Trap-depth measurements using ultracold collisions

D. Hoffmann, S. Bali, and T. Walker
Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706
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We measure the depth of an optical atom trap using repulsive trap-loss collisions. These collisions involve excitation by a laser tuned to a frequency above the atomic resonance. Simple conservation of energy considerations give direct quantitative measurements of the trap depth. Further analysis allows measurement of the escape probability as a function of energy. We apply the methods to Rb traps, and use the results to form conclusions about ground-state hyperfine-changing collisions. [S1050-2947(96)51208-4]

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Laser cooling and trapping techniques produce high density samples of atoms for a great variety of experiments in atomic physics. These samples are of interest in their own right, being of sufficiently low temperature and high density to exhibit a wide variety of new phenomena. For example, interactions with electromagnetic fields strongly alter the dynamics of ultracold collisions of excited atoms [1]. New forms of high-resolution spectroscopy allow precision studies of both ground- and excited-state potentials of alkali-metal dimers [2]. Novel collective phenomena result from the long-range radiative interactions between the trapped atoms [3]. Atoms can be ordered in optical lattices [4]. Laser-cooled atoms also serve as a convenient starting point for many other experiments. These include atom interferometry, [5] quantum optics [6], and the recent observations of Bose condensation [7]. An application to more traditional atomic physics is the recent use of a laser trap for making reliable absolute measurements of electron-atom cross sections [8]. As with any tool, diagnostics are essential to understand the operation and characteristics of atom traps. To this end, a variety of techniques are used for measuring parameters such as temperatures [9–11], spring constants [12], friction coefficients [13], densities, spin-polarization [14], and fluorescence spectra [11,15].

In this paper we present a method for measuring a previously inaccessible trap parameter, the trap depth, which we define as the energy required to remove an atom from the trap. In general this energy depends on direction of motion of the atom, so the trap depth is anisotropic. The trap depth is important in a number of contexts. For example, ultracold collision studies often detect the collisions by measuring trap-loss rates [1]. Only collisions that transfer energy in excess of the trap depth can be detected by this method. The trap-loss rates due to several types of collision processes depend on the trap depth. The first, ground-state hyperfine-changing collisions, is trap-depth dependent because the energy release can be comparable to the trap depth. For weak Cs or Rb traps, the collisional loss rate rapidly decreases with increasing trap-laser intensity [16,17], because the increased trap depth at higher intensity no longer allows the atoms that have undergone a ground-state hyperfine-changing collision to escape the trap. The same phenomenon occurs for Li traps, except the collision mechanism involves a change in fine-structure state [18,19]. Another collision process, radiative escape, depends sensitively on trap depth, and that dependence was studied in some detail by Ritchie *et al.* [20], who reported significant disagreements between theory and experiment. These results depended on a theoretical model of the trap depth. Clearly, it would have been advantageous to have direct experimental measurements of the trap depth and its anisotropy. The method for measuring electron-scattering cross sections using trap loss relies on the production of traps with very small depths [8]. Finally, the capture velocity for a trap [10] is also related to its depth.

We recently demonstrated [21] a collision mechanism, repulsive trap loss, which is directly related to the trap depth. Here we exploit its frequency dependence to measure the trap depth, or, more generally, the escape probability as a function of energy. We apply this to the problem of ground-state hyperfine-changing collisions, and find that atoms can be ejected from the trap only if both atoms change hyperfine states.

Figure 1 depicts the mechanism for repulsive trap-loss collisions. As two colliding atoms approach each other, they come into resonance with a ''catalysis'' laser, tuned an amount Δ (typically several GHz) above the atomic resonance frequency ν_0, which excites them to a repulsive molecular potential curve. The atoms repel each other, and in much less than one excited-state lifetime they each acquire a kinetic energy of $h\Delta/2$. If this energy exceeds the trap depth,

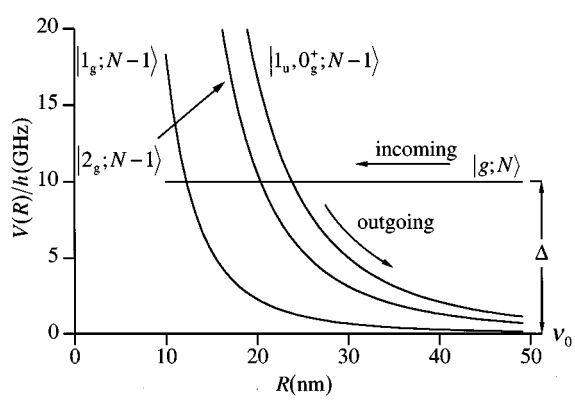

FIG. 1. Mechanism for repulsive trap loss. The ground-state potential curve labeled $|g;N\rangle$ has been shifted up by one photon energy. Atoms incident on this curve are transferred to one of several possible $|e;N-1\rangle$ curves, and are then accelerated to large enough energies to escape the trap.

the atoms escape the trap. The trap-loss collision mechanism is closely related to other collision processes involving repulsive states, where the energy transfer is smaller [22].

Thus the collisional loss rate induced by the catalysis laser, measured as a function of Δ, will sharply increase when $h\Delta > 2E_t$, where E_t is the trap depth. Further increases in Δ cause a decrease in the collisional loss rate. This may be explained by noting that at low laser intensity the cross section for repulsive trap loss is $\sigma = \pi R^2 f$, where $V(R) = h\Delta$ defines the interatomic separation where the laser is resonant with the colliding atoms and f is the excitation probability. We keep $f < 0.1$ to avoid interesting complications that arise at high intensities [21,22]. For the case of many potential curves, the cross sections for excitation to different curves add. The excitation probability is proportional to the resonant interaction time, while the interaction time is inversely proportional to the slope of the potential dV/dR. Thus $\sigma \propto R^2 dR/dV$. Since both R and dR/dV decrease with increasing Δ, the collision rate decreases. For an R^{-3} potential curve, $\sigma \propto \Delta^{-2}$. Both Landau-Zener (LZ) [21] and Gallagher-Pritchard (GP) [23] models for ultracold collisions give this result.

We measured the depth of a Rb magneto-optical trap (MOT). Hoffmann *et al.* [24] describe the apparatus in detail. The MOT consists of six laser beams of total intensity $I_t = 2$ mW/cm^2, beam diameter 6.3 mm, tuned typically $\Delta_t = -5$ MHz from the $5S_{1/2}(F = I + 1/2) \rightarrow 5P_{3/2}(F' = I + 3/2)$ transition of either ^{85}Rb ($I = 5/2$) or ^{87}Rb ($I = 3/2$). The magnetic-field gradient was 20 G/cm. The trap is loaded directly from a background Rb vapor, confining typically 3×10^6 atoms at a density of 3×10^{10} cm^{-3}. A tunable single-mode Ti:sapphire laser provided catalysis laser light of 1–5 W/cm^2 intensity at detunings Δ ranging from 0 to 100 GHz to the high-frequency side of the trapping transition. We measured Δ with an 8-GHz spectrum analyzer. The catalysis laser was chopped at 1.2 kHz with a duty cycle d that was variable in the range 0–50 %.

The catalysis laser ejects atoms from the trap at a rate $\langle \beta n \rangle N d$, where β is the rate coefficient of interest, n is the density distribution of the cloud of trapped atoms, the brackets denote an average over that spatial distribution, and N is the number of trapped atoms. Collisions with hot background atoms or those caused by the trapping lasers also remove atoms at a rate $\Gamma_t N$. Loading at a rate L from the background vapor balances these losses, producing a steady-state number of atoms

$$N = \frac{L}{\Gamma_t + \langle \beta n \rangle d}. \tag{1}$$

In order to determine accurate relative values of β for different catalysis laser detunings, it is necessary to ensure that the density distribution remains constant. We accomplished this by changing d in order to hold N constant. We checked that L was unaffected by the presence of the catalysis laser.

Figure 2 shows measurements of β as a function of Δ for ^{85}Rb and ^{87}Rb. As expected, the trap-loss rate first increases rapidly, then decreases with increasing Δ. The figure shows that Δ must be in excess of 15 GHz for the atoms to escape with high probability. Since the energy $h\Delta$ is divided equally between the two atoms, the trap depth is clearly close to 7.5 GHz. In a MOT, the trap depth is primarily determined by the damping force and the laser beam geometry [17,20,25,26], with a weak dependence on magnetic field. MOT models give trap depths reasonably consistent with our observations.

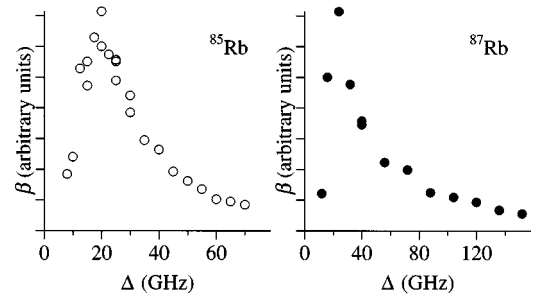

FIG. 2. Measurements of repulsive trap-loss rates β as a function of catalysis-laser detuning Δ for Rb MOTs. The trap laser intensity, detuning, and beam diameter were 2.0 mW/cm^2, −5 MHz, and 6.3 mm, respectively.

So far, our discussion of trap depth has been largely model independent, relying on conservation of energy arguments. We now consider extracting further information about the anisotropy of the trap, i.e., the possibility that the trap has different depths for different escape directions. Such anisotropies may arise from a number of sources, including the nonspherical laser-beam geometry, the Gaussian beam profiles, and the anisotropic magnetic field. Assuming R^{-3} potential curves, both LZ and GP models predict

$$\beta \propto \frac{P(h\Delta/2)}{\Delta^2} \tag{2}$$

for the trap-loss collision rate as a function of detuning at fixed low laser intensity. The escape probability $P(E)$, a function of energy E, is the fraction of the total solid angle for which $E > h\Delta$. A plot of $\beta\Delta^2$ vs Δ gives $P(E)$. The relation $P(\infty) = 1$ calibrates the scale for $P(E)$.

The deduced $P(E)$ data for ^{85}Rb are shown in Fig. 3 for two different sets of trap parameters. As expected, the escape

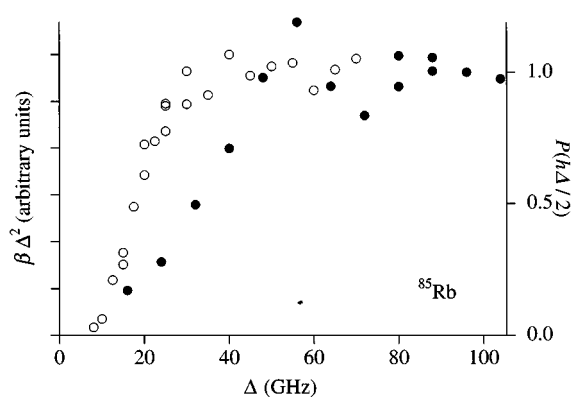

FIG. 3. Measurements of $\beta\Delta^2$, which is proportional to the escape probability $P(h\Delta/2)$, as a function of Δ for ^{85}Rb MOTs. ○, trap detuning and intensity of −5 MHz and 2.0 mW/cm^2; ●, −9.4 MHz and 3.2 mW/cm^2.

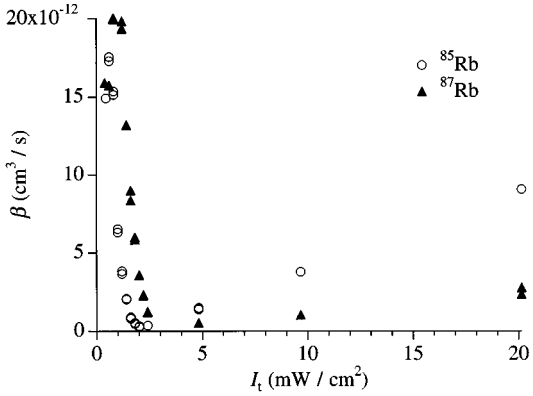

FIG. 4. Trap-loss rates as a function of trapping-laser intensity for Rb MOTs, showing suppression of ground-state hyperfine-changing collisions as the trap depth is increased. Adapted from Wallace *et al.* [17].

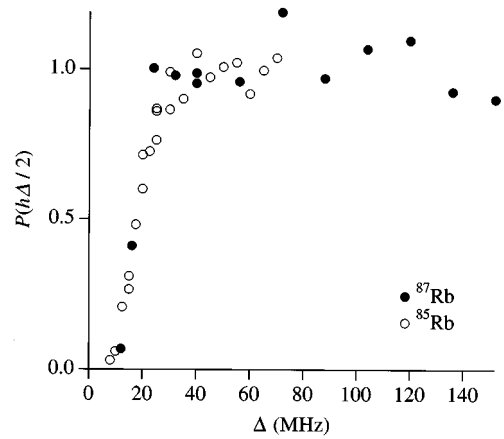

FIG. 5. Escape probability as a function of Δ for Rb MOTs. Trap parameters are -5 MHz and 2.0 mW/cm^2.

probabilities decrease at a given detuning Δ for deeper traps. Studies of several different sets of trap parameters show that deeper traps also have greater anisotropies.

One interesting problem that can be discussed in light of Fig. 3 is hyperfine-changing collisions. Inelastic hyperfine-changing collisions between two ground-state atoms in a MOT occur via two possible processes. Either one atom changes its hyperfine state from $F_+ = I + \frac{1}{2}$ to $F_- = I - \frac{1}{2}$:

$$\mathrm{Rb}(F_+) + \mathrm{Rb}(F_+) \rightarrow \mathrm{Rb}(F_+) + \mathrm{Rb}(F_-) \tag{3}$$

with an energy release of $\Delta E = E_{\mathrm{HFS}}$, or both do:

$$\mathrm{Rb}(F_+) + \mathrm{Rb}(F_+) \rightarrow \mathrm{Rb}(F_-) + \mathrm{Rb}(F_-), \tag{4}$$

with $\Delta E = 2E_{\mathrm{HFS}}$. Sesko *et al.* [16] and Wallace *et al.* [17] (Fig. 4) found evidence for hyperfine-changing collisions from studying the trap-laser intensity dependence of the trap-loss rate. The observed steep decrease in trap-loss rate with increasing intensity occurs because the fast atoms resulting from hyperfine-changing collisions are captured by the trap with increasing probability. The indirect detection of the collisions precluded identification of whether (3) or (4) was being observed.

We chose the parameters of the shallower MOT of Fig. 3 to roughly correspond to those that gave the minimum loss rate for ^{85}Rb observed by Wallace *et al.* [17] in their study of the intensity-dependent trap loss from Rb MOTs. The only significant difference is the larger field gradient, in our case, needed to obtain a higher trapped-atom density. This should not affect the trap depth significantly [25]. Under these trap conditions the MOT captures the ^{85}Rb ground-state hyperfine-changing collisions. The ^{87}Rb hyperfine-changing collisions are not completely captured, however. Figure 4 shows that the escape probability is about 0.2, found by taking the ratio of the loss rate at 2.0 mW/cm^2 to the maximum observed loss rate. This agrees very closely with our measurements from Fig. 3, if we assume that process (4) is dominant. Indeed, for $\Delta = 2 \times 6.8$ GHz, we deduce an escape probability of 0.23. From this we identify process (4) as being responsible for the data of Fig. 4.

As another example of an application for this method, we note that Ritchie *et al.* [20], in their studies of the radiative escape trap-loss mechanism for ultracold Li collisions, constructed a three-dimensional model of the trap depth for their Li trap. They then used this model to compare experimental measurements to two different theories for radiative escape. They found agreement with a simple GP-type theory but disagreed with the more sophisticated theory of Julienne *et al.* [28]. Measurements of the escape probability would eliminate the need for the trap-depth model, making the comparison between theory and experiment more direct.

When we plot $\beta\Delta^2$ vs Δ for ^{87}Rb we find that at large detunings the trap-loss rate varies as $\Delta^{-1.3}$, rather than as Δ^{-2}. Thus the method used for ^{85}Rb, based on the GP or LZ model, will not work for deducing the escape probability as a function of energy for ^{87}Rb. It is natural to attribute this effect to the large hyperfine interactions for ^{87}Rb. Using the calculated potential curves including hyperfine interactions from Ref. [27], we have attempted to simulate such an effect. Indeed, we find that for detunings up to about 30 GHz the trap-loss rate decays with detuning at roughly Δ^{-1}, but at larger detunings it should go as Δ^{-2}. We have made measurements out past 100 GHz, and still find too slow a falloff with detuning. One possible explanation is that the hyperfine interactions change the oscillator strengths and therefore the excitation rates in a detuning-dependent way. This might account for the difference in the behaviors of ^{87}Rb and ^{85}Rb. However, we have repeated the intensity-dependence experiment reported in Ref. [21] for ^{87}Rb and find maxima at very nearly the same intensities as for ^{85}Rb.

Despite the anomalous detuning dependence for ^{87}Rb, with additional assumptions it is still possible to extract the escape probability, albeit with less certainty. To do this, we note that $\beta(\Delta) = P(h\Delta/2)F(\Delta)$, where $F(\Delta)$ is the repulsive trap-loss rate that would be measured if the escape probability were unity. Assuming the $F(\Delta) \sim \Delta^{-1.3}$ dependence seen at large Δ extends to small Δ as well, we obtain the escape probability using $P(h\Delta/2) \propto \Delta^{1.3}\beta(\Delta)$. As seen from Fig. 5, this procedure applied to ^{87}Rb gives results for $P(E)$ that agree well with an identical ^{85}Rb trap.

In summary, we measured the depth of MOTs using the detuning dependence of repulsive trap-loss collisions. A

measure of the trap depth results directly from conservation of energy. Further analysis gives the escape probability as a function of energy. We demonstrated this with a conventional MOT, but the method should also work with other types of light-force traps, such as spin-polarized traps [14] and the optical pumping trap [29].

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[1] T. Walker and P. Feng, Adv. At. Mol. Opt. Phys. **34**, 125 (1995).
[2] P. Lett, P. Julienne, and W. Phillips, Annu. Rev. Phys. Chem. **46**, 423 (1995).
[3] T. Walker, D. Sesko, and C. Wieman, Phys. Rev. Lett. 64, 408 (1990); D. Sesko, T. Walker, and C. Wieman, J. Opt. Soc. Am. B **8**, 946 (1991).
[4] A. Kastberg *et al.*, Phys. Rev. Lett. **74**, 1542 (1995).
[5] C. Adams, M. Sigel, and J. Mlynek, Phys. Rep. **240,** 143 (1994).
[6] A. Lambrecht *et al.*, Appl. Phys. B **60,** 129 (1995).
[7] M. Anderson *et al.*, Science **269**, 198 (1995); C. Bradley *et al.*, Phys. Rev. Lett. **75**, 1687 (1995).
[8] R. S. Schappe *et al.*, Europhys. Lett. **29,** 439 (1995).
[9] P. Lett *et al.*, J. Opt. Soc. Am. B **6**, 2084 (1989); D. Meacher *et al.*, Phys. Rev. A **50**, R1992 (1994); M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992).
[10] C. Monroe *et al.*, Phys. Rev. Lett **65,** 1571 (1990).
[11] S. Bali *et al.*, Phys. Rev. A **53**, 3469 (1996).
[12] C. Wallace *et al.*, J. Opt. Soc. Am. B **11,** 703 (1994).
[13] M. Drewsen *et al.*, Appl. Phys. B **59,** 283 (1994).
[14] T. Walker *et al.*, Phys. Rev. Lett. **69,** 2305 (1992).
[15] C. Westbrook *et al.*, Phys. Rev. Lett. **65**, 33 (1990); C. Jurczak *et al.*, Opt. Commun. **115**, 480 (1995).
[16] D. Sesko *et al.*, Phys. Rev. Lett. **63,** 961 (1989).
[17] C. Wallace *et al.*, Phys. Rev. Lett. **69**, 897 (1992).
[18] J. Kawanake *et al.*, Phys. Rev. A **48,** R883 (1993).
[19] N. Ritchie *et al.*, Phys. Rev. A **51,** R890 (1995).
[20] N. Ritchie, E. Abraham, and R. Hulet, Laser Phys. **4,** 1066 (1994).
[21] S. Bali, D. Hoffmann, and T. Walker, Europhys. Lett. **27,** 273 (1994).
[22] L. Marcassa *et al.*, Phys. Rev. Lett. **73**, 1911 (1996); H. Katori and F. Shimizu, *ibid.* **73**, 2555 (1994); M. Walhout *et al.*, *ibid.* **74**, 506 (1995); V. Sanchez-Villicana *et al.*, *ibid.* **74**, 4619 (1995); S. Zilio *et al.*, *ibid.* **76**, 2033 (1996).
[23] A. Gallagher and D. Pritchard, Phys. Rev. Lett. **63,** 957 (1989).
[24] D. Hoffmann, P. Feng, and T. Walker, J. Opt. Soc. Am. B **11**, 712 (1994).
[25] K. Lindquist, M. Stephens, and C. Wieman, Phys. Rev. A **46,** 4082 (1992).
[26] K. E. Gibble, S. Kasapi, and S. Chu, Opt. Lett. **17,** 526 (1992).
[27] T. Walker and D. Pritchard, Laser Phys. **4,** 1085 (1994).
[28] P. Julienne *et al.*, Laser Phys. **4,** 1076 (1994).
[29] P. Bouyer *et al.*, Europhys. Lett. **27,** 569 (1994).