Charged excitons in the fractional quantum Hall regime

G. Yusa, H. Shtrikman, and I. Bar-Joseph

Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

Abstract

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 electrons 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 like $e^2/l$, where $l$ is the magnetic length, and it crosses the singlet slightly above 15 T.

PACS:
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. In a PL measurement an electron is photo-excited from the valence to the conduction band. The hole, which is created at the valence band, relaxes into the top of that band and recombines with an electron from the Fermi sea. The interpretation of the recombination spectrum is complicated, however, due to the presence of \(e - h\) Coulomb interaction. The equality (up to a sign) of the \(e - e\) and \(e - h\) interactions may give rise to mutual cancellation of their contributions. It was shown that in a symmetric system at the lowest Landau level this cancellation renders all many-body effects invisible, and the only feature that remains in the spectrum is the exciton \([1]\). This symmetry, known as the hidden symmetry, is partially broken in realistic systems. Experimental studies at the fractional quantum Hall (FQH) regime revealed profound changes in the PL spectrum at fractional filling factors \([2, 3]\): the PL intensity exhibits strong minima or maxima and new lines appear in the spectrum at the corresponding magnetic fields. However, these changes could not be linked to a concrete physical picture that takes into account the many-body \(e - e\) and \(e - h\) interactions on equal footing.

An important development in the understanding of the behavior of the many electron+\(h\) system came through experimental studies of the PL 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 \((J = 0)\), and at high magnetic field another state, where the electrons are a spin-triplet \((J = 1)\), becomes bound \([7, 8]\). These observations triggered an intensive experimental and theoretical work aimed at better understanding its behavior, as it became clear that the \(X^-\) may play an important role in the PL of higher density 2DEG at high magnetic fields. Yet, there was a significant qualitative discrepancy between the predicted behavior of these bound states 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 anti-symmetric spatial wavefunction. 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. The experimental data showed, however, a different behavior: the triplet binding energy was found to rise and then saturate at a constant value. Surprisingly, no signature of singlet-triplet crossing was observed up to very high fields. A solution to this disagreement was recently proposed by Wojs et al. By calculating the energy spectra of $2e + h$ states 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 was termed the ”bright” triplet. The other state could decay only by a scattering assisted process and was termed the ”dark” triplet. It was argued that the behavior observed experimentally is consistent with that of the ”bright” triplet. On the other hand, the ”dark” triplet is the one that crosses the singlet and becomes the ground state at high fields. Since it can not recombine radiatively it should remain invisible. A recent PL measurement at very high magnetic field (up to 40 T) showed evidences to the existence of this dark state.

In this work we study the PL spectrum of a low density ($\nu < 1$) 2DEG at high magnetic fields ($B < 15$ T) and low temperatures ($T = 20$ mK). 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. Using a gated structure we are able to follow the dependence of the PL spectrum on the filling factor, $\nu = en_e/hB$, not only by ramping 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 charged-exciton 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 like $e^2/l$, 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$^2$/Vs. The MBE 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 $5 \times 10^9$ to $2 \times 10^{11}$ 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 Ti-sapphire laser with a photon energy of 1.6 eV and a power density of 2 mW/cm$^2$. The PL was collected using a fiber system and circular polarizers. All spectra shown in this paper are at the $\sigma^-$ 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 [15]. The accuracy of this method is better than $\sim 2 \times 10^9$ cm$^{-2}$.

Figure 1 shows the PL spectrum at very low densities ($n_e \sim 5 \times 10^9$ cm$^{-2}$) for the $\sigma^-$ circular polarization. Let us first focus on the temperature dependence of the spectrum, which is shown in Fig. 1a for 9 T. The spectrum at 4 K is well studied and understood [8,9]: it consists of three main peaks associated with the neutral exciton ($X^0$) and two charged-exciton peaks, labeled as $X^-_s$ and $X^-_{t1}$. The two charged-exciton peaks are due to $e-h$ 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 to 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 $\sigma^-$ polarization and do not have a Zeeman-split counterpart. In Fig. 2b we show the binding energy of each charged-exciton 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 than saturate at a constant value. This behavior was reported in several previous works \[8,9\]. 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 for the ”dark” triplet \[11,13\]. 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 $\varepsilon$ is the dielectric constant). This functional dependence is indeed predicted for an ideal two-dimensional gas in the lowest Landau level \[10\], with a numerical coefficient of 0.0544. The discrepancy in the coefficient is settled in theoretical calculations that takes into account the finite well width and mixing with higher Landau levels \[11,13\]. The magnetic field at which the singlet-triplet crossing occurs, $\sim 15$ T, is, however, substantially lower than predicted in these works ($30 - 40$ T). Very recent calculations indicate that a slight displacement (of 0.5 nm) between the electron and hole would shift this crossing magnetic field to the range observed in our experiment \[16\]. Such a displacement might naturally occur in our gated quantum well. We believe that this conclusive observation puts to rest the debate over the triplet charged exciton. 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$^{-2}$) \[14\]. However, the reported behavior at low fields is inconsistent with that expected for a triplet charged exciton: Ref.
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 $1 \times 10^{10}$ to $1.2 \times 10^{11}$ cm$^{-2}$, at a constant magnetic field of 10 T. This density range corresponds to varying $\nu$ between 0.04 to 0.5. In Fig. 3b we present the peak energies of the neutral and charged exciton lines as a function of $\nu$. It is seen that as $\nu$ is increased from 0.04 to 0.13 the $X^-$ spectrum remains unchanged, but the neutral exciton 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 electron interactions become important and 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 at $\nu \approx 2/3$ (a weak recovery is observed at $\nu = 1$). 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 vary with magnetic field, but the merging of the two triplets at $\nu = 1/3$ is clearly evident in all the images. This observed behavior is in excellent quantitative and qualitative agreement with that recently predicted by Wojs et al. [13], who calculated the recombination energy and oscillator strength of $e-X^-$ states of a low density 2DEG. These calculations correctly predicts 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 $\nu$. 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 charged excitons in understanding the PL at the FQH regime.

We now wish to examine the dependence of the PL intensity on $\nu$ (Fig. 5). The behavior at $\nu < 1/3$ is marked by a gradual decrease of $X_{t1}$ intensity and a corresponding increase
of $X^{-}_{2}$ with increasing $\nu$. The higher density range is characterized by a more drastic dependence of the PL intensity on $\nu$: the merged triplet exhibits strong enhancement at exactly $\nu = 1/3$ (and a weaker one at 2/5), and the singlet increases in a step-like fashion slightly above $\nu = 1/3$. This behavior is general and is seen throughout the magnetic field range: the inset of Fig. 5 shows that the enhancements of the triplet occur consistently at $\nu = 1/3$ and 2/5. Comparing this behavior with the calculations of Ref. [13] we find a qualitative agreement at $\nu < 1/3$, but significant discrepancies around 1/3.

The interaction of the charged-exciton with the surrounding electrons is sensitive to the compressibility of the 2DEG. In the absence of the hole the 2DEG is spin polarized at the lowest Zeeman level and forms incompressible states at fractional filling factors. 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 doubly occupied bound state. In a dilute 2DEG ($\nu \ll 1/3$) this implies bringing two electrons to the vicinity of the hole, forming either a spin-singlet 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: the quasi-hole that is formed at the lowest Zeeman level tends to migrate to the vicinity of the electron pair, while the remaining electrons move away into larger orbits [17]. Thus, the bound state is an $X^{-}$ that is effectively isolated from the 2DEG, as manifested in the spectra near $\nu = 0$. As we approach $\nu = 1/3$ interactions with the rest of the electrons and the formation of an incompressible state have to be taken into account. The enhancement of the triplet PL intensity at 1/3 and 2/5 is, therefore, surprising: as explained above, the triplet has a non-vanishing total angular momentum, hence it can recombine through scattering assisted processes only. The incompressibility of the 2DEG at $\nu = 1/3$ should suppress $e-e$ scattering, and thus, give rise to a reduction in the triplet intensity. A possible explanation is that the incompressibility of the 2DEG suppresses also its effectiveness in screening the remote donors potential, and the fluctuations at the 2DEG plane grow. This fluctuating potential can scatter the triplet charged excitons and enable their recombination. It should be noted that the triplet state is not dark throughout the
filling factor range: its intensity is significantly higher than calculated and is nearly the same as that of the singlet. This implies that scattering processes can efficiently transfer its excess angular momentum and enable it to recombine radiatively. The fluctuating donors potential could explain this behavior as well.

We wish to acknowledge very fruitful discussion with A. Stern and A. Esser. Special thanks to D. Sprinzak and Y. Ji for their assistance in the dilution refrigerator. This research was supported by the Minerva Foundation.
FIGURES

Fig. 1: (a) The PL spectrum at 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 $B$.

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

Fig. 4: Contour plots of the PL spectra as a function of $\nu$ 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 PL peak intensity of the three charged-exciton lines as a function of $\nu$. Inset: The value of $\nu$ where the PL intensity of $X_{\nu 2}$ is enhanced as a function of magnetic field.
REFERENCES

[1] A.H. MacDonald and E.H. Rezayi, Phys. Rev. B 42, 3224 (1990). A. B. Dzyubenko and Yu. E. Lozovik, J. Phys. A 24, 415 (1991). V.M. Apalkov and E.I. Rashba, Phys. Rev. B 46, 1628 (1992).

[2] A. J. Turberfield et al., Phys. Rev. Lett. 65, 637 (1990).

[3] B. B. Goldberg et al., Phys. Rev. Lett. 65, 641 (1990).

[4] Kim et al., Phys. Rev. B 61, 4492 (2000).

[5] K. Kheng et al., Phys. Rev. Lett. 71, 1752 (1993).

[6] G. Finkelstein, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. Lett. 74, R976 (1995).

[7] A.J. Shields et al., Phys. Rev. B 52, R5523 (1995).

[8] A.J. Shields et al., Phys. Rev. B 52, 7841 (1995).

[9] G. Finkelstein, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. B 53, R1709 (1996).

[10] J. J. Palacios, D. Yoshioka, and A. H. MacDonald, Phys. Rev. B 54, R2296 (1996).

[11] D. M. Whittaker and A. J. Shields, Phys. Rev. B 56, 15185 (1997).

[12] M. Hayne et al., Phys. Rev. B 59, 2927 (1999).

[13] A. Wojs, J. J. Quinn, and P. Hawrylak, Phys. Rev. B 62, 4630 (2000), and Physica E 8, 254 (2000).

[14] F. M. Munteanu et al., Phys. Rev. B 61, 4731 (2000) and 62, 16835 (2000).

[15] F. Plentz, et al., Phys. Rev. B 57, 1370 (1998); J. L. Osborne et al., ibid 58, R4227 (1998).

[16] I. Szlufarska, A. Wojs, and J. J. Quinn, Phys. Rev. B 63, 085305 (2001).

[17] Z. X. Jiang, B. D. McCombe, and P. Hawrylak, Phys. Rev. Lett. 81, 3499 (1998).
Fig. 1 Yusa et al.
Fig. 2 Yusa et al.

(a) Peak Energy (eV) vs. Magnetic Field (T)

(b) Binding Energy (meV) vs. Magnetic Field (T)

Energy peaks labeled as $X^{0}$, $X_{s}^{-}$, $X_{t1}^{-}$, and $X_{t2}^{-}$.
Fig. 3 Yusa et al.

(a) PL Intensity (arb. units) vs. Photon Energy (eV) for different filling factors $\nu$. The curves are labeled with the filling factor values: $\nu = 0.50$, 0.47, 0.38, 0.33, 0.27, 0.20, 0.13, 0.04.

(b) Filling Factor $\nu$ vs. Peak Energy (eV) for different excitons $X_t^-$, $X_{t1}^-$, $X_{t2}^-$, and $X_s^-$. The graph shows the change in peak energy with varying filling factor.
This figure "Figure4.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0103561v1
Fig. 5 Yusa et al.

PL Peak Intensity (arb. units) vs. Filling Factor $\nu$ for $X_{t_2}^-$ and $X_s^-$. The plot shows a peak intensity at a specific filling factor, with magnetic field (T) on the x-axis and filling factor $\nu$ on the y-axis.