Guiding Neutral Atoms with a Wire

Johannes Denschlag, Donatella Cassettari, and Jörg Schmiedmayer
Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria

(Received 2 September 1998)

We demonstrate guiding of cold neutral atoms along a current carrying wire. Atoms either move in Kepler-like orbits *around* the wire or are guided in a potential tube *on the side* of the wire which is created by applying an additional homogeneous bias field. These atom guides are very versatile and promising for applications in atom optics. [S0031-9007(99)08635-4]

PACS numbers: 03.75.Be, 32.80.Pj, 39.10.+j, 52.55.−s

In atom optics [1] it is usually desirable to separate atoms as far as possible from material objects in order to obtain pure and isolated quantum systems. With cooling and trapping techniques [2] well established, there is now an interest in bringing the atoms close to material macroscopic objects. The proximity of the atoms to the object allows the design of tailored and easily controllable potentials which can be used to build novel atom optical elements.

In this Letter we demonstrate two simple and versatile atom guides that are based on magnetic trapping potentials created by a thin current carrying wire: the "Kepler guide" and the "side guide." In our experiments we study the transport of cold lithium atoms from a magneto-optical trap in these guiding potentials. We were able to measure scaling properties and extract characteristic atomic velocity distributions for each guide. The side guide is especially interesting because it can be miniaturized and combined with other guides to form mesoscopic atom optical networks.

We start with discussing the interaction of a neutral atom and a current carrying wire and then describe our guiding experiments.

Kepler guide.—The magnetic field of a rectilinear current I is given by

$$B = \frac{\mu_0}{2\pi}\,\frac{I}{r}\,\hat{e}_\varphi\,, \tag{1}$$

where $\hat{e}_\varphi$ is the circular unit vector in cylindrical coordinates. An atom with magnetic moment $\vec{\mu}$ experiences the interaction potential $V_{\text{mag}} = -\vec{\mu}\cdot\vec{B}$. In general the vector coupling $\vec{\mu}\cdot\vec{B}$ results in a very complicated motion for the atom. However, in our experiments the Larmor precession (ω_L) of the magnetic moment is much faster than the apparent change of direction of the magnetic field in the rest frame of the atom (ω_B). An adiabatic approximation can be applied and the motion is governed by a scalar $1/r$ potential. For $\vec{\mu}$ "parallel" to $\vec{B}$ ($\vec{\mu}\cdot\vec{B} > 0$), the atom is in its *high-field-seeking state,* and the interaction between the atom and the wire is attractive (see Fig. 1). Atoms in this state can be trapped and move in Kepler-like orbits around the wire [3–6].

Side guide.—Combining the field of the current carrying wire with a homogeneous magnetic bias field B_b perpendicular to the wire breaks the rotational symmetry resulting in unstable orbits for the strong field seeking atoms [7]. In addition the bias field has the effect of exactly canceling the circular magnetic field of the wire along a line parallel to the wire at a distance $r_s = (\mu_0/2\pi)(I/B_b)$. Around this line the magnetic field increases in all directions and forms a tube with a magnetic field minimum in its center. Atoms in the *low-field-seeking state* ($\vec{\mu}\cdot\vec{B} < 0$) can be trapped in this tube and guided along the wire as shown in Fig. 1b.

Our experiments investigating the Kepler guide and the side guide are carried out in the following four steps:

(a) First we load about 2×10^7 lithium atoms into a magneto-optic trap (MOT) [8,9], displaced typically 1 mm from a 50-μm thick and 10-cm long tungsten wire. The MOT is loaded at a distance to the wire in order to prevent trap losses due to atoms hitting the wire [10].

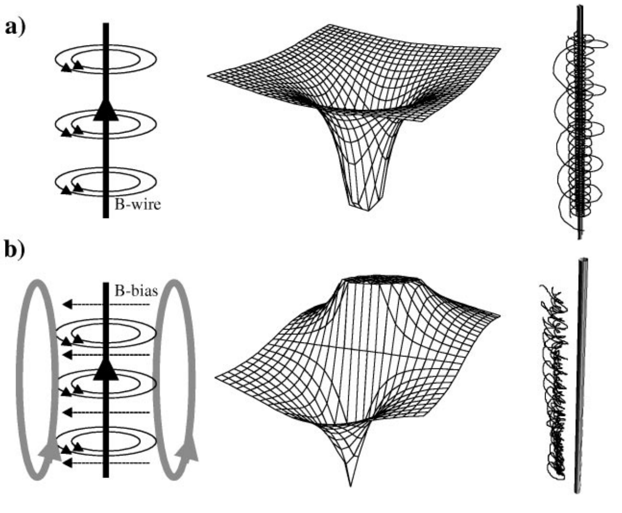

FIG. 1. Two configurations for guiding neutral atoms with a current carrying wire. The left graphs display the magnetic field configurations, the middle shows the corresponding guiding potentials, and on the right hand side typical trajectories of guided atoms are drawn. (a) Guiding atoms in their *high-field-seeking* state that circle in Kepler orbits *around* the wire. (b) Guiding atoms in their *low-field-seeking* state along a line of magnetic field minimum *on the side* of the wire.

0031-9007/99/82(10)/2014(4)$15.00

(b) After loading the trap we shut off the slower beam and shift the atoms within 5 ms to the position where they are loaded into the atom guide. This shifting is done by applying an additional magnetic offset field and moving the center of the magnetic quadrupole field, which defines the position of the MOT. Simultaneously the frequency and intensity of the trapping lasers are changed to control the size and temperature of the atom cloud [typically 1.6 mm diameter (FWHM) and $T \sim 200\ \mu$K which corresponds to a velocity of about 0.5 m/s].

(c) We then release the atoms from the MOT by switching off the laser light, the MOT magnetic fields, and the shifting fields within 0.5 ms. At this point the current through the wire (typically 1 A) and, if desired, a bias magnetic field is switched on within 100 μs. From then on the atoms move in the tailored guiding potential [11]. Starting from an initially well localized, unpolarized atom cloud the density distribution expands and changes shape according to the forces on the atoms. Only those atoms which are in the correct spin state can be trapped and guided.

(d) After a given guiding/trapping time, the spatial distribution of the atoms is measured by imaging the fluorescence from optical molasses [2] using a CCD (charge-coupled device) camera. For this the guiding fields (current through the wire and bias field) are switched off and molasses laser beams are switched on for a short time (typically <1 ms). Pictures are taken from above (looking in the wire direction) and from the side (looking onto the wire from an orthogonal direction). This allows one to study both the radial confinement and the guiding of the atoms along the wire.

Typical pictures of atoms orbiting around the current carrying wire (Kepler guide) and being guided on the side of the wire (side guide) are shown in Fig. 2.

The left set of graphs visually demonstrates loading and guiding of atoms with the Kepler guide: The atoms are released from the MOT at $t = 0$ at the center of the wire. Some fraction of these atoms will be bound by the guiding potential; the rest forms an expanding cloud that quickly fades away within about 15 ms. The bound atoms are guided along the wire corresponding to their initial velocity component in this direction. Consequently, a cylindrical atomic cloud forms around the wire that expands along the wire. For long guiding times the bound atoms leave the field of view, and the fluorescence signal of the atoms decreases. The top view images show a round atom cloud that is centered on the wire suggesting that atoms circle around the wire.

The graphs on the right hand side of Fig. 2 show atoms that are bound to the side guide after 20 ms of guiding time. The distance of the guide from the wire changes clearly with the current through the wire (1 and 0.5 A) as will be discussed later (see also Fig. 6).

The CCD pictures can be used for further analysis as illustrated in Fig. 3 for the Kepler guide. For this the CCD images are integrated yielding a projection of the density distribution of the atoms in a direction perpendicular to the wire. Figure 3a shows two such distributions: one corresponding to free expansion of the atomic cloud with no current through the wire. This yields a Gaussian distribution which is typical for atoms released from a MOT. The other one, corresponding to atoms interacting

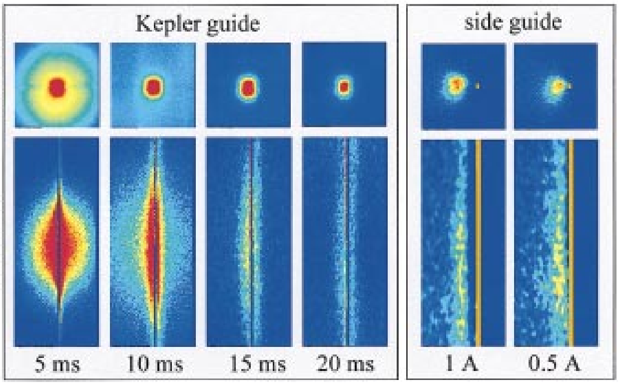

FIG. 2(color). Guiding of atoms along a current carrying wire. Pictures of the atomic clouds taken from above and from the side are shown. (left) Series of pictures illustrating the guiding of atoms in their *strong-field-seeking* state (Kepler guide) along a wire carrying a current of 1.2 A. For times shorter than 15 ms the expanding cloud of untrapped atoms is also visible. (right) By adding a bias field atoms in the *weak-field-seeking* state are guided *on the side* of the wire (20 ms guiding time). Choosing different currents through the wire (here 0.5 and 1 A) the distance of the side trap from the wire can be controlled. The location of the wire is indicated with an orange line (dot). The pictures show a 2-cm-long section of the wire that is illuminated by the trapping beams.

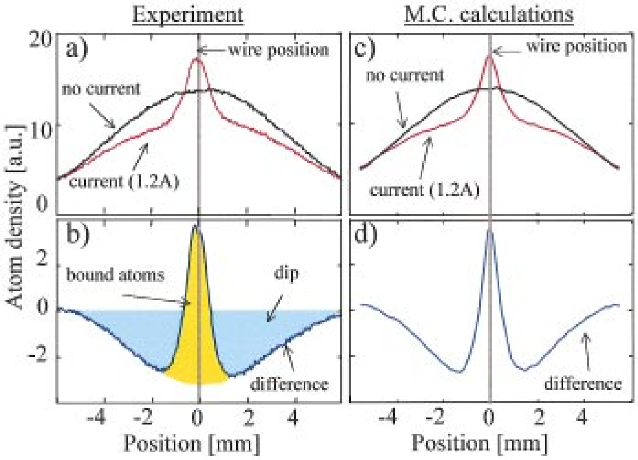

FIG. 3(color). Radial atomic density distribution for the Kepler guide after 7.5 ms of interaction time; (left) measurement; (right) Monte Carlo calculation. The upper graphs show the atomic distributions for a current of 1.2 A through the wire and without current (free expansion). The difference between the two distributions is shown below. The central peak is due to 2-dimensional trapping of atoms in the guide. The orange shaded area, determined by fitting the sum of two Gaussians to the data, is a measure of the number of trapped atoms.

with a current carrying wire, exhibits a pronounced peak centered around the wire which is due to trapped atoms orbiting the wire. The peak sits on top of the broad distribution of nontrapped atoms. In order to extract the effects of the magnetic guiding potential on the atomic cloud, the two curves are subtracted from each other (Fig. 3b). The peak of the trapped atoms now sits in a broader dip, which is caused by repulsion of atoms in low field seeking states from the wire and by the fact that atoms trapped around the wire are now missing from the expanding atomic cloud. Our experimental data agree well with numerical simulations of the atomic density distributions as shown in Figs. 3c and 3d.

From an analysis such as the one in Fig. 3 we can also extract the loading efficiency into these guides. In this specific experiment about 10% for atoms from an unpolarized atomic sample are loaded into a Kepler guide with 1 A current. This agrees well with our Monte Carlo (MC) calculations which predict 11% loading efficiency for the measured trap parameters of ~1.6 mm FWHM and $T \sim 200\ \mu$K (see solid line in Fig. 4). Using the same procedure we also measured the loading of the *side guide* to 4% for a 1 A current and a 2 G bias field, which is also in agreement with our MC calculations. This smaller loading efficiency is mainly due to the smaller depth and "size" of the used side guide potential. By optically pumping the atoms and better "mode matching" the temperature and the size of the cloud one can obtain loading rates of 40% and higher for both guides.

Figure 4 shows how the number of detected atoms, bound to the Kepler guide, decreases as a function of guiding time. The data are given as the fraction of the total number of atoms of the MOT. The decrease of the observed atom number is mainly due to the expanding atomic cloud that gradually leaves the detection region given by the 2 cm diameter laser beams. The solid line represents a calculation of the atomic signal for the pure Kepler potential taking into account the ballistic expansion of the atomic cloud along the wire. We attribute the additional loss observed in the experiment to magnetic stray fields that render the atomic orbits unstable; i.e., atoms will hit the wire and are lost. There will also be a small contribution to the losses because of a decrease in the wire current over time, caused by the increasing resistance due to Ohmic heating of the wire.

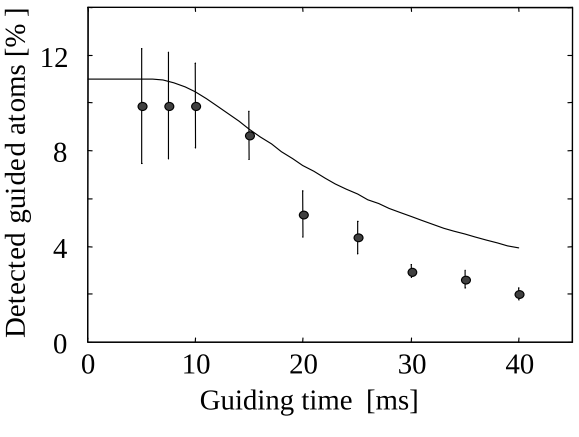

FIG. 4. Detected fraction of the MOT atoms that are bound to the Kepler guide: Atoms are detected only as long as they are located within the width (2 cm) of the MOT laser beams that are used to illuminate the atoms. The solid line is a theoretical *ab initio* prediction for a pure Kepler guide that is based on the measured parameters of the MOT. The experimentally observed additional loss at higher interaction times is most likely due to uncompensated bias fields.

Other valuable information about the transverse confinement can be extracted by measuring the momentum distribution of the trapped atoms. After switching off the guiding potential and waiting a few ms for ballistic expansion, the spatial distribution represents the velocity distribution of the atoms. Figure 5 shows the spatial atomic distribution 9 (7) ms after switching off the guides. A clear distinction can be seen between the two types of guides. Atoms in the Kepler guide, where atoms circle around the wire, expand in a ring (Fig. 5, left), showing clearly that there are no zero-velocity atoms. This is because in order to be trapped in stable orbits *around* the wire the atoms have to meet the constraint that the perihelion of their Kepler orbit is located outside the wire. This restricts stable motion only to atoms with nonvanishing velocity. The low-field-seeker atoms of the side guide, however, do not have this constraint. Their velocity distribution is a standard Gaussian (Fig. 5, right).

Moreover, the side guide exhibits interesting scaling properties: With a fixed trap depth (given by the *magnitude* of the bias field) the trap size and its distance from the wire can be controlled by the current in the wire. The paradoxical situation arises that the trap gets smaller (size $\propto I/B_b$) and steeper (gradient $\propto B_b^2/I$) for *decreasing* current in the wire. The smallest and steepest trap achievable with a fixed bias field is limited only by the

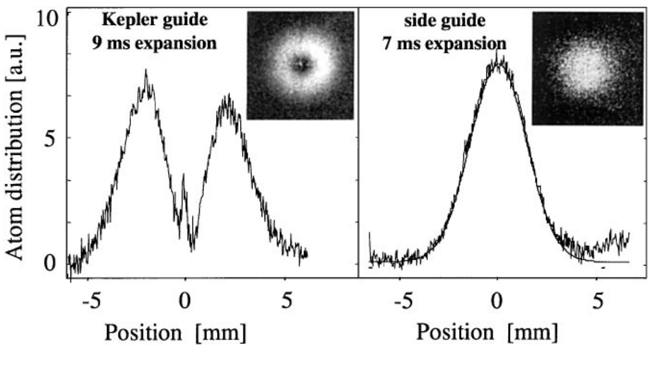

FIG. 5. Atomic distribution after free expansion of 9(7) ms for atoms that have been guided along the wire. The two profiles that are shown are cuts through the center of the respective CCD images in the right upper corner. For the high-field-seeker guide (left) the expanded cloud is doughnut-shaped due to the orbital motion of the atoms around the wire. For guiding on the side (right) we obtain a Gaussian distribution.

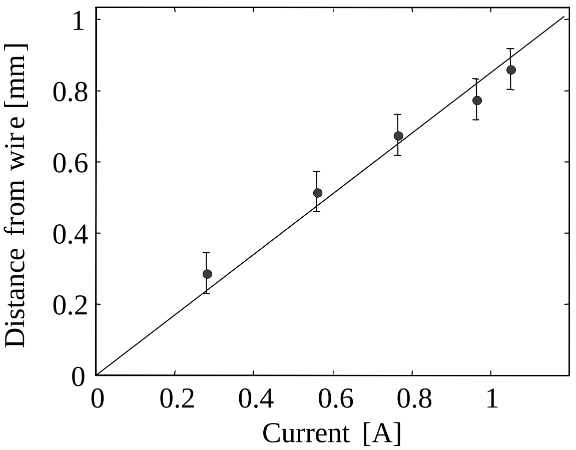

FIG. 6. Position of guided atoms vs the current through the wire for the side guide. Decreasing the current brings the trap closer to the wire and consequently makes it smaller and steeper.

requirement that it must be located outside the wire. A simple calculation shows, for example, that a trap with a gradient of over 1000 G/cm can be achieved with a moderate current of 0.5 A and an offset field of 10 G. The trap would be located 100 μm away from the wire center. Figure 6 illustrates this linear scaling for r_s, the distance of the side guide from the wire, as a function of the wire current (see also the right hand side of Fig. 2).

The side guide represents a promising technique for future applications in atom optics, because of its simplicity and versatility. (a) It can be mounted on a surface, with the atoms guided above the surface along the wires. This renders the wires more stable and at the same time allows for efficient cooling which enables also very thin, nanofabricated wires to support sizable currents (see also [12]). (b) Achieving the ultrahigh vacuum conditions required for coherent guiding is very simple, since the propagation of atoms is in the open and *not* in an enclosed space as in a hollow optical fiber [13]. (c) By combining different wires we can construct beam splitters [14], interferometers, or more complex matter wave networks [15]. This will open the door for a new generation of atom optical experiments where many nanofabricated atom optical elements are combined into one single quantum circuit in the near future, similar to modern integrated electronics.

We thank H. Batelaan for help in the early stages of the experiments and A. Zeilinger for his generous support. This work was supported by the Austrian Science Foundation (FWF), Project No. S065-05, the Jubiläums Fonds der Österreichischen Nationalbank, Project No. 6400, and by the European Union, Contract No. TMRX-CT96-0002.

---

[1] For an overview, see C. S. Adams, M. Sigel, and J. Mlynek, Phys. Rep. **240**, 143 (1994); *Atom Interferometry*, edited by P. Berman (Academic Press, New York, 1997).

[2] For recent reviews, see *Laser Manipulation of Atoms and Ions*, edited by E. Arimondo, W. D. Phillips, and F. Strumia (North-Holland, Amsterdam, 1992); S. Chu, Rev. Mod. Phys. **70**, 685 (1998); C. Cohen-Tannoudji, Rev. Mod. Phys. **70**, 707 (1998); W. D. Phillips, Rev. Mod. Phys. **70**, 721 (1998).

[3] V. V. Vladimirskii, Sov. Phys. JETP **12**, 740 (1961).

[4] J. Schmiedmayer, in *XVIII International Conference on Quantum Electronics*, Technical Digest, edited by G. Magerl (Technische Universität Wien, Vienna, 1992), Series 1992, Vol. 9, p. 284; Appl. Phys. B **60**, 169 (1995); Phys. Rev. A **52**, R13 (1995).

[5] Actually the adiabatic approximation results in an additional precession of the Kepler orbits around the wire as described in J. Schmiedmayer and A. Scrinzi, Phys. Rev. A **54**, R2525 (1996); Quantum Semiclass. Opt. **8**, 693 (1996).

[6] For quantum calculations, see G. P. Pron'kov and Yu. G. Stroganov, Zh. Eksp. Teor. Fiz. **72**, 2048 (1977) [Sov. Phys. JETP **45**, 1075 (1977)]; R. Blümel and K. Dietrich, Phys. Lett. A **139**, 236 (1989); Phys. Rev. A **43**, 22 (1991); A. I. Voronin, Phys. Rev. A **43**, 29 (1991); L. Hau *et al.*, Phys. Rev. Lett. **74**, 3138 (1995).

[7] With rotational symmetry broken, angular momentum is not conserved. This results in unstable orbits for the strong-field-seeking atoms which will finally hit the wire; J. Denschlag, Ph.D. thesis, Universität Innsbruck, 1998.

[8] E. L. Raab *et al.*, Phys. Rev. Lett. **59**, 2631 (1987).

[9] The atoms are loaded into the MOT for 20 sec out of an effusive beam at a red laser detuning of 25 MHz and a total laser power of about 150 mW. An electro-optic modulator produces sidebands of 812 MHz (30%), one of which is used as a repumper. To increase the loading rate we use an additional slower beam (20 mW, 100 MHz red detuned) directed through the MOT into the oven.

[10] J. Denschlag, G. Umshaus, and J. Schmiedmayer, Phys. Rev. Lett. **81**, 737 (1998).

[11] In our experiments we load the guides from a pulsed source, the MOT. Continuous loading can be achieved by using a (slow) atomic beam and nonadiabatic entry into the potential or by loading from a magnetic trap.

[12] J. D. Weinstein and K. Libbrecht, Phys. Rev. A **52**, 4004 (1995); M. Drndic *et al.*, Appl. Phys. Lett. **72**, 2906 (1998).

[13] Guiding in hollow fibers is a standard technology in neutron optics: M. A. Kumakhov and V. A. Sharov, Nature (London) **357**, 390 (1992); H. Chen *et al.*, Nature (London)) **357**, 391 (1992). For atoms it was proposed in M. A. Ol'Shanii *et al.*, Opt. Commun. **98**, 77 (1993); S. Marksteiner *et al.*, Phys. Rev. A **50**, 2680 (1994); and experimentally demonstrated by M. J. Renn *et al.*, Phys. Rev. Lett. **75**, 3253 (1995); H. Ito *et al.*, Phys. Rev. Lett. **76**, 4500 (1996).

[14] We are currently testing a beam splitter for guided atoms formed by two intersecting current carrying wires.

[15] J. Schmiedmayer, Habilitationsschrift, Universität Innsbruck, 1996; J. Denschlag and J. Schmiedmayer, in *Proceedings of the International Quantum Coherence Conference, Boston, 1997* (World Scientific, Singapore, 1997); J. Schmiedmayer, Eur. Phys. J. D **4**, 57 (1998).