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# Reduction of light-assisted collisional loss rate from a low-pressure vapor-cell trap

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We have demonstrated an order of magnitude increase in the number and in the lifetime of magneto-optically trapped $^{87}$Rb atoms collected from a low-pressure vapor. The improvement results from the reduction of light-assisted collision losses and is achieved by shelving the atomic population into the lower hyperfine ground state. Large fractional populations of the lower hyperfine ground state have been obtained by blocking the hyperfine repumping light in the region of the trapped atoms and by application of laser light that optically pumps the atoms into that state. We have observed trap lifetimes in excess of 700 s at our highest vacuum levels. At the rubidium pressure that maximizes the product of the number and lifetime of trapped atoms we observe a lifetime of 240 s with $5\times10^7$ trapped atoms, under conditions for which an ordinary magneto-optical trap has a lifetime of only 14 s with $3\times10^6$ atoms.

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In experiments using magneto-optical traps (MOT's), such as precision spectroscopy and trapping of rare isotopes [1], one desires both long trap lifetimes and large numbers of trapped atoms. Other experiments relevant to progress towards Bose-Einstein condensation, such as the study of ground-state collisions or cooling by evaporation, require that large numbers of atoms are transferred from a MOT to a long lived purely magnetic trap [2,3]. When trapping from a vapor one generally finds a discouraging tradeoff between lifetime and number with the consequence that long lifetimes imply low numbers. In this paper we describe a technique that overcomes this limit to a large extent by reduction of light-assisted collisional loss.

The rate equation for the number $N$ of trapped atoms (e.g., $^{87}$Rb) has the form

$$\frac{dN}{dt}=R-N\left(\frac{1}{\tau_b}+\frac{1}{\tau_{\mathrm{Rb}}}\right)-\beta\int n^2(\mathbf{r},t)d^3r, \qquad (1)$$

where $R$ is the collection rate out of a low-pressure rubidium vapor, $\tau_{\mathrm{Rb}}$ is the lifetime associated with collisions with room temperature rubidium, and $\tau_b$ represents the loss due to collisions with other background gases. The last term represents the intratrap collisional loss rate due to light-assisted collisions for trapped atoms with a density profile $n(\mathbf{r})$ and loss coefficient $\beta$ [4–7]. Both $R$ and $1/\tau_{\mathrm{Rb}}$ are proportional to the background rubidium pressure and at high pressure overwhelm the light-assisted collision term. Thus, at high rubidium pressure the number of trapped atoms tends to a maximum pressure-independent value $N_{\mathrm{lim}}=R\tau_{\mathrm{Rb}}$ [8]. Under high-vacuum conditions light-assisted collisions dominate the loss from the trap. By elimination of light-assisted collisions, both long lifetimes and large numbers can be realized simultaneously, and the trap will fill to $N_{\mathrm{lim}}$, provided $1/\tau_b \ll 1/\tau_{\mathrm{Rb}}$.

For $^{87}$Rb the trapping and cooling forces in a MOT are provided by relatively intense laser beams tuned to the red of the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$ cycling transition. Atoms in the $F=2$ ground state are thus "bright." For $^{87}$Rb approximately one out of every thousand photon scattering events drives an off-resonant transition to the $F'=2$ excited state from where it can decay to the "dark" $F=1$ ground state, where the atoms are no longer subject to a confining force. For this reason, a second set of laser beams, tuned to the $5S_{1/2}(F=1)\rightarrow 5P_{3/2}(F'=2)$ transition, optically pumps the atoms back to the bright $F=2$ ground state. It was the idea of Ketterle and colleagues [9] to cast a shadow in the center of the repumping beams allowing the trapped atoms to optically pump into the dark state. Outside the central region the trapping forces operate at full efficiency. Ketterle's intent was to use the dark-spot trap to maximize the density of the trapped atoms by reducing the radiation trapping force [10]. In contrast, we use the dark-spot trap to strongly suppress light-assisted collisions.

The dark-spot trap reduces the loss rate due to light-assisted collisions by two different mechanisms. First, atoms in the dark state are isolated from the pernicious effects of the trapping laser light by the 6.5 GHz hyperfine splitting of the ground states. Second, Ketterle showed that when the trap density is limited by temperature, the density actually *decreases* when more atoms are shelved into the dark state. A reduction in density reduces intratrap collision processes. Although not generally important for deep traps, hyperfine changing collisional loss is also quenched for atoms trapped in the dark state.

In a typical MOT the conditions that optimize the collection rate produce forces far in excess of that required for mere confinement and cause an unnecessarily high loss rate. Our philosophy is to first maximize the number of trapped atoms by spatially separating the trapping from the collection process and afterwards optimize the density by jumping the trap-laser detuning and magnetic-field gradient [11] or by readjusting the fraction of atoms in the dark state [9]. The trap density equilibrates in time scales short enough that loss mechanisms are unimportant during the final compression.

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Our setup uses a MOT in the standard configuration. The total trapping laser intensity of 50 mW $\mathrm{cm}^{-2}$ is provided by external-grating feedback diode lasers with a beam full width at half maximum of about 0.7 cm at the trap. The trap is located in a pyrex cell, 2.5 cm square by 7 cm long, mounted onto a UHV chamber which is pumped with a 25 $\mathrm{l\,s}^{-1}$ ion pump and with a titanium sublimation pump. The base pressure is estimated to be in the range of $10^{-11}$ Torr. The hyperfine repumping beams, with the 3 mm dark spot formed at the center by optical imaging, are married with the trapping beams and cross in the horizontal plane.

The success of trapping with a dark-spot trap rests largely on there being a high fractional population in the dark state, $p_{\mathrm{dark}}$, which in turn depends on the rate at which the dark state is populated by the trap laser and depopulated by the repumping laser. As a result of Zeeman and Doppler broadening mechanisms, the pumping rates depend on the position in the trapping and collection region. In initial experiments we reduced the hyperfine repumping intensity to a level $I_{\min}$ just adequate to preserve the collection rate $R$, and then inserted the dark-spot mask. In our trap, the dark spot reduces the central intensity by a factor of 20, with the lower limit set by scattered repumping light. (Diffraction effects are eliminated by optical imaging.) However, even with a central intensity of $I_{\min}/20$ we observed fractional populations of the dark state to be no more than $p_{\mathrm{dark}} \sim 0.5$. This observation suggests that $I_{\min}$ is much larger than the intensity required for complete repumping (i.e., saturation intensity) for atoms at the trap center. Because the repumping transition is broadened for the fast atoms entering the edge of the collection volume (due to Zeeman and Doppler shifts) as compared to the trapped atoms at zero magnetic field, the saturation intensity for the repumping transition decreases towards the center of the collection volume. Hence, the (resonant) repumping saturation intensity at the *edge* of the collection volume determines $I_{\min}$.

Scattered repumping light poses a difficult problem for a MOT operating in a small glass cell because the scattering surfaces lie in close proximity to the trapped atoms. We have developed two methods that increase $p_{\mathrm{dark}}$ in the presence of scattered repumping light, which we refer to as the *detuned* dark-spot trap and the *forced* dark-spot trap. For the detuned dark-spot trap we detune the repumping laser from the repumping transition by 3–4 linewidths. The detuning helps to increase the saturation intensity of the repumping rate at the trap center relative to the edge of the collection volume. The second and more successful method of increasing $p_{\mathrm{dark}}$ is to image light resonant with the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=2)$ transition onto the dark spot, effectively forcing the atoms into the dark ground state. With the forced dark-spot trap we increased the dark-state population to $p_{\mathrm{dark}} \geqslant 0.97$. Because the 2-2 beams are matched to the 3 mm dark spot they represent a small fraction of the total collection volume.

During the course of the several hundred seconds it takes to fill the dark-spot trap (at low pressures), we monitor the collection process every 10 s. A bypass beam of repumping light floods the dark spot for a period 50 ms and, for the forced dark spot, the 2-2 light is turned off. This nondestructive probe technique momentarily puts the atoms back up into the bright state, causing a flash of fluorescence with intensity proportional to the number of accumulated atoms. The sequence of probe flashes forms a collection profile, from which the collection rate $R$, the steady-state value of the number collected $N$, and the time $\tau$ for the trap to fill to $1/e$ of its steady-state value are determined. We use this definition of the lifetime even in the presence of intratrap collisions which give rise to fill profiles that are not strictly exponential [12].

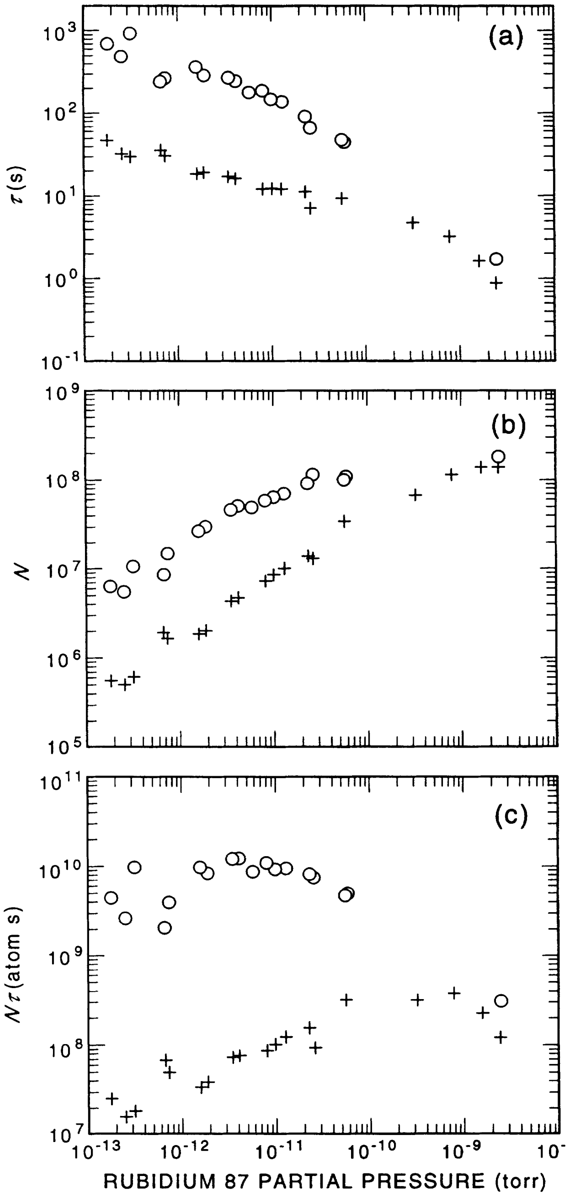

FIG. 1. (a) Lifetime $\tau$ of the forced dark-spot trap (circles) vs the partial pressure of $^{87}$Rb, as compared to an ordinary MOT (crosses). (Note: 1 Torr = 133 Pa.) (b) Number $N$ of trapped atoms. (c) The product $N\tau$. At the trap center the repumping light is blocked by the shadow of a dark spot. Further forcing of the population into the $F=1$ dark state is achieved by applying light resonant with the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=2)$ transition onto the trapped atoms (see text). The fractional dark-state population is $\geqslant 0.97$.

We first discuss the detuned dark-spot trap. The best performance is obtained with a repumping intensity of

$I=1.8I_{\rm min}$. We observe lifetimes as high as $\tau=170$ s for $^{87}$Rb pressures of $\sim 7\times 10^{-13}$ Torr, which should be compared to a light-assisted collision limited lifetime in an ordinary MOT (under identical conditions) of 20 s. The number and lifetime do not increase in the same proportion, reflecting a decreasing collection rate $R$ as the detuning $\delta$ of the repumping laser increases. We observe a sevenfold increase in the number up to $N=7\times 10^6$ at $|\delta|=25$ MHz, for which $p_{\rm dark}\simeq 0.8$ [13]. For $|\delta|\gtrsim 30$ MHz, $\tau$ becomes shorter as the trap becomes weak and the loss rate due to light-assisted collisions and hyperfine changing collisions for atoms remaining in the bright state increases [5]. Typically, the number of trapped atoms is a maximum between the point of maximum $\tau$ and the point where $R$ begins to decline, illustrating the tradeoff between increasing $p_{\rm dark}$ and decreasing $R$ as the detuning is increased.

For the forced dark-spot trap, the hyperfine repumping laser operates at $|\delta|=15$ MHz and $I=1.8I_{\rm min}$, which gives the largest $p_{\rm dark}$ while maintaining a peak collection rate. Figure 1 shows the lifetime $\tau$ and number $N$ of trapped atoms as a function of rubidium partial pressure. The most notable features are the extremely long lifetimes ($>$ 700 s) of the dark-spot trap for low rubidium pressures and the corresponding increase in number as compared to the normal MOT of greater than a factor of 10 [14]. Note that $N_{\rm lim}$ is observed in the dark-spot trap at much lower pressures than for the MOT. For the highest levels of 2-2 light we measure a reduction in $R$ of about 20–40 %. In the figure this is seen as a slightly larger increase in the lifetime as compared to the number. Note that the 2-2 light can *stimulate* light-assisted collisions for atoms in the bright state [6,4]. However, if the 2-2 light is intense enough, then essentially all the population is in the dark state and the lifetimes become very long. The data shown in Fig. 1 were taken with $p_{\rm dark}\geqslant 0.97$. At this value of $p_{\rm dark}$ the atoms expand to fill the entire dark spot so that the density is well below that for the MOT [9].

In some experiments, the appropriate figure of merit is the product of the number of trapped atoms and the trap lifetime, $N\tau$. For example, $N\tau$ is proportional to the ratio of the rate of elastic collisions in a magnetic trap to the loss rate from background gas collisions; this ratio is a key figure of merit for evaporative cooling [3]. When light-assisted collisions are negligible one expects $N\tau$ to peak when $N\simeq(1/2)N_{\rm lim}$, which occurs when the loss rate due to rubidium collisions equals the loss rate due to other background gases. Figure 1(c) shows this product $N\tau$ as a function of rubidium partial pressure. We obtain a maximum value of $N\tau=10^{10}$ atom s which is about 100 times better than the MOT at the same pressure and about 30 times greater than the maximum value obtainable in the MOT at a partial pressure of about $5\times 10^{-10}$ Torr. A noticeable decline in $N\tau$ begins to appear at a rubidium pressure of about $4\times 10^{-12}$ Torr, where the lifetime is about 240 s and $N=5\times 10^7$, which, as expected, is about half of the rubidium pressure-limited number for our trap, $N_{\rm lim}=1.4\times 10^8$.

At the highest pressures intratrap light-assisted collisions play no role, yet we observe a doubling of the lifetime when the dark spot is inserted. We attribute the longer lifetime in the dark-spot trap to the quenching of collisions of *excited*-state trapped atoms with untrapped rubidium atoms in the ground state. The interaction between excited-state and ground-state atoms is via the much longer dipole-dipole interaction leading to a larger cross section for the ejection of excited-state atoms than for ground-state atoms [15,16]. Our measurements suggest a threefold increase in the ejection rate of an excited-state atom compared to a ground-state atom. The dark-spot trap could provide a useful method for studying this type of light-assisted collision loss mechanism.

We have also used the forced dark-spot trap to trap the $^{85}$Rb isotope with tenfold improvements in the number and lifetime over the MOT. However, for pressure conditions giving a lifetime of 320 s for $^{87}$Rb, we observe a lifetime of 150 s for $^{85}$Rb, suggesting that the trap lifetime of $^{85}$Rb is still limited by light-assisted collisions, which could be a consequence of the smaller (3 GHz) hyperfine splitting between the ground states. Hence, atoms in the dark ground state experience the trapping laser less detuned for $^{85}$Rb than for $^{87}$Rb. This implies that the ability of the forced dark-spot trap to reduce light-assisted collisions may be better suited to alkali atoms with a large ground-state hyperfine splitting such as rubidium, cesium, and francium.

Light-assisted collisional loss is important not only for vapor-cell traps but also for traps collecting from slowed atom sources such as Zeeman slowers, chirped stopping lasers, or double MOT arrangements. These methods function by increasing the collection rate $R$ (as well as by reducing the number of hot background atoms). However, the MOT must still be biased towards a high collection efficiency (i.e., capture velocity much higher than trapped atom thermal velocity) since it is generally impractical to cool the incoming atoms to much less than 10–20 m s$^{-1}$, with the result that the lifetime of the fill cycle is often limited by light-assisted collisions. Finally, light-assisted collisions are especially important for MOT's using high-power lasers because the high laser intensity increases the rate of light-assisted collisions. The techniques demonstrated here will suppress the effects of light-assisted collisions and allow further exploitation of slowed atom sources and high-power trapping lasers.

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[12] Numerical integration of Eq. (1) yields a fill profile which is remarkably exponential, even with a large nonlinear loss term. The nonlinearity causes a surprising asymmetry between a fill profile and its related loss profile.

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