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BEC-BCS-Laser Crossover theory of Exciton-Polariton Systems

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In semiconductor exciton-polariton systems, Bose-Einstein condensation (BEC) of exciton-polaritons has been observed in recent years [1]. In contrast, this system is potentially capable of achieving the Bardeen-Cooper-Schrieffer (BCS) state and normal photon lasing in high-excitation regimes [2, 3], depending on quasi-equilibrium and non-equilibrium situations. The relationships among the BEC, BCS, and lasers are now one of the most exciting topics experimentally studied [4]. However, from a theoretical viewpoint, it is difficult to describe such phenomena in a unified way because the system includes many different types of physics, e.g. dissociations of electron-hole (e-h) pairs depending on the carrier densities, the non-equilibration of the system due to the pumping and losses, and so on.

In this study, within the Hartree-Fock approximation, we show a unified theory (BEC-BCS-laser crossover theory) [5] by extending the non-equilibrium Green's function for two-level systems [6]. The theory becomes identical to the BCS gap equation when the system is in quasi-equilibrium, whereas it results in the Maxwell-Semiconductor-Bloch equations describing the laser actions when non-equilibration of the system becomes essential. This means that we can discuss the BEC, BCS, laser physics by using only one theory. Furthermore, as a result of this theory, it is found that the single-particle spectral functions for the conduction and valence bands ($A_{cc}(\nu;\boldsymbol{k})$ and $A_{vv}(\nu;\boldsymbol{k})$) have quite simple expressions:

$$A_{cc/vv}(\nu;\boldsymbol{k}) = 2|u_{\boldsymbol{k}}|^2 L(\nu,\mp E_{\boldsymbol{k}}) + 2|v_{\boldsymbol{k}}|^2 L(\nu,\pm E_{\boldsymbol{k}}), \qquad (1)$$

where $u_{\boldsymbol{k}}$, $v_{\boldsymbol{k}}$, and $E_{\boldsymbol{k}}$ are the Bogoliubov coefficients and $L(\nu, \pm E_{\boldsymbol{k}})$ is the Lorentz function broadened by the e-h thermalization rate γ [7]. Here, one can notice that there are remarkable similarities to the superconductivities. The important point is, however, that Eq. (1) can be used *regardless of the BEC, BCS, and laser regime*.

In Fig. 1, we show typical peak positions of A_{cc} in a lasing regime, which is equivalent to the renormalized conduction-band structure. In this situation, μ corresponds to the laser frequency and the gap is opened mainly due to the Rabi splitting. Here, it should be noted that the existence of the gap indicates that there are light-induced e-h pairs even when the lasing occurs in contrast to the common belief. Such renormalization effects are also reflected in the gain spectra (not shown) which would be accessible by experiments. Details will be presented at the conference. This work is supported by the JSPS through its FIRST Program, and DYCE, KAKENHI 20104008.

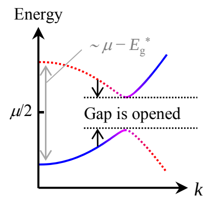

Fig. 1: Renormalized conduction band structure in the lasing regime. In this regime, μ is the laser frequency and E_g^* is the renormalized band gap due to the Coulomb interactions.

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