Strongly Correlated Quantum Gas Prepared by Direct Laser Cooling

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We create a one-dimensional strongly correlated quantum gas of 133Cs atoms with attractive interactions by direct laser cooling in 300 ms. After compressing and cooling the optically trapped atoms to the vibrational ground state along two tightly confined directions, the emergence of a non-Gaussian time-of-flight distribution along the third, weakly confined direction reveals that the system enters a quantum degenerate regime. We observe a reduction of two- and three-body spatial correlations and infer that the atoms are directly cooled into a highly correlated excited metastable state, known as a super-Tonks-Girardeau gas.

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Laser trapping and cooling techniques enable the preparation of atomic ensembles at ultracold temperatures, where quantum effects dominate [1,2]. However, exclusively using optical cooling to reach the quantum degenerate regime is challenging: rescattering of cooling light inside an optically dense ensemble causes excess recoil heating [3], while atomic collisions in the presence of light can lead to heating or molecule formation [4]. For these reasons, the standard final step to quantum degeneracy is evaporative cooling [5–9]. However, evaporation is relatively slow, relies on favorable atomic collisional properties, and requires substantial atom loss.

Schemes based on laser cooling alone have recently succeeded in reaching quantum degeneracy [10–12]. Common to those techniques is the reduction of detrimental effects of the cooling light, either by shielding the densest region from the light (for 84Sr) [10] or by using far-off-resonance cooling light (for 87Rb) [11,12] to reduce light-induced collisions. In both cases, the system was in a weakly correlated state with repulsive two-body interactions (scattering length \(a > 0\)), such that the condensate is stable against collapse.

Among the alkali atoms, 133Cs is notoriously difficult to evaporatively cool. It features large two- and three-body inelastic collision rates [13–15], while its large negative scattering length [13,14,16,17] and associated strong attractive atom-atom interaction result in collapse of a three-dimensional condensate. Condensation of 133Cs was eventually achieved through slow evaporation at low density in a combination of optical and magnetic traps [18] using a magnetic Feshbach resonance to tune the scattering length to a positive value [13,16,17].

A particularly interesting situation arises when the degenerate gas is in a strongly correlated state that cannot be described by a mean-field theory. Such a regime is reached, e.g., when a quantum gas with strong repulsive interactions is so tightly confined in two directions that it becomes effectively one dimensional (1D) [19–24]. Then at sufficiently low linear density, the atoms avoid each other, effectively behaving like fermions in a regime known as a Tonks-Girardeau gas [19,21–23,25–27]. Surprisingly, this behavior persists even at large negative scattering length, in spite of the strong attraction, where the atoms enter a strongly correlated metastable many-body state [28–31]. Such a “super-Tonks-Girardeau” (sTG) gas was previously generated in a pioneering experiment by transferring a Bose-Einstein condensate adiabatically into a two-dimensional (2D) optical lattice [31].

In this Letter, we demonstrate direct laser cooling of a quantum gas with attractive interactions into a strongly correlated sTG state that cannot be described by mean-field theory. The motion along two tightly confined directions \(x, y\) is continuously cooled to the quantum ground state by degenerate Raman sideband cooling (dRSC) [32–36]. Along the third, weakly confined \(z\) direction, atomic collisions transfer energy to the tightly trapped directions. After compression of the gas of 133Cs atoms into a small array of optical traps and cooling, a non-Gaussian momentum distribution along \(z\) emerges, evidencing the onset of quantum degeneracy in this quasi-1D system with large negative scattering length \(a = -130\) nm \([13,14]\). Measurements of inelastic collisions show that spatial two- and three-body correlations are suppressed by almost one and two orders of magnitude, respectively. We infer that the system is directly cooled into a metastable excited gaslike state (sTG gas), stabilized by the strong attractive interaction [28]. Using resonant light for the optical pumping process in dRSC, the sTG gas is prepared in less than 300 ms, more than ten times
faster than previous condensation of $^{133}$Cs by evaporative cooling [18,37].

The process begins by loading $^{133}$Cs atoms from a magneto-optical trap into a standing-wave trap operating at a wavelength $\lambda = 1064$ nm ($x$ trap, beam waist $w_x = 17$ $\mu$m). We then perform dRSC on the 2D gas, optically pumping the atoms into the lowest-energy hyperfine and magnetic sublevel ($F = 3, m = 3$) of the electronic ground state $^6S_{1/2}$. Trapping light with finely tuned polarization drives Raman transitions transferring atoms to the neighboring magnetic sublevel ($F = 3, m = 2$) while reducing the vibration quantum number by one. Optical pumping via the $^6P_{3/2}, F' = 2$ hyperfine manifold back into ($F = 3, m = 3$) continuously removes entropy from the system. [See Fig. 1(b) for the atomic level structure and Supplemental Material (SM) [38] for details on trap parameters and cooling procedure.]

After 100 ms of cooling, the 2D gas reaches a temperature of $T = 2.5$ $\mu$K and peak classical phase space density (PSD) of PSD $\sim 0.1$ (see SM [38] for the exact definition). If the cooling were to continue in this geometry, the PSD would subsequently decrease due to light-induced atom loss [4]. We then turn on a second lattice trap ($y$ trap, waist $w_y = 6.5$ $\mu$m) transverse to the first one [see Fig. 1(a)]. This configuration creates a 2D array of elongated cigar-shaped traps along the $z$ direction. Immediately after switching on the $y$ trap we adiabatically turn the $x$ trap off and back on to remove atoms not confined to the overlap region of the two traps (see SM for details [38]). This prepares $N \approx 1000$ atoms distributed in an array of cigar-shaped traps with root mean square size of $1.3 \times 2.5$ traps, and a peak occupation of $N_1 \approx 50$ atoms per trap, as depicted in Fig. 1(c). Because of the spatial compression when turning off the $x$ trap, the atoms’ temperature is increased to $T \approx 5$ $\mu$K, at constant PSD [see Fig. 2(a)].

The final cooling stage employs two-dimensional dRSC along $x$ and $y$. The trapping frequencies are $\omega_{x,y} = 2\pi \times 50$ kHz in the transverse directions and $\omega_z = 2\pi \times 2.9$ kHz along the weakly confined direction. After 120 ms of cooling, the 2D ground state in the $xy$ plane is reached [see Fig. 2(b)]. We determine the gas temperature $T_{x,y}$ in the transverse direction by measuring the excess kinetic energy over the harmonic oscillator zero point energy, obtaining $T_{x,y} = (0.2 \pm 0.2)$ $\mu$K. For our experimental parameters and observed kinetic energy $K_z$ along the $z$ direction, the corresponding temperature $T_z$ is still close to its classical value $T_z = 2K_z/k_B$ [40,41], yielding $T_z \approx (1.2 \pm 0.1)$ $\mu$K. The cooling limit along $z$ is likely set by the collisional thermalization rate between the directly cooled $xy$ directions and the $z$ direction. This rate is exponentially suppressed at $k_B T_{x,y} \ll \hbar \omega_{x,y}$ [42,43], and we estimate a minimum possible temperature of $T_z \sim 0.8$ $\mu$K for our

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**FIG. 1.** Experimental setup. (a) Two crossed optical standing waves create a lattice of highly anisotropic cigar-shaped traps. An optical-pumping beam is applied along the $y$ axis, with a magnetic field at a small angle ($\alpha \approx 10^\circ$) to the $x$ axis. (b) Atomic level structure and cooling procedure. The red arrows represent optical pumping, and the blue arrows represent Raman transitions driven by the trap light. The Raman transition removes one quantum of vibrational energy, while the optical pumping restores the initial internal state. (c) By varying the powers of the two trapping beams in combination with laser cooling, the atoms are compressed into a small number of traps, where a final cooling yields a sTG gas.

**FIG. 2.** (a) Phase space density during the cooling sequence. Following a precooling stage (red region), the atoms are compressed in 40 ms into fewer traps (see text). During the final cooling stage the system crosses over into a quantum degenerate region. The inset shows the efficiency of the cooling, displaying the PSD against the remaining atom number. The blue shaded region in the inset represents the PSD at which quantum degeneracy becomes observable. (b) Kinetic energies $K_z$ (red dots) and $K_{x,y}$ (blue triangles) of the atoms after sudden release from the trap in a time-of-flight measurement, as a function of cooling time. The inset shows the atom number as a function of cooling time.
parameters (see SM [38]). The higher observed $T_z$ could be explained by some residual heating in the $z$ direction.

During cooling, atoms are lost at a moderate rate due to light-assisted inelastic collisions; once the atoms are cooled to the 2D ground state, the loss rate is substantially reduced, presumably due to the lower cooling and associated photon scattering rate. The two-body loss acts to equalize the populations in different traps, and after 200 ms of two-dimensional dRSC we have 50 mostly equally filled traps with $N_f = 6 \pm 2$ atoms in each, for a total atom number $N \approx 300 \pm 100$. (Here the dominant uncertainty is the systematic uncertainty in total atom number, see SM [38].) The local peak density is $n_0 = 1.1 \times 10^{15}$ cm$^{-3}$.

The evolution of the classical PSD throughout the cooling sequence is shown in Fig. 2(a). The cooling efficiency in the presence of atom loss can be characterized by the logarithmic slope of PSD increase to atom number loss, $\eta = -[d(\ln \text{PSD})/d(\ln N)]$. During the precooling stage, up to PSD $\sim 0.5$, we observe a very high efficiency $\eta = 10 \pm 0.3$ [see inset of Fig. 2(a)], whereas a typical evaporative cooling has $\eta \sim 3$–4, with the highest reported values $\eta \approx 6$ [37,44]. For values PSD $\geq 0.5$, the classical PSD no longer coincides with the (higher) occupation per quantum state, and should only be regarded as a qualitative measure of cooling efficiency.

During the final cooling stage [Fig. 2(b)], the momentum distribution observed in a time-of-flight (TOF) measurement remains Gaussian in the tightly confined direction, while a non-Gaussian momentum distribution emerges along the $z$ direction (Fig. 3). The observed $z$ momentum distribution qualitatively agrees with theoretical simulations of a one-dimensional trapped gas of hard-core bosons at similar temperatures in the quantum degenerate regime [41,45]. We employ a bimodal fit to characterize the degree of quantum degeneracy by the ratio $N_0/N$ of the area $N_0$ under a central peak and the total area under the TOF curve $N$ (see SM for details [38]). We observe a maximum ratio $N_0/N \approx 0.37$ after 400 ms of cooling [see Fig. 3(d)]. 1D systems exhibit a smooth crossover to quantum-degeneracy [46,47], and we observe a small quantum degenerate component even for PSD $< 1$.

The cooling prepares the system in a strongly correlated, effectively 1D state that survives at large negative scattering length and high density, and is largely immune to two-body radiative losses and three-body recombination loss. Effectively 1D systems can be characterized by the combination of linear density $n_{1D}$ and 1D scattering length, given by $a_{1D} = -a_{\perp}[(a_{\perp}/a) - C]$, where $a_{\perp} = \sqrt{\hbar/m a_{x,y}}$ is the ground-state size in the transverse directions, $m$ the atomic mass, $a$ the three-dimensional scattering length, and $C \approx 1.0326$ a constant [25]. The strength of the interactions is characterized by the dimensionless parameter $\gamma = 2/(\langle r_{1D}^2 | a_{1D} \rangle)$ that can be interpreted as the ratio of interaction energy to kinetic energy [22,23], $\gamma \ll 1$ corresponds to a weakly interacting Bose gas, while $\gamma \gg 1$ describes a strongly interacting Tonks-Girardeau gas (sTG gas) for $a_{1D} < 0$ ($a_{1D} > 0$).

For our parameters with three-dimensional scattering length $a = -130$ nm and $|a| > a_{\perp} = 39$ nm, the system is in the unitary regime with $a_{\perp} \approx a_{1D} = 52$ nm. According to Ref. [41], the spatial in-trap distribution along $z$ at our temperatures is still well approximated by a thermal Gaussian distribution. Then the local density approximation yields a value $\gamma_0 = 8 \pm 3$ at the trap center, with the uncertainty being dominated by that of the atom number $N_1$. An sTG gas has been predicted to be stable against attraction-induced collapse for $\gamma > \gamma_c = 5.7$ [28], and we observed a lifetime exceeding several hundred ms. The near-coincidence $\gamma_0 \approx \gamma_c$ may indicate that the number of atoms in our traps is limited by the stability condition of the sTG gas.

Similar to the Tonks-Girardeau gas, the sTG gas is a highly correlated state where the spatial wave function of the bosons is “fermionized.” The associated suppression of two- and three-body short-range correlations $g^{(2)}$ and $g^{(3)}$ has been previously observed for the Tonks gas with repulsive interactions [21,48], but not for the sTG gas. In the following, we investigate experimentally this suppression $g^{(2)}, g^{(3)} < 1$ that is expected to persist even at finite temperature [28,30].

The two-body short-range atom-atom correlation function $g^{(2)}$ can be probed with light-assisted loss [49]. The loss rate constant $\Gamma$ with $\hat{N} = -\Gamma N$, is given by $\Gamma = G g^{(2)}(n)$, where $G$ is the light-induced loss rate constant.
The density-normalized two-body loss rate as a function of dimensionality between 1D and 2D. The fractional error in $g_{1D}$ is large due to model-dependent uncertainties.

The dominant uncertainty in $g_{1D}$ arises from the systematic uncertainty in atom number per trap $N_i$. Both for the 1D and 2D gas we observe a time dependence that is well fitted by three-body decay [Fig. 4(b)]. Surprisingly, for an intermediate regime between 1D and 2D (red circles), the loss rate is halved compared to the 1D gas. This provides strong evidence that the 1D nature of the system is protecting the dense gas from three-body loss.

In conclusion, we have demonstrated direct laser cooling into a strongly interacting metastable excited phase, an sTG gas. The method is fast and robust, preparing a strongly correlated quantum gas in 300 ms, and enabling measurements with high signal-to-noise ratio. In the future, it will be interesting to tune the scattering length by means of a Feshbach resonance [13,14,16,17,18] and expand previous studies of Tonks-Girardeau [22,23] and sTG [31] gases with improved signal-to-noise ratio. The demonstrated scheme presents a promising tool for reaching quantum degeneracy in atoms with unfavorable collision properties, and can potentially be extended to optically trapped molecules [51].
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