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Magneto-Spectroscopy of Two-Dimensional Systems: Many- and Few-Body Effects

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We present a classification of states and exact optical selection rules for charged electron–hole (e-h) complexes in magnetic fields that follow from magnetic translations and axial symmetry. A possibility to observe photoluminescence of dark X^- states in angle-resolved experiments is discussed. The effect of excess electrons on internal transitions of negatively charged excitons X^- in GaAs quantum wells is studied theoretically and experimentally (by optically detected resonance (ODR) spectroscopy). An experimentally observed blue shift with excess electron density is explained in terms of collective excitations—magnetoplasmons bound to a mobile valence band hole.

KEY WORDS: quantum wells; magneto-optical properties; magnetic translational invariance.

1. INTRODUCTION

Spin-singlet and spin-triplet negatively charged excitons, or trions, X^- are observed in magneto-optical spectra of a low-density two-dimensional electron gas (2DEG) (see, e.g., [1–10] and references therein) and have been the subject of many theoretical studies (e.g., [11–16] and references therein). The negatively charged exciton is often considered to be the semiconductor analog of the negatively charged hydrogen ion (H^-) of atomic physics, which provides a central example of the role of electron–electron (e-e) correlations in determining the spectra of bound few-particle states. In addition, these charged complexes in quantum well (QW) structures offer opportunities for exploring new physics relative to H^-: (1) the positively charged particles in semiconductors (holes) have a mass comparable to the electron mass; and (2) in QWs the density of excess electrons can be controlled and varied. At zero field, the X^- -feature at low electron densities evolves into the Fermi-edge singularity of the electron–hole (e-h) plasma with increasing density; the density at which the crossover takes place depends on the inherent disorder in the sample [2,4,6,9]. For samples in which the electrons and holes are confined in the same spatial region, with increasing magnetic field the magneto-photoluminescence (PL) or magnetoabsorption changes rather abruptly at Landau level (LL) filling factor $\nu = 2$ from LL to LL-like transitions that are linear in B ($\nu > 2$) to exciton-like behavior ($\nu < 2$) irrespective of the electron density [4,9,17]. The nature of the "exciton-like" states at high fields and at high electron densities is still not clear. A full appreciation of this complex many-body system depends on first understanding the behavior of neutral and negatively charged exciton systems in the presence of a low density of excess electrons. Theoretically, a three-particle charged hydrogenic problem in a magnetic field with finite masses of all particles is of considerable interest. A symmetry associated with the free center-of-mass motion (magnetic translational invariance) leads to a new, exact electric-dipole selection rule that imposes severe limitations on interband PL transitions of isolated X^- complexes [13,16]. It also prohibits [13] certain bound-to-bound internal intraband

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transitions between families of X^- states belonging to different LLs. In particular, the X^--singlet and -triplet bound-to-bound transitions that dominate [18,31] the spectra of D^- (two electrons bound to a charged donor) are strictly forbidden for X^-; the selection rule permits only bound-to-continuum transitions to the first electron LL that gain strength with increasing magnetic field [13]. Internal exciton transitions (IETs) probe directly the ground and excited states and yield important insight into their properties [13,19]. The IETs thus offer an additional experimental tool for probing the excitonic state in the dilute situation and its evolution with excess electron density and magnetic field.

The remainder of the paper is structured as follows: In Section 2, we discuss the classification of states and present an outline of the relevant theory of the internal transitions of negatively charged excitons. In Section 3, we discuss the selection rules for interband transitions, their relationship to the "hidden symmetry" in e-h systems, and present some recent work on the angular dependence of dark states in magneto-PL. We follow this by a brief description of the experimental technique and samples. In Section 5, we present results of optically detected resonance (ODR) experiments, analysis and comparison with theory, initially on negatively charged excitons followed by the effects of excess electrons in the QWs. Finally, we summarize and conclude.

2. THEORY

The theory of charged quasi-2D excitons in magnetic fields has been developed in a number of papers [11–16]. In the limit of strong magnetic field, there exists only one bound triplet X^- state in the strictly-2D system in the zero LL; there are no bound singlet X^- states in this limit [11,12]. At zero magnetic field, on the other hand, it is the singlet X^- state that is bound in 2D and in 3D systems. In quasi-2D systems, therefore, a singlet–triplet crossing should occur at finite magnetic fields. The values of the magnetic field at which the crossing occurs turn out to be very sensitive to the particulars of the system such as the electron and hole effective masses, the width and the depth of the QW, and to the approximations made [12,15].

Considerations of neutral magnetoexcitons based on an exact symmetry, magnetic translations, is now a standard treatment [20]. The importance of magnetic translations for classification of states of charged e-h complexes and for deriving exact and surprisingly simple optical selection rules was revealed only recently [13,16]. For a system of charged interacting particles in a uniform magnetic field $\mathbf{B} = (0, 0, B)$, the operator of magnetic translations is given by $\hat{\mathbf{K}} = \Sigma_j(\hat{\boldsymbol{\pi}}_j - \frac{e_j}{c}\mathbf{r}_j \times \mathbf{B})$, where $\hat{\boldsymbol{\pi}}_j = -i\hbar\boldsymbol{\nabla}_j - \frac{e_j}{c}\mathbf{A}(\mathbf{r}_j)$ are the kinematic momentum operators of individual particles (see, e.g, [20–22]). The operator $\hat{\mathbf{K}}$ commutes with the Hamiltonian of the system, $[\hat{\mathbf{K}}, H] = 0$, i.e., it is an exact integral of the motion. For a charged system with the net charge $Q \equiv \Sigma_j e_j \neq 0$ its components commute as canonically conjugate operators $[\hat{K}_x, \hat{K}_y] = -i\frac{\hbar B}{c}Q$. The existence of two Hermitian operators, $\hat{K}_x$ and $\hat{K}_z$, which commute with the Hamiltonian but do not commute with each other, leads to a degeneracy, which, in this case, is the macroscopic Landau degeneracy in the position of the "orbit center." This is also closely connected with the fact that the group of magnetic translations is non-Abelian for charged systems with $Q \neq 0$. Also, the above commutation relation allows one to construct raising and lowering operators for the whole system: when the net charge is, for example, negative $Q < 0$ the properly normalized raising and lowering Bose ladder operators are, respectively, $\hat{k}_- = \alpha(\hat{K}_z - i\hat{K}_y)$ and $\hat{k}_+ = \alpha(\hat{K}_z + i\hat{K}_y)$. Here $\alpha = (c/2\hbar|Q|)^{1/2}$ is the normalization factor, so that $[\hat{k}_-, \hat{k}_+] = 1$.

It is very instructive to preserve both the translational and axial symmetry at the level of the Hamiltonian. This is achieved by choosing the symmetric gauge of the vector potential $\mathbf{A} = \frac{1}{2}\mathbf{B} \times \mathbf{r}$. This choice brings another exact integral of the motion, the total angular momentum projection with the operator $\hat{L}_z = \Sigma_j[\mathbf{r}_j \times (-i\boldsymbol{\nabla}_j)]_z$ and an integer eigenvalue, M_z. Because $[\hat{L}_z, \hat{\mathbf{K}}^2] = 0$, the exact eigenstates of the interacting system can be labeled simultaneously by M_z and by the oscillator quantum number k, which takes on integer nonnegative values $k = 0, 1, \ldots$; the eigenvalue of $\hat{\mathbf{K}}^2$ is $\alpha^2(2k + 1)$.

In order to illustrate this classification of states, we consider the eigenspectra of the X^--triplet states in the strictly-2D high-field limit in two lowest LLs (Fig. 1). We label the eigenstates by the total spin of two electrons $S_e = 1$ and by the orbital quantum numbers M_z and k. The latter characterizes the center of the cyclotron motion of the charged complex as a whole, and incorporates the Landau degeneracy of energy. The degenerate states that have different quantum numbers k comprise a family of states that starts with a Parent State that has $k = 0$ (roughly speaking, rotates about the origin) and a particular value of M_z, which for an interacting system can only be determined by solving the Schrödinger

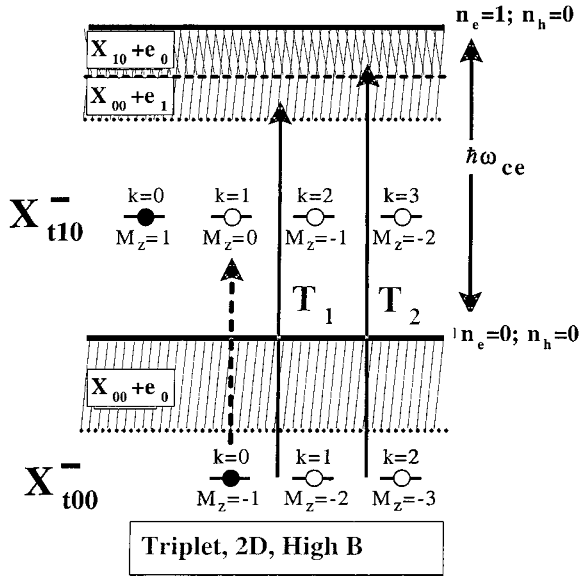

Fig. 1. Schematic energy level diagram of the X^- triplet in two lowest electron Landau levels in the strictly-2D system in the limit of strong magnetic fields after Ref. [13].

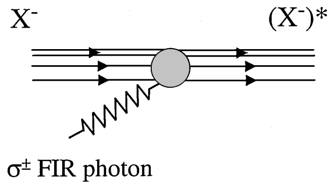

Fig. 2. A radiation process describing internal intraband transitions of a trion X^-. The final state $(X^-)^*$ may be bound or belong to the continuous sector of the $X + e^-$ eigenstates. The exact selection rules for the dipole-allowed transition are $\Delta k = 0$ and $\Delta M_z = +1$ for the σ^+-polarized photon [13].

equation. Importantly, because of the commutation relation $[\hat{L}_z, \hat{k}_-] = -\hat{k}_-$, an increase in k leads to a corresponding lowering of M_z. As a result, in each family of states the quantum numbers k and M_z are not independent (see Fig. 1). The same classification holds also for the unbound three-particle states $X + e^-$ (a neutral magnetoexciton X plus one electron in a scattering state) that form the continua below the free LLs. A more detailed theoretical description and the formalism that allows one to separate one center-of-mass degree of freedom while keeping intact both axial symmetry (rotations about the B-axis) and magnetic translations can be found in Refs. [13, 16]. Formally, fixing simultaneously M_z and k requires a proper summation of an infinite number of states of individual particles in given LLs. This leads to the appearance of new effective particles in magnetic field with modified interparticle interactions; also, in the Fock space of oscillator states, a new vacuum state is generated that turns out to be a two-mode squeezed old vacuum state, which has very interesting properties [16].

The fact that in each family of degenerate states the quantum numbers k and M_z are not independent represents a coupling of the center-of-mass and internal motions in a magnetic field. This plays a qualitatively important role for charged e-h complexes in magnetic fields and leads, in particular, to stringent limitations on allowed optical transitions [13]. This can be physically understood as follows: In the dipole approximation, when the photon momentum is neglected, the optical selection rule following from the translational invariance for a charged system in a magnetic field [13,21] is conservation of "the orbit center," $\Delta k = 0$. Fixing Δk, however, also fixes ΔM_z, so that the second selection rule—for M_z—cannot in general be satisfied [13].

As an important example, consider the exact optical selection rules for the dipole-allowed intraband internal X^- transitions in the σ^+ polarization, which are [13] $\Delta M_z = +1$ and $\Delta k = 0$ (Fig. 2). The combination of selection rules prohibits the bound-to-bound transition to the first electron LL (dashed line in Fig. 1). As a result, only the bound-to-continuum photoionizing transitions T_1 and T_2 to the edges of the two overlapping magnetoexciton (MX) continua in the first electron LL are allowed; these gain strength with increasing magnetic field. The same qualitative features hold also for the singlet and triplet X^- states that exist in quasi-2D QWs at finite magnetic fields. A comparison between the theory predictions for internal X^--singlet and -triplet transitions and the experimental results are given later in Section 5.

3. HOW DARK ARE "DARK" X^- STATES?

3.1. Magneto-PL Selection Rules

Magnetic translational invariance also has important consequences for magneto-PL of charged excitons $X^- \to e^- +$ photon. The combination of the exact selection rules for the envelope functions in this case is $\Delta M_z = 0$ and $\Delta k = 0$ and leads to a very simple but far-reaching result: For a family of X^- states for which the Parent State has the total angular momentum projection M_z, the electron in the final state can only belong [13] to the LL with the quantum number $n = M_z$ (Fig. 3). This means, in particular, that the triplet X^- state with $M_z = -1$ is dark in PL. Also,

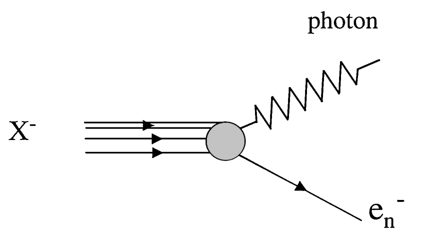

Fig. 3. An interband radiative process describing X^- magneto-photoluminescence in which the electron is left in the nth Landau level in the final state. The exact selection rule for the dipole-allowed transition is $n = M_z$, where M_z is the angular momentum projection of the Parent X^- state [13].

X^- shake-up processes [5] in which the electron is left in the various final states in different LLs are prohibited. These results follow from the axial and translational symmetries, and therefore they hold as long as these symmetries are preserved in the system. For example, they hold at finite magnetic fields, in realistic quasi-2D QWs, in a semiconductor with a complex valence band structure.

A closely connected process determined by the Coulomb interparticle interactions is "Combined Exciton-Cyclotron Resonance" (ExCR) [23]. It is the interband magnetoabsorption in the presence of the low-density 2DEG in which one electron is excited to a higher LLs; more exactly, the final state in ExCR (that may be bound) belongs to a higher LL. Considerations of magnetic translations allows one to establish exact ExCR selection rules and to predict a double-peak ExCR structure in high fields [24].

3.2. Relation to the "Hidden Symmetry"

Interestingly, there is another symmetry that also governs interband optical transitions of charged MXs but is operative under much more limited conditions. Both symmetries predict, in particular, that the ground X^--triplet state must be dark in PL. This other so-called hidden symmetry [25–28] is applicable to 2D symmetric e-h systems in the limit of strong magnetic fields, when no LL mixing is allowed. The requirement on the interaction potentials is that all are identical up to the sign: $U_{ee} = U_{hh} = -U_e$. In such systems the neutral MXs of zero total momentum $\mathbf{K} = 0$ form an ideal gas of noninteracting composite Bosons. This was first shown diagrammatically by Lerner and Lozovik [25] and later was established by direct quantum-mechanical considerations in a number of papers. A very straightforward way is to consider [26] the exact quantum equation of motion $[H_{\rm int}, Q_0] = -E_0 Q_0$, which involves the interaction Hamiltonian of the two-component e-h system in the extreme magnetic quantum limit $H_{\rm int}$, and the annihilation operator of a 2D MX of zero center-of-mass momentum $Q_0 = \Sigma_m a_m b_m$. Here a_m (b_m) is the electron (hole) annihilation operator in zero LL with the single-particle oscillator quantum number m, $E_0 = \sqrt{\frac{\pi}{2}}\frac{e^2}{\epsilon l_B}$ is the isolated MX binding energy, and $l_B = \sqrt{\hbar c/eB}$ is the magnetic length. Physically the above result means that the particles Q_0 form an *ideal* gas of composite Bosons that do not interact with each other or with other particles (electrons, holes, other excitons Q_k).

The relevance of this result for optics of 2D systems (both two-component electron–hole and one-component electron systems) in strong magnetic fields can be understood from considerations of the luminescence operator that describes annihilation of an e-h pair, $\hat{\mathcal{L}}_{\rm PL} = p_{\rm cv}\int d\mathbf{r}\,\hat{\mathbf{\Psi}}_{\rm e}(\mathbf{r})\hat{\mathbf{\Psi}}_{\rm h}(\mathbf{r})$ where $p_{\rm cv}$ is the interband dipole transition matrix element. After projecting the operator $\hat{\mathcal{L}}_{\rm PL}$ onto zero LLs one obtains an interesting and important result, $\hat{\mathcal{L}}_{\rm PL} = p_{\rm cv} Q_0$, that shows that the PL operator $\hat{\mathcal{L}}_{\rm PL}$, up to some factor, coincides with the annihilation operator of the 2D neutral MX Q_0. Taking into account that the $\mathrm{K} = 0$ 2D MXs form an ideal gas in symmetric e-h systems [25,26] we arrive at the well-known result [27,28] that the PL emission from such systems consists of a single line at the energy of an isolated 2D neutral MX. Formally, this follows from the fact that the matrix elements of $\hat{\mathcal{L}}_{\rm PL}$ are nonzero only between the exact many-body states of the Hamiltonian $H_{\rm int}$ that differ in energy exactly by the isolated MX binding energy E_0. Physically, this result means that the PL is not sensitive to many-body correlations in strictly-2D symmetric systems in the strong magnetic field limit. In particular, when applied to the X^--triplet state that has energy $-1.043E_0$, which is lower than that of the neutral MX $-E_0$, the hidden symmetry prohibits [11] PL of the X^- triplet. Since the hidden symmetry is an approximate symmetry, it was expected that the X^- triplet in quasi-2D QWs at finite fields would have small but finite oscillator strength, which was "consistent" with the result of various numerical calculations (see, e.g., [12]). Somewhat later it became clear [13] that X^--triplet ground state is dark because of a more robust symmetry and that its finite oscillator strength is only due to breaking of this symmetry—by scattering and disorder in real samples or by not maintaining the magnetic translational invariance in theoretical considerations.

3.3. Angle-Resolved Spectroscopy

The above results hold, however, only for emission of light perpendicular to the QW. Importantly, because the translational invariance is broken along the growth direction in quasi-2D systems, all neutral excitons within the light cone, i.e., with momenta $|\mathbf{K}| < K_0 = nE_{\text{gap}}/\hbar c$, are optically active [29,30]; here n is the index of refraction; for GaAs $K_0 = 2.7 \times 10^5\ \text{cm}^{-1}$. Optically active excitons with $|\mathbf{K}| \neq 0$ emit light at finite angles relative to the normal of the 2D structure (see inset to Fig. 4). In the strong magnetic field limit, the PL operator describing such emission is $\hat{\mathcal{L}}_{\text{PL}}(\mathbf{q}) = p_{\text{cv}} \int d\mathbf{r} \exp(i\mathbf{q}\cdot\mathbf{r}) \hat{\Psi}_{\text{e}}(\mathbf{r}) \hat{\Psi}_{\text{e}}(\mathbf{r})$, where $\mathbf{q} = (\mathbf{K}, q_z)$ is the momentum of the 3D photon. Projecting this operator onto zero LLs we obtain $\hat{\mathcal{L}}_{\text{PL}}(\mathbf{q}) = p_{\text{cv}} Q_{\mathbf{K}}$, which means that now the operators of MXs with finite in-plane momenta $Q_{\mathbf{K}}$ are involved. Since finite momenta excitons $Q_{\mathbf{K}}$ do not form an ideal gas, the angle-resolved PL should therefore be sensitive to many-body correlations.

Here, as an important example, we consider the angle-resolved emission of the "dark" $M_z = -1$ X^--triplet state in the strictly-2D high-magnetic field limit. This state can participate in the emission of light, when the photon is allowed to carry away the angular momentum $m_z = -1$. Using the usual language of atomic physics, we will call such emission a *quadrupole* emission. The angle dependence of its intensity is given by $I_T(\Theta) \sim (K_0 a)^2 (1 + \cos^2\Theta)\sin^2\Theta$. Note that this holds in the absence of scattering (by disorder, 2DEG) in which case the emission is zero in the direction perpendicular to the QW: $I_T(\Theta = 0) = 0$ (see Fig. 4). This result is very sensitive to the various scattering processes and, for example, should not hold for *localized* trions. Higher multipole emission channels (corresponding to higher photon magnetic quantum numbers m_z and/or breaking of the $\Delta k = 0$ selection rule) are also open but are suppressed as higher powers of the dimensionless parameter $(K_0 a)^2$. Here a is the effective "radiation" size of the system, which is related to the geometric size of the e-h complex but, strictly speaking, differs from it. The X^--triplet effective size turns out to be surprisingly large $a = 4.1 l_B$ so that, for example, at $B = 10$ T the parameter $(K_0 a)^2 = 0.8$ and is not small. This means that the quadrupole X^-triplet emission is not expected to be very weak. Can this emission be observed experimentally? Note that the angle Θ in the above considerations is the angle *inside* a semiconductor QW structure. Because of a relatively high index of refraction of GaAs QWs and because of the complete internal reflection, the quadrupole X^--triplet emission should mainly propagate along the QW plane and come out from "the sides" of the sample. Observation of such an emission in the X^--triplet spectral range would be an indication of a relatively small effect of disorder and scattering. If, on the other hand, the angle-resolved X^--triplet emission has a maximum at $\Theta = 0$, this would mean that the dipole channel is open and that disorder and/or scattering by the 2DEG determine the optics of the X^--triplet ground state in real samples. Note that the "bright" singlet X^- state has $M_z = 0$ and participates in the usual dipole emission with the PL angular dependence $I_s(\Theta) \sim (1 + \cos^2\Theta)$. The singlet PL intensity $I_s(\Theta)$ does not contain the factor $(K_0 a)^2$ and has its maximum at $\Theta = 0$. In general, dark X^- states that have $M_z < 0$ (such states exist in higher LLs [16]) become optically active in higher multipole emission channels: The lowest multiplicity of an allowed PL from an X^- state with some fixed value of $M_z < 0$ is $|M_z| + 2$.

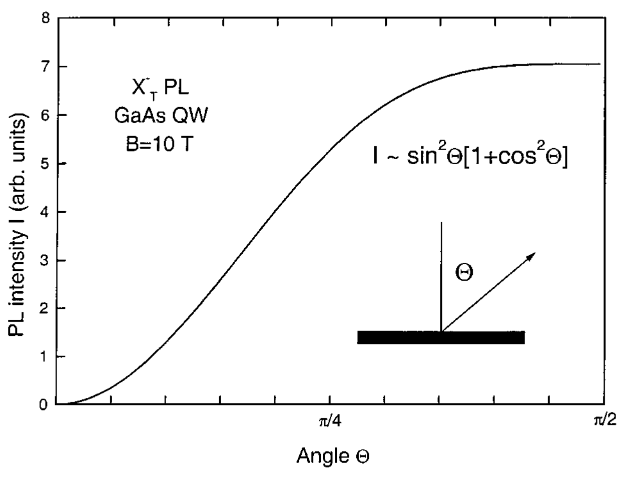

Fig. 4. Angular dependence of the quadrupole emission from the dark triplet X^- in a 2D system in the limit of strong magnetic fields. The inset shows the considered geometry.

4. EXPERIMENT AND SAMPLES

Several GaAs/AlGaAs multiple quantum well (MQW) samples were investigated by ODR spectroscopy. ODR spectroscopy is a highly sensitive technique in which the PL signal excited by a visible or near infrared laser is monitored, typically as a function of magnetic field, while the sample is simultaneously illuminated with a far infrared (FIR) laser beam. Resonant absorption of the FIR beam modulates the intensity of the PL. A particular PL feature is tracked by the spectrometer window as the magnetic field is scanned; changes in the strength of the PL that are synchronous with the chopped FIR beam are detected by a Si photodiode or a photomultiplier tube. Very weak absorption features can be detected under the proper conditions. In the present experiments electrons, holes, and excitons were continuously excited with the 632.8-nm line of a He–Ne laser coupled to the sample (at low temperature in the Faraday geometry at the field center of a 15/17 T superconducting magnet) via an optical fiber; PL was collected with a second fiber [19]. Results from five MBE-grown GaAs/$Al_{0.3}Ga_{0.7}As$ MQW samples are presented in the following sections. Samples 1 and 2 are nominally undoped with 20-nm GaAs wells and $Al_{0.3}Ga_{0.7}As$-barriers: sample 1–20 wells with 60-nm barriers; sample 2–10 wells with 20-nm barriers. Sample 3 also has 20-nm wells but is modulation δ-doped with Si in the centers of the 40-nm barriers at 2×10^{10} cm^{-2}, and there are 40 repetitions. Samples 4 and 5 have 24-nm wells and are Si-doped in the central third of the barriers at sheet densities of 8×10^{10} and 2.8×10^{11} cm^{-2}, respectively: sample 4 (sample 5) has 20 (10) wells with 48- (24-) nm barriers.

5. RESULTS AND DISCUSSION

5.1. Isolated X^-

Raw ODR data from samples 1 and 3 at several FIR laser photon energies taken while tracking the neutral heavy-hole exciton are shown in Fig. 5. Very similar, but negative-going features are observed when tracking X^-. A sharp, strong electron cyclotron resonance (e-CR) and several weaker features are apparent. Three features are attributed to X^- internal transitions (S_1, S_2, and T_1). The shoulder on the low-field side of e-CR, and most apparent at FIR photon energies of 10.53 and 6.73 meV, is ascribed to the dominant triplet ionizing transition T_1. The peak of this band occurs for transitions terminating near the edge of the continuum, and so the observed peak is shifted to higher energies than e-CR (lower fields) by an amount equal to the small triplet binding energy and there is a tail to higher energies (lower fields). The labeling for the singlet transitions S_1 and S_2 is analogous to that for the triplet in Fig. 1. The singlet binding energy at finite fields and finite confinement is significantly larger than that of the triplet and so the singlet features occur at substantially lower fields. Figure 6

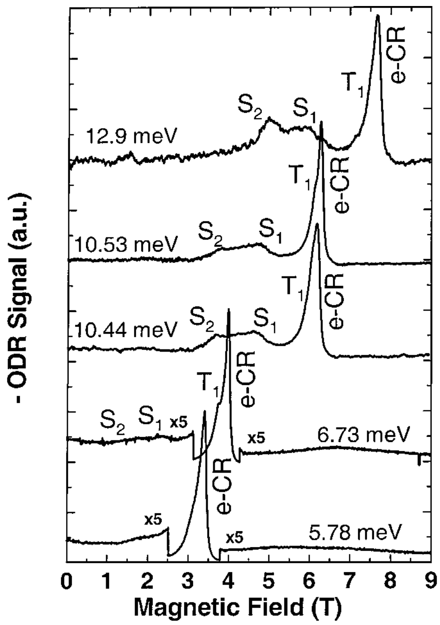

Fig. 5. Optically detected resonance spectra for sample 1 at five far infrared laser photon energies. The features labeled S_1, S_2, and T_1 are the singlet and triplet transitions of X^- discussed in the text. Data were obtained by tracking the neutral exciton.

shows a comparison of the ODR spectra for samples 1 and 3 taken at a FIR photon energy of 10.44 meV while tracking the X^- PL. For sample 3 (with a low density of excess electrons in the wells from the modulation doping) there is a dramatic increase in the relative strength of the features associated with the X^- internal transitions relative to that of e-CR. The weaker S_1 line in this sample is masked by the

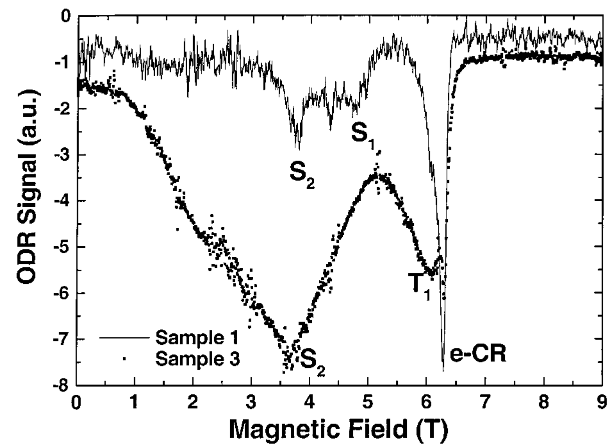

Fig. 6. Comparison of 4.5 K optically detected resonance spectra for samples 1 (solid line) and 3 (dots) at a far infrared laser photon energy of 10.44 meV. Data were obtained by tracking the X^- PL.

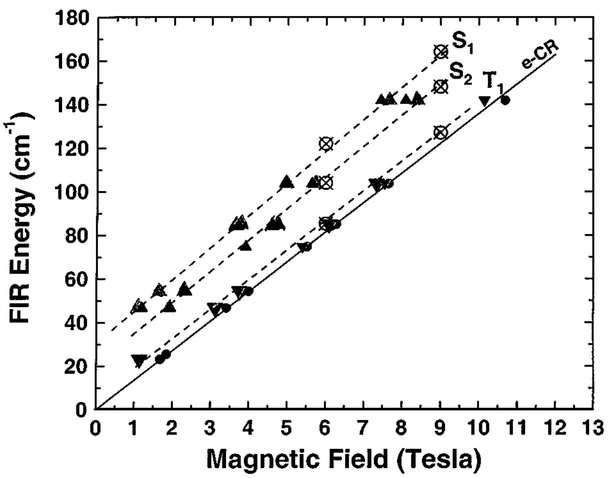

Fig. 7. Summary plot of internal singlet (S_1, S_2), triplet (T_1) transitions and comparison with numerical calculations (crossed circles) after Ref. [10].

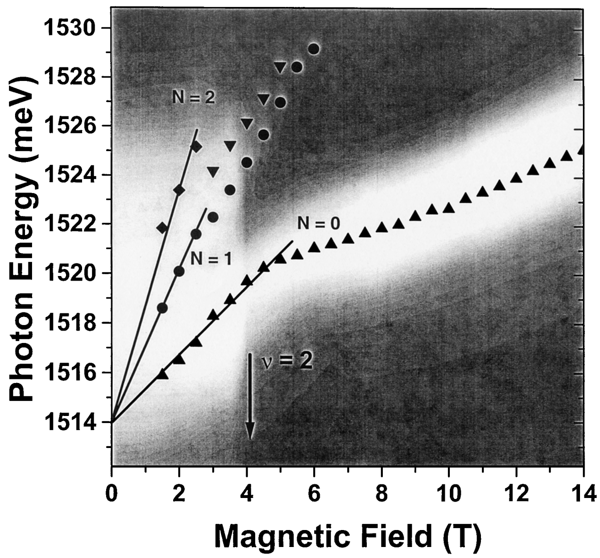

Fig. 8. Magneto-photoluminescence (PL) for a multiple quantum well sample having nominal electron density in the wells of $2.8 \times 10^{11}\mathrm{cm}^{-2}$ (actual density $2.4 \times 10^{11}\mathrm{cm}^{-2}$). The background is a grey scale representation of the intensity of the PL; white is the brightest PL. The straight lines are guides to the eye. The field position of filling factor $\nu = 2$ for a density of $2.4 \times 10^{11}\mathrm{cm}^{-2}$ is indicated.

tail of the triplet transition(s). However, studies of the temperature dependence (up to 20 K) of the ODR spectra for this sample reveal the S_1 band clearly at about 10 K. There is also evidence of the T_2 band in these data. This comparison lends support to the assignment of these features to internal transitions of X^-.

The most compelling evidence supporting this assignment, however, is provided by detailed numerical calculations of the positions of the singlet and triplet bands for 20-nm wells. Figure 7 shows a summary of the energy positions of these features for samples 1 and 2 vs. magnetic field compared with quantitative numerical calculations (see [10] for details) for a 20-nm well. There is excellent agreement between these calculations and the experimental results, which lends additional credence to and provides quantitative support for the assignment of the observed features.

5.2. Effects of Excess Electrons

Figure 8 shows magneto-PL data for sample 5. Overlaying grey-scale contour plot are data points indicating peak positions that were obtained by peak-fitting the individual magneto-PL spectra. The solid lines indicating LL to LL-like recombination are guides to the eye. Note the sharp demarcation between the linear behavior and the "exciton-like" behavior (nearly quadratic in magnetic field) near filling factor $\nu = 2$. This is characteristic of samples having electrons and holes localized in the same region along the growth direction. To explore further the effects of large densities of excess electrons and the difference in behavior of the magneto-PL at fields above and below $\nu = 2$, we have investigated two modulation-doped samples (samples 4 and 5) by ODR at a series of FIR photon energies such that the internal transitions occur at fields corresponding to both $\nu \geq 2$ and $\nu < 2$.

Figure 9a shows ODR spectra for sample 4 for several FIR laser photon energies. These data were obtained by tracking the main PL feature with magnetic field. The magnetic field corresponding to filling factor $\nu = 2$ occurs at $B = 1.66$ T for this sample. The sharp feature present in all traces is e-CR. Note that no feature is observed in any scan at a higher magnetic field than that of e-CR, in agreement with the selection rule [13], prohibiting bound-to-bound IETs of X^-. Two other lines are observed in the ODR spectra for high FIR photon energies. These features, which are blue-shifted from those observed in the undoped GaAs samples, are attributed to bands of ionizing singlet- (vertical arrows) and triplet-like (diagonal arrows) internal transitions of X^-. The resonant fields for both singlet- and triplet-like X^- transitions occur for $\nu < 2$ (*above* the field corresponding to $\nu = 2$). At lower FIR photon energies, the triplet feature remains strong, but the singlet feature weakens and is

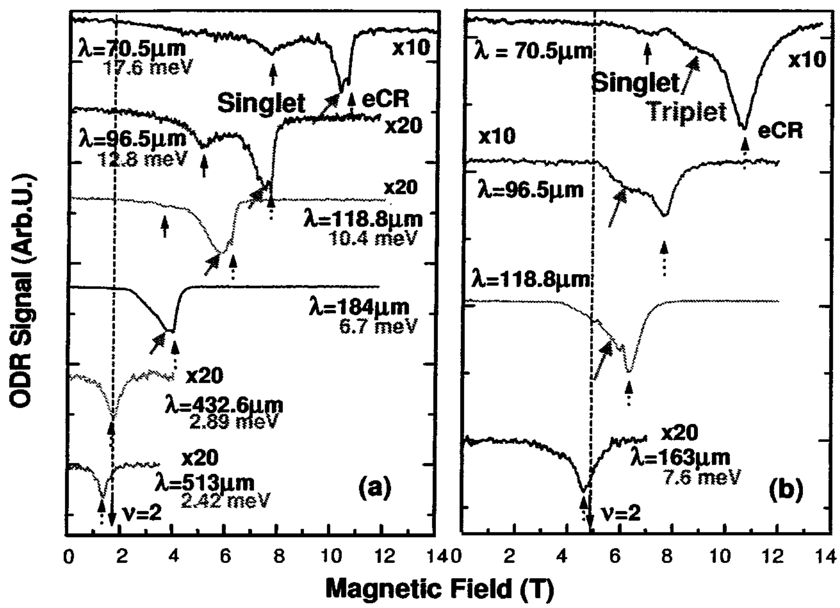

Fig. 9. Optically detected resonance scans for two modulation-doped multiple quantum well samples. (a) sample 4: $8 \times 10^{10}\mathrm{cm}^{-2}$, and (b) sample 5: $2.8 \times 10^{11}\mathrm{cm}^{-2}$ (nominal). Arrows indicate the singlet- and triplet-like transitions after Ref. [10].

not observable at 6.7 meV (the predicted field position corresponds to $\nu > 2$). For the heavily doped sample 5 these features become generally weaker and are further blue-shifted as shown in Fig. 9b. Note that when e-CR occurs at fields at or below that corresponding to $\nu = 2$ the line becomes symmetric and no evidence of the triplet-like or singlet-like transitions is seen in either sample. Figure 10 summarizes the measured positions of the singlet (sample 1) and singlet-like (samples 4 and 5) S_2 transitions and illustrates the observed blue shift. This demonstrates clearly that the transitions in the presence of many electrons are collective and the transition energies are clearly influenced substantially by the interaction.

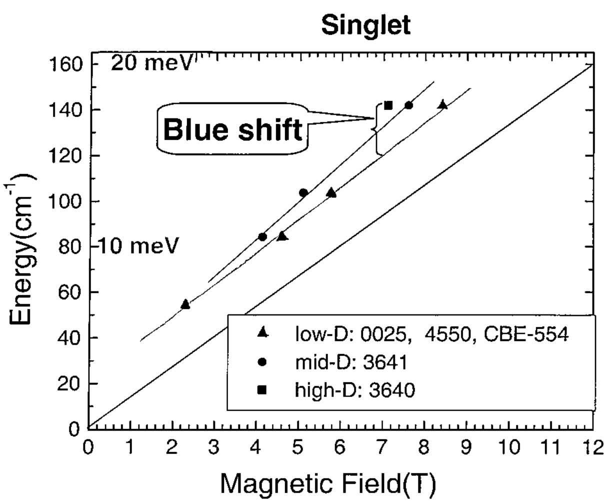

Fig. 10. Summary of the positions of the singlet and singlet-like S_2 transitions for several samples showing the blue shift.

In the presence of a large density of excess electrons, the picture of a screened X^- state is no longer applicable. The surprising robustness of the charged trions X^- in the magneto-PL spectra for $\nu < 2$ (as if they are embedded in the sea of electrons and barely feel them) can be understood to some extent by hidden symmetry arguments [17]. However, as we see from the above, no such exact compensation of the e-e and e-h interactions occurs in intraband transitions [10]. This can be qualitatively understood by considering intraband excitations from the ground state of the 2D system with integer filling of electron LLs $\nu = 1, 2$ containing a low-density gas of mobile valence band holes. The collective excitations correspond to transitions to the correlated e-h final state that can be considered as a positive trion X^+ that contains the conduction band hole in an otherwise filled zero LL. Similar ideas were proposed [31] and used earlier for a description of the D^--transitions [32,33] in the presence of excess electrons (for work on interband PL from the 2DEG in high fields see, e.g., [17,34,35]). Our calculations for 2D systems with integer-filling factors $\nu = 1, 2$ show that in the region of energies larger

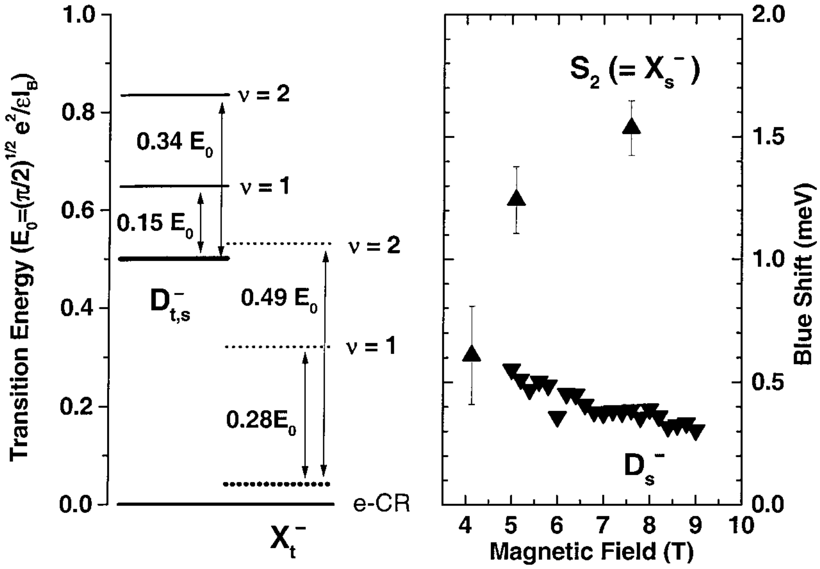

Fig. 11. Comparison of the blue shift for X^- and D^-. Left panel: theory for 2D high-field limit. Right panel: experiment. The data were taken for the singlet transition in both cases on modulation-doped samples with the same nominal electron density and approximately the same well-widths (20 nm for the D^- and 24 nm for the X^-) after Ref. [10].

than $\hbar\omega_c$ there is one prominent absorption peak. It corresponds to a magnetoplasmon bound to the mobile hole. These excitations resemble the magnetoplasma modes bound to the fixed donor ion D^+ in the presence of many electrons, but the magnetic translational invariance is broken for the latter. Energies of bound collective modes experience discontinuities at integer ν and increase with increasing ν, reflecting the enhanced contribution of the exchange-correlation effects and explaining the blue shift. As seen in Fig. 11 the measured blue shifts for the singlet X^- with the mobile hole are, larger than those for the D^- for fields above 5 T. This is in qualitative agreement with theory for the blue shift of the X^--triplet internal transition (see Fig. 11). The larger blue shift for the X^- compared to D^- results from the diminished negative contribution of the Coulomb e-h interaction to the final state energy for the mobile hole.

6. SUMMARY AND CONCLUSIONS

The present experimental observation and studies of internal transitions of X^- in GaAs QW structures as functions of excess electron density and magnetic field provide new insight and a deeper understanding of this complex system. At low excess electron densities, intraband triplet bound-to-bound transitions are absent and both singlet and triplet internal transition features appear as bands, with positions in excellent quantitative agreement with numerical calculations for the bound-to-continuum transitions. At higher excess electron densities $\nu > 2$, internal transitions are not observed, while for $\nu < 2$ internal transitions are observed, but they are blue-shifted in energy from their low-density counterparts. This work thus provides clear experimental verification of the predicted consequences of the magnetic translational symmetry [13] for charged electron–hole complexes, and also shows that the feature identified as X^- in interband measurements in high-density samples represents the collective response of a few-hole/many-electron system—a magnetoplasmon bound to a mobile valence band hole [10].

A possibility of probing few- and many-body correlations in 2D systems in high magnetic fields by angle-resolved PL has been suggested. It has been shown, in particular, that the "dark" X^- states become PL-active in the quadrupole emission, which is sensitive to disorder and X^- scattering. This deserves, in our opinion, further theoretical and experimental investigation.

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