Evaporative Cooling of Sodium Atoms

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We have observed evaporative cooling of magnetically trapped sodium atoms. A novel technique, rf induced evaporation, was used to reduce the temperature by a factor of 12 and increase the phase space density by more than 2 orders of magnitude. The elastic collision cross section of cold sodium atoms in the $F = 1$, $m_F = -1$ hyperfine state was determined to be 6×10^{-12} cm^2, which implies a positive value of the scattering length.

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Cooling neutral atoms to submicrokelvin temperatures offers the exciting possibility of studying novel phenomena at long de Broglie wavelengths, most notably quantum degeneracy effects. Furthermore, such cold atoms are promising for a host of scientific applications such as precision measurements, high resolution atom lithography, and atom interferometry. Recently, several techniques have been demonstrated which allow the cooling of atoms to temperatures below the recoil limit. Optical techniques such as velocity selective coherent population trapping [1] and Raman cooling [2] have achieved subrecoil temperatures in one or two dimensions. They work best at low atomic densities. At high densities, temperature and density are eventually limited by the absorption of incident or scattered light [3,4] and by heating and trap loss due to excited state collisions [5]. The technique of forced evaporative cooling relies on collisional thermalization and has no recoil limit to overcome; therefore it seems ideally suited to reaching very low temperatures in dense atomic samples. Unfortunately, it requires high initial densities which could until recently only be prepared by cryogenic methods applicable solely to atomic hydrogen [6,7].

In this paper we elaborate on our initial demonstration of evaporative cooling for an atom different from hydrogen, Na [8], that was contemporaneous with the announcement of similar results in Rb [9]. Very recently, evaporative cooling of Na has also been observed in an optical trap [10]. By using a combination of different cooling and trapping techniques involving lasers and magnetic fields we were able to obtain the high initial density required for evaporative cooling. This closes the gap between optical cooling at relatively low density and collisional cooling which requires high density, and frees evaporative cooling from the restrictions of a cryogenic environment by using laser cooling as the precooling stage. Furthermore, it has been pointed out that alkali atoms have advantages for evaporative cooling due to the large elastic cross section [11].

Evaporative cooling requires the selective removal of the most energetic atoms from the trap. When the remaining atoms rethermalize there is a net cooling effect [12]. The selection of evaporating atoms is usually done by lowering the height of the trapping potential [6]. Using this scheme in a spherical quadrupole trap would weaken the confinement, thus lowering the density and slowing down the evaporation process. This can be avoided in more complicated trapping geometries [6], but the spherical quadrupole trap provides the tightest confinement and therefore has advantages for evaporative cooling [13]. In this paper, we demonstrate a novel evaporation technique, rf induced evaporation, which was originally suggested in Ref. [14]. Atoms are removed from the trap by inducing an rf transition to an untrapped state without varying the trapping potential. Using this technique we observed strong evaporation of magnetically trapped sodium atoms lowering the temperature by a factor of 12 and increasing the phase space density by a factor of more than 100.

A high density of magnetically trapped atoms is obtained in a multistep procedure. Atoms were initially slowed in a Zeeman slower and loaded into a dark SPOT [3]. Typically, 10^9 to 10^{10} atoms were confined at densities of 5×10^{11} cm^{-3}. Sub-Doppler temperatures of 100 μK were achieved by turning off the weak quadrupole magnetic field and applying a dark version of polarization gradient cooling. By employing very weak repumping sidebands, the density of atoms in the $F = 2$ state is kept low enough to avoid absorption of the cooling light. This method should avoid heating effects due to high optical density as observed in Cs [15]. The laser light was quickly (<1 ms) shut off and a magnetic quadrupole field of 100 G/cm switched on. Care was taken to provide a magnetic potential which is neither too steep (which would add too much potential energy, causing heating) nor too shallow (which would result in a loss of density as the cloud expands). The density in the magnetic trap is a factor of 10 lower than in the light trap because only about one-third of the atoms are in the trapped $F = 1$, $m_F = -1$ state, and because of some expansion of the cloud. Subsequently, the magnetic field gradient was increased to 1000 G/cm.

Adiabatic increase of a linear potential by a factor of η results in an increase in density by a factor of η and in temperature by a factor of $\eta^{2/3}$. The adiabaticity of the

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compression was verified by expanding the cloud again and retrieving the initial temperature to within 10%. The adiabatic increase of the field gradient by a factor of 10 led to an enhancement of the elastic collision rate by a factor of 20 which was crucial for obtaining fast evaporation. The sample of atoms prepared in this way had typically 8×10^8 atoms at a peak density of 5×10^{11} and a temperature of 1 mK.

The number, the density, the temperature, and, also, the spatial distribution of the trapped atoms were determined by absorption imaging. Identical results obtained with two successive images of the same atoms verified that the probing was nonperturbative. Indeed, the number of absorbed photons was much less than one per atom. Atoms in our spherical quadrupole trap oscillate with an effective frequency on the order of kHz. This makes it rather difficult to *suddenly* switch off the magnetic trap and image the atoms at zero magnetic field. Therefore, the absorption images were taken *in situ* inside the magnetic trap and were compared to simulations that included the full hyperfine Hamiltonian and the varying magnetic field direction with respect to the probe polarization [16]. If the probe frequency is in resonance with a Zeeman shifted hyperfine transition in the spatial wings of the cloud, the absorption image appears wider. However, identical temperatures and densities were obtained from the fits to images taken with different probe frequencies.

The major goal of this multistep procedure of cooling and compressing atoms was to obtain a sample of magnetically trapped atoms with an elastic collision rate much higher than the loss rate due to background gas collisions. A residual pressure of about 5×10^{-11} mbar resulted in a trapping time of 30 s. In previous work [17] the time between collisions and the trapping time were both approximately 15 s. For our highest density samples, the average time between collisions was 20 ms (see below), resulting in 1500 collisions per trapping time, more than sufficient to study elastic collisions and observe evaporative cooling.

The driving process for evaporative cooling is elastic collisions. For submillikelvin sodium atoms only one or two partial waves (s and d wave) contribute to the scattering. Depending on the s-wave scattering phase shift, the zero-temperature cross section varies between zero and infinity. The phase shift depends critically on the binding energy of the last bound vibrational level and is very sensitive to fine details of the interaction potential.

We were able to deduce the elastic collision cross section by observing the thermalization of an atom cloud. For this a nonthermal distribution was prepared by temporarily displacing the trap center by about 1 mm along the symmetry axis (z axis). This was accomplished by suddenly imbalancing the current through the two solenoids of the spherical quadrupole trap. Within 100 ms, anharmonicities lead to dephasing of the initial oscillations, resulting in a cloud which was elongated along the z direction. Using absorption imagining, the relaxation of the anisotropic energy distribution was observed by recording the shape of the cloud as a function of time [17]. In principle, equilibration might happen due to the ergodic evolution of orbits in the trap independent of collisions. However, Monte Carlo simulations showed that the spherical quadrupole trap is nonergodic for periods of at least 10 s. In addition, we lowered the density by a factor of 12 by optically pumping atoms to nontrapped states using off resonant laser light, and found the $1/e$ relaxation time τ to be inversely proportional to the product of peak density n_0 times velocity (Fig. 1). From that we estimate a lower bound for the ergodic mixing time of 30 s, completely negligible to the observed relaxation time of 1 s. Note that we determined relaxation times for the uncompressed cloud. Assuming constant elastic cross section, adiabatic compression to the maximum field gradient reduced the relaxation time to about 50 ms, comparable to the dephasing time.

According to calculations by Snoke and Wolfe it takes five elastic collisions for complete thermalization [18]. Monte Carlo calculations gave 2.7 for the ratio of elastic collision rate to the relaxation rate $1/\tau$ which describes the cross-sectional relaxation of a cloud with an anisotropic energy distribution [17].

We determine the elastic cross section σ from the equation $n_{\text{eff}} \sigma v = 2.7/\tau$, where $v = 4(k_B T/\pi m)^{1/2}$. The effective density is defined by $n_{\text{eff}} = \int n^2(\mathbf{r})\, dV / \int n(\mathbf{r})\, dV$, which is $n_0/8$ for an equilibrium distribution in a linear potential. The result is $\sigma = (6.0 \pm 3.0) \times 10^{-12}$ cm^2 for the elastic cross section. The estimated uncertainty mainly reflects three standard deviations of the fit with smaller contributions from the determinations of density and temperature.

The measurement was preformed at 200 μK, well below the temperature at which one expects d-wave

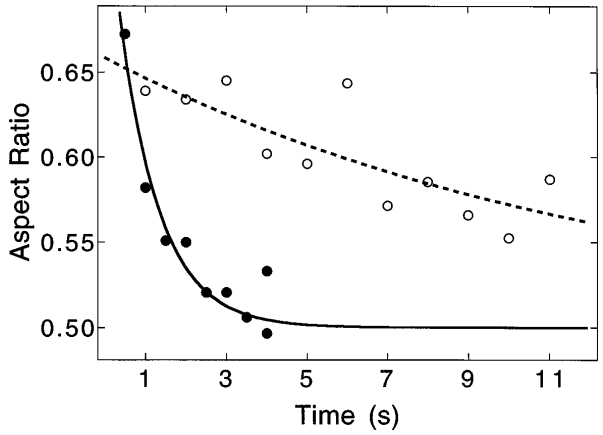

FIG. 1. Thermal relaxation of an atom cloud after one-dimensional heating. The figure shows the time variation of the aspect ratio of the cloud for two different initial densities (solid circles: 5×10^{10} cm^{-3}; open circles: 4×10^9 cm^{-3}). The lines represent simple exponential fits with time constants of 1.0 and 13 s, respectively.

contributions or a temperature dependence of the s-wave cross section [19,20]. We can therefore deduce the scattering length $a = \pm(92 \pm 25)a_0$ using the relation $\sigma = 8\pi a^2$.

Recently, accurate calculations of the scattering length of cold sodium atoms have been performed [21,22]. For sodium atoms in the $F = 1$, $m_F = 1$ state the result was $56a_0 < a < 154a_0$, and for an alternative choice of potentials $-36a_0 < a < 154a_0$ [21]. Thus negative values of the scattering length which would result in an unstable Bose condensate could not be ruled out. Our experimental result, together with the theoretical prediction, shows that sodium in the $F = 1$, $m_F = -1$ state has a large positive scattering length and is therefore an ideal choice for the pursuit of Bose-Einstein condensation in alkali atoms.

In rf induced evaporation, atoms are spin flipped to an untrapped state when they are in resonance with an applied rf field. Because this resonance frequency is a function of magnetic field B, atoms are selectively removed at a specific value of B. In the case of transitions between magnetic sublevels m_F one has $\omega_{\rm rf} = |g|\mu_B B/\hbar$, where g is the g factor. Since the trapping potential is given by $m_F g \mu_B B(\mathbf{r})$, only atoms which have a total energy $E > \hbar\omega_{\rm rf}|m_F|$ will evaporate, or, in other words, application of rf radiation of frequency $\omega_{\rm rf}$ creates a trap lip with a height of $\hbar\omega_{\rm rf}|m_F|$. An advantage is that the "lip" exists over a large surface rather than a small surface saddle point region of the trap [6].

For a more detailed description of the evaporation process one has to use the dressed-atom formalism to obtain the eigenvalues of an atoms in a combined magnetic and rf field. These solutions represent the adiabatic potential for the motion of the atoms. Slowly moving atoms follow the avoided crossing and stay on the lowest potential surface. The "spin-flip" process is a two-photon adiabatic transition from a trapped to an untrapped state. If, as in our experiments, the strength of the rf magnetic field is not strong enough to ensure adiabaticity, one has to use Landau-Zener probabilities for spin flips at the avoided crossings. The evaporation of atoms saturates when the Landau-Zener probability is comparable to the ratio of oscillation time to equilibration time.

Forced evaporative cooling requires a continuous decrease of the potential depth to maintain it at an optimum value proportional to the decreasing temperature [12]. This was accomplished by ramping down the rf frequency. If the rf frequency changes too quickly, the atomic distribution is only truncated without increase in phase-space density; if it changes too slowly, more atoms than necessary are lost due to background gas collisions during the evaporation. The optimum result is obtained when the rf sweep keeps pace with the collisional thermalization [13,23]. As discussed in Ref. [24] the phase-space density increase in evaporative cooling is due to the combined effect of truncation and collisions; neither process alone would increase phase-phase density.

Forced evaporation can also be obtained by adiabaticity compressing the atoms at fixed rf frequency. We used a combination of both methods. After the initial loading a constant rf frequency of 30 MHz was applied and the magnetic field gradient increased by a factor of 10 in 1 s. With the rf off, this increased the temperature by a factor of 5, whereas with evaporative cooling the temperature went up by only 20%. Subsequently, the rf frequency was reduced linearly to 7 MHz within 200 ms. The temperature and density of the cloud were probed at various stages of the evaporation process after decompression to the initial field gradient. This ensured identical conditions for probing atoms and avoided very high optical densities and small clouds.

The results are shown in Fig. 2. We observed temperature reduction by a factor of 12 and a simultaneous increase in density by a factor of 4.6, resulting in an increased phase space density by a factor of 190. This means that the elastic collision rate, which is proportional to nv, was increasing during evaporation. At the intermediate stage of evaporation in Fig. 2, the elastic collision rate had doubled and then went down slightly, probably due to the loss of atoms by Majorana flops (see below). This means we are already in the regime of self-accelerating evaporation.

Indeed, one expects runaway evaporation when the number of collisions during a trapping time exceeded 25 [13]. With an estimated collision rate of 50/s in the compressed cloud we exceed this value by a factor of about 60. The cloud after evaporation had a temperature of 80 μK and a density of 2×10^{12} cm^{-3}, as inferred from 17 μK and 1.8×10^{11} cm^{-3} measured after adiabatic de-

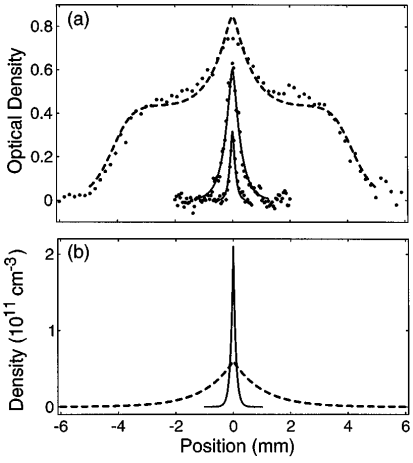

FIG. 2. Optical density (a) and density (b) before and after evaporative cooling. (a) The initial cloud was cooled by adiabatic compression at constant rf frequency (middle trace) and further cooled by decreasing the rf frequency. The lines are fits to the observed profiles. The "bumpy" structure of the initial profile is a result of Zeeman shifts of the transitions used for probing the atoms. (b) Density before and after evaporation as obtained form the fits to the optical density profiles (temperatures are 200 and 17 μK, respectively).

compression. The uncertainties on temperature and density are estimated to be 10% and 20%, respectively. Our final phase-space density is 2×10^4 times smaller than that required for Bose-Einstein condensation.

The current limitation of our evaporative cooling is an observed increased trap loss for small atom clouds. For the coldest temperatures achieved, the trapping time decreases from 30 s to a few seconds. This is most probably due to Majorana flops, nonadiabatic transitions to an untrapped state which happen in the center of the trap near the zero of the magnetic field. It may be shown that this loss rate is proportional to the ratio of the area of the "nonadiabatic" region around the center to the cross-sectional area of the cloud. From a Landau-Zener model we estimate the lifetime to be $500d^2$ (in seconds), where d is the cloud diameter in mm. The observed decrease in trapping time for cloud sizes of 100 μm is in qualitative agreement with this model.

In conclusion, we have evaporatively cooled alkali atoms and increased the phase-space density by more than 2 orders or magnitude. We have achieved the initial conditions necessary for accelerated evaporation and identified nonadiabatic transitions in the center of the trap as the current limitation. Further progress should be possible after transferring the atoms into a trap with a different field geometry which does not have magnetic field in the center.

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