

Two-Dimensional Bose-Einstein Condensate in an Optical Surface Trap

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We report on the creation of a two-dimensional Bose-Einstein condensate of cesium atoms in a gravito-optical surface trap. The condensate is produced a few μm above a dielectric surface on an evanescent-wave atom mirror. After evaporative cooling by all-optical means, expansion measurements for the tightly confined vertical motion show energies well below the vibrational energy quantum. The presence of a condensate is observed in two independent ways by a magnetically induced collapse at negative scattering length and by measurements of the horizontal expansion.

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Quantum gases in lower dimensions [1] currently attract considerable interest as model systems to study a wide range of phenomena related to statistical physics, condensed matter physics, and other areas. Dimensionally reduced systems may exhibit strikingly new properties in comparison to the three-dimensional case. Bose-Einstein condensation (BEC) does not occur in 1D or 2D in the case of an infinite homogeneous system [2], but it is possible in highly anisotropic traps at finite particle number [3]. Only recently, experiments have entered regimes of BEC in 1D [4,5] or 2D [4].

The interest in 2D BEC goes back to early experiments on spin-polarized hydrogen on a liquid-helium surface [6], for which evidence of quantum degeneracy has been obtained [7]. The gradual onset of coherence and formation of quasicondensates have already been discussed in this context [8]. Ultracold, laser-manipulated atomic quantum gases offer many more intriguing features such as precise control of the external confinement, tunability of interatomic interactions, and superb experimental access. Novel phenomena like modified interaction properties have been predicted for 2D quantum gases tightly confined in one direction [9]. The exploration of these phenomena relies on the development of appropriate trapping schemes.

In this Letter, we report on the creation of a two-dimensional BEC of cesium atoms by evaporative cooling in a highly anisotropic surface trap. Our gravito-optical surface trap (GOST) is based on an evanescent-wave (EW) atom mirror in combination with a horizontally confining optical dipole potential [10]; see the illustration in Fig. 1. The repulsive EW is formed on the surface of a prism by a blue-detuned laser beam undergoing total internal reflection. Since gravity pushes the atoms onto the prism, the vertical motion is tightly confined in a gravito-optical potential,

$$U(z) = U_0 e^{-2z/\Lambda} + mgz, \quad (1)$$

where z is the vertical distance from the surface and U_0 , m , and g denote the maximum EW potential, the atomic mass, and the gravitational acceleration, respectively.

The EW field decay length is given by $\Lambda = \lambda/2\pi \times (n^2 \sin^2 \theta - 1)^{-1/2}$, where n is the refractive index of the medium. The potential minimum is located at a height $z_0 = \frac{1}{2} \Lambda \ln(2U_0/mg\Lambda)$ and provides a trap frequency of $\omega_z = (2g/\Lambda)^{1/2}$. The quantized nature of the motion in such a trap and the behavior of a bosonic gas were theoretically investigated in [11,12].

The trap loading procedure is based on methods described in our previous work [13,14]. We release cesium atoms from a magneto-optical trap (MOT) into a large-volume GOST where horizontal confinement is realized with a blue-detuned hollow beam (diameter 0.8 mm, power 50 mW, detuning 50 GHz). In this stage, the EW is realized with a 100-mW diode laser and tuned a few GHz above resonance with atoms in the lower hyperfine state ($F = 3$). Evanescent-wave Sisyphus cooling provides a sample of 10^7 Cs atoms in $F = 3$ at a temperature of $\sim 10 \mu\text{K}$. Then we introduce the focused, vertically propagating 5-W laser beam of an Yb fiber laser (wavelength 1064 nm, beam waist $130 \mu\text{m}$) to provide a narrow dimple potential in the center of the trapped atom cloud with a depth of $\sim 50 \mu\text{K}$ and a horizontal oscillation frequency of 130 Hz. We wait for 1 s until the dimple is

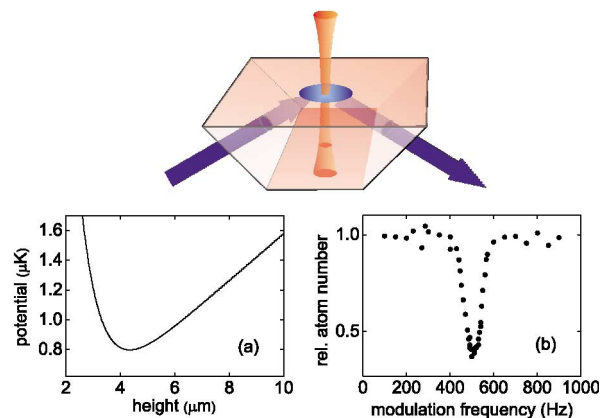


FIG. 1 (color online). Illustration of the gravito-optical surface trap together with (a) the calculated vertical potential and (b) a measurement of the vertical trap frequency.

filled through elastic collisions with a high-density sample of unpolarized Cs atoms in $F = 3$. Finally the blue-detuned hollow beam is turned off.

For further experiments, it is crucial to strongly suppress photon scattering and light-induced loss. Therefore the near-resonant EW is replaced by a far-detuned EW, which is derived from the 700-mW beam of a Ti:sapphire laser at a wavelength of 839 nm. This EW is produced in a nearly round spot on the surface of the fused-silica prism ($n = 1.45$) with a diameter of $500 \mu\text{m}$ ($1/e^2$ intensity drop) and maximum potential height of $U_0 \approx k_B \times 50 \mu\text{K}$. The angle of incidence θ is set 4.2 (1.5) mrad above the critical angle, which leads to calculated values of the decay length and the vertical trap frequency of $\Lambda = 1.4(3) \mu\text{m}$ and $\omega_z/2\pi = 600(50)$ Hz. The corresponding gravito-optical potential is shown in Fig. 1(a). The potential minimum is located about $4 \mu\text{m}$ above the surface. The trap frequency can be measured by parametric excitation. Figure 1(b) shows a loss feature induced by modulating the EW power at the trap frequency yielding $\omega_z/2\pi = 550(50)$ Hz [15].

For evaporative cooling, we optically pump the atoms into the lowest spin state $F = 3$, $m_F = 3$, which offers very favorable scattering properties. In this state, two-body loss is completely suppressed and convenient magnetic tuning of the s -wave scattering length a is possible over a wide range [16]. At a magnetic field of 26.8 G where $a = 440 a_0$ (a_0 is Bohr's radius), we find an optimum situation with a large elastic cross section for evaporative cooling at moderate three-body loss [17,18]. At this stage, we have a sample of 10^6 atoms at a temperature of $9 \mu\text{K}$ with peak values for number and phase-space density of the order of $4 \times 10^{12} \text{cm}^{-3}$ and 5×10^{-4} , respectively.

Forced evaporative cooling is performed by ramping down the power of the red-detuned beam by more than 3 orders of magnitude. The total ramp consists of two subsequent exponential ramps. The first ramp reduces the power from initially 5 W down to 470 mW within 2 s, the second ramp lowers the power further to a final ramp power P_f of typically a few mW in 3.5 s. To counteract the density decrease when the potential is ramped down, we adiabatically reduce the waist of the red-detuned beam to $64 \mu\text{m}$ by moving the focusing lens synchronously with the 5.5 -s ramp.

A release-and-recapture method [13,14,19] is applied to observe the vertical expansion of the sample and thus to measure the vertical expansion energy E_{exp} . We turn off the EW for a short variable release time. Without EW the sample drops onto the surface while undergoing a vertical expansion. Those atoms that hit the room-temperature surface get lost. After the short release time the EW is turned on again to prevent the remaining atoms from hitting the surface, and their number is measured after recapture into the MOT by taking a fluorescence image. Corresponding measurements without release are used to normalize the data and to determine the remaining frac-

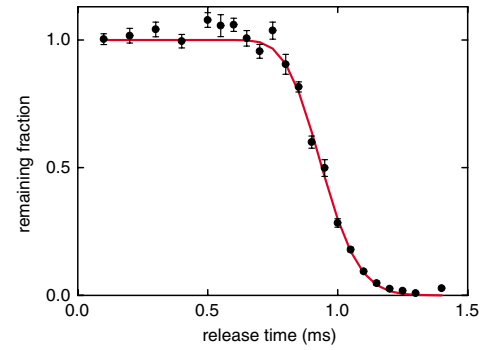


FIG. 2 (color online). Measurement of the vertical expansion energy with 2400 atoms left after deep evaporative cooling down to $P_f = 1.6$ mW. The fraction of remaining atoms is plotted as a function of the release time. The fit of an error function to the data (solid lines) yields an expansion energy of $\frac{1}{2}k_B \times 16(2)$ nK together with a release height of $4.3(1) \mu\text{m}$.

tion as a function of the release time. In the classical regime of a thermal gas with negligible effect of the quantized vertical motion, E_{exp} is directly related to the temperature T by $E_{\text{exp}} = \frac{1}{2}k_B T$, where k_B is Boltzmann's constant. This classical regime ranges down to temperatures of ~ 100 nK.

Figure 2 shows a measurement taken with 2400 atoms remaining at $P_f = 1.6$ mW, where the horizontal trap frequency is 10 Hz. We will show later that this sample is Bose condensed. The position of the sharp edge corresponds to the release height and the steepness is related to the energy spread. A corresponding fit of an error function to the data yields a release height of $z_0 = 4.3(1) \mu\text{m}$ and an expansion energy $E_{\text{exp}} = \frac{1}{2}k_B \times 16(2)$ nK.

The measured vertical expansion energy is shown as a function of the final ramp power P_f in Fig. 3. With decreasing power down to about 3 mW, we observe that E_{exp} linearly follows the reduced horizontal trap depth \hat{U} (see solid line). This shows that evaporative cooling takes place with an approximately fixed relation between

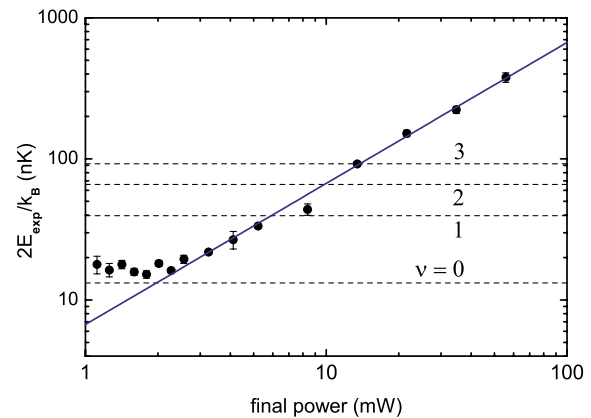


FIG. 3 (color online). Vertical expansion energy versus final power P_f of the evaporation ramp. The solid line illustrates the proportionality to the horizontal trap depth above 3 mW. The dashed lines indicate the expansion energies for the four lowest vibrational levels.

temperature T and trap depth \hat{U} ($k_B T / \hat{U} \approx 6$). For power values below 3 mW, we observe that E_{exp} levels off at about $\frac{1}{2}k_B \times 16$ nK. This value is well below the vibrational energy quantum $\hbar\omega = k_B \times 26$ nK and close to the zero-point energy of $k_B \times 13$ nK. A comparison with the energies $E_\nu = (\nu + \frac{1}{2})\hbar\omega_z$ of the quantum states in the vertical motion (see dashed lines in Fig. 3) shows that a two-dimensional gas is realized. This atomic ‘‘pancake’’ is created in a surface trap with an aspect ratio of about 50:1.

According to a calculation of the phase-space density based on the measured temperatures and the known trap frequencies, we expect the onset of BEC approximately at a final ramp power $P_f \approx 10$ mW. Unfortunately, our release-and-recapture method does not provide sufficient information to extract two-component distributions in that regime. For the dependence $E_{\text{exp}}(P_f)$, only a small deviation from the behavior of a classical gas can be expected [20]; in particular, in our case of a large scattering length leading to a substantial mean-field contribution to E_{exp} . Therefore, the data of Fig. 3 do not reveal the phase transition. To show the presence of a BEC in the surface trap, we thus rely on two other methods.

Our first way to prove BEC relies on a controlled collapse of the condensate at negative scattering length [21], a phenomenon that does not occur in a thermal gas. The scattering length is known to be negative for magnetic fields below 17 G, and the collapse of a Cs BEC below that field has been demonstrated in [17]. In a series of collapse measurements performed with a trapped sample at $P_f = 1.6$ mW, we switched the magnetic field from the evaporation field of 26.8 G to a variable field between 0 G ($a \approx -3000 a_0$) and 40 G ($a \approx 1000 a_0$) for a short time interval of 20 ms and measured the resulting loss. When the scattering length is negative, the contraction of the BEC leads to a dramatic increase in density. In this case, three-body recombination causes very fast loss. In a thermal gas, no contraction can happen and three-body loss at moderate scattering length is too slow to cause any significant reduction of the trapped atom number.

The magnetically induced collapse is demonstrated by the data in Fig. 4. For fields above the zero crossing at 17 G, switching at $a > 0$ does not induce any significant loss. Below 17 G where $a < 0$, a rapid decrease in the trapped atom number is observed. Already at $a = -150 a_0$ realized at 14.7 G almost half of the atoms are lost. This rapid loss at a field where the three-body loss coefficient is relatively small can be explained only by the huge density increase occurring during the condensate collapse.

In order to identify the final evaporation ramp power P_f where the phase transition occurs, we measure the induced collapse loss as a function of P_f . In Fig. 5(a), we plot the fraction of atoms that is observed to remain after a 20-ms application of a collapse field of 14.7 G. Above $P_f \approx 20$ mW, no significant loss is observed as expected

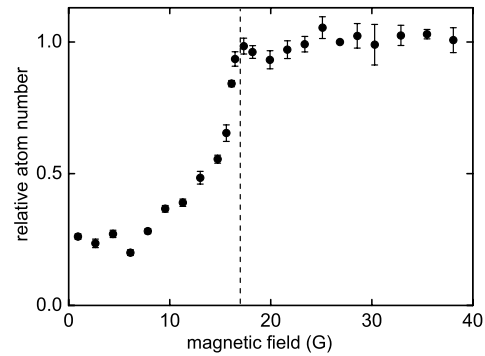


FIG. 4. Atom loss showing the magnetically induced BEC collapse at $P_f = 1.6$ mW. The magnetic field is switched to a variable value for a short time interval of 20 ms. The dashed line indicates the zero crossing of the scattering length, below which the self-interaction is attractive.

for a thermal gas, which cannot undergo a collapse. Below 20 mW rapidly increasing loss sets in, which we interpret as the collapse of a growing condensate fraction. From this observation, we infer that the phase transition takes place at a power of $P_f \approx 20$ mW, where we have 15 000 atoms left at a temperature of 150 nK. This is somewhat above the ramp power of ~ 10 mW that we would expect from calculations of the phase-space density, but still lies in the corresponding error range.

Our second method to observe the onset of BEC is based on a horizontal release-and-recapture technique. After evaporation with a final ramp power P_f , we turn off the horizontally confining attractive laser beam for a long time interval of 400 ms. For recapturing the remaining atoms, we then turn on the horizontally confining beam at a fixed power of 22 mW. No atoms are recaptured for

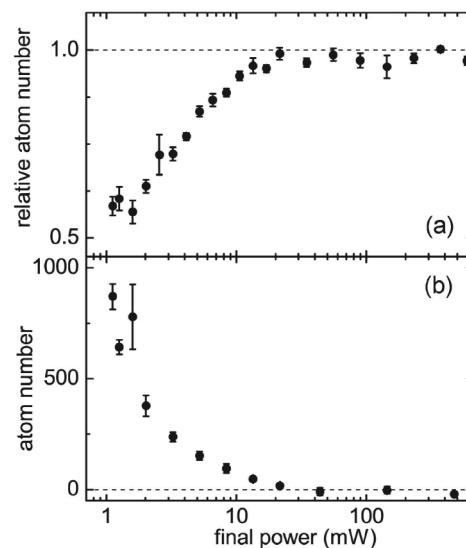


FIG. 5. Observation of the phase transition by two different methods. (a) The fraction of atoms remaining after a magnetically induced condensate collapse at $a = -150 a_0$ is plotted as a function of the final ramp power P_f . (b) The horizontal release-and-recapture measurements show the remaining number of atoms after 400 ms of horizontal expansion.

thermal samples ($P_f > 20$ mW) as shown in Fig. 5(b). For deeper evaporation with P_f below 20 mW, we observe a rapidly increasing number of recaptured atoms which we interpret as a consequence of the much slower expansion of a condensate. The fact that the recapture signal occurs at the same final power as the onset of the collapse loss strongly supports this interpretation.

In the horizontal expansion measurements, we observe significant recapture signals even after a few seconds of free evolution on the EW without the horizontally confining beam. This cannot be explained by a slow expansion alone but rather indicates the presence of a horizontal trapping mechanism. An explanation might be the roughness of an EW atom mirror [22] leading to shallow potential wells. Surface imperfections of the prism or the interference with residual stray light can produce corrugations in the optical potential of the evanescent wave. A trapping effect could thus emerge from the pinning of the condensate to such defects [23].

With better knowledge on the phase transition, we finally revisit the data of Fig. 3. The transition takes place at $P_f \approx 20$ mW in a 3D regime when the thermal component populates about five vertical quantum states. With decreasing values of P_f a crossover to a 2D regime takes place. For $P_f \lesssim 2$ mW, a 2D BEC is formed, for which we estimate a chemical potential of $k_B \times 5$ nK. In this 2D regime, the zero-point energy of $k_B \times 13$ nK dominates the vertical motion.

In order to further explore the properties of the 2D BEC in our GOST, we are presently developing a new apparatus that offers much faster magnetic field control and much better optical access. These improvements will enable us to implement both *in situ* and expansion imaging techniques. Magnetic levitation will allow us to overcompensate gravity and thus to observe a freely expanding atom cloud after release from the surface trap. For enhancing the anisotropy, the two options are magnetic compression against the EW or the application of an additional attractive EW [19]. The trapped two-dimensional condensate will allow us to study elementary excitations such as solitons and vortices, the properties of which may exhibit striking differences as compared to the three-dimensional case. Further intriguing possibilities are offered by the creation of optical surface lattices created through the interference of different evanescent waves.

In conclusion, we have realized BEC in an optical surface trap based on an evanescent-wave atom mirror. During evaporative cooling, we reach the phase transition in a 3D situation before the condensate is brought into the 2D regime by further increasing the trap anisotropy. The system opens up new possibilities to study the widely unexplored properties of degenerate quantum gases in two dimensions.

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