



## Phase-Sensitive Recombination of Two Bose-Einstein Condensates on an Atom Chip

G.-B. Jo, J.-H. Choi, C. A. Christensen, T. A. Pasquini, Y.-R. Lee, W. Ketterle, and D. E. Pritchard\*

*MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, Department of Physics,  
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 28 February 2007; published 30 April 2007)

The recombination of two split Bose-Einstein condensates on an atom chip is shown to result in heating which depends on the relative phase of the two condensates. This heating reduces the number of condensate atoms between 10% and 40% and provides a robust way to read out the phase of an atom interferometer without the need for ballistic expansion. The heating may be caused by the dissipation of dark solitons created during the merging of the condensates.

DOI: [10.1103/PhysRevLett.98.180401](https://doi.org/10.1103/PhysRevLett.98.180401)

PACS numbers: 03.75.Dg, 03.75.Lm, 39.20.+q

Most experiments in atom interferometry use freely propagating atom clouds [1–3]. Alternative geometries are confined-atom interferometers where atoms [3] are guided or confined in trapping potentials [4], often realized by using atom chips [5]. These geometries are promising in terms of compactness and portability, and also offer the prospect of extending interrogation times beyond the typical 0.5 s achievable in the atomic fountains. Such interferometers can be used to study atom-surface interactions [6] and Josephson phenomena [7].

Many discussions of confined-atom interferometers propose a readout by merging the two separated clouds [8–10]. These discussions usually assume noninteracting atoms [8,11] and do not address the deleterious effects of atomic interactions, including dephasing, collisional shifts, and phase diffusion [12–17]. A recent study showed that the recombination process is much more sensitive to atomic interactions than the splitting process since merging clouds with the opposite phase involves excited modes of the recombined potential and can lead to exponential growth of unstable modes [18]. To circumvent these problems, previous realizations of confined-atom interferometry used ballistic expansion of the two spatially independent condensates, which decreases the atomic density before overlap [4,19–21] or worked at very low atom densities and pushed the clouds into each other with photon recoil [22,23]. While this avoids the deleterious effects of atom-atom interactions during the recombination, it lacks the inherent simplicity and robustness of in-trap recombination. Furthermore, in-trap recombination, combined with dispersive, *in situ*, imaging [24], could make it possible to recycle the condensate for the next measurement cycle after resetting the temperature through evaporating cooling. The detection optics for *in situ* imaging may even be integrated onto the atom chip [25]. Moreover, a trapped sample at high optical density can be read out with subshot noise precision using cavity-enhanced atom detection [26].

In this Letter, we show that in-trap recombination leads indeed to heating of the atomic cloud. However, this heating is phase dependent and can be used as a robust and sensitive readout of the atom interferometer. The resulting

oscillations of the condensate atom number are dramatic (typically  $\sim 25\%$  contrast), occur over a wide range of recombination rates, and permit high signal to noise ratios since they simply require a measurement of the total number of condensate atoms in the trap.

The implications of phase-sensitive recombination extend beyond atom interferometry. Recombination with uncontrolled phase was used to replenish a continuous Bose-Einstein condensate (BEC) [27] or to create vortices [28]. An extreme case of the merge process, where two condensates are suddenly connected, has been studied by optically imprinting a dark soliton into a single trapped condensate [29,30]. Here we use methods of atom interferometry to prepare two condensates with well-defined relative phase and study the merging process for variable recombination times.

Two special cases of the merging process can be exactly described (Fig. 1). Two noninteracting separated condensates with the same phase should adiabatically evolve into the ground state of the combined potential, whereas a  $\pi$ -relative phase should result in the lowest lying antisymmetric state with excitation energy  $N\hbar\omega$ , where  $N$  is the total number of atoms in a trap and  $\omega$  is the transverse frequency of the trapping potential. The other limiting case is a merging process where a thin membrane separates two interacting condensates until the potentials are merged, and then is suddenly removed. For the 0-relative phase, the merged condensate is in its Thomas-Fermi ground state. For a  $\pi$ -relative phase, however, the merged condensate contains a dark soliton. Although the wave function differs from the ground state only in a thin layer, the total energy of this excited state is proportional to  $N\hbar\omega$ , as the lowest antisymmetric state in the noninteracting case [31].

Our working assumption is that the phase-sensitive excitation of the cloud decays quickly, on the order of  $\sim 1$  ms in our system, and leads to an increase in temperature on the order of  $\hbar\omega/k_B \simeq 100$  nK for the case of  $\Delta\phi = \pi$ , and less for other values of  $\Delta\phi$ , where  $k_B$  is the Boltzmann constant. The parameters of our experiment were intermediate between limiting cases of suddenness or adiabaticity, and we found a window of recombination times for

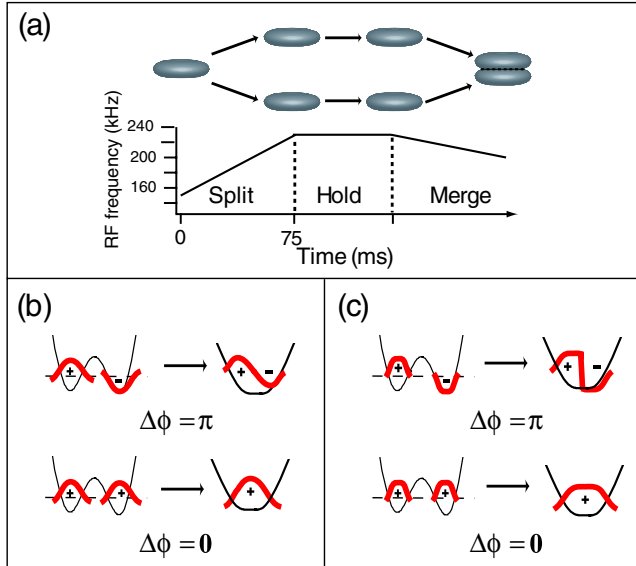


FIG. 1 (color online). Schematic of the in-trap recombination with a well-defined relative phase. (a) The phase-coherent condensates were prepared using a radio frequency induced double-well potential on an atom chip [21]. The splitting was done within 75 ms by ramping up the rf frequency from 140 to 225 kHz. During the hold time, the relative phase of two independent condensates evolved with time at  $\sim 500$  Hz. After a variable time, the double-well potential was deformed into a single well and the two trapped condensates were merged by decreasing the rf frequency by 33 kHz over a variable “recombination time.” The condensates started to spill over the barrier after  $\leq 10\%$  of the recombination time or  $\sim 3$  kHz decrease of the rf frequency. (b),(c) The merged matter-wave functions are shown for the cases of an adiabatic merger of noninteracting condensates and for a sudden merger of interacting condensates.

the phase-sensitive readout to which none of these descriptions apply.

Bose-Einstein condensates of  $\sim 4 \times 10^5$   $^{23}\text{Na}$  atoms in the  $|F = 1, m_F = -1\rangle$  state were transferred into a magnetic trap generated by the trapping wire on an atom chip and an external bias field [19]. The cloud had a condensate fraction  $\approx 90\%$  and the temperature was  $\sim 1/2$  of the BEC transition temperature, well above 0.1 when axial phase fluctuations are excited. Using adiabatic rf-induced splitting [20,32], a double-well potential in the horizontal plane was formed. Typically, the separation of the two wells was  $d \sim 6 \mu\text{m}$ , the height of the trap barrier was  $U \sim h \times 10 \text{ kHz}$ , and the chemical potential of the condensates, measured from the trap bottom, was  $\mu \sim h \times 6 \text{ kHz}$ , where  $h$  is Planck’s constant. In the experiment, the coherence time of two separated condensates was at least  $\sim 50$  ms [21]. The recombination of two split condensates was realized by reducing the rf frequency as described in Fig. 1(a), which decreases the trap barrier height. The merging occurred slowly compared to the time scale determined by the radial trap frequency ( $\sim 1$  kHz) to minimize mechanical excitation.

To monitor the energy increase after recombination, we measured the central atom density during ballistic expansion. Phase-sensitive collective excitations, in addition to mechanical excitations from the splitting and merging processes, heat the cloud and lower the condensate fraction and, therefore, reduce the central density. In the experiment, the split condensates were held in the double-well potential for varying hold times, merged into a single potential, and released by turning off the trapping potential within  $30 \mu\text{s}$ . After 8 ms time of flight, we measured the number of atoms in a fixed area which is comparable to the size of (expanded) Thomas-Fermi radius [dotted box in Fig. 2(c)]. While the total atom number was conserved, the number within the fixed area decreased, indicating that the temperature had increased. The fractional loss of condensate atoms was obtained as the ratio of atom number after recombination to the atom number before splitting.

The fractional loss of condensate atoms was reproducible for a given hold time, and observed to oscillate between 15% and 35% as a function of hold time at a rate of 500 Hz (Figs. 2 and 3). The observed oscillations are sinusoidal, although the nonlinear interactions can give rise to nonsinusoidal variations [16]. To confirm that this oscillatory heating was associated with the relative phase of the split condensates, we measured the relative phase as the spatial phase of the interference pattern when the split condensates were suddenly released and interfered during ballistic expansion [Fig. 2(a)] [4]. The strong correlation between the two measurements [Fig. 2(b)] is the central result of this Letter. As the relative phase increased from 0 to  $\pi$ , the atom loss after recombination increased [Fig. 2(b)]; the  $\pi$ -relative phase (0-relative phase) difference leads to maximum (minimum) loss of condensate atoms.

The use of phase-sensitive recombination as a readout for an atom interferometer is demonstrated in Fig. 3. The separated condensates accumulate relative phase for an evolution time of up to 6 ms which is read out after in-trap recombination. The phase-sensitive recombination signal showed high contrast over a wide range of recombination times [Figs. 3 and 4(a)]. The observed largest amplitudes of condensate atom loss correspond to a change in temperature on the order of  $\sim 100$  nK, in agreement with the estimate in the introduction. This is testimony to the insensitivity of the energy of phase-dependent excitations against changes in the exact recombination parameters, and is promising for further applications of chip-based atom interferometry.

The dependence of the condensate atom loss on the recombination time allows us to speculate about different excitations caused by the merging process. The 1 ms recombination time shows little contrast [Fig. 3(d)]. This time scale is comparable to the period of radial oscillations, and one would expect breakdown of adiabaticity and excitation of collective excitations independent of the relative phase. Significant loss ( $\sim 30\%$ ) was observed for all relative phases and masked or suppressed any phase-sensitive signal. The loss of contrast for the long recombination

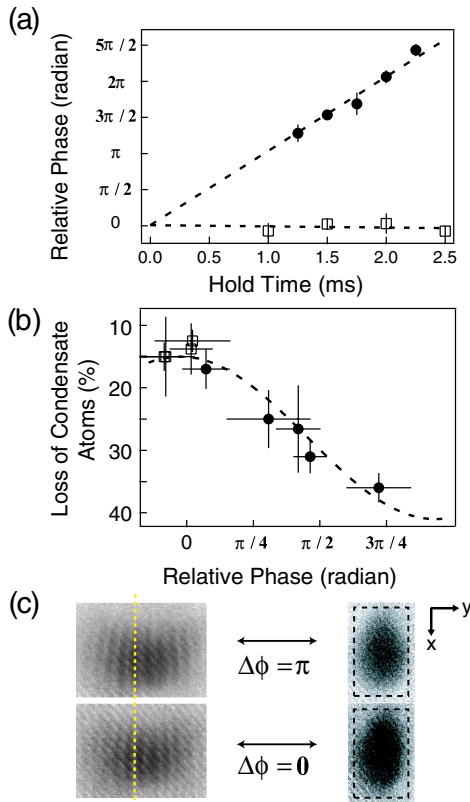


FIG. 2 (color online). Phase-sensitive recombination of two separate condensates. (a) The relative phase of two split condensates was monitored for various hold time after splitting by suddenly releasing the two condensates and observing interference fringes. For the independent condensates (solid circle), the evolution rate of the relative phase was determined from the linear fit to be  $\sim 500$  Hz. For the weakly coupled condensates (open square), the relative phase did not evolve. At 0 ms hold time, the relative phase was set to zero for both cases. (b) For the same range of delay times as in (a), the condensate atom loss after in-trap recombination was determined. The relative phase ( $x$  axis) was obtained from interference patterns as in (a). The merging time was 5 ms. (c) The matter-wave interference patterns (after 9 ms time of flight) and absorption images of merged clouds (after 8 ms time of flight) show the correlation between phase shift and absorption signal. The field of view is  $260 \times 200 \mu\text{m}$  and  $160 \times 240 \mu\text{m}$  for matter-wave interferences and merged clouds, respectively.

times could be caused by relaxation of the phase-sensitive collective excitation during the merging process when the condensates are connected only by a region of low density, and solitonlike excitations have lower energy. An alternative explanation is the evolution of the relative phase (at  $\sim 500$  Hz) during the effective recombination time. In a simple picture assuming a thin membrane being slowly pulled out between the condensates, a phase evolution during this time would create local solitons with phases varying between 0 and  $\pi$ . This could wash out the phase-sensitive signal to an average value. Since the data for 100 ms recombination time show low loss [comparable to the zero relative phase loss for faster recombination

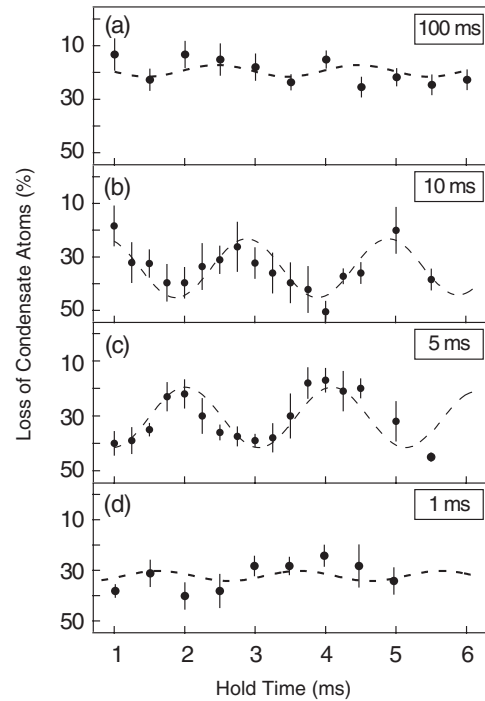


FIG. 3. Oscillations of condensate atom loss after recombination reflecting the coherent phase evolution. The condensate atom loss was monitored during a variable hold time for the two split condensates whose relative phase evolved at  $\sim 500$  Hz. The merging was done for different values of the recombination time: 100 (a), 10 (b), 5 (c), and 1 ms (d). The dotted lines are sinusoidal curves fitted with fixed frequency  $\sim 500$  Hz. The reproducible phase shift for the 5 and 10 ms data occurred during the recombination process. The data points represent the average of 6 measurements.

times, Fig. 3(d)], we favor the first explanation. Furthermore, it is not clear during what fraction of the ramp time of the rf frequency (called the recombination time) the effective merging of the condensates and the creation of a phase-sensitive collective excitation occurs. The time between when the barrier equals the chemical potential and when the barrier reaches  $\sim 70\%$  of the chemical potential is 10% of the recombination time. Another open question is what the rate of phase evolution is at the moment of the merger. It is plausible that during splitting, the condensates have the same chemical potential, and that the observed difference is created only when the condensates are further separated by ramping up the barrier. This would imply that during recombination, the situation reverses, the chemical potential difference is reduced and reaches near zero when the condensates merge. In any case, our work raises intriguing questions for further experimental and theoretical studies: What kind of phase-sensitive excitations are created during a merger process? How and when do they dissipate, and what would happen when two condensates with different chemical potentials are merged?

The present work demonstrates that interactions between atoms and collective excitations are not necessarily deleterious to direct recombination of separated trapped

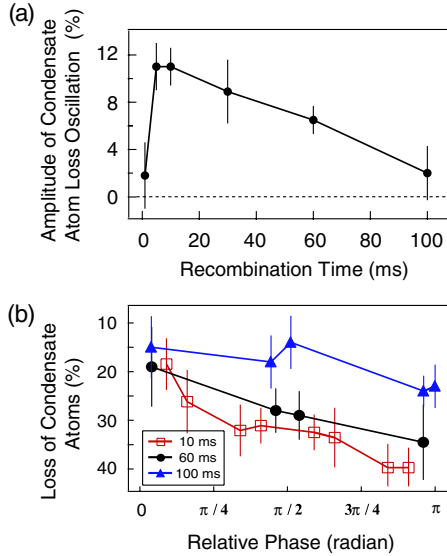


FIG. 4 (color online). Recombination time and atom loss. (a) The amplitude of atom loss oscillations was determined for various recombination times. (b) Assuming that minimum atom loss occurs at 0-relative phase of the two condensates, relative phases were obtained from the fitted atom loss oscillations in Fig. 3.

condensates that have acquired a relative phase in atom interferometry. In contrast, the phase-sensitive generation of collective excitations is used to monitor the relative phase. This complements our previous work where atomic interactions were shown to enhance the coherence time by preparing a number squeezed state with the help of atomic interactions during the beam splitting process [21]. So the merger between condensed matter and atomic physics goes both ways. In recent years, atomic physics has developed powerful tools to study many-body physics [33], and, as we have shown here, many-body physics provides methods and tools to atom optics.

This work was funded by DARPA, NSF, and ONR. G.-B. Jo and Y.-R. Lee acknowledge additional support from the Samsung Foundation. We would like to acknowledge Y. Shin for useful discussions, and M. Vengalattore and M. Prentiss for atom chip fabrication.

\*Electronic address: [http://cua.mit.edu/ketterle\\_group/](http://cua.mit.edu/ketterle_group/)

- [1] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, *Phys. Rev. Lett.* **66**, 2693 (1991).
- [2] M. Kasevich and S. Chu, *Phys. Rev. Lett.* **67**, 181 (1991).
- [3] P. Berman, *Atom Interferometry* (Academic, New York, 1997).
- [4] Y. Shin, M. Saba, T. A. Pasquini, W. Ketterle, D. E. Pritchard, and A. E. Leanhardt, *Phys. Rev. Lett.* **92**, 050405 (2004).
- [5] J. Fortagh and C. Zimmermann, *Rev. Mod. Phys.* **79**, 235 (2007).
- [6] J. D. Perreault and A. D. Cronin, *Phys. Rev. Lett.* **95**, 133201 (2005).
- [7] M. Albiez, R. Gati, J. Fölling, S. Hunsmann, M. Cristiani, and M. K. Oberthaler, *Phys. Rev. Lett.* **95**, 010402 (2005).
- [8] W. Hänsel, J. Reichel, P. Hommelhoff, and T. W. Hänsch, *Phys. Rev. A* **64**, 063607 (2001).
- [9] J. A. Stickney and A. A. Zozulya, *Phys. Rev. A* **66**, 053601 (2002).
- [10] A. Negretti and C. Henkel, *J. Phys. B* **37**, L385 (2004).
- [11] E. Andersson, T. Calarco, R. Folman, M. Andersson, B. Hessmo, and J. Schmiedmayer, *Phys. Rev. Lett.* **88**, 100401 (2002).
- [12] Y. Castin and J. Dalibard, *Phys. Rev. A* **55**, 4330 (1997).
- [13] M. Lewenstein and L. You, *Phys. Rev. Lett.* **77**, 3489 (1996).
- [14] E. M. Wright, D. F. Walls, and J. C. Garrison, *Phys. Rev. Lett.* **77**, 2158 (1996).
- [15] J. Javanainen and M. Wilkens, *Phys. Rev. Lett.* **78**, 4675 (1997).
- [16] A. J. Leggett and F. Sols, *Phys. Rev. Lett.* **81**, 1344 (1998).
- [17] J. Javanainen and M. Wilkens, *Phys. Rev. Lett.* **81**, 1345 (1998).
- [18] J. A. Stickney and A. A. Zozulya, *Phys. Rev. A* **68**, 013611 (2003).
- [19] Y. Shin, C. Sanner, G.-B. Jo, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss, *Phys. Rev. A* **72**, 021604 (2005).
- [20] T. Schumm, S. Hofferberth, L. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger, *Nature Phys.* **1**, 57 (2005).
- [21] G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss, *Phys. Rev. Lett.* **98**, 030407 (2007).
- [22] O. Garcia, B. Deissler, K. J. Hughes, J. M. Reeves, and C. A. Sackett, *Phys. Rev. A* **74**, 031601(R) (2006).
- [23] E. Su, S. Wu, and M. Prentiss, physics/0701018.
- [24] M. R. Andrews, M.-O. Mewes, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, *Science* **273**, 84 (1996).
- [25] T. Steinmetz, A. Balocchi, Y. Colombe, D. Hunger, T. Hänsch, R. Warburton, and J. Reichel, physics/0606231.
- [26] I. Teper, Y.-J. Lin, and V. Vuletic, *Phys. Rev. Lett.* **97**, 023002 (2006).
- [27] A. P. Chikkatur, Y. Shin, A. E. Leanhardt, D. Kielpinski, E. Tsikata, T. L. Gustavson, D. E. Pritchard, and W. Ketterle, *Science* **296**, 2193 (2002).
- [28] D. R. Scherer, C. N. Weiler, T. W. Neely, and B. P. Anderson, cond-mat/0610187.
- [29] S. Burger, K. Bongs, S. Dettmer, W. Ertmer, K. Sengstock, A. Sanpera, G. V. Shlyapnikov, and M. Lewenstein, *Phys. Rev. Lett.* **83**, 5198 (1999).
- [30] J. Denschlag, J. E. Simsarian, D. L. Feder, C. W. Clark, L. A. Collins, J. Cubizolles, L. Deng, E. W. Hagley, K. Helmerson, and W. P. Reinhardt *et al.*, *Science* **287**, 97 (2000).
- [31] In a layer on the order of the healing length  $\xi$ , the soliton has a kinetic energy per atom proportional to  $(1/\xi)^2$ . With the Thomas-Fermi radius proportional to  $\hbar/(\omega\xi)$ , the number of atoms covered by the soliton is proportional to  $N\omega\xi^2$ , and the total energy to  $N\hbar\omega$ . If the condensates were merged along their long axis, the soliton energy would be smaller by the aspect ratio, that is,  $\sim 200$ .
- [32] O. Zobay and B. M. Garraway, *Phys. Rev. Lett.* **86**, 1195 (2001).
- [33] J. R. Anglin and W. Ketterle, *Nature (London)* **416**, 211 (2002).