Bose-Einstein condensates in radio-frequency-dressed potentials on an atom chip

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1 Introduction

This thesis deals with experiments on clouds of ultra cold ($\lesssim\mu$K) rubidium gas trapped in magnetic fields. At such low temperatures rubidium has some remarkable properties. Amazingly, in these experiments the rubidium does not solidify, but stays a gas. Even more surprisingly, at this low temperature, quantum statistics and the bosonic nature of the rubidium starts to play a role. That is: all the atoms collect in the lowest-energy state and start to show collective behavior, as one big quantum-mechanical object. This state of matter is called a Bose-Einstein condensate (BEC) and in our experimental setup we make, manipulate and study it. This thesis deals especially with experiments in which we manipulate Bose-Einstein condensates through both static and radio frequency (rf) magnetic fields in microscopic potentials produced on a microfabricated chip.

Experiments like these are relatively complicated as they involve a fair amount of technology and experience to get them working. So before concentrating on the details of our particular setup this introductory chapter gives some background information about the physics and especially about the technology involved. First, in Sec. 1.1 we discuss the historic developments that led to the idea of Bose-Einstein condensation as well as some important inventions such as the laser and microfabrication in the semi-conductor industry. Section 1.2 introduces the research field of cold neutral atoms and mentions some of the developments that led to the production of the first BEC. In Sec. 1.3 we discuss the device that we use to create magnetic fields and that is essential to our experimental setup: the atom chip. Section 1.4 provides some more information about the experimental setup. After a short description of a typical experiment, the history of the setup is described and the relation of this thesis to other results is indicated. This chapter concludes with an outline of the remainder of this thesis.

1.1 Historic perspective

The developments described in this section have had a profound influence on both physics and everyday-life. Often they were important enough to be acknowledged with Nobel prizes. As a matter of fact, the press-releases from the Royal Swedish Academy of Sciences accompanying the prizes served as an excellent source of information for this chapter. They make interesting reading for those interested in many of the most important developments in physics since 1900 [1–6].

1.1.1 Conception of Bose-Einstein condensation

At the end the of 19th century German physicist Max Planck was trying to find a rigorous derivation and a good physical understanding of Wien's law for black-body radiation [7]. After working on the subject for some time, Planck found that he had to determine the entropy, and to determine the entropy he needed to count the number of ways a given amount of energy can be distributed among a certain number of oscillators. To be able to do the counting, Plank divided the energy up into portions, for which he introduced a new constant, h [8].

Now we look at this moment as the start of a new kind of physics, quantum physics, but at the time the quantization of energy was just seen as a mathematical trick and was not regarded as a new founding principle. There was no doubt that the nature of light was continuous due to diffraction and interference behavior. Light was wave-like and surely did not come in lumps. As time would go by and understanding of light would improve, physics would surely do away with the quantization again, at least that was the idea. Even when Einstein got the Nobel prize in 1921 for the discovery of the law of the photoelectric effect the majority of physicists still considered light as a wave phenomenon, despite the fact that the photoelectric effect can be regarded as a manifestation of the quantum nature of light [9].

In 1924 the Indian physicist Bose, however, did think of light as consisting of particles and developed a new statistics for them. The idea of light particles (photons) was still not without controversy, as can be seen from the fact that the scientific journal 'Philosophical Magazine' rejected the work of Bose for publication [10]. He sent his work to Einstein who recognized its importance. Einstein personally made sure the work of Bose got published [11] and also generalized the work of Bose to identical particles with nonzero mass with the number of particles conserved [12–14]. The Bose-Einstein distribution function is

$$N(E) = \frac{1}{\exp\left(\frac{E-\mu}{k_{\mathrm{B}}T}\right) - 1},$$

with k_{B} Boltzmann's constant, T the temperature E the energy and μ the chemical potential*. This distribution coincides with the classical (Boltzmann) distribution at high temperatures, but at very low temperatures it has the peculiar property that in a sample of atoms for a given total energy, the entropy is maximized if there were a substantial fraction of the atoms in the ground state, and infinitesimal fractions of the atoms in each of the discrete excited states. The substantial fraction of atoms in the ground state is called the Bose-Einstein condensate or quantum degenerate gas [15].

Experimental verification of the Bose-Einstein condensate remained absent for a long time. Only in 1938 Fritz London suggested to interpret the HeI–HeII transition as a Bose-Einstein condensation [16]. The experimentally measured temperature of

*Taking $\mu = 0$ gives the distribution function for photons.

the transition point of 2.19 K coincides rather well with the theoretical value of 3.1 K. But we now know that the strong interactions of the atoms in this system complicate the behavior and only about 9% of the atoms is in the condensate [17,18]. It would take until 1995 before dilute atomic vapors, systems with weak interactions, could be cooled to sufficiently low temperatures, in order to realize Bose-Einstein condensation in a well-controlled experimental system [6,19–23].

1.1.2 Technological advances

Microelectronics

The transistor was invented in 1947, and in 1956 William Bradford Shockley, John Bardeen and Walter Houser Brattain received the Nobel prize for "their researches on semiconductors and their discovery of the transistor effect" [1,24]. It marked the start of the age of solid-state electronics replacing the vacuum tube as an electronic component. The maximum number of these tubes in machines was limited to about a thousand due to their size, reliability and their energy consumption. With the smaller, more reliable and more energy efficient transistors, more complex machines were possible as they could be applied in greater numbers. However the complexity of machines was still limited by the number of transistors as they all had to be connected, typically by making solder connections [5].

The interconnection problem was solved by the invention of the integrated circuit. In 1958 Jack Kilby showed that it was possible to fabricate all discrete electrical components needed for an oscillator in semi-conductor materials like silicon and germanium. As obvious as it may seem now, at the time it was a bizarre idea to not only use expensive silicon for transistors but also for passive components that could be made of other, cheaper, materials [25,26]. Robert Noyce also worked on the integration of electrical components in silicon. He showed that the electrical components in silicon could well be connected with deposited aluminum strips as aluminum adheres very well to both silicon and silicon oxide [27]. This method would become the standard in the industry for many years to come.

Between the early days around 1960 and today the semiconductor industry has made unbelievable progress. The feature size has decreased from 5 μm in the late 1960s [28] to 65 nm today [29]. Layers only several atoms thick can be made reliably and materials purity is controlled in the ppb range [5].

Lasers

The invention of the laser can be dated to 1958 with the publication in Physical Review of a paper with the title 'Infrared and Optical Masers' by Schawlow and Townes [30]. The essence of their idea was that the principles of the maser could be extended to the optical region of the electromagnetic spectrum. They applied for a patent and received it in 1960. In 1964 Townes shared the Nobel Prize in Physics with A. Prokhorov and N. Basov for "fundamental work in the field of quantum electronics which has led to the construction of oscillators and amplifiers based on the maser-laser principle" [2]. In 1981, Schawlow also received the Nobel Prize, together with Nicolaas Bloembergen for "their contribution to the development of laser spectroscopy" [3]. The acronym laser (Light Amplification by Stimulated Emission of Radiation) is attributed to Gordon Gould, a graduate student at Columbia University, who wrote it in his notebook in November 1957 together with a description of the essential elements of the device. He introduced the term to the public in a conference paper in 1959 [31].

In 1960 Theodore Harold Maiman constructed the first laser. The then-new Physical Review Letters summarily rejected his report of making an "optical maser" as "just another maser paper." Maiman therefore wrote a short report which was immediately accepted for publication in Nature where it appeared August 6, 1960 [32]. Maiman later published a more detailed analysis of the first working laser in Physical Review [31, 33].

Around 1957 Kroemer presented the first worked-out proposal for a better transistor using a heterostructure. A heterostructure is a combination of 2 or more dissimilar semiconductor layers. These semiconductor materials have unequal band gaps. By using multiple (thin) semiconducting layers, one can tune the band gap, electron affinity and work function and the properties of the transistor improved. In practice this meant faster transistors (up to $\geq$ 100 GHz) and less noise [5].

Kroemer and Alferov independently suggested the principle of the double heterostructure laser in 1963 [34]. In this type of laser both the charge carriers and the photons are confined to the heterostructure making for more efficient lasing. Initially it was impossible to reliably fabricate these structures, but in 1970 the first heterostructure lasers were made having considerably lower threshold current, and the possibility of continuous operation without additional cooling [5]†.

1.2 Cooling and trapping of neutral atoms

As already mentioned in Sec. 1.1.1, Bose-Einstein condensation was achieved for the first time in dilute atomic vapors in 1995 [19–23], finally confirming the predictions that Einstein had made 70 years earlier. This achievement had become possible as a result of developments in the field of laser cooling and trapping of neutral atoms [35–37] that had started in 1975 with a proposal by Hänsch and Schawlow [38]. A few highlights of the developments since then are listed below.

The Ioffe-Pritchard magnetic trap is used often nowadays in experiments with cold neutral atoms. It was suggested in 1983 by Pritchard [39] and is similar in design to traps developed by Ioffe [40]. It has harmonic confinement in all directions and a non-zero field in the potential minimum at the center, which makes it a good alternative for quadrupole traps in which atoms are lost because of the absence of a field in the potential minimum.

The magneto-optical trap (MOT), suggested by Dalibard [35], was realized first

†In our experimental setup we use diode lasers. Although the double heterostructure laser was surpassed by more advanced types of diode lasers in the 1980s and 1990s, our setup would surely look very different without the work by Kroemer and Alferov.

by Raab et al. [41] in 1987. It uses a small spatially varying magnetic field to make the light force on the atoms position dependent yielding a much deeper trap (0.4 K) than a purely magnetic trap, allowing atoms to be collected from a room temperature gas and cooled to the μK regime. The MOT soon became the starting point of numerous experiments employing cold atoms.

Early on it was realized that laser cooling could possibly provide a route to BEC [42], but along the way it turned out that laser cooling alone was insufficient due to atomic recoil caused by photon (re)scattering. Some additional way of cooling the atoms without lasers and increasing phase space density was needed. The missing technique turned out to be evaporative cooling. In evaporative cooling atoms with an energy higher than average are removed from the trap by continuously reducing the trap depth. The remaining atoms re-equilibrate through collisions to a lower temperature [43]. The technique was first proposed by Hess in 1986 [44] for hydrogen and later successfully applied to trapped gases of alkali atoms [45]. Until today, evaporative cooling also remains an indispensable tool for reaching quantum degeneracy.

1.3 Atom chips

The experiments with cooled and trapped alkali atoms that led to Bose-Einstein condensation in 1995 were performed using traps made with cm-sized electromagnetic coils. In the beginning of the 1990s it was realized that miniaturizing the magnetic trap would allow for tighter traps since magnetic field gradients scale as $1/r^2$ with r the distance from the field generating element. In 1995 Weinstein and Libbrecht proposed the first conservative three-dimensional magnetic trapping potential with miniaturized conductors in a single plane which could be intregrated on an electronic chip [46]. In 2001 quantum degeneracy was reached also in these micro-fabricated traps [47, 48].

These traps, called atom chips, guide atoms above a surface much like electrons are guided through conductors in conventional electronic chips, and have proven themselves as powerful tools in cold atom research [49–51]. They offer a number of advantages over the conventional BEC experiments. The tighter magnetic confinement shortens the experimental cycle time and relaxes the demands on the quality of the vacuum. Furthermore it is relatively easy on an atom chip to scale up from one magnetic trap to arrays containing many traps [52–55]. Atom chips also offer the possibility of integrating different atom optical elements such as waveguides, beam splitters and interferometers. Apart from magnetic traps it has been shown that electrodes for electrostatic manipulation [56] and optical fibers and cavities for single atom detection [57–61] can be integrated on a chip.

The fabrication of atom chips benefits tremendously from techniques developed in the semiconductor industry over the last decades. They contain μm-size magnetic structures on a planar substrate typically several cm^2 large. Normally these structures are current-carrying wires that support current densities up to 10^{11} A/m^2 [62] and that are fabricated in specific patterns to make particular magnetic potentials [63–65]. Instead of wires sometimes magnetic films are used, while hybrid chips try to combine both current-carrying wires and permanent magnetic material [66–69]. Atoms are trapped at a distance between several micrometers and several hundred micrometers from the surface. Near the surface (<10 μm) the trapped atoms suffer from currents induced by Johnson noise and the attractive Casimir-Polder potential [70, 71], while at large distances ($\gg$ 100 μm) the advantage of the strong magnetic confinement is lost.

After having secured their own niche in cold atoms research, the prospects of atom chips are excellent. Atom chips employing current-carrying wires are very well suited for studying (nearly) one-dimensional quantum gases. The magnetic field gradient of a wire is used to increase the confinement such that in the transverse direction only the ground state is populated. The weakly interacting 1D Bose gas has recently been realized on our own and other atom chips [72, 73] and efforts to also make the strongly interacting gas [74–77] are still continuing. 1D systems attract much attention because they allow exactly solvable models to be compared to experiments.

Radio-frequency-dressed potentials[‡] are becoming a popular tool in atom chip experiments [78–84]. These potentials come about when the Zeeman states of trapped atoms are actively coupled by radio-frequency radiation. They have become popular because rf-dressed potentials can be given shapes that are difficult to achieve with static potentials, such as a double-well potential. Such elongated double-well potentials allow studies of the intriguing coherence properties of (nearly) 1D gases [72,82]. The use of rf-dressed potentials is not limited to atom chips, but the close proximity of the field producing elements to the atoms, makes it especially easy to create large amplitude radio-frequency magnetic fields on atom chips.

Finally, atom chips are mentioned in relation with quantum information processing (QIP). In recent years significant progress has been made in the coherent control of atom clouds on atom chips [85]. The addition of state-dependent control enabled by rf-dressed potentials [80] and the easy scalability of atom chip potentials [55] are interesting for QIP applications [86, 87].

1.4 The *Celsius* experiment

This thesis describes the development of, and experiments performed using the *Celsius* setup (Chip Experiment for Low-dimensional Strongly Interacting Ultracold Systems) initiated in 2002 at the University of Amsterdam. The setup involves a single-chamber ultra-high vacuum (UHV) system. The atom under study is the boson ^{87}Rb that is brought into the system by resistive heating of dispensers mounted inside the vacuum system. A simple laser setup containing 3 diode lasers delivers the 780-nm light for laser cooling. After laser cooling the atoms are trapped in the magnetic field of an atom chip with current-carrying wires. On the chip the

[‡]These potentials are referred to in the literature as *adiabatic potentials* or *rf-dressed adiabatic potentials* or *rf-dressed potentials*. We feel that the rf-dressing is the most noticeable feature distinguishing them from static magnetic potentials, so we call them *rf-dressed potentials*.

atoms are evaporatively cooled to BEC. Resonant absorption imaging after ballistic expansion is used to detect the atoms.

In 2002, Aaldert van Amerongen was the first graduate student to work on the project. Starting with an empty lab (locally known as C513), he achieved magneto-optical trapping in November 2003. Around that same time the author of this thesis started as the second graduate student on the project beginning with fabrication of the atom chip. During 2004 and 2005 buildup continued and the first BEC was produced in April 2006 on an atom chip of the third generation. The remainder of 2006 measurements were performed on 1D gases [73] and phase-fluctuations. In 2007 measurements involving rf-dressed potentials were performed several of which are described in this thesis.

The present thesis has been written to complement the thesis by Van Amerongen [88], while at the same time providing sufficient detail so that it can be read independently. Together they give a complete overview of the experimental setup and the procedure used to achieve BEC. Also the equations for the static magnetic field can be applied to the experiments in both theses. The character of the experiments is very different. Van Amerongen focused on the physics related to the one-dimensional character of the quantum gases (in a single-well magnetic trap) while this thesis describes the use of radio-frequency fields to modify the trapping potential including novel possibilities that these modified potentials offer to study quantum gases, with particular emphasis on the possibilities of the elongated double-well potential for studying coherence properties of the trapped degenerate gases.

1.5 This thesis

The outline of this thesis is as follows.

Chapter 2 discusses the theoretical background of the experiments. Its main subjects are the static magnetic field created by the atom chip in our setup and the rf-dressed potential that is created by adding oscillating radio frequency magnetic fields to the static fields.

Chapter 3 is concerned with the atom chip we use for our experiments. Its design and fabrication are detailed. We characterize the chip by describing the chip wire resistances, the maximum current it can handle and a measurement of the roughness of the magnetic potential it produces.

Chapter 4 deals with the experimental setup except the atom chip. Parts of the setup, such as the vacuum system, the laser system, the chip mount and the imaging system have already been described in detail by van Amerongen [88]. We have included a summary of these components in this thesis mainly for convenience of the reader and because some details have changed. A more complete description is given of the parts that have not been described before, such as the computer system controlling the experiment and the rf signal generation via direct digital synthesis (DDS).

Chapter 5 describes several experiments that were done to characterize the rf-dressed potential in our experiment and compare it to the bare (un-dressed) potential. We pay special attention to the reduced sensitivity of the rf dressed potential to small static magnetic field variations in the longitudinal directions. The calculations of the rf-dressed potential in Chap. 2 and the experiments in Chap. 5 match very well.

In **chapter 6** we use the rf-dressing field to create a double-well potential. By releasing BECs from this potential we can create matter-wave interference, similar to Young's two-slit experiment in optics. The results are a clear illustration of the wave-particle duality of matter. The initial results on characterizing the coherence properties of elongated BECs in the double-well trap are presented.