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Number-triggered loading and collisional redistribution of neutral atoms in a standing wave dipole trap

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Abstract. We implement a technique for loading a preset number of up to 19 atoms from a magneto-optical trap into a standing wave optical dipole trap. The efficiency of our technique is characterized by measuring the atom number before and after the loading process. Our analysis reveals details of the trap dynamics that are usually masked when working with larger atomic ensembles. In particular, we identify a low-loss collisional blockade mechanism. It forces the atoms to redistribute in the periodic potential until they are all stored in individual trapping sites, thereby strongly reducing site occupation number fluctuations.

The preparation and manipulation of single or few laser-cooled neutral atoms is of interest for a number of applications including atomic nanofabrication, cold collision physics, precision measurements, cavity quantum electrodynamics, and quantum information processing. For a large class of these applications, the magneto-optical trap (MOT) has proven to be a useful and versatile tool. Trapping and observation of single atoms using MOTs was first accomplished about a decade ago [1]–[3]. More recently, the Poissonian fluctuations of the number of trapped atoms due to the stochastic loading and loss mechanisms in the MOT have been overcome by feedback-control of the loading and loss rates through external parameters [4, 5]. However, owing to its dissipative nature that relies on the near-resonant scattering of light, the MOT is not appropriate if one aims at a coherent manipulation of trapped atoms.

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In this case, the atoms will have to be transferred from the MOT into a conservative trapping potential, provided, e.g., by an optical dipole trap (DT). It has previously been demonstrated that such a transfer can be realized with a close to unity efficiency [6]. Moreover, it has been shown that losses due to light-induced inelastic two-body collisions during the MOT–DT transfer process can lead to a modification of the atom number statistics in the DT. This collisional blockade effect has, e.g., been employed to lock the number of atoms present in a single spot DT, overlapped with and continuously loaded from a MOT, to zero or one at most [7, 8]. Furthermore, collisional blockade schemes have been used to reduce and to measure the number of multiply occupied trapping sites for atoms stored in a three-dimensional (3D) optical lattice [9].

Here, we transfer a predetermined number of up to 19 atoms from a MOT in a standing wave DT, observing a redistribution of the atoms in the periodic potential through a low-loss collisional blockade mechanism. The desired number of atoms in the MOT is prepared by means of a computer-controlled loading sequence that monitors the atom number via the MOT fluorescence level. The MOT and the DT are then overlapped and, initially, the atoms are randomly loaded into the trapping sites of the DT. Subsequently, the atoms in multiply occupied sites undergo light-induced collisions due to the presence of the near-resonant MOT laser light and are expelled from the respective trapping site. However, instead of being lost, they are recaptured by the MOT and are reloaded into the DT with a high efficiency. This process continues until all atoms are trapped in individual trapping sites, resulting in a string of trapped atoms that contains either zero or one atom per trapping site. Using this method, we prepare strings of up to 19 atoms. We measure the preparation efficiency as a function of the number of atoms and of the MOT–DT overlap time. Finally, we present a theoretical model that describes our experimental data.

Our experimental set-up is schematically depicted in figure 1. The standing wave DT is created by two counter-propagating Nd:YAG laser beams with a wavelength of $\lambda = 1064$ nm, focused to a 19 μm waist. The DT is spatially overlapped with a specially designed MOT [10], serving as the source of cold caesium atoms. The MOT is loaded from the caesium background vapour and operates with a variable magnetic field gradient of either 30 Gauss cm^{-1} (low) or 340 Gauss cm^{-1} (high). In order to load the MOT, we apply the low gradient for a period τ_{load}, ranging from 10 ms to several 100 ms, depending on the desired mean number of atoms. Subsequently, the gradient is switched to high, resulting in a strong reduction of the loading rate [11], thereby effectively 'freezing' the loading dynamics. Using this method, the mean number of atoms trapped in the high gradient MOT can be adjusted between zero and a few ten.

The actual number of loaded atoms, subject to Poissonian statistics, is then inferred from the fluorescence light of the MOT. For this purpose, the fluorescence is collected with a high numerical aperture objective [12] and imaged onto an APD, operated in photon counting mode. We record the number of fluorescence photon counts N (integration time $\tau_{\mathrm{int}} = 60$ ms) with a personal computer (PC). Since each atom contributes the same fluorescence count rate to this signal, the corresponding histogram exhibits discrete peaks, each associated with a specific number of atoms trapped in the MOT, see figure 2(a). Based on this information, the PC then determines the number of trapped atoms using a software-based discriminator. If this number corresponds to the desired number of atoms n, the atoms are transferred into the DT. Otherwise, the atoms are released from the MOT by switching off the MOT lasers for 30 ms, and the loading sequence is started over again (see left part of figure 3).

In order to correctly determine the number of trapped atoms n with better than 95% certainty, the standard deviation of the photon counts N_n must be less than one fourth of the inter-peak separation. The average number of detected photons is given by $\langle N_n \rangle = (n \cdot R_1 + R_{\mathrm{stray}}) \cdot \tau_{\mathrm{int}}$,

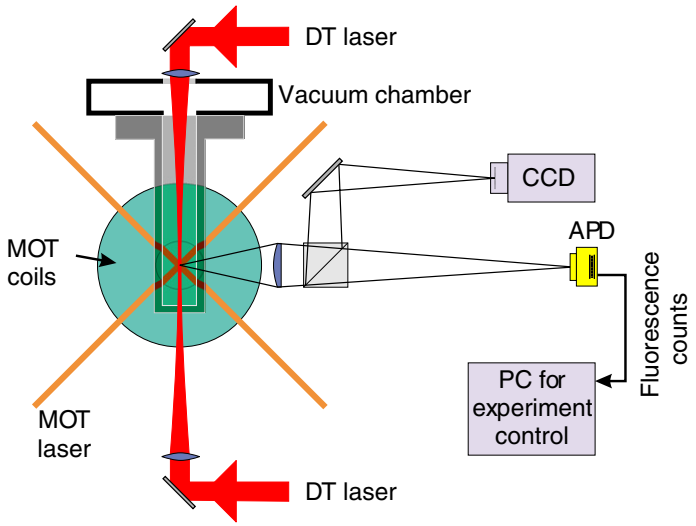

Figure 1. Experimental set-up: the MOT provides cold caesium atoms to the standing wave DT, generated by two counter propagating laser beams. Using an objective lens, we image the fluorescence light of the MOT on to a photon counting avalanche photodiode (APD). The APD signal is then fed to a software discriminator which determines the number of trapped atoms. Depending on this number, either the MOT loading process is repeated or, if the atom number equals the desired one, the atoms are transferred into the DT. Imaging the fluorescence light of atoms trapped in the DT onto an intensified CCD camera allows the measurement of their positions along the trap axis.

where $R_1 \approx 35\,000\,\mathrm{s}^{-1}$ denotes the fluorescence count rate from a single atom and $R_{\mathrm{stray}} \approx 25\,000\,\mathrm{s}^{-1}$ is the count rate due to stray light and detector dark counts, see figure 2(a). The maximum number of atoms for which 95% certainty can be reached is limited to $n \approx 20$ in our case, due to technical fluctuations of R_1 and R_{stray} [13]. This limit is approximately reached at our integration time of $\tau_{\mathrm{int}} = 60\,\mathrm{ms}$.

The transfer of the atoms from the MOT into the DT is realized by switching on the DT laser beams within 1 ms, while the MOT is still running. The two traps are then operated simultaneously for a time $\tau_{\mathrm{ovl}} = 45\,\mathrm{ms}$ before switching off the MOT. In order to check our capability of successfully transferring the desired number of atoms into the DT, the number of atoms present in the DT has to be measured. Even under illumination with near-resonant optical molasses, however, the fluorescence rate of atoms in our DT is too low for a reliable determination of their number. We therefore transfer the atoms back into the MOT and determine their number as above from the MOT fluorescence. The entire sequence for the preparation and the verification of a desired number of atoms in the DT is shown in figure 3.

As an example, figure 2(b) shows the histogram of fluorescence counts for the verification of the preparation of $n = 5$ atoms. The peak corresponding to five atoms comprises 88% of all events. We define this percentage as the preparation efficiency for five atoms, $p_{\mathrm{success}}(n = 5)$. In the other events, atoms have been lost or an additional atom has been captured. We denote the probabilities of losing one or two atoms by $p_{1\,\mathrm{lost}}(n = 5)$ and $p_{2\,\mathrm{lost}}(n = 5)$, respectively. Since the atoms are transferred back into the MOT for counting, taking additional time and causing

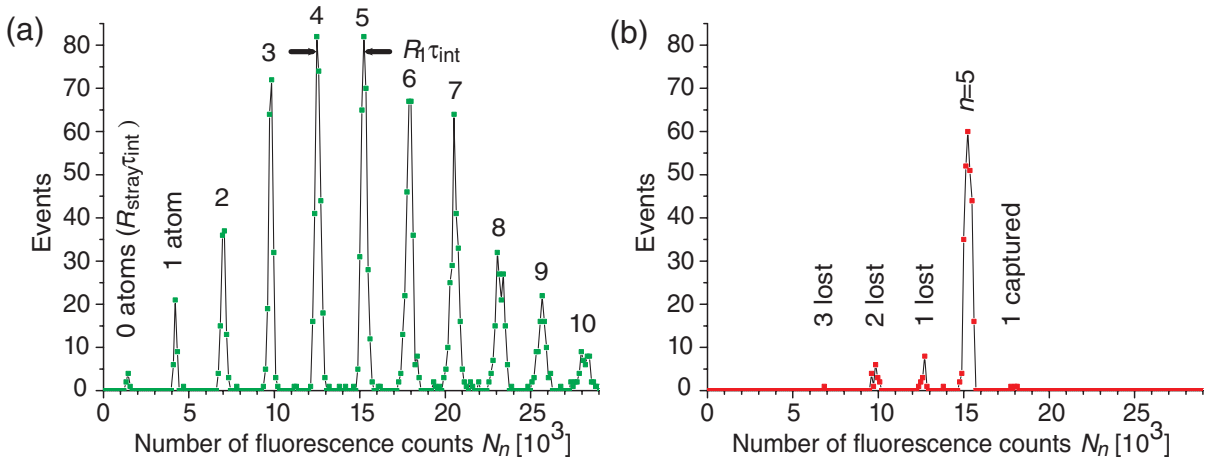

Figure 2. Histograms of fluorescence counts from the MOT integrated over $\tau_{int} = 60$ ms (bin size: 120 counts). Each peak corresponds to a specific number of trapped atoms. In panel (a), the fluorescence was measured directly after loading the MOT with five atoms on average. The actual number of atoms in the MOT follows Poissonian statistics to a good approximation, leading to the observed distribution of peak areas. For events where the software discriminator detected five atoms in the MOT, the atoms were transferred to the DT. These atoms were counted by transferring them back to the MOT where the fluorescence was measured a second time, leading to the final histogram in panel (b).

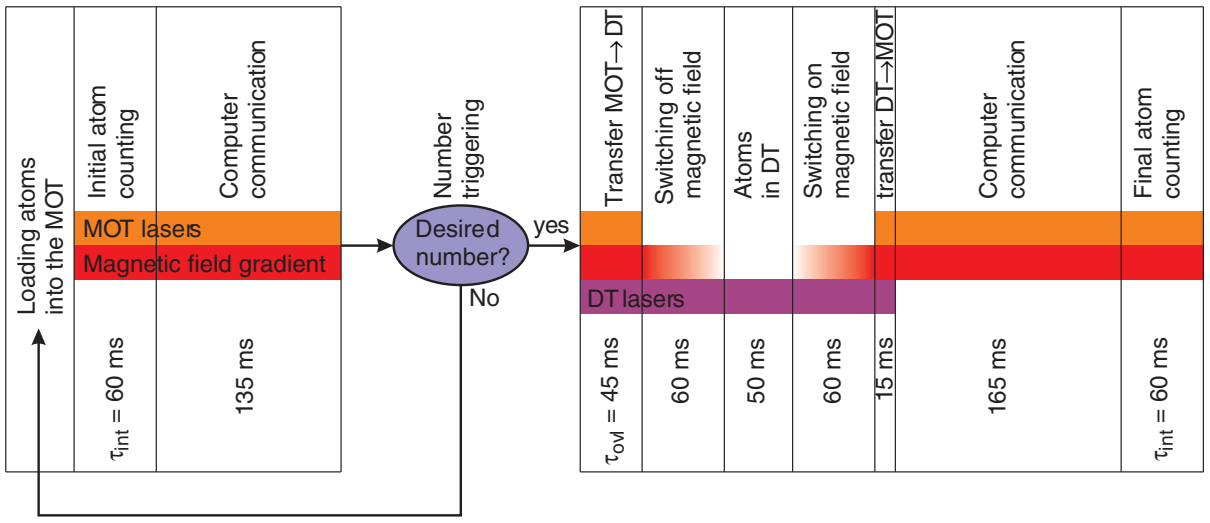

Figure 3. Experimental sequence for preparing a desired number of atoms n in the DT using our number-triggered loading scheme. At the end of the sequence, the atoms are transferred back into the MOT in order to measure their number.

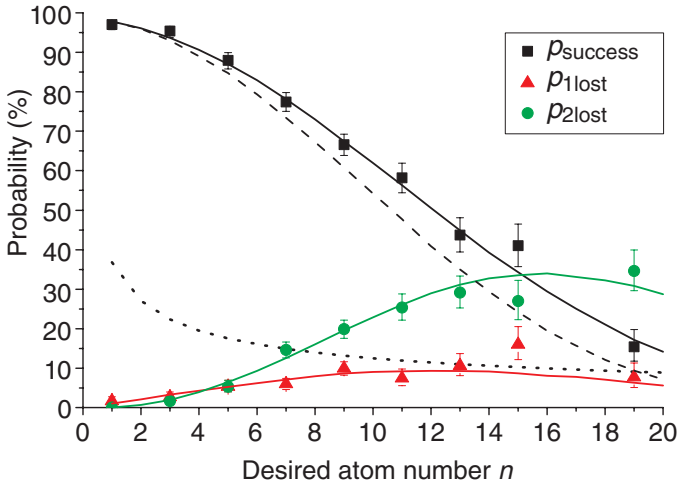

Figure 4. Preparation efficiency. The black squares show the measured efficiency $p_{\text{success}}(n)$ of preparing a desired number of atoms n in the DT. The probabilities of losing one or two atoms are shown as red triangles and green circles, respectively. The solid lines show the results of our simulation. Our model assumes a low-loss collisional redistribution of the atoms during the loading process of the DT. A model with higher losses significantly deviates from the experimental data, see dashed line. The dotted line shows the maximum probability of obtaining n atoms without our number-triggered loading scheme according to Poissonian statistics.

additional losses, $p_{\text{success}}(n = 5)$ is a lower bound for the actual probability of preparing five atoms in the DT.

The capturing of an additional atom from the caesium background vapour can occur, while the MOT is operating in between the initial and final determination of the atom number. This effect is independent of the trapped atom number and can be parameterized by the phenomenological rate coefficient $r_{\text{capt}} = (0.029 \pm 0.009)\,\text{s}^{-1}$, independently determined by measuring the probability of capturing one atom within a fixed time interval of MOT operation.

Figure 4 shows the preparation efficiency $p_{\text{success}}(n)$ for different desired atom numbers n (■). The probability of successfully preparing a single atom in the DT is $p_{\text{success}}(n = 1) = 97.1^{+1.1}_{-1.3}\,\%$. Comparing this value with the maximum probability of preparing one atom when loading the DT without number-triggering (36% according to Poissonian statistics, see dotted line) reveals a 2.5-fold enhancement. The preparation efficiency for ten atoms in the DT, $p_{\text{success}}(n = 10) \approx 60\%$, is even a factor of five higher than what is theoretically achievable without number-triggering, according to Poisson statistics. When carrying out experiments that require a fixed initial number of atoms in the DT, our number-triggered loading technique thus allows us to significantly speed up the collection of data as compared to unconditionally running the experimental sequences (typical duration of the order of seconds) with a Poissonian distributed atom number and post-selecting the relevant events.

In figure 4, we also show the probabilities $p_{1\,\text{lost}}(n)$ and $p_{2\,\text{lost}}(n)$ of losing exactly one or exactly two atoms during the sequence, respectively.[2] From these data, we can deduce quantitative

[2] The sum of the three plotted probabilities differs from one for larger desired atom numbers due to the increasing probabilities of losing three or more atoms, not plotted here.

results concerning the underlying loss mechanisms. One-atom loss is primarily due to collisions of the trapped atoms with the thermal background gas present in the vacuum chamber. It results in a constant loss rate throughout the entire experimental sequence, manifesting itself in an independently measured storage time of $\tau_{\mathrm{bg}} = 55 \pm 8\,\mathrm{s}$ for a single atom in the DT.

Two atom loss, on the other hand, is caused by inelastic cold collisions between atoms in the MOT and also in the DT, especially in the presence of additional near-resonant light during the transfer between the traps. These losses account, e.g., for the comparatively high value of $p_{2\,\mathrm{lost}}(n = 5)$ in figure 2(b). Different collisional mechanisms such as radiative escape (RE), hyperfine changing collisions (HCC), and fine structure changing collisions (FCC) have been extensively studied in the past [14]–[17].

In our high gradient MOT, the contributions of all three mechanisms to the total collision-induced loss rate are of the same order of magnitude [18]. For n atoms in the MOT, the two atom loss rate is given by $n(n-1)\,\alpha_{2\mathrm{at}}^{\mathrm{MOT}}$. Furthermore, we observe that part of the inelastic cold collisions lead to loss of one atom only. This effect has already been observed in former work by our group [18] and leads to a contribution to the one atom loss rate given by $n(n-1)\,\alpha_{1\mathrm{at}}^{\mathrm{MOT}}$.

The collisional MOT losses influence our preparation efficiency $p_{\mathrm{success}}(n)$. In order to quantify these effects, we determined the values of $\alpha_{2\mathrm{at}}^{\mathrm{MOT}}$ and $\alpha_{1\mathrm{at}}^{\mathrm{MOT}}$ in an independent measurement: we prepared 1–19 atoms in the MOT and measured their final number after storing them in the MOT for 270 ms. This measurement yields a preparation efficiency curve similar to that shown in figure 4 and, correspondingly, the probabilities of losing exactly one or two atoms. Using the known values of the background gas loss rate and the capture rate of our MOT, we fit this data with a numerical model (see below) yielding $\alpha_{2\mathrm{at}}^{\mathrm{MOT}} = 8 \times 10^{-3}\,\mathrm{s}^{-1}$ and $\alpha_{1\mathrm{at}}^{\mathrm{MOT}} = 9 \times 10^{-4}\,\mathrm{s}^{-1}$.

While the atoms are trapped in the DT, on the other hand, one atom loss is only caused by background gas collisions while two-atom loss can only occur if two atoms are confined in the same potential well of the DT. It is then dominated by HCCs, i.e., the only inelastic collision process between ground state atoms, prepared in the $F = 4$ hyperfine level in our case. The rate of HCCs is estimated by $n(n-1)\beta_{\mathrm{HCC}}/V_{\mathrm{eff}}$. Here, the collision rate coefficient $\beta_{\mathrm{HCC}} = 1.1 \times 10^{-11}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ is taken from [19] and the effective volume $V_{\mathrm{eff}} = 15\,\mu\mathrm{m}^3$ is calculated from the spatial distribution of the atoms with a temperature of 100 μK in a potential well with a depth of 1 mK. For two atoms in one well, the resulting collision rate is $0.7\,\mathrm{s}^{-1}$.

In the following, we now investigate in detail the transfer process of atoms between the MOT and the DT. For a single atom, transferred into the DT and back into the MOT, we detect no measurable increase in the losses as compared to continuously storing it in the MOT. In this case, the losses can thus be entirely explained by background gas collisions, justifying the assumption of a single atom transfer efficiency of 100% between the two traps in the following analysis. Furthermore, an independent measurement (see below) shows that atoms are rapidly (<1 ms) cooled into the potential wells of the DT when overlapping it with the MOT.

When transferring more than one atom into the DT, inelastic collisions play a distinctively different role during the overlap time of the MOT and the DT than for the case where atoms are solely stored in the MOT: atoms trapped in individual wells of the standing wave potential are separated by at least 0.5 μm and will thus not undergo any collisions. At the same time, however, atoms in multiply occupied potential wells are confined in a volume more than two orders of magnitude smaller than the trapping volume of the MOT itself. They are thus much more likely to undergo an inelastic collision than in the MOT alone. In addition, as we will see in the following, these collisions result in a redistribution of atoms in the DT.

In order to model these processes, we first measured the spatial distribution of atoms in the DT. For this purpose, we transfer 3–5 atoms per run from the MOT into the DT and determine their positions using an intensified charge-coupled device (CCD) camera [20]. The distribution reconstructed in this way is well described by a Gaussian function with a standard deviation of $\sigma_{\text{transfer}} = 5.0 \pm 0.5\,\mu$m. Thus, the atoms are distributed over about 20 potential wells.

In the presence of the near-resonant MOT light, the by far dominating collisional process during the overlap time τ_{ovl} of the MOT and the DT is RE. In contrast to FCCs and HCCs, RE has a continuous energy spectrum and the probability of releasing a kinetic energy greater than E is given by [15]

$$P_{\text{RE}}(E) \propto E^{-5/6}. \tag{1}$$

$P_{\text{RE}}(E)$ hence decreases with increasing energy E. Accordingly, the rate of RE collisions leading to loss from the DT (depth 1 mK) is two orders of magnitude larger than the rate of RE collisions leading to loss from the MOT (effective depth $\approx$400 mK [18]). In other words, more than 99% of all atoms removed from the DT by a RE collision are recaptured by the MOT. Subsequently, they are thus cooled back into the DT, leading to a collision-induced redistribution of atoms during the overlap time. The processes leading to the redistribution are parameterized by the rate of collision-induced DT loss events for n atoms confined to the same potential well, $n(n-1)\,\alpha_{\text{RE}}$, and the probability of recapture by the MOT, ρ. The values of α_{RE} and ρ are determined in an independent measurement (see below).

We have numerically simulated the experimental sequence illustrated in figure 3 for different initial numbers of atoms n, taking into account all processes described above (background gas collisions, inelastic collisions in the MOT and in the DT, and collisional redistribution). In this Monte Carlo simulation, the sequence is divided in time steps of 1 ms. For each time step, the probability of the different loss mechanisms is computed and, with this probability, the number of atoms is updated correspondingly. We simulated 10^6 runs of the sequence for each initial number of atoms n. The results are displayed as solid lines in figure 4. The only free parameter used in this simulation is the probability ρ of recapturing atoms that underwent a RE collision during the transfer between the traps. The fitted value of $\rho = 99\%$ agrees very well with $\rho \approx 99\%$ calculated from equation (1)). For comparison, we also simulated the experimental sequence for lower values of ρ and found a significant deviation from the data when reaching $\rho = 90\%$ (see dashed line in figure 4), yielding a lower limit for ρ in this case.

The good quantitative agreement between the simulation and the measured values of p_{success}, $p_{1\,\text{lost}}$ and $p_{2\,\text{lost}}$ indicates that the underlying physical mechanisms are well described by our model. In particular, according to our model, one therefore expects a collisional redistribution of the atoms during the overlap time of MOT and DT, finally leading to a sub-Poissonian distribution of atoms in the standing wave potential with at most one atom per potential well. Once this situation is reached, further collisions should be suppressed and the redistribution should cease.

In order to find experimental evidence of this redistribution process, we designed a method for detecting the presence of multiply occupied potential wells in our DT. It again relies on light-induced inelastic collisions between atoms in the DT under illumination with near-resonant light, supplied by the MOT laser beams. However, instead of operating them in the MOT configuration, the magnetic field remains switched off, thus realising an optical molasses. While atoms in singly occupied wells are cooled by this molasses, we have verified in an independent measurement that atoms in multiply occupied wells undergo RE collisions and escape from the DT with a time

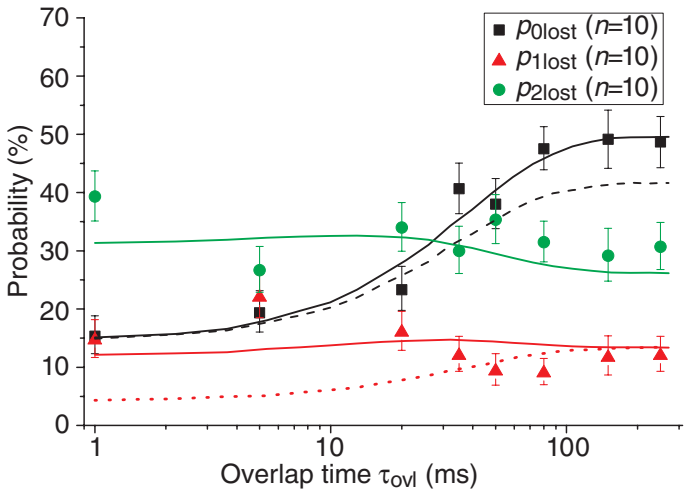

Figure 5. Collisional redistribution. The data points show the probabilities of losing zero, one and two atoms from an initially prepared number of 10 atoms. Here, the overlap time τ_{ovl} between MOT and DT is varied revealing the time dependence of the redistribution process. The solid lines are results of the Monte Carlo simulation for a recapture probability of $\rho = 90\%$. For comparison, the simulated probability of not losing an atom for $\rho = 80\%$ is given by the dashed line. It significantly deviates from the measured data, proving that $\rho > 80\%$. Our model assumes that a major part of the one atom losses is induced by collisions. When neglecting this process, the theoretical prediction significantly deviates from the data for $p_{1\,\text{lost}}$, see dotted line.

constant of about 40 ms [21]. Here, in contrast to the collisional redistribution process described above, these atoms are not recaptured and will diffuse out of the molasses region [21]. The loss of atoms induced by the optical molasses is thus a direct measure of the number of atoms in multiply occupied wells.

Using this method, we investigated the dependence of the redistribution process on the MOT–DT overlap time τ_{ovl}. The experimental sequence was similar to that of figure 3, with a variable overlap time τ_{ovl} between 1 and 250 ms and an additional optical molasses applied for 300 ms, while storing the atoms in the DT. The measured values of $p_{0\,\text{lost}}$, $p_{1\,\text{lost}}$ and $p_{2\,\text{lost}}$ for initially ten atoms are shown in figure 5. For long overlap times, the redistribution process is completed and no collisions take place during the illumination with the molasses. In this case, the probability $p_{0\,\text{lost}}$ of obtaining ten atoms in the end approximately equals $p_{\text{success}}(n = 10)$ from figure 4. For short overlap times, on the other hand, little redistribution has taken place and the molasses causes significant atom loss. The single atom transfer efficiency between the two traps remains above 99% for overlap times down to 1 ms, as we have verified by carrying out the same experimental sequence with one instead of ten atoms. The reduction of $p_{0\,\text{lost}}$ for $\tau_{\text{ovl}} < 150$ ms is thus solely due to RE collisions in multiply occupied potential wells.

As has already been observed for collision-induced losses in the MOT (see above), we also expect part of these RE collisions to lead to the loss of only one atom. The order of magnitude of this fraction can be estimated by considering the kinematics of classical inelastic collision processes between atoms at a finite temperature trapped in the same potential well: in the

centre-of-mass reference frame of the colliding atoms, the energy released by the RE collision is equally shared by both atoms which move apart with equal velocities in opposite directions. However, in the laboratory frame, the thermal centre-of-mass motion of the pair of atoms is superposed on this motion. Adding up the corresponding velocities in general yields a difference in the resulting kinetic energies of the atoms which can then lead to the loss of one atom only from the DT. For 1 mK trap depth and an ensemble of atoms with a temperature of 50–100 μK, a simple estimation assuming a Boltzmann distribution of initial velocities and using the energy spectrum of the RE collisions predicts that a fraction of 40–60% of all atom losses following an RE collision should be one atom loss events.

In our numerical modelling of the data in figure 5, we account for this process by assuming a probability of 50% for RE collision-induced one atom losses during the operation of the optical molasses. The result of our simulation is given by the solid lines in figure 5, using a recapture probability of $\rho = 90\%$ and a loss rate coefficient $\alpha_{\mathrm{RE}} = 25\,\mathrm{s}^{-1}$. The good agreement between experiment and theory confirms the presence of the low-loss collisional redistribution. For comparison, we have also calculated the theoretical prediction for $p_{1\,\mathrm{lost}}$ when assuming absence of collision-induced one atom losses during the molasses stage. It clearly deviates from the experimental data for short overlap times (dotted line in figure 5).

In order to determine a lower bound for the recapture probability, we again carried out simulations using smaller values for ρ, while keeping the values of all other parameters constant until the model significantly deviates from the data. In this way, we estimate a lower bound of $\rho = 80\%$, see dashed line in figure 5. The reduced value of ρ compared to at least 90% obtained from modelling the data of figure 4 could be due to imperfect alignment. In particular, the spatial overlap of the MOT and the DT might play a crucial role in the recapture efficiency. This assumption is supported by the high sensitivity of all preparation efficiencies on the alignment of the set-up, observed in our experiments.

Summarizing, we implement a computer-based technique for controlling the number of atoms loaded into our standing wave DT. We prepare up to $n = 19$ atoms with a preparation efficiency of better than 60% for $n \leqslant 10$ and better than 90% for $n \leqslant 5$. In addition, our capability of directly identifying one, two, and more atom loss events allows us to reveal details of the loss processes that are usually masked when working with large atom numbers. In particular, we identify and characterize a low-loss collisional redistribution process during the MOT–DT transfer which rearranges the trapped atoms until the DT contains at most one atom per lattice site.

Compared to loading the DT with a Poisson distributed number of atoms from the MOT, our number-triggered loading technique allows us to significantly speed up the collection of data in experiments requiring a preset number of atoms. It was already employed for the preparation of a string of seven equidistant atoms using optical tweezers [22]. Moreover, our technique will be especially useful for future experiments relying on the controlled interaction between simultaneously trapped atoms via cavity QED [23] or controlled cold collisions [24, 25]. These experiments will also benefit from the fact that each atom occupies its own potential well, allowing, in principle, to apply individual manipulations to each atom.

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