Realization of a Magnetic Mirror for Cold Atoms

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We have demonstrated that cold atoms can be retroflected from a ferromagnetic surface by the Stern-Gerlach effect. When the surface is magnetized periodically, the reflectivity for suitably polarized atoms is (94 ± 8)% and the reflection is specular. A demagnetized surface is also highly reflecting but the reflections are diffuse. These magnetic processes are of interest for atom optics because they permit the manipulation of cold atoms without the use of laser beams. In our experiments, Rb atoms released from a magneto-optic trap (MOT) fall under gravity until they are reflected, after which they are recaptured in the MOT. Multiple bounces of these atoms have been studied for times up to 600 ms.

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Over the last few years, it has become possible to prepare extremely cold atomic vapors by means of laser cooling and trapping [1]. This has generated a surge of interest in techniques for manipulating atoms and has given birth to the field of atom optics [2], in which atoms and their associated de Broglie waves can be made to display many features of photon optics, including reflection, diffraction, and interference. In addition, one can expect novel effects in atom optics because atoms have large mass and a wide variety of internal structures which do not exist in the more traditional optics of photons, electrons, or neutrons. In this Letter we report the first demonstration of atomic retroreflection from a surface with microscopic magnetic structure, opening the way to a simple new technique for atom manipulation without the use of laser light.

Normal incidence atomic mirrors are interesting because they can be used to focus atoms, to store atoms, and perhaps even to build a Fabry-Pérot resonator for atomic de Broglie waves [3]. Retroreflectors to date [3,4] have used the electric dipole force in an evanescent light wave, where the intensity gradient makes a strongly repulsive potential due to the ac Stark effect. We have now demonstrated a new mirror for atoms based on the gradient of the magnetic dipole interaction, i.e., the Stern-Gerlach effect at normal incidence, which has the advantage of not requiring a laser.

The idea of magnetic mirrors for neutral particles was discussed long ago by Vladimirskiî [6] in the context of cold neutrons. He pointed out that a sheet of spatially alternating currents produces a magnetic field whose magnitude $|\mathbf{B}|$ decreases with the distance z from the surface as $\exp(-kz)$ and is independent of the transverse position (x, y) ($k = 2\pi/\lambda$, where λ is the spatial period). A neutron in the spin-up state will be repelled from the current sheet provided that its motion through the spatially varying field is adiabatic. A more recent discussion by Opat, Wark, and Cimmino [6] considers both electric and magnetic mirrors and suggests the possibility of reflecting or diffracting atoms from the surface of a magnetic recording medium. Such media can be written with periods <1 μm and fields >1 kG, giving a surface potential far stronger and a range much shorter than those achievable with current-carrying wires. The short range of the potential may be of practical importance since it gives a correspondingly short interaction time (~10 μs for an atom dropped from a few cm height). In addition, magnetic media can be made accurately flat or curved to make elements for focusing or confining atoms. We have been able to realize a magnetic reflector in the laboratory using the field produced by a strip of magnetic audio tape with sinusoidal magnetization $\mathbf{M} = M_0 \cos(kx)\,\hat{\mathbf{x}}$ along its length. In order to compute the field outside the tape, one can replace the magnetization by fictitious surface current densities $\mathbf{j} = \nabla \times \mathbf{M}$ on the front and back surfaces of the thin magnetic coating. When the tape is fully magnetized, M_0 is constant throughout the thickness t of the coating, and $\mathbf{M}$ is therefore equivalent to two opposing sinusoidally modulated current sheets $\mathbf{j} = \pm M_0 \cos(kx)\,\hat{\mathbf{y}}$, separated by t. Although the direction of the magnetic field has a complicated spatial dependence, its magnitude outside the tape is simply

$$B = \tfrac{1}{2} B_0 (1 - e^{-kt})\, e^{-kz} = B_{\max} e^{-kz}, \qquad (1)$$

where $B_0 = \mu_0 M_0$ is the field inside the tape. An atom whose magnetic moment μ is aligned antiparallel to the magnetic field experiences an exponentially increasing repulsive potential μB as it adiabatically approaches the surface of the tape. Much of the work published on evanescent wave reflectors, e.g., Ref. [7], can be applied to our magnetic mirror because both have an exponential potential.

In a preliminary experiment, we saturated 15 lengths of Denon HD-M/100 oxide-free tape with a dc signal. By pulling them through a coil of wire and measuring the induced electromotive force, we determined that the internal field is $B_0 = 2.4$ kG. We also recorded sine waves of various wavelengths using a commercial recording head; the signal is recorded on four tracks of 0.6 mm width, covering 63% of the 3.8 mm wide tape. In order to make a direct measurement of the field above the surface of the tape as a test of Eq. (1), we held a wire of 75 μm diameter against the surface and translated the tape at high speed under the wire. The induced electromotive force allowed us to determine the average of B_z over the cross section of the wire, and hence to deduce the value of $B_{\max}$ [8]. For wavelengths in the range 200–2000 μm these measurements confirm Eq. (1) at the 20% level and show that the thickness of the recording is equal to the physical thickness of the magnetic layer (4 μm). Our magnetic mirror for atoms was a tape recording of a 5 kHz sine wave, for which the wavelength λ is 9.5 μm. For such a short wavelength, the electromotive force induced along the probe wire was not large enough for us to measure, but according to Eq. (1), the maximum field outside the tape is $B_{\max} = 1.1$ kG, and the decay length $1/k = \lambda/2\pi$ is 1.5 μm. The maximum interaction energy between this field and an alkali atom (magnetic moment of 1 Bohr magneton) is 1×10^{-24} J and is as large as that achieved by the best evanescent wave mirrors to date [9]. Such a mirror should be able to reflect rubidium atoms dropped from a height of 0.8 m [10].

Our experimental arrangement and the relevant atomic levels are sketched in Fig. 1. Atoms of ^{85}Rb atoms are collected from vapor in a vacuum chamber by a magneto-optic trap (MOT) [11,12]. This consists of a quadrupole magnetic field (not shown) whose gradient is 7 G/cm and three pairs of optical (780 nm) trapping beams, each collimated and apertured to a diameter of 10 mm. The beams are tuned 10 MHz below the 3-4 hyperfine line of the $D2$ transition ($5S_{1/2}$-$5P_{3/2}$, natural width 6 MHz) and propagate along mutually orthogonal axes, each making an angle of $\sim 55°$ with the vertical. A weak repumping laser beam superimposed on the trapping beams returns any $F = 2$ ground-state atoms to the $F = 3$ ground state. The trapping and repumping beams are produced by two separate diode lasers. Rb vapor is supplied by a heated source held in a side arm of the vacuum chamber. The time constant for filling the trap can be varied from 1 up to 20 s by adjusting the temperature of the Rb source to control the pressure of vapor in the chamber. After turning on the trap, we monitor the number of captured atoms by focusing the fluorescence of the atom cloud onto a photodiode. When enough atoms have been loaded, we lower the frequency of the trapping light over a period of 2 ms to a detuning of -30 MHz, where it remains for 1 ms in order to cool the atoms. Finally, the trapping light is rapidly switched off using an acousto-optic modulator, and an electronic circuit drives the current in the magnet coils to zero in 0.1 ms. As the atoms begin to fall, we optically pump them to enhance the population of the weak-field-seeking positive m_F sublevels in the $F = 3$ ground state. The atomic orientation is maintained by a uniform magnetic field of ~ 100 mG along the optical pumping axis, which is always on. The pumping light, derived from the "trapping" diode laser still detuned to -30 MHz, is formed into a pair of counterpropagating, optical pumping beams, shown in Fig. 1, which are switched on for 5 ms. During this time, the atoms typically scatter 15–20 photons, pumping $\sim 80\%$ of the population into the $m_F = +3$ and $+2$ magnetic sublevels. We have measured the temperature of atoms prepared in this manner to be 30 ± 5 μK, using a time-of-flight technique. We do not drive the population fully into $m_F = +3$ because this increases the temperature of the atoms unacceptably.

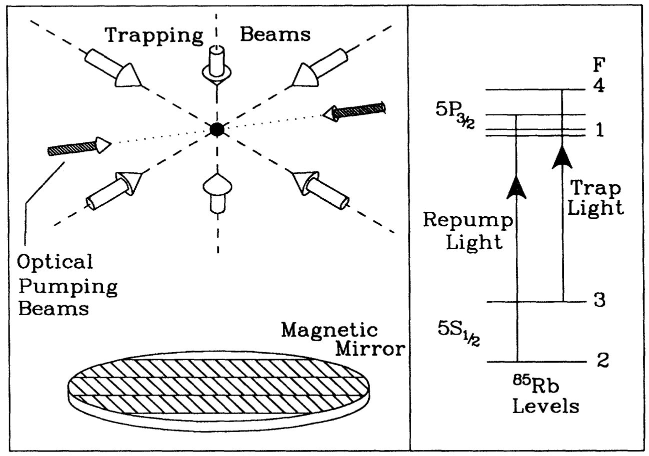

FIG. 1. Rb atoms are collected and cooled in a magneto-optic trap. After being released and optically pumped, they fall onto a magnetic mirror made from an audio cassette tape. Atoms reflected from the tape are recaptured by turning on the trapping beams again and are detected by their fluorescence. The energy level diagram shows the transitions used.

In our first experiment we loaded $\sim 10^7$ atoms into the trap, released and polarized them, and allowed them to fall 24.5 mm under gravity onto the magnetic mirror below (see Fig. 1). This consisted of three strips of audio tape (prepared as described above) glued side by side on a 25 mm diameter flat glass substrate. After a suitable time delay, we measured the number of reflected atoms by switching the trap back on for a period of 25 ms and observing the fluorescence from atoms that were recaptured during that interval. Repetitions of the experiment with various time delays allowed us to build up a measurement of the number of atoms in the recapture volume as a function of time. The solid data points, plotted in Fig. 2, show atoms bouncing for 500 ms or more on the magnetic mirror. This mirror was then replaced in an otherwise identical arrangement by demagnetized tape, in which the microscopic magnetization is the same but the domains (<0.5 μm in size) are randomly oriented. The experiment was repeated, with results shown as open circles in Fig. 2. In this case the number of atoms recaptured after one bounce was much lower and no multiple bounces could be detected at all [13]. The solid line is generated by a simple numerical model, which provides good quantitative understanding of both these experiments, as we now discuss.

The magnetic mirror signal in Fig. 2 decreases with time for several reasons. Much of the loss is due to the atomic cloud expanding beyond the trapping region and past the edge of the atomic mirror, as a result of its thermal

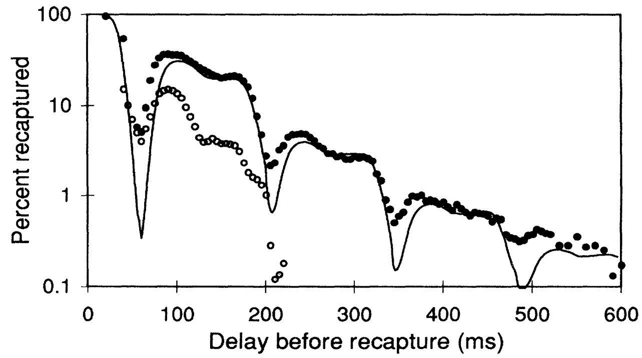

FIG. 2. Fraction of atoms recaptured as a function of time after their release from the trap. Solid circles: data from magnetized tape. Open circles: data from demagnetized tape. Line: a numerical simulation discussed in the text.

energy. A similar contribution comes from the imperfect reflectivity of the tape, mainly because of the demagnetized regions between the tracks. Finally, there is a small loss resulting from collisions with the background gas. Our computer simulation takes these effects into account and allows us to determine the reflectivity of the magnetized area. In the model, atoms are released from the center of the trap with a distribution of velocities corresponding to the measured temperature (30 μK). After falling freely through the known height (24.5 mm), those that hit the tape are reflected with probability R. In the experiment, reflected atoms entering any of the trapping beam pairs are pushed by the one-dimensional magneto-optic force into the trap region where the six beams overlap. Once collected, the atoms move quickly to the center of the trap where their fluorescence is recorded 25 ms after the light was turned on. We simulate this in our model by detecting any atom that enters a region where it will be captured by the trapping light. In both the experimental data and the simulation, the bounces are double peaked (see Fig. 2). The dip occurs near the center of each bounce because at that time the atoms have rebounded to their original height, where the three beam pairs are overlapping and the collection region has a minimum cross section. At earlier and later times, more of the atomic cloud is recaptured because the atoms are below the center of the trap where the light beams are spread out. The two peaks are of different height mainly because the cloud is expanding, but also because of the collisional loss. This allows us to separate collisional losses from those due to imperfect reflectivity of the mirror. The collisional loss is modeled by an attenuation factor $\exp(-\delta t)$, where t is the time since release and the mean loss rate γ is our first free parameter. The only other adjustable parameter is the reflectivity R of the tape.

In the experiment, 63% of the atoms land on a magnetized portion of the tape, the remainder striking the demagnetized region between the tracks. The signal corresponding to a completely magnetized tape is found by subtracting from the mirror data (solid circles in Fig. 2) 37% of the signal from completely demagnetized tape (open circles) and dividing by 0.63. Figure 3 shows the result of this subtraction for the first bounce. The solid line is our fit to the model, in which γ has been adjusted to give the correct ratio of heights for the two peaks in the first bounce, while R has been chosen to reproduce the absolute peak heights. The shape of the signal predicted by our simple two-parameter model is in strikingly good agreement with the observations, except that the leading edge of each bounce starts a little too late for reasons which we do not yet understand. The value of γ derived in this way is 1.9(7) s^{-1}, which is 10 times larger than the 0.2 s^{-1} loss rate from the trap suggested by the 5 s trap loading time. This indicates that atoms in free fall are more easily deflected by collisions than those in the trap. The reflectivity R is found to be $R = 0.94(8)$. This represents a lower limit on the actual reflectivity of the magnetized area because the model assumes perfect optical pumping, a perfectly flat mirror surface, and perfectly vertical release of the atoms.

Having determined γ and R from the first bounce, our model can predict the signal in subsequent bounces due to reflection from the magnetized portions of the tape. This is shown as the full curve in Fig. 2. It should not coincide everywhere with the solid data points because atoms reflected from the demagnetized regions make a significant contribution at the beginning of each bounce (as we know from the first-bounce data). However, the latter part of each bounce should be well reproduced, and it is, giving us some confidence that the model is essentially correct.

A simple variant of the experiment was used to check that the reflectivity is magnetic in origin. Instead of optically pumping to enhance the positive m_F levels, we pumped to enhance the negative m_F levels, expecting that the number of reflected atoms should decrease. Indeed, the number of atoms seen on the first bounce was reduced by a factor of 5 for both magnetized and demagnetized tape, confirming that the reflectivity of the surface is strongly

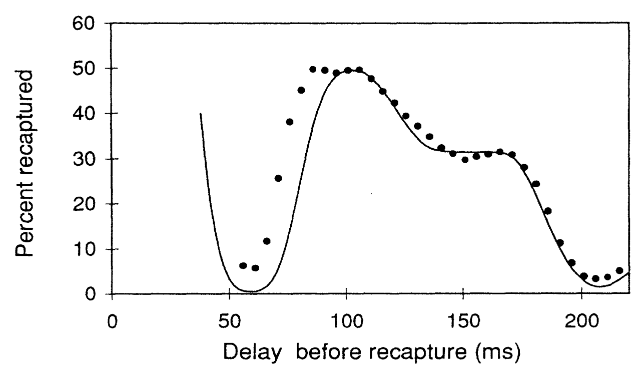

FIG. 3. Fraction of atoms recaptured on the first bounce from magnetized tape, corrected for the demagnetized regions between tracks. The solid line shows a fit using our simple, two-parameter numerical model. The same parameters give the solid curve in Fig. 2.

spin dependent in both the magnetized and demagnetized regions. We remark here that the 1.1 kG field at the surface of the tape is strong enough to partially undo the hyperfine coupling, so that only atoms in the $m_F = -3$ and -2 levels are attracted all the way to the surface; the others ($\sim$20% for our optical pumping conditions) are ultimately repelled and give rise to the signal we observe. It is possible also that some atoms are reflected because of nonadiabatic transitions induced by the inhomogeneous magnetic field of the tape. In that case, however, one would expect a stronger depolarization on demagnetized regions of the tape, where the field varies on a much shorter length scale (1 μm vs 10 μm). Since the reflected fraction is 20% for both tapes, we conclude that Majorana spin flips are a small effect in comparison with the incomplete optical pumping. In our main experiment, where the optical pumping is towards positive m_F, the asymmetry with respect to magnetic sublevels makes the reflectivity less sensitive to depolarizing effects.

The optical pumping experiments above show that the spin dependence of the reflected signal is high on demagnetized as well as magnetized tape, and yet it is clear from Fig. 2 that the bounce signals for the two cases are very different. A simple explanation for this is that the reflection from demagnetized tape is diffuse, with many of the atoms leaving the surface at large angles of reflection because the equipotentials of the random magnetic field are not smooth. Some atoms can be recaptured on their way up after the first bounce, but thereafter they have moved too far to the side and are lost. In order to check that this idea is correct, we modified the simulation program to give a distribution in the angles of reflection that is uniform over the upper hemisphere. Figure 4 shows the calculated signal for $R = 0.8$ and $\gamma = 1.9\ \mathrm{s}^{-1}$, together with the experimental data. Although the result of this simple model does not reproduce the details of the data, it is similar in shape and size and clearly supports the idea that reflection from the demagnetized tape is far from specular. Specular reflection, by contrast, is completely incompatible with the data for any reasonable choice of the parameters R and γ. It may be possible to infer the angular distribution of the reflected atoms from our data, but such a calculation is beyond the scope of this Letter.

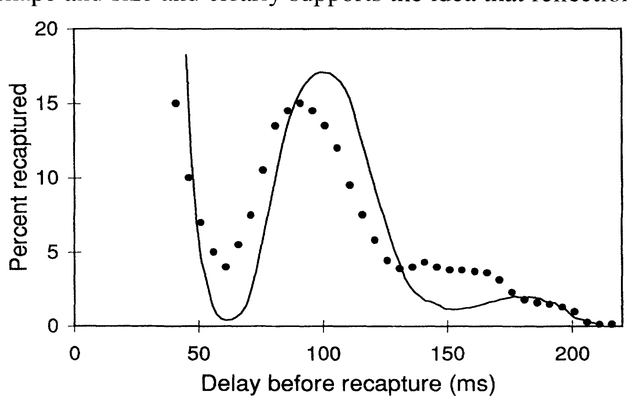

FIG. 4. Fraction of atoms recaptured on the first bounce from demagnetized tape. The solid line, our simulation with isotropically distributed angles of reflection, shows a signal of similar shape and size.

To summarize, we have shown that atoms falling at normal incidence onto a sinusoidally magnetized surface are specularly reflected with a reflectivity that is spin dependent and can be close to unity. Further, we have shown that demagnetized audio tape also has a high, spin-dependent reflectivity and that the reflection in that case is not specular. We conclude that suitably magnetized surfaces can be usefully employed in the storage and manipulation of cold atoms.

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