PHYSICAL REVIEW A VOLUME 52, NUMBER 1 JULY 1995

Guiding and trapping a neutral atom on a wire

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(Received 17 May 1994)

A neutral atom with a magnetic moment can be bound to a current carrying wire. The atom is trapped in the *high-field-seeking state* and stabilized by angular momentum. In an atomic-beam experiment the guiding of Na atoms along a 1-m-long, 150-μm-diam, current carrying, tungsten wire is demonstrated. By adding a charged ring around the wire one can create a three-dimensional microscopic trap for neutral atoms. These traps confine the atoms in the *lowest*-energy spin state.

PACS number(s): 32.80.Pj, 52.55.Lf, 03.75.Be

In recent years remarkable success was achieved in trapping neutral particles possessing a magnetic moment in static magnetic fields [1]. Neutrons [2], hydrogen [3], and alkali atoms [4] were trapped in magnetic storage rings, bottles, and traps. In all of these experiments the particles were trapped in a local minimum of the magnetic field. However, this *weak-field-seeking state* is not the minimum energy state for the particle-field system. The stored potential energy, which is always larger than the trap depth, can be released in bipolar relaxation collisions and the particle will leave the trap [5].

An ideal magnetic trap would collect atoms in a *maximum* of the magnetic field, in the *high-field-seeking state*, which is the *lowest-energy* spin state and hence the ground state of the particle-field system. In such traps energy conservation prohibits the two-body spin flip process, and the trap is more stable at high densities. However, the classical Earnshaw theorem forbids the creation of a local maximum of static magnetic field in free space [6]. A way around that is to apply time varying fields, which has been used in ion traps [1]. Using the same principles, neutral atoms were recently trapped with microwave radiation [7] and using far off resonant light [8].

We describe here a different way to circumvent the Earnshaw theorem by using the maximum of a static magnetic field in a region of nonzero current [9]. The simplest system is a current carrying wire [10]. To sustain a stable trap, the particle has to be kept away from the source of the field, the wire. This can be achieved by the centripetal potential barrier $V_L = L/2Mr^2$ created by angular momentum L. Then trapping an atom with static fields in the lowest-energy spin state becomes possible. V_L can compensate for all regular potentials that diverge less rapidly than r^{-2} as $r \rightarrow 0$.

To illustrate and experimentally demonstrate the above principle for trapping in a *high-field-seeking state* we used a current carrying wire to trap a neutral atom (Fig. 1). The magnetic field at the distance r from the wire is given (in Gaussian units) by

$$\vec{B}(\vec{r}) = \frac{2}{c} \vec{I} \times \hat{\vec{r}} \frac{1}{r} . \quad (1)$$

An atom with total spin $\vec{S}$ and magnetic moment $\vec{\mu} = g_S \mu_B \vec{S}$ experiences the potential $V = -\vec{\mu} \cdot \vec{B} = -g_S \mu_B m_S B$, where m_S is the projection of $\vec{S}$ on $\vec{B}$. For $\vec{\mu}$ parallel to $\vec{B}$ the interaction potential is attractive.

First we consider a classical trajectory around the wire. The atom, moving around the wire, will encounter a changing magnetic field in its rest frame. If the magnetic moment can adiabatically follow the direction of the field, the resulting interaction potential is Coulomb-like ($1/r$) and the atom moves in Kepler-like orbits. For the adiabatic following to hold, the Larmor precession (ω_L) of the magnetic moment has to be much faster than the local apparent rotation of the magnetic field [11]. For a circular orbit, this rotation is identical to the orbit frequency (ω_0). For an atom in a circular orbit with angular momentum $L = \hbar l$, we find $\omega_L / \omega_0 = l/m_S$. For $l \gg m_S$, the adiabatic approximation is valid. Typical parameters for trapping a Na atom on a current carrying wire are shown in Table I.

For currents of 2 A and orbits with $r \approx 100$ μm the binding energy of a sodium atom in an $m_S = 2$ state ($\mu = \mu_B$) is on the order of 10^{-7} eV. The atom has a velocity of about 1 m/sec, $l \sim 35 \times 10^3$, and the motion is classical. A more quantal regime can be reached using a current of 200 μA and $r \approx 2$ μm. This orbit has $l \approx 50$ and the binding energy of $\approx 5 \times 10^{-10}$ eV is well within the reach of laser cooled at-

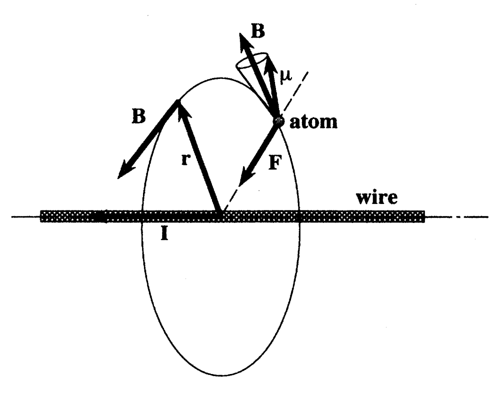

FIG. 1. Schematic of the interaction of a neutral atom (magnetic moment $\vec{\mu}$) with the magnetic field $\vec{B}$ of a wire carrying a current $\vec{I}$. $\vec{F} = -\nabla(\vec{\mu} \cdot \vec{B})$ is the classical force on the atom.

TABLE I. Typical parameters for Na atoms trapped on a current carrying wire.

Current	Orbit radius (μm)	Binding energy (eV)	l	ω_0 (rad s^{-1})
2 A	100	1.2×10^{-7}	35700	9855
200 μA	2	5.8×10^{-10}	50	24600

oms. Typical level spacing is in the range of a few kHz. Using a thin (1-μm-diam) wire we expect lifetimes in excess of 1000 sec for nearly circular states, as estimated from the tunneling probability through the centripetal potential barrier.

In the classical regime the atoms move in Kepler-like orbits. In the quantum regime, the system looks like a two-dimensional hydrogen atom in (nearly circular) Rydberg states. The wire resembles the *"nucleus"* and the atom now takes the place of the *"electron."* Nevertheless, it differs from the two-dimensional Coulomb problem by the fact that the atom acquires a geometric phase $\Phi_{geom}=2\pi m_S$ caused by the parallel transport of the magnetic moment along the orbit [12]. This additional geometric phase results in a shift of the quantum mechanical energy levels, as can be seen in the semiclassical quantization rule for adiabatic motion [13] $\oint_{\rm orbit}P\, dX=2\pi\hbar n+\Phi_{geom}$. This shift is nicely illustrated by comparing the exact solutions for a spin $\frac{1}{2}$ neutron in a magnetic field of a linear current [14]: $E_n=-E_0(1/n^2)$ to the solution for the two-dimensional hydrogen atom with a spin $\frac{1}{2}$ electron [15] $E_n=-E_0[1/(n-1/2)^2]$ (n is a integer in both cases).

We will now describe a simple experiment demonstrating the *guiding* of atoms along a current carrying wire, in the classical regime: In the two-dimensional geometry of a wire where the motion in the third dimension, along the wire, is free, only the transverse motion is important. The length of the wire and the longitudinal velocity together limit the time the atom spends in the two-dimensional trap. Collimating an atomic beam to better than 10^{-3} rad, the transverse motion is well within the regime required for trapping (Table I). Introducing a small bend in the wire ($\sim10^{-3}$ rad), one can guide atoms along the wire around a beam stop.

The experiments were performed using an effusive sodium atomic beam [16] of mean velocity $\sim$ 600 m/sec emitted from a 1-mm-diam nozzle in a 100 °C oven. Good collimation was achieved by two specially shaped apertures spaced 1 m apart (Fig. 2). The collimating apertures also held the 1-m-long, 150-μm-diam, *W* wire to guide the atoms. Applying a constant current of up to 2.0 A heats the wire significantly. To compensate for the thermal expansion (a few millimeters) the second aperture (it holds the far end of the wire) was mounted on a translation stage. A small tension was applied to the wire with a spring to keep it taut. Halfway between the two apertures was a movable beam blocker with its edge parallel to the bottom of the first aperture and perpendicular to the slit of the second collimator (Fig. 2). It could be moved, with an accuracy of better than 0.05 mm, from above into the beam. It blocked the direct beam in a well defined manner, and in addition bent the wire. The shadow of the shutter, as seen behind the second aperture was a good measure of the bending angle.

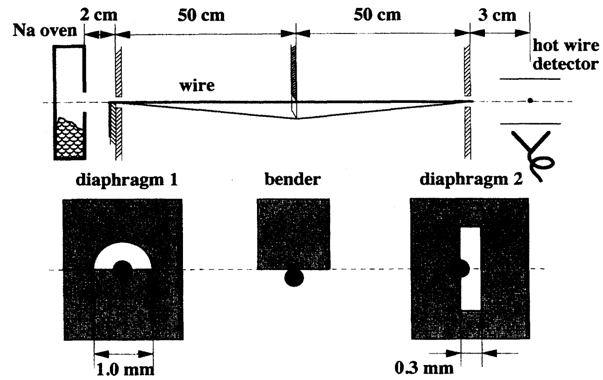

FIG. 2. Basic schematic of the experimental setup. Na atoms are emitted from the oven. The two-beam defining diaphragms hold the wire. The wire bender and the movable detector are shown. The insets below show in detail the relative geometric arrangement between the apertures, the movable beam shutter used to bend the wire, and how the wire is mounted. Through diaphragm 1 atoms enter the guide only from above the wire. This ensures that the bender casts a well defined shadow. Diaphragm 2, together with the movable detector, allows a detailed measurement of the spatial distribution of the guided atoms.

Single sodium atoms were detected using a Re hot wire detector [16] mounted on a translation stage about 3 cm behind the second aperture. By moving the 250-μm-diam hot wire along the slit, the beam profile perpendicular to the bending direction can be measured. For typical operating conditions the background was on the order of 10 counts/sec with better than a millisecond time resolution.

In the experiment, the position of the wire was first determined by looking at its shadow behind the slit with the shutter-bender out of the beam. If the shutter-bender was moved in the beam its shadow then determined its relative position and the angle at which the wire was bent.

To measure trapping unambiguously, the atom flux is measured with and without current through the wire. Since typical time constants for the resistive heating of the wire were on the order of seconds, uniform conditions could be achieved by rapidly alternating the periods with the current on and current off. In a measurement cycle, atoms were

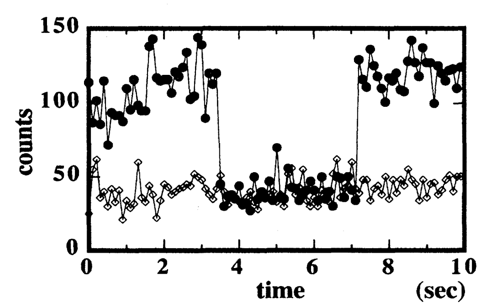

FIG. 3. Raw data from an experiment with 1-A current and a bend of 0.5 mrad. Measurements were done alternatively with the current on for 100 msec (●) and the current off for 100 msec (◇). Between 3.5 and 7.2 sec the current was switched off completely and both count rates agree within the error.

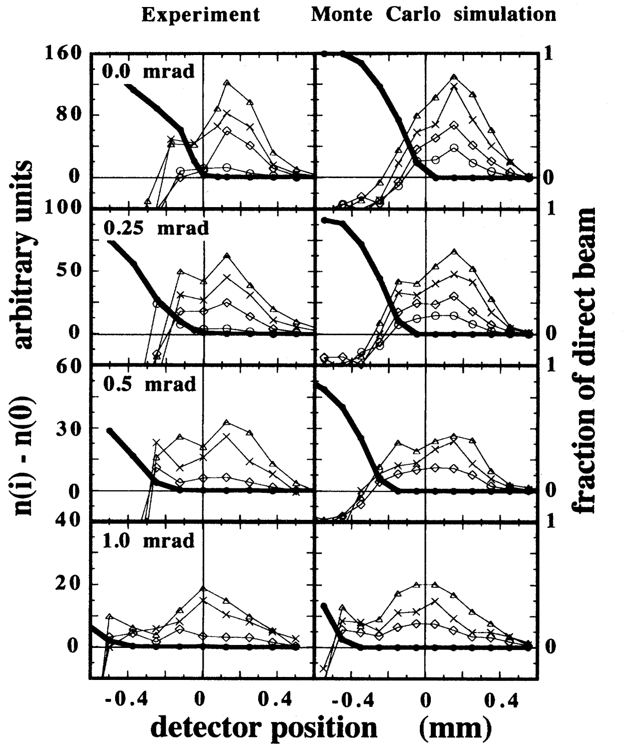

FIG. 4. Na atoms being guided along a 1-m-long, 150-μm-diam, W wire (at detector position 0 indicated by the vertical line). Experimental data (left) and Monte Carlo simulations (right) are shown for a 0.0, 0.25, 0.50, and 1.00 mrad bend in the wire. The data are given as the difference $n(i)$-$n(0)$, where $n(i)$ is the number of atoms reaching the detector with current on and $n(0)$ is the number of atoms reaching the detector with current off. The different symbols are for 0.5-A (o), 1.0-A (◇), 1.5-A (×), and 2.0-A (△) current through the wire. The thick line shows the fraction of the direct beam reaching the detector. The steep slope shows the shadow cast by the bender.

counted for time t_{count} (typically 100 ms) with the current off. Then the current was switched on and a delay of t_{wait} (typically 10 ms) was allowed before atoms were counted again for t_{count}. The current was then switched off again and a time t_{wait} was allowed before starting the counting cycle again. A switching time of approximately 100 ms was long compared to the flight time of the atoms along the wire (2 ms) and the detector response time (typically 1 ms). The experimental results were found to be independent over a wide range of the times t_{count} and t_{wait} used in the measurement cycle. Figure 3 shows an experimental run where one trace shows the count rate of atoms with the current on and one with the current off. To demonstrate the effect of the current on trapping, the current was switched off completely for the time between 3.5 and 7 sec.

Experiments were performed with various currents up to 2.0 A. The wire was bent up to 1.5 mrad. From the detector scans along the exit slit, the beam profile behind the wire was determined. The data are shown in the right hand graphs in Fig. 4. The thick dark line indicates the shadow of the bender moving to increasingly negative positions as the wire is bent. The thin line with the symbols is the difference of Na

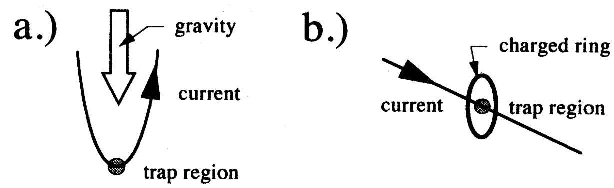

FIG. 5. Two arrangements of an atom wire cavity. The radial confinement is given by the interaction of the magnetic moment of the atom with the magnetic field of the current in the wire. In (a) the trap is closed in the axial direction by gravity; in (b) the longitudinal confinement is achieved by the electric field of a charged ring.

atoms counted with the current on $n(i)$ and the current off $n(0)$. The peak around the wire position (thin vertical line at position 0) is clear evidence of the guiding of the atoms along the wire and around the bend.

Monte Carlo calculations of atoms guided in the magnetic field of the wire were performed using the adiabatic approximation ($l \gg 1$). The atom enters the first collimating aperture at a random position with a random velocity chosen from the velocity distribution of atoms coming from the effusive source. The internal state of the atom is randomly selected as well as its magnetic quantum number defining the attractive or repulsive nature of the potential $V = -\vec{\mu} \cdot \vec{B}$. Atoms move in Kepler orbits in the plane transverse to the wire and free along the wire up to the bender. From here they move in new orbits, determined by the bend, to the exit slit. Atoms that hit the wire, the bender, or collimators are regarded as absorbed. Calculations for the parameters used in the wire experiment show that atoms, mainly from the low-energy tail of the effusive beam, are being guided along the wire, performing a few orbits in each section. The calculated distributions of atoms emerging after the guide are shown in the right hand graphs of Fig. 4. They show good agreement with the experimental data shown in the left hand graphs.

In the above experiment, the motion along the wire is free. A three-dimensional *high-field-seeking* trap for cold atoms can be realized by hanging the wire in the shape of a ∪ and gravity will close the trap [Fig. 5(a)]. In a different, more elegant way a charged ring around the wire can give longitudinal confinement [Fig. 5(b)].

The interaction potential of a neutral atom with a wire (radius r_w) that is on potential U_e relative to a concentric cylinder (radius r_g) is given by [17]

$$V_{pol}(r) = -\frac{1}{2}\alpha E(r)^2 = -\frac{1}{2}\alpha \frac{1}{r^2}\left(\frac{U_e}{\ln\left(\frac{r_g}{r_w}\right)}\right)^2, \qquad (2)$$

where α is the electric polarizability of the atom. This interaction is always attractive. Replacing the cylinder with a charged ring makes V_{pol} dependent on the position along the wire, which results in longitudinal confinement, a *"wire-ring"* atom trap. For 50 V on a ring with 0.5-mm radius around a 1-μm wire, one finds a typical potential depth of 10^{-9} eV. The spacing of the quantum levels for motion in such a trap is on the order of kHz [18].

Another interesting property of V_{pol} is that it has the same radial dependence ($1/r^2$) as the repulsive angular momentum potential [17]. To keep the effective potential in the radial equation of motion the same, the additional attractive $1/r^2$ potential will require the orbit to have higher angular momentum. Changing the potential difference U_e allows us then to change the degree of adiabaticity of the motion. Eventually, the adiabatic approximation will no longer be valid and trapping in the strong-field-seeking state in the nonadiabatic regime can be studied in these guides and traps.

In conclusion we have proposed and demonstrated experimentally that a neutral particle with a magnetic moment can be trapped in the *high-field-seeking state* using static potentials. The atom is trapped in two dimensions around a current carrying wire and angular momentum prevents the particle from hitting the wire. For $l \gg 1$ the motion is adiabatic and the atom moves in Kepler-like orbits. In experiments using laser cooled atoms and thin wires the regime $l < 100$ will be accessible. In this regime the system can be viewed as similar to a two-dimensional hydrogen atom in Rydberg states. A quantum waveguide for de Broglie matter waves and microscopic quantum traps for neutral atoms will be possible.

J.S. wishes to thank Professor Jene Golovchenko for his invitation to Harvard and the Rowland Institute of Science. Special thanks go to Mike Burns, Lene Hau, Jene Golovchenko, and all the other colleagues at the Rowland Institute of Science for numerous discussions, their hospitality, and support for these experiments. J.S. is supported partly by the Austrian Academy of Sciences and by Grant No. S065-05 of the Austrian Fond zur Förderung der wissenschaftlichen Forschung.

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