Laser Cooling to Quantum Degeneracy

Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

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We report on Bose-Einstein condensation in a gas of strontium atoms, using laser cooling as the only cooling mechanism. The condensate is formed within a sample that is continuously Doppler cooled to below 1 μK on a narrow-linewidth transition. The critical phase-space density for condensation is reached in a central region of the sample, in which atoms are rendered transparent for laser cooling photons. The density in this region is enhanced by an additional dipole trap potential. Thermal equilibrium between the gas in this central region and the surrounding laser cooled part of the cloud is established by elastic collisions. Condensates of up to 10^5 atoms can be repeatedly formed on a time scale of 100 ms, with prospects for the generation of a continuous atom laser.

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Laser cooling has revolutionized contemporary atomic and molecular physics in many respects, for example pushing the precision of clocks by orders of magnitude, and enabling ion quantum computation [1]. Since the early days of laser cooling, the question has been asked if the quantum degenerate regime could be reached using this efficient method as the only cooling process. Despite significant experimental and theoretical effort to overcome the limitations of laser cooling this goal has been elusive. Up until now, laser cooling had to be followed by evaporative cooling to reach quantum degeneracy [2].

A gas of bosonic atoms with number density n and temperature T enters the quantum-degenerate regime and forms a Bose-Einstein condensate (BEC) if its phase-space density $n\lambda_{\rm dB}^3$ exceeds a critical value of 2.612. Here, $\lambda_{\rm dB} = h/(2\pi m k_B T)^{1/2}$ is the thermal de Broglie wavelength, where h and k_B are Planck's and Boltzmann's constant, respectively, and m is the mass of an atom. Since $n\lambda_{\rm dB}^3 \propto nT^{-3/2}$, low temperatures in combination with high densities have to be reached to obtain quantum degeneracy. Numerous studies, mainly carried out in the 1980s and 1990s, have paved the way to the present state of the art of laser cooling and have identified the limitations of this technique [3].

The long-standing goal of reaching the quantum degenerate regime by laser cooling [4–8] can be discussed in terms of three main experimental challenges. First, temperatures in the low microkelvin regime have to be reached. Only here, quantum degeneracy can be obtained at a density that is low enough to avoid fast decay of the gas by molecule formation. This challenge has been met with several laser cooling techniques, as for example Sisyphus cooling [9,10], velocity selective coherent population trapping [11], Raman cooling [12], Raman sideband cooling [13], or Doppler cooling on narrow lines [14,15]. The second challenge is the implementation of an efficient trapping scheme that allows for accumulation of atoms at high density in a particular region [16–18]. The third, and most severe challenge is to avoid the detrimental effects of the laser cooling photons, which impede the required density increase. One such effect is loss by light-assisted inelastic collisions [19,20]. Another is the reabsorption of photons scattered during laser cooling [21], which leads to an effective repulsion between the atoms and to heating of atoms in the lowest energy states. Both effects increase with density and make it impossible to reach quantum degeneracy. For low phase-space density samples, this challenge has been overcome by rendering the atoms transparent to laser cooling photons [22–24] or by decreasing the photon scattering rate below the frequency of a confining trap [5,7,25]. It has also been proposed to reduce reabsorption by dimensional reduction of the sample [7]. The solutions to the three challenges implemented so far are insufficient to reach quantum degeneracy. The highest phase-space densities ever attained are 1 order of magnitude too low [14,26]. Surprisingly, this last order of magnitude has been an insurmountable obstacle for a decade.

In this Letter, we present an experiment that overcomes all three challenges and creates a BEC of strontium by laser cooling. Our scheme essentially relies on the combination of three techniques, favored by the properties of this element. Strontium possesses a transition with such a narrow linewidth ($\Gamma/2\pi = 7.4$ kHz) that simple Doppler cooling can reach temperatures down to 350 nK [14,27,28]. Using this transition, we prepare a laser cooled sample of 10^7 ^{84}Sr atoms in a large "reservoir" dipole trap. To avoid the detrimental effects of laser cooling photons, we render atoms transparent for these photons in a small spatial region within the laser cooled cloud. Transparency is induced by a light shift on the optically excited state of the laser cooling transition. In the region of transparency, we are able to increase the density of the gas, by accumulating atoms in an additional, small "dimple" dipole trap [16,18].

Atoms in the dimple thermalize with the reservoir of laser-cooled atoms by elastic collisions and form a BEC. Earlier work [16] has shown that Bose-Einstein condensation can be attained in a conservative dimple potential, if the reservoir is evaporatively precooled close to quantum degeneracy and the dimple is finally applied in the absence of near resonant cooling light. In contrast, a striking feature of our technique is that the BEC is created within a sample that is being *continuously* laser cooled.

The details of our scheme are shown in Fig. 1. Based on our previous work [29–31], we use several stages of laser cooling to prepare a sample of ^{84}Sr atoms in the reservoir trap [32]. The trap consists of an infrared laser beam (wavelength 1065 nm) propagating horizontally (x direction). The beam profile is strongly elliptic, with a beam waist of 300 μm in the horizontal direction (y direction) and 17 μm along the field of gravity (z direction). The depth of the reservoir trap is kept constant at $k_B \times 9\ \mu$K. After preparation of the sample, another laser cooling stage is performed on the narrow $^1S_0$-$^3P_1$ intercombination line, using a single laser beam propagating vertically upwards. The detuning of the laser cooling beam from resonance is $\sim -2\Gamma$ and the peak intensity is 0.15 μW/cm^2, which is 0.05 of the transition's saturation intensity. These parameters result in a photon scattering rate of $\sim$70 s^{-1}. At this point, the ultracold gas contains 9×10^6 atoms at a temperature of 900 nK.

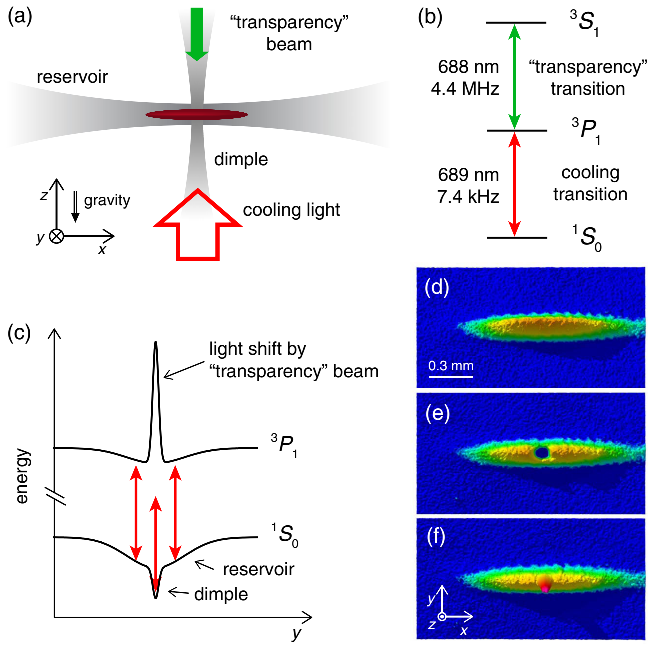

FIG. 1 (color online). Scheme to reach quantum degeneracy by laser cooling. (a) A cloud of atoms is confined in a deep reservoir dipole trap and exposed to a single laser cooling beam (red arrow). Atoms are rendered transparent by a "transparency" laser beam (green arrow) and accumulate in a dimple dipole trap by elastic collisions. (b) Level scheme showing the laser cooling transition and the transparency transition. (c) Potential experienced by $^1S_0$ ground-state atoms and atoms excited to the $^3P_1$ state. The transparency laser induces a light shift on the $^3P_1$ state, which tunes the atoms out of resonance with laser cooling photons. (d)–(f) Absorption images of the atomic cloud recorded using the laser cooling transition. The images show the cloud from above and demonstrate the effect of the transparency laser (e) and the dimple (f). (d) is a reference image without these two laser beams.

To render the atoms transparent to cooling light in a central region of the laser cooled cloud, we induce a light shift on the $^3P_1$ state, using a "transparency" laser beam 15 GHz blue detuned to the $^3P_1$-$^3S_1$ transition [32]. This beam propagates downwards under a small angle of 15° to vertical and has a beam waist of 26 μm in the plane of the reservoir trap (xy plane). The beam has a peak intensity of 0.7 kW/cm^2. It upshifts the $^3P_1$ state by more than 10 MHz and also influences the nearest molecular level tied to the $^3P_1$ state significantly [32,33]. Related schemes of light-shift engineering were used to image the density distribution of atoms [34,35], to improve spectroscopy [36], or to enhance loading of dipole traps [23,24]. To demonstrate the effect of the transparency laser beam, we take absorption images of the cloud on the laser cooling transition. Figure 1(d) shows a reference image without the transparency beam. In the presence of this laser beam, atoms in the central part of the cloud are transparent for the probe beam, as can be seen in Fig. 1(e).

To increase the density of the cloud, a dimple trap is added to the system. It consists of an infrared laser beam (wavelength 1065 nm) propagating upwards under a small angle of 22° to vertical and crossing the laser cooled cloud in the region of transparency. In the plane of the reservoir trap, the dimple beam has a waist of 22 μm. The dimple is ramped to a depth of $k_B \times 2.6\ \mu$K, where it has trap oscillation frequencies of 250 Hz in the horizontal plane. Confinement in the vertical direction is only provided by the reservoir trap and results in a vertical trap oscillation frequency of 600 Hz. Figure 1(f) shows a demonstration of the dimple trap in absence of the transparency beam. The density in the region of the dimple increases substantially. However, with the dimple alone no BEC is formed because of photon reabsorption.

The combination of the transparency laser beam and the dimple trap leads to Bose-Einstein condensation. Starting from the laser cooled cloud held in the reservoir trap, we switch on the transparency laser beam and ramp the dimple trap to a depth of $k_B \times 2.6\ \mu$K. The potentials of the $^1S_0$ and $^3P_1$ states in this situation are shown in Fig. 1(c). Atoms accumulate in the dimple without being disturbed by photon scattering. Elastic collisions thermalize atoms in the dimple with the laser cooled reservoir. The phase-space density in the dimple increases and a BEC emerges.

We detect the BEC by taking absorption images 24 ms after switching off all laser beams. Figure 2(a) shows the momentum distribution 20 ms after switching on the

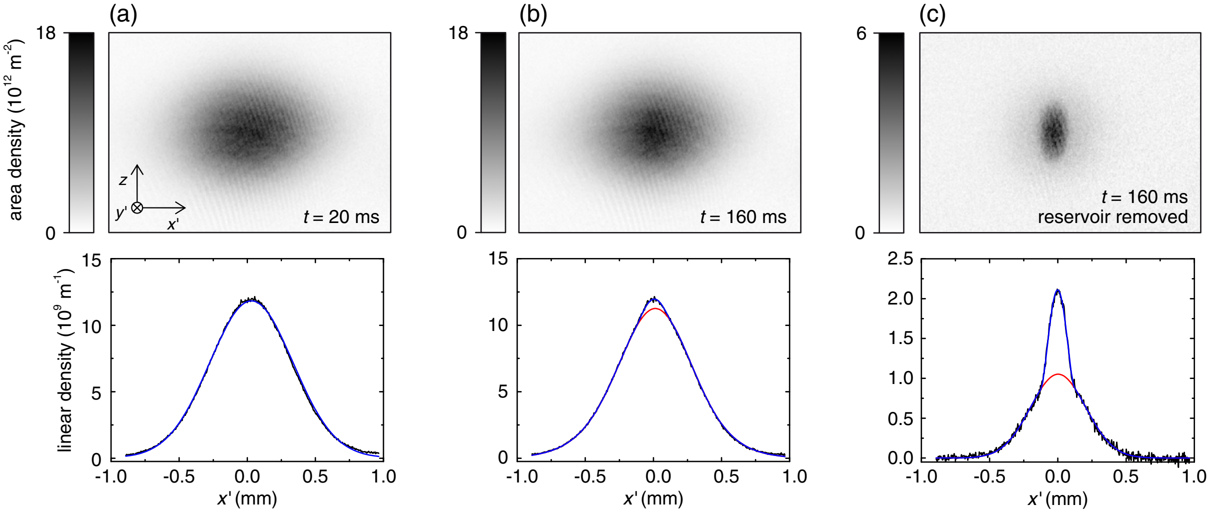

FIG. 2 (color online). Creation of a BEC by laser cooling. Shown are time-of-flight absorption images and integrated density profiles of the atomic cloud for different times t after the transparency laser has been switched on, recorded after 24 ms of free expansion. (a), (b) The appearance of an elliptic core at $t = 160$ ms indicates the creation of a BEC. (c) Same as in (b), but to increase the visibility of the BEC, atoms in the reservoir trap were removed before the image was taken. The fits (blue lines) consist of Gaussian distributions to describe the thermal background and an integrated Thomas-Fermi distribution describing the BEC. The red lines show the component of the fit corresponding to the thermal background. The $x'y'$ plane is rotated by 45° around the z axis with respect to the xy plane and the field of view of the absorption images is 2 mm × 1.4 mm.

transparency beam, which is well described by a thermal distribution. By contrast, we observe that 140 ms later, an additional, central elliptical feature has developed; see Fig. 2(b). This is the hallmark of the BEC. Although clearly present, the BEC is not very well visible in Fig. 2(b), because it is shrouded by 8×10^6 thermal atoms originating from the reservoir. To show the BEC with higher contrast, we have developed a background reduction technique. We remove the reservoir atoms by an intense flash of light on the $^1S_0$-$^3P_1$ transition applied for 10 ms. Atoms in the region of transparency remain unaffected by this flash. Only 5×10^5 thermal atoms in the dimple remain and the BEC stands out clearly; see Fig. 2(c). We use this background reduction technique only for demonstration purposes, but not for measuring atom numbers or temperatures.

Quantitative data on our experiment are obtained by two-dimensional fits to time-of-flight absorption images [32]. The atom number of the thermal cloud and of the BEC are extracted from fits to 24-ms expansion images, consisting of Gaussian distributions describing the thermal background and an integrated Thomas-Fermi distribution describing the BEC. Further absorption images taken after 4 ms expansion time are used to determine atom number and temperature of the gas in the reservoir and the dimple, respectively.

We now analyze the dynamics of the system after the transparency laser beam has been switched on. As we increase the dimple strength to its final depth in 10 ms, 10^6 atoms accumulate in it and the temperature of the dimple gas increases; see Figs. 3(a) and 3(b). During the next ~100 ms the dimple gas thermalizes with the reservoir gas by elastic collisions [32,37,38]. The temperature of the reservoir gas is hereby not increased, since the energy transferred to it is dissipated by laser cooling. We carefully check that evaporation is negligible even for the highest temperatures of the gas [32]. Already after 60 ms a BEC is detected. Its atom number saturates at 1.1×10^5 after 150 ms, as shown in Fig. 3(c). The atom number in the reservoir decreases slightly, initially because of migration into the dimple and on longer time scales because of light assisted loss processes in the laser cooled cloud.

The continuous laser cooling of the reservoir provides a dissipation mechanism, which renders our system resilient against perturbations. To demonstrate this fact, we repeatedly destroy the BEC and let it re-form (Fig. 4). To destroy the BEC, we pulse the dimple trap depth to $k_B \times 15\ \mu$K for 2 ms, which increases the temperature of the dimple gas by a factor 2. We follow the evolution of the BEC atom number while the heating pulse is applied every 200 ms. A new BEC starts forming a few 10 ms after each heating pulse for more than 30 pulses. We find that the observed decrease in the BEC size from pulse to pulse stems from the reduction of the total atom number in the system.

To clarify the role laser cooling plays in our scheme, we perform a variation of the experiment. Here, we switch off the laser cooling beam before ramping up the dimple and we do not use the transparency beam. Heat released while ramping up the dimple or after a heating pulse is again distributed from the dimple to the whole system by elastic collisions, but this time not dissipated by laser cooling. Since the reservoir gas has a ten times higher atom number

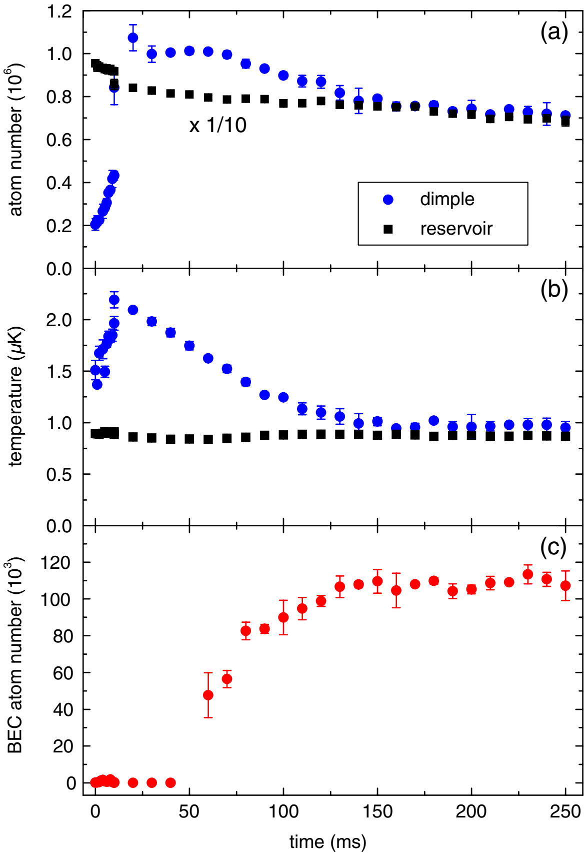

FIG. 3 (color online). Characterization of the BEC formation process after the transparency laser is switched on. The evolution of the atom number in the dimple and the reservoir (a), the evolution of temperature in these regions (b), and the BEC atom number (c), are shown. During the first 10 ms of this evolution, the dimple trap is ramped on. After 60 ms a BEC is detected.

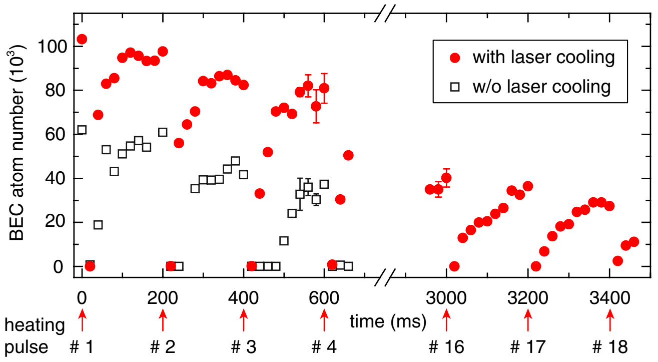

FIG. 4 (color online). Repeated destruction and reformation of the BEC. Shown is the evolution of BEC atom number while the BEC is destroyed every 200 ms (arrows) by suddenly increasing the depth of the dimple trap. If the system is laser cooled, the BEC atom number quickly increases again, which is shown here for up to 18 cycles (filled red circles). Without laser cooling, a BEC is detectable for at most five heating cycles, of which the first three are shown here (open black squares). Sample error bars indicate the statistical errors of three experimental realizations.

than the dimple gas, the temperature after thermalization is only increased by a small amount. If the final temperature in the dimple is below the critical temperature, a BEC is formed. This scheme resembles the formation of a BEC by trap deformation, as demonstrated in [16] using a sample of atoms cooled by evaporation. We test the performance of this BEC creation scheme again by repeated heating pulses. We can detect a BEC after at most five pulses. For more pulses, the temperature of the gas in the dimple remains too high to allow the formation of a BEC. This poor behavior stands in stark contrast to the resilience of BEC formation to heating, if the system is continuously laser cooled.

The ability to reach the quantum degenerate regime by laser cooling has many exciting prospects. This method can be applied to any element possessing a laser cooling transition with a linewidth in the kHz range and suitable collision properties. Besides strontium this encompasses several lanthanides [39,40]. The technique can also cool fermions to quantum degeneracy and it can be extended to sympathetic cooling in mixtures of isotopes or elements. Another tantalizing prospect enabled by variations of our technique is the realization of a truly continuous atom laser, which has for example applications in atom interferometry [41]. The crucial and so far missing element to construct such an atom laser is a device that continuously converts a thermal beam of atoms into a laserlike beam. Our ability to create a BEC within a laser cooled sample paves the way to a simple implementation of such a device. The thermal beam can be fed into the laser cooled reservoir, where the atoms are further cooled and transferred into the BEC. Then a continuous beam of condensed atoms is outcoupled, while being protected from the cooling light by a transparency beam. Using magnetic species such as dysprosium or erbium, outcoupling from the BEC is possible by changing the internal state and thereby the magnetic force on the atoms [42,43]. Alternatively, the reservoir can be connected to an outcoupling dipole trap, creating a narrow channel where atoms can escape and condense by evaporation in the radial direction [44].

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