Light Traps Using Spontaneous Forces

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We show that the optical Earnshaw theorem does not always apply to atoms and that it is possible to confine atoms by spontaneous light forces produced by static laser beams. A necessary condition for such traps is that the atomic transition rate cannot depend only on the light intensity. We give several general approaches by which this condition can be met and present a number of specific trap designs illustrating these approaches. These traps have depths on the order of a kelvin and volumes of several cubic centimeters.

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Since the optical Earnshaw theorem (OET) was proven,[1] it has been widely believed that it is impossible to confine atoms with static configurations of laser beams by use of only light forces associated with spontaneous emission. In this Letter we show that this theorem does not necessarily apply to atom traps and suggest general approaches for making stable "spontaneous-force" light traps for atoms. We also present several examples of possible traps which have cubic-centimeter volumes and depths on the order of a kelvin. These numbers are orders of magnitude larger than those predicted for other static-light-force traps and thereby open up an entirely new range of possible applications.

There are two types of radiation forces that can be used to trap neutral particles.[2] The first is the gradient force arising from the interaction of the induced dipole moment with the field-intensity gradient. The second is the scattering force associated with the transfer of momentum from photons to particles by the scattering of light. This latter force was used to cool beams of thermal atoms[3-5] and to viscously damp a collection of already cold atoms.[6] Minogin[7] and Minogin and Javainen[8] proposed that a trap could be constructed using only the scattering force. However, Ashkin and Gordon showed that, in analogy with the Earnshaw theorem of electrostatics, such traps are fundamentally unstable,[1] thereby discrediting these proposals and discouraging any others. The current avenues of investigation have therefore been restricted to ac spontaneous-force light traps and the relatively shallow gradient-force traps. The former type was first proposed by Ashkin[9] and uses time-varying light intensities and/or frequencies to circumvent the OET in much the same way that rf ion traps overcome the traditional Earnshaw's theorem.

The key idea underlying the OET is that, in the absence of sources or sinks of radiation, the divergence of the Poynting vector of a static laser beam must be zero. Hence, if the force is proportional to the laser intensity, the force must also be divergenceless, thus ruling out the possibility of having an inward force everywhere on a closed surface. An example is shown in Fig. 1 where the Poynting vector is inward in the x-y plane at $z=0$, but outward along the z axis. On axis there is no Poynting vector at $z=0$ if the intensities of the right- and left-moving laser beams (R and L) are equal. However, the outward Poynting vector, and hence the force, increases in proportion to $|z|$ due to the focusing and consequent increase in intensity of the laser beam traveling away from the origin.

Ashkin and Gordon proved the OET for the scattering force on particles with "scalar polarizability" whose "dipole is linearly related to the field."[1] [These conditions assure that the scattering force is proportional to the Poynting vector but the word "dipole" does not imply that the gradient (also known as dipole or induced) force is involved in the present discussion.] They applied the theorem to atoms and atom traps without considering the internal degrees of freedom of the atoms. This was appropriate for traps of

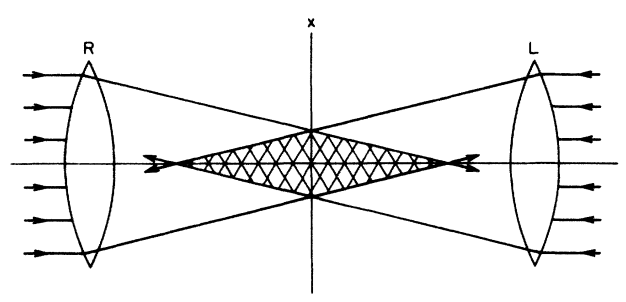

FIG. 1. Basic trap configuration. $f/2$ optics are used.

the Minogin type. However, the OET does not generally apply to the spontaneous force in atoms because this force is not always proportional to the intensity, and therefore the corollary that "the scattering force by itself cannot form a trap"[1] does not rule out atom traps based on spontaneous force. Note our use of the terms "scattering force" to apply to light forces that obey the OET and "spontaneous force" for the analogous forces in atoms (which do not). These two terms have been used interchangeably by previous authors.

The basic point of this paper is that the internal degrees of freedom of the atom can change the proportionality constant between force and Poynting vector in a position-dependent way, and thus allow static spontaneous-force traps. Such a change can result, for example, from external fields which shift the resonant frequency or orientation of an atom, or optical pumping which changes the state of the atom. These and other ideas can be exploited to violate strict proportionality and create stable optical traps using spontaneous forces, especially if one uses multibeam arrangements.

In the remainder of this paper we give three specific examples of how the sources of disproportionality mentioned above can be used to produce stable traps. For this purpose we shall restrict out attention to the simple two-beam configuration shown in Fig. 1. While this is almost certainly not the best practical design for a trap, it will serve to illustrate the general principles. The configuration shown in Fig. 1 is already stable in the x-y plane. For it to be stable along the z axis and hence form a trap, we must make an atom at $z>0$ absorb more strongly from the left-moving laser beam (L) than from the right-moving beam (R) even though the left-moving beam is less intense.

We first show how this can be done by use of a static external field to shift the resonant frequency of the atoms. Consider a two-level atom and imagine that R is tuned below its resonant frequency while L is tuned above it. Assume also that the intensities are adjusted so that there is no force at $z=0$ and that there is a magnetic field gradient in the $\hat{\mathbf{z}}$ direction, $dB_z/dz>0$. As the atom moves toward positive z, its transition frequency will be Zeeman tuned toward the blue, bringing it closer into resonance with L and farther from resonance with R. Obviously if dB_z/dz is sufficiently large, the increased absorption of photons from L will more than offset its decreased intensity, resulting in a net spontaneous force back toward $z=0$ and consequent stability along $\hat{\mathbf{z}}$. Since this configuration is already stable along $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$, it is a spontaneous light-force trap in violation of the OET. To achieve damping of the velocity (a useful trap must have cooling in addition to stability), R should be detuned slightly below resonance ($\sim\Gamma/2$ for maximum damping where Γ is the natural linewidth) and L should be tuned either close to resonance or several Γ above it. The velocity dependence of the force from R, which provides damping, is much greater than that from L and hence dominates and cools. For either tuning, to make the center of the trap an equilibrium point, the powers in the two beams must be different.

Although real atoms have more than two levels, a spin-polarized alkali atom, such as sodium in the $F,M=2,2$ level excited with circularly polarized ($\sigma+$) light, is a sufficiently good approximation to this two-level case. A plot of acceleration versus longitudinal position and velocity for sodium in such a trap is shown in Fig. 2. Stability results from the fact that the spatial derivative of the force is negative near $z=0$ (and for zero velocity the sign of the force changes). Damping occurs because the higher the velocity of the atom, the larger is the force which is opposing it.

In the second example we demonstrate how a static field which changes the orientation of the atoms can be used to produce a stable trap. In this case the laser beams have different linear polarizations, say R polarized along $\hat{\mathbf{x}}$ and L along $\hat{\mathbf{y}}$. Application of a magnetic field of constant amplitude but changing direction can cause atoms to interact differently with the two beams provided that the atoms follow the field adiabatically. In particular, for Na atoms in the $F,M=2,2$ state, transitions to $F,M=3,3$ are not excited by light polarized parallel to the axis of quantization (the local magnetic field). Consequently, if the B field is a helix that twists toward $\hat{\mathbf{x}}$ for $z>0$ and toward $\hat{\mathbf{y}}$ for $z<0$, the configuration can be made stable. If the atom moves

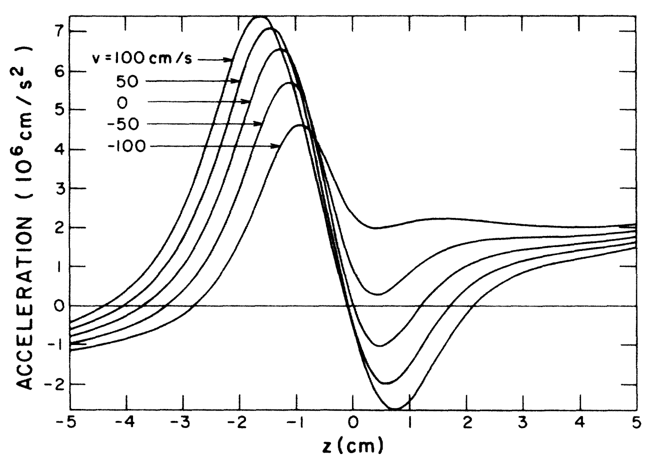

FIG. 2. Accelerations felt by sodium atoms with various velocities in a light trap having frequency-discriminated counter-propagating beams and a magnetic field gradient of 4 G/cm. At $z=0$, beam L, tuned $\Gamma/2$ to the red side of resonance, has an intensity $I_L=0.8I_{\rm sat}$; beam R, tuned $\Gamma/10$ to the blue side of resonance, $I_R=0.15I_{\rm sat}$. Both L and R are right-circularly polarized and use $f/2$ optics.

sufficiently far in the $+\hat{z}$ direction, B will be parallel to $\hat{y}$ and the atom will absorb photons only from the (weaker) L beam. Motion in the $-\hat{z}$ direction will produce a similar restoring force from the R beam. Moreover, both beams can be tuned on the red side of the resonance to provide viscous damping of the velocity. Since the light is not circularly polarized, transitions to $F=3$, $M=2$ or 1, which destroy the polarization, may also occur unless the magnetic field causes sufficient Zeeman splitting. Approximate modeling shows that a high fraction of population can be maintained in the $F,M=2,2$ state for appropriate B fields and laser detunings.

Our final example demonstrates how optical pumping of the atoms can be used to obtain a stable trap. Assume now that the laser beams have opposite angular momentum (e.g., σ^+ for L and σ^- for R). Consider a transition where the F quantum number of the excited state is less than that of the ground state but not equal to zero (e.g., Cs, $F=3 \rightarrow F'=2$, which must decay back to $F=3$). If atoms are exposed to two beams of different intensity, the atoms become optically pumped so that they absorb more photons from the weaker beam than from the stronger. This can be understood from the transition probabilities shown in Fig. 3. An atom in the $M=0$ state, for $z>0$ will be quickly pumped into the $M=2$ or 3 sublevel by the stronger σ^+ beam. At that point, the atom can *only* absorb σ^- photons from the other beam which is directed toward the center of the trap. In addition, since the matrix elements strongly favor $M=+1$ decays, the atom will continue to absorb mostly σ^- photons, thus generating an average longitudinal restoring force. This peculiar intensity dependence makes it necessary to tune the laser *above* resonance to provide longitudinal velocity damping. This weakly heats the atoms in the transverse direction. Thus in a real trap it would be necessary to provide additional transverse damping, for example, by use of an asymmetric trap geometry or adding weak "optical molasses"[6] beams along $\hat{x}$ and $\hat{y}$. Phase-space trajectories for an atom in this trap with such additional cooling beams are shown in Fig. 4. These show that the atoms quickly are compressed into a region which is a fraction of a millimeter in size and have residual random velocities on the order of several centimeters per second corresponding to T. A weaker version of this trap results from use of orthogonal linear polarizations.

We have calculated the performance of the above traps and variations on them. While it is not the purpose of this paper to give detailed results, it seems worthwhile to give the general scale to stimulate consideration of optical traps based on the concepts of this paper. With available dye-laser powers, spontaneous-

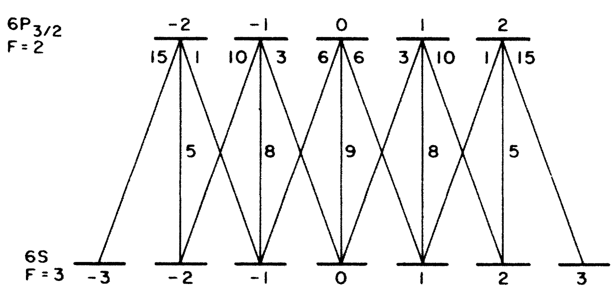

FIG. 3. Relative transition probabilities for the $6S(F=3)$-$6P_{3/2}(F=2)$ transition in cesium.

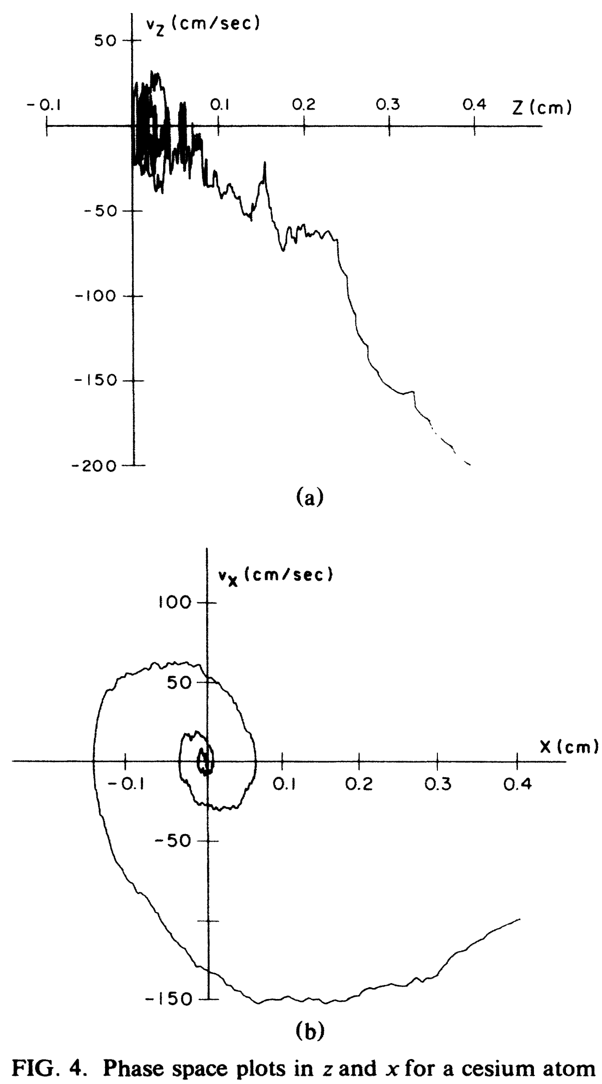

FIG. 4. Phase space plots in z and x for a cesium atom of particular initial position and velocity in a light trap having polarization discriminated (σ^+ and σ^-) counterpropagating beams along the z axis and weak optical "molasses" in the x-y plane. At $z=0$ the trap beam characteristics are area 1 cm^2, intensity 0.5 mW/cm^2, $f/2$, and detuning $\Gamma/2$. The "optical-molasses" beams are plane waves with an intensity of 0.025 mW/cm^2 and detuning of $-\Gamma/2$.

force traps such as those we have described can be constructed with ~ 10-cm dimensions, but 1 cm is more practical with inexpensive optics. The 1-cm size has confinement forces that are a fraction ($<\frac{1}{4}$) of the unidirectional spontaneous force. Integration of this force over the size of the trap gives a depth of several kelvins. However, a particle of this energy will not necessarily be confined in the trap since Doppler shifts can cause the forces to be significantly smaller for atoms with this much energy. For example, a 1-K Cs atom has a Doppler shift of $\sim 6\Gamma$ and will interact much more weakly with the radiation than the above calculation of the depth assumes. This trap depth is nearly 100 times deeper and 10^{15} times larger than that obtained for gradient-force traps of the type recently demonstrated by Chu *et al.*[10]

The spontaneous-force optical traps we have proposed are relatively simple ones designed to illustrate general ways in which the optical Earnshaw theorem can be circumvented. More complicated geometries can probably exploit these approaches more fully, particularly ones which provide more direct cooling and confining in the x-y plane. As a simple example, the addition of weak optical molasses along $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$, mentioned above, will make any of these traps perform better. Also, additional beams may be needed to ensure that trapped atoms do not escape to untrapped hyperfine ground states such as exist in all alkali atoms.

The particular examples we have chosen illustrate three ways the internal degrees of freedom of the atom can be exploited to trap atoms, but there are many additional possibilities. Other types of optical pumping exist, such as pumping between two different hyperfine levels. Also, external static or oscillating fields can be used in a variety of ways to affect how an atom absorbs radiation.[11] Probably all of these can be used to produce light-force traps. Finally, it may be possible to avoid the restrictions of the optical Earnshaw theorem by use of saturation[1] or absorption. The latter is particularly attractive: An optically dense cloud of Na will experience a maximum spontaneous radiative pressure of $\sim 10^{-7}$ N/m^2 (corresponding to 5 mW/cm^2), enough to contain an atom density of 5×10^{13}/cm^3 at $T=0.25$ mK according to the perfect-gas law. Indeed, gas pressure limits the confinement density of a spontaneous-force trap, but this limit may be increased by using a weaker transition with a correspondingly lower ultimate temperature.

We have pointed out ways in which spontaneous light forces may be used to make traps for atoms or ions. The advantages of this spontaneous-force approach as compared to other proposed neutral-particle light traps include large physical extent, reasonably deep wells, and experimental simplicity. Time-varying laser intensity or frequency is not required and the simple designs proposed are quite forgiving to optical misalignment or intensity mismatch. We hope our suggestions will remove the optical Earnshaw theorem as a practical barrier to the design of spontaneous-force light traps and will open the way to the realization of successful traps of different types.

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[11]While these fields do exert forces themselves on the atoms, here we are limiting our discussions to cases, such as the magnetic fields mentioned above, where such forces are many orders of magnitude weaker than the spontaneous force. Hence it is most useful to think of the fields as merely providing a control for the spontaneous force. It is possible to have hybrid traps which are produced by a combination of forces from large static fields and radiation pressure. An interesting possibility for such a trap which employs a large magnetic field for confinement and detuning has been pointed out to us by P. Gould, private communication.