rf Spectroscopy of Trapped Neutral Atoms

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We report the first observation of rf-induced transitions of trapped neutral atoms. An rf resonance curve for a sample of trapped Na atoms has been obtained by measuring the relative population of two trapped magnetic substates as a function of applied rf frequency. The shape of the resonance curve has been used to determine the energy distribution of the trapped atoms.

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Recent progress in the field of neutral-atom trapping has been very rapid; in the last year three new traps have been developed with orders of magnitude improvements in the number of trapped atoms and confinement times.[1-4] At present, the emphasis is on applying the traps to new scientific measurements, such as the study of ultracold collisions,[4,5] and developing new techniques to monitor and/or manipulate the trapped atoms. This paper reports the first demonstration of rf-induced transitions and rf spectroscopy of a sample of trapped neutral atoms. rf spectroscopy is an important development for neutral-atom traps because it not only provides a powerful high-resolution probe of trap conditions, but also may be used to manipulate the atoms, and may ultimately lead to high-resolution spectroscopy. Our present experiments demonstrate the use of rf transitions to measure the energy distribution of a sample of trapped atoms; this can lead to interesting applications, such as the identification of a Bose condensate, which would have a very narrow spike in its rf spectrum. We also demonstrate the use of rf transitions to selectively change the magnetic-sublevel population of the trapped atoms; in this context its use has been proposed as part of a "cyclic" cooling scheme[6] which may permit cooling of the trapped atoms to μK temperatures.

In our present experiments, we have applied resonant rf pulses to samples of trapped neutral Na atoms confined in a magnetic trap. We have been able to populate all four of the trapped magnetic substates, and have obtained a resonance curve for one of the rf transitions by measuring the relative populations of the initial and final magnetic substates using laser-induced fluorescence. Modeling of the trapped atoms has allowed us to reproduce the measured rf line shape and extract from it their energy distribution.

The experiments were performed on a gas of $\sim 2\times 10^{10}$ Na atoms confined in a volume of ~ 100 cm^3 by a superconducting magnetic trap.[1] The trap consists of a local, nonzero, minimum of the magnetic field in free space which confines "weak-field seeking" atoms, i.e., atoms in a state whose energy increases with magnetic field. For Na in its ground state there are four trapped levels: $|F=2,M=2,1,0,-1>$ (which adiabatically join the $F=2$ hyperfine multiplet as the magnetic field approaches zero, see Fig. 1). dE/dB, and therefore the trapping potentials, are the same for the four trapped states to within $\sim 5\%$ for the range of magnetic fields used in this trap. Atoms in the other four levels of the ground-state manifold are repelled from the field minimum and expelled from the trap.

The minimum of the magnetic field (~ 1500 G) is produced between two "pinch" coils in the trap's longitudinal (vertical) direction, and by a superposed octupole field in the radial (horizontal) direction. The trapped atoms experience a confining potential with a predominantly r^6 radial dependence, and an axial dependence which is approximately quadratic at the minimum of the trap. The trap depth is limited radially to ~ 800 G (~ 60 mK for Na) where the octupole field meets the trap enclosure. The radial octupole field and the small radial component of the pinch field combine to give an

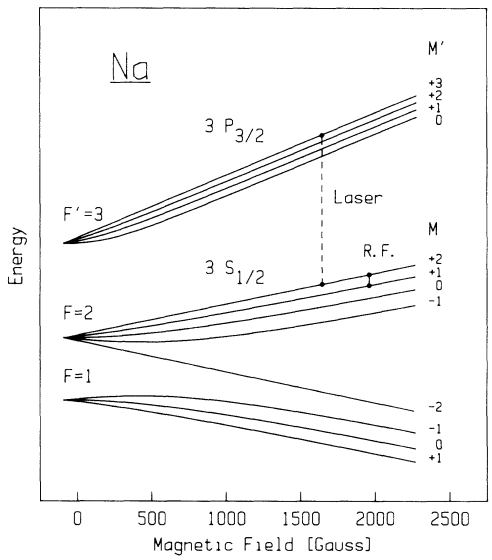

FIG. 1. Relevant energy levels of Na $3^2S_{1/2}$ and $3^2P_{3/2}$ in a magnetic field (not to scale).

off-axis annular trap minimum which is ~ 8 G lower than the field at the center.[7] Low-order multipole "contaminants" in the radial field will further split this into several small local minima of a few gauss, and produce "lumpy" equipotentials. The atoms follow complex trajectories within the trap, with oscillation frequencies in the ≥ 10-Hz range, with mixing of the radial and axial motions on the $\gtrsim 1$-sec time scale (i.e., angular momentum is not conserved on this time scale).

An ~ 40-cm-long, shorted, two-wire transmission line, ~ 0.3 cm from the wall of the trap, was used to produce an oscillating rf magnetic field. The rf signal was generated by a Fluke model 6060A frequency synthesizer followed by a 3-W rf amplifier, and fed to the transmission line via a coaxial cable. At this power level, the rf magnetic field in the trap region was ~ 10 mG, inducing magnetic dipole transitions amongst the trapped magnetic substates with a Rabi frequency $\Omega_R/2\pi$ of ~ 2 kHz.

The trap is loaded from a thermal atomic beam of sodium with use of lasers to slow and cool the atoms (see Ref. 1). After the loading of a sample of atoms into the trap, the loading lasers and atomic beam are blocked, and measurements are performed on the isolated, trapped atoms. A typical fluorescence spectrum for trapped atoms near the field minimum is shown in Fig. 2, scan *a*. The fluorescence was induced by a weak probe laser beam (~ 1 μW/cm^2 and 1 cm in diameter) and monitored with use of a 2.5-cm-long photodiode placed on the wall of the trap enclosure. The trap loading process leaves the atoms in the $|F=2,M=2>$ magnetic substate,[1] and hence only one peak is observed, corresponding to the $|F=2,M=2> \rightarrow |F'=3,M'=3>$ transition (which must decay back to the $|F=2,M=2>$ state to conserve angular momentum).

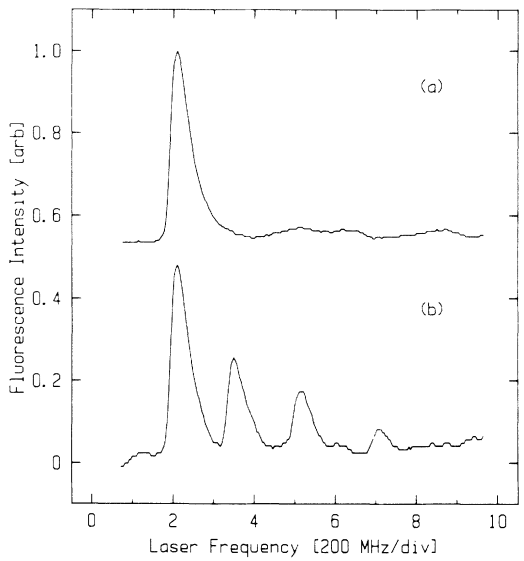

FIG. 2. Fluorescence spectrum for trapped Na atoms induced by a weak circularly polarized probe laser beam. Scan *a*, before the application of the rf pulses, with all the atoms in the $|F=2,M=2>$ state; scan *b*, after the rf pulses, showing population in all four trapped magnetic substates, $|F=2,M=2, 1,0,-1>$.

rf transitions transfer populations between the four trapped magnetic substates $|F=2,M=2,1,0,-1>$ (see Fig. 1), which have fluorescence peaks at different laser frequencies. Figure 2, scan *b* shows a fluorescence spectrum after repeated application of rf pulses at 330, 378, 455 MHz. These frequencies correspond to the three possible $\Delta M = \pm 1$ magnetic dipole transitions among the four trapped substates at the minimum magnetic field in the trap. These frequencies are the most effective for transferring population, as all the trapped atoms, regardless of their total energy, eventually pass close to the field minimum during their motion in the trap. The applied rf pulses were of sufficient power ($\Omega_R/2\pi$- ~ 2 kHz) and duration (~ 5 sec) to ensure that the populations of the four magnetic substates were approximately equalized. [The difference in the four peak heights in Fig. 2(b) is mainly due to optical pumping by the circularly polarized probe laser and disappears at low enough laser power: The branching ratios for decay of the various excited states determine the number of times each atom can be cycled, and therefore the height of the peak.]

An rf resonance curve (Fig 3) for a sample of trapped atoms for the $|F=2,M=2>$ to $|F=2,M=1>$ transition was obtained by inducing rf transitions, and subsequently measuring the relative peak heights for the two states in the fluorescence spectrum as a function of the frequency of the applied rf pulse. As the energy difference between the two levels increases monotonically with magnetic field [$d(E/h)/dB \sim 60$ kHz/G], the rf frequency is resonant only with atoms at one value of the magnetic field. At low rf frequencies, no transitions are induced, since no trapped atoms can be in a magnetic field below the trap minimum ($B_{\min}=1520$ G). The sharp rise of the curve at ~ 328.5 MHz corresponds to atoms at the trap minimum. As the frequency is further increased, the rf resonates with atoms at higher magnetic fields; since it will never resonate with atoms whose total energy is insufficient to allow them to reach this value of the field, the height of the curve decreases monotonically at higher fields. At approximately 360 MHz the lowest edge of the trap is reached (~ 2300 G); nearly all atoms energetic enough to reach this value of the field escape from the trap within the time scale of these measurements (tens of seconds), and so the signal is essentially zero above this value.[8]

The applied rf pulses were of sufficient power and duration [number of Rabi flops: (5 sec) $\times \Omega_R/2\pi \sim 1 \times 10^4$] so that equilibrium was reached in the transfer of population between the two states. At the peak of the resonance curve, a reduction in rf application time by a factor of 5 resulted in only a $\sim 5\%$ decrease in the ratio of the measured peak heights. Our calculations indicate

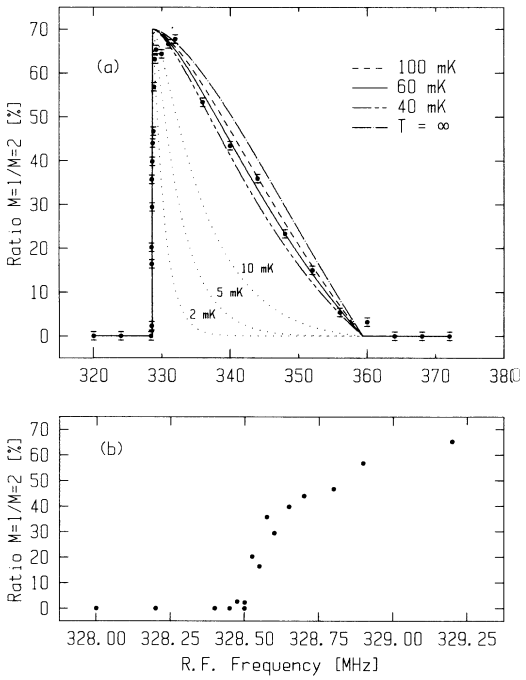

FIG. 3. rf resonance line shape (points) for the $|F=2,M=2>$ to $|F=2,M=1>$ transition. The calculated line shapes (curves) allow us to estimate the temperature of the trapped atoms to be 60^{+40}_{-20} mK. A $T=\infty$ curve is also included for comparison. The calculations for 2, 5, and 10 mK show the greatly increased sensitivity to temperature for colder samples. The sharp rise at 328.5 MHz, expanded in (b), corresponds to atoms at the minimum magnetic field of the trap (error bars are about the size of the points).

that the transition was also saturated away from the trap minimum. The height of the resonance curve at each frequency is therefore determined by the fraction of atoms energetic enough to reach the corresponding magnetic field, and line shape becomes a direct measure of the energy distribution of the atoms in the trap.[9]

The rf line shape has been modeled by assuming a truncated Boltzmann distribution for the atoms in the trap (i.e., all atoms with $E > E_{\text{escape}}$ are assumed to have left the trap), and assuming saturation in the transfer of population between the two states for all atoms energetic enough to come into resonance. Figure 3(a) shows results for three different temperatures (100, 60, and 40 mK), from which we obtain an estimate of 60^{+40}_{-20} mK for the temperature of the atoms in the trap. (Some lack of saturation away from the trap minimum could lower the apparent temperature.)

As $kT \geq E_{\text{escape}}$, the atoms are close to being uniformly spread over all possible states within the trap, and the energy distribution is mainly characterized by the truncation at E_{escape} [as is evident by the $T=\infty$ curve of Fig. 3(a)]. This measurement of the energy distribution is in poor agreement with our previous estimate of 4–20 mK for the temperature of the atoms,[1] which was based on a combination of relative fluorescence intensity measurements for different photodetectors in the trap, and estimates of cooling-laser detuning.[10]

The main point is that the atoms are much hotter than the usual Doppler-cooling limit[11] of ~ 240 μK for Doppler-cooled Na. We attribute this to heating in the transverse direction by the 10 mW/cm^2 standing-wave laser beam, detuned ~ 80 MHz to the red for atoms at the bottom of the trap, used to stop the atoms in the trap.[1] This beam rapidly cools the longitudinal motion of the atoms in the trap[12–14]; cooling of the transverse motion is achieved only through the coupling of the transverse and longitudinal motions of the atoms by the trap, and occurs over time scales of $\gtrsim 1$ sec.

If the intensity of the standing wave were reduced to make the transverse heating rate slow compared to the coupling rate of transverse to longitudinal motion, and the application time correspondingly extended, sample temperatures a few times the usual Doppler limit should be achievable. Figure 3(a) shows the rf line shapes that would be obtained for sample temperatures of 2, 5, and 10 mK. The rf line shape is obviously much more sensitive to temperature variations at these lower temperatures, which will make rf spectroscopy an accurate thermometer in future experiments where these lower temperatures are achieved.

A detailed scan of the rising edge of the resonance curve was performed [Fig. 3(b)], showing a width of ~ 250 kHz. This width may be a reflection of a lack of saturation in the process of population transfer in this region of the curve: The atoms may not have time, within the time scales of these measurements, to find the trap minimum. Other sources of broadening also exist, such as power broadening due to the rf field, and transit-time broadening due to the motion of the atoms through the resonance region. These effects could contribute ~ 100 kHz to the width of the edge. The magnetic field irregularities discussed earlier will also contribute to the width, and may possibly be the origin of the apparent structure in the leading edge of the curve. These field irregularities may be overcome in future experiments by the use of a quadrupole radial field in the trap.

To perform high-resolution rf spectroscopy of the trapped atoms, one must use field-independent transition points, where to first order the transition frequency is independent of magnetic field. For example, at ~ 1 mK the linewidth of the $|F=2,M=2> \rightarrow |F=2,M=1>$ transition at ~ 13.3 kG is ~ 20 Hz. Further cooling of the sample to μK temperatures by currently demonstrated[15] or proposed[6,16] cooling schemes would yield much narrower linewidths, making magnetic traps a promising candidate for high-resolution rf spectroscopy.

In summary, this Letter reports the first rf spectroscopy of trapped neutral atoms. All four trapped magnetic substates of a sample of trapped Na atoms have been populated, and we have obtained an rf resonance curve

by measuring the relative population of the $M=1$ and $M=2$ magnetic substates as a function of applied rf frequency. We have used the technique to determine the energy distribution of a sample of trapped atoms by fitting the measured resonance line shape with that of a model of the atoms in the trap. The demonstration of rf resonance on samples of trapped neutral atoms offers an important diagnostic on the atoms as well as a way to selectively alter their magnetic sublevels. It also opens the way for demonstration of proposed supercooling schemes,[6] which if successful, offer possibilities in high-resolution trapped-neutral-atom spectroscopy and in the study of collective effects such as Bose condensation.

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[9]Since our population ratios are measurements of atomic density in a restricted volume element of the trap over which the magnetic field varies by only ± 10 G, there is no coordinate-space density-of-states dependence, making the shape of the spectrum independent of the trap potential.

[10]The temperature of the trapped atoms seems to depend on experimental parameters such as the loading-laser detuning. We have seen temperatures as low as ~ 25 mK in other rf scans, closer to the values reported in Ref. 3, but not in the ~ 1-mK regime as reported in Science **237**, 26 (1987) and D. E. Pritchard, Phys. Today **41**, No. 1, S-32 (1988). Observation of gravitational effects at the observed temperatures is precluded.

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