Loading of a Rb magneto-optic trap from a getter source

Umakant D. Rapol, Ajay Wasan, and Vasant Natarajan*

Department of Physics, Indian Institute of Science, Bangalore 560 012, India

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We study the properties of a Rb magneto-optic trap loaded from a commercial getter source. The source provides a large flux of atoms for the trap along with the capability of rapid turn off necessary for obtaining long trap lifetimes. We have studied the trap loading at two different values of background pressure to determine the cross section for Rb-N$_2$ collisions to be $3.5(4) \times 10^{-14}$ cm^2 and that for Rb-Rb collisions to be of order 3×10^{-13} cm^2. At a background pressure of 1.3×10^{-9} torr, we load more than 10^8 atoms into the trap with a time constant of 3.3 s. The $1/e$ lifetime of trapped atoms is 13 s limited only by background collisions.

Laser cooling and trapping has now become a standard technique for atomic physics experiments whenever a cold dense sample of atoms is required. The workhorse in this field is the magneto-optic trap (MOT) [1]. For instance, a MOT is the starting point for laser cooling experiments involving Bose-Einstein condensation, cold collisions, optical lattices, precision spectroscopy, atomic fountain clocks, etc. [2]. The source of atoms for the MOT is typically an oven inside the vacuum chamber containing a small amount of pure metal. The MOT is loaded in one of two ways: from a thermal beam slowed by a counter-propagating laser beam (Zeeman slower or chirp slower), or from the slow atom tail of hot background vapor (so called vapor-cell traps). In both cases, the atom density has to be quite high for the MOT to be loaded with a large number of atoms in a short time. But the high density usually limits the lifetime of the trap due to collisions with untrapped atoms unless the source can be turned off rapidly. This problem is solved in traps loaded with slowed atomic beams by using shutters to block the beam. In vapor-cell traps, one solution is to use a double MOT, where the atoms are first loaded into a MOT located in a region of high vapor pressure, and then transferred through a differentially pumped line to a MOT in a region with much better vacuum where the lifetime is several orders of magnitude higher.

To address the same problem, we have been studying the loading of a MOT for Rb atoms from a commercial getter source [3]. Rb getter sources release atomic Rb when resistively heated with a few A of current. They are inexpensive, easy to handle inside ultra-high vacuum (UHV) systems, and have the advantage that the supply of atoms can be rapidly switched off by turning down the heating current below a threshold value. Such sources have started being used in laser cooling experiments only recently [4,5]. In Ref. [5], fast loading of a Rb MOT was achieved by placing the source within 30 mm of the trap center and operating it in a pulsed mode. By contrast, our source is placed about 90 mm away from the trap center and is operated continuously. We use the source as a thermal source much like the background vapor in vapor-cell traps, but with the capability of rapid turn off. Even though the stainless steel boat holding the source rises

to a few hundred degrees C during operation, there are enough atoms within the velocity capture range of the laser cooling beams to load the MOT with more than 10^8 atoms in a few seconds. To characterize the collisional loss mechanisms operating during the loading process, we have studied the properties of the MOT at different source currents and background pressures. From this, we extract the cross section for Rb-N$_2$ and Rb-Rb collisions. In addition, we have measured the steady-state trap population as a function of laser detuning and magnetic-field gradient since optimal values of these parameters depend on the velocity distribution of Rb atoms emanating from the source. These results indicate that getter sources are compatible with fast loading of a large number of atoms into the MOT, along with a long trap lifetime after turn off.

I. GETTER SOURCE DETAILS

The getter source is a commercially available dispenser of alkali atoms designed for industrial applications. The source we use contains a Rb compound and a reducing agent enclosed in a stainless-steel boat. The compound is stable at room temperature and the boat can be handled easily without fear of contamination. When a few A of current is passed through the boat, its temperature rises to several hundred degrees C. At these high temperatures, the Rb compound undergoes a reduction reaction and atomic Rb is released. Since the reaction is a threshold process, no Rb vapor is released below a threshold value of current, typically about 2.7 A.

We have installed the source in our vacuum system by attaching it to a UHV feedthrough using Cu-Be screw-type connectors. We have also tried spot welding the source to the feedthrough leads to reduce contact resistance, and find no significant difference in its performance. We prefer the screw-type connectors since this makes replacement of the source easier. Once inside the vacuum system, it is important to degas the source very well because this limits the ultimate base pressure in the chamber. We therefore operate the source at a current just below threshold for several hours during the initial bakeout of the system. When we first start using the source after bakeout, we find that no Rb is released even up to a current of 5 A. To get it started, we need to raise
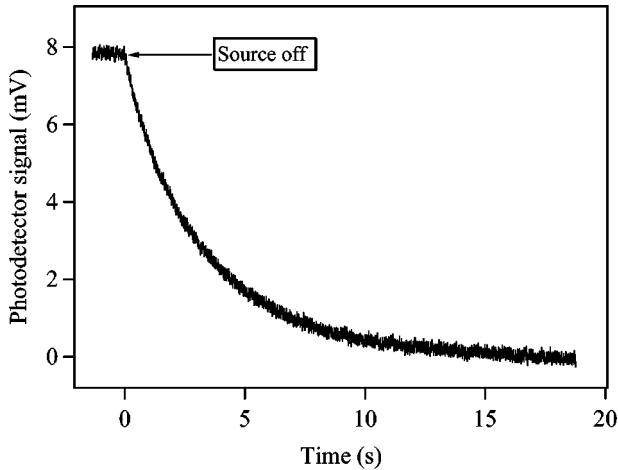
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FIG. 1. Decay of atoms from the source. The photodetector signal measures the fluorescence from Rb atoms in the background vapor. The source current is turned off at $t=0$, after which the fluorescence decays exponentially with a time constant of about 3 s.
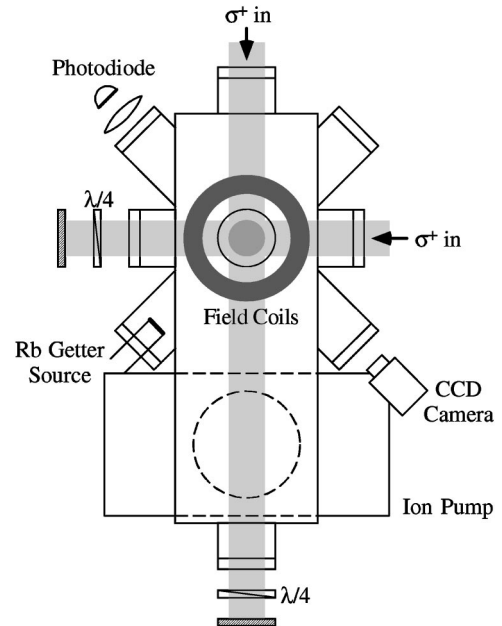

FIG. 2. Schematic of the experiment. The chamber is made of stainless steel and has nine optical ports. Two of the three pairs of counterpropagating laser beams are shown, a third pair is along the magnetic field axis. The Rb getter source is located about 9 cm from the center of the trap.

the current to about 8 A for a short duration of 2–5 s. After several such high-current pulses, the source becomes very reproducible and has a well defined threshold current of 2.7 A. We speculate that these pulses are essential to get rid of a surface crust that forms during storage and bakeout.

We have probed the Rb vapor density inside the vacuum system at different source currents using near-resonant laser light. Above the threshold current of 2.7 A, the fluorescence signal from the vapor increases rapidly with source current. At a current of 4 A, the vapor becomes optically dense. Around 4.5 A, the boat starts to glow red indicating a temperature near 600 °C. Above 8 A, so much Rb is released that the walls of the chamber get a metallic coating visible to the naked eye. We therefore load the MOT at source currents in the range of 3.0–3.8 A, which gives us an adequate flux of atoms without overloading the vacuum system. The fast turn-off capability of the source is seen in Fig. 1, where we plot the decay of the background fluorescence after the current is turned off. The $1/e$ time constant is only about 3 s and is independent of source current in the wide range of 3–4 A. This indicates that the cooling of the source is very rapid and the time constant is probably limited by the pumping speed near the trapping region.

We find the source to be very robust. There is no noticeable change in the Rb flux at a given current even after a year of regular use. Though the supplier specifies a "use-before" date of 1 year from the date of manufacture, we have installed it in our system even after three years without any problems. Contrary to what is reported in Ref. [5], the source does not appear to undergo "irreversible contamination" if the pressure rises by several orders of magnitude during initial degassing. Perhaps what they call irreversible contamination is similar to our observation that Rb atoms are not released even at currents of 5 A when the source is operated the first few times after bakeout. But, as mentioned earlier, this can be reversed by applying high-current pulses to evaporate any surface layer that might have formed.

II. EXPERIMENTAL DETAILS

The experiments are done in a vacuum chamber consisting of a 100 mm-o.d. stainless steel tube with ten intersecting 38 mm-o.d. ports, as shown schematically in Fig. 2. Nine of the ten ports have commercial glass view ports for optical access, and one port holds the feedthrough for the getter source. The source is located about 90 mm from the center of the MOT. The chamber is pumped by a 300/s ion pump through a 100 mm-o.d. port. The ion pump has a liquid-nitrogen cooled cryopanel to get better base pressure. Under normal conditions, the pressure inside the chamber is about 1×10^{-8} torr, which goes down to about 1×10^{-9} torr with the cryopanel cooled to 77 K.

The MOT laser beams are derived from two home-built grating feedback stabilized diode lasers operating at 780 nm. The first laser is the cooling laser that is locked near the $5S_{1/2}, F=2 \rightarrow 5P_{3/2}, F'=3$ cycling transition in ^{87}Rb using saturated absorption spectroscopy in a room temperature vapor cell. The error signal is obtained by passing the laser beam through an acousto-optic modulator (AOM) and dithering the frequency shift in the AOM. The center frequency of the AOM is used to get variable detunings in the range of -0.5Γ to -4Γ, where $\Gamma=2\pi\times6.1$ MHz is the natural linewidth of the transition. Each of the three beams for the MOT is circularly polarized with a power of around 4 mW and a $1/e^2$ radius of 9 mm. The hyperfine repumping beam is derived from a second stabilized diode laser that is locked to the $5S_{1/2}, F=1 \rightarrow 5P_{3/2}, F'=2$ transition in a vapor cell. The error signal for this laser is obtained by modulating the diode injection current. The resulting variation of a few MHz in the repumping frequency is inconsequential for operation of the MOT. About 2 mW/cm^2 of the repumping light is mixed

with the cooling beams in a polarizing beamsplitter cube. The six laser beams intersect over a volume of 3 cm^3. A spherical quadrupole magnetic field is superposed on the intersection region using a pair of anti-Helmholtz coils (10 cm diameter, 60 turns each) placed 10 cm apart. The field gradient at the center can be varied from 5 to 17 G/cm by varying the current through the coils in the range of 2 to 7 A.

The fluorescence from the trapped cloud of atoms is imaged on to both a charge-couple device (CCD) camera for viewing, and a calibrated silicon photodiode for quantitative measurements. To estimate the number of trapped atoms N, we fit the total optical power P at the photodiode to the following expression:

$$P = \frac{hc}{\lambda} \frac{\Omega}{4\pi} N \gamma_{sc},\qquad(1)$$

where Ω is the solid angle subtended by the detector at the cloud and γ_{sc} is the photon scattering rate given by

$$\gamma_{sc} = \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + (2\Delta/\Gamma)^2},\qquad(2)$$

with I the total beam intensity from the six trapping beams, I_0 the saturation intensity for the transition (1.6 mW/cm^2), and Δ the detuning.

III. RESULTS

We have studied the loading characteristics of the MOT by measuring the trap fluorescence as a function of time after the laser beams are turned on. The source is turned on a few minutes before the light beams so that the flux of Rb atoms reaches a steady state. The loading of atoms into the trap is determined by a balance between the capture rate and the loss rate. This results in the following rate equation:

$$\frac{dN}{dt} = R - \frac{N}{\tau},\qquad(3)$$

where N is the number of atoms in the trap, R is the rate at which atoms are captured from the background vapor, and τ is the loading-time constant determined by losses due to collisions [6]. The loss rate depends both on collisions with background atoms as well collisions with hot, untrapped Rb atoms:

$$\frac{1}{\tau} = n_b \sigma_b \bar{v}_b + n_{Rb} \sigma_{Rb} \bar{v}_{Rb},\qquad(4)$$

where n is the density of scattering particles, σ is the collisional scattering cross section and $\bar{v}$ is the average velocity. The subscript indicates whether the scattering is from the background (b) or from the Rb source (Rb). The solution to Eq. (3) is an exponential growth in the number of trapped atoms:

$$N = N_s[1 - \exp(-t/\tau)],\qquad(5)$$

with a steady state value of $N_s = R\tau$. Since the trap fluorescence is directly related to the number of trapped atoms
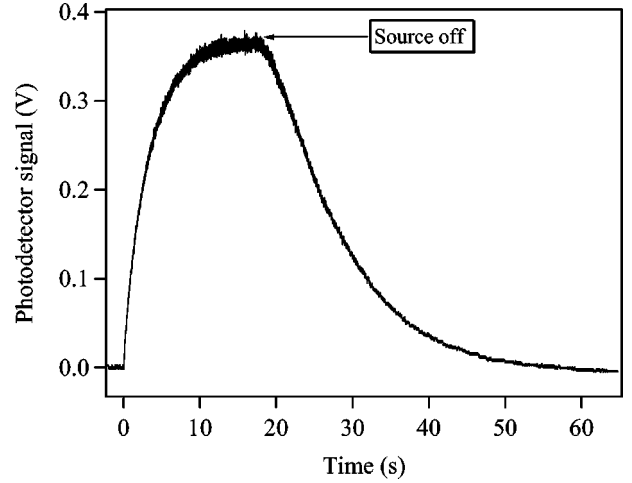

FIG. 3. Loading and decay of the MOT. The plot shows a typical measurement of the trap fluorescence as a function of time. The photodetector signal is proportional to the number of trapped atoms. The trapping beams are turned on at $t=0$, after which the signal shows an exponential growth with a time constant of about 4 s [see Eq. (5) in the text]. The signal decays exponentially after the source is turned off with a $1/e$ lifetime of about 13 s. The data were taken with a source current of 3.8 A.

[from Eq. (1)], the photodetector signal after the laser beams are turned on is of the above form. The trap lifetime τ_d after the source is shut off is determined solely by losses due to collisions with non-Rb background atoms. Therefore, the photodetector signal after the source is turned off shows an exponential decay with a time constant independent of the steady state population. A typical trap loading and decay curve taken at a source current of 3.8 A is shown in Fig. 3.

To estimate the values of σ_b and σ_{Rb} in Eq. (4), we have studied the trap loading and decay properties at different source currents and two values of background pressure, namely 1.5×10^{-8} torr and 1.3×10^{-9} torr. The results are listed in Table I. Several features of the data are to be noted. First of all, at the higher pressure the loading time τ is 1 s independent of the source current, indicating that background gas collisions dominate the loss rate. Next, at the lower pressure, τ goes down from 4.6 s at 3.0 A to 3.3 s at 3.8 A as the flux of atoms from the source increases. The steady-state trap population N_s increases correspondingly from 1.1×10^7 to 1.1×10^8. Finally, the trap lifetime τ_d is

TABLE I. The table lists the values of τ, N_s, and τ_d measured at different source currents at two values of background pressure. All the data were taken with an intensity of about 4 mW/cm^2 in each laser beam, a detuning of -2Γ and a magnetic-field gradient of 10 G/cm.

Source current (A)	Pressure $= 1.5 \times 10^{-8}$ torr			Pressure $= 1.3 \times 10^{-9}$ torr		
	τ (s)	N_s	τ_d (s)	τ (s)	N_s	τ_d (s)
3.0	1.0(2)	3.4×10^6	5.5(4)	4.6(2)	1.1×10^7	13.3(11)
3.3	1.06(2)	1.1×10^7	5.5(3)	4.2(2)	3.5×10^7	13.2(7)
3.8	1.05(1)	5.0×10^7	5.3(3)	3.3(1)	1.1×10^8	13.3(5)

independent of source current (and N_s) at both values of pressure. This is consistent with the fact that the lifetime depends only on background gas collisions. However, at the higher pressure, one would expect that background collisions would limit the lifetime to a value around 1 s in order to be consistent with the background-limited loading time of 1 s, but the measured value is actually 5.5 s. This difference arises because the source has a decay constant of 3 s after turn off (see Fig. 1) and the trap continues to be loaded even after the source is off. At lower pressure, the measured lifetime of the trap is 13.3 s; here the 3 s decay of the source can be neglected and the turn off can be assumed to be instantaneous.

We use the values of τ for different pressures at the *same source current* to eliminate the effect of the Rb term in Eq. (4) and obtain the cross section for background gas collisions from the following expression:

$$\frac{1}{(\tau)_h} - \frac{1}{(\tau)_l} = [(n_b)_h - (n_b)_l]\sigma_b\bar{v}_b, \qquad (6)$$

where the subscripts h and l indicate higher and lower pressure respectively. Assuming the background is predominantly nitrogen, which seems reasonable given the considerable drop in pressure when the cryopanel is cooled to 77 K, we can calculate the values of n_b and $\bar{v}_b$ at room temperature for a given pressure. The above equation then yields the value of σ_b. The average value of σ_b obtained from the values of τ at source currents of 3.0 A and 3.3 A is 3.5(4) $\times 10^{-14}$ cm^2. We can also obtain the value of σ_b from the 13.3 s trap lifetime at lower pressure assuming that the loss is solely due to background gas collisions. This yields a value of 3.8×10^{-14} cm^2, consistent with the above result. These values are also comparable to the cross section of 3.3×10^{-14} cm^2 for Na-N$_2$ collisions reported in Ref. [7].

Using the above value of σ_b, we obtain the value of σ_{Rb} in the following manner. We first calculate the capture rate R by assuming, for simplicity, that all atoms entering the trap volume with a velocity less than a critical velocity v_c are slowed by the laser beams and captured. If we further assume that the background vapor has a thermal distribution, the number of such atoms per unit time can be calculated from kinetic theory [6], which yields:

$$R = \frac{2}{\pi^2} n_{Rb} A \frac{v_c^4}{\bar{v}_{Rb}^3}, \qquad (7)$$

where A is the surface area of the trapping region determined by the overlap of the laser beams (10 cm^2 in our trap). From a one-dimensional laser-cooling model, v_c is the velocity at which the Doppler shift takes the atom out of resonance by one linewidth, therefore it is given by $(|\Delta| + \Gamma)\lambda/2\pi$, about 14 m/s for a typical detuning of -2Γ. Using Eq. (4) for τ, and Eq. (7) for R, we obtain

$$\sigma_{Rb} = \frac{2}{\pi^2}\frac{A}{N_s}\left(\frac{v_c}{\bar{v}_{Rb}}\right)^4 [1 - \tau(n_b\sigma_b\bar{v}_b)], \qquad (8)$$
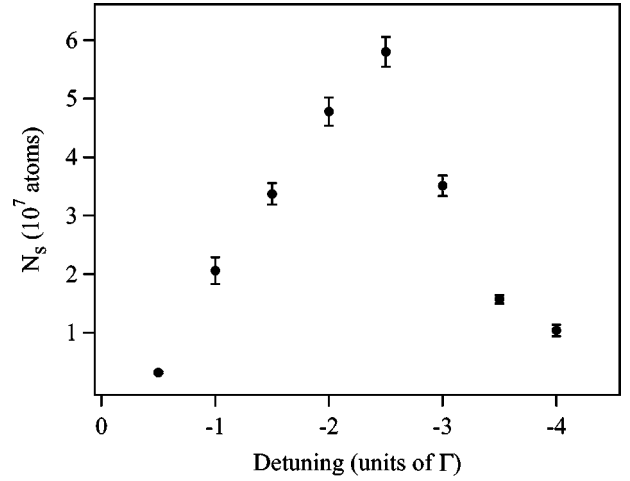

FIG. 4. N_s vs detuning. The plot shows the steady-state number of trapped atoms as a function of detuning for a constant magnetic-field gradient of 10 G/cm. The number is sharply peaked at a detuning near -2.5Γ. The error bars represent statistical errors and do not include systematic errors in scaling the photodetector signal to the number of atoms. Such systematic errors, however, will not affect the observed trend.

that can be used to calculate σ_{Rb} if $\bar{v}_{Rb}$ is known. Assuming a value of 355 m/s for $\bar{v}_{Rb}$ (corresponding to a temperature of 250 °C), we determine a value of 3×10^{-13} cm^2 for σ_{Rb} from the data at 3.0 A. This value compares well with the following theoretical estimate for the scattering cross section which assumes that the dominant scattering mechanism is resonant dipole-dipole scattering [8]:

$$\sigma_{Rb} = \pi\left(\frac{4C_3}{m_{Rb}v_{esc}\bar{v}_{Rb}}\right)^{2/3} \qquad (9)$$

where $C_3 = 5.8 \times 10^{-48}$ J m^3 for Rb. Using $v_c = 14$ m/s for v_{esc} and 355 m/s for $\bar{v}_{Rb}$ yields a value of 3.2×10^{-13} cm^2 for σ_{Rb}. Therefore, our assumption that the temperature of the vapor is around 250 °C seems reasonable. At higher currents of 3.3 A and 3.8 A, the measured values of τ lead to smaller estimates of σ_{Rb}. This is probably because nonlinear loss terms [9] become important at high atom densities and Eq. (3) is no longer valid. It is difficult to extract better estimates of the Rb-Rb cross section without a more complete knowledge of the distribution of atoms coming out of the source at different currents.

The velocity distribution of atoms emanating from the source is also important in determining optimal values of detuning and magnetic-field gradient for the MOT. This is because the detuning determines the capture velocity, and, as we will see below, the field gradient determines the effective slowing distance. We have therefore studied the steady-state trap population N_s as a function of these parameters. The dependence on detuning is shown in Fig. 4. The number of trapped atoms is maximized at a detuning of -2.5Γ for a field gradient of 10 G/cm. The dependence can be understood from the following physical picture. At low values of detuning, the critical velocity v_c for slowing is small, and
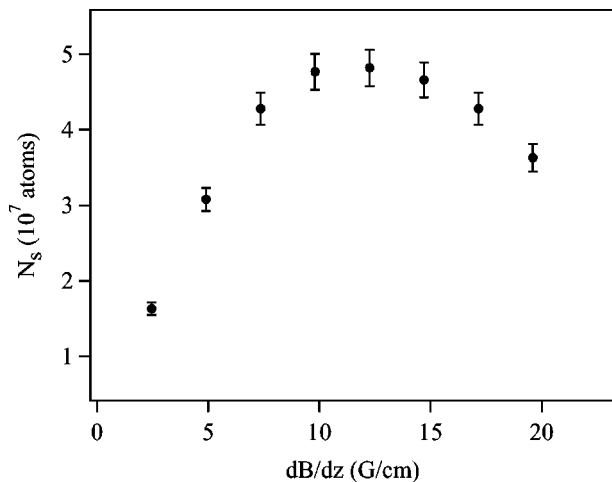
FIG. 5. N_s vs magnetic-field gradient. The plot shows the steady-state number of trapped atoms as a function of axial field gradient for a fixed detuning of -2Γ. The number shows a broad maximum at values of dB/dz around 12 G/cm. The error bars again represent only statistical errors, but as for Fig. 4, systematic errors are not important for the trend.

fewer atoms are captured since R varies as v_c^4 [see Eq. (7)]: for example, when $\Delta = -\Gamma$, v_c is only 9.5 m/s. At high values of detuning, even though v_c increases, the slowing distance also increases and atoms are not slowed within the 9 mm size of the laser beams. Thus, when $\Delta = -4\Gamma$, v_c increases to 24 m/s but the slowing distance is about 11 mm. The optimal value of detuning that we measure is similar to what is observed in a MOT loaded from room-temperature vapor [10].

The dependence of N_s on the magnetic-field gradient for a fixed detuning is shown in Fig. 5. The trap population is again maximized at an optimum value of field gradient. The trend can be understood as follows. At low values of the field gradient, the trap is shallow and atoms leave the trap easily. At high values of the gradient, the Zeeman shift, which increases rapidly away from the trap center, makes laser cooling ineffective because it changes the effective detuning to a smaller value that is less optimal for cooling. For example, the Zeeman shift for $F = 2 \rightarrow F' = 3$ transitions driven by circularly polarized light is 1.4 MHz/G. If the detuning is -2Γ and the field gradient is 17 G/cm, the atoms become resonant with the laser at a distance of 5 mm from the trap center and are not cooled beyond this point. The optimal

value of the field gradient we measure is comparable to values obtained in vapor-cell MOTs [10]. The consistency of optimal values of detuning and field gradient with results from vapor-cell traps indicate that the velocity distribution emanating from the source is thermal.

IV. CONCLUSIONS

We have demonstrated that a MOT can be loaded efficiently from a getter source. The source combines the advantages of providing a large flux of atoms that can be captured by the MOT with a fast turn off necessary for getting a long trap lifetime. The loading rate is determined both by collisions with background atoms and hot untrapped Rb atoms. We have estimated the cross section for Rb-N_2 and Rb-Rb collisions by measuring the trap properties at two values of background pressure. The value of σ_b is 3.5(4) $\times 10^{-14}$ cm^2, comparable to a value reported for Na-N_2 collisions, and the value of σ_{Rb} is of order 3×10^{-13} cm^2 consistent with a theoretical estimate based on resonant dipole-dipole scattering. At a pressure of 1.3×10^{-9} torr, we load more than 10^8 atoms into the MOT with a time constant of 3.3 s. At a background pressure of 1.5×10^{-8} torr, the loading time constant is 1 s independent of the source current, indicating that collisions with the background are dominant. We have also measured optimal values of detuning and magnetic-field gradient that maximize the trap population. These values are consistent with observations in vapor-cell MOTs, indicating that the velocity distribution of Rb atoms from the source is thermal. The trap lifetime at a pressure of 1.3×10^{-9} torr is 13 s and is limited only by the background pressure since the supply of Rb atoms stops almost instantaneously. We are in the process of changing over to a new vacuum system with a Ti-sublimation pump that should give us base pressure in the range of 10^{-11} torr where we estimate that the trap lifetime will be a few minutes.

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