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## Trapping of Atoms by Resonance Radiation Pressure

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A method of stably trapping, cooling, and manipulating atoms on a continuous-wave basis is proposed using resonance radiation pressure forces. Use of highly focused laser beams and atomic beam injection should give a very deep trap for confining single atoms or gases at temperatures  $\sim 10^{-6}$  °K. An analysis of the saturation properties of radiation pressure forces is given.

A method of optically trapping and cooling atoms on a continuous-wave (cw) basis is proposed based on radiation pressure forces. The new trap geometry provides stable confinement, optical damping, and means for optical manipulation of trapped atoms. Injection into the trap is from an atomic beam. The radiation pressure trapping forces used are the scattering force due to spontaneous emission<sup>1-4</sup> and the ponderomotive force<sup>5-9</sup> which exists on the induced atomic dipole in an optical field gradient. It is known that the scattering force can increase,<sup>1,2,4</sup> decrease,<sup>3</sup> or deflect<sup>2,10</sup> atomic velocities. Dipole gradient forces can be attractive or repulsive giving optical self-defocusing or self-focusing<sup>5</sup> as well as novel beam interaction forces<sup>6</sup> and a possible means of accelerating atoms.<sup>8</sup> Proposals exist for optically trapping atoms dynamically<sup>2</sup> and statically.<sup>9</sup> This proposal, based on a new treatment of the saturation of these forces and a new geometry, results in a trap with remarkable properties. The trapping energy is more than two orders of magnitude greater than previous proposals,<sup>9</sup> it can accept  $\sim 10^7$  atoms, cool them to about a single photon momentum ( $\sim 10^{-6}$  °K), and hold them indefinitely even as single atoms. The technique should have wide application in experiments in atomic physics.

Consider the behavior of the proposed trap

qualitatively. Light from two opposing TEM<sub>00</sub> mode beams is focused at points  $Q_1$  and  $Q_2$  located symmetrically about point  $E$  [see Fig. 1(a)]. The beams grow in radius from  $w_0$  to  $13w_0$  in going

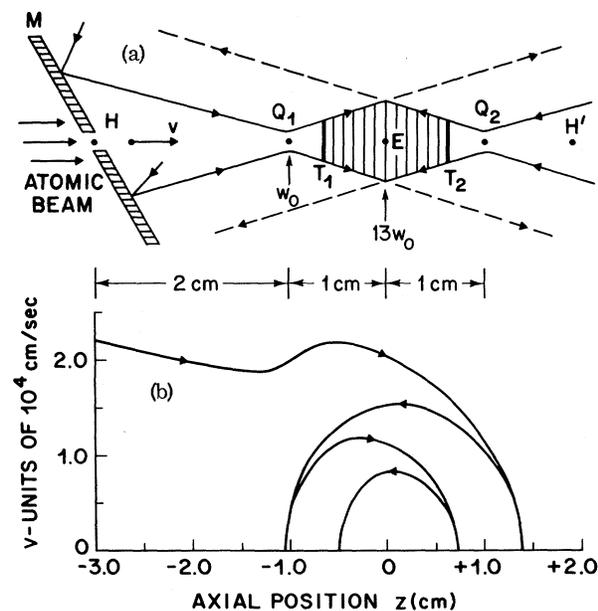


FIG. 1. (a) Sketch of the proposed optical trap for atoms;  $w_0 \cong 12 \mu\text{m}$ . (b) Calculated trajectory of an atom injected through  $H$  with  $v = 2 \times 10^4$  cm/sec.

1 cm from the foci to  $E$  ( $w_0 \approx 12 \mu\text{m}$  for  $\lambda \approx 5900 \text{ \AA}$ ). Each beam is tuned  $50\gamma_N$  (the natural width) below the sodium  $D$  resonance frequency, for example, and has a cw power of 200 mW.  $E$  is a point of stable equilibrium since any displacement of an atom from  $E$  results in a restoring force. There is an axial restoring force from scattering due to intensity imbalance and a radial restoring dipole force due to radial field gradients when tuned below resonance. To trap atoms one needs damping. Damping due to the Doppler shift occurs when tuned below resonance since moving atoms interact more strongly with the opposing beam. An atomic beam with average velocity  $v_{av} = 6 \times 10^4 \text{ cm/sec}$  is injected into the trap through a hole  $H$  in mirror  $M$ . Atoms traversing the trap with transverse velocity  $v_T < 5 \times 10^2 \text{ cm/sec}$  are confined radially by dipole forces. Those with proper axial velocities damp down and stop in the trap along the axis  $HH'$ . For example, an atom entering with  $2 \times 10^4 \text{ cm/sec}$  stops at a point  $\sim 4 \text{ mm}$  beyond  $Q_2$ . It then recoils and executes a damped oscillation about  $E$ . Several cycles of this motion are shown in Fig. 1(b).

Next consider the effect of the standing-wave fringes which exist with varying depths within the trap. Because of the dipole force from the axial field gradient, atoms are attracted to the peaks of the fringes (i.e., the standing wave loops) with decreasing strength away from  $E$ . Beyond planes  $T_1$  and  $T_2$  this attractive force becomes less than the scattering force toward  $E$ . Thus atoms executing a damped oscillation about  $E$  can only be trapped on a loop if they come to rest inside the region from  $T_1$  to  $T_2$ . Once trapped, atoms continue to be damped due to Doppler shift down to about a single photon momentum. Atoms trapped on loops can be manipulated by slowly moving the loops toward one of the  $T$  planes by changing the optical path of one of the beams. This drags the atoms along and deposits them on just a few loops near  $T$ . These can then be retracted to  $E$  where they are axially most stable and held indefinitely.

Consider the trapping forces following Ashkin,<sup>2</sup> who used rate equations to describe the saturation of the scattering force  $F_{\text{scat}}$  of a single beam acting on a two-level atom.  $F_{\text{scat}}$  depends on the fraction of time  $f$  an atom spends in the upper state

$$F_{\text{scat}} = (\hbar/\lambda\tau_N)f, \quad (1)$$

where  $\hbar/\lambda$  is the photon momentum,  $\tau_N$  the natu-

al lifetime, and

$$f = \frac{1}{2}[1 + 1/p(\nu)]^{-1}. \quad (2)$$

$p(\nu)$  is a saturation parameter given by  $BW(\nu)/A$ , the ratio of the (Einstein  $B$  coefficient) stimulated absorption rate to the (Einstein  $A$  coefficient) spontaneous emission rate, multiplied by  $W(\nu)$  the energy density:

$$p(\nu) = \frac{\lambda_0^2 I(\nu) S(\nu)}{2\pi \hbar \nu 4\tau_N} \left( \frac{1}{\tau_N} \right)^{-1} = \frac{I S(\nu)}{I_{\text{sat}} 4\tau_N}, \quad (3)$$

where  $\lambda_0^2/2\pi$  is the absorption cross section at the resonance frequency  $\nu_0$ ,  $I(\nu)$  the intensity at frequency  $\nu$ , and  $S(\nu)/4\tau_N$  is a line-shape factor

$$\frac{S(\nu)}{4\tau_N} = \frac{\gamma_N^2/4}{(\nu - \nu_0)^2 + \gamma_N^2/4}, \quad (4)$$

$\gamma_N = \frac{1}{2}\pi\tau_N$  is the natural width. For high intensities  $p(\nu)$  is large,  $f \approx \frac{1}{2}$ , and  $F_{\text{scat}}^{\text{max}} \approx \hbar/2\lambda\tau_N$ .

Suppose an atom at rest is irradiated by two opposing beams of different intensities and frequencies  $I_R, \nu_R$  and  $I_L, \nu_L$ . For  $|\nu_R - \nu_L| > \tau_N^{-1}$ , the time-averaged force on the atom is determined by the average number of photons absorbed from each beam [ $\sim p(\nu)$ ] and the interference effects of the two opposite beams can essentially be ignored. Thus the  $f$  value for the atom is derived from  $p_{\text{tot}} = p(\nu_R) + p(\nu_L)$ , which determines the total force  $F_{\text{tot}} = |F_R| + |F_L|$ . The ratio of the  $|F_R|/|F_L|$  is the ratio of the number of photons absorbed from each beam  $p(\nu_R)/p(\nu_L)$ , which gives

$$|F_R| = \frac{\hbar}{\lambda} \frac{1}{2\tau_N} \frac{p(\nu_R)}{1 + p_{\text{tot}}}, \quad (5)$$

$$|F_L| = \frac{\hbar}{\lambda} \frac{1}{2\tau_N} \frac{p(\nu_L)}{1 + p_{\text{tot}}}. \quad (6)$$

Atoms moving in the trap see different  $\nu_R$  and  $\nu_L$  because of the Doppler shift, and different  $I_R$  and  $I_L$  because of trap geometry. The trap is detuned below resonance by  $\nu_0 - \nu = q\gamma_N$ . Therefore  $\nu_0 - \nu_R = (q - b)\gamma_N$  and  $\nu_0 - \nu_L = (q + b)\gamma_N$ , where  $b = v/\lambda\gamma_N$  is the Doppler shift in units of  $\gamma_N$ . Equations (5) and (6) accurately describe the scattering forces acting on an atom injected into the trap over most of its velocity range ( $v > 2 \times 10^3 \text{ cm/sec}$ ) and were thus used to compute the damping curves of Fig. 1(b) by calculating the forces and velocity changes on an incremental basis. This damping calculation neglected dipole forces which would only cause a slight modulation of the computed velocities.

Consider next the dipole or ponderomotive force  $F_{\text{dip}}$  acting on an optically produced atomic dipole of moment  $\alpha E$  placed in a region of electric field gradient.  $\alpha$  is the atomic polarizability. As shown by Gordon,<sup>7</sup> for example,  $F_{\text{dip}} = \frac{1}{2}\alpha \nabla E^2$ . The magnitude of  $\alpha$ , however, depends on the field strength  $E$ . If  $\alpha_0$  is the zero-field polarizability, at higher field there is a contribution to the dispersion of  $-\alpha_0 f$  from the population of the upper state and  $\alpha_0(1-f)$  from the ground state giving

$$\alpha = \alpha_0(1-2f) = \alpha_0/[1+p(\nu)], \quad (7)$$

$$\alpha_0 = \frac{-\lambda_0^3 \gamma_N}{16\pi^3} \frac{\nu - \nu_0}{2(\nu - \nu_0)^2 + \gamma_N^2/4}. \quad (8)$$

Thus  $\alpha$  saturates to zero as  $1/E^2$  at high field where we can neglect unity compared to  $p(\nu)$  in (7). For the specific case of a Gaussian beam  $E^2 = E_0^2 \exp(-2r^2/w_0^2)$ , the radial dipole force at saturation is

$$F_{\text{dip}}^{\text{sat}} = -\frac{1}{2}\alpha_0 E_{\text{sat}}^2 \frac{4\tau_N}{S(\nu)} \frac{4r}{w_0^2} = h(\nu - \nu_0) \frac{4r}{w_0^2}, \quad (9)$$

where we have used  $I_{\text{sat}} = cE_{\text{sat}}^2/4\pi$  in (3). In general we have the exact expression

$$F_{\text{dip}} = \frac{\alpha_0/2}{1+p(\nu)} \nabla \left( \frac{E_{\text{sat}}^2}{S(\nu)/4\tau_N} p(\nu) \right) \equiv -\nabla U, \quad (10)$$

where  $U$  is a potential having the value

$$U = h(\nu - \nu_0) \ln[1+p(\nu)]. \quad (11)$$

The factor  $4r/w_0^2$  in (9) is a shape factor arising from the radial variation of  $\alpha$  and the gradient of  $E^2$ . Also the force (9) is independent of  $E_0^2$  as long as  $p(\nu) \gg 1$ . To calculate the effectiveness of this radial confining force, assume saturation out to  $r=R$  [i.e.,  $p(\nu)=1$  at  $r=R$ ] and neglect the force for  $r>R$ . Then the trapping energy

$$\left| \int_0^R F_{\text{dip}}^{\text{sat}} dr \right| = -h(\nu - \nu_0) 2R^2/w_0^2.$$

Thus the trapping energy continues to rise with increasing power. If, for example,  $R=2w_0$  the trapping energy is  $\sim [-8h(\nu - \nu_0)]$ . This implies  $p(\nu) = e^3$  at  $r=0$  and therefore  $|U| \approx -8h(\nu - \nu_0)$  at  $r=0$ . Thus the approximate trapping energy based on (9) and the potential energy (11) agree for large  $p(\nu)$ . Note that the trapping energy increases in proportion to the detuning  $(\nu - \nu_0)$ .

Next consider the axial or  $z$  component of  $F_{\text{dip}}$  for an atom at rest in a simple standing wave  $E = 2E_0 \cos \omega t \cos kz$  due to two equal opposing beams.

The same procedure gives  $F_{\text{dip}}^{\text{sat}}(z) = h(\nu - \nu_0) 2k \times \sin kz / \cos kz$ . This disagrees with Ref. 9, which apparently neglects the variation of  $\alpha$  with  $z$ . More generally for two unequal opposing beams there is a standing wave plus a running wave.  $\alpha$  is determined by  $p_{\text{tot}}$  due to absorption from the standing wave  $S$  and the running wave  $R$ .  $p_{\text{tot}} = p_S(\nu) + p_R(\nu)$  and

$$F_{\text{dip}} = \frac{1}{2}\alpha_{\text{tot}} \nabla E_S^2 = \frac{1}{2}\alpha_0 [1 + p_S(\nu) + p_R(\nu)]^{-1} \nabla E_S^2. \quad (12)$$

If now  $p_R(\nu) \gg 1$  and  $p_R(\nu) \gg p_S(\nu)$ ,

$$F_{\text{dip}}(z) = (4E_0^2/E_R^2) h(\nu - \nu_0) \sin 2kz. \quad (13)$$

Thus the trapping force of the standing wave is reduced by the addition of a strong saturating running wave. At the foci  $Q_1$  and  $Q_2$  of the trap  $F_{\text{scat}} = 1.7 F_{\text{dip}}^{\text{max}}(z)$ ; so no trapping on loops is possible. At the plane  $T_1$  and  $T_2$  the two forces just balance.

Knowing the potential  $U$  at point  $E$  we get the maximum transverse velocity of a trapped atom using  $\frac{1}{2} m (v_T^{\text{max}})^2 = U$ . From  $w_0 = 12 \mu\text{m}$  and the total intensity we find  $p_{\text{tot}}(\nu) \approx 2.5$  at  $E$ . Thus  $U = 62.5 h \gamma_N$  and  $v_T^{\text{max}} = 480 \text{ cm/sec}$ . Using  $v_T^{\text{max}}$  and the range of axial velocities captured by the trap (0 cm/sec to  $\sim 3 \times 10^4$  cm/sec) we estimate a trapping rate of  $\sim 10^6$  atoms/sec and a trap capacity of  $\sim 3 \times 10^7$  atoms. With the trap filled and the source off the  $3 \times 10^7$  atoms cool axially to a velocity of  $\sim 3$  cm/sec corresponding to a single photon momentum. In time, collisions among trapped atoms should thermalize all velocity components to  $\sim 3$  cm/sec or  $T \approx 10^{-6}$  °K. If needed one can damp the transverse components by adding two pairs of opposing beams tuned below resonance but weak enough not to reduce the trapping by additional saturation. This saturation effect, which was neglected in Ref. 9, reduces their trapping energy by a factor of 3. As  $T$  approaches  $10^{-6}$  °K, the gas density approaches that of a solid and atoms may be lost by condensation. However, one should easily trap and observe low densities or even single atoms since a trapped atom scatters  $\sim 10^8$  photons/sec and can be observed free of background gas. Once cooled to a few centimeters per second, the trapping light can be shut off for times  $\sim 4 \times 10^{-4}$  sec without atoms drifting out of the trap. This time is adequate to perform even long lifetime spectroscopic measurements under strictly Doppler-free conditions. One can apply strong external

fields on trapped atoms. Also one can study reactions between different types of cooled atoms by manipulating two traps so that they overlap.

Consider now modified trap geometries. Shifting the foci  $Q_1$  and  $Q_2$  into coincidence at  $E$  gives a confocal-type trap 4.8 times deeper in energy but lacking the features which allow coalescence of atoms trapped on different loops. This trap geometry can also be made using an optical resonator with much reduced power. Finally there is perhaps the conceptually simplest trap: a single highly focused Gaussian beam tuned well below resonance. Such a TEM<sub>00</sub> mode beam has radially inward dipole forces as discussed and also strong axial dipole forces  $F_{\text{dip}}'(z)$  directed toward the focus due to the axial intensity gradient. (This axial contribution was negligible in previous traps where the focusing was weaker.) Further, there is the saturated axial scattering force  $F_{\text{scat}}(z)$  in the direction of the light. If  $F_{\text{dip}}'(z)$  ever exceeds  $F_{\text{scat}}(z)$ , there is a barrier to the escape of atoms from the focal region and a stable trap exists. This condition, i.e.,  $R = F_{\text{dip}}'(z)/F_{\text{scat}}(z) > 1$ , is easily met for a saturated beam with tight focusing. At  $z = \pi w_0^2/\sqrt{3} \lambda$ , the position of maximum axial gradient,  $R = \sqrt{3} q \lambda^2/2\pi^2 w_0^2$ . For a power of 25 mW,  $q = 400$ , and  $w_0 = 2.5 \mu\text{m}$ , then  $p(\nu) = 10$ ,  $R = 2.0$  and strong trapping exists. However, atomic beam injection into such a small trap is difficult. It can only damp and trap velocities  $\sim 10^3$  cm/sec within narrow limits. The flux of such atoms is low,  $\sim 1$ – $10$  atoms/sec, or even less if low velocities are depleted. One can, however, transfer cooled atoms into a single beam trap from a two-beam-type trap.

In the above Na was treated as an ideal two-level atom. In fact, the ground state is split into two hyperfine components. To avoid problems due to transfer of atoms to the other hyperfine component by optical pumping, one can use two laser frequencies, one tuned below each of the two hyperfine components. In geometries where the intensity is high enough a single frequency can saturate both components. One can also couple the two components with rf fields and thus avoid loss of atoms from the trap.<sup>11</sup>

Thus, based on a new analysis of the forces we propose use of high-intensity, strictly cw, highly

focused beams tuned well below resonance to give strong damping and transverse gradient forces for trapping and cooling individual atoms to  $\sim 10^{-6}$  °K. These traps are remarkably similar in both geometry and general behavior to those used to trap and levitate macroscopic dielectric spheres by radiation pressure.<sup>11,12</sup> With atomic beam injection, one gets background-free operation; there is no need to cool large volumes<sup>3,9</sup> or to shift the light frequency adiabatically<sup>9</sup> to resonance with its loss of trap depth. The proposed trap should be useful not only for novel experiments on cooled atoms but also for studies on the resonance radiation pressure forces themselves using, for example, monoenergetic atoms injected into the trap by an atomic beam velocity selector.

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