Localization of Atoms in a Three-Dimensional Standing Wave

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We have used a heterodyne technique to observe the spectrum of resonance fluorescence from sodium atoms in optical molasses. The spectra show a very narrow feature which we attribute to Dicke narrowing of the fluorescence from atoms localized to less than an optical wavelength in three-dimensional standing-wave potential wells.

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Among the earliest ideas for laser trapping of atoms are those of Letokhov[1] and later Ashkin,[2] who proposed the use of a single laser frequency both to trap and cool atoms in a standing wave. Reference 1 pointed out that the Doppler widths of the spectra of such trapped atoms would be Dicke narrowed.[3] It was later realized that for a two-level atom the depth of the trap is of the same order as the mean kinetic energy to which the atoms can be cooled, so that the atoms are not strongly localized.[4] Recent work on optical molasses has shown that the temperatures of multilevel atoms in light fields containing polarization gradients can be much lower than two-level theories predict.[5-9] Because the atoms are so cold, the standing-wave potential wells can be significantly deeper than the atoms' kinetic energy, providing stronger localization. We present experimental evidence that atoms are localized in a standing wave to less than a wavelength in three dimensions, as suggested in Refs. 1 and 2.

We observe the effect of this localization on the spectrum of the elastic component of the atomic resonance fluorescence from Na optical molasses using a heterodyne technique. Optical molasses is a three-dimensional configuration of counterpropagating laser beams that both cools and viscously confines nearly resonant atoms.[6,10] We find a spectrum with approximately the Doppler width and, in addition, a much narrower peak centered on the Doppler profile. We interpret this narrow peak as Dicke narrowing of the fluorescence spectrum due to trapping of the atoms in three-dimensional potential wells formed by the standing waves.

Previous workers have demonstrated three-dimensional laser traps,[11] but these traps did not confine atoms to less than a wavelength. Other experiments have observed one-dimensional "channeling" by laser light,[12] but those experiments depended on injecting collimated atomic beams into a one-dimensional standing wave, so that the atoms' transverse kinetic energy was small compared to the potential-well depth. The atoms remained channeled if their interaction time was short enough that heating effects were not important. In our experiment, the laser cools atoms with a large initial velocity until they are cold enough to be localized in three dimensions.

Our measurement technique also provides a novel probe of laser-cooled atoms. Previous optical-molasses experiments have relied on ballistic techniques (in which the atoms' ballistic motion is studied after their release from molasses) to measure atom velocities.[5,6,9,10] These methods have the disadvantage of not measuring the velocities while the atoms are interacting with the light. By directly measuring the distribution of Doppler shifts in molasses, a spectral technique complements ballistic measurements. In addition, this technique reveals microscopic features of the atomic dynamics, e.g., trapping in standing-wave potential wells.

We used a heterodyne technique,[13] shown schematically in Fig. 1, to observe the spectrum. The fluorescence imaged from a small region in the molasses is combined with a strong local-oscillator laser beam on a photodiode. The local oscillator is derived from the laser that produces the molasses. The local-oscillator power is

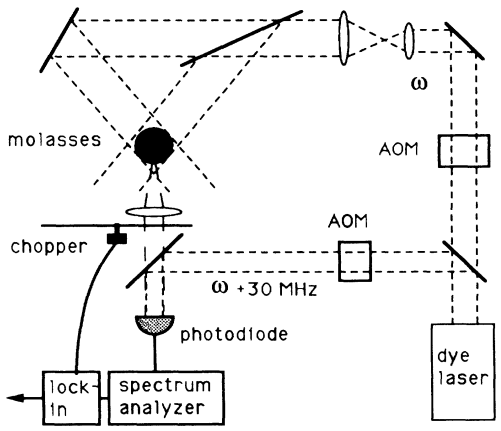

FIG. 1. Schematic diagram of the apparatus.

a few mW, enough so that the shot noise of the light exceeds the detector noise. Both beams are shifted by acousto-optic modulators with a relative shift of 30 MHz. The spectrum of the beat signal is detected with an rf spectrum analyzer.

The only light contributing to the heterodyne signal is that which falls onto the photodiode in the same spatial mode as that of the local-oscillator beam.[13] Thus the coherence volume (that part of the molasses which emits into the correct spatial mode) is approximately the confocal volume of the local-oscillator beam if it were retroreflected and focused onto the molasses by the imaging lens. We use a 250-mm focal-length lens and a local-oscillator beam diameter of approximately 2 mm, producing a coherence volume of about 6×10^{-5} cm^3. Our largest molasses densities are about 10^8 atoms/cm^3, so the coherence volume contains fewer than 10^4 atoms. If each atom isotropically scatters photons at 10^7 s^{-1}, we can at best detect $\sim10^5$ photons/s in the entire spectrum.

Our molasses[5,6] is formed at the intersection of three mutually orthogonal pairs of counterpropagating, linearly polarized laser beams. They are tuned 10 to 30 MHz below the Na $3S_{1/2}(F=2)$-$3P_{3/2}(F=3)$ transition ($\lambda=589$ nm) for which the natural width $\Gamma/2\pi=10$ MHz. In addition, sidebands at ±1732 MHz are impressed on the molasses beams to repump atoms out of the $F=1$ ground state. The local oscillator does not have sidebands. Each of the six molasses beams has an on-axis intensity of about 20 mW/cm^2 and an e^{-2} radius of 4 mm. The saturation intensity I_0 of the transition (intensity at which Rabi frequency equals $\Gamma/\sqrt{2}$) averaged over the Zeeman sublevels is 13 mW/cm^2. At an intensity well below saturation, a stationary atom scatters all the light elastically, i.e., not with a spectral width corresponding to the natural linewidth.[14] For our typical conditions, a two-level atom with this I_0 inelastically scatters about half the light into the Mollow triplet,[15] having a frequency distribution broader than Γ. The remaining, elastically scattered light forms a δ function superimposed on this triplet. We note that our heterodyne technique is ideally suited for making low-temperature Doppler measurements while traditional spectroscopic techniques fail: We are unaffected by either the natural or laser linewidth.

In a simplified view of the experiment, the elastically scattered light will be Doppler broadened to a profile reflecting the distribution of atomic velocities in the molasses. The frequency shift of the scattered light is given by $\Delta\omega=\mathbf{v}\cdot\Delta\mathbf{k}$, where the difference wave vector $\Delta\mathbf{k}=\mathbf{k}_{\text{incident}}-\mathbf{k}_{\text{scattered}}$ and $\mathbf{v}$ is the velocity of the atom. In our experiment, the six $\mathbf{k}_{\text{incident}}$ vectors are determined by the molasses beams and lie along the three space coordinate axes. The $\mathbf{k}_{\text{scattered}}$ vector is determined by our observation direction and lies along the $(1,1,\sqrt{2})$ direction. Therefore an isotropic Maxwell-Boltzmann distribution of velocities should yield a distribution of $\Delta\omega$'s consisting of the sum of six Gaussians:

$$\mathcal{S}(\Delta\omega;v_{\text{rms}})=\sum_{i=1}^{6}A_i\exp\left[-\frac{1}{2}\left(\frac{\Delta\omega}{v_{\text{rms}}\Delta k_i}\right)^2\right], \qquad (1)$$

where $v_{\text{rms}}^2=k_BT/m$ is the one-dimensional rms velocity of the atoms and we assume that the laser beams act independently. We thus neglect cross saturation and multiphoton effects. The A_i's are weighting factors depending on the elastic light-scattering cross section of an atom for the appropriate polarizations and scattering angle. For Na atoms with a temperature of 70 μK ($v_{\text{rms}}=16$ cm/s), the FWHM of $\mathcal{S}$ is 700 kHz. The spectral density of the Mollow triplet is too small to be observed with our present experimental sensitivity and available bandwidth.

Figure 2 shows spectra of the molasses fluorescence at various detunings Δ (laser frequency minus atomic resonance frequency), taken with a resolution bandwidth of 30 kHz. The integration time necessary to obtain each spectrum in Fig. 2 ranged from 1 to 6 h. At the larger detunings the data show a narrow feature on top of a broad distribution. The FWHM of the broad peak at $\Delta=-2\Gamma$ is approximately 700 kHz, nearly the same as we expect [based on the time-of-flight (TOF) method[5]] from Doppler broadening. The width of the narrow peak is about 70 kHz, significantly narrower than the 140-kHz width predicted by Eq. (1) if v_{rms} were equal to the "recoil limit" in Na ($v_{\text{recoil}}=\hbar k/m=3$ cm/s). Using the TOF method, we have ruled out the possibility that our spectral shapes are due to a two-temperature atomic velocity distribution. We have also verified that the nar-

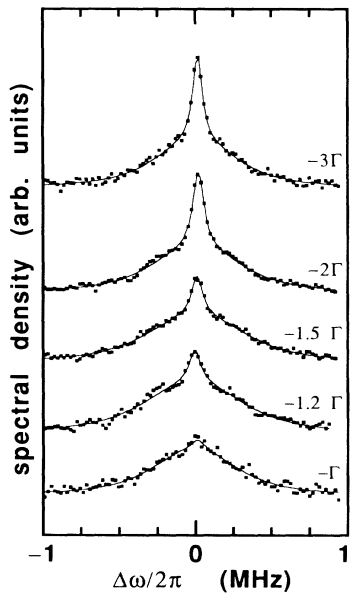

FIG. 2. Heterodyne spectra with a resolution bandwidth of 30 kHz. The detuning is noted at the right. The relative vertical scale between the spectra is arbitrary. The χ^2 per degree of freedom for each fit is approximately 1.

row peak is not caused by spurious scattering of laser light into the detector.

We explain the 70-kHz-wide peak as Dicke narrowing of the radiated spectrum. Dicke narrowing is the suppression of the Doppler width resulting from confinement of the radiating atom to a distance less than a wavelength.[3] One way this could come about is by viscous damping forces in molasses (analogous to collision-induced narrowing in a gas). We rule out this possibility as follows: The damping constant α of Na optical molasses as measured in Ref. 6 yields a characteristic damping length, $l=v_{\rm rms}\alpha/m$, of 1 μm at $T=60$ μK. The condition for significant narrowing is $l<\lambda/2\pi\sim 0.1$ μm, and so the viscous damping provided by the molasses should result in negligible narrowing of the Doppler-broadened spectrum. Furthermore, narrowing by viscous confinement would tend to smoothly deform the Gaussian profile into a Lorentzian,[16] inconsistent with the data.

We ascribe the Dicke narrowing of the fluorescence to confinement of atoms in optical potential wells formed by standing waves in the molasses. For a two-level atom, the standing-wave optical field produces a dipole potential of the form[4] $U(\mathbf{x})=(\hbar\Delta/2)\ln[1+s(\mathbf{x})]$, where $s(\mathbf{x})=[I(\mathbf{x})/I_0]/[1+(2\Delta/\Gamma)^2]$. The intensity $I(\mathbf{x})$ can produce local potential wells of depth U/k_B on the order of 100 μK for our experimental conditions, with a size of $\lambda/2$ (oscillation frequency about 400 kHz). Such wells should trap the atoms for a time sufficient to produce a narrow Lorentzian peak. Interpretating the 70-kHz width of the narrow peak as being due to finite trapping time gives a lower limit of 2.3 μs for the trapping lifetime.

We have fitted the data of Fig. 2 by a seven-parameter function of the form

$$N(\Delta\omega)=a\,\mathcal{G}(\Delta\omega-\omega_{\mathcal{G}};v_{\rm rms})+b\,\mathcal{L}(\Delta\omega-\omega_{\mathcal{L}};\gamma)+c\,, \quad (2)$$

where $\mathcal{G}$ is the sum of six Gaussians as defined by Eq. (1) with the A_i's and Δk_i's fixed by our geometry and $\mathcal{L}$ is a Lorentzian of FWHM γ which describes the contribution of the Dicke-narrowed fluorescence. Figure 2 shows the fits superimposed on the data. The fitted values of the centers $\omega_{\mathcal{G}}$ and $\omega_{\mathcal{L}}$ differ negligibly. The ratio of the areas of $\mathcal{L}$ and $\mathcal{G}$ ranges from less than 0.05 at $\Delta=-\Gamma$ to 0.3 at $\Delta=-3\Gamma$. Fitting the data by two Lorentzians or by two Gaussians does not significantly change the fitted FWHMs. We show in Fig. 3 the FWHMs derived from fits to the data. The error bars shown are the standard deviations of the mean of several runs under the same conditions which were added to produce the spectra in Fig. 2. These error bars are a factor of 2–3 larger than the statistical errors derived from the fitting routine, presumably because experimental parameters such as laser intensity, beam alignment, etc., were not under sufficient control.

We can explain some of the qualitative features of the

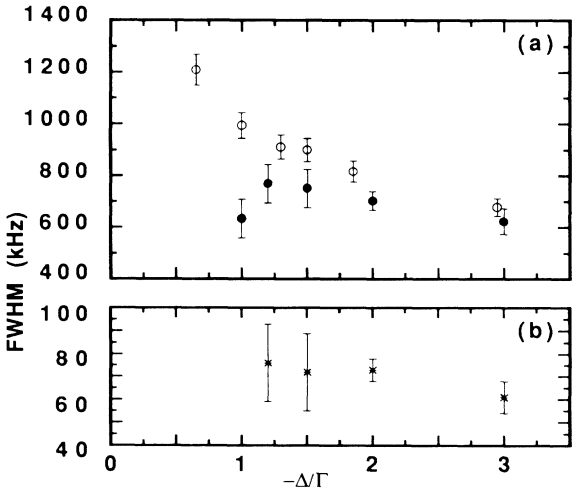

FIG. 3. (a) Widths of the broad peak vs detuning Δ. Solid circles are fits to the data in Fig. 2. Open circles are inferred from TOF measurements. The error bars are standard deviations of the means of repeated measurements. The TOF error bars do not include a possible overall systematic shift of $\approx\pm 100$ kHz. (b) Fitted widths of the narrow peak corrected for our 30-kHz-resolution bandwidth.

data on the basis of ballistic measurements of the detuning dependence of the molasses temperature. The narrow-peak height decreases as the tuning approaches resonance and is nearly zero at $\Delta=-\Gamma$. From TOF measurements (see Fig. 3) we know that the temperature of molasses increases dramatically close to resonance, doubling between $\Delta=-2\Gamma$ and $\Delta=-\Gamma$. On the other hand, the well depth only changes by 30% over the range of detunings used in this experiment. Therefore it is reasonable that the trapping and thus the narrow peak should disappear at small detunings. The change in temperature between -2Γ and -3Γ is much less dramatic and so we expect less change in the narrow-peak height at large detunings. The ratio of the areas of the narrow and broad peaks is a lower limit on the ratio of trapped to untrapped atoms. This is because trapped atoms will radiate some fraction of their total emitted power into the narrow peak,[3] while untrapped atoms contribute nothing to it. Therefore, at the largest detunings we can place a lower limit of 30% on the ratio of trapped to untrapped atoms.

We expect the width of the broad peak to be the Doppler width of the elastically scattered light. While this is borne out at the largest detunings, the broad-peak width at small detunings is almost a factor of 2 smaller than what the TOF measurements predict. We have not found an explanation for the width of the peak at $\Delta=-\Gamma$. We have measured the damping constant in our molasses at detunings of -1Γ, -2Γ, and -3Γ using the method described in Ref. 6. The measured damping constant is no more than a factor of 2 larger at $\Delta=-\Gamma$ than it is at -2Γ or -3Γ. Assuming that the

simple diffusion analysis given in Ref. 6 is correct, we cannot account for the width of the heterodyne signal at $\Delta = -\Gamma$ by diffusive narrowing.

We have developed a Monte Carlo simulation of a radiating two-level atom moving classically in a three-dimensional periodic potential. Of course, such a model neglects many possibly important aspects of the problem: the multilevel nature of the atom, cross-saturation effects, polarization gradients, and the quantum-mechanical motion of particles in wells with a small number of eigenstates. Some of these features are, in fact, responsible for the sub-Doppler-limit temperatures found in molasses; nevertheless, the model should exhibit Dicke narrowing. In our model, the atom continuously emits radiation and is subject to damping and random heating forces adjusted to give the temperatures and damping times measured with TOF techniques.[6] In the absence of potential wells, the model produces the Doppler-broadened spectrum expected for the assumed temperature. With artificially increased damping, the model shows a diffusive narrowing of the spectrum, which smoothly deforms the Gaussian into a Lorentzian distribution, as expected. For damping times as measured with TOF techniques this diffusive narrowing has less than a 10% effect on the width of the spectrum. When potential wells appropriate for two-level atoms under our experimental conditions are included, the model shows strong Dicke narrowing. Unfortunately, the spectral shape is very sensitive to the input parameters, and does not reproduce the detailed form of the measured spectrum for the most reasonable choice of parameters. This is not too surprising considering the many aspects of the problem that are absent from this model. The simulation does not show any signs of the anomalously narrow broad peak present in the data at small detunings. The failures of this simple model suggest that the multilevel, and perhaps quantum-mechanical, aspects of the problem are very important in the formation of the fluorescence spectrum. However, the model does lend confidence to the interpretation of the narrow peak as being due to Dicke narrowing from atoms trapped in wavelength-sized potential wells.

The unexplained narrowness of the broad peak at small detunings remains an intriguing mystery, and we expect to gain new insights from improved measurements. We hope to use the small coherence volume of the technique to observe the molasses with position sensitivity. It also should be possible to observe the fluorescence from other types of laser-cooled samples such as atoms in magneto-optical traps and laser traps.[11] The nondestructive nature of the heterodyne technique should allow many new measurements of cold atoms in laser fields.

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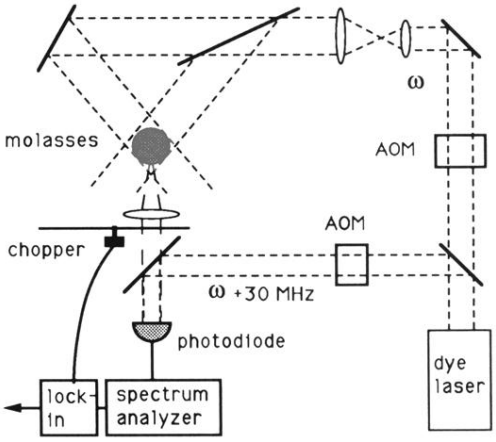

FIG. 1. Schematic diagram of the apparatus.