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Localization and many-body interactions in the quantum Hall effect determined by polarized optical emission

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Polarization analysis of optical emission from the electron gas in GaAs single quantum wells discriminates the separate contributions from spin-split electron states. In the extreme quantum limit, the vastly different electron populations of these two states allows the study of many-body phenomena in the presence of localization. Reduction in electron screening of the hole at $\nu = 1$ appears to cause energy shifts in narrow quantum wells, while electron-hole binding dominates in wider wells. Evidence of a technique probing the spin-configuration of fractional quantum Hall states is also presented.

Recent experiments on the magneto-luminescence from two-dimensional (2D) electrons have associated spectral features with many-body phenomena in the integral and fractional quantum Hall regimes.[1–4] The region of interest coincides roughly with the extreme quantum limit ($\nu = 1$), where the occupation of the two lowest-energy electron spin states is changing rapidly as a function of magnetic field. However, precise level identification is obscured in unpolarized luminescence by both the small g factor in GaAs, and strong angular momentum mixing in the hole states. Polarization studies determine the initial spin-state configuration and can distinguish among the different features of the luminescence. In the past, such polarization analysis has proved to be a simple and effective tool, useful in determining the extent of valence hole level mixing[5] and yielding the temperature-dependent occupation of spin-split states at $\nu = 1$.[6] Future interest in polarized light measurement is being generated by the possibility of directly measuring the degree of spin polarization in fractional quantum Hall states. Transport experiments show that the ground and excited states of various fractional quantum Hall states are not fully polarized, but rather consist of partial or unpolarized spins.[7,8]

In this paper we study many-body effects in the optical recombination of electrons in a 2D electron gas with holes in the valence subband. We observe energy shifts and intensity changes of two initial spin-split electron states, selected through polarization analysis of the optical emission. Separating the emission from the two spin states near $\nu = 1$ allows the study of the various contributions to the many-body electron and hole self-energies and interactions which depend differently on the initial-state occupancy. For instance, the exchange energy and vertex (exciton) corrections depend directly on occupancy, while the correlation hole (local charge-density changes) depends on Landau level population only through the dielectric function.[9,10] The data display the surprising result that both polarization components of emission from narrower quantum wells (≈ 250 Å) are subject to a similar blue shift in energy at low temperature at $\nu = 1$. This is remarkable, since the two initial spin states have very different populations; one is fully occupied and the other nearly empty. This shows that changes near the valence-band hole, associated with the Coulomb hole of the hole, are the primary cause of the energy shift. For wider quantum wells and greater electron-hole separation, the situation changes, and a red shift at $\nu = 1$ shows that the screening becomes less important in favor of electron-hole Coulomb binding (vertex corrections).

These measurements consist of photoluminescence spectra from one-side modulation-doped $GaAs/Al_xGa_{1-x}As$ single quantum wells and heterojunctions of high mobility; $\mu=(3.0\text{–}8.5)\times 10^6$ $cm^2/V\,s$. The photoluminescence was excited with an unpolarized, low-power laser source of $p \leq 5\times 10^{-4}$ W/cm^2 at 1580 meV, and analyzed by an *in situ* circular polarizer with an extinction ratio greater than 30:1. Figure 1 displays both the left- (LCP) and right-circularly polarized (RCP) luminescence. At low fields ($4 \geq \nu \geq 1$), the luminescence shows a single feature in each polarization. The initial conduction-band states are identified as $m_j = -\frac{1}{2}$ for the RCP (higher energy) component and $m_j = +\frac{1}{2}$ for the LCP. At higher fields ($\nu \leq 1$), the Fermi energy drops down into the lower-energy conduction spin state. The depopulation of the upper spin state causes the RCP emission to vanish and thus the luminescence becomes nearly fully polarized in σ^- or LCP (100:1 at 18 T). Fig-

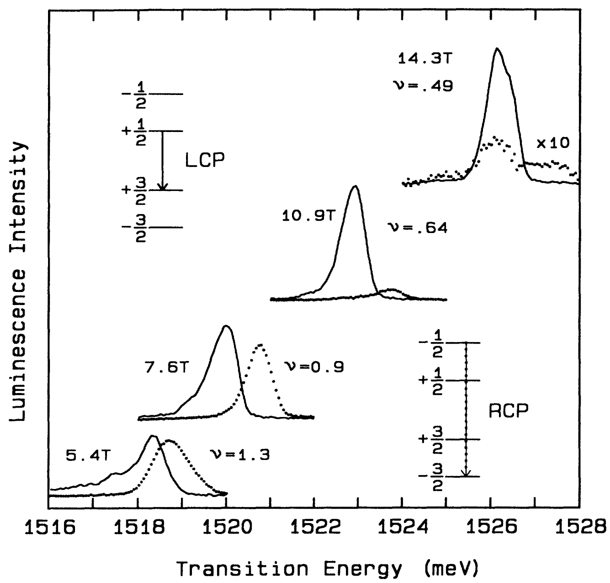

FIG. 1. Emission spectra of sample (A) with $\mu = 3.2 \times 10^6$ $cm^2/V\,s$, a narrow width of $L_w = 250$ Å, and $n_s = 1.83 \times 10^{11}$ cm^{-2} at T=0.56 K excited by a 1580-meV laser source ($p = 1.2 \times 10^{-4}$ W/cm^2). Solid lines show the left circularly polarized (LCP) emission σ^-, and dots the right circularly polarized (RCP) emission spectra σ^+. Note the marked decrease in the emission from electrons in the upper spin state at fields beyond $\nu = 1$. The emission at 14.3 at the LCP energy represents leakage through the polarizer (extinction 30:1). Note also the splitting in the LCP emission in the high-field region. Thus the emission does not represent emission from separate electron spin levels (Ref. 15), but proves that the changes are all associated with action in the ground-state transition, $+\frac{1}{2} \to +\frac{3}{2}$.

ure 2 shows the transition energy and peak intensity of the emission in both polarizations, and the rapid decrease beyond $\nu = 1$ in RCP emission is apparent.

The importance of the data in Fig. 2 is the near identical energy shifts of the recombination from electrons in both initial spin states at $\nu = 1$, even though they have vastly different populations. Energy shifts and intensity minima at integral and fractional filling factors are understood as due to the inability of the electron gas to respond when the Fermi energy is in the localized state region between Landau levels.[1,3] The optical phenomena are associated with the position of the Fermi energy in localized transport states because the B field extent of the shifts and matrix element reductions correlate directly with the extent of the ρ_{xy} plateau and ρ_{xx} zero as the temperature is reduced. While spectral shifts at $\nu = 1$ have been interpreted as many-body enhancement of the electron exchange energy,[11] our data show no large g-factor enhancement in emission. The two electron spin states should increase their energy separation under g-factor enhancement, creating *opposing* spectral shifts in the different polarizations, but the data (Fig. 2) show that the transition energy shift of both components is nearly identical (see also the absorption data in Ref. 5). Even in the wider well samples and single heterojunc-

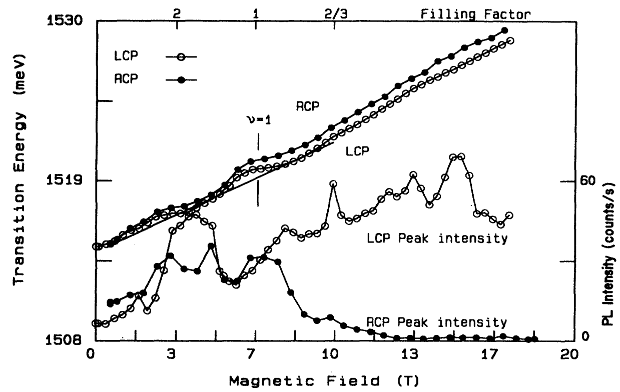

FIG. 2. The transition energy (scale at left) and peak intensity (scale at right) as a function of magnetic field B at T=0.56 K in LCP (open symbols) and RCP (closed symbols). The field of the extreme quantum limit where the upper spin state is nearly depopulated is indicated ($\nu = 1$).

tions where a difference exists between the energy shift of the two polarizations at $\nu = 1$, both shifts are in the same direction (red shifted).

The interesting physics occurs with the Fermi level in a gap: The density of states at E_F tends toward zero at $\nu = 1$ and 2, and this lack of low-energy excitations prevents the formation of screening charge in the vicinity of the hole. The reduction of this correlation energy, or Coulomb hole of the hole, reduces the hole self-energy thereby altering the transition energy. Theoretical calculations of recombination[9,10] identify the many-body contributions as the screened-exchange and the Coulomb-hole self-energy terms, but suggest that the Coulomb hole of the hole is paramount, since the exchange and correlation effectively cancel for electrons and not enough holes exist to make the exchange term for the holes relevant.

With the Fermi energy in the $\nu = 1$ gap and the electrons occupying a full spin-up electron state, the system has no available response to the presence of a hole. Thus, the electron screening of the hole (active for $\nu \neq 1$) ceases, affecting the emission energy of both spin states equally. The cancellation of the electron exchange and electron correlation hole terms must be close to exact, and the vertex term relatively unimportant for either spin state, since a large difference in the occupation of the initial state causes a negligible difference in the energy shift. In this regard, both theory and experiment indicate that in narrow quantum wells the correlation hole of the hole is the primary mechanism of the energy shift associated with the integral quantum Hall effect. Less clear is the role of coupling to higher Landau levels, which become an important factor with E_F in a gap and no low-energy, intralevel excitations allowed.

The quenching of the ground-state emission ($+\frac{1}{2} \to +\frac{3}{2}$) in *all* samples at $\nu = 2$, 1, and $\frac{2}{3}$ is especially apparent in earlier results,[2] but also visible in the data presented here. We believe the decrease in oscillator strength is due to the disappearance of electron screening in the quantum Hall regime and the resulting localization of electron and hole. It is understood that the decrease in screening in the quantum Hall regime increases the potential fluctuations due to remote ionized impurities and well width fluctuations.[12] Strong potential fluctuations could localize both electron and hole states, and under potential confinement electrons and holes localize in different regions of space due to their opposite charge. Such increased spatial separation reduces the wave-function overlap and optical matrix element, quenching the luminescence. Supporting this conjecture is the large amount of emission on the low-energy side of the ground state at integer filling.

An interesting aspect of our study is the effect on many-body interactions when increasing the separation between the hole and the 2D plane of electrons. In wider quantum wells of 400 and 500 Å widths and single heterojunctions the recombination data are significantly different. Figure 3 exhibits the unpolarized luminescence from a 400-Å single quantum well, where a kinetic energy line has been subtracted to better display the energy shifts at $\nu = 1$ and 2. We identify the higher-energy emission as RCP and the lower as LCP, in analogy to Figs. 1 and 2. Note that the energy shift of both spin states at $\nu = 1$ and 2 is toward lower energy (red shift). The changes in matrix elements are different too, with the quenching of the ground-state emission accompanied by an increase in the intensity of electrons recombining from both the upper spin state and the $n = 1$ excited subband (exhibited in Ref. 2). The red shift in recombination energy indicates more electron-hole binding (vertex correction). The increase in oscillator strength of the $n = 1$ excited subband and upper-spin state also point to a larger vertex correction through greater wave-function overlap. While the LCP and RCP energy shifts at $\nu = 1$ in the narrower samples were identical, the wider wells exhibit a distinctly weaker shift in RCP $(-\frac{1}{2})$ than in LCP $(+\frac{1}{2})$ emission. Both the energy shift and the intensity changes depend upon initial-state occupancy and hence vertex corrections are driving the recombination physics at large electron-hole separation. It makes sense that the polarization clouds surrounding the electron and hole, which are the physical manifestation of the hole correlation term,[13] will have a reduced effect as the electron and hole are pulled further apart than a few screening lengths ($\sim$ 200 Å). A positively charged hole in the midst of the 2D electron gas would be fully screened, but a hole at finite separation will have an extended field. It does seem unusual, however, that while Coulomb binding of the electron-hole pair must also decrease, it appears to do so as a slower function of electron-hole separation than the screening.

Turning to the fractional quantum Hall regime, Fig. 4 shows that the luminescence at $\nu = \frac{2}{3}$ displays a sudden

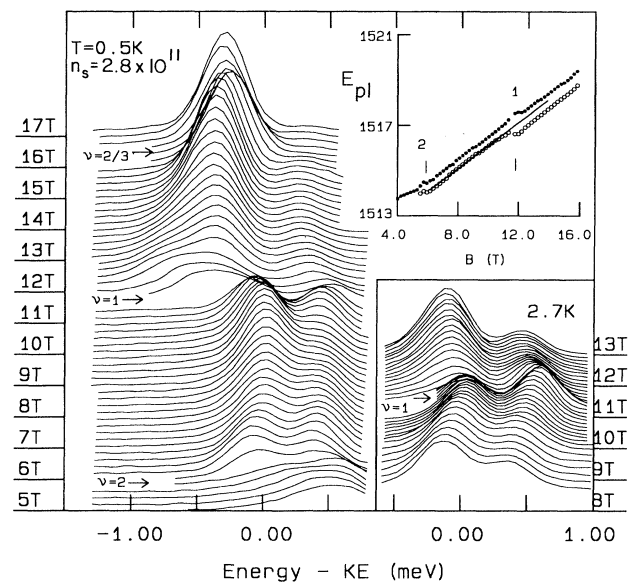

FIG. 3. Unpolarized spectra from sample (B) with $n_s = 2.8 \times 10^{11}$ cm^{-2} and a wide, 400 Å width. A kinetic energy line drawn through the lower-energy transition between $\nu = 1$ and 2 has been subtracted to better show the red shift at $\nu = 1$. [The linear term subtracted is 0.51 meV/T, with a $B = 0$ offset of 1511 meV. Most of the tuning is due to the single-particle kinetic energy of $\frac{1}{2}\hbar\omega_c$. The additional contribution reducing the tuning is possibly due to the generally increasing (negative) effect of the correlation hole as the density of states increases with increasing field (Ref. 10).] The higher-energy peak is the RCP component and the lower is the LCP component, in analogy to the results with an *in situ* polarizer. The upper inset plots the transition energy in both polarizations as a function of magnetic field. The lower inset shows the spectra at elevated temperatures near $\nu = 1$.

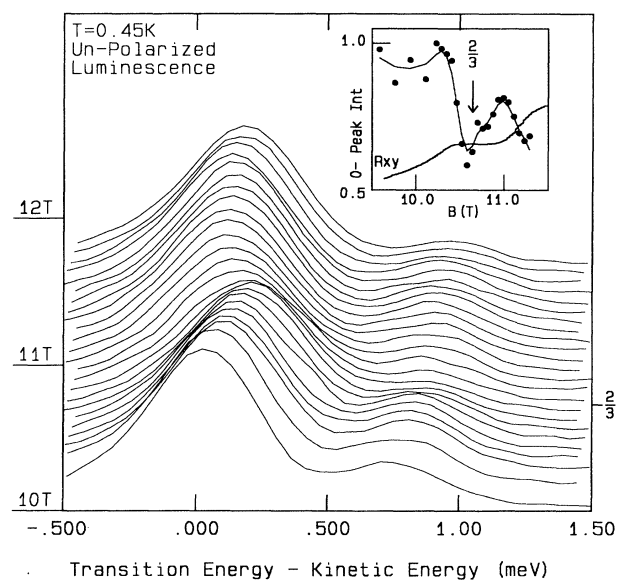

FIG. 4. Unpolarized emission spectra from sample (C) with $n_s = 1.81 \times 10^{11}$ cm^{-2} and $\mu = 3.8 \times 10^6$ cm^2/Vs and a narrow well width, L_w=250 Å. Note the strong reduction in the upper spin-state emission coupled with the shift of the LCP component at the precise $\nu = \frac{2}{3}$ filling factor. The inset shows the 40% reduction in $-\frac{1}{2}$ emission along with the plateau in the simultaneously measured R_{xy} at $\nu = \frac{2}{3}$.

peak shift in the $+\frac{1}{2}$ emission accompanied by an intensity minima in both $+\frac{1}{2}$ and $-\frac{1}{2}$ emission. The more fascinating feature is the stronger reduction in the intensity of the upper spin state, quantitatively displayed in the inset of Fig. 4. The quenching of emission from the $-\frac{1}{2}$ state at $\nu = \frac{2}{3}$ is near 40%, much larger than the reduction in the lower (LCP) electron spin-state emission. To consider this difference, we note that changes in intensity are due to variations in the population of electrons or holes or their optical matrix element. It is unlikely that the hole population would alter significantly over so small a range in magnetic field from energy shifts of the hole states. Additionally, the opening of a gap at E_F diminishes available scattering channels, tending to reduce the relaxation rate, increasing rather than decreasing the excited-state hole population. Thus, we believe the large reduction in upper spin-state emission is tied to the condensation of the electrons into the fractional quantum Hall effect $\frac{2}{3}$ ground state through a sharp decrease in either the up-spin population or up-spin matrix element. Since the $\nu = \frac{2}{3}$ ground state is expected to be spin-polarized at these fields,[14] one might expect some extra energy cost to maintaining a number of opposite spins in the presence of a polarized ground state. Changing the magnetic field slightly into the correlated spin-polarized $\frac{2}{3}$ state could thus decrease the population of the upper spin state over the simple Fermi distribution operating at $\nu \neq \frac{2}{3}$, thereby reducing the intensity sharply. Other samples, of both larger width and higher density, show the same behavior (Fig. 3 exhibits these effects at $\nu = \frac{2}{3}$ at 16 T).

In conclusion, we have used the polarization of the luminescence from ultrahigh mobility single quantum wells and heterojunctions to address the many-body screening in the integral and fractional Hall regimes. We have shown that the electron screening of the hole which ceases in the integral quantum Hall regime is the main factor in the recombination in the narrower samples since both spin components are subject to nearly the same energy shift at low temperature at $\nu = 1$, whereas the Coulomb binding of the electron-hole pair becomes dominant for the wider wells and single heterojunctions. We also show that g-factor enhancement cannot explain the energy shifts at $\nu = 1$. Additionally, the reduction in upper spin-state emission just at $\frac{2}{3}$ may be indicative of the spin-polarized nature of this fractional ground state, and indicates that new physics may be learned from polarized optical studies of these systems.

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