Creation of a Bose-condensed gas of $^{87}$Rb by laser cooling

Jiazhong Hu,* † Alban Urvoy,* Zachary Vendeiro, Valentin Crépel, Wenlan Chen, Vladan Vuletić†

Protocols for attaining quantum degeneracy in atomic gases almost exclusively rely on evaporative cooling, a time-consuming final step associated with substantial atom loss. We demonstrate direct laser cooling of a gas of rubidium-87 ($^{87}$Rb) atoms to quantum degeneracy. The method is fast and induces little atom loss. The atoms are trapped in a two-dimensional optical lattice that enables cycles of compression to increase the density, followed by Raman sideband cooling to decrease the temperature. From a starting number of 2000 atoms, 1400 atoms reach quantum degeneracy in 300 milliseconds, as confirmed by a bimodal velocity distribution. The method should be broadly applicable to many bosonic and fermionic species and to systems where evaporative cooling is not possible.

Fig. 1. Experimental setup and procedure. (A) $^{87}$Rb atoms are trapped in a 2D lattice formed by two orthogonal retroreflected trapping beams at 1064 nm. The cooling light at 795 nm propagates along the magnetic field ($z$) and is $\sigma^-$-polarized. (B) Simplified atomic-level structure for dRSC. The Zeeman splitting between two magnetic sublevels is matched to the vibrational splitting in the tightly confined direction. (C) Release-and-retrap compression sequence used to increase the atomic density. Starting from a sparsely filled 2D lattice, we perform dRSC (I) and then switch off the $Y$ trapping beam to compress the atoms along $y$ in the $X$ trapping beam (II). After a short thermalization time, we switch back to the 2D lattice with an increased occupation number per trap (III). The procedure is repeated for the $X$ beam to compress the atoms into a small number of tubes (IV). A final dRSC in this system (V) then yields a condensate.

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

*These authors contributed equally to this work.

†Corresponding author. Email: jiazhong@mit.edu (J.H.); vuletic@mit.edu (V.V.)
atoms' position (Fig. 1). The incoming beams are vertically polarized, whereas the polarizations of the reflected beams are rotated by $\theta = 80^\circ$. This induces a polarization gradient in the lattice that provides the required Raman coupling for dRSC (23). The two retroreflected beams provide a trap depth of $U/h = 13 \text{ MHz}$ each (where $h$ is Planck's constant), at an axial (tight) vibrational frequency of $\omega_{\text{ax}}/(2\pi) = 180 \text{ kHz}$ and a radial vibrational frequency along the vertical (z) direction of $\omega_{\text{r}} = \sqrt{2\omega_{\text{ax}}/2\pi} = 2\pi \times 6.3 \text{ kHz}$. (Here, $\omega_{\text{ax}}/(2\pi) = 4.5 \text{ kHz}$ is the radial vibrational frequency for a single 1D lattice beam.) A magnetic field $B = 0.23 \text{ G}$ along $z$ is set to match the Zeeman splitting between the magnetic sublevels $|F = 2, m = -2\rangle \rightarrow |F = 2, m = -1\rangle$ to $\hbar \omega_{\text{ax}}$, where $F$ is the total angular momentum; $m$, magnetic quantum number; $\hbar$, reduced Planck's constant).

A cooling cycle consists of a Raman transition $|2, -2\rangle \rightarrow |2, -1\rangle$ induced by the trapping light, which removes one vibrational quantum in the tightly confined direction (Fig. 1B), followed by optical pumping back to $|2, -2\rangle$. This reduces an atom's motional energy by $-\hbar \omega_{\text{ax}}$ per optical pumping cycle. The very-far-detuned trap light that drives the Raman transition (wavelength $\lambda_s = 1064 \text{ nm}$) does not produce any appreciable atom loss, but the optical pumping can induce inelastic binary collisions as an atom pair is excited to a molecular potential that accelerates the atoms before they decay back to the ground state (9). To reduce this process relative to photon scattering by individual atoms (15), we use a co-polarized optical pumping beam tuned below the $D_1$ line away from photoassociation resonances (9, 15). Because an excited atom can also decay to $F = 1$, we use bichromatic light with detunings $\Delta p/(2\pi) = -630 \text{ MHz}$ and $\Delta s/(2\pi) = -660 \text{ MHz}$ relative to the $|S_{1/2}, F = 2\rangle \rightarrow |P_{1/2}, F = 2\rangle$ and $|S_{1/2}, F = 1\rangle \rightarrow |P_{1/2}, F = 2\rangle$ transitions, respectively. This far-detuned $D_1$-line optical pumping configuration reduces light-induced inelastic collisions by at least an order of magnitude.

The experimental sequence starts by accumulating $^{87}\text{Rb}$ atoms in a magneto-optical trap, loading them into the 2D lattice by means of polarization gradient cooling (16), and applying dRSC for 100 ms. This prepares the atoms near the vibrational ground state in the strongly confined $x$ and $y$ directions [the kinetic energy measured by time-of-flight imaging is $K_{\text{kin}}/h = 50 \text{ kHz}$, close to $\omega_{\text{ax}} (2\pi)/(2\pi) = 45 \text{ kHz}$], whereas in the vertical direction (z), the atoms are cooled to $T_z = 12 \mu\text{K}$ ($K_{\text{kin}}/h = 120 \text{ kHz}$) through collisional thermalization between the axial and radial directions of the tubes. At this point, there are $N = 2000$ atoms in the 2D lattice with a peak occupation of $N_1 = 1$ atom per tube, corresponding to a peak phase space density $D = 0.02$ and peak density $n_0 = 2.2 \times 10^4 \text{ cm}^{-3}$. To further increase $n_0$ and $D$, we apply release-and-retrap compression (16) by adiabatically turning off (in 400 ms) the $Y$ trapping beam, so that the cloud shrinks in the $y$ direction thanks to the radial confinement of the $X$ trapping beam (Fig. 1C). After thermalization for 10 ms, the spatial extent of the cloud can be estimated by $z = \sqrt{\hbar k_T/\rho} = 1.1 \mu\text{m}$, where $T_z = 10 \mu\text{K}$ is the measured radial temperature, $\rho$ is the $^{87}\text{Rb}$ mass, and $k_T$ is Boltzmann's constant. The $X$ lattice beam is then turned back on in 1 ms. This loads the compressed ensemble back into a 2D lattice, resulting in a higher temperature ($T \sim 50 \mu\text{K}$), and we again apply dRSC for 100 ms. This yields again $K_{\text{kin}}/h = 100 \text{ kHz}$ but at a peak occupation number of $N_1 = 6.9 \text{ atoms per tube for a total number } N = 1700 \text{ atoms}$. We repeat this procedure for the $X$ lattice beam and end up with $N = 1400 \text{ and } N_1 = 47$ at a peak density $n_0 = 1 \times 10^6 \text{ cm}^{-3}$. At this point, the ensemble is below our optical resolution of 8 $\mu\text{m}$, and $N_1$ is estimated from the measured temperatures in the corresponding 1D lattices and the separately measured trap vibration frequencies. Figure 2D shows the evolution of $N_1$, $N_2$, and $D$ during the sequence that brings the system close to $D = 1$. We emphasize that evaporation is not occurring at any point because temperature reduction is only observed when the cooling light is on, and $k_B T < 0.1 \mu\text{K}$ at all times.

When we subsequently apply the final dRSC stage for up to 100 ms, we observe the gradual appearance of a characteristic signature of condensate formation: a bimodal distribution of the velocity along the $z$ direction that becomes more pronounced with longer dRSC time $t$ (Fig. 2). A fit to the observed distribution for $t = 80 \text{ ms}$ with a single Gaussian curve yields a reduced $\chi^2 = 137$ (Fig. 2C), as opposed to $\chi^2 = 0.91$ for a bimodal distribution.

---

**Fig. 2. Evidence of the formation of a Bose-condensed gas during optical cooling.** A bimodal velocity distribution emerges during the final laser cooling stage, indicating macroscopic population of the ground state. (A to C) Observed optical depth (OD) along $z$ after a ballistic expansion of 1.3 ms for cooling times of 5 ms (A), 20 ms (B), and 80 ms (C), averaged over 200 repetitions of the experiment. The red lines are Gaussian fits to the wings of the distributions, and green lines are quadratic fits to the remaining distribution in the center (19). Here the intensity of the trapping beams is ramped down in 400 $\mu\text{s}$—slowly compared with the axial trapping frequency but quickly with regard to the motion along $z$—to reduce the interaction energy. (D) Evolution of the total atom number $N$ (blue) or atom number per lattice tube $N_1$ (red) versus the phase space density $D$ during the sequence, with the steps labeled 1 to V as defined in Fig. 1B. The solid lines represent the dRSC process, and the dotted lines represent the spatial compression. Each cooling step enhances $D$ by one order of magnitude, then the release-and-retrap compression increases the peak occupation number $N_1$ while slightly decreasing $D$. (E) Velocity distribution along $z$ for the same parameters as in (C), but observed for a 2D gas after releasing the atoms into the 1D lattice $Y$. 

---

**RESEARCH | REPORT**


2 of 3

Downloaded from http://science.sciencemag.org on January 1, 2019
We observe very limited atom loss (<5% at a peak density of \(n_0 = 1 \times 10^{28} \text{ cm}^{-3}\), inset in Fig. 3A), confirming that light-induced losses are strongly suppressed. Figure 3C shows the condensate fraction \(N_c/N\) versus the calculated inverse phase space density \(1/D\), where \(N_c\) is the number of condensed atoms. In the absence of a detailed 1D theory, \(N_c/N\) is estimated as the fractional area under the narrower peak in the bimodal distribution. The onset of the bimodal distribution is observed near \(D = 0.7\). In 1D systems, only a smooth crossover to a quantum-degenerate gas occurs (19–21), which is in agreement with our observation for \(N_c/N\). For our parameters, the system is in the crossover region between a weakly interacting 1D gas (22) and a strongly interacting Tonks-Girardeau gas (23, 24) (the calculated dimensionless interaction parameter is \(\gamma = 2.7\) at the peak local density), as well as in the crossover region between a 1D Bose gas and a 3D finite-size condensate (19, 25). Although the character of the condensate is therefore ambiguous, the velocity distribution (Fig. 2) reveals a macroscopic population of the ground state.

Because the atomic cloud is below our optical resolution, the atomic density cannot be directly determined through optical imaging. However, an independent verification is possible by measuring three-body loss, where the loss coefficient \(K = 1.1 \times 10^{28} \text{ cm}^{-5} \text{ s}^{-1}\) for a 3D thermal gas (26) has been previously determined. In a 1D gas with \(\gamma = 2.7\), the three-body loss is strongly suppressed by a factor of \(\sim 100\) (27, 28), and indeed we do not detect any loss in the 1D tubes. Instead, we measure the three-body recombination in the 1D lattice (i.e., for a 2D gas), where we observe a lifetime of 300 ms; from this, we determine a peak density of \(5.3 \times 10^{14} \text{ cm}^{-3}\) in the 2D gas, corresponding to a peak atom number of \(N_c \approx 45\) atoms per tube and a phase space density \(D = 1.1\) at the onset of quantum degeneracy (19), both in agreement with the previous estimation.

In our experiment, both the large red-detuning of the optical pumping light and the near-1D confinement observably reduce light-induced loss, whereas a photon-scattering rate below the loss, whereas a photon-scattering rate below the...
Creation of a Bose-condensed gas of $^{87}$Rb by laser cooling
Jiazhong Hu, Alban Urvoy, Zachary Vendeiro, Valentin Crépel, Wenlan Chen and Vladan Vuletic

*Science* 358 (6366), 1078-1080.
DOI: 10.1126/science.aan5614

**Packing rubidium into quantum degeneracy**
When atomic gases, such as those of alkali elements, are cooled to very low temperatures, they can reach a state of quantum degeneracy, where their quantum nature comes to the fore. In this process, the very last step is evaporative cooling, in which the hottest atoms are coaxed into leaving the gas. Hu *et al.* devised a protocol that evades the evaporative cooling step, is faster, and suffers less atom loss. The method rests on iteratively manipulating the laser beams of an optical lattice in which a gas of $^{87}$Rb atoms is held so that the gas becomes progressively denser. The method should be widely applicable to other atomic species.

*Science*, this issue p. 1078