Shake-up Processes in Intersubband Magneto-photoabsorption of a Two-Dimensional Electron Gas

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I theoretically study shake-up processes in photoabsorption of an interacting low-density two-dimensional electron gas (2DEG) in magnetic fields. Such processes, in which an incident photon creates an electron-hole pair and simultaneously excites one electron to one of the higher Landau levels, were observed experimentally [D.R. Yakovlev et al., Phys. Rev. Lett. 79, 3974 (1997)] and were called combined exciton-cyclotron resonance (ExCR). The recently developed theory of ExCR [A.B. Dzyubenko, Phys. Rev. B 64, 241101 (2001)] allows for a consistent treatment of the Coulomb correlations, establishes the exact ExCR selection rules, and predicts the high field features of ExCR. In this work, I generalize the existing theory of high-field ExCR in the 2DEG to the case when the hole is excited to higher hole Landau levels.

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I. INTRODUCTION

Correlation effects in a two-dimensional electron gas (2DEG) in magnetic fields lead to a number of spectacular phenomena like the Fractional Quantum Hall Effect and Wigner crystallization. Photoluminescence (PL) spectroscopy of the 2DEG in a perpendicular magnetic field proved to be an effective tool for studying few- and many-body correlation effects. An interesting optical manifestation of many-body effects in an interacting 2DEG are shake-up processes in magneto-PL: After the recombination of the electron-hole (e-h) pair, one electron is excited to one of the higher Landau levels \( n_l \). A closely related phenomenon, combined exciton-cyclotron resonance (ExCR), was also identified in low-density 2DEG systems: Here, an incident photon creates an electron-hole pair and simultaneously excites one electron to one of the higher Landau levels \( n_l \). ExCR may be considered to be a shake-up process in magneto-photoabsorption of the 2DEG or, a radiative Auger process as well. These phenomena and the relation between them remain only partially understood [1,2,3,4].

In the extreme magnetic quantum limit, when electrons occupy the lowest spin-polarized zero Landau level with filling factor \( n_e = 2\pi l_B^2 n_e \ll 1 \), ExCR can be considered to be a three-particle resonance \( e_0^+ + \text{photon} \to 2e^- h \), involving a charged system of two electrons and one hole, \( 2e^- h \), in the final state. In this limit, it turned out possible to develop a theory of ExCR with a consistent treatment of the Coulomb interparticle correlations [4]. Also, general and exact ExCR selection rules, which follow from the existing symmetries, magnetic translations and rotations about the magnetic field axis, were found. This allows one to establish the characteristic features of the high-field ExCR; in particular, the double-peak structure of the transitions to the first electron Landau level was predicted. Some experimental indications of the double-peak structure of the ExCR line were reported recently [5].

Magneto-PL spectroscopy proved very effective for conduction band electrons and is able to provide a detailed information about the rich spectrum of electron Landau levels (LL’s) and the various fine structures associated with electron correlation effects (see, e.g., [5] and more recent experimental work [6,7,8] and references therein). On the other hand, magneto-spectroscopy of valence band holes is less effective and magneto-PL spectra of quantum well (QW) samples containing a two-dimensional hole gas (2DHG) are often featureless and are characterized by broad lines, associated with the Zeeman split levels. This is mainly because of a large difference in electron and hole effective masses. For example, in GaAs QW’s the electron and hole cyclotron energies, are \( \hbar \omega_{ce}/B = 1.7 \text{ meV/T} \) and \( \hbar \omega_{ch}/B = 0.2 \text{ meV/T} \), respectively, and differ by nearly an order of magnitude [9]. Recently, however, by examining the low energy tail of the magneto-PL spectrum of a low-density 2DHG Glasberg et al. [10] succeeded in resolving several groups of recombination lines, each consisting of several equidistant peaks directly related to the valence band LL’s (see also [10,11]). In particular, the shake-up recombination lines of the positively charged exciton, \( X^+ \) were observed.

Recent progress in spectroscopy of valence band holes in quasi-2D QW’s makes it interesting to theoretically investigate correlation effects in states in which the valence band hole is present in higher hole LL’s. In this work, I study ExCR transitions in the 2DEG in which the hole – in the presence of excess electrons – are excited to higher hole LL’s. The theory predicts the shape and fine structure of the high-energy tail of the main magneto-absorption peak of the 2DEG.
II. Theory

I study interband transitions in the 2DEG from spin-polarized zero electron LL \( n = 0 \uparrow \), \( e^{0}_\uparrow \) + photon \( \rightarrow \) 2e-h to the final three-particle 2e-h states that belong to the first hole LL, while electrons still reside in their zero LL’s; such transitions will be called hole-ExCR (ExCR\(_h\)). The classification of states according to the electron and hole LL’s is valid in sufficiently strong magnetic fields \( B \) such that

\[
\hbar \omega_{ee}, \hbar \omega_{ch} > E_0 = \sqrt{\frac{\pi}{2}} \frac{e^2}{\varepsilon d_B}.
\]

Here \( l_B = (\hbar c/eB)^{1/2} \) is the magnetic length and \( E_0 \) is the characteristic energy of the Coulomb interactions. The 2e-h states can be obtained in this regime as an expansion in electron and hole LL’s. The heavy holes are described in this work in the effective mass approximation and the states of light holes are neglected. The unitary transformations that allow one to construct a complete orthonormal basis set of charged e-h states in \( B \) compatible with both axial and translational symmetries and the details of the matrix elements calculations have been described in detail elsewhere [12, 13, 14]. This procedure allows one to obtain the spectra of the 2e-h states in higher hole LL’s with a consistent treatment of the Coulomb interactions. Charged 2e-h states form families of degenerate states; each family is labeled by the index \( \nu \) that plays a role of the principal quantum number and can be discrete (bound states) or continuous (unbound states forming a continuum) [12, 14]. There is a macroscopic number of degenerate states in each family labeled by the discrete exact oscillator quantum number \( k = 0, 1, \ldots \). This quantum number is associated with magnetic translations \( A_s, A_h \) and physically describes the position of the center of the “cyclotron” orbit of the composite charged complex in \( B \). Each family starts with its Parent State \( |\Psi_{k=0,M_s,S_s,s_i}^{\nu}\rangle \) that has \( k = 0 \) (rotates about the origin) and has the largest possible in the family value of the total angular momentum projection \( M_z \); it is this value that enters into the optical selection [14]. In addition, the three-particle states are characterized by the total spin of two electrons, either \( S_e = 0 \) (electron spin-singlet states, \( s \)) or \( S_e = 1 \) (electron spin-triplet states, \( t \)) and by the spin state of the heavy hole \( S_h = 3/2, S_{hz} = \pm 3/2 \).

The exact optical selection rules for ExCR can be derived as follows: Interband transitions with e-h pair creation can be described by the luminescence operator \( \hat{L}_{PL} = p_{\nu} \int dr \hat{\Psi}_{\nu}^\dagger(r) \hat{\Psi}_{\nu}(r) \), where \( p_{\nu} \) is the interband momentum matrix element. When an e-h pair is photogenerated in the presence of the low-density 2DEG in the 0-th LL, the dipole transition matrix element can be written as

\[
D(\nu) = \langle \Psi_{M_s,S_s,S_t,\nu}\vert \hat{L}_{PL}\vert e^{0}_\uparrow \rangle,
\]

where the final state three-particle correlations are only taken into account. The combination of the two exact dipole selection rules, (i) conservation of the oscillator quantum number \( \Delta k = 0 \) (the centers-of-rotation of charged complexes in the initial and final states is conserved) and (ii) no change in the total angular momentum \( \Delta M_z = 0 \) for the envelope functions, leads to a very simple but powerful result: \( D(\nu) \sim \delta_{n=0,M_z} \), where \( M_z \) is the angular momentum projection of the Parent State in the \( \nu \)-th family. Therefore, in the ExCR processes involving electrons from the 0-th LL, the achievable final 2e-h states must have \( M_z = 0 \) and may belong to different final LL’s. If the 2DEG is spin-up \( \uparrow \) polarized, the photon of \( \sigma^+ (\sigma^-) \) circular polarization produces the electron singlet (triplet) final states (see Fig. 1).

III. Results and Discussion

The considered ExCR absorption processes involve one conduction band electron \( e^{0}_\uparrow \) (the initial state) and charged three-particle 2e-h final states \( \vert \Psi_{M_s,s(t)\nu}\rangle \) in the electron (a) spin-singlet, \( s \), and (b) spin-triplet, \( t \), states (see Figs. 1, 2). In the states \( \vert \Psi_{M_s,s(t)\nu}\rangle \) all three particles may be bound (thus forming charged excitons, or trions, \( X^- \) or may belong to the continuum (neutral exciton \( X \) plus one electron in a scattering state). Here and in what follows the hole spin quantum numbers are suppressed for brevity.

The allowed ExCR transitions to the first hole LL
and the calculated final singlet and triplet states are schematically shown in Fig. 2. The shaded areas of width 0.57$E_0$ in Fig. 2 depict the three-particle continuum that corresponds to the motion of the bound neutral $e$-$h$ pair, a magnetoexciton $X_{01}$ formed by the electron $e$ in the zero LL and the hole $h$ in the first LL; the second electron is detached from $X_{01}$ (is in a scattering state in the zero LL). The lower continuum edge lies at the $X_{01}$ ground state energy $-0.574E_0$, which, for the isolated neutral magnetoexciton, is achieved at a finite center-of-mass momentum $K$. As a result, the density of $X_{01}$ states at this energy has the inverse square-root van Hove singularity typical for 2D excitations. This may lead to peculiarities in the $e^{-}e^{-}$ scattering on the neutral exciton $X_{01}$, in particular, one might expect formation of quasibound three-particle states (resonances). One such ExCR-active resonance (see below) lying within the three-particle continuum and denoted $X_{s01}^*$ is shown in Fig. 2. Two other open dots below the lower continuum edge in Fig. 2 represent truly bound three-particle states, electron spin-triplet $X_{t01}$ and electron spin-singlet trions $X_{s01}$. The binding energies of the singlet $X_{s01}$ and triplet $X_{t01}$ states are, respectively, 0.009$E_0$ and 0.024$E_0$. Note that there are many other low-lying triplet $X_{t01}$ and singlet $X_{s01}$ bound states of negatively charged magnetoexcitons associated with the first hole LL (not shown). The states only depicted in Fig. 2 all have $M_z = 0$ and, according to the ExCR selection rule $D(\nu) \sim \delta_{\nu=0,M_z}$, are ExCR-active (are the final states in the ExCR transitions). We conclude that the ExCR transitions in 2DEG to the first hole LL can terminate both in the bound states of charged magnetoexcitons, $e_0^- + \nu$-photon $\rightarrow X_{s01}$, and in the continuum. This is in contrast to the situation with transitions to the first electron LL, when transitions to the continuum are only allowed 

The calculated dipole matrix elements and energies of transitions in two circular polarizations $\sigma^+$ and $\sigma^-$ that terminate, respectively, in the final singlet $|\Psi_{s01}^{(01)}\rangle$ and triplet $|\Psi_{s01}^{(01)}\rangle$ states in the zero electron and first hole LL’s, (01), are shown in Fig. 2. These hole-ExCR transitions require the extra photon energy $\sim \hbar \omega_{ch}$ relative to the fundamental band-gap absorption $E_{\text{gap}}(B)$ with final states in the lowest LL’s. Also, the corresponding Zeeman energies $\mu_B(g_e S_{er} + g_h S_{eh})B \sim B$ must be added to the Coulomb interaction energies $\sim B^{1/2}$ that are only shown in Fig. 3. Because of the small binding energies of the trions $X_{s01}$ and $X_{t01}$ in the first hole LL, transitions to these states merge, in the presence of moderate broadening, with the strong transitions that terminate near the lower continuum edge (transitions 1 and 2 in Figs. 2 and 3); these transitions dominate the hole-ExCR spectra. The present theory predicts in high fields another strong feature, the second higher-lying peak in the hole-ExCR that can only be observed in the $\sigma^+$ polarization. This polarization dependence is due to different $e^{-}e^{-}$ correlations in the final singlet ($\sigma^+$ polarization) and triplet ($\sigma^-$ polarization) $2e^-h$ states: the final singlet $2e^-h$ states are characterized by stronger $e^{-}e^{-}$ repulsion. The second ExCR peak may be associated with a formation of a quasi-bound three-particle electron magnetoexciton state (resonance) $X_{s01}^*$ within the three-particle continuum. This is because the amplitude of finding all three particles in the same region of real space is large

![FIG. 2: Schematic drawing of the hole-ExCR optical transitions in the low-density 2DEG from spin-polarized $n = 0 \uparrow$ electron LL to the final three-particle $2e^-h$ states in two circular polarizations $\sigma^\pm$ (the hole is in its first LL). Open dots depict three-particle bound states of charged magnetoexcitons. The shaded area is the three-particle continuum. See also Fig. 3.](image)

![FIG. 3: Energies and dipole matrix elements of the hole-ExCR ($\text{ExCR}_h$) transitions from the spin-polarized $n = 0 \uparrow$ LL to the first hole LL in two circular polarizations $\sigma^\pm$. The representative case $E_0 = \hbar \omega_{ch}$ is shown. Spectra have been convoluted with a Gaussian of the 0.015$E_0$. Labeling of the peaks is explained in Fig. 2. The spin Zeeman energies are not included.](image)
for a well-defined resonance, which may lead to large optical oscillator strengths. The existence of the $2e-h$ resonances is physically plausible because of the 2D van Hove singularity in the $X_{10}$ density of states. Another well-developed Fano-resonances were revealed recently\cite{Dzyubenko1992} in the spectra of intraband internal $X^-$ transitions and in interband ExCR transitions to the first electron LL\cite{Dzyubenko1991}.

The present theory shows that the main hole-ExCR peaks have intrinsic finite linewidths, in high fields $\sim 0.1E_0$ and have asymmetric lineshapes with high-energy tails. It should also be noted that all ExCR transitions in 2DEG are only because of electron LL mixing\cite{Dzyubenko1991} and, therefore, the hole-ExCR transitions are suppressed in strong fields as $\nu_\alpha|D|^2 \sim n_eI_{D0}^2(E_0/\hbar\omega_{ce})^2 \sim B^{-2}$. It is interesting to note here that very similar final states to those in interband hole-ExCR transitions in 2DEG to higher hole LL’s may also be reached by internal intraband excitations\cite{Dzyubenko1992} of negatively charged excitons $X^-$ with transition terminating in the states belonging to higher hole LL’s.

It is important to note here also that while shake-up (ExCR) processes in magneto-photoabsorption of the low-density 2DEG are allowed, the exact selection rules\cite{Dzyubenko1991} prohibit shake-up processes in magneto-PL of isolated negative $X^-$ and positive $X^+$ charged trions. Common experimental observations in the dilute limit of the shake-up processes\cite{Dzyubenko1991} and magneto-PL of the “dark” triplet $X^-$ states (see\cite{Sanvitto2002} and references therein) may be interpreted as an indication toward the relevance of the scattering by disorder and/or the remaining 2DEG (for $X^-$) or 2DHG ($X^+$).

IV. SUMMARY

I have theoretically considered combined hole-ExCR in a low-density 2DEG, a resonance in the 2DEG photoabsorption in which the hole is excited to higher hole Landau levels. This resonance may be observed in high magnetic fields as a fine structure in the high-energy tail of the main magnetoabsorption peak of the 2DEG. It has been shown, in particular, that the high-field hole-ExCR has different absorption patterns in two different circular polarizations $\sigma^\pm$, which may be useful for magneto-optical studies of electron-hole correlations in quantum wells in strong magnetic fields.

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