Reconstruction of a Cold Atom Cloud by Magnetic Focusing

C. V. Saba, P. A. Barton, M. G. Boshier, I. G. Hughes, P. Rosenbusch, B. E. Sauer, and E. A. Hinds*

Sussex Centre for Optical and Atomic Physics, University of Sussex, Brighton, BN1 9QH, United Kingdom

(Received 3 September 1998)

We have imaged an 18 μK cloud of ^{85}Rb atoms bouncing freely on a horizontal, concave magnetic atom mirror (radius of curvature R). A high-quality image is observed even after 14 reflections. Initially compact, the cloud is alternately collimated (odd bounces) and brought back to a focus (even bounces) when dropped from a height $R/4$. This multiple reconstruction of a thermally expanding cloud hinges on the microscopic reversal of the atomic motion. We discuss the factors limiting the resolution of the mirror and describe the method of construction. [S0031-9007(98)08251-9]

PACS numbers: 03.75.Be, 32.80.Pj, 32.80.Lg

Until recently the manipulation of atoms in flight has been largely restricted to small angle deflections of atomic or molecular beams. Focusing is typically achieved by electric quadrupole or magnetic hexapole fields whose gradients provide a force proportional to the distance from the axis [1,2]. In two special cases atomic beams have also been focused by quantum reflection from a mirror: H from liquid He [3] and He from silicon [4]. With the advent of laser cooling [5], it is now possible to prepare extremely cold atomic clouds which have such low thermal velocity that they fall almost vertically under gravity. This has generated a surge of interest in methods for manipulating cold atoms [6]. In this Letter we demonstrate a magnetic mirror that is able to reconstruct a cloud of cold atoms by specular reflection. This mirror has very high resolution, large acceptance and can be used to focus any paramagnetic species.

Several groups have previously investigated retroreflection of atoms using evanescent light wave mirrors [7]. Here atoms are repelled from the surface of the mirror by the gradient of the ac Stark effect—the so-called optical dipole force [8]. However, the reconstruction of an atom cloud has not been achieved using evanescent wave mirrors. Recent work at the Institute d'Optique in Orsay [9,10] has shown that the specularity of these mirrors is extremely sensitive to small amounts of light scattered by the glass surface used to form the evanescent wave.

The present experiment uses the Stern-Gerlach force above a surface x-y of alternating magnetization, $\mathbf{M} = M_0 \cos(kx)\hat{\mathbf{x}}$. The magnetic field above the surface $B_0 e^{-kz}[-\cos(kx)\hat{\mathbf{x}} + \sin(kx)\hat{\mathbf{z}}]$ forms periodic loops as shown in Fig. 1(a), but the magnitude of the magnetic field at height z takes the simple form $B = B_0 \exp(-kz)$. For atoms that move slowly in the field of the mirror, the magnetic quantum number is a constant of the motion, resulting in a Stern-Gerlach force that is normal to the surface [11], as illustrated in Fig. 1(b). This was first demonstrated as a method for retroreflecting cold atoms by Roach *et al.* [12], using an audio tape with sine waves recorded on it, and by Sidorov *et al.* [13] using an array of permanent magnets. Although the atoms were reflected somewhat specularly from the recording tracks on the tape, the cloud could not be focused because of diffuse reflection from the regions in between the tracks. Subsequently we made a floppy disk mirror whose surface was covered completely by positioning the record head to write overlapping tracks. This produced a smoother reflector but still diffused the atoms by ± 48 mrad [14], making it impossible to observe any focusing of the cloud. This roughness was due to second and third harmonics in the magnetization and to the discontinuities between one track and the next [15].

Now we have made a much improved magnetic reflector using commercial half-inch video tape (Ampex 398

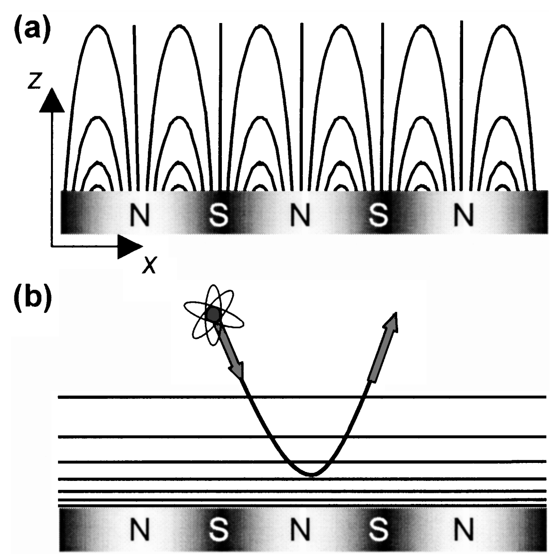

FIG. 1. (a) Magnetic field lines above a sinusoidally magnetized surface used to reflect atoms. The wavelength of the pattern is $\lambda = 12$ μm. The magnetic interaction of an atom with the surface is proportional to the strength of the magnetic field. (b) Although the direction of the field varies in a complicated way, the contours of constant strength are simple planes and the strength decreases as $\exp(-2\pi z/\lambda)$. Consequently, the interaction of the atom with the magnetic reflector produces a short-range perpendicular force and the atom undergoes an elastic, specular reflection.

 0031-9007/99/82(3)/468(4)$15.00

Betacam SP) and have succeeded in focusing a freely bouncing atom cloud, a realization of geometrical atom optics which we have observed directly. This was made possible by several essential advances which reduced the mirror roughness by an order of magnitude. (i) The sine wave, of wavelength 12 μm, is recorded in a single 12 mm wide track across the full width of the reflector so that we no longer have the roughness due to track boundaries. (ii) The field at the surface of the tape is approximately 1 kG. This is 4 times stronger than it was above the floppy disk and therefore keeps the atoms further away from the surface. In our experiments the closest approach is $z = 7.5$ μm where the magnetic field is smaller than the surface value by a factor e^{-kz} of 0.02. At this large distance from the surface, the mirror is smooth because the nth harmonics, having wave vector nk, are suppressed by factors of $(0.02)^n$ and only the fundamental frequency component remains significant. (iii) We have developed a new method of producing curved mirrors. A short length of the tape is glued across the end of a thin-walled ceramic tube using high-vacuum epoxy. A high-quality convex lens is pressed onto the tape, forcing it to be curved (radius $R = 54$ mm is this particular case). Epoxy poured into the back of the tube holds this shape when the lens is removed.

We tested the optical quality of the mirror surface by imaging a point source at the center of curvature. The 125 μm width of the image indicated a 0.5 mrad angular deviation of the mirror surface from spherical over the 8 mm diameter region illuminated. On illuminating the same region in a 633 nm Twyman-Green interferometer [16], we find six smooth concentric fringes, showing that the angular variation is almost entirely due to a gradual departure from spherical. We measured the microscopic roughness of the surface with an atomic force microscope and found a height variation of 20 nm rms.

The reflector is installed in a high-vacuum chamber, pumped down to a pressure of 2×10^{-9} Torr [17]. A magneto-optical trap [5] collects approximately 5×10^6 atoms of ^{85}Rb in a 1 mm cloud situated 13.5 mm above the reflector. The height $R/4$ is the focal plane of the mirror, a factor of 2 different from ordinary optics because the atoms fall under gravity on parabolic trajectories [14]. After being released from the trap, the atoms are cooled by optical molasses [5] for 20 ms, then optically pumped for 1 ms by a retroreflected σ^+ light beam, which transfers the majority of them to the most favorable state for magnetic reflection ($F = 3$, $M_F = +3$). Now the cloud falls freely in the dark until we flash on the optical pumping beam once again, this time for detection purposes. The scattered photons are collected by a Princeton Instruments MicroMax768 CCD camera which records the atom distribution at that time. We were careful to ensure that the detection process itself did not blur or displace the image of the cloud by virtue of the radiation pressure exerted on the atoms. Specifically, we used a 1 ms pulse at half the resonant saturation intensity and 10 MHz red detuning.

Figure 2 is a sequence of images taken with increasing time delays, viewed at a slight angle so that the surface of the magnetic reflector is visible at the bottom of each frame. The first nine pictures show the cloud falling freely under gravity. Its radius is determined partly by the original size and partly by the thermal expansion at 4.2 cm/s rms due to the cloud temperature of 18 μK. In the ninth frame we see that the atoms have almost fallen out of the detection beam, and in the tenth they cannot be seen at all. Still, we know from the measured expansion rate that the cloud diameter must be 4.4 mm rms when it reaches the mirror, and knowing that the mirror diameter is 11 mm we calculate that 95% of the atoms should strike the mirror. In the second row we see the cloud reappearing at 60 ms with just the width anticipated and subsequent frames show it rising to its original height without further expansion. This shows that the atoms are collimated; i.e., the atomic velocities are all vertical and the diameter of the cloud is determined by the thermal spread at the moment when it landed on the reflector. Although the original horizontal thermal velocity of each atom has been removed by its interaction with the reflector, that velocity remains encoded in the transverse position of the atom. In the third strip of Fig. 2 the collimated atom cloud falls back down towards the mirror. Once again there are frames at the end where the cloud is too low to be seen, but at 165 ms it reappears after the second reflection. The last strip shows the atoms coming to a focus in which the original cloud is eventually reconstituted. This happens because the second reflection imparts a transverse velocity to each atom that is just the reverse of its original thermal velocity.

It is straightforward to show that in this atom optics, the image formed after two reflections should be inverted with unit magnification. This is demonstrated in Fig. 2 where the initial cloud is displaced to the left of the optic axis by 1.5 mm, while the image formed after the second reflection is equally displaced to the right. Subsequent images alternate between the left and the right.

We are able to increase the temperature of the cloud up to 100 μK by altering the intensity and duration of the optical molasses stage. At this higher temperature we expect a broader cloud and a loss of atoms after the first reflection because they are spread more widely than the diameter of the mirror. By contrast, the size of the final image cloud is expected to be independent of temperature. All these features have been confirmed experimentally. We have also studied the behavior of clouds released from $R/2$, the analog in photon optics of placing the light source at the center of curvature. We see as predicted [14] that the original atom cloud is now reconstituted at the peak of the first bounce and that the focusing is again independent of temperature.

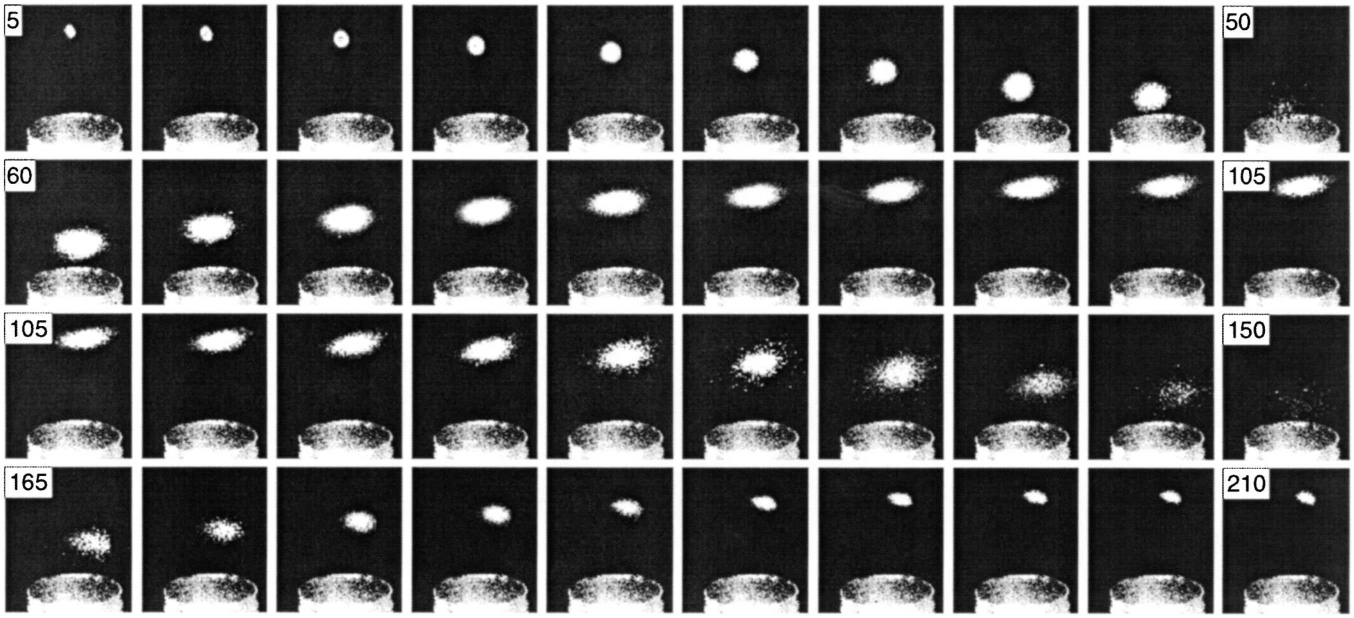

FIG. 2. Motion of atoms bouncing on the magnetic reflector after release from height $R/4$. The images of the cloud viewed at 5 ms intervals are formed by scattered laser light. Each frame is the average of several acquisitions with a background subtracted and the white level set at 80% of the peak. The number of acquisitions ranges from one to twenty, depending on the size of the cloud and the number of atoms imaged. The magnetic reflector is seen at the bottom of each frame with the time delay shown in milliseconds in the upper left corner. First strip: The cloud expands as it falls, its center following a parabolic trajectory. When the atoms are very close to the surface, they have fallen out of the probe beam and the frame at 55 ms is therefore omitted. Second strip: The collimated cloud rises with constant width after the first reflection from the surface, becoming pancake shaped at the top of its trajectory. Third strip: The collimated cloud falls to the mirror (blank frames at 155 and 160 ms are omitted). Fourth strip: The atoms interact with the mirror for a second time and rise to a focus which reconstructs the original cloud.

The image formed at 210 ms is slightly broadened, indicating an aberration of the mirror or some interaction with the environment as the atoms propagate between reflections. In order to study this we recorded all the image clouds up to the seventh, formed after fourteen reflections at 1.5 s, which is shown as an inset in Fig. 3.

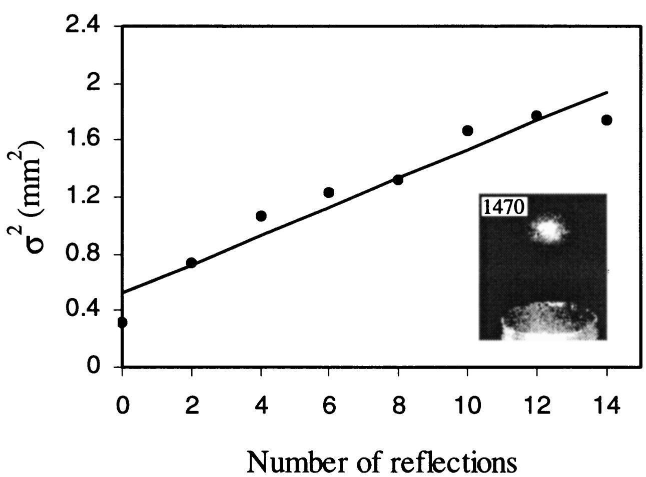

FIG. 3. Inset: Atoms form an image of the original cloud at 1470 ms after 14 reflections from the mirror. Graph: Data points show the mean square radius σ^2 of the refocused cloud versus the number of reflections n from the mirror. The line is a fit to the form $\sigma^2 = \sigma_0^2 + n\alpha^2$.

We found that the horizontal intensity profiles are well characterized by Gaussians whose mean square widths σ^2 grow as $\sigma_0^2 + n\alpha^2$. This is illustrated in Fig. 3 which shows σ^2 versus the number of reflections n. A least-squares fit yields initial width $\sigma_0 = 0.72$ mm and growth per bounce $\alpha = 0.32$ mm. Although this growth is small, it nevertheless limits the resolution of the atom optics and therefore its origin is of interest. If we suppose that an rms variation σ_θ in the angle of the mirror surface is responsible, a straightforward but tedious derivation shows that $\alpha = R\sigma_\theta$ for our geometry and hence that σ_θ is 6 mrad. Our optical study of the mirror shows that the angle of the surface varies by 0.5 mrad, which is far too small to explain the observed rate of growth. However, the atoms are reflected not from the physical surface but from an interaction equipotential some 7.5 μm above. Variations in the magnetization of the tape cause fluctuations in the height of this potential, which in turn lead to a diffusion of the focused cloud. We have measured the magnetic field above the tape using a magnetic force microscope and have analyzed the noise in the field to determine the angular fluctuations of the reflecting potential for our particular drop height. We find an angular noise of 5 mrad rms, due mainly to long-wavelength random noise components of the magnetization which beat against the 12 μm recorded field. This is the principal cause of the atom diffusion.

We believe that it is due to variations in the density of magnetic particles in the tape material [18] and probably cannot be reduced without new developments in the fabrication of the mirror. One new direction is the microfabricated electromagnet mirror [19]. Its ultimate flatness may prove to be better than one can achieve with recorded media, although it is at too early a stage of development to know.

Other possible contributions to the diffusion of the cloud have proved to be small. We find that α is not affected by an order of magnitude increase in the pressure of background gas or by reducing the number of atoms in the cloud, and therefore we do not believe atomic collisions make a significant contribution. The reflecting surface of the mirror, which has constant field strength $B = 20$ G, becomes corrugated in the presence of an additional uniform field b anywhere in the x-z plane. The angular variation is $b/\sqrt{2}B$. In this experiment we were careful to null the ambient field below the level of 50 mG where it does not contribute significantly to α. There is also no significant effect from the scattering of stray light because we are careful to block the laser beams while the atomic cloud is in free flight.

Successive images of the atom cloud also grow vertically, but in this direction the behavior is more complicated. Atoms initially below the trap center have a shorter bounce time and are already moving downwards when the shape of the cloud is recorded. Those starting too high have a longer bouncing period and have not yet risen to the center. After only two bounces, the cloud is fully reconstructed because this effect is negligible, but after fourteen bounces from a perfect mirror we would expect a thin pancake-shaped image coming from the central 0.3 mm of the initial cloud with a long, low-intensity tail below. This is not what we see in the inset in Fig. 3. Here the intensity of the tail is too low to see and the vertical extent of the cloud is principally due to the roughness of the mirror, which diffuses the cloud vertically as well as horizontally. A numerical simulation with a 6 mrad mirror roughness reproduces the image we see, but because of the complexity of the motion in this direction, we do not consider this a good way to determine the roughness.

In this experiment we have succeeded in imaging a cold atomic cloud by means of a magnetic mirror which is virtually free of aberrations. The diameter of this mirror is approximately equal to its focal length. Ultimately, of course, the bouncing atoms must satisfy the Schrödinger equation and if they are sufficiently coherent should exhibit interference effects. From this point of view, the reflector in our experiment can be considered as a resonant cavity, closed physically at the bottom and by gravity at the top [20]. The motion we have observed is then reminiscent of a confocal cavity in which the waist size of the propagating beam alternates between large and small. In the present case, however, the longitudinal mode spacing is very much smaller than the thermal energy spread of the cloud, so many modes are occupied and the resonances cannot be detected. Moreover, it remains to be determined how well the magnetic mirror preserves transverse coherence of the de Broglie wave. In the near future, it will be possible to bind the atoms to the mirror much more strongly, either magnetically [21] or electrostatically [22]. This will produce a large longitudinal mode spacing, opening the way to a two-dimensional waveguide for atom optics.

This research was funded by EPSRC (U.K.) and P. R. was supported by DAAD (Germany). We also acknowledge the expert assistance of Serge Ferré in building the Twyman-Green interferometer and encouragement by A. Aspect. We thank Kevin O'Grady for advice on magnetic materials and the use of his magnetic force microscope.

*Email address: e.a.hinds@sussex.ac.uk

[1] N. F. Ramsey, *Molecular Beams* (OUP, Oxford, 1985).
[2] W. G. Kaenders *et al.*, Nature (London) **375**, 214 (1995).
[3] J. J. Berkhout *et al.*, Phys. Rev. Lett. **63**, 1689 (1989).
[4] B. Holst and W. Allison, Nature (London) **390**, 244 (1997).
[5] C. S. Adams and E. Riis, Prog. Quantum Electron. **21**, 1 (1997).
[6] *Atom Optics*, edited by M. G. Prentiss and W. D. Phillips SPIE Proceedings Vol. 2995 (SPIE-International Society for Optical Engineering, Bellingham, WA, 1997).
[7] J. P. Dowling and J. Gea-Banacloche, Adv. At. Mol. Opt. Phys. **37**, 1 (1996).
[8] R. J. Cook and R. K. Hill, Opt. Commun. **43**, 258 (1982).
[9] A. Landragin *et al.*, Opt. Lett. **21**, 1591 (1996).
[10] C. Henkel *et al.*, Phys. Rev. A **55**, 1160 (1997).
[11] G. I. Opat, S. J. Wark, and A. Cimmino, Appl. Phys. B **54**, 396 (1992).
[12] T. M. Roach *et al.*, Phys. Rev. Lett. **75**, 629 (1995).
[13] A. I. Sidorov *et al.*, Quantum Semiclass. Opt. **8**, 713 (1996).
[14] I. G. Hughes *et al.*, J. Phys. B **30**, 647 (1997).
[15] I. G. Hughes, P. A. Barton, T. M. Roach, and E. A. Hinds, J. Phys. B **30**, 2119 (1997).
[16] M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1980), 6th ed., p. 303.
[17] It is worth noting that all the recording media we have studied evolve remarkably little gas in high-vacuum conditions.
[18] G. N. Coverdale, R. W. Chantrell, A. Satoh, and R. Vietch, J. Appl. Phys. **81**, 3818 (1997).
[19] M. Drndic *et al.*, Appl. Phys. Lett. **72**, 2906 (1998); K. S. Johnson *et al.*, Phys. Rev. Lett. **81**, 1137 (1998); D. C. Lau *et al.*, Eur. Phys. J. D (to be published).
[20] H. Wallis, J. Dalibard, and C. Cohen-Tannoudji, Appl. Phys. B **54**, 407 (1992).
[21] E. A. Hinds, M. G. Boshier, and I. G. Hughes, Phys. Rev. Lett. **80**, 645 (1998).
[22] J. Schmiedmayer, Eur. Phys. J. D **4**, 57 (1998); E. A. Hinds, in *New Directions in Atomic Physics*, edited by C. T. Whelan (Plenum, New York, 1999).