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Evidence of inter-layer interaction in magneto-luminescence spectra of electron bilayers

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Abstract

Magneto-luminescence studies in electron bilayers reveal the hallmarks of the even-denominator and other quantum Hall states in the intensities and energies of the inter-band optical recombination lines. In the presence of a small tunneling gap between the layers the magneto-optical emission from the lowest antisymmetric subband, not populated in a single-electron picture, displays maxima at filling factors 1 and 2/3. These findings uncover a loss of pseudospin polarization, where the pseudospin describes the layer index degree of freedom, that is linked to an anomalous population of the antisymmetric level due to excitonic correlations. The results demonstrate a new realm to probe the impact of inter-layer Coulomb interaction in quantum Hall bilayers.

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The terms of Coulomb interaction that arise from the spatial separation of electrons in double layer semiconductor heterostructures are at the origin of several new phenomena that occur in the quantum Hall (QH) regime[1]. The prominent physics linked to the impact of inter-layer electron interaction dramatically manifests in the even-denominator QH state at total filling factor $\nu_T = 1/2$[2]. Much attention was devoted to the quantum phase diagram of bilayers at $\nu_T = 1$ as a function of Δ_{SAS}/E_c and d/l_B (Δ_{SAS} is the tunneling gap, $E_c = e^2/\epsilon l_B$, l_B is the magnetic length, d is the inter-layer distance)[3,4]. The description of inter-layer correlated states frequently employs a pseudospin degree of freedom that labels the electron occupation of the the left and right layers. In pseudospin language, for example, the inter-layer correlated QH state at $\nu_T = 1$ and $\Delta_{SAS} = 0$ is described as an easy-plane pseudospin ferromagnetic phase with a spontaneously broken symmetry[5]. Alternatively, this quantum phase can be regarded as an inter-layer exciton condensate[6].

Several experiments have highlighted the unique properties of the intriguing $\nu_T = 1$ state that emerges at $\Delta_{SAS} = 0$. These experiments have uncovered evidence of counterflow superfluid-like behavior[7] and have established the existence of a finite-temperature phase transition[8,9]. At finite values of the tunneling gap, on the other hand, the pseudospins align along a specific direction in the plane, in a manner that is linked to the electron occupation of the symmetric combination (S) of the lowest-energy quantum well Landau levels (LL). However, if the tunneling gap remains sufficiently small, quantum fluctuations can lead to a suppression of the pseudospin ordering, which in turn leads to an anomalous occupation of the lowest antisymmetric spin-up (AS↑) Landau level. Indeed a loss of pseudospin order was probed at $\nu_T = 1$ by inelastic light scattering methods[10].

While extensive investigations of quantum Hall bilayers were carried out by magneto-transport techniques, light scattering[9–12] and NMR[13], little efforts were devoted to studies of magneto-photoluminescence (magneto-PL)[14]. This is surprising since in single layers the magneto-PL is a powerful probe of electron-correlation and of spin polarization in the regimes of the integer and fractional quantum Hall effects[15–20]. Some impacts of Coulomb interactions in magneto-PL, however, are hidden in symmetric modulation-doped heterostructures where the optical emission lines display a cross-over from Landau-level (linear) to excitonic (quadratic) behavior that, irrespective of the electron density, occurs exactly at $\nu = 2$. This effect, termed *hidden symmetry* (HS)[21], results from a cancellation between the Coulomb interaction among the electrons in the conduction band and with the photo-generated hole in the valence band. Ideally, it requires the square modulus of the electron and hole envelope functions to be similar in shape. Experimentally, the HS cross-over has been observed in both symmetric and asymmetric quantum well samples[22].

Motivated by this scenario, here we report the magneto-PL study of QH states in coupled electron bilayers. For a bilayer sample with vanishing tunneling gap the intensity minima of the lowest energy emission line at $\nu_T = 1$ and at $\nu_T = 1/2$ represent unambiguous manifestations of the occurrence of such inter-layer correlated quantum Hall states in magneto-PL. The evolution of the magneto-PL line intensities in a bilayer with a finite value of the tunneling gap confirms the loss of pseudospin polarization at $\nu_T = 1$ that arises from excitonic correlations in the ground state and reveals a similar but more pronounced effect at $\nu_T = 2/3$. In addition, in both samples we observe the characteristic signature of the hidden-symmetry transition which, contrary to conventional single layer systems, is seen at $\nu_T = 4$ due to the impact of the pseudospin degree of freedom. Indeed the HS requires both electrons and holes to be in the lowest LL. In double layers, because of the simultaneous presence of spin and pseudospin degrees of freedom, each LL consists of four sublevels with similar envelope function profile and hence the HS becomes valid for $\nu < 4$, independently of the presence of a finite tunneling gap.

Measurements were performed on samples mounted in a dilution refrigerator with a base temperature of 50 mK under light illumination. Two samples were studied. The first is a nominally symmetric modulation-doped $Al_{0.1}Ga_{0.9}As/GaAs$ double quantum well structure with AlAs barrier in between the wells, having well width of 18 nm and barrier width of 7 nm. The large barrier ensures that the tunneling gap is vanishingly small ($\Delta_{SAS} \to 0$). The total electron density is $n_T \sim 6.9 \times 10^{10}$ cm^{-2} and the electron mobility is above 10^6 cm^2/Vs. At $\nu_T = 1$, it has $d/l_B \approx 1.65$. The other sample is also a nominally symmetric modulation-doped $Al_{0.1}Ga_{0.9}As/GaAs$ double quantum well structure identical to the first one but with an $Al_{0.1}Ga_{0.9}As$ barrier in between the wells, leading to a tunneling gap at zero magnetic field of $\Delta_{SAS} = 0.36$ meV[10]. This sample has a total electron density of $n_T \sim 1.1 \times 10^{11}$ cm^{-2} and electron mobility above 10^6 cm^2/Vs. At $\nu_T = 1$, it has $d/l_B \approx 2.18$ and $\Delta_{SAS}/(e^2/\epsilon l_B) \approx 0.038$.

A perpendicular magnetic field was applied to the electron bilayer. The magneto-PL spectra were measured after excitation with a single-mode tunable Ti-Sapphire laser at 795 nm. Laser power densities were kept at $\sim 10^{-4}$ W/cm^2 to avoid electron heating effects

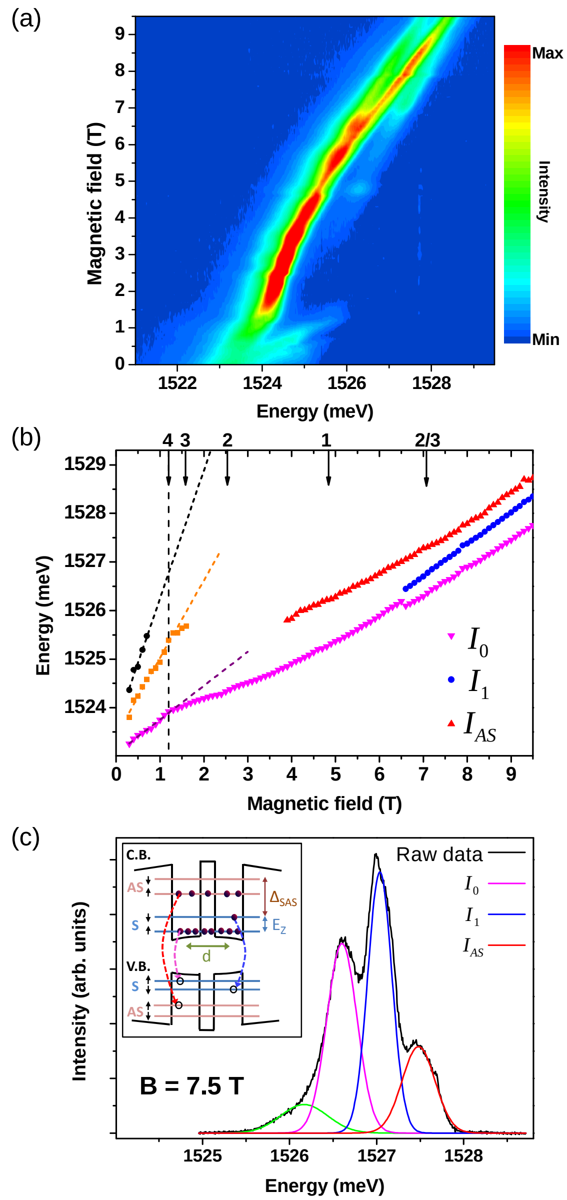

FIG. 1. (Color online) Left-circularly (σ^-) polarized data from the finite tunneling gap sample. (a) Color plot of the spectra in the range 0 - 9.5 T. (b) Peak energies vs magnetic field. The filling factors of the QH states observed in transport experiments are indicated in the upper axis. The short-dashed lines represent the best linear fits to the energy data at low magnetic fields. (c) Representative spectrum at B = 7.5 T and 50 mK fitted with Gaussian lines. The inset is a schematic representation of the electron states in the lowest Landau level (LL) in the conduction and valence bands. S and AS label the symmetric and anti-symmetric combinations of the quantum well levels, respectively. Each LL is further split by the Zeeman term E_Z.

and circularly-polarized configurations were exploited to have access to spin states. A triple-grating spectrometer equipped with a CCD detector was used to detect the emitted light.

Figure 1(a) is a color plot of the magneto-PL in σ^- polarization from the sample with a finite tunneling gap. We can identify two different regions: a low-field region (B $<$ 1.5 T) where a Landau fan of three peaks can be noticed, and a high-field region (B $>$ 1.5 T) where the main emission line deviates from the linear behavior and in addition it displays several intensity oscillations. The plot of the peak energies is shown in Fig. 1(b).

If (n,m) denotes the optical recombination of the electron in the n LL with the heavy-hole in the m LL, then the linear energy variations of the peaks in the triangular, square and circle scatter plots in Fig. 1(b) are compatible with the (0,0), (0,2) and (1,1) recombinations, respectively[23].

At $\nu_T = 4$ the magnetic-field dependence of the ground emission energy changes abruptly from linear to quadratic, indicating the formation of a bound state between the hole and the 2DEG. In analogy to magneto-PL studies in single layers[21,22] we interpret this changeover as due to the onset of the HS. This observation extends the validity of the HS to coupled bilayers, where the lowest LL consists of four sublevels owing to the presence of both spin and pseudospin degrees of freedom.

At high magnetic fields, three main peaks are observed, as shown in the illustrative PL spectrum of Fig. 1(c) taken at B = 7.5 T. The additional low-energy shoulder (green line in Fig. 1(c)) follows the evolution of the main PL line. We ascribe it to a disorder assisted recombination and it will not be further discussed in the following.

The behavior of the two most intense peaks, labelled I_0 (lower energy) and I_1 (higher energy), is similar to that of dark and bright triplet charged excitons observed in single layers[24]. In fact, they split at nearly 7 T, where the single layers have a filling factor of $\nu_T = 1/3$, with an energy difference remaining lower than 2 meV. Furthermore, I_1 is the most intense line in the spectra.

The highest energy peak (I_{AS}) in Fig. 1(c) is instead a novelty brought by the layer degree of freedom. In contrast to neutral excitons in single layers, its energy separation from the dark triplet remains constant, as can be seen in Fig. 1(b), and the peak disappears for B $>$ 9.5T. It can be linked to the recombination of an electron and hole occupying antisymmetric states, in agreement with a previous magneto-PL comparative study of single and double quantum wells[14].

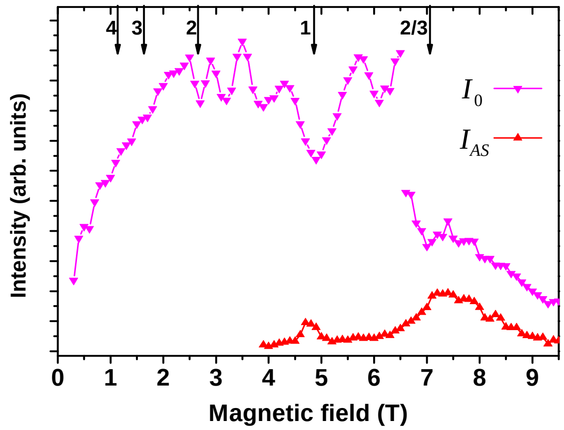

FIG. 2. (Color online) Integrated intensities vs magnetic field for the σ^- polarized PL spectra from the finite tunneling gap sample at 50 mK. The filling factors of the QH states observed in transport experiments are indicated with arrows in the upper axis.

The magnetic field dependence of the peak intensities is shown in Fig. 2, and reveals several intensity oscillations of I_0. The minima at 2.6, 4.8 and 7.1 T are linked to the occurrence of QH states with $\nu_T = 2$, 1 and 2/3, respectively, which are also observed in transport measurements (data not shown here). In addition, the emission from the antisymmetric spin-up level displays maxima around $\nu_T = 1$ and 2/3, suggesting that at these two QH states a fraction of electrons populates the AS level as a consequence of a loss of pseudospin polarization. At $\nu_T = 1$ the loss of pseudospin polarization was previously observed in inelastic light scattering spectra[10] and interpreted as a result of the formation of electron-hole excitonic pairs across Δ_{SAS}. At $\nu_T = 2/3$ no evidence was reported so far. Furthermore the emission intensity from the AS state increases by a factor of two passing from $\nu_T = 1$ to $\nu_T = 2/3$, suggesting that the loss of pseudospin polarization is more pronounced for the 2/3 state.

We focus now on the sample with vanishing tunneling gap. The σ^- polarized spectra from this sample are shown in the color plot of Fig. 3(a).

At low magnetic fields, two emission peaks are observed, labelled I_0(lower energy) and I_2(higher energy), whose energies vary linearly with magnetic field as shown in Fig. 3(b). The slopes of the energy vs B curves for I_0 and I_2 are compatible[23] with the (0,0) and (0,1) recombinations, respectively.

Again the lowest energy line (I_0) displays an abrupt change-over from linear (single

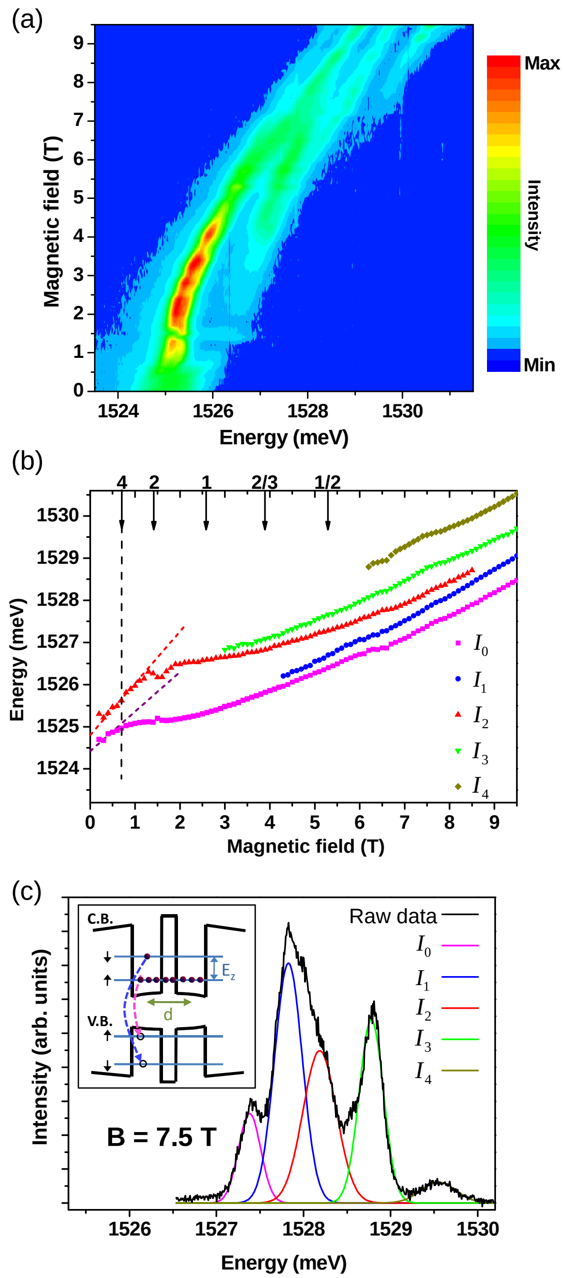

FIG. 3. (Color online) σ^- polarized PL data from the sample with vanishing tunneling gap at 50 mK. (a) Color plot of the spectra in the range 0 - 9.5 T. (b) Peak energies as a function of magnetic field. The filling factors of the observed QH states are shown in the upper axis. Short-dashed lines represent the best linear fits to the energy curves at low magnetic fields. (c) Representative spectrum at B = 7.5 T fitted with Gaussian lines. The inset represents a schematic of the spin-split states in the lowest Landau level in the conduction and valence bands. Each spin state has a double pseudospin degeneracy.

particle) to quadratic (excitonic) behavior at $\nu_T = 4$, suggesting the impact of the HS and of the pseudospin degree of freedom also in this case. The linear-to-quadratic change occurs at $\nu_T = 2$ for the I_2 line. Indeed this emission line involves holes from a higher LL ($m = 1$) and therefore it is not subject to the HS mechanism.

Other peaks appear at higher magnetic fields, as illustrated in the representative σ^- polarized spectrum in Fig. 3(c). Five emission lines are identified, which we label I_0, I_1, I_2, I_3 and I_4 in increasing order of energy. Understanding the physical origin of these emission lines remains a goal of future work.

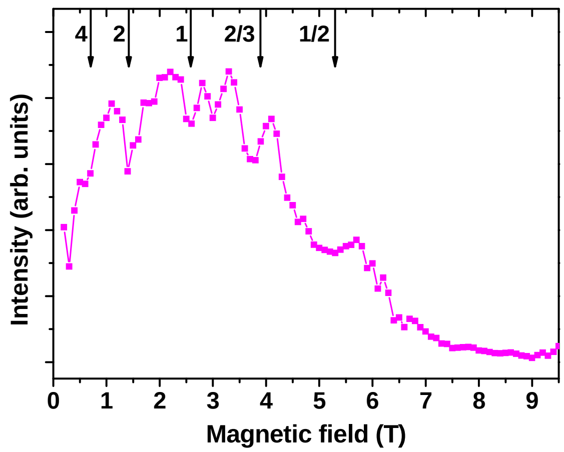

FIG. 4. (Color online) I_0 integrated intensity as a function of magnetic field for the σ^- polarized PL spectra from the zero tunneling gap sample at 50 mK. The filling factors of the observed QH states are shown in the upper axis.

The magnetic field positions of the QH states at $\nu_T = 4$, 2, 1, 2/3 and 1/2 as identified in magneto-transport data (not shown) are indicated with arrows in Fig. 4. The lowest energy line I_0 displays intensity minima (see Fig. 4) in correspondence to the occurrence of such QH states. The intensity minima appear independently from the value of the laser excitation wavelength (data not shown), which rules out the possibility that they could result from magnetic field-induced changes in the absorption. The quenching of the emission is indeed a manifestation of the QH states and can be linked to the reduction of the optical matrix element associated with the onset of QH phases. The latter follows from the localization of electrons and holes in the disorder potential, which increases in the gapped QH phases because of the reduced electron screening[25]. We remark that the observed QH states with $\nu_T = 1$ and 1/2 are genuinely linked to the impact of inter-layer correlations. In particular the $\nu_T = 1/2$ state has no counterpart in single-layer single-component systems.

In conclusion we have studied the magneto-PL spectra in coupled bilayers in the QH regime. The evolution of the intensities of the emission lines in a magnetic field reveals a loss of pseudospin polarization at $\nu_T = 1$ in a sample with a finite moderate value of Δ_{SAS} and signals the occurrence of inter-layer correlated QH states at $\nu_T = 1$ and 1/2 in the vanishing Δ_{SAS} sample. The energy evolution of the emission lines reveals the onset of the hidden symmetry at $\nu_T = 4$ owing to the presence of both spin and pseudospin degrees of freedom. From these results magneto-PL emerges as a promising technique to investigate the role of inter-layer correlation in bilayers.

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