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FREE AND DONOR-BOUND CHARGED MAGNETOEXCITONS IN QUANTUM WELLS

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We consider eigenstates and magneto-optical transitions of free and donor-bound spin-singlet and spin-triplet charged magnetoexcitons in quasi-two-dimensional quantum wells. We show that the bright singlet state remains always bound while spin-triplet dark and bright states become unbound when the distance to the donor ion becomes smaller than certain critical values, which depend on the magnetic field strength. We demonstrate that main magneto-photoluminescence lines of free and donor-bound charged excitons exhibit very similar features. However, shake-up processes in photoluminescence of free trions are strictly prohibited. Therefore, shake-up transitions are distinct features indicating that symmetry-breaking mechanisms are present in the system.

Keywords: Charged Magnetoexciotons; Magnetophotoluminescence.

Optical signatures of spin-singlet X_s^- and spin-triplet X_t^- charged excitons are commonly observed in semiconductor nanostructures in magnetic fields. Despite the status of X^- as one of the simplest few-body system with Coulomb interactions and a large amount of experimental and theoretical work, some important issues remain unresolved. In particular, the degree of localization of charged excitons in quantum wells (QW's) and how localization of X^- manifests itself in optics remains a controversial issue.[1,2] In this work, we discuss differences in magneto-optical transitions of free trions, X^-, and donor-bound trions, (D^+, X^-); the latter can also be considered as excitons bound to a neutral donor, (D^0, X).

Classification of states of *free* charged electron-hole complexes in magnetic fields is based on magnetic translations and the axial symmetry about the magnetic field direction.[2] The corresponding orbital quantum numbers are the oscillator quantum number $k = 0, 1, 2, \ldots$ and the total angular momentum projection, M_z. The former determines the mean squared distance to the orbit guiding center. Correspondingly, there is an infinite-fold Landau degeneracy in k. Each family of degenerate X^- states starts with its parent $k = 0$ state that has some specific value of M_z, which follows from a solution of the Schrödinger equation. Degenerate daughter states $k = 1, 2, \ldots$ have values $M_z - 1, M_z - 2, \ldots$ for the total angular momentum projection. Selection rules for interband transitions are $\Delta M_z = 0$ and $\Delta k = 0$ and lead to the following results: Photoluminescence (PL) of a free X^- must leave an electron in a LL with the number n equal to the angular momentum M_z of the parent state, $X^- \to \hbar\omega_{X^-} + e^-_{n=M_z}$. Therefore, (i) families of X^- states that start with $M_z < 0$ are dark in PL and (ii) shake-ups to multiple Landau levels (LL's) are strictly prohibited.[2]

The presence of a donor ion D^+ breaks the translational symmetry, lifts the degeneracy in k, and makes many of the previously prohibited transitions allowed. Let us discuss spectroscopic consequences of the remaining axial symmetry for a donor-bound state (D^+, X^-) with angular momentum M_z and wavefunction $\Psi_{M_z}(\mathbf{r}_{e1}, \mathbf{r}_{e2}; \mathbf{r}_h)$. The dipole matrix element for interband transition to a final D^0 state described by a wavefunction $\Phi_{m_z}(\mathbf{r})$ is

$$d = p_{\rm cv} \int d\mathbf{r} \int d\mathbf{r}' \, \Phi^*_{m_z}(\mathbf{r}) \, \Psi_{M_z}(\mathbf{r}, \mathbf{r}'; \mathbf{r}') \sim \delta_{M_z, m_z} \, . \tag{1}$$

Conservation of angular momentum $M_z = m_z$ can be satisfied for a number of final states $\Phi_{m_z}(\mathbf{r})$ belonging to different LL's. Therefore, shake-up processes become allowed in PL. More than that, PL of (D^+, X^-) states with $M_z > 0$ must proceed via shake-ups to higher LL's.[3] This is because electron states with angular momenta $m_z = M_z > 0$ are only available in $n = M_z$ or higher LL's. Note that the shake-up processes are due to the Coulomb induced admixture of LL's and are suppressed in strong fields as B^{-2}.

Stability for the donor-bound charged exciton is determined with respect to its dissociation to a neutral donor and a free exciton, $(D^+, X^-) \to D^0 + X$. Accordingly, the binding energy of a stable (D^+, X^-) is defined as the energy difference between the total Coulomb energies

$$E^{\rm b}_{(D^+,X^-)} = E^{\rm Coul}_{D^0} + E^{\rm Coul}_{X} - E^{\rm Coul}_{(D^+,X^-)} > 0 \, , \tag{2}$$

with D^0 and X being in their ground states. Binding energy (2) determines the energy difference between the PL lines of a neutral free exciton and a donor-bound charged exciton, $\hbar\omega_X - \hbar\omega_{(D^+,X^-)} = E^{\rm b}_{(D^+,X^-)}$.

We obtain the energies and wavefunctions of the (D^+, X^-) and free X^- excitons by numerical diagonalization of the interaction Hamiltonian. We construct the basis states out of the in-plane wavefunctions in LL's and size quantization levels in a QW.[4] The calculated binding energies of the various charged excitons in a 100 Å GaAs QW as functions of the distance L to the donor ion are shown in Fig. 1. The limiting case $L = \infty$ corresponds to free charged excitons X^-. There are three documented bound states in this limit: the bright singlet X^-_s with $M_z = 0$, the dark

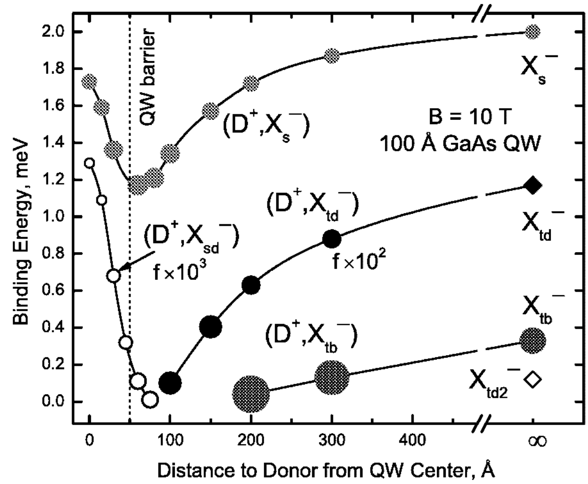

Fig. 1. Binding energies of charged excitons X^- in a GaAs/$Al_{0.3}Ga_{0.7}$As QW. Sizes of the dots are proportional to the interband dipole transition matrix elements squared $f = |d|^2$. The solid diamond designates the dark triplet state $X^-_{\rm td}$.

triplet $X^-_{\rm td}$ with $M_z = -1$, and the bright triplet $X^-_{\rm tb}$ with $M_z = 0$ (see Refs. 2, 5, 6 and the literature cited therein). Our results show that the parent bright singlet state X^-_s with $M_z = 0$ remains always bound. Its binding energy initially decreases with decreasing L, reaches its minimum when the donor D^+ is very close to the heteroboundary, and then increases again. We interpret this as an indication toward a rearrangement of the type of binding in the (D^+, X^-_s) ground state: At very large distances L, the donor ion binds X^-_s as a whole barely affecting its internal structure. In the opposite limit of an in-well donor, the interaction of electrons with the D^+ is stronger than that with the hole. The donor-bound complex formed in this case is better described as an exciton bound to a neutral donor (D^0, X).

We found just one state that only exists in the presence of the D^+ and does not have its free $L = \infty$ counterpart. This is the singlet state $(D^+, X^-_{\rm sd})$ with $M_z = 1$. It only becomes bound when the D^+ is located in a QW or very near to it. This is also the only donor-bound state that remains stable in the strictly 2D high-field limit in symmetric electron-hole systems.[3] According to the selection rule discussed after Eq. (1), the PL from this state goes mostly via shake-ups to $n = 1$ electron LL. As a result, the dipole transition matrix elements for PL from this state shown in Fig. 1 are very small.

In contrast to singlet states, the dark $X^-_{\rm td}$ and bright $X^-_{\rm tb}$ triplet states survive only for sufficiently large distances L to the donor ion D^+ (Fig. 1). This is because electrons in triplet states cannot simultaneously occupy the s-state in the lowest LL and, therefore, it is difficult for them to find a configuration in which electron-donor interactions would be optimized. Notice the finite oscillator strengths for

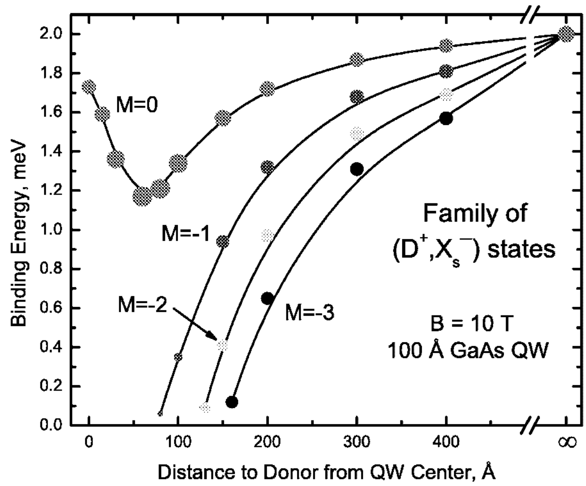

Fig. 2. Lifting of the Landau degeneracy in the family of bright singlet states X_s^-. The states are characterized by different total angular momentum projections $M_z = 0, -1, -2, \ldots$ (denoted as M in the graph) and all are optically active.

the PL from the donor-bound complex $(D^+, X_{\rm td}^-)$ originating from the dark triplet state. Notice also a systematic change in the dipole transition matrix elements $|d|^2$ in Fig. 1. This is explained by the notion of "giant oscillator strengths":[7] as the binding energy of a complex decreases, its spatial extent increases leading to the increase in $|d|^2$.

We stress that each free X^- state gives rise to a family of degenerate states; only the evolution of the parent X^- states is shown in Fig. 1. The degeneracy in the in-plane position of the guiding center (quantum number k) is lifted in the presence of the donor ion D^+. We illustrate this effect in Fig. 2 on the example of a family of singlet bright states X_s^-. When the distance to the donor L decreases, all but one singlet state (with $M_z = 0$) become one by one unbound. This leads to a number of optically active states with large oscillator strengths. These additional optically-active states have smaller binding energies, i.e., are excited states. These may be populated at elevated temperatures or under non-equilibrium conditions (optical excitation) and may contribute to broadening of lines or may even be observed in the magneto-PL spectra as additional peaks.

The spectra of PL transitions from the singlet (D^+, X_s^-) state with the on-center D^+ are shown in Fig. 3. The binding energies and oscillator strengths of the (D^+, X_s^-) state and of free X_s^- are similar (Fig. 1). As a result, the main PL peaks are very similar too. The shake-up processes, however, are distinct features of the (D^+, X_s^-) complex that are strictly prohibited in PL of free trions.[2] The final states in these transitions are not free electrons in LL's but rather bound neutral donors in higher $n^{\rm th}$ LL's, $(D^+, X_s^-) \to \hbar\omega + D_n^0$. This leads to lower slopes of the SU_n lines vs magnetic field (in comparison to transitions to free LL's), which is consistent

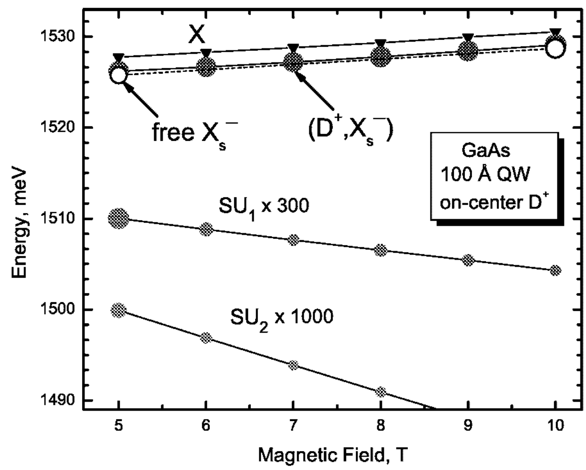

Fig. 3. PL transitions from the singlet donor-bound (D^+, X_s^-) state in a GaAs/$Al_{0.3}Ga_{0.7}As$ QW. Open symbols connected by the dashed line: PL transitions of free trions X_s^-. Sizes of the dots are proportional to $|d|^2$. The solid triangles: PL transitions of a neutral exciton X.

with experiment.[8] Note that shake-up processes in magneto-photoabsorption of a low-density 2DEG leading to formation of correlated three-particle states in higher LL's are allowed processes[9] and have been observed experimentally.[10]

In conclusion, we have shown there is a multitude of donor-bound X^- states that may exhibit relatively weak dependencies of binding energies and oscillator strengths on positions of remote donors. Our results may be relevant for explanation of the PL from the dark triplet state X_{td}^-, of the multiple PL peaks observed in different experiments, and of the X^- shake-ups in PL.

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