QLIMNES – „Quantum effects in many-body light-matter non-equilibrium systems"

The proposed research, lying at the border of ultracold atomic gases, condensed matter and quantum optics, will describe quantum particles that are immersed in a many-body quantum system and coupled to photons in optical cavities. Recent experimental breakthroughs in systems where mobile impurities interact with a quantum environment composed of bosonic or fermionic particles showed that a new type of composite particles emerges, called polarons, in as distinct systems as ultracold atomic gases and solid-state platforms based on monolayer semiconductors. The goal of this project is to investigate the interaction of these novel particles with light, and to study their optical response and many-body quantum effects such as spontaneous symmetry breaking in non-equilibrium conditions.

QLIMNES will investigate two relevant platforms in which polarons were experimentally observed: ultracold mixtures of atomic gases interacting with light in optical resonators and doped monolayer semiconductors immersed into optical cavities. QLIMNES will study how the polaron formation is modified by the presence of external drive and photon loss, as well as it will investigate non-equilibrium processes, such as optical response, emitted light, non-thermal distribution of particles, transport properties or relaxation rates to stationary states. In the project, the methodology will be employed that is based on non-equilibrium quantum field theory tailored to driven-dissipative systems, which has a promising potential for unifying description of many complex systems.

QLIMNES is focused on the proposed research because polaron physics is important for understanding a range of phenomena such as colossal magnetoresistance materials, helium-3/helium-4 mixtures, high temperature superconductors and optical response of doped monolayer semiconductors. Moreover, in recent research, highly imbalanced mixtures hosting polarons were mostly treated either in thermodynamic equilibrium or as closed systems. However, hybrid light-matter systems are inevitably non-equilibrium in nature due to external drive and photon loss through cavity mirrors. Such complex systems are now attracting attention in the scientific community because they allow for leaving the paradigm of thermodynamics and pave the way for exploring novel states of matter that have no counterpart in equilibrium physics. Therefore, QLIMNES will go beyond this vast majority of current research, and will describe highly imbalanced quantum gases interacting with light. Nowadays, with the possibility to control atomic mixtures of gases at near-zero temperatures and discoveries of monolayer semiconductors, it becomes experimentally possible to investigate the interplay of interactions between many massive particles and photons. Such systems were already realized with ultracold atomic and solid-state platforms, but their interpretation mostly relied on equilibrium theory. To uncover new relationships and novel effects a new approach is needed, but to develop a theory for such complex systems is challenging as it requires to include not only dynamical processes but also quantum coherences, which are responsible for the formation of polarons, on equal footing with dissipation and drive in the form of external pump and photon loss. Finally, hybrid light-matter systems hold the potential for quantum technologies, ranging from applications as novel means to control quantum materials, quantum-light sources or enhanced sensing. QLIMNES will take this step to investigate the nonlinear optical response of the systems and their potential as a source of nonclassical light, as well as the use of impurities as sensors.

The results of QLIMNES will lead to development of a theory describing quantum impurity physics, and advancing our knowledge about these non-equilibrium systems both in stationary states as well as in the relaxation dynamics. Therefore, the project will provide support for current experiments in this rapidly developing field. QLIMNES will supply a promising framework for broad future theoretical investigations of light-matter many-body quantum systems that are out of equilibrium. Since atoms and solid-state platforms host polaron physics, each of the systems can be used for simulating the other, therefore, providing potential realizations of quantum simulators. Furthermore, with the theory at hand, QLIMNES will pave the way for exploring novel probes of strongly correlated states of matter, and it will show how to use a precise control of the hybrid light-matter systems in order to probe the properties of the environment or to deliberately generate non-classical correlations between the impurities or impurities and the bath, for instance, for quantum-enhanced metrology. The possibility to tune the properties of matter and light separately may lead to highly nonlinear optics or to engineering of scalable optoelectronic devices. Therefore, in the long term, QLIMNES may find potential applications in quantum technologies and may advance the European landscape in this emerging field.