# Dynamics of Impurities in Quantum Gases

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## 1 Introduction

Within this PhD project we will investigate the physics of quantum impurities under non-equilibrium conditions. When a mobile impurity particle is immersed into a Bosonic quantum gas, such as an atomic Bose-Einstein condensate, it can form a so-called polaron. Such quasi-particles have first been introduced by Landau [1] to describe the interaction of electrons and phonon excitations in a solid-state material, and have since been studied intensively to better understand a range of phenomena in condensed matter physics.

Correspondingly, the physics of impurities in ultracold atomic gases has attracted great attention as a means to study polarons under well controlled conditions. Two recent experiments [2, 3] have now succeeded to observe signatures of polaron formation in a Bosonic quantum gas, which we choose as the major system to be studied in this PhD thesis project. One outstanding capability of utracold-atom experiments is that they permit to isolate a quantum system from its environment and to probe quantum many-body dynamics far from equilibrium in a highly controlled manner. Likewise, the ability to introduce impurities into atomic quantum gases presents unique opportunities for exploring the formation and dynamics of polarons, which will be the central subject of this PhD thesis. Below we outline some specific questions and challenges that are planned to be addressed during the project.

On all of these problems Kristian will draw from his experience from related studies of fermionic systems embedded in bosonic gases during his Master's thesis, and he will be able to interact closely with a postdoc in my group, Luis Pena Ardila, who has ample expertise on numerical descriptions of Bose polarons. Moreover, the PhD thesis is ideally positioned for drawing close links with the groups of Georg Bruun and Jan Arlt. Indeed, we anticipate joint work with Georg Bruun on the theoretical description of Bose-polarons as well as collaborations on the closely related experiments in the "Ultracold Quantum Gases Group" to emerge during this project.

## 2 One-body dynamics of impurities

One major challenge will be to find appropriate and tractable approaches to describe the quantum dynamics of impurities on all relevant timescales. To this end, we will follow an open systems approach to develop a master equation description where the Bose Einstein

Condensate plays the role of a bath. For simplicity this work will start from the weak-interaction regime where the physics can be described by the so-called Fröhlich Hamiltonian [4]. Ultimately, the aim is to obtain a theoretical framework that fully accounts for non-Markovian effects of the impurity-gas interactions, which enable us to describe a range of problems, including the formation of polarons after quenches, the dynamics of correlations in driven systems or relaxation processes for moving impurities. In particular, the goal is to understand the transition to the Markovian limit and to draw connections to other theoretical approaches as, e.g., developed in the group of Georg Bruun. Generally, the aim is to develop a comprehensive picture that extends from slow dynamics to fast timescales and provides a better understanding of the conditions leading to the emergence of simplified descriptions of impurity dynamics such as quantum Boltzmann equations. Simultaneously, we will explore suitable experimental probes of (fast) impurity dynamics and perform corresponding feasibility studies in relation to technological capabilities in the Arlt-lab.

Ultimately, these studies will be extended towards the strong interaction regime [5], which will permit to describe, e.g., quench dynamics and eventual polaron formation driven by strong interactions, and may provide an improved understanding of spectroscopy experiments close to and at unitarity. This part of the project is among the most challenging ones, and will benefit from close interactions with the group of Georg Bruun.

# 3 Many-body dynamics of impurities

Having gained a better understanding of the physics and technical aspects of the impurity- and polaron-dynamics we will consider situations involving multiple polarons starting from the two-body problem. The goal is again to find the underlying Master equation for the impurity system, including Hermitian and non-Hermitian two-body terms, i.e. effective impurity interactions and two-body decoherence. Of particular interest will be the non-Markovian contributions, corresponding to retardation effects of the emerging impurity interactions which may become relevant for the settings described below.

# 4 Quantum optical settings

As one potential application going beyond the sole impurity problem we will consider situations in which the impurities are strongly coupled to mobile photons. Such a setting is, e.g., possible for the approach taken in the experiments at AU where the impurity is created in a single-species Bose Einstein condensate by changing the internal state of a small number of atoms via microwave or optical fields. Under conditions of strong atom photon coupling this can then result in the formation of a polariton composed of a photon and an atomic excitation – the impurity. Owing to its photonic component the resulting impurity-polariton is now endowed with a tunable and typically much higher mobility than that of the atoms [6], which presents unique opportunities for studying fast polaron dynamics and non-Markovian effects. Moreover, the anticipated results of the work outlined in section 3 will allow us to study emerging interactions between the formed impurity polaritons. Overall this suggests a promising route to photonic many-body physics and a novel platform for generating optical nonlinearities at the single-photon level [7], which we will study in this project. Here, the exploration of more exotic phenomena, e.g. related to nontrivial band topology [8], resulting from the optical coupling presents one of the interesting perspectives to be explored towards the end of the PhD work. During his Master's thesis Kristian has already gained experience on related problems, thus, proving to be a clear asset for the proposed PhD project.

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