An all optical dynamical dark trap for neutral atoms

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Abstract: We describe the experimental realization of a dynamical optical trap for atoms: the Rotating Off-resonant Dipole Optical (RO-DiO) Trap. A blue detuned circularly scanned laser beam creates a time averaged "box" for the atoms. We characterized this novel confinement technique by varying the trapping geometry and the laser beam parameters. Our observations agree well with a numerical model.

OCIS codes: (270.0270, 300.0300) General

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#29456 - $15.00 US
Received December 18, 2000; Revised January 12, 2001

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Trapping neutral atoms[1, 2, 3] has been accomplished using a variety of electric, magnetic and electromagnetic fields. However, the fields which comprises each of these traps almost continually perturb the confined atoms, thereby placing limits on trap performance, atomic coherence times, etc. As a consequence, there has been an increased interest in weakly perturbative optical traps such as the far off-resonant dipole trap [4, 5]. More recently, there has been great interest in creating an entirely nonperturbative trap - simply put, a dark "atom box". Ideally, the trap would interact with the atoms only at its boundaries, preventing their escape, but would otherwise leave them unaffected.

Most of dark-box strategies investigated have been exclusively static in nature. For instance, a blue detuned off-resonant Laguerre-Gaussian laser beam [6] was used to trap atoms about the central node of the applied laser field, whereas in another case, multiple sheets of blue detuned laser light combined with gravity were used to confine atoms [7]. Quite recently, a new phase interference technique was proposed[8] and subsequently demonstrated[9] which produces a dark region around the focal point of a blue detuned dipole trap. An altogether distinct approach is to dynamically trap the atoms with a time dependent potential[10, 11, 12, 13]. To date, non-optical dynamical traps have played a key role in experiments on ultra cold atoms[14, 15]. Indeed BEC was first achieved using a dynamical magnetic trap. Still, a dynamical *optical* trap has only recently been realized[11, 10].

We report the demonstration of the "RODiO" trap, an all optical dynamical dark trap demonstrated to confine ultra-cold neutral atoms[11]. Our approach is to create a time averaged repulsive potential wall surrounding the atoms by scanning a blue detuned laser beam around the atomic cloud. The trap makes use of the conservative dipole force, which, for a two-level atom (TLA), can be described in terms of a pseudopotential $\mathrm{U(x)}=\frac{1}{2}\hbar\Delta\ln[1+g(\Delta)\mathrm{I(x)}/\mathrm{I_{sat}}]$ where $g(\Delta)=(\Gamma/2)^2/[(\Gamma/2)^2+\Delta^2]$ [16]. Here, Γ is the spontaneous emission rate, I_{sat} is the TLA transition saturation intensity and Δ is the detuning from resonance ($\Gamma\approx(16\mathrm{nsec})^{-1}$ and $I_{sat}\approx 6\mathrm{mW/cm}^2$ for Na). U(x) gives rise to a force which expels the atoms from high intensity regions of a blue detuned ($\Delta>0$) laser field.

The RODiO beam is derived from a ring dye laser blue detuned by 4-50GHz with respect to the $3S_{1/2}(F=2)\rightarrow 3P_{3/2}(F'=3)$ D2 transition. The power in the RODiO beam is 500mW, and the beam is focused near the trap region into a 200μm beam waist, with a corresponding Rayleigh range of 1mm. Thus, the instantaneous optical barrier height of the RODiO beam is $\leq$6.5mK. A circular scan of radius 1-5mm is created using two perpendicular linear scans phase-shifted by 90 degrees. In this way, we create an average trap potential with a spatially averaged height of $\leq 240\mu$K. The scanning of the RODiO laser beam was performed in two distinct ways: for 2kHz, we used audio speakers with a mirror attached to their centers. For higher scan rates (5- and 11kHz), phase locked resonant mechanical scanners were used[17]. After passing through the vacuum chamber, the RODiO beam was re-imaged in an orthogonal direction with respect to the original, providing three-dimensional confinement.

#29456 - $15.00 US
Received December 18, 2000; Revised January 12, 2001

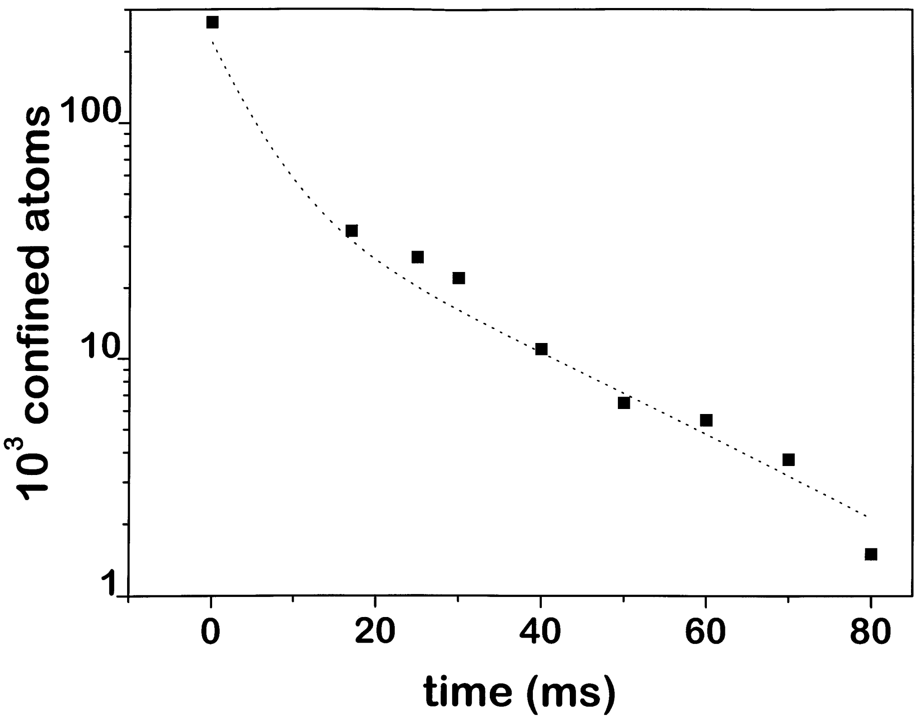

Fig. 1. Characteristic plot of the number of atoms confined versus time for the RODiO trap directly loaded from a MOT.

Our experiments begin with a dense ($n \sim 10^{10}\text{cm}^{-3}$) sample of $\sim 10^6$ cooled and trapped sodium atoms cooled to near the Doppler temperature ($\sim 240\mu$K as measured using a release and recapture method) in a MOT. The trapping light, provided by a single mode dye laser, passes through an acousto-optic frequency modulator (AOM), which is used to rapidly (<40ns) shutter the MOT light on and off. Before reaching the trap, the light is transmitted through a single mode optical fiber, which spatially filters the beams and assures reproducible alignment of the light at the trap. A magnetic field gradient of 25 G/cm (axially) is supplied by a pair of coils in the anti-Helmholtz configuration.

The procedure to study the performance of the RODiO trap was as follows: after the MOT was fully loaded, the MOT was turned off as the RODiO beam was turned on with a temporal overlap between the two traps of 2-5ms. The RODiO was then left on for a variable time duration, Δt. Just after the RODiO beam was switched off, a one-dimensional resonant probe was applied and the fluorescence of the remaining atoms was measured using a calibrated PMT. The MOT was then reloaded and the cycle repeated in order to average over at least ten data sets. Figure 1 shows a typical plot of retention of atoms over time. Here the RODiO was operated at Δ =30GHz in the 3-D configuration and at an 11kHz scan rate.Approximately 10^5 atoms were trapped for over 80ms. The retention curve displays two distinct time constants: a decay of τ_{init} ~5ms as the RODiO is turned on, which corresponds to ballistic expansion of atoms at the high end of the velocity distribution - atoms that escape the trap immediately - and a slower decay at $\tau_{RODiO} > 45$ms, corresponding to trapping due to the RODiO beams.

We then verified that the loading efficiency from the MOT into the RODiO trap was qualitatively sensitive to the initial temperature of the atomic cloud. In general, the

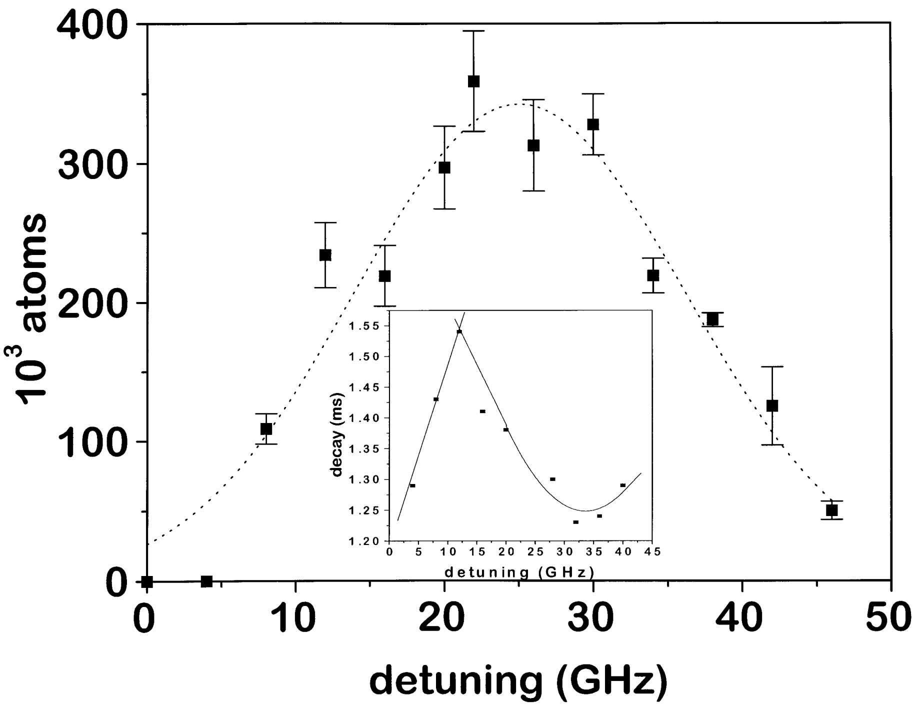

Fig. 2. Number of atoms captured by the RODiO as a function of RODiO laser detuning. The initial MOT contained $\sim 10^6$ atoms. The inset shows the *1/e* expansion and escape time of the atom cloud released from RODiO as probed by induced fluorescence. The decay time reflects the velocity distribution of the atoms confined by the RODiO just before their release.

efficiency was increased by over an order of magnitude when the MOT was operated at relatively large red detunings ($\Delta \approx 1.75\Gamma$) and when the MOT was extinguished using a stepped sideband method similar to that employed by Chu *et al* [7].

Despite the relatively large detunings ($\Delta \gg \Gamma$) in our experiments, the dipole force in the RODiO beam only becomes comparable to the scattering force at Δ ~10GHz, becoming larger than the scattering force for Δ >10GHz. As a result, the behavior of our RODiO reflects the interplay of these two light pressure forces. To explore the role of the different optical forces in the RODiO operation we investigated the number of atoms retained by the RODiO as a function of Δ at a fixed observation time Δt. At a given detuning, the initial value of the probe fluorescence signal was used to determine the number of confined atoms, while the decay time of the fluorescence, τ_F, was used to characterize the atomic velocity distribution (the fluorescence decay is dominated by ballistic escape of atoms from the probe beam). In Figure 2 we show results for the number of RODiO trapped atoms as a function of Δ for Δt = 40ms. Initially, we observed a steady increase in confinement with increasing Δ. We attribute this to the fact that, for small Δ, U(x) increases (here U(x)~ Δ). Above Δ =30GHz, confinement falls off because U(x) now begins to decreases (as $1/\Delta$), and eventually the RODiO trap depth falls below the initial temperature of the atoms.

Consider the inset of Figure 2. Here we show the dependence of τ_F (and hence the trapped cloud temperature) as a function of Δ. These results reflect not only the trade-off between the dipole trapping forces and the scattering force, but the interplay of the RODiO trap depth with the initial velocity distribution of the cloud. At small detunings ($\Delta \sim$ 5GHz), we observe short fluorescence decay times ($\tau_F \sim$ 1.25ms). As

#29456 - $15.00 US
Received December 18, 2000; Revised January 12, 2001

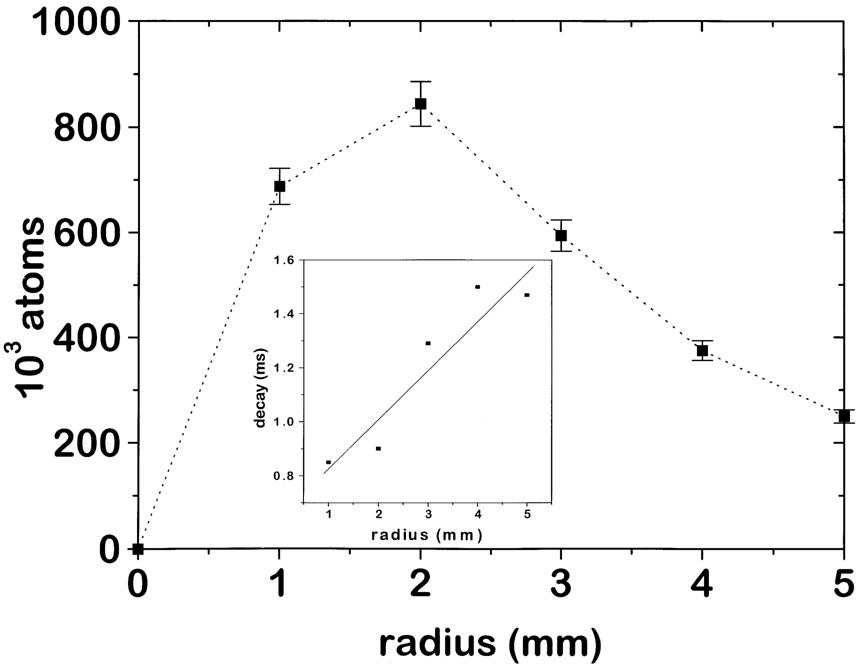

Fig. 3. Number of atoms captured by the RODiO as a function of trap radius. The decay time reflects the velocity distribution of the atoms confined by the RODiO just before their release (see text and caption, Figure 2).

Δ increases, τ_F increases, peaking at 1.55ms when Δ = 12GHz (corresponding to a 40% colder sample than at 5GHz!) In this region the scattering force is changing most rapidly, decreasing as $1/\Delta^2$, and hence the heating effects of the scattering force are decreasing with increasing Δ. The heating effect of the scattering force also explain the short trap lifetimes (τ_{RODiO} < 40ms) observed in this detuning regime. At larger detunings (Δ =12 to 30GHz), the dipole force begins to dominate and the trap depth increases. As the trap depth increases, an increasing fraction of the initial cloud is trapped, reaching a maximum when the trap depth becomes comparable with the initial temperature. This is observed to occur as Δ approaches 30GHz. The net result is that the atoms retained by the RODiO for Δ = 30GHz, although not so rapidly heated by the scattering force, nevertheless still have a *higher* mean velocity than for $\Delta \sim$ 12GHz. Hence we again observe shorter decay times around Δ = 30GHz. This discussion agrees with the fact that the number of atoms trapped peaks near Δ = 30GHz. As Δ increases beyond 30GHz, the trap becomes shallower, less atoms are trapped, only slower atoms are confined, and τ_F increases.

We have also investigated the atomic confinement at different scan radii. The data, shown in Figure 3, were taken after a 30ms RODiO at Δ =30GHz. For low radii, the circumferetially averaged potential well is deep, but the trap beam cuts into the initial atomic sample, excluding many atoms. As the inset shows, the decay time is also faster in this regime because the interaction time with the light is significant. When the radius is increased, the interaction time and the time averaged scattering force decrease, causing the number of atoms trapped to rise sharply. At higher radii, the spatially averaged trap depth decreases, resulting in less atoms retained. However, as the inset suggests, the minimal loss induced by the scattering force results in a slower decay time for those atoms which are trapped.

In addition to the radial and detuning studies, we examined the dependence of

Received December 18, 2000; Revised January 12, 2001

confinement time τ_{RODiO} on scan rate by implementing a two-dimensional RODiO at 2-, 5- and 11kHz scan rates. In this 2-D arrangement, the one-dimensional molasses ($I \leq 1\text{mW/cm}^2$) was continually applied along the direction of propagation of the RODiO beam in order to retain atoms which were otherwise free to leave the trapping region by traveling axially. This two-dimensional geometry was chosen because it allowed us to isolate the losses due to radial escape from the RODiO from losses due to the residual RODiO scattering force. For the 11kHz case, we found $\tau_{RODiO} \sim 40$ms at the optimum conditions of $\Delta = 30$GHz. At 5kHz, $\tau_{RODiO} \sim$13ms and retention was observed beyond 25 ms. For 2kHz, $\tau_{RODiO} \sim$ 6ms and finite retention was seen well beyond 10 ms. The observed variation of τ_{RODiO} with scan frequency is consistent with model predictions (see below). Additionally, we measured the confinement fraction as the detuning was varied. Although the absolute number of confined atoms was quite different than in 3-D, the detuning dependence was qualitatively similar to the three dimensional RODiO data.

To better interpret the behavior of the RODiO, we have developed a numerical model to deterministically follow a sample of atoms. The model accounts for the initial temperature distribution measured in the MOT and both the time dependent dipole force and the spontaneous, or scattering forces encountered by the atoms. Overall, the experimental data agrees well with the results of this model: two temporal decays are observed, an initial decay time of a few ms, followed by a second decay time (the RODiO lifetime) often more than 10 times longer than the first, short decay time.

One advantage of the model is the ability to separate different contributions to the overall trap lifetime. When we eliminated the scattering force, the trap lifetime became very large ($\tau_{RODiO} \rightarrow \infty$) indicating that the observed trap lifetime is set by residual heating from the scattering force. By following the atomic trajectories we were able to estimate the interaction time of the atoms with the light that comprises the trap. For the same conditions as Figure 1, the atoms spend on average 0.5% of their time in the light, corresponding to an average scattering rate of about 500 photons/s. In this case, by 50ms, the scattering force can accelerated a typical atom to the capture velocity of the time averaged (RODiO) potential well, in excellent agreement with our observed lifetime. The spontaneous heating associated with the random nature of spontaneous emission for this interaction time is small in comparison with the heating due to pure pushing and the dipole diffusive heating contribution is negligible as well. Another possible heating mechanism which is unique to dynamic traps is that due to the mechanical stirring, an effect known as viscous heating[14, 20]. We have seen no evidence of this type of heating in our model for scan rates up to 50kHz and confinement times as long as 10s. For larger scan rates or longer times, however, viscous heating can be important. Finally, we note that background collisions yielded a MOT lifetime of 0.9s and were therefore not included in our model.

We also utilized the model to further investigate the behavior of the RODiO for different scanning rates. To model the experimental conditions, we assumed confinement for a 2-D RODiO with perfect axial confinement. The model indicated that for a Na cloud prepared at our initial MOT temperatures, the critical frequency above which complete confinement occurs is 10kHz. This minimum scan rate results from the fact that the distance the atoms traverse until they receive sufficient momentum kicks to reverse direction must be less than half the RODiO beam waist. Otherwise, the atoms pass through the beam scanning region and escape. In fact, it is exactly this low critical frequency which enabled us to use mechanical laser beam scanning methods, eliminating the need for faster, more expensive and more cumbersome modulators.

From the data and our model, we conclude that the observed lifetime of our RODiO was determined by the effects of the scattering force imposed by the RODiO beam.

In essence, the residual scattering force pushed the atoms out of the trapping region even though the dipole force was three times larger than the spontaneous force at Δ=30GHz and for our experimental parameters. This forced escape has a clear physical interpretation: an atom which has bounced several times against the RODiO beam may simultaneously accumulate enough momentum in the direction of the beam propagation to escape from the trap. We note that in our 3-D trap geometry, the pushing of atoms in the direction of beam propagation was particularly detremental to long lifetimes because it resulted in a net force toward the trap corner where the laser beams were starting to diverge and consequently the trap barrier is at a minimum. The unwanted effects of the scattering force could be alleviated by retroreflecting and reimaging the RODiO beam back onto itself, or, more simply, by introducing a third pass of the beam in a direction which ensures that the vector addition of the three scattering forces cancel. However, the best means to eliminate the deleterious scattering force would be to go beyond our proof of principle experiment and to use a different RODiO laser, one capable of operating at larger detunings and simultaneously able to provide increased power.

While our investigations were carried out at $\Delta \approx 10^3\Gamma$, the computer model and extrapolations from the data imply that simply implementing a RODiO with a heavier alkali will result in enormous gains in trap lifetime and photon scattering rate. For example, our 3-D model predicts that a cesium RODiO constructed with a 1 watt Ti:Sa laser operating at Δ =60GHz should increase τ_{RODiO} into the regime where background collisions will dominate the trap loss. To support this we used our model to track the time averaged number of bounces from the spatially averaged potential well versus atomic velocity, a number which is proportional to the effective interaction time of the trapped atoms with the trapping field. Heavier, colder and slower moving atoms tend to have less interaction with the trapping light and therefore have longer retention times in the trap. In addition to single species atom trapping, we point out that a far off resonant RODiO trap has promise for trapping multiple atomic species[21] and ultra-cold molecules[19].

In summary, we have achieved and modeled the first dynamical, optical atom trap. We characterized our trap in the available ranges of laser detuning, scan rate, and scan radius, and the performance agrees well with our computer model. Additionally, we studied the effect of this method of confinement on the atomic velocity distribution. Our analysis shows that this trap operates optimally at moderate scan rates easily achieved by inexpensive mechanical scanners and conclude that it may be extended to a variety of laser systems for experiments in trapping of atoms and molecules.

Unlike other traps which use sheets of off-resonant light[7] or evanescent waves[22] the RODiO offers more flexibility with half the number of laser beams. Additionally, the atoms in a RODiO trap may be confined in an arbitrarily sized dark region, unlike the Laguerre potential[6] in which there is only one point in space of zero field. Finally, unlike the phase interference method[9], the interior of the RODiO is *completely* dark. The RODiO also provides scaleability to larger volumes, laser field strengths, and numbers of atoms because it may be extended trivially to utilize any commercial, high power laser system. Another promising advantage of the RODiO is that it could be concentrically enclosed with repumper light in order to achieve Sisyphus cooling during the interaction of the atoms with the scanning laser. As several revolutions of the RODiO beam are required for an atom to be "bounced" from the time averaged wall, the dynamical nature of our trap can be exploited to achieve several cooling events per bounce[23].

The authors are grateful to I. Tuchman of E.O.P. for providing the phase locked resonant optical scanners for this experiment. This work was supported by the National Science Foundation, the David and Lucile Packard Foundation, the Army Research Office and the Office of Naval Research.