

# Atom Optics with Magnetic Surfaces I: Storage of Cold Atoms in a Curved “Floppy Disk”

I. G. Hughes <sup>a</sup>, P. A. Barton <sup>a</sup>, T. M. Roach <sup>b</sup>, M. G. Boshier <sup>a,b</sup> and E. A. Hinds <sup>a,b</sup>

<sup>a</sup>*Sussex Centre for Optical and Atomic Physics,  
University of Sussex, Brighton, BN1 9QH, U.K.*

<sup>b</sup>*Physics Department, Yale University,  
P.O. Box 208120, New Haven Connecticut 06520-8120*

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

## Abstract

We have demonstrated that a suitably magnetised surface can be used to retroreflect cold atoms for applications in atom optics. This has some advantages relative to evanescent wave mirrors because no light is involved. Multiple bounces of cold rubidium atoms have been observed for times up to one second in a cavity formed by gravity and a 2 cm-diameter spherical mirror made from a flexible computer disk (“floppy disk”). We have studied the dynamics of the atoms bouncing in this trap from several different heights up to 40.5 mm and we conclude that the atoms are reflected specularly and with reflectivity 1.01(3). The performance of this mirror is limited at present by collisions with background gas and by unwanted harmonics in the magnetisation of the surface. This is the first in a series of papers concerning the use of magnetised surfaces in atom optics.

## 1. Introduction

Over the last few years it has become possible to prepare extremely cold atomic vapours 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.

The first realisation of an atomic mirror utilised the strong optical dipole force in evanescent light waves formed by the total internal reflection of a laser beam at the glass vacuum interface of a prism. With blue detuning relative to atomic resonance the dipole force is repulsive, and the surface forms an atomic mirror [3], as was first demonstrated with an atomic beam [4], and then with cold atoms [5]. Cold atoms have also been trapped for several bounces in a curved evanescent wave mirror [6], known as a “gravity cavity”. The potential reflecting the atoms from these mir-

rors is simply the light shift of the atomic ground state, which is proportional to  $I/\delta$ , where  $I$  is the intensity of the light in the evanescent wave, and  $\delta$  is the detuning. One disadvantage of this method is that atoms are heated by spontaneous emission. Since this imparts random momentum to the atoms at a rate proportional to  $I/\delta^2$ , the effect can be reduced by choosing a sufficiently large detuning, but at the expense of requiring higher intensity. It is possible to enhance the evanescent wave intensity by means of a waveguide on the prism surface [7,8], however, this technique has not yet been demonstrated for a curved mirror because it is difficult to couple light effectively into a waveguide on a curved surface.

Following a suggestion by Opat *et al* [9] we were able in 1995 to demonstrate a new kind of atomic mirror based on the Zeeman interaction between a ground-state atom and the field above a magnetised strip of audio tape [10], and recently, Sidorov *et al* [11] have made a magneto-static mirror based on the same principle, using a macro-

scopic assembly of permanent magnets. In both cases the atoms bounced with high reflectivity, but were quickly lost because of the thermal spread of the atomic cloud. We therefore pursued the possibility of making a curved magnetic mirror which could store atoms for long times without the problem of momentum diffusion due to spontaneous emission. Much of the work published on evanescent wave reflectors can be applied to our magnetic mirror because both have an exponential potential.

A short conference paper [12] recently announced the observation in our laboratory of atom reflection from a curved, magnetised floppy disk [13]. This paper now provides the first full account of our experiments to use a floppy disk as a magnetic mirror for the storage of cold atoms.

## 2. Principles of the Magnetic Mirror

The idea of magnetic mirrors for neutral particles was discussed long ago by Vladimirkii [14] in the context of cold neutrons. He pointed out that a spatially alternating current sheet  $j \cos(kx)\hat{\mathbf{z}}$  produces a magnetic field whose magnitude  $B$  decreases with the distance  $y$  from the surface as  $\exp(-ky)$ , and is independent of the transverse position  $(x, z)$ . 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. The more recent discussion by Opat *et al* [9] considers both electric and magnetic mirrors and suggests the possibility of reflecting or diffracting atoms from the surface of a magnetic recording medium. We have been able to realise this idea in the laboratory using the field produced by part of a floppy disk with sinusoidal magnetisation  $\mathbf{M} = M_0 \cos(kx)\hat{\mathbf{x}}$  in the plane of the disk. In order to compute the field outside the surface, one can replace the magnetisation by fictitious surface current densities  $\mathbf{j} = \nabla \times \mathbf{M}$  on the front and back surfaces of the thin magnetic coating. When the disk is fully magnetised,  $M_0$  is constant throughout the thickness  $b$  of the coating, and  $\mathbf{M}$  is therefore equivalent to two opposing sinusoidally modulated current sheets,  $\mathbf{j} = \pm M_0 \cos(kx)\hat{\mathbf{z}}$  separated by  $b$ . Hence the magnitude of the field outside the disk is

$$B = \frac{1}{2} B_0 (1 - e^{-kb}) e^{-ky} = B_{\max} e^{-ky} \quad (1)$$

where  $B_0 = \mu_0 M_0$  is the remanence field.

An atom in the magnetic field has the magnetic dipole interaction energy  $U = -\mu_\zeta B$ , where  $\mu_\zeta$  is the projection of its magnetic moment onto the field direction. Provided the magnetic field changes slowly enough (and it does for the cold atoms in our experiments), the magnetic moment follows the field adiabatically and the angle between them is constant. In this adiabatic regime the potential energy of the atom depends on the field magnitude  $B$ , but not its direction. Hence an atom having negative  $\mu_\zeta$  experiences an exponentially increasing repulsive potential  $-\mu_\zeta B$  as it adiabatically approaches the magnetic surface. To give a sense of the energy scale, we remark that a 15 G surface field is sufficient to reflect rubidium atoms in the  $(5S_{1/2} F=3, m_F=3)$  state dropped from a height of 1 cm.

The operation of the mirror relies on atoms remaining in the desired magnetic sublevel as they move through the inhomogeneous magnetic field. The probability for an atom to make a non-adiabatic (Majorana) transition to another magnetic sublevel is greatest when the field seen by the atom is small and rapidly changing. We guard against this by applying a weak uniform ‘holding’ field of  $\sim 100$  mG along the  $z$ -axis (in the plane of the disk but perpendicular to the magnetisation), which prevents the total field from going to zero at any point.

If the magnetic mirror is made using a standard commercial recording medium such as audio tape or a floppy disk, the wavelength can easily be as short as  $10 \mu\text{m}$  (5kHz for a normal audio cassette system), and the surface field will typically exceed 100 G (and can be as much as 2 kG for certain audio tapes). For atoms dropped onto such a mirror, the reflecting potential is very steep in comparison with the gravitational one and the atom turns around in a very short distance. For many purposes it is therefore sufficient to regard this potential as a step at which the atomic velocity is instantaneously reversed.

## 3. The Floppy Disk Mirror

### 3.1. Motivation

In a previous publication [10] we reported a normal-incidence atomic mirror based on the magnetic dipole force above a flat strip of audio tape. We showed that regions where the tape was sinusoidally magnetised could reflect specularly and

with high reflectivity provided the atoms were in suitable magnetic sublevels. In between the recorded tracks no sine wave was recorded, and there the tape behaved as a diffuse reflector. When a ball of cold atoms was released from a magneto-optical trap and allowed to fall onto the mirror below, multiple bounces were observed indicating that the mirror and gravity together formed a kind of trap. The main losses from this cavity were due to the thermal spreading of the atomic cloud - with no lateral confinement there was nothing to stop the atoms from walking off the mirror after a few bounces - and the diffuse reflections from the regions between tracks. These limitations can be removed by the use of a concave mirror (to provide lateral confinement) whose surface is completely covered by the sinusoidal signal. Since the audio tape has a tendency to curl and wrinkle when glued down it is not suitable for making a curved reflector, whereas a floppy disk has a large uniform area, and is relatively thick ( $80\ \mu\text{m}$  versus  $12\ \mu\text{m}$  for the audio tape) which makes it quite easy to handle. Moreover, it is easy to record over the whole surface of a floppy disk. For these reasons we chose to use a floppy disk as the basis of our atomic mirror in the experiments to be described.

### 3.2. Physical properties

The magnetic properties of the 5.25 inch disk used in this work (Sony MD-2D) are listed in Table 1. The 700 G residual flux density together with the  $2.5\ \mu\text{m}$  coating thickness can be substituted into Equation (1) to determine the field  $B_{\text{max}}$  at the surface of the disk. For the  $14\ \mu\text{m}$  wavelength of our recording one finds  $B_{\text{max}} = 236\ \text{G}$ . This is significantly weaker than the 1.1 kG surface field for the metal audio tape (Denon HD-M) used in our previous work [10], but it is still sufficient to reflect polarised  $m_F = 3$  rubidium atoms dropped from heights up to 15 cm.

**Table 1.** Manufacturer's specifications for the Sony MD-2D floppy disk used to make our magnetic mirror

Magnetic material	$\gamma\text{Fe}_2\text{O}_3$
Disk thickness	$80\ \mu\text{m}$
Coating thickness	$2.5\ \mu\text{m}$
Coercivity	290 Oe
Residual flux density	700 G

To make a mirror curved in both directions, it is necessary to stretch the material. A 25 mm di-

ameter circle was cut out of the disk and glued with Torr Seal epoxy to a short section of stainless steel tubing. When the tube is evacuated, the disk becomes concave under the influence of atmospheric pressure. It is then gently heated by hot air ( $50\text{-}100^\circ\text{C}$ ) to relax the tension so that the curvature is retained when the pressure difference is removed (this has no effect on the magnetisation of the disk). However, if the disk is subsequently reheated it becomes flat once again. Consequently, one has to take care when baking the vacuum system not to overheat the mirror. It is simple to measure the radius of curvature using an expanded He-Ne laser beam because the surface of the disk is quite shiny. With a 20 mm diameter mirror we were able to set the radius of curvature anywhere in the range  $35 \rightarrow \infty\ \text{mm}$ . We chose 70 mm for the experiments reported here.

### 3.2. Recording signals on the disk

A standard 5.25 inch double density floppy disk drive (Qumetrack 142) records data on 40 circular tracks, each  $330\ \mu\text{m}$  wide, and spaced  $530\ \mu\text{m}$  apart radially. (The more modern high-density drives with narrower tracks are actually less suitable for our purpose because more tracks are required to cover the surface). We were able to eliminate the  $200\ \mu\text{m}$  wide unrecorded strip between the tracks by modifying the drive circuit for the stepper motor, so that the recording head moved in steps of half the usual size. In the overlap region, the later signal completely erases the earlier one, resulting in 80 adjacent  $256\ \mu\text{m}$  wide tracks.

The signal was written onto the disk by applying a voltage directly across the record head and the recorded pattern could be read back by means of the same head, which generates an EMF proportional to the derivative of the magnetisation. At low frequencies, the recorded pattern saturates when the drive voltage is high enough, leaving a square wave magnetisation on the disk which appears as a series of alternating spikes on play-back. However, at higher frequency the behaviour is somewhat different. As the drive voltage is increased the amplitude of the play-back signal levels off but its shape remains approximately sinusoidal. The persistence at high frequency of an approximately sinusoidal pattern even when the disk is being driven into saturation is a consequence of several factors [15] including the speed

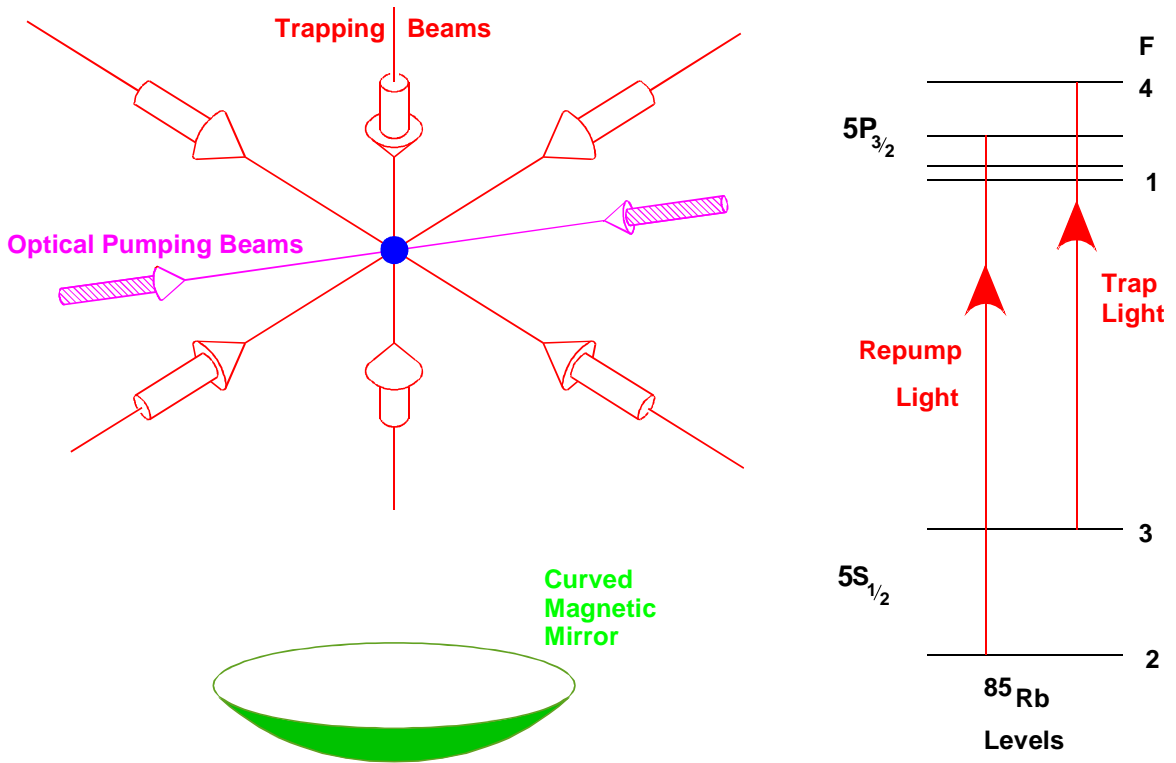
with which the disk surface moves through the head relative to the period of the driving field, and the range of the fringe fields around the head relative to the wavelength of the recorded pattern. Our magnetic mirror was made using a 100 kHz signal of 2.75 V peak-to-peak amplitude to drive the head. At this level the peak of the magnetisation was saturated but the waveform played back still appeared roughly sinusoidal. We find that the wavelength of the recording ranged from 11  $\mu\text{m}$  on the inner radius to 18  $\mu\text{m}$  at the outer edge.

## 4. Experiment

### 4.1. Apparatus

Our experimental arrangement and the relevant atomic levels are sketched in Figure 1. Atoms of  $^{85}\text{Rb}$  are collected from vapour in a vacuum chamber by a magneto-optic trap (MOT) [16,17]. The magnetic field gradient of the trap is made by two 480-turn water-cooled coils of approximately

75 mm diameter, mounted outside the vacuum chamber with a spacing of 170 mm. These carry a current of 4 A in the anti-Helmholtz configuration to produce field gradients at the centre of  $10\text{ G cm}^{-1}$  in the axial direction and  $5\text{ G cm}^{-1}$  transversely. The six laser beams of the trap consist of three pairs of mutually orthogonal 1 mW beams, each making an angle of  $\sim 55^\circ$  with the vertical, which are retroreflected through quarter-wave plates to produce the required circular polarisations. Each beam is collimated and apertured to a diameter of 10 mm. The trap laser is tuned 10 MHz below the 3-4 hyperfine line of the  $5S_{1/2} - 5P_{3/2}$  D2 transition at 780 nm, for which the natural width is 6 MHz. A weak repumping laser beam is superimposed on the trapping beams in order to return any  $F = 2$  ground-state atoms to the  $F = 3$  ground state. The trapping and repumping beams are produced by two separate grating-stabilised, external-cavity diode lasers [18]. Rb vapour is supplied by a heated source held in a side arm of the vacuum chamber.



**Figure 1.** Rubidium atoms are collected and cooled in a magneto-optic trap. After being released and optically pumped, they fall onto a magnetic mirror made from a sinusoidally magnetised piece of a floppy disk. Atoms reflected from the disk are recaptured by turning on the trapping beams again and are detected by their fluorescence. The energy level diagram shows the transitions used.

The time constant for filling the trap can be varied from 1 s up to 20 s by adjusting the temperature of the Rb source to control the pressure of vapour 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 photo-diode. 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.

Once the atoms are released, we optically pump them along the direction of the 100 mG holding field to enhance the population of positive  $m_F$  sublevels in the  $F = 3$  ground state. The pumping light, derived from the "trapping" diode laser (still detuned to  $-30$  MHz), is formed into a pair of spatially filtered counter-propagating, optical pumping beams, centred on the trap as shown in Figure 1. Each beam has a power of order  $25 \mu\text{W}$  and a diameter of 6 mm. When we increase the duration of the optical pumping pulse the number of atoms reflected from the magnetic mirror increases at first, then reaches a maximum and eventually decreases. This is because the recoil from spontaneous emissions eventually increases the temperature of the atoms to a point where the mirror is unable to contain the transverse motion. Typically we use a pulse length of 4 ms. This adjustment needs to be redone each day because the intensity of the optical pumping light depends strongly on the alignment of the laser beam with the spatial filter and because the polarisation of the atoms in the MOT varies somewhat with the alignment of the trapping beams.

We have measured the temperature of atoms prepared in this way to be  $30 \pm 5 \mu\text{K}$ , using a time-of-flight technique. A CCD camera was used to image the cold atom cloud and showed that its initial diameter is less than 1 mm.

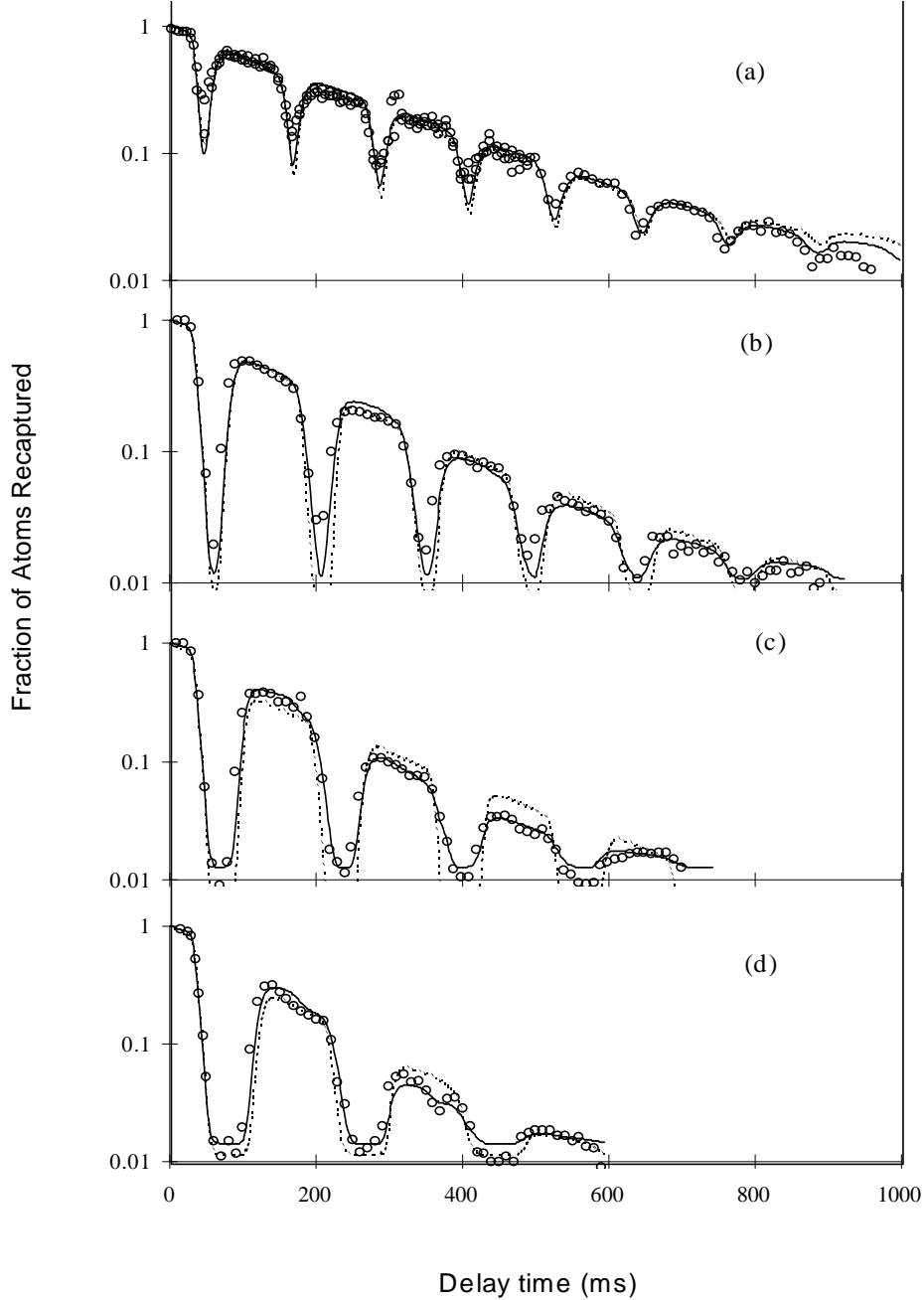
#### 4.2. Experimental procedure and results

In an experimental run we load approximately  $10^7$  atoms into the trap. These are released, optically pumped, and allowed to drop a few centimetres onto the magnetic mirror. The number of reflected atoms is measured after a chosen time delay by turning on the trap for a period of 25 ms.

This is sufficient time to recapture cold atoms that have bounced back into the laser beams, but it is not enough to accumulate a significant number of thermal atoms from the Rb vapour. The fluorescence signal from the recaptured atoms is monitored and compared with the original trap fluorescence to find the fraction of atoms that are recaptured. For each time delay we averaged five such measurements, and by varying the delay we are able to determine the fraction of recaptured atoms as a function of time.

The circles in Figure 2 show the fraction of recaptured rubidium atoms as a function of the time delay between release and recapture for four different drop heights  $h$ . In curve (a), for which  $h = 17.5$  mm, seven or eight bounces are clearly seen for times up to 900 ms. This represents a significant improvement on our audio tape results [10], where 3 bounces up to 500 ms were observed. Curve (b) shows data up to a similar time, but with fewer bounces, since the atoms are dropped from a larger height of 25.5 mm. One also sees that the bounces become more clearly resolved because the cloud is better able to leave the region of the trapping laser beams. This trend continues in curves (c) and (d) for which  $h = 32.5$  mm and 40.5 mm. In addition, the signal is seen to decay more rapidly for larger drop heights, with a particularly strong attenuation when we go from (c) to (d). These observations are the first demonstration that atoms can be reflected and focused by a curved magnetised floppy disk.

When we reversed the helicity of the optical pumping light, thereby preparing the atoms in the negative  $m_F$  states, the reflected atom signal was very small - less than 0.04 at the peak of the first bounce for a 17.5 mm drop height. This confirms that the reflectivity is indeed due to the magnetic interaction between the atoms and the floppy disk. We also repeated the experiment without any optical pumping light, and in that case the reflected atom signal was five times smaller. This is not entirely surprising because the atoms in the MOT tend to be pumped into the negative  $m_F$  states (with respect to the local magnetic field) and the MOT field is turned off adiabatically. Thus it would seem that only about 20% of the atoms in the MOT have  $m_F > 0$ .



**Figure 2.** Fraction of atoms recaptured as a function of time after their release from the trap. Curves (a), (b), (c) and (d) correspond to drop heights of 17.5, 25.5, 32.5 and 40.5 mm, respectively. Circles show experimental results. Dotted curves show computer simulations without any corrugation of the reflecting surface. Qualitative features are reproduced in this simulation but the  $\chi^2$  is too high. Full curves show computer simulations including corrugation of the reflecting surface and have a satisfactory  $\chi^2$ . In this fit, the lifetime for collisional loss is  $\tau = 224(15)$  ms, the reflectivity is  $R = 1.10(3)$  and the RMS angular variations of the reflecting surface are given in table 2 for each drop height.

In order to understand the detailed form of the data shown in Figure 2, we have developed a computer simulation model. A Monte Carlo method is used to select the initial velocities and positions of atoms as they are released. The ve-

locity distribution corresponds to the measured temperature of  $30 \mu\text{K}$ , and a Gaussian spatial distribution of FWHM 1 mm is assumed, corresponding roughly to the cloud in our trap. (In fact, this cloud diameter is small enough that

there is no significant finite size effect). Ballistic atomic trajectories are calculated as the atoms fall under gravity. The mirror is described by a smooth spherical surface with radius of curvature  $R_m = 70$  mm and diameter 20 mm. Owing to the very short range of the potential ( $\sim 2$   $\mu\text{m}$ ), the interaction is treated as a hard collision in which each atom has a probability  $R$  (the mirror reflectivity) of rebounding elastically from the surface. Atoms are counted as retrapped if they enter any one of the trapping beams. The geometrical layout of the trapping beams, mirror and cold atom source are all incorporated into the program.

For a realistic simulation of the experiment, three more parameters are required in addition to the reflectivity. First, the loss of cold atoms due to collisions with hot background gas is included as a steady attenuation  $\exp(-t/\tau)$ . Second, the incomplete optical pumping leaves a small fraction  $1-\eta$  (approximately 0.2) of the atoms in magnetic sublevels  $m_F \leq 0$  that are not reflected, and it is assumed that these are lost in the first collision with the mirror. Finally, we include a constant background signal level, arising from stray scattered light reaching the photo-diode.

The parameters of the theory were adjusted to fit the four curves in Figure 2 by minimising the  $\chi^2$  parameter. Each curve was allowed its own optical pumping efficiency  $\eta$  because the optical pumping beams had been adjusted before each run, but the values of  $R$  and  $\tau$  were applied globally. After this fit, the simulation reproduced all the qualitative features of the data as shown in Figure 2. This demonstrates that the atoms are bouncing largely as expected, but it is also clear that there are systematic discrepancies between the model and the data. Most notably, the troughs between bounces in curves (b), (c), and (d) are consistently too wide in the simulation, and in (c) and (d) the peak heights are not so well reproduced. Furthermore, the best  $\chi^2$  is twice as large as one could reasonably expect for a good fit.

We find that a satisfactory  $\chi^2$  can be achieved by allowing the spherical reflecting surface to be slightly corrugated, producing a small spread in the angle of reflection of the atoms. Such a spread is to be expected because the magnetisation of the surface is not a pure sine wave. The presence of higher harmonics in the magnetic field alters the interaction between the atom and the surface so that the equipotentials become corrugated [9]. For example, a fraction  $f$  of second harmonic content causes the direction of the

Stern-Gerlach force to vary by an angle  $f e^{-ky} \sin kx$ , where  $y$  is the height above the surface and  $k$  is the wavevector of the fundamental [9,19]. Atoms dropped from rest from a height  $h$  above the mirror reach their turning point at a height  $y_0$  where the magnetic potential energy,  $-\mu_\zeta B_{\text{max}} e^{-ky_0}$ , is equal to the initial potential energy of the atom,  $mgh$ . Consequently the direction of the Stern-Gerlach force at the turning point varies by an angle of order  $f mgh / \mu_\zeta B_{\text{max}}$ , which is linear in the drop height. When the amplitude of the second harmonic is 10% of the fundamental this angle amounts to approximately 40 mrad for a drop height of 40 mm. It is also possible that the physical roughness of the floppy disk makes an additional contribution to the angular spread of the reflected atoms.

**Table 2.** The RMS angular variation of the reflecting surface as a function of the height  $h$  from which the atoms are dropped. This is a measure both of the corrugations due to harmonic distortion of the magnetisation and of the physical roughness of the surface.

Drop height $h$ (mm)	$\Delta\theta$ (mrad)
17.5	24(3)
25.5	32(3)
32.5	36(3)
40.5	38(5)

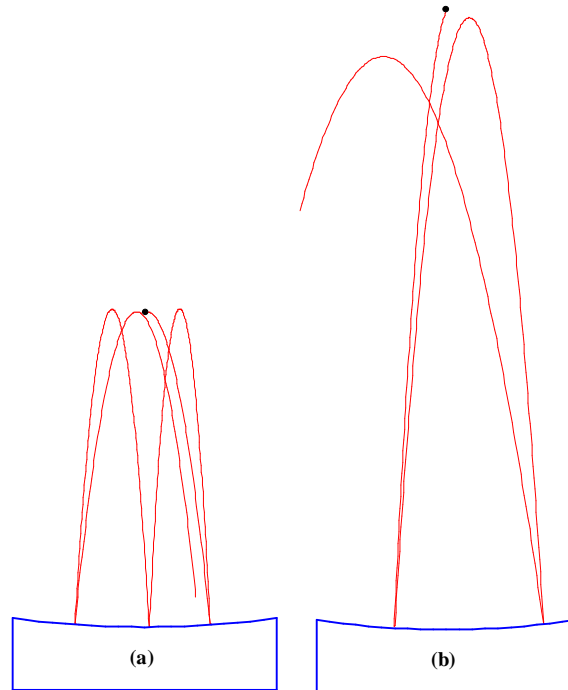
Motivated by these arguments, we allowed the spherical reflecting surface in our simulations to have angular corrugation  $\vartheta \cos kx$  and adjusted  $\vartheta$  as an additional fitting parameter for each of the four curves. This new degree of freedom improved the fit substantially as shown in Figure 3 and yielded the fitting parameters,  $\tau = 224(15)$  ms,  $R = 1.01(3)$ , where the numbers in parentheses are the standard deviations. The optical pumping efficiency parameters  $\eta$  are of no particular interest, but we note that the values were between 77% and 89%, corresponding within a factor of two to the scattering of ten photons. Finally, the fit gave the rms angular variation due to corrugations of the surface,  $\Delta\vartheta = \vartheta / \sqrt{2}$ , for each drop heights as listed in Table 2. We see that the angular variation does indeed increase with drop height as one would expect from harmonic distortion and we believe that this is probably due to a second harmonic amplitude of about 15%. We have now started to study the magnetic field of the mirror directly by

means of magnetic force microscopy and we see clear evidence of harmonic distortion at this level. We have also begun to look at the surface topography of the disk by atomic force microscopy. It is hoped that these studies will produce a quantitative explanation of the mirror properties measured here and will allow us to assess how good the optical quality of floppy disk mirrors can ultimately be. This will be the subject of the second paper in this series.

#### 4.3. Discussion of atom dynamics in the trap

The motion of atoms in the magnetic mirror trap depends on their initial position and velocity and on the size and radius of curvature  $R_m$  of the mirror. For our small cold cloud of atoms released close to the optic axis, the Monte Carlo simulations show that the trajectories belong to two general classes according to whether the drop height  $h$  is less than or greater than  $R_m/2$ . In the first class ( $h < 35$  mm), more than 93% of the atoms are contained indefinitely by the smooth reflecting surface of 20 mm diameter which rep-

resents our mirror. Those that are lost come from the high transverse-velocity tail of the Maxwell-Boltzmann distribution. For most drop heights in this range the atoms that walk off the mirror do so in the first few bounces and this is the case for runs (b) and (c) ( $h = 25.5$  and  $32.5$  mm). Figure 4(a) shows a typical trajectory for these atoms: the direction of the horizontal velocity is reversed on the first bounce and the magnitude is reduced. The limiting case for this class is  $h = R_m/2$ , when the first bounce reverses the horizontal velocity exactly and the atoms simply retrace their paths. Another special case within this class of stable trajectories is that of  $h = R_m/4$  for which the horizontal velocity is reduced to zero by the first bounce. In this case, our simulation shows that the hot atoms leave the trap anomalously slowly, and this motivated our choice of  $h = 17.5$  mm for run (a). When  $h > R_m/2$ , the horizontal speed increases after each bounce and the atoms quickly walk off the mirror as shown in Figure 4(b). Run (d) is of this type.



**Figure 3.** Scale drawing showing typical stable and unstable trajectories with a 70 mm radius of curvature mirror. (a) 25mm drop height. After the first bounce the atom's horizontal velocity is reversed in direction and reduced in magnitude. The subsequent motion is confined. (b) 45mm drop height. The horizontal speed of the atom increases after each bounce until the atom walks off the mirror surface.

Some aspects of these numerical results are elucidated by a simple analytical approximation [20] which assumes that the initial transverse velocity is much less than  $\sqrt{2gh}$  and that the surface of the reflector is parabolic. Using this approach, Wallis *et al* have shown that when an atom bounces on the mirror surface, successive points of contact cover a circle of radius  $\rho_M$  given by a rather complicated expression (Equation 38 of reference [20]). For a given velocity this radius is practically constant when  $h < R_m / 2$ . For these drop heights,  $\rho_M$  is smaller than the 10 mm radius of our mirror for 93% of the velocity distribution, and therefore most atoms follow stable trajectories. By contrast, if  $h$  exceeds  $R_m / 2$ ,  $\rho_M$  grows very rapidly so that when  $h = 40.5$  mm (our run (d)) a typical value is 28 mm. The loss rate is then large and all the atoms eventually walk off the mirror.

Although this simple analytical picture provides some physical insight, the behaviour of atoms reflecting from a real surface is quite different and still must be calculated numerically. This is because any transverse momentum kicks imparted by corrugations or other imperfections of the mirror (including photon scattering in the case of the evanescent wave) allow trapped atoms to diffuse from the stable region of phase space to the unstable one. In our simulation this appears as a decay of the number of atoms in the trap which persists even after the initial transient associated with the loss of hot atoms, although it should be made clear that this loss rate is far less than the collisional loss in our present experiments. Another manifestation of the corrugations can be seen as a filling-in of the troughs between bounces when one compares Figs. 2 and 3. This is due to an increase in the number of atoms near the edge of the mirror, a region that is more efficiently recaptured by the laser beams because of the geometry. Finally, this diffusion makes the difference between runs (c) and (d) less dramatic than it would be in the ideal case because the atoms dropped from just below  $R_m / 2$  are readily destabilised by the corrugations.

#### 4.4. Comparison with audio tape and evanescent wave mirrors

Previously [10], we studied the reflection of atoms from flat strips of sinusoidally magnetised audio tape. With the floppy disk we find, as in the case of audio tape, that the reflectivity of the

magnetic mirror is essentially unity. However, in this case we have been able to cover the whole surface with the magnetic pattern to make a practical device of high average reflectivity. Curving the mirror is also a significant advance: with a transverse thermal velocity of some 7 cm/s (30 $\mu$ K), the atoms quickly walk off a flat mirror, but most of the atoms in the Maxwell-Boltzmann distribution can be confined indefinitely by a perfect curved mirror to the extent that there are no collisions. It is interesting to compare the collisional lifetimes for the trapped and free-falling atoms in the two experiments. In the audio tape experiment, the trap lifetime was  $\sim 5$  s and the collisional loss lifetime for the bouncing atoms was  $526^{+300}_{-140}$  ms, whereas the corresponding figures for the floppy disk experiment were  $\sim 10$  s and 224(15) ms respectively. With this doubling of the trap lifetime one might have expected a corresponding decrease in the collisional loss, and since that is the dominant loss for the present experiment, one might have hoped for storage times in excess of 1s for atoms bouncing on the curved floppy disk mirror. However, atoms in the MOT are partly in the excited state, which makes them particularly sensitive to the background pressure of rubidium because of the resonance interaction. By contrast, the ground-state atoms in free fall are very sensitive to the presence of any background gas and have no particular sensitivity to rubidium. Thus the shorter collisional lifetime in the floppy disk experiment suggests that the disk outgases more than the tape. Since this is the limiting factor in the storage time, we plan in future experiments to try sealing the surface by overcoating it with titanium [21]. According to our simulations, which incorporate the corrugations of the reflecting surface, storage times of tens of seconds may be possible if the pressure loss can be eliminated.

A recent investigation of the evanescent wave mirror [22] reveals that the atoms do not reflect specularly unless the surface supporting the evanescent wave is of extraordinarily high quality. In order to reduce the transverse momentum spread to the level of a few photon recoils per bounce, it was necessary to achieve an rms surface roughness of order 0.1 nm, which imposes stringent limits on evanescent wave mirrors in atom optics experiments! In this context, it is interesting to consider how many photons would have to be scattered by our rubidium atoms to produce the angular spread per bounce meas-

ured in our experiment. For a drop height of 17.5 mm, the angular spread of the reflected atoms (twice that of the surface) is 48 mrad (see Table 2). This implies a transverse velocity of 2.8 cm/s or 5 times the photon recoil velocity. Since the linearity of the magnetic recording can certainly be improved, it seems likely that the floppy disk can compete effectively with evanescent wave mirrors in this regard: the absence of spontaneous emission is clearly an advantage.

The size of the evanescent wave mirrors is typically 0.5 mm, governed by the need for sufficient intensity. By contrast, the magnetic mirror described in our work here is an order of magnitude larger in diameter and there are no fundamental reasons why even larger mirrors with uniform reflectivity could not be fabricated.

The high specular reflectivity of the floppy disk magnetic mirror leads us to conclude that it is a promising development for atom optics. However, we do not know to what extent the optical quality of such a mirror will ultimately be limited by the momentum diffusion due to corrugation of the reflecting surface. This question is now under investigation in our laboratory and will be the subject of a second paper in this series.

### Acknowledgements

This work was supported by the EPSRC and by the University of Sussex.

### References

- 1 For a recent review, see Metcalf H and van der Straten P 1994 *Phys. Rep.* **244** 204
- 2 *Quantum Semiclass. Opt.* 1996 **8** Special issue on Atom Optics
- 3 Cook R J and Hill R K 1982 *Opt. Comm.* **43** 258
- 4 Balykin V I, Letokhov V S, Ovchinnikov Yu B and Sidorov A I 1987 *JETP Lett.* **45** 353
- 5 Kasevich M A, Weiss D S and Chu S 1990 *Opt. Lett.* **15** 607
- 6 Aminoff C G, Steane A M, Bouyer P, Desbiolles P, Dalibard J and Cohen-Tannoudji C 1993 *Phys. Rev. Lett.* **71** 3083
- 7 Labeyrie G, Landragin A, von Zanthier J, Kaiser R, Vansteenkiste N, Westbrook C and Aspect A 1996 *Quantum Semiclass. Opt.* **8** 603
- 8 Seifert W, Kaiser R, Aspect A and Mlynek J 1994 *Opt. Comm.* **111** 566
- 9 Opat G I, Wark S J and Cimmino A 1992 *Appl. Phys. B* **54** 396
- 10 Roach T M, Abele H, Boshier M G, Grossman H L, Zetie K P and Hinds E A 1995 *Phys. Rev. Lett.* **75** 629
- 11 Sidorov A I, McLean R J, Rowlands W J, Lau D C, Murphy J E, Walkiewicz M, Opat G I and Hannaford P 1996 *Quantum Semiclass. Opt.* **8** 713
- 12 Roach T M, Abele H, Boshier M G, Grossman H L, Zetie K P and Hinds E A 1996 in *Laser Spectroscopy, XII International Conference*, edited by M. Inguscio, M. Allegrini, and A. Sasso (World Scientific, Singapore) p 113.
- 13 Roach T M 1996 *Interaction of Laser-Cooled Atoms and Magnetic Surfaces*, Ph.D. Thesis, Yale University, Unpublished.
- 14 Vladimirskiĭ V V 1961 *Sov. Phys. JETP* **12** 740
- 15 Bertram H Neal 1994 *Theory of Magnetic Recording* (Cambridge University Press); Mee C Denis 1986 *The Physics of Magnetic Recording*, (North Holland, New York)
- 16 Raab E L, Prentiss M, Cable A, Chu S and Pritchard D E 1987 *Phys. Rev. Lett.* **59** 2631
- 17 Monroe C, Swann W, Robinson H and Wieman C 1990 *Phys. Rev. Lett.* **65** 1571
- 18 Boshier M G, Berkeland D, Hinds E A and Sandoghdar V 1991 *Opt. Comm.* **85** 355
- 19 A paper giving a full discussion of the harmonic distortion effects is in preparation.
- 20 Wallis H, Dalibard J and Cohen-Tannoudji C 1992 *Appl. Phys. B* **54** 407
- 21 We are indebted to J. Dalibard for this suggestion.
- 22 Landragin A, Labeyrie G, Henkel C, Kaiser R, Vansteenkiste N, Westbrook C I and Aspect A 1996 Submitted to *Optics Letters*