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Rubidium atomic funnel

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A low-velocity beam of rubidium atoms is produced from a two-dimensional magneto-optic trap or atomic funnel. Atoms from a thermal beam are slowed by chirped laser cooling and then loaded into the funnel. The cold atoms are ejected by moving molasses formed with frequency-shifted laser beams. The resultant atomic beam has a controllable velocity in the range of 3 to 10 m/s, a temperature of 500 μK, and a flux of 10^{10} atoms/s.
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1. INTRODUCTION

The recent development of laser-cooling techniques has opened the way to experiments with very slow atoms.[1] This is particularly valuable to atomic-beam research, which has played an important role in the development of physics in this century. Slow atoms allow for longer interaction times, hence, better frequency resolution, and also reduce Doppler effects that normally broaden or shift resonance lines. Unfortunately, an atomic beam that is slowed in one dimension will suffer large transverse divergence as the longitudinal velocity is reduced to a value of the order of the transverse velocity. To alleviate this problem, one can use position-dependent trapping forces to compress the beam spatially. One promising technique to achieve this is based on magneto-optic trapping, which permits spatial and velocity compression of atoms in appropriately designed magnetic and laser fields.[2] In this paper we report on the use of a two-dimensional magneto-optic trap or atomic funnel to produce a low-velocity atomic rubidium beam. An atomic funnel for sodium was first demonstrated by Riis *et al.*[3] Related work has been reported by Nellessen *et al.*[4] with sodium and by Yu *et al.*[5] with cesium.

In the standard three-dimensional magneto-optic trap, a spherical quadrupole magnetic field is used, wherein the magnetic field is zero at the origin and increases linearly along any direction.[2] Three pairs of counterpropagating laser beams with appropriate circular polarization are directed along the three coordinate axes. The lasers are detuned to the red of the resonance to provide optical molasses damping of the velocity. The Zeeman shift introduces a differential absorption rate between oppositely directed σ^+ and σ^- laser beams, forcing atoms within the intersecting laser beams to the origin. Such a three-dimensional trap has proved useful for a wide variety of experiments. The atomic funnel is the two-dimensional version of such a trap, with no spatial confinement along the third dimension or axis of the funnel. A slow atomic beam can be generated along this axis by adjustment of the laser-beam frequencies. Such a beam, with a controllable velocity and a narrow velocity distribution, will prove useful in new experiments including atom interferometry, high-resolution spectroscopy, time standards, and low-velocity collisions. It will also permit old experiments to be revisited with increased precision.

The atomic funnel reported on here is loaded with atoms from a thermal beam that is slowed by chirped laser cooling.[6] Slow atoms that drift into the trap are compressed in the two spatial dimensions transverse to the funnel axis to a size of the order of 500 μm. The atomic velocity distribution is compressed in all three dimensions to yield a temperature of approximately 500 μK. By adjustment of the laser-beam frequencies, atoms are ejected from the funnel with controllable mean velocities in the range of 3–10 m/s. In contrast to the experiment of Riis *et al.*[3] we have three-dimensional velocity compression without using a laser along the funnel axis, which allows unlimited downstream access to the beam. The other funnel experiments used velocity compression in only the two transverse directions.[4,5]

2. EXPERIMENT

A schematic diagram of the experiment is shown in Fig. 1. The thermal rubidium beam is produced by an effusive oven source with an aperture of 1-mm diameter. The oven is operated at a temperature of 235 °C and has a recirculation system to increase the time interval between oven reloadings.[7] The atomic beam propagates along the positive x direction 1 m to the funnel region and is slowed by a counterpropagating laser beam with a frequency chirp to compensate for the changing Doppler shift of the decelerating atoms.[6] Atoms with initial velocities less than 350 m/s are slowed to approximately 20 m/s before the slowing laser frequency is quickly changed to turn off the slowing mechanism. This value of the final velocity is chosen to maximize the number of atoms loaded into the trap; atoms with larger velocities cannot be trapped, and atoms with smaller velocities tend to miss the trap because of their transverse velocity acquired during the one-dimensional slowing. The slowing chirp is repeated with a frequency of 24 Hz, producing a pulsed source of atoms to load into the funnel. The slowing and the trapping are done with the ^{85}Rb $5S_{1/2}\ F = 3 \rightarrow 5P_{3/2}\ F' = 4$ transition. Secondary lasers are used to repump atoms lost to the other hyperfine level of the ground state.

The funnel is defined by the two-dimensional magnetic

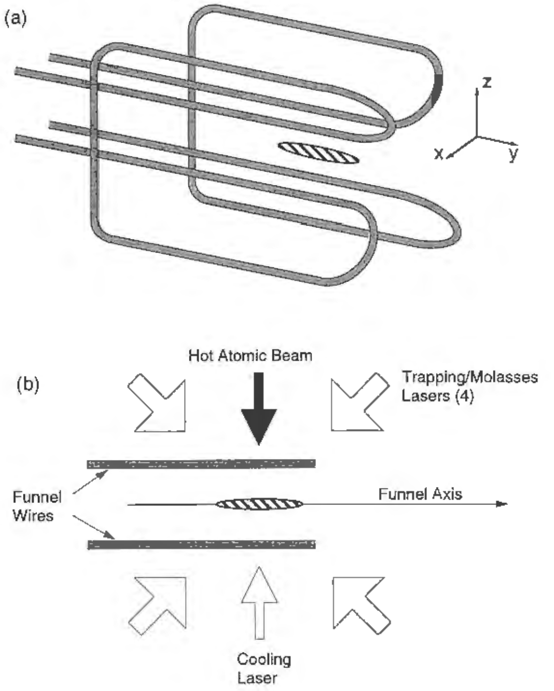

Fig. 1. (a) Funnel magnetic-field wires in a hairpin geometry. (b) Schematic of funnel showing lasers in the horizontal (xy) plane. The origin of the coordinate system (shown displaced for clarity) is at the intersection of the funnel axis and the hot atomic beam. The striped area represents the region of trapping.

quadrupole field, which has its axis along the y axis. The magnetic field is formed by four parallel wires (copper tubing) arranged at the corners of a 2.5-cm square, with alternating current directions. Each wire has a return path in a hairpin geometry,[3] as shown in Fig. 1. The return paths are located at the corners of a 6.3-cm square and decrease the field by 20%. The wires carry a current of 70 A and are water cooled. The maximum field gradient is 13 G/cm in the xz plane and decreases to 15% of this value 1 cm outside the end of the funnel.

The three orthogonal pairs of laser beams overlap at the intersection of the thermal beam and the funnel axis. The intensity in each beam is 8 mW/cm^2, or five times the saturation intensity. One counterpropagating σ^+–σ^- pair is along the z axis, while the other two pairs are in the xy plane and make angles of 45° with respect to the x and the y axes. The beams along the z axis are from a single laser at a frequency f. The beams with a propagation component along the positive y axis come from a second laser tuned to a frequency $f + \Delta f$. The beams with a propagation component along the negative y axis come from a third laser tuned to a frequency $f - \Delta f$. In the presence of the frequency shift Δf, atoms at rest will experience a force in the positive y direction because of the imbalance in the scattering rates from the beams in the xy plane. This moving molasses configuration[8] will result in a drift velocity $v = \sqrt{2}\lambda\Delta f$ [1.1 (m/s)/MHz for Rb] of the transversely trapped atoms. Atoms moving at the drift velocity see all six laser beams at the frequency f,[3] which permits the possibility of orientational cooling.[9]

The lasers used in this experiment are grating-stabilized diode lasers operating near 780 nm.[10] Optical feedback from the Littrow mounted diffraction grating reduces the laser linewidth from 50 MHz to 150 kHz. The trapping lasers used in the funnel are each frequency offset locked to a master laser that is stabilized to a polarization spectroscopy signal from a rubidium vapor cell.[10] The frequency differences among the three trapping lasers were measured to have stabilities of the order of 20 kHz. This ensures that the mean velocity of the emerging atomic beam is stable to 2 cm/s.

Fluorescence from atoms in the funnel is collected with a photomultiplier tube and a CCD camera. The photomultiplier-tube signal indicates that approximately 4×10^8 atoms are loaded into the funnel with each chirp, yielding a funnel output of 10^{10} atoms/s. The atoms leave the funnel in a pulse with approximately the same width (~6 ms) as the input pulse from the chirped cooling. The CCD image is used to optimize laser-beam alignment in the funnel and to estimate the size of the atomic beam. To characterize the motion of the atoms, we place a standing-wave probe downstream of the funnel. The probe beam is 1 mm wide (along the atomic-beam direction) and 3 mm high and is placed 10 mm downstream from the end of the funnel. Fluorescence from this probe region is collected with a second photomultiplier tube and can also be viewed with a CCD camera.

To measure the velocity of the atomic beam, we use a time-of-flight technique.[3] Atoms near the exit end of the funnel are deflected with a resonant laser beam. The frequency of this laser is shifted off resonance for 2–3 ms to allow a short pulse of atoms to travel to the probe region. The transit time and the spreading of this pulse as measured with the downstream probe fluorescence yield the mean beam velocity and the longitudinal temperature. The measured signals are fit to a function that models the funnel as a line of point sources, each with the same mean drift velocity and velocity spread.

3. RESULTS AND DISCUSSION

A sample fluorescence signal and the resultant fit from the model are shown in Fig. 2. In this experiment the

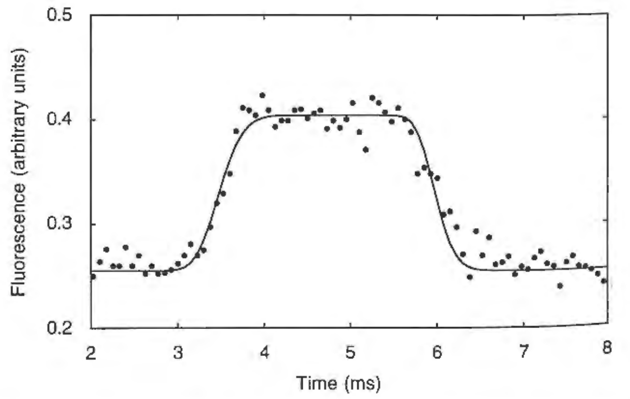

Fig. 2. Fluorescent signal from the downstream probe laser used in time-of-flight analysis (filled circles). The curve is a fit to the signal and yields the mean beam velocity and longitudinal temperature.

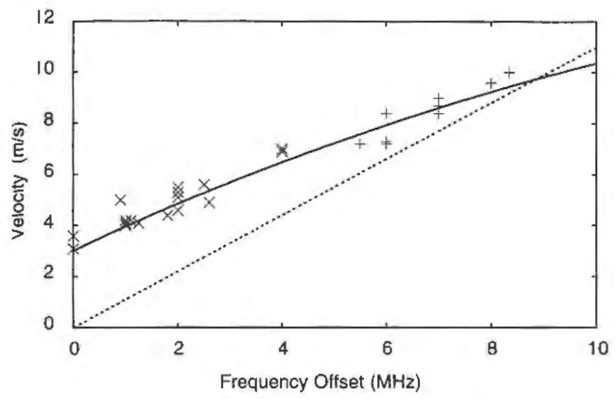

Fig. 3. Measured velocity of atoms leaving the funnel as a function of the frequency offset Δf of the horizontal lasers. The $\times$ symbols (+ symbols) correspond to a mean laser detuning of 2Γ (3Γ) from resonance. The dotted line is the expected velocity of a moving molasses. The solid curve represents a more detailed model that includes an axial magnetic field (4G) and the finite damping time (1.2 ms) of the atoms in the molasses.

pulse of atoms is long enough that the mean beam velocity is determined primarily by the delay of the leading edge of the pulse with respect to the gate, and the longitudinal temperature is determined primarily by the slopes of the leading and the trailing edges of the pulse. Data were taken for a range of values of the detuning Δf of the horizontal lasers from the vertical laser. The mean detuning of the trapping lasers was 2Γ (3Γ) below resonance for values of Δf below (above) 5 MHz. Figure 3 shows the results of the measured beam velocity. The expected straight line $v = \sqrt{2}\lambda\Delta f$ is shown as a dotted line. The data show consistently higher velocities over the complete range of detuning. Intensity imbalances in our system are small and cannot explain the large deviations seen. Displacement of the trapped atoms from the axis of the trap would subject them to axial magnetic fields that could shift the expected drift velocity of the beam. This effect is estimated to be less than 0.3 m/s for our experiment.

The deviation of the data from the expected moving molasses result is most likely caused by a combination of two effects. The atoms experience an axial magnetic field caused by the earth's field and other magnetic equipment in the vicinity of the vacuum chamber. In the case of Doppler cooling, a magnetic field B along the axis of $\sigma^+ - \sigma^-$ molasses leads to a drift velocity of the atoms of $v = -g_e \mu_B B/\hbar k$, where g_e is the excited-state Lande factor, μ_B is the Bohr magneton, and k is the laser-beam wave vector.[11] This effect would result in a change in the offset of the dotted line shown in Fig. 3 but would not affect the slope. A change in slope can be explained by examining the dynamics of atoms in the trap. Atoms are damped to their final velocity with a characteristic time τ. If the transit time of the atoms through the funnel is of the order of or less than the damping time, then the atoms will not have enough time to accelerate to the final expected velocity. If rubidium were a simple two-level atom, then the damping time in the funnel would be of the order of 600 μs (800 μs) for the detuning of 2Γ (3Γ).[12] We expect it to be somewhat larger than this because rubidium is not a two-level system, nor is there a single laser polarization in the funnel.

We combined these two effects in a simple model that accounts for a finite damping time in the funnel and an axial magnetic field. The solid curve in Fig. 3 shows the result of this model for an axial magnetic field of 4G and a damping time of 1.2 ms. The agreement between the data and this model is quite good, suggesting that these effects explain the observed discrepancies from the simple moving molasses values.

The time-of-flight signals yield a longitudinal temperature of 500^{+500}_{-250} μK. The transverse temperature is determined by CCD images of the atoms in the probe region. The expansion of the atoms at this point indicates a transverse temperature of 380^{+80}_{-70} μK. Both of these values are consistent with the Doppler cooling limit for rubidium of 300 μK (for a detuning of 2Γ), suggesting that orientational cooling is not present in our funnel.

4. CONCLUSION

In summary, we have produced a source of slow, cold rubidium atoms. The low velocities and the high flux should make this an attractive source for new experiments. Possible improvements include loading the funnel with a continuous slow beam, as from a Zeeman slower.[13] This would increase the atomic-beam flux since chirped cooling is duty cycle limited. In addition, the transverse temperature of the atomic beam could be reduced with downstream orientational cooling.[9] Finally, it may be possible to simplify the experiment by performing it in a vapor cell,[14] which would make for a very compact and inexpensive cold atomic beam.

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