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Smoothing a current-carrying atomic mirror

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Abstract. – We have measured the magnitude and roughness of the reflecting potential produced by a current-carrying magnetic mirror from which cold rubidium atoms have been bounced at normal incidence. By varying the current in the mirror, a study of the potential barrier from which the atoms in different magnetic substates bounce has been made. A combination of time-of-flight and imaging techniques allowed us to study the roughness of the reflecting potential. We have demonstrated that the observed roughness can be reduced by additional wires to compensate for the finite-size effects, and by careful control of the direction of the magnetic bias field.

With the maturing of the field of atom optics, atomic mirrors have been studied extensively over the past few years. Most mirrors rely on the interaction of either an induced atomic electric dipole moment with an evanescent wave [1], or a permanent atomic magnetic moment with a magnetic field. The latter type, first discussed theoretically in refs. [2] and [3], generally consists of an alternating periodic array of magnetic elements. Experiments of this type have been carried out using magnetic recording media [4, 5], an array of permanent magnets [6] and recently, arrays of current-carrying wires [7-9].

Two characteristics of the barrier potential from which atoms bounce are crucial: first the maximum barrier height, which determines the maximum incident kinetic energy that can be reflected, and second, its roughness, the deviation of equipotential surfaces from a plane (or from the appropriate shape in the case of a focusing mirror [5, 10]), which determines how diffuse the reflection is. When it is not necessary to consider the wave nature of the bouncing

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atoms, the diffuse character of the reflection can be parameterised by the angular standard deviation, $\theta_{\rm diff}$, of the reflection angles of the atoms around the specular direction of reflection.

In this paper, we present a quantitative experimental study of the diffuse atomic reflection from a microfabricated current-carrying magnetic mirror. In particular for the first time we demonstrate experimentally how to reduce the diffuseness of the atomic reflection with the addition of extra wires at the edges of the mirror. These carried a current different from that in the rest of the mirror and were used to compensate, in the centre of the mirror, for the finite-size effects. We have also made quantitative measurements of the effect of an improperly oriented bias field on the roughness, and of the reflectivity of the mirror as a function of the current. Comparisons with theoretical models show that there still exists room for improvement towards perfectly specular current-carrying magnetic mirrors.

The reflecting potential of a magnetic mirror is due to the interaction of the magnetic dipole of the atom with the magnetic field created by the mirror, **B**. If it is assumed that the atom adiabatically follows the magnetic field then it remains in a specific magnetic substate m_F, and to second order in the magnetic field, for the case of ^{85}Rb atoms in the $F = 3$ electronic ground state, the reflecting potential may be written as

$$U = g_F m_F \mu_{\rm B} B + (9 - m_F^2)(g_F \mu_{\rm B} B)^2/(\hbar\Omega_{\rm hf}), \tag{1}$$

where $g_F = 1/3$ is the Landé factor, $\mu_{\rm B}$ is the Bohr magneton, B is the modulus of the magnetic field **B** and $\Omega_{\rm hf}/2\pi = 3.0\,{\rm GHz}$ is the frequency between the hyperfine ground states.

If a mirror consists of an infinite array of infinitely long wires spaced by $a/2$, alternately carrying current in opposite directions, the magnetic field far from the mirror ($z \gg a$) can be written as [8]

$$\mathbf{B}(\mathbf{r}) = \frac{2\mu_0 I}{a} e^{-2\pi z/a} \left[\hat{\mathbf{x}} \cos 2\pi x/a + \hat{\mathbf{z}} \sin 2\pi x/a\right], \tag{2}$$

where I is the current in the wires, μ_0 is the permeability of free space and the directions correspond to those in fig. 1a. Since the potential U seen by the atoms is only determined by the magnitude B of the magnetic field, it is independent of x and y for a given z, and the mirror is flat.

The magnetic field created by a real mirror is different from the ideal case for many reasons. At finite distances from the mirror additional terms must be added to eq. (2). These are higher-order harmonics of the fundamental period a and add roughness to the potential. They depend critically upon the wire shape [3, 11] and decrease exponentially with z, faster than the fundamental term given in eq. (2).

The finite extent of the mirror in the x direction also introduces effects which modify the magnetic field. A qualitative understanding can be gained by considering the magnetic field to be that due to an infinite mirror minus the field due to the missing wires. The missing wires would create a field in the xz-plane that near the centre of the mirror varies only slowly with x and z. The sum of this field and that of eq. (2) does not have a constant magnitude at a constant z, and a corresponding roughness appears in the equipotential surfaces. To diminish these finite-size effects, a field can be added which approximates that due to the semi-infinite planes of missing wires. As a first approximation, this may be done by energising the last wire on each edge of the array with half the current of the other wires [6, 8, 9, 11].

A constant bias magnetic field that has a component in the xz-plane will also add roughness to the mirror. Since a bias field was necessary to ensure the adiabatic following of the magnetic substates, this field was carefully aligned along the y-axis.

We have studied the reflecting potential using two different techniques. Simple absorption measurements in a time-of-flight probe beam allowed us to study the number of atoms reflected

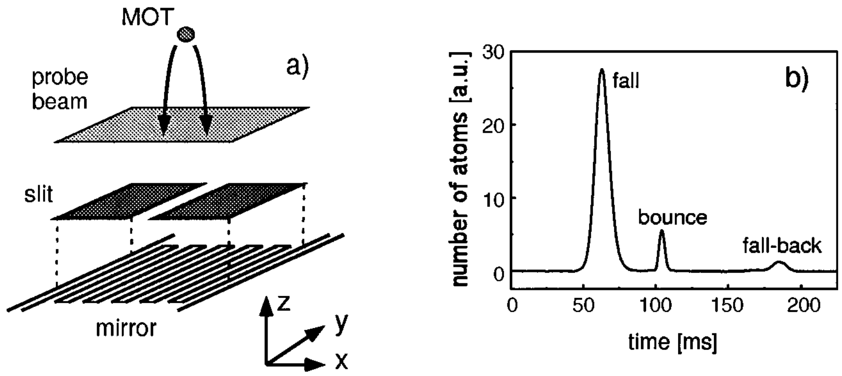

Fig. 1. – a) Schematic of the experimental set-up: atoms from a MOT were dropped onto the electromagnetic mirror, above which a slit was placed. The mirror was composed of 101 wires (only a small number of which are represented in the diagram) and two additional "compensating wires". A probe beam above the slit, which could be switched on and off as required, was used to detect the atoms. b) Typical time-of-flight curves. The three peaks, obtained in different runs, correspond to the fall, the bounce and the fall back.

by the mirror and gave an insight into important parameters which can affect the barrier height. Fluorescence imaging of the atomic cloud after reflection enabled a quantitative study of the roughness of the mirror.

The mirror used in our experiments consisted of a parallel array of 103 current-carrying gold wires, which alternately carried the current in opposite directions as indicated in fig. 1a. The fabrication of such mirrors has been described elsewhere [12]. The choice of an odd number of wires reduces the mirror roughness [9, 11]. The mirror had overall dimensions of 1 cm by 1 cm and the wires had a spacing of $100\,\mu$m ($=a/2$). Their width was $\sim 70\,\mu$m and height $\sim 7\,\mu$m. The first and the last wires had separate connections so that they could be independently supplied with a current different from the rest of the mirror. These were used as the "compensating wires" to correct for the finite-size effects. The mirror was cooled close to liquid-nitrogen temperature and the current, varied between 0 and 3.4 A, was turned on for only 5 ms every 1.5 s cycle to avoid thermal damage.

The experimental set-up was the same as that used in ref. [13]. Every 1.5 s, approximately 3×10^7 ^{85}Rb atoms were loaded into a magneto-optical trap (MOT), cooled in optical molasses for 15 ms, and dropped onto the mirror situated 19.6 mm below the centre of the MOT. To restrict bouncing to the central section of the mirror and to perform a selection of velocity in the transverse direction, a slit was placed ~ 3 mm above the mirror (see fig. 1a). The slit had a width of 1 mm, so the atoms only bounced on a central slice of the mirror. We detected the number of reflected atoms by measuring the absorption in a retroreflected probe beam located between the mirror and the MOT. A typical experimental signal is shown in fig. 1b. The loss of signal between the fall and bounce was primarily due to the selection of the slit. The probe beam propagated along x at 90° to the slit; this allowed a selection in position along the y-axis. The width of the probe beam could be varied from 1 mm to 1 cm in the y-direction and its FWHM in the z-direction was 1.4 mm .

Figure 2 shows the number of reflected atoms as a function of the current I in the mirror when the incident atoms were not polarised. We clearly observe a series of steps, corresponding to the thresholds for different m_F states. This is predicted by eq. (1) since B is proportional to I.

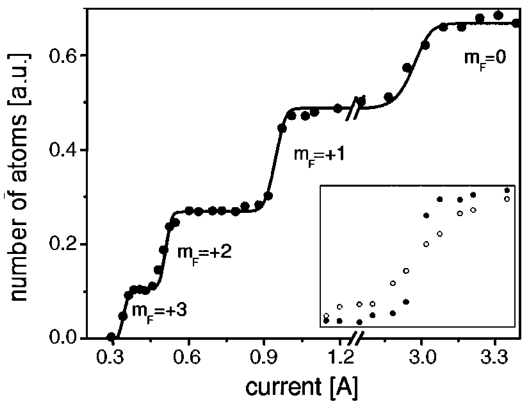

Fig. 2. – Number of atoms detected after a bounce as a function of the current in the mirror. The atoms are not optically pumped. The inset shows the difference between the small (solid) and large (open) probe beams for the detail of one of the steps (data rescaled along the vertical axis for comparison). The solid curve is a theoretical model of the number of atoms bounced, as is discussed in the text. The magnitude of the magnetic field at the turning point of the atomic trajectory is $\sim$30 G for atoms in the $m_F = +3$ state.

We analysed the steps by assuming an infinitely steep threshold convolved with the energy distribution of the incident atoms, primarily due to the initial spatial distribution in the MOT. The solid line in fig. 2 shows a fit based on this assumption in which the only fitting parameters are the constant of proportionality between the measured current and the magnetic field, and the populations of the various m_F levels. The quadratic Zeeman effect amounts to a 13% correction in the position of the $m_F = 1$ step and is entirely responsible for the $m_F = 0$ step. We have compared the measured constant of proportionality with the result of a simple model where we calculated the field above the surface of a mirror consisting of a series of flat, current-carrying, 70 μm wide ribbons. The magnetic potential at the surface of the mirror varies with x, therefore near the threshold current atoms will only be reflected over part of the wire period. Thus we expect the average reflectivity of the mirror to increase over a range of currents. Defining the threshold current as that for which 50% of the atoms are reflected, we found good agreement with our measurements. However using this model to calculate the steepness of the steps, we found steps about 3 times less steep than we observed. A lack of agreement is not surprising since we know that the potential close to the surface depends very critically on the shape of the wires [11]. The steepness of the experimental steps is striking, however, and it would be interesting to pursue more sophisticated modeling of the threshold shape.

The step shape gives us some insight into the homogeneity of the mirror. We show in the inset to fig. 2 the effect of using a wide probe beam (1 cm). In this case we were sensitive to atoms reflected all along the length of the slit. The steps (only one is shown in the inset) are much less steep than for the narrow probe (1 mm). We conclude that this is due to the inhomogeneity of the potential. Note that we only used the centre of the mirror for the roughness studies presented below.

Since atoms in different magnetic substates bounce at different heights above the mirror, the corresponding roughness is expected to be different and hence we optically pumped the atoms into a single level, $5^2S_{1/2}\ m_F = +3$, before they bounced from the mirror. This was done using a circularly polarised laser beam. A bias magnetic field of approximately 70 μT

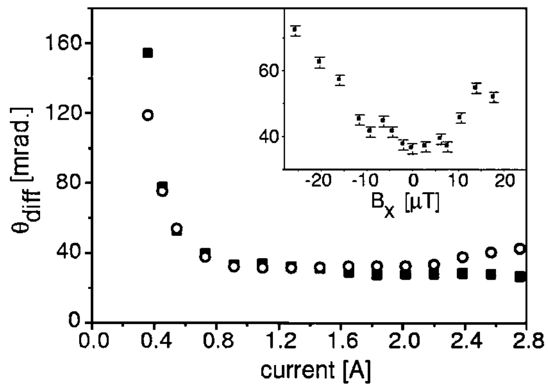

Fig. 3. – The roughness of the mirror as a function of the current. The circles are for an odd number of wires and the squares for the same mirror in which the compensating wires were energised. The inset shows the roughness as a function of the component B_x of the bias magnetic field for a current of 1.6 A without compensating wires. Every point is the result of 20 averages.

was used to lift the degeneracy between Zeeman sublevels during the optical pumping. In order that the atoms remained in the same Zeeman sublevel, a bias field of approximately the same magnitude was maintained throughout the bounce. The bias field could be slowly rotated while the atoms fell onto the mirror. This permitted us to choose the direction of the bias field when the atoms were interacting with the mirror.

In order to study the roughness, we observed the expansion of the atomic cloud by imaging the fluorescing atoms as they passed through the large retroreflected probe beam onto a CCD camera. The beam had an intensity of $1\,\mathrm{mW/cm^2}$ and a detuning of 5 MHz below the atomic resonance. Its height could be varied, and by switching the beam on at the appropriate time, we could observe the atoms either on their way up (bounce) or back down (fall back). Thus the expansion of the cloud could be measured for times as long as t=110 ms after the reflection from the mirror.

The images were analysed to obtain the roughness of the mirror. A Gaussian of the form $e^{-x^2/2\sigma_{\mathrm{exp}}^2}$ was fitted to a slice elongated along x and 0.4 mm wide along y. We calculated the resolution function of our experiment using a Monte Carlo simulation of atoms bouncing on a perfectly flat mirror, including the distribution in position and velocity of the atoms, the presence of the slit, the pulsed nature of the mirror, the detection time and the diffusion of the atoms in the probe beam. For typical times of 100 ms after the bounce, this function is well approximated by a Gaussian of width σ_{spec} and therefore we define the expansion of the atomic cloud due to the roughness of the mirror by $\sigma_{\mathrm{diff}}^2 = \sigma_{\mathrm{exp}}^2 - \sigma_{\mathrm{spec}}^2$. Since we find that σ_{diff} varies linearly with t, we immediately obtain the rms width of the angular distribution of the reflection angles $\theta_{\mathrm{diff}} = \sigma_{\mathrm{diff}}/(v_{\mathrm{m}}t)$, where v_{m} is the average vertical impact velocity of the atoms at the mirror. For our experiment θ_{spec} $(= \sigma_{\mathrm{spec}}/v_{\mathrm{m}}t)$ is 19 mrad.

As an illustration of this technique, we show in the inset to fig. 3 the effect on θ_{diff} of the x-component of the bias field. We find a clear minimum, corresponding to the orientation of the bias field along the y-axis as explained above. A similar behavior was observed for the z-component of the bias field. For a correctly oriented field we observed no change as its magnitude was changed from 5 to 30 μT.

From this demonstration of the dramatic influence of stray fields on the roughness, it is clear that it is very important to compensate the fields due to the finite-size effects discussed above. Figure 3 shows the effect of compensating wires at each x edge of the mirror. With no compensation (open circles) θ_{diff} *vs.* I displays a dramatic decrease followed by a slow rise. If we energise the compensating wires with one half the current in the rest of the mirror (black squares) the behavior of θ_{diff} is almost identical for small currents but continues to decrease slowly as the current is increased. At the highest current we tested, the improvement due to the compensation is almost a factor of 2. This behavior is easily understood qualitatively: at low currents, the atoms bounce very close to the mirror and the roughness in the centre of the mirror is determined mainly by higher-order corrections to eq. (2). At large currents, the atoms bounce further away from the wires ($70\,\mu$m at $I = 2.8$A) and it is the field due to the "missing wires" that most influences the roughness. In this region the compensating wires have more effect.

The minimum value of θ_{diff} we have observed is 26 mrad for a current of 2.8 A. If we define the roughness as the rms deviation of an effective reflecting surface from perfectly flat, (σ_θ as defined in ref. [5]) we obtain half this value, a roughness of 13 mrad. This latter figure is to be compared with other magnetic mirrors: 6 mrad quoted in ref. [5] and 22.5 mrad in ref. [6]. The best measurement with an evanescent wave mirror gave 5 mrad for the rms deviation of the effective reflecting surface [14].

A theoretical model assuming rectangular wires indicates that the mirror should have been flatter. Calculations similar to those of ref. [11] predict σ_θ of the order of 1 mrad for a turning point height of $a/3$. There are many possible explanations for our larger observed value. First, the mirror may contain imperfections in the cross-section and spacing of the wires. Second, although we nulled the DC component of the residual field along x, there could be AC components (*e.g.*, at 50 Hz) remaining. The inset to fig. 3 indicates that an AC field of less than $10\,\mu$T could have a significant effect on the observed roughness. Future experiments should be performed in a magnetically shielded environment. Including compensating wires in the x-direction may also be desirable [11].

To conclude, we have experimentally demonstrated a significant reduction of the roughness of a current-carrying magnetic mirror by compensating finite-size effects. We have also carried out other quantitative studies precise enough to show some discrepancies with theoretical models, although general trends seem to be well understood. Further investigations of these discrepancies should yield a guide for the realization of improved atomic mirrors.

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