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Sub-Doppler magneto-optical trap for calcium

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We explore an efficient method for preparing large samples of ultracold calcium atoms. An optimized conventional (Doppler-limited) magneto-optical trap collects atoms from a Zeeman cooled atomic beam using a strong dipole transition within the singlet system. This transition is not completely closed thus yielding an intense flux of atoms into the metastable triplet state $^3P_2$. A second magneto-optical trap sharing the same magnetic-field gradient is superimposed which captures and further cools the metastables using the narrow-band infrared transition $^3P_2 \rightarrow {}^3D_3$. In our present experiment we were able to prepare 3×10^8 atoms at temperatures below 20 microkelvin within 250 ms. Minor technical improvements of our setup promise to yield above 10^{10} atoms at submicrokelvin temperatures within 1 s.

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Earth alkaline atoms show a number of outstanding features connected to their two-valence electrons. The simple structure of their zero spin ground state makes them particularly suited for precise comparisons between theory and experiments in cold collision studies [1,2]. The existence of extremely narrow intercombination transitions, nearly unperturbed by electric and magnetic fields, appears ideal for future time and length standards in the optical domain which promise unprecedented precision [3–5]. The unique spectroscopic features of two-electron systems could also contribute a wealth of new physics to the growing field of Bose-Einstein condensation [6,7]. Such exciting perspectives, however, rely on whether the impressive success of laser cooling mainly obtained for alkalis can be extended to provide samples of earth alkaline atoms which are not only ultracold but also comprise very high atom numbers.

Unfortunately, there are two obstacles that seem to frustrate this desire. Because of the absence of ground-state Zeeman structure, conventional laser cooling exploiting the principle fluorescence lines [8,9] is constrained by the Doppler limit which amounts to temperatures in the millikelvin range in contrast to microkelvin temperatures usually obtained for alkalis. Second, the cooling transitions — with the exception of magnesium — have a built-in loss channel that can be closed only incompletely by additional repumping, thus limiting the size of samples that can be captured. Magnesium, unfortunately, provides the additional difficulty of a cooling transition in the UV.

In the recent past, extended research has been devoted to develop refined laser cooling schemes opening the microkelvin range for earth alkaline atoms. A number of experiments have explored the combination of precooling on the principal fluorescence lines with a final cooling step using narrow intercombination lines which can provide microkelvin-Doppler temperatures. For strontium this concept has turned out very successful due to its relatively broad intercombination line (7 kHz) which provides sufficient velocity capture range [10]. In this experiment typically a few times 10^7 atoms could be trapped and cooled slightly below 1 μK within a time interval on the order of 100 ms. Calcium with its significantly more narrow (408 Hz) intercombination line at 657 nm (used in today's definition of the meter [11]) offers a particularly attractive combination of readily accessible transition wavelengths and high spectroscopic precision. Ultracold samples of calcium are thus highly desirable, however, their preparation presents a particular challenge. Very recent experiments have explored the extension of narrow line Doppler cooling to calcium. An additional quenching laser was used to increase the photon scattering rate on the otherwise too narrow intercombination line [12]. In this way about 10^6 atoms could be trapped and cooled within typically 50 ms close to the effective recoil limit of 5.6 μK connected with the blue quenching photons. Related work using a one-dimensional (1D) pulsed scheme has led to similar results with 1D temperatures around 4 μK [13]. While these cooling schemes offer reduced temperatures they are not opimized for achieving high atom numbers at the same time.

In this paper we explore a particularly efficient method for the production of large samples of ultracold calcium atoms exploiting the existence of extremely long-lived metastable states in combination with a narrow band, closed cycle, infrared transition. Our approach offers the combination of very low temperatures below those achieved in the two experiments of Refs. [12,13] with remarkably large sample sizes, which opens up perspectives to reach quantum degeneracy in forthcoming experiments. In our present unoptimized experiments operating in a fully continuous way we obtain more than 10^8 ground-state atoms in 250 ms at temperatures below 20 μK and densities around 5×10^{10} cm^{-3}. Our preparation scheme is not limited by undesired loss channels and further minor optimization of our apparatus promises the production of submicrokelvin atoms at very high rates above 10^{10} s^{-1}. Such calcium samples may prove useful as an inverted medium for matter wave amplification [14]. The principle of our scheme is as follows: atoms are trapped and precooled in a Doppler-limited standard magneto-optical trap (MOT) using the strong 423 nm fluorescence line (cf. Fig. 1). The metastable triplet state $^3P_2$ (lifetime 118 min [15]) is continuously loaded from this MOT. A second MOT operating at 1978 nm is superimposed

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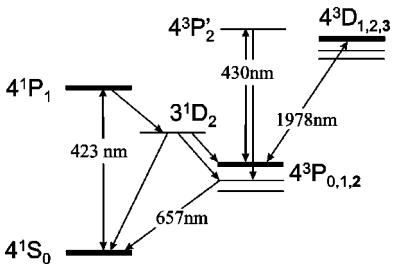

FIG. 1. Relevant energy levels and transitions in ^{40}Ca including the strong cooling and trapping line at 423 nm, the cooling and probing transitions for metastable $^3P_2$ atoms at 1978 and 430 nm, respectively, and the intercombination line at 657 nm.

acting on the $^3P_2$ state. The narrow linewidth together with the soft single-photon recoil energy of this transition promises final temperatures in the submicrokelvin range.

Our starting point is a Zeeman cooled atomic beam loading a MOT (referred to as $^1S_0$-MOT) operating on the $^1S_0 \rightarrow {}^1P_1$ transition at 423 nm ($\Gamma/2\pi = 34.6$ MHz). We are presently able to collect up to 2×10^8 atoms in the ground-state $^1S_0$ within the trap decay time of 22 ms. This trap decay time is limited by a decay of the $^1P_1$ state into the lower-lying $^1D_2$ state with a rate of approximately $\gamma_1 = 2180\ \mathrm{s}^{-1}$ [8]. About 78% of these atoms return to the ground state in approximately 3 ms either directly in a quadrupole transition or via the $^3P_1$ state. These atoms travel freely during this time, however, the illuminated volume of the $^1S_0$-MOT is sufficiently large ($\emptyset = 8$ mm) to recapture them completely when they return to the ground state. The remaining 22% are transfered to the metastable $^3P_2$ state and are lost from the $^1S_0$-MOT. In our experiment the production of $^3P_2$ atoms is the dominant trap loss mechanism and thus occurs at a rate given by the capture rate of the $^1S_0$-MOT. Measurement of the $^1P_1$-population $N(^1P_1) = 2\times10^7$ by observation of the 423 nm fluorescence lets us determine this rate as $R = N(^1P_1)\times\gamma_1\times0.22 = 2\times10^{10}$ atoms per second.

The $^3P_2$ atoms are produced at a temperature of about 2 mK slightly above the Doppler cooling limit for the 423 nm cooling line of 0.8 mK. This is sufficiently low to capture them in a second MOT (referred to as $^3P_2$-MOT) employing the closed $^3P_2 \rightarrow {}^3D_3$ transition at 1978 nm. The narrow linewidth of this transition of about 57 kHz [16] together with its large wavelength provide a very low Doppler limit of only 1.3 μK and a recoil limit of 122 nK. Moreover, the $J = 2 \rightarrow J = 3$ level structure allows for polarization gradient cooling (PGC) with the promise of temperatures approaching the recoil limit, such that temperatures below a microkelvin should be obtained. In our experiment we use the same magnetic-field gradient of 15 G/cm for both MOTs in order to let us operate our experiment in an entirely continuous mode. This represents a compromise between the best value for the $^1S_0$-MOT of 60 G/cm — which optimizes the capturing of atoms from the atomic beam — and a value below one G/cm which would account for the narrow linewidth of the 1978 nm transition. In order to enable operation of the $^3P_2$-MOT at 15 G/cm and to extend its velocity capture range, we strongly saturate the $^3P_2 \rightarrow {}^3D_3$ transition. We use about 5 mW in each of the infrared beams of about 8 mm diameter, yielding an intensity I which is 1.6×10^4 times the saturation intensity of $I_S = 1.28\ \mu\mathrm{W\ cm}^{-2}$. For this mode of operation the Doppler limit amounts to $T_D = \hbar\Gamma_I/2k_B = 170\ \mu$K, where $\Gamma_I = \Gamma\sqrt{1+I/I_S}$ denotes the power-broadened transition linewidth. This appears to be an undesirably high temperature, however the presence of PGC should allow us to go significantly beyond the Doppler limit. Further temperature decrease into the nanokelvin range should be possible by ramping down the magnetic field as well as laser intensity and detuning.

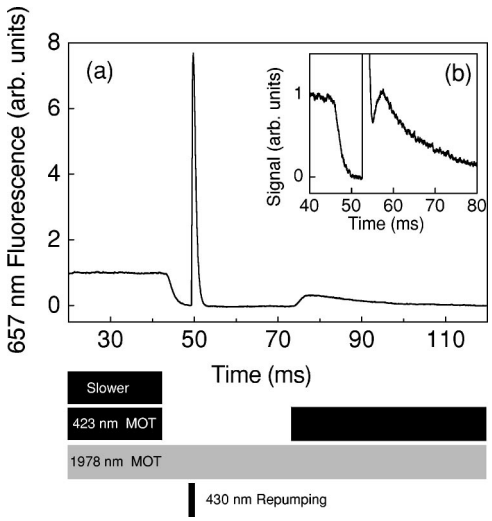

FIG. 2. A typical loading and detection cycle. The gray bars below the time axis indicate which of the laser beams are active. The $^1S_0$-MOT and slower beams are turned off after both traps have been loaded for 250 ms. Following a variable delay time τ_1 a pulse of 430 nm light optically pumps all $^3P_2$ atoms into the $^3P_1$ state, yielding a burst of 657 nm fluorescence. The atomic sample is now subject to gravity and ballistic expansion during a time interval τ_2. Finally, the $^1S_0$-MOT beams are turned on again recapturing a fraction of these atoms, which leads to a revival of 657 nm fluorescence.

A typical loading and detection cycle is shown in Fig. 2. Before $t = 43$ ms both lasers at 423 and 1978 nm are activated for 250 ms loading 3×10^8 atoms into the $^3P_2$ state. The operation of the $^1S_0$-MOT is monitored by the red fluorescence at 657 nm resulting from atoms pumped into the $^3P_1$ state which decays within 0.4 ms to the ground state. At $t = 43$ ms the $^1S_0$-MOT and Zeeman slower beams are blocked, i.e., only the $^3P_2$-MOT continues to operate and the red fluorescence terminates within a few ms (limited by the lifetime of the singlet D-state $^1D_2$). After a variable delay time τ_1 which amounts to 5 ms in the specific case of Fig. 2, i.e., at $t = 48$ ms, a 2 ms long pulse of 430 nm light is applied which optically pumps all $^3P_2$ atoms into the $^3P_1$ state, yielding a burst of 657 nm fluorescence. The atomic sample is now in the ground state and subject to gravity and ballistic expansion. After a variable delay time τ_2 (25 ms in Fig. 2) the $^1S_0$-MOT beams are turned on again (at $t = 73$ ms in Fig. 2) recapturing a fraction of these atoms, which leads to a revival of 657 nm fluorescence. This fluorescence finally dies out in accordance with the 22 ms trap decay time of the $^1S_0$-MOT resulting from the transfer of the

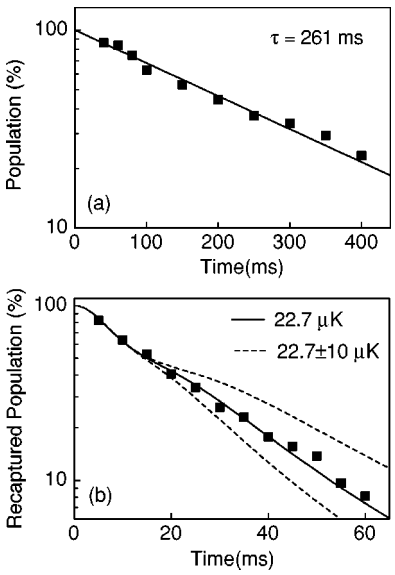

FIG. 3. (a) Trap decay time measurement of the $^3P_2$-MOT. The solid line shows an exponential fit. (b) The number of atoms recaptured in the $^1S_0$-MOT is plotted versus ballistic expansion time τ_2. The solid line shows a theoretical fit using a bimodal thermal distribution as explained in the text. We find a temperature of 22.7 μK for the cold fraction of atoms cooled by PGC and a temperature of 409 μK for atoms only subjected to Doppler cooling. For comparison the dashed lines show the theoretical fits for 22.7 ± 10 μK.

atoms into the $^3P_2$ state again. The detail (b) shows the case when the free flight duration is only $\tau_2 = 10$ ms. Note that the number of recaptured atoms exceeds the number of atoms initially trapped in the $^1S_0$-MOT. Measurements as shown in Fig. 2 allow us to determine the trap decay time of the $^3P_2$-MOT if we vary τ_1 and observe the size of the 657 nm fluorescence peak. In Fig. 3(a) we show the resulting trap decay time of $\tau_{IR} = 261$ ms which we attribute to our imperfect vacuum of only 10^{-8} mbar. At the present precision that we can achieve in such measurements (which is limited by laser frequency drifts) we do not recognize any nonexponential decay component, that would indicate collisional loss. We can also estimate the temperature via a simple recapture measurement, as shown in Fig. 3(b), where we have varied τ_2 and recorded the size of the recapture signal. The temperature of the atomic sample is expected to be due to PGC in the center of the trap. The region where PGC can operate is roughly determined by the condition that the Zeeman shift should not exceed the light shift. For the parameters used in our experiment this region is expected to be on the order of 2 mm in diameter. In fact, by recording the optical pumping efficiency of the 430 nm laser beam versus its diameter, we find that about 50% of the atomic population is located outside a sphere of 2 mm diameter. This indicates the possible existence of a non-Gaussian velocity distribution consisting of a colder core with a temperature determined by PGC and a hotter halo exhibiting the Doppler temperature increased by power broadening. This complicates the interpretation of recapture data. In order to obtain a rough estimate of the temperature we can resort to the somewhat oversimplified picture saying that the decay rate observed in Fig. 3(b) is given by the mean velocity $\bar{v}$ of the atoms divided by the radius $r = 4$ mm of the capture volume of the $^1S_0$-MOT. With $\bar{v} = 2/\sqrt{\pi}\sqrt{2k_BT/m}$ this yields a temperature of about 50 μK. We have to employ a slightly more subtle model in order to better understand our data. We assume a bimodal thermal distribution of the $^3P_2$ atoms with different widths and temperatures and let each fraction expand ballistically. We use the initial width σ_h, temperature T_h, and relative particle number N_h of the hot fraction, and the temperature of the cold fraction T_c as fit parameters. In Fig. 3(b) a best fit is obtained for $\sigma_h = 6.1$ mm, $T_h = 409$ μK — which amounts to 2.5 times the Doppler temperature corresponding to our strongly saturated mode of operation — $N_h = 2.2$ and $T_c = 22.7$ μK. These results nicely confirm our expectations of a bimodal thermal distribution with a cold core prepared by PGC surrounded by a hotter cloud only subject to Doppler cooling. The dashed curves show the predictions when T_c is increased or decreased by 10 μK. The optical pumping transition at 430 nm connects the $^3P_2$ and $^3P_1$ states to a higher-lying $^3P_2$ $(4p^2)$ state with a line strengths ratio of 3:1. Thus, in the optical pumping of $^3P_2$ atoms into $^3P_1$ on average four photons are absorbed from the 430 nm laser beam and, together with a 657 nm photon, spontaneously emitted. This leads to a temperature increase of 3.8 μK and a center of mass velocity change of 9 cm/s. In a time interval of 20 ms this amounts to a 1.8 mm horizontal displacement of the atomic cloud, together with a vertical displacement of 2 mm due to gravity. These effects have not been taken into account in our model such that our temperature estimations are to be referred to as upper bounds. The value $T_c = 22.7$ μK found for the recaptured ground-state atoms indicates an upper bound of 19 μK for the temperature of the $^3P_2$ MOT.

We can determine our transfer rate from the $^1S_0$-MOT into the $^3P_2$-MOT as follows. By setting τ_2 to zero in Fig. 2 we recapture about 1.5 times the original $^1S_0$-MOT population, which amounts to $N_{IR} = 3 \times 10^8$ atoms. Thus, the loading rate of the $^3P_2$-MOT is $N_{IR}\tau_{IR}^{-1} = 1.1 \times 10^9$ atoms/s. This is about one order of magnitude lower than our production rate of $^3P_2$ metastables $R = 2 \times 10^{10}$ atom/s, i.e., only about 6% of the metastables are captured. The reason is, that the infrared laser beams due to limited access to the vaccum chamber are only 8 mm in diameter whereas the cloud of metastables produced via decay from the $^1D_2$ state is expected to have a width of around 20 mm, because this decay takes on average 10 ms and the 2 mK cold atoms can fly 10 mm during this time. This mismatch of the capture volume fully accounts for the 6% capture efficiency. Employing slightly larger laser beams should allow us to make use of the full rate R. In our present experiments light-assisted inelastic two-body collisions in the $^1S_0$-MOT are not yet hampering the production of metastables. However, a further increase of the Zeeman-cooler efficiency would eventually take us into the regime where such collisions contribute a second loss channel comparable to the production of $^3P_2$ atoms. It turns out that an order of magnitude improvement

is possible before this regime is reached. A tenfold increase of the Zeeman-cooler efficiency would still translate into a sevenfold increase of R [17].

The continuous mode of operation of our trap described above is optimized for collecting cold metastable atoms at a high rate at the price of not fully exploiting the cooling potential of our scheme. In order to obtain this large production rate at a temperature in the nanokelvin range, in forthcoming experiments we will combine a capture phase as described above with a duration of the trap decay time of the $^3P_2$-MOT with a several 10 ms long cooling phase where the magnetic-field gradient and the infrared laser intensity and detuning are synchronously ramped down. In a further step we plan to transfer the atoms into an optical dipole trap operating in the infrared, which provides comparable light shifts for the $^1S_0$ and $^3P_1$, $m=\pm 1$ states. This should allow us to apply resolved sideband cooling on the intercombination line with the promise of all-optical (and therefore fast) access to the quantum degenerate regime.

In summary, we have demonstrated a scheme for producing large samples of very cold calcium atoms. While at present we can produce about 10^9 atoms/s at a temperature below 20 μK, minor technical improvements promise rates above 10^{10} atoms/s. A principal upper limit due to light-assisted two-body collisions is expected only at above 10^{11} atoms/s. Our experiment can be optimized for far lower temperatures (below 1 μK) when operated in a pulsed mode including a phase of high-capture efficiency as described in this paper and a short cooling phase, where the magnetic-field gradient as well as the laser intensity and detuning are reduced.

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