

Bose-Einstein Condensation in a Surface Microtrap

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Bose-Einstein condensation has been achieved in a magnetic surface microtrap with 4×10^5 ^{87}Rb atoms. The strongly anisotropic trapping potential is generated by a microstructure which consists of microfabricated linear copper conductor of widths ranging from 3 to 30 μm . After loading a high number of atoms from a pulsed thermal source directly into a magneto-optical trap the magnetically stored atoms are transferred into the microtrap by adiabatic transformation of the trapping potential. In the microtrap the atoms are cooled to condensation using forced rf-evaporation. The complete *in vacuo* trap design is compatible with ultrahigh vacuum below 2×10^{-11} mbar.

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Trapped ultracold atoms are fascinating model systems for studying quantum statistical many particle phenomena. Confined in optical or magnetic trapping potentials, the atomic gas reaches quantum degeneracy at ultralow temperatures ($<1 \mu\text{K}$) and very small densities ($\sim 10^{14} \text{ cm}^{-3}$). In this regime, the interaction between the atoms is still weak and the system is accessible to precise theoretical description [1]. One of the most intriguing properties of such ultracold atomic ensembles is the formation of macroscopic matter waves with extraordinary large coherence lengths. For single thermal atoms the coherence length is determined by the thermal de Broglie wavelength and is thus limited to the micrometer range, even for temperatures as small as $1 \mu\text{K}$. In contrary, a Bose-Einstein condensate may show coherence effects over a much larger distance [2,3]. It is, therefore, an exciting vision to combine degenerate quantum gases with magnetic micropotentials [4] which may allow for coherent atom optics on the surface of a microstructured “atom chip” [5]. Yet, it is an experimentally open question how a degenerate Bose gas behaves in a waveguide structure where it acquires a quasi-one-dimensional character [6,7].

All recent experiments using microfabricated structures have been carried out with thermal, nondegenerate atomic ensembles and therefore small coherence lengths [8–13]. Experiments with Bose-Einstein condensates are so far restricted to straightforward harmonic trapping potentials with relatively small anisotropy [14–16]. These trapping potentials are generated by large scale current coils and can hardly be structured on a scale much smaller than the dimensions of the coils. Some flexibility has been achieved by using optical potentials [17,18]; however, this approach does not allow for long and strongly confining waveguides due to diffraction of the employed laser light.

In our experiment we have, for the first time, generated a Bose-Einstein condensate in a microstructured magnetic surface trap. Our setup allows for investigating coherence phenomena of degenerate quantum gases in extremely anisotropic magnetic waveguides. A long lifetime of the trapped atoms and a large number of atoms in the condensate have been achieved with a fully *in vacuo* trap

design. We optically precool the atoms in a magneto-optical trap (MOT) which is directly loaded from a pulsed thermal source. This fast and easy technique avoids the standard sophisticated double MOT system [19]. The surface microtrap is loaded by adiabatic transformation of the initially shallow magnetic trapping potential into the geometry of the microtrap.

The central element in our experiment is the microstructure. It consists of seven 25 mm long parallel copper conductors at a width of 3, 11, and 30 μm which are electroplated on an Al_2O_3 substrate (Fig. 1). The total width of the microstructure is 100 μm . Test experiments with a set of identical microstructures revealed breakthrough currents of 1.5, 0.8, and 0.4 A for the 30, 11, and 3 μm conductors. This corresponds to maximum current densities of 2.0×10^6 , 2.9×10^6 , and $5.3 \times 10^6 \text{ A/cm}^2$, respectively. The current in each conductor can be controlled individually. The configuration of the conductors allows us to build a variety of trapping potentials. If the currents in all conductors are driven in the same direction, a linear quadrupole trapping potential is formed by the combined field of the conductors and an additional homogeneous bias field which is oriented perpendicular to the long axis of the microstructure. By subsequently

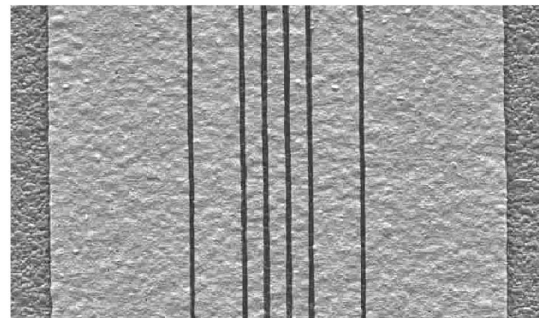


FIG. 1. The scanning electron microscope image of the microstructure shows a part of the 25 mm long Al_2O_3 substrate with seven parallel electroplated copper conductors. The widths of the conductors are 30, 11, 3, 3, 3, 11, and 30 μm each. The height of the copper layer is 2.5 μm .

turning off the current in the outer conductors the field gradient is increased while the trap depth is kept constant. To avoid for Majorana spin flips, this linear quadrupole field is superimposed with a magnetic offset field that is oriented parallel to the direction of the waveguide. It is generated by two extra wire loops that are mounted directly onto the microstructure substrate, one at each end of the waveguide.

The unusual length of the microstructure of 25 mm provides a large flexibility for investigating quantum gas dynamics in long waveguides. A set of parallel waveguides can be formed by a suitable choice of currents in the inner conductors of the microstructure [20]. The two guides may be merged and separated by varying the strength of the longitudinal offset field along the guides, thus allowing for the realization of on-chip interferometers. In the experiment described in this Letter we used the microstructure in the most basic mode of operation: all conductors are driven in the same direction and we apply an external bias field. The radial and axial trap frequency are adjusted to $\omega_r = 2\pi \times 840$ Hz and $\omega_a = 2\pi \times 14$ Hz.

The adiabatic transfer of atoms into the microstructure is achieved by means of a pair of “transfer coils.” The microstructure is mounted horizontally on a 2×2 mm² copper rod (“compression wire”) that is embedded in a heat sink at the bottom of the upper transfer coil (Fig. 2). The conductors on the microstructure are oriented parallel to the compression wire. The setup is completed by a vertical copper wire with 2 mm diameter (“Ioffe wire”) that is oriented parallel to the symmetry axis of the transfer coils but displaced by 4 mm. At a current of 3 A the transfer coils generate a spherical quadrupole field with a gradient of 58 G/cm along the symmetry axis. This field forms a relatively shallow magnetic trap where atoms can be conveniently stored with standard techniques. By increasing the current in the Ioffe wire, the center of the spherical quadrupole is shifted and transformed into a Ioffe-type trapping field [21]. At a current of 13 A in the Ioffe wire the resulting harmonic trap potential is characterized by an axial oscillation frequency of $2\pi \times 14$ Hz, a radial oscillation frequency of $2\pi \times 110$ Hz, and an offset field of 0.7 G. The transfer from the Ioffe-type trap into the microstructure is completed by changing the currents in the upper and lower coils. This shifts the magnetic field minimum onto the surface of the microstructure.

For the initial preparation of atoms in a magneto-optical trap we use a second pair of coils (“MOT coils”) which is separated 34 mm from the transfer coils (Fig. 2). Both pairs of coils overlap and an adiabatic transfer of magnetically trapped atoms can be performed with the quadrupole potential minimum moving on a straight line from the center of the MOT coils to the center of the transfer coils [22,23]. The separation of the MOT coils and the transfer coils guarantees a good optical access to the MOT and allows for a high flexibility in mounting different microtrap geometries. The entire trap setup is placed in a UHV chamber at a pressure below 2×10^{-11} mbar.

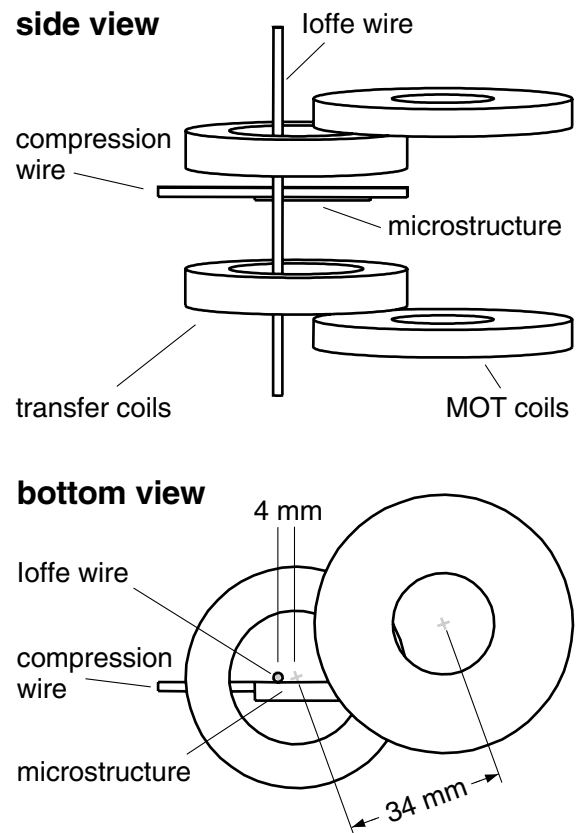


FIG. 2. Trap setup: The microstructure (Fig. 1) is mounted upside down on the compression wire and the microtrap is formed below the microstructure.

In the present experiment we use our apparatus as follows. We load the MOT within 20 s from a pulsed thermal source [24] (“dispenser”) that is mounted at a distance of 50 mm from the MOT. The dispenser is heated by a 12 s long current pulse of 7 A. After the current pulse the MOT is operated for another 8 s. During this time the vacuum recovers and a trap lifetime of 100 s is achieved. We collect up to 5×10^8 ⁸⁷Rb atoms with a six beam MOT configuration, with 20 mm beam diameter, and 20 mW laser power in each beam. After 5 ms of polarization gradient cooling we optically pump the atoms in the $|F = 2, m_F = 2\rangle$ hyperfine ground state and load a 70 μ K cold cloud of 2×10^8 atoms into the spherical quadrupole trap formed by the MOT coils at a field gradient of 45 G/cm. Next, the atoms are transferred into the Ioffe-type trap within 1 s and then cooled for 20 s by radio frequency evaporation to a temperature of 5 μ K. The phase space density increases from 10^{-7} to 10^{-3} , the peak density grows from 5×10^{10} to 1×10^{12} cm⁻³, and the elastic collision rate eventually reaches 60 s⁻¹. The precooled ensemble is now adiabatically compressed from the large volume Ioffe-type trap into the microsurface trap as described above (Fig. 3a). The compression is completed by inverting the current in the compression wire and the atoms are now confined

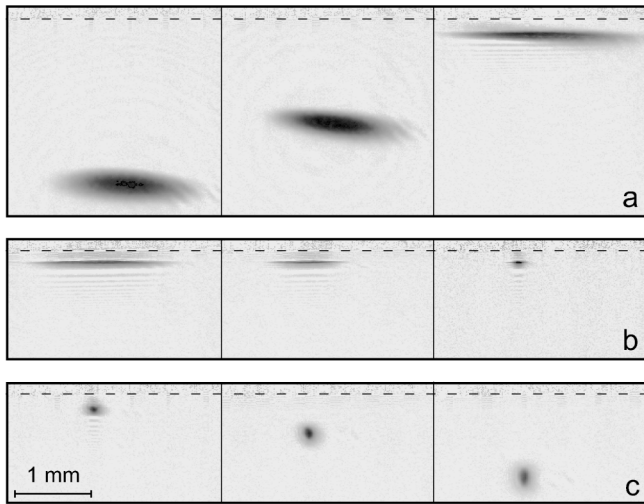


FIG. 3. Absorption images of the compression and the final cooling stage. The dashed line indicates the surface of the microstructure. (a) Transfer and compression of the Ioffe-type trap into the microtrap. (b) rf cooling in the microtrap. The image on the right side shows the condensate in the trap. (c) Release of the condensate. The images are taken after 5, 10, and 15 ms time of flight.

in the final trap for condensation. Best conditions for condensation are achieved with a current of 2 A in the microstructure and -10 A in the compression wire which corresponds to trap frequencies of $\omega_r = 2\pi \times 840$ Hz and $\omega_a = 2\pi \times 14$ Hz. The trap minimum is then located at a distance of $270 \mu\text{m}$ from the surface. During transfer and compression the radio frequency is turned off. The compression heats the atomic cloud to $35 \mu\text{K}$ and boosts the elastic collision rate up to 600 s^{-1} . By now ramping the radio frequency from 10 to 1 MHz within 7 s the phase transition occurs and Bose-Einstein condensation is achieved (Fig. 3b).

The properties of the condensate have been determined by fitting absorption images taken after 20 ms time of flight (Fig. 4). For a pure condensate we obtain a chemical potential $\mu/k_B = 380$ nK, a density $n_0 = 1 \times 10^{15} \text{ cm}^{-3}$, and a number of atoms $N_0 = 400\,000$. We derive a critical temperature of 900 nK for 1×10^6 atoms. The lifetime of the condensate is limited by three body collisions [25] to 100 ms. After relaxation of the trapping potential the lifetime is increased to 1 s. We do not observe any heating and applying a radio frequency shield has no effect. Further compression of the condensate into the microtrap leads to enhanced three body collisions and loss of the condensate. To optimize the number of atoms which can be loaded into a magnetic waveguide it will be important to study the collision properties of the condensate in strongly anisotropic traps and quasi-one-dimensional situations.

For further experiments, an even steeper trapping potential can be achieved with the microstructure by inverting the currents in the outer conductors. Then, the bias field is formed by the outer conductors alone and no external

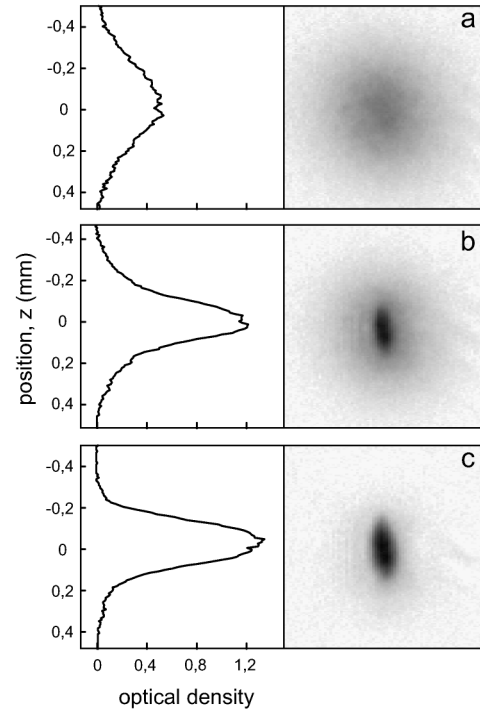


FIG. 4. Absorption images of the condensation. The images are taken after 20 ms time of flight at different temperatures. The left part of the picture shows a vertical scan through the middle of the cloud. Temperature, number of atoms, density, and the chemical potential are determined by fitting the scans. The oscillation frequencies of the trap are $\omega_r = 2\pi \times 840$ Hz and $\omega_a = 2\pi \times 14$ Hz. (a) Thermal cloud: $T = 970$ nK, $N = 1 \times 10^6$, $n_0 = 2 \times 10^{14} \text{ cm}^{-3}$. (b) Thermal cloud and condensate fraction: $T = 730$ nK, $N = 7.5 \times 10^5$, $N_0 = 2 \times 10^5$, $n_0 = 7 \times 10^{14} \text{ cm}^{-3}$, $\mu/k_B = 285$ nK. (c) Almost pure condensate: $T < 500$ nK, $N = 5 \times 10^5$, $N_0 = 4 \times 10^5$, $n_0 = 1 \times 10^{15} \text{ cm}^{-3}$, $\mu/k_B = 380$ nK.

field is required. In this configuration the magnetic field gradient exceeds $500\,000 \text{ G/cm}$ at the maximum possible current densities. With a longitudinal offset field of 1 G, the radial curvature of the magnetic field modulus amounts to $2.5 \times 10^{11} \text{ G/cm}^2$. For ^{87}Rb atoms trapped in the $|F = 2, m_F = 2\rangle$ ground state this corresponds to a radial oscillation frequency of $\omega_r = 2\pi \times 600\,000$ Hz. Our microtrap combines the advantage of a deep magnetic trapping potential with the possibility to vary the ratio of the oscillation frequencies over a wide range. This offers a promising testing ground for investigations of phase transition in highly anisotropic traps that is in the focus of present theoretical and experimental work [26].

In summary, we have demonstrated that Bose-Einstein condensation is possible in a surface microtrap with a large number of atoms (4×10^5). The *in vacuo* trap design is compatible with UHV requirements ($p < 2 \times 10^{-11}$ mbar) where the lifetime of the atomic cloud exceeds 100 s. We have shown that a commercially available alkali dispenser can be effectively used as pulsed thermal source for rubidium atoms. This represents an

attractive alternative to sophisticated double-MOT or Zeeman-slower systems. We have introduced a novel magnetic transfer scheme which adiabatically transforms a large volume spherical quadrupole potential into the geometry of the small sized parabolic microtrap with 100% efficiency. The evidence of Bose-Einstein condensation in a microtrap opens a wide range of possibilities for investigations of coherence phenomena in waveguides and atom optical devices as well as for studies of different regimes of the quantum degeneracy.

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Note added in proof.—In a similar experiment a group in Munich has also achieved Bose-Einstein condensation in a magnetic surface trap [27].

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