are introduced. In Ch. 4, there are two excited and two ground states with two driven cavity modes. Finally, in Ch. 5, instead of the cavity, the atoms are driven, and two orthogonally polarized cavity modes are considered, however, in this problem, the mean-field equations are not used.

2.2 Experimental methods

Frequency Stabilized Lasers and Cavities

The experimental setup relies on a series of highly stabilized, narrow-linewidth laser sources (see Fig. 2), each devoted to specific roles within the experiment. The frequencies of the lasers are fixed in the long term against drifts induced by a variety of environmental effects (temperature, pressure, humidity, etc.), and they are synchronized to each other, and ultimately, to an atomic resonance as reference. The employed lasers and cavities are the following:

1. Reference laser: A laser locked to a rubidium reference, used as frequency standard for other lasers, furthermore, for optical pumping and absorption imaging.

2. Repumper laser: Whenever other lasers can pump the atoms from the $F = 2$ ground state to $F = 1$, this laser is used to compensate by pumping the atoms back.

3. MOT laser: A laser with a tapered amplifier, driving the $F = 2 \rightarrow F' = 3$ cooling transition, necessary for the magneto-optical trap.

4. 'Science' laser: A laser with tunable frequency, used to manipulate the atoms in the cavity. One part of its light drives the cavity, the other one drives the atoms directly, from up and down, in a direction perpendicular to the cavity axis (transverse drive).

5. 'Transfer' cavity: A high-finesse optical resonator, used to transfer the frequency stability of the reference laser to the 'science' cavity.

6. 'Science' cavity: A high-finesse optical resonator in the vacuum chamber where

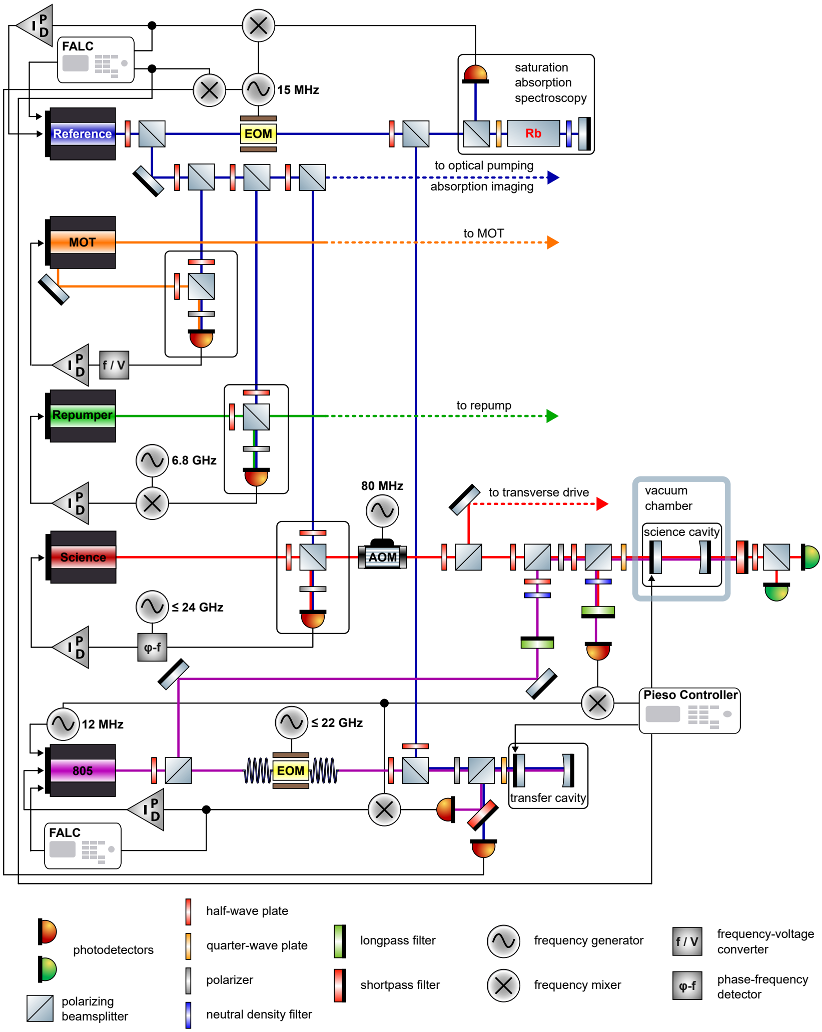

Figure 2: *Scheme of the frequency-stabilized and synchronized laser sources of our CQED laboratory. My responsibilities included operating and maintaining the setup, along with several developments such as testing, calibrating, and improving the Pieso Controller (used to stabilize the science and transfer cavities), implementing real-time control of the EOM for the 805 laser, developing the phase-locked loop for the science laser, installing and integrating new detectors at the science cavity output, and building the optical path of the transverse drive (represented only by a dashed line).*

the atom-light interaction takes place.

7. '805' laser: A laser with a wavelength of $805\,\mathrm{nm}$ used to stabilize the 'science' cavity and to realize an intra-cavity optical dipole lattice.

Experimental Protocol

The experimental protocol comprises a sequence of cooling, trapping, and transporting rubidium atoms into the science cavity for interaction. The whole experimental cycle is controlled by an ADwin-Pro II real-time process controller. For defining experimental sequences, we use a Python front-end developed in our group. The steps of the sample preparation are as follows:

1. Magneto-optical trapping: a standard method to produce cold atomic sample with high density and large atom numbers [17]. The atoms are illuminated by three counter-propagating $\sigma^+ - \sigma^-$ pairs of red detuned laser beams, while a quadrupole magnetic field is present, centred at the intersection of the optical beams. This trap simultaneously confines spatially and cools the atoms. Approximately 10^6 atoms are collected over a time duration of $\sim$1–30 s. Their temperature at this stage is $\sim 150\,\mu\mathrm{K}$.

2. Polarization gradient cooling: a method allowing for cooling below the Doppler limit ($146\,\mu\mathrm{K}$ for the $\mathrm{D_2}$ line of $^{87}\mathrm{Rb}$ [18]), based on laser polarization gradients [19]. Temperatures of $\sim$10–20 $\mu\mathrm{K}$ of the atom cloud have been achieved.

3. Optical pumping: the process of gathering atoms in a specific Zeeman sublevel by means of a resonant circularly polarized light, with a weak homogeneous magnetic field defining the quantization axis.

4. Magnetic trapping: A pair of coils driven in anti-Helmholtz configuration, produces a quadrupole field, which creates a linear potential for the atoms. Approximately $5 \cdot 10^5$ atoms are collected in the magnetic trap. Their temperature is close to that achieved by the polarization gradient cooling, but due to

imperfect matching of the centre of the magnetic trap and that of the cloud, additional heating can take place.

5. Magnetic transport to the cavity: The magnetic transport from the MOT centre to the cavity is performed by lowering the centre of the quadrupole magnetic trap adiabatically. The ramps follow a smooth function (tangent hyperbolic), in order to avoid sudden jerks.

6. Intra-cavity dipole lattice: Atoms in a standing wave, red detuned from resonance, experience a periodic potential, with minima in the antinodes, proportional to the intensity of the field. This potential, called optical dipole lattice [20], is created in the science cavity by the 805 laser used for stabilization.

3 Contributions of the thesis

The **first thesis group** summarizes the results of the publication [T1]. Detailed discussion can be found in Ch. 3.

I/1. I have shown that a first-order, driven-dissipative phase transition can be realized between hyperfine ground states of atoms loaded in a high-finesse optical cavity, by laser driving the resonator and the atoms. I have identified the intensities of the external fields as control parameters of the phase transition, and the mean intra-cavity photon number as an order parameter. Using semiclassical approximation, I have determined the phase diagram of the interacting system, in which two macroscopically discernible phases (dark and bright) are apparent, with a bistability region between the two.

I/2. I have experimentally observed the phase transition described in Thesis I/1 between hyperfine ground states $F = 1$ and $F = 2$ of laser cooled and magnetically trapped rubidium-87 atoms. Varying the intensities of the laser drive of the cavity mode and that of the atoms, I have identified the dark and bright phases, performed fast switching between them, and demonstrated bistability by measuring hysteresis curves on scanning the control parameters across the bistability region.

The **second thesis group** summarizes the results of the publication [T2]. Detailed discussion can be found in Ch. 4.

II/1. I have constructed a cavity QED model based on two driven cavity modes resonant with electronic transitions from different hyperfine ground states of atoms. Using semiclassical approximation, I have determined the phase diagram of the system under different cooperativities. Beyond the macroscopically discernible dark and bright phases and the bistable region, I have identified multistable regions as well, up to 4 coexisting phases.

II/2. I have performed a finite-size scaling of the phase transition, and showed that in the thermodynamic limit (that is in the case of infinite cooperativity), the phases correspond to pure quantum states: hyperfine ground states of atoms, and the bistability extends to the total range of the ratio of the two control parameters.

The **third thesis group** summarizes the results of the publication [T3]. Detailed discussion can be found in Chapter 5.

III/1. By loading cold rubidium atoms in an intra-cavity optical dipole lattice with a wavelength incommensurate with that of the atomic resonance, and illuminating them with laser perpendicularly to the cavity axis, I have observed subradiant scattering from the array of atoms. I have found that the subradiant atomic ensemble does not decouple from the cavity mode: I have measured the spectrum of the photon noise arising from the fluctuations in the configuration of the atoms, and it shows vacuum Rabi splitting, the hallmark of strong collective coupling.

III/2. I have observed a significant polarization rotation effect by the atom array described in Thesis III/1. The incoherent scattering from the atoms is enhanced by the cavity also into the mode with polarization orthogonal to that of the incoming field. I have provided an explanation of the polarization rotation in terms of a two-photon Raman transition within the atomic hyperfine ground state manifold.

4 Összefoglalás

Dolgozatomban nagy jósági tényezőjű optikai rezonátorhoz csatolt hideg rubídium-87 atomok rendszerén vizsgáltam hajtott-veszteséges fázisátalakulásokat és az atomok kollektív szórási tulajdonságait. Munkám, melyet a HUN–REN Wigner Fizikai Kutatóközpont Kvantumoptika "Lendület" Kutatócsoportjában végeztem, mind kísérleti, mind elméleti szempontból hozzájárul a kollektív erős csatolás mellett megvalósuló fény-anyag kölcsönhatások megértéséhez.

Külső lézeres gerjesztések intenzitásaival vezérelt fázisátalakulást mutattam ki atomok hiperfinom állapotai között, optikai rezonátorban. A fázisdiagram elkülönülő sötét és világos fázisokat mutat, köztük bistabil tartománnyal. Az átalakulást kísérletileg is megfigyeltem, kimérve a bistabilitáshoz tartozó hiszterézisgörbéket.

E rendszer elméleti kiterjesztéseként megalkottam egy olyan modellt, amely a bistabilitásban extrém tulajdonságokhoz vezet. A fázisdiagramok különböző kooperativitás-paraméterek mellett – vagyis végesméret-skálázásban – azt mutatják, hogy a termodinamikai határesetben tiszta, kollektív kvantumállapotokkal megvalósított fázisok együtt létezhetnek a kontrollparaméterek széles tartományában.

Hideg rubídiumatomok optikai rezonátorban mutatott kollektív szórási tulajdonságait vizsgáltam, a rezonátor tengelyére merőleges irányú megvilágítás mellett. A fotonzaj spektrumát mérve igazoltam a kollektív erős csatolást az atomok és a rezonátor között a vákuum-Rabi-felhasadás megfigyelésével, valamint a szubradianciát az atomok számának változtatásával.

A csoportban eltöltött idő alatt hozzájárultam a laboratórium fejlesztéséhez és a kísérletek numerikus modellezéséhez. Részt vettem egy rezonátorstabilizáló eszköz fejlesztésében, új optikai utakat építettem ki, egyfoton-detektorokat implementáltam a kísérleti rendszerbe. Általános célú szimulációs csomagot készítettem atom-rezonátor rendszerek szemiklasszikus és kvantumos modellezésére.

Összefoglalva, dolgozatom olyan kísérleti és elméleti eredményekről ad számot, melyek hozzájárulnak a hajtott-veszteséges kvantumrendszerek mélyebb megértéséhez, és alkalmazási lehetőséget kínálnak a kvantuminformáció-tárolás terén. Munkám egyúttal eszközökkel és módszerekkel is szolgál a rezonátoros kvantumelektrodinamika és a kvantumtechnológia további kutatásához.

5 Publications

Publications included in thesis

[T1] B. Gábor, D. Nagy, A. Dombi, T. W. Clark, F. I. B. Williams, K. V. Adwaith, A. Vukics, and P. Domokos. “Ground-state bistability of cold atoms in a cavity”. In: *Phys. Rev. A* 107 (2 Feb. 2023), p. 023713. DOI: 10.1103/PhysRevA.107.023713. $\mathbf{IF}_{2024} = 2.9$

[T2] B. Gábor, D. Nagy, A. Vukics, and P. Domokos. “Quantum bistability in the hyperfine ground state of atoms”. In: *Phys. Rev. Res.* 5 (4 Dec. 2023), p. L042038. DOI: 10.1103/PhysRevResearch.5.L042038. $\mathbf{IF}_{2024} = 4.2$

[T3] B. Gábor, A. K. Varooli, D. Varga, B. Sárközi, Á. Kurkó, A. Dombi, T. W. Clark, F. I. B. Williams, D. Nagy, A. Vukics, and P. Domokos. “Demonstration of strong coupling of a subradiant atom array to a cavity vacuum”. In: *EPJ Quantum Technology* 12.1 (Aug. 2025), p. 93. DOI: 10.1140/epjqt/s40507-025-00401-x. $\mathbf{IF}_{2024} = 5.6$

$\Sigma\mathbf{IF} = 12.7$

Further related publications

[F1] D. Varga, B. Gábor, B. Sárközi, K. Adwaith, D. Nagy, A. Dombi, T. Clark, F. Williams, P. Domokos, and A. Vukics. "Loading atoms from a large magnetic trap to a small intra-cavity optical lattice". In: *Physics Letters A* 505 (2024), p. 129444. DOI: 10.1016/j.physleta.2024.129444. $\mathbf{IF}_{2024} = 2.6$

$\Sigma\Sigma\mathbf{IF} = 15.3$

References

[1] H. Ritsch et al. "Cold atoms in cavity-generated dynamical optical potentials". In: *Rev. Mod. Phys.* 85 (Apr. 2013). Publisher: American Physical Society, pp. 553–601.

[2] H. Tanji-Suzuki et al. "Interaction between Atomic Ensembles and Optical Resonators". en. In: *Advances In Atomic, Molecular, and Optical Physics* 60 (2011), pp. 201–237. DOI: 10.1016/B978-0-12-385508-4.00004-8.

[3] F. Mivehvar et al. "Cavity QED with quantum gases: new paradigms in many-body physics". en. In: *Advances in Physics* 70.1 (Jan. 2021), pp. 1–153. DOI: 10.1080/00018732.2021.1969727.

[4] D. Walls et al. *Quantum Optics*. Springer Berlin Heidelberg, 2008, pp. 127–141. DOI: 10.1007/978-3-540-28574-8_7.

[5] H. M. Wiseman et al. *Quantum Measurement and Control*. Cambridge: Cambridge University Press, 2009. DOI: 10.1017/CBO9780511813948.

[6] D. Nagy et al. "Dicke-Model Phase Transition in the Quantum Motion of a Bose-Einstein Condensate in an Optical Cavity". In: *Phys. Rev. Lett.* 104 (Apr. 2010). Publisher: American Physical Society, p. 130401.

[7] K. Baumann et al. “Dicke quantum phase transition with a superfluid gas in an optical cavity”. In: *Nature* 464 (Apr. 2010). Publisher: Macmillan Publishers Limited. All rights reserved, pp. 1301–1306. DOI: 10.1038/nature09009.

[8] K. J. Arnold et al. “Self-Organization Threshold Scaling for Thermal Atoms Coupled to a Cavity”. In: *Physical Review Letters* 109.15 (Oct. 2012), p. 153002. DOI: 10.1103/PhysRevLett.109.153002.

[9] D. Schmidt et al. “Dynamical Instability of a Bose-Einstein Condensate in an Optical Ring Resonator”. In: *Phys. Rev. Lett.* 112 (Mar. 2014). Publisher: American Physical Society, p. 115302.

[10] J. Klinder et al. “Dynamical phase transition in the open Dicke model”. In: *P. Natl. Acad. Sci. USA* (Mar. 2015). Publisher: National Academy of Sciences, p. 201417132.

[11] J. Léonard et al. “Supersolid formation in a quantum gas breaking a continuous translational symmetry”. In: *Nature* 543.7643 (Mar. 2017), pp. 87–90. DOI: 10.1038/nature21067.

[12] A. J. Kollár et al. “Supermode-density-wave-polariton condensation with a Bose–Einstein condensate in a multimode cavity”. In: *Nature Communications* 8.1 (Feb. 2017), p. 14386. DOI: 10.1038/ncomms14386.

[13] T. Fink et al. “Signatures of a dissipative phase transition in photon correlation measurements”. In: *Nature Physics* 14.4 (Apr. 2018), pp. 365–369. DOI: 10.1038/s41567-017-0020-9.

[14] *Official webpage of the Quantum Optics Group*. https://wigner.hu/en/quantum-optics-and-quantum-information/quantum-optics-group. Visited on 2024.09.19.

[15] A. Dombi et al. “Collective self-trapping of atoms in a cavity”. In: *New Journal of Physics* 23.8 (Aug. 2021), p. 083036. DOI: 10.1088/1367-2630/ac1a3c.

[16] T. W. Clark et al. “Time-resolved observation of a dynamical phase transition with atoms in a cavity”. In: *Phys. Rev. A* 105 (6 June 2022), p. 063712. DOI: 10.1103/PhysRevA.105.063712.

[17] C. G. Townsend et al. “Phase-space density in the magneto-optical trap”. In: *Phys. Rev. A* 52 (2 Aug. 1995), pp. 1423–1440. DOI: 10.1103/PhysRevA.52.1423.

[18] D. A. Steck. *Rubidium 87 D Line Data*. http://steck.us/alkalidata. (revision 2.3.2, 10 September 2023).

[19] J. Dalibard et al. “Laser cooling below the Doppler limit by polarization gradients: simple theoretical models”. In: *J. Opt. Soc. Am. B* 6.11 (Nov. 1989), pp. 2023–2045. DOI: 10.1364/JOSAB.6.002023.

[20] R. Grimm et al. “Optical dipole traps for neutral atoms”. In: *Advances in atomic, molecular, and optical physics*. Vol. 42. Elsevier, 2000, pp. 95–170.

Társszerzői nyilatkozat

Alulírottak nyilatkozunk arról, hogy Gábor Bence *Collective Effects of Laser-Driven Cold Atoms in an Optical Cavity* című doktori értekezésének I/1., I/2., II/1., II/2., III/1. és III/2. tézispontjaiban szereplő, az alábbi cikkekben közösen publikált eredmények elérésében a jelölt szerepe meghatározó volt. Ezeket az eredményeket korábban nem használtuk tudományos fokozat megszerzésére, és ezt a jövőben sem tesszük.

[T1] B. Gábor, D. Nagy, A. Dombi, T. W. Clark, F. I. B. Williams, K. V. Adwaith, A. Vukics, and P. Domokos. "Ground-state bistability of cold atoms in a cavity". In: *Phys. Rev. A* 107 (2 Feb. 2023), p. 023713. DOI: 10.1103/PhysRevA.107.023713.

[T2] B. Gábor, D. Nagy, A. Vukics, and P. Domokos. "Quantum bistability in the hyperfine ground state of atoms". In: *Phys. Rev. Res.* 5 (4 Dec. 2023), p. L042038. DOI: 10.1103/PhysRevResearch.5.L042038.

[T3] B. Gábor, A. K. Varooli, D. Varga, B. Sárközi, Á. Kurkó, A. Dombi, T. W. Clark, F. I. B. Williams, D. Nagy, A. Vukics, and P. Domokos. "Demonstration of strong coupling of a subradiant atom array to a cavity vacuum". In: *EPJ Quantum Technology* 12.1 (Aug. 2025), p. 93. DOI: 10.1140/epjqt/s40507-025-00401-x.

Budapest, 2025. augusztus 5.

Dr. Domokos Péter

Dr. Nagy Dávid	Varga Dániel
Dr. Dombi András	Sárközi Bálint
Dr. Vukics András	Kurkó Árpád