NONLINEAR OPTICS

Shocking superfluids

How shock waves travel through a superfluid provides clues to understanding the deeper nature of Bose–Einstein condensation. An optical analogue that behaves as a pure superfluid could tell us what these clues mean.

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A Bose–Einstein condensate is one of the most intriguing states of matter. Its existence was predicted by Bose and Einstein in the 1920s and it has been particularly clearly demonstrated in recent years with laser-cooled, trapped atomic gases[1]. In these condensates, millions of atoms occupy the same quantum state — all atoms are in 'lock step' with each other and behave in many ways as a single entity — which leads to a number of interesting properties[2]. For example, a condensate shows superfluidity and can therefore flow without damping or dissipation. Similarly, Bose–Einstein condensation is responsible for the superfluid properties of helium below 2.17 K, and for the lossless conduction of electrical currents in superconductors. Yet there is much we do not know about Bose–Einstein condensation and superfluid behaviour.

A particularly interesting way of probing the inner workings of Bose–Einstein condensates (BECs) is to study how shock waves are generated and propagate within them. In real BECs this is challenging, and there have been only a few experimental studies[3–6]. In these experiments done in cooled atom clouds, a small component of non-condensed atoms co-exists with the condensate and creates interactions with propagating shock waves that are complex and of fundamental importance for the understanding of superfluidity. To identify these interactions, it is important to separate out the shock wave dynamics due entirely to the condensate component. On page 46 of this issue, Wan and colleagues describe a system for studying superfluid-like phenomena[7]. By taking advantage of the fact that the interaction of laser light with certain types of nonlinear optical crystals is governed by similar equations to those that govern the dynamics in BECs, they demonstrate an experimentally simple, all-optical system for studying superfluid-like shock waves. Because laser fields are perfectly coherent, the optical system mimics the behaviour of a pure condensate — one that is free from the influence of non-condensed components.

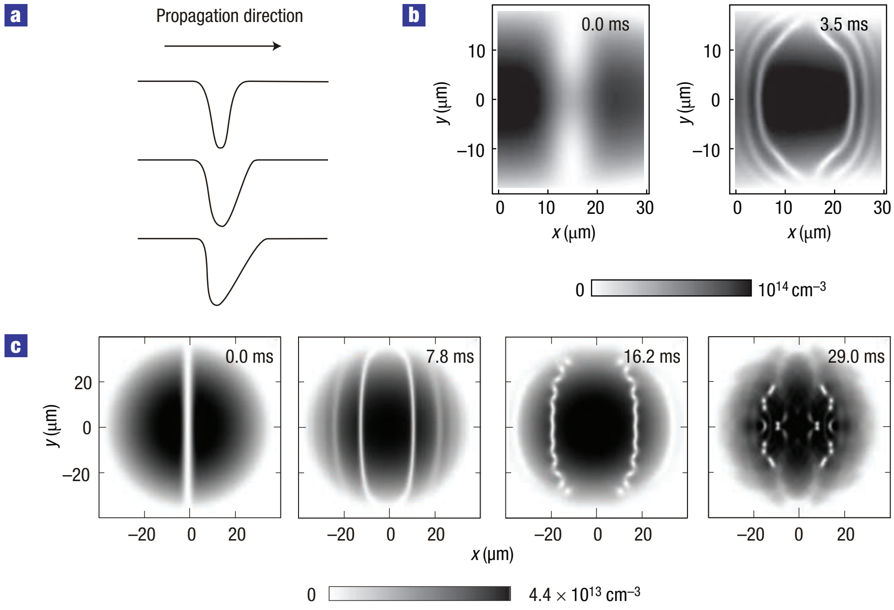


Figure 1 Exotic physics caused by shock waves in a Bose–Einstein condensate. **a**, The density-dependent speed of sound causes a propagating 'dark' shock front (characterized by a drop in density relative to the surrounding medium) to broaden at its leading edge, and sharpen at its trailing edge. **b**, An initial dip in the density of an otherwise dense (black) BEC (at $t = 0.0$ ms) develops into a shock front that sheds 'dark solitons' in its wake. The solitons are observed as curved, low-density (white) fronts (at $t = 3.5$ ms). These nonlinear excitations maintain their shape over large propagation distances owing to cancellation of dispersive effects by nonlinear atom–atom interactions in the fluid. The bar indicates the grey scale for atom density. (Numerical simulations: Naomi Ginsberg, Harvard Univ., thesis in preparation.) **c**, A density depression in a BEC ($t = 0.0$ ms) develops into a shock front that sheds dark solitons ($t = 7.8$ ms). Variation of atom density along the soliton front leads to a peculiar 'snake' instability ($t = 16.2$ ms). The points of high curvature along the front subsequently act as nucleation sites for quantized vortices seen as white (low-density) cores ($t = 29.0$ ms). The vortices are created in pairs of opposite circulation. (Reprinted from *Europhys. News* **35,** 33–39; 2004. Copyright EPS and EDP Sciences.)

Shock waves have startling effects, experienced in everyday life when sonic booms are generated by supersonic aircraft, and they have been studied in the context of classical gases and fluids for many years. When a fluid body is subject to a localized disturbance in its density, such as that caused by an object passing through it or by an injected laser pulse, it will generate sound waves that propagate outwards from the disturbance. If this disturbance is sufficiently strong, for instance when caused by a high-speed impact or by a high-energy laser pulse, the speed of sound, which increases with density, varies greatly across the disturbance. For a local density increase ('hump'), the central, dense part of the propagating wave will rapidly catch up with the leading edge of the wave. This in turn generates the steep front edge of a shock wave's characteristic asymmetric shape. If a localized density depletion ('dark hump') is induced instead, the back edge of the disturbance develops a shock front (see Fig. 1a).

In a classical fluid, wave dynamics is dominated by dissipative effects caused by viscosity in the fluid. This results in well-defined, propagating shock fronts where density and velocity change abruptly in a localized region across the front. But in superfluid BECs, the dynamics of shock waves is governed by dispersion rather than dissipation, and this greatly alters the behaviour. As a consequence of the coherent (lock-step) nature of a BEC, when a density hump is induced, the longitudinal shape of the resulting propagating shock fronts develops pronounced wiggles. These wiggles are a result of nonlinear wave mixing and interference effects in the coherent fluid.

In addition to the potential insights they provide into the physics of BECs and related systems, superfluid shock waves are of interest in their own right for their rich nonlinear excitation behaviour (Fig. 1b and c). The creation of particle-like excitations such as 'dark solitons' and quantized vortices (the superfluid equivalent of classical tornadoes) represents just some of the many peculiar phenomena that have been seen to emerge from the propagation of shock waves through BECs[3]. But, just as in high-energy physics where the most interesting physics is found when two particles collide, the real fun begins when multiple superfluid shock waves interact. For example, in shock collision experiments in sodium BECs, new, compound 'particles' with a very complex structure have been discovered[4]. Clearly, a rich field is emerging where interesting discrepancies with theory exist. In this respect, the platform for studying superfluid-like phenomena presented by Wan *et al.* could be very useful.

The crystal that forms the heart of Wan's system is one that shows a negative, Kerr-type optical nonlinearity. The authors illuminate the input face of the crystal with a laser field that consists of a gaussian peak superimposed on a uniform background (a 'hump-on-background' profile). As the field propagates through the crystal, the nonlinear response of the crystal causes the gaussian peak to spread in a way that directly mimics the outward propagation of a shock wave in a two-dimensional BEC. The light field at the output face of the crystal is imaged by a CCD camera. The strength of the shock is controlled simply by changing the amplitude of the gaussian peak with respect to the background field. And more importantly, by superimposing multiple peaks on this field, the system allows the generation and study of multiple colliding shock fronts.

The theory with which the authors analyse their results is based on Maxwell's equations. Although the Gross–Pitaevskii equation, with which shock behaviour in atomic condensates is usually analysed, provides a similar mean-field description, inevitable differences between the two exist. Moreover, it should be noted that the steep gradients in density and velocity that develop at shock fronts could lead to a local breakdown of the mean-field description, which could exacerbate these differences. Recent calculations indicate that a depletion of an atomic BEC may take place at shock fronts originating from dark humps induced in the condensate[8]. This depletion is associated with local excitations of atoms out of the condensate and would cause non-condensed atoms to fill the otherwise depleted cores of dark solitons and, probably, of vortices as well.

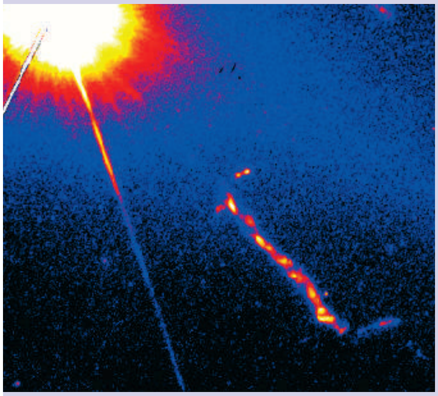
At the very least, being able to compare shock waves propagating in an atomic BEC with those in the optical system should allow the contribution to shock dynamics from the BEC component to be identified and separated from dynamics induced by, for example, interactions of quantized vortices with non-condensed atoms. Indeed, such insight could be of great value to our understanding of the breakdown of superfluidity and superconductivity — an issue that even on its own is of tremendous importance, from a fundamental perspective and for practical applications.

References

1. Anderson, M. H., Ensher, J. R., Matthews, M. R., Wieman, C. E. & Cornell, E. A. *Science* **269,** 198–201 (1995).
2. Pitaevskii, L. & Stingari, S. *Bose–Einstein Condensation* (Clarendon, Oxford, 2003).
3. Dutton, Z., Budde, M., Slowe, C. & Hau, L. V. *Science* **293,** 663–668 (2001).
4. Ginsberg, N., Brand, J. & Hau L. V. *Phys. Rev. Lett.* **94,** 040403 (2005).
5. Simula, T. P. *et al. Phys. Rev. Lett.* **94,** 080404 (2005).
6. Hoefer, M. A. *et al. Phys. Rev. A* **74,** 023623 (2006).
7. Wan, W., Jia, S. & Fleischer, J. W. *Nature Phys.* **3,** 46–51 (2007).
8. Damski, B. *Phys. Rev. A* **73,** 043601 (2006).

ASTROPARTICLE PHYSICS

X-ray diagnosis of a quasar



Quasars, along with supernovae and γ-ray bursts, are the most energetic sources of electromagnetic radiation in the Universe. About two billion light-years away, the nearest bright quasar, 3C 273 in the Virgo constellation, emits a powerful radio jet. Markos Georganopoulos *et al.* propose to use X-ray emission from the jet to investigate its origin (*Astrophys. J.,* in the press).

Although most astronomers believe that a quasar is powered by a supermassive black hole, it's not clear how that black-hole engine lights up a quasar. Information on the energy transport mechanism would reveal how black holes were formed in the early Universe. Similarly, it might explain why there are no such quasars in active galaxies nearby.

There are two main theories for the X-ray emission: inverse external Compton (EC) scattering from relativistic electrons that scatter cosmic microwave background (CMB) photons; and synchrotron emission from TeV electrons — the same mechanism as for radio emission from the jet, but from another population of electrons.

To complicate matters, synchrotron radiation would also scatter CMB photons, so would look similar to the EC model. But as the two candidate processes involve electron energies differing by two orders of magnitude, the two energy scales should lead to different γ-ray dynamics. Georganopoulos *et al.* have come up with a set of diagnostics to distinguish the two models using existing and future γ-ray detectors.

If no GeV or TeV emission is detected, or only low-level GeV, there would be no additional constraint for the synchrotron model but the EC model would lose support. Detection of high-level GeV or TeV emission would confirm the synchrotron model. Although the authors believe that the latter is the most likely outcome, they acknowledge that future observations could refute both hypotheses.

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