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Barcelona, April 15th 2019

PhD thesis report

Candidate: Michał Parniak

Multimode Quantum Optics with Spin waves and Photons

Summary:

The PhD of Michał Parniak, done at the University of Warsaw under the supervision of Prof Wojciech Wasilewski, is in the field of experimental quantum optics with laser cooled atomic ensembles. In particular, the thesis deals with the development of multiplexed optical quantum memories based on cold atoms, and on the coherent control of collective spin waves in these memories. Optical quantum memories are crucial devices for applications in quantum information science. These devices enable the coupling of quantum information between light used to communicate and atoms used to store and process quantum information. There is currently an intense worldwide theoretical and experimental effort to develop quantum light-matter interfaces and the thesis of Michał Parniak represents significant progress in that field.

In this thesis, the physical system used consists of an ensemble of cold rubidium atoms in a magneto-optical trap, with an optical depth up to 200. This system provides a platform to study quantum light-matter interactions with a very high degree of control. Quantum memory protocols such as the Duan-Lukin-Cirac-Zoller and the ac-Stark shift echo memory are used. A particular emphasis is put on spatial multiplexing in the memory and in the manipulation of spin wave states using spatially dependent ac-Stark shifts.

The thesis contains experimental investigations on several aspects of multimode quantum optics with spin waves and photons. A major result of the thesis is the demonstration of a spatially multiplexed cold atom quantum memory with up to 665 modes, the highest number of modes stored so far in a quantum memory. Another important aspect is the demonstration of the control of collective spin waves using AC Stark shifts induced by a laser beam, which is used to demonstrate Hong-Ou-Mandel interference between two spin waves, and more complex interference effects with stored spin waves. Finally, an experiment showing the generation of photon pair from spin waves is proposed and demonstrated experimentally. The work done during the thesis is mostly experimental, although some theoretical work is also included.

Thesis Content:

The manuscript is organized in 7 main chapters in addition to an introduction and a conclusion chapter. The content of these chapters in summarized below.

The introduction chapter presents the background of the research and introduces important concepts such as bosonic interference, optical quantum memories and an introduction to multiplexed quantum storage. In addition, a detailed description of the contributions and recent development in the group is presented, highlighting the key contributions of Mr Parniak in the presented work.

Chapter 2 introduces the theoretical tools required for the rest of the thesis, in particular the theory of light-matter interactions. The chapter includes a short introduction on quantum optics and on quantum light matter interactions with two level and multi-level atoms. The concept of collective atomic spin excitations, so-called spin waves is also introduced.

Chapter 3 presents the experimental setup used for the experiments. In particular, the cold atomic trap and the single photon resolving camera are described. The magneto optical trap has been designed and built mostly by the PhD candidate. The procedure to generate coherent spin waves is also highlighted, as well as the filtering technique used to isolate the single photon light fields generated by the memory, from the exciting lasers. Finally, the shaping of the ac-Stark beam is presented. This is an essential tool for the ac-Stark manipulations of spin waves presented in the thesis.

Chapter 4 presents one of the main result of the thesis: the realization of a spatially multiplexed quantum memory. The memory is based on a DLCZ protocol, with angular multiplexing. Write photons generated by spontaneous Raman scattering in the ensemble are detected at multiple angles by a single photon-resolving camera. The process generate spin waves in up to 665 angular modes. The spin waves can then be read-out and transferred to a single photon using a resonant read pulse, and directing the read photons to another part of the camera. The single photon camera is used to measure the second order cross-correlation between write and read modes and the unconditional autocorrelation of the two fields, allowing to test the Cauchy Schwartz inequality. Large non-classical cross correlations between write and read photons are measured in the multiples angular modes. Finally, the decay of the cross correlation with the storage time is measured for a few modes, with decay times between 50 and 100 us. The work presented in this chapter has been published in Nature Communications

Chapter 5 presents experimental implementation of ac-Stark shift control of the atomic spin waves. The idea is to use ac-Stark vector shifts created by an off resonant laser modulated by a spatial light modulator to emulate a fictitious magnetic field. This effect will be used in the next two chapters. The work presented in this chapter has been published in Optics Letters.

In Chapter 6, the PhD candidate uses the ac-Stark shift controlled developed in Chapter 5 to perform an experiment demonstrating Hong-Ou-Mandel interference between a pair of spin waves in the memory. This is achieved by implementing a beam splitter for spin waves using a diffraction effect created by a spatially periodic ac-Stark shift. The effect of spin wave diffraction is first demonstrated and characterized using coherent spin-wave states, with an occupation number of 10^5. Then, two single spin waves in two spatial modes are heralded by the detection of two single photons, and a three-way spin wave splitter is used to interfere the two spin waves. When counting the coincidences between the output modes, a Hong-Ou-Mandel interference with a visibility of 80 % is measured. The work presented in this chapter has been published in Physical Review Letters

Chapter 7 uses spatially dependent ac-Stark shifts to realize a spin wave multiport interferometric processor. Signal beams are sent to the ensemble in two spatial directions, and mapped onto spin waves using a control pulse. The spin waves are then manipulated using an ac Stark shift beam, showing a reconfigurable ac-Stark echo memory and programmable beamsplitting of the stored light. The work presented in this chapter has been published in NPJ Quantum Information.

Chapter 8 presents an experiment demonstrating that spin waves can serve as pump field for generating a pair of photons in a down-conversion process. The proposed and demonstrated scheme uses photon pair generation using cascaded emission from a ladder configuration. The main difference with already demonstrated schemes is that the starting point is having the atoms in spin wave states. In this first proof of principle experiment the creation of spin waves is seeded, leading to an initial coherent spin-wave state. The pair generation is then achieved by sending two pump fields to excite the atoms to the $^5D_{3/2}$ state, and then by cascaded spontaneous emission of two photons, coming back to the original ground state. The total photon pair creation corresponds then to a 6 wave mixing experiment. In the experiment, super-radiant emission is measured for the two photons, non-classical temporal correlation are measured between the two spontaneously emitted photons, as well as wavevector domain correlations. This scheme of photon pair generation from spin waves could lead to interesting new capabilities if the initial state was a single spin wave, for example the generation of photonic triplets.

Finally, a general conclusion is given, outlining the various perspectives offered by the work of Mr Parniak in the field of quantum light-matter interfaces for quantum information science.

General comments and evaluation.

The work of Michal Parniak represents significant advances in the field of quantum light-matter interfaces. In particular, the demonstration of a high capacity spatially multiplexed quantum memory and the demonstration of the manipulations of spin waves with ac-Stark shifts are very innovative and important contributions. The amount of work that the candidate has done is truly impressive. This is even more so taking into account the very high experimental complexity of this kind of quantum memory experiments, and the fact that the thesis work began with the construction of the cold atom apparatus. The work presented in the thesis resulted in several outstanding publications in high impact journals such as Nature Communications, Physical Review Letters and NJP Quantum Information.
The manuscript is well written and well organized. The state of the art of the field is well presented and the relevant literature correctly cited. From the manuscript, it is clear that the candidate possesses an excellent understanding of the field in general, and of his particular subject. The manuscript exposes also clearly what are the original contributions of the candidate.

In summary, both the manuscript and the presented work are in my opinion of excellent quality at the international level. It is clear from the work that the candidates masters the relevant experimental and theoretical techniques in a very complex and competitive field of physics. I therefore think that the thesis of Michał Parniak is ready to be defended, and that he should be awarded a PhD in physics from University of Warsaw.

In addition to the above mentioned evaluation, I would like to mention that in my opinion Mr Parniak clearly deserves the highest distinction for his thesis. His work represents an outstanding achievement in the field of optical quantum memories. He achieved an unprecedented degree of control over spin waves in a cold atomic ensemble, which will significantly advance the field of optical quantum memories. I was impressed by the work of Mr Parniak, both in terms of quantity of the results obtained and in terms of the quality and innovative aspect of the work.

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