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Miniaturized magnetic guide for neutral atoms

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Abstract. We describe the principle and realization of a miniaturized magnetic guide for neutral atoms. The magnetic guide in our experiment is formed by a micrometer-sized current-carrying wire which is attached to a second, thick wire. The conductors are electrically insulated from each other. The combined magnetic field of both conductors provides an approximately linear trapping potential which establishes a magnetic guide along the surface of the thin wire. The miniaturized waveguide is filled with rubidium atoms from a magneto-optical trap (MOT) by first loading the atoms into a spherical magnetic quadrupole trap which is subsequently transformed into the linear potential of the waveguide. As thermal source for Rb atoms we use an alkali metal dispenser which is located close to the center of the MOT. This novel method is compatible with ultrahigh vacuum conditions and we achieved lifetimes of the magnetically trapped atoms up to 100 s.

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The experimental success in the preparation of a Bose–Einstein condensate in the mid-90s [1–3] has motivated a large number of experiments concerning the physical properties of ultracold atomic ensembles in the regime of quantum degeneracy. In these experiments the atoms are trapped in a shallow harmonic potential with vibrational frequencies of up to several hundred Hz. The related energy separation is smaller than the mean field interaction energy between the atoms and thus the center-of-mass motion of a single atom is only marginally affected by the trapping potential. If one succeeds in building steep traps with high oscillation frequencies a new regime may be entered where the atomic motion is quantized due to strong localization. Particularly interesting is a "waveguide" geometry with strong lateral confinement and a quasi-free motion along the third dimension parallel to the symmetry axis of the guide. Such guides have been proposed by Weinstein and Libbrecht [4] and it seems conceivable to reach transverse oscillation frequencies of up to several MHz. Even moderate cooling by optical means or evaporative methods is then sufficient to freeze out the transverse motion and to create a quasi-one-dimensional gas. As the direct analog to optical single-mode fibers such a waveguide for atomic de Broglie waves would open a new field of fascinating physics such as integrated atom optics and interferometry, one-dimensional quantum gases and Luttinger liquids, and even novel versions of quantum gates.

A quantum waveguide for neutral atoms requires very high magnetic field gradients which can not be realized with conventional, even superconducting, current coils. A very promising approach, however, is the use of miniaturized magnetic-field-generating elements. The first progress in the development of such magnetic microtraps was by Weinstein and Libbrecht [4] who proposed a planar design for a magnetic guide for neutral atoms made of miniaturized current loops. With such structures it should be possible to generate magnetic-field gradients larger than $10^6\,\mathrm{G/cm}$. In the following, different schemes to involve magnetic-field elements for the trapping and guiding of neutral atoms have been reported [5–9]. Experimentally, a first microtrap for neutral atoms was realized with a ferromagnetic needle in combination with a permanent magnet, and a set of coils [10]. This setup forms a spherical quadrupole trap with a field gradient, that can be smoothly varied over a wide range which allows for an efficient loading scheme into the microtrap. With attainable magnetic-field gradients of $3\times10^5\,\mathrm{G/cm}$ the density of the trapped atoms (^{7}Li) could be adiabatically increased by a factor of about 275. The operation principle of a linear magnetic guide has first been demonstrated with a combination of micro-sized copper wires and a pair of anti-Helmholtz coils [11]. In the present article we give a detailed description of this experiment including a quantitative analysis of the loading scheme which forms the heart of the experiment and has some significance for the design of compact magnetic traps in general. We also report on new results concerning the use of an alkali metal dispenser as thermal source for rubidium atoms. It turned out that this compact and almost ideal source is compatible with long magnetic storage times ($>100\,\mathrm{s}$) and ultrahigh vacuum conditions in the range of 10^{-11} mbar.

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The article is organized as follows. We describe the experimental implementation of the magnetic guide followed by a qualitative description of the loading scheme. This mechanism is based on a variable magnetic-field geometry which is designed to adiabatically shift the atoms into the magnetic guide. At one stage during this transformation an intermediate trap with an Ioffe-type geometry is formed. As a by-product of our magnetic guiding experiment one obtains a uniquely simple realization of an Ioffe-type trap which provides a striking alternative to the sophisticated trap designs that are commonly used in conventional trapping experiments. Thus, the third section is devoted to an analytic description of the loading scheme and the intermediate Ioffe trap. The experimental results are reported in the following section and, finally, we present recent data for the storage time obtained with an alkali dispenser at ultrahigh vacuum.

1 Realization and loading of the magnetic guide

A miniaturized magnetic guide is typically based on a linear quadrupole field (with the symmetry axis parallel to the z axis) which may be combined with a homogeneous offset field in z direction in order to prevent Majorana spin-flips as the dominant loss mechanism in a spherical quadrupole trap [12]. In our setup the linear quadrupole field is provided by the combination of the circular magnetic field of a micro-sized conductor with a homogeneous bias field which is oriented perpendicular to the axis of the conductor. The steepness of the trapping potential at the field minimum in a plane perpendicular to the z axis can be found by evaluating the superposition of the magnetic field of the wire and the homogeneous bias field. For the magnitude of the combined magnetic field at a given current I one obtains

$$|\boldsymbol{B}|(\varrho,\varphi) = B_0 \frac{\varrho}{\sqrt{\varrho^2+\varrho_0^2+2\varrho\varrho_0\cos\varphi}}\,, \tag{1}$$

where $B_0 = \frac{\mu_0}{2\pi}\frac{I}{\varrho_0}$.

Here, B_0 is the magnitude of the homogeneous offset field and ϱ_0 defines the distance between the centers of the wire and the linear magnetic quadrupole. Spherical polar coordinates are used with the origin at the center of the linear quadrupole trap and the angle φ defined relative to the axis defined by the wire and the trap center. Thus, the gradient of the combined magnetic field is

$$\left.\frac{\mathrm{d}|\boldsymbol{B}|}{\mathrm{d}\varrho}\right|_{\varrho=0} = \frac{\mu_0}{2\pi}\frac{I}{\varrho_0^2} = \frac{2\pi}{\mu_0}\frac{B_0^2}{I}\,. \tag{2}$$

It is independent of φ, which indicates a circular symmetric guide (to first order). This is to be expected from the vanishing divergence of the magnetic field and the translation symmetry of the setup. Experimentally, we use a thin wire which is rigidly connected to the surface of a thick wire that provides the offset field B_0, as shown in Fig. 1. The currents in the wires are oppositely oriented. Then, the waveguide for the trapped atoms is established by the linear magnetic quadrupole field that appears in the vicinity of the surface of the wire.

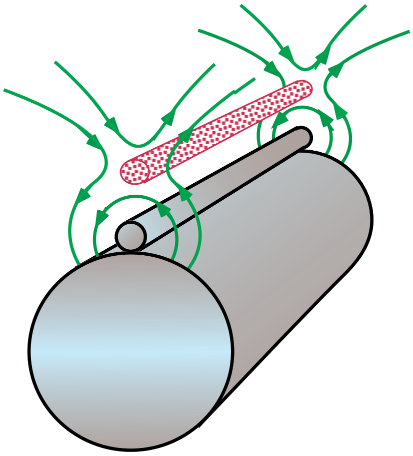

Fig. 1. Schematic drawing of the magnetic guide for neutral atoms. The guide consists of a thin wire which is cemented onto the surface of a second, thick wire. The combined magnetic field of the thin wire and the offset field of the supporting wire are shown

The magnetic guide is loaded with atoms from a spherical magnetic quadrupole potential which is generated by a pair of coils in anti-Helmholtz configuration (Fig. 2). For simplicity, let us first consider a single wire which is located parallel to the axis of symmetry of the pair of coils (z axis), as sketched in Fig. 2. In order to illustrate the loading scheme, we will discuss the geometry of the total magnetic field for a fixed current in the coils and a variable current in the wire. We regard the total magnetic field as a superposition of a spherical quadrupole and the field of an infinitely long and thin wire. At the center of the spherical quadrupole the field of the wire is approximately homogeneous and displaces the center of the quadrupole field slightly relative to the axis of symmetry. The shift occurs parallel to the local orientation of the magnetic field of the wire but in the opposite direction (positive y axis in Fig. 3). Vice versa, one obtains a similar field geometry at the location of the wire, where the spherical quadrupole field can be approximated to be homogeneous and parallel to the x axis. Close to the axis of the wire the radial components of the total magnetic field can therefore be described as a linear quadrupole field. The z component of the total field is entirely given by the spherical quadrupole field of the coils. In the following, we will term the field close to the wire as *linear* quadrupole field in contrast to the initially spherical quadrupole field of the coils which is termed *central* in Fig. 3.

If the electric current in the wire is increased, the points of zero magnetic field, i.e. the trap minima move towards each other within the x, y plane and finally merge, as shown schematically in Fig. 3. The path on which the two minima approach each other can be easily derived from a simple geometrical argument. The total magnetic field vanishes where both the magnetic field of the wire and the field of the pair of coils just compensate. This requires a parallel and opposite orientation of both magnetic fields. This condition is fulfilled, if the straight line between the origin and the point of zero magnetic field (A in Fig. 3) is perpendicular to the line B between the position of the wire and the point of a zero magnetic field. Obviously, the two lines define a rectangular triangle in the xy plane. At varying electric currents in the wire the resulting path for the point of a zero magnetic field is therefore given by the principle of the circle of Thales.

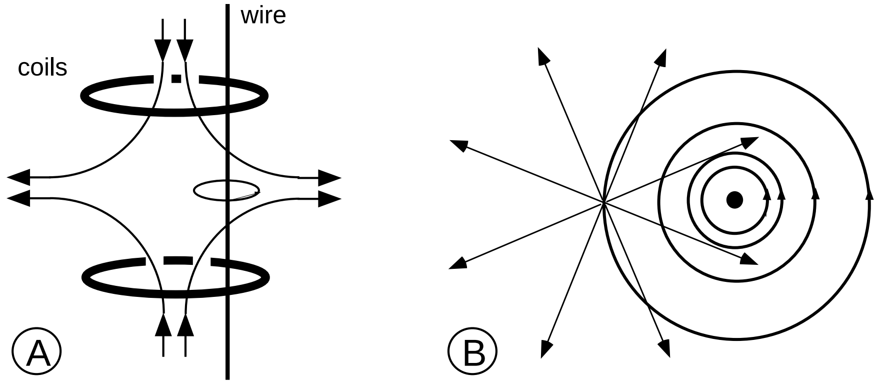

Fig. 2. Principle of the experimental implementation of the wire trap (*left*) and top view on the magnetic field components cut through a plane perpendicular to the axis of symmetry of the setup (*right*)

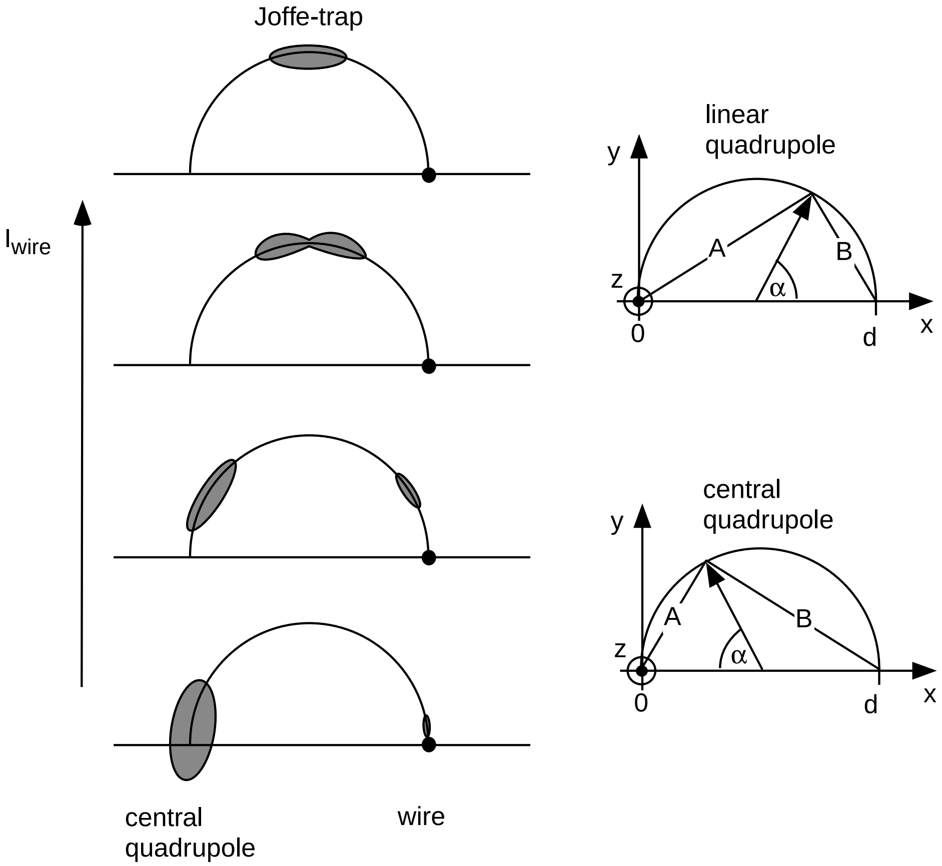

Fig. 3. Schematic drawing of the movement of the center of the magnetic field of both the spherical quadrupole and the wire trap with increasing current in the wire. At a critical current the centers merge to form an Ioffe-type trap

If both magnetic quadrupole fields merge, the linear components of the fields compensate along a straight line which is oriented parallel to the x axis across the zero-field center of the trap. The absolute value of the magnetic field in x direction has a shape of a parabola, according to the next dominating term in the multipole expansion of the total magnetic field. If the electric current in the wire is increased, the additional field component generated by the wire can be decomposed into the x and y directions. The y component moves the minimum value of the magnetic field towards positive y direction. In contrast, the x component superposes with the parabolic course of the magnetic field in x direction and lifts the otherwise vanishing value of the magnetic field at the center of the merged traps. The important result of this effect is a non-vanishing value of the magnetic field minimum which completes the geometry of an Ioffe-type trap. The transfer to the guide is now accomplished by first loading the central quadrupole trap and merging it with the empty linear quadrupole. Then, the current in the wire is slowly reduced which separates the two traps. Part of the atoms are transferred back to the central trap, however, a significant part are also transferred to the magnetic guide near the wire.

Since the critical current in the wire, which is necessary to merge the magnetic quadrupole fields to an Ioffe-type trap, turns out to be of the order of 10 A, we have added an additional wire parallel to the miniaturized wire. This auxiliary wire carries the high electric current during the loading procedure and has a several times larger diameter than the thin wire. During the transfer of the atoms which is exclusively mediated by the variation of the electric current in the thick wire, the current in the thin wire remains constant.

After the transfer, the thick wire can be used to provide the bias field B_0 and thus to increase the gradient of the magnetic guide. Finally, the current in the thick wire is slowly raised, but now in the opposite direction. The generated magnetic field adds to the bias field provided by the spherical quadrupole of the coils and shifts the center of the guide towards the surface of the thin wire. This can be compensated by simultaneously increasing the electric current in the thin wire. Since the magnetic field magnitude grows, the trapping potential is deepened and the gradient of the magnetic field is enhanced. In this situation, the influence of the magnetic field of the coils can be neglected with respect to the confinement of the trapped atoms in the plane perpendicular to the symmetry axis of the central magnetic quadrupole field. The electric current in the upper coil can be switched off, such that the axial confinement of the atoms is provided by the field of gravity and the residual magnetic field of the lower coil alone. Now, the electric current in the upper coil is turned on again, but poled in the opposite direction and the wire trap can be adiabatically transformed into the geometry of a Ioffe trap.

2 Quantitative description of the loading scheme

In this section we will investigate in general the properties of a magnetic guide for neutral atoms which is built up by the fields of a magnetic quadrupole and an infinitely extended wire carrying a current I and oriented parallel to the axis of symmetry of the magnetic quadrupole (z axis). The distance between the origin of the z axis and the wire is d. The extension of the wire in the x, y plane will be neglected. The superposition of the central quadrupole and the field of the wire is given by

$$\boldsymbol{B}(x,y,z) = \frac{I\mu_0}{2\pi r^2}\begin{pmatrix} -y \\ x-d \\ 0 \end{pmatrix} + \frac{1}{2} b_z \begin{pmatrix} x \\ y \\ 2z \end{pmatrix} . \tag{3}$$

Here, $r^2 = (x-d)^2 + y^2$ and the absolute value of the gradient of the quadrupole field in z direction is denoted by $\mathrm{d}B_z/\mathrm{d}z = b_z$. The coordinates of the points where the magnetic field is zero obeys the condition

$$x\left(\frac{r}{q}\right)^2 - y = 0,\; y\left(\frac{r}{q}\right)^2 + x - d = 0 \quad \text{and} \quad z = 0\,, \tag{4}$$

where the parameter $q \equiv ((\mu_0 I)/(\pi b_z))^{1/2}$ describes the variation of the field geometry as the current in the wire is varied. During the transfer the value of q varies between 0 and d. After transformation into cylindric polar coordinates we obtain from the second equation in (4) the relation

$$\sin\alpha = \frac{2q^2}{d^2} = \frac{I}{I_0}\,, \tag{5}$$

$$\text{where} \quad I_0 = \frac{1}{2}\frac{\pi}{\mu_0} b_z d^2\,.$$

For the definition of α see Fig. 3. At $I = I_0$, α amounts to 90°, and the centers of the two quadrupole traps merge and form a single Ioffe-type trap. One obtains the curvature of the trapping potential in x direction and the field gradient in y and z directions from expanding the field around the trap minimum at $x = d/2$ and $y = d/2$. By keeping only the first non-vanishing terms the expansion yields

$$\frac{\mathrm{d}|\boldsymbol{B}|}{\mathrm{d}y} = \frac{\mathrm{d}|\boldsymbol{B}|}{\mathrm{d}z} = b_z,\quad \frac{\mathrm{d}|\boldsymbol{B}|}{\mathrm{d}x} = 0, \quad \text{and} \quad \frac{\mathrm{d}^2|\boldsymbol{B}|}{\mathrm{d}x^2} = \frac{3b_z}{d}\,. \tag{6}$$

Inspection of (6) shows that the gradient of the magnetic field is equal in y and z directions and has the same value as the gradient of the spherical quadrupole in z direction. The curvature of the magnetic field in x direction is proportional to d^{-1} and may be increased by shifting the wire closer to the coils.

The depth of the wire trap is determined by the absolute value of the magnetic field at the saddle point between the two quadrupole fields. The necessary conditions for the existence of a saddle point can not be solved analytically. Nevertheless, one can find a set of coordinates x_s and y_s for the saddle point which obviously fulfil the necessary condition. In this ansatz, the coordinates of the saddle point are $x_\mathrm{s} = d - (q/\sqrt{2})$ and $y_\mathrm{s} = q/\sqrt{2}$. Hence, the saddle point moves along a straight line between the position of the Ioffe trap and the wire, if the current I is varied. The distance between the saddle point and the wire is given by the parameter q. The calculation of the magnetic field value at the saddle point results in

$$|\boldsymbol{B}| = \frac{1}{2} b_z \left(d - \sqrt{2}q\right)\,, \tag{7}$$

i.e., the depth of the trap potential increases linearly with decreasing distance of the saddle point from the wire. The maximum value of the trap depth is obtained, if the current in the wire vanishes. This value corresponds to the field strength of the spherical quadrupole at the location of the wire. In a ‘real’ trap the diameter of the wire is finite and the atoms will touch the wire at a certain maximum compression.

If one substitutes the homogeneous magnetic field B_0 given in (1) by the absolute value of the spherical magnetic quadrupole field at the location of the wire trap, the distance between the centers of the wire and the linear magnetic quadrupole ϱ_0 is given by $\varrho_0 = q^2/d$. The slope of the magnetic field modulus at $\varrho = 0$ can be expressed as

$$\left.\frac{\mathrm{d}|\boldsymbol{B}|}{\mathrm{d}\varrho}\right|_{\varrho=0} = \frac{b_z}{2}\frac{d^2}{q^2} = \frac{b_z}{2}\frac{d}{\varrho_0}\,, \tag{8}$$

i.e. the slope is, to first order, independent of the angle φ and increases proportionally to the reciprocal distance ϱ_0^{-1}. For a physical, extended wire the slope cannot exceed the limit, where the center of the trap merges with the surface of the wire, i.e. at $\varrho_0 = r_0$ (r_0 is the radius of the physical wire).

3 Waveguide experiments

The waveguide experiments were carried out in a stainless-steel ultrahigh vacuum apparatus, pumped by a turbo molecular pump in order to achieve a base pressure of 1×10^{-9} mbar. This is sufficient for demonstrating the principle of operation as described below. However, in future experiments a long trapping time is desirable. We, thus, have recently replaced the turbo molecular pump by an ion getter pump and added a titanium sublimation pump with an integrated copper shield that can be cooled with liquid nitrogen. With these measures the maximum pressure during the experiments has routinely been 3.5×10^{-11} mbar without engaging the liquid nitrogen cooling and was not measurably affected by the excess of Rb vapor during the loading of the magneto-optical trap (MOT). The remarkable insensibility of the base pressure was mediated through the use of a pulsed alkali metal dispenser which allows for fast loading the MOT and long trapping times after the loading has been completed. The alkali metal dispenser consists of a very compact steel container which is filled with an alkali chromate complex [14]. By a resistive heating of the dispenser the alkali metal is thermally activated at a temperature of about 400 °C and set free through a small slit on one side of the container. The dispenser has been located at a distance of 26 mm from the center of the MOT. The direct impact of thermal Rb atoms ejected from the dispenser into the center of the MOT has been obstructed by a screening wire of about 1 mm diameter which was mounted at a distance of 5 mm from the dispenser outlet. At first use the dispenser has to be carefully degassed with increasing operation current starting from 2 A. During this procedure the pressure must not increase above 10^{-8} mbar in order to avoid contamination of the getter material. The advantages of an alkali metal dispenser for experiments of magneto-optical trapping of neutral atoms have been recently discussed elsewhere [13]. In the last section of this article, we will present more recent data concerning the properties of the dispenser.

The trap setup consists of a pair of coils (56 loops of Capton-insulated copper wire of 0.6 mm diameter) mounted inside the vacuum chamber. The inner diameter, length, and distance of the coils are 20 mm, 10 mm, and 15 mm, respectively. The gradient of the magnetic quadrupole field generated by the pair of coils in anti-Helmholtz configuration is calculated to be 25.5 G/cm at 1 A and increases proportionally to the current in the coils. Up to a current of 2 A the pressure in the vacuum chamber is not affected during the run of the experiments by thermal heating of the coils. The wire trap has a length of 40 mm and is located parallel to the axis of symmetry of the pair of coils at a distance of 4 mm (for an overview of the trap setup, see Fig. 4). The wire trap consists of a thin copper wire of 90 µm diameter which is cemented onto the surface of a 1.4-mm-thick copper rod. The ceramic glue mediates a good thermal contact between the thin wire and the rod which therefore acts as a heat drain. The maximum electric current in the thin wire connected to the rod is about 4 A, in contrast to only 0.5 A in the case of an unsupported wire. However, at a current exceeding 2.5 A we observe degradiation of the vacuum. In this setup, the axial gradient b_z exceeds 50 G/cm. The distance between the small wire and the center of the pair of coils is about a few mm and we achieve a curvature of the Ioffe trap potential of 383 G/cm^2. The maximum gradient that can be realized in the vicinity of the surface of the wire in our trap geometry has been calculated as 2500 G/cm.

Two frequency-stabilized diode lasers [15] provide the light for the trapping and cooling as well as for repumping the ^{87}Rb atoms from the lower hyperfine state ($F = 1$). The cooling laser (22.0 mW) near 780.244 nm has been slightly detuned from the $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ transition. The light of the repumping laser (16.5 mW) has been combined with that of the cooling laser to repump Rb atoms from the $F = 1$ to the $F = 2$ ground-state hyperfine level. The laser beams could be switched by a system of mechanical shutters within 50 µs. We monitored the spatial distribution of the trapped atoms by illuminating the atomic cloud with a collimated laser beam and imaging the resonant absorption with a charge-coupled device (CCD) camera.

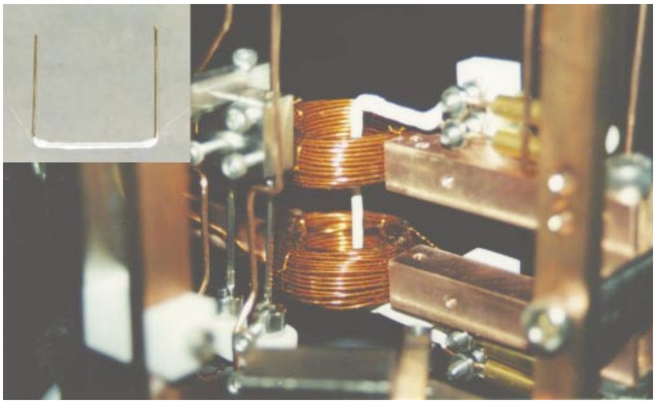

Fig. 4. Photograph taken from the experimental setup. The wire trap (close view in the inset) consists of a 90-µm-thin copper wire which is cemented on the surface of a rod of about 1.4 mm diameter. The white color of the rod is due to the ceramic glue which mediates a good thermal contact between the thin wire and the rod. The coils are mounted with the symmetry axis parallel to the wire

The MOT is formed by six counter-propagating laser beams with a diameter of 6 mm and 2 mW power each. About 2×10^7 atoms are loaded into the MOT within 4 s. The dispenser is set to a constant current of 4 A. With the diameter of the atomic cloud of about 0.75 mm we have estimated the density of the atomic ensemble to 9×10^{10} atoms/cm^3. The electric current in the pair of coils was thereafter increased from 0.7 to 2 A, which corresponds to a rise of the magnetic field gradient from $b_z = 18$ G/cm to $b_z = 51$ G/cm along the axial direction of the magnetic field. The re-pumping laser was blocked 1 ms after the cooling laser beams had been switched off to pump the atoms into the $F = 2$ state, in which the absorption imaging was performed. By an adiabatic transport of the magnetically trapped atoms from the spherical quadrupole field into the linear quadrupole field geometry, we transferred about 14% of the atoms into the magnetic wire trap at a temperature of 39 µK.

4 Transfer into the atomic guide

The data described in the following section have been obtained in the previous experimental setup [11] at a base pressure of 1×10^{-9} mbar. An absorption image of the magnetically trapped atoms is shown in Fig. 5. The image was taken 100 ms after the laser beams had been blocked. The integrated absorption amounts to 24% in the center of the atomic cloud, as denoted in Fig. 5. The asymmetric shape of the atomic cloud in the negative z direction is due to the influence of gravity. From the experimental data we calculate a number of 4.1×10^6 atoms which are magnetically trapped and an atomic density of 6.7×10^9 atoms/cm^3 in the center of the trap compared to 9×10^{10} atoms/cm^3 in the center of the magneto-optically trapped atomic ensemble. From the asymmetry of the cloud shape it is possible

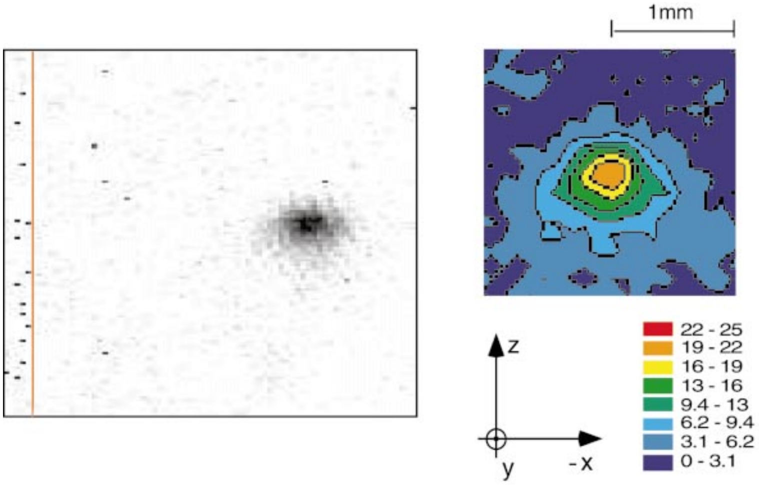

Fig. 5. Absorption image from the cloud of ^{87}Rb atoms which are magnetically trapped after preparation in a magneto-optical trap (*left*). The surface of the wire on the left part of the image is illustrated by the red line. The integrated absorption in percent derived from the absorption image is shown *right*

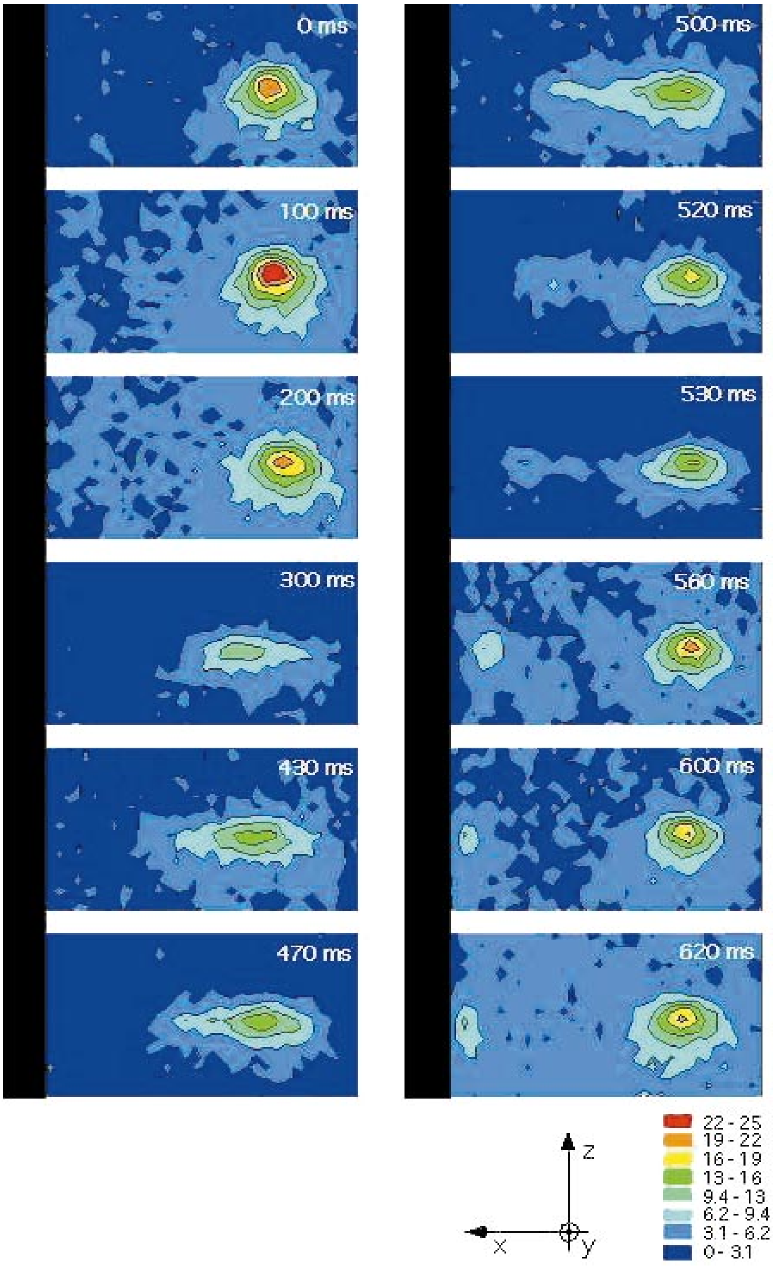

Fig. 6. Transfer of magnetically trapped atoms into the wire trap. The data have been calculated from a sequence of absorption images which has been taken subsequently during the transfer. The wire is located in the left part of the images

to find the hyperfine state of the trapped atoms. Atoms in a state with a larger g-factor are trapped in a steeper potential and are therefore less shifted by the gravitational field. The adaptation of the theoretical absorption profile on a central cut through the experimental data along the x axis yields an average magnetic momentum of the trapped atoms of $\mu = 4,43 \times 10^{-24}\,\mathrm{A\,m^2} \approx 0.48\,\mu_\mathrm{B}$. Hence, the atoms are predominately trapped in the $F = 2$, $m_F = 1$ Zeeman level of the ground level. The theoretical absorption profile has been obtained by integrating the resonant absorption of a thermalized atomic cloud along the observation axis. From the magnetic momentum and the 'thermal radius' of the atomic cloud $L = (k_\mathrm{B}T)/(\mu b_z) = 0.187\,\mathrm{mm}$ we calculate a temperature of the magnetically trapped atomic ensemble of $32.0\,\mu\mathrm{K}$.

The data in Fig. 6 have been extracted from a sequence of absorption images subsequently taken during the transfer of the magnetically trapped atoms into the wire trap. Since the method of absorption imaging destroys the trapped atomic ensemble, the experiment has been repeated several times to image the trapped atoms at different intervals after the transfer had been started. The transfer has been completed after 640 ms when the electric current in the thick wire rose from 0 to 9.1 A and was turned off afterwards. The current has been varied such that the acceleration and the deceleration of the trap centers occur at a constant value of $0.06\,\mathrm{m/s^2}$ to avoid non-adiabatic heating. This is a conservative value and has not yet been optimized. The current in the thin wire was kept constant at 1.4 A. Since the observation axis of the CCD camera was tilted by 49° with respect to the y axis, the atomic cloud seems to move only a little within the first half of the transfer. The maximum current in the thick wire of 9.1 A has been reached after 320 ms, when the trap potentials have merged to form an Ioffe trap. As is obvious from the sequence of the absorption images, only a fraction of the initially magnetically trapped atomic ensemble is transferred to the wire trap. By an analysis of the absorption data taken at 620 ms, we find that from 4.1×10^6 initially trapped atoms a number of 6.9×10^5 have been transferred into the wire trap. After the transfer, the atomic density in the wire trap has increased by a factor of 1.2 as compared to the initial value inside the central quadrupole trap. Similarly, the temperature has increased by a factor 1.23. Taking into account the experimentally derived decay parameter of $\gamma = 0.42\,\mathrm{s^{-1}}$ of the population inside the trap, the density of the atomic cloud decreases exponentially to $5.0 \times 10^9\,\mathrm{atoms/cm^3}$ in 620 ms. After correcting for collisional losses the phase space density in the wire trap has thus been reduced only by a factor of 1.22 with respect to the initially trapped atomic ensemble.

5 Alkali dispenser in ultrahigh vacuum

We now focus on the performance of the rubidium dispenser at a pressure of $3.5 \times 10^{-11}\,\mathrm{mbar}$. Different from the initial setup, the base pressure in the vacuum system has been improved by two orders of magnitude and the power of each MOT laser beam of 10 mm diameter was enhanced to 10 mW. Furthermore, an efficient screening of the alkali dispenser outlet has been installed. It consists of a thin wire (1.2 mm) in front of the Rb source which shields the magneto-optically trapped atoms from direct impact of thermal Rb atoms. The trapping region of the cooling beams, however, is only a little affected by the screening wire. With this improved setup, we collected up to 5×10^7 atoms in the MOT during a 5-s-long current pulse of dispenser current with a peak value of 8 A. After blocking the beams of the MOT the current in the coils is turned off and the atoms are pumped into the $F = 2$, $m_F = 2$ state of the ground-state hyperfine multiplet with a short pulse ($600\,\mu\mathrm{s}$) of circularly polarized light. After rapidly restoring the magnetic quadrupole field ($b_z = 38\,\mathrm{G/cm}$) about 45% of MOT population is magnetically trapped. About 55% of the magnetically trapped atoms then decay within 2 s. We attribute this fast decay to inelastic collisions which deplete the population in the ($F = 2$, $m_F = 1$) Zeeman level. The remaining atoms are in the double spin-polarized ($F = 2$, $m_F = 2$) state. The fast decay occurs also if a 25 s delay after turning off the dispenser current is introduced between the loading of the MOT and the transfer into the magnetic trap. This excludes a possible influence of the dispenser on the rapid initial decay. Furthermore, the delay ensures that all current-carrying elements of the dispenser source had cooled down and that the local Rb partial pressure in the trapping region has been equilibrated.

After the rapid decay, the fraction of magnetically trapped atoms in the ($F = 2$, $m_F = 2$) state decreases very slowly, as plotted in Fig. 7. This slow decay, however, cannot be described by a simple exponential law. With an ansatz of a time-dependent decay rate $\exp(-t/\tau(t))$ we find that the lifetime of the atomic ensemble in the trap is not constant but grows with increasing t up to about 100 s, as shown in the inset of Fig. 7. The result is surprising and might be associated with the outgassing of either the current-carrying elements or the alkali metal dispenser itself. Nevertheless, a full analysis of the effect requires further experimental data.

The above experiment demonstrates that an alkali metal dispenser can be easily used as an efficient and convenient atomic source in a simple experimental setup for the cooling and trapping of neutral atoms. It is important to emphasize that the ultrahigh vacuum is not affected by the use of the alkali metal dispenser which is an essential experimental condition for the long lifetimes of the trapped atomic ensemble achieved with the current setup. Hence, the dispenser provides, for example, an alternative to sophisticated double-MOT systems [16].

6 Summary and conclusion

We have described an experimental approach to set up and load a miniaturized guide for neutral atoms on the surface of a wire. This setup has been the first implementation of a magnetic trap of the Libbrecht type and combines the magnetic fields of a current-carrying micro-scaled wire on the surface of a second conductor. Both fields compensate along an axis parallel to the two conductors and build up a linear quadrupole potential. The magnetic waveguide is loaded with neutral Rb atoms by means of adiabatic transport and compression. The transfer scheme starts with an ensemble of cold Rb atoms from a magneto-optical trap which is transferred into the magnetic quadrupole potential of the wire trap. We have achieved a population in the miniaturized atomic guide of 6.9×10^5 atoms with the maximum

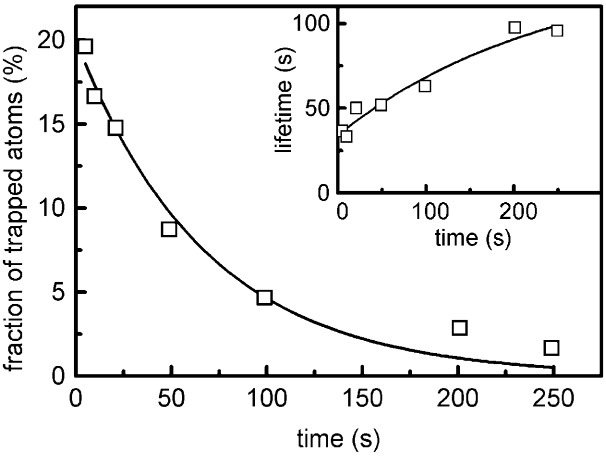

Fig. 7. Fraction of magnetically trapped atoms normalized to the number of atoms in the magneto-optical trap. The experimental data (*squares*) are compared with a simple exponential decay law (*solid line*). The lifetimes of an ensemble of ^{87}Rb atoms have been calculated under the assumption of a time-dependent time constant for the exponential decay of the atomic cloud (*inset*). The *curve* represents an exponential fit to the experimental data

atomic density of $6.0 \times 10^9\,\mathrm{atoms/cm^3}$ at a temperature of 39 μK. In this trap geometry the gradient in the plane perpendicular to the axis of symmetry of the magnetic quadrupole field could be increased, in principle, from 25 to 3000 G/cm which corresponds to an enhancement of the collision rate from $0.25\,\mathrm{s^{-1}}$ by a factor of 70 to $17.5\,\mathrm{s^{-1}}$. Here, high magnetic-field gradients are achievable at convenient electrical currents in the conducting elements, in contrast to conventional, i.e. non-miniaturized, trap geometries [17, 18]. A collision rate of the above magnitude and a lifetime of the experimentally achieved value are the typical starting values for the evaporative cooling in Bose–Einstein condensation experiments.

Hence, the current setup provides not only a novel experimental approach for the preparation of degenerated atomic ensembles, but opens also a promising new testing ground for the guiding and manipulation of neutral atoms by means of miniaturized magnetic elements. For example, it would be interesting to approach neutral atoms by means of magnetic forces to a surface in order to investigate the atom–solid interaction from a point of view where even no adsorption takes places. Miniaturized magnetic guides of a more complex geometry could be used to trap atomic ensembles in distinct sites above a surface. If a controlled transport of atomic ensembles or single atoms is possible, for instance in an optical cavity, new milestones in the implementation of quantum logic elements could be achieved. A new method to investigate the quantum physics and interaction of atomic ensembles could be the interference of two or more atomic clouds guided by miniaturized magnetic waveguides. Finally, miniaturized atomic waveguides provide an appealing tool for the generation of an one-dimensional quantum gas and the study of Luttinger liquids.

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