Atom Funnel for the Production of a Slow, High-Density Atomic Beam

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A new scheme has been developed that produces a slow atomic beam of high brightness with a narrow velocity distribution. The technique can provide long measurement times and high counting rates for future precision experiments. In our initial work, densities of 10^8 Na atoms/cm^3 at a velocity of 270 cm/s and at a temperature of ~ 200 μK were obtained.

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Atomic beams have proven to be useful for a variety of precision experiments, and in many cases the limiting precision is governed by the time of flight through the apparatus.[1] Laser cooling techniques give one the ability to obtain significantly longer measurement times. For example, atoms that have been cooled to temperatures of ~ 50 μK and have been directed upwards in a pulsed atomic fountain have produced a 2-Hz-wide resonance.[2] Since the precision of a spectroscopic measurement depends both on the Q of the resonance and the signal-to-noise ratio, it is important to create as high a flux of cold atoms as possible. Also, for many precision experiments a continuous beam is desirable.

The direct deceleration of atoms in a beam has previously been accompanied by a serious loss of atomic flux. The reason is simple: When the longitudinal velocity of atoms in a beam is reduced to a few hundred cm/s, the transverse velocity becomes comparable to the longitudinal velocity, and the atoms spray out in all directions. Also, the techniques used for reducing the longitudinal velocity usually increase the transverse velocity.[3,4] It is possible to subsequently focus and recollimate the atoms in several steps to preserve the flux of incident atoms,[5] but when the longitudinal velocities become less than $\sim 10^3$ cm/s, this method becomes inefficient. We have circumvented these problems by creating an "optical funnel" designed to accept atoms with velocities as large as 2×10^3 cm/s, cool them, and then direct them into a well localized and collimated beam. With the advent of optical molasses, the manipulation of atoms is no longer restricted to lensing elements. Because of the dissipative properties of optical molasses, the "funnel" has no optical analog and can produce a beam of atoms with far higher brightness than the original thermal beam.

The funnel is a two-dimensional version of the magneto-optic trap.[6] The use of a similar scheme to transversely compress atomic beams has been proposed and demonstrated by Nellessen *et al.*[7] In the three-dimensional trap, atoms are confined to a few-hundred-micron-diameter sphere by three intersecting standing waves of properly chosen circular polarization. The beams supply strong damping (optical molasses) and a relatively weak restoring force towards a zero point in a spherical magnetic quadrupole field. In our funnel, the quadrupole field is created by four current-carrying "hairpin" wires as shown in Fig. 1. The atoms are guided along the zero-field symmetry axis by transverse circularly polarized laser beams. The hairpin-wire geometry was chosen to obtain full access for the light near the end.

There is no trapping along the axis, but axial cooling is provided by a pair of counterpropagating laser beams. In order to form the slow beam, a drift velocity is imposed on the atoms in the axial direction. Beam velocities in the range 100–500 cm/s are obtained by introducing a difference in either the frequencies or the intensities of the two axial beams. In the latter case, the atoms drift at a velocity such that the scattering rates from the two opposing beams are the same. If the frequencies are different but the intensities the same, the atoms' rest frame will be one in which the laser beams are Doppler shifted to the same frequency, i.e., appear as a standing wave.[8,9] When ν and $\nu+\Delta\nu$ are the two frequencies, the atoms will move away from the high-frequency beam

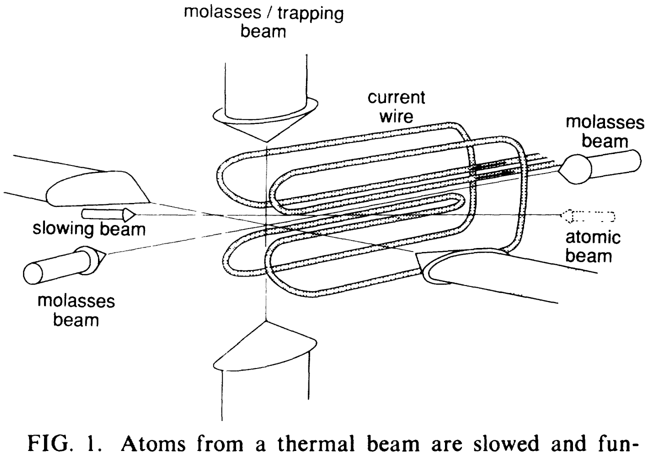

FIG. 1. Atoms from a thermal beam are slowed and funneled along the axis of the quadrupole field created by the four current-carrying "hairpin" wires. The square formed by the inner wires is 1.75 cm on a side. The upstream (right-hand side of figure) halves of the elliptical molasses-trapping beams are circularly polarized to trap the atoms transversely. The linearly polarized downstream (left) halves of these beams and the axial beams provide cooling. The axial beams also impose a drift velocity to the left.

with a velocity of $c\Delta\nu/2\nu$.

The magnetic field of the hairpin-wire geometry has been calculated by numerical integration (Fig. 2). The field inside the wires is predominantly a two-dimensional quadrupole field, with the axial component being less than 5% of the total. For our experimental conditions, the transverse magnetic-field gradient is 8 G/cm inside the trap. The field falls off gradually at the end of the hairpin wires, from 80% of its maximum value at the end of the trap to 10% of its maximum value 2.0 cm beyond.

Temperatures as low as ~20 μK have been observed for Na atoms cooled in optical molasses.[9,10] However, the cooling force responsible for this low temperature (orientational cooling in a laser field with a polarization gradient)[11,12] is reduced in the presence of a magnetic field.[9] Thus, for the fields used for the transverse confinement in the funnel, the expected temperature is on the order of 0.5 mK.[6] To further cool the atoms, they are transported away from the "trap" to a region of lower magnetic field while constantly imbedded in optical molasses. The transition from transverse trapping to pure molasses takes place where the hairpins start curving, and is accomplished by using large elliptical transverse beams (4.5×1.4 cm^2) of which only the halves closest to the wires are circularly polarized to provide the trapping. The linear polarizations of the other halves are chosen to provide orientational cooling in all directions.[13] As the atoms leave the region of transverse confinement, the beam has a diameter of ~0.15 cm. At an axial velocity of 290 cm/s it diffusively expands to ~0.4 cm while traveling through ~2.5 cm of molasses.

The overall experimental setup is similar to that described previously.[10] A cw dye laser is tuned near the Na $3^2S_{1/2},F=2\rightarrow 3^2P_{3/2},F=3$ transition and offset locked to a saturated absorption signal from a Na cell. To prevent the atoms from optically pumping into the $3^2S_{1/2},F=1$ level, an electro-optic modulator provides a sideband tuned close to the $F=1\rightarrow F=2$ transition. Typically 15% of the total power is in each sideband, separated from the carrier by 1716 MHz. The atoms from a Na oven (temperature ~325 °C, nozzle diameter 1 mm) 60 cm from the magnetic field coils are slowed using the chirped-cooling technique.[3] The first sideband from an electro-optic modulator is chirped continuously from 840 to 30 MHz below resonance at a rate of 650 Hz. The laser beam is matched in size to the atomic beam (~0.45 cm at the coils) and is softly focused on the oven. The thermal atomic beam and the axis of the trap intersect at an angle of ~7° in the horizontal plane, and are displaced ~0.4 cm vertically. The intensity in the chirped sideband is typically 50 mW/cm^2 near the funnel. The total intensity in the center of the transverse molasses-trapping beams is 3.6 MW/cm^2 and the carrier is tuned ~12 MHz below the line. The axial beams have an intensity of 5.5 MW/cm^2. When the drift velocity is imposed by an intensity imbalance, the downstream beam (opposing the motion of the atoms) is attenuated by up to a factor of 4. When a frequency difference imposes the drift velocity, the downstream beam is shifted to the red by up to 17 MHz relative to the other beams.

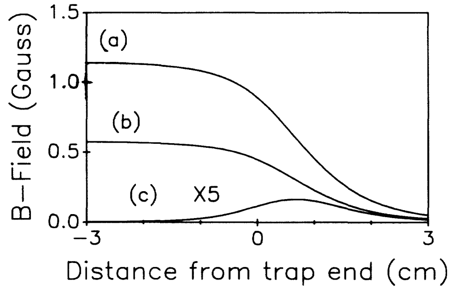

FIG. 2. Curves *a* and *b* show the total magnetic field 0.14 and 0.07 cm away from the axis, respectively, with 18 A running through the coils. Curve *c* shows the axial field 0.14 cm away from the axis. The zero on the length scale corresponds to where the centers of the three molasses beam pairs cross. The transverse trapping occurs between 0 and −1.2 cm.

The velocity and temperature of the slow atomic beam are measured using a time-of-flight technique. The atomic beam is deflected out of the molasses region by a ~3.5-MW laser beam which is 0.065 cm wide and 0.6 cm tall. This deflecting beam is gated off for short periods of time (0.4 to 2 ms), letting a length of the slow atomic beam pass. To allow this pulse of atoms to travel ballistically to the detection region, the molasses beams are turned off for 15 ms beginning when the deflecting beam is gated off. The atoms are detected near the end of the molasses region by a vertical standing-wave probe, a narrow section of which is imaged onto a photomultiplier tube. The probe is kept at a fixed distance from the trap, while the deflecting beam can be made to intercept the atomic beam at any point in the molasses region. The arrival time of the short pulse of atoms determines the beam velocity, whereas the width contains information about the axial temperature. In extracting this information from the time-of-flight signals, we model the initial distribution of atoms as a square pulse and ignore the slight heating and deflection near the ends of the pulse. The time-of-flight signals are fitted by a convolution of the initial square distribution and a Gaussian distribution of width $\sigma_\parallel=(k_BT_\parallel t^2/m+\sigma_p^2)^{1/2}$, where t is the time of flight, m the mass of a Na atom, and σ_p the width of the probe beam. Figure 3(a) shows the axial temperature as a function of distance from the end of the region of transverse trapping (the "trap"). Midway between the trap and the probe the temperature is ~180 μK, which corresponds to an rms velocity spread of 25 cm/s. As the atoms move toward weaker magnetic fields farther from the trap, we expect them to cool adiabatically with respect to the decreasing magnetic fields.[10] The effect of the magnetic field is exacerbated because the atoms are displaced ~0.2 cm into a region of higher field by an intensity imbalance caused by the edge of the

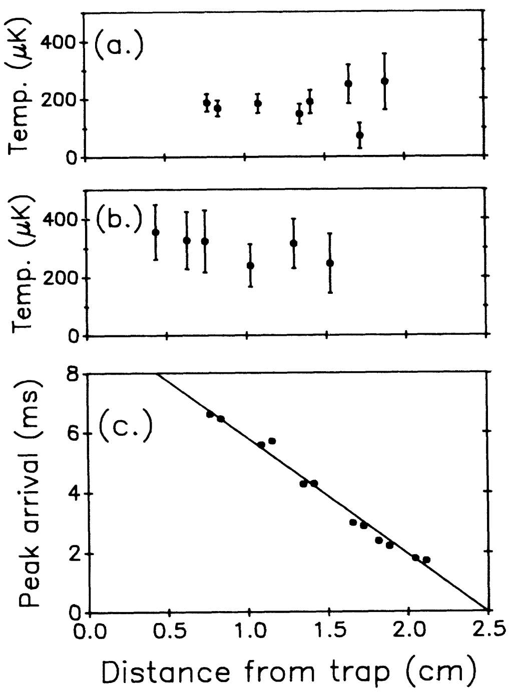

FIG. 3. Time-of-flight measurements taken with different separations between the deflecting beam and the probe. The probe is located 2.5 cm from the end of the trapping region. (a) Axial temperature. The mean value is 180 μK. (b) Transverse temperature. The mean value is 300 μK. (c) The time of flight of a pulse of the atomic beam. This data set gives a velocity of 260 cm/s.

quarter-wave plates. Temperature measurements taken with the deflecting beam close to the probe have higher errors because the atoms have not evolved ballistically for very long.

Figure 3(c) shows the arrival time of the pulse of atoms as a function of distance of the deflecting beam from the trap. The velocity of 260 cm/s obtained from this particular set of data agrees with the 8.5-MHz frequency difference between the two axial molasses beams.

In order to determine the transverse temperature we mapped out the transverse beam profile as a function of the separation between the deflection and probe beams. Each measured profile is fitted by a Gaussian with a width resulting from the thermal spreading of the beam, the instrumental resolution (due to the detector width), and the finite size of the atomic beam at deflecting beam. Figure 3(b) shows the transverse temperature, which is ~300 μK, as a function of distance from the trap. Slow drifts during the time-consuming measurements led to large uncertainties in these data.

Measurements were also made of the axial velocity and temperature with the drift velocity imposed by an intensity imbalance between the two axial molasses beams. In this configuration orientational cooling is not in effect, and data were taken with the light tuned 4 MHz below resonance. With the downstream beam attenuated by a factor of 3 we observe a velocity of 220 cm/s and a temperature of ~500 μK, in fair agreement with what is expected from Doppler cooling.

The flux integrated over the beam area is another important parameter that characterizes the slow beam. It varies only 20% for on-axis field gradients in the range 5–22 G/cm, and is maximized at 8 G/cm. We find that it is not affected by a factor of 2 change in intensity, nor by altering the detuning in the range 4–15 MHz below resonance. At larger than 15-MHz detuning we observe trapping in the axial direction, which the imposed drift velocity is not able to overcome. We conjecture that this magneto-optic trapping is caused by the axial-field extrema at the end of the magnet.

The density of atoms in the slow beam in the middle of the molasses region is measured to be the same as in the original thermal beam near the trap. Using a calibrated photomultiplier tube, we find that the integrated flux of the thermal beam is $\sim 10^{12}$ atoms/s, and that the integrated flux in the funneled beam is $\sim 10^{9}$ atoms/s at a velocity of 270 cm/s.

This represents a considerable improvement over previous slow atomic beam sources. Atomic beams with velocities in the range of 300 cm/s cannot be produced easily using the inhomogeneous-magnetic-field slowing technique.[4] (Slowly moving atoms experience strong magnetic lensing and flare out into a "skirt" at the exit of the magnetic field coils.) The flux of atoms from the funnel (atoms/cm^{2}s) is roughly 40 times greater and at a temperature 400 times colder than the flux we can obtain in our apparatus with just the chirped-cooling technique. Similar performance was obtained in the original chirped-cooling experiments.[3] Cooling atoms in an intense standing wave[14] has produced densities in excess of 10^8 atoms/cm^3, but with a longitudinal velocity spread of 10^3 cm/s and no transverse cooling. If we define the atomic beam source "brightness" to be the integrated flux of atoms (atoms/s) divided by the velocity spreads $\Delta v_x \Delta v_y \Delta v_z$, the funneled beam is 3×10^3 times brighter than the original beam.

The performance of the optical funnel can be improved in several ways. At present, only 10% of the atoms in the original atomic beam are addressed by the ~800-MHz sweep of our chirped beam. Also, the chirped-cooling technique has the fundamental problem that the atoms reach their terminal velocity at different points in space, after which transverse spreading causes them to miss the funnel. It should be possible to extend the funnel upstream around the beam in order to provide transverse confinement and cooling along the beam. Another possibility is to incorporate magnetic cooling[4,15] or stimulated cooling and confinement into the preliminary slowing stage.[14,16] After the atoms are transported from the funnel to a region free of magnetic fields, a final stage of polarization gradient cooling or Doppler cooling on a more forbidden line may be able to further reduce the transverse velocities to a few cm/s. With these improvements, the brightness of the atomic beam can be improved by another 3 orders of magnitude. Further transverse collimation may be achieved by using a magnetic sextapole lens, which can be used to sacrifice transverse localization for a lower transverse velocity spread. The high-flux atomic beam or fountain can be used for a variety of precision experiments such as electric-dipole moment measurements, charge-neutrality measurements, precision spectroscopy, and the creation of a neutral-atom optical frequency standard.

By exploiting the weak axial trapping which we observe under some experimental conditions, the funnel may also be used to trap a high-density cylinder of atoms. It may be possible to reach densities of 10^{11} atoms/cm^3 in the two-dimensional trap, since comparable densities have been reached in the three-dimensional magneto-optic trap.[6] A sample of atoms with this geometry and velocity spread would be useful in a variety of work such as nonlinear optics experiments where an optically thick sample of atoms nearly at rest would be useful, or parity-nonconversation experiments where the highest density of atoms with the smallest Doppler broadening is desired.[17]

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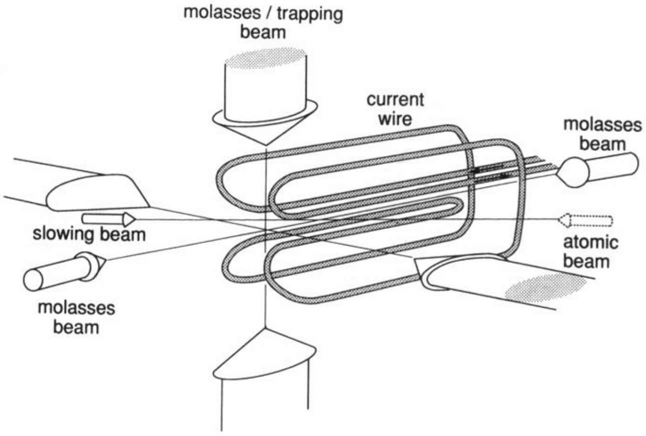

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