Electron-Electron Interactions in Emission from a Two-Dimensional Electron Gas in Quantizing Magnetic Fields

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The recombination of a thermalized valence band hole with a high quality two-dimensional electron gas shows clear spectral features due to electron-electron interactions in the regime of the integer quantum Hall effect. A pronounced doubletlike emission observed around odd filling factors $\nu = 3, 5$ is attributed to the destructive interferences between the optically created hole in the Fermi sea and the continuous spectrum of spin wave excitations. Redshifts in the spectral position at $\nu \sim 1, 2$ reveal the competition between the interband Coulomb binding and the electron-electron interaction in the final state in a spatially separated electron and valence hole system. [S0031-9007(98)05712-3]

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The two-dimensional electron gas (2DEG) is an example of the magnetic field tunable correlated fermion system, amenable to various experimental investigations [1,2]. The electron-electron interaction plays a crucial role in the regime of both the integer and the fractional quantum Hall effect (FQHE) [3]. Interband magneto-optics is an important, contactless probe of the bulk 2DEG. This method has been recently applied to study an interacting 2DEG in the regime of the FQHE [4]. In contrast, the signatures of many-body interactions identified in the magnetoluminescence spectra of a 2DEG [5] in the range of filling factors $\nu > 1$ [6–12] rely on magnetic field modulation of screening and band-gap renormalization [7,11,12]. Investigated effects, such as shake up and band-gap renormalization, have been mediated in an essential way by the presence of a valence hole. The role of Landau quantization has been merely to make them more visible through the appreciable modulation of the electronic density of states. The experiment [6,8–12] and theory [7,11,12] of luminescence in the range of integer filling factors have been mostly applied to systems with significant disorder. These studies did not show directly the consequences of electron-electron interactions in the quantum Hall system.

In this Letter we identify recombination processes characteristic of a disorder free but strongly interacting 2DEG under conditions of Landau quantization at filling factors $\nu \geq 1$. We have systematically observed unusual spectral features in the low-temperature magnetoluminescence of high quality 2DEG's. The most pronounced effects are the discontinuity and redshift of the ground-state emission around filling factors $\nu \sim 1, 2$ and a remarkable doubletlike splitting observed in the vicinity of odd filling factors $\nu = 3, 5$. We believe that these are the most characteristic "striking features" in the magnetoluminescence of a high quality 2DEG [13] and show that they are qualitatively well accounted for by the properties of the spectral function [14,15] of an optically created hole in a strongly interacting 2DEG at integer filling factors. Our approach to the regime of the integer quantum Hall effect follows the concepts developed in the case of the FQHE [4] and, in the limit of $\nu \sim 1$, overlaps with earlier works reported in [16]. The calculated spectral function [17] shows effects due to resonant electron-electron interactions beyond the scope of the perturbation theory. The abrupt redshifts around $\nu \sim 1, 2$ result from the discontinuous transition across the filling factor from a recombination dominated by the excitonic effect to a recombination process dominated by the much stronger electron-electron interaction effects [16,17]. For odd filling factors $\nu > 2$ spin-flip scattering of a hole in the lowest Landau level with excitations involving spin waves leads to splitting of the ground-state emission into two peaks concentrated outside the continuum of collective spin wave excitations.

Our observations are based on the measurements of magnetoluminescence from 2DEGs, confined in GaAs/GaAlAs one-side modulation doped quantum well structures (MDQW) with well widths of 25 and 40 nm and electron concentration under optical excitation in the range between 3×10^{11} cm^{-2} and 8×10^{11} cm^{-2}. Experiments were performed in the temperature range from 10 K down to 150 mK and in magnetic fields up to 32 T. The results presented here were obtained for a relatively high mobility ($\approx 10^6$ cm^2/V s) 40 nm wide quantum well structure. The sample was immersed in a bath temperature of $\simeq$150 mK and excited at about 10^{-4} W/cm^2 power density of a 514.5 nm line of an Ar^+ laser. The electron concentration 2.35×10^{11} cm^{-2} obtained under these excitation conditions was established on the basis of detailed analysis of the emission intensities, including the intensity analysis of different circular polarization components.

In the absence of a magnetic field, the luminescence of a one-side MDQW shows a relatively broad spectrum with an appreciable spectral weight shifted towards higher energies. Depending on the electron concentration and

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possible nonequilibrium occupation, the second subband might also be populated often leading to a relatively sharp peak on the high energy edge side of the slowly decaying spectrum. When a magnetic field is applied, the broad spectrum splits into separate emission peaks related to the conduction-band Landau levels. A representative Landau fan chart of the magnetoluminescence peaks observed in the σ^- circular polarization of the emitted light is shown in Fig. 1. The σ^- polarization has been chosen in order to investigate the optically allowed transition from the lowest spin-split Landau level. This transition dominates the magnetoluminescence as peaks related to higher Landau levels, visible due to a small degree of disorder and/or nonthermalized valence holes, are very weak. The emission from the first excited subband appears only at finite fields and shows nontrivial magneto-oscillations [9,11,18].

In the following we concentrate on the main magnetoluminescence transition, the ground-state transition which, within the one-particle model, is attributed to the recombination of a hole in the highest valence level with electrons from the lowest spin-up conduction-band Landau level. As shown in Fig. 1, this transition shows a pronounced redshift around filling factor $\nu = 1$ and a similar but weaker effect is also observed near $\nu = 2$. On the high field side of the $\nu = 3$ the ground-state transition shows an intriguing doublet structure which is also visible, but less resolved, at lower magnetic fields around $\nu = 5$. As shown in Fig. 2, the spectral features at $\nu = 1$ and 3 are easily recognized in the raw data. The observed effects are emphasized in the inset in Fig. 1, where the energy difference between the ground-state emission peaks, and somehow arbitrarily chosen noninteracting transition energy, is presented.

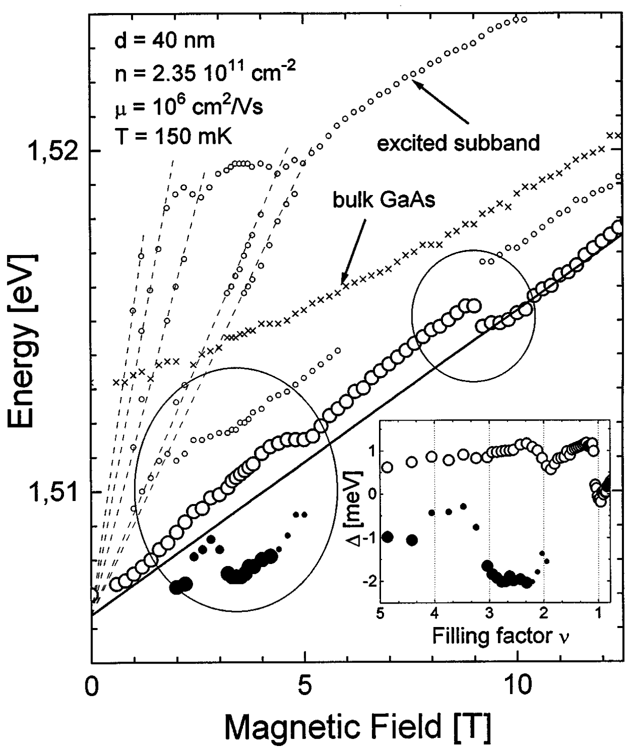

FIG. 1. A representative Landau fan chart of the magnetoluminescence peaks, arising from the recombination of a 2DEG with a spatially separated valence band hole, observed in the σ^- circular polarization of the emitted light. Big open and closed cirles denote the ground-state transition originating from the lowest spin-up conduction band Landau level. The inset shows the filling factor dependence of ground-state emission energies measured from the reference energy $E(B) = 1.5064$ eV + 0.89 meV/T, represented as a solid line in the main part of the figure. The cirles' sizes reflect the transition intensities. Note the redshift of the luminescence line in the vicinity of filling factor $\nu = 1, 2$ and the doubletlike ground state emission for $\nu > 2$.

Inspection of the existing literature on emission spectra of a 2DEG shows that the "anomalies" mentioned can also be also found in other experiments [10,13] on one-side MDQW's with relatively high mobilities ($\gtrsim 10^6$ cm^2/V s) and/or sufficiently narrow luminescence lines ($\lesssim 1$ meV). We have measured the $\nu = 1$ jump in magnetic fields up to 32 T and conclude that the observed energy shift scales as $B^{1/2}$. The redshift is very abrupt at low temperatures. On the other hand, fixing $\nu = 1$ at $B = 9.7$ T we hardly observe the redshift at $T = 10$ K, but a rather broad oscillation (spread over 2–3 T) in the energy position of the emission line. The effect of temperature on the doublet structure at $\nu = 3$ is to weaken the low energy component. The doublet splitting increases with the strength of the magnetic field. The ground-state emission represents a single peak when approaching $\nu = 2$, the doublet structure is rather weakly pronounced in the range of filling factor

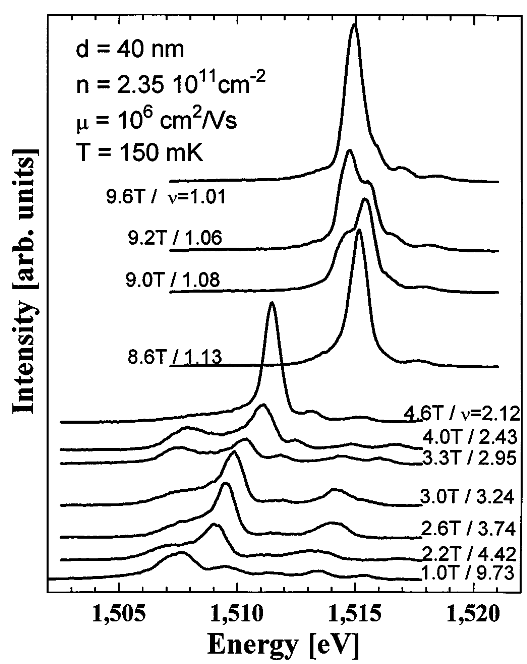

FIG. 2. σ^--emission spectra of a 2DEG confined in a GaAs quantum well measured at different magnetic fields corresponding to filling factors ν specified in the figure. The energy positions of the observed luminescence peaks measured with 0.2 T steps are plotted in Fig. 1.

$\nu \sim 4$, but reappears around $\nu = 5$ indicating its relation to the spin polarization of the 2DEG.

The redshift of the luminescence line around $\nu = 1$ can be understood as follows [16,17]. The initial state involved in the recombination process at filling factors slightly smaller than 1 ($\nu = 1^-$) consists of a filled conduction band Landau level and a valence hole. In the final state, a hole appears in the filled Landau level. The resulting recombination energy is lowered from the one particle gap by the Hartree-Fock self-energy $E_0 = \sqrt{\pi/2}\, e^2/\kappa l_B$ ($l_B = \sqrt{eB/h}$ and κ are, respectively, the magnetic length and the dielectric constant). In the case of $\nu = 1^+$ the initial state consists of an interband exciton involving an electron from an empty spin-down Landau level. An electron is optically removed from the spin-up Landau level and a spin-wave excitation with zero angular momentum is left in the final state. The Hamiltonian does not depend on total spin and the energy of the final state is just the Zeeman energy. The recombination energy for $\nu = 1^+$ is lowered from the one particle energy gap by the interband exciton binding E_{cv}. In the investigated asymmetric structure $\delta = E_0 - E_{cv} > 0$ and a redshift, of the order $\delta \sim e^2/\kappa l_B \sim B^{1/2}$, is expected when passing $\nu = 1$ towards high magnetic field. Similar reasoning, but based on Kohn's theorem, accounts for the redshifts of the luminescence line at higher filling factors, and, in particular, at $\nu = 2$ [17]. In the latter case, the expected shift, if observed at the same magnetic field, is half that at $\nu = 1$. After accounting for the strength of the magnetic field, the data presented in Fig. 1 show that the magnitude of the redshift at $\nu = 2$ is indeed about half the one observed at $\nu = 1$.

We believe that the doubletlike ground state luminescence around filling factors $\nu = 3, 5$ reflects a new effect in the physics of recombination processes from a 2DEG. The splitting is most pronounced on the high magnetic field side of $\nu = 3$, and we concentrate on this particular case. Our sample is simulated by a disk of area A with N_e electrons in a perpendicular magnetic field B [15]. In a symmetrical gauge the single particle states are $|m, n, \sigma\rangle$, with energies $E_{mn,\sigma} = \omega_c(n + \frac{1}{2}) + g\mu_B B\sigma$, where n labels Landau levels, and m labels degenerate intra-Landau level states. ω_c, g, and μ_B are, correspondingly, the cyclotron energy, the effective Landé factor, and the Bohr magneton. Denoting by $c_i^\dagger$ (c_i) the electron creation (annihilation) operators the Hamiltonian is written as

$$H = \sum_i E_i c_i^\dagger c_i + \frac{1}{2} \sum_{i_1 i_2 i_3 i_4} \langle i_1, i_2 | V_{ee} | i_3, i_4 \rangle c_{i_1}^\dagger c_{i_2}^\dagger c_{i_3} c_{i_4} . \tag{1}$$

Here $|i\rangle = |m, n, \sigma\rangle$ and $\langle i_1, i_2 | V_{ee} | i_3, i_4 \rangle$ is the electron-electron Coulomb matrix element [15]. The positive background is included in the calculations [15].

At filling factor $\nu = 3$ electrons occupy all spin-down and spin-up states $m = 0, 1, \ldots, N - 1$ of the $n = 0$ Landau level but only spin-up states of the $n = 1$ Landau level. In the recombination process involving a free hole from the highest valence band Landau level, a spin-up hole, $c_{0,0,-}|\nu = 3\rangle$, is created in the $n = 0$ conduction band Landau level [see Fig. 3(a)]. The recombination spectrum reduces to a spectral function of the hole [14,15]:

$$E^-(\omega) = \sum_f |\langle f | c_{0,0,-} | \nu = 3 \rangle|^2 \delta(E_f + \omega - E_{\nu=3}) . \tag{2}$$

The state $c_{0,0,-}|\nu = 3\rangle$ of a spin up hole in the $n = 0$ Landau level is degenerate with many other final states $|f\rangle$ involving more than one quasiparticle. The arrows in Figs. 3(b) and 3(c) identify different processes by which configurations (b) and (c) can be obtained from configuration (a) conserving the total energy and spin.

The entire Fock space of final states with zero total angular momentum and total spin has been constructed and exact diagonalization was carried out as a function of the system size N_e. We find it illuminating to narrow down the Fock space to an essential segment, involving

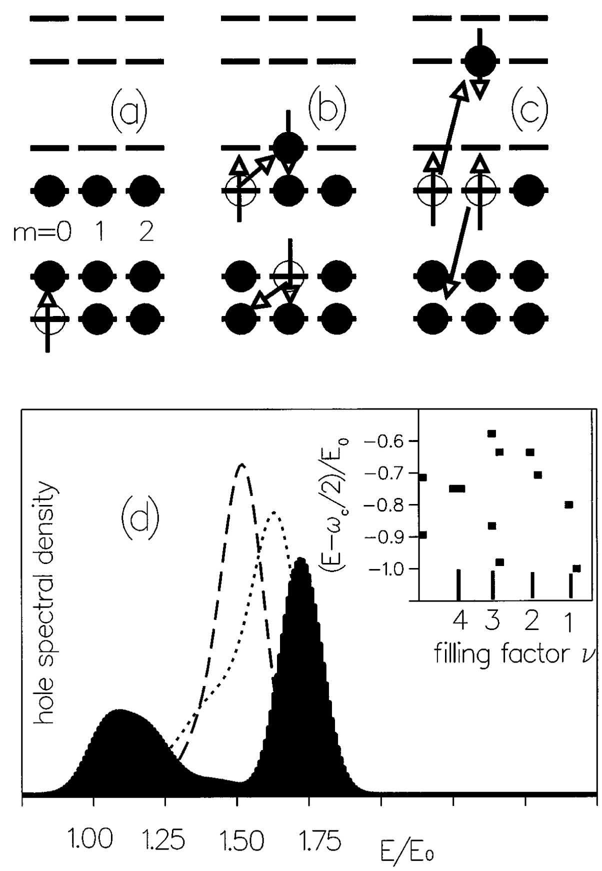

FIG. 3. (a)–(c) A schematic picture of resonant electronic configurations for filling factor 3^-. The black dots correspond to electrons occupying states $|m, n, \sigma\rangle$. For each m, states with increasing Zeeman and cyclotron energy are shown. (d) Hole spectral function at filling factor 3^- for Auger configurations (c) (dashed line), all configurations (full line). The density of states of the spin flip excitation in the second Landau level is shown as a dotted line. The inset shows calculated shifts and splittings of recombination energies as a function of the filling factor.

a single hole $c_{0,0-}|\nu = 3\rangle$, and a set of collective states $|k\rangle = [(1/\sqrt{N})\sum_m B_m^k c_{m,1,+}^\dagger c_{m,1,-}]c_{0,0,+}|\nu = 3\rangle$. These latter states correspond to spin-flip excitations in the $n = 1$ Landau level attached to a spin-down hole in the $n = 0$ Landau level. The energy of the lowest collective state, $|k = 0\rangle = [(1/\sqrt{N})\sum_m c_{m,1,+}^\dagger c_{m,1,-}]c_{0,0,+}|\nu = 3\rangle$, is just the energy of the $n = 0$ hole with spin down, i.e., E_0. The highest energy of the collective state is $1.75E_0$ since it involves the ionized spin-flip exciton, with energy $0.75E_0$, in the $n = 1$ Landau level. The energy of the $c_{0,0,-}|\nu = 3\rangle$ hole is $1.5E_0$ and falls within the continuum of collective states $|k\rangle$. The Coulomb coupling between a particular collective state and the optically created hole $c_{0,0,-}|\nu = 3\rangle$ is $\sim 1/\sqrt{N}$, and vanishes in the thermodynamic limit. However, the coupling with all N collective states is finite. If we identify the collective states with the extended states in the Anderson model and the hole state $c_{0,0,-}|\nu = 3\rangle$ with the localized state, the problem maps onto the Fano-Anderson problem of a localized state in a continuum [19]. The dashed line in Fig. 3(d) shows the spectral function of the hole, coupled only to Auger-like configurations (c) for a disk with $N_e = 48$ electrons. The discrete levels of the finite size system were broadened using a Gaussian. The spectral function shows a broadened and slightly shifted peak. However, when the Coulomb interaction between the optically created hole and configurations (b) is included, the spectral function (full curve) of the hole splits into two peaks of almost equal weight. These two peaks are related to the edges of the continuum of spin-flip excitations, shown as a dotted line. A similar behavior, with a smaller splitting, is obtained at larger odd filling factors [17]. We summarize our results by plotting the calculated position of recombination lines as a function of the filling factor for a model electron hole separation ($E_{cv} = 0.8E_0$). We see that the jumps and splittings at odd filling factors of the calculated emission spectrum agree qualitatively with the measured one shown in the inset in Fig. 1.

In summary, we have shown that the recombination spectrum of a high quality 2DEG in strong magnetic fields measures directly the spectral function of a hole in the 2DEG. The electron-electron interactions play a significant role in the recombination spectrum. The interesting result is the splitting of the recombination line in the vicinity of odd filling factors. This splitting, due to resonant many-body interactions with a continuum of spin excitations of the 2DEG, is a many-body analog of the Fano-Anderson resonance [19], an interesting demonstration of recent ideas of localization in the Fock space [20].

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