Bose-Einstein Condensates in Magnetic Micro Traps

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Abstract

In a recent experiment we have demonstrated the generation of a Rubidium condensate inside a magnetic micro trap. The lifetime and the heating rate of the atomic cloud at different distances from the trap surface has been determined. A surface induced potential structure of unknown origin has been identified by observing a periodic fragmentation of the atomic cloud.

1 Magnetic Micro Potentials

Precise quantum control of the position and the motion of a single atom is a fascinating and intriguing vision. If this control is accomplished by tiny potentials that can be shaped on the micron scale, one may arrive at a new technology which allows for the construction of complex atom optics devices integrated on miniaturized "atom chip". This scenario seems in fact possible with trapping potentials that are formed by the magnetic fields of thin wires or, ultimately, microfabricated current conductors[1][5][3][10][2]. With these micro potentials atoms can be guided only several μm above the surface of a substrate that, in principle, may carry a variety of elements such as wave guides, beam splitters, storage rings, linear and ring resonators, gates, etc.[4].Fig.1 shows an example:

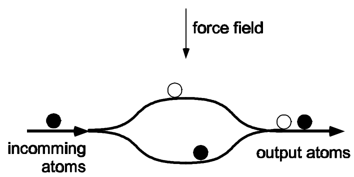

Figure 1: An atom chip interferometer.

An atomic wave packet entering from the left in a magnetic wave guide is split by a beam splitter into two parts that are subsequently recombined by the second beam splitter. Constructive interference behind the second splitter occurs, if the relative phase between the wave packets is preserved. However, a force applied from the side, would shift the relative phase due to the difference in the time of flight along the two paths: In the upper path the atom is decelerated first and than accelerated, while in the lower path the situation is vice versa.

The average velocity is smaller for the upper path which leads to an overall phase shift at the second beam splitter. The force can tune the interferometer to destructive interference such that the atom does not pass the interferometer. The force which is required to tune the interferometer from constructive to destructive interference depends on the included area A and the input velocity v of the atom. With reasonable values ($A = 100{}^1\mathrm{m}^2; V = 100\frac{m}{s}$) the force can be as small as $10^{\text{¡}27}$N which is 10000 times smaller than the gravitational weight of the atom. Besides gravity, the interferometer would be sensitive also to electric or magnetic interactions or forces due to acceleration.

In this example it is assumed, that the transverse motion of the atom in the wave guide is e®ectively suppressed analogous to a photon in an optical single mode ¯ber. Such single mode propagation is guaranteed if the energy separation between the transverse modes signi¯cantly exceeds the thermal energy of the atom. Then, the transverse motion is frozen out and the atomic wave packet can be described as a superposition of only the longitudinal modes of the wave guide. The temperatures required for single transverse mode trapping may be well below of what is feasible with standard optical cooling methods. In our experiment [5] we therefor pursue a "bottom up" approach and start with a Bose-Einstein condensate that we generate inside a magnetic micro trap. In a condensate the atoms are prepared in the ground state of the system from where they may be excited into well controlled states of the micro potential. In the next chapter we brie°y describe the technical aspects of the experiment and then report on ¯rst experimental results: Already at distances of several hundred ¹m we observe an unexpectedly large e®ect of the surface on the shape and the life time of the atomic cloud. The article concludes with an outlook on possible future experiments.

2 Experimental Details

We use two types of traps. One is formed by a copper wire (90 ¹m diameter) that is cemented to the edge of a copper bar with a quadratic cross section and a width of 2 mm (¯g.2). The current in the wire ("thin wire") is reversed relative to the current in the bar ("compression wire"). The combined magnetic ¯elds of the two conductors form a linear magnetic quadrupole ¯eld parallel to the surface of thin wire in which the atoms are radially con¯ned[6]. Axial con¯nement is established by an additional magnetic ¯eld with a shallow curvature along the axis of the wire. As a result one obtains a very elongated cigar shaped trap with a radial oscillation frequency of up to 5 kHz and an axial frequency of 14 Hz (for Rubidium atoms in the $F = 2; m_F = 2$ state). The second trap is formed by a set of micro fabricated copper conductors on an Al_2O_3 ceramic substrate [7](¯g.3). It is also mounted on the compression wire and works by the same principle as the wire trap, however, with the di®erence that conductors of several widths can be used. For the smallest conductor with a width of 3 ¹m the radial oscillation frequency may reach values of 500 kHz. Then, the trap mini-

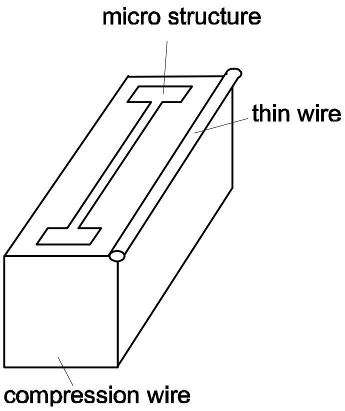

Figure 2: Micro trap setup. The trap is formed by the combined magnetic fields of the compression wire and either the thin wire or the current conductors that are microfabricated onto the subtrate of the micro structure.

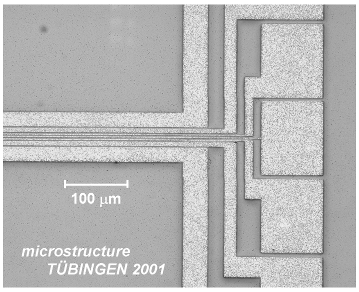

Figure 3: The microstructure consists of seven parallel copper conductors with a width of 30, 11, 3, 3, 3, 11, and 30 μm and a height of 2.5 μm. On the right side the contact pads are visible (microscope image).

mum is positioned only a few ¹m above the surface of the micro structure. Both traps can be loaded with a condensate that contains about 500000 atoms. The complete setup is shown in ¯g.4. The atoms are initially collected in a magneto-

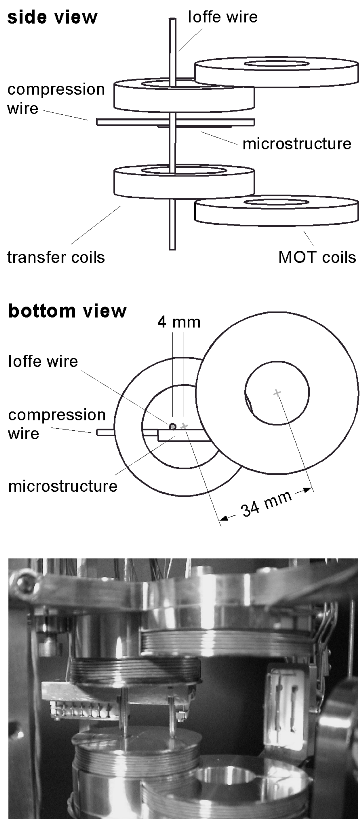

Figure 4: The compression wire, the microstructure and the thin copper wire are mounted on a heat sink between the transfer coils. The photograph shows the mounted trap setup and the dispenser sources behind the MOT-coils.

optic trap and then transferred into a shallow magnetic quadrupole potential. By continuously changing the shape of the magnetic ¯eld the atoms are adiabatically transferred into the tightly con¯ning potential of the micro trap. The magneto-optic trap is ¯lled with Rubidium from resistively heated dispensers that can be turned o® after the loading has been completed [8]. Sophisticated double-chamber systems can be avoided this way. The entire setup including Rb source and all magnetic elements is mounted on a single standard vacuum °ange with 150 mm diameter. The vacuum system avoids mechanical pumps and is based on an ion pump (80 l/s) and a Titanium sublimation pump (2500 l/s). The microstructure is operated with special low noise current drivers that have been optimized by the manufacturer (HighFinesse) for our experimental application. The complex timing of the experiment is accomplished by a commercial digital control system (AdwinPro, Keithley). Miniaturized magnetic traps have the advantage of relatively small electric power consumption. While conventional traps dissipate up to 10 kW the total power of our setup stays below 25 W. The dominant heat source is the microstructure with up to 10 W, followed by the coils that are necessary for the operation of the MOT and the adiabatic transfer. The small heating power allows to place all the current carrying elements inside the vacuum with almost no extra cooling precautions. Nevertheless, we extract the heat from the setup with a 20 cm long and 1 cm thick copper rod, that reaches through the vacuum lid and can be cooled by water or liquid nitrogen. For extended experimental data taking cooling guaranties stable operation during the day. The experiment is carried out in cycles of 60 s. 20 s are used to load the magneto-optic trap. Evaporative cooling and transfer into the microstructure take another 25 s. The large compression that is offered by the strong confinement in the micro trap may in principle allow for evaporative cooling within a few seconds. In our experiment, however, this is of little practical use, since the loading time of the MOT can hardly be shortened. Further details are found in [9].

3 Experimental observations

For future experiments with atom chips the interaction between the atoms and the surface will be of great importance. Regarding the enormous temperature difference between the surface and the atoms one would expect heating processes setting in at some critical distance from the surface. It is thus surprising that this is not the dominant effect. Already at a distance of 300 μm we observe an increased exponential decay with a life time that scales linearly in distance between 20 s at 300 μm and 0.7 s at 20 μm. We use a thermal cloud at a temperature slightly above the T_c and control the distance by reducing the current in the conductor that forms the linear micro trap. Care is taken to keep the density low enough to exclude lifetime effects due three body collisions. Repeating the experiment with the micro trap formed by the thin wire we observe a similar behavior. A consistent explanation is possible if we assume that the losses are caused by residual current noise in the micro trap conductor that leads to a fluctuating magnetic field. Frequency components in the MHz range are than able to induce transitions from low field to high field seeking states. For a linear conductor one would expect the amplitude of the noise field to scale with the inverse distance leading to a linear decrease in lifetime. Because we use low noise current drivers it is unlikely that the noise is generated inside the current source. However, we can not exclude that there is some radio frequency pick up in the driver electronics or in the current feeds that connect the drivers and the micro trap conductor. Further tests are necessary to verify the model and to clarify the possible origin of a high frequency magnetic noise. We also checked the heating rate and found values of about 400 nK=s: This is considerably enhanced relative to the reference value of 40 nK=s for large separations (>2 mm), however, there is no signi¯cant change within the range from 50 ¹m to 300 ¹m.

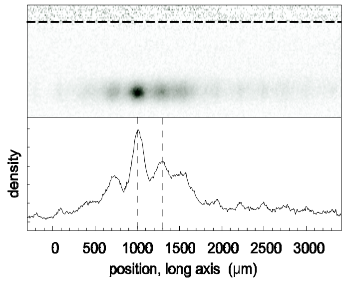

Figure 5: The spatial density modulation of an expanding atomic cloud in the waveguide indicates a periodic potential structure along the current carrying copper conductor. For the experiment, an ultracold cloud of 5:6 ¢ 10^5 atoms at the temperature of 1 ¹K was released into the waveguide by turning o® the axial con¯nement of the trap within 400ms. The waveguide with a radial con¯nement of !$_r$ = 2¼ ¢ 1000Hz was located at a distance of approximately 150 ¹m to the microfabricated conductor. The absorption images were taken after 10ms time of °ight. The integrated scan (lower part) shows a periodicity of 300 ¹m in the density distribution of the cloud.

More surprising is an observation which is presented in ¯g.5. It shows the time of °ight image of the thermal cloud which has been trapped at a distance of 150 ¹m from the surface. The cloud disintegrates and forms a linear array of droplets separated by 300 ¹m. This structure can even be observed if the weak axial potential of the micro trap is completely turned o®. If the experiment is carried out with a condensate, one ¯nds that the condensate is still trapped also along the long axis, obviously by a potential, that is generated by the surface of the micro trap. Again, the experiment can be repeated with the wire, essentially with the same results, however with a period of 220 ¹m. This suggests that the unexpected periodic surface potential is connected to some fundamental property of linear copper conductors. Similar observations have been reported by the group of W. Ketterle [10] and E. Hinds [11]. For future atom chip experiments it will be decisive to control these surface potentials since they may impose serious restriction on the degree of miniaturization and the maximum radial con¯nement that can be achieved.

4 Outlook

Trapping and manipulating atoms in magnetic micro traps is a very young ¯eld and it is di±cult to make predictions about future developments. Nevertheless, one can speculate about future research topics. The experiments presented here show a strong in°uence of a nearby surface on a condensate. This suggests the use of the condensate as a probe to study an arbitrary surface. The sample surface can be either metallic or dielectric or a combination of both. Electric or magnetic surface forces, acting on the condensate will structure its density distribution. This can be observed with a variety of well established imaging techniques. In this case the resolution is limited by the imaging system to the micron range. A better resolution may be achieved by imaging the condensate after some milliseconds of free expansion in the gravitational ¯eld. Since such time of °ight images re°ect the initial velocity distribution of the condensates, they would provide information about the phase gradients inside the condensate as imprinted by the surface under investigation. Such an approach can be regarded as an extension of recent experiments with condensates in three dimensional optical lattices [12].

Besides such surface studies the general line for future research with micro traps would be the development of elements for integrated atom optical devices. If condensates can be split and recombined with temporal or spatial beam splitters it is conceivable to construct interferometers that are sensitive to rotations and forces. Micropotentials can also be used to control the relative position between di®erent atomic clouds or even single atoms. This allows for a tunable interaction between atoms and can be used for novel approaches to construct quantum gates [13].

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