High Densities of Cold Atoms in a *Dark* Spontaneous-Force Optical Trap

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A new magneto-optical trap is demonstrated which confines atoms predominantly in a "dark" hyperfine level, that does not interact with the trapping light. This leads to much higher atomic densities as repulsive forces between atoms due to rescattered radiation are reduced and trap loss due to excited-state collisions is diminished. In such a trap, more than 10^{10} sodium atoms have been confined to densities approaching 10^{12} atoms cm^{-3}.

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Although the original suggestion [1] that spontaneous light forces could be used to trap atoms included several general ways to do this, the development of the magneto-optical trap (MOT) [2-4] opened the way to the practical use of slow atoms in several different types of experiments involving cold collisions, quantum optics, and atom interferometers [5]. Recently, there has been a resurgence of interest in light traps which offer the possibility of containing polarized atoms [6] or higher density samples [7,8]. Overcoming the density limit of $\sim 10^{11}$ atoms/cm^3 in a MOT may open the way to study collective effects like Bose-Einstein condensation and spin waves, and free-bound transitions in long-range molecules.

The density limit is set by two processes: First, by collisions between ground- and excited-state atoms in which part of the excitation energy can be transformed into kinetic energy, resulting in a trap loss rate per atom βn with $\beta \approx (1-5)\times 10^{11}$ cm^3/s [9]. For densities n approaching 10^{11} atoms/cm^3, the loading time of the trap is limited to less than 1 s. The second limit is due to repulsive forces between the atoms caused by reabsorption of scattered photons (radiation trapping) [10]. At a certain atomic density, the outward radiation pressure of the fluorescence light balances the confining forces of the trapping laser beams. Further increase of the number of trapped atoms leads to larger atom clouds, but not to higher densities. As a practical matter, the power of the rescattered light sets a limit to the *number* of atoms which can be confined in a magneto-optical trap: 10^{11} atoms scatter about 100 mW of near-resonant laser light.

In this paper, we demonstrate a dark spontaneous-force optical trap ("dark SPOT"), in which all the above-mentioned limitations are mitigated by confining the atoms mainly in a ("dark") hyperfine ground state which does not interact with the trapping light. The key idea is that optimum confinement of atoms is not necessarily achieved with the maximum light force because of the limitations mentioned above. Light forces which are orders of magnitude smaller than the saturated scattering force are still strong enough to confine atoms tightly, e.g., 1 m/s sodium atoms (corresponding to a temperature of 1 mK) can be stopped in a distance of 100 μm at 1% saturation. All spontaneous-light-force traps realized so far have operated with close to saturated excitation, whereas our dark SPOT works at scattering rates 2 orders of magnitude smaller.

The simple model used to explain the density limit in a MOT [10] is readily generalized to include a "dark" and a "bright" hyperfine ground state. The trapping force is $\mathbf{F}_T = -kpr\hat{\mathbf{r}}$, where p denotes the probability that the atom is in the bright hyperfine state and k the spring constant of the normal MOT (i.e., for $p=1$). Attenuation of the trapping light and radiation trapping give rise to a density-dependent repulsive force which is quadratic in p because it involves two scattering events: $\mathbf{F}_R = k(n/n_0)p^2 r\hat{\mathbf{r}}$, where n_0 is a constant. From the stability criterion $|\mathbf{F}_T| > |\mathbf{F}_R|$, one obtains one limit for the maximum atom density in a MOT: $n < n_0/p$. For a very large number of atoms, the *column density* of atoms is limited by the fact that the atom cloud of diameter d has to be transparent for the trapping light [11], i.e., $ndp < b_0$, where b_0 is a constant. Substituting $d^3 = N/n$, one obtains a second limit for n: $n < (b_0/p)^{3/2} N^{-1/2}$. Finally, for small p, the density is limited by the fact that the volume of low-density gas at fixed temperature varies as $p^{-3/2}$, as the spring constant of confinement is proportional to p. This results in a third limit to the atomic density: $n < Np^{3/2}/d_0^3$ (d_0 is the cloud diameter in a standard MOT for low N). The constants n_0, b_0, and d_0 depend on experimental parameters and are typically 5×10^{10} cm^{-3}, 5×10^9 cm^{-2}, and 200 μm [10].

In a simplified model, the atom density in a MOT is the largest value compatible with the three limits as shown in Fig. 1. The value of p which maximizes density depends on N and is smaller for larger N. The Stanford group [12] and our group have recently succeeded in trapping more than 10^{10} atoms in a normal MOT. For such an N, the predicted optimum p of ~ 0.01 corresponds to a density increase of more than 2 orders of magnitude over the normal MOT (Fig. 1).

In the case of sodium, the bright and dark hyperfine states are the $F=2$ and $F=1$ hyperfine levels of the $3S_{1/2}$ ground state, respectively. Spontaneous light forces are

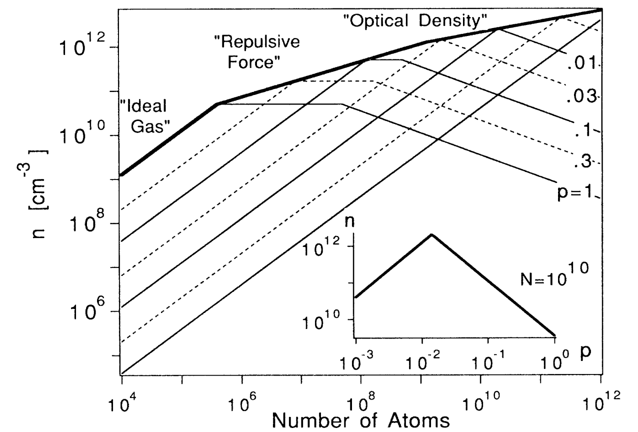

FIG. 1. Atomic densities n vs number N of trapped atoms for different values of the fractional population p of the "bright" hyperfine state. The thick line shows the highest density obtainable with an optimum value of p. For large N, this density is much higher than the one obtained in the normal MOT ($p=1$). For 10^{10} trapped atoms (inset), the optimum trap is 100 times "darker" than the normal MOT, resulting in more than 2 orders of magnitude increase in density.

applied using the cycling $F=2 \rightarrow F'=3$ transition to the excited $3P_{3/2}$ state. As a result of nonresonant excitation of the $2 \rightarrow 2$ transition, atoms are optically pumped into the $F=1$ ground state via a spontaneous Raman process. In all optical cooling and trapping experiments it has been necessary therefore to add repumping light resonant with the $1 \rightarrow 2$ transition to pump atoms back to the $F=2$ state. Usually, the intensity of the repumping light has been high enough to keep the atoms mostly in $F=2$. In a dark SPOT with $p=0.01$, the atoms spend most of their time ($\sim 99\%$) in $F=1$; this is accomplished by appropriately reducing the intensity of the repumping light.

Although a small excitation rate is superior for confining large numbers of atoms at high density, the maximum possible excitation rate is necessary to efficiently capture atoms from a thermal background or a slow atom beam, and load them into the trap. Therefore, a dark SPOT requires a "bright" capturing region which is separated from the dark trap spatially or temporally. In the bright region, the sodium atoms are mainly in the $F=2$ level and experience the maximum light force. The temporal separation is accomplished by loading atoms into a normal MOT and then switching to a dark trap, and will be discussed later. Spatial separation is superior since it allows continuous loading of atoms into a dark trap. This was accomplished by using a normal MOT and applying only weak or no repumping light to the center of the trap ("a MOT with a dark spot").

In our experimental setup, a crucial part was a slow-atom source employing an increasing-field Zeeman slower [13] capable of producing $> 10^{12}$ sodium atoms/s at 100 m/s and $\sim 10^{11}$ atoms/s at 30 m/s [14]. With this slower, $\gtrsim 10^{10}$ atoms/s could be loaded into our MOT. The trap consisted of three orthogonal retroreflected beams with diameters of ~ 3 cm and intensities of ~ 10 mW/cm^2 per beam. The frequency was tuned to the red of the $2 \rightarrow 3$ transition by 15–25 MHz. All beams were circularly polarized with helicities appropriate for magneto-optical trapping; they intersected at the center of a quadrupole magnetic field with a gradient of 10–15 G/cm. Repumping light close to resonance with the $1 \rightarrow 2$ transition was passed through a glass plate with a black dot, which was imaged into the trap center with an image size of ~ 10 mm. With a second similar repumping beam (diameter 3 cm, intensity 3 mW/cm^2) at an angle of $\sim 20°$ to the first, the whole trapping region was efficiently repumped except for the center, where the dark regions of the two beams intersected.

Additional repumping light could be added to the trapping laser beams by means of an electro-optical modulator (EOM) operated at 1.71 GHz. With EOM sidebands of variable intensity, p could be smoothly varied between a value $p_{\min}$ and ~ 1. $p_{\min}$ was determined by two processes: (i) stray light from the repumping beams scattered by windows and the atomic beam, and (ii) spontaneous Raman transitions induced by the trapping light. With an estimated rate of $\sim 10^3$ s^{-1}, the Raman process alone should cause $\sim 0.1\%$ equilibrium population in $F=2$. As it turned out that $p_{\min}$ was close to the optimum value of p (see Fig. 1), most of the experiments were done without EOM sidebands.

In a normal MOT we observed a cloud of atoms ~ 1 cm in diameter containing roughly 10^{10} atoms. In a dark SPOT, one could clearly see a dark central region in the fluorescence of the thermal beam corresponding to the dark spots in the repumping beams. In the center was a compact ball of trapped atoms (2–4 mm in diameter) with an apparent brightness lower than the normal MOT, but still much brighter than the background fluorescence.

The density in the dark SPOT was determined by absorption spectroscopy using a weak probe beam with an intensity of ~ 1 μW/cm^2 and a photodiode. The probe laser beam was split off the trapping or repumping light and could be scanned by ± 120 MHz with two acousto-optic modulators. Figure 2 shows an absorption spectrum of the trapped atoms. As at the highest densities the excited-state hyperfine structure could no longer be resolved, optical densities were deduced by fitting a theoretical spectrum to the one observed. The diameter of the cloud of trapped atoms was determined by imaging the fluorescence onto a charge-coupled-device camera or by recording spatially resolved absorption giving the same result.

An independent determination of the number of trapped atoms was performed by switching off the trapping and repumping beams and rapidly switching on a strong probe laser beam (diameter 10 mm, 0.5 mW/cm^2) close to resonance with $F=1$ atoms, optically pumping them into the $F=2$ state. From the transient absorption

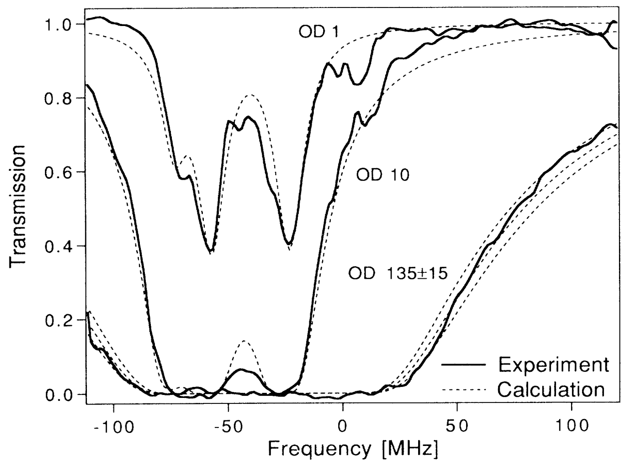

FIG. 2. Absorption spectrum of a 4 mm diam cloud of sodium atoms trapped in a dark SPOT. The best fit yields an optical density (OD) of 135 which corresponds to an atomic density of 7×10^{11} cm^{-3} and $\sim5\times10^{10}$ trapped atoms. Traces with lower OD were recorded with a reduced number of atoms. The dashed lines are calculated spectra for OD=1, 10, 120, 135, and 150, respectively.

signal, the number of absorbed photons was obtained. This number, divided by the number q of photons needed to optically pump one atom, gives directly the number of atoms in the trap. q was obtained from a knowledge of the matrix elements and a simple model of radiation trapping. The number of trapped atoms deduced should be accurate to within a factor of 2.

The highest density was observed for a 3.0 ± 0.5 mm cloud of atoms with an optical density of 110 ± 10 implying a density $n=(8\pm2)\times10^{11}$ cm^{-3}. Another (less accurate) value for n derived from the number of atoms $N=1.5\times10^{10}$ and the diameter agreed to within 30%. In slightly larger clouds, optical densities up to 160 and 5×10^{10} trapped atoms were observed. This combination of number and density is unprecedented in light traps: Slightly smaller densities have been reported to date only for at least 100 times fewer atoms [3,7,10,15]. A similar number of atoms has been trapped by light forces only at densities 20 times lower [12]. In some of the previous work, large detunings were used [12,15,16] to reduce the reabsorption of scattered photons. This and other ways to affect n_0, b_0, and d_0 may eventually be combined with our approach of reduced repumping to achieve even higher densities.

The maximum optical density (~2) observed when probing atoms in the bright state ($F=2$) was only about 2 times smaller than the value obtained in a bright MOT for the same experimental parameters (except for the dark spot in the repumping light). This shows that eventually the dark SPOT has similar limitations as the normal MOT, but at much higher densities. The direct comparison between dark SPOT and bright MOT showed a density ratio of ~100 in agreement with Fig. 1. The temperature of the trapped atoms was determined by switching off the trapping light and recording the decay of the absorption signal. The temperature of 1.2 ± 0.5 mK is in agreement with the prediction of ~0.8 mK for Doppler molasses [17] at the detuning and laser intensities used. Trap loading and decay times were 1 to 2 s and limited by collisions with the thermal atomic beam rather than with the residual gas at a pressure of 10^{-9} Torr. The long trapping time clearly demonstrates the reduced trap loss by excited-state collisions in a dark SPOT since extrapolating trap losses observed in a normal MOT [9] to our densities implies trapping times of only ~50 ms.

The repumping of the trapped atoms was mainly due to light scattered from the repumping beams into the "dark" trapping region. An absorption spectrum for $F=2$ atoms showed that about 1% of the atoms were in $F=2$, close to the optimum p predicted for $\sim10^{10}$ trapped atoms. To vary the population in $F=2$, we switched off the repumping light and switched on EOM generated sidebands of the trapping light with variable intensity. In agreement with the prediction of Fig. 1, a maximum in atomic density was found for a sideband intensity of about 0.1%. The traps with very weak repumping showed larger trap loss, probably due to the smaller potential well depth and therefore increased radiative escape rate [18]. [Since the trapped atoms are mainly in the lowest hyperfine state ($F=1$), inelastic hyperfine changing collisions cannot account for the extra loss rate observed.] When atoms were loaded into a normal MOT and the intensity of the repumping light was rapidly decreased, a considerable increase in density was observed ("temporal" separation between bright capturing and dark trapping). However, the densities thus obtained were 30% lower than those achieved by loading directly into a dark trap. The probable reason is larger trap loss during the loading phase due to both collisions and leakage of atoms out of the trap because of imperfect beam profile (one could clearly see rays of atoms leading out of the bright trap). It should be noted that the trap works even without any repumping light at all—sufficient repumping is provided by spontaneous Raman scattering of the trapping light. This offers an alternative explanation for the trapping of Rb in a MOT without repumping light reported recently [19].

The realization of a dark SPOT for other alkali atoms seems rather straightforward. In Cs (or Rb) the atom cycles many times on the bright transition before it falls into the dark $F=3$ state due to the very large hyperfine splittings. This cycling time could be shortened by using weak additional "depumping" light in resonance with the $4\rightarrow3$ or $4\rightarrow4$ transitions. The smaller rate of spontaneous Raman repumping might allow observation of trapping in a square well potential (*bounce trap*), where the atoms move freely in the central (nonrepumped) region of the trap (having $p\approx0$) and are reflected at the boundary with the outer (repumped) region. For very weak repumping the transition from the usual case of strong overdamping (damping rate $\alpha \gg \omega$, the oscillation frequency) to the oscillatory regime could be observed because $\alpha \propto p$ and $\omega \propto \sqrt{p}$. Generally, it appears that a larger hyperfine splitting is advantageous for the dark SPOT because off-resonant optical pumping processes are less important and the dwell times of the atom in the bright and dark states can be controlled independently by applying additional laser frequencies.

The high densities achieved in a dark SPOT are promising for the study of cold collisions and for the observation of evaporative cooling after transferring the atoms into a magnetic trap. At densities of 10^{12} cm^{-3}, the estimated elastic collision rate is already 100 s^{-1}, much larger than the trap loss rate due to collisions with the background gas.

The dark SPOT is the first cooling and trapping scheme in which the repumping light is intentionally reduced to "shelve" the atoms, i.e., cooling and trapping forces are only exerted on a small fraction of the atoms, while most of the atoms are kept in the dark, thus avoiding strong absorption of the cooling light. This concept should allow polarization-gradient cooling of trapped atoms below higher ultimate temperatures observed at high atomic densities [15]. Another possibility for realizing a dark trap would be repumping on the $1 \rightarrow 1$ transition of the D_1 line with elliptically polarized light. This transition has a coherent dark state only for magnetic fields $B=0$ [20] which inhibits repumping in the center of the trap. Recently, a new scheme in velocity-selective coherent population trapping (VSCPT) has been suggested which, in addition to the momentum diffusion process, features a weak damping force towards low velocities [21]. A simple way of combining strong damping and VSCPT would be the use of polarization-gradient molasses acting on the bright hyperfine state together with a velocity-selective repumping scheme. Alternatively, polarized cold atoms could be obtained by using a repumping scheme which does not repump atoms from a certain m_F level (e.g., σ^+ light and a 1-1 transition). This could be implemented in the recently demonstrated vortex-force trap which confines polarized atoms at nonvanishing magnetic field [6]. Finally, a tapered two-dimensional version of the dark SPOT, a dark funnel [22], should allow the compression of intense slow atomic beams to unprecedented brightness.

In conclusion, we have demonstrated a dark spontaneous-force optical trap, which confines atoms predominantly ($\sim$99%) in a dark hyperfine ground state. In this way, limitations of the normal magneto-optical trap have been overcome and densities close to 10^{12} cm^{-3} for more than 10^{10} trapped atoms have been achieved.

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[1] D. E. Pritchard *et al.*, Phys. Rev. Lett. **57**, 310 (1986).
[2] D. E. Pritchard and E. L. Raab, in *Advances in Laser Science II*, edited by M. Lapp, W. C. Stwalley, and G. A. Kenney-Wallace (AIP, New York, 1987), p. 329.
[3] E. L. Raab *et al.*, Phys. Rev. Lett. **59**, 2631 (1987).
[4] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
[5] "Laser Manipulation of Atoms and Ions," Proceedings of the Varenna Summer School, edited by E. Arimondo and W. D. Phillips (North-Holland, Amsterdam, to be published).
[6] T. Walker, P. Feng, D. Hoffmann, and R. S. Williamson III, Phys. Rev. Lett. **69**, 2168 (1992).
[7] O. Emile, F. Bardou, and C. Salomon (to be published).
[8] W. D. Phillips, in "Laser Manipulation of Atoms and Ions" (Ref. [5]); D. J. Heinzen, J. D. Miller, and R. A. Cline, in The Thirteenth International Conference on Atomic Physics, Munich, 1992, Book of Abstracts, Paper C4.
[9] M. Prentiss *et al.*, Opt. Lett. **13**, 452 (1988); L. Marcassa *et al.* (to be published).
[10] T. Walker, D. Sesko, and C. Wieman, Phys. Rev. Lett. **64**, 408 (1990).
[11] K. Lindquist, M. Stephens, and C. Wieman, Phys. Rev. A **46**, 4082 (1992).
[12] K. E. Gibble, S. Kasapi, and S. Chu, Opt. Lett. **17**, 526 (1992).
[13] T. E. Barrett, S. W. Dapore-Schwartz, M. D. Ray, and G. P. Lafyatis, Phys. Rev. Lett. **67**, 3483 (1991).
[14] M. A. Joffe, W. Ketterle, A. Martin, and D. E. Pritchard, in The Thirteenth International Conference on Atomic Physics, Munich, 1992, Book of Abstracts, Paper C9.
[15] A. Clairon *et al.*, in Proceedings of the Sixth European Time and Frequency Forum, Noordwijk, Netherlands, 1992, edited by J. J. Hunt (to be published).
[16] E. A. Cornell and C. R. Monroe (private communication).
[17] P. D. Lett *et al.*, J. Opt. Soc. Am. B **6**, 2084 (1989).
[18] P. S. Julienne and J. Vigué, Phys. Rev. A **44**, 4464 (1991).
[19] P. Kohns *et al.*, in International Conference on Quantum Electronics, 1992, Technical Digest Series, Vol. 9, p. 258.
[20] A. M. Tumaikin and V. I. Yudin, Zh. Eksp. Teor. Fiz. **98**, 81 (1990) [Sov. Phys. JETP **71**, 43 (1990)].
[21] F. Mauri and E. Arimondo, Europhys. Lett. **16**, 717 (1991).
[22] E. Riis, D. S. Weiss, K. A. Moler, and S. Chu, Phys. Rev. Lett. **64**, 1658 (1990); J. Nellessen, J. Werner, and W. Ertmer, Opt. Commun. **78**, 300 (1990).