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LETTER

Preparation of a single atom in an optical microtrap

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Abstract
We investigate the use of light assisted collisions for the deterministic preparation of individual atoms in a microtrap. Blue detuned light is used in order to ensure that only one of the collision partners is lost from the trap. We obtain a 91% loading efficiency of single ^{85}Rb atoms. This can be achieved within a total preparation time of 542 ms. A numerical model of the process quantitatively agrees with the experiment giving an in-depth understanding of the dynamics of the process and allowing us to identify the factors that still limit the loading efficiency. The fast loading time in combination with the high efficiency may be sufficient for loading quantum registers at the size required for competitive quantum computing.

(Some figures may appear in colour only in the online journal)

1. Introduction

The ability to control microscopic systems drives the development of a wide range of modern technologies. Recent years have witnessed tremendous progress towards complete control of individual atoms [1–3]. This is of strong interest due to their potential use as qubits in a quantum logic device [1, 4–7]. Neutral atoms in far off-resonance optical microtraps have favorable properties for quantum information processing: a qubit can be encoded into the internal states of each atom, the atoms are well shielded from the environment, and long range entangling interactions can be switched on and off [8–10].

Several schemes for quantum gate operations using cold neutral atoms have been investigated experimentally [9–11]. Two qubit entangling operations have been demonstrated using Rydberg mediated dipolar interactions [9, 10, 12]. Operations involving more than two qubits require a fast way to deterministically prepare single trapped atoms that can be individually addressed. The use of degenerate gases for creating Mott insulators [13, 2], atom sorting [3], or the isolation of fermions in single trap geometries [14] lead to complicated experiments with long loading times and sometimes come with restrictions on the geometries that can be implemented. The Rydberg blockade mechanism has been proposed as a fast deterministic loading scheme, but is yet to be demonstrated experimentally [15]. Finally, a range of experiments has used light assisted collisions. Collisions induced by red detuned light have been used to redistribute atoms in a 1D optical lattice [16] and to load single atoms into traps [17–19]. When red detuned light is used to induce the collisions the energy released can be very high leaving both colliding atoms with enough energy to escape from the trap. This limits the single atom loading efficiency as the pair can leave together [20–22]. Our previous work showed that using blue detuned light could increase the efficiency to 83% [23]. In blue detuned collisions the energy released can be controlled such that it is enough for one of the collision partners to be lost but not enough for both. One of the partners must then take up the major part of the energy released in order to be lost. We proposed several effects that could contribute to the high loading efficiency but their relative

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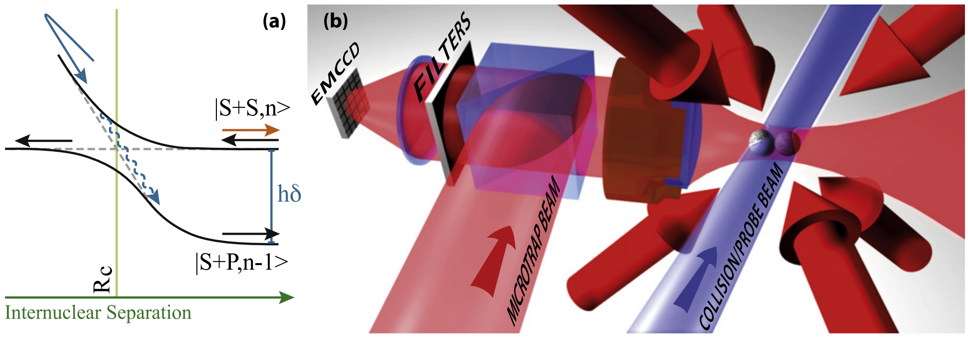

Figure 1. (a) Dressed state picture of light assisted collisions. Arrows: black (up, right): two ground atoms state approaching; black (left): LZ transition; black (low): inelastic collision; orange: elastic collision; continuous blue: adiabatic transition; dashed wavy blue: LZ transition. (b) Sketch of the apparatus. A high numerical aperture lens focuses a red detuned laser beam to create an optical microtrap. The microtrap is loaded with cold ^{85}Rb atoms using a magneto-optical trap. A blue detuned collision beam induces repulsive collisions between the atoms. A probe beam excites the atoms and their fluorescence is directed onto an electron-multiplying charge-coupled device (EMCCD).

significance and the details of the dynamics remained unclear. The limitations of the method could therefore not be assessed.

An error free quantum register requires an array of microtraps each loaded with a single atom. This could potentially be achieved by loading the sites of the array in parallel using a similar method to [17]. However the probability for error free loading of the whole register is P^N where P is the loading efficiency of a single site and N the number of sites. Thirty to fifty qubits is considered the minimum quantum register size for quantum computing to exceed the limitations of classical computing [24]. The previously reported single atom loading efficiency of 83% is insufficient for loading quantum registers of this size. Improvement in speed and in particular loading efficiency is therefore required.

In this work we report a loading efficiency of single ^{85}Rb atoms of 91% using a combination of laser cooling to remove excess energy, and blue detuned light assisted collisions. The loading procedure can be completed within 542 ms. We explain the mechanism and present a model that shows quantitative agreement with the experiment. The detailed understanding allows us to identify the factors still limiting the loading efficiency and we find that none of these apparently represent a fundamental barrier.

2. Background

Our method relies crucially on the ability to control the energy released in a light assisted collision. The controlled energy release offered by blue detuned light can be understood through the simplified two-level model illustrated in the dressed state picture in figure 1(a) [25]. The $|S+S\rangle$ asymptote represents the two atoms in their ground states, offset by one photon energy, and $|S+P\rangle$ represents one atom in the ground state and one in the excited state. The $|S+P\rangle$ is below that of $|S+S\rangle$ when the light is blue detuned and above when it is red detuned. As the resonance condition depends on the internuclear separation the dressed states will cross each other in the absence of coupling. The coupling by the light makes the crossing of the states an avoided crossing. The Condon point R_c is the interatomic distance at which the light frequency matches the energy difference between the two molecular states. When two atoms approaching on the $|S+S\rangle$ asymptote cross R_c, they may undergo a Landau–Zener (LZ) transition to the other dressed state or follow their initial state adiabatically. In a collision the atoms cross R_c twice: when they approach and again when they move apart. For a collision to be inelastic the atoms must undergo an adiabatic passage and a LZ transition leaving them to separate on the $|S+P\rangle$ asymptote. This releases an energy of up to $h\delta$, where δ is the detuning of the light. The probability for an inelastic collision is $P_I = 2P_{LZ}(1 - P_{LZ})$, with P_{LZ} the probability for a LZ transition [25]. For small detunings the $|S+P\rangle$ curve can be approximated by its C_3/R^3 asymptote (with R the interatomic distance and C_3 a constant) giving that $P_{LZ} = \exp(\frac{-2\pi\hbar\Omega^2 R_c^4}{3C_3 v})$, where Ω is the on-resonance Rabi-frequency and v the relative radial speed of the atom pair at R_c. As we will see, balancing the collisional energy transfer with laser cooling allows preferential ejection of single atoms from the trap. Thus, the atoms are lost one by one until only a single atom remains and the collisions cease.

3. Experimental apparatus and sequence

Figure 1(b) shows a sketch of the experimental setup. A high numerical aperture lens mounted inside the vacuum chamber focuses a far off-resonance ($\lambda = 828$ nm) laser beam with power 30 mW to a waist of 1.8 μm. The resulting $U_0 = h \times 85$ MHz $= k_B \times 4.1$ mK deep optical microtrap is loaded with ^{85}Rb atoms using a magneto-optical trap (MOT) followed by a compressed MOT and an optical molasses stage (k_B is Boltzmann's constant). The sequence loads on average 10–80 atoms depending on the MOT stage duration.

Figure 2 illustrates how we isolate and detect a single atom from the initial ensemble. With the MOT beams reconfigured for cooling the atoms in the microtrap, we add a 'collision beam' of controllable pulse duration. The collision beam has a radius of ~150 μm at the position of the microtrap

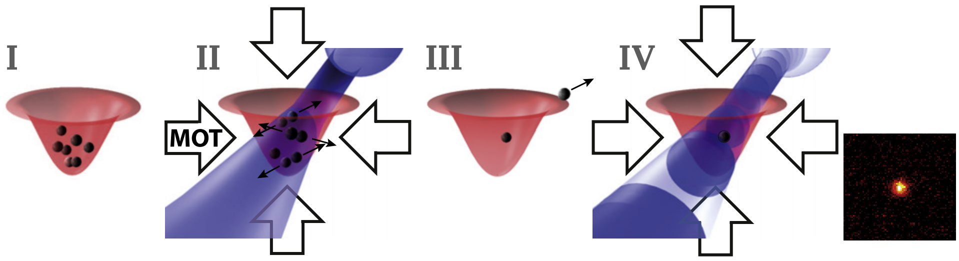

Figure 2. Experimental sequence. In I several atoms are loaded in the optical microtrap. In II the collision beam together with the six cooling beams induce collisions making the atoms escape the trap one by one. In III the collisions stop when there is a single atom left. In IV the probe beam together with the six cooling beams are used to detect the single atom. An image of a single atom is shown in the last frame.

and is blue detuned by Δ_c from the D1 $F = 2$ to $F' = 3$ transition at the center of the trap (see figure 3). Although its exact polarization is not crucial, for practical reasons we use vertically polarized light. After the collision pulse, the final step is to take an image of the atomic sample to measure the atom number. The method for imaging and counting the atoms is described in [26].

The collision stage (frame II and III in figure 2) determines the efficiency with which a single atom is prepared. Two mechanisms can reduce this to a value below the ideal 100%. First: as a single atom can be prepared before the end of the collision stage, any process leading to its subsequent loss will reduce the probability of retaining the atom until imaging. Second: collisional processes by which both partners are lost reduce the efficiency as the final pair can be lost together.

The mechanism for inelastic collisions where only one of the collision partners is lost relies on releasing sufficient energy for one atom to be lost but not enough for both. The pair should share their total energy (E_p) unevenly, so one of the atoms has a sufficient fraction to escape. This requires a significant center of mass motion of the pair before the collision. In our experiments, we aim to favor inelastic collisions when E_p before the collision is larger than zero but less than U_0. Releasing an energy equal to U_0 gives a finite probability for one atom to be lost, but the probability that both are lost is zero. Previous experiments in a high-gradient MOT identified a similar process where only one atom was lost as a result of a light assisted collision [27].

For the method to be efficient we need a mechanism to suppress the following scenario: most collisions occur such that $U_0 < E_p < 2U_0$, but with each atom having $E < U_0$ so that neither is lost. A second inelastic collision will leave the pair with enough energy for both atoms to escape. It is therefore important to remove some of the pair's energy between collisions. This is the primary role of the spectrally reconfigured MOT cooling beams during the collisions in stage II of figure 2. In this stage, each of the cooling beams has a peak intensity of $I_M = 35$ W m^{-2} and are 4 MHz red detuned from the D2 $F = 3$ to $F' = 3$ transition for atoms averaged across the magnetic sublevels at the center of the trap (see figure 3). By preparing single atoms, heating them to $\sim$1 mK, exposing them to a collision/cooling light pulse of variable duration, and measuring their temperature [28], we

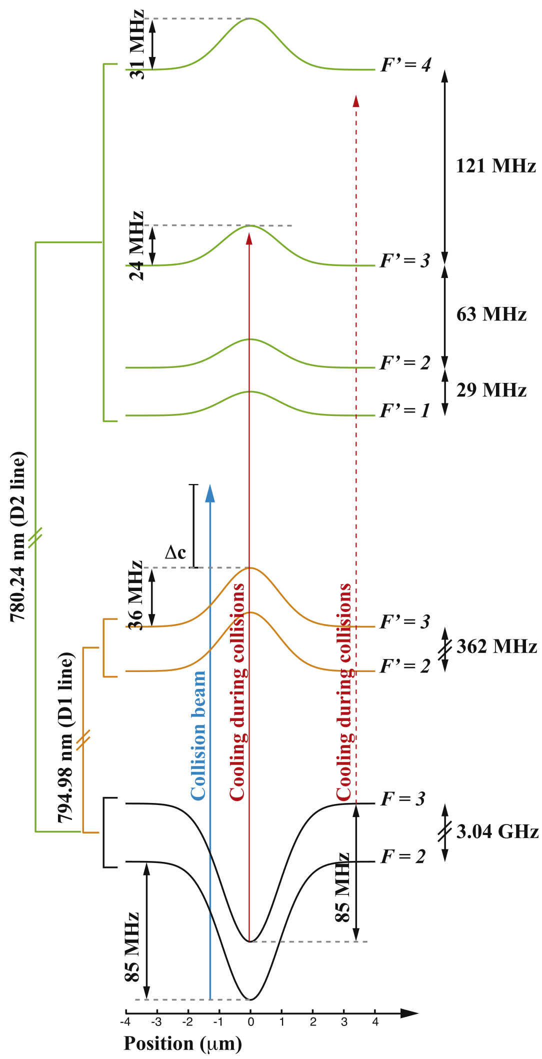

Figure 3. Energy levels of a ^{85}Rb atom showing the D1 and D2 lines shifted by the microtrap. The shifts are shown at the focus and along the radial direction of the beam.

determine the temperature evolution of single atoms exposed to collision/cooling light. It is an exponential decay with time constant of 5 ms to an equilibrium temperature of $\sim$250 μK. In addition, the cooling beams provide efficient optical pumping of atoms into the desired $F = 2$ ground state in the center of the trap where collisions are likely

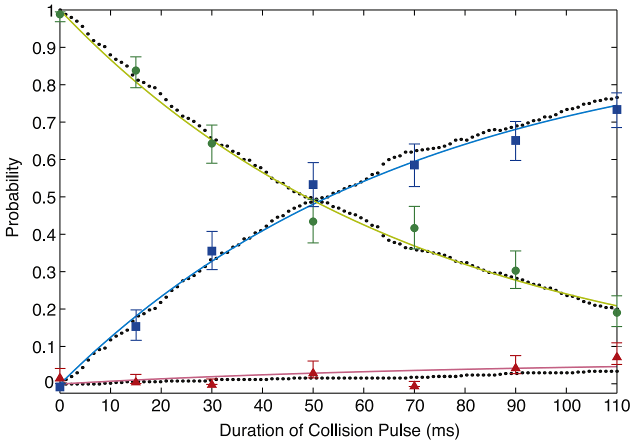

Figure 4. Atom pair evolution as a function of the collision light pulse duration. The green circles, blue squares and red triangles show the probabilities of two, one, or zero atoms respectively after the collision pulse. The solid lines are a fit of the experimental data. The dotted lines show the result of a simulation of the experiment. Error bars represent throughout the paper a 68.3% confidence interval based on binomial statistics.

to happen. The inelastic collision rate drops with increasing E_p such that the cooling beams typically lower the energy of pairs with $E_p > U_0$ before another inelastic collision occurs. This happens because the atomic density drops with increasing E_p, and because we operate our collision beam in a parameter regime where P_I drops with v. Thus, this enhances the probability of loading a single atom in the trap by avoiding collisions between hot atoms.

4. Results

We study the evolution of pairs of atoms in the microtrap when they are subjected to a collision/cooling pulse and compare it with a numerical model. A collision/cooling pulse isolates individual atoms from an initial sample in the microtrap. We give the dependence of the single atom loading efficiencies on experimental parameters and identify the factors limiting the loading efficiency.

To investigate the ejection of atoms from the microtrap we loaded pairs of atoms and measured the number of atoms left after a collision/cooling pulse. The pairs are prepared by loading a low number of atoms, taking an image, and selecting those realizations with two atoms present. Figure 4 shows the probability of measuring zero, one, and two atoms as a function of the collision pulse duration using $P_c = 11\ \mu$W of collision beam power with a detuning of $\Delta_c = 85$ MHz. The dotted lines in figure 4 show a simulation of our two atom experiment. In it the motion of two atoms in the Gaussian potential is treated classically. A Doppler cooling model, with parameters adjusted to reproduce the measured temperature evolution of single atoms, damps the motion of energetic trapped atoms. It is implemented by including the possibility for photon scattering from any of the six cooling beams in each time step. The probability for a photon scattering event is determined using the two-level Doppler shifted absorption rate [29]. When a photon scattering event occurs the momentum of the absorbed and spontaneously emitted photon is transferred to the atom. When the distance between the two atoms reaches R_c they undergo an inelastic collision with probability P_I. The collision conserves center of mass momentum while releasing an energy of $h\Delta_c$. When an atom reaches an energy above the trap depth it is lost. The probabilities are generated from 500 pairs and show good agreement with the experiment. To compensate for the simple two-level model in predicting P_I, we adjusted the Rabi-frequency in P_{LZ} such that the decay time of pairs matches the experimental value. Using $P_c = 7\ \mu$W and $\Delta_c = 185$ MHz we repeated the measurement and simulation of figure 4. Similar agreement was found for these parameters, and the adjustment factor for the Rabi-frequency matched that from figure 4 within 7.5%.

Figure 5(a) shows the histogram of the integrated fluorescence for 3200 realizations of the experiment using the parameters of figure 4. The single atom loading efficiency of 91% (statistical error less than 0.01%) is represented by

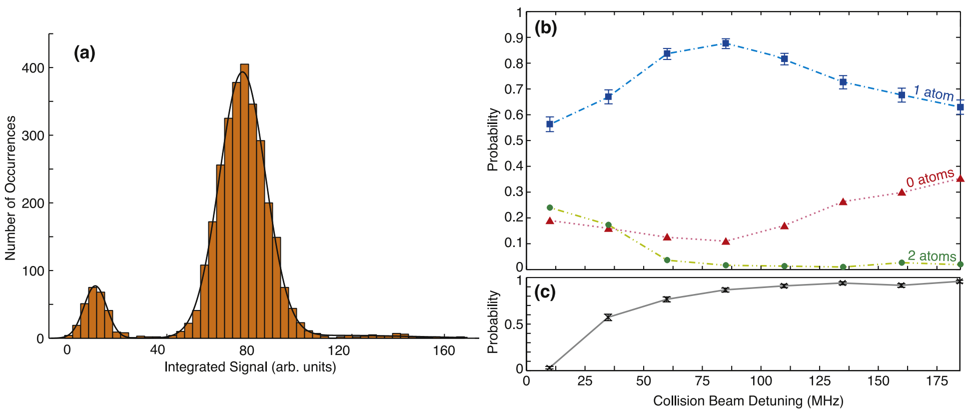

Figure 5. (a) Histogram of the integrated fluorescence for 3200 realizations of the experiment, showing 91% loading efficiency. (b) Probabilities versus detuning of the collision beam (Δ_c). Symbols are as in figure 4. (c) Single atom survival probability after a collision pulse of 3.5 s.

the large peak. The total time required to do this is 542 ms (50 ms MOT, 102 ms CMOT, 5 ms molasses to load on average 19 atoms into the microtrap, and a 385 ms collision pulse). These parameters ensure that we are unable to detect any realization with zero atoms before the collision stage. A lower initial atom number does not significantly decrease the required collision pulse duration as the nonlinear nature of the process ensures rapid loss when the number is high.

Figure 5(b) shows the single atom loading efficiency as a function of Δ_c, and the probabilities of loading zero or two atoms. The MOT parameters and the duration of the collision pulse were fixed at the values used in figure 5(a) while P_c was adjusted to maximize the probability of loading one atom. A critical feature for efficient loading is a long lifetime of the single atom once it has been prepared. To monitor this, we prepared single atoms, exposed them to a collision pulse of duration 3.5 s, and measured the probability that the atom remained trapped (the result is displayed in figure 5(c)). The lifetime decreases when the collision beam frequency is close to resonance due to increased heating from radiation pressure, leading to a higher equilibrium temperature. Although the temperature remains below the trap depth there is a finite probability that the atom will occupy the high energy tail of the distribution and thus be lost. The reduction of the lifetime at small detunings leads to a drop in the single atom loading efficiency.

To understand the reduction in single atom loading probability observed for large detunings we measured the time evolution of pairs in a similar way to figure 4, but with collision beam parameters identical to those of the $\Delta_c = 185$ MHz point in figure 5(b). In most cases, both collision partners were lost together as the energy released in each collision event is enough for both atoms to escape. This explains the reduction on single atom loading efficiency observed at large detunings in figure 5(b).

Figure 6 shows how the single atom loading efficiency evolves as a function of the collision beam power P_c. For each P_c we have adjusted the duration of the pulse (shown in the inset) in order to maximize the probability of loading one atom. The other parameters are the same as in figure 4. Although the single atom lifetime increases at low P_c the loading efficiency drops. This happens because the long collision pulses required leave enough time for the cooling beams to induce light assisted collisions. We measured the decay time for cooling beams induced loss to be ∼4 s for a pair. In each event both atoms were lost, as expected, since the cooling beams are ∼3 GHz red detuned for atoms colliding in the $F = 2$ ground state [17, 18]. We attribute the reduction in the loading efficiency at high P_c to the reduced single atom lifetime due to increased heating from radiation pressure. A notable distinction between this experiment and our previous work in [23] is that the collision beam is not a standing wave. A blue detuned standing wave produces a Sisyphus cooling effect on the atoms [26, 29]. Although the Sisyphus cooling effect will suppress the heating from radiation pressure, we found better long term stability of the loading efficiency without it. We ascribe that to the effective intensity fluctuations that relative drift between the

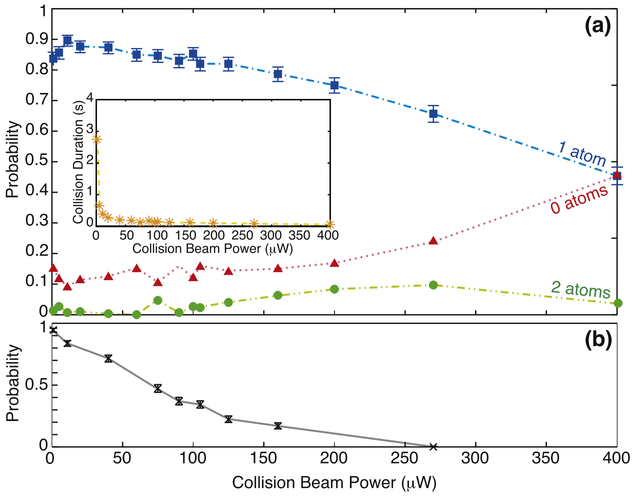

Figure 6. (a) Loading probabilities as a function of the collision beam power P_c. Symbols are as in previous figures. Inset: duration of the collision pulse. (b) Single atom survival probability after a collision pulse of 3.5 s.

phase of the standing wave and the atomic position may cause. The reported efficiencies are results of runs taken over several days, thereby averaging over the effective intensity fluctuations reducing the measured loading efficiency from its maximum value in the previously reported experiments [23]. Using a running wave in the present experiments removes this effect and is a main cause for the improvement in the loading efficiency that we report here. Naturally the unwanted relative drifts between the phase of the standing wave and the position of the microtrap could be eliminated by actively stabilizing it. In this way one would remove the effective intensity fluctuation while still benefitting from the Sisyphus cooling mechanism.

We estimate the contributions of a series of processes to the unsuccessful 9% of the realizations. Our single atom detection efficiency of 99.5% gives a contribution of ∼0.5% of the realizations where a single atom is loaded but not detected. By running a simple simulation for the loading process as described below we estimate, based on the measured single atom lifetime of ∼22 s, that the single atom loss contributes ∼1.5%. Based on the ∼4 s pair decay time caused by the cooling beams only, we estimate that ∼1.7% are due to inelastic collisions induced by the cooling beams during the collision process. Of the remaining ∼5.3%, the simulation in figure 4 predicts that 3.6% comes from collision events that occur at sufficiently high E_p leading to the escape of both partners. The remaining contribution could come from inelastic collisions that change the atomic hyperfine state.

The above mentioned loading simulation starts each run with the mean initial trapped number of atoms. In each time step the atoms can be lost due to the finite single atom lifetime or through light assisted collisions with a rate coefficient determined from figure 4. In case of collisional induced loss the probabilities for losing one or two atoms are also found from figure 4. (For a more detailed description on this simulation refer to the supplementary material of [23].)

5. Outlook and conclusions

To estimate the potential of our method to load error free quantum registers we consider the following experiment. Instead of the single microtrap that we currently use we consider an array of microtraps. Initially several atoms will be loaded into each microtrap and the atoms in excess of one are expelled using our blue detuned light assisted collision method. This approach is similar to the loading of optical lattices using red detuned collisions [17, 19]. Assuming a loading efficiency of $P = 91\%$ of each microtrap the probability for loading a quantum register of thirty sites without error is $0.91^{30} \simeq 0.06$. Using a detection pulse it will be determined if the loading was successful; if not, the procedure will be repeated. Assuming that an attempt takes 542 ms as in the present experiment it will typically take about 10 s between attempts where all thirty sites are loaded successfully. For fifty microtraps the time required would be 1 min. Based on this estimation it appears that our method can be used to load error free quantum registers of the size needed for competitive quantum computing without the need of consecutive atom sorting [3]. The increase in efficiency and speed over our previous work [23] represents a considerable decrease in time required to reach this goal; for example 31 fold for a fully loaded thirty atom quantum register. Because of the strong dependence on the single atom loading probability for loading quantum registers, a modest increase in efficiency entails a considerable improvement.

Several experiments have recently demonstrated the cooling of individual atoms to their quantum ground state both in optical microtraps [30, 31] and in optical lattices [32, 33]. The method we have described in this work can be directly applied to such experiments to deterministically load the atoms, providing a route to a deterministic quantum source of individual atoms.

It would be interesting to use atomic species such as ^{87}Rb or Cs. Their larger hyperfine splittings may suppress the unwanted effects from the cooling light and hyperfine changing collisions leading to loading efficiencies in excess of 95%. This is because their larger hyperfine splittings would allow the use of a deeper trap in which larger collision beam detunings could be used. This would reduce the heating due to radiation pressure and the single atom lifetime would thus be longer. An additional advantage of their larger hyperfine splitting, is that the inelastic collisions induced by the cooling beams during the collision process would decrease. (Above we estimated that $\sim$1.7% was the contribution of this process.) The loss coming from inelastic collisions that change the atomic hyperfine state may also be suppressed. (This contribution was also $\sim$1.7%.) Finally, as the collision parameters were chosen as a compromise between two atom loss and single atom lifetime (see figure 5(b)) and we are now reducing these factors, we could reduce the collision rate (the intensity of the collision beam) and increase the pulse duration to lower the probability of having collision events at high $E_{\rm p}$ (the contribution of this effect was estimated in 3.6%).

In conclusion, we have demonstrated a single atom loading efficiency of 91% in a red detuned optical microtrap. We have used blue detuned light assisted collisions in combination with laser cooling in order to eject atoms from the trap one by one. A model of the process quantitatively agrees with the experimental measurements and allows us to understand the different mechanisms participating during the ejection process.

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