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

Project title: Theoretical characteristics of two-photon absorption for classical and quantum fields

1.1. Project goals

Over decades of exploration, classical single- and two-photon absorption methods have become fundamental tools in modern optical imaging. In contrast, entangled two-photon absorption has recently emerged as a dynamic technique for probing atoms and molecules, particularly in scenarios of low light intensities. Exploiting quantum correlations introduces fresh perspectives for investigating different physical regimes, such as the presence of intermediate levels or virtual-level-mediated transitions and their dynamics.

Experimentally, the phenomenon of entangled two-photon absorption has been recently demonstrated, in particular, by the collaborators of this project. However, discrepancies persist among the outcomes of various experimental realizations: different laboratories reporting seemingly contradictory results regarding measured entangled two-photon absorption cross-sections. This project aims to address these inconsistencies and contribute to understanding the favourable conditions and identifying the key parameters for entangled two-photon absorption. We aim to characterise the absorption process depending on the properties of model molecules in which the absorption occurs, and the state of impinging light, to eventually allow for better system design and application targeting. Ultimately, our goal is to facilitate system design for two-photon absorption experiments and applications.

The aim of the project is the investigation of the interaction of an atomic system with a propagating light prepared in a two-photon state. The starting point of the study is the analytical formula for the probability of two-photon absorption for the three-level atom of ladder configuration obtained within the input-output formalism. We plan to study the time-dependent probability of the excitation of the system.

One of the principal goals of the project is to obtain the optimization of the pulse shape to achieve the highest value of probability of two-photon absorption. We plan to investigate how the effectiveness of this process depends on the state of light and the parameters of the atom such as the lifetime of the excited states. For this purpose, we plan to use the numerical and analytical tools. The goal is to find and compare the solutions to this problem for different states of light, including entangled and unentangled photon pairs for two-photon states. We are going to consider different kinds of the two-photon states achievable in the laboratory.

1.2. Outline

The work involves collaboration with researchers from abroad. In particular, with Rob Thew, who heads a research group at the University of Geneva, Switzerland, and Alexander Olaya-Castro from University College London, UK. Scientists at the Geneva laboratory have experience in two-photon light experiments and research into the use of entangled photons in the two-photon state to excite molecules and atoms and study two-photon absorption. Professor Alexander Olaya-Castro is a theoretical physicist concerned with describing the evolution of open systems.

The proposed supervisors are experienced in working on the theoretical description of the interaction of quantum systems with the field prepared in the single-photon state, N-photon state, squeezed N-photon state, and the evolution of open systems.

The student's task will be to write code to optimise the light pulse parameters to obtain the maximum two-photon absorption probability value.

The plan is to consider different types of two-photon states and describe their parameters and characteristics.

1.3. Work plan

12 months: To learn a description of the dynamics of open systems, e.g. by the set of hierarchical master equations. To study the properties of light in the N-photon state in time and frequency domains. To develop Python codes optimising the parameters of coherent and two-photon pulses to obtain the maximum two-photon absorption probability value for bidirectional fields. To determine the dependence of two-photon absorption probability values on atomic properties.

12 months: Learn the grounds of quantum information and theory of quantifying entanglement. Investigation of the properties of the two-photon state maximising the two-photon absorption probability for unidirectional and bidirectional fields. Investigating the degree of entanglement between photons for the optimal state.

12 months: To develop codes to optimise the parameters of coherent and two-photon pulses to obtain the maximum two-photon absorption probability. Investigation of different families of entangled two-photon states achievable in the laboratory.

12 months: To plan, describe and simulate an experiment to test the results obtained. Preparation of the thesis.

1.4. Literature *(max. 10 listed, as a suggestion for a PhD candidate)*

1. D. Tabakaev,, A. Djorović., L. La Volpe, G. Gaulier, S. Ghosh, L. Bonacina, and R. T. Thew. Spatial properties of entangled two-photon absorption. Phys. Rev.Lett., 129(18), 183601. (2022)
2. D. Tabakaev, ,M. Montagnese, G. Haack, L. Bonacina, J.P. Wolf, H. Zbinden, and R.T. Thew, Energy-time-entangled two-photon molecular absorption. Phys. Rev. A, 103(3), 033701 (2021)
3. M. G. Raymer, T. Landes, and A. H. Marcus, Entangled two-photon absorption by atoms and molecules: A quantum optics tutorial, J. Chem. Phys. 155, 081501 (2021)
4. F. Schlawin, A. Buchleitner, Theory of coherent control with quantum light, New J. Phys. 19, 013009 (2017)
5. E.G. Carnio, A. Buchleitner, and F. Schlawin, How to optimize the absorption of two entangled photons, SciPost Phys. Core 4, 028 (2021)
6. A. Dąbrowska, G. Sarbicki, D. Chruściński, Quantum trajectories for a system interacting with environment in a single-photon state: counting and diffusive processes. Phys. Rev. A 96, 053819-1--053819-11 (2017)
7. A. Dąbrowska, G. Sarbicki, D. Chruściński, Quantum trajectories for a system interacting with environment in N-photon state. Phys. A: Math. Theor. 52, 105303-1--105303-22 (2019)
8. R. Loudon, The Quantum Theory of Light, third edition, (Oxford University Press, Oxford, (2000)
9. H. M. Wiseman, G. J. Milburn, Quantum measurement and control. University Press, Cambridge (2010)
10. M. O. Scully, M.S. Zubairy, Quantum Optics. Cambridge University Press, Cambridge (1997)

1.5. Required initial knowledge and skills of the PhD candidate

Required knowledge: fundamentals of quantum mechanics, basic knowledge of programming, basic knowledge of numerical methods

Welcome: basic knowledge of quantum optics

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

The project combines various aspects of science and new technology. The student will gain and enhance knowledge of

- quantum optics,
- open systems theory,
- quantum information.

The candidate will obtain and extend the following skills:
- Python programming and modelling,
- modelling the dynamics of quantum open systems,
- individual and group work, international cooperation,
- presentation of scientific results in the form of articles and conference reports.