Autoreferat

I. NAME.

Michał Parniak-Niedojadło

II. DIPLOMAS, DEGREES CONFERRED IN SPECIFIC AREAS OF SCIENCE OR ARTS, INCLUDING THE NAME OF THE INSTITUTION WHICH CONFERRED THE DEGREE, YEAR OF DEGREE CONFERMENT, TITLE OF THE PHD DISSERTATION

1. BSc in physics, Faculty of Physics, University of Warsaw
    - date of award: 28.06.2013
    - supervisor: dr hab. Wojciech Wasilewski, prof. UW
2. MSc in physics, Faculty of Physics, University of Warsaw
    - date of award: 30.07.2015
    - supervisor: dr hab. Wojciech Wasilewski, prof. UW
3. PhD in physics, Faculty of Physics, University of Warsaw
    - date of award: 20.05.2019; date of defence: 13.05.2019
    - title of dissertation: Multimode Quantum Optics with Spin Waves and Photons
    - awarded with distinction
    - supervisor: dr hab. Wojciech Wasilewski, prof. UW

III. INFORMATION ON EMPLOYMENT IN RESEARCH INSTITUTES OR FACULTIES/DEPARTMENTS OR SCHOOL OF ARTS.

1. Research Assistant, University of Copenhagen, Niels Bohr Institute, December 2018 - May 2019
2. Postdoc, University of Copenhagen, Niels Bohr Institute, May 2019 - June 2020 (full-time), from July 2020 (fraction of full-time)
3. Assistant professor, research group leader, Center for Quantum Optical Technologies, Center of New Technologies, University of Warsaw, from July 2020

IV. DESCRIPTION OF THE ACHIEVEMENTS, SET OUT IN ART. 219 PARA 1 POINT 2 OF THE ACT

1. Title of the achievement

The achievement is a series of thematically related publications under the title

Generation and characterization of macroscopic quantum states of light and matter

2. List of publications which are part of the achievment

[A1] I. Galinskiy, Y. Tsaturyan, **M. Parniak**, E. S. Polzik†, „Phonon counting thermometry of an ultracoherent membrane resonator near its motional ground state", Optica **7**, 718-725 (2020)

[A2] R. A. Thomas*, **M. Parniak***, C. Østfeldt*, C. B. Møller*, C. Bærentsen, Y. Tsaturyan, A. Schliesser, J. Appel, E. Zeuthen, E. S. Polzik†, „Entanglement between Distant Macroscopic Mechanical and Spin Systems", Nature Physics **17**, 228-233 (2021)

[A3] **M. Parniak***†, I. Galinskiy*, T. Zwettler, E. S. Polzik, „High-frequency broadband laser phase noise cancellation using a delay line", Optics Express **29**, 6935 (2021)

[A4] R. A. Thomas, C. Østfeldt, C. Bærentsen, **M. Parniak**, E. S. Polzik†, „Calibration of Spin-Light Coupling by Coherently Induced Faraday Rotation", Optics Express **29**, 23637 (2021)

[A5] M. Lipka, **M. Parniak**†, „Fast imaging of multimode transverse–spectral correlations for twin photons", Optics Letters **46**, 3009 (2021)

[A6] M. Lipka*, M. Mazelanik*, A. Leszczyński, W. Wasilewski, **M. Parniak**†, „Massively-multiplexed generation of Bell-type entanglement using a quantum memory", Communications Physics **4**, 46 (2021)

[A7] M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, **M. Parniak**†, „Real-time ghost imaging of Bell-nonlocal entanglement between a photon and a quantum memory", Quantum **5**, 493 (2021)

[A8] M. Lipka, M. Mazelanik, **M. Parniak**†, „Entanglement distribution with wavevector-multiplexed quantum memory", New Journal of Physics **23**, 053012 (2021)

* = equal contribution, † = corresponding author

3. Description of the achievment

The series of works presented here is a summary of efforts in creating and characterization of various quantum states of light and matter, which can be considered macroscopic due to their different properties. In the series of works presented here, the key elements are the three physical systems with which I have worked: atoms, light and membranes which are mechanical oscillators. To control these systems light was used each time, which indicates the existence of two interfaces: light-atoms and optomechanical. In both cases, the task was to produce entanglement or to facilitate the exchange of excitations between the material system and light.

The generation of macroscopic quantum states is a challenge for modern physics and offers hope for exploring the boundaries between the classical and quantum worlds, defined strictly by appropriate inequalities. Typically, the quantum character of the states we studied in the described ecperiments were: coherent superposition, entanglement with another object, or cooling of the system to the ground state. Experimentally, we observe these features, for example, by studying interference, non-classical correlations, or just particularly low levels of recorded noise in the measurement. Obtaining states exhibiting the discussed properties in macroscopic systems presents an experimental challenge. It requires preparation of the object tested, construction of appropriate experimental apparatus together with the necessary modern elements of automation, carrying out precise calibration measurements, as well as the development of theoretical models which allow in particular, to correctly define the problem and balance the priority expectations and, finally, the preparation of data analysis tools which allow for correct verification of the experimental results and making of „on the fly" modifications to the experiment necessary to achieve the desired objectives.

Macroscopicity can be understood very broadly. We may have to deal with a macroscopically large object in space or consisting of many particles. In this case, the mass of the system becomes an important paramter. In practice, often an object can be macroscopically large only in some dimensions. Usually quantum properties will manifest in only one or a few modes of a given macroscopic system. For example, working with an ensemble of 10^9 spins we study only the collective operators describing the total spin. In other cases, we may be dealing with mechanical motion in a particular mode, or a large number of photons in a single mode of the electromagnetic field. A slightly different approach to macroscopicity, then, is to gain control over a large number of modes, which is a significant step beyond typical experiments. Due to the fact that in virtually all cases only some features of the studied system can be considered macroscopic, a more appropriate word may be *mesoscopic*. From the experimental side, as macroscopicity increases all systems become more susceptible to decoherence. It becomes difficult to maintain phase coherence between constituent particles or modes of the system and, at the same time, the number of channels of coupling to the environment increases.

In the presented cycle, I have adopoted a series of approaches and the systems I studied exhibited different macroscopic features. The system of particular importance in the work [A1-A2] was a mechanical oscillator in the form of a thin (12 nm), but wide (several mm) membrane made of silicon nitride (Si_3N_4)[1]. The nitride layer is produced on

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[1] Y. Tsaturyan et al., „Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution," Nature Nanotechnology **12**, 776–783 (2017)

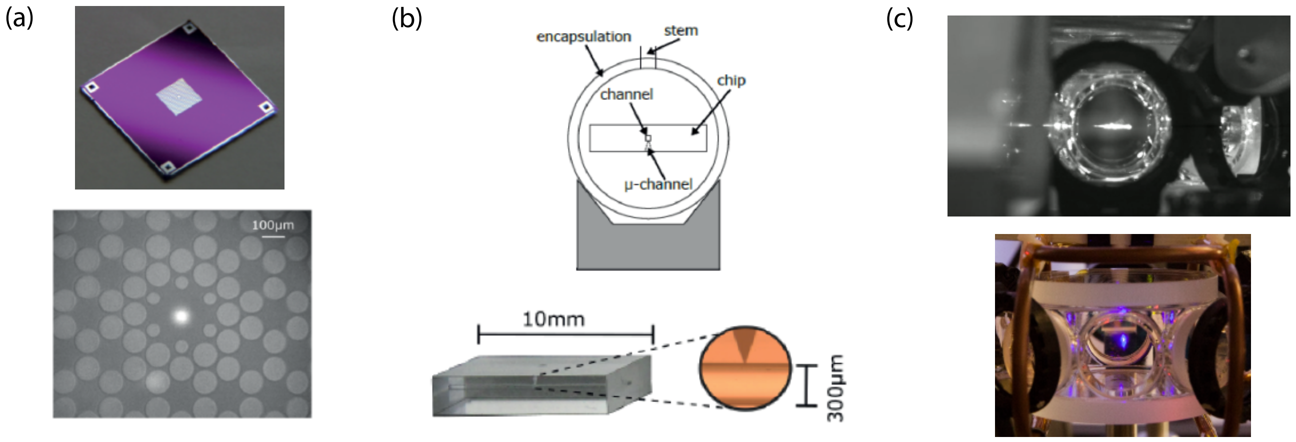

Figure 1 The material systems studied in the cycle: (a) optomechanical membrane and close-up on a defect in a phononic crystal that defines a high quality factor mode whose oscillations we control, (b) a microchannel cell with cesium atoms, (c) an ensemble of laser-cooled rubidium atoms (side and front view).

a silicon substrate, which we remove in the middle by etching. We conduct the preparation so that the membrane stretched on the silicon frame is very tensioned. In this way an oscillator of high quality factor is formed. To make the quality factor of the oscillator even higher, we etch a phononic crystal in the membrane structure to modulate the speed of sound in the structure. In the very center we place a defect of the crystal, which becomes the actual oscillator, vide the photo in Figure 1a. The oscillation frequency of the defect lies in the center of the phononic energy band gap of the crystal, so this mode is solitary in the energy (frequency) domain and at the same time perfectly isolated from the environment. In our membranes, the defect mode eigenfrequency was $\Omega_M/2\pi = 1.3 \sim 1.5$ MHz with a quality factor of $Q = \Omega_M/\gamma_M = 0.5 \sim 1 \times 10^9$. The membrane being placed in a helium cryostat couples to an environment containing $n_{th} = k_B T/\hbar\Omega_M \approx 2 \times 10^5$ thermal excitations per mode on average. The classical decay constant of the oscillator is $\gamma_M \approx$2 mHz (over 8 minutes). This allows us to predict the inverse of the quantum coherence time $n_{th}\gamma_M$ at about 400 Hz.

The second material system central to the cycle was the and atomic spin ensemble, in two distinct forms. The first form is the caesium (Cs) atoms used in the [A2-A3] work at temperatures slightly above room temperature (310-330 K). The gas of such atoms fills a thin (300 μm) and long (1 cm) vacuum microchannel. It is made into a glass cuboid, called a chip, which in turn is placed inside the glass cell so that the ends of the channel tightly touch (seal) the windows of the cell. In order to preserve the coherence of the spin states, the channel is coated on the inside with a layer of alkene - this preserves the spin of the atoms upon collisions. The vacuum channel is connected by a narrow conical hole to the rest of the cell where the cesium droplet is located. In the studied system, the object of interest is the collective spin of all atoms. This spin, placed in a magnetic field, undergoes precession with a frequency that can be controlled up to several MHz. The inverse of the spin coherence time is about 1 kHz in this system.

The second form of atomic system is the laser-cooled atomic cloud used in the papers [A6] and [A7] obtained via a magneto-optical trap (MOT) system and cooled to temperatures of the order of (20-100 μK). This system was also the subject of theoretical considerations in the paper [A8]. The experiment itself is more technically complex due to the sequence required to cool and trap the atoms. After these steps and releasing the atoms from the trap, the suspended cloud of atoms ($0.3 \times 0.3 \times 10$ mm^3 cloud size) serves as a quantum memory for light. While we similarly use the collective states of many atoms as before, in this arrangement we can use multiple spatial modes. This is possible because the atoms only make a small amount of movement during the experiment due to the low temperature. Thus, it makes sense to generate, process and read-out states with different types of atomic coherence dependence on position, i.e. spin waves. In the experiments, we used collective excitations between hyperfine ^{87}Rb states energetically 6.8 GHz apart. Depending on the spatial modes used, we achieved coherence times of 50-500 μs. The multimode detector itself, i.e. the camera, the upgraded version of which is discussed and tested in the paper [A5], is an important element here.

Concluding the initial description of atomic systems, it is worth noting their similarities and differences. Interestingly, in both cases we are dealing with about 10^9 atoms in a similar volume. In the case of hot atoms, we can interact mainly with collective spin, while in the case of cold atoms, coherence can be maintained by multiple spatial modes, which I think is the most significant difference. A less significant difference is that atoms of a different element were used. Rubidium and cesium have similar properties in this type of experiment, and they also work with similar wavelengths of light. In practice, the use of either rubidium or cesium often depends on the apparatus available in a given laboratory. Cesium has a slightly higher vapor pressure at room temperature, which removes the need for significant heating of the cell (which could harm the anti-relaxation alkene coating). In addition, in systems with hot atoms, we often use significant laser detuning (beyond the Doppler width), on the order of 1.5 GHz. In caesium, we have to deal with larger hyperfine splittings than in rubidium (9.2 GHz in caesium vs. 6.8 GHz in rubidium), which gives better selectivity for excitation of atoms in the hot system. On the other hand, rubidium is more commonly used in cold-atom systems, and the literature on rubidium laser-cooling optimization is extremely rich.

Light was used to both connect, control, and probe the presented material systems throughout the presented cycle. In particular, from the experimental side in the works [A4] and [A5], light was also the main tool and also the object of study.

The papers in the series can be divided into fundamental results on the generation of quantum states [A1, A2, A6, A7], papers on developing closely related solutions to experimental problems and demonstrating methods for calibrating measurements or characterizing systems [A3, A4, A5], and one paper proposing the use of the generated state in quantum communication [A8]. Of the total papers, four [A1-A4] represent results obtained in the QUANTOP laboratory at the Niels Bohr Institute (NBI) at the University of Copenhagen, and the remaining four [A5-A8] results obtained in, or in collaboration with, the Center for Quantum Optical Technologies at the University of Warsaw.

The work presented in the articles was carried out between 2019 and 2021. During this period, I worked as a postdoc at the University of Copenhagen, and from July 2020 as an assistant professor - group leader at the University of Warsaw (UW). Prior to this date, I also worked intensively with a team from UW.

Macroscopic quantum systems are exciting both for fundamental reasons and for possible applications. One of the most relevant is quantum metrology. In general, the metrological applicability of macroscopic systems can be understood as the gain from their high susceptibility to interaction with the environment. In quantum metrology, we use this susceptibility to detect perturbing signals in the system with very high precision, such as electric and magnetic fields in the case of atoms, or mechanical forces in the case of a membrane.

Another application in which the systems studied in the presented series are applicable is the transmission of quantum information over long distances, particularly for QKD applications.

Theoretical introduction

An important aspect linking the systems studied in the cycle is the virtually the same nature of their interaction with light. Consider one mode of electromagnetic field $\hat{a}$ coupled to a mode of mechanical oscillations $\hat{b}$ or excitation of collective spin of atoms. The most general form of the Hamiltonian, adequate for all cases considered, is the combination of exchange interaction (beamsplitter type) and two-mode squeezing, of the form:

$$\hat{H} = \eta(\hat{a}^\dagger \hat{b}^\dagger + \hat{b}\hat{a}) + \mu(\hat{a}\hat{b}^\dagger + \hat{b}\hat{a}^\dagger) \tag{1}$$

The first term of the Hamiltonian $\hat{a}^\dagger \hat{b}^\dagger$ describes the process of creating atoms-light excitation pairs, i.e. photons and phonons/spin excitations. We deal with the same Hamiltonian, for example, in the process of parametric down-conversion in a nonlinear crystal, where one photon of a strong pumping beam (the coherent state represented by η) can split into two photons in the $\hat{a}$ and $\hat{b}$ modes (which can be of different wavelengths). We would also describe the process of cascaded photon pair emission from an atom or biexciton in a quantum dot analogously. If we wanted to obtain pure pair generation in the case of an oscillating membrane, it would be necessary to place it in a cavity tuned to the red sideband of the excitation laser $\hat{a}$, with a sideband detuning equal to the frequency of the membrane main defect mode $\hat{b}$[2]. In atomic systems, on the other hand, pair creation occurs by spontaneous Raman scattering, which can be achieved both at room temperature and in cold atoms. In order for pair generation to dominate over the exchange (beamsplitter) $\eta \gg \mu$ process, we pump the atoms to a well-defined state $|g\rangle$ and apply a laser pulse slightly detuned from the transition from this state to the excited state. The processes of absorption of the photon

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[2] It is worth noting that here we remain within the linear optomechanics approximation, were to single-photon optomechanical coupling is weak, and the interaction is enhanced by cavity coherent light (carrier). In the case of strong coupling, the Hamiltonian is actually nonlinear.

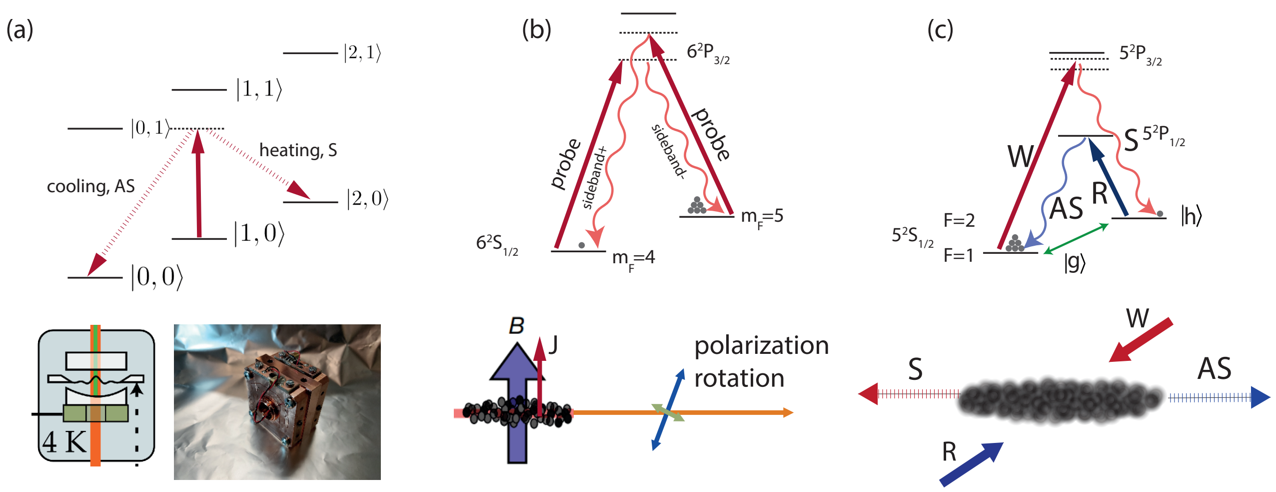

Figure 2 The arrangement of levels used in the optomechanical interface (a) and in the atomic interfaces (b, c) and (in the row below) the realizations of each interface. In the case of (a), we are dealing with a ladder of energy levels of a harmonic (mechanical) oscillator coupled to a ladder of photonic Fock states of the cavity. By tuning the cavity to the red sideband of the laser, and by selecting the width of the cavity resonance of the order of the frequency of the membrane oscillation, it is possible to cause a preferential anti-Stokes scattering, that is, a cooling process. The realization of the interface is the membrane placed in the optical cavity. In the case of (b), we have Cs atoms optically pumped to the maximum spin projection in the direction transverse to the laser propagation within one hyperfine level. The levels are split by a magnetic field, parallel to the spin, with an energy corresponding to the Larmor frequency. Applying a laser (probe) detuned from the resonance induces Stokes and anti-Stokes scattering with very similar amplitudes, and sidebands of different frequencies, and opposite circular polarizations are generated. At the same time, the atoms are excited and deviate from the maximum spin. We observe the total spin of the illuminated atoms. Thus, the realization of the interface is a laser beam passing through the atoms which undergoes periodic rotation of polarization, i.e., in particular, the sidebands on the orthogonal polarization are excited. In the case of (c), we use hyperfine levels in the Rb atom to induce Stokes and anti-Stokes transitions again. Here the processes are fully selective, i.e., we use closely tuned lasers to generate only single sidebands with a frequency offset corresponding to the hyperfine splitting. Additional information is contained in the scattering angle of the photon relative to the laser driving beam. Here, too, some atoms undergo excitation, but with a position-dependent phase that corresponds to the photon's scattering angle. Thus, we can interact with multiple spatial modes at the same time. The realization is a cloud of cold atoms (which allows us to preserve spatial phase information) illuminated by lasers at angles.

from the strong laser beam (again: coherent state represented by η) and simultaneous emission of the anti-Stokes photon into the $\hat{a}$ mode and creation of an atomic excitation in the Dicke state occur: $1/N \sum_i \exp(iKr_i)\sigma_{hg}^{(i)}|gg\ldots g\rangle$ where the operator $\sigma_{hg}^{(i)}$ transfers the i-th atom from the state $|g\rangle$ to the final state $|h\rangle$, while the wavevector $K = k_p - k_a$ is equal to the difference between the wave vectors of the photon absorbed from the laser and the scattered photon.

Similarly, we can consider processes where, separately, only the exchange interaction $\mu(\hat{a}\hat{b}^\dagger + \hat{b}^\dagger\hat{a})$ will occur. In nonlinear optics, this would be the process of summing the frequency of a strong laser field (coherent state represented by μ) and photons e.g. telecommunication-wavelenth mode $\hat{a}$ can be subjected to frequency conversion to yield a visible-wavelength mode $\hat{b}$. In the case of an oscillating membrane, acting with such a Hamiltonian can lead to its cooling. To do this, we tune the cavity to the blue sideband of the excitation laser. Any phonons that reside in the mode of the membrane $\hat{b}$ can now be exchanged into the optical mode of the cavity $\hat{a}$ (we often write: excitations of the membrane - phonons - were read-out as photons) and then leak out of the cavity. Hence we obtain the process of *sideband cooling*, also known and often used with trapped ions. In atomic systems we obtain $\mu \gg \eta$ by tuning the laser close to the transition from the $|h\rangle$ state to some excited state from which the transition to $|g\rangle$ is strong. Then the absorption of the photon $\hat{a}$ and the stimulated emission of the photon into the laser mode (the coherent state represented by μ) leads to a two-photon transition and the formation of the excitation described previously. The reverse process is also possible, i.e. conversion of excited quantum memory to photon and empty memory.

Collective spin experiments such as in the [A2] and [A4] papers typically use a different, compatible description, with the creation and annihilation operators converted to canonical momentum and position (which works for both light and the material system):

$$\hat{x} = \frac{\hat{a} + \hat{a}^\dagger}{2} \qquad \hat{p} = \frac{\hat{a} - \hat{a}^\dagger}{2i}, \tag{2}$$

It is also possible to relate these quantities to the collective spin $\hat{J}$ in a different, compatible way. Assuming atoms strongly polarized in the direction x (in real space), we have $\hat{x}_S = \hat{J}_z/\sqrt{|J_x|}$, $\hat{p}_S = -\mathrm{sgn}(J_x)\hat{J}_y/\sqrt{|J_x|}$ (S for spins). In this case, the atoms interact with the polarization of light, so it also becomes convenient to relate optical quadratures to Stokes operators: $\hat{x}_L = \hat{S}_z/\sqrt{S_x}$, $\hat{p}_L = -\hat{S}_y/\sqrt{S_x}$ (L for light). The relations remain sensible within the Holstein-Primakoff approximation.

Quantum Nondemolition Mesurement (QND) is generated by the described Hamiltonian when $\mu = \eta$. It can then be rewritten to the product of position quadrature operators $\hat{x}_a\hat{x}_b$. Operation with such a Hamiltonian preserves the values of position quadratures (hence non-destructive) while momentum quadratures undergo a transformation $\hat{p}_a' = \hat{p}_a + \kappa\hat{x}_b$ and analogously for atoms (membrane). While the measurement does not destroy the position quadrature we are measuring, it does change the momentum quadrature, adding a contribution to it called the quantum measurement back-action. In particular, if we use squeezed states of light with low momentum quadrature variance $\langle\delta p_a\rangle < 1/2$ so that the measurement of the final value of $\hat{p}_a'$ for outgoing light gives as much information as possible about $\hat{x}_b$ then at the same time we add more noise to the final distribution of $\hat{p}_b'$. From a quantum-mechanical point of view, of course, this must be the case, because a more accurate measurement of the value of $\hat{x}_b$ that remains unchanged after the interaction leads to the production of a squeezed state of atoms around the measured value - since we squeezed it by any method in $\hat{x}_b$, it must have expanded in $\hat{p}_b$.

We used the described interaction in atoms, where obtaining the condition $\mu \simeq \eta$ is possible for large offsets, when the offsets from both states $|h\rangle$ and $|g\rangle$ become comparable. In fact, corrections from $\mu \neq \eta$ are significant and require the preparation of appropriately corrected theoretical models for each experiment. Obtaining QND is also possible in a membrane when both sidebands of the drive laser fall within cavity resonance width. Then we have a situation when the cavity erases the distinguishability of these sidebands and, from the point of view of the cavity modes leakage of which we observe, both sidebands are described by the same operator $\hat{a}$.

Also requiring comment is the subtlety associated with the fact that atoms or membranes also undergo oscillatory evolution in our case, which swaps momentum and position in phase space with the resonant frequency. This means that making a truly non-destructive measurement $\hat{x}_b$, would require making it only once per oscillation period - such a technique is called stroboscopic measurement. Nevertheless, light-related operators are not subject to this consideration, and it can be strictly said that all information is mapped to the momentum quadrature of light $\hat{p}_a$, while the position quadrature $\hat{x}_a$ remains unchanged. We shall in any case call the desribed Hamiltonian a QND.

Discussion of individual works

[A1] I. Galinskiy, Y. Tsaturyan, M. Parniak, E. S. Polzik, Optica 7, 718-725 (2020)

In this work, our central goal was to generate and characterize an optomechanical membrane in a state very close to the ground state by counting scattered Stokes and anti-Stokes photons. When the membrane is in the ground state, the intensity of the sidebands of scattered light changes. The anti-Stokes sideband weakens, due to the fact that there are no more phonons in the system to read. By examining the relative intensities of the sidebands Γ_S and Γ_AS we can determine the occupancy of the oscillator $\bar{n}$. Such a measurement is easiest to make via homodyne detection, since we are dealing with fields only 1–2 MHz detuned from the laser. However, it is only by using ultra-narrowband fiters and physically separating the (anti-)Stokes photons from the drive laser that they can be converted or transmitted to other systems. In particular, one of these options is to show the thermal character of the state by directly measuring the second-order coherence function. Further options that our work makes possible are deeper in the quantum regime. The crowning achievement will be the demonstration of first generating a photon-phonon pair, then reading that phonon and showing that in the meantime the membrane was in the conditionally prepared Fock $|1\rangle$. This work has laid the groundwork for this demonstration, which, it is worth adding, should come to fruition in the coming year.

The already described membrane, which was designed, fabricated and placed in the cavity by Y. Tsaturyan, was the central object of the system and was located in an optical cavity with a finesse of 10,000 in a helium cryostat. The cavity was stabilized to the laser with a piezoelectric acctuator moving one of the mirrors. The silicon membrane frame rested on a flat mirror. We implemented the cavity stabilization together with I. Galinskiy using an FPGA, and

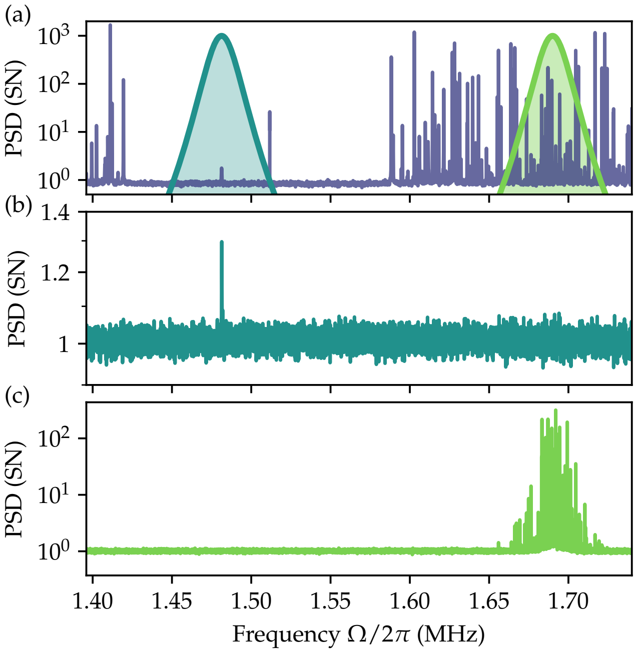

Figure 3 A narrow slice of the spectrum of light coming from the optomechanical cavity (dark blue) with superimposed cavity transmission filtering for two cavity settings (dark green and green, respectively). In the spectrum of light from the cavity, one can see a forest of lines corresponding to various modes of vibration of the membrane together with the surroundings and in the center around 200kHz the area in which the photonic crystal isolation works. In the very center of this area one can see a rather strong peak of interference coming directly from the laser, and at the frequency of 1.48MHz a proper sideband of anti-Stokes scattering. The filter cavities can be set at different offsets relative to the laser, which means that we are filtering different parts of the spectrum (b,c). In particular, in (b) we are filtering the correct anti-Stokes scattering mod. Importantly, in the filtered spectrum, neither the interference from the laser nor the other vibration modes (of the membrane including the suspension and the whole system) are no longer visible, other modes remain. The measurement shown is made homodyne and is essential for verifying the purity of the ekperimental situation, before proceeding to photon counting. The figure is from the work of [A1]. The spectra are normalized to shot-noise units.

took care of optimal coupling to the cavity and laser light preparation.

In particular, the laser must first have a wavelength such that the position of the membrane is optimal in the standing wave in the cavity. This maximizes the coupling constant in the Hamiltonian. Because of the simultaneous need to satisfy the cavity resonance condition, the wavelength of the laser and the distance of the cavity mirrors must be controlled. We set up the system so that the laser is tuned away from the cavity resonance by about the frequency of the membrane mode Ω_m=1.5 MHz. This causes the readout of the phonons (anti-Stokes scattering) to be much stronger than their creation. This is despite the fact that the cavity was about 2 MHz wide, so the creation process was not completely blocked. In this case, the back-action limit of sideband cooling is given by:

$$\bar{n}_{\mathrm{ba}} = (A_-/A_+ - 1)^{-1} \approx 0.185, \tag{3}$$

where $A_\pm$ denote the rates of addition and subtraction of excitations:

$$A_\pm = g_0^2 \bar{n}_{\mathrm{cav}} \frac{\kappa}{(\Delta \mp \Omega_\mathrm{m})^2 + \frac{\kappa^2}{4}} \tag{4}$$

The quotient in particular depends only on the detuning Δ, membrane resonance frequency Ω_m and cavity width κ. The quotient, however, does not depend on the optomechanical coupling constant g_0 (so-called *single-photon optomechanical coupling*) or the number of photons at if light at the carrier frequency in the cavity $\bar{n}_{\mathrm{cav}}$. These rates $A_\pm$, on the other hand, are related to the fluxes of Stokes and anti-Stokes photons:

$$\Gamma_{\mathrm{AS}} = \bar{n}A_-, \quad \Gamma_{\mathrm{S}} = (\bar{n}+1)A_+, \tag{5}$$

Simultaneously, we experimentally examine the ratio $R = \Gamma_{\mathrm{S}}/\Gamma_{\mathrm{AS}}$ and estimate the real occupancy as:

$$\begin{aligned}\bar{n}_{\mathrm{est}} &= \frac{RA_+}{A_- - RA_+} \\ &= \frac{R((\Delta+\Omega_{\mathrm{m}})^2+\kappa^2/4)}{((\Delta-\Omega_{\mathrm{m}})^2+\kappa^2/4) - R((\Delta+\Omega_{\mathrm{m}})^2+\kappa^2/4)},\end{aligned} \tag{6}$$

Which depends on the measured ratio and parameters (Δ, κ,Ω_{m}) which we calibrate using optomechanically induced transparency (OMIT)[3].

We measured the fluxes of Stokes and anti-Stokes photons by tuning narrow filters to the corresponding sidebands. It was these filters that were a significant challenge in the work. It is necessary to filter the signal from the carrier frequency and other scatterers (other modes, in particular out-of-bandgap modes). It is these other scatterers that dictate that the filters must be as narrow as the phononic band gap of the membrane. The merit, then, becomes the attenuation of the filter system at an detuning of about Δ=150 kHz. For several reasons, it is worth to use several filter cavities in such a case, instead of, for example, one very long cavity. In the $\kappa, \kappa' \ll \Delta$ regime, using n filters, we obtain an attenuation of $(\Delta/\kappa)^{-2n}$, compared to $(\Delta/\kappa')^{-2}$ for a single cavity. So to achieve the same attenuation, we need to have $\kappa' = \Delta(\kappa/\Delta)^n$. In comparison, for $\kappa = 30$ kHz and $n = 4$ we would have to have $\kappa' = 250$ Hz. A single cavity also introduces a huge delay of filtered photons $\tau' \sim 1/\kappa' = 4$ ms, as opposed to four cavities with a delay of $\tau \sim 4/\kappa \approx 10\ \mu$s[4]. The filter cavities had a finesse of about 8,000. To achieve the required cavity width, therefore, they are about 60 cm long. In order for such narrow cavities to remain in resonance with the light of interest, it was necessary to stabilize the laser itself beforehand to another reference cavity. The cavity itself was also tuned in length so that it could be slowly adjusted, and so the laser remained in resonance with both the reference cavity and the optomechanical cavity. Thus, in the end, the experiment contained 6 actively stabilized cavities. All cavities except the optomechanical cavity were in a mechanically isolated vacuum system. The filtering cavities were alternately stabilized with an additional shifted laser beam (each lock was based on the piezo-dithering method), and used without stabilization during the actual filtering. We showed that they could remain in their very narrow resonance by themselves for up to 10 seconds.

In an experiment using the described system, we measured the membrane occupancy for different laser powers, alternately aligning the cavities on the two sidebands by tuning the reference laser. We achieved a record occupancy (for systems not using dilution refrigerators) of $\bar{n} \approx 0.2$. In addition, we showed that the generated photon state is thermal with a (second order) coherence time corresponding to the optical broadening of the mechanical oscillator.

In summary:

Main achievement:: generation and verification of the ground state of a macroscopic mechanical oscillator using photon counting

My contribution: system design, measurements, data development and analysis, article writing, theoretical modeling, revisions, contribution of about 27%

[A2] R. A. Thomas, M. Parniak, C. Østfeldt, C. B. Møller, C. Bærentsen, Y. Tsaturyan, A. Schliesser, J. Appel, E. Zeuthen, E. S. Polzik, Nature Physics 17, 228-233 (2021)

In this work, our central goal was to generate Einstein-Podolsky-Rosen (EPR)[5] type entanglement between the membrane and the spin ensemble of cesium atoms. The basic idea of the experiment is a non-destructive measurement of the sum-position quadrature of the two systems $x_m + x_s$. We did this by passing a single beam through both systems configured for QND measurement. Measuring such a quadrature gives a chance, under additional conditions, for the combined state of both systems to be conditionally projected onto an entangled state. In our case, however, both systems are oscillators (let's say with the same frequency), which causes us to alternately measure

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[3] S. Weis et al., "Optomechanically induced transparency," Science **330**, 1520–1523 (2010)

[4] For a series of cavities the temporal transfer function actually becomes non-exponential, but the mean delay scales linearly with the number of cavities nevertheless.

[5] A. Einstein et al., „Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," Phys. Rev. **47**, 777 (1935)

$\hat{x}_m + \hat{x}_s$ and $\hat{p}_m + \hat{p}_s$. These operators do not commute, so we cannot measure them with high precision simultaneously. In practice, the back-action mapped onto the second quadrature will increase the noise and we will not get entanglement. Thus, the essential trick is to engineer the spin oscillator in such a way that the evolution takes place there with a de facto negative frequency $\omega_s = -\omega_m$. It turns out that it is enough to reverse the relative orientation of the collective spin and magnetic field - naturally, precession then occurs in the other direction. Then, we alternately measure $\hat{x}_{\text{EPR}} = \hat{x}_m + \hat{x}_s$ and $\hat{p}_{\text{EPR}} = \hat{p}_m - \hat{p}_s$. These variables commute, so they are measurable separately and independently. A pair of such variables also corresponds to the famous EPR thought-experiment. Noise from the measurement response is mapped to an unobserved combinations of $\hat{x}_m - \hat{x}_s$ and $\hat{p}_m + \hat{p}_s$. To detect entanglement, it is sufficient to examine, for example, the sum of variances of EPR variables[6]. This approach can be understood as finding a quantum-mechanics-free subspace[7].

The groundwork for the experiment had been laid before I joined the group, when in 2017 Professor Polzik's team first demonstrated the interference between the back-action noises imprinted onto atoms and the membrane[8]. However, it quickly became apparent that neither the atoms, the membrane, nor the optical link could be used to generate entanglement due to both the mismatch and the insufficient quality of the individual elements. In addition, there was a lack of theory to calibrate the system and estimate the generated entanglement. In 2018, before I joined the group, the team (PhD student C. Østfeldt, postdoc C. B. Møller and Professor J. Appel) had begun the design of a new tunable cavity in which to place the membrane. Importantly, in this cavity both mirrors are controlled by piezoelectric acctuators, so that the resonance of the cavity and the optimal position of the membrane in the standing wave can be independently achieved. So there is no need to tune the laser as in the [A1] work, which is important here because the light must be in resonance with the Cs atoms. This substantial project took a considerable amount of time due to the need to minimize all sources of vibration. I personally joined this effort toward the end of the work on the cavity itself, participating extensively in the development of the laser-to-cavity/cavity-to-laser stabilization algorithms. I introduced a digital stabilization system for use in the experiment (previously only an analog Lockbox-type system had been used) based on an FPGA system with Red Pitaya STEMLab ADCs and DACs. The system allowed us to stabilize the system over a wide range of conditions by introducing a loop-tightening algorithm and gradually switching between the Lorentzian slope stabilization method of the cavity line profiles and the Pound-Drever-Hall method. This proved especially important at low temperatures, where the high mechanical quality factor of the membrane easily causes large oscillations of the resonance of the cavity itself. We also investigated a couple of important experimental problems, such as working on the system jointly with C. B. Møller and C. Østfeldt, I developed optimal methods for applying liquid Helium to the cryostat so as to optimize the operating time and avoid the perennial problem of cavity-disrupting bubbles. I developed dynamic stabilization methods to optically quench unwanted and excessive membrane oscillations before the actual experiment. Another challenge related to optomechanics itself was to study and calibrate the operation of the optomechanical cavity, especially under cryogenic conditions. I developed, with the help of the team, a method (presented in the supplement to [A2]) that allowed for a largely independent recovery of the thermodynamic reservoir (a.k.a. bath) temperature interacting with the membrane mode. The method involved taking the spectra of the squeezed light for several laser-cavity detunings and performing a global least-square curve fit.

At the same time, I joined the effort to improve the atomic part of the system, on which doctoral student R. A. Thomas had previously worked. We developed new methods for calibrating the coupling and pumping, and for stabilizing the phases in the interferometer containing the atoms. The system also underwent modifications relative to its original state, particularly to improve optical pumping. I also programmed a digital magnetic field controller. We also developed completly new callibration methods.

The next step was to combine the two systems. Together with the team, we designed the lens and interferometer system. I also proposed an improvement to add a Faraday rotator (effectively an insulator) to the path, so that unwanted light from the optomechanical system could not return to the atomic system. Otherwise, the system becomes unusually sensitive to the phase of this feedback, as shown by T. M. Karg et al.[9]. In addition, we developed interferometers stabilized again with an FPGA system that allowed digital phase adjustment. Before the final measurements, the system had to undergo very precise alignment to avoid, for example, drifts or unwanted scattered light beams.

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[6] L.-M. Duan et al., „Inseparability criterion for continuous variable systems," Phys. Rev. Lett. **84**, 2722–2725 (2000)

[7] M. Tsang, C. M. Caves, „Evading quantum mechanics: Engineering a classical subsystem within a quantum environment," Phys. Rev. X 2, 031016 (2012)

[8] C. B. Møller et al., „Quantum back-action-evading measurement of motion in a negative mass reference frame," Nature **547**, 191–195 (2017)

[9] T. M. Karg et al., Light-mediated strong coupling between a mechanical oscillator and atomic spins 1 meter apart, Science 369, 174-179 (2020)

After obtaining the first results, I became intensively involved in collaboration with theorist E. Zeuthen and we began to adapt the theory so that it could be applied to the experiment. In this part, I performed data analysis and theoretical models in python, and together with E. Zeuthen we developed the analytical theory (also in Mathematica), in particular, my contribution was also to automate the process of solving the Wiener-Hopf equation. Initial considerations were based on theoretical papers[10,11] and previous experiments with two atomic systems [12]. However, these approaches were completely inadequate due to the more complicated relationships (and correlations) of noise and signal in the new system. We have established that the mechanism for generating entanglement can be twofold in the actual system. First, two-mode squeezing in the atoms (a side effect of the complex level structure) leads to the formation of entanglement between light and atoms. Then, this light can be stored in the membrane state, which generates entanglement. The variance of the EPR-type quadrature is thus reduced unconditionally. This mechanism is somewhat incidental and was not the main purpose of this work. The main mechanism for the generation of entanglement was the non-destructive measurement of both systems using the same light beam. In this case, the generated entangled state must be estimated. Such a state is Gaussian, so it is sufficient to study its mean and (co)variance. In such a case, the general combination of position and momentum operators written as a vector $\boldsymbol{Q}$ can be estimated by some linear filter $\boldsymbol{K}$ acting on the signal i (homodyne detector current):

$$\boldsymbol{Q}^{c}_{\infty}(t) = \int_{-\infty}^{t} \mathbf{K}(t'-t)i(t')\,\mathrm{d}t', \tag{7}$$

The optimal filter $\boldsymbol{K}$ minimizes the state variance and satisfies the Wiener-Hopf equation:

$$\int_{0}^{\infty} \mathbf{K}^{\intercal}(-t'')\bar{C}_{ii}(t'-t'')\,\mathrm{d}t'' = \bar{\mathbf{C}}_{\mathbf{Q}i}(t') \quad \forall\, t' \geq 0. \tag{8}$$

To solve the equation, we need to know the autocorrelation of the measured signal C_{ii} and the correlation between the measurement and the relevant variable $\mathbf{C}_{\mathbf{Q}i}$. When the filter satisfies this equation, the conditional variance of any variable X, $\mathrm{Var}_c[X]$ is given by the difference of the unconditional variance $\mathrm{Var}[X]$ and the variance of the best estimate $\mathrm{Var}[X^c]$:

$$\mathrm{Var}_c[X] = \mathrm{Var}[X] - \mathrm{Var}[X^c]. \tag{9}$$

In general, in the given case of two systems, we operate on covariance matrices.

In particular, let's look at the sum of the variances of the quadratures of interest, which is what detects entanglement when it is less than 1:

$$V_{\mathrm{u}} = \mathrm{Var}[\hat{x}_{\mathrm{EPR}}] + \mathrm{Var}[\hat{p}_{\mathrm{EPR}}] < 1 \text{ (entangled state)}, \tag{10}$$

which also holds for conditional entanglement:

$$V_{\mathrm{c}} = \mathrm{Var}_c[\hat{x}_{\mathrm{EPR}}] + \mathrm{Var}_c[\hat{p}_{\mathrm{EPR}}] < 1 \text{ (conditionally entangled state)} \tag{11}$$

As an example of how the conditional state preparation mechanism works, consider the measurement of a single system (e.g., only atoms). If we have only one system (oscillator) which we measure by non-destructive measurement, its unconditional variance is:

$$V_{\mathrm{u}}^{(1)} = (1+2n)(1+C_{\mathrm{q}}) \tag{12}$$

where the parameter $C_{\mathrm{q}} = \Gamma/(\gamma[2n+1])$ is called the quantum cooperativity and n is the thermal occupancy and γ is the decay constant of the system, while Γ its strength of coupling with light. As we can see, measurement increases the variance through the back action, but this knowledge allows estimation of the state with conditional variance:

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[10] K. Hammerer et al., „Establishing Einstein-Poldosky[sic!]-Rosen Channels between Nanomechanics and Atomic Ensembles," Phys. Rev. Lett. **102**, 020501 (2009)

[11] X. Huang et al., „Engineering asymmetric steady-state Einstein-Podolsky-Rosen steering in macroscopic hybrid systems," Phys. Rev. A **100**, 012318 (2019)

[12] H. Krauter et al., „Entanglement Generated by Dissipation and Steady State Entanglement of Two Macroscopic Objects," Phys. Rev. Lett. **107**, 080503 (2011)

$$V_c{}^{(1)} \approx \sqrt{1/(2\eta)}\sqrt{1+(\gamma/\Gamma)V_u{}^{(1)}} = \sqrt{1/\eta}\sqrt{1+1/(2C_q)} \tag{13}$$

where η is the efficiency of the detector. Here we have a smaller variance, but V_c reaches minimally 1, i.e. the (conditional) ground state. Now, for a pair of systems matched as in our case, and with the same couplings $\Gamma_M = \Gamma_S \equiv \Gamma$ the conditional variance reaches:

$$V_c \approx \frac{1}{\sqrt{\eta}}\sqrt{\frac{1}{2C_q}}, \tag{14}$$

which shows that the variance reaches values below 1, indicating conditional entanglement, for large C_q.

To perform such a conditional analysis in an experiment, it was necessary to adapt the problem to the experimental data. Thus, to solve the equation, we measure the autocorrelation of the signal (by measuring the signal's noise power spectrum) and recover the correlations between the signal and quadrature by fine calibrations of all the system parameters. In the experiment, these functions take the form of discrete vectors, and the Wiener-Hopf equation becomes a matrix equation. In particular, C_{ii} is a Toeplitz matrix, which allows the equation to be solved efficiently using the Levinson-Durbin recursive algorithm (we used an implementation with `scipy.linalg`, function `solve_toeplitz`[13]). The computationally efficient solution of the equation turns out to be important when we want to perform Markov Chain Monte Carlo error analysis [14].

In the final experiment, we measured a large number of time traces of homodyne current, which allows both to perform the Wiener filtering procedure, and to precisely match the theory to the noise power spectra, of course supported by many calibrations. Basically, recovering the variance itself does not require applying a filter, but only finding the variance of the estimator of the variable X as $\int_0^\infty K_X(t)C_{Xi}(t)\mathrm{d}t$. I applied the procedure of global fitting of multiple spectra for slightly different parameters. Then, the aforementioned MCMC method was used to vary the parameters (based on the calibration priors) and thus we obtained the uncertainty of the final result, including a full posterior distributions of resulting variance and paramters. The best result for the conditional variance was $V_c = 0.83 \pm 0.02$, which showed the entanglement of atoms and membrane to a very good uncertainty.

In summary:

Main achievement: generation of the entangled state of a macroscopic mechanical oscillator and an ensemble of atomic spins

My contribution: system design, development of calibration methods, development of data analysis tools, theoretical modeling, article writing, revisions, contribution of about 25%

[A3] M. Parniak, I. Galinskiy, T. Zwettler, E. S. Polzik, Optics Express 29, 6935 (2021)

In this work, our central goal was to optimize the laser noise so that the light from this laser could be used for laser cooling of the membrane to record-breaking occupancies. Laser noise is an important limitation in the Raman cooling of the membrane. For an ideal coherent state of the carrier wave, the sideband at the resonance frequency of the membrane is in a vacuum state. The cooling process itself involves the transfer of excitations from the membrane to this sideband. However, when the sideband itself is in a thermal state due to laser phase noise, the transfer of excitations will go both ways. In practice, this means that cooling still works, but only up to a certain point. The overall ccupancy limit due to laser noise is largely dependent of the quantum limits mentioned earlier (back-action limit), but in particular when the quantum limit is significantly smaller, as in the case of a narrow cavity ($\kappa \ll \Omega_m$), the limit will be given by:

$$\bar{n} \approx \sqrt{\frac{n_{th}\gamma_m}{g_0^2}\Omega_m^2 \bar{S}_{\varphi\varphi}(\Omega_m)} \tag{15}$$

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[13] https://docs.scipy.org/doc/scipy/reference/generated/scipy.linalg.solve_toeplitz.html

[14] https://emcee.readthedocs.io/en/stable/

So we can see that we care about reducing the spectral density of phase noise $\bar{S}_{\varphi\varphi}(\Omega_{\mathrm{m}})$ in particular around the resonance frequency Ω_{m}. The spectral density of phase noise is directly related to the laser frequency noise. Reducing this power spectral density is a somewhat different issue than the more typical laser line narrowing problem, where we reduce phase noise at low frequencies, often even at the expense of noise at high frequencies. Considering other works, the frequency of 1.5 MHz considered here can be considered high.

The source of the phase noise considered here is the very nature of laser operation. Already Schawlow and Townes have shown[15] that even an ideal laser, despite the absence of amplitude noise, has phase noise, so also a finite linewidth. This limit is related to the no-cloning theoreom for photon states. The Ti:Sa continuous-wave laser we used obviously has more phase noise, and, furthermore, exhibits large amplitude noise at a frequency of about 700 kHz associated with the relaxation-oscillation process. This, however, is irrelevant to the target optomechanical experiment.

In this work, we used 50 m of optical fiber to construct an unbalanced Mach-Zhender interferometer. We then slowly stabilized the interferometer at half-fringe. Both optical outputs of the interferometer impinge onto the differential detector (custom made). Its signal will be proportional to the phase difference associated with the propagation in the two arms, so that the frequency domain response function of the overall phase detector is:

$$G(f) = 1 - e^{-2\pi i\tau f}. \tag{16}$$

When measuring low frequencies, the longest possible optical fiber [16] is used. Here we can use the optimal length, so that $\tau = f/2$, providing the best sensitivity at the frequency f we are interested in.

We used the described circuit to compensate for laser noise. Having the results of the real-time noise measurement, we close the feedback loop. For phase comepensation, we chose a free-space phase electro-optical modulator, which simultaneously allows the beam to be modulated at a frequency of 1.5 MHz and transfer the necessary 100 mW of light without significant losses. Given the nature of the measurement system's response to phase disturbances, a proportional or integral controller would not be an adequate solution here. Instead, we used an I/Q modulator with an internal gain, which allows modulation at a frequency of about 1.5 MHz and some preset bandwidth, with a controllable phase shift between the signal being measured and sent to the modulator. Due to processing delays in the FPGA board, the bandwidth of such feedback was limited to a maximum of 300 kHz, but importantly the central frequency is reprogrammable. The closed-loop signal sent to the electro-optical modulator turns out to be very small, with a power of less than -10 dBm, despite a half-wave modulator voltage of 100 V. This shows the precision of our method and how small (yet significant!) noise we remove.

Finally, we demonstrated a reduction in laser noise by up to 10 dB in the context of the power spectral density of the noise. Such a reduction will make it possible to achieve membrane oscillator occupancies below 0.1 phonons. Our circuit can find particularly significant applications in a system operating at even slightly lower frequencies where the noise is higher. The advantages of the solution are high efficiency (i.e., only 10 mW used to measure the noise, and even several hundred mW can be modulated and used in the experiment), lack of introduced amplitude noise and easy tunability.

An additional result of our work was the measurement of the noise of the optical fiber itself. Naturally, such a measurement was made possible by using two delay lines with two identical optical fibers simultaneously. The correlated noise coming from the laser was subject to subtraction, leaving the shot noise (the power spectral density of which is easily calibrated) and the optical fiber noise. It turned out that previous measurements tended to go up to only 100 kHz, so our experiment provided completely new data (here for the PM780-HP fiber) and showed agreement with the theoretical model proposed by L. Duan[17].

The experiment itself required several iterations to achieve the expected parameters. Under the supervision of myself and I. Galinskiy, Master's student T. Zwettler constructed the first version of the unbalanced interferometer and demonstrated that it could be used to measure the phase noise of the laser. Together we also made preliminary estimates of the noise of the optical fiber itself, estimating that it would be small enough in the band around the frequency of 1.5 MHz. I personally took care of preparing data acquisition methods to precisely calibrate the system. Together with I. Galinsky, we built two final versions of the interferometers. Currently, the system is used in further experiments, remaining practically always activated during measurements[18]

In summary:

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[15] A. L. Schawlow, C. H. Townes, „Infrared and optical masers," Phys. Rev. **112**, 1940–1949 (1958)

[16] D. Li et al., „Efficient laser noise reduction method via actively stabilized optical delay line," Optics Express **25**, 9071-9077 (2017)

[17] L. Duan, „General treatment of the thermal noises in optical fibers," Phys. Rev. A **86**, 023817 (2012)

[18] Interestingly, during most experiments we need to both narrow the laser line using a reference cavities, as in [A1], and simultaneously use the noise reduction system from the publication [A3].

Main achievement: laser noise reduction enabling laser cooling of mechanical oscillators to baseline (<0.1 residual occupancy)

My contributions: idea development, circuit design, measurements and data analysis, article writing, revisions, contribution of about 50

[A4] R. A. Thomas, C. Østfeldt, C. Bærentsen, M. Parniak, E. S. Polzik, Optics Express 29, 23637 (2021)

In this work, our goal was to develop a method for characterizing the mapping between atoms and light, which is extremely important for determining the state of atoms. One of the most important problems in the work [A2] in determining the entanglement limit is the calibration of the readout of the system under study, i.e. how exactly $\hat{x}_S$ maps to $\hat{x}_L$ (and vice versa). I developed the idea of this method together with R. A. Thomas. Junior doctoral students worked on the actual measurements and analysis of calibration uncertainties. Personally, however, I took care of understanding the additional broadband response of atoms, also described in the paper.

The central idea presented in the paper is based on the input-output relation for the quadrature of light passing through atoms. If we go beyond the approximations used so far, a single atom has in itself already a rather complex Hamiltonian of interaction with light, depending on the fundamental properties of atoms. This Hamiltonian can be simplified when collectively interacting in a particular geometry to:

$$\hat{H}_\mathrm{S}/\hbar = \frac{\omega_\mathrm{S}}{2}(\hat{x}_\mathrm{S}^2 + \hat{p}_\mathrm{S}^2) - 2\sqrt{\Gamma_\mathrm{S}}\left(\hat{x}_\mathrm{S}\hat{x}_\mathrm{L} + \zeta_\mathrm{S}\hat{p}_\mathrm{S}\hat{p}_\mathrm{L}\right), \tag{17}$$

where ω_S is again the Larmor frequency. Here, however, the coupling constants Γ_S and ζ_S are no longer given by the structure of the atom itself, but depend on the total number and density of atoms, optical pumping, geometry of the system, propagation, or polarization of light. Thus, an experimental calibration is needed, operating under conditions similar to the actual experiment (here specifically the one described in the paper [A2]), giving mainly a coupling constant Γ_S. We usually treat the second constant ζ_S as a small correction to the typical QND Hamiltonian, and typically consider it equal to 0 in many cases. In the paper we actually calibrated it as well, but in the description here I will focus on the main constant Γ_S, also known as the readout rate.

The signal called CIFAR (*coherently induced Faraday rotation*) is a representation of the response of atoms to light modulation, observed in transmitted light. The signal is obtained by lock-in detection, and due to the nature of the experiment we are interested in frequencies mainly around the Larmor frequency. We calculate our signal by looking at the detected quadrature $p_\mathrm{L}^\mathrm{det}$:

$$\begin{aligned}|\mathrm{CIFAR}|^2 \equiv \left|p_\mathrm{L}^\mathrm{det}\right|^2 &= \left|p_\mathrm{L}^\mathrm{out}\cos\phi + x_\mathrm{L}^\mathrm{out}\sin\phi\right|^2 \\ &= \Big|\left(1 - 2\Gamma_\mathrm{S}\zeta_\mathrm{S}\left(\tfrac{\gamma_\mathrm{S}}{2} - i\omega_\mathrm{RF}\right)\chi_\mathrm{S}(\omega_\mathrm{RF})\right)\sin(\theta+\phi) \\ &\quad + \Gamma_\mathrm{S}\omega_\mathrm{S}\chi_\mathrm{S}(\omega_\mathrm{RF})\left[(1-\zeta_\mathrm{S}^2)\cos(\theta-\phi) + (1+\zeta_\mathrm{S}^2)\cos(\theta+\phi)\right]\Big|^2 |G|^2.\end{aligned} \tag{18}$$

The signal, parametrized by modulation/demodulation frequency ω_RF, is at first glance quite complex, and depends, among other things, on the susceptibility of the spin oscillator (atoms) χ_S and modulation and detection angles θ and ϕ, and modulation depth G. However, with a clever choice of modulation and detection angles, which we can set permanently with interferometers and/or waveplates, the signal takes a much simpler (normalized) form:

$$|\mathrm{CIFAR}_0|^2 = 1 + \frac{\Gamma_\mathrm{S}^2 - 2\Gamma_\mathrm{S}\Delta_\mathrm{RF}}{\Delta_\mathrm{RF}^2 + (\gamma_\mathrm{S0}/2)^2}. \tag{19}$$

The minimum and maximum of this signal are separated in frequency by just the sought-after value $\sim \sqrt{\Gamma_\mathrm{S}^2 + \gamma_\mathrm{S}^2}$ which converges to Γ_S for strong coupling $\Gamma_\mathrm{S} \gg \gamma_\mathrm{S}$. The strength of the coupling can thus be directly read off a single lock-in sweep as this separation. In general, we used least-square curve fitting, but this simple approach to interpreting the signal is also extremely helpful. In the work itself, we showed a number of such sweeps and accurately determined the parameters of the system at different temperatures. We also observed, for the first time, a coherent broadband response of non-uniform spatial modes that normally add the so-called broadband spin noise[19] which also happens to exhibit various power spectral densities depending on the nature of the system.

In summary:

Main achievement of the work: development of a new method to calibrate the ground state of an ensemble of spins and map this state to light quadrature by calibrating the coupling strength, observation of the broadband coherent response of an ensemble of atoms to modulation

My contribution: idea development, development of data analysis methods and theory, initial measurements, writing and revising the article, contribution of about 22%

[A5] M. Lipka, M. Parniak, Optics Letters 46, 3009 (2021)

In this work, we presented a very fast and low-noise spatial photon detector that was used to characterize a correlated state of light that exhibited non-trivial correlations in both space and frequency. Characterization of complex entangled states, especially multi-mode states as in the works [A6] and [A7] can be very time consuming without a suitable detector, hence our effort in developing a suitable tool.

In the process of characterizing a quantum state, statistics plays an essential role. The ability to repeat an experiment multiple times is particularly important when we want to measure a state that depends on variables that can take on multiple values. In the experiment in question, we measured the probability of generating a pair of photons as a function of direction k and frequency ω of each $|\psi(k,\omega,k',\omega')|^2$. If we wish to distinguish between 50 directions and 50 frequencies then we have to fill 50^4 (more than 6 million) bins in which we would like to collect statistics. Since a pair of photons is generated on average once every few iterations of the experiment, so that the probability of generating two pairs is sufficiently small, the necessary huge number of repetitions of the experiment is feasible provided we have a detector that can repeat measurements frequently. In our laboratory, we have several unique cameras built with this requirement in mind. The camera used in the work [A6] and [A7] can collect up to 500 frames per second, thanks to the best technology available to us when it was built 10 years ago. We have now gone down to a lower level and used an CMOS sensor capable of digitizing one million lines of image per second. The data from this sensor (up to 28 Gbps) goes to a custom-made FPGA-based system where we have implemented a real-time algorithm for detection of ”photon flashes” positions. This enables easy data transmission (as data size is at this point greatly reduced) and collection of large statistics.

The experiment described here was designed to test the suitability of the developed device under conditions typical of the single photon experiments we conduct. In this experiment, the photon pairs came from the process of parametric downconversion (SPDC) in a nonlinear crystal, making the system uncomplicated in construction and theoretical description. We built (effectievly) two imaging spectrometers whose input slits were inserted in the far field relative to the crystal and the output image was projected onto two camera fragments. The experiment confirmed the correctness of the camera and its suitability in the photon pair detection regime. At the same time, this was the first measurement of the simultaneous wavevector-frequency correlation function for biphotons. Such a measurement is particularly important in the developing study of hyperentangled states, especially of high-dimensionality Hilbert spaces.

As part of the work, I proposed and developed the idea of the experiment, and M. Lipka programmed the camera and made the measurements. We collaborated on the construction of the system, data analysis and writing of the article.

In summary:

Main achievement: development of a new technical method for the characterization of multimode entangled light

My contribution idea development, development of data analysis methods, article writing, revisions, coordination, contribution of about 40%

[A6] M. Lipka, M. Mazelanik, A. Leszczynski, W. Wasilewski, M. Parniak, Communications Physics 4, 46 (2021)

In this paper, we showed the generation of Bell-type entanglement between spin waves stored in Rb atoms, and the photons emitted in multiple spatial modes simultaneously.

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[19] R. Shaham et al., „Quantum dynamics of collective spin states in a thermal gas,” Phys. Rev. A **102**, 012822 (2020)

Multimode quantum memory in the process of spontaneous Raman emission (write) generates an entangled state that can be transformed to a multimode Bell state using interferometers. The memory is initially prepared with all atoms in the $|g\rangle$ state and then subjected to a laser pulse with a well-determined wavevector k. The laser pulse is detuned by several natural widths from the transition that excites the atoms, so spontaneous Raman scattering with atom transfer to another state can occur. By selecting the polarization of the pulses and observing photons scattered with a polarization perpendicular to the laser polarization, one can limit themselves to considering one target state of atoms $|h\rangle$. The photons scattered in this process can be observed in the far field. In our experiment we observed a rectangular field of side size ~ 100 mrad next to the writing/reading beam. The generated state can be written as $\sum_K \hat{a}^\dagger_{k-K}\hat{b}^\dagger_K|0\rangle$ where the wave vector K enumerates the collective excitation modes of the atomic cloud created by operator $\hat{b}^\dagger_K$, while $\hat{a}^\dagger_{k-K}$ creates a photon with wavevector $k-K$. After generating the described state, we subject the photon to such a transformation that the combined state of the atoms and photons is of the Bell-type. Let's divide the far field of the scattered photons into two halves and overlap them on the polarizer, in such a way that for the initial horizontal polarization there is no change in the wave vectors $\hat{h}_k = \hat{a}_k$ while for the vertical there is a shift by the differences between the centers of the two halves of the combined fields $\hat{v}_k = \hat{a}_{k+\kappa}$. After some time, the spin waves $\hat{b}^\dagger_K$ can be converted to light in the reading process using, in our case, a laser almost tuned to transition from the $|h\rangle$ state. The reading process is generated by acting with the exchange (beamsplitter-type) operator of the type $H_R \propto \sum_K \hat{a'}^\dagger_{-k+K}\hat{b}_K + \text{h.c.}$. We subject the read photons to completely the same division (with respect to direction) into two areas, and then combination on the polarizer - exactly as for the photons generated in the writing process. In view of this, the combined state of the photons generated in the writing process and the photons read-out after storage, takes the form of $\sum_k |1_{hk}1_{h'-k}\rangle + |1_{vk}1_{v'-k}\rangle$. In other words, for each direction k of the outgoing photon plane wave from the first polarizer-combiner and the conjugate direction $-k$ of the outgoing photon plane wave, we obtain a Bell state on which we can measure polarization correlations.

In the experiment, the measurement of polarization correlations follows the same procedure as always, that is, we use wave plates to make a rotation of the sphere of polarization in the recording arm and other plates to make a rotation in the reading arm. Then, in each of these arms, we use a polarization analyzer and a detector. The latter is different than in typical experiments, as the detector is a camera with an image intensifier, recording the positions of photons in the far field. We direct both analyzers' output ports to four separate areas on the same camera.

Relatively the most complex experimental issue is to correctly set up the system to realize the transformations given above with the assumed phases, that is, not to introduce different phase delays for the different possible photon paths. Especially, it is important to eliminate or at least measure the directional dependence of the phase delay between the components of the Bell superposition. To solve this problem, we developed the following original method. The memory, after cleaning, is subjected to a stimulated write (seeding) operation, that is, we operate the $H_W \propto \sum_K \hat{a'}^\dagger_{k-K}\hat{b}^\dagger_K + \text{h.c.}$ operator in the presence of weak laser light with frequencies closely corresponding to the frequencies of photons that are scattered spontaneously. Part of the light is amplified and spin waves with controlled wave vectors and phase relations are created. The proces is similar to seeding of an optical paramteric oscillator. Weak light is prepared in a system of two serial Mach-Zhender interferometers that allow populations of a wide portion of the h field and the v field. The turning mirrors of the interferometers are combined at opposite foci of the lens inserted between the interferometers. Thus, the tilt of the mirrors of the first interferometer controls the beam shift, while the tilt of the second controls the relative shift by a vector κ equal to the reciprocal-space shift between the fields. Part of the faint light passes through the memory without absorption, undergoes combination on the polarizer-combiner and continues through the waveplate assembly and analyzer identically to single photons. The absorbed light is stored and moments later read back and samples the path and measurement system of the read-out. Quantum memory is used in such a calibration in the macroscopic regime, where individual wavevector modes are prepared with significant excitation amplitude. However, the phase relations remain the same and can be quickly measured, calibrated and the optical system improved. For efficient alignment, a great help is the ability to move the sample beams in the near field described above, moving in the near field generates fringes on the camera. Via setting the fringes to be dense enough (a dozen or so in the observed image) we can recover their phase by using the Hilbert transform, as in a shearing interferometer. This is the fastest way to check the full correspondence of the density of the fringes in the recording and reading arm, proving the absence of phase delay dependence on the wave vector. Then we switch the test beam generation system to plane waves and check that, the waves spaced by κ are overlapped in both optical paths. In practice, we have prepared appropriate real-time camera image analysis software for this.

We directed the measurements performed to calculate the CHSH combination map as a function of direction k. As the storage time of spin waves in memory increases, the value of this combination inevitably decreases. For simplicity, we take as the entanglement lifetime the time for which the CHSH combination drops to the value of 2,

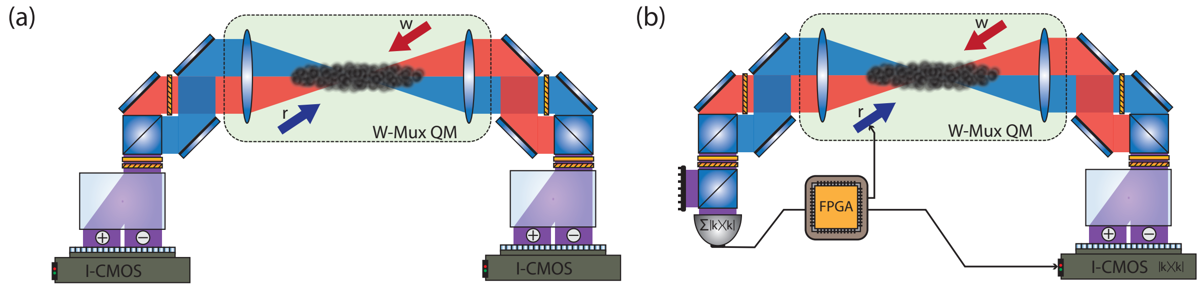

Figure 4 Simple comparison of ways to use quantum memory (W-Mux QM, i.e., *wavevector multiplexed quantum memory*) in detection systems in the papers [A6] (a), and [A7] (b). It is worth mentioning that in work (a) photons are directed so that they fall on four different fragments of the same I-sCMOS sensor. Figure based on [A7]

getting a lifetime of at least 50 μs.

One of the additional significant achievements of the work is the development of a self-consistent and effective phenomenological model of noise in memory.

In the experiment, A. Leszczyński and M. Mazelanik worked mainly on the experimental set-up with the support of W. Wasilewski, and M. Lipka on data analysis. I personally coordinated the work and was involved in developing the theory and writing the manuscript, together with M. Lipka and M. Mazelanik. I also worked on part of the system design.

In summary:

Main achievement: development and demonstration of a method to generate multiple states of entangled photons in parallel

My contribution: idea development, layout design, development of data analysis methods, article writing, revisions, coordination, contribution of about 22%

[A7] M. Mazelanik, A. Leszczynski, M. Lipka, W. Wasilewski, M. Parniak, Quantum 5, 493 (2021)

In this paper, we demonstrated the possibility of performing a conditional readout from memory and obtaining an entangled state. The starting point was the experimental setup from the paper [A6] with modifications that are summarized in Figure 4. In the recording arm, we inserted an avalanche photodiode coupled via a multimode fiber as a detector, which gave information about the occurrence and polarization of the photon while not its direction k. After preparing a cold cloud of atoms, we made many attempts to spontaneously store the photon-wave spin pair in memory. Due to the 50% efficiency of the detector, the approximately 50% loss of filters stopping the noise photons, and the natural stochastic nature of the process, it takes several attempts to record a photon. After each failed attempt, the memory is cleaned via optical pumping. About a dozen state generation attempts can be made before the cloud of atoms falls below the laser beam axis and dissipates thermally into the vacuum. A successful attempt is announced by a signal from the detector which arrives with a delay of several nanoseconds. After this signal, and only after it, a specially prepared FPGA switches the pulse sequence into readout mode. The minimum delay we are able to achieve in such a mode of operation between writing and reading is about 500 ns, and is limited by the speed of the acousto-optic modulators we use to generate the pulses. The read photon impinges, depending on its polarization, on one of the two areas of the camera where its wave vector is recorded. To measure the value of the CHSH combination, we specifically introduced a controlled phase gradient as a function of emission direction in this setup. Thus, repeating the experiment without changing the analyzer settings leads to an image of fringes and recovering the CHSH combination value requires (only) two analyzer settings in the recording arm.

With some modification of the inequality itself, however, it turns out, as we have shown in the paper, that only one image is enough to prove entanglement - assuming, of course, that correct, identical copies of the state are generated in each direction. In this case, we define Bell's parameter by the Freedman-Clauser formula [20] with appropriate modification described in the paper.

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[20] S. J. Freedman, J. F. Clauser, „Experimental Test of Local Hidden-Variable Theories," Physical Review Letters 28, 938 (1972)

The work itself combines the issue of Bell's inequality with a second interesting quantum effect known as *ghost imaging*. In a typical *ghost imaging* experiment in the arm of one of the correlated photons we insert a detector with spatial resolution, and in the arm of the other we insert an object and a bucket detector. By studying the correlations, we can recover the image. In our experiment, thanks to the use of conditional operations, such an image is obtained directly. It could be any image, amplitude and/or phase. In our case, we use holographic patterns which allow us to beat the Bell-type inequalities. The only previous demonstration[21] of a similar scheme used a very complicated image delay line - our quantum memory, however, is a much more effective and a natural tool of choice here.

Thus, the fundamental achievement of the described experiment is to test the possibility of performing conditional operations in the memory, conditioned in particular by the results of measurements with a delay much smaller than the lifetime of the state in memory.

During the work, most of the measurements were made by M. Mazelanik, with the support of M. Lipka and A. Leszczyński. I developed the idea and plan of the experiment, and then worked closely with M. Mazelanik on measurements (in particular, improvements to the FPGA code for implementing conditional operations) and data analysis, and then on writing the paper and developing the theory.

In summary:

Main achievement of the work: demonstration of Bell entanglement between photons and quantum memory in real time

My contribution: idea development, setup design, development of data analysis methods, article writing, revisions, coordination, contribution of about 22%

[A8] M. Lipka, M. Mazelanik, M. Parniak, New Journal of Physics 23, 053012 (2021)

In this paper, we made a theoretical analysis of the possibility of using the state generator described above in a quantum repeater for generating entanglement over long distances. Long-distance fiber optic entanglement distribution succeeds only when both photons from a pair reach their destination, which is exponentially more difficult with distance - succeeding once in $\exp(L/\Lambda)$ attempts - where Λ is on the order of 10 km in a telecommunications fiber. In the best known DLCZ protocol[22] this is based on the creation of entanglement in quantum memory (could be a Bell state, like the one in [A6]) and swapping the entanglement between neighboring quantum memories distant by about Λ, then at a distance of 2Λ, 4Λ etc. according to a tree diagram until entanglement is produced at full distance. Since after each entanglement swapping it is known whether it was successful. If unsuccessful, only part of the link needs to be re-established, which is statistically shorter then the entire link. Hence, we obtain a more favourable scaling with the total length. One may wonder whether modification of the repeater scheme in which we use the memory from the [A6] work at the beginning (that is, we have at our disposal at the start not one pair for several trials, but on average many Bell pairs) would result in acceleration?

In the work under discussion, we have proposed and analyzed the particular protocol and shown that enhancement is observed. The protocol consists of two typical steps, entanglement generation and entanglement connection (swapping). During entanglement generation, we try to generate entanglement between distant multimode quantum memories. We proposed to use a multimode channel to allow photons with all wavevectors to travel the midpoint station. In the station, the photons are interfered in order to herald generation of two Bell-type states of two memories. Since we use M modes, we may herlad generation of entanglement of any two wavevector mode pairs (one mode-pair per each memory). Hence, there are $\mathcal{O}(M^2)$ possible options, which can make this step quasi-deterministic. This means we can keep the generation rate small (and hence the photon purity good) per mode, but almost always obtain an entangled state of memories. Subsequent entanglement swapping requires proper redirection of photons. Redirection is carried out by means of two switches (e.g., in the form of acousto-optic modulators/deflectors) directing the read photons always to the same pre-selected mod. Since there is enough time between the writing and reading process to control the laser pulses, as we demonstrated in the work [A7], such a procedure is feasible. With such control, the acceleration (enhancement) can scale not linearly (trivially), but quadratically with the number of quantum memory modes used.

The presented work containes detailed descriptions of how the protocol would work, as well as analysis of its performance and comparison with several other approaches. As part of the work, we developed the idea originally together with M. Mazelanik, and then most of the development of the theory was done by M. Lipka. Together we prepared the article.

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[21] P.-A. Moreau, „Imaging Bell-type nonlocal behavior", Science Advances **5**, aaw2563 (2019)

[22] L.-M. Duan et al., „Long-distance quantum communication with atomic ensembles and linear optics", Nature **414**, 413-418 (2001)

In summary:

Main achievement of the work: proposal and analysis of an entanglement distribution protocol that uses the generator demonstrated in [A6]

My contribution: idea development, theoretical analysis, article writing, revisions, coordination, contribution of about 30%

Influence and distinctions

The article [A2] was highlighted by the editors by making a "News & Views" type note published in the same issue of Nature Physics: `https://www.nature.com/articles/s41567-020-1020-8`. Similarly, the article [A7] was highlighted by the editors with a "Perspective" in "Quantum Views": `https://quantum-journal.org/views/qv-2021-08-26-58/`. The article [A5] was also highlighted on the Communications Physics home page with an embedded photo of a magneto-optical trap from our lab.

The papers [A1-A8] have been cited according to Web of Science a total of 37 times. This figure does not take into account an additional 50 or so citations from recently published preprints as shown by Google Scholar. Due to the nature of the papers, they received quite diverse citation counts, in particular, the best-cited papers [A1] and [A2] are referenced by articles in, among others, Science[23,24]. Other papers mostly received first citations from new publications and preprints[25,26,27,28], including from my group due to its natural usefulness in further research[29].

The results related to the achievement were presented by me at international conferences. I presented the results of work [A1-A4] at the Quantum Optics X conference in Torun as an invited talk. Preliminary results from the work [A6-A8] (before they were published) I presented in part at the Quantum Speedup conference (online) in 2020. I presented the results of work [A5-A7] in a broader context at the DAMOP conference in 2021 (online) and in the form of a poster at the EQTC 2021 conference (online). I presented results from the work [A2] in the form of an online poster at the Hot Atoms Workshop in 2021. I also presented results from the work [A1, A2, A3, A5] at the Optical Seminar in Warsaw in 2022, and (then preliminary results) at the NCBJ seminar in 2020 (online). Likewise, I also presented results at seminars on Quantum Information in Warsaw in 2020 (paper [A2]) and 2022 (mainly papers [A1] and [A3]), and at an optics seminar in Olomouc (2022).

Finally, it is worth mentioning the research is also related to other research conducted in Poland, in particular on the theoretical side in the field of optomechanics in Poznan[30], on the theoretical side in the field of quantum memories in Torun[31] as well as on the experimental side in quantum communication[32] and work with high-finesse cavities[33], on the theoretical side in the field of entanglement in Gdansk[34], on the experimental side in the use of spins of atoms e.g. for magnetometry in Krakow[35], and in the broader context of quantum metrology and precision measurements[36], which is obviously not a complete list anyway.

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[23] L. Mercier de Lepinay, „Quantum mechanics–free subsystem with mechanical oscillators", Science **372**, 625-629 (2021)

[24] S. Kotler et al., „Direct observation of deterministic macroscopic entanglement", Science **372**, 622-625 (2021)

[25] V. Semenenko et al., „Entanglement generation in a quantum network with finite quantum memory lifetime featured", AVS Quantum Science 4, 012002 (2022)

[26] S. Wang et al., „Long-lived and multiplexed atom-photon entanglement interface with feed-forward-controlled readouts", Communications Physics 4, 168 (2021)

[27] M. Wang et al., „Generation of highly retrievable atom photon entanglement with a millisecond lifetime via a spatially multiplexed cavity", arXiv:2204.05794 (2022)

[28] L. Zhang et al., „Modeling and optimization of an unbalanced delay interferometer based OPLL system", Optics Express 30, 1994-2005 (2022)

[29] For example, the device and methods from [A5] were used in a slightly different context in the paper [C4] (M. Lipka, M. Parniak, Phys. Rev. Lett. 127, 163601 (2021))

[30] Y. Li et al., „Vector optomechanical entanglement", Nanophotonics **11**, 67-77 (2021)

[31] A. Raczyński, J. Zaremba, S. Zielińska-Raczyńska, „Beam splitting and Hong-Ou-Mandel interference for stored light," Phys. Rev. A **75**, 013810 (2007)

[32] K. Sędziak et al., „Reducing detection noise of a photon pair in a dispersive medium by controlling its spectral entanglement", Optica **4**, 84-89 (2017)

[33] K. Bielska et al., „Frequency-based dispersion Lamb-dip spectroscopy in a high finesse optical cavity", Optics Express **29**, 39449-39460 (2021)

[34] R. Horodecki et al., „Quantum entanglement", Rev. Mod. Phys. **81**, 865 (2009)

[35] W. Chalupczak et al., „Room temperature femtotesla radio-frequency atomic magnetometer", Appl. Phys. Lett. 100, 242401 (2012)

[36] R. Demkowicz-Dobrzański et al., „Fundamental quantum interferometry bound for the squeezed-light-enhanced gravitational-wave detector GEO600", Phys. Rev. A **88**, 041802(R) (2013)

V. PRESENTATION OF SIGNIFICANT SCIENTIFIC OR ARTISTIC ACTIVITY CARRIED OUT AT MORE THAN ONE UNIVERSITY, SCIENTIFIC OR CULTURAL INSTITUTION, ESPECIALLY AT FOREIGN INSTITUTIONS.

I started my scientific work during my undergraduate studies, studying the diffusion of spin-polarized Rb [B1] atoms. Between my bachelor's and master's studies, I did a three-month internship at ICFO near Barcelona. During my graduate studies, I worked on developing a light-atom interface based on four-wave mixing processes that contained higher excited states (e.g., 5D) of Rb atoms in vacuum cells [B2, B3, B5, B6, B7]. In a separate project, I worked on a theory describing competing wave mixing processes during light propagation in Raman scattering [B4]. I continued my doctoral studies on the same topic, including through a project under the "Diamentowy Grant" program. As part of my PhD, with the team I constructed a magneto-optical trap that allowed for high-quality results in the context of generated light-atom correlations. The doctoral work consisted primarily of papers [B10], [B11], [B15], [B16] and [C1]. This work dealt with the very basics of cold-atom quantum memory [B10], the manipulation of the spin waves stored in it [B11, B15, B16], and the realization of the four-photon interface (previously studied in atoms in cells) in the quantum regime [C1]. Other results that were not part of the dissertation were research on EPR-type entanglement in photon positions and momenta in real space [B8, B13], more technical works on lasers and detectors [B9, B12], work on spin-wave lensing in quantum memory [B17], and research on super-resolution imaging where I collaborated with theorists (Prof. Konrad Banaszek and Prof. Rafał Demkowicz-Dobrzański) on the implementation of the new [B14] protocol.

My post-doctoral research activities initially focused on the [A1-A8] series of papers presented in para. 4. [A1-A8]. The work [A1-A4] was entirely done during my internship at the NBI at the University of Copenhagen. Other post-doctoral work was on super-resolution imaging in a theoretical approach [C2] and time-frequency domain imaging using quantum memory [C3]. Since 2021, I have taken on the role of group leader in the Quantum Optical Technologies project, where I have addressed, among other things, the results published in papers [A4-A8], and the development of new methods for quantum spectroscopy, including using the Hong-Ou-Mandel effect [C4] and super-resolution spectroscopy under the protocol implemented in quantum memory [C5]. In one of the most recent works, in close collaboration with theoreticians (with the group of Rafal Demkowicz-Dobrzanski and Alexander Streltsov), we studied the role of quantum asymmetry (quantum coherence) in multimode [C6] interferometry.

Current work (available as preprints for the moment), meanwhile, includes microwave detection with Rydberg atoms [D1] and characterization of ultrashort pulses with new methods operating in the quantum regime [D2] (in collaboration with Dr. Nicolas Fabre of the Universidad Compultense de Madrid). I am also working on the development of methods based on interacting spin waves and polaritons, including in collaboration with Dr. Krzysztof Jachymski and Dr. Rafal Oldziejewski.

In summary, I have been scientifically active mainly at the University of Warsaw - including at the Faculty of Physics as a student/doctoral fellow and at the Center of New Technologies as an assistant professor since 2021, and at the Niels Bohr Institute in Denmark since December 2018 (full time commitment until 2021, then partial). I also did a short internship at ICFO in Spain in 2013.

In the lists below I have included information regarding publications, distinctions, awards, reviews, scholarships and patents/patent applications.

See also `https://orcid.org/0000-0002-6849-4671` for the full list of papers.

Works published before conferring the doctoral degree

[B1] **M. Parniak**, W. Wasilewski, "Direct observation of atomic diffusion in warm rubidium ensembles", Applied Physics B **116**, 415 (2014)

[B2] M. Dąbrowski**, M. Parniak**, D. Pęcak, R. Chrapkiewicz, W. Wasilewski, "Spontaneous and parametric processes in warm rubidium vapours", Latvian Journal of Physics and Technical Sciences **51**, 21-34 (2014)

[B3] **M. Parniak**, W. Wasilewski, "Interference and nonlinear properties of four-wave-mixing resonances in thermal vapor: Analytical results and experimental verification", Physical Review A **91**, 023418 (2015)

[B4] **M. Parniak**, D. Pęcak, W. Wasilewski, "Multimode Raman light-atom interface in warm atomic ensemble as multiple three-mode quantum operations", Journal of Modern Optics **63**, 2039 (2016)

[B5] **M. Parniak**, A. Leszczynski, W. Wasilewski, "Magneto-optical polarization rotation in a ladder-type atomic system for tunable offset locking", Applied Physics Letters **108**, 161103 (2016)

[B6] **M. Parniak**, A. Leszczynski, W. Wasilewski, "Coupling of four-wave mixing and Raman scattering by ground-state atomic coherence", Physical Review A **93**, 053821 (2016)

[B7] A. Leszczynski, **M. Parniak**, W. Wasilewski, "Phase matching alters spatial multiphoton processes in dense atomic ensembles", Optics Express **25**, 284 (2017)

[B8] M. Dąbrowski, **M. Parniak**, W. Wasilewski, "Einstein-Podolsky-Rosen paradox in a hybrid bipartite system", Optica **4**, 272 (2017)

[B9] M. Lipka, **M. Parniak**, W. Wasilewski, "Optical Frequency Locked Loop for long-term stabilization of broad-line DFB lasers frequency difference", Applied Physics B **123**, 238 (2017)

[B10] **M. Parniak**, M. Dąbrowski, M. Mazelanik, A. Leszczynski, M. Lipka, W. Wasilewski, ”Wavevector-multiplexed quantum memory via spatially-resolved single-photon detection", Nature Communications **8**, 2140 (2017)

[B11] A. Leszczynski, M. Mazelanik, M. Lipka, **M. Parniak**, M. Dąbrowski, W. Wasilewski, "Spatially-resolved control of fictitious magnetic fields in a cold atomic ensemble", Optics Letters **43**, 1147 (2018)

[B12] M. Lipka, **M. Parniak**, W. Wasilewski, "Microchannel plate cross-talk mitigation for spatial autocorrelation measurements", Applied Physics Letters **112**, 211105 (2018)

[B13] M. Dąbrowski, M. Mazelanik, **M. Parniak**, A. Leszczyński, M. Lipka, W. Wasilewski, "Certification of high-dimensional entanglement and Einstein-Podolsky-Rosen steering with cold atomic quantum memory", Physical Review A **98**, 042126 (2018)

[B14] **M. Parniak**, S. Borówka, K. Boroszko, W. Wasilewski, K. Banaszek, R. Demkowicz-Dobrzanski, "Beating the Rayleigh limit using two-photon interference", Physical Review Letters **121**, 250503 (2018)

[B15] **M. Parniak**, M. Mazelanik, A. Leszczynski, M. Lipka, M. Dąbrowski, W. Wasilewski, "Quantum Optics of Spin Waves Through Ac-Stark Modulation", Physical Review Letters **122**, 063604 (2019)

[B16] M. Mazelanik, **M. Parniak**, A. Leszczyński, M. Lipka, W. Wasilewski, "Coherent spin-wave processor of stored optical pulses", npj Quantum Information **5**, 22 (2019)

[B17] M. Lipka, A. Leszczyński, M. Mazelanik, **M. Parniak**, W. Wasilewski, "Spatial spin-wave modulator for quantum memory assisted adaptive measurements", Physical Review Applied **11**, 034039 (2019)

One of the papers [C1] that was part of my doctorate was published already after receiving the doctoral degree.

Works published after conferring the doctoral degree, but not part of the achivement listed in pt. 4.

[C1] M. Mazelanik, A. Leszczynski, M. Lipka, W. Wasilewski, **M. Parniak**, "Superradiant parametric conversion of spin waves", Physical Review A **100** (5), 053850 (2019)

[C2] Y. L. Len, C. Datta, **M. Parniak**, K. Banaszek, "Resolution limits of spatial mode demultiplexing with noisy detection", International Journal of Quantum Information **18** (01), 1941015 (2020)

[C3] M. Mazelanik, A. Leszczynski, M. Lipka, **M. Parniak**, W. Wasilewski, "Temporal imaging for ultra-narrowband few-photon states of light", Optica **7**(3), 203-208 (2020)

[C4] M. Lipka, **M. Parniak**, "Single-photon hologram of a zero-area pulse", Physical Review Letters **127** (16), 163601 (2021)

[C5] M. Mazelanik, A. Leszczyński, **M. Parniak**, "Optical-domain spectral super-resolution via a quantum-memory-based time-frequency processor", Nature Communications **13**, 691 (2022)

[C6] F. Albarelli, M. Mazelanik, M. Lipka, A. Streltsov, **M. Parniak**, R. Demkowicz-Dobrzański, „Quantum asymmetry and noisy multi-mode interferometry”, Physical Review Letters **128**, 240504 (2022)

Works under review (preprints)

[D1] S. Borówka, U. Pylypenko, M. Mazelanik, **M. Parniak**, „Sensitivity of Rydberg-atom receiver to frequency and amplitude modulation of microwaves", arXiv:2206.11829 (2022)

[D2] S. Kurzyna, M. Jastrzębski, N. Fabre, W. Wasilewski, M. Lipka, **M. Parniak**, „Variable electro-optic shearing interferometry for ultrafast single-photon-level pulse characterization", arXiv:2207.14049 (2022)

Distinctions

Some of the papers in lists B and C were also highlighted upon publication. The article [B8] was highlighted in Optics&Photonics News: `https://www.optica-opn.org/home/newsroom/2017/march/one_photon_a_trillion_atoms/`. The article [B15] was highlighted on the cover issue of Physical Review Letters (`https://journals.aps.org/prl/issues/122/6`). The article [C5] was highlighted in the collection "Focus: Optics and photonics" by Nature Communications (`https://www.nature.com/collections/eabghdjbcd`).

Reviews

- I have been active as a reviewer for scientific journals since 2016. I have reviewed a total of approx. 40 manuscripts for the journals: Physical Review A, Physical Review Letters, Physical Review Research, PRX Quantum, Optica, Optics Express, Optics Letters, Applied Optics, OSA Continuum, npj Quantum Information, Scientific Reports, Communications Physics, EPJ Plus, New Journal of Physics, Japanese Journal of Applied Physics, Acta Physica Polonica A
- In 2022, I prepared a review of a grant application for Fulbright Poland

Patents and Patent Applications

- I am a co-author of a patent in the Polish Patent Office No. PAT.235172 entitled "A method of calibrating an image intensfier to reduce crosstalk signals at the input to a microchannel system and an image intensifier calibration kit"; authors: M. Lipka, W. Wasilewski, M. Mazelanik, **M. Parniak-Niedojadło**;
- I am a co-author of a patent in the Polish Patent Office granted (subject to payment) under application no. P.434142 entitled "A system for generating polarization entangled photon pairs of multi-mode quantum memory for long-distance quantum signal regeneration", and related international patent application no. WO2021245529; authors: W. Wasilewski, M. Lipka, M. Mazelanik, **M. Parniak-Niedojadło**, K. Zdanowski, A. Ostasiuk, A. Leszczynski;
- I am a co-author of a patent application in the Polish Patent Office No. P.441074 entitled. , "System and method of characterization of very weak femtosecond pulses at the single-photon level by second-order interferometry in a configuration with a temporal and a spatial modulator"; authors: W. Wasilewski, M. Lipka, **M. Parniak-Niedojadło**, M. Jastrzębski, S. Kurzyna;

Awards and Scholarships

- START Scholarship from the Foundation for Polish Science, awarded with distinction (2019)
- Scholarship from the Minister of Science and Higher Education for the best doctoral students in the 2018/2019 academic year
- Polish Physical Society (PTF) Arkadiusz Piekara Award for the best master's thesis in 2015[37]

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[37] `https://www.ptf.net.pl/pl/programy/medal-i-nagrody/nagrody-naukowe-ptf/`

- National Center for Quantum Informatics (KCIK) Award for the best doctoral thesis in 2019[38]
- Frank Wilczek Award (2nd edition, 2022) for „developing new experimental platforms for quantum research and technology and their use to demonstrate state-of-the-art quantum phenomena and protocols”[39]

VI. PRESENTATION OF TEACHING AND ORGANIZATIONAL ACHIEVEMENTS AS WELL AS ACHIEVEMENTS IN POPULARIZATION OF SCIENCE OR ART

Teaching (classes)

1. Individual Introductory Lab B (1100-1Ind08) classes - for the first year of individual studies in physics at the UW Faculty of Physics, in the academic years 2015/2016, 2016/2017 and 2017/2018
2. Supervision of Optics Laboratory I (1100-4OL) exercises, Individual Research Laboratory Work (1100-3Ind04), Photonics Laboratory III (1103-4Fot22), and Photonics Specialized Laboratory (1103-5Fot11) performed by students completing these subjects in the laboratory under my supervision

Theses (supervision, reviews)

1. Supervisor of the master’s theses of Andrzej Ostasiuk (2021, thesis was on fiber-optic polarization controller) and Krzysztof Zdanowski (2021, thesis was on super-resolved homodyne spectroscopy)
2. Reviewer of undergraduate thesis of Tomasz Szawełło (2020, UW) and master’s thesis of Michał Lipka (2020, UW)
3. Committee member (reviewer) in doctoral thesis of Jessica O. de Almeida (2022, ICFO and Universidad Politecnica de Catalunya), supervisors: dr. Michalis Skoteiniotis (Universidad Autonoma de Barcelona) and prof. Maciej Lewenstein (ICFO, ICREA)
4. Supervisor for Marcin Jastrzębski and Stanisław Kurzyna (3rd year of individual studies) and supervisor of their undergraduate theses (defended in July 2022), on time-frequency manipulation of quantum light. The students receive stipends to conduct research in my research group from the “Quantum Optical Technologies” project. The research group also includes third-year individual student Uliana Pylypenko who is working on projects under my supervision. As of July 2022, second-year individual studies students Jan Nowosielski and Bartosz Niewelt have also joined my group.
5. Supervisor of master’s theses in preparation by Sebastian Borówka (thesis is on microwave field sensing using Rydberg atoms) and Tomasz Szawełło (thesis is on simulation of propagation of Rydberg polaritons in three dimensions)
6. Assistant/second supervisor of Michał Lipka (2nd year PhD student) in the School of Natural Sciences and Sciences at UW (main supervisor is Wojciech Wasilewski); Michał Lipka is a member of my research group within the “Quantum Optical Technologies” project

Organization

1. Head of the Quantum Optical Devices Lab research group within the “Quantum Optical Technologies” project (FNP International Research Agenda). Established in 2020, the group has 5 students and 1 PhD student in addition to myself. I obtained the position of group leader through a competitive process, preparing, among other things, a detailed research plan, evaluated, among other things, during an interview before the Center’s International Scientific Council.
2. President of the UW Optics and Photonics Students Assoc. ”KNOF” and OSA (currently Optica) Student Chapter in 2013-2015
3. Conferences:

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[38] https://kcik.ug.edu.pl/nagrody-kcik/
[39] https://fw-prize.fais.uj.edu.pl/pl_PL/start

   (a) Member of the organizing and steering committee in the Quantum Speedup 2021 conference, jointly organized online by the Center for Optical Quantum Technologies (University of Warsaw) and the International Center for Quantum Technology Theory (University of Gdansk); in organizing the conference, among other things, I set the conference program, moderated the panel discussion and chaired the paper session. The conference had more than 60 active participants from 10 Polish and several foreign institutions.
   (b) Co-organization of the Optics and Photonics Student Association's trip to the Developments in Optics and Communications 2014 conference (Riga, Latvia)
   (c) Member of the abstract evaluation committee for the Minimody student conference oraganized by the UW Scientific Circle of Optics and Photonics in 2021 in Chęciny

Funding (as PI)

1. PRELUDIUM Grant from the National Science Center (2018-2020), role: PI, grant topic: Development of quantum imaging techniques in optical and atomic systems
2. Diamond Grant awarded by the Ministry of Science and Higher Education, 2014-2018, role: PI, grant topic: Development of fundamentals of quantum atoms-light interface based on four-photon scattering in atomic pairs[40]
3. SONATA Grant from the National Science Center, from 2022, role: PI, grant topic: Bridging microwave and optical domains with nonlinear quantum optics enabled by Rydberg atoms

Publication

1. Presentations of experiments at the Science Picnic and on one occasion coordination of demos of the UW Optics and Photonics Student Assoc. (during MSc and PhD studies)
2. Organization of demos as part of the 2018 Ochota Campus Open Days (DOKO) at the Quantum Memories Laboratory of the UW Faculty of Physics
3. Participation in the preparation of press releases for articles of my authorship. My participation consisted of either drafting and editing the text and illustrations, or providing substantive comments and/or coordinating the work[41].
   (a) "The quantum processor has practical applications: improves measurements in spectroscopy", `https://www.fuw.edu.pl/informacja-prasowa/news7398.html`
   (b) "Quantum memory as an optical time telescope with record resolution", `https://www.fuw.edu.pl/informacja-prasowa/news6292.html`
   (c) "Spin waves pair up like photons", `https://www.fuw.edu.pl/informacja-prasowa/news5833.html`
   (d) "Record-capacity quantum memory based on laser-cooled atoms", `https://www.fuw.edu.pl/informacja-prasowa/news5224.html`
   (e) "Quantum entanglement between a trillion atoms and a single photon", `https://www.fuw.edu.pl/informacja-prasowa/news4866.html`
   (f) "Quantum entanglement realized between distant large objects", `https://nbi.ku.dk/english/news/news20/quantum-entanglement-realized-between-distant-large-objects/`
   (g) "Very unusual entangled pair": `https://www.fnp.org.pl/bardzo-nietypowa-splatana-para/`
4. Short videos of lab work published on YouTube: `https://www.youtube.com/playlist?list=PLL33SchGlmmtqHDKJdcgxlXFct7Hk8qqg`
5. Regular publicity by publishing popular science summaries of scientific articles and other descriptions or photos of lab work on Twitter (@michalparniak).

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[40] Unoficial translation
[41] Titles below are translated if they were originally in Polish

6. Popular Science Lectures:
    (a) For the UW Students Association of Optics and Photonics (2022, UW Faculty of Physics, Warsaw)
    (b) For the finalists of the 71st Physics Olympiad (2022, Institute of Physics of the Polish Academy of Sciences, Warsaw)
7. Interviews on radio and online portals about scientific results:
    (a) Academic Radio ”Kampus”:
        i. On the entanglement of two macroscopic objects: `https://www.fuw.edu.pl/tl_files/press/broadcasts/FUW_2021-02-09.mp3`
        ii. On memory for quantum computers: `https://www.fuw.edu.pl/tl_files/press/broadcasts/0109fiz.mp3`
    (b) Polish Radio ”RDC”
        i. “From another planet: the Einstein-Podolsky-Rosen paradox”: `https://www.rdc.pl/podcast/z-innej-planety-paradok-einsteina-podolskiego-rosena/`
        ii. “From another planet: UW scientists build Poland’s first quantum processor”: `https://www.rdc.pl/podcast/z-innej-planety-naukowcy-z-uw-zbudowali-pierwszy-w-polsce-procesor-kwantowy/`
    (c) Podcast on Onet/KomputerSwiat: `https://www.komputerswiat.pl/artykuly/redakcyjne/procesor-kwantowy-z-polski-ma-szanse-zmienic-swiat-wspolczesne-komputery-kwantowe-sa/k6b88cn`
    (d) “Storing light in the record-breaking memory” - `https://naukawpolsce.pl/aktualnosci/news%2C77319%2Czapisac-swiatlo-w-rekordowo-pojemnej-pamieci.html`
    (e) Interview for ITWiz portal: “Polish quantum processor: from spectroscopy to.... quantum computing“- `https://itwiz.pl/polski-procesor-kwantowy-od-spektroskopii-do-obliczen-kwantowych/`

VII. APART FROM INFORMATION SET OUT IN 1-6 ABOVE, THE APPLICANT MAY INCLUDE OTHER INFORMATION ABOUT HIS/HER PROFESSIONAL CAREER, WHICH HE DEEMS IMPORTANT

N/A

MParniak

Elektronicznie
podpisany przez
Michał Parniak-
Niedojadło; UW
Data: 2022.08.08
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