Annals of Physics 329 (2013) 51–72

Contents lists available at SciVerse ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Exciton correlations and input–output relations in non-equilibrium exciton superfluids

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ARTICLE INFO

Article history:
Received 25 June 2012
Accepted 14 October 2012
Available online 22 October 2012

Keywords:
Photoluminescence measurements
Transport measurements
Violations of the fluctuation and dissipation theorem
Input–output relations
Non-equilibrium superfluid
Equilibrium dissipative superfluid

ABSTRACT

The photoluminescence (PL) measurements on photons and the transport measurements on excitons are the two types of independent and complementary detection tools to search for possible exciton superfluids in electron–hole semi-conductor bilayer systems. In fact, it was believed that the transport measurements can provide more direct evidences on superfluids than the spectroscopic measurements. It is important to establish the relations between the two kinds of measurements. In this paper, using quantum Heisenberg–Langevin equations, we establish such a connection by calculating various exciton correlation functions in the putative exciton superfluids. These correlation functions include both normal and anomalous greater, lesser, advanced, retarded, and time-ordered exciton Green functions and also various two exciton correlation functions. We also evaluate the corresponding normal and anomalous spectral weights and the Keldysh distribution functions. We stress the violations of the fluctuation and dissipation theorem among these various exciton correlation functions in the non-equilibrium exciton superfluids. We also explore the input–output relations between various exciton correlation functions and those of emitted photons such as the angle resolved photon power spectrum, phase sensitive two mode squeezing spectrum and two photon correlations. Applications to possible superfluids in the exciton–polariton systems are also mentioned.

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0003-4916/$ – see front matter
doi:10.1016/j.aop.2012.10.006

For a comparison, using conventional imaginary time formalism, we also calculate all the exciton correlation functions in an equilibrium dissipative exciton superfluid in the electron–electron coupled semi-conductor bilayers at the quantum Hall regime at the total filling factor $\nu_T = 1$. We stress the analogies and also important differences between the correlations functions in the two exciton superfluid systems.

1. Introduction

An exciton is a bound state of an electron and a hole in the band structure of a solid. When excitons are sufficiently apart from each other, they may behave as bosons. Although Bose–Einstein condensation (BEC) of excitons was proposed more than 3 decades ago [1,2], no exciton superfluid phase has been observed in any bulk solids yet. Recently, degenerate exciton systems in quasi-two-dimensional semiconductor GaAs/AlGaAs electron–hole coupled bilayers (EHBL) [3] have been produced by many experimental groups with photo-generated method [4] or gate-voltage generated method [5,6] and electron–electron coupled bilayers at quantum Hall regime at the total filling factor $\nu_T = 1$ (BLQH) [7–9]. It was widely believed that EHBL and BLQH are two of the most promising systems to observe BEC of excitons among any solid state systems. Indeed, there have been extensive experimental searches for exciton superfluids in both systems [4,5,10,7]. Now it was more or less established that an exciton superfluid subject to substantial dissipations has been observed in BLQH system [7–9]. But there are still no convincing experimental evidences that the exciton superfluids (ESF) have been formed in EHBL at the present experimental conditions [4–6]. In the photo-generated electron–hole bilayer (EHBL) samples [4], various kinds of photoluminescence (PL) measurements were made by different groups [4]. More recently, taking advantage of the long lifetimes of the indirect excitons, researchers started to be able to manipulate the excitons movements and perform various transport properties of the excitons [11–13]. In the undoped electron–hole bilayer (EHBL) samples [5,6] which is a heterostructures insulated-gate field effect transistors, separate gates can be connected to electron layer and hole layer, so the densities of electron and holes can be tuned independently by varying the gate voltages. Transport properties such as the Coulomb drag or counterflow can be performed in this experimental set-up. The PL signals, although weaker than those in the photo-generated samples, is still measurable. The transport measurements in [5,6,11–13] and the PL measurements in [4] are complementary to each other. It is important to search for exciton superfluid from both experimental methods. Any signatures of the exciton condensations should show up in both type of experiments. In fact, it was believed that the transport measurements can provide more direct evidences on superfluids than the spectroscopic measurements. Indeed, it is all the peculiar transport properties which proved the existence of superfluid in the liquid ^{4}He at very low temperatures.

There are previous theoretical works studying various photon emission spectra from the putative ESF [14–16]. In [14,15], assuming the ESF has been formed in the EHBL, the authors studied the angle resolved photon spectrum, momentum distribution curve, energy distribution curve, two mode phase sensitive squeezing spectrum and two photon correlation functions from such an ESF. They found these photoluminescence (PL) display many unique and unusual features not shared by any other atomic or condensed matter systems. Observing all these salient features by possible future angle resolved power spectrum, phase sensitive homodyne experiment and Hanbury-Brown–Twiss type of experiment could lead to conclusive evidences of exciton superfluid in these systems. However, all the previous theoretical works focused on the PL of the emitted photons, but various properties of the excitons themselves have not been addressed. There are also some previous theoretical work [17,18] on the Coulomb drag in electron–hole bilayer in the BCS side by using weak coupling mean field BCS theory. However, as analyzed in [14,15], for the experimental relevant density regime $n \sim 10^{10}\ \mathrm{cm}^{-2}$, the excitons are tightly bound pairs in real space, so all the experiments are in the BEC regime, so it remains interesting to study the exciton correlations in the strong coupling BEC limit.