1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan, all in English)

Project title: Single photon techniques for atomic system analysis

1.1. Project goals

- ***Single-photon absorption.*** The improved version of the existing confocal microscope will be used to increase the efficiency of the interaction between photons and color centers. This setup will be utilized to investigate the absorption of photon states with well defined number (Fock states) by pure diamond samples containing single or groups of color centers and potentially other systems identified. *The risk is moderate to high.* While the proof-of-principle experiment on photon interaction with an ensemble of atom-like systems has already been done, the challenge is to do it with only a single atom-like system.
- ***Fluorescence microscopy with spatial entanglement.*** The SPDC pump beam steering technique will be used to modify the spatial modes of the produced photon pairs. SPDC photons prepared in such a way will be used in fluorescence microscopy. This will allow to improve the spatial resolution and minimize photon loss of this technique. *The risk is moderate.* While the theory is known, its experimental implementation is challenging. The SPDC source must allow for integration of free-space propagating photons and a microscope.
- ***Cryogenic experiments with single photons.*** The experiment on optically detected magnetic resonance with single-photon excitation of color centers (NV, SiV, GeV) will be attempted. *The risk is high.* A similar experiment has not been reported in the literature so far. The risk will be minimized by the collaboration with experts in the field of color centers in diamonds (from Jagiellonian University in Cracow and Ulm University).
- ***Two-photon absorption enhancement with spectral entanglement.*** The source of photon pairs with optimized temporal correlation will be used in an attempt to observe the effect of the entangled two-photon absorption. The efficiency of the process will be first characterized at the single photon level using attenuated pulsed laser. *The risk is high.* It is still not known whether the two-photon absorption efficiency is going to be sufficient to observe the interaction of an absorber with pairs of photons from SPDC source, especially when the chromatic dispersion in the optical setup is significant. The risk will be minimized by using a source allowing for the best possible photon-pair coupling efficiency. The pairs will feature correlation in the temporal mode, which has already proven to be useful in minimizing diffraction problems during the light propagation in dispersive media. This will be the same or slightly modified source as used for fiber based quantum communication [Sedziak 2019].

1.2. Outline

The goal of the project is to apply the unique set of technological skills developed at Single Photon Applications Laboratory (SPALab) to observe **interaction of quantum light with quantum system.** The fundamental idea of the research is based on the ability to generate, control and detect single photons, which will be further developed in the project.

Due to a very good quality of the emitted photons, huge flexibility in terms of their wavelengths and relatively low cost, the most popular sources of quantum light are currently based on the spontaneous parametric down conversion (SPDC) process. Here a photon from the pump laser beam, when traveling through a nonlinear crystal, spontaneously decays into a pair of lower energy photons. The detection of one of the light particles produced in this way can be used to herald the existence of the other one. Therefore, devices based on SPDC process are frequently used as singlephoton sources. Such single photons or photon pairs can be used in the confocal microscopy setting to investigate the absorption effects of a defined number of light quanta by an atomic system. Moreover, photon pairs produced by an SPDC source can feature non-classical correlations, called entanglement. This is the basic component of quantum technology, providing the security to quantum communication protocols.

The theory of the interaction of an atomic system with a single quantum of electromagnetic field has been extensively explored for decades. This basic idea and its follow-ups have great impact on our understanding of fundamental mechanisms of quantum mechanics. They also lead to many practical applications, based on our ability to control the absorption and emission processes in an atomic system. An example of such application is quantum microscopy, which relies on the absorption of a well-defined number of photons and the capability to measure temporal, spectral and spatial characteristics of the emitted fluorescence. Another example are quantum memories, the working principle of which takes advantage of our ability to store a single qubit, encoded typically in one of the photon’s degrees of freedom, in an atomic system. While in principle we know how these things can be done, their implementations are often challenging due to many practical problems. However, recently the PI and his colleagues have experimentally demonstrated that a single photon can be absorbed in an atomic medium and the resulting fluorescence can be detected in the controlled laboratory conditions with the use of a typical microscopy setting [Gieysztor 2019]. More importantly, the experiment was done without any interaction-enhancing mechanisms, like stimulated emission or cavities. This opens up a plethora of new experimental avenues.

One of the main advantages of photon sources based on SPDC process is their unmatched capability to control the state generated in one arm of the setup through the heralding process conducted in the other arm. In particular, when using photon-number-resolving detectors it is possible to herald a well-defined photon number state. This ability can be used to control the number of photons absorbed by an atomic system or a group of individual isolated quantum systems. Also the spectral modes of SPDC photon pairs can be engineered to meet requirements for efficient multiple-photon absorption. Moreover, since the propagation directions of SPDC photons can be strongly correlated, it is possible to remotely prepare the spatial mode of the heralded photon (the one used for illumination) by the proper choice of the spatial mode of the heralding photon, done during the measurement process. This effect can be used to reduce the size of the illumination mode and, in consequence, improve the spatial resolution of the microscope [Gieysztor 2020]. The similar effect, but in the spectral domain, has already been predicted and demonstrated [Sedziak 2017, 2019].

While in the case of conventional fluorescence microscopy an absorption of single photons with a specified energy can be observed, two-photon absorption is based on the near-simultaneous absorption of two photons, which energies sum up to the transition energy of the medium. However, the process is very inefficient by its nature, and therefore requires using high-energy pulses, which can destroy the sample. This problem can be potentially solved by utilizing entangled pairs of photons [Dayan 2007]. The goal of the project is to conduct a series of experiments, which will finally lead to the observation of the entangled two-photon absorption (ETPA). The preliminary results suggest that the spectral entanglement will be the key enabler to observe the effects by significantly increasing the absorption efficiency.

1.3. Work plan

1. Single-photon absorption. The improved version of the existing confocal microscope will be used to increase the efficiency of the interaction between photons and color centers.
2. Fluorescence microscopy with spatial entanglement. The SPDC pump beam steering technique will be used to modify the spatial modes of the produced photon pairs.
3. Cryogenic experiments with single photons and atomic systems.
4. Two-photon absorption enhancement with spectral entanglement.

1.4. Literature

[Brito 2016] J. Brito, S. Kucera, P. Eich, P. Müller & J. Eschner, Doubly-heralded single-photon absorption by a single atom, Appl. Phys. B 122, 1 (2016).

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[Sadana 2019] S. Sadana, D. Ghosh, K. Joarder, A. N. Lakshmi, B. C. Sanders & U. Sinha, Near-100% two-photon-like coincidence-visibility dip with classical light and the role of complementarity, Phys. Rev. A 100, 013839 (2019).

[Sedziak 2017] K. Sedziak, M. Lasota & P. Kolenderski, Reducing detection noise of a photon pair in a medium by controlling its entanglement, Optica, 4, 84-89 (2017).

[Sedziak 2019] K. Sedziak-Kacprowicz, M. Lasota & P. Kolenderski, Remote temporal wavepacket narrowing, Sci. Rep. 9, 3111 (2019).

[Shalm 2015] L. K. Shalm et al., A strong loophole-free test of local realism, Phys. Rev. Lett. 115, 250402 (2015).

1.5. Required initial knowledge and skills of the PhD candidate

- Background in experimental atomic physics or quantum optics or quantum information.
- Preferably, experience in confocal microscopy, experiments involving cryogenic temperatures.
- Strong oral and written communication skills in English.

1.6. Expected development of the PhD candidate's knowledge and skills

- Good understanding of practical aspects of quantum confocal microscopy, fluorescence analysis and superradiance.
- Experience in performing experiments with single photons and isolated quantum systems.
- Experience in co-operation with foreign scientific partner on international research project.