Charged Excitons in the Fractional Quantum Hall Regime

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We study the photoluminescence spectrum of a low-density ($\nu < 1$) two-dimensional electron gas at high magnetic fields and low temperatures. We find that the spectrum in the fractional quantum Hall regime can be understood in terms of singlet and triplet charged excitons. We show that these spectral lines are sensitive probes for the electron compressibility. We identify the dark triplet charged exciton and show that it is visible at the spectrum at $T < 2$ K. We find that its binding energy scales as $0.1e^2/l$, where l is the magnetic length, and it crosses the singlet slightly above 15 T.

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The behavior of electrons in semiconductor heterostructures subjected to a high magnetic field is governed by their mutual interactions. An important tool, which has been intensively used for studying this behavior, is photoluminescence (PL) spectroscopy. Indeed, experimental studies at the fractional quantum Hall (FQH) regime revealed profound changes in the PL spectrum at fractional filling factors [1–3]: The PL intensity exhibits strong minima or maxima and new lines appear in the spectrum at the corresponding magnetic fields. The interpretation of the recombination spectrum has, however, proven to be complicated due to the presence of strong Coulomb interaction between the photoexcited valence-band hole and the rest of the electrons. This interaction is of the same size as the electron-electron interaction, and cannot be considered as a small perturbation. In fact, it was argued that in a symmetric two-dimensional system at the lowest Landau level there is a cancellation of the contributions of these two interactions that renders all many-body effects invisible, and the only feature that should remain in the spectrum is the exciton [4].

An important development in the understanding of the behavior of the many electron + hole system came through spectroscopical studies of a dilute two-dimensional electron gas (2DEG) system. It was found that the ground state of this system is the negatively charged exciton, X^-, which consists of two electrons bound to a hole [5,6]. It was shown that at zero magnetic field the two electrons are a spin-singlet, and at high magnetic field another state, where the electrons are a spin-triplet, becomes bound [7,8]. There appeared, however, a significant qualitative discrepancy between the behavior predicted by theory and the experimental results. It was argued that at the extreme magnetic field limit the triplet should be the ground state of the system. This is a manifestation of Hund's rule, which minimizes the repulsive electrostatic energy of the electrons by having an antisymmetric spatial wave function. At zero magnetic field the Pauli exclusion principle sets an energy price for the formation of such a state; hence, the singlet is preferred. However, at high magnetic fields a triplet state can be formed at no cost of kinetic energy, since the two electrons can occupy degenerate angular momentum states. Thus, a crossing behavior of the singlet and triplet lines was predicted [9–11]. The experimental data showed, however, a different behavior: The triplet binding energy was found to rise and then saturate at a constant value, and no signature of singlet-triplet crossing was observed up to very high fields [7,12]. A solution to this discrepancy was recently proposed by Wojs *et al.* [13]. By calculating the energy spectra of a dilute 2DEG system it was found that *two different triplet states* are bound at high magnetic fields. These states are distinguished by their total angular momentum L, one having $L = 0$ and the other $L = -1$. Consequently, the first could decay radiatively, and is termed the "bright" triplet, while the other could decay only by a scattering assisted process, and is termed the "dark" triplet. It was argued that the dark triplet is the one that crosses the singlet and becomes the ground state at high fields, but since it cannot recombine radiatively it is invisible. Thus, the behavior observed experimentally is that of the bright triplet.

In this work we study the PL spectrum of a low density ($\nu < 1$) 2DEG at high magnetic fields and low temperatures. Our work is motivated by recent theoretical studies that have suggested that the charged excitons could be useful in describing the PL spectrum of a 2DEG at the FQH regime [10,13]. Using a gated structure, we are able to follow the dependence of the PL spectrum on the filling factor, $\nu = hcn_e/eB$, not only by changing the magnetic field at a constant density, as is commonly done in PL experiments, but also by varying the density at constant magnetic field. Our main finding is that the singlet and triplet X^- lines evolve *continuously* from the dilute limit into the FQH regime, where they are sensitive probes for the many-body interactions. We identify conclusively the dark triplet and show that it is visible at the spectrum at $T < 2$ K. We find that its binding energy scales as $0.1e^2/l$, where l is the magnetic length, and it should cross the singlet slightly above 15 T.

The sample that we investigated is a single 20 nm $GaAs/Al_{0.37}Ga_{0.67}As$ modulation-doped quantum well

with electron mobility of $\sim 1 \times 10^6$ cm^2/V s. The molecular-beam epitaxy grown wafer is processed to a mesa structure with a transparent gate electrode. The gated structure enables us to tune the electron density n_e continuously from 5×10^9 to 2×10^{11} cm^{-2}. Most of our measurements were done in a dilution refrigerator at a base temperature of 20 mK, and a magnetic field of up to 15 T that is applied along the growth direction of the wafer. The higher temperature measurements ($T > 1.5$ K) were done in a pumped He^4 cryostat. The sample was illuminated by a Ti-sapphire laser with a photon energy of 1.6 eV and a power density of 0.5 mW/cm^2. The PL was collected using a fiber system and circular polarizers. All spectra shown in this paper are for the σ^- circular polarization, in which a spin-up electron from the lower Zeeman level recombines with a valence-band hole. The electron density under illumination is measured by finding the values of the magnetic field B that correspond to $\nu = 1$ and 2, where drastic changes of the PL spectrum are observed [14]. The accuracy of this method is better than $\sim 2 \times 10^9$ cm^{-2}; the higher the density, the more accurate it is.

Figure 1 shows the PL spectrum at very low densities ($n_e \sim 5 \times 10^9$ cm^{-2}). The temperature dependence of the spectrum is shown in Fig. 1a for 9 T. The spectrum at 4 K is well studied and understood [7,8]: It consists of three main peaks associated with the neutral exciton (X^0) and two charged-exciton (X^-) peaks, labeled as X_s^- and X_{t1}^-. The two X^- peaks are due to recombination from singlet or triple initial states, respectively. It is clearly seen that as the temperature is decreased an additional peak, labeled as X_{t2}^-, gradually appears between X_s^- and X_{t1}^-, and becomes well resolved at 20 mK. In the following, we show that X_{t1}^- and X_{t2}^- are the bright and dark triplets, respectively.

Figure 1b describes the evolution of the spectrum as the magnetic field is varied between 0 and 15 T at 20 mK. It is seen that at low fields ($B < 4$ T) the spectrum consists of only two peaks, the well-known $X^0 - X_s^-$ doublet [5,6]. This simple spectrum changes at higher fields as two additional peaks, X_{t1}^- and X_{t2}^-, split from the exciton and gradually shift to lower energies with increasing magnetic field. Figure 2a summarizes the magnetic field dependence of the peak energies. It can be clearly seen that both X_{t1}^- and X_{t2}^- are unbound at zero magnetic field, and become bound at some finite magnetic field. Examining their polarization properties, we find that both appear only at the σ^- polarization and do not have a Zeeman-split counterpart. In Fig. 2b we show the binding energy of each X^- state, defined as its energy distance from X^0. It is seen that the binding energies of X_s^- and X_{t1}^- exhibit a rapid growth at low magnetic fields ($B < 6$ T) and then saturate at a constant value. This behavior is similar to

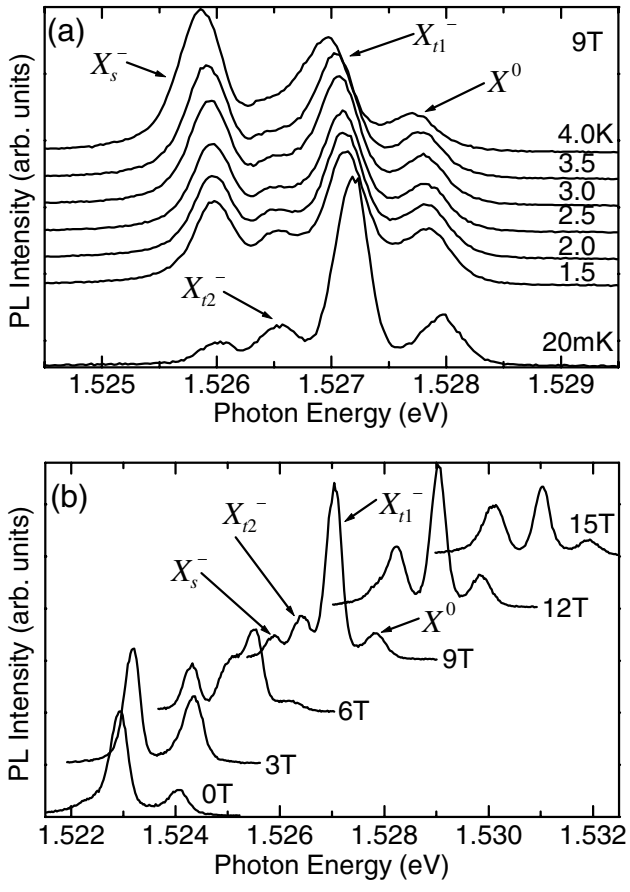

FIG. 1. (a) The PL spectrum at low electron density, $n_e \sim 5 \times 10^9$ cm^{-2}, as a function of temperature. (b) The PL spectrum at 20 mK as a function of magnetic field.

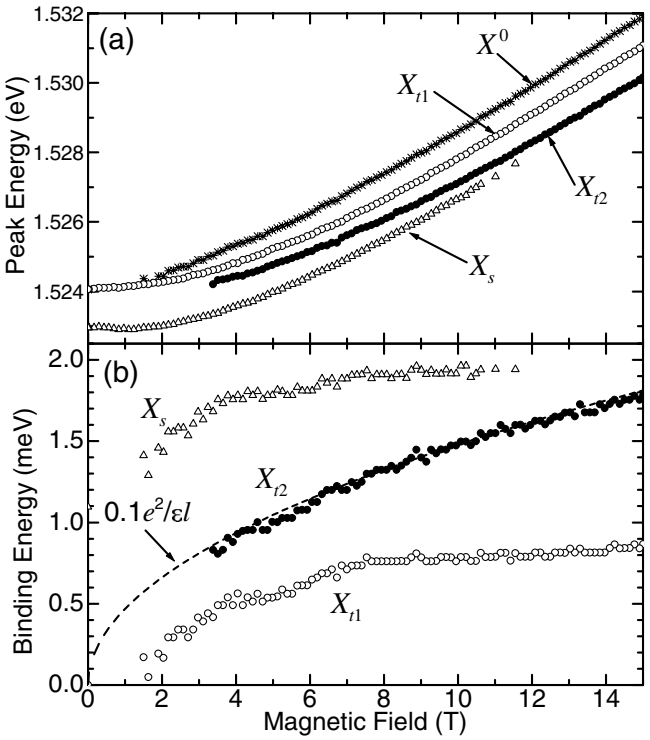

FIG. 2. (a) The peak energies and (b) binding energies of a dilute 2DEG ($n \sim 5 \times 10^9$ cm^{-2}) as a function of B.

that reported in several previous works [7,8]. The binding energy of X_{t2}^-, on the other hand, grows monotonically with increasing the magnetic field and nearly crosses that of the X_s^- at 15 T, consistent with the behavior predicted by theory [11,13]. A quantitative verification comes from the dependence of its binding energy on the magnetic field. It can be seen that it is very well described by $0.1e^2/\varepsilon l$ (where ε is the dielectric constant). This dependence is indeed predicted for an ideal 2DEG in the lowest Landau level [10], with a numerical coefficient of 0.0544. The discrepancy in the coefficient is settled in theoretical calculations that take into account the finite well width and mixing with higher Landau levels [11,13]. The magnetic field at which the singlet-triplet crossing occurs, ~15 T, is, however, substantially lower than predicted in these papers (30–40 T). Very recent calculations indicate that a slight displacement (of 0.5 nm) between the electron and hole within the X^- shifts this crossing magnetic field to the range observed in our experiment [15]. Such a displacement might naturally occur in our asymmetric structure. We believe that this conclusive observation puts to rest the debate over the triplet X^-. It should be noted that an observation of the dark triplet was recently reported by Munteanu *et al.,* who have reinterpreted their previous high magnetic field experiment on a high density 2DEG ($n_e = 1.6 \times 10^{11}$ cm^{-2}) [16]. However, the reported behavior at low fields is inconsistent with that expected for a triplet X^-: Reference [16] shows a very large zero-field binding energy, while the triplet is expected to be unbound.

Let us turn now to examine the dependence of the spectrum on filling factor. In Fig. 3a we show the measured spectra as the density is changed from 1×10^{10} to 1.2×10^{11} cm^{-2}, at a constant magnetic field of 10 T. This density range corresponds to $0.04 < \nu < 0.5$. In Fig. 3b we present the peak energies of the neutral and charged exciton lines as a function of ν at the same magnetic field of 10 T. It is seen that as ν is increased from 0.04 to 0.13 the X^- spectrum remains unchanged, but the X^0 disappears. At this low density range the 2DEG is most likely strongly localized, and does not form quantum Hall states. With a further increase of the density the X^- spectrum undergoes a drastic change: The two triplet lines, X_{t1}^- and X_{t2}^-, gradually merge and at $\nu = 1/3$ they form a single strong peak. At $\nu > 1/3$ this merged peak gradually weakens, until it disappears from the spectrum just above $\nu = 2/3$. The energy of the singlet state, on the other hand, changes smoothly as we cross $\nu = 1/3$, with no shift or cusp. This dependence on filling factor is general and is observed throughout the magnetic field range, as demonstrated by the images of Fig. 4. Each horizontal line in these images corresponds to a spectrum taken at a different gate voltage, with the PL intensity being coded by colors. It is seen that the energy separation between the lines varies with magnetic field, but the merging of the two triplets at $\nu = 1/3$ is clearly evident in all the images.

Wojs *et al.* have recently calculated the recombination energy and oscillator strength of $e - X^-$ states of a low-density 2DEG [13]. These calculations correctly predict the energy dependence of the various lines, and, in particular, the merging of the two triplets at $\nu = 1/3$ and the relative insensitivity of the singlet state to ν. The fact that one can accurately obtain the PL spectrum around $\nu = 1/3$ by considering the $e - X^-$ interaction only is an important reassuring evidence for the usefulness of the X^- in understanding the PL at the FQH regime. The underlying physical picture is the following: The introduction of a positively charged hole into the 2DEG creates a strong Coulomb attractive potential near it, and the system minimizes its energy by creating a bound state. This implies bringing two electrons to the vicinity of the hole, forming either a spin-singlet state or triplet states. Earlier studies of the D^- recombination in the presence of a 2DEG have shown that this bound state is only weakly coupled to the rest of the electrons due to the short-range nature of the interaction potential. The quasihole that is formed at the lowest Zeeman level tends to migrate to the vicinity of the electron pair, while the remaining electrons move

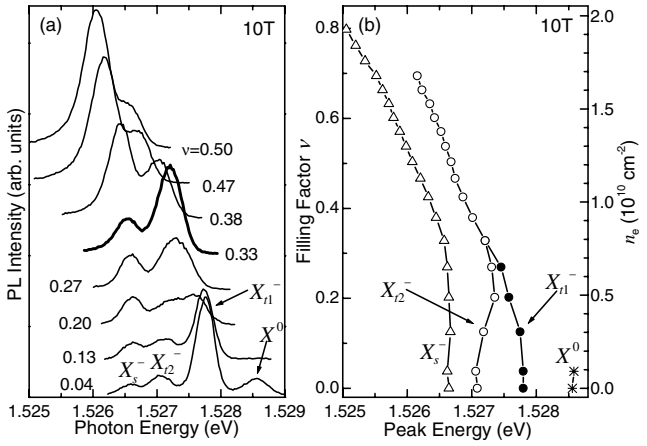

FIG. 3. (a) The PL spectra at 10 T for $0.04 < \nu < 0.50$. (b) The peak energies as a function of ν.

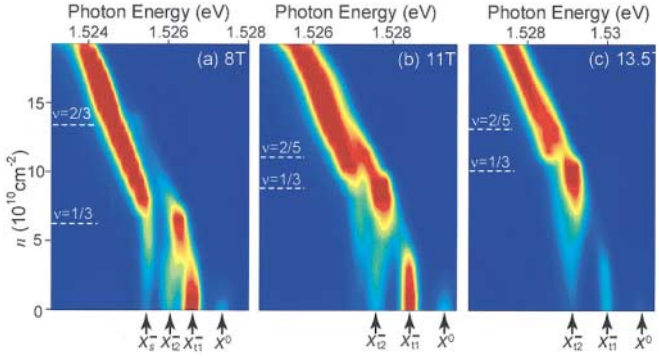

FIG. 4 (color). Contour plots of the PL spectra as a function of ν at different magnetic fields; (a) $B = 8$ T, (b) 11 T, and (c) 13.5 T. The PL intensity is color coded, such that blue is low and red is high.

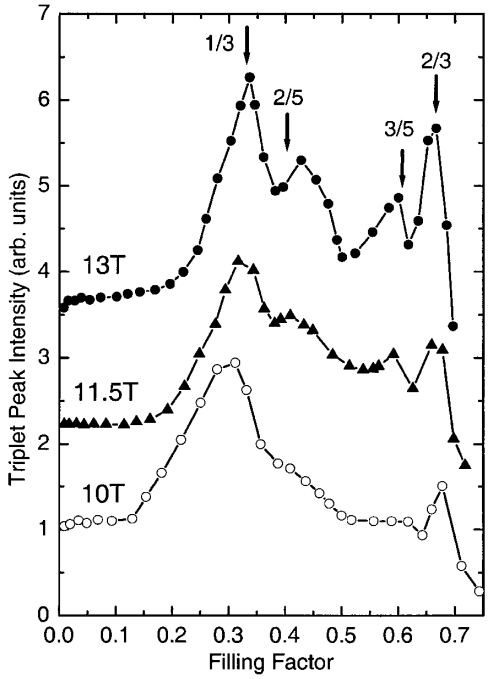

FIG. 5. The triplet PL peak intensity as a function of ν at three different magnetic fields.

away into larger orbits [17]. Thus, the bound state is effectively isolated from the 2DEG.

In that context it is interesting to examine the behavior of the triplet intensity. In Fig. 5 we show the intensity of the triplet as a function of ν, for three magnetic fields of 10, 11.5, and 13 T. It is seen that well resolved enhancements of the triplet intensity occur at $\nu = 1/3, 2/5, 3/5$, and $2/3$ (a weak recovery is observed also at $\nu = 1$). These enhancements gradually disappear as the temperature is raised, and cannot be resolved above 1.5 K. Their existence is surprising: As stated above, theoretical calculations predict that this state should be dark, and could recombine only through a scattering process that changes its total angular momentum. However, at fractional ν, the 2DEG becomes incompressible and e-e scattering is suppressed [18] Indeed, calculations of the triplet oscillator strength do not show any such enhancements at fractional ν [13]. Hence, another scattering mechanism, which is especially efficient at these filling factors, is responsible for the triplet emission. We argue that the random potential induced by the remote ionized donors is a very plausible candidate for that scattering mechanism. It is well known that the presence of a random distribution of ionized donors at a close proximity (a few tens of nm) to the 2DEG causes strong electrostatic potential fluctuations at the 2DEG plane [19]. Indeed, we have previously shown that this donor potential localizes the X^- at zero magnetic field and low electron density [20]. A similar scenario occurs at integer or fractional ν: the incompressible electrons cannot screen effectively this potential, and the fluctuations grow. They give rise to the formation of small compressible and incompressible regions of electrons [21,22]. This rough landscape can act as an efficient scattering mechanism for the triplet X^- and its effectiveness increases at fractional ν. In that sense the triplet intensity is a good measure of the electron compressibility: The more incompressible the electrons, the more intense it is. It is, therefore, a sensitive probe for FQH states.

In conclusion, we present here a coherent picture of the PL at the FQH regime. This picture views the spectrum as consisting of singlet and triplet charged excitons, and calls for reconsideration of the assignment of the various spectral lines in previous experiments in that regime.

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