

The so-called first quantum revolution, which took place nearly a century ago, completely transformed our understanding of the microscopic world, enabling us to uncover the laws that govern it. Now, on the brink of the second quantum revolution, we are witnessing technological breakthroughs that could shape the future. Quantum phenomena have already been used to ensure the security of transmitted information. The first quantum computers have been built, promising to solve problems currently beyond the reach of classical computation. Quantum effects have also been shown to improve the precision of measurements, paving the way for advances in fields that rely on ultra-precise measurements.

While significant progress has been made in quantum communication, information processing, and metrology, many questions remain about how quantum states of light interact with matter and how they can improve measurements by replacing the classical laser beam, for example in microscopy. This is especially true for condensed matter such as crystals, solutions, and polymers-the very materials used to construct practical devices. Motivated by this gap, we decided to combine our expertise in studying dynamical phenomena in matter and in developing sources of entangled photon pairs to systematically investigate the interactions between quantum states of light and condensed matter.

One of the most remarkable quantum phenomena is called entanglement. It occurs in systems consisting of two or more objects, such as photons. When two photons are entangled, their properties are linked in such a way that measuring a property of one photon (unknown before the measurement) instantly determines the corresponding property of the other photon, regardless of the distance between them. Theoretical models and preliminary experimental studies suggest that entangled photon pairs interact with matter in a fundamentally different way than classical light. For example, the process by which two photons are simultaneously absorbed by an atom or molecule - known as two-photon absorption - is much more likely to occur when the absorbed photons are entangled than when they are independent.

We aim to construct sources of entangled photon pairs that will allow the study of two-photon absorption in a much wider range of materials than has been possible to date, including various organic compounds and so-called color centers in diamond. By expanding our understanding of two-photon absorption with entangled photons, we aim to pave the way for practical applications of this phenomenon, such as microscopy with improved resolution.

Photon pairs allow the observation of time-resolved processes occurring in matter after it has been excited by light, such as electron or proton transfer in organic molecules. This is possible in a setup where one photon of the pair excites the molecule under study, and the probability of the second (delayed) photon interacting with the molecule depends on the changes that have occurred in the molecule between the interactions with the first and second photons. Using classical methods, such experiments require lasers capable of producing intense, ultrashort pulses of light. Quantum entanglement, however, should make it possible to observe these phenomena using just one pair of photons generated in a special crystal illuminated by a low-power continuous-wave laser.

As part of the project, we will also study the processes that occur in chemical molecules after photon absorption and how these processes influence the interaction of photon pairs with the molecules. Some of the molecules used in our experiments have a fascinating property: their structure contains two hydrogen atoms that can jump between two equivalent positions. This change in the position of the hydrogen atoms does not change the chemical structure of the molecule, but it does affect its interaction with light. The probability that such a molecule will interact with a pair of entangled photons depends on both the rate of hydrogen transfer and the time interval between the photons in the pair. These groundbreaking experiments will pioneer the use of changes in the properties of entangled photon pairs to control the probability of their interaction with matter.

The results of our work will include the development of new experimental methods to study the interactions between quantum states of light and condensed matter. These methods will be used to answer many open questions about such interactions. In addition, we will explore the possibility of controlling the interactions of quantum states of light with matter by modifying the quantum states themselves. Our research will bring us closer to the practical implementation of quantum technologies in compact, real-world devices.