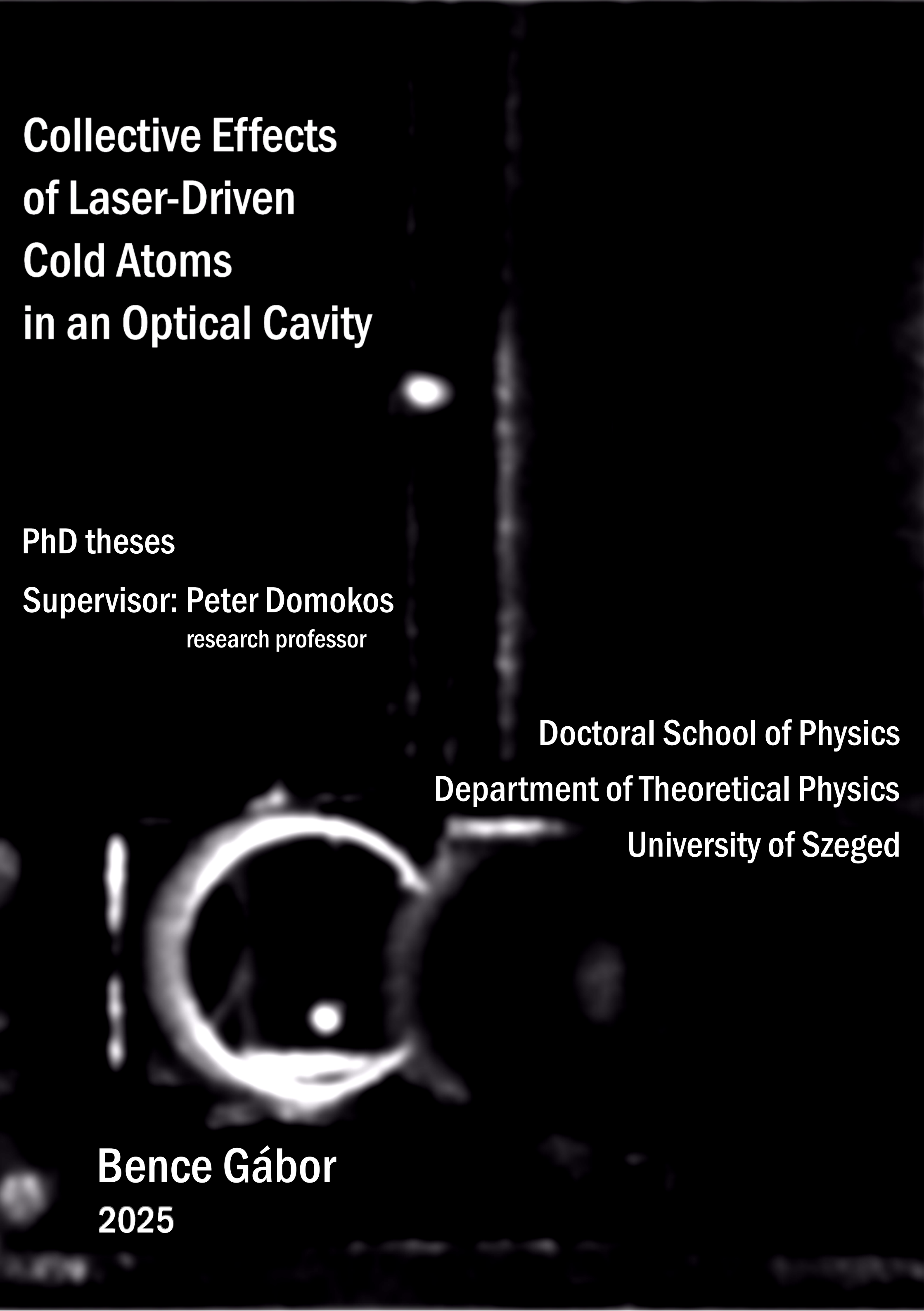

Collective Effects of Laser-Driven Cold Atoms in an Optical Cavity

PhD theses

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Theses of the PhD thesis

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1 Introduction

If physicists were asked to name the birthdate of quantum theory, many would probably say 14 December 1900. This was the day when Planck published his theory about the quantum nature of light [1], in which he heuristically introduced the quantum of action, denoted by h, a proportionality constant, which relates the energy of light quanta to their frequency, ν through formula $E = h\nu$, in order to explain the spectrum of thermal blackbody radiation. This groundbreaking idea inspired a series of developments such as the photoelectric effect and stimulated emission by Einstein [2–4], a new model of the atom by Bohr [5], the concept of matter waves by de Broglie [6], and many more, each contributing to the formulation of quantum mechanics as a distinct branch of physics. A comprehensive quantum theory was proposed by Heisenberg [7] and Schrödinger [8], in the form of matrix and wave mechanics, respectively. The equivalence of the two was shown by von Neumann, who also constructed a mathematically rigorous framework for quantum mechanics [9]. This early history of quantum mechanics, briefly outlined above, usually referred to as the *first quantum revolution* [10–12] had set the stage for an optics and solid-state physics based on quantum mechanics, which revealed the deeper nature of light and matter. It could be then exploited in various applications, such as transistors, LEDs, lasers etc.

By today, in the era of the *second quantum revolution*, manipulating, and what is more, designing and constructing individual quantum systems, such as atoms and photons have become possible. Since the foundation of quantum mechanics, advances in spectroscopy and high-level manipulation of atoms had been achieved, taking full advantage of the invention of lasers as well-controlled sources of light. Optical pumping [13–15], magnetic trapping [16], laser cooling and trapping [17–20] of atoms are techniques that have been developed since the second half of the 20th century, and are now routinely employed in experiments studying their interaction with electromagnetic radiation. The primary objective extends beyond a deeper understanding of light-matter interactions to the development of new technologies based on the quantum nature of these systems. Key research directions include quantum sensing [21], quantum metrology [22], quantum cryptography [23], quantum communication [24] and quantum computing [25].

Various platforms are suitable for such investigations: beyond different neutral atoms (mostly but not exclusively alkaline and alkaline earth metals) [26], ions [27], nanoparticles [28] and artificial atoms [29] can be exposed to electromagnetic radiation, which may take the form of microwave, infrared (IR), visible light or ultraviolet (UV). For the latter three, continuous wave (cw) lasers play a key role, as narrow-linewidth, coherent sources of radiation. Since their invention, laser technology has seen remarkable advancements in both linewidth and stability [30], which had an influence on the improvement of our ability of manipulating atomic matter. Lasers with linewidth well below that of the addressed atomic transitions are available today, allowing for precise spectroscopic measurements and well-controlled experiments.

The effect of electromagnetic radiation can be further enhanced and modified by means of optical resonators. The research field of cavity quantum electrodynamics (CQED), arising from the application of optical cavities, reveals a genuinely distinct regime of light-matter interactions. In many cases of interest, matter is considered as means of manipulating light: it can modify the properties of propagation (e.g. via scattering or dispersion), the frequency (through Raman scattering, harmonic generation etc.), the polarization (through birefringence or dichroism) or the intensity (by amplification or absorption). By contrast, as mentioned above, light can also be used as a tool to manipulate matter. Cavity QED combines the two domains of phenomena in a coupled dynamics of light and matter, in which they can mutually influence each other. This interaction becomes 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.

Strong atom-cavity coupling can be achieved by either cavity design, as the coupling constant is determined by the geometry, or by making use of the collective behaviour of multiple identical atoms interacting with the same cavity mode. When an ensemble of atoms interacts with a mode of a resonator, each atom couples to the mode, and its electronic state and spatial position influences the mode. This field, in turn, acts back on the state and position of all the atoms. As a consequence, the atoms communicate with each other via the cavity field, regardless of their spatial separation. This approach also allows for tuning the collective coupling by adjusting the number of atoms in the mode volume.

Cavity QED schemes typically involve few degrees of freedom that are relevant to the atom-light interaction. The field is composed of only a single or several modes, and the interacting atoms can be represented by a small set of electronic states. In these systems, cold atoms can be held in a magneto-optical trap (MOT), or loaded into a cavity-sustained optical dipole trap, or be tightly confined in atom-chip based magnetic traps [31]. Such physical realizations of CQED systems have a multitude of applications in quantum information processing and quantum sensing: the cavity can enable sensitive measurement of the atomic dynamics or state at spectroscopic sensitivity below the standard quantum limit for coherent spin states [32, 33], real-time monitoring of the spatial distribution [34] or the atom number in evaporative cooling of atoms [35]. Superradiance decoherence caused by long-range Rydberg atom pair interactions, too, has been demonstrated by using cavity-assisted measurements [36]. Another prospect of strongly coupled atom-cavity systems is given by optical lattice clocks, which are based on lasing on a narrow atomic transition within a resonator [37–40]. The cavity mode can have a dynamical role such that the hybrid atom-photon excitations introduce new features to non-linear optics. For example, in the case of multiple laser drives, the suppression of polariton excitation by quantum interference [41] and the proof-of-principle of a multiplexed quantum memory based on spin-waves [42] have been demonstrated.

Within this general perspective of strongly-coupled, interacting atom-light sys-

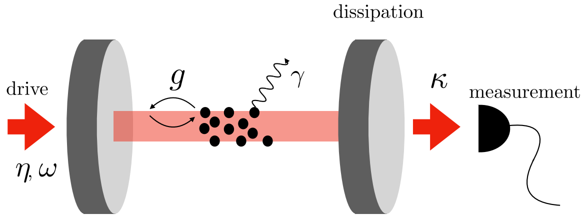

Figure 1: *A scheme of a generic CQED system. Atoms with natural linewidth γ are positioned between the mirrors of an optical resonator, coupled to its mode with coupling strength g. The cavity is driven coherently with angular frequency ω and drive amplitude η. The cavity mode decays through one of 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.*

tem, CQED is an outstanding platform to study phase transitions in driven-dissipative open quantum systems [43–45]. 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 [46]. 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 [47], 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 [48–55].

In 2016, the Quantum Optics Group of the HUN-REN Wigner Research Centre for Physics started to build a CQED laboratory [56]. The aim was to realize quantum technological applications based on atoms and photons. Today, the laboratory, called

Atom-photon interface, is capable of routinely trapping and cooling rubidium atoms, coupling them to a single mode of a high-finesse optical resonator, in which the quantum information can be exchanged between photons and atoms. By the time I joined in 2021, the group had already published experimental results [57, 58]. 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.

The thesis is structured in two parts. In Part I, both the theoretical and experimental background of my work are reviewed. In Ch. 1, a semiclassical, mean-field model is invoked to describe the interaction of multiple atoms and a single mode of a high-finesse optical cavity. In Ch. 2, I describe the laboratory setup in detail: all the employed lasers and cavities are enumerated with the connections between them, elaborating on the stabilization techniques applied on them. After a brief description of the vacuum chamber and the detection system, the whole cold atom sample preparation cycle is explained. Part II is devoted to the results of the three major research projects I participated in during the three-year period spent in the Quantum Optics Group. The first study (Ch. 3) reports on the observation of a finite-size realization of a dissipative quantum phase transition (DQPT) between hyperfine ground states of cold rubidium atoms interacting with a single mode of a high-finesse optical cavity and an external laser field. The phase diagram of the phase transition is determined by means of a semi-classical mean-field model. The remarkable feature of the phase diagram is that it predicts the co-existence of phases comprising atoms very close to their hyperfine ground states. Although the predicted bistability region is rather limited in range for the control parameters, the bistability effect has been confirmed by recording hysteresis curves. Enhancement of intensity fluctuations well above the shot-noise level, accompanying the phase transition, is also revealed and investigated. The second project (Ch. 4) is a theoretical study to extend the concept of phase transitions between ground states: whether it is possible to enlarge the bistability domain and achieve phases which include pure quantum states in the thermodynamic limit? The initial idea was to consider the case when instead of the external laser field, another driven cavity mode excites the atoms. This configuration is not available in the existing experimental setup, because the free spectral range of our cavity is larger than the hyperfine splitting. However, we could study this system on the basis of the mean-field model, constructed for the first study, extending it with the dynamical variable of the new cavity mode, and another excited state of the atoms coupled to it. A non-trivial phase diagram is obtained, and the finite-size scaling of the phase transition towards the thermodynamic limit shows that pure quantum states represent the co-existing phases and, ultimately, the bistability sets in the full range of the ratio of the control parameters. The third and last work in this thesis (Ch. 5) demonstrates strong collective coupling between a subradiant atom array and undriven modes of a high-finesse optical cavity. The vacuum Rabi splitting spectrum, an evidence of the strong collective coupling, predicted by the simple linear polarizability model of the atoms, is measured in a specific geometry. The atoms, placed in an optical lattice incommensurate with the resonant wavelength, and hence forming a subradiant array, are driven by a closely resonant external laser field in a direction perpendicular to the cavity axis. The linearity and the subradiance of the scattering is confirmed by scaling with the driving power and the number of atoms, respectively. Polarization rotation, exceeding the range of the linear polarizability model, is also observed and accounted for. The results presented in this thesis were published in [T1, T2, T3], which form the basis of the corresponding chapters, and the theses formulated from page 14.

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 ω_{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 ω_{C}. The cavity is driven by a laser field with amplitude $\tilde{\eta}$, and angular frequency ω. Since the atoms are much smaller than the optical wavelengths ($248\,\mathrm{pm}$ and $780\,\mathrm{nm}$ for the radius of the Rb atom and the wavelength of its D_2 line, respectively), their interaction with the electromagnetic field can be described in dipole approximation, meaning that 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:

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

where $\Delta_{\mathrm{C}} \equiv \omega - \omega_{\mathrm{C}}$, $\Delta_{\mathrm{A}} \equiv \omega - \omega_{\mathrm{A}}$ are detunings of the laser from the cavity and from the atoms, respectively, $\tilde{g}^{(i)} = \sqrt{\frac{\omega_{\mathrm{C}}}{2\epsilon_0\hbar\mathcal{V}}} d_{eg}\cos\left(kx^{(i)}\right)$ 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 $k = \omega_{\mathrm{C}}/c$ the wavenumber of the cavity mode). The terms $a\sigma^{(i)}$ and $a^\dagger\sigma^{(i)\dagger}$ have been omitted according to the rotating wave approximation (RWA), as they rotate at $\omega_{\mathrm{C}} + \omega_{\mathrm{A}} \approx 2\omega$, and average out during the time scale of the atom-cavity interaction, determined by the coupling coefficient, having the order of magnitude of several MHz.

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:

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

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

Global coupling, which is a crucial assumption to close the set of equations, 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

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

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, each devoted to specific roles within the experiment. The frequencies of the lasers are fixed on long term, 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 Toptica external-cavity diode laser (ECDL), locked to the rubidium reference. The frequencies of all the other lasers are derived from it. Parts of its beam are directly used as imaging and optical pumping lights.

2. MOT laser: A Toptica tapered amplifier (TA) Pro used for magneto-optical trap (MOT) and polarization gradient cooling. It is locked directly to the reference laser.

3. Repumper: a home-made laser, based on a distributed-feedback (DFB) laser diode, phase-locked to the reference laser. It is used to counteract other lasers pumping the atoms out of the hyperfine ground state manifold ($F = 2$) that takes part in the interaction cycle (during MOT, optical pumping or an experiment).

4. 'Science' laser: initially, a Toptica ECDL, locked to the reference, later, a Toptica tapered amplifier (TA) Pro, phase-locked to the reference. It is used to manipulate the atoms in the cavity. Its beam is split into two, so that one part can drive the science cavity mode, the other can drive the atoms from a direction perpendicular to the cavity axis (transverse drive).

5. 'Transfer' cavity: A temperature stabilized high-finesse cavity in an invar tube utilized to transfer the frequency stability of the reference laser to the science cavity at a wavelength far from the ones involved in the light-atom interaction effects studied. The length of the cavity is adjustable by means of a piezo crystal, fixed on one of the mirrors. Voltage control and feedback on the piezo is governed by a specific device, developed together with our group.

6. 'Science' cavity: Another high-finesse resonator, used for the CQED experiments, placed inside the vacuum chamber. It can be driven by the 'science' light, and locked by using the same electronic control device as that for the transfer cavity.

7. Reference transfer laser: A Toptica ECDL similar to the reference, used for locking the science cavity. Its wavelength must be very far from any atomic resonances so that the lock laser does not influence the atom-cavity system under study, therefore, it is tuned to $805\,\mathrm{nm}$.

Rubidium-87 Atoms in the Vacuum Chamber

Rubidium-87 atoms are collected, trapped and cooled in a vacuum chamber with a pressure of $\sim 7 \times 10^{-11}\,\mathrm{mbar}$ in it. Two pairs of identical cylindrical copper coils are placed in the chamber, with their axis aligned, and with a separation of $34\,\mathrm{mm}$ between the middle coils. The centre of symmetry defines the centre of the MOT. The chamber is surrounded by two pairs of rectangular coils, compensating the background magnetic field (e.g. that of the Earth) together with the intra-vacuo coils, used for MOT and magnetic trapping. A rubidium dispenser is placed in the chamber with its opening oriented towards the centre of the MOT. When current ($\sim 3.8\,\mathrm{A}$) flows through the dispenser, Rb vapour is released due to the heat, and the atoms are captured by the MOT.

Detection

The cavity output can be detected with a Thorlabs APD410A/M avalanche photodiode (APD), Laser Components COUNT-500N-FC avalanche single photon counter (SPC) modules or an ID Quantique ID218 superconducting nanowire single photon detector (SNSPD). The single photon detectors are connected to an ID900 Time Controller, a time tagger capable of ps resolution, allowing for precise time course and photon correlation measurements.

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, that allows for timing digital and analogue output signals with a precision of $500\,\mathrm{ns}$, and acquire analogue input signals with a resolution down to $250\,\mathrm{ns}$. 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 [59]. 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. The principle of operation lies in the spatially varying Zeeman shift on the atoms, caused by the inhomogeneous magnetic field. This leads to a spatially dependent radiation pressure force, induced by the laser fields, restoring the atoms towards the trap centre. At the same time, velocity dependence arises from the Doppler effect, and leads to motional damping (Doppler cooling). As a result, 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 $\sim 150\,\mu\mathrm{K}$. The fluorescence image of the cloud is constantly monitored for diagnostic purposes with a CCD camera placed at one of the viewports of the vacuum chamber.

2. Polarization gradient cooling: a method allowing for cooling below the Doppler limit ($146\,\mu\mathrm{K}$ for the D_2 line of ^{87}Rb [60]), based on laser polarization gradients [19]. In the $\sigma^+ - \sigma^-$ configuration, implemented in our system, the net polarization is linear, and rotates around the propagation axis with a periodicity of the wavelength. When an atom is moving in such a field, in the frame moving with the atom and rotating in accordance with the local polarization, an extra inertial interaction will take place, coupling together the external and internal degrees of freedom (the velocity and the angular momentum) of the atom. This coupling leads to a motion induced population difference among the Zeeman sublevels of the ground state, resulting in an imbalance between the radiation pressures of the two counter-propagating waves, realizing a net friction force on the atom.

   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 quantum state. A homogeneous magnetic field is necessary to define a quantization axis, and to lift the degeneracy of the Zeeman sublevels. The atoms are excited by a resonant, circularly polarized light pulse with a duration of a few tens of microseconds, propagating along the direction of the magnetic field. Each time an

atom absorbs a circularly polarized photon, its m_F quantum number changes by 1 (with a sign according to the handedness of the polarization and the direction of the magnetic field). When the atom relaxes, m_F changes randomly by plus or minus 1, or does not change at all (for σ^+, σ^- and π transitions, respectively). As a result, after several cycles (in tens of microseconds), the atoms end up in an extremal m_F state (stretched state). Optical pumping has to be kept short because this illumination by resonant light induces heating of the cloud.

4. Magnetic trapping: Particles with magnetic moment, $\boldsymbol{\mu}$ in a magnetic field, $\mathbf{B}$ experience a potential, given by $U = -\boldsymbol{\mu} \cdot \mathbf{B}$. A pair of coils driven in anti-Helmholtz configuration, produces a quadrupole field, which creates a linear potential for these particles. 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 is called optical dipole lattice [61]. As the 805 light is coupled into the science cavity mode, the wavelength being far red detuned from any resonance in question, there is an optical dipole lattice in the cavity. Due to the large volume mismatch of the traps, loading the atoms into this lattice from the magnetic trap is a non-trivial task, worked out and optimized by our group [F1].

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 co-existing 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 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.

[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, K. V. Adwaith, D. Varga, B. Sárközi, 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*. Under review at Communications Physics. 2024. arXiv: 2408.17079 [quant-ph].

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: https://doi.org/10.1016/j.physleta.2024.129444.

References

[1] M. Planck. “Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum”. In: *Berlin* (1900), pp. 237–245.

[2] A. Einstein. “Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt”. In: *Annalen der Physik* 322.6 (Jan. 1905), pp. 132–148. DOI: 10.1002/andp.19053220607.

[3] A. Einstein. “Strahlungs-Emission und Absorption nach der Quantentheorie”. In: *Deutsche Physikalische Gesellschaft* 18 (Jan. 1916), pp. 318–323.

[4] A. Einstein. “Zur Quantentheorie der Strahlung”. In: *Physikalische Zeitschrift* 18 (Jan. 1917), pp. 121–128.

[5] N. Bohr. “I. On the constitution of atoms and molecules”. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 26.151 (1913), pp. 1–25. DOI: 10.1080/14786441308634955. eprint: https://doi.org/10.1080/14786441308634955.

[6] De Broglie, Louis. “Recherches sur la théorie des Quanta”. In: *Ann. Phys.* 10.3 (1925), pp. 22–128. DOI: 10.1051/anphys/192510030022.

[7] W. Heisenberg. “Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen.” In: *Zeitschrift fur Physik* 33.1 (Dec. 1925), pp. 879–893. DOI: 10.1007/BF01328377.

[8] E. Schrödinger. “Quantisierung als Eigenwertproblem”. In: *Annalen der Physik* 384.4 (1926), pp. 361–376. DOI: 10.1002/andp.19263840404. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/andp.19263840404.

[9] J. von Neumann. *Mathematische Grundlagen der Quantenmechanik*. Berlin: Springer, 1932.

[10] A. G. J. Macfarlane et al. “Quantum technology: the second quantum revolution”. In: *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361.1809 (2003), pp. 1655–1674.

[11] E. B. Kania et al. *QUANTUM HEGEMONY?: China’s Ambitions and the Challenge to U.S. Innovation Leadership*. Tech. rep. Center for a New American Security, 2018, pp. 3–5.

[12] A. Manzalini. “The Second Quantum Revolution is underway”. In: *TIM notiziariotecnico, year* 29 (2020).

[13] A. L. Bloom. “OPTICAL PUMPING”. In: *Scientific American* 203.4 (1960), pp. 72–81.

[14] C. Cohen-Tannoudji et al. “I Optical Pumping”. In: ed. by E. Wolf. Vol. 5. Progress in Optics. Elsevier, 1966, pp. 1–81. DOI: https://doi.org/10.1016/S0079-6638(08)70450-5.

[15] W. HAPPER. “Optical Pumping”. In: *Rev. Mod. Phys.* 44 (2 Apr. 1972), pp. 169–249. DOI: 10.1103/RevModPhys.44.169.

[16] A. L. Migdall et al. “First Observation of Magnetically Trapped Neutral Atoms”. In: *Phys. Rev. Lett.* 54 (24 June 1985), pp. 2596–2599. DOI: 10.1103/PhysRevLett.54.2596.

[17] D. J. Wineland et al. “Laser cooling of atoms”. In: *Physical Review A* 20.4 (1979), p. 1521.

[18] E. L. Raab et al. “Trapping of Neutral Sodium Atoms with Radiation Pressure”. In: *Phys. Rev. Lett.* 59 (23 Dec. 1987), pp. 2631–2634. DOI: 10.1103/PhysRevLett.59.2631.

[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] J. Miller et al. “Far-off-resonance optical trapping of atoms”. In: *Physical Review A* 47.6 (1993), R4567.

[21] C. L. Degen et al. “Quantum sensing”. In: *Reviews of modern physics* 89.3 (2017), p. 035002.

[22] V. Giovannetti et al. “Advances in quantum metrology”. In: *Nature photonics* 5.4 (2011), pp. 222–229.

[23] S. Pirandola et al. “Advances in quantum cryptography”. In: *Advances in optics and photonics* 12.4 (2020), pp. 1012–1236.

[24] N. Gisin et al. “Quantum communication”. In: *Nature Photonics* 1.3 (Mar. 2007), pp. 165–171. DOI: 10.1038/nphoton.2007.22.

[25] L. Henriet et al. “Quantum computing with neutral atoms”. In: *Quantum* 4 (2020), p. 327.

[26] H. Ritsch et al. “Cold atoms in cavity-generated dynamical optical potentials”. In: *Rev. Mod. Phys.* 85 (2 Apr. 2013), pp. 553–601. DOI: 10.1103/RevModPhys.85.553.

[27] C. D. Bruzewicz et al. “Trapped-ion quantum computing: Progress and challenges”. In: *Applied Physics Reviews* 6.2 (2019).

[28] J. Millen et al. “Optomechanics with levitated particles”. In: *Reports on Progress in Physics* 83.2 (2020), p. 026401.

[29] J.-Q. You et al. “Atomic physics and quantum optics using superconducting circuits”. In: *Nature* 474.7353 (2011), pp. 589–597.

[30] Z. Bai et al. “A comprehensive review on the development and applications of narrow-linewidth lasers”. In: *Microwave and Optical Technology Letters* 64.12 (2022), pp. 2244–2255.

[31] J. Kohler et al. “Negative-Mass Instability of the Spin and Motion of an Atomic Gas Driven by Optical Cavity Backaction”. en. In: *Physical Review Letters* 120.1 (Jan. 2018), p. 013601. DOI: 10.1103/PhysRevLett.120.013601.

[32] Z. Chen et al. “Cavity-aided nondemolition measurements for atom counting and spin squeezing”. en. In: *Physical Review A* 89.4 (Apr. 2014), p. 043837. DOI: 10.1103/PhysRevA.89.043837.

[33] H. Zhang et al. “Collective State Measurement of Mesoscopic Ensembles with Single-Atom Resolution”. en. In: *Physical Review Letters* 109.13 (Sept. 2012), p. 133603. DOI: 10.1103/PhysRevLett.109.133603.

[34] R. D. Niederriter et al. “Cavity probe for real-time detection of atom dynamics in an optical lattice”. en. In: *Physical Review A* 102.5 (Nov. 2020), p. 051301. DOI: 10.1103/PhysRevA.102.051301.

[35] J. Zeiher et al. “Tracking Evaporative Cooling of a Mesoscopic Atomic Quantum Gas in Real Time”. en. In: *Physical Review X* 11.4 (Oct. 2021), p. 041017. DOI: 10.1103/PhysRevX.11.041017.

[36] E. Suarez et al. “Superradiance decoherence caused by long-range Rydberg-atom pair interactions”. en. In: *Physical Review A* 105.4 (Apr. 2022), p. L041302. DOI: 10.1103/PhysRevA.105.L041302.

[37] J. A. Muniz et al. “Cavity-QED measurements of the Sr 87 millihertz optical clock transition and determination of its natural linewidth”. en. In: *Physical Review Research* 3.2 (May 2021), p. 023152. DOI: 10.1103/PhysRevResearch.3.023152.

[38] G. Vallet et al. “A noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime”. In: *New Journal of Physics* 19.8 (Aug. 2017), p. 083002. DOI: 10.1088/1367-2630/aa7c84.

[39] R. Hobson et al. “Cavity-enhanced non-destructive detection of atoms for an optical lattice clock”. en. In: *Optics Express* 27.26 (Dec. 2019), p. 37099. DOI: 10.1364/OE.27.037099.

[40] S. A. Schäffer et al. “Lasing on a narrow transition in a cold thermal strontium ensemble”. en. In: *Physical Review A* 101.1 (Jan. 2020), p. 013819. DOI: 10.1103/PhysRevA.101.013819.

[41] G. Yang et al. “Interference control of nonlinear excitation in a multi-atom cavity quantum electrodynamics system”. en. In: *Optics Letters* 39.23 (Dec. 2014), p. 6695. DOI: 10.1364/OL.39.006695.

[42] K. C. Cox et al. “Spin-Wave Multiplexed Atom-Cavity Electrodynamics”. en. In: *Physical Review Letters* 123.26 (Dec. 2019), p. 263601. DOI: 10.1103/PhysRevLett.123.263601.

[43] 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.

[44] 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.

[45] 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.

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

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

[48] 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.

[49] 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.

[50] 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.

[51] 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.

[52] 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.

[53] 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.

[54] 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.

[55] 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.

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

[57] 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.

[58] 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.

[59] 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.

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

[61] 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, K. V. Adwaith, D. Varga, B. Sárközi, 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*. Under review at Communications Physics. 2024. arXiv: `2408.17079 [quant-ph]`.

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