Mechanism of shakeup processes in the photoluminescence of a two-dimensional electron gas at high magnetic fields

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We observe shakeup processes in the photoluminescence spectra of a two-dimensional electron gas in a GaAs/$Al_xGa_{1-x}As$ quantum well at high magnetic fields. We find that when the electrons occupy only the lowest Landau level these processes are strongly suppressed. We show that this behavior can be accounted for by first-principles calculations. We use the same considerations to explain the giant intensity of the shakeup line, which appears just below the main luminescence line. [S0163-1829(97)08439-7]

I. INTRODUCTION

Shakeup (SU) is a fundamental many-body process that occurs in optical transitions in the presence of an electron gas. In this process, a recombining electron-hole pair excites the surrounding electrons via the Coulomb interaction. This results in a decrease of the emitted photon energy by the amount left to the electron gas. Shakeup processes in magnetic fields were recently reported in the photoluminescence spectra of a two-dimensional electron gas (2DEG) in $In_xGa_{1-x}As$ quantum wells.[1–3] A series of peaks was observed, with energies $\sim n\hbar\omega_c^e$ below the main luminescence line, where $\omega_c^e = eB/mc$ is the electron cyclotron frequency and $n = 1,2,3, \ldots$. These satellite lines were explained as being due to shakeup processes, where recombination of one electron from the lowest Landau level (LL) is accompanied by the creation of a magnetoplasmon,[4–6] a collective excitation of an electron from one LL to a higher LL.

In this work we report new experimental results on the shakeup processes in the photoluminescence of a two-dimensional electron gas at high magnetic fields. We discuss the implications of the experimental findings on our understanding of these processes, and present a first-principles model, which gives an insight into the mechanism of shakeup at high magnetic fields. Specifically, we report on the first observation of shakeup lines in the GaAs material system at high magnetic fields, and clearly demonstrate their many-body nature. The low background impurity concentration of this material system, which is manifested in the high mobility of the 2DEG, enables us to investigate the intrinsic properties of the shakeup process. Our central experimental finding is that when the electrons occupy only the lowest Landau level, $\nu<2$, the intensity of the shakeup lines is strongly suppressed. We present a rigorous explanation of this suppression, and show how to estimate the relative intensities of the various shakeup lines. In particular, we point out the specific processes, which give rise to the giant intensity of SU_0, the shakeup line just below the main luminescence peak. We show that the suppression of the shakeup intensity below $\nu=2$ is related to a general hidden symmetry of the electron-hole system. This symmetry was previously used to explain the suppression of intra-LL many-body processes in the photoluminescence spectrum of a 2DEG in strong magnetic fields.[7–9] We show that this symmetry is also relevant for inter-LL processes.

The paper is organized as follows. We first describe our samples and experimental findings in Sec. II. In particular, we demonstrate the dramatic reduction of the shakeup intensity at $\nu<2$. In Sec. III this observation is explained and the relation to the hidden symmetry of the electron-hole system on the lowest LL is established. In Sec. IV we derive the quantum-mechanical transition amplitude of a shakeup process from the perturbation theory, which allows us to get some physical insight into the mechanism of shakeup processes. We clarify the origin of the SU_0 line and estimate its intensity relative to the intensities of other shakeup lines in Sec. V. In Sec. VI we experimentally demonstrate the many-body nature of the excitations involved in the shakeup processes.

II. THE MAIN EXPERIMENTAL RESULTS

Our samples consist of a buffer superlattice, a 20-nm GaAs quantum well, an undoped $Al_{0.35}Ga_{0.65}As$ spacer layer, a Si δ-doped region, another layer of 100-nm undoped $Al_{0.35}Ga_{0.65}As$, a 20-nm uniformly doped $Al_{0.35}Ga_{0.65}As$ (Si, $n=2.5\times10^{18}$ cm^{-3}), and a 10-nm GaAs cap.[10] We studied extensively two samples with the same structure except for the different spacer width, which was nominally 50 nm in one and 15 nm in the other. The corresponding electron densities after illumination were about 2×10^{11} and 5.5×10^{11} cm^{-2}, respectively. The mobility was in excess of 10^6 cm^2/V sec in both samples. The main features of the experiment were also observed in several other samples. The incident laser power density was kept very low, $\lesssim 100$ μW/cm^2 at a wavelength of 632.8 nm, which results in a photon energy below the band gap of the $Al_{0.35}Ga_{0.65}As$ barriers. The measurements were performed at magnetic fields up to 9 T normal to the 2DEG plane at temperatures of 4.2 K and 1.5 K. The light was delivered to the sample and collected back by optical fibers. The photoluminescence was dispersed by a 0.5-m spectrometer and detected by a charged-coupled-device camera.

Figure 1 displays several photoluminescence spectra of the lower density sample at $T=4.2$ K and magnetic fields $B=1.9$, 2.6, and 5.5 T, corresponding to filling factors $\nu=4$, 3, and 1.4, and at $B=0$. The spectral features marked LL_0

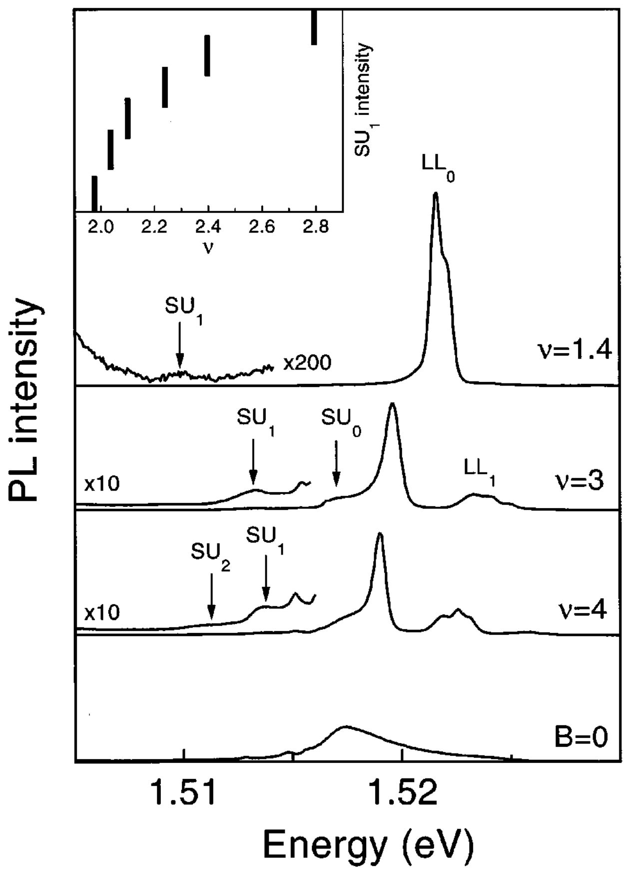

FIG. 1. The photoluminescence spectra of the $n \approx 2 \times 10^{11}/\mathrm{cm}^2$ sample at several filling factors and $T = 4.2$ K. The sharp feature at 1.515 eV is the bulk GaAs exciton. Inset: The intensity of the SU_1 line as a function of ν at $T = 1.5$ K.

and LL_1 are due to a recombination of electrons from the two lowest LL's with the photoexcited holes. It can be seen that the intensity of the LL_1 line is greatly reduced at $\nu < 2$, where there are almost no electrons left on the corresponding LL. The mixing of the valence-band LL in high magnetic fields partially breaks the selection rules and allows transitions between electrons from LL_1 and holes from different LL. This is manifested in the fine structure of the LL_1 line. A similar behavior is observed at the LL_2 line. When extracting the energy of the LL_n transition we take the lowest-energy peak from the corresponding set. Then the difference between LL_{n+1} and LL_n is the electron cyclotron energy $\hbar\omega_c^e$.[11]

Let us turn to the discussion of the shakeup lines. Zooming in on the low-energy tail of the emission spectrum, we observe two shakeup lines SU_1 and SU_2 below the main recombination peak LL_0. The SU_1 and SU_2 energies decrease linearly with magnetic field (Fig. 2). Following previous observations we associate these shakeup lines with a recombination of one electron accompanied by shaking another electron to a higher LL.[1–3] Here we denote the shakeup line which appears at energy $\sim n\hbar\omega_c^e$ below the main luminescence line as SU_n. This is to our knowledge the first observation of shakeup lines in the $GaAs/Al_xGa_{1-x}As$ quantum wells at high magnetic fields.

Following the SU_1 line, we observe a remarkable reduction in its intensity in a narrow magnetic-field range around $\nu = 2$ (inset of Fig. 1). It can be seen that the SU_1 line at

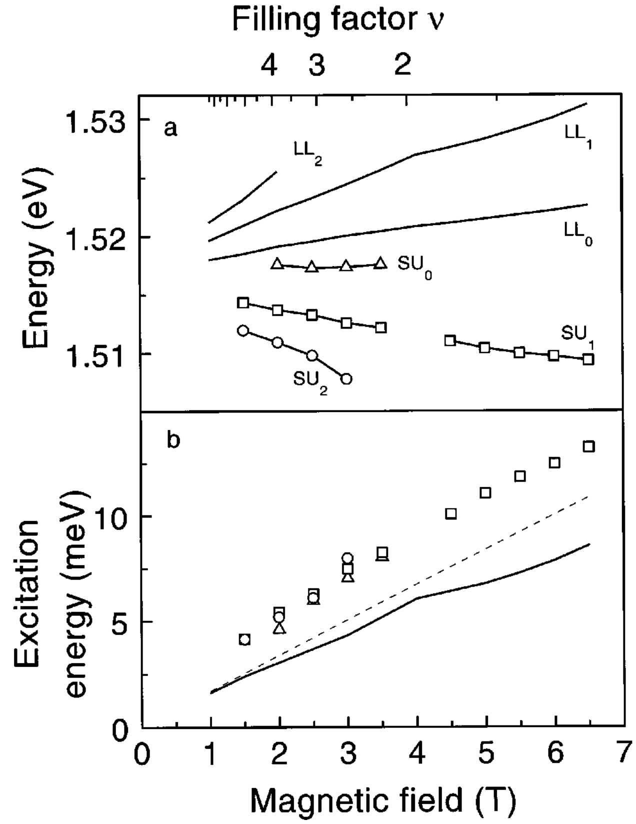

FIG. 2. (a) The energies of the various LL and shakeup peaks as a function of magnetic field for the $n \approx 2 \times 10^{11}/\mathrm{cm}^2$ sample at $T = 4.2$ K. (b) The energies of the excitations involved in SU_0 (triangles), SU_1 (squares), and SU_2 (circles), measured as an energy separation of the corresponding shakeup lines from the LL_1 line. We subtracted the measured $\hbar\omega_c^e$ and $2\hbar\omega_c^e$ from the last two energies. The solid line is $\hbar\omega_c^e$, measured as the energy difference between LL_1 and LL_0 peaks and the dashed line is the calculated $\hbar\omega_c^e$.

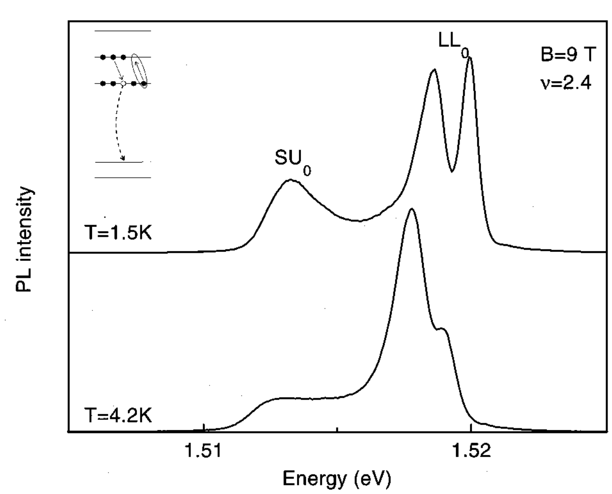

FIG. 3. The photoluminescence spectra of the $n \approx 5.5 \times 10^{11}/\mathrm{cm}^2$ sample at $B = 9$ T and temperatures of $T = 1.5$ K and 4.2 K. Inset: A schematic description of a resonant process which contributes to the SU_0 line.

$\nu=1.4$ is ~ 50 times weaker than at $\nu=3$ and 4 (Fig. 1). The understanding of this abrupt drop in intensity will be the main focus of our paper. We shall show that it sheds light on the mechanism of the shakeup recombination in 2DEG in a magnetic field.

Figure 3 displays the photoluminescence spectra of the higher-density sample at $B=9$ T and temperatures of 1.5 and 4.2 K. In this sample we also observed the SU_1 and SU_2 peaks (not shown), at energies that depend on the magnetic field in a way similar to that of the low-density sample. A prominent feature of the photoluminescence spectra in Fig. 3 is a peak, marked as SU_0, just below the Zeeman split LL_0 recombination line. This peak is seen also at the lower-density sample photoluminescence spectra, as a broad shoulder at $\nu>2$ (Fig. 1). In both samples it is larger by an order of magnitude or more as compared to the SU_1 line. The SU_0 intensity is also strongly suppressed at $\nu<2$, similarly to the SU_1 behavior. This line was also observed as a shoulder in InGaAs quantum wells.[2] It was explained as being due to electron recombination from LL_1, accompanied by creation of a magnetoplasmon with energy $\gtrsim \hbar\omega_c^e$.

III. THE THEORETICAL MODEL

The important observation in Fig. 1 is the strong suppression of the SU_1 and SU_0 lines at $\nu<2$. In this section we present a model that explains this behavior and provides an insight into the mechanism of shakeup at high magnetic fields. Our goal is to calculate to the lowest order the transition amplitude $W_n \propto \langle f(SU_n)|R|i\rangle$, where $|i\rangle$ and $|f(SU_n)\rangle$ are the initial and final states of the electron system in a SU_n recombination process and $R=\Sigma_{m,q}a_m(q)b_m(-q)$ is the electron-hole recombination operator. The shakeup line intensity will be straightforwardly given by $|W_n|^2$. We assume that both electrons and holes are delocalized and characterize them by the LL number m and the wave vector q in the Landau gauge. The Hamiltonian of the system is given by

$$\begin{aligned}H=H_0+H_{\text{int}}=&\sum_{m,q}\hbar\omega_c^e(m+1/2)a_m^\dagger(q)a_m(q)\\&+\sum_{m,q}[E_{\text{gap}}+\hbar\omega_c^h(m+1/2)]b_m^\dagger(q)b_m(q)\\&+\frac{1}{2}\sum V_{i,j,k,l}^{e\text{-}e}a_i^\dagger a_j^\dagger a_k a_l\\&+\sum V_{i,j,k,l}^{e\text{-}h}a_i^\dagger b_j^\dagger b_k a_l\\&+\frac{1}{2}\sum V_{i,j,k,l}^{h\text{-}h}b_i^\dagger b_j^\dagger b_k b_l.\end{aligned}\tag{1}$$

We first calculate the commutator between the Hamiltonian and the recombination operator $R_m=\Sigma_q a_m(q)b_m(-q)$ of an electron and a hole from the mth LL. It can be easily shown that this commutator can be written as

$$[H,R_m]=[E_{\text{gap}}+\hbar(\omega_c^e+\omega_c^h)(m+1/2)]R_m+\Delta R_m,\tag{2}$$

where

$$\begin{aligned}\Delta R_m=&\sum_{i,k,l}V_{i,m,k,l}^{e\text{-}e}a_i^\dagger b_m a_k a_l+\sum_{i,k,l}V_{i,m,k,l}^{e\text{-}h}a_i^\dagger b_k a_m a_l\\&-\sum_{i,k,l}V_{i,m,k,l}^{h\text{-}h}b_i^\dagger a_m b_k b_l-\sum_{i,k,l}V_{i,m,k,l}^{e\text{-}h}b_i^\dagger a_k b_m b_l\\&-\sum_{k,l}V_{m,m,k,l}^{e\text{-}h}a_l b_k.\end{aligned}\tag{3}$$

Next, we calculate the matrix element of the left- and right-hand sides of Eq. (2) between the wave functions $|i\rangle$ and $|f\rangle$:

$$\begin{aligned}(E_f-E_i)\langle f|R_m|i\rangle=&-[E_{\text{gap}}+\hbar(\omega_c^e+\omega_c^h)(m+1/2)]\langle f|R_m|i\rangle\\&+\langle f|\Delta R_m|i\rangle.\end{aligned}\tag{4}$$

Here E_f-E_i is the energy difference between the final and the initial states of the electron-hole system. By energy conservation it is equal to the energy of the emitted photon E_{ph}. We may thus express $\langle f|R_m|i\rangle$ in terms of $\langle f|\Delta R_m|i\rangle$ in the form

$$\langle f|R_m|i\rangle=\frac{\langle f|\Delta R_m|i\rangle}{E_{\text{gap}}+\hbar(\omega_c^e+\omega_c^h)(m+1/2)-E_{\text{ph}}}.\tag{5}$$

The derivation so far did not relate to any specific final state. To apply it to the case of the shakeup process we have to consider the final states where an electron-hole pair recombined and another electron was excited to a higher LL. For such final states only the first two terms in Eq. (3) are important. The next two terms are nonzero only if two holes are present in the initial state and are irrelevant to our experiment. (They result in a shakeup intensity proportional to the square of the laser intensity.) The fifth term is a two-fermion operator and gives shakeup only in higher orders of the perturbation theory, due to LL mixing. Substituting the first two terms of Eq. (3) into Eq. (5) we get

$$\begin{aligned}W_n=&\sum_m\frac{\sum_{i,k,l}V_{i,m,k,l}^{e\text{-}e}\langle f(SU_n)|a_i^\dagger b_m a_k a_l|i\rangle}{E_{\text{gap}}+\left(m+\frac{1}{2}\right)\hbar(\omega_c^e+\omega_c^h)-E_{\text{ph}}}\\&+\sum_m\frac{\sum_{i,k,l}V_{i,m,k,l}^{e\text{-}h}\langle f(SU_n)|a_i^\dagger b_k a_m a_l|i\rangle}{E_{\text{gap}}+\left(m+\frac{1}{2}\right)\hbar(\omega_c^e+\omega_c^h)-E_{\text{ph}}}.\end{aligned}\tag{6}$$

In our experiment the hole in the initial state is assumed to be on the lowest LL, so that $m=0$ in the first term and $k=0$ in the second one. Let us also assume, that the electron-electron and electron-hole Coulomb interactions in the plane are equal in absolute value, yielding $V_{i,j,k,l}^{e\text{-}h}=-V_{i,k,j,l}^{e\text{-}e}$. We then may interchange indexes k and m in the second term of Eq. (6) and combine the two terms to finally get

$$W_n=\sum_{m,l} V^{e\text{-}e}_{n+m+l,0,m,l}\langle f(\mathrm{SU}_n)|a^{\dagger}_{n+m+l}b_0a_ma_l|i\rangle \times\left[\frac{1}{E_{\mathrm{gap}}+\frac{1}{2}\hbar(\omega_c^e+\omega_c^h)-E_{\mathrm{ph}}} - \frac{1}{E_{\mathrm{gap}}+\left(m+\frac{1}{2}\right)\hbar(\omega_c^e+\omega_c^h)-E_{\mathrm{ph}}}\right]. \tag{7}$$

In Eq. (7) we have substituted $i=n+m+l$. This is a direct consequence of energy conservation: in the matrix element $\langle f(\mathrm{SU}_n)|a_i^{\dagger}b_0a_ma_l|i\rangle$ we eliminate two electrons with energies $\sim m\hbar\omega_c^e$ and $\sim l\hbar\omega_c^e$ and create an electron at $\sim i\hbar\omega_c^e$. Since we are considering an emission of a photon at an energy $\sim n\hbar\omega_c^e$ below the main luminescence line, then $i-(m+l)$ should be equal to n.

Equation (7) gives the total transition amplitude of the shakeup process. It is now easy to see why the shakeup process is suppressed at $\nu<2$. At these filling factors the electrons occupy only the lowest LL, so the indexes m and l of the annihilation operators a_m and a_l in the matrix element $\langle f(\mathrm{SU}_n)|a^{\dagger}_{n+m+l}b_0a_ma_l|i\rangle$ should be zero. However, if $m=0$ the two terms in the square brackets of Eq. (7) exactly cancel each other, and W_n vanishes. We note that the shakeup intensity is nonzero in this case due to higher-order processes or due to deviations form the assumptions we used. In particular, it occurs due to the LL mixing, hole localization, and the difference between the absolute values of the electron-electron and electron-hole interactions. As a result, SU_1 is still observed as a very weak line at $\nu<2$. The situation is clearly different at $\nu>2$, where there is a finite occupation of higher LL's. Then the index m of the annihilated electron in $\langle f(\mathrm{SU}_n)|a^{\dagger}_{n+m+l}b_0a_ma_l|i\rangle$ may be nonzero, so there is no cancellation in Eq. (7), and the shakeup probability is finite.

It is interesting to consider our results in the context of the hidden symmetry of the electron-hole system on the lowest LL.[7–9] It was shown that there is a special commutation relation,

$$[H,R_0]=-E_{\mathrm{ex}}R_0 \tag{8}$$

between the projection of the Hamiltonian of an electron-hole system on the lowest LL and the recombination operator from the same level, where E_{ex} is the exciton recombination energy. [This result directly follows from Eq. (2), if all the LL indexes are set to be zero.] This commutation relation shows that if the initial state $|i\rangle$ is an eigenfunction of H, then the final state $R_0|i\rangle$ is also an eigenfunction with an energy lowered by E_{ex}. Thus the optical spectrum is not affected by the many-body interactions and consists of only one line at exactly E_{ex}.[7–9] The basic assumption of Refs. 7–9 is that there is only one LL, i.e., $\hbar\omega_c^e$, $\hbar\omega_c^h\to\infty$. In our derivation we go beyond this approximation and take higher LL's into account. As a result, the exact commutation relation of Eq. (8) does not hold anymore. At $\nu>2$, this breaking of the hidden symmetry is manifested in the appearance of the shakeup lines. The suppression of the shakeup intensity at $\nu<2$ indicates that the hidden symmetry is partially restored, when only the lowest LL is occupied. Indeed, in this filling factor range the matrix element $\langle f(\mathrm{SU}_n)|\Delta R_m|i\rangle$ vanishes (to the lowest order), and Eq. (2) effectively reduces to Eq. (8).

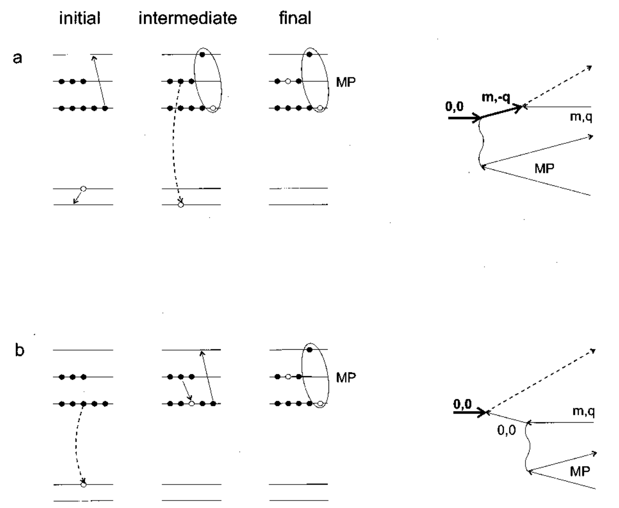

FIG. 4. Right: the Feynman diagrams of the transition amplitude W_n for a SU_n process. The electron, hole, photon, and Coulomb interaction are shown by thin, thick, dashed, and wavy lines, respectively. Left: a schematic description of the two contributions to SU_1 at $\nu>2$.

IV. THE MECHANISM OF A GENERAL SHAKEUP PROCESS

In order to illustrate the physical meaning of Eq. (7) we calculated to the lowest order the transition amplitude W_n by perturbation theory. We neglect in this simplified calculation the inter-LL mixing due to the Coulomb interaction. This assumption is valid for integer filling factors. There are two general processes which give rise to the emission of a photon at the SU_n energy. In the first, the magnetoplasmon is excited by the valence-band hole, while in the second—by the recombining electron. These two processes are described schematically in Figs. 4(a) and 4(b), together with the corresponding Feynman diagrams. The transition amplitudes associated with these processes are

$$W_n^{(1)}\propto\sum_x \langle f(\mathrm{SU}_n)|R|x\rangle\langle x|H^{e\text{-}h}_{\mathrm{int}}|i\rangle/(E_i-E_x), \tag{9}$$

$$W_n^{(2)}\propto\sum_x \langle f(\mathrm{SU}_n)|R|x\rangle\langle x|H^{e\text{-}e}_{\mathrm{int}}|i\rangle/(E_i-E_x) + \sum_x \langle f(\mathrm{SU}_n)|H^{e\text{-}e}_{\mathrm{int}}|x\rangle\langle x|R|i\rangle/(E_i-E_x-E_{\mathrm{ph}}). \tag{10}$$

The two terms of Eq. (10) correspond to the two possible time orderings of the recombination and electron-electron scattering processes. Let us neglect the Coulomb corrections to the energy differences in the denominators, which correspond to higher orders in the perturbation parameter. Then we may sum over the intermediate state $|x\rangle$. Assuming that the hole in the initial state is at the highest valence-band LL we obtain

$$W_n^{(1)} \propto \sum_{m,l} V^{e\text{-}h}_{n+m+l,m,0,l} \langle f(\mathrm{SU}_n)|a^\dagger_{n+m+l} b_0 a_m a_l|i\rangle / [n\hbar\omega_c^e + m(\hbar\omega_c^e + \hbar\omega_c^h)], \tag{11}$$

$$W_n^{(2)} \propto [(1-\nu_0/2)+\nu_0/2] \times \sum_{m,l} V^{e\text{-}e}_{n+m+l,0,m,l} \langle f(\mathrm{SU}_n)|a^\dagger_{n+m+l} b_0 a_m a_l|i\rangle / n\hbar\omega_c^e. \tag{12}$$

Note, that the two terms of Eq. (10) give complementary contributions, proportional to $(1-\nu_0/2)$ and $\nu_0/2$, where ν_0 is the lowest LL filling. Substituting $V^{e\text{-}h}_{i,j,k,l} = -V^{e\text{-}e}_{i,k,j,l}$ we finally get

$$W_n \propto \sum_{m,l} V^{e\text{-}e}_{n+m+l,0,m,l} \langle f(\mathrm{SU}_n)|a^\dagger_{n+m+l} b_0 a_m a_l|i\rangle \times \left[\frac{1}{n\hbar\omega_c^e} - \frac{1}{n\hbar\omega_c^e + m(\hbar\omega_c^e + \hbar\omega_c^h)} \right]. \tag{13}$$

This result coincides with Eq. (7), except for the approximated form of the denominator.

The derivation of Eq. (13) enables us to trace the physical meaning of the indexes in the matrix element $\langle f(\mathrm{SU}_n)|a^\dagger_{n+ml} b_0 a_m a_l|i\rangle$: it is the electron from LL_m that recombines with the valence-band hole. This process is mediated by the excitation of another electron from LL_l to LL_{n+m+l}. We also recover the cancellation of the two terms in the square brackets at $m=0$. We note that the two terms in the square brackets of Eq. (13) originate from $W_n^{(1)}$ and $W_n^{(2)}$. Thus the vanishing of W_n is due to the fact that these two transition amplitudes exactly cancel each other.

We may understand the physical reason for the suppression of the shakeup intensity when the recombining electron is from the lowest LL $(m=0)$ by the following intuitive argument. Let us view the hole as a lack of an electron in the valence band.[7–9] In this picture, the recombining electron descends from the lowest LL in the conduction band to the highest LL in the valence band, retaining its wave function. This process does not create any perturbation of the charge distribution in the 2DEG, and thus does not result in shakeup. On the other hand, if the electron recombines from another LL, then the charge distribution is suddenly perturbed, and the shakeup excitation may be created.

V. THE SU_0 LINE

It is now straightforward to understand the nature of the SU_0 line and the reason for its giant intensity at $\nu>2$.[12] For simplicity we shall discuss the case of $4>\nu>2$, were $m=1$. The SU_0 process can be viewed as a recombination of an electron from LL_1 with the valence-band hole and an excitation of another electron across the cyclotron gap. The resulting photon energy is $E_{\mathrm{ph}} = E_{\mathrm{gap}} + \frac{1}{2}\hbar(\omega_c^e + \omega_c^h) - \Delta E$, where $\Delta E < \hbar\omega_c^e$ is a correction due to Coulomb interaction. Substituting E_{ph} in Eq. (7) one can easily see that the first term in the square brackets is proportional to $1/\Delta E$, while the second term is much smaller, proportional to $1/(\hbar\omega_c^e + \hbar\omega_c^h)$. (One of the relevant processes is schematically depicted in the inset of Fig. 3.) The probability of the SU_0 process is therefore proportional to ΔE^{-2}. Similarly, the probability of SU_1 processes is proportional to $(\hbar\omega_c^e)^{-2}$. Thus, the SU_0 line is enhanced due to the resonant denominator by a factor $\sim[(\hbar\omega_c^e)/\Delta E]^2$ with respect to the nonresonant SU_1 process. Experimentally, ΔE is of the order of the energy splitting between LL_0 and SU_0 in the photoluminescence spectra. For $\Delta E \sim 0.3\hbar\omega_c^e$ this factor gives an order of magnitude enhancement of SU_0 with respect to SU_1. The measured ratio of SU_0 and SU_1 intensities is in reasonable agreement with the above estimation.

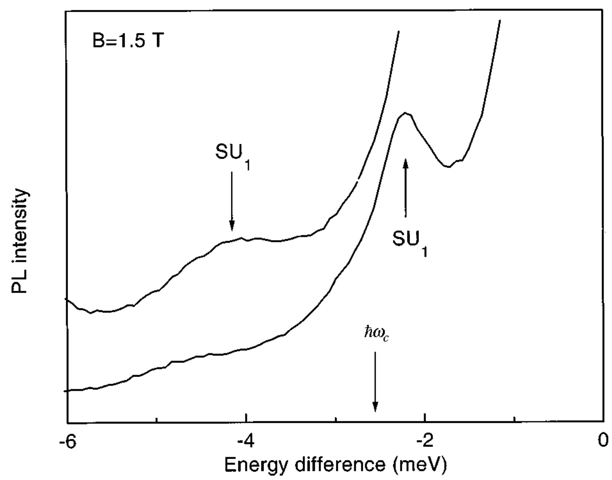

FIG. 5. The photoluminescence spectra of the lower-density sample around the SU_1 energy at 1.5 T for two gate voltages. The energy is measured from the main photoluminescence line. The upper and lower curves correspond to the metallic and insulating states of the 2DEG, respectively.

It is interesting to compare the SU_0 line shape at 4.2 and 1.5 K (Fig. 3). It can be seen that the low-energy part of the line exhibits a strong enhancement with decreasing temperature, which we do not understand. We note, however, that the characteristic temperature at which this enhancement develops is very small, $\lesssim 0.5$ meV, suggesting that it is related to a spin splitting or to some many-body effect.

VI. THE MANY-BODY NATURE OF THE SHAKEUP EXCITATIONS

Let us discuss now the nature of the excitations of the 2DEG, involved in the shakeup processes. We have shown that at $\nu>2$ the shaken electron is excited from LL_l to LL_{n+m+l}, creating an excitation with energy $\sim(n+m)\hbar\omega_c^e$, where $m>0$. In particular, the excitations created during SU_0, SU_1, and SU_2 processes at $4>\nu>2$ have energies of $\sim\hbar\omega_c^e$, $\sim 2\hbar\omega_c^e$, and $\sim 3\hbar\omega_c^e$, respectively. However, Fig 2(b) clearly shows that the energy of the excitation involved in each SU_n process is larger than $(n+1)\hbar\omega_c^e$. This excess energy was explained as being due to the collective nature of the magnetoplasmon.[2] Examining the data in Fig. 2(b) we can see that the excess energy is almost independent of the shakeup number n. This finding is rather surprising in view of the different dispersions of the various magnetoplasmons.[5,6] A weighted average of the magnetoplasmons dispersion curves should be done to check the consistency of our results with the theoretical calculations. It should also be noted that the final state of the recombination process contains not simply a magnetoplasmon, but rather two quasiholes and an electron, for which a mutual three-body interaction might be important.

To prove that the excess energy is indeed due to many-body interactions, we experimentally realized a situation where these interactions are absent. This is done by applying a gate voltage, causing the electrons in the 2DEG to become localized. We have previously shown that at this insulating state the photoluminescence becomes excitonic, consisting of a neutral and a negatively charged exciton line.[10] Applying a magnetic field, one observes shakeup lines, associated with the negatively charged exciton: when one electron in this complex recombines with the hole, the remaining electron is excited to a higher LL. This excitation is of a *single particle*, and therefore the shakeup lines should appear at an energy $n\hbar\omega_c^e$ below the charged exciton line.[13] Thus, by varying the gate voltage we should be able to observe the change in the nature of the shakeup processes, from being due to a single particle to a collective excitation.

Following the evolution of the SU_1 line with gate voltage at $B=1.5$ T we observe clear changes in its energy and lineshape (Fig. 5). The energy drops from $\approx 1.5\hbar\omega_c^e$ for a metallic 2DEG to $\approx\hbar\omega_c^e$ for a negatively charged exciton, implying that the excess energy indeed vanishes. The line in the metallic state is much broader, reflecting the excitation dispersion. One can, therefore, conclude that the many-body nature of the shakeup excitation is indeed manifested in the shape and energy of the shakeup lines.

VII. SUMMARY

In conclusion, we have presented a coherent picture of the shakeup processes in a high-mobility 2DEG. We have observed and explained the suppression of the shakeup lines at electron filling factor $\nu<2$. The same considerations helped us to clarify the origin of the giant SU_0 line. We have proved the collective nature of the excitation involved in the shakeup process, but a detailed theory, which would relate the shakeup energies to the theoretical magnetoplasmon dispersion curves, is still needed.

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