Evanescent-wave trapping and evaporative cooling of an atomic gas near two-dimensionality

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A dense gas of cesium atoms at the crossover to two-dimensionality is prepared in a highly anisotropic surface trap that is realized with two evanescent light waves. Temperatures as low as 100 nK are reached with 20,000 atoms at a phase-space density close to 0.1. The lowest quantum state in the tightly confined direction is populated by more than 60%. The system offers intriguing prospects for future experiments on degenerate quantum gases in two dimensions.

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Systems with reduced dimensionality have attracted considerable attention in various areas of physics as they exhibit strikingly different properties in comparison to the three-dimensional case. In the field of atomic quantum gases, there has been long-standing interest in two-dimensional systems in view of the phase transition to a quantum-degenerate gas [1], the onset of coherence [2], and modifications of interaction properties [3]. Spin-polarized hydrogen on a liquid-helium surface represents a 2D quantum gas as the adsorbed atoms occupy a single quantum state [4], and evidence of quantum degeneracy has been obtained [5]. The required cryogenic set-up and the lack of efficient optical diagnostics, however, makes detailed experimental studies on 2D gases of hydrogen very difficult, and thus there is great interest to realize analogous systems by using more readily accessible laser-manipulated atoms.

Few experiments with laser-cooled atoms have so far approached 2D. In standing-wave traps conditions were obtained with the predominant population of the lowest quantum state in one dimension [6, 7, 8]. In such traps, however, many individual traps are populated simultaneously so that phenomena related to individual systems are hardly accessible. Another approach is an anisotropic optical trap made of an elliptically focused laser beam and loaded with a Bose-Einstein condensate [9]; this trap however is diffraction-limited and thus provides relatively small level spacing. Optical surface traps combine tight confinement in one direction with a single potential well. Recent surface trapping experiments [10, 11] have approached 2D by populating a few bound states, yet far away from quantum degeneracy.

In this Letter, we report on trapping and evaporative cooling of a dense gas of Cs atoms in the combined field of two evanescence light waves. In this highly anisotropic surface trap, evaporative cooling is performed by ramping down the trap potential, and temperatures as low as 100 nK are reached with 20,000 atoms at a phase-space density close to 0.1. In the tightly confined direction a ground-state population of more than 60% is achieved, and a gas at the crossover to two-dimensionality is realized.

The double evanescent-wave trap (DEW trap, see illustration in Fig. 1) was suggested by Ovchinnikov, Shul’ga, and Balykin already in 1991 [12] and has been discussed in various contexts, like 2D gases [13, 14], atom coupling to microspheres [15], cavity-induced cooling [16], quantum reflection [17], integrated optical waveguides [18], and nano-traps [19]. Despite of this considerable interest, the DEW trap has not been experimentally realized until now, which may be explained by the difficulty of loading a narrow potential well very close to a material wall. We have accomplished efficient loading by transfer from a cold and dense reservoir of cesium atoms. In our case, this is provided by the non-dissipative optical surface trap introduced in Ref. [20]. The demonstrated principle of loading from a dense reservoir is universal.
and may be also implemented with other optical or magnetic trapping schemes.

The DEW trap relies on the optical dipole force in a combination of a repulsive and an attractive EW field, produced on the surface of a dielectric prism by total internal reflection of two laser beams. The two fields with wavelengths $\lambda_i$ ($i = r, b$) are created by laser sources tuned below and above the atomic transition (red and blue detuning), respectively. Normal to the surface the two fields decay exponentially with characteristic lengths of $\Lambda_i = \lambda_i/2\pi \times (n^2 \sin^2 \theta_i - 1)^{-1/2}$, determined by the angle of incidence $\theta_i$, the optical wavelength $\lambda_i$, and the refractive index $n$. A narrow, wavelength-sized potential well is created close to the surface when the decay length $\Lambda_b$ of the repulsive EW is short compared to $\Lambda_r$ of the attractive field. This is reached by setting the red-detuned laser beam near to the critical angle $\theta_c = \arcsin(1/n)$ of total internal reflection and the blue one much further away. Typical angles are $\theta_c - \theta_r$ of a few tens of a degree and $\theta_r - \theta_c$ of a few degrees. In addition to this tight confinement normal to the surface, lateral confinement is achieved when the extension of the attractive EW field is smaller than the one of the repulsive EW field; this can be obtained by an appropriate choice of the Gaussian beam waists $w_i$ of the two applied laser beams.

In our experiment, the repulsive EW is generated with the beam of a Titanium-Sapphire laser at a wavelength of $\lambda_b = 850.5$ nm (1.6 nm blue detuning with respect to the Cs D2 line at 852.1 nm). The angle of incidence is set to $\theta_b = 46.8^\circ$, i.e. 3.2° above the critical angle of the fused silica prism ($n = 1.45$). The beam for the attractive EW is derived from an Yb fiber laser with $\lambda_r = 1064$ nm and set to 0.2° above $\theta_c$. The resulting decay lengths are $\Lambda_b = 395$ nm and $\Lambda_r = 2.0$ $\mu$m. The beams are focused to waists of $w_b = 400$ $\mu$m and $w_r = 160$ $\mu$m.

The total trap potential can be written as

$$U(r) = U_b(x,y)e^{-2z/\Lambda_b} - U_r(x,y)e^{-2z/\Lambda_r} - \omega_{\text{D}W} z^{-3} (1 + 2z/\lambda_{\text{eff}})^{-1} + mgz,$$

where $U_i(x,y) = \hat{U}_i \exp(-2x^2/w_i^2 - 2y^2/w_i^2 \cos^2 \theta_i)$ are the optical potentials directly at the surface ($z = 0$). For the maximum potentials in the center of the trap we calculate $U_b/k_B = 325$ $\mu$K and $U_r/k_B = 43$ $\mu$K at typical beam powers of $P_b = 1.15$ W and $P_r = 1.2$ W, respectively; $k_B$ denotes Boltzmann’s constant. The laser beams are linearly polarized in the plane of incidence (TM polarization) to maximize the EW field. The third term in Eq. 1 describes the van der Waals surface attraction [21, 22] with a coefficient $\omega_{\text{D}W} = 2.8 \times 10^{-49} \text{kg m}^3 \text{s}^{-2}$ and an effective wavelength $\lambda_{\text{eff}} = 866$ nm corresponding to the line center of the D-line doublet; this surface attraction is found to play a minor role for our experimental conditions. The last term in Eq. 1 represents the gravitational potential with $m$ denoting the mass of a Cs atom and $g$ representing the gravitational acceleration.

Fig. 1 shows the calculated potential in the center of the trap ($x, y = 0$). For $P_r = 1.2$ W, the power that we use for loading, a 13 $\mu$K deep well is realized with its minimum located 0.9 $\mu$m away from the surface. For decreasing power of the attractive EW the well becomes shallower and the minimum moves away from the surface. Without attractive EW (dashed line) the vertical motion is still confined because of gravity, but without any horizontal confinement.

The multi-stage loading sequence proceeds as follows: Atoms are released from a magneto-optical trap (MOT) into the gravito-optical surface trap (GOST) of Ref. [23], where an unpolarized sample in the lower hyperfine state ($F = 3$) is produced by evanescent-wave Sisyphus cooling. A part of the atoms is then transferred through elastic collisions into a narrow, far-detuned intense laser beam perpendicularly intersecting the evanescent-wave in the center of the GOST [20]; this beam has a Gaussian beam waist of 160$\mu$m and is derived with an initial power of 7.2 W from the same Yb-fiber laser that later on produces the attractive field of the DEW trap. The repulsive evanescent wave applied at this stage is already the one that is later used in the DEW trap. The sample is then further cooled adiabatically and evaporatively by exponentially ramping down the power of the horizontally confining beam to 2 W in 2 s. In this way, we obtain our surface reservoir of $1 \times 10^6$ atoms at a temperature of 3.0 $\mu$K, corresponding to a peak number density of $\sim 10^{13}$ cm$^{-3}$. The peak phase-space density is $\sim 10^{-3}$ under the assumption of a fully unpolarized sample equally distributed among the seven magnetic sublevels.

Transfer into the DEW trap from the reservoir is then accomplished in a time interval of 50 ms by ramping down the power of the red-detuned beam from 2 W to zero simultaneously with ramping up the power of the attractive EW from zero to the optimum loading power $P_l = 1.2$ W. The lateral confinement of the reservoir beam and the DEW trap are approximately matched, so that the loading process is governed by the vertical motion. Up to $10^5$ atoms are observed in the DEW trap after 150 ms when the unbound atoms remaining from the reservoir have laterally escaped. Measurements of the atom number are performed by recapture into the MOT and detection of the integrated fluorescence signal by means of a calibrated CCD camera; the systematic calibration error is below a factor of 1.5. The observed transfer ratio of $\sim 5\%$ roughly corresponds to the volume ratio of the DEW trap and the reservoir.

A very important parameter is the vertical trap frequency $\nu_z$, corresponding to the vibrational energy quantum $h\nu_z$ in the tightly confined direction. We measure the trap frequency as a function of the power $P_l$ by parametric heating [24]. After loading the DEW trap under fixed conditions ($P_l = 1.2$ W), we ramp $P_l$ to a variable value in 50 ms and apply a sinusoidal power modulation with a typical depth of 10% to the repulsive EW.
for 150 ms. We then wait 100 ms to let unbound atoms escape and measure the number of remaining atoms. A typical trap-frequency measurement is shown in Fig. 2(a) for $P_r = 0.9\ W$, it exhibits clear minima at the trap frequency and its second harmonics. Fig. 2(b) shows the measured trap frequency versus $P_r$ in comparison with a calculation based on Eq. [3].

FIG. 2: Measurements of the trap frequency in the tightly confined $z$-direction. (a) Fraction of atoms remaining trapped for $P_r = 0.9\ W$ after 150 ms of parametric excitation at a variable frequency. (b) Measured trap frequency versus $P_r$ in comparison with a calculation based on Eq. [3].

The sample then undergoes a ballistic expansion in the field of gravity and atoms hitting the room-temperature surface are immediately lost. After a short release time the repulsive EW is turned on again to prevent further atoms from hitting the surface, and the number of remaining atoms is measured in the standard way by recapture into the MOT. A theoretical model based on the assumption of a thermal distribution in the known trap potential is then used to fit the data with a single parameter and thus to accurately determine the mean kinetic energy of the released sample. At temperatures down to a few 100 nK a classical approximation holds and the model directly provides the temperature. At lower temperatures the quantum nature of the vertical motion has to be taken into account. We find that, for all measurements reported here, corrections to the classical approximation due to the zero-point energy and the discrete level spacing stay well below 20% and can be introduced within a simple harmonic oscillator model. Fig. 3 shows two examples of temperature measurements obtained for a ‘hot’ (2.7 $\mu$K) and a ‘cold’ (100 nK) sample.

Forced evaporative cooling is implemented by ramping down the power $P_r$ of the attractive EW. In this way, a two-dimensional evaporation scheme is realized in which energetic atoms can escape horizontally from the trap. In the vertical direction no evaporation can take place because of the gravitational potential. The scheme decompresses the sample and provides simultaneous adiabatic and evaporative cooling; thus a drastic reduction of the temperature is realized. Immediately after loading we apply an exponential ramp that reduces $P_r$ to 3.5% of its initial value in 400 ms. As it takes about 150 ms for the untrapped reservoir atoms to disappear, we can perform measurements on the number $N$ and temperature $T$ of the trapped sample for evaporation times $t_{\text{ev}} \geq 150$ ms.

Fig. 4 displays the forced evaporation results. For $t_{\text{ev}} \geq 270$ ms the temperature data level off at $T \approx 100$ nK, and for $t_{\text{ev}} \geq 300$ ms an increased loss is observed and reliable temperature measurements are no longer possible. The highest attained phase-space densities are of the order of 0.1, when an equal distribution among the seven magnetic sublevels is assumed. This compares to the highest phase-space densities so far obtained with cesium [23].

In view of a 2D gas, we discuss the results in terms of a reduced temperature $\tau = k_B T / \hbar \nu_z$ by relating the thermal energy to the vibrational energy quantum of the tightly confined direction. For this purpose, we use the calculated $\nu_z(P_r)$ as displayed in Fig. 5(b). The lower
becomes inefficient for the horizontal-vertical thermalization by elastic collisions [26], which leads to heating and trap loss. Second, the ground state is not stable against inelastic two-body collisions: First, the unpolarized Cs sample in the ground state population of 63%. Thus a situation at the crossover to a 2D atom gas is reached.

Our experiment is presently limited by two main factors: First, the unpolarized Cs sample in the $F = 3$ ground state is not stable against inelastic two-body collisions [24], which leads to heating and trap loss. Second, the horizontal-vertical thermalization by elastic collisions becomes inefficient for $\tau \leq 1$ [8]. In our horizontal evaporation scheme this inhibits vertical cooling when two-dimensionality is approached and may thus explain our present limitation to $\tau \approx 1$.

In future experiments, both limitations can be overcome by polarizing the atoms into the lowest substate ($F = 3, m = 3$). The polarized sample will be stable against two-body decay and, moreover, offers magnetic tunability of $s$-wave scattering by low-field Feshbach resonances [27]. Gravity can be compensated by using magnetic gradients so that atoms can be evaporated vertically out of the trap. With these modifications, quantum degeneracy of cesium may be reached in the DEW trap under conditions where the trap supports just a single vertical bound state. This would constitute a unique system with strong analogies to H on liquid He, but with full optical access and magnetically tunable interactions.

In conclusion, we have realized a cold and dense gas of Cs atoms in a highly anisotropic optical trap with intriguing prospects for experiments on 2D quantum gases. By evaporative cooling we have already reached conditions at the crossover to two-dimensionality. With further improvements the system opens up a new road to study the fascinating and widely unexplored properties of degenerate quantum gases in two dimensions.

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