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Magneto-optical trapping of Stark-slowed metastable He atoms

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Abstract. We report on the first successful loading of a magneto-optical trap (MOT) with metastable He atoms from a Stark-slower. Thereby, deceleration of the atoms relies on laser-atom interaction in an inhomogeneous electric field. We show that the results obtained are comparable with early results from other groups achieved with a Zeeman slower. The Stark slower, which is able to fully control the final velocity of the atomic He beam, is the first step in achieving complete spin independent kinematic control based solely on electric fields.

PACS. 32.80.-t Photon interactions with atoms – 32.80.Pj Optical cooling of atoms; trapping

1 Introduction

The standard technique to cool and trap neutral atoms is based on laser-atom interaction in an inhomogeneous magnetic field [1,2]. Essential for the process is the energetic shift of atomic levels in the magnetic field. Thereby, the spin of the atomic system is involved in the kinematical control. In order to avoid this link and to establish an alternate kinematical control, laser-atom interaction in electric fields can be exploited in which the spin is not involved.

So far only laser deceleration of atoms in electric fields has been experimentally demonstrated [3,4]. Techniques for trapping neutral atoms in inhomogeneous electric fields have been proposed, but not yet realized [5–8]. However, oscillating inhomogeneous electric fields have been proven to be extremely successful in slowing and trapping polar molecules with a constant dipole moment [9]. Furthermore, a quasi static electric regime for trapping has been realized by Chapman *et al.* who trapped Rb atoms in the focus of crossed CO_2 laser beams [10] with the laser frequency far below the first allowed atomic transition.

Deceleration of alkali atoms in static electric fields with laser cooling techniques have been reported recently [3,4]. Similar to the well established Zeeman slowing technique [11] the procedure relies on the compensation of the changing Doppler shift during the deceleration by shift of an atomic transition. The appropriate Stark shift of the transition is achieved with an inhomogeneous electric field along the path of the atoms to compensate the Doppler shift. In contrast to the Zeeman technique and as mentioned before, deceleration of atomic species in electric fields does not depend on the atom's spin: the electric interaction is spin independent.

Although the first slowing experiments on atoms were successful, the method seems to be only of limited value. The small electric polarizability of the first excited atomic states, which were used in the experiments [3,4], requires high electric field strengths to shift the atomic levels appropriately to compensate for the Doppler effect. In the case of slowing a beam of Na atoms [3] a few hundred kV/cm has to be applied.

Recently, we have presented a method to decelerate metastable He atoms by means of a Stark-slower [12]. The major improvement reported in this paper is the use of a higher excited state as upper level in the slowing process, namely the $3p\ ^3$P level in He. The high polarizability of the excited state, which is about a factor 50 higher than for the first excited $2p\ ^3$P state [13], allows for relatively moderate electric field strengths of less than 35 kV/cm. These field strengths can be produced by moderate voltages (up to 26 kV) applied to field plates with a minimum separation of around 0.75 cm. Final atomic velocities of less than 200 m/s have been reached indicating that a quasi two level cooling transition could be realized and that the compensation of the changing Doppler shift during deceleration had been successful. However, final velocities reported in the earlier work [12] were still at or above the upper limit at which efficient trap loading is expected.

In this paper we focus on laser deceleration of metastable He atoms in inhomogeneous electric fields to efficiently load a magneto-optical trap (MOT). The present study deals with the refinement of the slowing section to provide final atomic velocities well in the velocity capture range of the MOT. We will show that the slowing procedure is suitable for routinely and efficiently loading of a magneto-optical trap. The ability to control the final velocities with the Stark slower is the first step in our attempt to decelerate and store metastable He atoms

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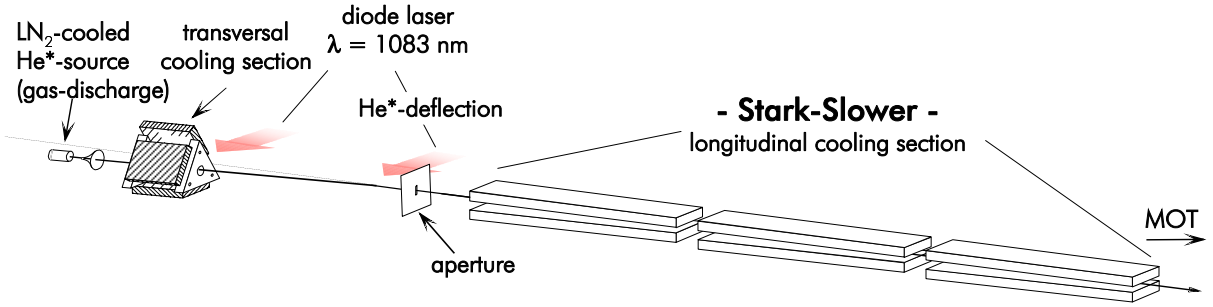

Fig. 1. Shown is a schematic view of our LN_2 cooled He discharge source and Stark-slower. Further explanations are given in the text.

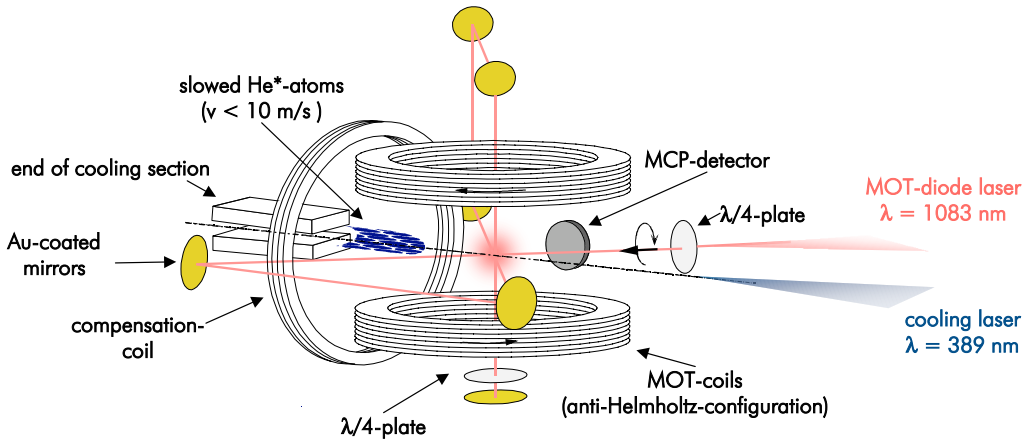

Fig. 2. Shown is the MOT section of our apparatus. For clarity only one of the compensation coils is shown.

solely by means of electric fields. The MOT will later be replaced by an electric quadrupole trap to study spin dependent collisional processes.

2 Experimental setup

The experimental setup is shown in Figures 1 and 2. The Stark-slower shown in Figure 1 is similar to the one described in [12]. However, significant modifications have been made, in particular to the design of the field plates to optimize the slowing procedure.

As shown in Figure 1 metastable He atoms are produced in a liquid N_2 cooled discharge source. This precooling reduces the initial velocity of the atoms by a factor of 2 to less than 1000 m/s. The cooled helium source produces 1.2×10^{14} metastable atoms per $s^{-1}sr^{-1}$. The discharge source is slightly tilted against the cooling axis by 0.5 degree. A diode laser tuned to the $2s\ ^3S$–$2p\ ^3P$ resonance transition pushes the metastable He atoms in the triplet state back on to the axis, while atoms in the ground state or in the singlet metastable state are blocked and do not reach the slower section. A further advantage of this setup is the possibility to chop the atomic beam by switching on and off the diode laser light. The same diode laser also provides light for transverse cooling to further collimate the atomic beam. This diode laser together with the trap diode laser presented later are locked on the $2s\ ^3S$–$2p\ ^3P$ transition in a He discharge gas cell by means of saturation spectroscopy. Fine tuning of the diode laser is possible *via* Zeeman shifting of the transition in the gas cell.

The deceleration proceeds on the Stark-shifted transition $2s\ ^3S$–$3p\ ^3P$ at 389 nm in an inhomogeneous electric field. We produce about 150 mW blue light at 389 nm by frequency doubling a titanium:sapphire laser in an external ring cavity. The laser beam is shaped by two cylindrical lenses to optimize the overlap with the atomic beam.

The inhomogeneous electric field $F_z(x)$ along the atomic beam axis x is provided by a three segment arrangement for the field plates. A constant high voltage is applied to each segment of the Stark-slower [12]. Compared to our previous setup, the required electric field strength $F_z(x)$ according to equation (1) in reference [12] is better approximated in the current experiment. $F_z(x)$ has been calculated using equation (1) in reference [12], where we assume a constant deceleration of about 20% of the maximum possible deceleration.

Each pair of field plates in the three segments is 50 cm long and 4 cm wide. It is designed to provide the calculated field strength at 21 sample points, with an interpolation in between. This is achieved with one flat field plate and the other one specifically machined. At fixed separation at the beginning and the end of the two field plates

(between 7–15 mm) a constant high voltage is applied to one plate, while the other is grounded. It is worth mentioning that the length of our current slowing section is shorter than comparable Zeeman-slower setups, in single cases almost up to a factor of two [14]. Assuming a larger deceleration the Stark-slower could be shortened further. However, this might result in a higher loss of atoms from the cooling cycle. This is expected particularly, if the saturation of the transition is fluctuating *e.g.* due to laser intensity fluctuations. The possibility of shortening the slower even more will be investigated in further experiments.

The maximum initial velocity of the atoms entering the first segment is about 850 m/s. With a constant voltage of 12 kV applied to the segment the final velocity for the atoms after leaving the first segment is 680 m/s. The second segment is designed for an initial velocity of the atoms of 700 m/s and a voltage of 18 kV. This results in a final velocity of 480 m/s. Finally, the last segment decelerates atoms from 500 m/s down to at least 55 m/s with a voltage of 24 kV.

About 0.2 m after the Stark-slower section the atoms enter a standard magneto-optical trap shown in Figure 2. The magnetic coils for the anti Helmholtz configuration are placed outside the vacuum. They have a diameter of 0.18 m and a separation of 0.11 m. With moderate currents of about 20–30 A we reach a magnetic field gradient of $2-3\times10^{-3}$ T/cm. As trapping laser we use either a grating stabilized diode laser or a Distributed Bragg Reflector (DBR) laser diode with about 30 mW of power each tuned near the resonance transition at 1 083 nm. The circularly polarized laser light is guided through the apparatus by means of six gold-coated mirrors to provide light from all six directions as required for the trapping operation. The diameter of each laser beam is about 2.5 cm.

The Stark slowing method is sensitive to small magnetic fields as has been described in [12]. Therefore, we have to compensate stray magnetic fields from the MOT reaching into the slowing section. The magnetic stray fields interrupt the Stark slowing process at an early stage and left the atoms with velocities well above the velocity capture range of the MOT. Two additional compensation coils are installed perpendicular to the MOT magnetic coils. The first one, shown in Figure 2, compensates for the magnetic field of the MOT reaching into the slower section. The other coil, located on the opposite side of the trap, compensates for the magnetic field in the MOT due to the first compensation coil. Typical operating currents are in the range of a few amperes to compensate stray fields of a few Gauss.

In order to detect neutral metastable He atoms or ions from the trap region a double microchannel plate detector (MCP) is placed about 0.07 m from the center of the MOT perpendicular to the atomic beam and in the center plane of the Helmholtz setup. We can use it either in ion counting or analog mode. Ionizing collisions between metastable atoms and background gas lead to a detectable number of ions that can be used to monitor the trap continuously.

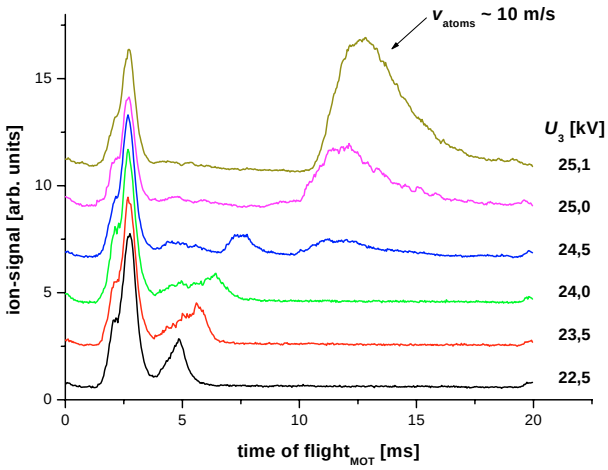

Fig. 3. Time of flight spectra of laser cooled metastable He atoms for different voltages at the third field plate segment. The spectra are offset for better comparison.

A voltage of about −2 kV applied to the front of the MCP pulls all ions within a few μs towards the detector.

3 Results and discussion

The first set of experiments was performed to show the improved ability of our Stark-slower to decelerate metastable He atoms to arbitrary velocities well in the capture range of a MOT. The blue laser for deceleration was detuned by 2.4 GHz below the atomic resonance. Together with the field strength at the beginning of the slowing section atoms with an initial velocity of $\leq$1 000 m/s participate in the slowing process.

In order to detect slower atoms with velocities below 200 m/s efficiently we shine in an auxiliary laser at 1 083 nm under an angle of 45 degrees opposite to the atomic beam. This laser beam is in fact one of the trap laser beams as indicated in Figure 2. Its frequency is tuned around 20 MHz below resonance. Atoms with velocities below 80 m/s interact with the laser beam and are pushed towards the detector. Here, we exploit the possibility of detecting neutral metastable He atoms directly with the MCP. This is possible due to their high internal excitation energy of roughly 20 eV.

In Figure 3 we show spectra recorded at fixed voltages applied to the first two segments. The voltage applied to the last segment of the cooling section was changed in small steps. Visible in all spectra shown in Figure 3 are fast atoms which are not interacting with the cooling laser giving rise to the first peak at 2.5 ms. The signal stems from ion production due to collisions of the metastable He beam with the background gas. Clearly visible in the bottom spectrum at 22.5 kV is a second peak originating from atoms slowed down in the first two segments. Increasing the voltage applied to the third segment results in a further deceleration of atoms and consequently in a shift of the second peak to larger travel times. At 24.5 kV we clearly see a peak at 7.5 ms. Additionally, a new peak

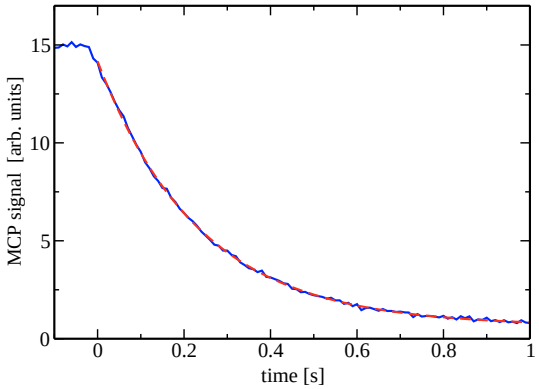

Fig. 4. Ion signal as a function of time after the trap laser has been blocked. Also drawn is a fit to the data, which perfectly overlaps.

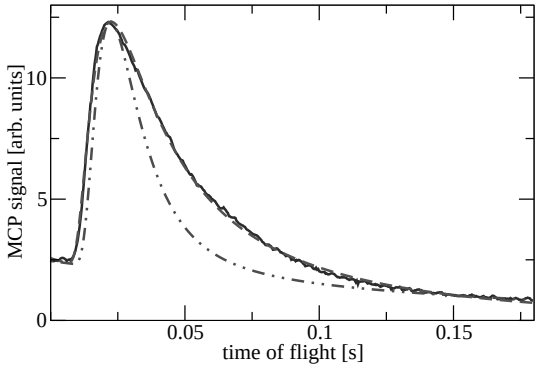

Fig. 5. Time of flight distribution of atoms released from the trap. A one-dimensional Maxwell distribution is fitted to the data (dashed curve). For comparison, the expected three-dimensional Maxwell distribution is shown (dot-dashed curve).

appears at 11 ms. This peak can be explained by the fact that a fraction of slow He atoms in the metastable triplet state becomes resonant with the auxiliary laser pushing them towards the detector. As a result a largely enhanced number of slow atoms is detected. We mention that the timing difference of the two peaks originates from the much longer time of flight of the neutral atoms towards the detector than for ions, which are accelerated by the high voltage applied to the front of the MCP detector. At even higher voltages applied to the field plates the intensity of the last peak increases significantly as more and more slower atoms are shifted into resonance. The peak originating from the collisions of slow atoms with the background gas is no longer visible.

As a matter of fact the time of flight does not directly give the final velocity. We deduce it from simple models associated with the Stark-slowing process [12]. In the case of the upper spectrum in Figure 3 we obtain a velocity of 10 m/s at the maximum signal. This number lies well in the velocity capture range to successfully load a standard MOT. The value for the final velocity of the atoms is also in accord with the shift of the MOT laser transition frequency with respect to the Doppler free transition frequency. We note that by tuning the voltage on the last slowing segment we can adjust the final atomic beam velocity to match the optimal capture velocity.

The absolute number of decelerated atoms cannot be extracted from the recorded spectra. To answer the question whether the Stark-slower allows for an efficient loading of a MOT we study the trapping characteristics of our MOT in a second set of experiments.

We apply a current of about 20 A to the MOT coils and tune the trap laser about 20 MHz below the resonance transition frequency. We observe an increase in the measured ion signal as a result of enhanced ionization by collisions of background gas with trapped metastable He atoms. Fine tuning of the voltage applied to the last slower segment allows us to provide the optimal capture velocity to trap He atoms. After loading for a few seconds the transversal diode laser is blocked to interrupt the atomic beam and we record the decreasing ion signal as function of time as shown in Figure 4. It is a clear exponential decay indicating that the ion signal predominantly stems from the collision with background gas. Penning ionization of trapped atoms should depend quadratically on the atomic density in the trap. Penning ionization processes for excited $2p$ states have a much higher cross-section than for atoms in the $2s$ state [15]. Due to the relatively far detuned trap laser too few atoms are in the upper $2p$ level to result in a non-exponential decay. On the other hand, the density of atoms in our trap, which is at least a factor of ten too low, and the high background pressure does not allow observation of Penning ionization of He*$(2s)$-atoms.

Trap lifetimes at typical trap parameters are about 240 ms. This is in accord with the relatively high background pressure of a few times 10^{-8} mbar in our MOT chamber and is also measured in other MOT's with similar conditions [16].

In order to measure the temperature of the trapped He atoms the trapping laser was shut off and the time of flight distribution of the metastable He atoms released from the trap is measured. Figure 5 shows the time of flight spectrum of the He atoms at a laser detuning of about -20 MHz. Only neutral atoms could be detected. As can be seen from Figure 5 there is a background signal present before the atoms released from the trap hit the detector. We attribute the origin of the background signal to atoms, which are not trapped, but slow enough to be pushed to the detector by one of the trap laser. The background signal decreases to zero when the trap is blocked. We corrected the measured signal for the background and fitted a Maxwell velocity distribution to the data. Surprisingly, the distribution is in very good agreement with a one-dimensional thermal Maxwell distribution with a mean velocity of 2 m/s corresponding to a temperature of 2 mK. For comparison, we added in Figure 5 a three-dimensional Maxwell distribution, which clearly shows the abundant fraction of slow atoms in our data. So far the origin of the deviation from the expected distribution is unknown. One would expect to measure a one-dimensional distribution, if the detected solid angle approaches 2π. In this case the measured distribution depends only on one velocity component and is independent of the two others.

However, our detector area (5 cm^2) is too small to provide such a condition. Finally, we note that we typically measure temperatures, which lie in the range between 1 and 3 mK.

Using the detector in the ion counting mode we can count the number of atoms released from the trap. We obtain on the order of a few thousand detected atoms. Assuming an isotropic expansion of the neutral atoms and 100% detection efficiency for metastable He atoms we can estimate the absolute number of stored atoms from the detected solid angle to be about 5×10^5. Unfortunately, we are only able to make a crude measurement of the trap size. Therefore, the density of atoms can only be estimated to be between $10^8/cm^3$ and $10^9/cm^3$. The number of trapped atoms is comparable with earlier reports on magneto optical trapping of Zeeman slowed He* atoms [14,15]. More recent reports on refined systems, however, allow for trapping of a substantially higher number of atoms [17–19].

4 Conclusion

We have demonstrated the successful loading of a standard MOT with metastable He atoms from a Stark-slower. The number of atoms in our trap and its lifetime are comparable with early reports on magneto-optical trapping of He loaded with atoms from a Zeeman-slower from other groups. We expect, as for Zeeman slowers, that further refinements on the Stark slower as well as on the trapping parameters will increase the atomic density. The length of the Stark-slower is shorter than comparable Zeeman-slowers. Further optimization could result in a length of the slower of less than 1 m. We stress that the slowing procedure does not rely on the atom's spin and thus represents an alternate kinematic control. Providing arbitrary low velocities with the Stark-slower is the first step in our goal to slow and trap He atoms spin independently solely based on inhomogeneous electric fields.

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