Probing Bose-Einstein Condensates by Electron Impact Ionization

P. Würtz, T. Gericke, T. Langen, A. Koglbauer, and H. Ott
Institute of Physics, 55099 Mainz, Germany
E-mail: ott@uni-mainz.de

Abstract. We describe an experiment that allows for the study of ultracold quantum gases by electron impact ionization. The setup combines a scanning electron microscope and an apparatus for the production of Bose-Einstein condensates of rubidium atoms. With a diameter as small as 50 nm, the electron beam locally interacts with the much larger condensate. The produced ions are used to probe the many-body system with single atom sensitivity. We discuss the general scheme of this technique with special emphasis on the technical equipment and on the specific phenomenology of the particular collisional system.

1. Introduction
The spatial structure of a composite quantum system is usually probed with scattering experiments, where the outgoing waves carry the information on the target structure [1, 2, 3, 4, 5]. Small structures are transformed into large scattering angles and vice versa. Real space microscopy offers an alternative approach in which smooth and irregular variations in the target structure are easier to detect and spatial correlations in the system are directly accessible. Whereas atoms are too small in order to image their electronic configuration, an atom as a whole can be imaged with various techniques. In solid state systems, modern scanning probe techniques [6] have been used with great success to reveal the distribution of individual atoms on a surface. In these experiments, the position of the atoms is a priori fixed due to strong interactions with the environment. A qualitatively new regime is entered when the imaged atoms have to be described by quantum mechanical wave functions and the detection process becomes probabilistic.

Ultracold quantum gases combine an almost perfect isolation from the environment with a macroscopic extension [7]. Therefore, they offer an ideal testing ground for microscopy applied to pure quantum systems. In most experiments on ultracold gases the atomic cloud is probed by resonant laser light whose absorption generates a shadow which is imaged on a CCD camera [8]. While absorption imaging has not yet been demonstrated to achieve single atom sensitivity, fluorescence imaging [9, 10], outcoupling of single atoms by a radio frequency field [11] or direct particle detection in time of flight [12] are alternative approaches which can detect single atoms. However, none of these techniques has yet been applied to image the distribution of single atoms in a quantum gas. The high atomic density and the limited spatial resolution of 1 μm are the two main difficulties that arise.

We have developed a new imaging technique based on scanning electron microscopy that overcomes both limitations. It allows for the detection of single atoms in an ultracold quantum
gas with a spatial resolution of better than 150 nm. The technique is not only suited for microscopic studies of ultracold quantum gases. It is also a novel experimental platform for electron-atom scattering processes which could have interesting perspectives for the investigation of new collisional phenomena. In this article, we first introduce the working principle of the imaging technique (section 2) and describe the experimental setup (section 3). First results are summarized in sections 4 and 5. A discussion of possible applications for future scattering experiments concludes this paper (section 6).

2. Working principle
The standard diffraction limit of optical microscopy can be overcome by passing from photons to massive particles. Scanning electron microscopy has achieved a spatial resolution of better than 0.1 nm [13]. In order to transfer such a principle to ultracold atoms, a suitable interaction mechanism and a clear detection signal have to be chosen. Electron impact ionisation with subsequent ion detection combines an efficient interaction mechanism with single particle sensitivity. The working principle is sketched in Fig.1. A focussed electron beam intersects the atomic cloud which is prepared in a single beam optical dipole trap formed by a focussed CO$_2$-laser beam [14]. We can produce thermal or Bose-Einstein condensed ensembles of $^{87}$Rb atoms with about $10^5$ atoms at a temperature of 80 nK. The elongated cloud is cylindrically symmetric and has a size of $6 \mu m \times 100 \mu m$. The electron microscope is operated at an energy of 6 keV and the electron beam, which can be focussed to less than 100 nm FWHM diameter, can be scanned in both transverse directions within a field of view of $1 mm \times 1 mm$. During the imaging procedure, the electron beam is scanned across the cloud and locally produces ions. A small electrostatic field is applied in order to extract the ions and guide them towards a channeltron detector. A multi channel scaling card records the events from which the image is obtained. The spatial resolution of the imaging technique is set by the size of the electron beam.

3. Experimental setup
In Fig. 2 we show the main components of the experimental setup. For the preparation of the Bose-Einstein condensate we employ standard laser cooling and trapping techniques [14]. In order to prevent a deflection or distortion of the electron beam by magnetic trapping fields we have chosen an all-optical approach. The use of a single beam CO$_2$ laser dipole trap is especially attractive as it provides an easy and robust way for the production of a condensate [15]. We use a
custom made electron column which is optimized for high beam currents and ultra high vacuum conditions. The electron beam is generated with a thermal Schottky emitter (6 keV beam energy) and collimated by a magnetic condenser lens. After passing various electron optical elements the beam is focussed by a magnetic objective lens on the atoms which are located at a working distance of 13 mm. The beam is scanned with help of an electrostatic post lens deflection unit. We achieve the following combinations of beam current and diameter (FWHM): 9 nA for 70 nm, 24 nA for 100 nm, 100 nA for 240 nm, and 300 nA for 700 nm. The relevant length scales in an ultracold quantum gas such as the average interatomic distance, the spacing in an optical lattice and the healing length are on the order of a few hundreded nanometer. Therefore, a spatial resolution of 100 nm (corresponding to a FWHM beam diameter of the same size) suffices for most applications. The half aperture angle of the electron beam depends on the chosen settings of the column and varies between 1 mrad and 5 mrad. This small value ensures a large depth of focus of a few ten micrometer. For the calibration and alignment of the electron beam, several copper test targets and a secondary electron detector are mounted on a manipulator which can be moved inside and outside the electron beam.

The ion optics and a channeltron detector (Fig. 3) are mounted in the horizontal symmetry plane of the chamber. Three electrodes guide the ions towards a short drift tube (5 cm length) before they enter the channeltron detector (DeTech, 402A-H). With a conversion dynode setting of 4.8 kV and a channeltron voltage of 2.2 kV we achieve a detector efficiency of about 30 %. As a replacement of the detector in our apparatus is extremely time-consuming, we have chosen...
Figure 3. Ion optics and ion detector. (a) Image of the assembled detector. An RF antenna is implemented on the detector for possible spin manipulations on the trapped atoms. (b) Scheme of the inner part of the ion detector. The drift tube with 5 cm length connects the three entrance electrodes with the channeltron detector.

A very conservative voltage setting in order to guarantee a long lifetime. The geometry of our setup (Fig. 2c) shows no rotational symmetry and additional spatial constraints require that the detector is mounted under 45° with respect to the dipole trap axis. As a consequence, this makes the application of a homogeneous electrostatic extraction field impossible. In fact, the ion optics is designed in favour of a maximal flexibility for the field configuration. For typical voltage settings of the electrodes of a few hundred volts, we calculate a electrostatic field strength at the location of the atoms of about 5 V/cm.

4. Electron-atom interaction

Elastic, inelastic and ionizing collisions have to be considered in our approach. For the collisional system electron on rubidium at 6 keV energy we can calculate the relevant cross sections in first Born approximation. For the elastic channel we obtain $\sigma_{\text{el}} = 0.7 \times 10^{-17} \text{ cm}^2$. For the inelastic channel the dominant excitation is on the $5S - 5P$ transition with a calculated cross section of $\sigma_{5S-5P} = 4.8 \times 10^{-17} \text{ cm}^2$. The total ionization cross section has been calculated in Ref. [16] and amounts to $\sigma_{\text{ion}} = 3.4 \times 10^{-17} \text{ cm}^2$. As only the ionization channel contributes to the signal the maximum detection efficiency is limited to 40%. This ratio is consistent with experimental data at an electron energy of 500 eV [17, 18]. In both, elastic and inelastic collisions, the kinetic energy transfer to the atom is much larger than the depth of the optical dipole trap and the atoms can escape from the trap.

In order to characterize the ionization process quantitatively we have recorded a time of flight spectrum (Fig. 4). The peaks in the spectrum can be clearly assigned to the different charge states up to Rb$^{7+}$. The relative height of the peaks indicates that 80% of the detected ions are singly charged. However, as we cannot calibrate the channeltron detector for the different charge states we cannot infer the direct ratio for the production of the different charge states. As we are operating the detector at a comparably low voltage, higher charged states are likely to have a higher detection efficiency. In the future, a more thorough investigation is necessary. The general trend of the data is similar to early work on multiple ionization of alkali atoms at somewhat lower energies [19].

5. Electron-condensate interaction

The main focus of the described experiment lies on the imaging of ultracold quantum gases. To this purpose, the beam is scanned in a rectangular pattern across the atomic cloud while the
Figure 4. Time of flight spectrum for 6 keV electrons on rubidium. After production of the condensate, the electron beam is pulsed for 100 ns and the spectrum is recorded for 30 µs. The sequence is repeated 1000 times with a single condensate. Upon completion a new condensate is produced and the sequence starts again.

ion detector signal is recorded (Fig. 1). Post processing of the data results in an image as shown in Fig. 5a. Each plotted dot corresponds to a detected atom. Note, that only a small fraction of the atoms is detected in the imaging process. The density distribution of the atomic cloud can be obtained by binning a single image or summing over many images (Fig. 5b). For a more detailed description of the imaging process and a quantitative evaluation of the measured density profiles of the condensate we refer to Ref. [20]. Here, we will discuss an aspect that is different from scattering experiments with non-degenerate targets. Compared to COLTRIMS [21] and MOTRIMS [22, 23, 24] experiments the temperature of our target is at least 1000 times lower. At this low temperature Bose-Einstein condensation occurs and a macroscopic number of atoms occupy the same quantum state. The many-body wave function ψ of the condensate is then given by the product of N identical single particle wave functions φ: ψ(⃗x₁, ..., ⃗xₙ) = ∏ᵢ₌₁ⁿ φ(⃗xᵢ), with N being the number of atoms in the condensate. As the single particle wave function φ is as large as the condensate, the electron beam is much smaller than the wave function of the target atoms. Therefore, the detection of an atom must be understood as a projective measurement.

Figure 5. Scanning electron microscope images of a Bose-Einstein condensate. (a) Image with 350 detected ions. Every dot (pixel size of 300 nm × 300 nm) corresponds to a detected ion. (b) Sum over 300 individual images. The cigar shape of the condensate is clearly visible. A quantitative analysis of the images can be found in [20].
in position space. As a consequence, the retrieved image is intrinsically probabilistic. This is in contrast to almost all microscopy images revealing the distribution of individual atoms. In these cases the location of the atoms is already fixed prior to their detection. In scattering experiments, the wave function of the outgoing particles usually collapses due to the coupling with the macroscopic detector. Here, the electron beam itself can be considered as a microscopic detector that collapses the atomic wave function directly within the sample.

6. Discussion
The described experiment is a new and versatile tool for the investigation of ultracold quantum gases. It combines single atom detection capability with high spatial resolution and opens many possibilities for the microscopic analysis of these quantum systems. But it is also a new platform for collisional studies in atomic physics and we conclude this article discussing a possibly interesting application in the context of scattering experiments which is related to the elastic and inelastic scattering channels. These collisions are not directly observable in our system. With aid of absorption imaging however, these collisions can be observed in the limit of vanishing transverse momentum transfer. The corresponding scenario is depicted in Fig. 6 and consists of a short electron beam pulse followed by period of free propagation and a final absorption image. The dipole trap is kept on in order to retain the unaffected atoms. As both collisions are binary, momentum conservation enforces the scattered atoms to form an expanding sphere in the laboratory frame with the trapped cloud located at the north pole (Fig. 6). Scattered atoms close to the north pole are slow enough to be detected by the final absorption image. A distinction between elastic and inelastic scattering is possible taking into account the hyperfine structure of the atoms. In the actual experiment the rubidium atoms are prepared in the $|F = 1\rangle$ ground state, equally distributed among the magnetic substates. For an elastic collision, the atom stays in the $|F = 1\rangle$ ground state, whereas for an inelastic collision, the atom can decay after the excitation into the $|F = 1\rangle$ or $|F = 2\rangle$ ground state. Thus, imaging atoms in the $|F = 2\rangle$ ground state exclusively reveals a fraction of the inelastic scattering channel whereas the $|F = 1\rangle$ population represents a mixture of both channels. Such a scheme would allow for extremely small angle scattering experiments.

Whether this experimental platform will develop into a versatile technique for studying collisional physics is an open question. We believe that there are interesting aspects that are worth pursuing in the future. It will also help to better understand the limitations and the prospects of this technique. It would be fascinating if the extremely low temperature of the target atoms can be exploited in future experiments. Note, that the relative energy difference between the projectile and the target is 15 orders of magnitude.

Finally, the degeneracy of the target atoms – which so far entered the discussion only from
a conceptional point of view – could open new perspectives for the observation of many-body scattering effects in the spirit of recent experiments on molecular photodissociation [25].

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