Bibliography

[1] This is a revised version of [93], with the addition of a comparison to the exicitation spectrum when only the changing number in the condensate is taken into account.

[2] This chapter is a revised version of [105] and [75], with the addition of an introduction and data showing radial separation of condensates in real time.

[3] This is a revised version of [76], including an analysis of the randomization of the relative phase due to experimental noise.

[4] This is a revised version of Matthews(/cond-mat/9906288). Additions include two plots further describing our "phase-twisting" model, and another plot comparing theory to experiment in another regime.

[5] This chapter is a revised version of Matthews(/cond-mat/9908209), with the addition of data showing an interferogram of our "ball and shell", non-vortex mixture of condensates.

[6] J. Williams and M. Holland, cond-mat/9909163.

[7] The observed transition temperature is $T' = 0.94(5)$ [60].

[8] In our previous study of condensate excitations at $T' \approx 0.48$, we used the $m = 0$ non-condensate mode for $T' \approx 1.3$ to calibrate the trap frequency. The present work indicates that this caused the values of ν/ν_r given in Ref. 4 to be too low by 1%. We thank W. Ketterle for pointing out this possible source of systematic error.

[9] To check that any systematic error due to frequency noise is small we have also determined the standard deviation of the measured cloud widths for time intervals corresponding to a couple oscillation periods. Obtaining γ from the exponential decay of these standard deviations is consistent with the damped sine wave fits.

[10] This is based on the approximation that $n^2 - 1 \simeq 2(n-1)$. This is only true when $\Delta \gg \gamma$. For condensates of $\sim 10^{15}$ cm^{-3}, this correction is 1% in real part of n at $\Delta = 100$ MHz.

[11] A. Toepler, 1864.

[12] F. Zernike, in Nobel Lectures, Physics (Elsevier, Amsterdam, 1964), p.239, text of 1953 Nobel Prize lecture.

[13] Equations 5.3 can be indeed generalized to include effects beyond TF approximation. This has been done, for instance, by Pérez-García, Phys. Rev. Lett. **77**, 5320 (1996). For the condensate used in the present work we have numerically checked that the corresponding changes in the final value of a_1/a_2 are much smaller than the experimental uncertainty.

[14] M. R. Andrews *et al.*, Science **275**, 637 (1997). Due to technical noise, the intrinsically random nature of the relative phase was not conclusively established.

[15] One can equally well describe our experimental system as a single condensate in a coherent superposition of internal states, *or* as two separate condensates with a particular relative phase. It would be customary in condensed-matter physics, with a typical coherent sample size of $\sim 10^{20}$ particles, to use the latter description. On the other hand, an expert in atom interferometry, with a typical coherent sample size of 1 particle, would be more likely to use the former.

[16] We define "coherence" as the predictability of the relative quantum phase. For interesting discussions of quantum coherence, see Refs. [100] and [137].

[17] The microwave and rf frequencies are produced by synthesizers locked to global-positioning system (GPS) signals. The manufacturer of the receiver claims a root Allan variance better than 10^{-10}.

[18] C. H. Greene, (private communication).

[19] Atom interferometry between *thermal* beams is a well-established technique. See, for example, D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, Phys. Rev. Lett. **66**, 2693 (1991). An early condensate interferometer is described in H.-J. Miesner and W. Ketterle, Solid State Commun.

[20] We separate the "environment" into two categories: an "intimate" environment, which includes interactions with thermal atoms as well as with internal modes within the condensate itself; and an "external" environment which includes such experimental factors as uncontrolled fluctuations in the magnetic fields. The former are intrinsic to the physics of the problem, whereas the latter can (in principle) be suppressed. In practice, we experience difficulty in keeping the external environment from intruding on our measurements; only in the modes of quietest operation are the oscillations of Fig. 6.3 observable. When coherence is observed, perturbations due to *both* the intimate and the external environments must be small; when coherence

is washed out, *either* may be responsible. For these reasons, we have not attempted in this paper to quantify the loss of coherence at longer times.

[21] Quantum fluctuations introduce an additional uncertainty that grows linearly in time in a process akin to the spreading of a Gaussian wavepacket in space; see Refs. [49, 134, 89, 102, 84]. We estimate the time scale for this process to be much longer than the duration of an individual measurement.

[22] We take the average of a $\sim 14\ \mu$m wide (post-expansion) vertical swath down the middle of the condensate density profile and extract the amplitude of the pixel at the center of the condensate image (*i.e.*, at the center of the overlap region).

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[24] For other recent experimental work on multi-component BEC, see [129], and H.-J. Miesner *et al.*, Phys. Rev. Lett. **82**, 2228 (1999).

[25] The probe beam does impose a small, reproducible shift on the energy difference between the $|1\rangle$ and $|2\rangle$ states, a measurable shift for which we correct.

[26] The simulation is a numerical integration of the coupled Gross-Pitaevski equations in. See [133] for more detail.

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[34] The normalized difference is defined as $(2d_{|1\rangle|2\rangle} - d_{|2\rangle} - d_{|1\rangle})/(2\sqrt{d_{|1\rangle}d_{|2\rangle}})$ where $d_{|i\rangle}$ is the local density for the ith state and $d_{|1\rangle|2\rangle}$ for the interferogram (Fig. 8.3b). This is not exactly the cosine of the phase difference ϕ between the vortex and interior state due to small effects, such as incomplete overlap between the states along the line of sight and uncertainties in the zero levels.

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