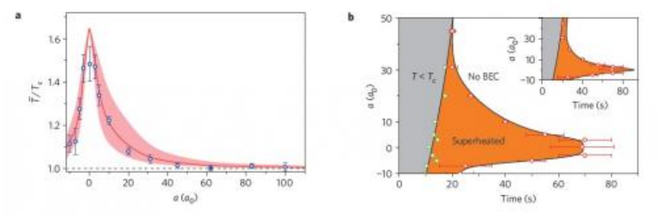
Superheated Bose-Einstein condensate exists above critical temperature

10 April 2013, by Lisa Zyga



(a) Physicists created a BEC that can persist at up to 1.5 times hotter than the critical temperature at which it normally decays. (b) The BEC can survive in the superheated regime for more than a minute when different components of the boson gas are not in equilibrium. Credit: Alexander L. Gaunt, et al. ©2013 Macmillan Publishers Limited

(Phys.org) —At very low temperatures, near absolute zero, multiple particles called bosons can form an unusual state of matter in which a large fraction of the bosons in a gas occupy the same quantum state—the lowest one—to form a Bose-Einstein condensate (BEC). In a sense, the bosons lose their individual identities and behave like a single, very large atom. But while previously BECs have only existed below a critical temperature, scientists in a new study have shown that BECs can exist above this critical temperature for more than a minute when different components of the gas evolve at different rates.

The physicists, Alexander L. Gaunt, Richard J. Fletcher, Robert P. Smith, and Zoran Hadzibabic at the University of Cambridge in the UK, have published their study on the superheated BEC in a recent issue of *Nature Physics*.

As the physicists explain, a superheated BEC is reminiscent of superheated distilled water (water that has had many of its impurities removed), which remains liquid above 100 °C, the temperature at which it would normally boil into a gas. In both cases, the temperature—as defined by the average energy per particle (boson or water molecule)—rises above a critical temperature at which the phase transition should occur, and yet it doesn't.

In BECs and distilled water, the inhibition of a phase transition at the critical temperature occurs for different reasons. In general, there are two types of phase transitions. The boiling of water is a first-order phase transition, and it can be inhibited in clean water because, in the absence of impurities, there is in an energy barrier that "protects" the liquid from boiling away. On the other hand, boiling a BEC is a second-order phase transition. In this case, superheating occurs because the BEC component and the remaining thermal (non-condensed) component decouple and evolve as two separate equilibrium systems.

The physicists explain how this mechanism works in more detail. In equilibrium, a BEC can only exist below a critical transition temperature. If the temperature is increased towards the critical value, the BEC should gradually decay into the thermal component. The particles flow between the two components until they have the same chemical potential (a measure of how much energy it takes to add a particle to either component), or in other words, until they are in equilibrium with each other. However, maintaining this equilibrium relies on the interactions between the particles.

Here, the researchers demonstrated that in an optically trapped potassium-39 gas the strength of interactions can be reduced just enough so that the two components remain at the same temperature, but the particle flow between them is slowed down and their chemical potentials decouple. This condition makes it possible for the BEC to maintain a higher chemical potential than the surrounding thermal component, and thus survive far above its equilibrium transition temperature.

"The thing that prompted this work was a previous paper of ours on measuring the equilibrium BEC transition temperature as a function of the interparticle interaction strength," Smith told *Phys.org*. "At the time we noticed that something funny was happening at very low interaction strengths: the transition temperature seemed higher than it should be by up to 5%. We realized that this was probably due to non-equilibrium effects, but could not explain it fully. Also, the effect was much smaller than we demonstrated now. Only after fully understanding the equilibrium properties of a BEC in an interacting gas we could come back to this problem, demonstrate a much clearer effect, and explain it quantitatively."

In the new study, the physicists experimentally demonstrated that a BEC could persist in the superheated regime (at temperatures above the critical temperature) for more than a minute. They also showed that that they could cause the BEC to rapidly boil away by strengthening the interatomic interactions to their normal levels, confirming the presence of the superheated state.

The scientists predict that extending a BEC's lifetime by tuning the interactions could have several applications.

"Generally, atomic BECs are increasingly used for applications such as atom interferometry and precision measurements, and might also find applications in quantum information processing and computing," Smith said. "For all those applications one wishes to preserve the coherent BEC for as long as possible, e.g., to perform a longer (hence more precise) measurement or more quantum-information type operations. Our work shows that it is possible to significantly extend the lifetime of a coherent BEC exposed to the experimentally unavoidable decohering thermal environment."

In the future, the researchers plan to further investigate the physical mechanism behind superheating.

"We are primarily interested in further fundamental understanding of the superheating phenomenon," Smith said. "The funny thing is that the system is simultaneously in equilibrium in some respects (e.g., the BEC and the thermal component have the same temperature, the BEC has an equilibrium shape for the given number of condensed atoms, etc.) and out of equilibrium in other ways (primarily the fact that the number of condensed atoms is much higher than expected in equilibrium). This poses new question about how we define equilibrium in a quantum system, which we would like to understand better. Practical applications might come later, fully exploiting their potential being reliant on more complete fundamental understanding.

"Also, it turns out that condensation in 2D systems is even more interesting than in 3D, and we plan to study superheating and other non-equilibrium phenomena for an ultracold 2D Bose gas."

More information: Alexander L. Gaunt, et al. "A superheated Bose-condensed gas." *Nature Physics*. DOI: 10.1038/NPHYS2587

Related: R. P. Smith, et al. "Effects of interactions on the critical temperature of a trapped Bose gas." *Phys. Rev. Lett*. 106, 250403 (2011) DOI: 10.1103/PhysRevLett.106.250403