Collective Behavior of Optically Trapped Neutral Atoms

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We describe experiments that show collective behavior in clouds of optically trapped neutral atoms. This collective behavior is demonstrated in a variety of observed spatial distributions with abrupt bistable transitions between them. These distributions include stable rings of atoms around a small core and clumps of atoms rotating about the core. The size of the cloud grows rapidly as more atoms are loaded into it, implying a strong long-range repulsive force between the atoms. We show that a force arising from radiation trapping can explain much of this behavior.

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In the past few years there have been major advances in the trapping and cooling of neutral atoms using laser light. It has recently become possible to hold relatively large samples of atoms for minutes at a time and cool them to a fraction of a mK using a spontaneous-force optical trap.[1,2] One would expect these atoms to behave like any other sample of neutral atoms, namely they would move independently as in an ideal gas, except when they undergo short-range collisions with other atoms.

In this paper we report on experiments which show that contrary to these expectations, optically trapped atoms behave in a highly collective fashion under most conditions. The spatial distribution of the cloud of atoms is profoundly different from that of an ideal gas, and we observe dramatic dynamic behavior in the clouds. We believe that this unusual behavior arises from a long-range repulsive force between the atoms which is the result of multiple scattering of photons by the trapped atoms. This force is sensitive to the modification of the emission and absorption profiles of the atom in the laser field. In the past, this force has been neglected in any system smaller and colder than stars. However, because of the extremely low temperature and relatively high densities of optically trapped atoms, it becomes very important.

The apparatus for this experiment has been described elsewhere.[3,4] The trap was a Zeeman-shift spontaneous-force trap,[2] and was formed by the intersection of three orthogonal retro-reflected laser beams. The beams came from a diode laser tuned 5-10 MHz below the $6S_{1/2}$ $F=4$ to $6P_{3/2}$ $F=5$ transition frequency of cesium. The beams were circularly polarized with the retro-reflected beams possessing the opposite circular polarization. A magnetic field was applied that was zero at the center of trap and had a vertical field gradient (5-20 G/cm) 2 times larger than the horizontal field gradient. Bunches of slowed cesium atoms from an atomic beam were loaded into the trap by chirping a counterpropagating "stopping" laser at 20 times a second.[4] We were able to load about 2×10^6 atoms per cooling chirp. The number of atoms in the trap was determined by the loading rate and the collisional loss[3] rate. Two other lasers were used to deplete the $F=3$ hyperfine ground state in both the trapped atoms and the atomic beam. All the lasers were diode lasers with long-term stabilities and linewidths well under 1 MHz.

The trapped atoms were observed by a photodiode, which monitored the total fluorescence, and a charge-coupled-device (CCD) television camera, which showed the size and shape of the cloud of atoms. The optical thickness of the cloud was determined by measuring the absorption of a weak probe beam 1 ms after the trap light was turned off. To measure the temperature of the atoms, the probe beam was moved a few mm to the side of the trap and the time-of-flight spectrum was observed after the trap light was rapidly turned off, as described in Ref. 5. By pushing the atoms with an additional laser, as was done in Ref. 2, we determined that the trapping potential was harmonic out to a radius of 1 mm with a spring constant of 6 K/cm^2.

In this experiment, care was taken to obtain a symmetric trapping potential. The Earth's magnetic field was zeroed to 0.01 G, and the trapping laser beams were spatially filtered, collimated, and carefully aligned with respect to the magnetic field zero. Before these precautions were taken we observed a variety of random shapes and large density variations within the trap.

Three separate well-defined modes of the trapped atoms were observed, depending on the number of atoms in the trap and on how we aligned the trapping beams. The "ideal-gas" mode occurred when the number of trapped atoms was less than 40000. The atoms formed a small sphere with a constant diameter of approximately 0.2 mm. In this regime, the density of the sphere had a Gaussian distribution, as expected for a damped harmonic potential, and increased linearly in proportion to the number of atoms. The atoms in this case behaved just as one would expect for an ideal gas with the measured temperature and trap potential.

When the number of atoms was increased past 40000, the behavior deviated dramatically from an ideal gas, and strong long-range repulsions between the atoms became apparent. In this "static" mode the diameter of the cloud smoothly increased with increasing numbers of atoms. Instead of a Gaussian distribution, the atoms in the trap were distributed fairly uniformly, as shown in Fig. 1(a). To study the growth of the cloud we measured the number of atoms versus the diameter of the cloud using a calibrated CCD camera. The results are shown in Fig. 2. To fully understand the growth mechanism the temperature as a function of diameter was also measured. For a detuning of 7.5 MHz, the temperature increased from the asymptotic value of 0.3 up to 1.0 mK as the cloud grew to a 3 mm diam. If the cloud were an ideal gas, the temperature increase would need to be orders of magnitude higher to explain this expansion. One distinctive feature of this regime is that the density did not increase as we added more atoms to the trap.

When all the trapping beams were reflected exactly back on themselves we obtained a maximum of 3.0×10^8 atoms in this distribution. In contrast, if the beams were slightly misaligned in the horizontal plane, we observed unexpected and dramatic changes in the distribution of the atoms. The atoms would collectively and abruptly jump to "orbital" modes when the cloud contained approximately 10^8 atoms. The number of atoms needed for a transition depended on the degree of misalignment.

The shapes of these orbital modes are illustrated in Fig. 1 [1(b), 1(c), and 1(d) show the top view, and 1(e) shows the view from the side]. We first observed the ring around a center shown in Fig. 1(b) and then, by strobing the camera, discovered it was actually a clump of atoms orbiting counterclockwise about a central ball

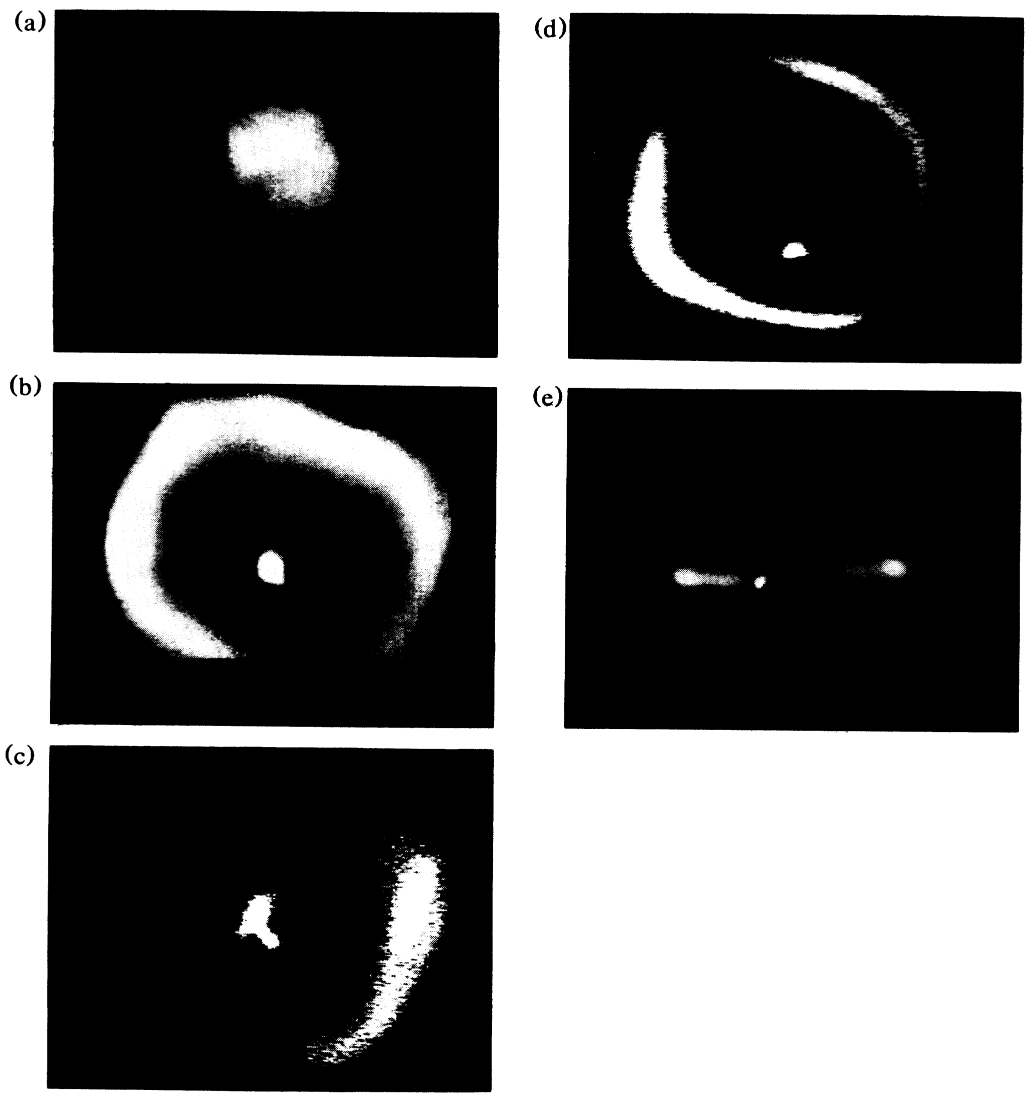

FIG. 1. Spatial distributions of trapped atoms. (a) Below 10^8 atoms the cloud forms a uniform density sphere. (b) Top view of rotating clump of atoms without strobing. (c) Top view of (b) with the camera strobed at 110 Hz. (d) Top view of a continuous ring. (e) Side view of (d). Horizontal full scale for (a), (d), and (e) is 1.0 cm; for (b) and (c) it is 0.8 cm.

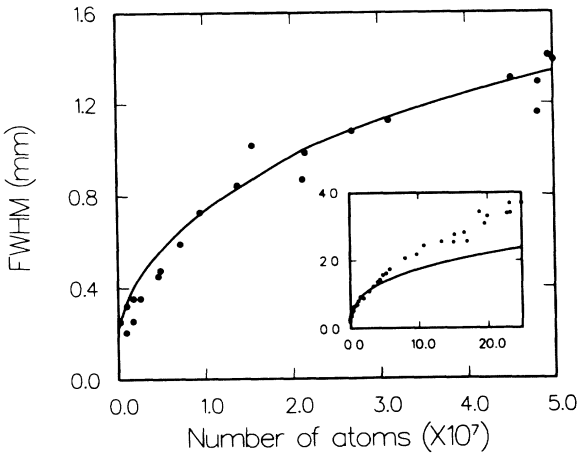

FIG. 2. Plot of the diameter (FWHM) of the cloud of atoms as a function of the number of atoms contained in the cloud. For the full figure the magnetic field gradient is 9 G/cm and 16.5 G/cm for the inset. The laser detuning is -7.5 MHz, and the total laser intensity is 12 mW/cm^2. The solid lines show the predictions of the model described in the text.

as shown in Fig. 1(c). Note that there is a tenuous connection between the clump and the center, and that the core has an asymmetry which rotates around with the clump. As more atoms were slowly added to the trap there were several abrupt increases in the radius of these orbits. The clumps orbited at well-defined frequencies between 80 and 130 Hz. We have also observed a continuous ring encircling a ball of atoms as shown in Fig. 1(d). In this case we assume that the atoms are still orbiting, but no clumping of the atoms was seen and there was no connection between the ring and the central ball. We observed only one stable radius (2.5 mm) for this ring. The ring is shaped by the intersection geometry of the laser beams with the corners of the ring corresponding to the centers of the beams. The atoms lie in a horizontal plane about 0.5 mm thick [Fig. 1(e)].

As mentioned above, the formation of these stable orbital modes depended on the alignment of the trapping beams in the horizontal plane. The beams had a Gaussian width of 6 mm and the return beams were misaligned horizontally by 1–2 mm (4–8 mrad) at the trap region. It was observed that the direction of the rotation corresponded to the torque produced by the misalignment. The degree of the misalignment affected which of the orbital modes would occur. Typically, the atoms would switch into the rotating clump for misalignments of 1–1.5 mm and into the continuous ring for 1.5–2 mm. If the light beams were misaligned even further, the cloud would be in the ring mode for any number of atoms.

The rotational frequencies of the atoms were measured by strobing the image viewed by the camera or by observing a sinusoidal modulation of the fluorescence of the atoms on a photodiode. The frequency depended on the detuning of the trapping laser, the magnetic field gradient, and the average intensity of the trapping light. For each of these, the frequency of the rotation increased as the spring constant of the trap was increased. We also discovered we could induce the atoms to jump into rotating clumps by modulating the magnetic field gradient at a frequency within 8 Hz of the rotational frequency.

The transition between the static and orbital modes showed pronounced hysteresis. When the number of atoms was slowly increased until it reached 10^8, the cloud would jump in <20 msec from the static mode to the rotating clump and the trap would then lose approximately half its atoms in the next 50–100 msec. This orbital mode would remain stable until there was a small fluctuation in the loading rate. Then the cloud would suddenly switch back to the static mode without losing any atoms. The number of atoms would have to build up to 10^8 again before it would jump back into the orbital mode. We have also observed hysteresis between the static and orbital modes when the trap would jump into the continuous ring. The trap started with 10^8 atoms in the static mode and then 80% of these atoms would jump into a continuous ring with the remaining 20% in the central ball. For certain loading rates the cloud would repeatedly switch back and forth between the two modes.

The expansion of the cloud with increasing numbers of atoms and the various collective rotational behaviors clearly show that strong, long-range forces dominate the behavior of the atomic cloud. Since normal interatomic forces are negligible for the atom densities in the trap (10^{10}–10^{11} cm^{-3}), other forces must be at work. In particular, since the optical depth for the trap lasers is on the order of 0.1 for our atom clouds (3 for the probe absorption at the resonance peak), forces resulting from attenuation of the lasers or radiation trapping can be important. The attenuation force is due to the intensity gradients produced by absorption of the trapping lasers, and has been discussed by Dalibard in the context of optical molasses.[6] This force compresses the atomic cloud and so cannot explain our observations. In the following, we demonstrate that radiation trapping produces a repulsive force between atoms which is larger than this attenuation force and thus causes the atomic cloud to expand. We will also show how radiation trapping leads to the rotational orbits we observe.

The attenuation force, $\mathbf{F}_A$, for small absorption, obeys the relation

$$\nabla \cdot \mathbf{F}_A = -6\sigma_L^2 I_\infty n/c \,. \tag{1}$$

The atom density is n, the cross section for absorption of the laser light is σ_L, and the incident intensity of a single laser beam is I_∞.

The absorbed photons must subsequently be reemitted and can then collide with other atoms. Although this was neglected in Ref. 6, this reabsorption of the light (radiation trapping) provides a repulsive force, $\mathbf{F}_R$, which is larger than $\mathbf{F}_A$. Two atoms separated a distance d in a laser field of intensity I repel each other with a force

$$|\mathbf{F}_R| = \sigma_R \sigma_L I / 4\pi c d^2 , \tag{2}$$

where for simplicity we have assumed isotropic radiation and unpolarized atoms. (The observed fluorescence is unpolarized.) The cross section σ_R for absorption of the scattered light is in general different than σ_L due to the differing polarization and frequency properties of the scattered light.[7] For a collection of atoms in an optical trap, the radiation trapping force obeys

$$\nabla \cdot \mathbf{F}_R = 6\sigma_L \sigma_R I_\infty n / c . \tag{3}$$

Comparison of (1) and (3) shows that the net force between atoms due to laser attenuation and radiation trapping is repulsive when $\sigma_R > \sigma_L$. In the limit that the temperature can be neglected, $\mathbf{F}_R + \mathbf{F}_A$ must balance the trapping force $-k\mathbf{r}$. This implies a maximum achievable density in the trap of $n_{\max} = ck/2\sigma_L(\sigma_R - \sigma_L)I_\infty$.

This allows us to explain the behavior shown in Fig. 1. Once the density reaches $n_{\max}$, increasing the number of atoms only produces an increase in the size of the atomic cloud. To compare this model to experiment we numerically solve the above equations with the finite temperature taken into account. The only free parameter in the calculation is $\sigma_R/\sigma_L - 1$. A value of $\sigma_R/\sigma_L - 1 = 0.3$ gives the solid curve shown in Fig. 2, which agrees well with experiment.

We have estimated σ_R/σ_L by convoluting the emission and absorption profiles for a two-level atom[7] in a 1D standing wave field. The intense laser light causes ac-Stark shifts, giving rise to the well-known Mollow triplet emission spectrum. The absorption profile is also modified by the laser light, being strongly peaked near the blue-shifted component of the Mollow triplet, causing the average absorption cross section for the emitted light to be greater than that for the laser light. We calculate $\sigma_R/\sigma_L - 1 = 0.2$ for our detuning and intensity ($I_\infty = 2$ mW/cm^2). While this is less than the value of 0.3 needed to match the data in Fig. 2, it is very reasonable that our twenty-level atom in a 3D field should differ from our simple estimate by this amount.

The inset of Fig. 2 shows that the expansion of the cloud deviates from this model for sizes greater than 1.5 mm. However, the precise behavior in this region is very sensitive to alignment and is not very reproducible. Other effects not included in the above model, such as magnetic field broadening, optical pumping, multiple levels of the atom, the spatial dependence of the laser fields, and multiple (>2) scattering of the light may also be important in this region.

We can explain the rings of Fig. 1 by considering the motion of atoms in the x-y plane when the laser beams are misaligned. A first approximation to the force produced by this misalignment is $\mathbf{F}_I = k'\hat{\mathbf{z}} \times \mathbf{r}$. The atoms are also subject to a harmonic restoring force $-k\mathbf{r}$ and a damping force $-\gamma d\mathbf{r}/dt$. If we neglect radiation trapping, we find circular orbits can exist with angular frequency $\omega = k'/\gamma$, if $k'/\gamma = (k/m)^{1/2}$. Since the orbits may have any radius, this clearly does not explain the formation of rings. If, however, we add a force $(aN/r^2)\hat{\mathbf{r}}$ due to the radiation pressure from a cloud of N atoms within the orbit radius R, we find circular orbits exist only for

$$R = \left[\frac{aN}{k - m\omega^2} \right]^{1/3} , \tag{4}$$

if $\omega < (k/m)^{1/2}$. Thus the effect of the radiation from the inner cloud of atoms is to cause circular orbits at a particular radius (i.e., rings are formed), and to allow circular orbits for a large range of misalignments. This is in accord with our observations that the orbits always encompass a small ball of atoms (Fig. 1). We have done a more detailed calculation including the Gaussian profiles of the lasers which gives a rotational frequency of 130 Hz and an orbit diameter of 3.5 mm for the conditions of Fig. 1(d).

While the simple model of the radiation trapping force we have presented explains the expansion of the cloud and the existence of the circular rings, there are several interesting aspects of the observed phenomena which are not explained. These include the formation of rotating clumps of atoms and the dynamics of the transitions between different distributions.

We have produced dense cold samples of optically trapped atoms. We find that this unique new physical system shows a fascinating array of unexpected collective behavior at densities orders of magnitude below where such behavior was expected. Much of this collective behavior can be explained by the interaction between the atoms in the trap due to their radiation fields. However, the detailed distributions and the transition dynamics deserve considerable future study.

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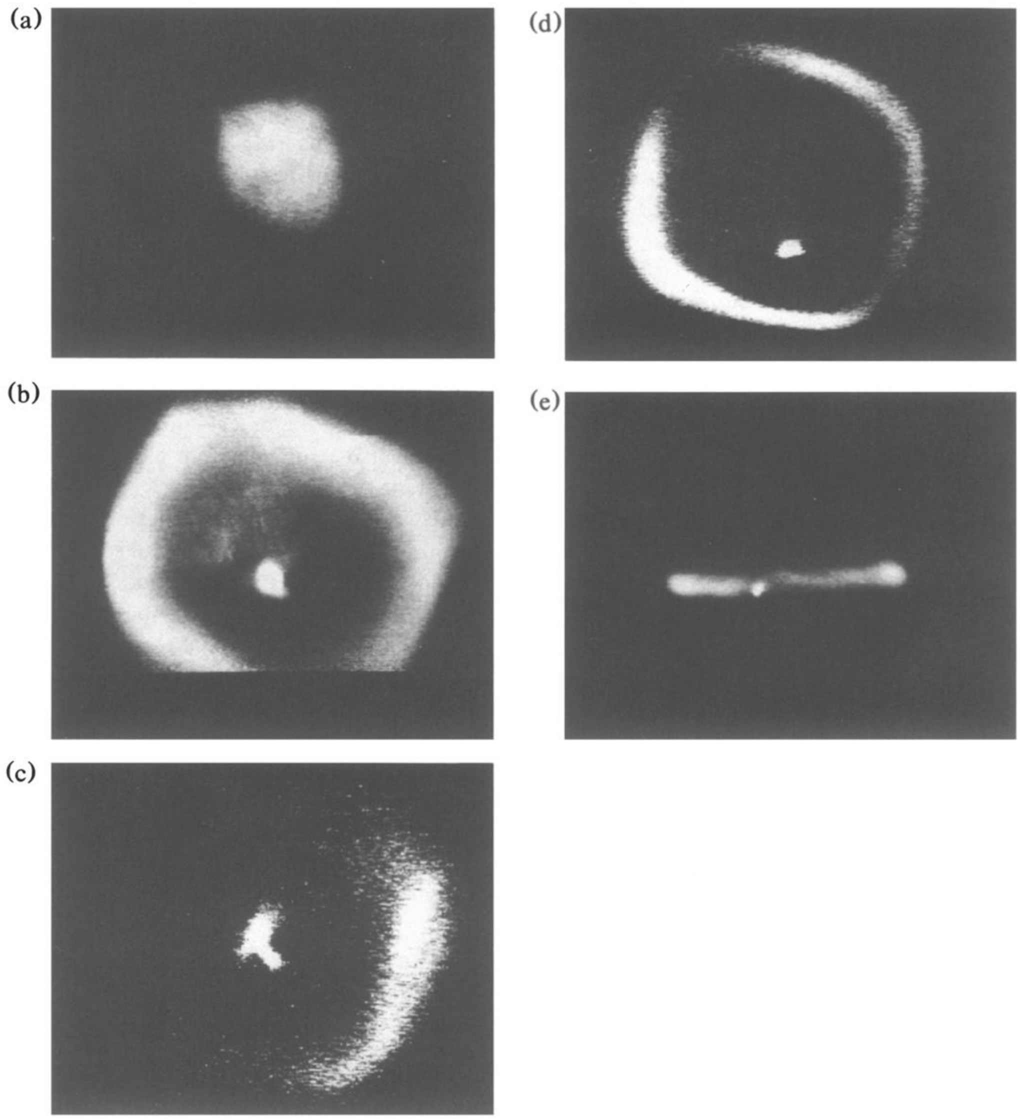

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