A proposal for continuous loading of an optical dipole trap with magnetically guided ultra-cold atoms

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Abstract
The capture of a moving atom by a non-dissipative trap, such as an optical dipole trap, requires the removal of the excessive kinetic energy of the atom. In this paper, we develop a mechanism to harvest ultra-cold atoms from a guided atom beam into an optical dipole trap by removing their directed kinetic energy. We propose a continuous loading scheme where this is accomplished via deceleration by a magnetic potential barrier followed by optical pumping to the energetically lowest Zeeman sublevel. We theoretically investigate the application of this scheme to the transfer of ultra-cold chromium atoms from a magnetically guided atom beam into a deep optical dipole trap. We discuss the realization of a suitable magnetic field configuration. Based on numerical simulations of the loading process, we analyse the feasibility and efficiency of our loading scheme.

1. Introduction

The production of a Bose–Einstein condensate (BEC) is typically performed by a time sequence of cooling steps leading to an average yield of $10^5$–$10^6$ atoms $s^{-1}$ for the best alkali experiments and $10^3$ atoms $s^{-1}$ for a chromium BEC [1]. In order to overcome the inherent limitations of sequential BEC production processes, considerable effort has been invested into alternative concepts based on magnetic guides loaded with ultra-cold atoms [2]. Magnetic guides allow us to spatially separate and perform simultaneously otherwise interfering cooling steps. They offer thus the prospect of preparing BECs continuously with considerably increased production rates. A spectacular application of this would be the realization of a truly continuously pumped atom laser [3], the matter wave analogue to an optical cw laser. Atom lasers could so far only be realized in the pulsed and quasi-continuous mode [4–10]. A continuous atom laser would constitute a uniquely bright and coherent source of quantum matter with applications ranging from fundamental research on atomic physics to microscopy and lithography.

Several methods have been demonstrated to load a magnetic guide from a magneto optical trap (MOT), resulting in loading rates of up to $7 \times 10^9$ atoms $s^{-1}$ [11]. For chromium, our group has recently reported a continuous loading of $>10^9$ atoms $s^{-1}$ by operating a moving molasses MOT in the field of a magnetic guide [12]. This is a good starting point for a continuously refilled reservoir of atoms. Efficient transfer of the atomic flux from a guide into an optical dipole trap (ODT) would open the possibility of reaching degeneracy via evaporative cooling inside the ODT. It would thus constitute an important step towards high flux and even continuous BEC production.

The capture of a moving atom by an ODT requires, due to the conservative character of the ODT potential, that the excessive kinetic energy of the atom be removed. Typical atom velocities in a guide are on the order of few m $s^{-1}$, the amount of kinetic energy that needs to be dissipated therefore can exceed typical trap depths of an ODT by more than one order of magnitude. In this paper, we propose and analyse a loading method which employs deceleration by an additional magnetic field inside the ODT region and subsequent optical pumping to the energetically lowest Zeeman sublevel. This process
bears similarities to a single Sisyphus-cooling cycle [13–16]. The feasibility and efficiency of this method is investigated by numerical simulations.

2. Principle of the ODT loading mechanism

The loading mechanism we propose is ideally applicable to chromium atoms, which due to their relatively high ground-state magnetic moment of 6 $\mu_B$ are especially well suited for magnetic guiding. Recent experiments in our group have demonstrated the injection of ultra-cold $^{52}$Cr atoms out of a moving molasses MOT [17] into a horizontal magnetic guide [18]. A continuous flux of up to $6 \times 10^9$ atoms s$^{-1}$ with tuneable velocities between 2 and 20 m s$^{-1}$ and temperatures ranging from 1–2 mK could be achieved with this set-up [12]. The goal of this project is the continuous transfer of the atomic sample into a deep ODT generated by an intense fibre laser.

In the following, we develop our theoretical considerations in close reference to our experimental set-up. The magnetic guide consists of four parallel bars with rectangularly arranged centres (see figure 1). We choose the coordinate system such that the axis of the guide, its axis of symmetry, coincides with the z-axis. The four bars intersect the xy-plane at the points $(d/2, d/2, 0)$, $(d/2, -d/2, 0)$, $(-d/2, d/2, 0)$ and $(-d/2, -d/2, 0)$, respectively. Here $d$ corresponds to the distance of two neighbouring bars. The current $I_0$ flows through the bars in alternating opposing directions. The resulting magnetic field $\mathbf{B}_2$ inside the atom guide can be well approximated by a 2D quadrupol field:

$$\mathbf{B}_2(\mathbf{r}) = \frac{4\pi I_0}{d^2} (-x, y, 0).$$

An atom interacts with the field via its magnetic moment. Its resulting potential energy $U_\alpha$ depends only on the radial distance $\rho = (x^2 + y^2)^{1/2}$ from the guide axis. With equation (1) its potential energy can be expressed as

$$U_\alpha(\rho) = \mu_B g J m_J \left| \nabla \mathbf{B}_2(\rho) \right| \rho,$$

with $\mu_B$ representing the Bohr magneton, $g_J$ representing the Landé g-factor and $m_J$ representing the magnetic quantum number of the atom. The term $\left| \nabla \mathbf{B}_2(\rho) \right|$ is a constant here and denoted as a ‘magnetic field gradient’. The guide potential described by equation (2) leaves the atoms unconfined in the axial direction. It scales linear with $\rho$ and can, depending on the value of $m_J$, either be attractive, repulsive or equal to zero. Thus, only atoms in specific Zeeman substates, the so-called ‘low-field seeking states’, are confined by the guide.

In order to explain the transfer of atoms from the magnetic guide into an ODT, we assume that the ODT is generated by a far red detuned Gaussian laser beam with focal waist $w_0$ and Rayleigh range $z_R$. We further assume that the optical axis of the beam coincides with the guide axis and that the focus is located at the origin of our coordinate system. For a total beam power $P_0$ the trap potential $U_0$ of the ODT is then given by

$$U_d(\mathbf{r}) = \frac{P_0 h}{w_0^2} \left(1 + \frac{z^2}{2z_R^2}\right)^{-1} \exp \left(-\frac{2\rho^2}{w_0^2}\left(1 + \frac{z^2}{2z_R^2}\right)^{-1}\right),$$

where $h$ is Planck’s constant and the parameter $\kappa$ describes the coupling between the trap beam and the trapped atom [19]. In the following, we regard $^{52}$Cr ground-state atoms trapped by a laser beam with 300 W total power, 1070 nm wavelength and a focal waist of 30 $\mu$m. For these settings, equation (3) yields an optical trap depth of 3.6 mK.

From equation (3), it can be seen that the extension of the ODT in the axial direction is essentially marked by $z_R$ and in the radial direction by $w_0$. An atom can be regarded as trapped inside the ODT when the sum of its kinetic energy and its potential energy is lower than the ODT potential threshold. In order to load an atom into the ODT, we not only require a process capable of removing a substantial part of the initial kinetic energy of the atom, but in addition it is also essential that the removal takes place in close proximity to the centre of the ODT.

Since only atoms that are in a low-field seeking Zeeman substate are transmitted inside the magnetic guide, an additional magnetic field can be used to generate a magnetic potential barrier inside the ODT that exerts a repulsive force on an atom approaching it from the guide. An atom that is decelerated by the barrier converts kinetic energy into potential energy up to the point where it either transcends the barrier or reaches a turning point of its trajectory. The position and orientation of the barrier with respect to the guide and the ODT have to be chosen such that this point of minimal axial kinetic energy lies as close as possible to the centre.
Figure 2. (a) $^{52}\text{Cr}$ energy levels (not to scale) with optical transitions used for laser cooling and optical pumping. Atoms are guided in the $^7\text{S}_3$ ground state. (b) Optical pumping to the $^7\text{P}_3$ state can be used to transfer atoms successively from $m_J = +3$ to the $m_J = -3$ Zeeman sublevel of the ground state.

Figure 3. Illustration of the proposed scheme for continuously loading the ODT from the atom guide. A Cr atom in the low-field seeking $m_J = +3$ ground state approaches the centre of the ODT and is decelerated by a magnetic potential barrier. The atom thereby converts kinetic into potential energy. At the centre of the ODT, where the atom has minimized its kinetic energy, it enters a beam of $\sigma^-$-polarized light, which pumps the atom to the high-field seeking $m_J = -3$ Zeeman sublevel. The pumping removes the gained potential energy and leaves the atom close to the bottom of a trap potential, which is generated by the ODT and the now attractive magnetic potential. Depending on the remaining kinetic energy, the atom remains trapped.

For our proposed loading scheme to be effective, it requires a suitable optical transition that allows the optical pumping to proceed both within a period much shorter than the average length of stay near the barrier peak and without causing excessive heating of the trapped atoms. For $^{52}\text{Cr}$, a transition that fulfils these requirements is presented by the $^7\text{S}_3 \rightarrow ^7\text{P}_3$ transition, which is depicted in figure 2(a). The excited state has a lifetime of 33 ns. It decays with a branching ratio $>10^3 : 1$ into the ground state. Figure 2(b) illustrates subsequent optical pumping cycles driving an atom from the $^7\text{S}_3 m_J = +3$ to the $m_J = -3$ level, the latter being a dark state. When $\sigma^-$ light is used, on average 6.2 photons are scattered during a single pumping cycle, causing negligible recoil-induced heating [20].

Figure 3 illustrates the loading scheme for $^{52}\text{Cr}$. An atom in the $m_J = +3$ sublevel of the $^7\text{S}_3$ ground state moves towards the ODT and is subsequently stopped at the centre of the ODT by a magnetic barrier superimposed with the ODT. At the point of return, it enters a $\sigma^-$-polarized pump laser beam that drives the atom quasi-instantaneously to the $m_J = -3$ $^7\text{S}_3$ level. As a result, the atom is trapped by the ODT and the inverted magnetic potential.

3. Magnetic field configuration and trap potentials

During the preceding description of the loading scheme, we have implicitly assumed the existence of a suitably shaped magnetic potential barrier. For a further analysis of the loading scheme, the magnetic field configuration has to be specified in more detail. It has to be considered here that the field $\mathbf{B}_m$ that
determines the shape of the potential barrier is in general a vector sum of the guide field $B_a$ and other additionally applied fields. An important requirement for $B_a$ is that its orientation has to be uniform inside the region where the optical pumping takes place in order to allow the preparation of purely $\sigma^+$-polarized pump light. Moreover, while it is desirable to have a field whose strength increases steeply towards the ODT centre in the axial direction, the curvature in the radial direction has to be sufficiently small in order to avoid a defocusing effect on the atomic beam in either the low-field or the high-field seeking state.

A suitable magnetic field can be obtained by adding a single circular current loop positioned concentrically with respect to the ODT and the magnetic guide, as shown in figure 1. The magnetic field $B_c$ produced by the current loop near the centre of the loop, which coincides with the ODT centre, is in line with the guide axis. Starting from the centre it increases slowly in the radial direction and decays on the length scale of the coil diameter in the axial direction. A general analytical expression for $B_c(r)$ can be given in terms of elliptical integrals [21]. Assuming the loop current $I_c$ to be oriented positively with respect to the $z$-axis, $B_c$ is along the $z$-axis, for a loop radius $R_c$ given by

$$B_c(z) = \frac{I_c \mu_0}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \hat{e}_z. \quad (4)$$

Having specified the magnetic field configuration, we can express the potential $U_0$, in which the atoms move during the loading, in terms of the fields of $B_a$ and $B_c$ and the ODT potential $U_d$ as

$$U_0 = \mu_a g_J m_J |B_a + B_c| + U_d. \quad (5)$$

The loop current has to be adjusted to the beam velocity $v_b$ such that the total height of the potential barrier at the origin cancels the axial kinetic energy component of the arriving atoms. From equations (3) and (4) it follows thus that $I_c$ has to obey

$$\frac{m v_b^2}{2} = \mu_a g_J m_J I_c \mu_0 \frac{2}{2R} + \frac{P_0 \hbar}{w_0^2}. \quad (6)$$

The equations above relate the geometry of the ODT and of the atom guide with the decelerating current loop. They can be used to find optimized values for the interdependent parameters $R$ and $I_c$. In a real experiment, however, there might be additional technical constraints that have to be considered. It might be difficult for example to work with extremely small coils and rather large current in an ultra high vacuum (UHV) environment. Moreover, it might be necessary to use the same coils with a range of beam velocities and an accordingly wide range of loop currents. With the objective of providing useful guidance for the design of an experiment, we assume throughout this paper a fixed loop radius of 0.5 mm and a magnetic field gradient of 350G cm$^{-1}$. From equation (6), it then follows that the coil current $I_c$ depends only on the beam velocity $v_b$. In the following, we thus regard the magnetic barrier field and the resulting potential configuration as functions of $v_b$. For assumed beam velocities ranging from 1 ms$^{-1}$ to 5 ms$^{-1}$, the loop has to carry currents between 1.3 A and 16.4 A. With technologies adapted from magnetic micro traps, it should be feasible to operate a coil subject to these requirements [22].

Colour coded contour plots of total potential $U_d$ in the $xz$-plane are shown in figure 4. An atom in the low-field seeking $m_J = +3$ state experiences a potential barrier as shown in figure 4(a). In contrast, an atom in the high-field seeking $m_J = -3$ state experiences a trap-shaped potential. In both cases the radial confinement is solely provided by the ODT. The depicted potentials correspond to a barrier height adjusted for a beam velocity of only 1.5 ms$^{-1}$. At higher velocities, the magnetic barrier height becomes so large that the contribution from the ODT would be hardly recognizable.

4. Simulation of the loading process

In order to assess the feasibility and the efficiency of our proposed loading scheme, we have numerically simulated the transfer of atoms from the guided atom beam into the ODT. For a given configuration of the atom beam and the trapping potential, we are interested in the overall loading efficiency $\Lambda$, which we define as the ratio between the fraction $\Phi_1$ of the atomic flux that remains trapped in the ODT after optical pumping and the total incoming flux $\Phi_0$. From experimental studies, it is known that the radial and axial distributions of atomic velocities and positions inside the chromium atom beam resemble thermal distributions. They can be well described by specifying the beam velocity $v_b$, the total flux $\Phi_0$, and the respective radial and axial beam temperatures $T_r$ and $T_z$ [12]. As outlined in the preceding section, we restrict our studies to a potential configuration that depends only on $v_b$. Moreover, we make the important assumption that the densities in the atom guide and the ODT remain low enough such that inter-atomic collisions can be safely neglected during the loading process. It follows that, under these premises, $\Lambda$ is density independent and can be regarded as a function of $v_b$, $T_r$ and $T_z$ alone.
Our simulations of the transfer of atoms from the atom guide into the ODT are based on the computation of a large number of individual atom trajectories and their subsequent analysis. For the computation of the trajectories, we have used the expression for the total potential energy stated in equation (5) to obtain analytical expressions for the corresponding equations of motion. In the absence of collisions, we can for given initial conditions obtain the full 3D trajectories by numerically integrating the equations of motion on a personal computer using standard commercial mathematical software.

We then use the resulting trajectory to estimate a likely position and velocity of the atom when it undergoes the optical pumping [23]. For this purpose, we require that the duration of the optical pumping process be negligibly short and that the pump beam be restricted to a narrow region near the top of the magnetic potential barrier. We then assume that as soon as the atom either has lost all its axial velocity ($v_b = 0$) or as soon as it reaches the maximum of the potential barrier ($z = 0$) it is pumped instantaneously into the high-field seeking state, where it is suddenly subject to an attractive potential. We regard the atom as successfully transferred into the ODT if the optical pumping process takes place inside the region of the final trap potential well and if the remaining total energy of the atom is lower than the trap potential threshold.

For the computation of the trajectories the atoms are all initialized at $z = -0.05$ m, which is chosen to be sufficiently far away from the ODT-centre, such that the initial potential energy distribution is only determined by the guide potential. For the initial radial distribution $n(\rho)$ follows from equation (2),

$$n(\rho) = \rho \beta^{-2} \exp\left[-\frac{\rho}{\beta}\right],$$

where

$$\beta = \frac{k_B T_r}{\mu_B g_{\mu_B} |B_t|}.$$  

The initial radial velocities $v_x$ and $v_y$ are distributed according to Maxwell–Boltzmann distributions with temperature $T_z$. The distribution $v(v_z)$ of the longitudinal velocities is described by a Maxwell–Boltzmann distribution with temperature $T_z$ centred around the beam velocity $v_b$, yielding

$$v(v_z) = \sqrt{\frac{m}{2\pi k_B T_z}} \exp\left[-\frac{m (v_z - v_b)^2}{2k_B T_z}\right].$$

In order to determine $\Lambda$, we have at each instance calculated a large number of trajectories ($> 5 \times 10^4$) with initial conditions randomly sampled according to the respective values of $T_r$, $T_t$ and $v_b$. The number of successful transfers divided by the total number of trajectories then yields the corresponding value of $\Lambda$.

The results of our simulations are presented in figure 5. We have concentrated our studies on the dependence of $\Lambda$ on the radial beam temperature (figure 5(a)) and on the beam velocity (figure 5(b)), respectively. With the objective to investigate the application of our loading scheme to a real experiment and to derive strategies for an optimization of the loading rate, we have in both cases regarded parameter ranges that we deem to be experimentally accessible with present atom beam preparation methods [12, 18]. As $T_z$ is typically roughly constant, we have used a, conservatively estimated, fixed value of $T_z = 1$ mK for the simulations presented in this paper.

The dependence of $\Lambda$ on $T_r$ is shown in figure 5(a). Two data sets are displayed, corresponding to two different beam velocities: $v_b = 2$ m s$^{-1}$ (red circles) and $v_b = 5$ m s$^{-1}$ (blue diamonds). The value of 2 m s$^{-1}$ represents the minimal velocity at which the beam can be effectively operated, while at approximately 5 m s$^{-1}$ the beam yields maximum atom flux [12]. Both data sets exhibit a steep increase of $\Lambda$ with decreasing $T_r$. We attribute this to the energy initially stored in the transverse degrees of freedom, which cannot be dissipated with our loading scheme, and which contributes on average with 3$k_B T_r$ to the total energy remaining after optical
pumping. The course of $\Lambda$ as a function of $T_r$ indicates that additional measures to decrease $T_b$ even if they are associated with a moderate reduction of $\Phi_0$, might be helpful in order to maximize the loading rate. At $T_b = 1$ mK, which represents the presently lowest values for the radial beam temperature [12], the graph yields $\Lambda = 0.35\%$ for $v_b = 5$ m s$^{-1}$. Doppler cooling in the radial direction might, for instance, be used to reduce the radial temperature further to 0.125 mK, the Doppler temperature of chromium. In this case, the loading efficiency would be expected to increase from 0.35\% to over 12\%.

From figure 5(a) we can learn that for $v_b = 5$ m s$^{-1}$ the loading efficiency is about three times smaller than for $v_b = 2$ m s$^{-1}$. This can be explained by the different respective height of the magnetic potential barrier that is needed in order to decelerate the atoms. An increased barrier height results in an increased radial curvature and thus lowers the effective depth of the trapping potential. For this reason, our loading scheme cannot be applied to arbitrarily high beam velocities. In figure 5(b) the dependence of $\Lambda$ on $v_b$ is shown in more detail for two different radial temperatures, $T_r = 1$ mK and $T_r = 0.1$mK. The results from the simulations have to be contrasted with the experimentally observed dependence of the total flux $\Phi_0$ on $v_b$, which exhibits a pronounced maximum between 5 ms$^{-1}$ and 6 ms$^{-1}$ and a steep decrease towards slower beam velocities [12]. Regarding the optimization of the loading rate, it appears to be evident that the decrease of $\Phi_0$ towards smaller beam velocities could possibly not be compensated for by a corresponding increase of $\Lambda$. Thus, it might not be advisable to reduce the beam velocity below 5 ms$^{-1}$ at the expense of a greatly reduced total flux.

Based on the values of $\Lambda$ presented in this article and the reported values of $\Phi_0$ [12], we obtain for a beam velocity of 5 ms$^{-1}$ and a radial temperature of 1 mK, an estimated loading rate of about $4 \times 10^6$ atoms s$^{-1}$. We estimate that under these conditions it would take less than 1 s to reach a steady state with more than $10^6$ atoms in the ODT. If at this point the loading process would be interrupted, this would already provide excellent starting conditions for the application of demagnetization cooling [24]. This technique provides highly efficient cooling without loss of atoms and has shown to work best in dense and hot clouds that provide high collision rates.

5. Conclusion

In this paper, we have outlined a scheme for the transfer of ultra-cold atoms from a magnetically guided atom beam into an optical dipole trap. The scheme compromises deceleration by a magnetic barrier superimposed with the ODT, followed by optical pumping to the energetically lowest Zeeman sublevel. We have provided an elaborate discussion of the application of this scheme to a beam of ultra-cold chromium atoms. The preparation of suitable potential field configurations for the deceleration and the trapping of the atoms have been treated. Using numerical simulations of the loading process, we have investigated the dependence of the loading efficiency on the initial radial beam temperature and on the beam velocity. Our simulations suggest that, based on recently reported experimental data [12], loading efficiencies of about 0.35\%, resulting in maximum loading rates of more than $10^6$ atoms s$^{-1}$, are feasible.

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