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Large numbers of cold metastable helium atoms in a magneto-optical trap

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We report loading of 1.5×10^9 metastable triplet helium atoms in a large magneto-optical trap, using far-red-detuned laser beams. We fully characterized this trap by measuring trap losses and absorption of a probe beam. From the highly nonexponential trap decay we derive Penning ionization loss rate coefficients for two detunings: $5.3(9)\times10^{-9}$ cm^3/s at -35 MHz and $3.7(6)\times10^{-9}$ cm^3/s at -44 MHz. Also, we find that the loss rate is maximum at -5 MHz detuning, where the rate is $1.3(3)\times10^{-8}$ cm^3/s, much larger than recent theoretical and experimental values. In the absence of light the S-S ionization rate constant is measured to be $1.3(2)\times10^{-10}$ cm^3/s. [S1050-2947(99)51408-X]

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Since the first report of Bose-Einstein condensation (BEC) in Rb, condensates of other alkali-metal atoms, Na and Li, and recently also H have been realized [1–4]. Metastable triplet helium (He*) is another interesting candidate. It is a light atom with good theoretical access, its mean-field interaction term is large, and two isotopes exist, obeying different quantum statistics: ^{4}He (boson) and ^{3}He (fermion). Until recently, however, a major obstacle appeared to be that a magneto-optical trap (MOT) cannot be loaded with more than $\sim10^6$ atoms because losses due to Penning ionization, $\text{He}^*+\text{He}^*\rightarrow\text{He}+\text{He}^++e^-$ (or $\rightarrow\text{He}_2^++e^-$), limit densities to $\sim10^9$ cm^{-3}. To overcome this problem, we have developed a large-sized, far-red-detuned helium MOT, in which we loaded a large number of He* atoms. These atoms will be transferred into a magnetostatic trap, where they will be spin-polarized. This will strongly suppress Penning ionization [5], and compression to much higher densities will become feasible. Evaporative cooling is expected to be an efficient process in spin-polarized triplet helium, because of a calculated large positive scattering length a [5], a large ratio of elastic to inelastic collisions [5], and a high collision rate. The Penning ionization loss mechanism results in decay products that can be detected easily, providing a direct probe for the density. This will substantially simplify diagnostics during evaporative cooling and provide an extra tool to investigate the transition to BEC.

Several groups have published data on the loading of a MOT with He* atoms, but with particle numbers $<10^6$ in a trap with a diameter <2 mm [6–8]. In a preliminary experiment [9] we already succeeded in trapping $\sim10^7$ atoms. For BEC experiments, however, more than 10^8 cold atoms are typically required. In this Rapid Communication we present results on a MOT containing a cloud with a full width at half maximum (FWHM) diameter of 7 mm and up to 1.5×10^9 atoms. In our MOT the laser beams are intense, far-red-detuned, and have a large diameter. The trap is positioned close to the exit of a Zeeman slower. This has the advantage that transverse spreading of the atomic beam is less important and more atoms can be captured. Here we report on the full characterization of this MOT. Penning ionization loss rates were measured and are compared with reported results, where recently a large discrepancy was pointed out [8].

Our setup consists of a liquid-nitrogen-cooled He* source, connected to a transverse cooling section, where the He* atoms are collimated and deflected, a two-part Zeeman slower, and a UHV chamber containing the MOT. The laser-cooling transition used is $2\,^3S_1$–$2\,^3P_2$ at 1083 nm [natural linewidth $\Gamma/(2\pi)=1.6$ MHz; saturation intensity $I_{\text{sat}}=0.16$ mW/cm^2 for the cycling transition]. For a detailed description of the setup we refer to earlier papers on the source and collimation section [10] and on the Zeeman slower and MOT [9], combined and modified for the present experiment.

The atomic beam is collimated vertically using the curved wave-front technique [10]. A slightly convergent laser beam is sent from above through the transverse cooling section and retroreflected. In the horizontal direction the geometry is similar. Here half of the retroreflecting mirror is blocked, so that atoms are collimated in the first half and deflected over an angle of 1° in the second half. This separates the metastable beam from the ground-state atoms. A knife edge is placed just outside the beam of collimated metastable atoms, and a 3-mm inner diameter tube is mounted in the geometric shadow of this knife edge. It blocks ground-state atoms, whereas He* atoms curve around the knife edge and enter the tube. With a tube instead of a diaphragm a better vacuum is achieved in our beam line.

The $\sim$230-mW output power of a Nd:LaMgAl$_{11}$O$_{19}$ (LNA) laser (pumped by 4 W from a Spectra-Physics Millennia solid-state laser at 532 nm) is split into two and used for the transverse cooling and MOT laser beams. For the slower beam, a diode laser (SDL-6702-H1) is used. To investigate the dependence of cloud parameters on detuning Δ, experiments were performed close to optimum performance at $\Delta=-35$ and -44 MHz, which is about -25Γ [9]. Experimental details are given in Table I.

To detect metastables and ions escaping from the trap independently we use two double microchannel plate (MCP) detectors, positioned about 7 cm from the center of the trap. One has an exposed negative voltage on its front plate and thus attracts all of the ions produced in the trap, while the

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TABLE I. Experimental details.

Slower	Laser detuning	-250 MHz
	Intensity	60 $\mathrm{mW/cm^2}$
MOT	Laser detuning	-35, -44 MHz
	$1/e^2$ beam diameter	~ 4 cm
	Horizontal intensity I_ρ	5 $\mathrm{mW/cm^2}$
	Vertical intensity I_z	1.4 $\mathrm{mW/cm^2}$
	Total intensity I_{tot}	24 $\mathrm{mW/cm^2}$
	Field gradient $\frac{\partial B}{\partial z}=2\frac{\partial B}{\partial \rho}$	20 G/cm

other has a grounded grid in front and detects only metastable atoms that exit the trap in its direction. An absolute calibration of the MCPs is not required [11].

The fluorescence of trapped atoms is monitored with a standard video camera, despite its low sensitivity at 1083 nm. The intensity profile measured with the camera appears to be Gaussian and allows for an estimate of the size of the cloud. Radiation trapping, however, hampers a precise determination.

For an accurate determination of the size of the cloud and its central density n_0 (and thus the absolute number of atoms), we measured the relative absorption of a probe beam in the cloud with a photodiode. The linearly polarized probe laser ($\Delta=0$, $I=0.04I_{\mathrm{sat}}$, with $I_{\mathrm{sat}}=0.27$ $\mathrm{mW/cm^2}$ assuming equal population of all magnetic sublevels M of the $2\,^3S_1$ state in the trap) is sent through the cloud at least 0.5 ms after the MOT coils and laser beams, and the last part of the Zeeman slower, have been turned off. This delay is necessary to ensure that residual magnetic fields can be neglected; the MOT is turned off within 20 μs, whereas eddy currents limit the switch-off time of the slower magnet to 0.5 ms. During the first 60 μs, absorption, which at trap center amounts to 80%, is constant. Thereafter radiation pressure pushes the atoms out of resonance and absorption decreases.

At both detunings the cloud has a Gaussian density distribution. With a central density n_0 and an rms radius σ_ρ (σ_z) in the horizontal (vertical) direction, the number of atoms in the cloud is $N=n_0V$, with volume $V=(2\pi)^{3/2}\sigma_\rho^2\sigma_z$ (68% of the atoms are within V). The experimental results are given in Table II. The values are corrected for the expansion of the cloud during the delay between turning off the MOT and turning on the probe beam. The temperature of the cloud, which is needed to model this expansion, is determined in two ways. First, we turn off the MOT and fit the time-of-flight signal on our metastables detector with a Maxwell-Boltzmann distribution. We find temperatures close to 1 mK. Second, and more accurately, the temperature is determined from the absorption measurements using different delays before switching on the probe beam. From the ballistic expansion of the cloud we can infer the rms velocity, in principle independently in the horizontal and vertical directions. We observe, however, a statistically marginal 0.2-mK difference for the two directions. The best results for n_0 and N are $n_0=4.5\times10^9$ $\mathrm{cm^{-3}}$ (at -35 MHz) and $N=1.5\times10^9$ (at -44 MHz), with typical results for N being a factor of 2 lower.

TABLE II. Typical experimental results. Errors correspond to one standard deviation.

Detuning	-35 MHz	-44 MHz
Temperature T (mK)	1.12(11)	1.18(17) horizontal 1.38(25) vertical
Horizontal radius σ_ρ (cm)	0.157(8)	0.235(12)
Vertical radius σ_z (cm)	0.306(15)	0.371(19)
Volume V ($\mathrm{cm^3}$)	0.12(1)	0.32(4)
Number of atoms N	$4.8(5)\times10^8$	$7.5(8)\times10^8$
Central density n_0 ($\mathrm{cm^{-3}}$)	$4.1(6)\times10^9$	$2.3(3)\times10^9$
Decay rate βn_0 ($\mathrm{s^{-1}}$)	21.3(14)	8.8(6)

The cloud is elongated in the vertical direction. The aspect ratio σ_z/σ_ρ varied from 1.9 at -35 MHz to 1.6 at -44 MHz. Assuming thermal equilibrium, the spring constants in the radial and vertical directions k_ρ and k_z are related via $k_\mathrm{B}T=k_\rho\langle\rho^2\rangle=k_z\langle z^2\rangle$, and therefore $\sigma_z/\sigma_\rho=\sqrt{k_\rho/k_z}$. The spring constant in each direction can be calculated with a two-level-atom model when intensity and field gradients are known [12], resulting in aspect ratios of 1.3 and sizes that are about 40% too small. A more elaborate numerical model for He*, incorporating Zeeman sublevels and their populations, slightly improves the comparison. A three-dimensional Monte Carlo simulation predicts a 50% temperature difference between the ρ and z directions (around 1.0 mK) and the correct aspect ratio for the clouds, but it still predicts sizes that are 35% smaller than those measured. When the force due to reabsorption of photons is taken into account, the calculated size increases only a few percent, as the central density is relatively small and the detuning of the light very large [13]. The gas is not unpolarized everywhere; at a radius of 2 mm, the populations of the $M=-1$, 0, and $+1$ sublevels can differ by 30%.

The two-body loss rate coefficient β in the trap due to collisions between metastable helium atoms is determined from the trap decay when the loading is interrupted by simultaneously blocking the deceleration laser and the light entering the deflection zone. For a Gaussian density profile the total losses in the trap as a function of time t then are [6]

$$\frac{\mathrm{d}n_0(t)}{\mathrm{d}t}=-\alpha n_0(t)-\frac{\beta}{2\sqrt{2}}n_0^2(t), \qquad (1)$$

with α the loss rate for collisions between He* and background atoms and β defined via $\mathrm{d}n/\mathrm{d}t=-\alpha n-\beta n^2$. The ion current ϕ on the MCP then becomes

$$\phi(t)=V\left(\epsilon_a\alpha n_0(t)+\frac{\epsilon_b\beta}{4\sqrt{2}}n_0^2(t)\right)+B, \qquad (2)$$

where B is a constant background signal and ϵ_a (ϵ_b) are the efficiencies with which ions are produced and detected for losses due to background and two-body collisions, respectively. Collisions that do not yield ions but induce trap losses include those with ground-state helium atoms, resulting in a reduced ϵ_a, and radiative escape [14], which may decrease ϵ_b.

The total loss rate coefficient β is a function of MOT laser-beam intensities and detuning at a given temperature.

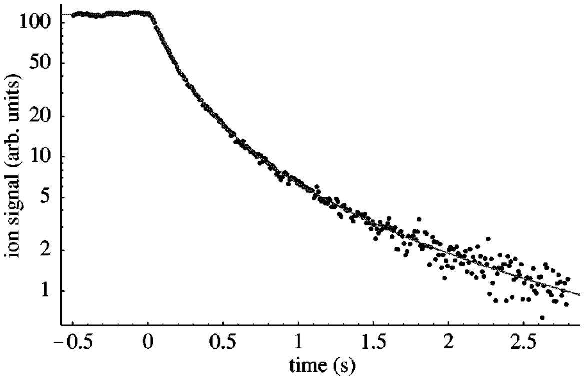

FIG. 1. Nonexponential trap decay after loading stopped at $t=0$ for a trap with $\beta n_0=9.4\ \mathrm{s}^{-1}$.

In our MOT the density and β are both high enough and the background pressure low enough ($\sim 1\times 10^{-9}$ mbar) to neglect the loss rate α. Solving Eqs. (1) and (2) leads to an ion signal that decreases in time after $t=0$ when the loading is stopped as

$$\phi(t)=\sqrt{2}\epsilon_b V n_0(0)\frac{\beta n_0(0)}{[2\sqrt{2}+\beta n_0(0)t]^2}+B. \tag{3}$$

This shows that to deduce β the central density must be well known. An example of such a highly nonexponential decay curve is shown in Fig. 1.

At $t=0$ those atoms that were just captured still take about 10 ms to spiral into the trap center. When Eq. (3) is fitted to the measured decay, points near $t=0$ are not used and a parameter t_0 is used in the fits. A fitted curve is also included in Fig. 1 and perfect agreement with experimental data is obtained. Using n_0 from the absorption measurements we find $\beta=5.3(9)\times 10^{-9}\ \mathrm{cm^3/s}$ at $\Delta=-35$ MHz and $\beta=3.7(6)\times 10^{-9}\ \mathrm{cm^3/s}$ at $\Delta=-44$ MHz. The uncertainty in the density is the main contribution to the experimental error. This low loss rate at large detunings is one of the reasons for the large number of atoms in our trap, another being the high trap-loading rate of $\beta n_0 N/2\sqrt{2}=5\times 10^9$ atoms/s. Compared with a He* flux entering the slower of 10^{11} atoms/s [10], this shows that as many as 5% of the atoms entering the Zeeman slower are decelerated and captured in the trap.

When the MOT is on we measure a constant flux of 4×10^8 metastable atoms per second escaping from the trap. We attribute these losses to radiative escape in optical collisions [14], where absorption of a photon followed by fluorescence produces two fast metastable atoms. Compared to Penning ionization the radiative escape process for He* is expected to be insignificant, due to the long lifetime of the $2\,^3P$ state [8]. At both our detunings (−35 and −44 MHz) the measured radiative escape loss rate was indeed small: $\beta_{\mathrm{RE}}\sim 1.3\times 10^{-10}\ \mathrm{cm^3/s}$, which is $\sim 3\%$ of the total β.

In the absence of light, losses are caused only by ionizing S-S collisions. The commonly used rate constant $K_{SS}=\beta_{\mathrm{off}}/2$ is measured, relative to the β when the trap lasers are on, by switching off the MOT laser and the deceleration laser for 100 μs each 0.2 s. The ion currents ϕ_{on} and ϕ_{off} for

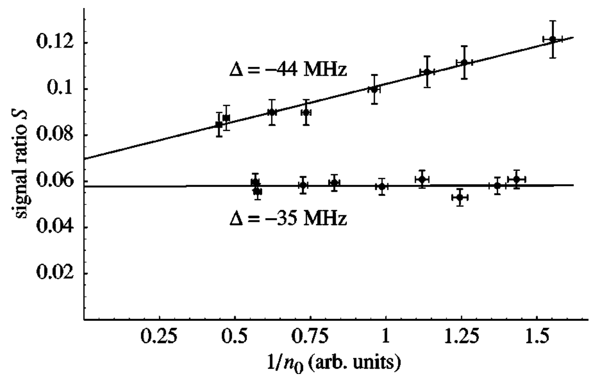

FIG. 2. Signal ratio S of Eq. (4) as a function of $1/n_0$ for two MOT detunings.

the situations with the MOT light on and off are given by Eq. (2), where $\beta_{\mathrm{off}}=2K_{SS}$ in the case of ϕ_{off}. We define a signal ratio S:

$$S=\frac{\phi_{\mathrm{off}}-B}{\phi_{\mathrm{on}}-\phi_{\mathrm{off}}}=\frac{4\sqrt{2}\,\frac{\epsilon_a}{\epsilon_b}\alpha}{\beta-2K_{SS}}\frac{1}{n_0}+\frac{2K_{SS}}{\beta-2K_{SS}}, \tag{4}$$

which is proportional to n_0^{-1} for constant MOT-laser intensity and detuning. Here, α/n_0 may not be negligible compared to K_{SS}. We could not measure α directly. However, by measuring S as a function of $1/n_0$ we can extrapolate to higher density, where α/n_0 is small, to determine the ratio β/K_{SS}. The results of such measurements are collected in Fig. 2. The horizontal scale is not the same for both detunings: at −35 MHz the density was much higher and the first term in Eq. (4) is almost negligible. The straight lines are fits of Eq. (4) to the experimental points, yielding the value $K_{SS}=1.3(2)\times 10^{-10}\ \mathrm{cm^3/s}$. Mastwijk *et al.* [8] reported a measured value of $2.7(12)\times 10^{-10}\ \mathrm{cm^3/s}$; their value, however, is an upper limit due to the presence of off-resonance light.

Theoretical estimates for the rate constant for ionizing collisions of unpolarized atoms have also been published. Julienne *et al.* [15] obtain $K_{SS}\geqslant 5\times 10^{-10}\ \mathrm{cm^3/s}$ in the $T\rightarrow 0$ limit and $K_{SS}\leqslant 10^{-9}\ \mathrm{cm^3/s}$ for the unitarity limit at 30 μK. Mastwijk *et al.* [8] calculated $K_{SS}=7.3\times 10^{-11}\ \mathrm{cm^3/s}$ at 1 mK using more recent potential curves. Our experimental value of $1.3(2)\times 10^{-10}\ \mathrm{cm^3/s}$ is twice as large as this last value.

To compare our loss rate coefficients with the trap light on, with contradictory results reported in literature, we performed a second series of measurements to determine the dependence of β on detuning. During a 100-μs MOT-off interval each 0.1 s, a linearly polarized 1083-nm laser beam is sent through the trap region ($I=24\ \mathrm{mW/cm^2}$, the same as in the MOT). The detuning from resonance is varied in steps of 0.8 MHz from −2 to +1 GHz. In this MOT-off interval we detect all ions and fast metastables escaping from the trap. At $\Delta\sim -5$ MHz we find a maximum in the ion production rate. The losses of fast metastables due to radiative escape contribute at the few percent level for all detunings. From the absolute values at −35 and −44 MHz we deduce $\beta_{\max}=1.3(3)\times 10^{-8}\ \mathrm{cm^3/s}$. Bardou *et al.* [6] in Paris measured the total loss rate coefficient from their MOT at $\Delta\approx -5$

MHz and at the same intensity. They report $\beta = 7\times10^{-8}$ cm^3/s with a factor of 4 uncertainty; this value is somewhat larger but in reasonable agreement with our value. Browaeys *et al.* [16] in Orsay find at $\Delta = -8$ MHz but at twice our intensity a loss rate of $\beta = 3\times10^{-8}$ cm^3/s with an uncertainty of a factor of 2, which also agrees with our value. Mastwijk *et al.* [8] in Utrecht measured the ion production rate β as a function of detuning by scanning their MOT-laser frequency quickly from -350 MHz to resonance. They observed a broad maximum near -10 MHz, also at twice our intensity and extract $\beta = 1.9(8)\times10^{-9}$ cm^3/s [17]. This value is a factor of 7 smaller than our result, although a larger value is expected at higher intensity. The interpretation of the Utrecht group relies on model calculations of the trap size, which we find to be correct only within a factor of 2; as the third power of the trap size is needed to determine β, this may explain part of the discrepancy. In addition, we noticed a much stronger dependence of β on detuning for $|\Delta| < 20$ MHz; this may be due to the large repetition rate used in the Utrecht experiment.

Mastwijk *et al.* [8] also obtain a theoretical value for the ion production rate in optical collisions at small detunings: $\beta = 4\times10^{-9}$ cm^3/s. This value is a factor of 3 smaller than our experimental value.

We conclude that model calculations of rate constants for Penning ionization with and without light do not agree with our experimental results. Despite the fact that the loss rate in a far-red-detuned He* MOT is much higher than in an alkali-metal MOT, we achieve particle numbers comparable to those in alkali-metal MOTs used to reach BEC. Prospects for further cooling and compression appear to be excellent. We therefore anticipate that Bose-Einstein condensation in triplet helium may be achieved in the near future.

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