RAMAN SIDEBAND COOLING IN AN OPTICAL LATTICE

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We demonstrate that degenerate Raman sideband cooling in Lamb-Dicke traps created by far detuned lattices can produce ultracold and very dense samples. With cesium atoms in a lattice at 1064 nm we achieve densities up to 10^{13} cm^{-3} at temperatures of a few μK. In the ultracold samples thus prepared we investigate the loss induced by far-detuned light. The variation of the losses as a function of ground-state s-wave scattering length a_s can be used to measure both the sign and the magnitude of a_s. In the vicinity of a Feshbach resonance, we observe narrow resonances of strongly increased loss that display characteristics of bound long-range 3-body molecular states and may be associated to Efimov states.

1 Optical cooling at high densities: towards the quantum degenerate regime

Although optical cooling can enormously increase the phase space density of atomic vapors starting at room temperature, only with evaporative cooling has it so far been possible to bridge the remaining gap of approximately six orders of magnitude necessary to reach the quantum degenerate regime. Forced evaporation in magnetic traps has been used to achieve Bose-Einstein condensation (BEC) for three different alkalis[1] and to approach unity phase space density in fermionic ^{40}K [2]. Notably, this technique has failed for cesium because of its large cross sections for inelastic collisions.[3] In spite of the great success of evaporative cooling, optical cooling into the quantum degenerate regime remains an important goal, particularly in view of the restrictions imposed by the elastic and inelastic collision properties of the magnetically trappable states, the relatively long time scales necessary for evaporation, and the accompanying significant reduction in atom number.

Recently, significant progress has been reported in optical cooling at high atomic densities in Lamb-Dicke traps, where the trap vibrational energy spacing exceeds the photon recoil energy.[4,5] Raman sideband cooling[4,6,7] uses two-photon transitions to resolve vibrational levels and to prepare a large fraction of the atomic population in the vibrational ground state of the trapping potential. Another method uses linearly polarized far-detuned optical lattices in which the atoms are held while being cooled with conventional polarization-gradient techniques.[5]

For optical cooling at high densities it is necessary to suppress both ground-state and excited-state inelastic collisions. Binary inelastic ground state collisions can be minimized if the cooling simultaneously spin-polarizes the atoms and prepares them in the lowest-energy (high-field seeking) magnetic sublevel, which is stable with respect to exothermic binary collisions. The heating and trap loss due to excited-state collisions can be reduced if the optical pumping, which is necessary in any cooling scheme to decrease the entropy of the atomic subsystem, proceeds at low saturation of the atomic transition. Also an optical pumping rate that is lower than the trap vibration frequencies (Festina Lente regime) is necessary to reduce the detrimental effects of photon reabsorption in dense trapped atomic samples.[8] Finally, the sign of the s-wave scattering length a_s is crucial to the stability of a condensate. For cesium in particular, a recently observed low-field Feshbach resonance[9] allows a_s to be tuned to a positive value for the lowest-energy ground state $F = m_F = 3$. We are currently investigating the stability of the dense cesium gas with respect to inelastic three-body collisions that lead to molecule formation in the vicinity of Feshbach resonances.[10,11]

2 Degenerate Raman sideband cooling of cesium in Lamb-Dicke traps

Our sideband cooling scheme for atoms stored in Lamb-Dicke traps created by optical lattices is depicted in Fig. 1.[4,6] In a small magnetic field of typically 100 mG, where the differential Zeeman energy shift between two neighboring magnetic sublevels equals the vibrational spacing, the atoms are first optically pumped to the lowest energy ground state $F = m_F = 3$. Subsequently an atom that is not in the vibrational ground state of the external trapping potential is transferred to the $m_F = 2$ sublevel by a degenerate Raman transition with two photons of equal frequency but different polarizations, while the vibrational quantum number is reduced. To complete the cycle, the atoms are optically pumped back to the initial internal state. Since the vibrational spacing far exceeds the recoil energy, the vibrational quantum number is likely to be preserved in the optical pumping process, leading to an average cooling of almost one quantum of vibrational energy per cycle. The atoms accumulate in the vibrational ground state of the sublevel $m_F = 3$, which is dark to both the optical pumping and the degenerate Raman transitions. Since the Raman transition is performed with two isoenergetic photons, it can be driven by the far-detuned trapping light itself, thus minimizing the number of necessary lasers and the population of atoms in the excited state.

In a 1D lattice trap created by counterpropagating linearly polarized laser

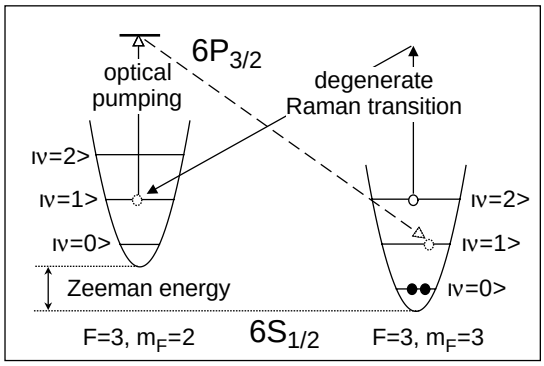

Figure 1. Degenerate Raman sideband cooling in a Lamb-Dicke trap using the two lowest-energy magnetic levels. One cooling cycle consists of a vibration-changing Raman transition followed by optical pumping back to the $m_F = 3$ sublevel. The atoms accumulate in the vibrational ground state of the $m_F = 3$ level (black dots) which is dark to both the optical pumping light and the Raman transitions.

beams, the Raman coupling strength can be adjusted simply by changing the angle between the polarizations of the two beams. For a coupling strength smaller than the spacing between vibrational levels, the cooling spectrum, i.e. the final temperature as a function of applied external magnetic field, reflects the vibrational level structure, and cooling on both the $\nu \rightarrow \nu$-1 and $\nu \rightarrow \nu$-2 transitions can be observed, where ν denotes the vibrational quantum number.[4,6] Cooling with similar final temperatures is also observed when the Raman coupling is further increased beyond the trap vibration frequency, although the different vibrational transitions can no longer be resolved in the cooling spectrum. This type of cooling at high two-photon rate when the vibrational levels are smeared out is particularly suited for fast cooling in 3D lattices, since it eliminates the necessity of creating isotropic lattice sites and allows high-lying vibrational states, where the vibration frequencies are lower than those near the bottom of the potential, to be cooled simultaneously.

For cesium atoms trapped in a far detuned 1D lattice trap at 1064 nm, we have been able to cool a high-density sample in 3D to a final temperature of 2.8 μK by applying 1D Raman sideband cooling along the direction of tight confinement.[4] The other degrees of freedom are cooled through elastic collisional coupling. The corresponding final peak density and phase space density are 1×10^{13} cm^{-3} and 1/180, respectively.

3 Beyond polarization gradient cooling in temperature and density

Degenerate Raman sideband cooling in 3D in conjunction with adiabatic release can significantly lower the kinetic energy of the atoms while preserving their bulk density. To cool atoms collected in a magnetooptical trap, we use a 3D lattice created by two counterpropagating beams and two perpendicular running waves. The four-beam geometry eliminates the need to control the time phases of the beams, since in this case fluctuating time phases do not change the lattice geometry, but merely translate the lattice in space. The polarizations of all four beams are linear and can be rotated with respect to each other to adjust the vibration frequencies and Raman coupling rates for the different directions. We find that the lowest temperatures and highest phase space densities achieved depend weakly on the exact lattice parameters as long as all the vibration frequencies exceed 20 kHz and the Raman rates are comparable to the vibration frequencies. Best cooling is observed for optical pumping with an elliptically polarized beam on the closed $6S_{1/2}$, F=3 to $6P_{3/2}$, F=2 transition, and a repumper on the F=4 to F=4 transition to empty the upper hyperfine level. The lowest 3D temperature we observe is 395 nK for 10 ms of cooling for small atom number, and for large and dense samples 650 nK, which is a factor 7 lower than we find for conventional red- or blue-detuned polarization gradient cooling at the same density of typically 3×10^{11} cm^{-3}. A laser power of 100 mW at a detuning of 10 GHz is sufficient to cool 5×10^{7} atoms close to the 3D vibrational ground state.

If the atoms are released into a trap rather than into free space, it is possible to increase the density with several cycles consisting of cooling, adiabatic release and adiabatic recapture, similar to the method demonstrated in Ref. 5 with direct polarization gradient cooling. In this case the maximum attainable density depends on the detuning of the lattice laser.

4 Limitations of Raman sideband cooling

The temperature and density limitations for Raman sideband cooling can be either due to the optical pumping or the lattice character of the traps. While the lattice detuning can be made so large that the excited state population is negligibly small and only ground-state collisional properties of the atoms are relevant, the optical pumping necessarily involves spontaneous scattering and a small, but non-negligible excited state population.

At high densities the major limitation associated with the optical pumping is reabsorption when the absorption length becomes shorter than the sample

size. While in general one would expect an additional heating of the gas by two recoil energies per reabsorption and reemission cycle, it has been theoretically shown that this additional heating can be avoided if the collective optical pumping rate is chosen to be smaller than the trap vibration frequencies.[8] In this case the additional photon scattering events are elastic and do not change the populations of the trap vibration levels. Additionally, strongly anisotropic traps alleviate the reabsorption problem.[8] Indeed we do observe a heating of the sample if the optical pumping rate is made too large, whereas for low optical pumping rates our final temperatures are independent of this rate. The transition roughly occurs at the lowest trap vibration frequency. At our highest densities for cigar-shaped atomic clouds the smallest sample size exceeds the absorption length by more than a factor of five.

If the additional heating due to reabsorption is avoided, reabsorption can still significantly slow down the collective optical pumping rate.[12] Even a slow process that depletes the final state can then impose a cooling limit. In the case of degenerate Raman sideband cooling, the dark vibrational ground state of the $m_F = 3$ potential can be emptied due to polarization impurities of the optical pumping beam, off-resonant Raman transitions, or light-induced collisions. Our best cooling results at very high densities always correspond to ground state populations of only 85%. Since the temperature depends logarithmically on the population of the excited state, it is experimentally very difficult to lower the temperature beyond a certain fraction, typically 0.4, of the vibrational spacing. For the important class of mesoscopic traps, which have one or two directions with tight Lamb-Dicke confinement and other large dimensions, and which can store large numbers of atoms, the temperature limit associated with a fixed fraction of the higher vibration frequency will limit the attainable density and phase space density.

Density limitations are also associated with the lattice that provides the trapping potential. For lattices with detunings smaller than 50 GHz, we observe a loss of atoms that can be attributed to radiative collisions and that limits the peak density in 3D lattices to about 5×10^{12} cm^{-3}. This value is comparable to the density of lattice sites. For a very far detuned 3D lattice at a wavelength of 1064 nm, we observe no radiative loss. However, there appears to be a strong heating of some of the atoms unless the lattice is turned on very slowly on a time scale that is much longer than the single-atom vibration frequency. This phenomenon observed at a density of several atoms per lattice site is still under investigation.

5 Condon point suppression of radiative collisions and novel narrow resonances

The losses induced in a high-density sample in the presence of a far-detuned light field (radiative collisions) are of crucial importance for optical cooling and for the stability of a condensate in an optical trap. They can also constitute an extremely useful new tool for the investigation of atomic ground state interaction parameters[13], since the radiative collision probability amplitude is proportional to the two-atom ground state wavefunction, evaluated at the Condon point[14]. As the Condon point can be varied by simply changing the detuning of the light, the light-induced losses can be used to map out the ground state pair correlation function, from which interaction parameters such as the s wave scattering length a_s and even the long-range part of the interatomic potential can be determined.[13] In particular, if the Condon point equals the magnitude of the scattering length, the radiative loss will be smaller for a positive than for a negative scattering length, because a node of the scattering wavefunction occurs near a_s for $a_s > 0$. This allows a very simple determination of the sign of a_s.

We have measured the reduction in radiative loss for positive scattering lengths using a Feshbach resonance for the state $F = m_F = 3$ near 30 G [9] to tune a_s through the whole continuum of values. In addition, we observe several narrow resonances of increased loss for certain values of the magnetic field.[13] Additional resonances appear at larger detuning of the light field. Such spectra for detunings of 0.06 nm and 8 nm are shown in Fig. 2. The positions of the resonances are independent of all other external parameters, in particular they do not depend on the detuning of the light that induces the loss and determines the Condon point. The relative heights of the resonances, however, are a function of the detuning. The resonances are asymmetric with a width proportional to the gas temperature. The loss rate is linear in the light intensity for small intensities and saturates at a value determined by the density for higher laser intensity. This supports the interpretation that a bound molecular state is scanned across the continuum of collision energies as the magnetic field is changed, with the loss induced by a single-photon transition to the excited-state continuum. When the (quasi-) bound molecular state is tuned into resonance with the collision energy, the atoms are more likely to be found at close range, and thus have an increased probability to be excited by the light at the Condon point, which produces trap loss.

To decide how many cesium atoms form the (quasi-) molecule, we have measured the time evolution of the atomic density. The observed time evolution definitely favors a 3-body over a 2-body process, although we cannot

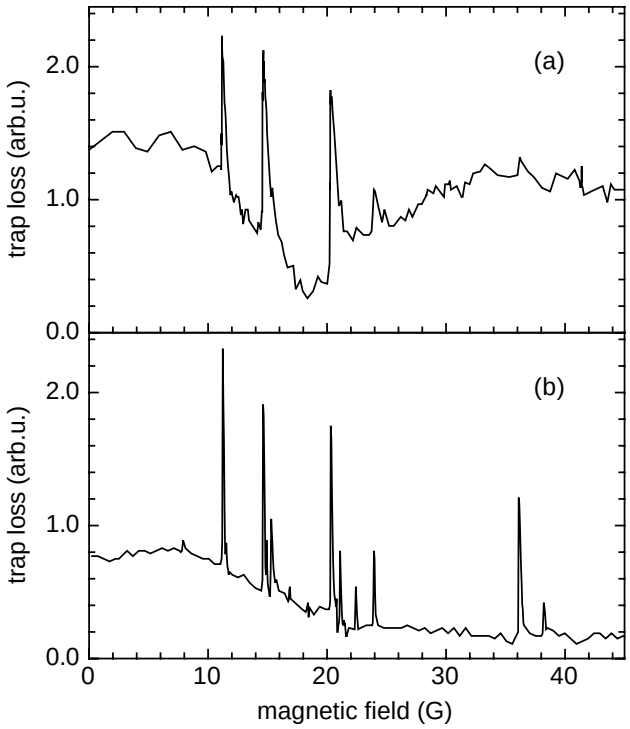

Figure 2. Radiative loss as a function of magnetic field for a detuning of 25 GHz (0.06nm) (a) and 8 nm (b). The broad feature corresponding to reduced loss in (a) is due to the suppression of radiative collisions when a positive scattering length is tuned to the Condon point.

completely rule out the latter. This implies that the bound state responsible for the increased loss is very likely to belong to a molecule consisting of three, rather than two, cesium atoms. The large number of resonances within a small magnetic field interval of only 10 G indicates closely spaced energy levels of a weakly bound, long-range molecule. This conclusion is further supported by the fact that several of the resonances are also observed for detunings as small as 10 GHz, corresponding to a Condon point of 100 Å for a two-atom system. Since the spacing of vibrational levels in a Cs_2 molecule is much too large to explain the large number of levels, possible explanations for the narrow resonances include long-range rotational states in the case of

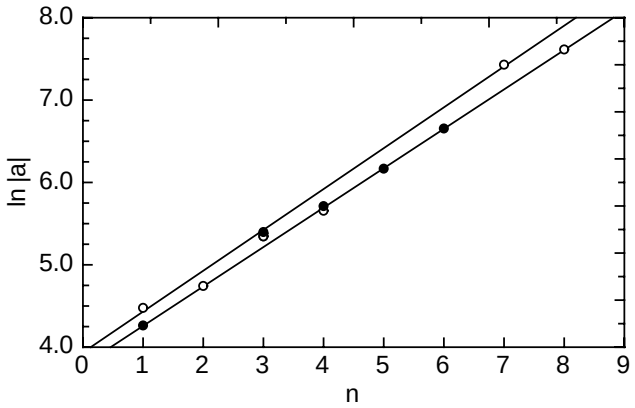

Figure 3. The logarithm of the magnitude of the calculated scattering lengths for the narrow resonances vs. resonance number. The open dots indicate negative and the solid dots indicate positive scattering lengths.

a two-body loss, or Efimov states[15] in the case of a three-body loss. The latter are weakly bound, long-range three-body states, that occur in systems with a large two-body scattering length of either sign. If the narrow peaks in Fig. 2 are associated with Efimov states, the resonances should be periodic in the quantity $\ln|a_s|$, since this quantity determines the WKB-like phase of the 3-body bound state.[15] This is equivalent to the condition that successive resonances should be spaced by a constant factor in the 2-body scattering length a_s. In the case of spin 0 particles[15], this factor is approximately $e^{\pi} \approx 22$. As Fig. 3 shows, we do in fact observe an approximately linear dependence of $\ln|a_s|$ on the resonance number, using scattering lengths that are calculated from a simple dispersive fit to the measured elastic cross section[9]. Furthermore, several of the resonances appear symmetrically for positive and negative a_s, as expected for Efimov states. However, successive resonances are spaced only by a factor $\approx$2 in $|a_s|$, which is much smaller than Efimov's prediction for spinless particles. This difference may be due to the Feshbach resonance tuning of the scattering length or the non-zero spin structure of cesium.

The association of these narrow resonances with Efimov states is supported by (1) the long-range character of the molecular states, (2) the observed time-evolution of the atomic density that strongly favors a 3-body process, (3) the symmetrical occurence of several resonances for both signs of a_s, (4) the observed asymmetric lineshape, and (5) the increase of a_s by

a roughly constant factor between successive resonances. It will be crucial to obtain decisive experimental evidence as to how many atoms make up the weakly bound (quasi-) molecule. Also, an improved theoretical understanding of Efimov states in molecules, when the two-body scattering length is tuned by means of an atomic Feshbach resonance, will be highly desirable.

6 Limitations to the parameter space where BEC of cesium is possible

Extraordinarily large inelastic binary collision cross sections have prevented the attainment of BEC in cesium using evaporation in magnetic traps.[3] These binary losses can be avoided by optically trapping the lowest-energy ground state $F = m_F = 3$. At low magnetic field, however, the scattering length of this state is negative and very large, which would allow only an exceedingly small number of condensed atoms for experimentally feasible traps. The recently discovered low-field Feshbach resonance[9] with a width larger than 13 G permits the scattering length of this state to be tuned to positive values in order to create a stable condensate with a repulsive mean interaction energy.

Unfortunately, large losses near a Feshbach resonance have been observed in a sodium BEC[11], and 3-body losses that scale as a_s^4 have been predicted to occur generally near Feshbach resonances[10]. At densities close to 1×10^{13} cm^{-3}, we observe density-dependent losses in the non-condensed cesium gas that vary as the scattering length is changed. As yet, we cannot determine with certainty if the losses are due to 2-body or 3-body collisions, although the 3-body fit is slightly better. Independent of the cause, these results and theoretical calculations[10] indicate that if the final gap in phase space density is to be bridged by evaporation, this will be feasible at best in a relatively narrow region of small and positive scattering lengths, because the inelastic losses will otherwise limit the lifetime of the sample to a value too short for evaporative cooling. If it is possible to cool the sample optically into the quantum degenerate regime on a short time scale, condensation in a larger region of scattering lengths should be possible. In both cases it will probably be necessary to expand the condensate to lower density in order to attain a metastable system that will be useful for further experiments.

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