A magnetic guide for cold atoms

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Abstract

We propose a novel method for guiding cold, neutral atoms using static magnetic fields. A theoretical study of the magnetic field produced by a tube consisting of two identical, interwound solenoids carrying equal but opposite currents is presented. This field is almost zero throughout the centre of the tube, but it increases with exponential rapidity as one approaches the walls formed by the current carrying wires. Hence, cold atoms passing through the tube may be reflected by magnetic mirror effects near the walls. Applying this technique to a free-falling cloud of magneto-optically cooled caesium atoms we hope to construct atomic guides to facilitate the manipulation of cold atomic beams.

1. Introduction

During recent years, with the advent of easily produced cold atomic sources, significant interest has been displayed in developing new and useful methods for manipulating and controlling cooled atoms. This has resulted in the realisation of many atom optical elements such as beam-splitters, mirrors and diffraction gratings. For a recent review on some of the progress in this field see, for example, ref. [1].

The majority of atom optical components rely on the effects either of magnetic fields or of light fields on neutral atoms. One clear example of this is shown by the different types of atomic mirrors which have successfully demonstrated atomic reflections. Permanent magnets forming an array of alternating magnetic poles [2, 3], ferromagnetic surface mirrors made from magnetic audio-tape [4] and current carrying wires arranged so that adjacent wires have equal but opposite currents [5, 6] all rely on the interaction of the permanent atomic magnetic dipole moment and a non-uniform magnetic field. An atom in an appropriate magnetic state is repelled by the magnetic field gradient. Specular reflection of thermal [7] and laser-cooled [8] atoms from the repulsive potential of a blue-detuned evanescent light wave has also been observed. This method is based on the interaction between an induced atomic electric dipole moment and the non-uniform field of an evanescent light wave [9].

A natural progression from the successful realisation of atomic mirrors has been the development of atomic guides based on the different reflection mechanisms. Until recently, guides relying on atomic reflections by evanescent light fields within a hollow optical fibre [10 - 12] have been the main candidates in this field. Several other guiding methods have been proposed [13 - 16].

In this paper we propose an atomic guide based on the reflection of cold atoms by current carrying wires. A suitable magnetic field gradient can be produced by two interwound solenoids carrying equal but opposite currents. We expect that such a guide will be more
adaptable to different experimental studies than the transfer technique used in [16], mainly due to the fact that it can be positioned very close to the MOT by placing it inside the vacuum chamber. Losses due to trap expansion are therefore minimised. When the MOT is operating the current through the guide can be switched off and there will be no distorting effects on the trap. This is in stark contrast to guide designs based on permanent magnets. The following sections present the concept behind the magnetic guide and the magnetic field configuration to be used.

2. The magnetic guide

Let us consider the interaction between atoms with an atomic magnetic dipole moment, \( \mu \), and a static inhomogeneous magnetic field, \( B \). In this case, the interaction potential is position dependent. We shall assume adiabaticity for the particular case of slowly moving, laser-cooled atoms. In other words, we assume that the projection of the atomic angular momentum onto the magnetic field direction remains constant during the atom-magnetic field interaction. The force on the laser-cooled atoms in the presence of the \( B \)-field is given by

\[
F = \nabla (\mu \cdot B) = -mg_FR \mu_B \nabla B,
\]  

(1)

where \( m \) is the magnetic quantum number, \( g_F \) is the Landé g-factor and \( \mu_B \) is the Bohr magneton. From eq. (1) we see that the atoms will be repelled by an increasing magnetic field gradient when the product \( mg_F \) is positive. This is the main principle behind magnetic mirrors.

As has been mentioned in the previous section, an effective and efficient type of mirror for cold, neutral atoms can be produced by reflection from a magnetic surface. Free-falling, laser-cooled caesium atoms pumped into the \( m = +4 \) hyperfine state have already been reflected from an atom mirror consisting of an array of current carrying wires, with the current in adjacent wires being equal but opposite in direction [6] as shown in fig. 1(a).

If we now consider an extension of this study, we can effectively imagine bending the wire array mentioned previously, in order to form a tube through which the atoms can pass. Each wire from the array now forms a current loop and this is represented schematically in fig. 1(b). The current in each loop is equal and the currents in two adjacent loops are in opposite directions. This design results in the atoms being reflected irrespective of the path they follow through the tube. The reflections cause the atoms to be trapped inside the tube rather than being absorbed on the walls. Therefore, the tube forms an atomic guide. A tube formed by adjacent current loops, as shown in fig. 1(b), can be approximated by two interwound solenoids. In the next section we will discuss the magnetic field of such an arrangement and show that it provides us with appropriate conditions for constructing an atomic guide. Theoretical magnetic field plots for our particular experimental conditions will also be presented.

3. Magnetic fields of helical solenoids

An expression for the magnetic field of an infinitely long solenoid can be found by exploiting its helical symmetries. Although these calculations are tedious to perform, the final result shows a definite magnetic field structure beyond that obtained via the usual elementary calculation based on Ampère’s circuital law and the current sheet approximation.
Let us consider a solenoid of radius $R$ and let $a$ be the distance between adjacent wires in the $z$-direction, i.e. along the long axis of the solenoid. Note that $a$ is the reciprocal of the number of turns of wire per unit length. The path of the wire wound in the solenoidal coil is given by $r = R$, $\phi = 2\pi n$ and $z = z_0 + av$ in cylindrical coordinates. \( v \) is a continuous parameter describing the number of turns of wire as counted from an arbitrary starting point, $z = z_0$. We are particularly interested in the magnetic field inside the solenoid (i.e. where $r < R$). It can be shown that the magnetic field components, $(B_r, B_\phi, B_z)$, are given by the following expressions [17]:

$$B_r = \frac{\mu_0 I a^2}{8} \sum_{n=0}^{\infty} \left(2n + 1\right) \sin \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}'(\rho_0) I_{2n+1}(\rho),$$

$$B_\phi = \frac{\mu_0 I a}{8 \pi} \sum_{n=0}^{\infty} \left(2n + 1\right) \cos \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}'(\rho_0) I_{2n+1}(\rho),$$

$$B_z = \frac{\mu_0 I a^2}{8} \sum_{n=0}^{\infty} \left(2n + 1\right) \cos \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}'(\rho_0) I_{2n+1}(\rho).$$

By definition, $\rho_0 \equiv 2\pi n R/a$ and $\rho \equiv 2\pi nr/a$. $I$ is the current in the solenoid and $z_0$ is an arbitrary point along the $z$-axis through which the wire passes. The $K_n(\rho)$ and the $I_n(\rho)$ are modified Bessel functions. The primes on the $K_n$ and $I_n$ indicate differentiation with respect to $\rho$.

In order to construct an atomic mirror, we know that we need an array of wires such that adjacent wires carry equal but opposite current. Extending this to the idea of an atomic guide it seems reasonable that two interwound solenoids will give us the correct magnetic field gradient to produce atomic reflections in all directions (c.f. fig. 1). Each solenoid is a single wire solenoid of radius $R$ and distance $a$ between adjacent turns of wire. The two solenoids must also carry equal but opposite currents. This is treated mathematically by giving each solenoid a different reference point $(0, 0, z_0)$ through which the wires pass. For one solenoid we take the current to be $I$ and $z_0 = 0$ and for the second coil the current is $-I$ and $z_0 = a/2$. Using eqs. (3), (4) and (6) we can easily obtain the solutions for the magnetic field $B$ produced by the double wound solenoid. We are again interested in the field inside the tube formed by the two solenoids (i.e. where $r < R$). The magnetic field components are given by

$$B_r = \frac{\mu_0 I a^2}{8} \sum_{n=0}^{\infty} \left(2n + 1\right) \sin \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}' \left(2n + 1\right) \frac{2\pi R}{a} I_{2n+1}' \left(2n + 1\right) \frac{2\pi r}{a},$$

$$B_\phi = \frac{\mu_0 I a}{8 \pi} \sum_{n=0}^{\infty} \left(2n + 1\right) \cos \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}' \left(2n + 1\right) \frac{2\pi R}{a} I_{2n+1} \left(2n + 1\right) \frac{2\pi r}{a},$$

$$B_z = -\frac{\mu_0 I a^2}{8} \sum_{n=0}^{\infty} \left(2n + 1\right) \cos \left(2n + 1\right) \left(\phi - \frac{2\pi z}{a}\right) K_{2n+1}' \left(2n + 1\right) \frac{2\pi R}{a} I_{2n+1} \left(2n + 1\right) \frac{2\pi r}{a}.$$
where the various symbols represent the same quantities as in eqs. (2), (3) and (4).

4. Magnetic field profiles

Figure 2(a) shows a vertical slice (i.e. along the $z$-axis) of the magnetic tube formed by the two solenoids. The magnetic field is calculated using eqs. (5), (6) and (7) and considering the first 10 terms of the Fourier series only. In this example, we have assumed that $a/R = 1.0$ and that a current of 0.5Amps flows through each solenoid. The field inside the tube is close to zero throughout the central region. This is identical to the result predicted using Ampère’s circuital law for two interwound solenoids. However, there is a large magnetic field gradient as one approaches the wires. Figure 2(b) is a horizontal view of the magnetic field ($z = 0$ plane), using the same parameters as in fig. 2(a). Free-falling, cold atoms enter the tube normal to the plane of the diagram. Any off-axis atoms will experience a steep field gradient near the walls and will be reflected back towards the centre. It is important that the magnetic force is large enough so that the atoms in the ballistically expanding cloud never quite reach the walls of the tube. This ensures that they will be reflected before striking the wires and thus, a high transport efficiency can be obtained for the guide, due to the low loss in flux from absorption.

Similar plots of the $B$-field are shown in fig. 3. In this case, the solenoids are more tightly wound than in fig. 2 so that $a/R = 0.1$. Again, we assume a current of 0.5Amps. Using these parameters we see that the magnetic field remains essentially uniform over a larger region than that shown in fig. 2. However, the magnetic field gradient is steeper and a higher efficiency of reflection should be obtained.

5. Design criteria

Ultra-high vacuum compatible, Kapton-coated wires of maximum diameter 0.86mm are suitable for making the magnetic guide. Considering an atom guide of radius 2.5mm this yields $a/R = 0.69$, which lies within the range we have studied. A typical transverse velocity for trapped Cs atoms is $\pm 6$cm/s. Let us assume that the entrance to the atom guide is located 1.5cm beneath the centre of the trapped cloud of atoms and the guide is 3.8cm long. Once the trap is switched off, we predict that 67% of the free-falling atoms will enter the guide. 45% of these atoms will strike the walls of the guide and be reflected. The other 55% of atoms will fall straight through. A longer guide would reflect a higher percentage of atoms. Figure 4 is a plot of the current needed to reflect atoms from the walls of the guide versus the distance from the centre of the tube at which the atoms will be reflected. From this graph we see that atoms close to the walls (2.2mm from the centre) require a current of approximately 0.1Amps to be reflected. Our practical limit of 0.5Amps is therefore largely sufficient.

6. Conclusion

We have presented a new scheme for constructing atomic guides, based on the reflection of cold atoms from current carrying wires. Magnetic mirrors consisting of a current carrying wire array have already been realised [8]. Our guide scheme is an extension of this technique. A suitable magnetic field configuration for the guide consists of two interwound solenoids. This magnetic atom guide has a zero-field region along its axis and a steep field gradient as one approaches the walls radially from the centre. In order to avoid non-adiabatic spin-flips
in the zero region of the $B$-field, it may be necessary to add a small bias field to the overall configuration by unbalancing the currents in the two solenoids by a small amount.

This magnetic guide design has a distinct advantage over other guiding schemes since it doesn’t require additional lasers and is, therefore, very cost effective and simple in construction. Because it is based on current carrying wires it can be switched on and off as required. Therefore its entrance can be positioned close to the MOT. Any constraints on the distance between the MOT and the atom guide arise from the diameter of the trapping laser beams and the radius of the guide itself. Therefore, by a judicious choice of these two parameters, the free-falling cloud of cold atoms should not expand appreciably before entering the magnetic tube. The entire experiment should be switched so that the MOT is on when the magnetic guide is off and vice versa and the guide should be switched on after the atoms have entered it. This avoids any problems that may arise from heat dissipation and distorting effects of the magnetic fields.

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Fig. 1: (a) Magnetic mirror formed using a continuous array of current carrying wires. The black arrows represent the direction of the current in each wire; (b) The same as (a) only each wire is folded through 360°, thus forming a tube of current loops.

Fig. 2: Magnetic field of a double wound solenoid for $a/R = 1.0$ and a current $I = 0.5A$. (a) Field magnitude for a vertical slice through the magnetic tube ($y = 0$ plane); (b) Field magnitude for a horizontal slice through the magnetic tube ($z = 0$ plane).

Fig. 3: Magnetic field of a double wound solenoid for $a/R = 0.1$ and a current $I = 0.5A$. (a) Field magnitude for a vertical slice through the magnetic tube ($y = 0$ plane); (b) Field magnitude for a horizontal slice through the magnetic tube ($z = 0$ plane).

Fig. 4: Plot of current through the solenoids versus distance from the centre at which an atom will be reflected. $a/R = 0.69$. It is assumed that the atoms are in the $m = +4$ state and have a transverse velocity of $\pm 6$cm/s. Atoms close to the walls of the guide will be reflected for currents $\leq 0.5$Amps.