Examination of effects of TEM_{01}^{*}-mode laser radiation in the trapping of neutral potassium atoms

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We present our study on the feasibility and limitations of a purely one-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 will be provided in the cavity of a high-power alexandrite laser operating in 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 ^{4}He atoms which are cooled to $\lesssim 1.5$ K, to drastically cool the K atoms to thermal energies well below the trap depth (expected to be ~ 10 K). We have also examined various loss mechanisms for the trapped atoms. 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 much higher energy than the vast majority of other atoms at 1.5 K, or if they form KHe (or KHe_2, etc.). Results from these investigations suggest crude lifetimes for trapped atoms of the order of 1 sec.

I. INTRODUCTION

Recently, much effort has been devoted to laser cooling[1–3] and laser trapping[2–10] of neutral atoms, inspired by the early work of Ashkin on the microscopic particles[11] and the successful radio-frequency (rf) quadrupole and Penning traps and laser cooling of atomic ions.[12–17] Related theoretical and experimental studies have also been carried out on atomic beams: deflection,[18–22] focusing,[23,24] and deceleration.[25–30] It is now possible to produce neutral sodium atoms virtually at rest (in the laboratory frame) corresponding to temperatures of less than 100 mK.[29–32] This progress in the production of "stationary" atomic gas paves the way for the realization[31] of neutral-atom traps. Other three-dimensional neutral-atom traps which have been proposed include a toroidal hexapole magnet[33] for atoms with spin, an electrostatic trap[34] for highly polarizable Rydberg atoms, a hybrid laser-magnetic trap[35] for spin-polarized atoms, and other purely magnetic traps.[31,36]

One of the main motivations for atom and ion traps is to be able to study these species as the temperature approaches zero and as the transition frequency becomes increasingly well defined. Other reasons for the traps include frequency standards,[37] ultimate limits on temperature,[38–42] Bose condensation,[43,44] atomic recombination,[45] etc.

In this paper, we study the feasibility and limitations of a purely one-laser trap concept, similar to those proposed by Ashkin,[2–4,6] a "corner cube trap" for trapping cold K atoms. In this trap concept (Fig. 1), the confinement of the atoms in the two dimensions perpendicular to the laser will be provided *within* the cavity of a high-power alexandrite laser operating in the cw TEM_{01}^{*} mode ("doughnut mode") tuned slightly to the blue side of the resonance line of the K atom, which generates a strong "transverse dipole" force pushing the K atoms into the central region of weaker light intensity. By reflecting the TEM_{01}^{*} laser back on itself, one "caps" the ends of the cylindrical trap, resulting in a slightly weaker end plug (the laser intensity at the Rayleigh range decreases by a factor of 2). This trap concept employs not laser cooling, but rather counterstreaming ^{4}He atoms, which are cooled to $\lesssim 1.5$ K, to drastically cool the K atoms to thermal energies well below the trap depth (approximately 10 K).

In the remaining sections of this paper, we will investigate various topics relevant to the above trap concepts: generation of the TEM_{01}^{*} mode (Sec. II), trap depth, laser

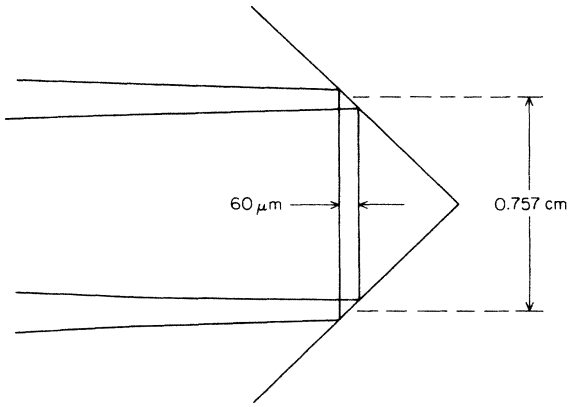

FIG. 1. Schematic diagram of the corner cube trap. The lines representing the points of maximum potential energy for trapped K atoms converge to a minimum diameter of 60 μm at the TEM_{01}^{*} laser beam waist (the waist itself is 43 μm). The two high-reflectance mirrors are also shown. See text for further description.

intensity, detuning, and other parameters (Sec. III), various loss mechanisms such as multiphoton ionization (Sec. IV), cooling and diffusional heating (Sec. V), thermal escape and recombination (Sec. VI), ac Stark shift and line broadening (Sec. VII), and detection (Sec. VIII). Our results here indicate that the lifetime for the trapped K atoms should be roughly of the order of 1 sec.

II. GENERATION OF TEM$_{01}^{*}$-MODE LASER FIELD

Because of the importance of the TEM$_{01}^{*}$-mode (doughnut mode) laser field in the proposed corner cube trap concept, we briefly summarize here works relevant to this particular mode of the laser field. The fundamentals of the theory of this laser mode can be found in Refs. 46–50. Rigrod[51] first reported the isolation of the fundamental modes in the cylindrical coordinates, including the doughnut mode. Recently, detailed study has been carried out on this mode and its properties in photon statistics.[52–54]

The doughnut mode laser field with a linear polarization can be generated in at least two ways. The first is to combine two degenerate (in frequency) TEM$_{01}$ and TEM$_{10}$ modes, where the labels 01 and 10 are in *Cartesian* coordinates, "in space and phase quadrature with each other."[51] This method results in the expression for the field of a *traveling* doughnut mode,

$$\mathbf{E}(r,\phi,z,t)=\hat{\epsilon}E_0(\cos\phi\cos\theta\pm\sin\phi\sin\theta)\times[w_0/w(z)][\sqrt{2}r/w(z)]\exp[-r^2/w^2(z)]\ , \tag{2.1}$$

where

$$\theta(r,z,t)=\omega t-kz-kr^2/2R(z)+2\tan^{-1}(z/z_0)\ . \tag{2.2}$$

Here $\hat{\epsilon}$ is the polarization vector, the cylindrical coordinates are defined by $\mathbf{r}=(r,\phi,z)$, the z axis is the laser beam axis, $w(z)$ is the beam spot size at z, $w_0=w(z=0)$ is the minimum spot size (beam waist), $R(z)$ is the radius of curvature at z, and z_0 is the Rayleigh range (for notation, see Ref. 55). The angular frequency of the field is ω, and $k=\omega/c$, where we have set the index of refraction to be one (which is true for our situation).

The second method is to generate the doughnut mode using fields of two different frequencies (different longitudinal modes), discussed in detail in Ref. 52–54. Assuming only two frequencies ω_1 and ω_2, the traveling field has the expression

$$\mathbf{E}(r,\phi,z,t)=\hat{\epsilon}E_0(\cos\phi\cos\theta_1\pm\sin\phi\cos\theta_2)\times[w_0/w(z)][\sqrt{2}r/w(z)]\times\exp[-r^2/w^2(z)]\ , \tag{2.3}$$

where θ_1 and θ_2 are defined similarly to θ in (2.2) with ω_1 and ω_2 and the corresponding wave vectors k_1 and k_2 replacing ω and k. The difference between ω_1 and ω_2 is related to the length of the resonance cavity L by $|\omega_1-\omega_2|=m2\pi c/2L$, where m is a positive integer.

There is at least one characteristic difference between the doughnut modes generated by Eqs. (2.1) and (2.3). In order to obtain a circularly symmetric intensity from Eq. (2.1), the time needed for the average is of the order of $2\pi/\omega$. This is, however, not true for the field in Eq. (2.3), which requires the time for the average to be of the order $2\pi/|\omega_1-\omega_2|$ as determined by the *beat* frequency. Thus, if the motion of the trapped atom is fast enough with a frequency comparable to the beat frequency, the optical trap due to this generation of the doughnut mode will be "leaky." Fortunately, our calculations of the motion of the trapped atom in the well show that the atom moves slowly compared with the beat frequency of the field with a laser cavity 150 cm long.

We have done some preliminary study on the laboratory generation of the TEM$_{01}^{*}$ mode using an argon-ion and a krypton-ion laser. We have found that, with circular reflectors, the doughnut modes produced include many longitudinal modes. This indicates that they are mixtures of both types described above. If an etalon is inserted, the doughnut mode generally has only two adjacent longitudinal modes, suggesting it has the field described in Eq. (2.3), in agreement with Refs. 52–54. In all these cases, the aperture in between the two reflectors must be enlarged appropriately so that no Gaussian or higher modes are present.[51] It is also observed that the doughnut modes can be generated only from high-gain lines.

Throughout this paper, we shall use the following single-frequency, *standing* wave with the expression for the field,

$$\mathbf{E}(r,\phi,z,t)=2\hat{\epsilon}E_0[w_0/w(z)][\sqrt{2}r/w(z)]\exp[-r^2/w^2(z)]\cos[kz+kr^2/2R(z)-2\tan^{-1}(z/z_0)]\times[\cos\phi\cos(\omega t)\pm\sin\phi\sin(\omega t)]\ , \tag{2.4}$$

for our calculations for the trap. This expression, representing a beam focused at $z=0$, can be obtained by adding two counterpropagating fields of the form in Eq. (2.1). The intensity at $z=0$ is therefore

$$I(r)=4I_0(r/r_0)^2\exp(-r^2/r_0^2)\ , \tag{2.5}$$

where $I_0=E_0^2/2\mu_0 c$, μ_0 is the vacuum permeability, and $r_0=w_0/\sqrt{2}$. It is obvious that the maximum intensity occurs at r_0.

III. TRAP WELL

The detuning of a TEM$_{01}^{*}$ laser to the blue side of resonance (e.g., the $4s\ ^2S_{1/2}$–$4p\ ^2P_{3/2}$ resonance line of the K atom) gives rise to a cylindrical trapping potential[6]

$$U(\Delta)=\tfrac{1}{2}h\Delta\ln\{1+(I/I_s)(\gamma/2)^2/[\Delta^2+(\gamma/2)^2]\}\simeq\tfrac{1}{2}h\Delta\ln[1+(I/I_s)(\gamma/2\Delta)^2]\ , \tag{3.1}$$

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 W (each direction)
Maximum intensity of TEM_{01}^{*} laser (at $w_0/\sqrt{2}$)	1.52×10^8 W/cm^2 (standing wave)
Trap depth (maximum) at $w_0/\sqrt{2}$	8.57 K
Trap depth (minimum) at $z_0/2$	7.26 K
Laser detuning to the blue of $^2S_{1/2}$-$^2P_{3/2}$	5.23×10^5 MHz
ac Stark shift to the red (at $w_0/\sqrt{2}$)	3.08×10^4 MHz
ac Stark full width at half maximum	9.13×10^4 MHz
Beam waist w_0	43 μm
Rayleigh range z_0	0.757 cm
Multiphoton ionization rate	1.2 sec^{-1}
Diffusional heating rate	4.3×10^3 K/sec
Thermal escape rate	$\sim$10 sec^{-1}
Recombination rate (if appropriate)	$\lesssim$1 sec^{-1}

where h is Planck's constant, Δ is the frequency detuning from resonance, I is the laser intensity, I_s is the saturation intensity, and γ is the natural linewidth. The approximation sign in Eq. (3.1) is valid for large detunings and laser intensities, which is the situation considered here. For large values of the laser intensities, Eq. (3.1) has a maximum value U_0 and an "optimal" detuning Δ_0,

$$\Delta_0=(I/4S_0I_s)^{1/2}, \tag{3.2}$$

$$U_0=h\Delta_0S_0/(1+S_0), \tag{3.3}$$

where $S_0\simeq3.92$. For the K atom, $I_s=5.3$ mW/cm^2 and $\gamma=6.11$ MHz, then

$$\Delta_0(\text{MHz})=(21.2)[I(\text{W/cm}^2)]^{1/2}, \tag{3.4}$$

$$U_0(\text{K})=(8.11\times10^{-4})[I(\text{W/cm}^2)]^{1/2}. \tag{3.5}$$

In the corner cube trap concept, we do not operate at the optimal detuning. The choice of the detuning for this concept is determined by the following considerations: (a) the maximum trap depth (at $z=0$ and $r=r_0$) and the minimum depth [at $z=z_0/2$ and $r=w(z)/\sqrt{2}$] must be large compared to the expected 1–1.5 K kinetic energy of the trapped atoms, (b) the multiphoton ionization rate of

TABLE II. Characteristics of the trap in Table I and of otherwise identical traps with 50% lesser or 50% greater detuning.

Detuning (MHz)	Well depth (K)	Energy of atom (K)	Average ionization rate (sec^{-1})	Average diffusional heating (K/sec)
		2.5	1.40	1.21×10^5
		2.0	0.625	6.86×10^4
		1.5	0.230	3.20×10^4
2.61×10^5	10.0			
		1.0	5.94×10^{-2}	1.05×10^4
		0.5	6.50×10^{-3}	1.45×10^3
		0.1	4.68×10^{-5}	12.6
		2.5	6.45	1.69×10^4
		2.0	3.06	9.39×10^3
		1.5	1.20	4.30×10^3
5.23×10^5	8.57			
		1.0	0.329	1.38×10^3
		0.5	3.82×10^{-2}	1.86×10^2
		0.1	2.88×10^{-4}	1.61
		2.5	15.9	4.83×10^3
		2.0	7.66	2.72×10^3
		1.5	3.04	1.26×10^3
7.84×10^5	6.81			
		1.0	0.850	4.05×10^2
		0.5	0.100	54.9
		0.1	7.68×10^{-4}	0.488

Note: All other parameters used in calculations are those listed in Table I.

the trapped atoms must be of the order of 1 sec^{-1}, and (c) the collisional cooling power from the cold ^{4}He must vastly exceed the diffusional heating of the trapped atoms. As our later calculations (Table II) will show, increasing the detuning will decrease the diffusional heating, but will also increase the multiphoton ionization rate. The detuning shown in Table I is chosen to satisfy the above three conditions.

Because the trap depth considered so far is calculated with the intensity of the laser at $z=0$ for a standing wave, there are other spots where the potential well vanishes because the intensity vanishes. This situation can be overcome by operating the laser in a multimode situation.

IV. MULTIPHOTON IONIZATION

Multiphoton ionization is a potential serious-loss process for trapped atoms. The multiphoton ionization rate is uncertain because of the uncertainty in the cross section and because the rate varies drastically with the kinetic energy of the trapped atom (hotter atoms sample higher laser intensities). In the calculation of the multiphoton ionization rates, we assume that the rates are dominated by those of the three-photon process. Bebb[56] calculated three-photon ionization rates for Na, K, Rb, and Cs over a wide range of energies (see Ref. 57 for near-resonance results). The average rates are calculated by

$$\langle W(\nu)\rangle = \oint W(r;\nu)dt \Big/ \oint dt \ , \tag{4.1}$$

where ν is the laser frequency, r is the distance of the trapped atom from the z axis, the local ionization rate is

$$W(r;\nu)=S(\nu)[I(r)/h\nu]^3 \ , \tag{4.2}$$

$S(\nu)$ is the "strength" of three-photon ionization calculated by Bebb,[56] and $I(r)$ is the laser intensity in Eq. (2.5). The integration can be done by using the relation $1/2Mv^2+U(r)=E_{\rm atom}$, where M is the mass and $E_{\rm atom}$ is the energy of the trapped atom, and $U(r)$ is the potential well obtained by using $I(r)$ in Eq. (2.1). The exact calculation is done numerically, and the results are shown in Table II.

For atomic energies small compared to the well depth, the well can be approximated by a simple-harmonic potential,

$$U(r)=\tfrac{1}{2}k_{0s}^2 r^2 \ , \tag{4.3}$$

where

$$k_{0s}\simeq h\Delta(4I_0/I_s)(\gamma/2\Delta)^2 r_0^{-2} \ . \tag{4.4}$$

With this approximation, the average ionization rates can be obtained in closed form. The period of motion of the trapped atom in this potential well is $\tau_{\rm cl}=2\pi/\omega_{0s}$, where $\omega_{0s}=(k_{0s}/M)^{1/2}$. The numerator in Eq. (4.1) can be shown to have the form

$$\oint W(r;\nu)dt\simeq(5!!/6!!)[2\pi S(\nu)/\omega_{0s}](4I_0/h\nu)^3(s_\pm)^6 \ , \tag{4.5}$$

where $s_\pm$ are the reduced classical turning radii satisfying the relation $s_\pm^2=2E_{\rm atom}/k_{0s}r_0^2$. Thus, the average rates are

$$\langle W(\nu)\rangle\simeq 8^3(5!!/6!!)S(\nu)(I_s/h\nu)^3(E_{\rm atom}/h\gamma)^3(\Delta/\gamma)^3 \ . \tag{4.6}$$

This expression reproduces the low-energy results of the more accurate numerical results.

As indicated by Eq. (4.6), higher atomic energy will result in higher multiphoton ionization rates, which is what is expected intuitively. However, it also indicates that, for low atomic energies, increasing the detuning also gives higher ionization rates. We also notice that the laser intensity does not play a role in (4.6). This is because, when the atom has a low enough energy, it is energetically impossible for the atom to go to high potential regions with stronger fields.

V. DIFFUSIONAL HEATING AND COOLING

The average diffusional heating rate can be calculated in a manner similar to Eq. (4.1), by using Eq. (30) of Ref. 6 for the local diffusional heating. Our numerical calculations of the heating rates show that the heating decreases with increasing detuning (Table II). Diffusional heating is the most serious objection to Ashkin's original traps. However, by introducing a vast excess of cold ^{4}He [e.g., $n_{\rm K}\simeq 10^6$ atoms/cm^3; $n_{^4{\rm He}}\simeq 10^{18}$ 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^{-1}, assuming a cross section of $\sim 10^{-14}$ cm^2). 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).

VI. THERMAL ESCAPE AND RECOMBINATION

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 distributions 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.[58] We have adopted a Lennard-Jones model potential for KHe with a well depth of 1.9 cm^{-1} ($\sim$2.7 K) and an equilibrium distance of $13.2a_0$. These numbers are the arithmetic means of Pascale's values for LiHe and CsHe.[58] 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

$$K = n_{KHe}/n_K n_{He} \simeq 6\times 10^{-21} . \quad (6.1)$$

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 the ^{3}He would reduce the KHe problem; lowering T (perhaps 1 K can be achieved by carefully considering the cooling by pumping of the 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} $cm^6/atom^2$ (as for $H + H + He \rightarrow H_2 + He$ at 4 K) gives ~ 1 sec^{-1} for recombination.

However, since the K atom spends a significant fraction of the time in an electronically excited state (causing stronger attraction) and since photodissociation or photoassociation processes will also be taking place, this equilibrium calculation can only be taken to suggest that KHe species must be considered in the trap as well as isolated K atoms.

VII. ac STARK SHIFT AND LINE BROADENING

When the trapping TEM_{01}^* laser is on, the potassium atoms interact with the intense laser radiation field. This interaction results in the shift of the resonance frequency and the power broadening of the linewidths.[59] Since the TEM_{01}^* mode has an intensity distribution that varies from zero at the laser axis to a maximum value at a distance $r = w(z)/\sqrt{2}$, atoms at different positions will therefore exhibit different shifts and line broadenings. In this section, we briefly discuss the shift and broadening at positions with the most intense fields, i.e., at $z=0$ and $r = r_0 = w_0/\sqrt{2}$. For the purpose of estimation, we ignore the effects of the motion of the atom and of the multiphoton ionization.

We will use the simple method of a three-state approximation, using state 0 for the $4s\ ^2S_{1/2}$, state 1 for $4p\ ^2P_{1/2}$, and state 2 for $4p\ ^2P_{3/2}$ states of the K atom. The line broadening and the Stark shift can be obtained numerically by solving the following equations of motion of the density matrix elements:[59]

$$\frac{1}{2\pi} i d\rho_{00}/dt = i(\gamma_1\rho_{11} + \gamma_2\rho_{22}) + V_1(\rho_{10} - \rho_{01}) + V_2(\rho_{20} - \rho_{02}) ,$$

$$\frac{1}{2\pi} i d\rho_{10}/dt = -(i\gamma_{10} + \Delta_{10})\rho_{10} + V_1(\rho_{00} - \rho_{11}) - V_2\rho_{12} ,$$

$$\frac{1}{2\pi} i d\rho_{20}/dt = -(i\gamma_{20} + \Delta_{20})\rho_{20} + V_2(\rho_{00} - \rho_{22}) - V_1\rho_{21} ,$$

$$\frac{1}{2\pi} i d\rho_{11}/dt = -i\gamma_1\rho_{11} + V_1(\rho_{01} - \rho_{10}) ,$$

$$\frac{1}{2\pi} i d\rho_{21}/dt = -(i\gamma_{21} + \Delta_{21})\rho_{21} - V_1\rho_{20} + V_2\rho_{01} ,$$

$$\frac{1}{2\pi} i d\rho_{22}/dt = -i\gamma_2\rho_{22} + V_2(\rho_{02} - \rho_{20}) ,$$

and their complex conjugates if necessary. Here, $V_1 = \langle 1 | -\boldsymbol{\mu}\cdot\mathbf{E}_0/2h | 0 \rangle$ and similarly for V_2, where $\mathbf{E}_0$ is the amplitude of the trapping field and $\boldsymbol{\mu}$ is the electric dipole operator. These forms of V_1 and V_2 imply that we have used the rotating-wave approximation. The detuning $\Delta_{10} = \Omega - \nu_{10}$, where Ω is the frequency of the field, and $h\nu_{10}$ is the energy difference between states 1 and 0. The detuning Δ_{20} is similarly defined, and $\Delta_{21} = \Delta_{20} - \Delta_{10}$. The constants γ_1 and $\gamma_2 = \gamma_1$ are the natural decay widths of the P states, and $\gamma_{ij} = \frac{1}{2}(\gamma_i + \gamma_j)$, with $\gamma_0 = 0$. Finally, we note that the above equations ensure that the probability in these three states are conserved, i.e., $(d/dt)(\rho_{00} + \rho_{11} + \rho_{22}) = 0$.

We then solve for the steady-state solution from the above equations using the laser field of the trap. The ac Stark shift is defined to be the difference between the value of the frequency which maximizes ρ_{22} for the given laser field and the field-free frequency ν_{20}. The broadening is determined from the numerical solution of ρ_{22}. The results are listed in Table I.

If a weak laser field is used to probe the effects of the trapping laser field on the atoms, the probe will detect atomic frequencies shifted by the trapping field. With a laser intensity of 1.52×10^8 W/cm^2 and a detuning $\Delta_{20} = 5.23\times 10^5$ MHz, our calculations show that the probe will detect that the $^2S_{1/2}$ state shifts upward by 1.51×10^5 MHz, the $^2P_{1/2}$ state shifts downward by 2.01×10^4 MHz, and the $^2P_{3/2}$ state shifts downward by 1.31×10^5 MHz.

VIII. DETECTION OF THE TRAPPED K ATOMS

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 would be straightforward using either the $5p \rightarrow 4s$ fluorescence (at ~ 404.5 nm) (or possibly the $4p_{1/2} \rightarrow 4s$ fluorescence at 769.9 nm). Use of the $4p_{3/2} \rightarrow 4s$ transition would involve extensive efforts to eliminate scattered light from the trapping laser. 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.

Note added. After this paper was submitted for publication, we learned of the first demonstration of laser trapping of Na atoms by Chu *et al.*[60]

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[1]V. I. Balykin, V. S. Letokhov, and V. I. Mishin, JETP Lett. **29**, 560 (1979).
[2]A. Ashkin and J. P. Gordon, Opt. Lett. **4**, 161 (1979).
[3]A. Ashkin, Science **210**, 1081 (1980).
[4]A. Ashkin, Phys. Rev. Lett. **40**, 721 (1978).
[5]V. S. Letokhov and V. G. Minogin, J. Opt. Soc. Am. **69**, 413 (1979).
[6]J. P. Gordon and A. Ashkin, Phys. Rev. A **21**, 1606 (1980).
[7]V. G. Minogin, Sov. J. Quantum Electron. **12**, 299 (1982).
[8]J. Dalibard, S. Reynaud, and C. Cohen-Tannoudji, Opt. Commun. **47**, 395 (1983).
[9]A. Ashkin, Opt. Lett. **9**, 454 (1984).
[10]J. Dalibard, S. Reynaud, and C. Cohen-Tannoudji, J. Phys. B **17**, 4577 (1984).
[11]A. Ashkin, Phys. Rev. Lett. **24**, 156 (1970).
[12]H. G. Dehmelt, Adv. At. Mol. Phys. **3**, 53 (1967).
[13]H. G. Dehmelt, Adv. At. Mol. Phys. **5**, 109 (1969).
[14]D. J. Wineland, R. E. Drullinger, and F. L. Walls, Phys. Rev. Lett. **40**, 1639 (1978).
[15]W. Neuhauser, M. Hohenstatt, P. Toschek, and H. Dehmelt, Phys. Rev. Lett. **42**, 233 (1978).
[16]W. Neuhauser, M. Hohenstatt, P. Toschek, and H. Dehmelt, Phys. Rev. A **22**, 1137 (1980).
[17]W. M. Itano and D. J. Wineland, Phys. Rev. A **25**, 35 (1982).
[18]A. Ashkin, Phys. Rev. Lett. **25**, 1321 (1970).
[19]E. Arimondo, H. Lew, and T. Oka, Phys. Rev. Lett. **43**, 753 (1979).
[20]A. F. Bernhardt and B. W. Shore, Phys. Rev. A **23**, 1290 (1981).
[21]J. E. Bjorkholm, R. R. Freeman, and D. B. Pearson, Phys. Rev. A **23**, 491 (1981).
[22]C. Tangny, S. Raynaud, and C. Cohen-Tannoudji, J. Phys. B **17**, 4623 (1984).
[23]J. E. Bjorkholm, R. R. Freeman, A. Ashkin, and D. B. Pearson, Phys. Rev. Lett. **41**, 1361 (1978).
[24]D. B. Pearson, R. R. Freeman, J. E. Bjorkholm, and A. Ashkin, Appl. Phys. Lett. **36**, 99 (1980).
[25]J. V. Prodan, W. D. Phillips, and H. Metcalf, Phys. Rev. Lett. **49**, 1149 (1982).
[26]R. Blatt, W. Ertmer, and J. L. Hall, Prog. Quantum Electron. **8**, 203 (1984).
[27]W. D. Phillips, J. V. Prodan, and H. Metcalf, Prog. Quantum Electron **8**, 119 (1984).
[28]W. D. Phillips and J. Prodan, in *Coherence and Quantum Optics,* edited by L. Mandel and E. Wolf (Plenum, New York, 1984), p. 15.
[29]J. Prodan, A. Migdall, W. D. Phillips, I. So, H. Metcalf, and J. Dalibard, Phys. Rev. Lett. **54**, 992 (1985).
[30]W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, Phys. Rev. Lett. **54**, 996 (1985).
[31]A. L. Migdall, J. V. Prodan, W. D. Phillips, T. H. Bergeman, and H. Metcalf, Phys. Rev. Lett. **54**, 2596 (1985).
[32]S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).
[33]V. S. Letokhov and V. G. Minogin, Opt. Commun. **35**, 199 (1980).
[34]W. H. Wing, Phys. Rev. Lett. **45**, 631 (1980).
[35]W. C. Stwalley, Prog. Quantum Electron. **8**, 203 (1984).
[36]D. Pritchard, Prog. Quantum Electron. **8**, 209 (1984).
[37]J. J. Bollinger, J. D. Prestage, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. **54**, 1000 (1984).
[38]F. Pobell, Physica (Utrecht) **109/110B**, 1485 (1982).
[39]O. V. Lounasmaa, Physica (Utrecht) **109/110B**, 1880 (1982).
[40]W. M. Fairbank, Physica (Utrecht) **109/110B**, 1404 (1982).
[41]W. Neuhauser, M. Hohenstatt, P. E. Toschek, and H. Dehmelt, Phys. Rev. A **22**, 1137 (1980).
[42]W. M. Itano and D. J. Wineland, Phys. Rev. A **25**, 35 (1982).
[43]W. C. Stwalley and L. H. Nosanow, Phys. Rev. Lett. **36**, 910 (1976).
[44]W. C. Stwalley, Y. H. Uang, R. F. Ferrante, and R. W. H. Webeler, J. Phys. (Paris) **41**, C7-27 (1980).
[45]I. F. Silvera, Physica (Utrecht) **109/110B**, 1499 (1982).
[46]A. G. Fox and T. Li, Bell System Tech. J. **40**, 453 (1961).
[47]G. D. Boyd and J. P. Gordon, Bell System Tech. J. **40**, 480 (1961).
[48]G. D. Boyd and J. P. Gordon, Bell System Tech. J. **41**, 1347 (1962).
[49]H. Kogelnik, Appl. Opt. **4**, 1562 (1968).
[50]H. Kogelnik and T. Li, Appl. Opt. **5**, 1550 (1966).
[51]W. W. Rigrod, Appl. Phys. Lett. **2**, 51 (1963).
[52]J. M. Vaughan and D. V. Willets, Opt. Commun. **30**, 263 (1979).
[53]J. M. Vaughan and D. V. Willets, J. Opt. Soc. Am. **73**, 1018 (1983).
[54]P. N. Pusey, J. M. Vaughan, and D. V. Willets, J. Opt. Soc. Am. **73**, 1013 (1983).
[55]A. Yariv, *Quantum Electronics* (Wiley, New York, 1978), Chap. 6.
[56]H. B. Bebb, Phys. Rev. **153**, 23 (1967).
[57]S. Geltman, J. Phys. B **13**, 115 (1980).
[58]J. Pascale, Phys. Rev. A **28**, 632 (1983).
[59]S. Stenholm, *Foundations of Laser Spectroscopy* (Wiley, New York, 1984), Chap. 4.
[60]S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett. **57**, 314 (1986).