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The purpose of this project is to construct and study a laser trap for neutral atoms, initially potassium (K). At low densities, such a trap could be used to address a number of fundamental questions, e.g. the interaction of an individual atom with an electromagnetic field, collision dynamics and recombination. We have studied the feasibility and limitations of a purely laser trap concept, a "corner cube trap", for trapping neutral K atoms. The confinement of the atoms in the two dimensions perpendicular to the laser is provided in the cavity of a newly constructed high power alexandrite laser operating in

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20. the CW TEM^*_{01} mode ("doughnut mode") tuned slightly to the blue side of the resonance line of the K atom. By reflecting the TEM^*_{01} laser back on itself with two mirrors, one "caps" the ends of the cylindrical trap, resulting in a slightly weaker end plug. This trap concept employs not laser cooling, but rather counterstreaming ^4He atoms which are cooled to ~1.5 K, to drastically cool the K atoms to thermal energies well below the trap depth (expected to be ~8.6 K). We have also examined various loss mechanism for the trapped atoms. In particular, K atoms are lost to the trap if they are multiphoton ionized, if they are heated by absorption and emission of many photons ("recoil" or "diffusional" heating), if they simply have much higher energy than the vast majority of other atoms at 1.5 K, or if they recombine with He to form KHe (or KHe_2, etc.). Results from these investigations are discussed, suggesting crude lifetimes for trapped atoms of the order of 1 second. Emphasis in the initial studies discussed herein is in development and characterization of the new alexandrite laser, demonstration of the trap at low densities, and determination of the spatial and velocity distribution of atoms in the trap.

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Final Report

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A Laser Trap for Neutral Atoms

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Final Report on Designing and Constructing a Laser Trap for Neutral Atoms

Recently there has been a great deal of interest in trapping neutral atoms for the reasons given in our recent work (e.g. [STW 84]) and also many more reasons in other contributions to the volume in which it appears. Purely magnetic traps are quite attractive and are being pursued successfully at NBS (Gaithersburg) [PRO 85], but are orders of magnitude weaker than the laser trap discussed here. Two-laser traps [DAL 83, DAL 84] are also quite promising, but we feel it is better to start with the simpler one-laser trap, as in our theoretical work [YAN 86, YAN 87] and the experiments of Chu et al. [CHU 86].

Our initial studies of neutral traps involved the laser-magnet hybrid trap [STW 84]. Because of the complex Zeeman structure of the atoms in the magnet field of the hybrid trap, however, a number of issues (diffusional heating, optical pumping, multiphoton ionization, etc.) become correspondingly complex. Hence we have decided to attempt initially to implement a purely laser trap, similar to those proposed by Ashkin [ASH 78, ASH 79, ASH 80, GOR 80] and then reconsider the laser-magnet trap at a later date. The primary differences in our laser trap concept (Figure 1) is that our "corner cube trap" (a) is within a TEM^{*}_{01} laser cavity; and (b) employs not laser cooling, but rather counterstreaming ^{4}He atoms (which do not interact significantly with the trapping laser) which have been cooled to $\lesssim$1.5 K to drastically cool K atoms (vaporized above room temperature) to thermal energies well below our estimated 8.6K trap depth. In contrast, the recent work of Chu et al. [CHU 86] involves an extracavity TEM_{00} laser beam of lower power and low trap depth (~5 mK) with "optical molasses" cooling to ~240 μK.

In particular, if the laser frequency is slightly to the blue of the atomic resonance frequency, the atom will experience a relatively strong "transverse dipole" force pushing it into the central region of weaker light

intensity. This force has been dramatically demonstrated in the Na atom focusing experiments of Bjorkholm and coworkers [BJO 78, BJO 80, PEA 80]. If one employs a TEM_{01}^{*} ("doughnut mode") laser beam, one confines the atom in two dimensions (x and y, $\perp$ to the laser). By reflecting the TEM_{01}^{*} laser beam back on itself with two mirrors, one "caps" the ends of the cylindrical trap, albeit with a slightly weaker end plug (the laser intensity is down by a factor of 2 at the Rayleigh range and the trap depth down by $\sqrt{2}$). We have used spatial filtering to reliably and stabily operate our new cw alexandrite laser as well as argon and krypton ion lasers in the TEM_{01}^{*} mode.

We have selected K atoms since a suitable high power tunable CW laser, the Allied alexandrite laser, is now available to us and since the multiphoton ionization rate is particularly low for K. The Allied alexandrite laser is not yet commercially available, but Allied has sold us the components for a CW alexandrite laser well in advance of commercialization. It has been operational intermittently in Iowa since February 1986. The initial CW alexandrite laser at Allied achieved 60 watts CW output; with a high reflector in place of the output coupler, 3000 watts intracavity should be obtainable. The lengthening of the cavity, and introduction of a tuning element and other optical surfaces will reduce this, but with this laser, the achievement of intracavity power densities exceeding 10^8 W/cm^2 (hence trap depths approaching 10 K) was a realistic near term goal.

Alexandrite is chromium-doped chrysoberyl, $BeAl_2O_4:Cr^{+3}$. Chrysoberyl is a member of the olivine family of crystals, and has a unit cell in an orthohombic structure of space group P_{nma}, with cell dimensions of a = 0.9404 nm, b = 0.5476 nm, and c = 0.4425 nm. The Cr^{+3} ions replace the mirror and inversion sites of Al^{+3}, with 78% of Cr^{+3} ions on the mirror sites (laser active) and 22% on the inversion sites [WAL 80]. The dopant concentration varies from 0.01 to 0.2 at. % (our two rods have 0.17 and 0.2 at. % concentrations). The

alexandrite rod is cut along the c-axis of the crystal. The emitted laser light is polarized along the b-axis.

The alexandrite laser is the first solid-state laser to operate at room temperature with improved performance with increasing temperature to 400 K. It has a wide range of fluorescence, peaking at 755 nm. During laser operation, the upper laser level is the $^4T_2$ multiplet with a lifetime of 6.6 μsec and the terminal lasing levels are the vibrationally excited levels of the ground state ($^4A_2$), which decay to the low vibrational levels by phonon relaxation. It is this wide range of the vibrationally excited ground state levels that make the laser continuously tunable from 701 to 818 nm [WAL 80A, WAL 80B, WAL 85]. This broad range of tunability makes it highly desirable for a wide range of applications. The typical output of our cw alexandrite laser is about 2.5 W (multimode).

During this grant, we have spent a disproportionate amount of effort maintaining and repairing the laser. First, the power supply broke down. We tried to fix it, but eventually, we had to ship it back to Allied-Signal Corp. for repair. They also had difficulties fixing it. They ended up shipping <u>their</u> power supply to us and keeping ours.

Then, plumbing for the cooling system started to develop leaks. Several leaks were quickly fixed. However, the one leak at the accumulator (a device designed to damp the water vibration from the pump to the laser rod) defied our best effort (because too much glue was used in the original construction of the accumulator to glue PCV and CPCV pipes together). The accumulator was finally sent back to Allied-Signal Corp. so that an identical one could be built for us. (In the meantime, Allied Signal Corp. was moving its laser research laboratory (Mt. Bethel) to its headquarters (Morristown), resulting in considerable delays in shipping back the components.)

After we assembled all components together, and during our trials to re-

start the laser, we discovered that one half of the elliptical reflector was damaged. It was replaced by a new one, and the water line was also changed. So, we finally have a system that seems to be free of electrical and plumbing problems.

We have now successfully restarted the alexandrite laser (at 2.8 kw lamp power). The laser can now be easily made to lase when two high reflectors are in place. However, we still have some difficulty to make it lase when one high reflector and one output coupler are used. This is so despite our best effort to align the mercury arc lamp and the laser rod along the two focal axes of the elliptical reflector, and to correctly orient the rod so that the b-axis is perpendicular to the lamp-rod plane for maximum pumping efficiency). Since we have only one output coupler from Allied, it is not clear whether the output coupler is damaged (visual check seems to suggest that it is good). We are now continuing our effort to investigate whether the problem comes from the output coupler and/or from the anti-reflection coatings on the end surfaces of the laser rod. In addition, we have found that during the summer the cooling water temperature sometimes becomes intolerably high. We aim to restore the laser output to its previous level of 2.5 W, and later improve it to higher power.

We have chosen ^{4}He for cooling initially because temperatures $\lesssim$1.5 K can be readily achieved with high cooling power by pumping on liquid helium and because ^{4}He is inexpensive. Future designs might employ ^{3}He (which is quite expensive) or even spin-polarized hydrogen (H↓) (which would add considerable complexity), but we shall not consider them here. See also the recent discussion of Bjorkholm concerning collision-limited lifetimes in atom traps [BJO 88].

The parameters we have chosen for our initial trap experiments (revised from [YAN 86]) are given in Table I (see also [YAN 87]). Note that the AC

Table I. Initial experimental parameters for the Iowa TEM_{01}^{*} Intracavity Laser Corner Cube Trap for ^{4}He-Cooled ^{39}K Atoms.

Maximum intensity of TEM_{01}^{*} 765.3 nm laser (at $w_o/\sqrt{2}$)	1.52×10^{8} W/cm^2 (standing wave)
Trap depth (maximum) at beam waist $w_o/\sqrt{2}$	8.6 K
Trap depth (minimum) at Rayleigh range z_o	5 K
Laser detuning to the blue of $^{2}S_{1/2}$ - $^{2}P_{3/2}$	5.23×10^{5} MHz
AC Stark shift to the red (at $w_o/\sqrt{2}$)	3.08×10^{4} MHz
AC Stark full width at half maximum (at $w_o/\sqrt{2}$)	9.13×10^{5} MHz
Beam waist w_o	14 μm
Rayleigh range z_o	0.76 mm
Multiphoton ionization rate	1.2 sec^{-1}
Diffusional heating rate	4.3×10^{3} K/sec
Thermal escape rate	~10 sec^{-1}
Recombination rate (if appropriate)	$\lesssim$1 sec^{-1}

Stark width greatly exceeds the ordinary (Doppler) width ($\lesssim 10^3$ MHz) of the K atomic line. Note also the various loss rates in Table I. In particular, K atoms can be lost to the trap if they are multiphoton ionized, if they are heated by absorption and emission of many photons ("recoil" or "diffusional" heating), if they simply have a much higher kinetic energy than the vast majority of other atoms at a temperature of 1.5 K, or if they form KHe (or KHe_2, etc.).

The choice of detuning is made through consideration of three important factors: well depth, multiphoton ionization rate and diffusional heating. As detuning increases, both well depth and diffusional heating decrease, but multiphoton ionization rate increases. We have chosen $\Delta = 2\Delta_o$, where Δ_o is the "optimal" detuning [GOR 80] for a given laser intensity, to satisfy the conditions: (a) the maximum and the minimum well depths are well over the expected temperature (1-1.5 K) of the trapped atoms; (b) the ^{4}He collisional cooling rate will significantly exceed the diffusional heating rate; and (c) the multiphoton ionization rate remains in the neighborhood of 1 sec^{-1}.

The multiphoton ionization rate is uncertain because of the uncertainty in the cross section and because the rate varies drastically with kinetic energy of the K atom (hotter atoms sample higher laser intensities). Nevertheless, rates in the range 0.1-10 sec^{-1} are expected.

Diffusional heating is the most serious objection to Ashkin's original traps. However, by introducing a large excess of cold ^{4}He (e.g. $n_K \simeq 10^6$ atoms/cm^3; $n_{^4He} \simeq 10^{18}$ atoms/cm^3 (which is roughly half the vapor pressure of liquid helium at 1.5 K)), each K atom undergoes a very large number of collisions ($\sim 10^8$/sec). This should provide more than adequate cooling, despite the 4300 K/sec which must be removed. Note that the "high" density of ^{4}He is still small enough that the pressure broadening of the K resonance line should be negligible ($\lesssim$100 MHz).

The thermal escape rate (assuming the diffusional heating problem is eliminated by ^{4}He cooling) will be comparable (perhaps somewhat larger) than the multiphoton ionization rate. In both cases, of course, atoms at the "hot" end of the kinetic energy distribution will be lost and it is not yet clear to us how fast the "hole" at the top of the thermal distribution will be refilled by collisions of initially colder atoms. In addition, the time for the K atoms to diffuse through the cold ^{4}He to the laser trap "walls" will be much slower than that given by collisionless motion.

A final loss mechanism is the formation of KHe. This species has, to our knowledge, never been observed, but theoretical calculations of the interaction potential between K and He do exist. Presumably the best of these is that of Pascale [PAS 83, PAS 85]. Using his potential with a well depth of 1.9 cm^{-1} (~2.7 K) and an equilibrium distance of 13.2 a_o, one calculates three levels bound by less than 0.25 cm^{-1} ($v = 0$, $J = 0$ and 1 and $v = 1$, $J = 0$) and two quasibound levels ($v = 0$, $J = 2$ and $v = 1$, $J = 1$). This corresponds to a vibrational-rotational partition function of ~13 in the limit that T is large compared to the binding energy. The corresponding equilibrium constant (for number densities in units of atoms/cm^3) is then at 1.5 K

$$K = (n_{KHe})/(n_K n_{He}) \simeq 6 \times 10^{-21}.$$

For $n_K = 10^6$ and $n_{He} = 10^{18}$ as above, $n_{KHe} = 6 \times 10^3$ or 0.6% of the K is tied up as KHe as equilibrium. If the well depth of the KHe potential was significantly greater, this percentage might be much higher; if the well depth were less, there might be fewer or even no bound states. Even if KHe is a concern, its interaction with the laser field remains to be examined (photodissociation; dipole force; multiphoton ionization; etc.). Use of ^{3}He would reduce the KHe problem; lowering T (perhaps 1 K can be achieved by carefully considering the cooling by pumping of liquid helium) would increase the recombination. The rate (as opposed to the equilibrium constant) is completely unknown

for K + He + He → KHe + He; a reasonable value of 10^{-36} $cm^6/atoms^2$ (as for H + H + He → H_2 + He at 4 K) gives ~1 sec^{-1} for recombination.

Assuming the fastest loss rates are ~1 sec^{-1}, we could simply study the decay rate of K concentration with time as the K source (filling the trap) was turned off. The detection is straightforward using either of the 5p → 4s fluorescences (at ~404.5 nm) (or possibly the $4p_{1/2}$ → 4s fluorescence at 769.9 nm). Variation in the laser intensity and ^{4}He density and detection of the KHe molecule could be used to attempt to sort out the competing trap losses. Room temperature experiments were carried out this past year to establish and optimize the high sensitivity of this detection method.

Finally, a major manuscript detailing our trap has appeared in Phys. Rev. A. [YAN 86] (slightly revised in [YAN 87]). The major future goal is to successfully operate the alexandrite laser with cryogenic intracavity mirrors and then to trap K atoms, cooled with counterstreaming He, between these mirrors in our TEM^*_{01} trap. We shall then try to observe novel ultracold atom effects such as optical molasses [LET 88], laser modified ultracold atomic collisions [JUL 88] and quantum-state-selective reflection [BAL 88].

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