Experimental studies of phase coherence of Bose gases in a two-dimensional optical anti-dot lattice

(二次元アンチドット光格子中におけるボース気体の位相コヒーレンスに関する実験的研究)

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論文要約

In this thesis, we report on the investigation of phase coherence in the ADL by releasing the Bose gases at different anti-dot heights and observing the matter wave interference. In the ADL, a series of potential hills are arranged on a two-dimensional (2D) square lattice. The ADL have a criss-crossing channels with zero AC Stark shift form a 2D mesh with multiple junctions and does not have classical bound state.

The outline of this thesis is as follows. In Chap. 2, we overview theoretical background of our experiment. We considerd a quantum mechanical effect on atoms in the ADL by introducing a periodic effective potential felt by the atoms on the mesh lines which is the result of the quantization of the faster atomic motion in the orthogonal direction. We present a simple model calculation for a quantum particle in the anti-dot lattice, based on the 2D Bose Hubbard model. We introduce a periodic 1D effective potential into the 2D Bose Hubbard model and numerically calculate the hopping energy and on-site interaction. We show that gases in the ADL are in the Josephson regime across the vast range of the anti-dot heights covered in the experiment.

In Chap.3, we explain our experimental apparatus to generate Bose condensed gas. Our approach for creating the quantum gas is called "All-optical" method. and we present a novel approach to circumvent the problems accompanying the method. We construct a double compressible crossed dipole trap (d-CDT) consisting of two independent CDTs with a high-power multi-mode fiber laser (m-CDT) and a single-mode fiber amplifier (s-CDT), both operated at 1μm. We employ polarization gradient cooling in a 3D optical lattice to cool the gas up to 1μK and load it into the large volume d-CDT created by a high-power multi-mode fiber laser. Then we move the zoom lens so that the s-CDT is minimized, while the m-CDT is compressed to a certain intermediate size to avoid severe heating of atoms.

The trap stiffness depends only on the tight s-CDT and the extremely high elastic collision rate allows us to rapidly lower the m-CDT power. We confirm very high evaporation efficiencies are maintained just before the BEC transition. We also show that evaporation during and after the compression significantly accelerates atom loading into the s-CDT center. This transfer is completed in 400 ms, much faster than that in any other known combination traps. Following evaporation in the s-CDT yields a nearly pure ^{87}Rb BEC of more than 10^6 atoms in the $|F, m_F>=|1,1>$ state after 3.6 sec of evaporation time.

In the next chapter, we explain the optical lattice setup and experimental methods. The lattice beam from a single-mode Ti:Sapphire laser (λ =773 nm) is delivered through a PM optical fiber and is split into two beams by a polarizing beam splitter. Two standing waves intersect at a right angle. Both are linearly polarized, perpendicular to the horizontal lattice plane. The beam radius is much larger than the BEC size and we safely neglect the inhomogeneity of the lattice potential. A retro-reflected beam is slightly focused to compensate for the power loss due to the reflection from the glass cell. Therefore, the lattice distortion is negligible since it is on the order of 1/400 times the anti-dot height and ~7% of the effective potential. The relative phase between the lattice axes ϕ is given by k_{laser} $|L_X$ - $L_Y|$ with a constant offset, where L_X and L are the distances between the return mirror and the BEC trapped in the s-CDT. We control the optical length is by a piezoelectric actuator mounted back the mirror. ϕ is monitored by a Michelson interferometer formed by a pair of dummy beams with the same frequency. The dummy beams are always turned on, co-propagating 3 mm below the lattice beams. The interference signal can be used as an error signal to actively feedback the PZA-1. The arm length difference is within 2 mm, making ϕ insensitive to the laser frequency. According to the classification based on the symmetry of the lattice, the relative phase can be classified into 0(anti-dot lattice), π/2(normal two-dimensional lattice), and between them. In the following chapters, we focused on ADL and NL and experimentally studied these two limits. We measure the relative phase of the lattice axes using the matter wave interference pattern, which reflects the geometry of the lattice. We also measured the temperature of atoms by ramping up and down the optical lattice.

Our main experimental results are presented in Chap. 5. We observe that the gas maintains macroscopic phase coherence even at very tall anti-dots while the hopping between junctions is significantly reduced. This can be characterized as the property of the gas in the Josephson regime. In this regime, the system acts like a bundle of weakly coupled tube-like gases. The interference fringes finally smear out at anti-dot heights approximately 400 times the lattice photon recoil energy. This is consistent with our calculation suggesting that the effective potential at extremely tall anti-dots sufficiently isolates atoms in the junctions as a result of negligible hopping within our experimental time scale. However, the observed decoherence cannot be explained solely by the reduced hopping. As mentioned above, by merging the nearly isolated gases together after adiabatically ramping down the ADL, we sometimes observe the formation of vortex-like structures which are not seen in similar experiments with the 2D simple square lattice. In Chap. 6, we discuss the effects of axial (intra-tube) and transverse (inter-tube) phase fluctuations in tube-like gases. In contrast to tightly confined 1D gases in the 2D square lattice, tube-like gases in the 2D ADL are affected by transverse phase fluctuations before axial phase fluctuations take effect. We explain the appearance of the vortex-like structures as a possible signature of the Berezinskii-Kosterlitz-Thouless (BKT) crossover in the 2D lattice plane.

The mean appearance probability of clearly defined vortex-like holes with respect to T/J. The probability starts to increase around T/J=0.3 (4 V_0=220 E_R) and peaks around T/J=1 (4 V_0 = 330 E_R). The visibility starts to decrease around the former height and abruptly drops at the latter height. Our results are consistent with the theoretical predictions by Trombettoni et al. We do not exclude the effect of the quantum fluctuation, but a slight increase of 0.07 π (200 E_R) to 0.09 π (330 E_R) does not explain the rapid increase of the appearance probability. A similar phenomenon has been reported by the JILA group. An array of 3D BECs was prepared in a 2D hexagonal lattice with negligible axial phase fluctuations. Vortex-pair unbinding and free vortex nucleation were observed when the gases merged together in the 2D lattice plane. In two different temperature ranges, it was confirmed that the vortex proliferation started at T/J ~ 0.3. Over T/J >3 (4V_0 > 450 E_R), cracks or dents are observed inside the clouds, but the appearance of clear vortices becomes rare. Possible causes are phase randomization from excessive vortices, formation of tilted and tangled vortices. In this regime, gases become isolated, so they are affected by increased axial phase fluctuations. Overheating may be another possible cause since the estimated T/T_c at 500 E_R is ~ 0.9. In order to fully understand the decoherence mechanism, we need to consider how these factors influence the reduction of visibility which remains a theoretically challenging task. Exploring the vortex phenomena across a wide range of parameters such as the atom number and a lattice hold time should provide new insights. Future studies include the vortex pinning around the anti-dots. The ADL is fundamentally different from all other optical lattices implemented so far due to its unique makeup. This new system allows much easier access to the Josephson regime which could lead to further exploration of the 2D Josephson dynamics. By combining the high controllability of the hopping rate, atom number, and temperature with the tuning of the interaction strength by Feshbach resonances, we can enhance quantum fluctuations so that they become more dominant than thermal ones. A new theoretical framework is required to describe the atom dynamics, particularly in the dimensional crossover region. In Chap. 7, we summarize the results and show prospects.

In summary, we explored the phase diagram of the Bose gas in blue detuned two-dimensional optical lattices as function of lattice depth (height) and the relative phase. We studied the phase diagram of bosons in two-dimensional anti-dot optical lattice in thermal equilibrium. We can also superimpose an additional 1D lattice in the vertical direction to further study the phase diagram of strictly 2D gases in the ADL which currently remain unexplored. The preservation of phase coherence across a wide range of anti-dot heights provides many parameters for experimentalists to play with which can be utilized for studies of quantum transport, quantum walks, and 2D Bloch oscillations. The ADL can be easily incorporated into existing optical lattice setups with comparative ease. By combining this system with multi-species BECs or quantum degenerate Fermi gases, the ADL provides a new platform for lattice experiments. We can also expand the research to the dynamic properties in the ADL and it will show rich physics.