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Manipulating Beams of Ultra-cold Atoms with a Static Magnetic Field*

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Abstract

We report preliminary results on the deflection of a beam of ultra-cold atoms by a static magnetic field. Caesium atoms trapped in a magneto-optical trap (MOT) are cooled using optical molasses, and then fall freely under gravity to form a beam of ultra-cold atoms. The atoms pass through a static inhomogeneous magnetic field produced by a single current-carrying wire, and are deflected by a force $\nabla(\mu . \boldsymbol{B})$ dependent on the magnetic substate of the atom. The population of atoms in various magnetic substates can be altered by using resonant laser radiation to optically pump the atoms.

1. Introduction

In recent years the mechanical effects of light have been used to manipulate the position and momentum of neutral atoms, allowing the production of samples of ultra-cold atoms with temperatures of order a few microkelvin or lower (see for example Foot 1991 and references therein). The extremely low velocities of laser-cooled atoms correspond to de Broglie wavelengths ($\lambda_{\mathrm{dB}} = h/mv$) that are comparable to optical wavelengths. Matter–wave experiments that have previously been the domain of electron and neutron physics can now be performed using slow atoms in the emerging field of atom optics (see for example Adams *et al.* 1994). Important in such applications of laser-cooled atoms is the development of atomic-optical elements, such as mirrors, beamsplitters and recombiners. Considerable progress has been made in developing mirrors and beamsplitters using optical electromagnetic fields, both as free-running laser beams (Martin *et al.* 1988; Riehle *et al.* 1991) and as evanescent fields (Cook and Hill 1982; Balykin *et al.* 1988; Hajnal and Opat 1989). A potentially simpler way of manipulating atoms with the electromagnetic force is to use the interaction between static inhomogeneous magnetic fields and the atomic magnetic dipole moment (Opat *et al.* 1992). In this paper we report preliminary results from experiments on the deflection of a beam of laser cooled atoms by the inhomogeneous magnetic field of a current-carrying wire. Although deflection of atoms using a single

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current-carrying wire may not be directly useful in atom optics experiments, the underlying principles and techniques are relevant to the production of atomic mirrors and diffraction gratings using static magnetic fields.

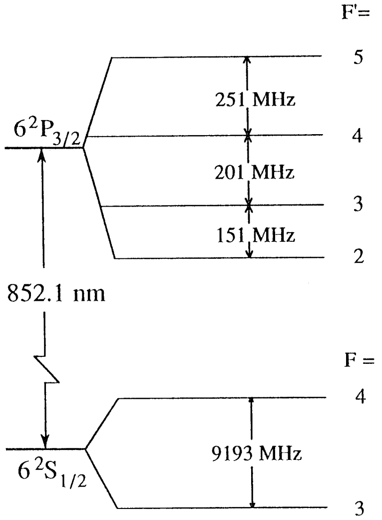

Fig. 1. Energy level diagram for the $6^2S_{1/2}$–$6^2P_{3/2}$ transition of ^{133}Cs.

2. An Ultra-cold Beam of Atoms

In the present experiment three mutually orthogonal pairs of counterpropagating σ^+–σ^- laser beams intersect at the zero-field point of a spherical quadrupole magnetic field produced by a pair of current-carrying coils in 'anti-Helmholtz' configuration, forming a magneto-optical trap (MOT) (Raab *et al.* 1987). The MOT is loaded with caesium atoms from a vapour in an ultra-high vacuum (UHV) chamber with background pressure $\leq 10^{-8}$ Torr (1 Torr = 133 Pa). The atomic transition used is the $6^2S_{1/2}$–$6^2P_{3/2}$ resonance at 852·1 nm, the upper level of which has a lifetime of 31 ns corresponding to a natural linewidth of 5 MHz. The trapping/cooling laser is tuned approximately one natural linewidth to the red of the $F = 4 \rightarrow F' = 5$ hyperfine transition. The hyperfine structure of caesium (see Fig. 1) leads to the possibility of atoms being optically pumped out of the trapping/cooling $F = 4 \leftrightarrow F' = 5$ cycle. (Although in principle this is a closed two-level system, there is leakage to the $F = 3$ ground state, via collisions or power broadening for example.) To counter this problem, a second 'repumping' laser is tuned to the $F = 3 \rightarrow F' = 4$ transition.

A schematic diagram of the experimental set-up is shown in Fig. 2. The trapping/cooling light is generated by a Coherent 899 titanium–sapphire laser, and the repumping light is from an extended-cavity diode laser developed for this project (McLean *et al.* 1993). With 15 mW of optical power in each 20 mm diameter trapping beam and a magnetic field gradient of $\sim$10 G cm^{-1} (1 G = 10^{-4} T), caesium atoms are trapped in a roughly spherical cloud with diameter $\sim$2 mm. Resonant laser radiation from another extended-cavity diode laser is used to probe the trapped atoms. Absorption measurements using the probe through the trap give the trap density as $\sim 3\times10^9$ atoms cm^{-3}, and the total number of trapped atoms as $\sim 8\times10^6$. The trap loading time is about 1·5 s, measured by observing

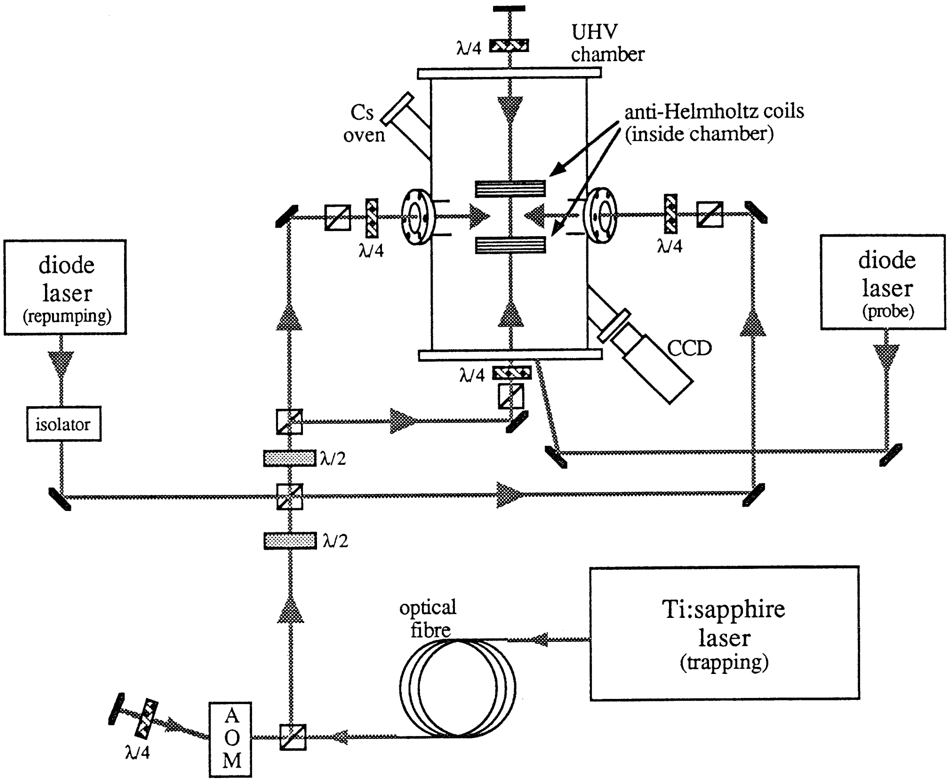

Fig. 2. Schematic diagram of the experimental layout for laser trapping and cooling of caesium atoms. The two laser beams that are drawn as entering the vacuum chamber horizontally actually enter at 45° to the plane of the page, and are retroreflected by mirrors beneath the chamber. AOM: acousto-optic modulator, CCD: charge-coupled-device camera, $\lambda/2$: half-wave plates, and $\lambda/4$: quarter-wave plates.

the fluorescence from the trap with a photomultiplier tube. After the trap has reached equilibrium, the inhomogeneous trapping magnetic field is rapidly (<1 ms) switched off, leaving the cloud of atoms to be further cooled in the mutually orthogonal counterpropagating σ^+–σ^- laser beams, known as 'optical molasses' (Chu *et al.* 1985). The experimental parameters for efficient cooling are different to those for optimal trapping (Dalibard and Cohen-Tannoudji 1989; Ungar *et al.* 1989); in particular for cooling in molasses, the laser frequency is detuned further to the red than for trapping and the cancellation of stray magnetic fields is crucial. When the trap is switched off, the frequency of the trapping/cooling laser is shifted down by a further 10 MHz using a double-pass acousto-optic modulator (AOM) arrangement. After 6 ms of cooling the AOM is used to completely cut off the trapping/cooling light. The atoms then fall freely in the Earth's gravitational field, forming a beam of ultra-cold atoms. A time-of-flight (TOF) measurement is used to determine the temperature of the falling atoms. The transmission of a resonant probe laser beam placed ~50 mm below the trap is measured as a function of time after the atoms are released from the trap (see Fig. 3). A curve fitted to the TOF data gives the 1-dimensional velocity distribution (see Fig. 4) which can then be used to determine the temperature of the atoms. In the work described here this yielded a temperature of $\sim 22\ \mu$K, corresponding to a spread in speed of ± 5 cm s^{-1}.

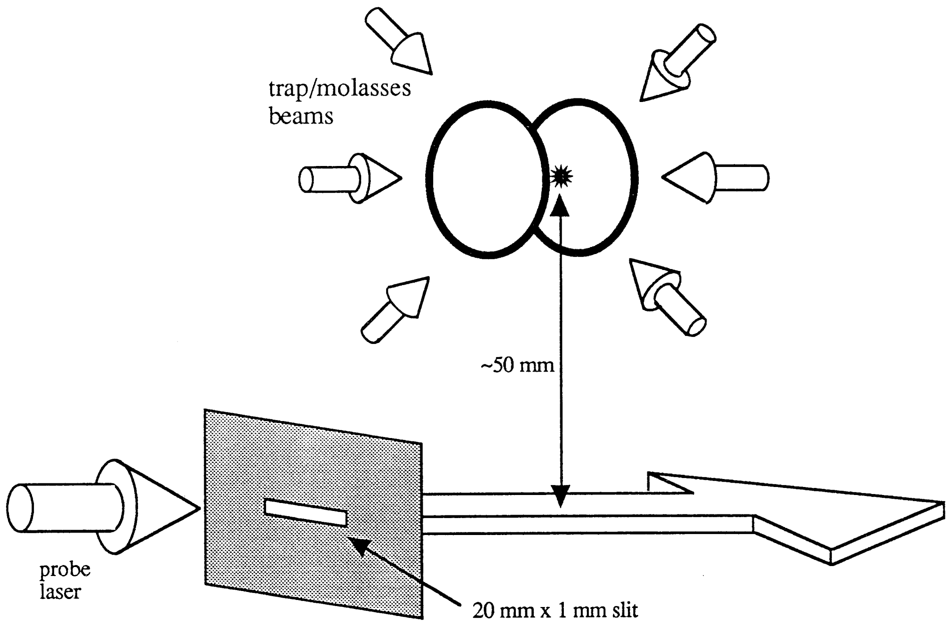

Fig. 3. Time-of-flight measurement of falling atoms by absorption of a 'ribbon' of resonant laser light.

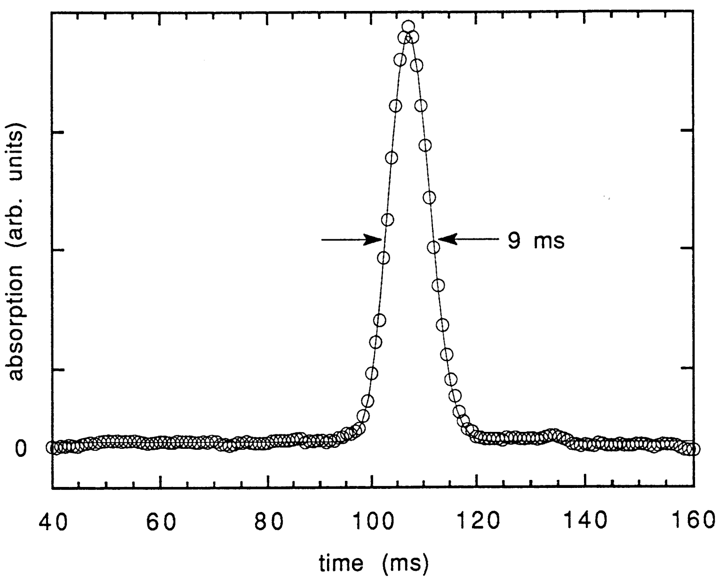

Fig. 4. Absorption signal from time-of-flight measurement. The circles are the experimental points; the solid line is a fitted curve giving a temperature of 22 μK. Horizontal axis is the time elapsed since the atoms are released from the trap.

3. Deflection of Atoms using Static Magnetic Fields

An atom with magnetic dipole moment μ in an external magnetic field $\boldsymbol{B}$ has a contribution to its internal energy given by $-\mu \cdot \boldsymbol{B}$. If the atom moves sufficiently slowly, and/or the external field varies slowly spatially and temporally, then the projection of the atom's magnetic dipole moment onto the external magnetic field will remain constant. This is the condition of adiabatic motion (see for example Schiff 1968). A consequence of this adiabatic motion is that the internal magnetic energy of the atom acts as a position-dependent potential, exerting a force proportional to the gradient of the magnetic field, $F = \nabla(\mu \cdot \boldsymbol{B}) = g_F\, m_F\, \mu_B\, \nabla \boldsymbol{B}$, where μ_B is the Bohr magneton, g_F is the Landé g-factor, and m_F is the magnetic substate of the atom. Various magnetic field configurations have been proposed that will produce reflecting and diffracting elements for slowly moving atoms (Opat *et al.* 1992).

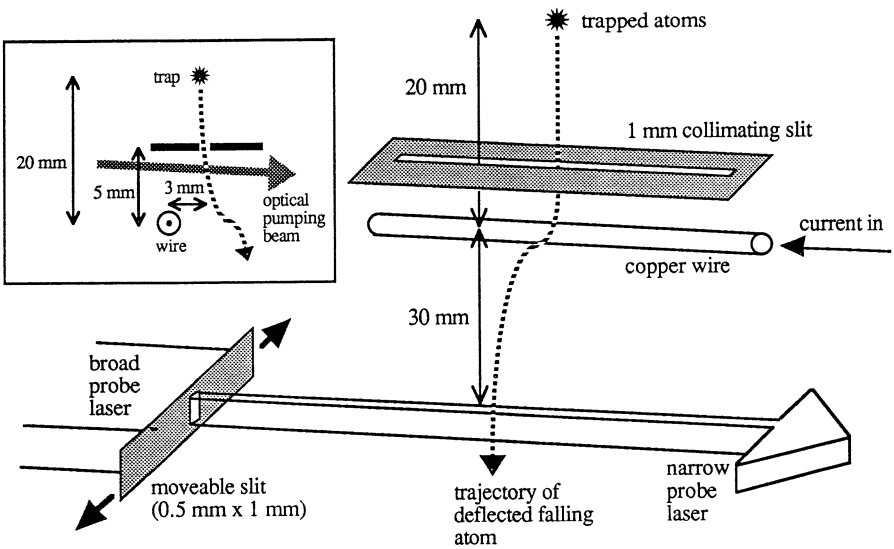

Fig. 5. Apparatus for deflecting slowly-moving atoms with the magnetic field from a current-carrying wire. Inset shows view end-on to the wire, indicating the position of the optical pumping laser beam.

In the present experiment the inhomogeneous magnetic field surrounding a single current-carrying wire is used to deflect slowly moving caesium atoms. A $1 \cdot 9$ mm diameter straight copper wire is placed horizontally approximately 20 mm below the cloud of atoms trapped in the MOT. A 1 mm slit is positioned 5 mm above the wire, which collimates the falling atoms so that their maximum speed transverse to the wire is $\sim$1 cm s^{-1}. The wire and collimating slit are positioned to allow the falling atoms to pass 3 mm to one side of the wire (see Fig. 5). The spatial distribution of the falling atoms is determined by measuring the transmission of a narrow probe laser beam, tuned to the $F = 4 \rightarrow F' = 5$ transition, positioned below the wire and running parallel to it. This narrow probe is spatially scanned transverse to the wire. Several TOF measurements are made for each transverse position of the probe, which are then averaged. The transmission of an additional spatially broad 'ribbon' probe laser beam placed below the scanning probe is used to normalise the number of falling atoms for consecutive trap/cool/release cycles of the MOT.

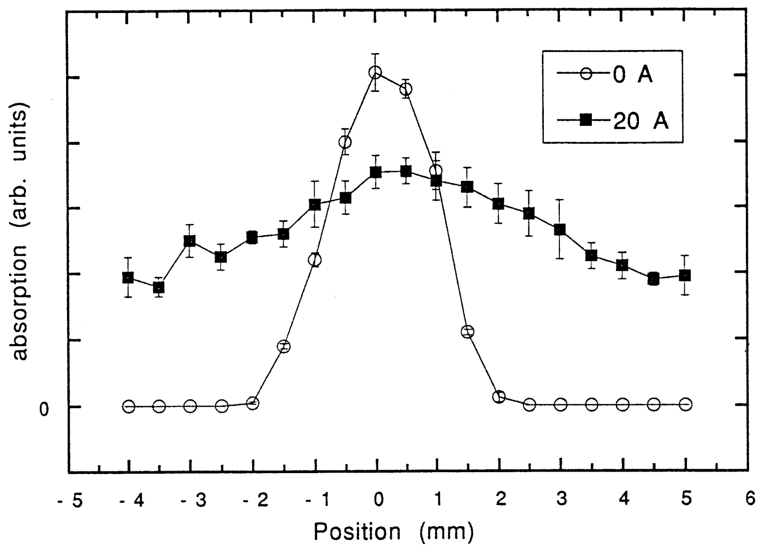

Fig. 6. Spatial distribution of atoms after moving past a wire carrying 0 A and 20 A. The 20 A curve has an exaggerated vertical scale; the area beneath the two curves should be equal. The origin of the horizontal axis is defined by the centre of the undeflected (0 A) distribution. Negative positions indicate deflection away from the wire, positive positions indicate deflection toward the wire.

An electric current of 0–20 A is switched rapidly (<1 ms) into the wire after the optical molasses has been switched off. It is important that the current does not flow before the molasses is turned off, since the magnetic field from the wire with even 2 A flowing is enough to upset the cooling mechanisms in the molasses. With no current through the wire, the spatial distribution of falling atoms is due entirely to collimation through the slit (Fig. 6). With 20 A through the wire, the spatial distribution of the atoms is much broader (Fig. 6), as the atoms are deflected through different angles depending on their magnetic substate. The distribution of atoms in the various magnetic substates is expected to be uniform, since the atoms have previously existed in the spatially complicated field of the optical molasses beams, which has no definite relationship to the wire's field, and are then suddenly immersed in the wire's field. A computer simulation of atomic trajectories (Fig. 7) shows well-defined positions below the wire for each of the nine magnetic substates of the $F = 4$ ground state. However, the spread of transverse atomic velocities, the finite size of the trapped atom cloud, and the width of the scanning probe laser all act to smooth out the observed spatial distribution. There is some evidence of spatial structure in the distribution of atoms that are repelled by the wire, which is discussed further in the next section.

4. Selective Deflection using Optical Pumping

The falling atoms can be deflected in a more controlled way if they are all in the same magnetic substate as they pass through the wire's magnetic field.

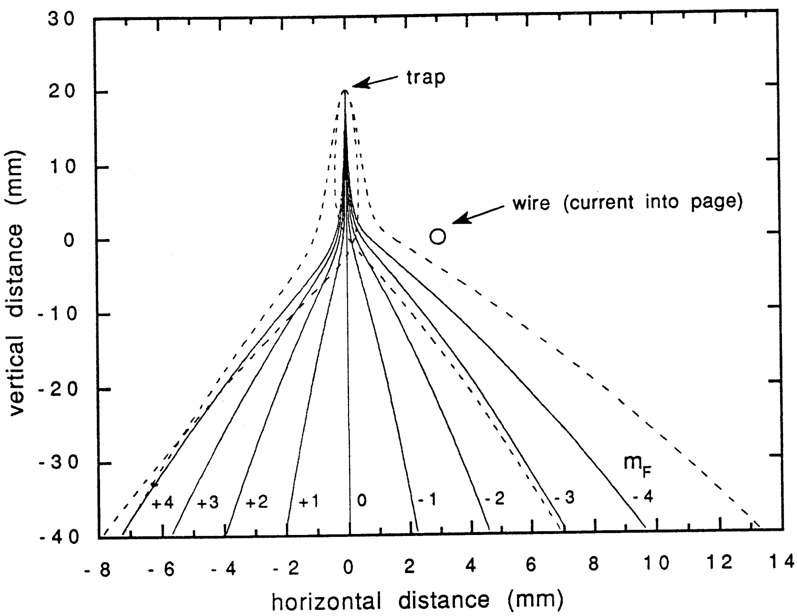

Fig. 7. Computer simulation of trajectories of atoms deflected by the magnetic field from a wire carrying 20 A. The solid lines indicate the trajectories for atoms in the nine possible magnetic substates, assuming zero initial velocity. The broken lines are for atoms in the $m_F = \pm F$ substates with initial transverse velocities of ± 1 cm s^{-1}, showing the converging (diverging) nature of the deflection for atoms in repulsive (attractive) substates.

This can be achieved by using circularly polarised light to optically pump the atoms between various magnetic substates, or sets of substates. To maintain the adiabatic condition, the magnetic field from the wire (of order 10 G) is used to define the quantisation axis. Laser light from the probe diode laser, tuned to the $F = 4 \rightarrow F' = 5$ transition, is expanded and collimated to produce a sheet of light approximately 20 mm$\times$0·5 mm. This sheet of light is circularly polarised, and travels between the wire and the collimating slit such that the wave vector is parallel to the magnetic field from the wire at the position where the atoms interact with the laser. Polarisation can be set as either right or left circular. The circularly polarised light drives either σ^+ or σ^- transitions, pumping the atoms toward the $m_F = +F$ or $-F$ substates. Since optical pumping consists of many cycles of absorption and spontaneous emission, the optical pumping light also exerts a radiation pressure force on the atoms. This deflects the falling atoms in the direction of the travelling optical pumping beam, as well as heating them due to the random nature of spontaneous emission. Both of these effects can be seen by comparing the distribution of atoms with and without the optical pumping laser when there is no current through the wire (Fig. 8). The optical deflection and heating imposes limitations on the intensity of the optical pumping light, since higher intensity will significantly move the atoms relative to the wire's magnetic field.

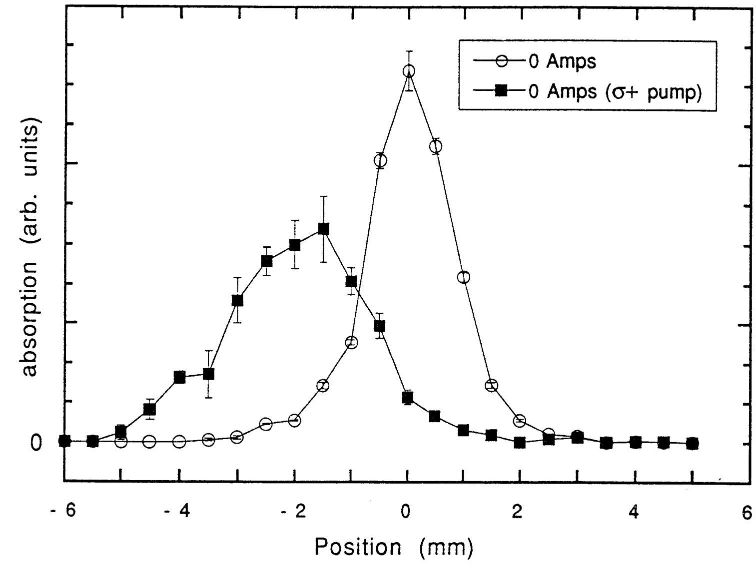

Fig. 8. Spatial distribution of falling atoms with and without optical pumping beam, with no current through the wire. The optical deflection is independent of the polarisation of the optical pumping radiation. The deflected distribution is broadened by the randomly directed momentum transferred to the atoms by each absorption/spontaneous emission cycle.

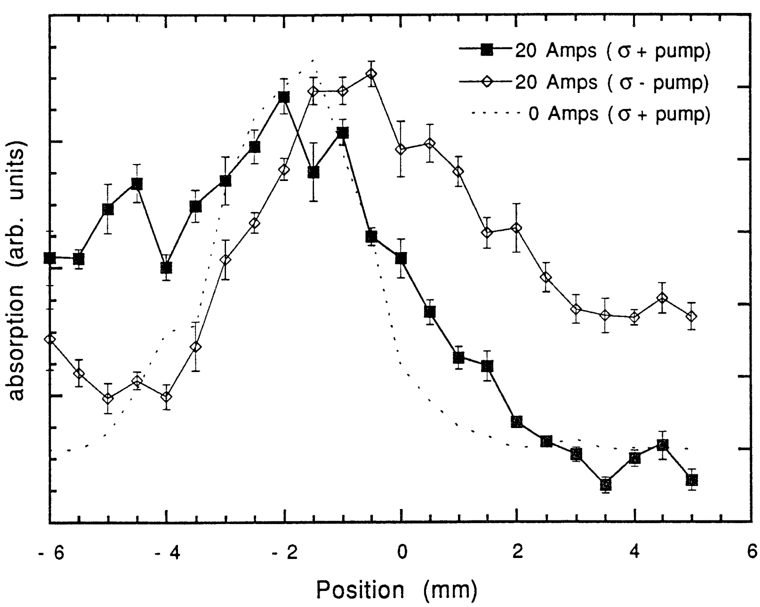

Fig. 9. Spatial distribution of optically pumped atoms falling past a wire carrying 20 A. Each sense of circular polarisation of the optical pumping radiation (given by $\pm 45^\circ$ rotation of quarter-wave plate) gives enhanced deflection to one side of the wire. The optically-pumped 0 A distribution is included to show the effect of optical deflection.

The spatial distribution of atoms after being optically pumped, shown in Fig. 9, is still broad but has obviously been modified. For each sense of circular polarisation, atoms are essentially deflected to one side only of the zero-current distribution. This indicates that the atoms have been optically pumped towards a single magnetic substate, but apparently not sufficiently to populate only one substate. This is supported by the magnitude of the optical deflection and heating of the atoms, which indicates that each atom undergoes approximately ten absorption/spontaneous emission cycles as it falls through the optical pumping beam. Relative transition probabilities for the magnetic substates (Fig. 10) show that ten transition cycles driven by σ^+ (σ^-) light will depopulate the negative (positive) substates, leaving significant populations in only the two most positive (negative) substates. Any small angle between the magnetic field produced by the wire and the wave vector of the optical pumping light will allow absorption via both σ^+ (or σ^-) and π transitions, which has little effect on the depopulation of the negative (positive) substates but significantly reduces the efficiency of optical pumping between the positive (negative) substates. In addition, the energies of the substates are Zeeman-shifted by the magnetic field from the wire. The magnitude of the Zeeman shift is given by $+351 m_F$ kHz G^{-1} for the $F = 4$ substates, and $+560 m_F$ kHz G^{-1} for the $F' = 5$ substates. At the position where the atoms interact with the optical pumping beam the field from the wire is $\sim$10 G, shifting the various transitions between magnetic substates by 0·5–3 natural linewidths. The σ^+ and σ^- transitions are shifted further from resonance with the optical pumping laser than are the π transitions, further reducing the efficiency of optical pumping.

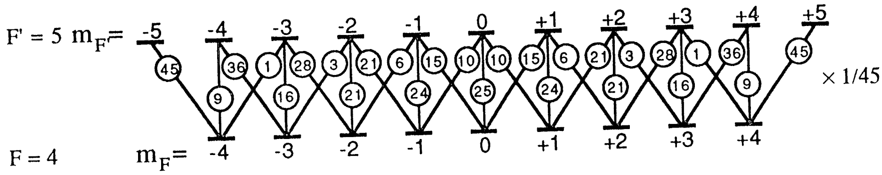

Fig. 10. Relative transition probabilities between magnetic substates of the $6^2S_{1/2}$ $F = 4$–$6^2P_{3/2}$ $F' = 5$ ^{133}Cs resonance. The number shown between each pair of substates must be multiplied by 1/45 to give the branching ratios. [From Schmidt *et al.* (1994).]

Although the atoms are not pumped into a single magnetic substate, there is clear evidence of structure in the spatial distribution of the deflected atomic beam (Fig. 9). The spatial structure is more sharply defined for the atoms that are optically pumped into substates that are deflected away from the wire (which we call 'repulsive' substates) than for atoms deflected toward the wire ('attractive' substates). This asymmetry was also evident to a lesser extent in the spatial distribution when no optical pumping was used (Fig. 6). The simulated trajectories (Fig. 7) show that the spread of atomic velocities transverse to the wire causes this asymmetry in the spatial contrast. Atoms in the repulsive substates are focussed by the inhomogeneous magnetic field, whereas those in the attractive substates are defocussed. The field from the wire can be thought of as a curved atomic mirror that is converging for repulsive substates and diverging for attractive substates.

5. Conclusions and Future Perspectives

We have observed the deflection of a beam of ultra-cold atoms in the inhomogeneous magnetic field of a current-carrying wire. With no modification of the atomic populations in the various magnetic substates the atomic beam is broadened as the atoms are simultaneously deflected through a large range of angles both repulsive and attractive. The use of circularly polarised laser light to optically pump the atoms toward a single magnetic substate reduces the broadening of the atomic beam as it is magnetically deflected.

An obvious improvement to the current experiment is to use a standing-wave laser beam to optically pump the atoms, reducing the optical deflection and heating effects. This would allow the atoms to undergo a greater number of optical pumping cycles without significantly changing their position in the external magnetic field, thus transferring more atoms into a single magnetic substate. Unfortunately the present experimental geometry does not allow the optical pumping laser beam to be retroreflected. A more accurate alignment of the optical pumping beam parallel to the magnetic field from the wire should also improve the pumping efficiency. Another possibility is to optically pump the atoms at a position where the magnetic field from the wire is weaker, thus reducing the effect of Zeeman shifts.

The single-wire deflection experiment described here can be considered as atomic reflection from a cylindrical magnetic mirror. An obvious extension of the present configuration is an array of parallel wires alternately carrying currents in opposite directions, producing a magnetic field that acts as a flat atomic mirror. Such a device would be compact and self-contained, allowing simple construction of multiple-element atomic-optical devices. In particular, this should prove important in the development of cold-atom matter–wave interferometers (Hannaford *et al.* 1994).

Acknowledgments

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