# Observations of sodium atoms in a magnetic molasses trap loaded by a continuous uncooled source

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We describe observations of atoms trapped in magnetic molasses made by using a simplified apparatus that is loaded by a continuous uncooled source of atoms. We also measured the cross section for collisions in which trapped sodium atoms are ejected from the trap by thermal sodium atoms and estimate that the cross section is 30 times larger than for collisions with other background thermal atoms.

In recent years the cooling and trapping of neutral atoms has been studied both theoretically and experimentally.[1-5] These studies have included investigations of the magnetic molasses trap, which is discussed in detail in Ref. 1. In this Letter we describe the construction of a magnetic molasses trap based on a new, simplified experimental apparatus with an uncooled atomic-sodium source. The cross section for collisions in which thermal Na atoms eject cold Na atoms from the trap has been measured. These results are used to suggest changes that should further improve the design. We hope that this simplified apparatus will encourage more experiments on cold atoms.

A magnetic molasses trap is composed of three pairs of orthogonal counterpropagating laser beams of opposite circular polarizations that intersect at the origin of a spherical quadrupole magnetic field. All six beams have the same intensity. The frequency of the laser light is detuned approximately one natural linewidth, $\Gamma$, below the atomic resonance. An atom in such a trap experiences both a viscous damping proportional to the atom's speed and an optical restoring force proportional to the atom's displacement from the origin.

Such a trap has been realized for Na atoms by using the $3S_{1/2} \rightarrow 3P_{3/2}$ transition.[1] The $3S_{1/2}$ Na ground state is composed of two hyperfine sublevels, $F = 1$ and $F = 2$. Sodium has been trapped by using light that contains two frequencies: one frequency detuned $\Gamma$ below a transition from the $F = 1$ sublevel and the other detuned $\Gamma$ below a transition from the $F = 2$ sublevel. The 1.7-GHz separation between the sublevels is much larger than $\Gamma \approx 10$ MHz, so that when there is no power broadening each frequency component interacts with only one of the transitions.

The sodium $3P_{3/2}$ excited state has four hyperfine sublevels ($F' = 0, 1, 2, 3$), so various combinations of transitions between the ground and excited sublevels are possible. In this apparatus we have trapped Na atoms by using two such combinations, referred to as Type I and II tunings.[2] In Type I tuning the transitions are $F = 2$ to $F' = 3$ and $F = 1$ to $F' = 2$. In Type II tuning the transitions are $F = 2$ to $F' = 2$ and $F = 1$ to $F' = 0$. For Type I tuning the visible diameter of the trapped atom cloud was ~0.3 mm, and for Type II it was ~3 mm. Although we did not continuously monitor the trap size in these experiments, we note that the size depended only weakly on the intensity of the trapping light for intensities from ~2 mW/cm$^2$ to 10 mW/cm$^2$.

The trap light was generated by a ring dye laser, which was tuned to one of the two transitions. The other frequency component was generated from the laser light by using a commercial acousto-optic modulator.[6] The alignment between the shifted and unshifted beams was ensured by passing both beams through the same single-mode optical fiber, which also served as a spatial filter for the light. The trapping light beam had a waist size of $2w_0 \approx 8$ mm. The intensity in each trapping beam was maintained at approximately 10 mW/cm$^2$. Although both tunings were successfully used for trapping in this apparatus, Type I tuning was used for all the quantitative measurements.

An important aspect of our apparatus is the use of a simplified atom source. Our trap was loaded directly from a thermal source, in contrast with previous traps, which were loaded from cooled atomic beams. The source consisted of a 2-g Na pellet, which filled one end of a 1.6-cm inner-diameter, 7.6-cm-long flexible stainless-steel tube. A heater and a thermometer attached to the outside of the tube were used to control the source temperature, $T_s$. The source was connected to a larger vacuum chamber through a 1.6-cm-diameter straight-through gate valve, which permitted isolation of the chamber from the source. The sodium pellet was located 18 cm from the origin of the magnetic field, which also coincided with the center of the larger chamber and the common intersection of the six trapping beams. In this geometry there were no apertures; therefore the atoms emerging from the source were not collimated as they entered the main chamber and flooded the entire trapping region. The direct path from the source to the trapping region was in the plane formed by two of the three sets of trapping beams and bisected the 90° angle between these two trapping beams.

The main vacuum chamber was much smaller than previous versions (a 6.3-cm inner-diameter, 15-cm-

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long right circular cylinder having a volume ~0.5 L). This designed reduced the optical path lengths and permitted the chamber to rest directly upon the optical table. All the optics were outside rather than inside the chamber, greatly simplifying their adjustment. Magnetic field coils were wound on the outside circumference of the 6.3-cm-diameter chamber. Two 100-turn coils formed an anti-Helmholtz pair and produced a measured linear field gradient of 4 G/cm at 1 amp. Reference 1 showed that for this configuration the resulting trap depth is of the order of 400 mK.[1]

The behavior of the trap was examined over a range of source and chamber temperatures. The trap loading and lifetime were strongly dependent on $T_s$, which was varied between 290 and 590 K (see below). At no time was the pressure contribution due to the Na distinguishable from background pressure on an ion gauge. The temperature of the chamber walls was also varied from room temperature to 380 K; however, the performance of the trap was relatively insensitive to chamber temperature. Typically the temperature of the chamber was held at 373 K.

The atoms in the main chamber were observed by monitoring their fluorescence both by eye and with a photomultiplier tube (PMT). The visible diameter of the trapped atom cloud was insensitive to $T_s$. The observations were characterized by three ranges of $T_s$. For $T_s$ between 270 and 300 K little fluorescence was seen outside the trapping region, and the trapped atom cloud was distinguishable by eye. However, the PMT signal due to the trap was not much larger than that due to scattered light resulting from stray reflections. For $310 \leq T_s \leq 430$ K the PMT signal due to the trap dominated the signal due both to the scattered light and to the background fluorescence caused by the atomic beam. At high $T_s$ ($T_s > 460$ K) the fluorescence background was brighter than the light from the trapped atom cloud, and all six light beams were clearly visible well outside their common intersection.[7]

The peak density in the trap was estimated from the fluorescence signal by using two techniques. In one method[1] the total number of trapped atoms, $N$, was estimated by using the known saturation intensity for the transition,[8] the PMT calibration, and the detuning $\Delta = \Gamma$ to find $N \approx 10^6$. This yielded an average density of $1 \times 10^9$ cm$^{-3}$. In the other method the $T_s$ was increased until the trap fluorescence was indistinguishable from the background (see above). This occurred at $T_s = 455$ K. From the known vapor pressure[9] of Na and a geometrical correction we found a trap density of $6 \times 10^8$ cm$^{-3}$, in reasonable agreement with the estimation from the first method.

The loading of the trap was measured by first blocking the light to empty the trap and then unblocking the light and monitoring the fluorescence of the trapped atom cloud as a function of time. Typical fluorescence signals measured with this technique are shown in Fig. 1 for three different $T_s$. To demonstrate that the trap was loaded exclusively by atoms coming directly from the source, we closed the gate valve between the source and the chamber. With the source completely blocked, the trap loading stopped for all wall temperatures investigated (up to 380 K). We conclude that the loading of the trap was dominated by atoms that came directly from the source and not from the chamber walls.

To determine the cross section $\sigma$ for collisions in which trapped Na atoms are ejected from the trap by untrapped thermal Na atoms, we use a simple rate equation to describe the trap population $N$: $dN/dt = \gamma - (1/\tau)N - \beta N^2/V^2$. Here $\gamma$ is the fill rate from the atomic beam and $\beta$ is the nonlinear loss term.[2] The decay rate for the trap is $1/\tau = 1/\tau_b + 1/\tau_s$, where $\tau_b$ and $\tau_s$ are the contributions to $\tau$ from the background gas and the atomic source, respectively. Because of the moderate densities achieved in this experiment, we began our analysis by neglecting the nonlinear term (i.e., let $\beta = 0$). In this limit $N(t)$ is described by a simple exponential recovery, $N(t) = N_0[1 - \exp(-t/\tau)]$, where $N_0 = \gamma\tau$.

The curves superimposed upon the data shown in Fig. 1 are the result of fitting the exponential to the data, using $\gamma$ and $\tau$ as the fitting parameters. A value of $N(t \to \infty)$ was also obtained by averaging the last 2 sec of the data. We find that this value agrees with the fitted value $N_0 = \gamma\tau$ (to within 5%). This is consistent with the assumed negligible contribution from the nonlinear term in the rate equation for $N(t)$. Because of this good agreement, we have not pursued a more rigorous analysis.

The maximum total number of trapped atoms can be increased by increasing the product of $\gamma\tau$. $\gamma$ can be increased by increasing $T_s$ and hence the flux from the source. Unfortunately, collisions between source atoms and trapped atoms can eject atoms from the trap, so $\tau$ will eventually decrease with increasing $T_s$. At low $T_s$, where trap losses are dominated by collisions between trapped atoms and atoms in the background gas, $\tau \sim \tau_b$, which is independent of $T_s$. At high $T_s$, where the trap losses are dominated by collisions between source atoms and trapped atoms, $\tau$ decreases with $T_s$. Since the increase in $\gamma$ with density is at most linear, there must be some $T_s$ above which increases in $T_s$ do not increase the number of trapped atoms.

In order to determine $\gamma(T_s)$ and $\tau(T_s)$ we studied the trap loading as a function of $T_s$. The final results are shown in Fig. 2. As anticipated, the steady-state number of trapped atoms $N_0(T_s)$ approaches a limit-

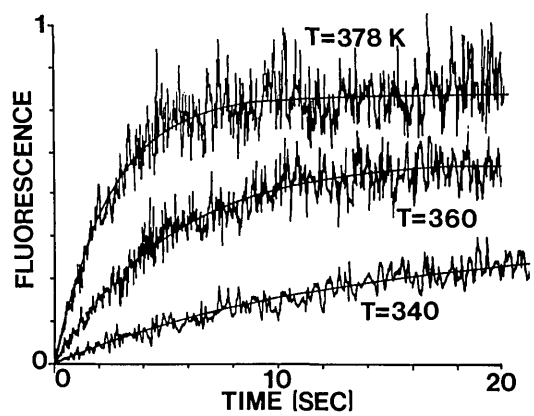


Fig. 1. Trap fluorescence as a function of time for three values of $T_s$. The solid curves are fits to the rate equation for trap population $N$ with $\gamma$ and $\tau$ as free parameters.

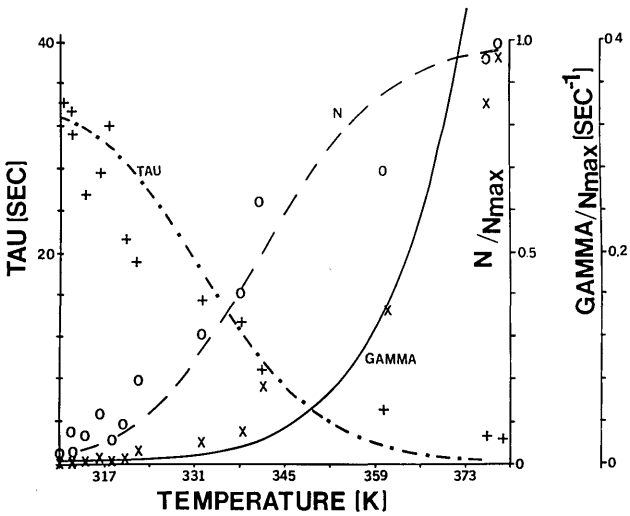


Fig. 2. Plot of $\tau(T_s)$, $\gamma(T_s)/N_{\max}$, and $N(T_s)/N_{\max}$ and the fits (see text). The $\tau$ values are shown as pluses, and the $\gamma/N_{\max}$ values are shown as crosses. The values of $N_0/N_{\max}$ are shown as open circles.

ing value for $T_s \approx 370$ K above which it is independent of $T_s$. However, we emphasize that increases in $T_s$ do increase the collision rate between the trapped atoms and the source atoms (and may therefore be useful for experiments that study such collisions).

To determine $\sigma$ from $\tau(T_s)$, $\gamma(T_s)$, and $N_0(T_s)$ it is convenient to define a capture area $A$ for the trap as well as an effective source intensity $I_0 = \bar{v}P(T_s)\Omega/(kT_s)$. Here $\bar{v}$ is the average velocity of a source atom, $\Omega$ is the solid angle subtended by the source, and $P(T_s)$ is the pressure of sodium from the source.[9] In these terms $\tau_s^{-1} = \sigma I_0(T_s)$ and $\gamma(T_s) = \alpha A I_0(T_s)$, where $\alpha = \alpha(r)$ is the fraction of atoms from the source, at a position $r$ from the center of the trap, that are slow enough to be trapped. $N_0(T_s) = \gamma\tau$ can then be expressed as $N_0(T_s) = \gamma(T_s)/(\tau_b^{-1} + I_0\sigma)$. The velocity-dependent capture area $\alpha A$ will depend on temperature and is nontrivial to calculate analytically. Fortunately, $\alpha A$ can be eliminated in this analysis by the use of the normalized variables $\gamma(T_s)/N_{\max} = \sigma I_0$ and $N_0(T_s)/N_{\max} = \sigma I_0 \tau$ where $N_{\max} = \alpha A/\sigma = N_0(T \to \infty)$ is experimentally determined.[10] The solid curves in Fig. 2 are the joint fits to the measured $N_0(T_s)/N_{\max}$, $\gamma(T_s)/N_{\max}$, and $\tau(T_s)$. We find that $\sigma \approx 1 \times 10^{-12}$ cm$^2$.

It is interesting to compare $\sigma$ with $\sigma_b = 3.3 \times 10^{-14}$ cm$^2$ for collisions in which a background gas atom ejects a Na atom from the trap.[2] The relation $\sigma \approx 30\sigma_b$ suggests that the Na atoms in the trap interact more strongly with other Na atoms than with atoms of other species; however, one would require more-detailed measurements with buffer gases of controlled composition before forming any definite conclusions.

The peak densities in the trap are limited by collisions in which the source atoms eject atoms from the trap. The limit on the maximum number of atoms in the trap could be greatly increased if collisions between source atoms and trapped atoms could be reduced without affecting the rate at which atoms fall into the trap. This might be accomplished by inserting a shield that shadows only the high-density region of the trap from the source. The trap loading should not be strongly affected since the volume with the high atomic density is only a small fraction of the total capture volume. Thus the temperature range over which the trap loss is independent of $T_s$ should extend to even higher $T_s$.

In the configuration described in this Letter the trap was formed from light containing two frequencies, corresponding to transitions from the $F = 1$ and $F = 2$ ground-state sublevels. If both frequencies are not present, the atoms are optically pumped into the undriven sublevel, and there is no trapping. We found that it was possible for the six beams that form the optical trap to contain only light nearly resonant with the $F = 2$ sublevel if there was a single additional light beam incident upon the trapping region. The additional beam was resonant with the transition from the $F = 1$ sublevel and thus acted as a repumper to prevent optical pumping. Such a simplified trapping configuration should be helpful for comparing future experiments with theory, as the resulting trapping force is due only to the one transition.

In summary, we have demonstrated a simple compact apparatus that cools and traps neutral atoms without a precooled atomic source. We have used this apparatus to determine that the cross section for collisions in which cold Na atoms are ejected from the trap by thermal Na atoms is of the order of $10^{-12}$ cm$^2$. We have considered the limit on the number of trapped atoms imposed by our source geometry and have suggested changes that should eliminate this constraint, permitting much higher densities of trapped atoms.

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6. Brimrose Co., Baltimore, Maryland, provides an efficient commercial acousto-optic modulator capable of 1.7-GHz frequency modulation.
7. We note that the ability to see all six trapping beams outside the trapping region facilitates light-beam alignment.
8. The saturation intensity for the $m_F = 2$ to $m_F = 3$ transition is $\approx 6$ mW/cm$^2$.
9. A. N. Nesmeyanov, *Vapor Pressure of the Chemical Elements* (Elsevier, New York, 1963).
10. The velocities of the atoms at the trap are well characterized by a Maxwell–Boltzmann distribution. Over this limited temperature range the change in the most probable velocity is relatively small. At 300 K, $\langle v \rangle \approx 311$ m/sec and, at 380 K, $\langle v \rangle \approx 350$ m/sec. The velocity-averaged capture area $A$ is therefore treated as temperature independent.