Interplay between screening and skyrmionic effects in integer quantum Hall photoluminescence

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Recently, photoluminescence (PL) in the quantum Hall (QH) systems, particularly at around the electron filling factor $\nu_e \sim 1$, has been intensively studied both experimentally and theoretically. When the conduction electrons and the photo-excited valence hole are confined in layers widely separated by a distance d, some discontinuous energy shift, Δ, is observed in the left-circularly polarized (LCP) photoemission. Previous theories interpreted this phenomenon as a transition from an unscreened to a screened state[1,2] by assuming that the electron spin is fully polarized. Then, recent experiments in the narrow quantum well (QW) exhibit unexpected behaviors; Δ suddenly vanishes with decreasing d. Thus, another investigation is required for the case of small Zeeman splitting, where the charged elementary excitation of electron system becomes a spin texture called skyrmion. In such case, the PL spectra should be affected by the multiple spin-flipping effects which entangle with the hole screening.

In this paper, we numerically investigated the Haldane's spherical system with 11 or 12 electrons in the presence of a valence hole, whose results are summarized in the following. For the diagonalization of the Hamiltonian, we adopted the method of coefficients of fractional parentage often used in the field of atomic physics.

At $\nu_e = 1$, the hole strongly attracts the electrons in the ground states at small d. Note that such a screening is allowed only under small Zeeman splitting, because the electron accumulation should accompany the multiple spin flips. In fact, our calculation shows that the ground state at $d = 0$ becomes a spin singlet state in the vanishing limit of Zeeman splitting. When d is increased, the screening suddenly vanishes at around $d \sim 0.2\ell$ (ℓ: magnetic length). Then, the electrons spread uniformly around the hole to form a ferromagnetic state following the Hund's rule.

When an electron is added to the system ($\nu_e = 1^+$), the ground state at small $d \lesssim 1.2\ell$ becomes a ferromagnetic state, since the hole is enough screened by a single additional electron. At $d \gtrsim 1.2\ell$, on the other hand, the electron distribution around the hole is gradually broadened by the electron-electron interaction. This broadening induces multiple spin flips, which leads to the formation of a skyrmionic exciton, i.e. a bound state consisting of a skyrmion and hole.[2]

The PL energy shift, Δ, is affected by such screening effects. They are strongly suppressed for small d, because the hole is well screened in the initial ground state both at $\nu_e = 1$ and 1^+. They are increased abruptly at around $d \sim 0.2\ell$ to be coincident with those in the large Zeeman energy limit. (In this case, the screened-to-unscreened transition occurs at $\nu_e = 1$.) This sudden change at $d \sim 0.2\ell$ can qualitatively explain the curious d-dependence (or electron-density dependence) of Δ which is recently observed in the narrow QW's or single heterojunctions. At $d \gtrsim 1.2\ell$, Δ gradually decreases, because the screening effect is suppressed both at $\nu_e = 1$ and 1^+.

[1] B. A. Muzykantskii, Sov. Phys. JETP 74, 897 (1992).
[2] N. R. Cooper and D. B. Chkolovskii, Phys. Rev. **B55**, 2436 (1997).

Supporting Figures

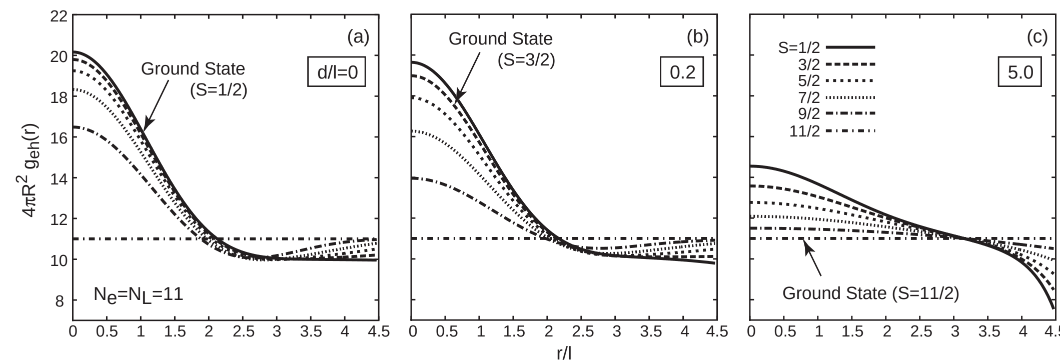

Figure 1: Electron radial distribution function $g(r)$ around the valence hole at $\nu_{\rm e}=1$ for the lowest energy states with total electron spin $1/2 \leq S \leq 11/2$. The ground states are indicated by the arrows. The numerical results at electron-hole layer distance $d = 0, 0.2\ell$ and 5ℓ are plotted in (a), (b) and (c), respectively. The calculation is performed on the Haldane sphere characterized by $N_e = N_L = 11$, where N_e and N_L denote electron number and the degeneracy of the lowest Landau level, respectively. The electron-hole chord distance r is measured in units of the magnetic length ℓ.

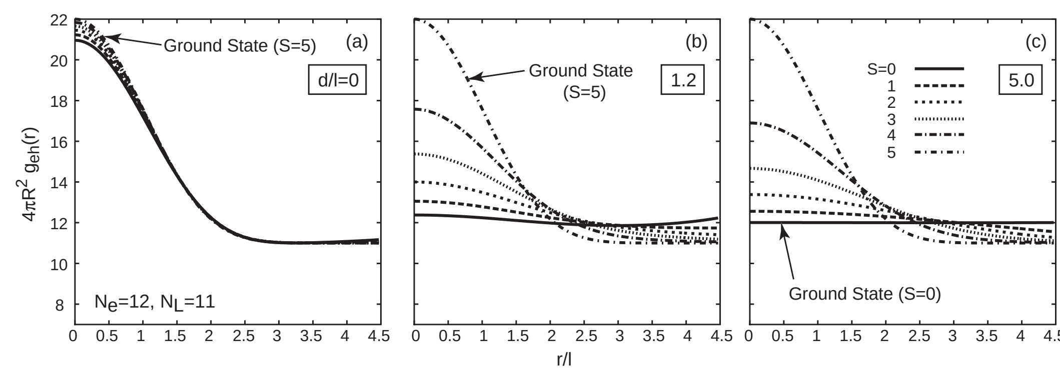

Figure 2: The same as the previous figure but calculated at $\nu_{\rm e}=1^+$. Distribution functions at $d = 0, 1.2\ell$ and 5ℓ are plotted for the lowest energy states with spin $0 \leq S \leq 5$ in (a), (b) and (c), respectively, where $N_e = 12$ and $N_L = 11$.