ВСЕ О ТРИОНАХ

<u>Trions at low electron density limit</u>

- **1. Charged exciton-electron complexes (trions)**
- **2. Singlet and triplet trion states**
- **3. Modulation doped QWs**
- **4. Trions in optical spectra**
- **5. Action of magnetic fields on the trions**

<u>Trions at high electron density limit</u>

- **6. Combined exciton cyclotron resonance**
- **7. Combined trion cyclotron resonance**
- **8. Combined exciton electron processes in PL spectra**
- **9. Trion Zeeman splitting**

LOW 2DEG DENSITY

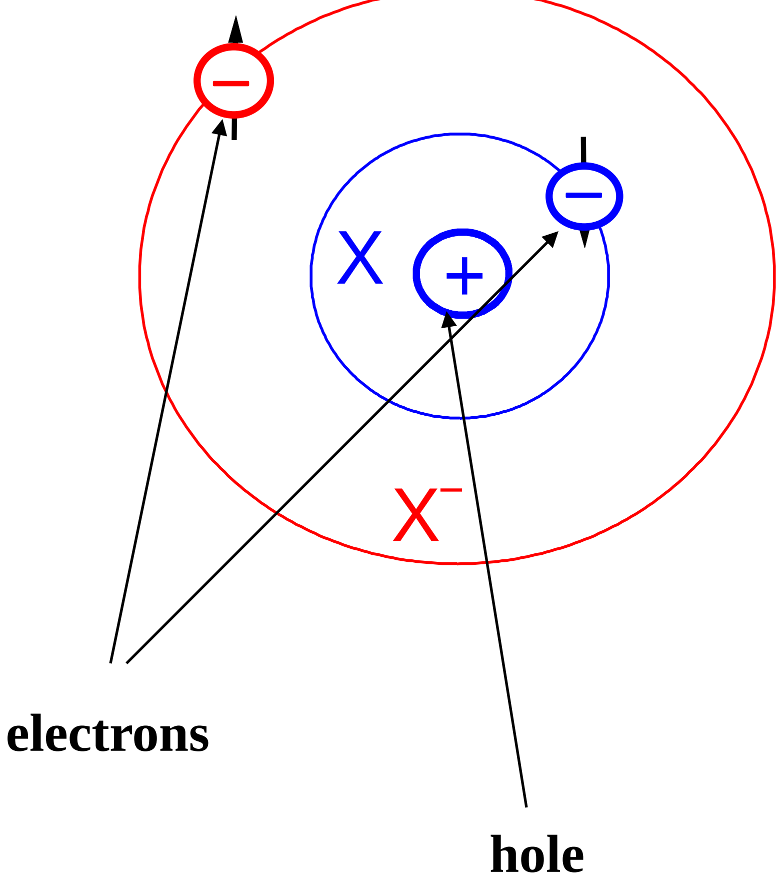
Two electrons+one hole states

- Trions at weak magnetic fields
- Trions at high magnetic fields
- Excited states of trion

Charged exciton – electron complex (trion)

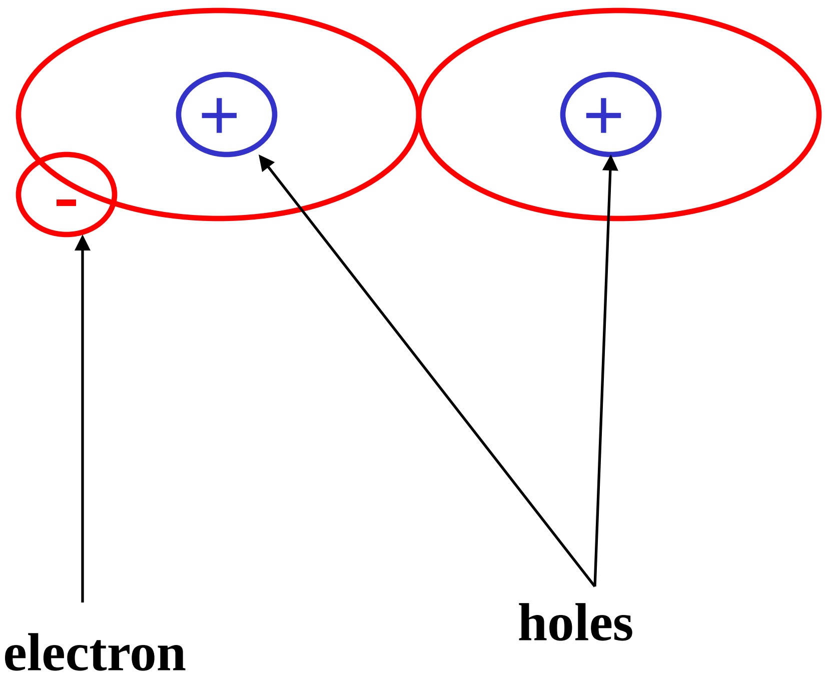
Negatively charged Trion *X*⁻

similar to ion H-



Positively charged Trion *X*⁺

Similar to ionized molecule H+



Singlet and Triplet trion states

Wavefunction for two electrons in the trion

$$\varphi(1,2) = U(1,2)\chi(1,2)$$

S_z = +1
S_z = 0
S_z = -1
triplet

Spatial part of the wavefunction

$$U^0_{nlm} = \frac{1}{\sqrt{2}}\left[u_1(\vec{r}_1)u_{nlm}(\vec{r}_2) \pm u_1(\vec{r}_2)u_{nlm}(\vec{r}_1)\right]$$

S_z = 0 **singlet**

Singlet state + **S_z = 0** $\propto e^{-\alpha(\vec{r}_1+\vec{r}_2)}$

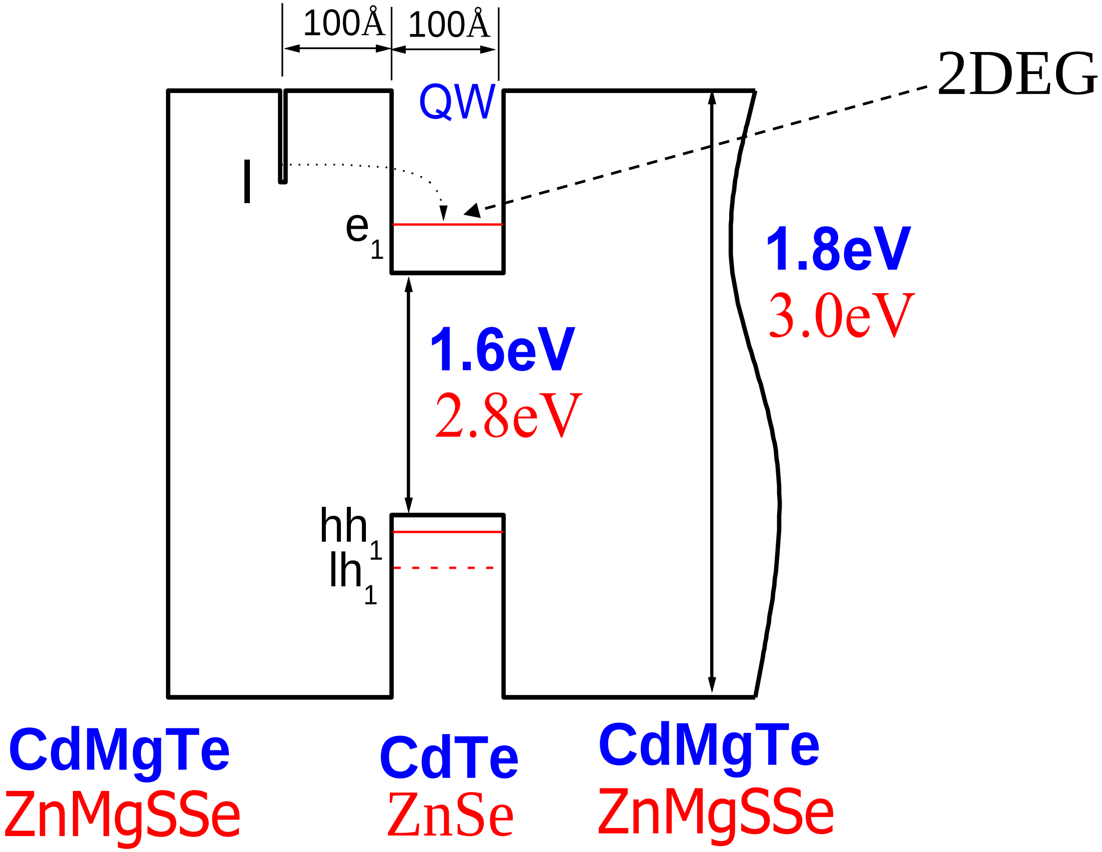
Triplet state - **$S_z = \pm 1,0$**

$U_{nlm} \neq 0$, if $l \neq 0$ one electron is in *1S* and the second is in *2P* state – dark triplet

Or if n $\neq$ 1 one electron is in *1S*, and the second is in a *2S* state bright triplet

Experimental studies of trions

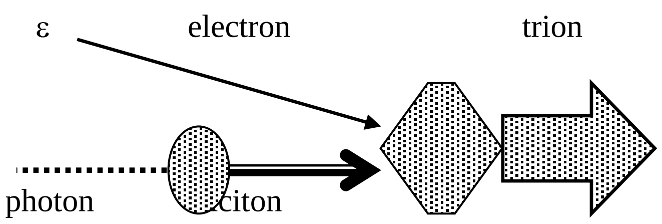
Modulation doped structures

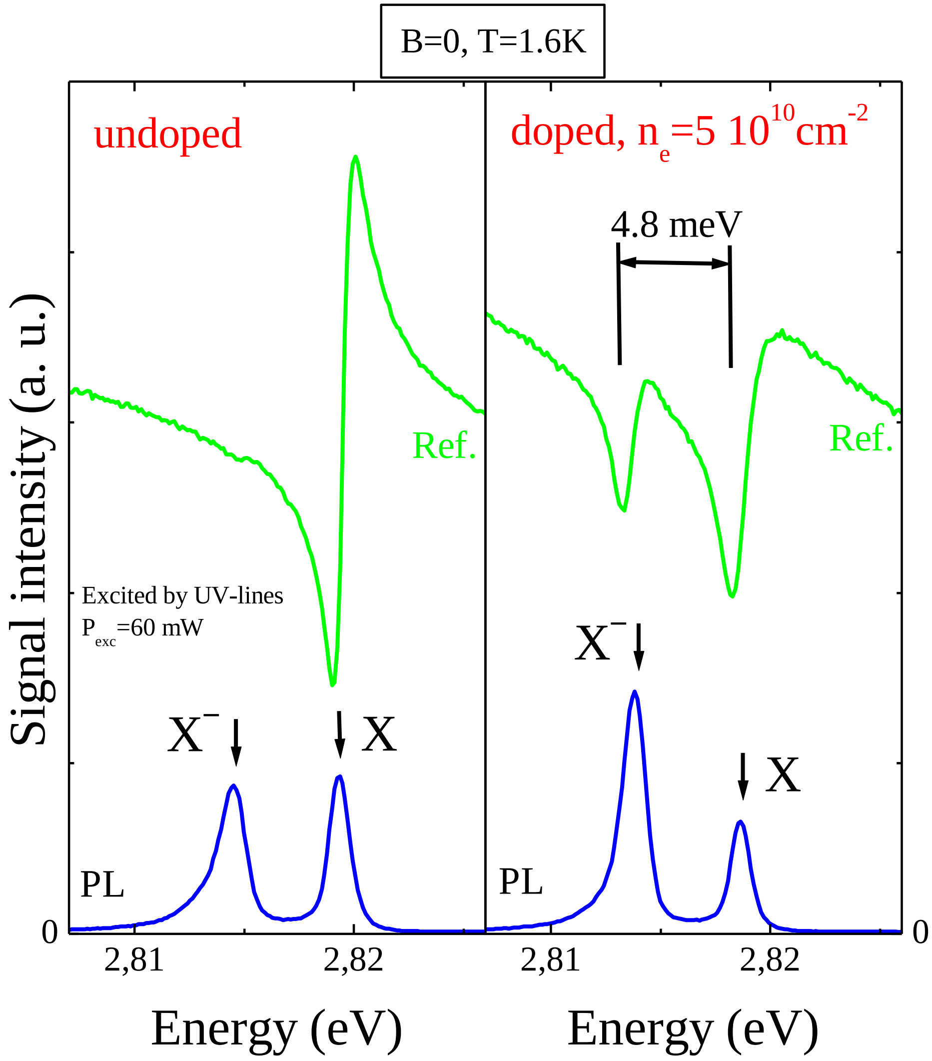


2DEG density varied from $\mathbf{n_e=5*10^9}$ **см$^{-2}$** to $\mathbf{9*10^{11}}$ **см$^{-2}$**

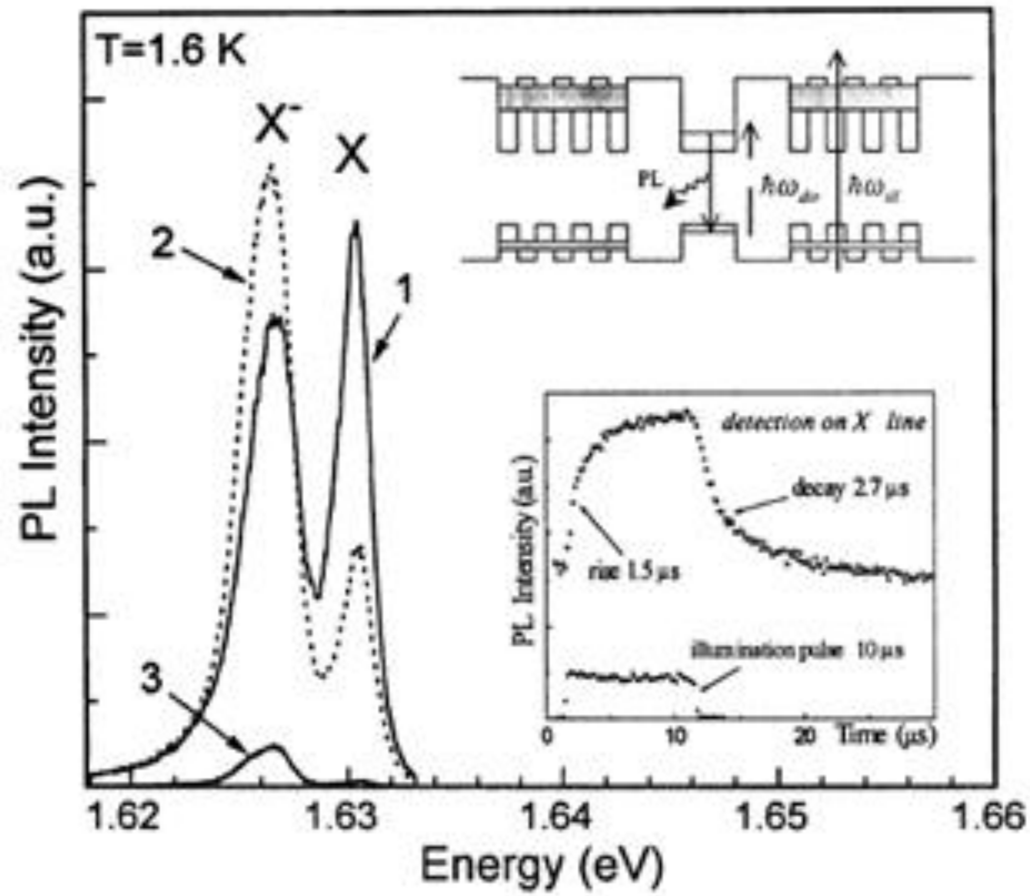
Optical processes with the trion participation

Trion formation time in ZnSe structures is of the order of 2 –4 psec

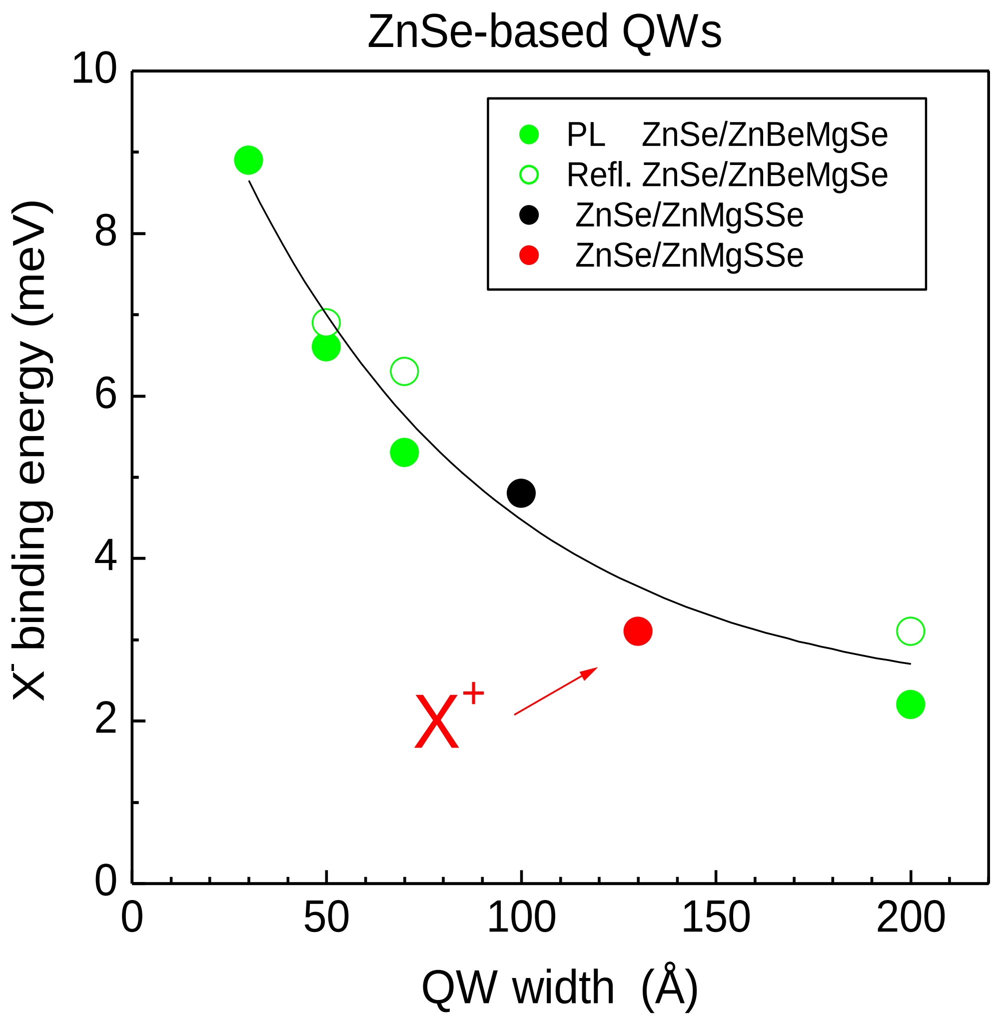




Изменение концентрации при подсветке

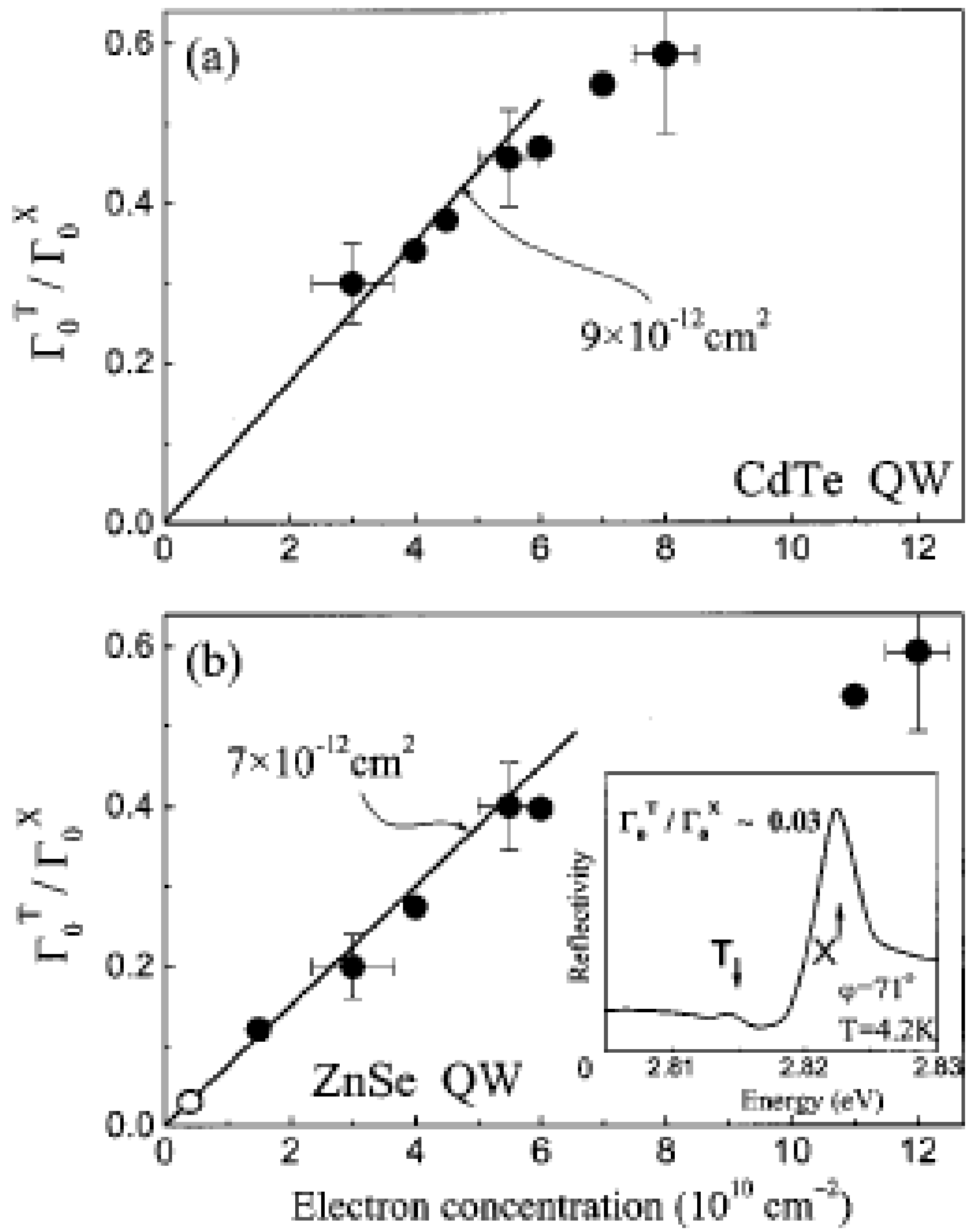


Зависимость энергии связи триона от ширины ямы



Сила осциллятора экситона приходящаяся на элементарную ячейку равна силе осциллятора триона на один электрон, также Как для связанных экситонов

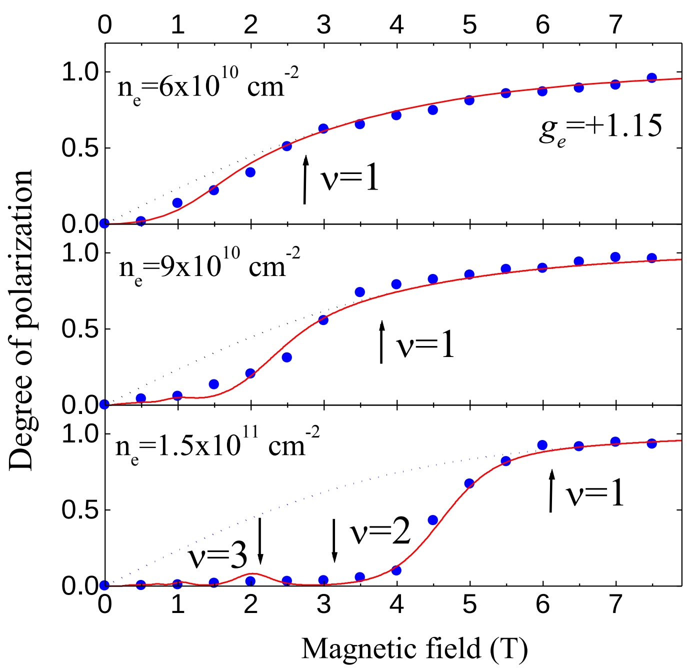
$$\frac{\Gamma_0^T}{\Gamma_0^X} = Cn_e$$

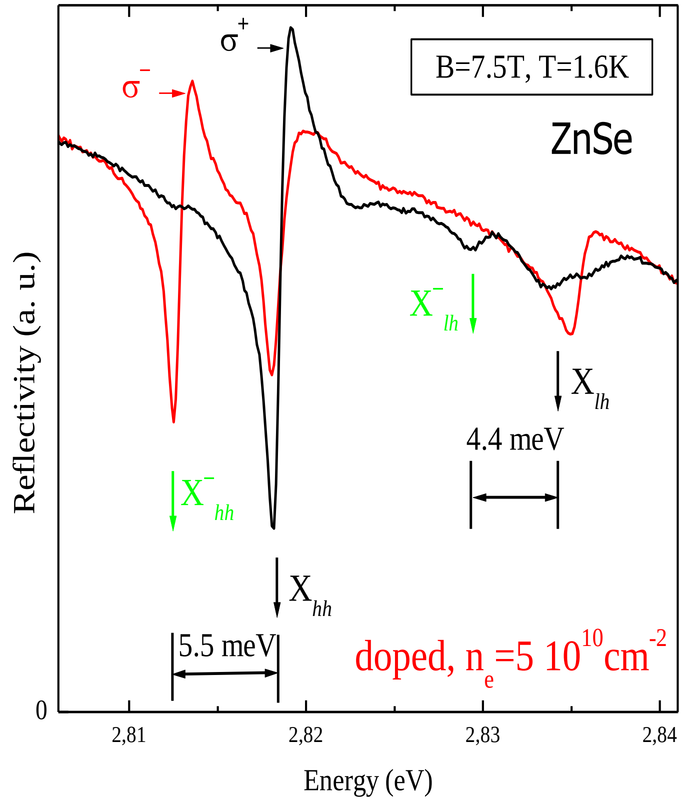


Singlet and Triplet

Trion states in magnetic fields

Singlet trion in magnetic fields

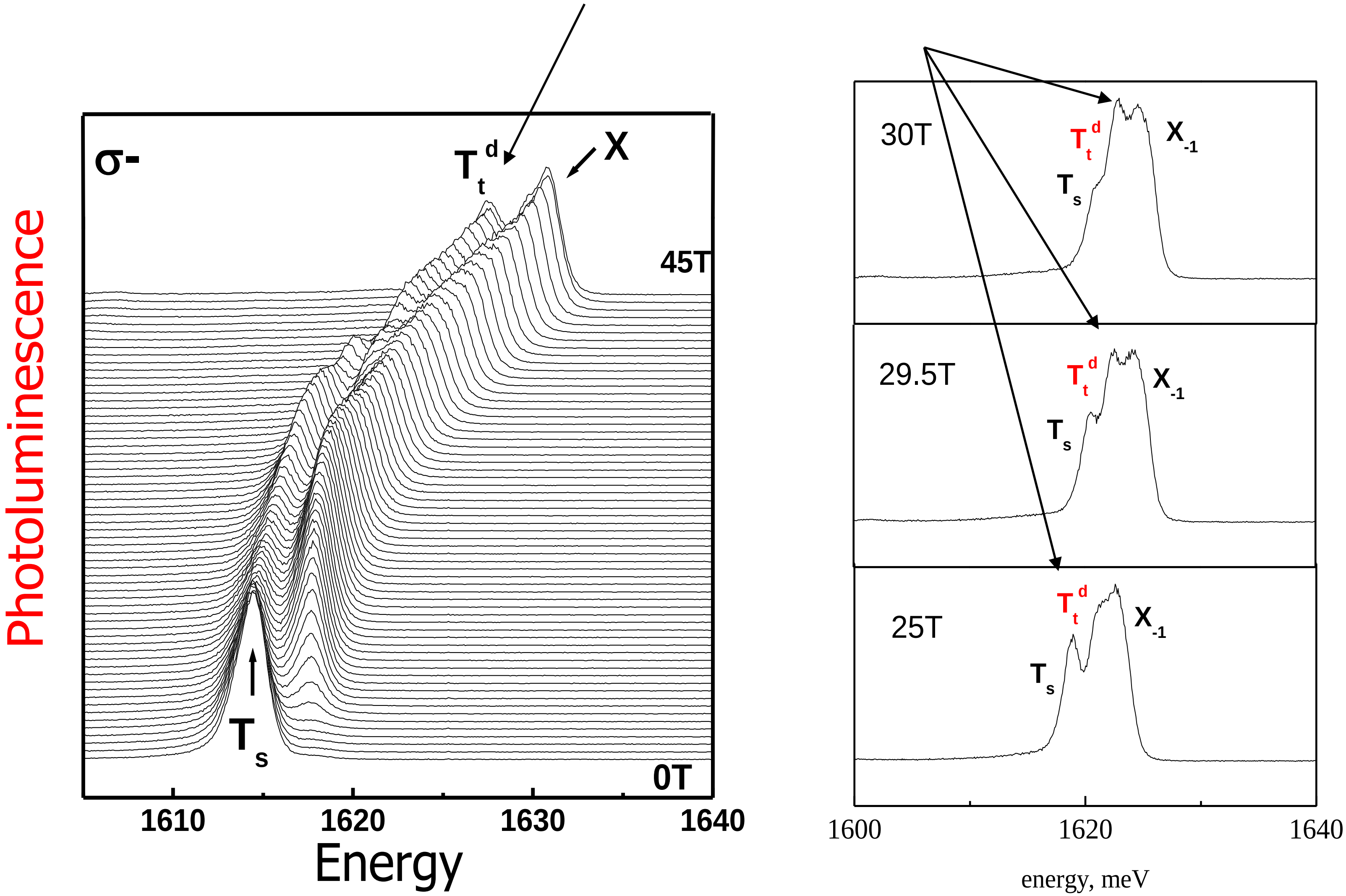




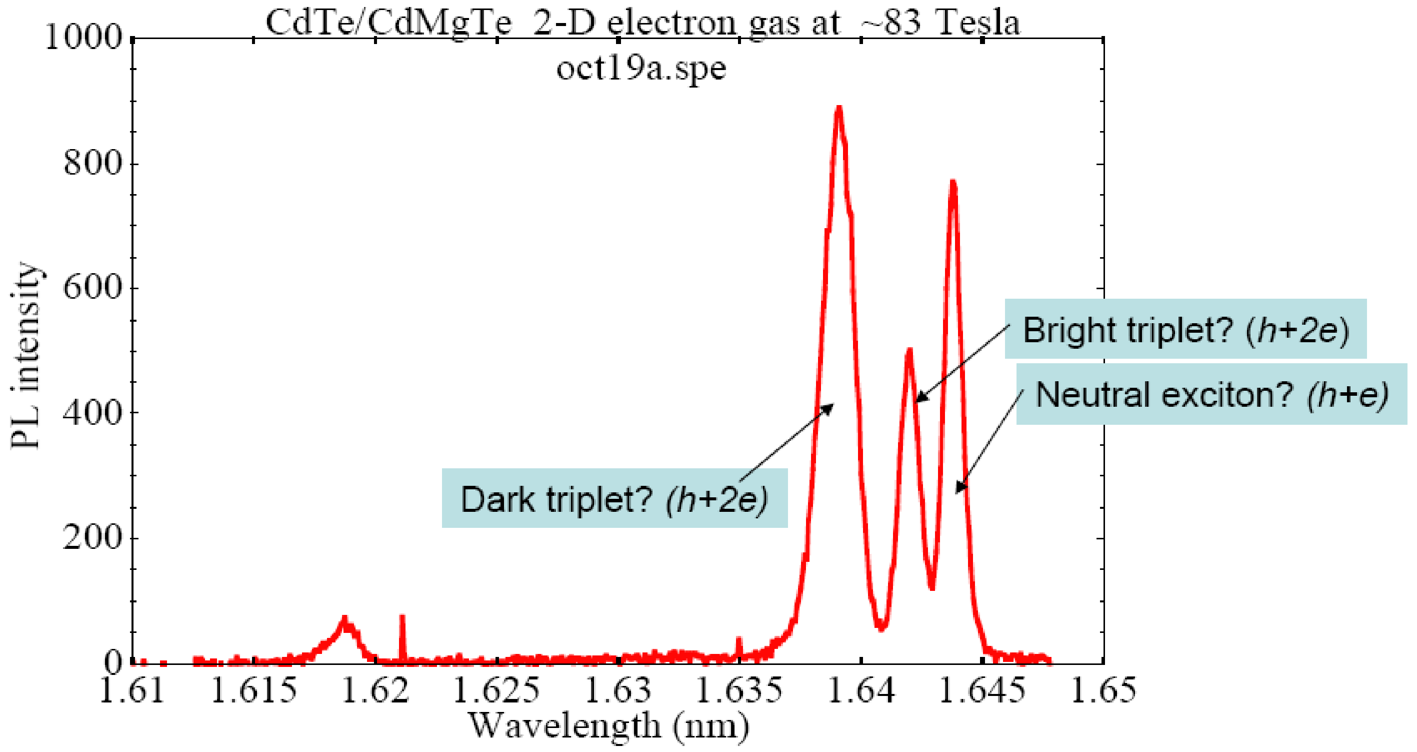
The circular polarization of the trion absorption (reflectivity line) in magnetic fields can be used to determine electron concentration by pure optical method

X^-_{hh} and X^-_{lh} resonances appear in opposite circular polarizations

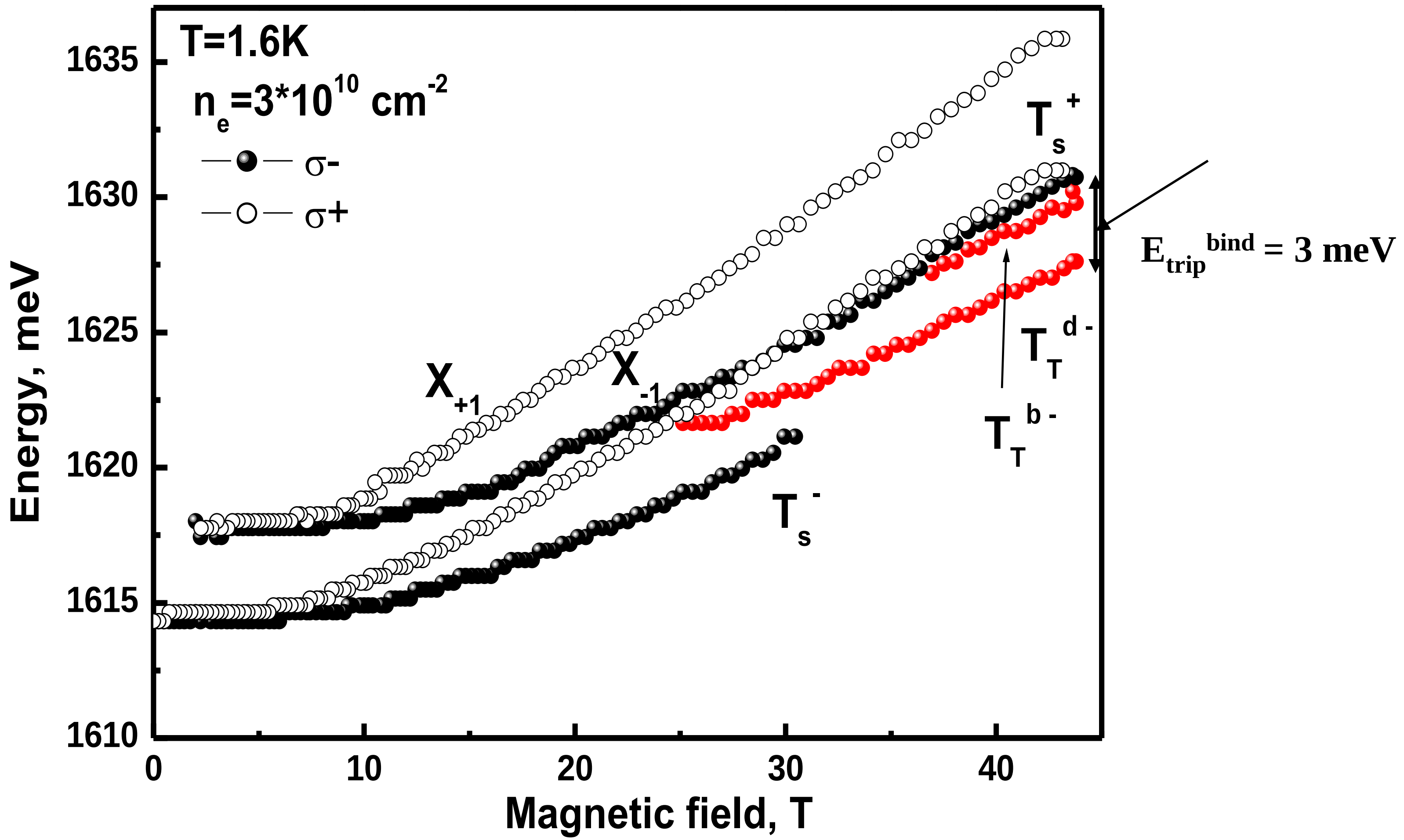
Triplet trion in high magnetic fields



PL spectra: CdTe/CdMgTe 2D electron gas at 1.5 K at ~83 T (in 100T LP)



Singlet and Triplet in high fields

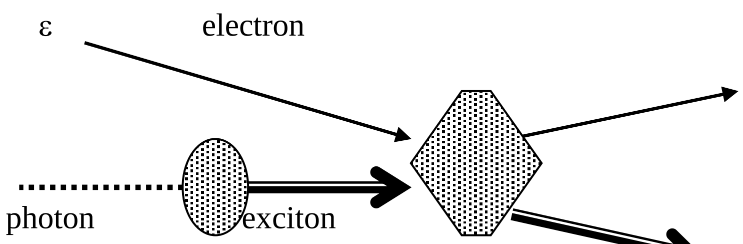


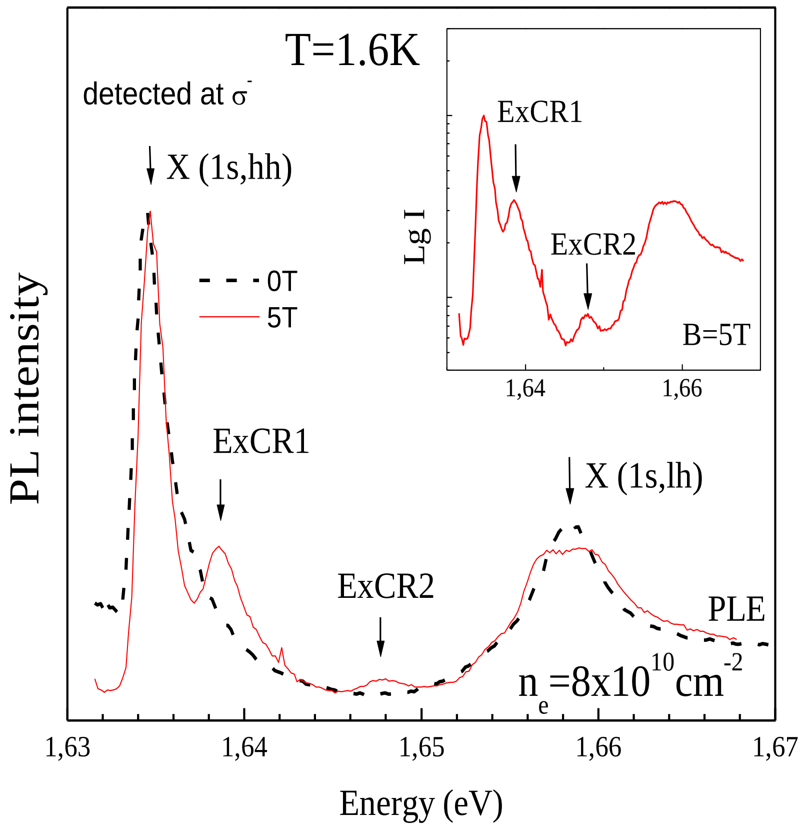
EXCITON-ELECTRON SCATTERING

(<u>excited states of a trion in magnetic fields</u>)

Exciton – electron scattering

Exciton – electron scattering





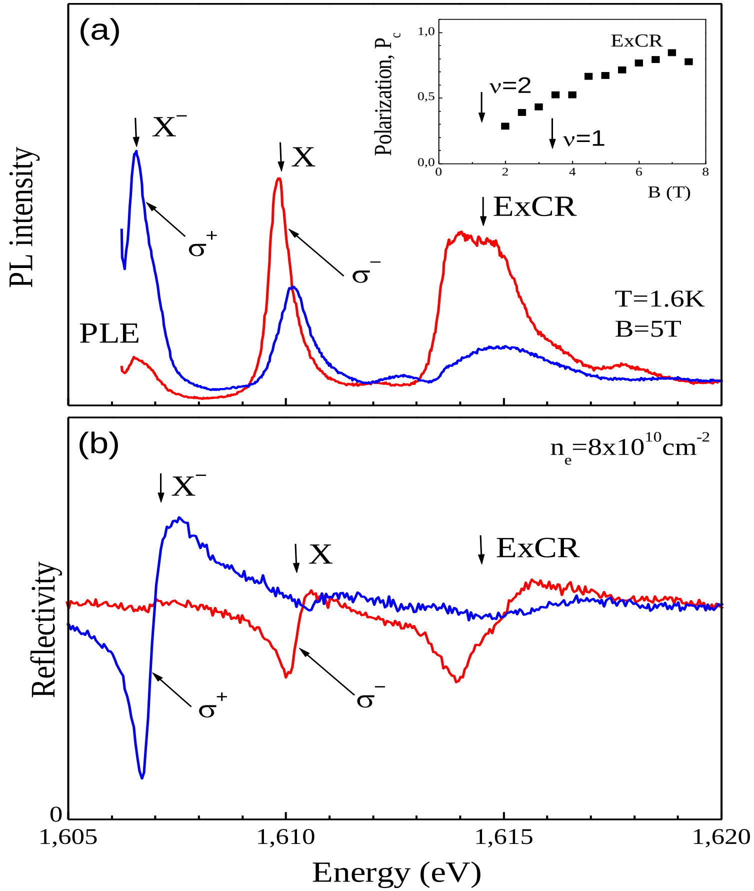
In magnetic fields in QWs the exciton electron scattering leads to the electron transitions between Landau levels - **ExCR**

The scattering leads to high energy tail of the exciton absorption line. In magnetic fields it splits into separate lines because the electron spectrum becomes discrete = excited states of trions in magnetic fields.

We can neglect the trion binding energy because $E^b_{ex} >> \hbar\omega_c >> E^b_{Tr}$

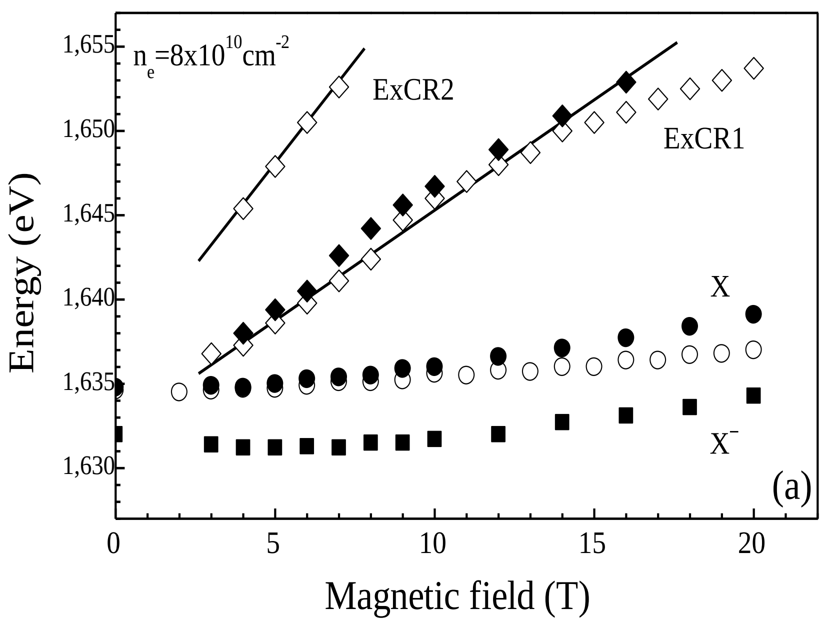
$$e + ph \Rightarrow Ex + e^*$$

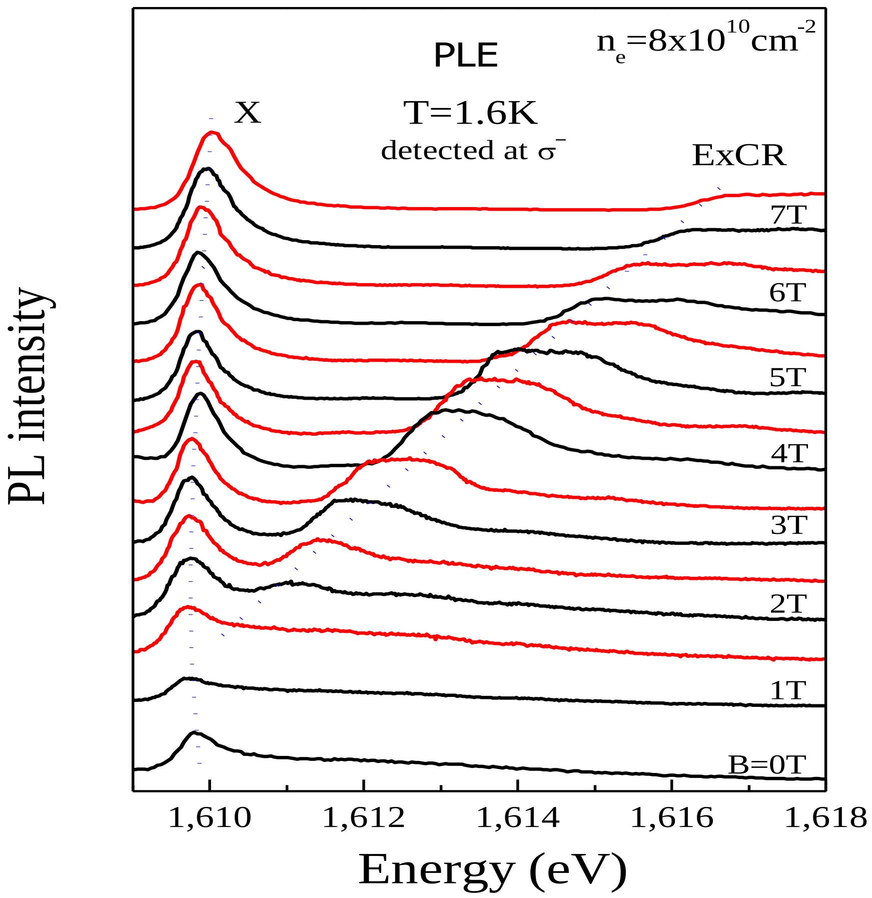
$$\frac{1}{2}\hbar\omega_e^c + \hbar\omega = E_{exc} + \frac{3}{2}\hbar\omega_e^c$$



The intensity of the ExCR absorption line is comparable with the intensity of the exciton line

Combined exciton –cyclotron resonance ExCR





The ExCR line shifts LINEARLY from the exciton resonance to high energies with increase of magnetic fields

$$\hbar\omega_{ExCR} = N\hbar\omega_e^c(1+\frac{m_e}{M})$$

Combined processes in Dense 2DEG

Three electrons+one hole states

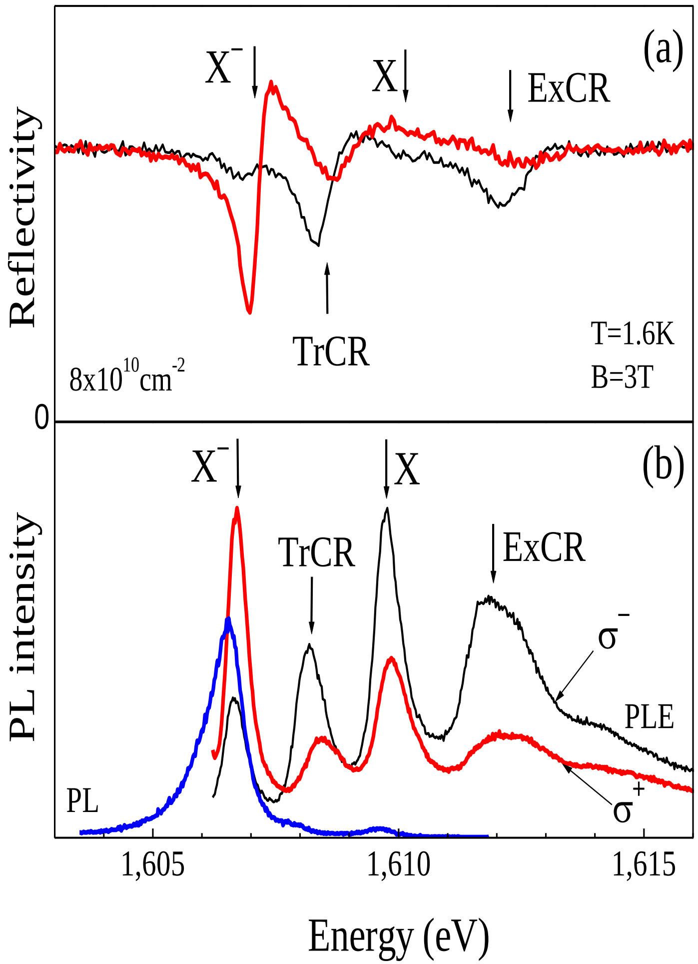
In the dense 2DEG two-electron processes emerge in the spectra
TrCR

There are two electrons in the initial state; an incident photon creates an exciton which binds with one of the electrons forming a trion; and the second electron excites on the second Landau level

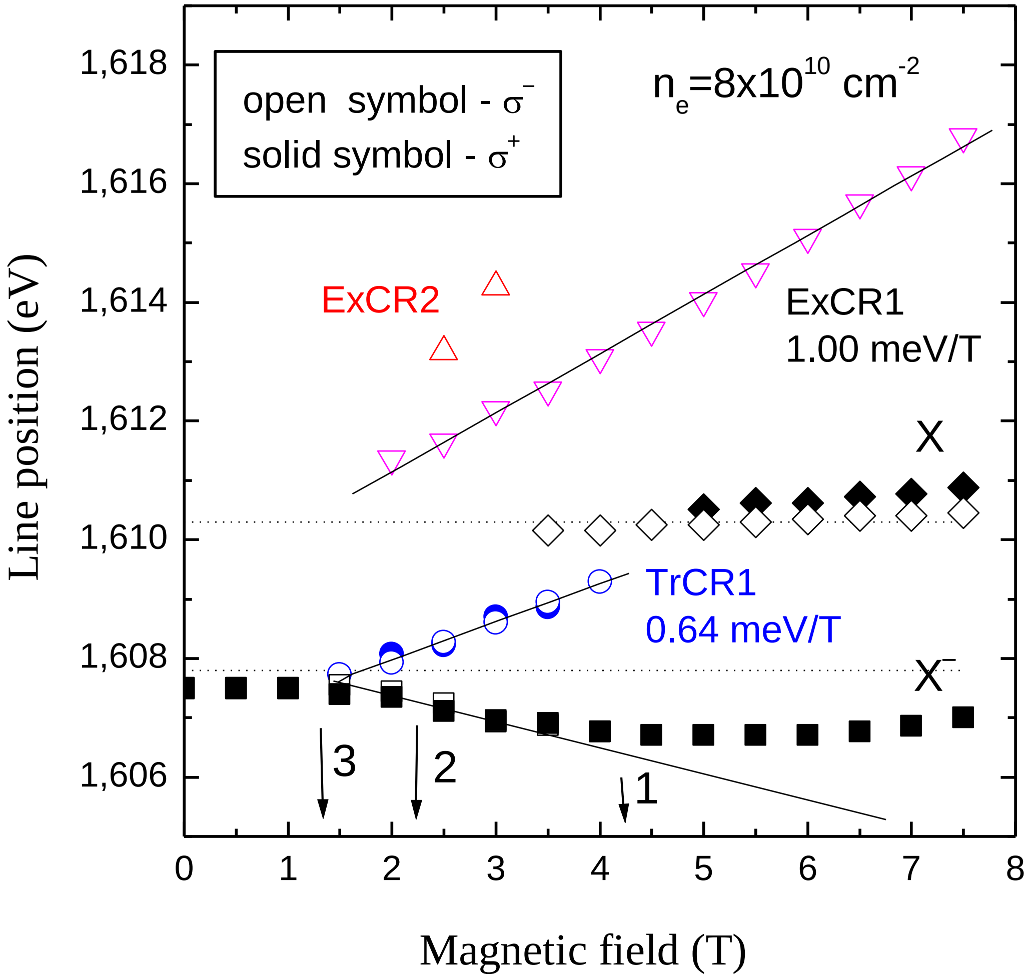
$$e + e + ph \Rightarrow Tr + e^{*}$$

$$\frac{1}{2}\hbar\omega_e^c + \frac{1}{2}\hbar\omega_e^c + \hbar\omega = E_{tr} + \frac{3}{2}\hbar\omega_e^c$$

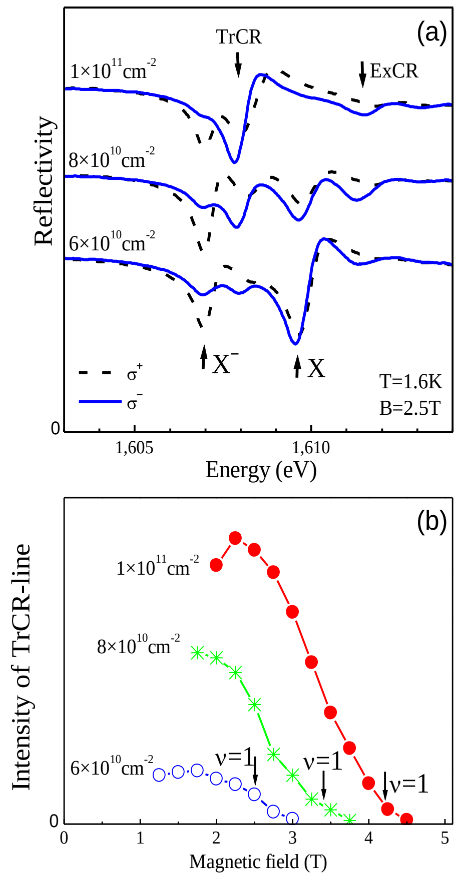
$$\hbar\omega = E_{tr} + \frac{1}{2}\hbar\omega_e^c$$

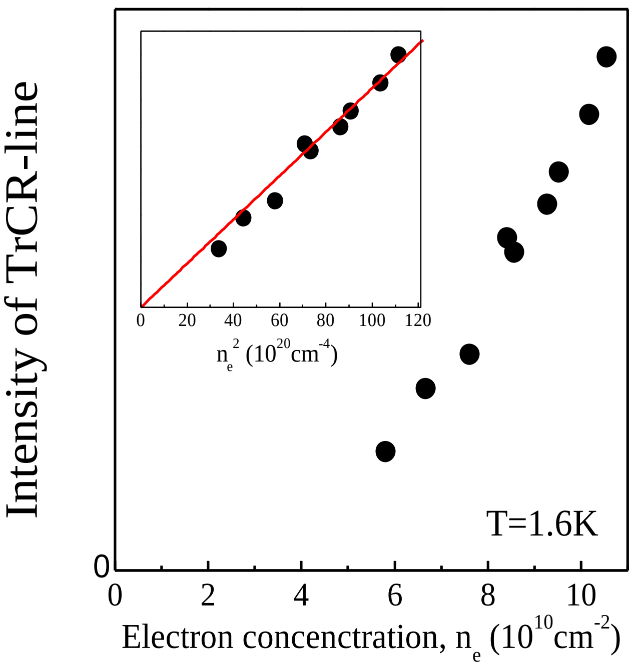


Trion Cyclotron Resonance



Line of the TrCR is observable at filling factors > 1. The intensity of the TrCR line is proportional to the second power of the 2DEG density

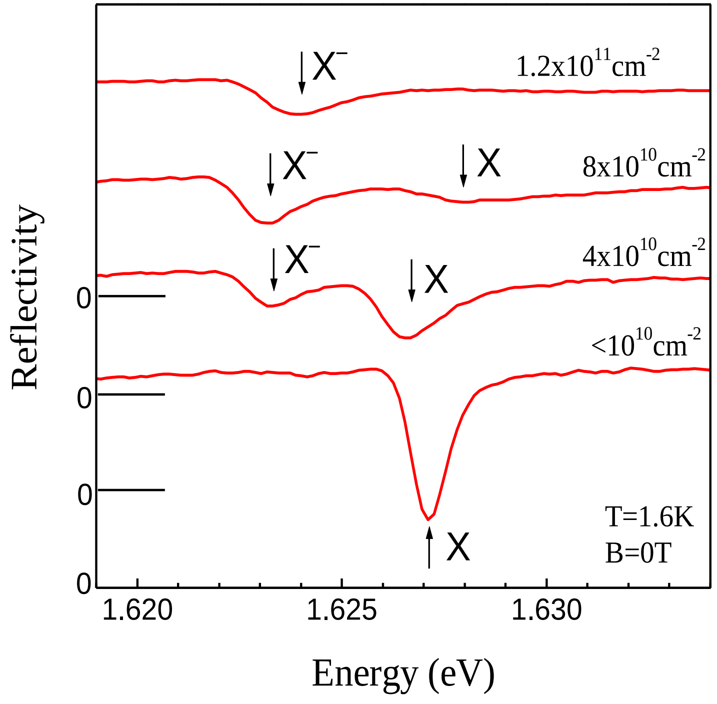




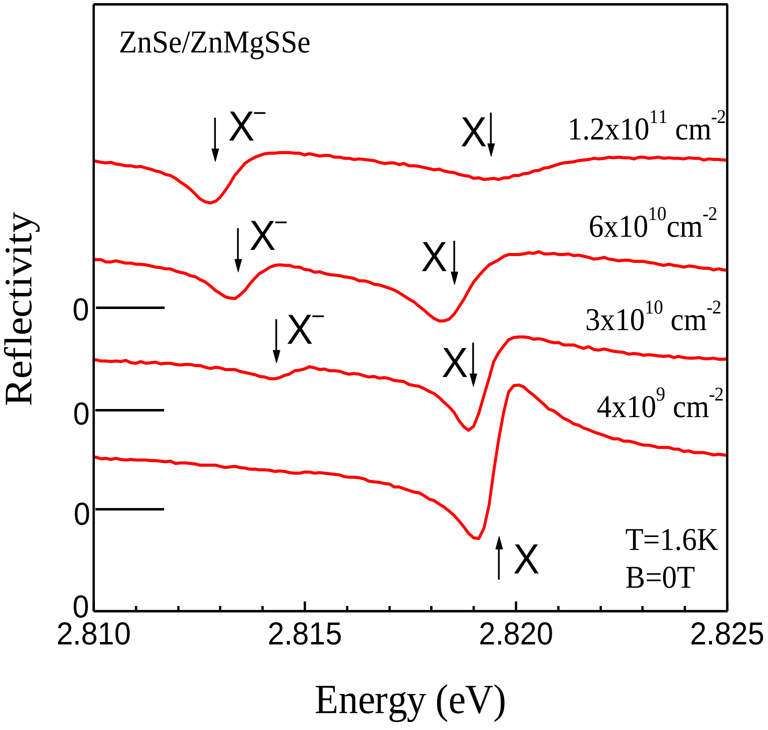
Surprising Trion stability against free electron screening

Экситон исчезает из спектра при относительно малых концентрациях электронов, а трион остается

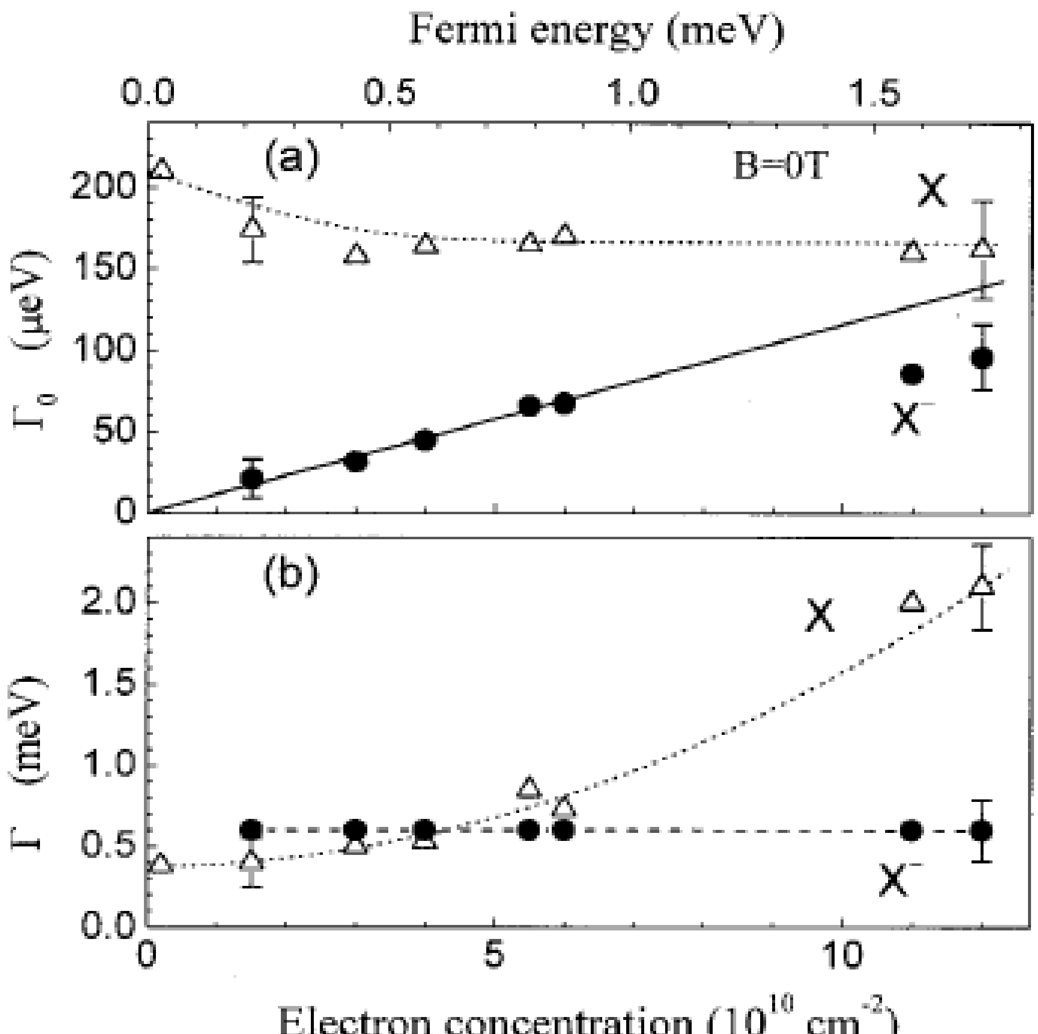
CdTe/CdMgTe 80A



ZnSe/ZnMgSSe 80A

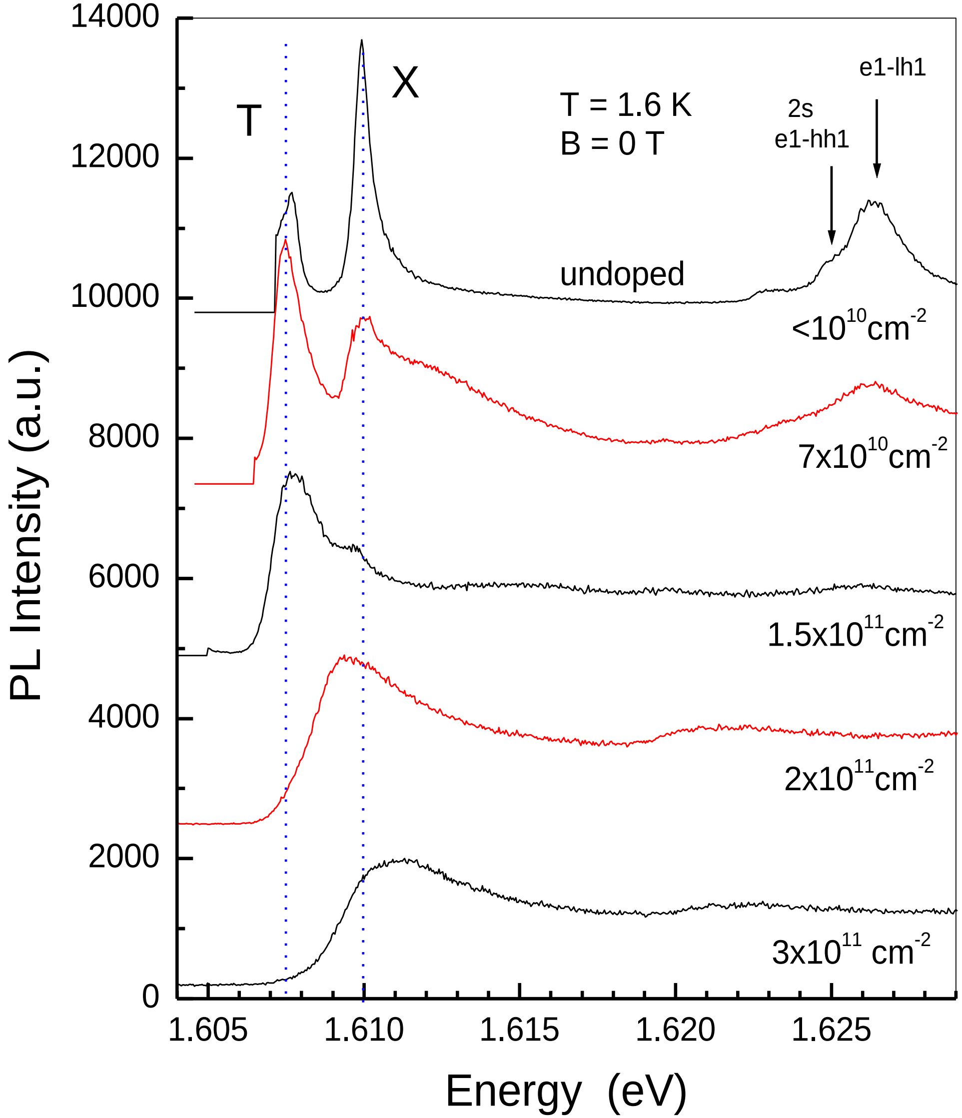


Сила осциллятора экситона не зависит от плотности 2DEG



Затухание экситона растет с ростом плотности

Спектры поглощения (PLE) как функция концентрации



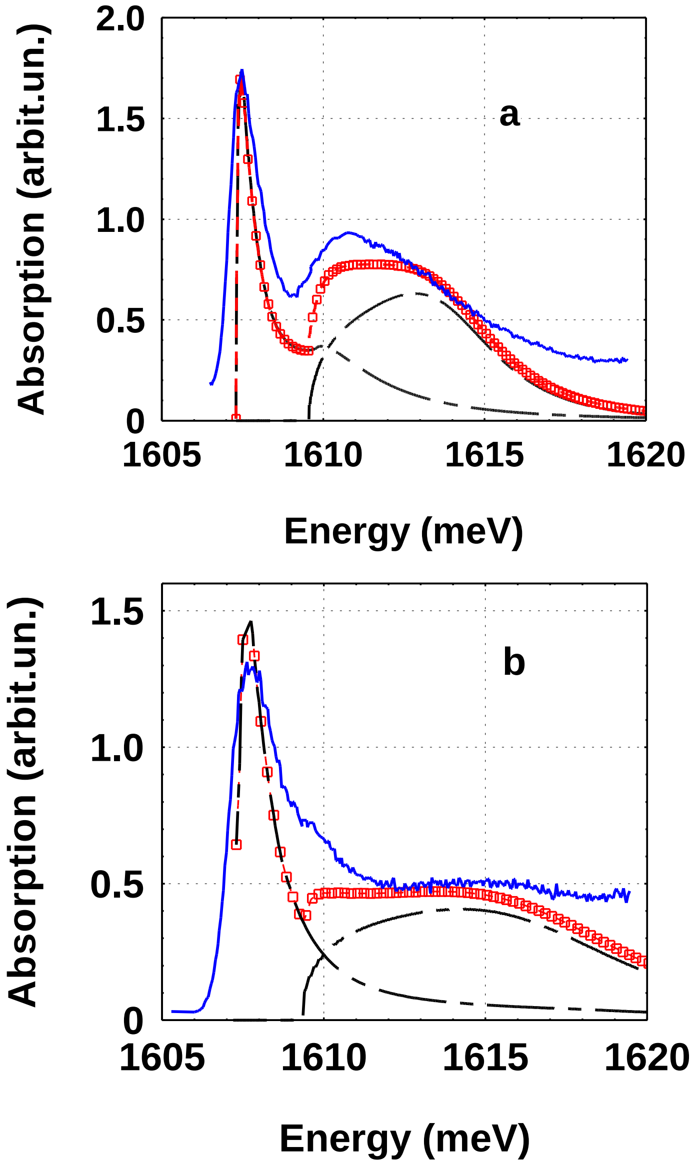


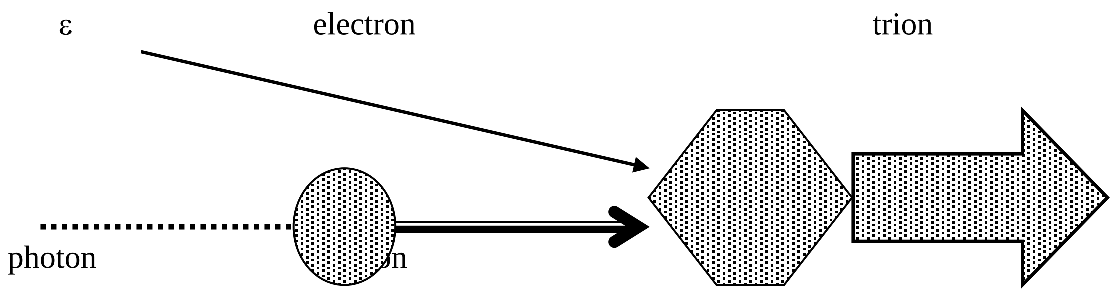
Figure 5: Absorption spectra of CdTe/CdMgTe quantum wells at different densities of free electrons. Solid lines are experimental spectra, symbols present results of calculation at $E_F = 2.5$ meV (upper panel) and $E_F = 10$ meV (lower panel), respectively. Dashed lines are contributions of trion and exciton.

Trion Zeeman splitting as a function of the electron density

The value of the exciton and trion Zeeman splitting?

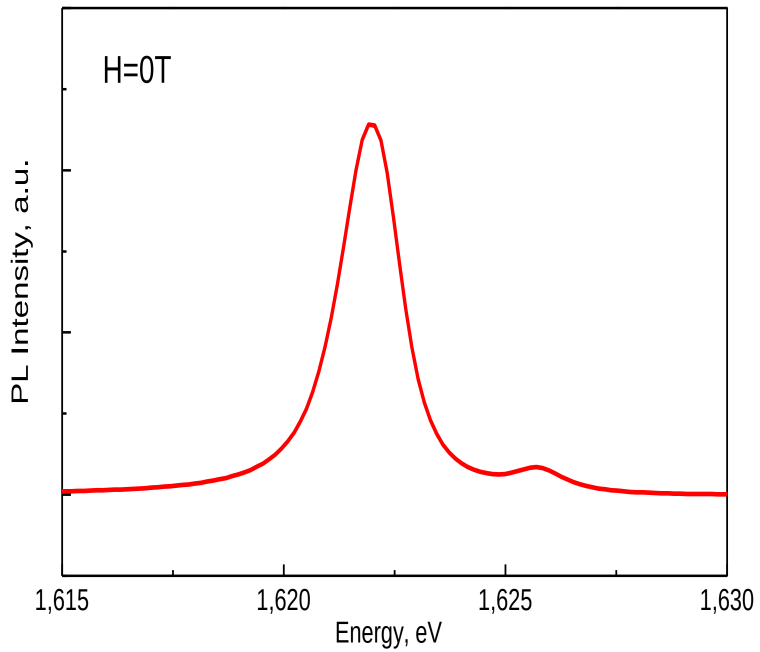
$$e_{init} + ph \rightarrow Tr = (Ex + e_{fin})$$

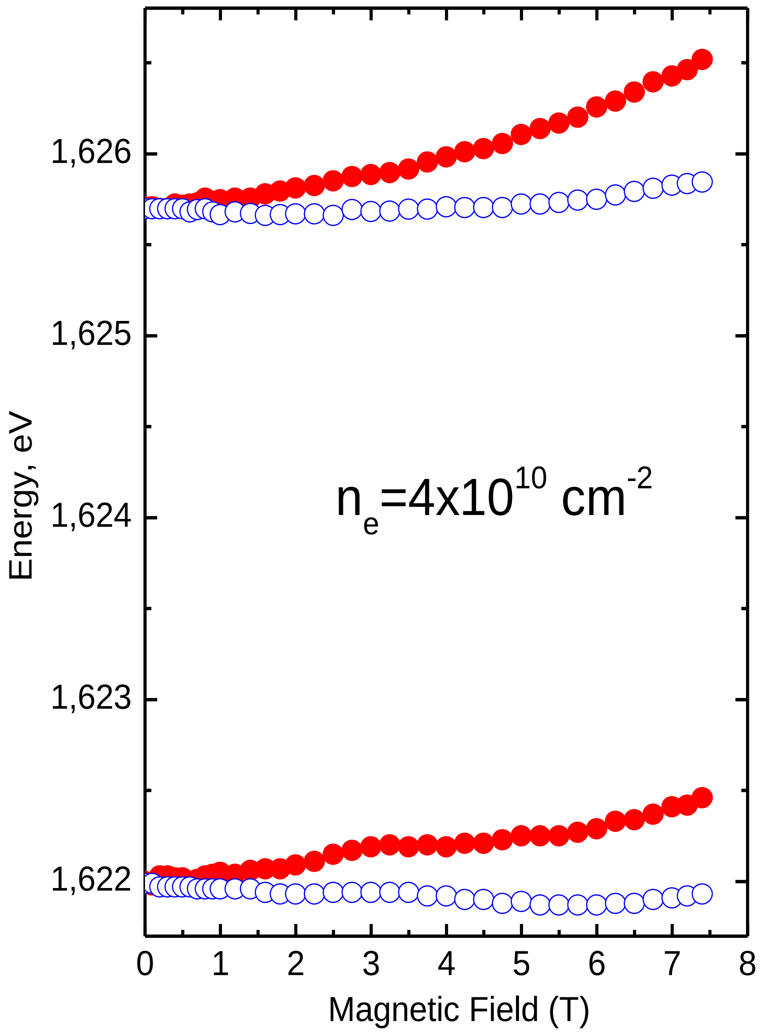
Because the initial and the final state of the electron are the same (the same spin and the same Landau level) we should see only the exciton Zeeman splitting on exciton and on trion line



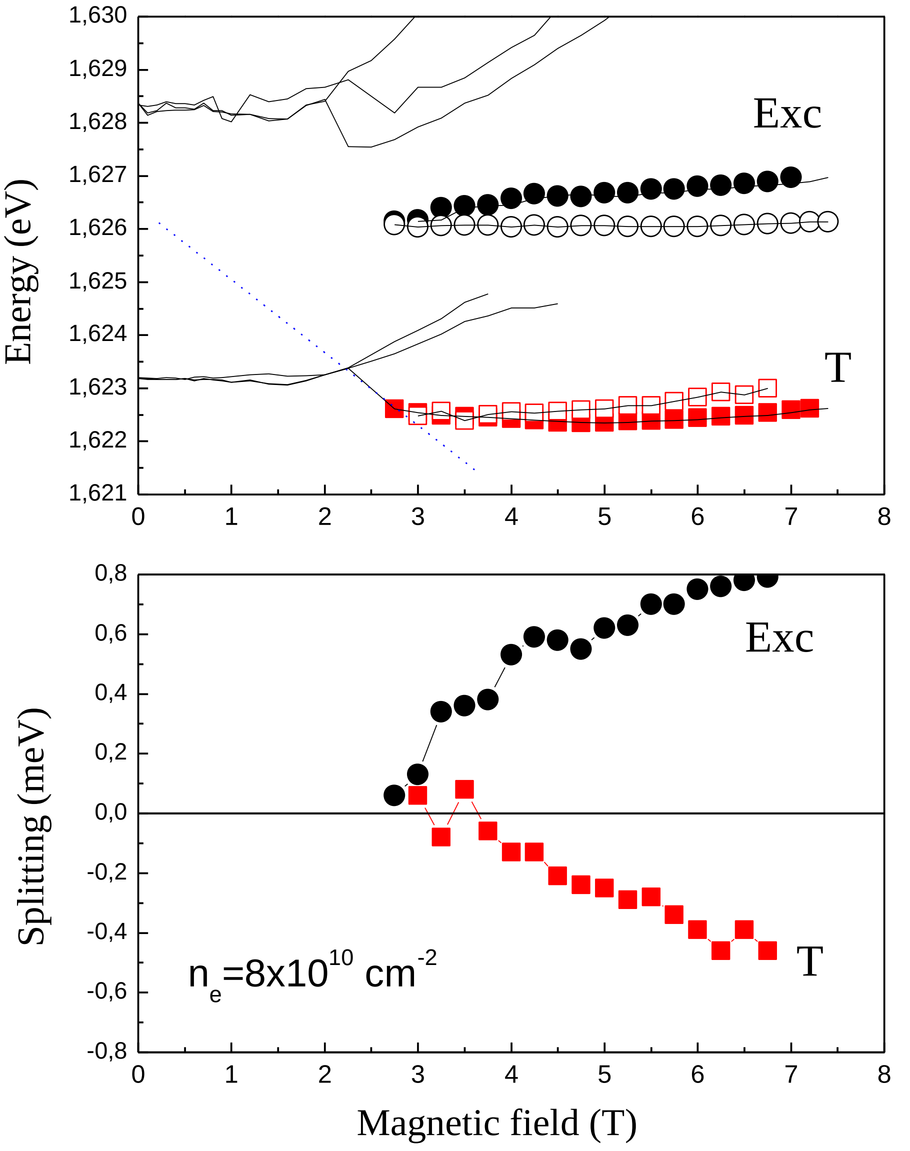
Photoluminescence

In PL the exciton and trion Zeeman splitting are equal





Exciton and trion Zeeman splitting at high electron concentrations



This is possible only in the case if the initial and final spin state of the electron are not the same – <u>we need spin-flip</u>

For spin-flip we need spin-orbital interaction.
This can be the triplet-singlet splitting of the trion

In the initial state the photon creates virtual state of the triplet trion. Because of very fast spin-flip of one of the electrons in the final state we have the singlet trion (already real).
This is the process reversal to the ExCR

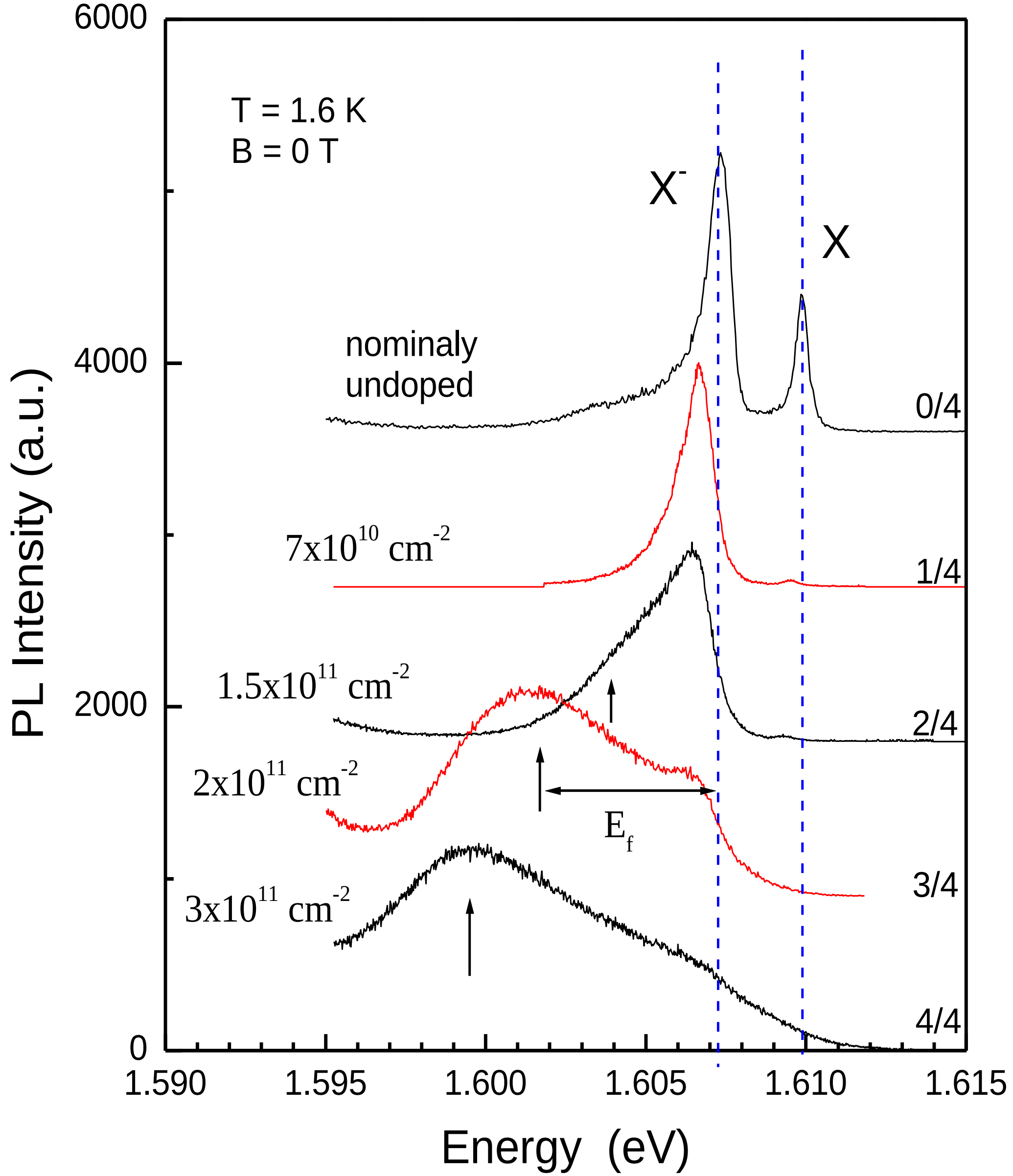
An incident photon creates a virtual trion in the triplet state. This trion produces a spin-flip with one of the electrons on the first Landau level. As a result, in the final state, we get a trion in the singlet state plus an electron on the second Landau level with opposite spin.

This reaction looks

$$e_1^{\uparrow} + e_2^{\uparrow} + ph \rightarrow Tr^{t} + e_1^{\uparrow} \rightarrow Tr^{s} + e_2^{\downarrow}$$

Фотолюминесценция трионов

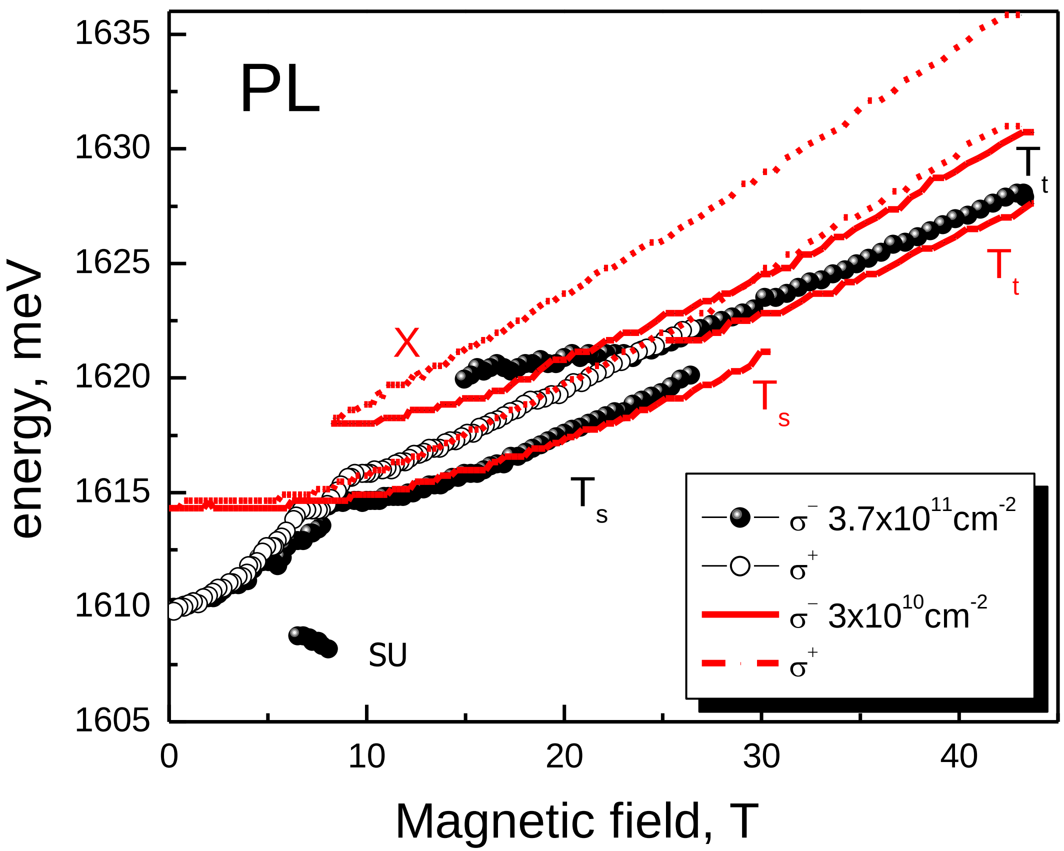
Спектры ФЛ в зависимости от концентрации электронов



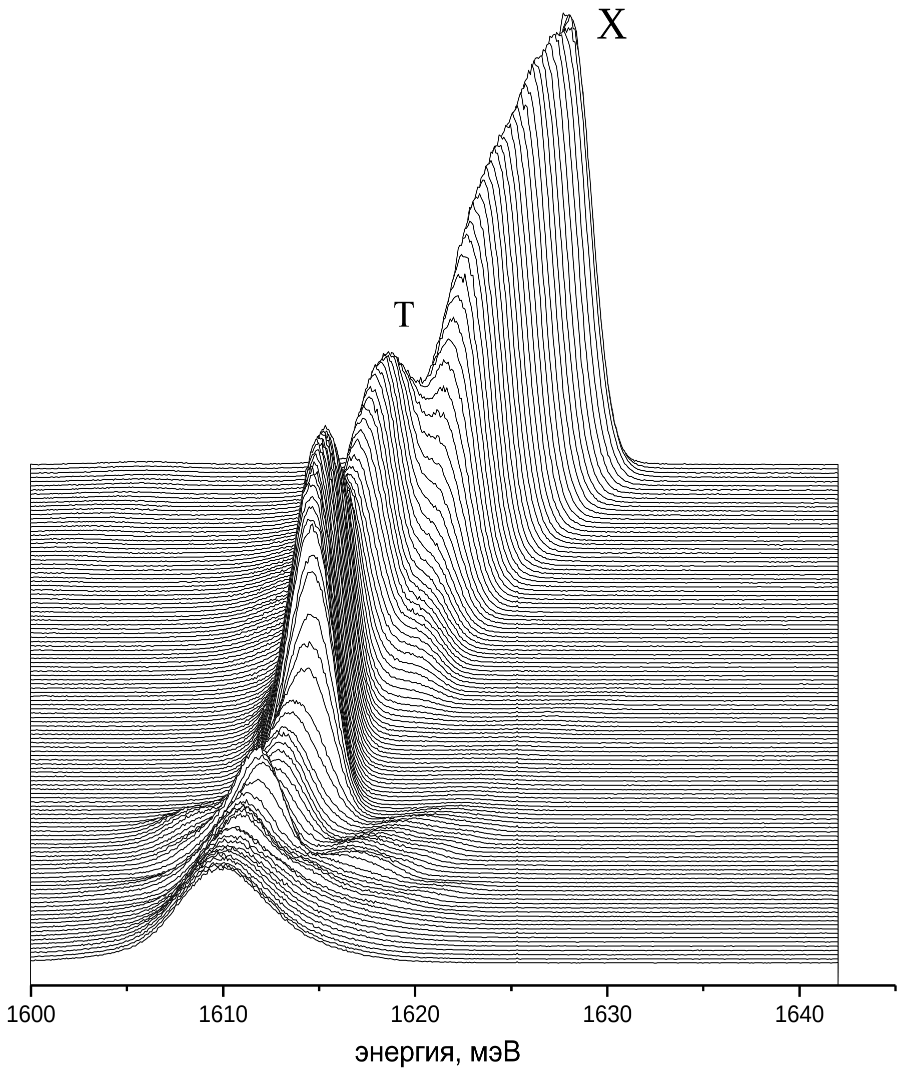
$E_b^{ex} >> E_F$

$E_b^{tr} \sim E_F$

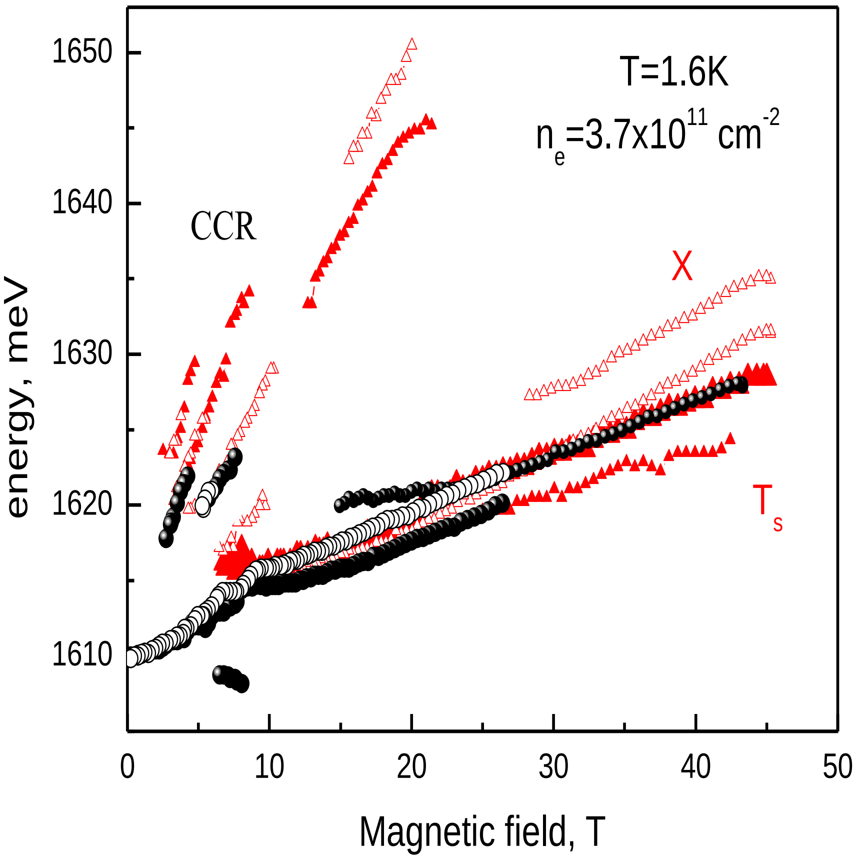
In heavily doped QW in zero magnetic fields the PL line is shifted to the low energies from its position in low doped structure. The value of this shift is of the order of Fermi energy



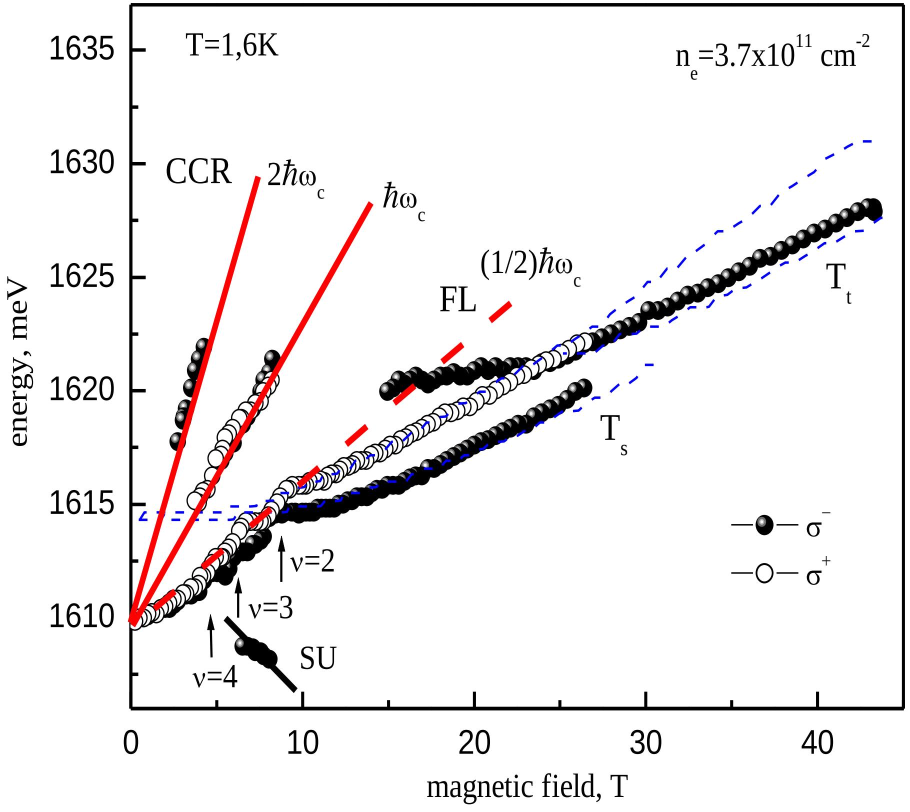
В магнитном поле линии триона и экситона «возрождаются»



Combined processes in PL



Comparison of PL and reflectivity



PL and SU

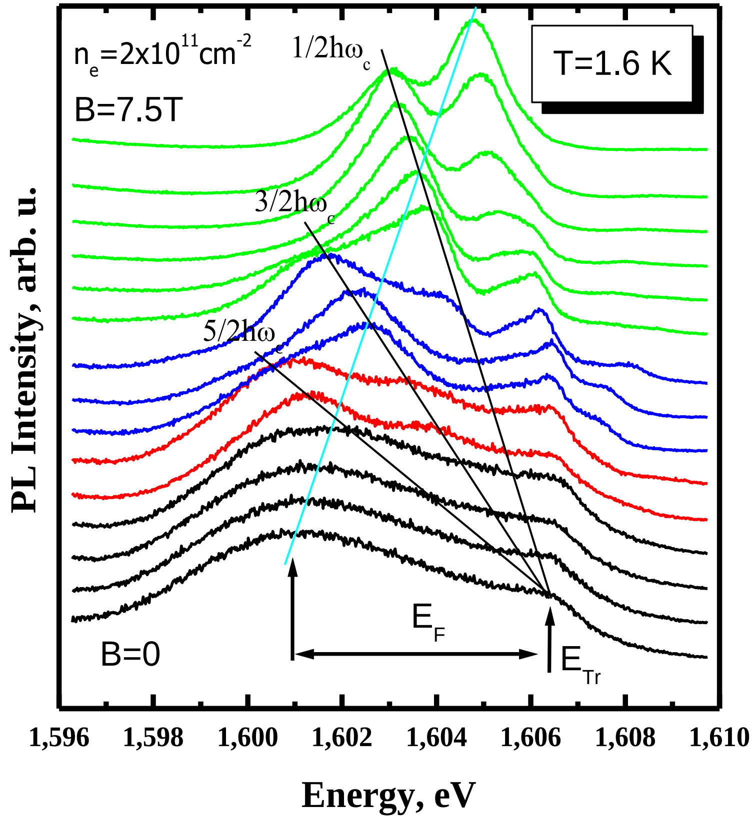
Shake-up

Shake up процессы SU

$$Tr \Rightarrow ph + e^{*}$$

$$E_{tr} = \hbar\omega + (N + \frac{1}{2})\hbar\omega_e^c$$

$$\hbar\omega = E_{tr} - (N + \frac{1}{2})\hbar\omega_e^c$$



In Emission the initial state is: trion in a ground or excited states;

$$\mathrm{T}r \rightarrow ph + e^*$$

the final state is: an electron above Fermi level

The energy of the transition is $$\hbar\omega = E_{Tr} - E^* \leq E_{Tr} - E_F$$

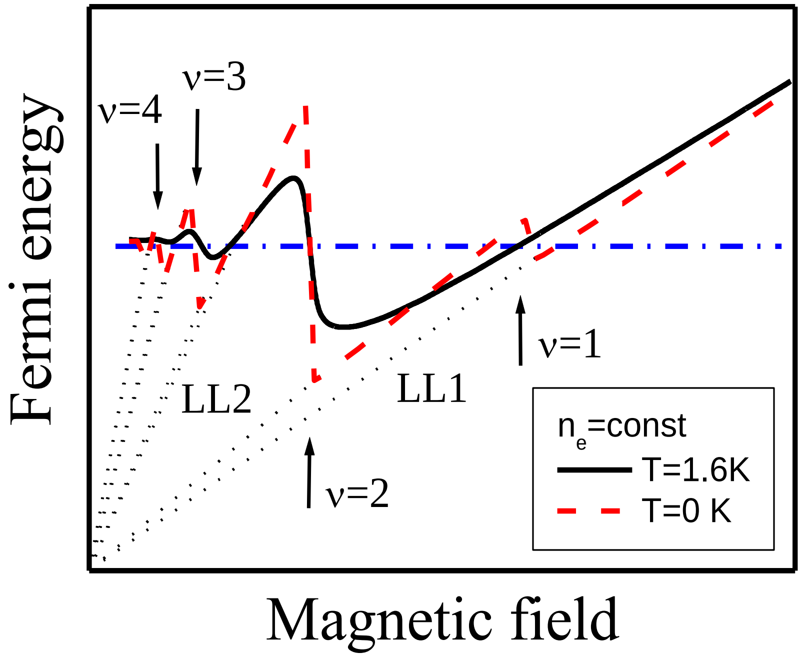
Linear shift of the trion line in magnetic fields

In the final state after the trion recombination a free electron remains. It can appears in the unoccupied states above Fermi level

$$E_{tr} = \hbar\omega + E_F \Rightarrow \hbar\omega = E_{tr} - E_F$$

In magnetic fields the Fermi energy decreases as

$$\frac{1}{2}\hbar\omega_e^c$$



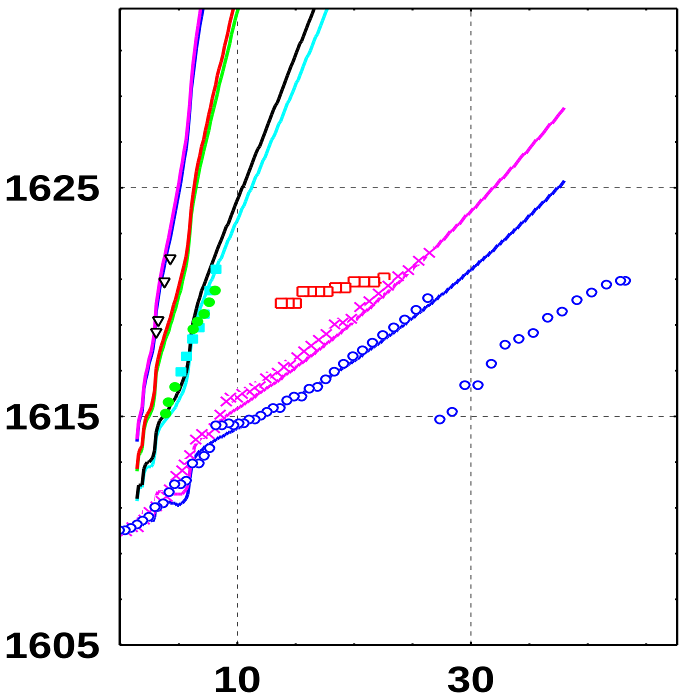
Theory

$$\hbar\omega_{ph}^{\pm} = \hbar\Omega_c(n) - E_{tr} \pm \Delta(B) - E_F(B) + \alpha B + \beta B^2 + E_G$$

Figure gives the energy positions of maxima of emitted bands which are described by equation

The shape of the states in presented by the Gaussian form

$$\rho_n^{\pm}(E) = \frac{eB/(4\pi\hbar)}{\sqrt{2\pi\Gamma_n^2(B)}} \exp\left\{-\left[E - \hbar\omega_{ph}^{\pm}(n)\right]^2 / \left[2\Gamma_n^2(B)\right]\right\}$$



Conclusions

In 2D structures containing electron gas the scattering effects are enhanced.

In the presence of magnetic fields the electron energy spectrum becomes discreet and the scattering processes revel as combined exciton-electron processes.

In such processes we can see directly only the exciton transition but the state of the additional electron, which we can not see, reveals only in the final result.