Bose-Einstein Condensate Interferometry

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With nearly all particles in perfect lock-step coherence, dilute gas Bose-Einstein condensates (BECs) represent the closest matter-state analogues to optical laser systems that technology has achieved so far. Many of the present-day BEC experiments observe the entire many-particle system to behave as a single particle quantum mechanical wave. By splitting this quantum wave into two spatially separated pieces or "arms" and by subsequently recombining them, the cold atom physicist can create an interferometer. From the interference fringes resulting from the recombination process, the observer can infer the difference of the rates at which the complex phases of each arm evolved and, hence, determine the external potential difference experienced by each arm. Simple back-of-the envelope estimates for the accuracy of such BEC-interferometer produced with a trapped table-top BEC-system of medium size (one million particles) promise a resolution that is competitive with state-of-the-art interferometers and other high-resolution small force measurement devices, such as gravimeters. Most of those high-resolution devices are bulky and difficult to transport in contrast to dilute gas BECs which, given recent advances in the production of BECs with prefabricated, compact, and easy-to-use units could conceivably be realized in hand-held devices in the near future.

An important source of the gain in resolution over other interferometers stems from the long time period that the two arms, split BEC-pieces contained in two potential minima of a double well cold atom potential trap, for instance, can spend apart before being recombined (the dwell time). However, many aspects of the dynamics of the BEC phase coherence in the splitting process, and of the long-time behavior of the relative phase dynamics while the pieces are spatially separated, remain to be investigated. Unquestionably, the interparticle interactions can degrade the phase coherence that is necessary for a high-resolution interferometer. These interactions can deplete atoms out of the condensate into other single particle states, especially in the delicate processes of splitting and recombining the BECs. In addition, the interparticle interactions tend to increase the quantum uncertainty of the relative phase difference shortly after the splitting of the BECs. Nevertheless, the initial growth of the quantum uncertainty of the relative phase reverses itself after some time and the relative phase is not destroyed by the interactions of the particles in the same arm at later times. Moreover, quantum optics

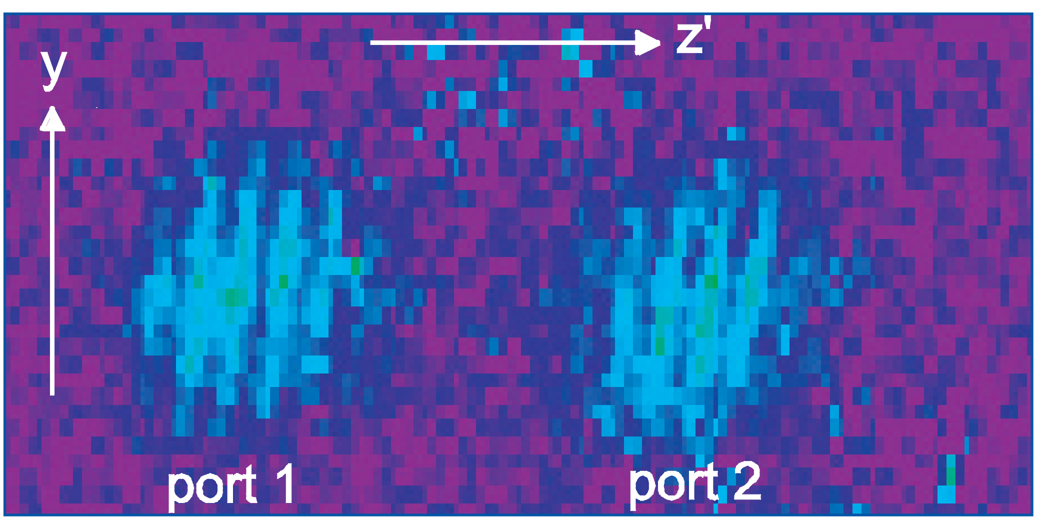
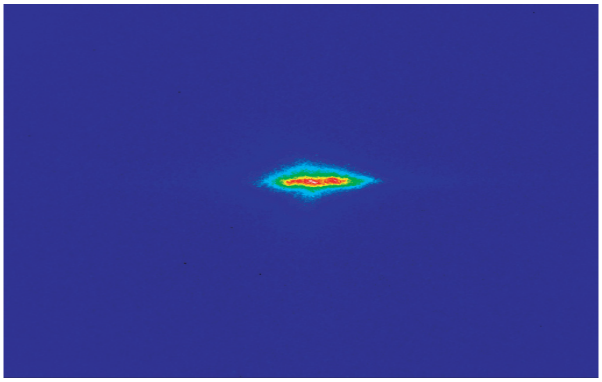
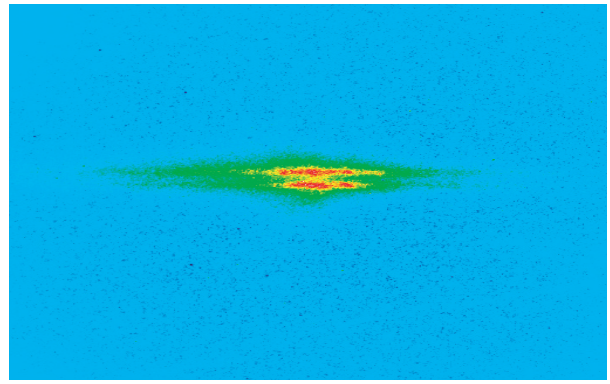


Figure 1—
Image that demonstrates the splitting of a Bose-Einstein condensate (BEC), after the BEC has been subjected to a light-induced standing wave pattern. The image was taken in the laboratory of Malcolm Boshier, Physics Division, LANL.





experts have pointed out that the interparticle interactions can help in creating a quantum entangled state of the BEC arms in which the relative phase uncertainty is minimized. The uncertainty could, in fact, reach to the ultimate quantum mechanical minimum, referred to as the Heisenberg limit. Such Heisenberg-limited interferometry with BECs would involve highly nonclassical many-body states that differ significantly from that of usual superfluids. Its realization would involve more elaborate BEC-splitting procedures. Perhaps, most importantly, some of these many-body states could be highly susceptible to decoherence (interactions with the environment that tend to destroy the desired entanglement).

In an effort that is spread out over three groups (T-4, T-13, and T-DO/QC), the T-Division members named in the author list are investigating the issues relevant to BEC-interferometry based on a simple splitting procedure and they are exploring the feasibility of many-body entanglement based BEC-interferometry. They also provide theoretical support for the two experimental groups that are part of this collaboration: Malcolm Boshier, Physics Division, and Xinxin Zhao, Chemistry Division, Los Alamos National Laboratory (LANL).

Figure 2—
Images of cold atom systems trapped in optical lattice potentials, obtained in the laboratory of Xinxin Zhao, Chemistry Division, LANL. On left: Well-aligned optical lattice, 34 Watt. Of CO_2 laser power, peak count ~3000, sub2.spe, 04/27/2004. On right: Ladder-potential, retro-reflected beam vertically shifted by 2*101.6 µm, peak count ~800, sub17.spe, 04/27/2004.