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potential of 2.5 mK/cm.

The experimental setup is an extension of that used in ref. 1. Fig. 1b provides a sketch of the relevant elements. Three beams with 8 mm in diameter and 20 mW power, detuned from resonance by two times the natural line width, are retroreflected in order to form the SMOT. Atoms are provided from a Zeeman-decelerated atomic beam. By observation of the 423 nm fluorescence we measure 4 $\times$ 10$^7$ atoms in the excited $^1P_1$ state of the SMOT. From the known transition rates (see e.g. ref. 1) we can deduce a transfer rate into the $^3P_2$ state of 1.9 $\times$ 10$^{10}$ atoms/s. The magnetic quadrupole field with horizontal symmetry axis ($z$-axis) has a trap depth of 20.6 mK and a magnetic field gradient (along the $z$-axis) of $b=26$ Gauss/cm in the origin. For monitoring the operation of the SMOT we record the fluorescence at 657 nm due to atoms decaying via $^1D_2$ and $^3P_1$ back to the ground state. In order to observe the $^3P_2$ atoms we optically pump them to the $^3P_1$ state by applying a 0.5 ms pulse of 430 nm light resonant with the $^3P_2(4s4p)\rightarrow^3P_2(4p4p)$ transition. The $1/\epsilon^2$-radius of this optical pumping beam is 3 mm. In order to work with a reduced optical pumping volume, a variable aperture placed inside this beam is imaged onto the atomic sample. The $^3P_1$ atoms decay to the $^1S_0$ singlet ground state in 0.4 ms and are subject to ballistic expansion. Temperature measurements are performed with a time of flight method (TOF). A 10 mm wide and 0.5 mm thick sheet of light resonant with the $^1S_0\rightarrow^1P_1$ transition is placed 9 mm below the center of the optical pumping beam (see Fig. 1b). The fluorescence in this light sheet is recorded by a photo multiplier from below. Because we operate the TMOT with the same magnetic quadrupole field, the narrow bandwidth (57 kHz) of the $^3P_2\rightarrow^3D_3$ transition is power-broadened to a peak value of 16 MHz, in order to obtain sufficient spatial capture volume. With 5 mW for each of the three retroreflected beams of 10 mm diameter the resonant peak saturation parameter is $7.6 \times 10^4$.

In Fig. 2 the operation of the magnetic trap is illustrated. Before $t=0$, for about 240 ms atoms are Zeeman cooled, loaded into the SMOT, and transferred to the magnetically trapped $^3P_2$ state. At $t=0$ the 423 nm beams are disabled, i.e. no further loading of the magnetic trap occurs which is seen from the drop of 657 nm fluorescence in trace (a). After a variable time delay the optical pumping pulse is applied which gives rise to a spike of 657 nm fluorescence, and a TOF spectrum is recorded (trace (b)). Alternatively, during the loading period before $t=0$ we may apply the TMOT. In this case the magnetic trap is not continuously loaded but at $t=0$ the $^3P_2$ atoms trapped and cooled in the TMOT are suddenly released into the magnetic trap. Detection is performed as in the case of SMOT loading. While TMOT loading allows for lower initial temperatures, an attractive feature of SMOT loading is its continuous character, i.e. the possibility to add particles to the trap without disturbing those already trapped, as recently discussed in ref. 4 and demonstrated for chromium atoms in ref. 5.

By varying the trapping time in Fig. 2 and observing the size of the 657 nm fluorescence peak in trace (a) we can measure the life time of the magnetic trap. The case of TMOT loading is shown in Fig. 3a (open rectangles). For comparison, the filled rectangles show the decay of the TMOT itself. A surprisingly high transverse efficiency of about 75% is observed. The fitted exponentials (solid lines in Fig. 3a) correspond to a model which neglects two-body collision losses. The decay time constants of $239 \pm 4$ ms in the upper trace and $229 \pm 8$ ms in the lower trace agree within the errors and are in accordance with the $10^{-8}$ mbar vacuum conditions. For SMOT loading the same decay time is found. Although a model accounting for inelastic two-body collisions yields slightly better fits for the lower trace in Fig. 3a, slow fluctuations of the initial sample sizes in our present data do not allow us to extract reliable values for the collision rate.
In Fig.3b TOF spectra are shown for three different cases. The upper trace (1) shows a TOF spectrum for atoms trapped in the TMOT for 370 ms with a loading period of 240 ms. In trace (2) the TMOT was loaded for 240 ms but subsequently the atoms were released into the magnetic trap and held there for 130 ms. In trace (3) the SMOT continuously loaded the magnetic trap for 240 ms followed by 130 ms without further loading. Note that in either case (2) and (3) the temperature found in the magnetic trap is significantly lower than that of the loaded atomic sample. In trace (3) the initial sample in the SMOT has a temperature of about 3 mK, while that of the magnetically trapped sample is only 611 μK. In (2) the initial sample temperature is 182 μK as seen in trace (1), while the temperature in the magnetic trap is only 134 μK. The fits in Fig.3b (solid black lines) used to evaluate temperatures are derived from a TOF model with three fit parameters: the initial vertical diameters and atom numbers of the fraction of atoms participating in the ballistic flight, and the temperatures. The initial sizes found in these fits are consistent with those observed.

The diameter of the TMOT is estimated to be 2 mm by scanning the 430 nm optical pumping beam with 0.5 mm diameter through the atomic sample and observing the 657 nm fluorescence peak of Fig.2a. This corresponds to the best fit in trace (1) obtained for 2.4 mm. The initial diameter for the TOF measurement of trace (2) is estimated similarly to be about 4 mm correspond-
ing to the value of 4.1 mm in the best fit. The best fit value of the initial diameter for trace (3) of 7.9 mm does not reflect the size of the trapped population but is determined by the 3 mm maximal radius of the optical pumping beam. In traces (2) and (3) we also recognize a hot fraction of atoms occurring at early times in the TOF-spectra which are not accounted for in our model. Particularly, in the case of TMOT loading (trace (2)) a well distinguished hot fraction (at several mK) is visible. For TMOT loading, TOF spectra recorded for trapping times shorter than 100 ms show additional structure which reflects non-equilibrium trap dynamics as is illustrated in Fig.4. The initial sharp peaks, resulting from the 430 nm depumping photons, indicate the release of the atoms from the magnetic trap. One recognizes an oscillation of population between hotter and colder fractions of atoms occurring at earlier or later times in the TOF spectra.

In order to explain the temperature decrease in the magnetic trap we first consider the case of SMOT loading in trace (3). The 3P2 trap potential is continuously loaded by the cold flux of atoms emerging from the trapping volume of the SMOT with ε=1 mm 1/e radius via intermediate population of the 1D2 state where the atoms spend on average 10 ms. During this process the atoms remain subjected to magnetic trapping since the 1D2 state itself provides a trap potential with 2/3 of the size of that of the 3P2 state. If the initial atomic sample is smaller than the equilibrium distribution inside the magnetic trap, an expansion occurs which reduces the mean kinetic energy of the initial sample kBT or the average potential energy of the final equilibrium distribution ρ minus the average potential energy of the initial distribution. Thus, for the quadrupole potential U the final kinetic energy is calculated to be kBTf = kBTi/3 + 0.172 × σ × U0. The second term corresponds to 90 K for SMOT loading and may be neglected as compared to typical initial SMOT temperatures of 3 mK. Thus, temperatures above 1 mK are expected, exceeding the observed 0.6 mK. In case of TMOT loading in trace (2) a similar deviation is found. Here 0.172 × σ × U0 amounts to 108 μK and thus the expected temperature is 169 μK as compared to 134 μK observed.

Let us next estimate the capture efficiencies beginning with SMOT loading. We first calculate the average Zeeman detuning δB experienced by the different Zeeman components of the 1P1 fraction of the SMOT sample in the quadrupole field U(x,y,z). With δ=k26 Ganns/cm we get δB(mJ)/Γ = 0.08 × mJ. Using these Zeeman detunings we calculate the average relative excitation probabilities of the 1P1 Zeeman components finding 37 % for the high field seeking mJ=1 state, 34 % for the non-magnetic state, and 29 % for the low field seeking mJ=1 state. With the help of the Clebsch–Gordan coefficients we derive the relative populations of the Zeeman sublevels in the 1D2 and 3P2 states respectively. We find 18 % population in the mJ=2, and 19 % population in the mJ=1 low field seeking component of the 3P2 level.
which are the two trapped states. In case of TMOT loading all atoms leaving the $1^1 P_1$ state should be captured in the TMOT and about 20% of those atoms should be transferred to each of the two magnetically trapped Zeeman sublevels. For SMOT loading only a fraction of the magnetically trapped atoms can contribute to the 657 nm fluorescence peak following the optical pumping pulse. In order to calculate the transfer efficiency by optical pumping we have numerically integrated the product of the thermal equilibrium distribution in the $3^3 P_2$ potential $\rho(x, y, z) = \frac{1}{\sqrt{2\pi k^3}} \frac{1}{\sqrt{2\pi k^3}} \frac{1}{\sqrt{2\pi k^3}} \exp(-U(x, y, z)/k_B T)$ and the local optical pumping probability during the 0.5 ms pumping pulse. To derive the local pumping probability we have solved a rate equation including all levels involved and account for the local intensity, polarization and the Zeeman detunings from resonance due to the magnetic quadrupole field. Temperatures are inserted as obtained from Fig.3b. For SMOT loading we find that a fraction of 39% of the $m_J = 2$ atoms and 14% of the $m_J = 1$ atoms is transferred. For TMOT loading no loss should occur in the optical pumping transfer.

For SMOT loading we typically observe a 657 nm fluorescence peak with $2.9 \times 10^7$ atoms. Accounting for the expected transfer efficiency by optical pumping discussed in the previous paragraph we obtain $5.4 \times 10^7$ trapped $m_J = 2$ atoms and $5.7 \times 10^7$ trapped $m_J = 1$ atoms. Assuming thermal equilibrium at 611 µK, the peak density is $3.4 \times 10^8 \text{cm}^{-3}$ for $m_J = 2$ atoms and $1 \times 10^8 \text{cm}^{-3}$ for $m_J = 1$ atoms. Accounting for the loading time of 240 ms a capture rate of the $m_J = 2$ component of $3.6 \times 10^8 \text{s}^{-1}$ is observed. This is to be compared with 18% of the overall transfer rate of $1.9 \times 10^{10} \text{s}^{-1}$, i.e. $3.4 \times 10^8 \text{s}^{-1}$. For TMOT loading we find $2.4 \times 10^8$ fluorescing atoms, and accordingly $1.2 \times 10^8$ atoms in each of the two magnetically trapped Zeeman sublevels. Assuming thermal equilibrium at 135 µK, we find a peak density of $6.7 \times 10^8 \text{cm}^{-3}$ for $m_J = 2$ atoms and $2 \times 10^8 \text{cm}^{-3}$ for $m_J = 1$ atoms. The observed $m_J = 2$ capture rate is $7.9 \times 10^7 \text{s}^{-1}$ and has to be compared with 20% of the overall transfer rate of $1.9 \times 10^{10} \text{s}^{-1}$, i.e. $3.8 \times 10^8 \text{s}^{-1}$. Presently, we cannot resolve the discrepancies between the expected and the observed capture rates which amount to a factor 9.4 for SMOT loading and a factor 4.8 for TMOT loading.

In summary, we have applied magnetic trapping to the group of earth alkaline atoms, preparing several times $10^8$ calcium atoms in the $3^3 P_2$ metastable state at peak densities near $10^{11} \text{cm}^{-3}$ and temperatures around 0.15 mK. This represents favorable starting conditions for the formation of a metastable calcium BEC. Technical improvements (e.g. an extra transient cooling phase in the TMOT scheme, as explained in ref. 4, or a simple decrease of the background pressure) promise at least an order of magnitude improvement of the initial phase space density.

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