Measurement of Critical correlations in an ultracold Bose gas by means of a temporal Talbot-Lau interferometery

Xuzong Chen[1]**, Wei Xiong**[1]**, Yueyang Zhai**[1]**, Xuguang Yue**[1]**, Biao Wu**[2]**, and Hongwei Xiong**[34]**, Xiaoji Zhou**[1]

[1] School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China
[2] International Center for Quantum Materials, Peking University, 100871, Beijing, China
[3] State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
[4] Department of Applied Physics, Zhejiang University of Technology, Hangzhou 310023, China

E-mail: `xuzongchen@pku.edu.cn`

Abstract.   We report the results of a study of measuring the correlation length at the Lambda critical phase transition point in an ultra-cold Bose gas with a temporal Talbot-Lau (TL) interferometery. Near the critical temperature, the correlation length increase exponentially and its critical exponent factor is measured around 0.67, which is a universal value in quantum gas. In the experiment we filtered the fraction of condensate from the thermal cloud at the Lambda critical phase transition point by means of the TL interferometer technique.

1. Introduction

Phase transition is a popular phenomena in nature, among them the transition from normal fluid to superfluid for helium is a famous one, since many abnormal phenomena appear around the transition point, one of them is the the Lambda point, while the temperature below it the normal fluid helium (helium I) would take transition to superfluid helium II. The point's name derives from the curve shape that results from plotting the specific heat capacity as a function of temperature, the specific heat capacity tends towards infinity as the temperature approaches the lambda point. The achievement of Bose-Einstein Condensation open a new field to the scientists, it has many similar properties as same as the helium liquid. Both of them are many body system , the interaction in the system is stronger for the helium and weaker for the Bose gas; There is also the Lambda phase transition point for Bose gas, while the temperature below the critical temperature, the normal Bose gas would take transition to quantum gas, which behaves as superfluid. There are several experiments to demonstrate the superfluid properties in quantum gas, the vortex appears both in helium quantum liquid and Bose quantum gas while they are both in superfluid state [1, 2]. Interference pattern the Bose Einstein Condensate in the weak depth of optical lattice is another evidence for Bose quantum gas in the superfluid state [3]. The phase transition from superfluid to Mott insulator is a well-known phenomena in the optical lattice experiment [4]. There are many characteristic parameters in the Lambda phase transition point both in helium and Bose gas, the correlation length is one of them. The correlation length

is the characteristic quantity to describe the correlation of the orientation of the spin of the atom in helium, in the phase of normal fluid , orientation of the spin of the atom in helium is random, the correlation length for the helium is small, as a critical point is approached, the correlation length grows to infinity. There will be the same phenomena for the Bose gas, the measurement of the correlation length at the critical point attracts many scientists interests, but the fluctuation is so large at the Lambda phase transition point that the measurement near the point becomes difficult. In 2007, Esslinger's group measured the correlation length at the critical point in the first time [5], they use the approach of interference of two components of BEC, but they only measured the right part of the exponential curve for the correlation length while it reach the Lambda the critical point. In this presentation, we demonstrate a new approach, a temporal Talbot-Lau (TL) interferometer , to measure correlation length. The whole correlation length cure at the Lambda critical phase transition point can be measured in an ultra-cold Bose gas with a temporal Talbot-Lau (TL) interferometer, and the critical exponent factors for the curve are also measured, which is equal to the universal value in quantum gas, 0.67.

2. Experiment and Procedure

For rubidium gas, while the temperature is much higher than the critical temperature (T_C), it behaves as thermal gas, we also call it as normal gas, while the temperature is reduced to the critical temperature, around hundred nano kelvin, the rubidium will alter from the normal gas to the quantum gas, the Bose-Einstein condensate will appear, while the temperature is reduced to far below the critical temperature, the rubidium appear as pure the Bose-Einstein condensate, which is the phase of superfluid (Fig. 1).
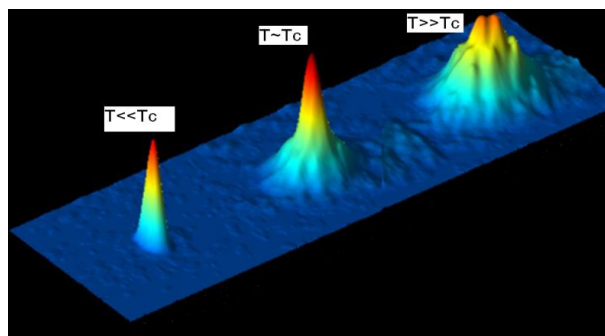

Figure 1. Phase transition of the rubidium gas at the critical temperature.

The phase transition takes at the critical point. Similar to the helium, the correlation length obey the following formula:

$$G(r) = \langle \Psi^\dagger(r)\Psi(0)\rangle \propto \frac{1}{r}exp(-r/\xi) \tag{1}$$

where r is the distance between two components in BEC and the ξ correlation length, which is described by:

$$\xi = \xi_0/(T - T_C)^\nu \tag{2}$$

where T is the temperature of the rubidium and T_C the critical temperature, ν is the critical exponent factor. The formula (2) indicates that: the correlation length ξ will exponentially decay around the Lambda phase transition point as Fig. 2. And the critical exponent factor is a universal value equal to 0.67.
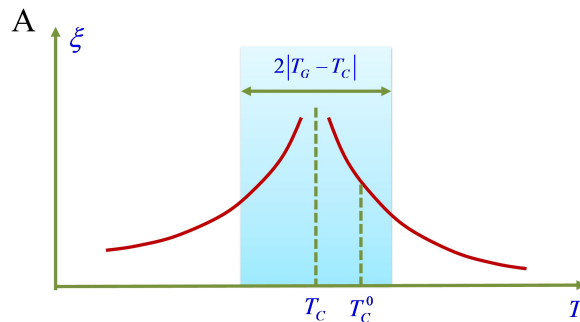
Figure 2. Correlation length curve exponentially decay around the critical temperature.

Since the correlation length ξ is proportional to reciprocal of the momentum width Δp, so we try to measure the momentum width Δp of rubidium gas around the critical temperature by a temporal Talbot-Lau (TL) interferometery. While the temperature reduces to the critical temperature, rubidium gas alters from normal gas to quantum gas, that is Bose-Einstein condensate, the amount of Bose-Einstein condensate is small, moreover the fluctuation of characterestics ,such as correlation length, become large, it becomes important to pick up information of Bose-Einstein condensate from the large background of thermal gas at the phase transition point. The temporal Talbot-Lau (TL) interferometer technique [6] is one way to pick up information of Bose-Einstein condensate from the large background of thermal gas with high signal to noise ratio.

Our TL interferometer (Fig. 3) consists of two optical lattice pulses separated by a time interval τ_f, which is equal to the odd times of half a Talbot time $T_T = m\lambda^2/2h$, where λ is the laser wavelength, m the atomic mass and h the Planck's constant. In this experiment, the wavelength $\lambda = 852nm$, the pulse width $\tau_0 = 3\mu s$, the time interval $\tau_f = 3T_T/2$, and the lattice depth $U_0 = 80E_R$ with E_R being the recoil energy of an atom absorbing one lattice photon. In our experiment, the ultra-cold atoms of ^{87}Rb were loaded a QUIC magnetic trap with axial frequency $20Hz$ and radial frequency $220Hz$ [7]. The TL interferometer was applied onto the ultra-cold atomic gas along the BECs axial direction. The time-of-flight (TOF) images are taken by means of the standard absorption imaging method after switching off the magnetic field and $30ms$ free expansion. In our experiment, after the evaporative cooling, the QUIC trap is switched off, and lattice pulse is shined on the cold atomic cloud, after the first lattice pulse, the cloud of atomic gas will be transferred to the momentum around $\pm 2n\hbar k(k = 2\pi/\lambda, n = 1, 2, 3, ...)$ with almost no atoms left at initial zero momentum; after the time interval $\tau_f = 3T_T/2$, the second optical lattice pulse is switched on, the atoms with momentum around $\pm 2n\hbar k$ will be scattered back to the momentum around $p = 0\hbar k$ [7]. The Talbot effect play a role to select the atoms near the peaks of $\pm 2n\hbar k$ to go back to zero momentum, the thermal parts of them, which are far from the peaks of $\pm 2n\hbar k$, will remain around the momentum region $\pm 2n\hbar k$, in this way, we could pick up the Bose Einstein condensate part from the thermal background.

3. Primary Results
Fig. 4 illustrates our measurements the momentum distribution of the cold rubidium gas with temperature above and below the critical temperature T_C. Fig. 4 (a1) and (a2) shows the momentum distribution for thermal gas with temperature above T_C, and from a3 to a5 in Fig. 4, the results show the bimodal momentum distribution for the cold gas, that is the mixture of Bose Einstein condensate and thermal gas, in which the amount of Bose-Einstein condensate is very small and it is difficult to figure out the Bose-Einstein condensate from the back ground
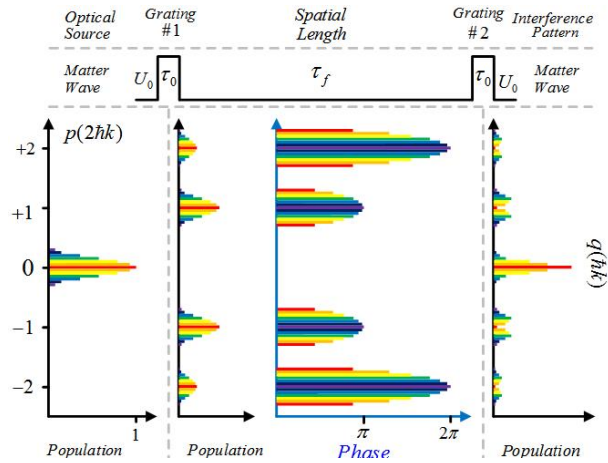
Figure 3. Experimental procedure for filtering of the momentum of Bose Einstein condensate near the $0\hbar k$ by means of Talbot-Lau interferometry.

of the thermal gas. From b1 to b5 in Fig. 4, the results illustrate the bimodal momentum distribution after Talbot-Lau interferometry for the cold gas corresponding to a1 to a5, in which the amount of Bose-Einstein condensate is distinguished from the back ground of the thermal gas. From c1 to c5 in Fig. 4 describe the comparison between the profiles of the bimodal momentum distribution of the cold gas corresponding in a and b,the solid black lines fits the momentum distribution after the Talbot-Lau interferometry, the small red peaks are the Bose-Einstein condensate.
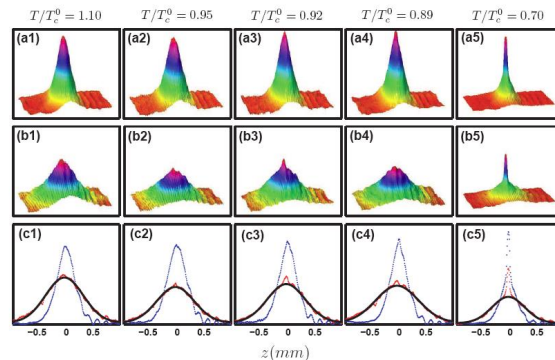

Figure 4. (color online) Illustrations of the critical phase transition from a thermal cloud to a BEC by the TL interferometry. The first row shows the momentum distributions of the atomic gases before the TL interferometery for five different temperatures T/T_C=1.10, 0.95, 0.92, 0.89, 0.70. The corresponding momentum distributions after the TL interferometer are in the second row. The dotted blue lines and dotted red lines in (c1)-(c5) show the profiles of the momentum distributions after the integration of the two-dimensional density distributions along the vertical direction for (a1)-(a5) and (b1)-(b5), respectively. A bi-modal structure emerges after the TL pulses in (b3) and reveals the critical phase transition occurring around $T/T_C = 0.92$. In (c1)-(c5), the solid black lines give the Gaussian fitting to the broad peak of the density distribution after the TL interferometery.

We implement two fitting approaches, the first one is based on the bi-mode fitting, that assume that the correlation length is proportional the amount of Bose-Einstein condensate filtered by TL interferometry. From the data fitting (see Fig. 5), we get the critical exponent factor $\nu = 0.70 \pm 0.08$ for the left side of the curve and $\nu' = 0.70 \pm 0.11$. These two critical exponents are very close to the theoretical value $\nu_T = 0.67$. The curve show the correlated length appears the lambda shape at the critical temperature, which is similar to helium liquid lambda phase transition. The results also show that the TL interferometry is an available approach to measure the correlated length near the lambda point. The second approach of fitting is based on the momentum window fitting, which assume that the correlation length is proportional the width of momentum of Bose-Einstein condensate filtered by TL interferometry. From the data fitting (see fig.6), we obtain the critical exponent factor $\nu = 0.65 \pm 0.05$ for the left side of the curve and $\nu' = 0.65 \pm 0.10$. These two critical exponents are very close to the theoretical value $\nu_T = 0.67$. The curve also show the correlated length appears the lambda shape at the critical point.
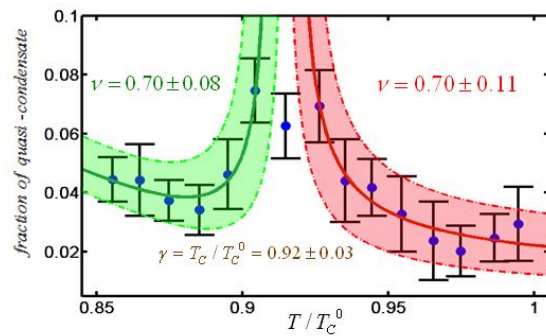

Figure 5. The fitting approach one shows that the critical exponent factor $\nu = 0.70 \pm 0.08$ for the left side of the curve and $\nu' = 0.70 \pm 0.11$. These two critical exponents are very close to the theoretical value $\nu_T = 0.67$.
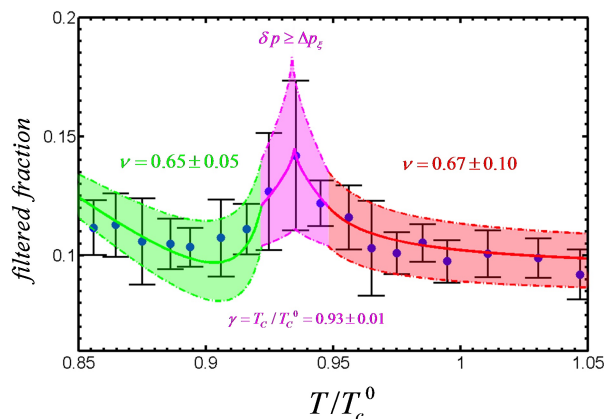

Figure 6. The fitting approach one shows that the critical exponent factor $\nu = 0.65 \pm 0.05$ for the left side of the curve and $\nu' = 0.67 \pm 0.10$. These two critical exponents are very close to the theoretical value $\nu_T = 0.67$.

4. Conclusion

We studied the correlation length at the Lambda critical phase transition point in an ultra-cold Bose gas with a temporal Talbot-Lau (TL) interferometery. Near the critical temperature, the correlation length increase exponentially and behaves as Lambda shape, its critical exponent factor is measured around 0.67, which is agreed with theoretical predication.

5. Acknowledgement

References

[1] K. W. Madison, F. Chevy, W. Wohlleben, J. Dalibard, *Phys. Rev. Lett.* **84**, 806 (2000).
[2] J.R. Abo-Shaeer, C. Raman, J.M. Vogels, and W. Ketterle, *Science* **292**, 476-479 (2001).
[3] Bo Lu, Thibault Vogt, Xinxing Liu, Xu Xu, Xiaoji Zhou, and Xuzong Chen *Phys. Rev.* A **83** 051608 (2011).
[4] M. Greiner et al., *Nature* **415**, 39 (2002).
[5] T. Donner, S. Ritter, T. Bourdel, A. Ottl, M. Köhl, and T. Esslinger, *Science* **315**, 1556 (2007).
[6] Wei Xiong, Xuguang Yue, Zhongkai Wang, Xiaoji Zhou and Xuzong Chen, *Phys. Rev.* A **84**, 043616 (2011).
[7] Xinxing Liu, Xiaoji ZhouWei Xiong, Thibault Vogt, and Xuzong Chen, *Phys. Rev.* A **83**, 063402 (2011).