Cooling of a one-dimensional Bose gas

B. Rauer, P. Grišins, I. E. Mazets, T. Schweigler, W. Rohringer, R. Geiger, T. Langen, and J. Schmiedmayer

Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria
Wolfgang Pauli Institute, 1090 Vienna, Austria

(Dated: June 18, 2015)

We experimentally study the dynamics of a degenerate one-dimensional Bose gas that is subject to a continuous outcoupling of atoms. Although standard evaporative cooling is rendered ineffective by the absence of thermalizing collisions in this system, we observe substantial cooling. This cooling proceeds through homogeneous particle dissipation and many-body dephasing, enabling the preparation of otherwise unexpectedly low temperatures. Our observations establish a scaling relation between temperature and particle number, and provide insights into equilibration in the quantum world.

PACS numbers: 03.75.Kk, 37.10.De, 67.85.De

Introduction. —Long coherence times, the tunability of many parameters and the ability to precisely probe and manipulate their quantum state make ultracold atomic gases a very promising and versatile tool to study the physics of quantum many-body systems [1]. The standard technique to reach the necessary ultracold temperatures in these systems is evaporative cooling [2–4], a fundamental process present in many physical systems from hot liquids to stellar clusters. It relies on the selective removal of the most energetic particles from a trapped gas and the subsequent re-thermalization of the gas to a lower temperature through elastic collisions. For efficient cooling this cycle is repeated continuously, increasing the phase-space density of a gas at the price of reducing the total number of atoms.

Intuitively, systems that do not thermalize can not be cooled through particle dissipation. In this letter we demonstrate that this notion is incomplete by studying the dissipative dynamics of a one-dimensional (1D) Bose gas with contact interactions. We observe a substantial decrease in temperature as a result of homogeneous particle dissipation, reaching temperatures far below $h\omega_{\perp}$, the energy characterizing the transverse confinement. In this deep 1D regime thermalization is strongly suppressed [5–6]: Thermalizing two-body collisions are frozen out [7] and three-body collisions [7,8] or phonon-phonon scattering [9–11] can be neglected on our timescales. We find that the observed cooling can be modeled as a continuous density reduction extracting energy from the density quadrature of the free phononic excitations. Together with a continuous many-body dephasing this reduces the occupation number of each phonon mode and leads to a colder system.

Experiment. —Our experimental system is a 1D Bose gas of $^{87}$Rb atoms prepared in the anisotropic magnetic trapping potential of an atom chip [12]. Initially, a precooled three-dimensional (3D) cloud of thermal atoms, prepared in the $|F,m_F\rangle = |2,2\rangle$ ground state is loaded into the trapping potential. The gas is then cooled through the condensate transition and into the 1D regime by conventional evaporative cooling. The evaporation is realized through a weak driving of energy-selective radio-frequency (RF) transitions to untrapped Zeeman states [13]. The cooling ramp of the RF frequency is performed over 1.6 s, with the final part being particularly slow to minimize collective excitations in the gas. The 1D regime is reached when both the temperature and the chemical potential drop below $h\omega_{\perp}$, the energy spacing between the ground state and the first excited state of the transverse confinement. At this point the condensate typically consists of 7000 to 10000 atoms at an initial temperature $T$ of 30 to 100 nK. The resulting macroscopic quantum system is a quasi-condensate described by a macroscopic wave function with a fluctuating phase [14].

This trapped 1D quasi-condensate is the starting point of our experiments. To investigate the effects of particle dissipation we monitor the further evolution of the system under continuous driving of transitions to untrapped states. The outcoupling rate is tuned in such a way that atoms are removed slowly from the quantum degenerate gas to avoid collective excitations. In contrast to conventional evaporative cooling the atoms are not outcoupled energy-selectively but at a nearly homogeneous rate. This is experimentally demonstrated in Fig. 1 by extracting a visible fraction of the gas using a single outcoupling pulse and analyzing its relation to the source cloud. The outcoupled atoms show the same average density profile as well as the same density speckle patterns, indicating a coherent and homogeneous outcoupling process.

Information about the system is extracted through absorption imaging in time-of-flight, transversal to the 1D axis [15]. To improve the individual images we employ a fringe removal algorithm [16]. The imaging provides access to the evolution of the atom number, the den-
FIG. 1. (color online). Analysis of the outcoupling mechanism. (a) A typical density speckle pattern formed by a 1D quasi-condensate expanding for 10.5 ms in time-of-flight. 2.5 ms before the gas was released a small fraction was outcoupled by a single 2 ms RF pulse. The outcoupled cloud is visible below the source cloud, showing the same speckle pattern. (b) Comparing the longitudinal density profiles of the source cloud (blue) and the outcoupled cloud (red) averaged over many realizations reveals the same form of the profile, indicating a homogeneous outcoupling process. (c) Sketch of the outcoupling mechanism. Transversal to the 1D axis the atoms occupy the ground state of the harmonic potential (blue). Outcoupling is achieved by coupling these atoms to untrapped states, e.g. $|2,0\rangle$ (red) which only feels the linear gravitational potential. The rate of this transition, taking only the transversal degrees of freedom into account, is plotted in (d) over the detuning of the driving field, given in units of the longitudinal trap frequency. The large width of this rate compared to the energy scale of the longitudinal dynamics leads to a nearly homogeneous outcoupling of atoms.

Density profile and the temperature of the gas. The latter is extracted from the longitudinal density speckle patterns forming in the time-of-flight expansion seen in Fig. 1. 17 18. These patterns are a direct result of the longitudinal phase fluctuations in the trapped gas. Extracting their normalized auto-correlation function and comparing it to simulated data generated through a stochastic Ornstein–Uhlenbeck process 19 allows us to infer the temperature of the gas.

Our results for the evolution of the atom number and the temperature for different initial conditions, outcoupling rates and measurement procedures are shown in Fig. 2. The outcoupling is achieved through RF transitions within the $F = 2$ manifold or microwave (MW) transitions to the anti-trapped $|1,1\rangle$ state. We find that in all cases the correlation functions of the density speckles in time-of-flight remain close to their thermal form for all data points. This is remarkable, as the system is close to an integrable point and thus can not thermalize on experimentally relevant timescales. In addition, the nearly homogeneous, energy independent out-coupling process would intuitively not lead to cooling. Nevertheless, we observe a significant decrease in temperature down to $k_B T \sim 0.1 \hbar \omega_\perp$. Moreover, even though the system constantly loses atoms the ratio $k_B T / \mu$ between the thermal energy and the interaction energy given by the chemical potential $\mu$ drops as well. In the coldest measurement presented in Fig. 2 (blue circles) it reaches values as low as $\sim 0.25$. The thermal coherence length $\lambda_T$ is inversely proportional to this ratio showing that the system be-
FIG. 3. (color online). The data from Fig. 2 is plotted rescaled to their respective initial temperature $T_0$ and atom number $N_0$ values revealing a clear linear scaling.

comes more coherent under dissipation.

Fig. 2 suggests that the temperature decreases linearly with the number of atoms. Rescaling the data points to their respective initial values $T_0$ and $N_0$ collapses the measurements to a single line, as shown in Fig. 3. This suggests a linear scaling relation between temperature and atom number

$$\frac{T}{T_0} = \frac{N}{N_0},$$

which is particularly interesting as these measurements are obtained from different experimental procedures and initial conditions.

Model.—In a pure 1D setting two-body collisions do not lead to a re-distribution of energy and momentum. However, in a quasi-1D trap with a tight transverse confinement this condition can be broken in collisions where there is enough energy available to access transverse excited states. These thermalizing two-body collisions are suppressed by a factor $\exp(-\hbar \omega_{\perp}/k_B T)$ \[7\] in a gas of non-degenerate bosons. For a degenerate gas the Bose enhancement of the ground state leads to an even stronger suppression. Consequently, these collisions freeze out as soon as the gas enters the 1D regime. Other processes that can lead to thermalization in our system are three-body collisions \[7, 8\] or phonon-phonon scattering \[9, 11\]. However, their expected thermalization time-scales are beyond the times probed in our experiment and can not explain the observed cooling. A different case of evaporative cooling in a 1D harmonic trap has been modeled by Witkowska et al. \[21\], assuming that atoms are out-coupled energy-selectively at the two ends of the cigar-shaped trap, which is not the physical situation in our experiment (see Fig. 4).

To find a simple mechanism consistent with our experimental observations we start by considering the outcoupling process. The rate of outcoupling via RF or MW transitions is determined by the overlap of the conden-
The experimentally investigated situation of a slow, continuous dissipation can be modeled as a series of small density reductions each followed by an immediate dephasing. This leads to a continuous decrease of the quasi-particle mode occupation, as illustrated in Fig. 4. The mode occupations react to a sudden decrease in density \( \rho \rightarrow \rho' \) as \( n_j' = \frac{1}{2} \sqrt{\alpha (\alpha^2 + 1)} n_j \), with \( \alpha = \rho'/\rho \) being the ratio by which the average density is reduced. For a series of small reductions under continuous dephasing we can expand this factor around \( \alpha = 1 \), which, to leading order, gives \( n_j' = \alpha^{3/2} n_j \). In the case of a harmonically trapped gas in the Thomas-Fermi limit where the central density scales as \( \rho' / \rho = (N' / N)^{2/3} \), this leads to a linear scaling of \( n_j \) with the particle number \( N \). As the degenerate system is still sufficiently hot, the observable low-energy modes are dominated by the Rayleigh-Jeans part of the system is still sufficiently hot, the observable low-energy modes are dominated by the Rayleigh-Jeans part of the spectrum, which is far below the region where thermalizing two body collisions freeze out, rendering standard evaporative cooling ineffective. The observed cooling allows us to go deep into the 1D regime and is therefore of direct relevance for experiments with 1D Bose gases. Our model also explains how previous experiments could observe such low temperatures \([32, 33]\).

Finally, our simple model suggests that the mechanism behind the observed cooling is not limited to 1D and could be relevant in 2D and 3D settings at very low temperatures where atoms are homogeneously outcoupled from the quantum degenerate gas and the dephasing of excitations is faster then their thermalization.

We would like to thank D. Adu Smith, M. Kuhnert and M. Gring for contributions in the early stage of the experiment, and J. Walraven, A. Polkovnikov, E. Demler and S. Weinfurtner for helpful discussions. This work was supported by the Austrian Science Fund (FWF) through the project P22590-N16 and the FWF FoQuS Project F4010 and by the EU through the projects SIQS and the ERC advance grant QuantumRelax. B.R., P.G. and T.S. thank the FWF Doctoral Programme CoQuS (W1210). R.G. acknowledges support by the FWF through the Lise Meitner Programme M-1423. T.L. acknowledges support by the Alexander von Humboldt Foundation through a Feodor Lynen Research Fellowship.

**References**

1. I. Bloch, J. Dalibard, and W. Zwerger, *Reviews of Modern Physics* **80**, 885 (2008).
2. H. F. Hess, *Physical Review B* **34**, 3476 (1986).
3. N. Masuhara, J. M. Doyle, J. C. Sandberg, D. Kleppner, T. J. Greytak, H. F. Hess, and G. P. Kochanski, *Physical Review Letters* **61**, 935 (1988).
4. O. J. Luiten, M. W. Reynolds, and J. T. M. Walraven, *Physical Review A* **53**, 381 (1996).
5. T. Kinoshita, T. Wenger, and D. S. Weiss, *Nature* **440**, 900 (2006).
6. M. Gring, M. Kuhnert, T. Langen, T. Kitagawa, B. Rauer, M. Schreitl, I. Mazets, D. A. Smith, E. Demler, and J. Schmiedmayer, *Science (New York, N.Y.)* **337**, 1318 (2012).
7. I. E. Mazets, T. Schumm, and J. Schmiedmayer, *Physical Review Letters* **100**, 210403 (2008).
8. S. Tan, M. Pustilnik, and L. I. Glazman, *Physical Review Letters* **105**, 090404 (2010).
9. A. Andreev, Sov. Phys. JETP **51**, 1038 (1980).
10. H.-P. Stimming, N. J. Mauser, J. Schmiedmayer, and I. E. Mazets, *Physical Review A* **83**, 023618 (2011).
11. M. Buchhold and S. Diehl, arXiv:1501.01027 (2015).
12. J. Reichel and V. Vuletić, *Atom Chips* (Wiley-VCH, Weinheim, Germany, 2011).
13. K. B. Davis, M.-O. Mewes, M. A. Joffe, M. R. Andrews, and W. Ketterle, *Physical Review Letters* **74**, 5202 (1995).
14. D. S. Petrov, G. V. Shlyapnikov, and J. T. M. Walraven, *Physical Review Letters* **85**, 3745 (2000).
15. D. A. Smith, S. Aigner, S. Hofferberth, M. Gring, M. Andersson, S. Wildermuth, P. Krüger, S. Schneider, T. Schumm, and J. Schmiedmayer, *Optics express* **19**, 5361 (2011).
[16] C. F. Ockeloen, A. F. Tauschinsky, R. J. C. Spreeuw, and S. Whitlock, Physical Review A \textbf{82}, 061606 (2010)

[17] A. Imambekov, I. E. Mazets, D. S. Petrov, V. Gritsev, S. Manz, S. Hofferberth, T. Schumm, E. Demler, and J. Schmiedmayer, Physical Review A \textbf{80}, 033604 (2009)

[18] S. Manz, R. Bücke, T. Betz, C. Koller, S. Hofferberth, I. E. Mazets, A. Imambekov, E. Demler, A. Perrin, J. Schmiedmayer, and T. Schumm, Physical Review A \textbf{81}, 031610 (2010)

[19] H.-P. Stimming, N. J. Mauser, J. Schmiedmayer, and I. E. Mazets, Physical Review Letters \textbf{105}, 015301 (2010)

[20] T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger, Nature Physics \textbf{1}, 57 (2005)

[21] E. Witkowska, P. Deuar, M. Gajda, and K. Rzżewski, Physical Review Letters \textbf{106}, 135301 (2011)

[22] T. Giamarchi, \textit{Quantum physics in one dimension} (Clarendon Press, Oxford, 2004)

[23] E. H. Lieb and W. Liniger, Physical Review \textbf{130}, 1605 (1963)

[24] M. Kuhnert, R. Geiger, T. Langen, M. Gring, B. Rauer, T. Kitagawa, E. Demler, D. Adu Smith, and J. Schmiedmayer, Physical Review Letters \textbf{110}, 090405 (2013)

[25] T. Langen, R. Geiger, M. Kuhnert, B. Rauer, and J. Schmiedmayer, Nature Physics \textbf{9}, 640 (2013)

[26] P. Griśins, B. Rauer, T. Langen, J. Schmiedmayer, and I. E. Mazets, arXiv:1411.4946 (2014).

[27] M. Rigol, V. Dunjko, V. Yurovsky, and M. Olshanii, Physical Review Letters \textbf{98}, 050405 (2007)

[28] T. Langen, S. Erne, R. Geiger, B. Rauer, T. Schweigler, M. Kuhnert, W. Rohringer, I. E. Mazets, T. Gasenzer, and J. Schmiedmayer, Science \textbf{348}, 207 (2015)

[29] W. Rohringer, D. Fischer, F. Steiner, I. E. Mazets, J. Schmiedmayer, and M. Trupke, Scientific Reports \textbf{5}, 9820 (2015)

[30] Y. Japha, S. Choi, K. Burnett, and Y. B. Band, Physical Review Letters \textbf{82}, 1079 (1999)

[31] X. Busch, I. Carusotto, and R. Parentani, Phys. Rev. A \textbf{89}, 043819 (2014)

[32] S. Hofferberth, I. Lesanovsky, T. Schumm, A. Imambekov, V. Gritsev, E. Demler, and J. Schmiedmayer, Nature Physics \textbf{4}, 489 (2008)

[33] T. Jacqmin, J. Armijo, T. Berrada, K. V. Kheruntsyan, and I. Bouchoule, Physical Review Letters \textbf{106}, 230405 (2011)