Critical Behavior of a Trapped Interacting Bose Gas

Authors: T. Donner, S. Ritter, T. Bourdel, A. Ottl, M. Kohl, T. Esslinger,

http://ArXiv:0704.1439

Science 315, 1556 (2007).

Recommended with a commentary by Tin-Lun (Jason) Ho, Ohio State University

A few years back, if one said that one could extract critical exponents from a gas of Bose-Einstein condensate, even with the numerous experimental successes in quantum gases, it would be likely to raise some eyebrows. This is because quantum gases are mesoscopic systems with 10^5-10^6 particles, ten orders of magnitudes more dilute that solid state materials. Extracting critical exponents from these small systems by measuring their thermodynamic properties such as specific heat as in bulk Helium will require measurement techniques with extraordinary sensitivity. Unless one can come up with other clever tricks, this seems to be a very difficult undertaking.

The publication mentioned above by Tilman Esslinger's group at ETH is the first effort to study critical behavior in quantum gases. The trick is not to study thermodynamic quantities, but to measure the single particle density matrix $<\psi^{+}(\vec{r})\psi(\vec{r}\,')>$ directly. The plan is to extract from this function the correlation length ξ. By repeating the experiment at different temperatures, one can obtain the correlation length exponent ν by fitting $\xi(T)$ to a power law, $\xi \propto |(T-T_c)/T_c|^{-\nu}$. This, of course, assumes one has an accurate determination of the density matrix $<\psi^{+}(\vec{r})\psi(\vec{r}\,')>$, temperature increments, as well as critical temperature T_c. The authors of this paper have come up with clever ways to do these.

The measurement of the authors on the single particle density matrix was built upon a previous experiments of theirs. The basic idea is shown in figure A and B. One selects in the condensate two horizontal planes separated by a vertical distance r and uses a well known method (not discussed here) to out-couple the atoms (i.e. letting the atoms leak out from the cloud). Due to the difference in gravitational potential, the atoms from the two planes will have different phases at the same location downstream in the atomic flow. As a result, an interference pattern is formed. Since one knows how free particles propagate in a gravitational field, by placing a detector downstream, one can deduce the density matrix $<\psi^{+}(z)\psi(z+r)>$ from the arrival time of the atom and from the intensity of the signal. Here, z belongs to the lower plane. Fitting the data to the form $e^{-r/\xi}/r$, one can then extract the correlation length ξ.

The next task is to determine the temperature. It turns out that in these systems, the heating rate coming from background gases and other sources is a constant, as verified by other type of measurements (such as expansion rates, etc). So if one lets the system sits by itself, its temperature will rise at a constant rate. Thus, by first preparing the system slightly below $T < T_c$, (of which one can be sure because of the emergence of a condensate) and then by holding it for successive time intervals dt before performing measurement on correlation length, one obtain the correlation length at different temperatures $T + n\Delta T$, where ΔT is the temperature increment in each time interval dt. By making the time interval dt very small, one can obtain a very high temperature resolution. At this point, one still does not know what T_c and ΔT are. However, if the correlation length obeys the relation $\xi \propto |(T - T_c)/T_c|^{\nu}$, there should be one set of values $(T_c, \Delta T, \nu)$ that fit all the data. The best of such fit gives a temperature resolution of ΔT=300 picokevin, and $\nu = 0.67 \pm 0.13$. Since Bose gas, like liquid Helium, belongs to the 3D xy universality class, the theoretical value for ν is known to be 0.6705. The surprisingly good agreement between the measured ν and the exact result is likely to be fortuitous, since the error bars is quite large. Nevertheless, as a first try to study critical behavior in a Bose gas, it is a good start. One can be sure that more experimental studies on critical behavior of Bose gas will appear in near future. Finally, the readers may be interested to know that this experiment is in fact the result of a class project for a course taught by Tilman Esslinger at ETH.

Fig.A

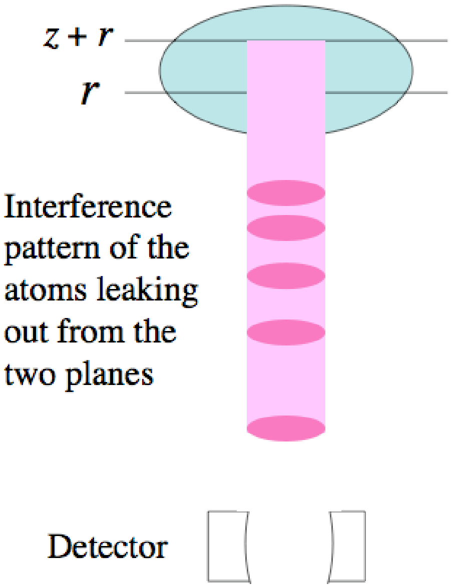

Fig.B

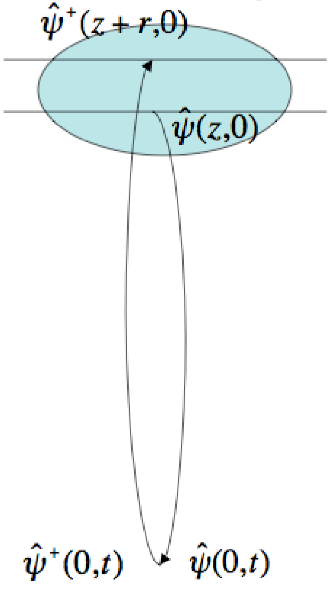

Fig.A shows that the atoms leaking out from the two selected planes will form an interference as they are pulled down by gravity. The atoms are detected by a detector placed downstream of the atomic flow.

Fig.B shows that now the density of detected at the detector at time t is related to the density matrix $<\psi^{+}(z)\psi(z+r)>$ at time t=0. The line connecting $\hat{\psi}(0,t)$ and $\hat{\psi}(z,0)$ is the Greens function of a particle that propagates from z at time t=0 to z=0 at time t under the influence of gravity.