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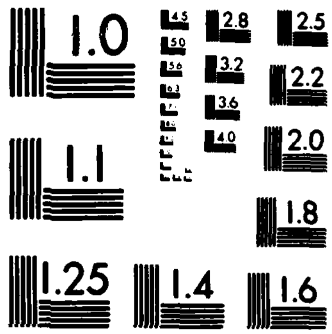

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this project was to theoretically study and design a laser trap for neutral atoms. At low atomic 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, recombination. In particular, after examining a variety of laser-magnet trap concepts, we studied the feasibility and limitations of a "corner cube" laser trap for potassium atoms based on a near-resonant CW TEM_{01}^{*} ("doughnut mode") alexandrite laser beam with cooling provided by ^4He atoms at $\lesssim$1.5 K and designed initial experiments.

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Office of Naval Research

Annual Summary Report

for

November 15, 1983-November 14, 1984

for

Contract N00014-83-K-0646

Task No. RR011-03-03

Theoretical Issues Involving Traps for Neutral Spin-Polarized Atoms

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Among the most exciting developments in atomic and molecular science in the past decade have been the prediction and preparation of bulk quantities of an entirely new (and metastable) form of matter, spin-polarized atoms, and the preparation and detection of very small numbers of various species (even individual ions or atoms). During the past year, we have been supported by the Office of Naval Research to study theoretically possible neutral atom traps. As a result of these theoretical studies, we developed a new laser concept for a low temperature trap for gaseous neutral atoms and designed experimental studies based upon it. Such a trap could be used at low density for unique studies of small numbers of cold atoms (and perhaps ultimately at high density for unique studies of spin-polarized atoms) without confining material walls.

Recently there has been a great deal of interest in trapping neutral atoms for the reasons discussed above and for a wide variety of other reasons (frequency standards, ultimate limits on temperature, Bose condensation, atomic recombination, etc.). Some of these reasons are given in our recent work[1,2] and also many more reasons in other contributions to the volumes in which they appear. Purely magnetic traps are quite attractive and are being pursued at NBS (Gaithersburg) and MIT (at least), but will not be discussed here. Two-laser traps[3] are also quite promising, but we feel it is better to start with the simpler one-laser trap.

Our initial studies of neutral traps involved the laser-magnet hybrid trap[1,2]. 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[4-7] and then reconsider the laser-magnet trap at a later date. The primary differences in our laser trap concept (Figure 1) are that our "corner cube trap" (a) is <u>within</u> a TEM_{01}^{*} laser cavity; and (b) employs not laser cooling, but rather counterstreaming ^{4}He atoms (which do not interact 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 10 K trap depth.

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[8-10]. 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 down by $\sqrt{2}$).

We have selected K atoms since a suitable high power tunable CW laser, the Allied alexandrite laser, is now available and since the multiphoton ionization rate[2] is particularly low for K.

Corner Cube Trap

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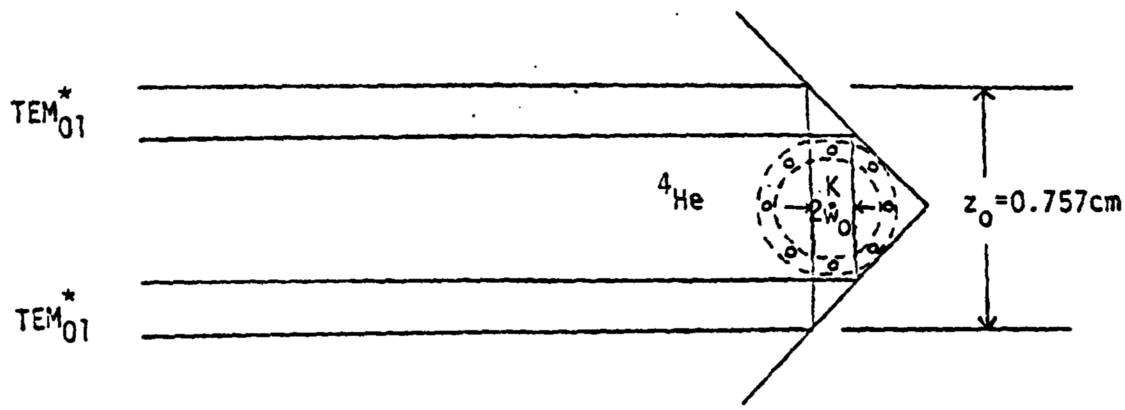


K: K atoms injected into the paper

^{4}He: Ring of ^{4}He beams out of the paper

Figure 1. Proposed Corner Cube Trap for Neutral Potassium Atoms. The laser beam is actually strongly focused at the beam waist w_o, so the trap has something like an hourglass shape.

The Allied alexandrite laser is not yet commercially available, but Allied has kindly consented to work with us by providing us a suitable CW alexandrite laser well in advance of commercialization for $50,000. In initial experiments, this laser has already achieved 60 watts CW output; with a high reflector in place of the output coupler, 3000 watts intracavity should be obtainable now without further improvements. The lengthening of the laser cavity and the introduction of a tuning element and other optical surfaces will reduce this, but with improvements the Allied scientists feel a 3000 watt intracavity power is a realistic near term goal.

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$\downarrow$) (which would add considerable complexity), but we shall not consider them here.

The parameters we have chosen for our initial trap are given in Table I. Note that the AC 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 multiphoton ionization rate is uncertain because of the uncertainty in the cross section and because the rate varies

Table I. Preliminary Parameters for TEM_{01}^{*} Intracavity Laser Corner Cube Trap for ^{4}He-Cooled ^{39}K Atoms.

Intracavity laser power at 765.3 nm	3000 Watts
Average intensity of TEM_{01}^{*} laser	5.175×10^{7} W/cm^{2}
Trap depth (maximum) at beam waist w_0	14 K
Trap depth (minimum) at Rayleigh range z_0	10 K
Laser detuning to the blue of $^{2}S_{1/2} - {}^{2}P_{3/2}$	6.10×10^{5} MHz
AC Stark shift to the red	2.62×10^{4} MHz
AC Stark full width at half maximum	8.73×10^{5} MHz
Beam waist w_0	43 μm
Rayleigh range z_0	0.757 cm
Multiphoton ionization rate	1.7 sec^{-1}
Diffusional heating rate	3.8×10^{3} K/sec
Thermal escape rate	~10 sec^{-1}
Recombination rate (if appropriate)	≤1 sec^{-1}

drastically with kinetic energy of the K atom (hotter atoms sample higher laser intensities[2]). 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 vast excess of cold ^4He (e.g. $n_K = 10^6$ atoms/cm^3; $n_{^4He} = 10^{18}$ 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 3800 K/sec which must be removed. Note that the "high" density of ^4He 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 ^4He 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 ^4He to the laser trap "walls" will be much slower than that given by collisionless motion.

A final loss mechanism is the formation of KHe. The 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[11]. Unfortunately, the potential curve is plotted on a very compressed scale, but not tabulated; recently, J. Pascale was in the U. S. and he has promised to send us his potential curve calculation when he returns to France. In the meantime, we have adopted a Lennard-Jones potential with the well depth of 1.9 cm^{-1} (~2.7 K) and an equilibrium distance of 13.2 a_o. These numbers are the arithmetic means of Pascale's values for LiHe and CsHe [reference 11]. With this potential, 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

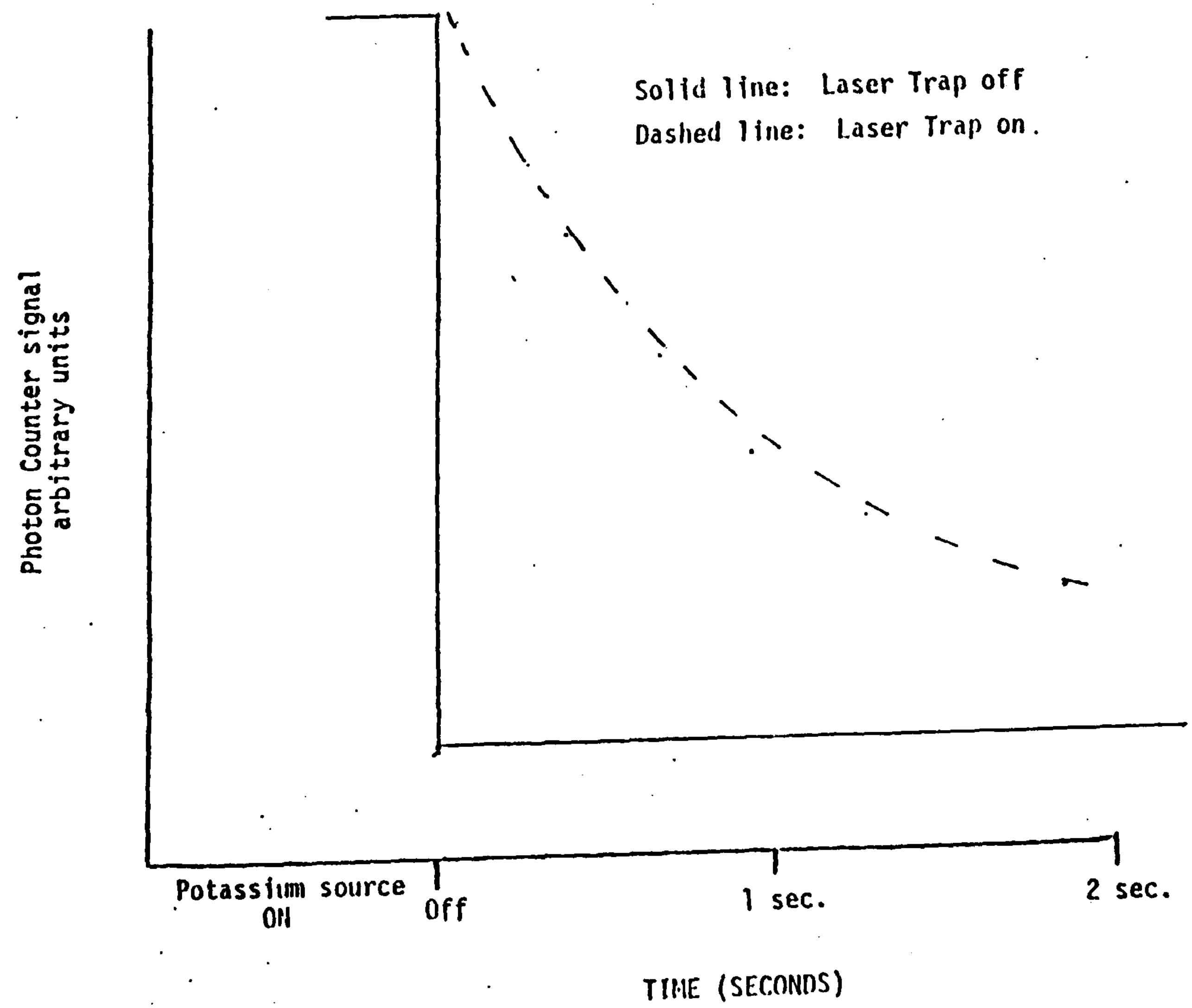
$$K = \frac{n_{KHe}}{n_K n_{He}} = 6 \times 10^{-21}.$$

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 ^3He 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 $\rightarrow$ KHe + He; a reasonable value of 10^{36} cm^6/$atoms^2$ (as for H + H + He $\rightarrow$

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 (see Figure 2). The detection would be straightforward using either 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.

Figure 2. Decay Profile of 4045Å Fluorescence in a 1 Second Trap



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