Construction and operation of a laser trap which captures sodium atoms from a vapor

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Abstract

We have produced a sample of trapped sodium atoms which were captured directly from a vapor in a heated cell. The atoms are confined by laser light in a magneto-optic trap in a manner similar to that recently reported for cesium. Despite the experimental complications arising from the need to heat the cell, we find the trapping to be very tolerant of departures of the apparatus from the ideal. For a sodium vapor at 80°C – corresponding to a vapor pressure of about 10^{-6} – we obtain a dense cloud of sodium with millimeter dimensions and densities up to 10^{11} atoms/cm^3. We describe the construction of the trap, outline experimental conditions we have found suitable for its operation, and discuss some of our initial observations.

I. Introduction

Manipulating atomic particles using laser light is a rapidly developing field of activity within atomic and optical physics. An especially intense effort is ongoing to use laser techniques to produce samples of neutral atoms with very high densities and very low temperatures. The expectation is that such samples will find a variety of uses; they have already proved valuable in studying very low energy atomic collisions[1]; they may find a role in ultra-high spectroscopy[2]; and it is hoped that sufficiently high densities and low temperatures will be realized to observe quantum collective effects such as a Bose condensation of weakly interacting particles. Until recently, producing laser cooled and/or trapped samples was a two step process[3,4,5,9]. An initial "slowing" stage was required to decelerate atoms to where the relatively weak laser light forces are effective for either trapping or deep cooling ("molasses"). In 1990, Cable et al.[6] captured and trapped sodium atoms from the low velocity tail of a thermal source effusing into the trapping region from an adjacent vacuum chamber. Recently, Wieman and coworkers[7] demonstrated that cesium atoms could be captured directly from the vapor in a heated cell and confined in a magneto-optical trap. Other groups have picked up on this idea and made similar "vapor cell" traps[8] of cesium. In this work we demonstrate that, despite technical difficulties arising from the need to operate at higher temperatures, sodium atoms may be confined in a similar fashion. Indeed, we found that, even for sodium, this sort of trap is convenient to use and surprisingly tolerant of departures from ideal experimental conditions. We describe in detail our experimental apparatus, conditions we found to be suitable for its operation, and some initial observations.

Fig. 1 is a schematic of the apparatus. A heated stainless steel chamber serves as the sodium cell. The body of the cell consists of a 10 cm diameter by 20 cm long 304 stainless steel tube. Isight "nipples" were welded to the tube to provide additional ports for laser

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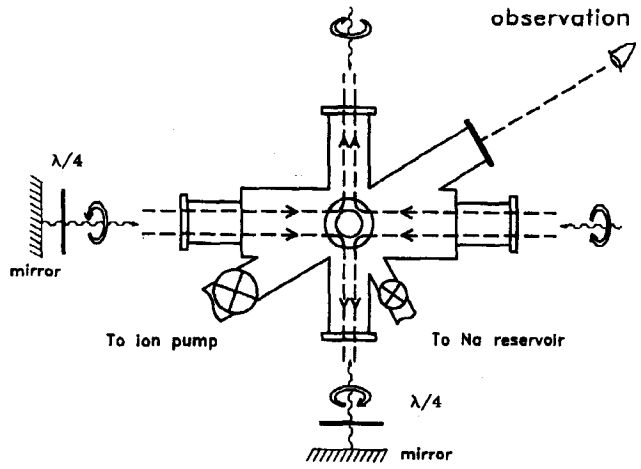

Figure 1. Schematic representation of the vapor cell and the laser beams. The dashed lines indicate the magnetic field direction. Each arm has a pair of counter-propogating laser beams about 0.8 cm in diameter with opposite circular polarization. The helicities of the polarizations are as indicated by the "swoosh" arrows. The magnetic field coil axis is vertical.

beams, observation windows, vacuum pumping, and introducing the sodium. Commercially available stainless steel knife edge - copper gasket vacuum seals were used throughout. We found that vacuuum valves using viton seals were adequate; though, they limited the bakeout temperature we could use. Before introducing the sodium, the chamber was cleaned with acetone and given a moderate (200°C, $\sim$ 12 hrs) vacuum bake into a turbo molecular pump that was subsequently valved out of the system. Residual gas analysis showed that the bake virtually eliminated water vapor and, at room temperature, the dominant remaining species were H_2 and CO. Typically, during operation of the trap, the chamber body is heated to 80°C, the windows on the apparatus to 90°C, and the small (30 l/s) ion pump for removing outgassing products, to 100°C. The pressure during operation, as estimated from the ion pump's current, was on the order of a few 10^{-6} Pa (133 Pa = -1 Torr).

The trap was "charged" by breaking a sodium ampoule in a separate leg of the vacuum chamber and heating the entire apparatud to about 120°. It took above 24 hours for the cell's surfaces to become saturaled with sodium; after the charging, the sodium ampoule was valved out of the system. To data, after running the trap for over 200 hours, we have seen no evidence of the ion pump's depleting the initial sodium charge.

Atoms are trapped using a "magneto optic trap". This type of tray was originally dermonstrated by Raab et al. in 1987[9]. Its layout consists of three mutually orthogonal, pairs of counterpropogating, oppositely circularly polarized laser beams which intersect at the center of a quadrupolar magnetic field. The field is created by a current in a pair of coils wired in an "anti-Helmholtz" configuration. Fig. 1 shows the relative directions of the magnetic field and the polarizations of the various laser beam.

The diameter of the coils is 9 cm; they are separated by 16 cm; and the total current in each coil is usually about 3000 A-turns. The required field is generated by running the current in the two coils in opposite directions. This produces a zero, of field at the trap center with field gradients of about 0.09 T/m along the coils' axis and 0.045 T/m in the transverse plane.

The laser beams used to trap atoms had diameters apertured to 0.8 cm and powers of 20 mW (each). The vacuum windows for the traping beams were AR coated. An Argon-ion pumped Coherent model 699 ring dye laser generated the light. To make the trap work, the laser frequency was tuned 5 to 10 MHz below the $3S_{1/2}(F = 2) \rightarrow 3P_{3/2}(F = 3)$ "trapping" transition. Occasionally, unwanted transitions to other $3P_{3/2}$ hyperfine levels were off-resonantly excited. These can decay to the F=1 level in the $3_{1/2}$ manifold. To return these atoms back to the 3S(F=2) level used in trapping, sidebands at 1712 MHz (about 20% of the laser power was in each sideband) were added to the beam just after the laser by an electro-optic frequency modulator. The upper sideband "repumps" atoms by exciting the $3S_{1/2}(F = 1)$ to $3P_{3/2}(F = 2)$ transition.

Within the context of Doppler cooling, the trap works because, at any location, the Zeeman shifts due to the quadrupolar field make an atom most resonant with those laser beams that push it toward the trap center at zero magnetic field. This situation requires the specific choice of circular polarizations for the different beams that is shown in Fig. 1. Laser cooling or damping of the atomic motion is ensured by detuning

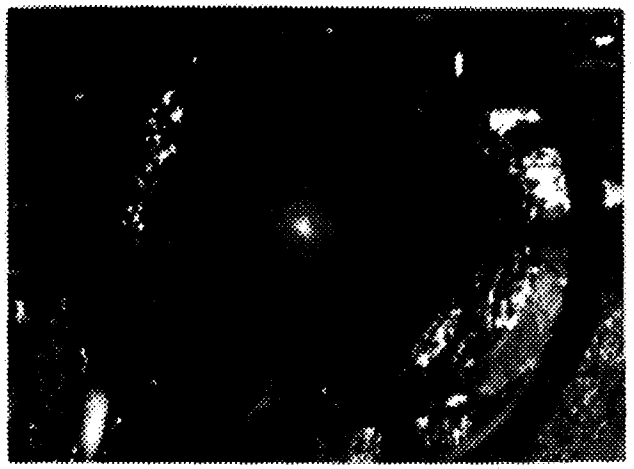

Figure 2. Visual observation of the trap. The size of the cold trapped atom cloudd (central brightest region) is on the order of 1mm in diameter and about 1000 times brighter than the background fluorescence.

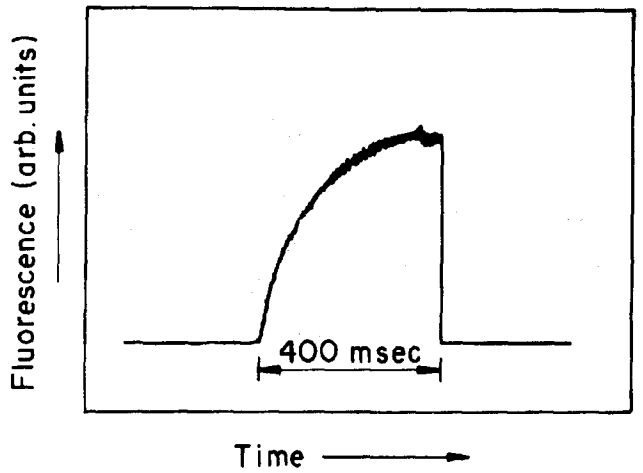

Figure 3. Time evolution of the trapped atom fluorescence after the trapping laser beams have been turned on. The characteristic time for the charging of the trap, $\tau_{1/e} \sim 200$ ms.

below resonance. Recent results[10] show that polarization gradient forces[11] are also important in the trapping and cooling.

For low velocity atoms, the net force distribution in the trap is that of a strongly overdamped harmonic oscillator. Atoms in the vapor which can interact with the laser are slowed by the damping and captured by the trap.

As is seen in Fig. 2, the trapped atoms appear as a bright ball of atoms about 1 mm in diameter in the center of the cell near the magnetic field zero. The fluorescence from the trapped atoms is roughly 1000 times brighter than the background fluorescence from the thermal sodium vapor.

Visually, the trap was insensitive to light intensity; reducing the intensity in one dimension by a factor of two barely affected the trap's appearance. The trap was also tolerant of small errors in the laser polarization; contaminating a beam with 20% of the "wrong" polarization had little apparent effect. Misalignment of laser beam and magnetic field axes produced traps with a variety of exotic shapes: "rings," "double clouds", "banana shapes," and "pancakes", were common. The ball and the ring shapes produced the most intense fluorescence. The trap's appearance was sensitive to the magnetic field gradient's strength: larger gradients produced smaller, brighter traps. 10% changes in the gradient were easily detected visually.

We investigated the loading of the trap by imaging it onto a photomultiplier detector and recording the increase in fluorescence as a function of time after the turn on of the laser beams. These data are shown in Fig. 3. The loading time exhibits a fairly weak dependence on laser frequency and the trap's field gradient. Characteristic times, $\tau_{1/e}$ (the time it take the fluorescence to build to within 1/e of its maximum value) on the order of 200 ms were typical.

We may use the measured ratio of the trap's brightness to that of the laser illuminated background sodium vapor to estimate the density of trapped atoms. A sample's brightness is proportional to its column density of *strongly fluorescing atoms.* In the trap, essentially *all* of the laser cooled atoms fluoresce at a near-saturation rate. The fraction of the atoms in the vapor that strongly fluoresce is approximately the ratio of the power broadened linewidth of th atomic transition, Δf_{at} to the vapor's Doppler linewidth, Δf_{Dop}. Thus, R, the ratio of the traps brightness to that of the vapor is:

$$R \sim \frac{n_{trap} d}{nl} \frac{\Delta f_{Dop}}{\Delta fat}$$

Where n_{trap} is the density of trapped atoms; d is the trap diameter; n is the density of atoms in the vapor, and l is the column length of the laser illuminated background vapor in the intensity comparision. For typical operation of our trap, n and l are $5 \cdot 10^8$ cm^{-3} and

1.2 cm. $\Delta f_{Dop}/\Delta f_{at}$ was about 50. For a 1 mm diameter trap, then, we estimate that our trap density is $\sim 10^{11}$ cm^{-3}. And the total number of trapped atoms, $N, \sim 10^8$. We are presently trying to measure independently the trap density using absorption of a weak probe laser.

We can use our measured fluorescence "build-up" time to estimate the efficience of our trap in capturing atoms from the vapor. The total number of trapped atoms is related to R, the rate at which atoms are captured from the vapor: $N \sim R \cdot \tau_{1/e}$. Using the above estimates for $\tau 1/e$ and N, we find R for our 1 mm diameter trap to be $5 \cdot 10^8$ atoms/s. Using arguments based on the kinetic theory of an ideal gas: $R \sim nV_c^{2/3}\left(\frac{m}{2k_BT}\right)^{3/2} v_c^4$ [7]. n is the sodium vapor density ($5 \cdot 10^8$), V_c the capture volume (the region of overlap of the three pairs of laser beams), m the mass of a sodium atom, k_B is Boltzmann' constant, T the vapor temperature and v_c, the maximum capture velocity. In this work, $V_c \sim 0.5$ cm^3, $T = 353$ K. If we solve this expression for v_c we find our trap captures those atoms in the Maxwellian distribution with velocities less than about 30 m/s.

Summarizing, we have successfully captured atoms from a sodium vapor in a cell and trapped them in a magneto optic trap. The trap seems very robust and is insensitive to moderate changes in laser intensity and polarization. We estimate trap densities of 10^{11} cm^{-3} and discussed our observations in terms of a simple kinetic theory analysis of the capture of particles from the vapor.

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