

Preface

*“Weil hab i erst des nötige Quantum do drin
dann merk i net was für a Trottl i bin”*

Gerhard Bronner and Helmut Qualtinger,
“Krügerl vor’m G’sicht”, 1960.

An interferometer is a device that makes use of the effect of wave interference. Optical interferometers rely on the interference of light waves. Since the middle of the nineteenth century, interferometry has become a key technique in physics, bringing new insight into the nature of light and the laws of nature. The celebrated interferometry experiment conducted by A. Michelson and E. Morley in 1887 is generally considered to have ruled out the theory of aether and indirectly contributed to the founding of special relativity. The development of lasers since the early 1960s has renewed the field of optics and considerably enhanced the power of interferometers by providing a bright, directed, and coherent source of light for interferometry. Today, optical interferometers range among the most sensitive measurement devices, both for fundamental (gravitational wave detection, astrophysics, ...) and technical (inertial sensing for navigation of planes, satellites, ...) applications.

Particle-wave duality, stated at the beginning of the twentieth century, enables the construction of interferometers for matter waves. Since the first observations demonstrating the wave nature of massive particles, ground-breaking interferometry experiments with electrons, neutrons, atoms, or molecules have allowed studying quantum phenomena, investigating the properties of matter, testing the fundamental laws of physics, and performing precision measurements [1].

Over the last decades, in particular with the progress of laser cooling and frequency combs, atom interferometers have evolved into devices at the leading edge of precision measurements. Long-lived coherent superpositions of internal atomic states have been used in atomic clocks to measure time with unprecedented accuracy, providing the definition of the second since 1967. Interferometers using quantum superposition of atomic motional states can also measure accelerations and

rotations to high precision. It has been argued that due to the high rest mass of atoms, compared to the energy of an optical photon, atom interferometers could yield a considerable gain in sensitivity to inertial forces.

Bose-Einstein condensates (BEC) are particular matter waves. Since the first realization of a BEC in an atomic vapor in 1995 [2], ultracold gases of bosons have been intensively studied as a unique example of a well-controllable system with enhanced quantum properties. In this context, matter-wave interferometry with BECs has proven to be a powerful tool to explore the rich physics of these many-body quantum systems. In particular, it is a unique probe to access the quantum phase of the condensate wavefunction and study its macroscopic coherence, i.e., the existence of a well-defined condensate phase in space and time.

Because of this macroscopic coherence, beautifully demonstrated by the first interference experiments from 1997 on [3], BECs have often been compared to atom lasers [4]. Indeed, like lasers, BEC are characterized by the macroscopic occupation of a single spatial mode. For this reason, it is natural to wonder whether BECs can provide to atom interferometry a similar boost as the laser brought to optical interferometry.

Because BECs are extremely sensitive probes of their environment, they are also fragile. In fact, only the development of ultrahigh vacuum techniques as well as “contract-free” methods to manipulate and trap atoms with optical and magnetic fields at the microscopic level has enabled the experimental realization of BECs. Developing techniques to preserve the phase coherence of atomic quantum superpositions is a challenging requirement for BEC interferometry.

One fundamental difference between atomic BECs and laser fields rises from the presence of interactions. Atom–atom interactions drive the physics of confined BECs, leading to a rich quantum phase diagram. In the context of atom interferometry, the impact of interactions is ambivalent. On the one hand, interactions are responsible for intrinsic phase diffusion effects which ultimately limit the coherence time of BEC interferometers. On the other hand, they can be exploited to generate nonclassical correlations between atoms and produce entangled states. Atomic squeezed states are an example of such nonseparable states, and have been shown to potentially reduce the effect of interaction-induced phase diffusion or improve the sensitivity of interferometric measurements beyond the sensitivity limit for uncorrelated particles, the standard quantum limit (SQL). For these reasons, studying the effect of atomic interactions is crucial to perform precise interferometric measurement with trapped BEC as well as to understand the physics of complex many-body quantum systems.

Condensates in a double-well potential implement the textbook case of a two-mode BEC. At the same time, they provide a prototypical configuration for matter-wave interferometry, reminiscent of Young’s double-slit experiment. For these reasons, they have stimulated great theoretical interest [5]. It was recognized very early that a BEC in a double well implements a cold atom analogue of a superconducting Josephson junction, where the Cooper pairs are replaced by neutral atoms and the thin insulating layer by a potential barrier, justifying the name of “bosonic Josephson junction” (BJJ). A tunable BJJ offers a conceptually simple

playground to investigate the interplay of tunnel coupling and atomic interactions in BECs, yielding a rich variety of dynamical regimes. Most importantly, tuning the parameters of a BJJ also offers a handle to engineer the many-body state of the BEC.

In this thesis, we present the implementation of a Mach-Zehnder interferometer for BECs on an atom chip setup, and its use for the study of interactions in our trapped, interacting BECs.

Since the first demonstration of the phase-preserving splitting of a BEC in 1998 [6], various techniques have been developed to build atom-optics analogues to beam splitters, phase shifters, or recombiners. Our scheme relies on the coherent manipulation of a condensate in a tunable double-well potential. The splitting was implemented by smoothly deforming the potential from a single to a double well. An adjustable phase shift was applied by imposing an energy difference between the two wells. In order to close the interferometric sequence, we developed two novel phase-sensitive recombiners for trapped BECs, the first one relying on controlled tunneling through the BJJ, the second on a fast manipulation of the confining potential.

Taking advantage of interactions during the splitting, we were able to produce and characterize a nonclassical “squeezed” atomic state featuring reduced number fluctuations with respect to a coherent state. We showed that the state produced in the interferometer could potentially yield a significant metrology gain beyond the SQL.

We used this state to study interaction-induced phase diffusion in our interferometer. For the first time, we could unambiguously evidence the link between fundamental atom number uncertainty and the rate of diffusion of the quantum phase, and demonstrated a coherence time extended by more than a factor of two by use of a nonclassical state.

This work constitutes an important step toward the use of BECs for quantum-enhanced matter-wave interferometry and contributes to the understanding of interactions in BECs. It opens new possibilities for the generation, manipulation, and detection of nonclassical quantum states, and calls for further studies of the role of interactions as a resource for matter-wave interferometry.

The manuscript is structured as follows:

- In Chap. 1, the theoretical framework which forms the basis for the results of this thesis is introduced. It comprises mainly a basic description of interacting BECs, with emphasis on elongated geometries, followed by a presentation of the two-mode model describing the physics of a condensate in a double-well potential.
- Chap. 2 is devoted to a description of the apparatus on which the experiments were conducted, with focus on the techniques of magnetic trapping on an atom chip, in particular the radio frequency-dressing used for the creation of double-well potentials, as well as the imaging systems used to probe the atoms.

- Chap. 3, which is the central part of this thesis, presents each stage of the Mach-Zehnder interferometric sequence and the corresponding results.
- Finally, Chap. 4 gives an outlook on effects beyond the two-mode description of the BJJ in the light of new experimental observations.

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