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Effects of disorder on quantum correlation of ultracold Bose gases released from a two-dimensional optical lattice

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Abstract. High-order quantum correlation provides powerful methods to reveal the quantum many-body behavior of ultracold atomic gases. In this work, the second-order quantum correlation is adopted to study the many-body behavior of ultracold Bose gases in the presence of both a two-dimensional optical lattice and weak disorder. According to investigations, it is found that even a weak disorder plays a significant role in the quantum many-body behavior, which manifests itself through the second-order quantum correlation. With the Bogoliubov theory, our studies show that both interatomic interactions and weak disorder would destroy the first-order quantum coherence of the condensate because of the depletion, and the resulting depletion has significant characteristic in the second-order correlation of the system.

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Key words: disorder, second-order correlation, ultracold atomic gases, optical lattice

1 Introduction

The high-order correlation was first used by Hanbury Brown and Twiss (HBT) to measure the size of a distant binary star [1]. Their pioneering experiment reveals that intensity fluctuations and resulting correlations contain information about the coherence and quantum statistics of probed system. This principle has found applications in many fields such as astronomy, high-energy physics, atomic physics, and condensed matter physics [2–5]. Recently, advances in atom cooling and detection have led to the observation of the atomic analog of the HBT effect [6, 7]. Henceforth the high-order correlation analysis becomes an increasingly important method for studies on complex quantum

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phases of ultracold atoms. Correlation techniques have been successfully employed in recent experiments such as the atomic analog of the HBT effect [8], density-density correlation for degenerate bosonic and fermionic atomic gases in an optical lattice [9–11], second-order correlation of an atom laser [12], and the observation of pair-correlated fermionic atoms based on second-order correlation [13].

The high-order correlation for ultracold atomic gases released from an optical lattice has been intensively studied both experimentally and theoretically. Relevant experiments show that ultracold atoms, being prepared in a optical lattice and in a Mott-insulator state, display sharp peaks in their spatial correlation when released from the optical lattice [9, 11]. These spatial correlation reveals the quantum statistics and the underlying order of bosonic or fermionic atoms in the optical lattices. In addition, the formalisms for describing the correlations observed between ultracold bosons released from an optical lattice have also been theoretically studied [14]. These formalisms, including the Bogoliubov method, the mean-field decoupling approach, and the particle-hole perturbative solution about the perfect Mott-insulator state are applicable for a broad range of behaviors in the lattice system and present numerous avenues for the future theoretical development.

On the other hand, physical effects driven by disorder in ultracold atom systems have become an active research field for many years [15]. As disorder is ubiquitous in nature and even only a weak disorder in quantum systems can have dramatic impact on the properties of the physical systems. Along this line, we theoretically investigate the problem of how weak disorder affects the second-order correlation of the ultracold Bose gas released from an optical lattice in the present paper. In the investigation, we mainly focus on the situation that the atoms are initially confined in a 2D optical lattice with weak quenched impurities and in a superfluid state. As is well known that the presence of external disorder leads to depletion in the ultracold Bose system [19, 20]. Our results prove that the depletion due to the external disorder produces correlation and pairing lines in the (normalized) second-order correlation due to the classical correlation of the disorder. The correlation of disorder by itself is resulted from classical interference between random scattering routes, which is generally very complex and unusual [17]. According to our investigation, it is shown that the classical correlation of the disorder, even being switched off, can be displayed by the second-order correlation of the released ultracold atoms.

This paper is organized as follows. In Section II we give a general description of the Bose system in a 2D optical lattice with the presence of weak disorder. Section III derives the second-order correlation function for a simplified problem in which atoms are prepared in a 2D optical lattice with the presence of disorder and then freely expand. The details in the correlation function are examined in this section. A summary is provided in Section IV.