Formation of Dispersive Shock Waves by Merging and Splitting Bose-Einstein Condensates

J. J. Chang and P. Engels[*]
, , , , . . 1 ,

M. A. Hoefer
T , , 030 , [+]

(Received 14 March 2008; published 23 October 2008)

The processes of merging and splitting dilute-gas Bose-Einstein condensates are studied in the nonadiabatic, high-density regime. Rich dynamics are found. Depending on the experimental parameters, uniform soliton trains containing more than ten solitons or the formation of a high-density bulge as well as dispersive shock waves are observed experimentally within merged BECs. Our numerical simulations indicate the formation of many vortex rings. In the case of splitting a BEC, the transition from sound-wave formation to dispersive shock-wave formation is studied by use of increasingly stronger splitting barriers. These experiments realize prototypical dispersive shock situations.

DOI: 10.1103/PhysRevLett.101.170404 PACS numbers: 03.75.Kk, 05.45.−a, 47.40.−x, 67.85.De

Dilute-gas Bose-Einstein condensates (BECs) are a powerful environment for the study of nonlinear dynamics. Dispersive shock waves (DSWs) are an example of nonlinear behavior which has generated interest among diverse areas of physics. First studied in water and plasma wave dynamics [1], DSWs have also been investigated in other areas where dispersive hydrodynamic behavior is possible including nonlinear optics [2], electronic magnetic trap, this would imply a chemical potential of □ = . Therefore, the presence of the dipole beam leads to two clearly separated BECs [Fig. 1(a)]. The beam is turned on before the atoms are evaporatively cooled to form a BEC. After a BEC has formed on both sides of the barrier and no surrounding thermal cloud is visible, the dipole beam is rapidly turned off within less than 250 ns. We let the dynamics evolve in the magnetic trap for a variable evolution period before starting the expansion imaging. Directly after turning the dipole barrier off, the condensates smoothly expand toward each other [Fig. 1(b)]. This behavior can be described by the well-known dam-breaking problem whereby a sharp density gradient develops into a rarefaction wave (as opposed to a shock wave) when the background density is zero (see, e.g., [8,10]). Shortly after the BECs have collided at the center of the trap, a pronounced bulge of higher atom density forms in the collision plane [Fig. 1(c)]. Very pronounced dark notches are observed to form within the high-density bulge as shown in Fig. 1(d). Subsequently, this density bulge spreads out from the center of the trap [Figs. 1(c)–1(e) and 1(n)], and more notches are formed to fill the extent of the density bulge with an average spacing of roughly to □ . After about 55 ms, the bulge and the notches have spread over the entire extent of the condensate [Fig. 1(e)]. The long lifetime, discrete nature, and large amplitude of the notches suggest that they are nonlinear coherent structures rather than simple sound waves. Our numerical simulations show that a soliton train initially develops and a bulge region is formed where the solitons decay into a large number of vortex rings, see Figs. 1(f)–1(m) and [20]. Experimentally, vortex rings in BECs have been observed in [17,21]. They are difficult to detect unambiguously in our experimental images that are integrated along the line of sight. Fine fringes appear adjacent to the bulge region as can be seen, e.g., in Figs. 1(d) and 1(i). The fine fringes, together with the steepness of the wave fronts delimiting the density bulge region, are indicative of DSWs. The merging process finally results in an axial breathing-mode excitation of the BEC.

The qualitative features of the evolution are fairly independent of most experimental parameters. For example, use of two BECs with an initial total atom number of dipole beams,

parameters in Figs. 4(a)–4(d), the measured propagation speed of the two