

Photoluminescence of p-doped quantum wells with strong spin splitting

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Thank you all

- **MBE growth**

M. Bertolini¹, S. Tatarenko¹

- **Spectroscopy and analysis**

D. Ferrand¹, J. Cibert^{1,4}, P. Kossacki^{1,2,3}, J.A. Gaj^{1,2}

- **Time resolved PL**

V.Ciulin³, B. Deveaud-Pledran³

- **Transmission at high magnetic fields**

M. Potemski⁵

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2 Institute of Experimental Physics, Warsaw University – POLAND

3 Institute of Quantum Electronics and Photonics, EPFL – SWITZERLAND

4 Laboratoire Louis Néel, CNRS, Grenoble - FRANCE

5 High magnetic field laboratory, CNRS, Grenoble - FRANCE

Outline

I Material and samples

(Cd,Mn)Te based p-type modulation doped QW

II PL versus spin splitting

- PL at vanishing hole density

Switching from X^+ to X

- PL at large hole density

Switching from X^+ to (D_{hi}, D_{low})

X^+ transition and hole gas polarization

III Characteristic energies

IV Back to the hole density determination

V Conclusion

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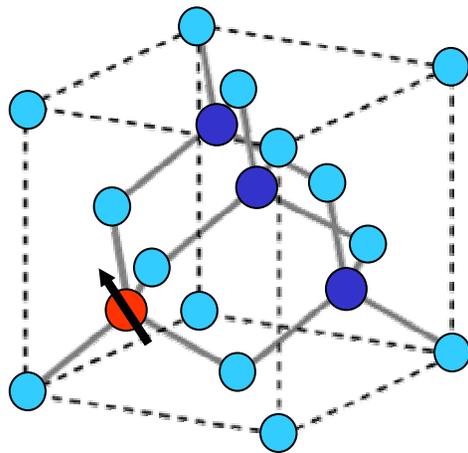
III Characteristic energies

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Diluted magnetic semiconductor: (Cd,Mn)Te

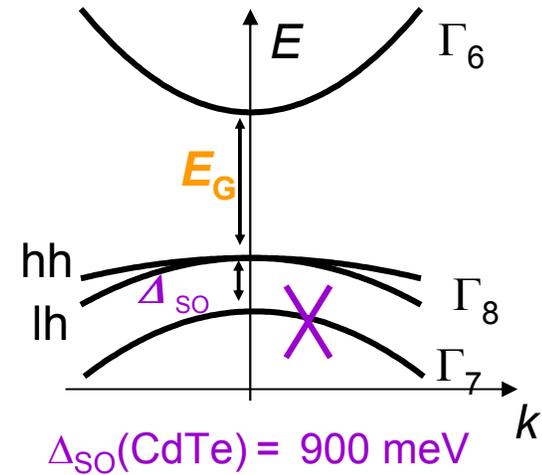
- Randomly distributed localised spins (Mn)



Semiconductor

- Cd
- Te

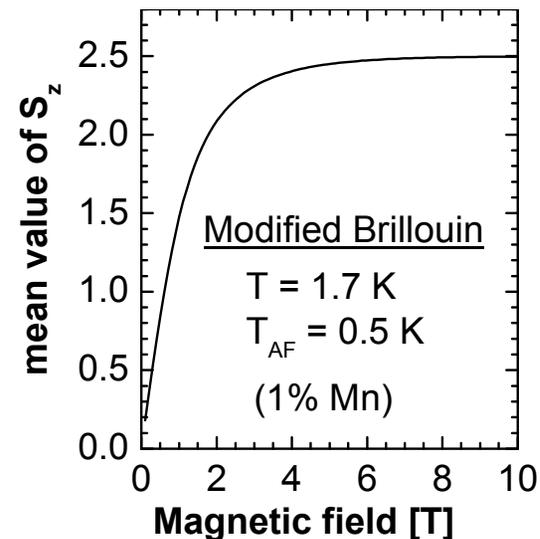
Localised Spins ($S = 5/2$)



Modified Brillouin function

$$M = \frac{5}{2} g \mu_B N_0 x_{eff} B_{\frac{5}{2}} \left(\frac{\frac{5}{2} g \mu_B B}{k_B (T + T_{AF})} \right)$$

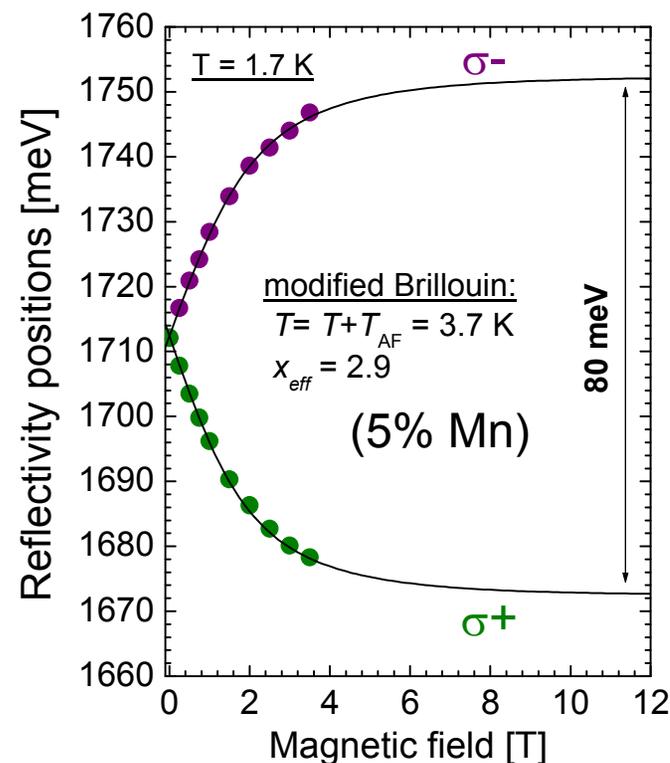
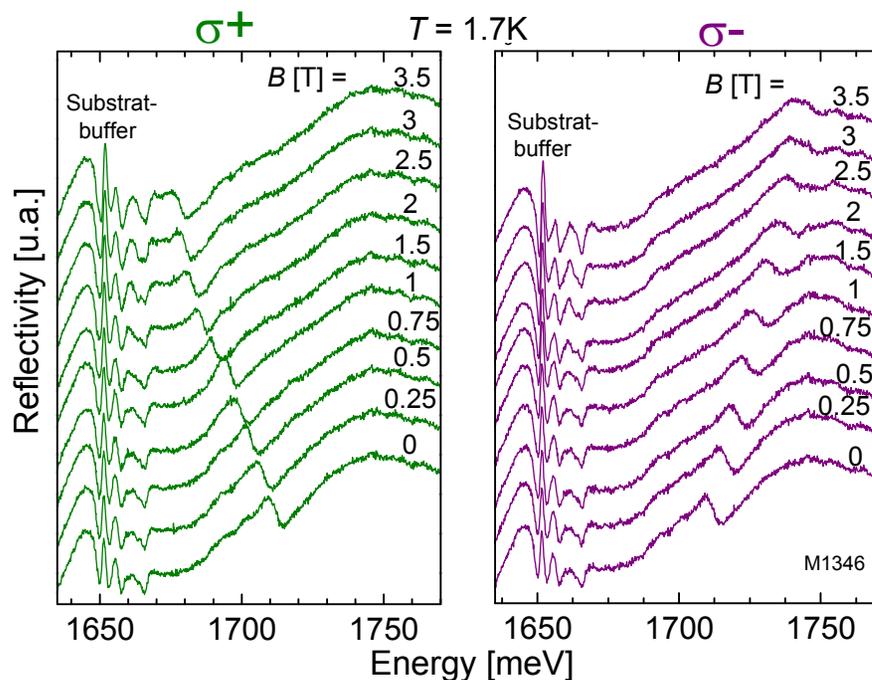
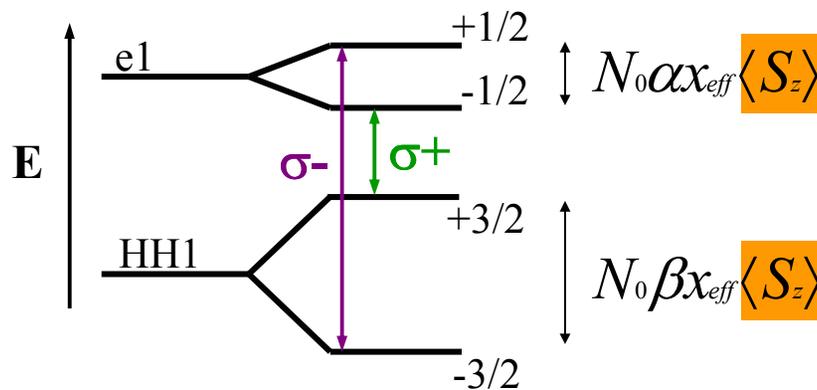
$$= g \mu_B N_0 x_{eff} \langle S_z \rangle$$



Diluted magnetic semiconductor: (Cd,Mn)Te

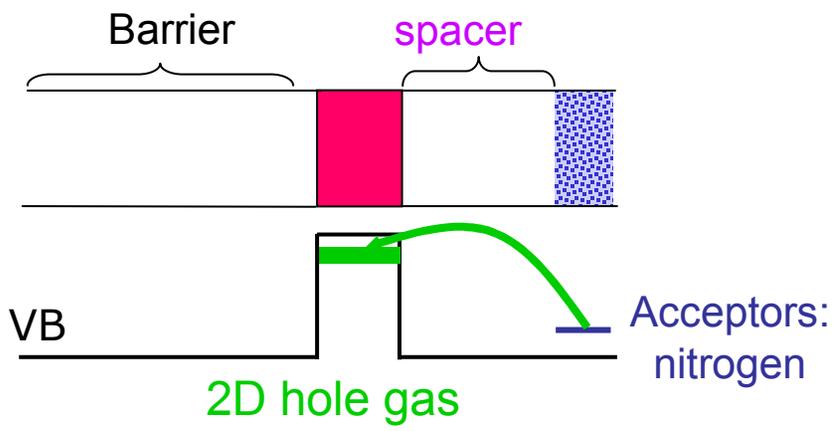
• Exchange interaction: 3d Mn states – s,p states of the semiconductor matrix

Giant Zeeman splitting



P-type doping and control

•Modulation doped



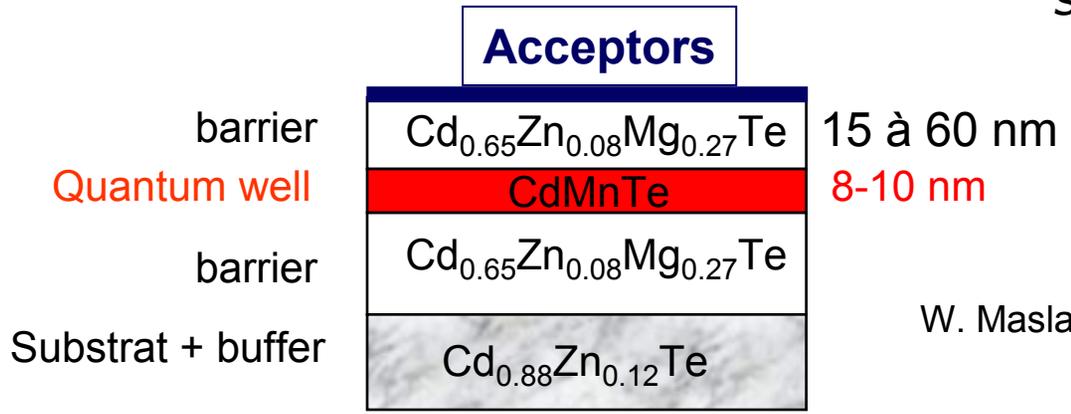
Control :

spacer thickness
acceptor concentration

•Surface doped

Control:

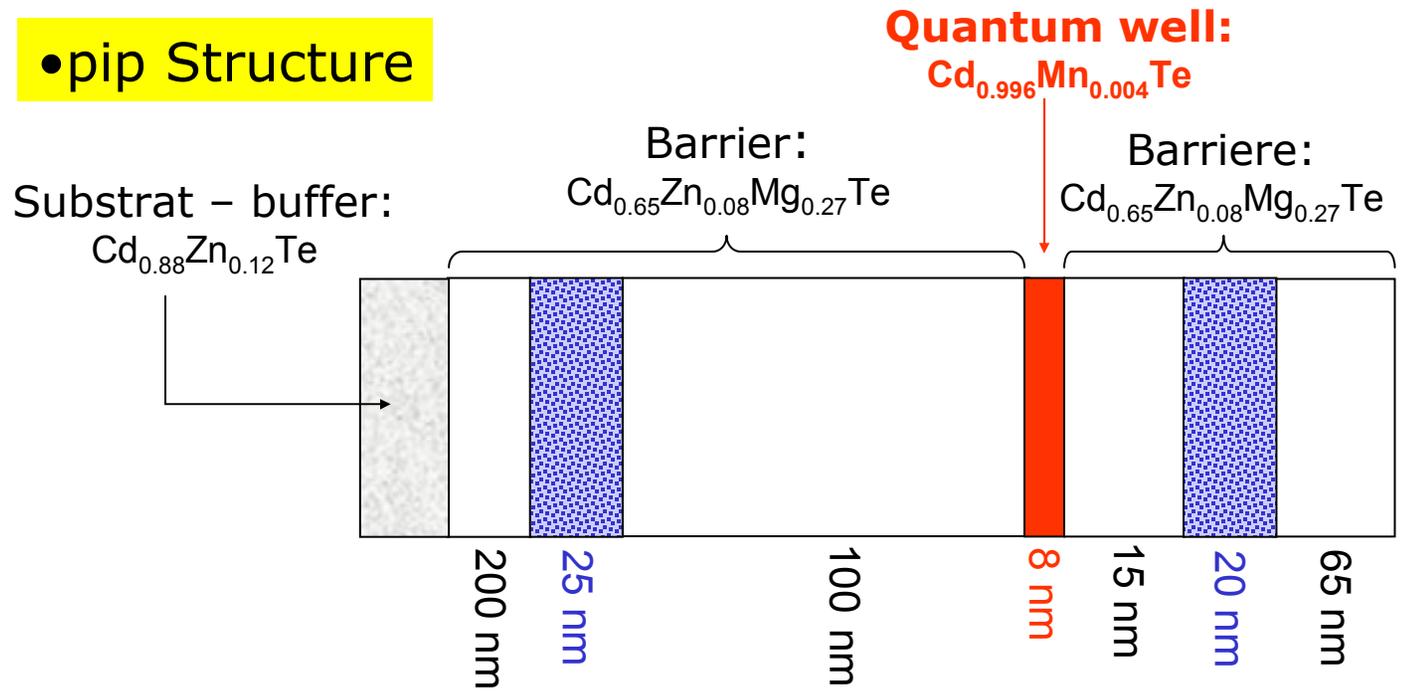
surface/quantum well Distance



W. Maslana et al., *Appl. Phys. Lett.* **82**, 1875 (2003)

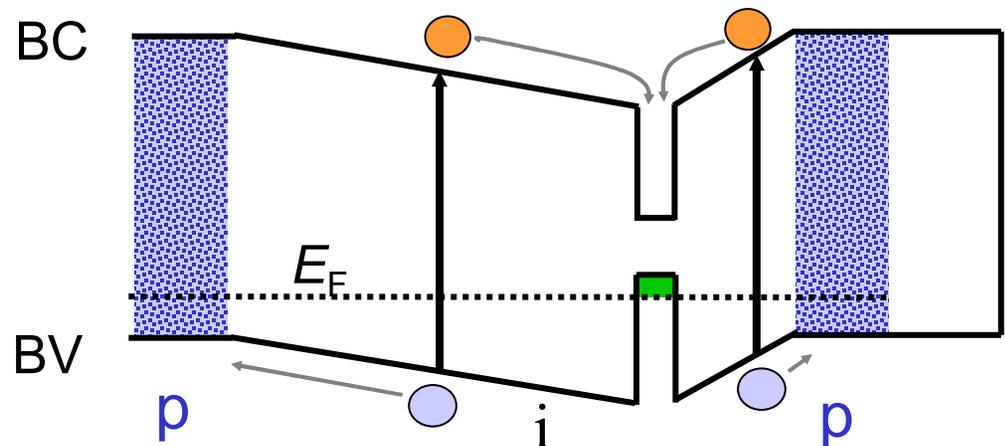
Optical control

•pip Structure



P-type doped (N)
($\approx 3 \cdot 10^{17}/\text{cm}^3$)

•Above barrier illumination



Electrical control of the hole density

•pin diode

p-type Nitrogen doped
($\approx 3 \cdot 10^{17}/\text{cm}^3$)

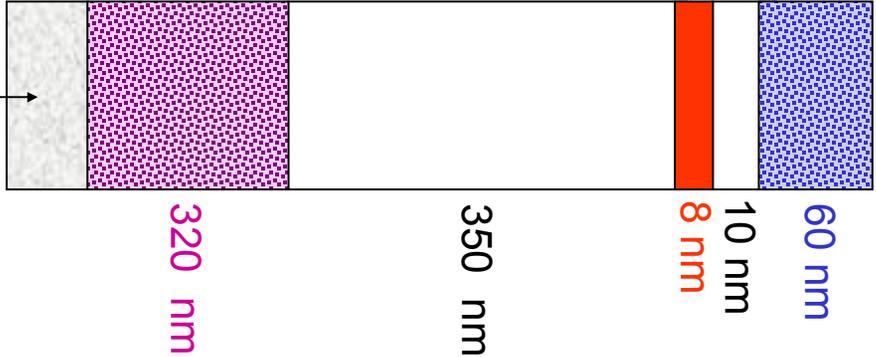
n-type Aluminium doped
($\approx 3 \cdot 10^{18}/\text{cm}^3$)

Substrat – buffer:
 $\text{Cd}_{0.88}\text{Zn}_{0.12}\text{Te}$

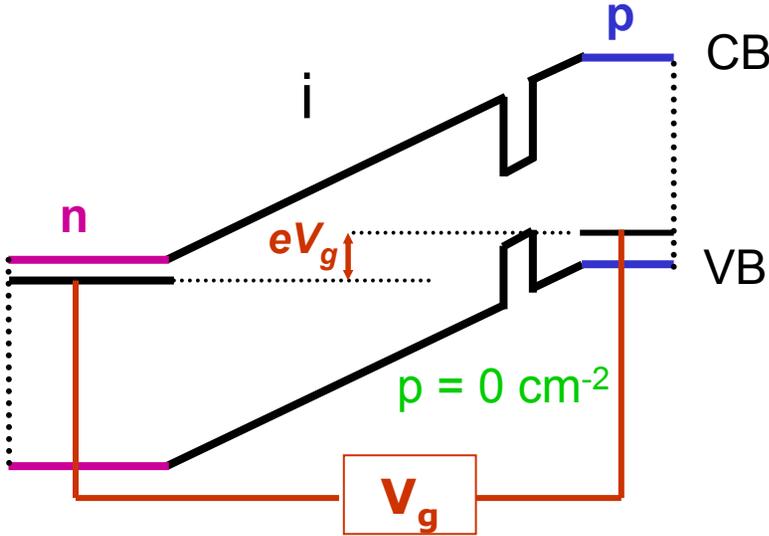
Barrier:
 $\text{Cd}_{0.65}\text{Zn}_{0.08}\text{Mg}_{0.27}\text{Te}$

Quantum well:
 $\text{Cd}_{0.95}\text{Mn}_{0.05}\text{Te}$

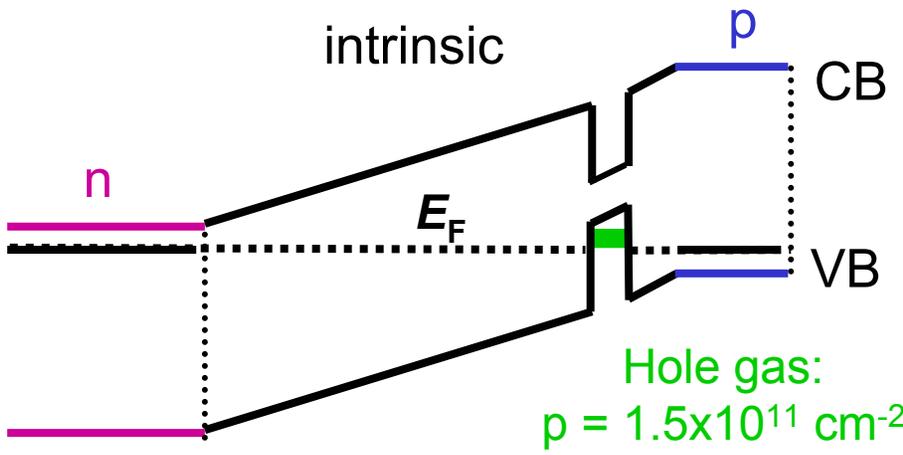
Barrier:
 $\text{Cd}_{0.65}\text{Zn}_{0.08}\text{Mg}_{0.27}\text{Te}$



•Reverse bias: $V_g < 0$



•Band structure at equilibrium

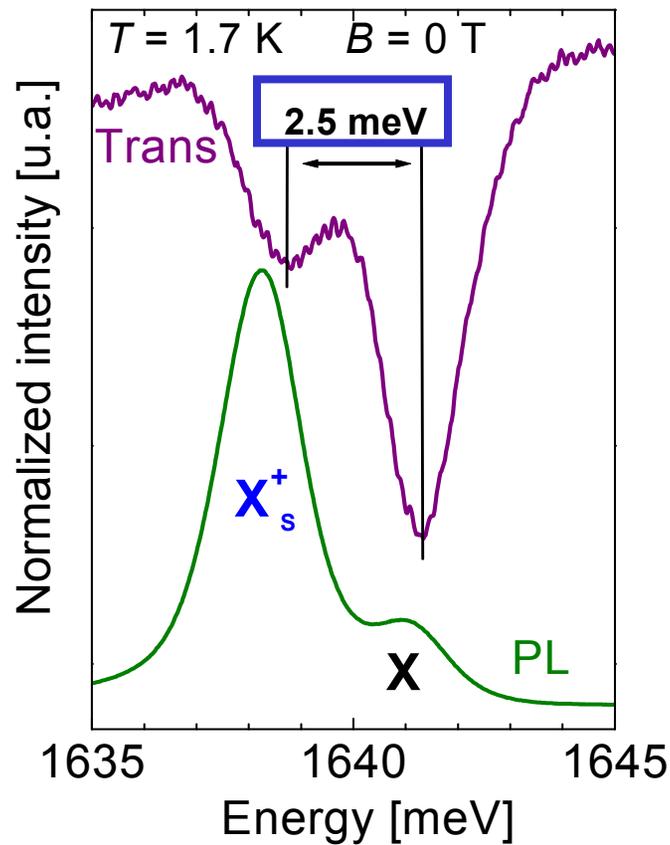


Important energies

Hole gas Fermi energy:

Max: $E_F = 3$ meV

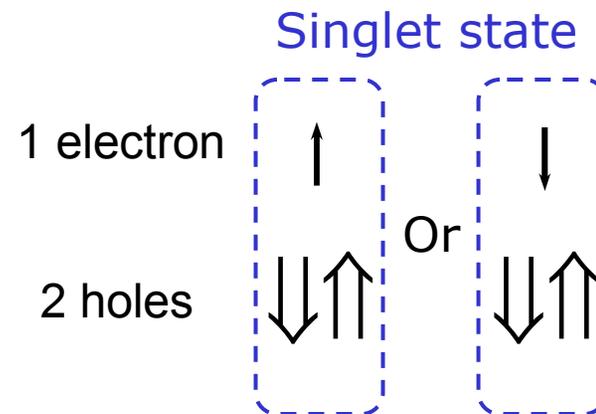
8 nm $\text{Cd}_{0.996}\text{Mn}_{0.004}\text{Te}/(\text{Cd,Zn,Mg})\text{Te}$ QW



Exciton binding energy: **X**

$E_b(\text{X}) \approx 20$ meV

Positively charged exciton: **X_s^+**



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Switching from X^+ to (D_{hi}, D_{low})

X^+ transition and hole gas polarization

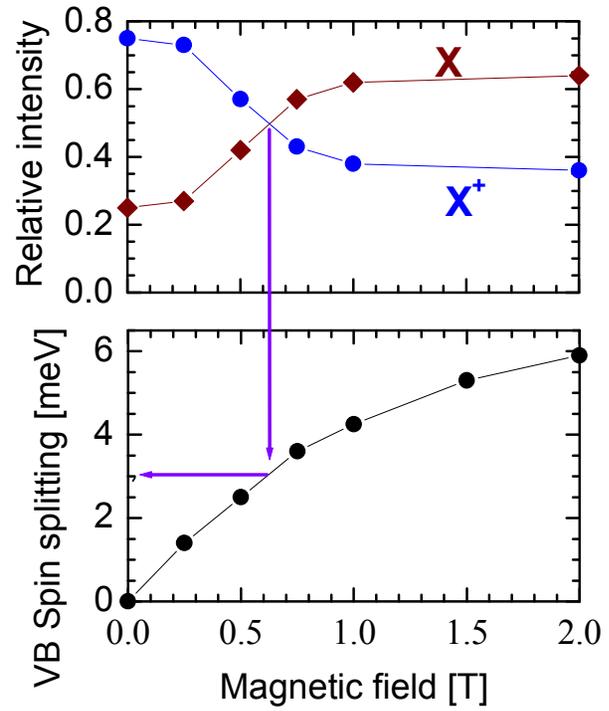
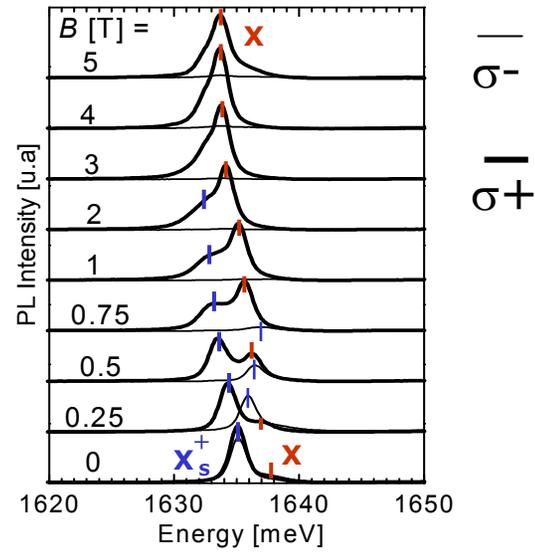
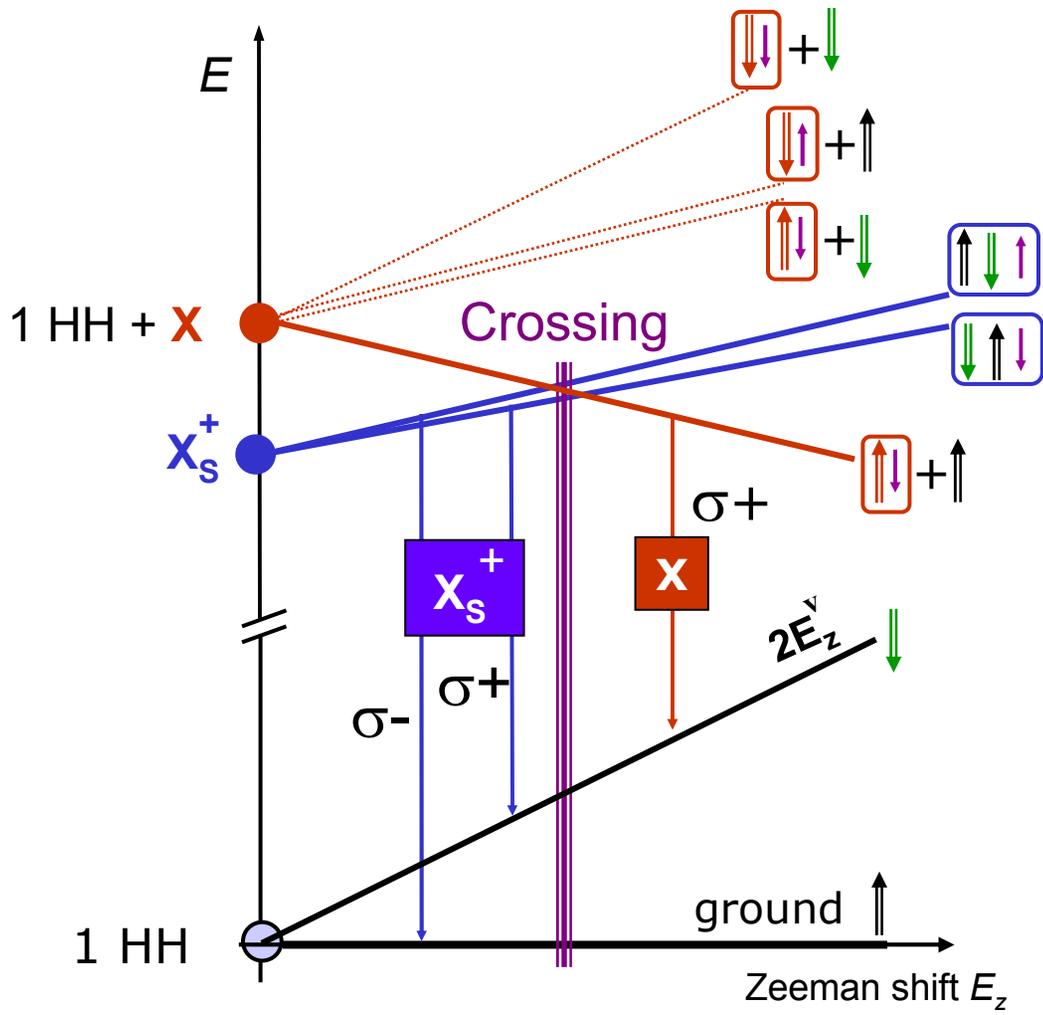
III Characteristic energies

IV Back to the hole density determination

V Conclusion

PL at vanishing hole density

$\bullet p \leq 2 \times 10^{10} \text{ cm}^{-2}$



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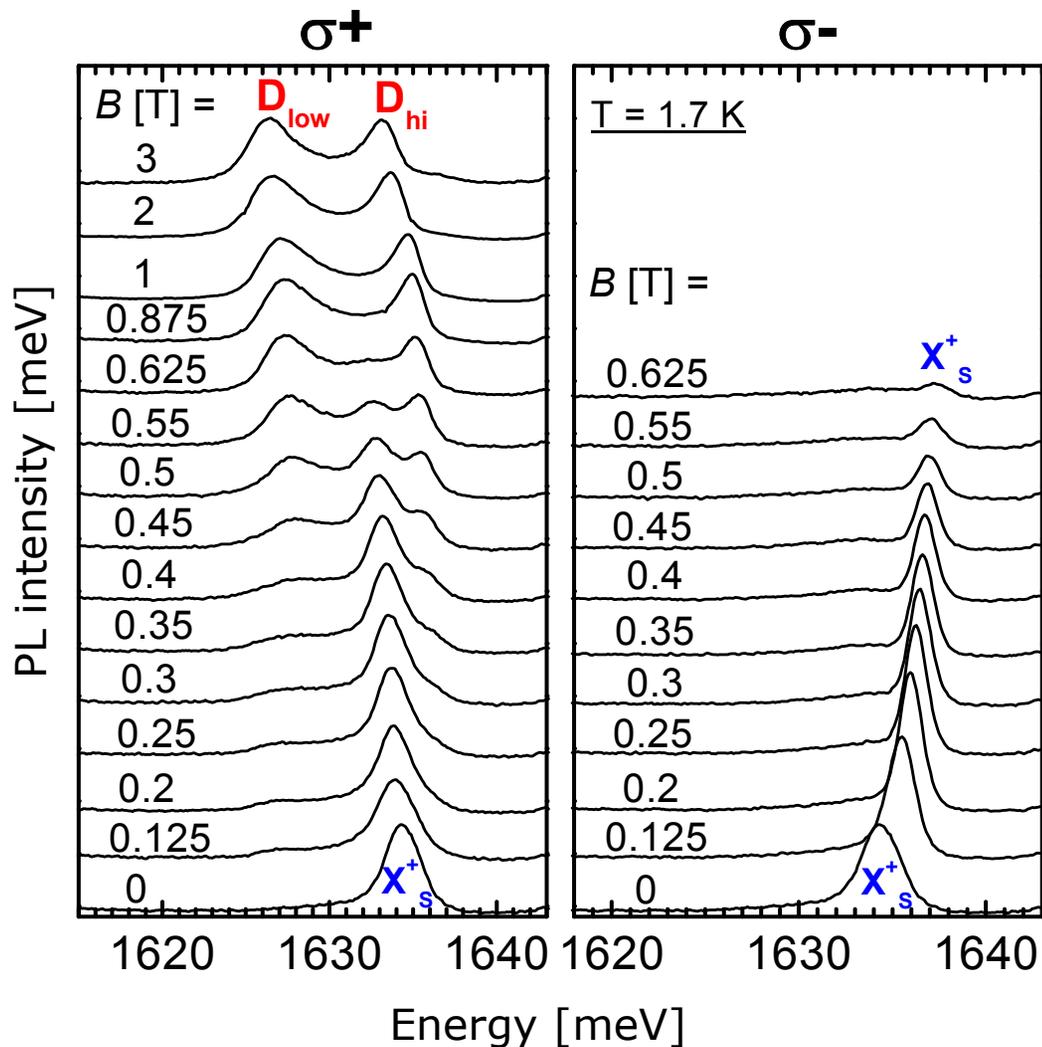
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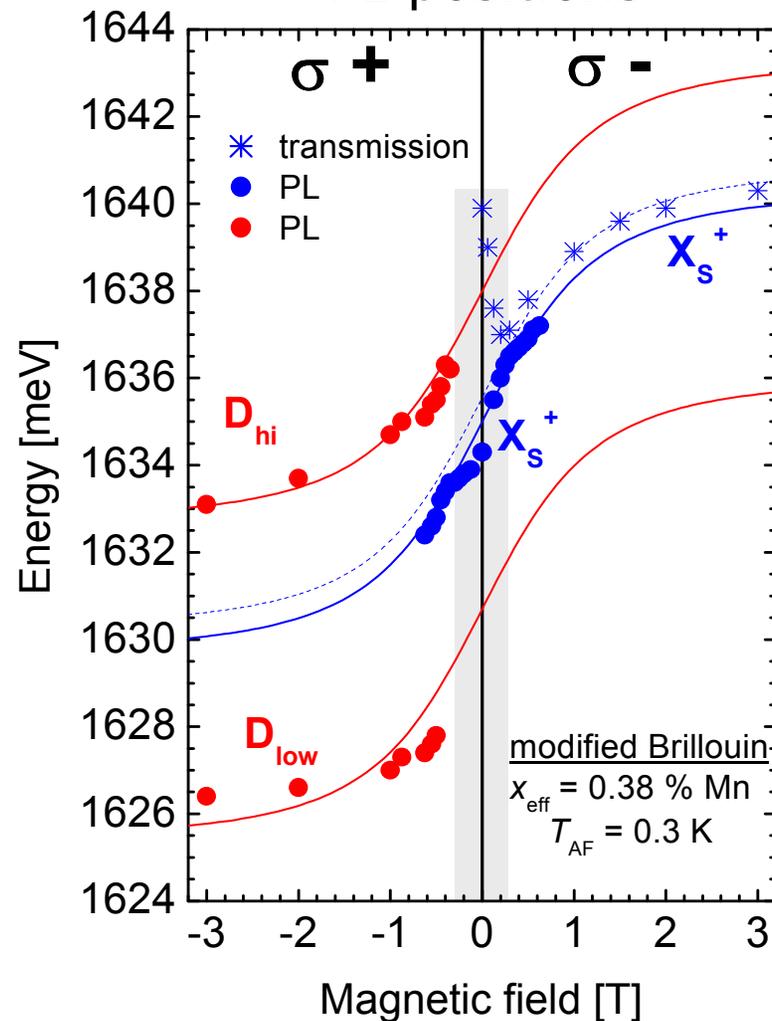
PL at larger hole density

$$\bullet p = 2.6 \times 10^{11} \text{ cm}^{-2}$$

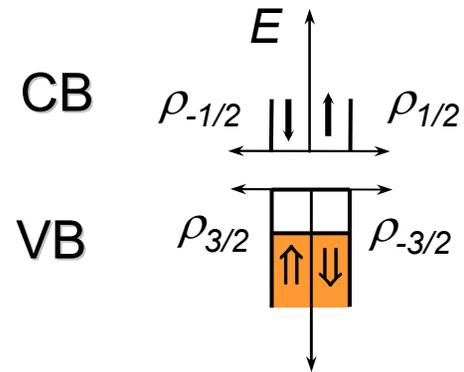
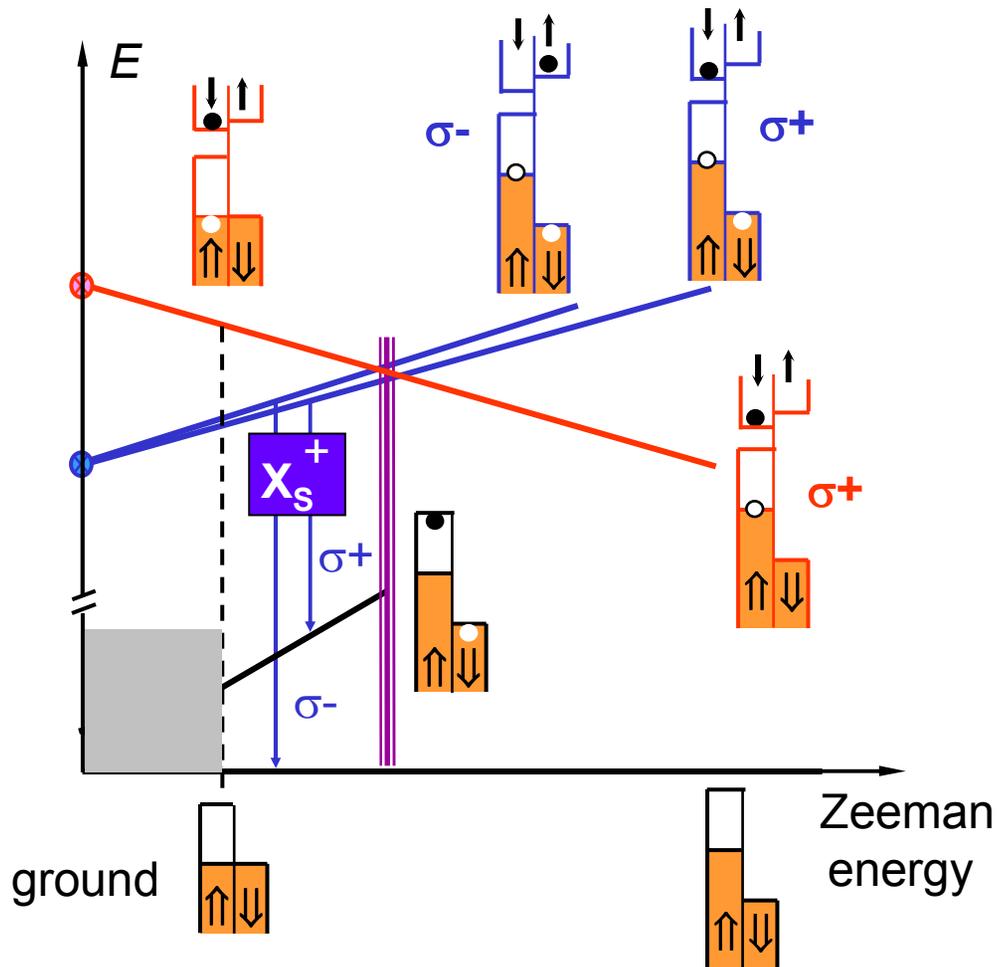
pip structure



PL positions

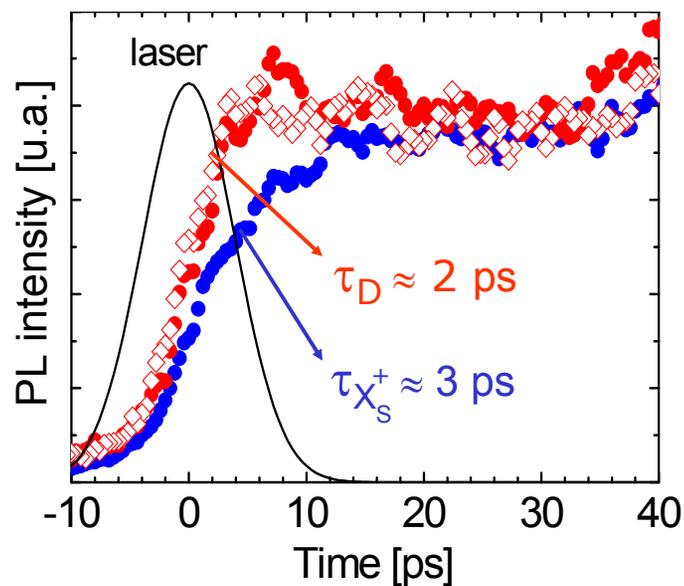
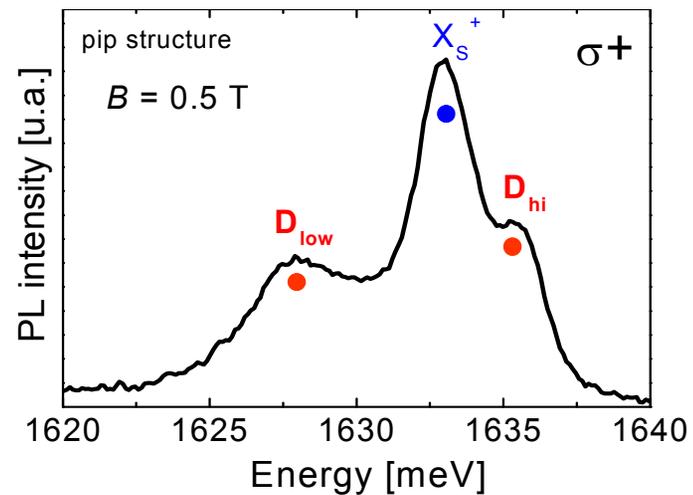
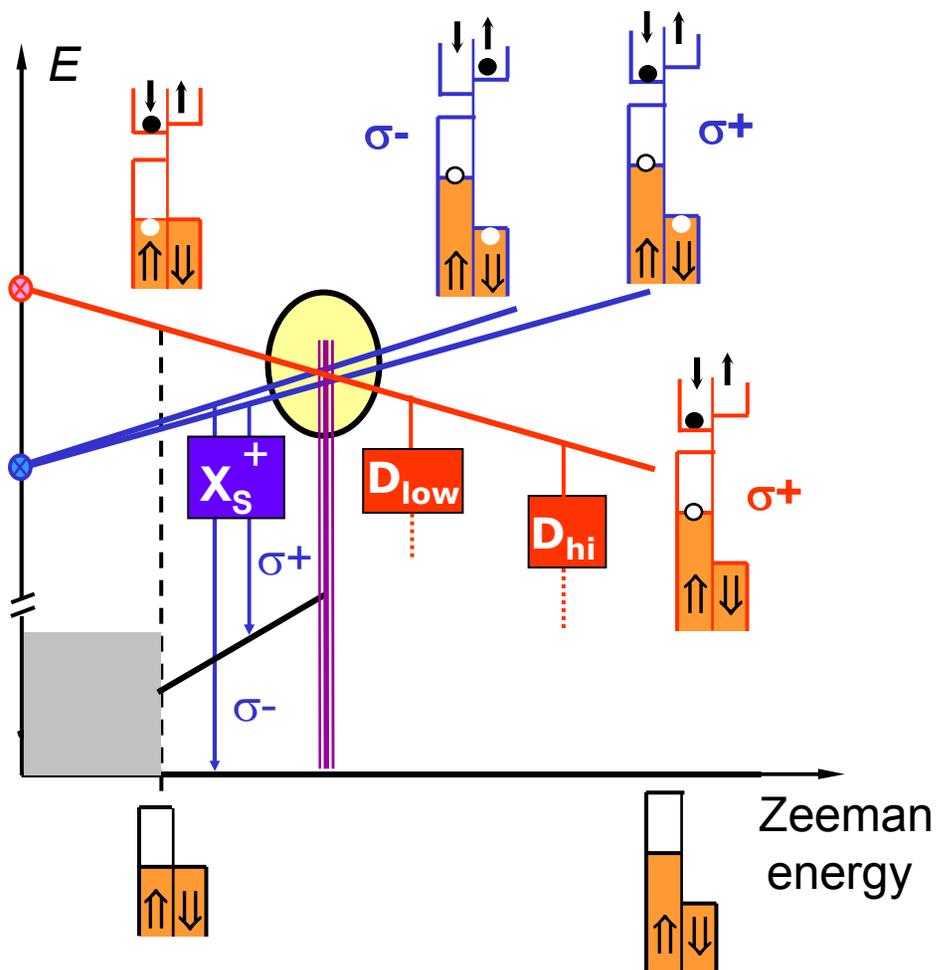


Destabilization of the singlet X^+

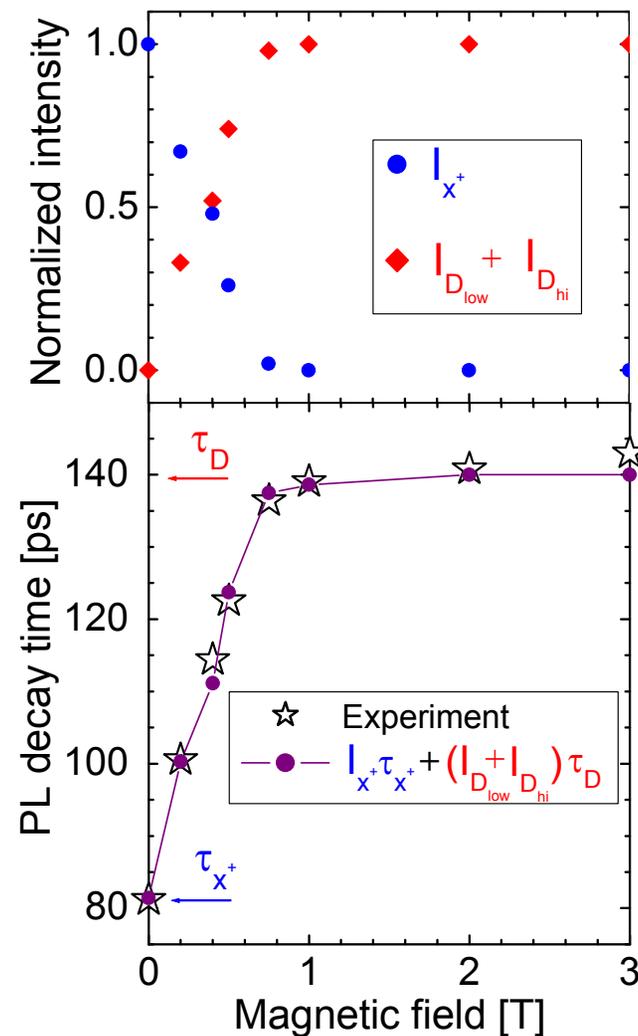
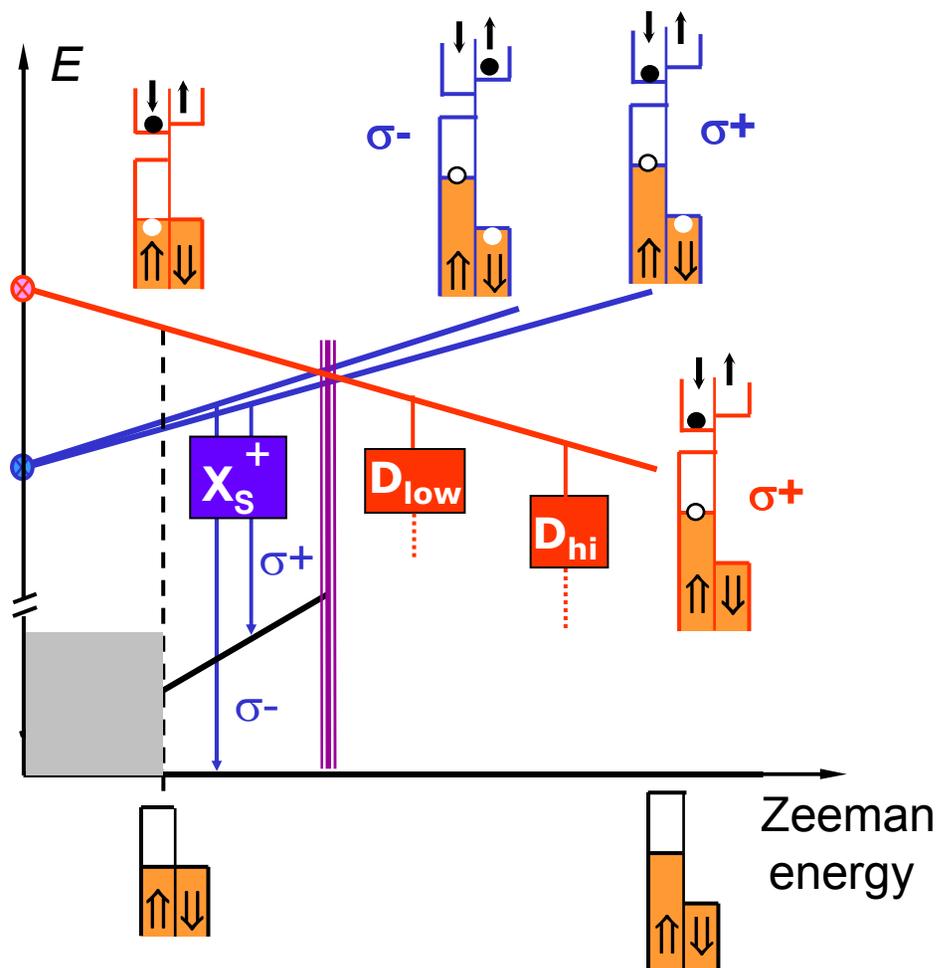


D_{hi} and D_{low} : the same initial state

•At the crossing point



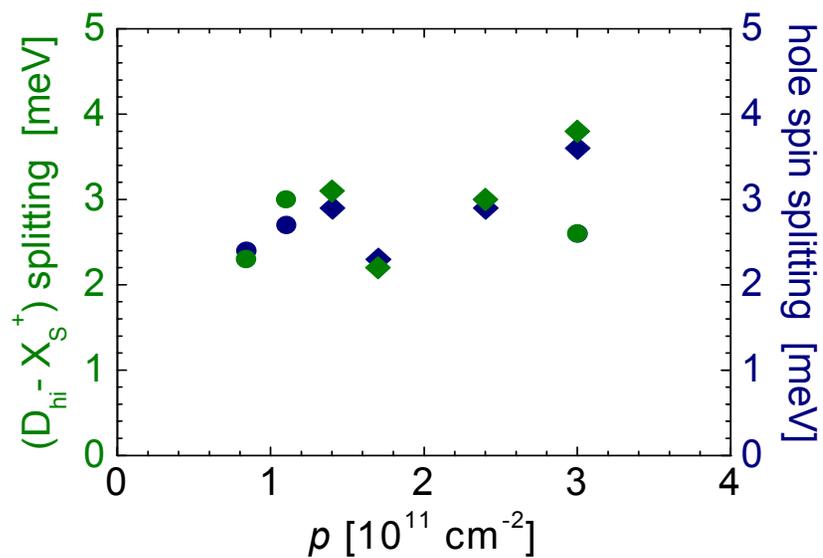
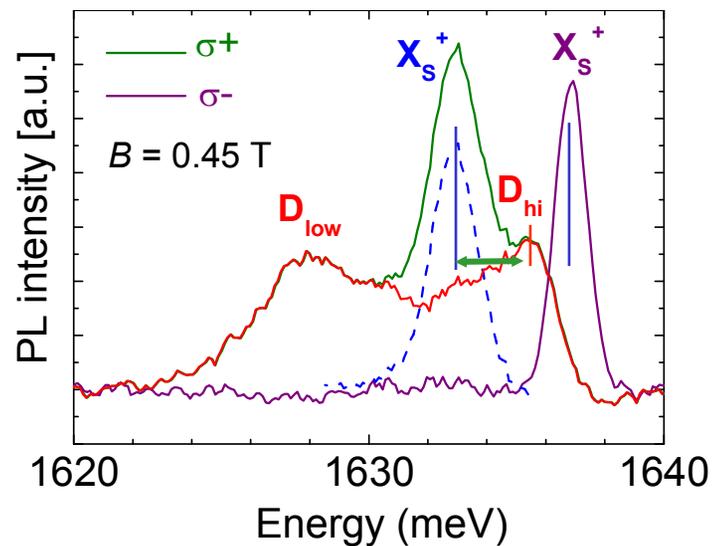
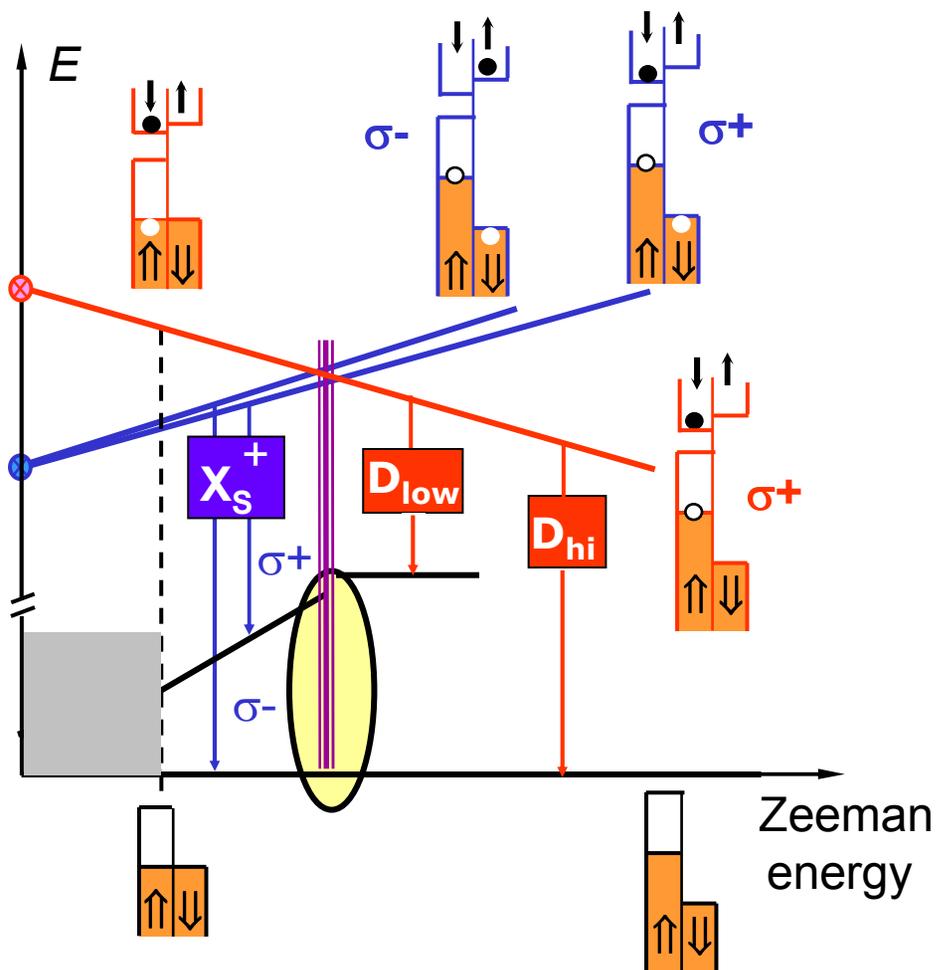
D_{hi} and D_{low} initial state – identification !



Transfer of oscillator strength from X^+ to a state with less correlated particles

D_{hi} and D_{low} final states

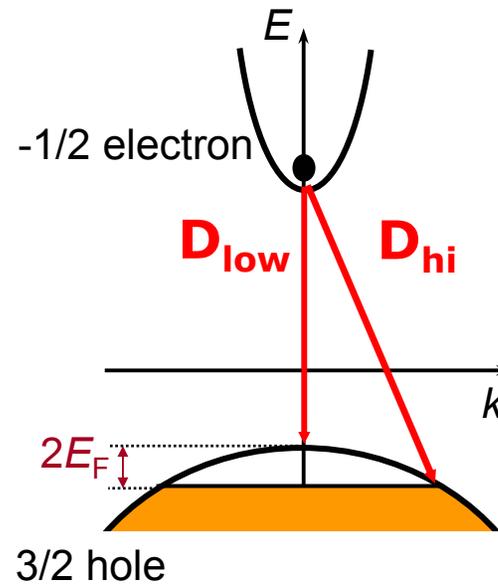
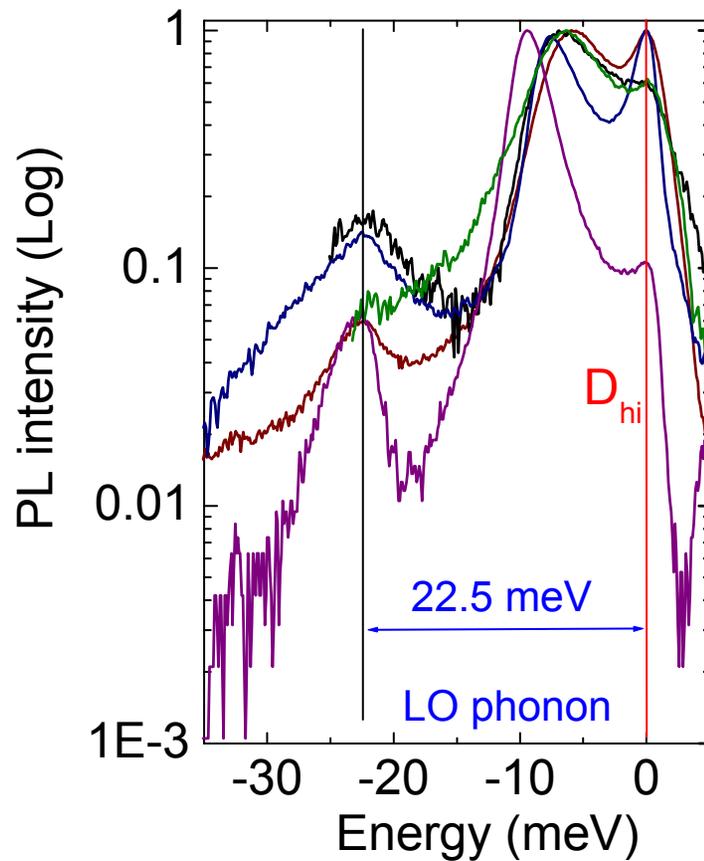
•At the crossing point



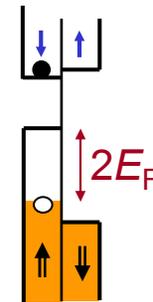
D_{hi} and D_{low} : indirect and direct transitions

σ^+ transitions

Phonon replica only associated to D_{hi}

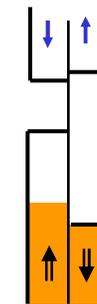


Initial state



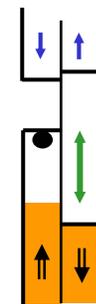
Final states

D_{hi}



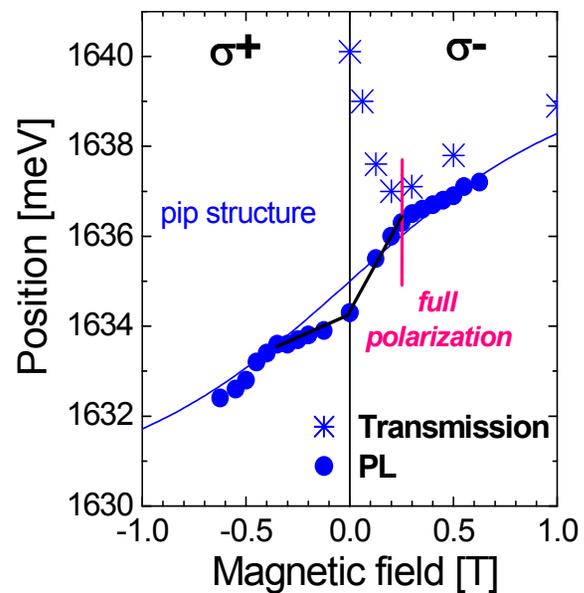
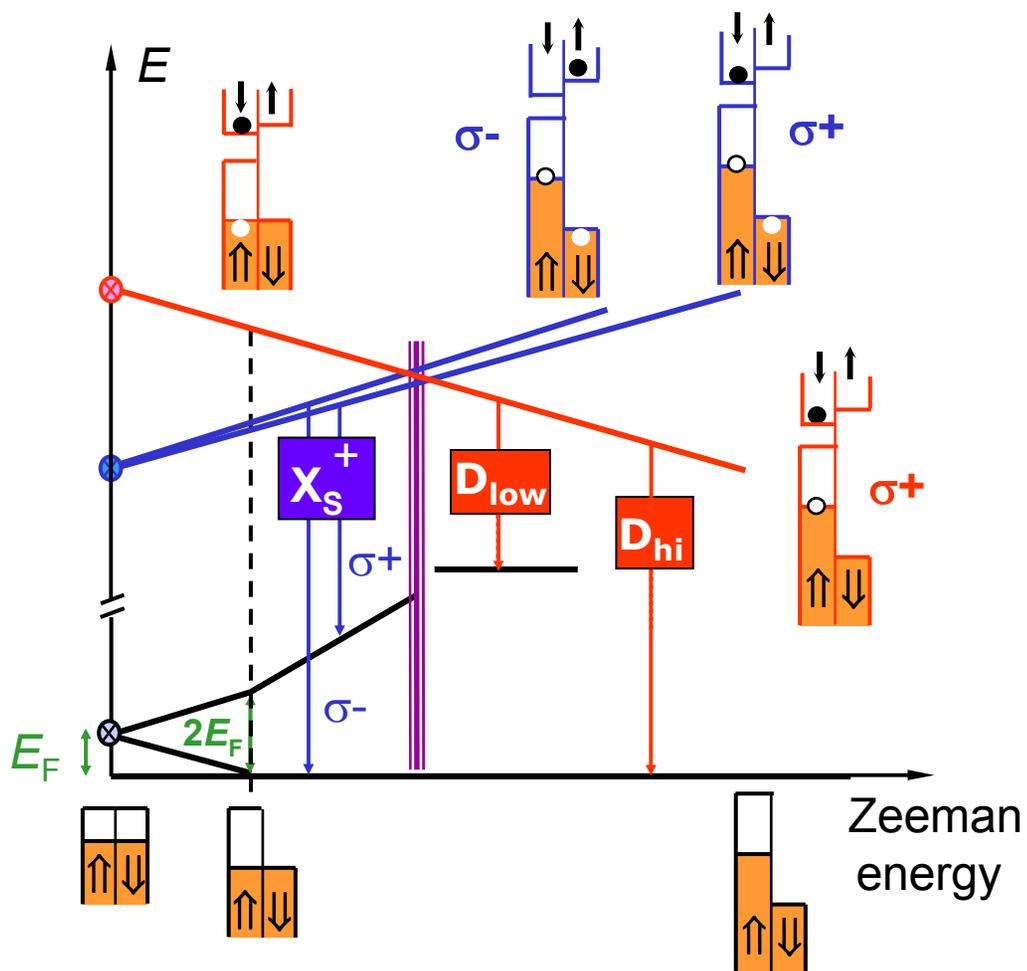
Ground

D_{low}

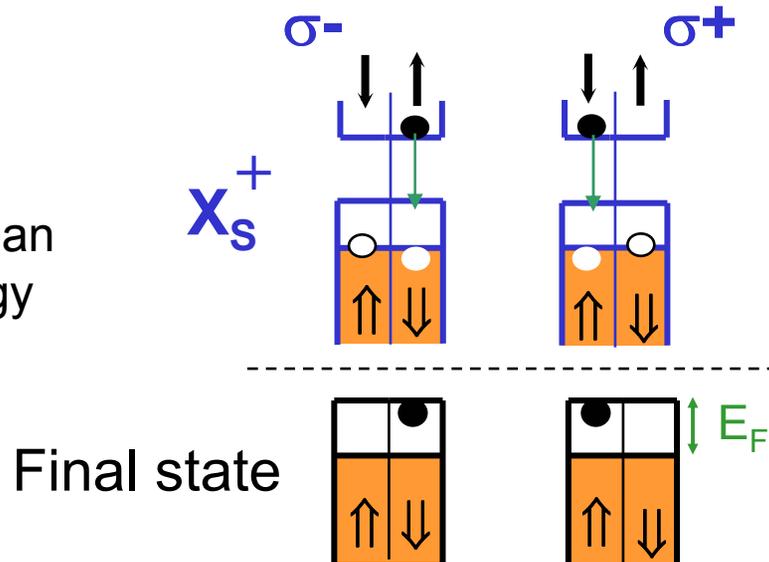


Excited

Small spin splitting: Polarization of the hole gas



At zero magnetic field



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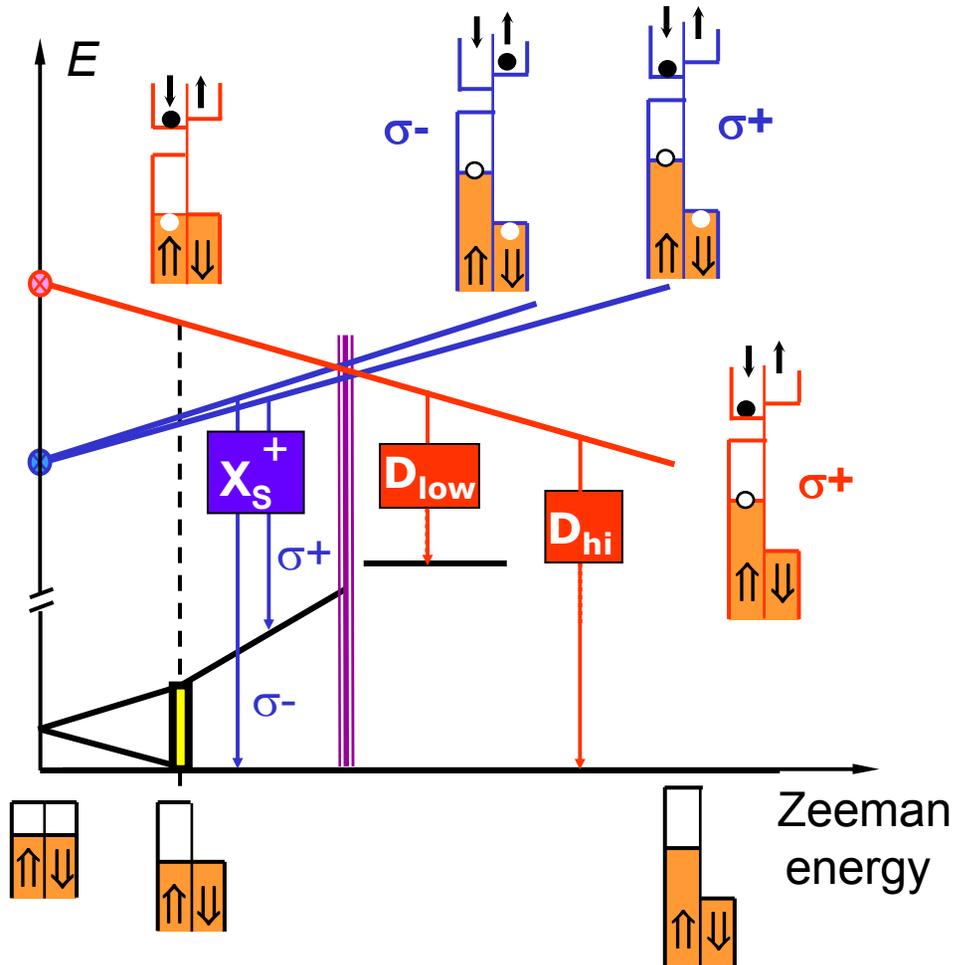
X^+ transition and hole gas polarization

III Characteristic energies

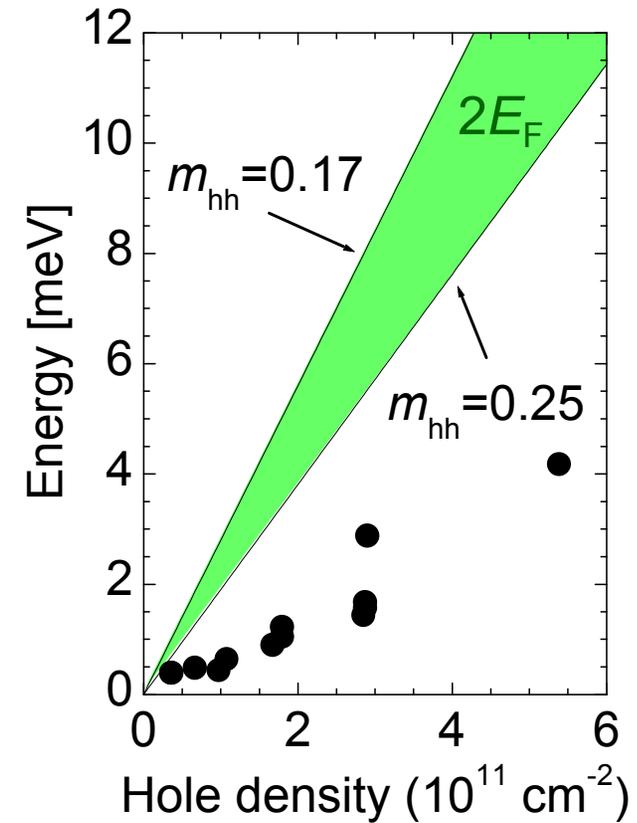
IV Back to the hole density determination

V Conclusion

Spin splitting at full polarization

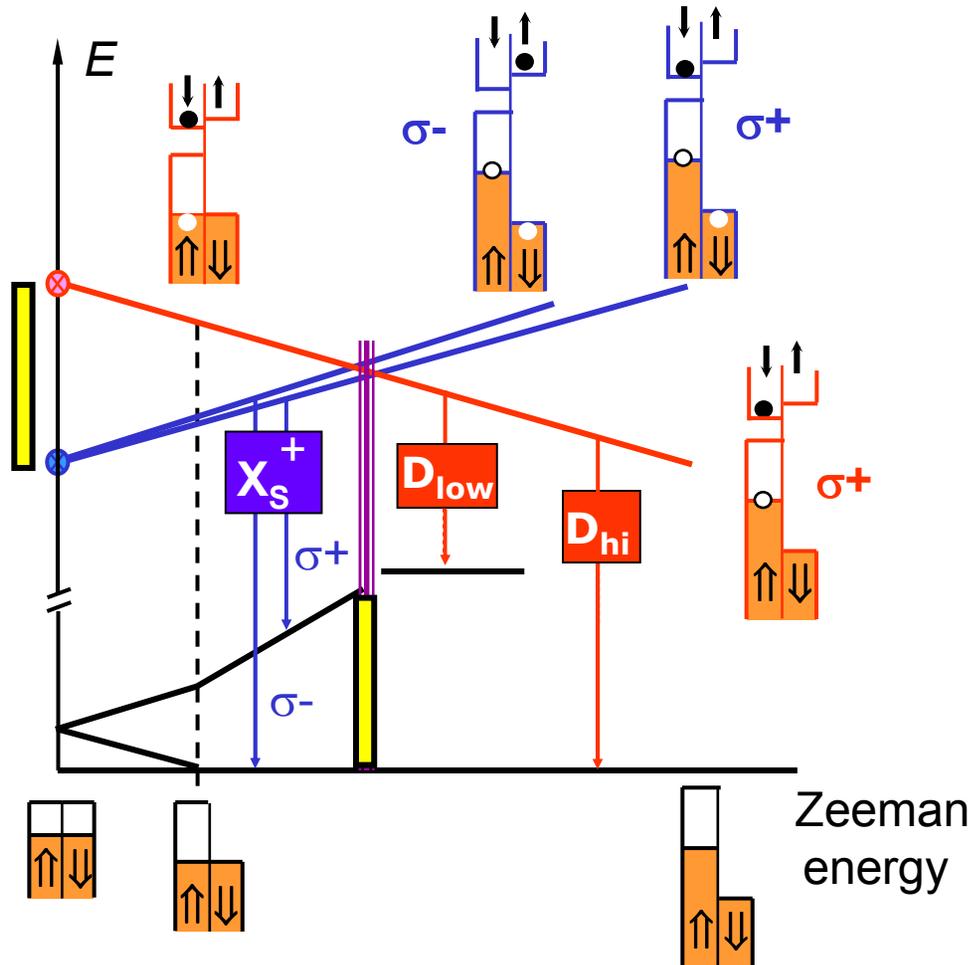


VB splitting at full polarization

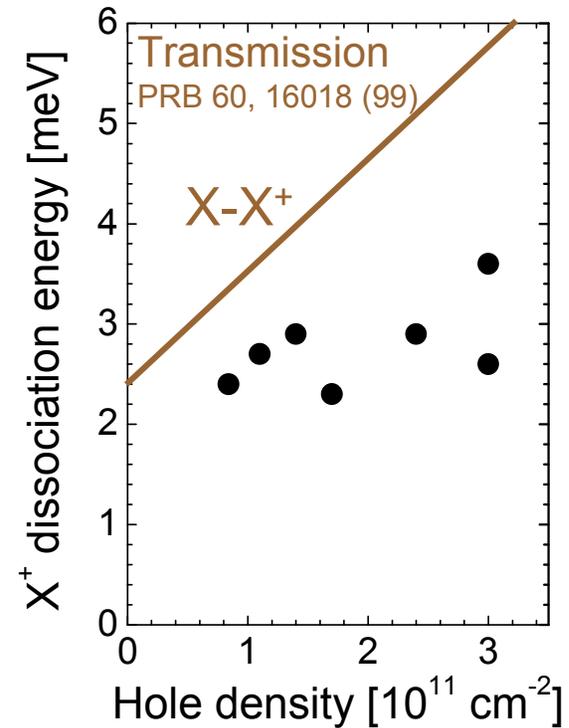


Hole-hole interactions !

Spin splitting needed to destabilize the singlet X^+

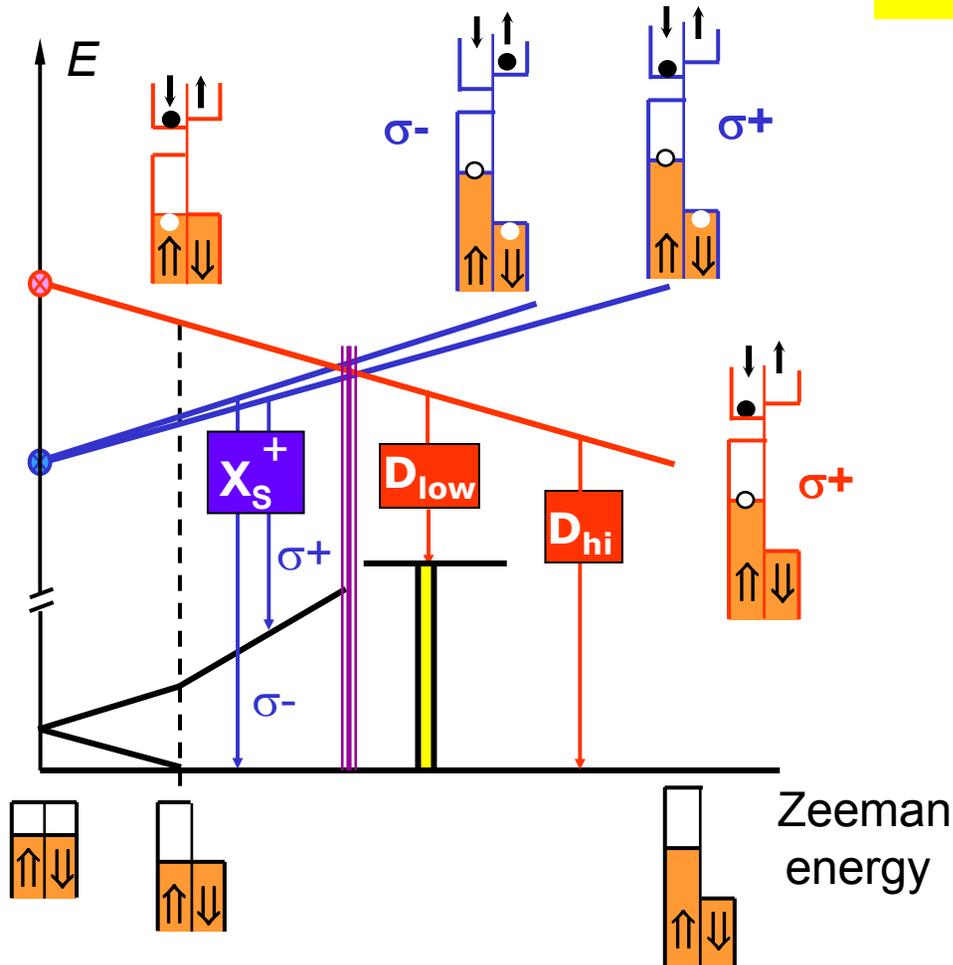


VB splitting at crossing point

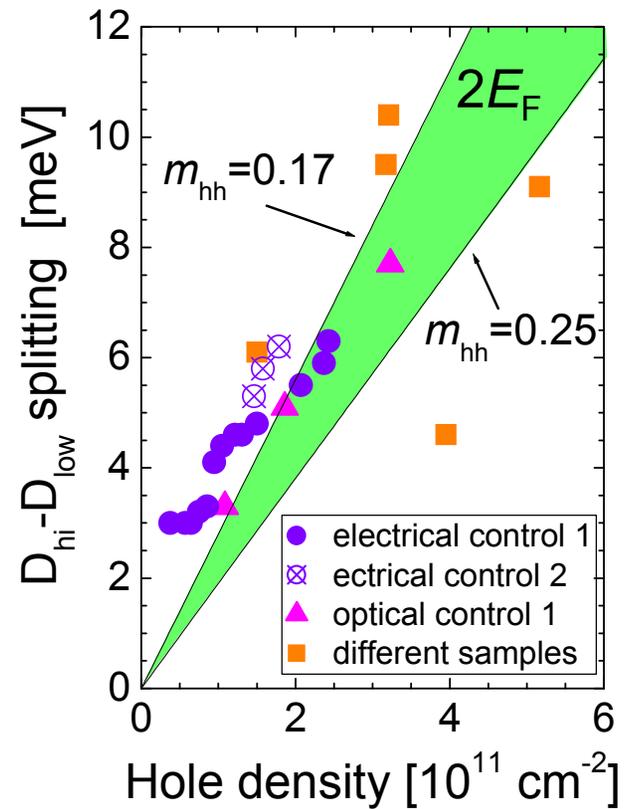


Binding energy !

Hole gas excitation



A measure of the energy left in the gas



Nature of the excitations !

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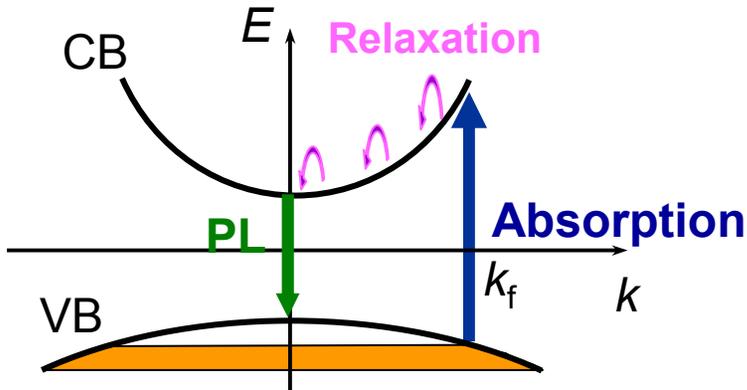
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In the band-to-band regim

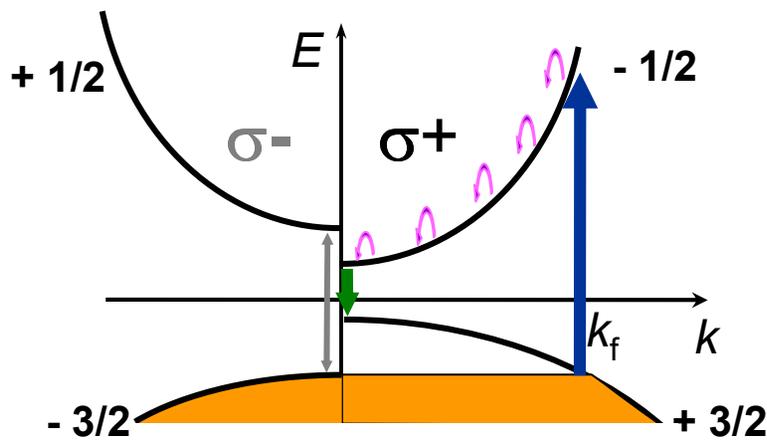
Moss-Burstein shift

Zero magnetic field



includes Stockes shift

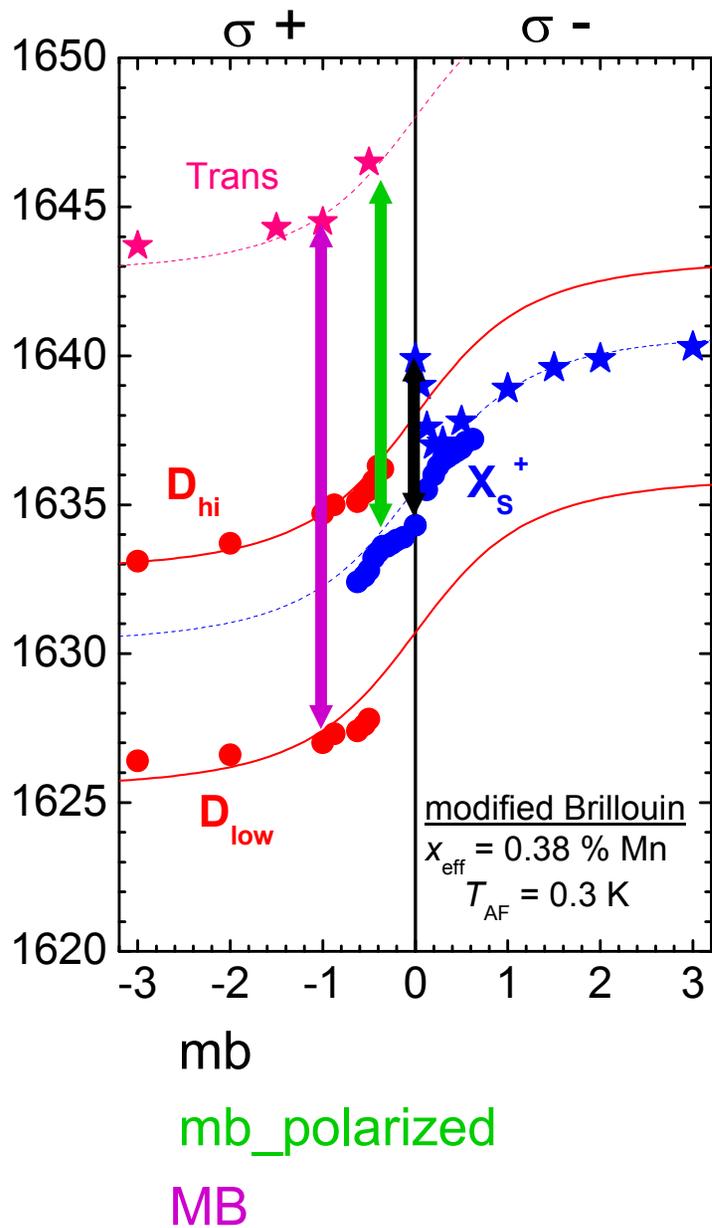
At the limit of full polarization



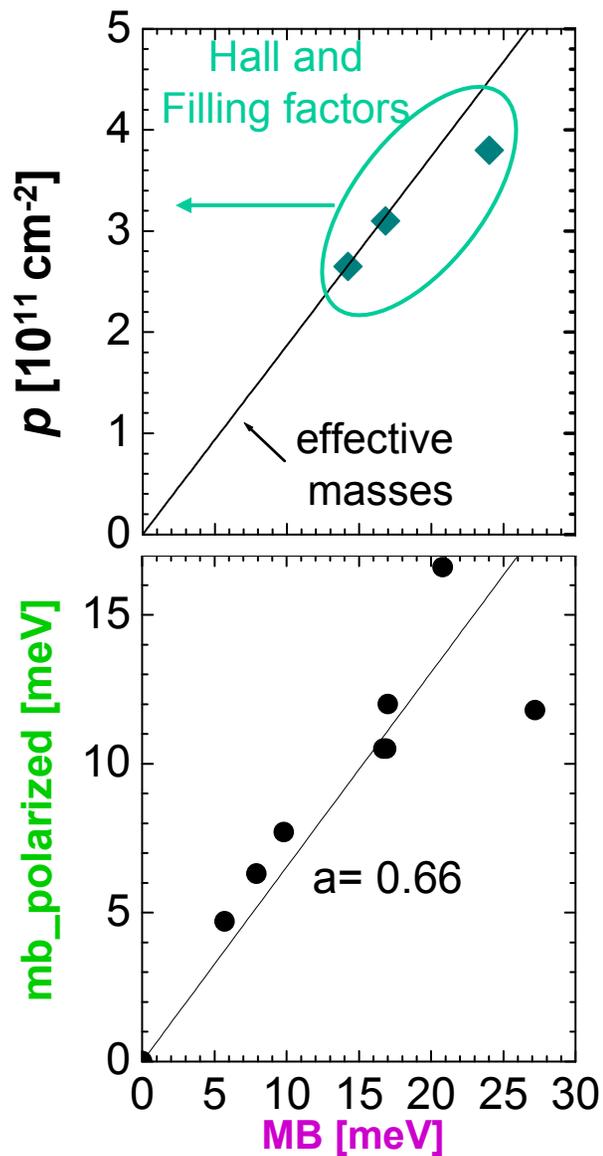
Enhance accuracy

- 2 times larger E_F
- Extract the Stockes shift in σ^-

Moss-Burstein and X^+ ?

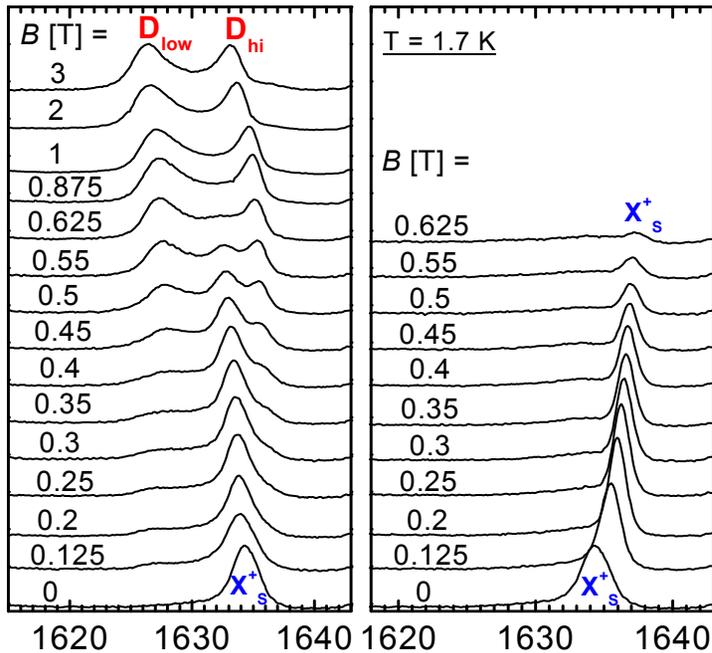


Calibration

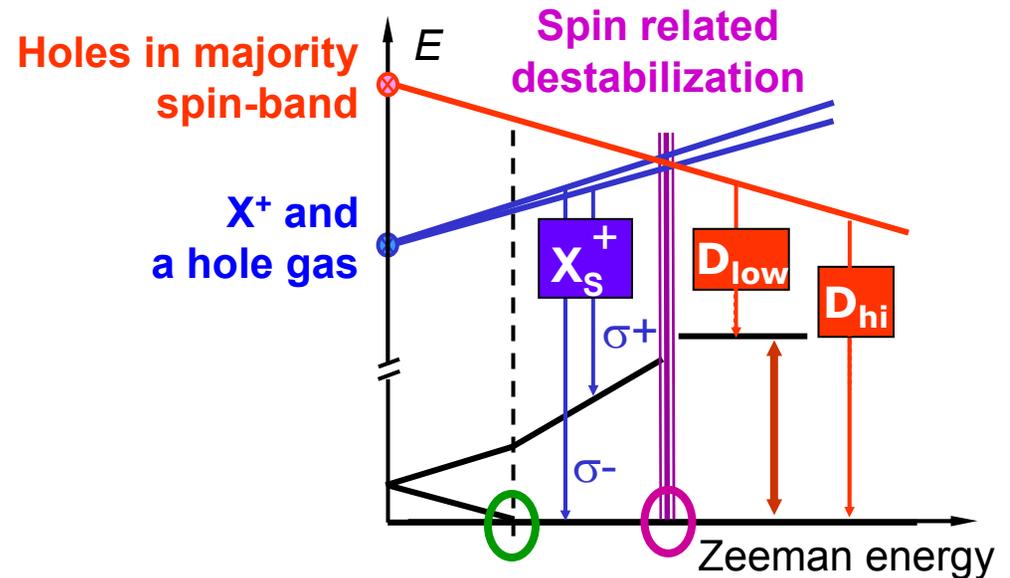


Conclusion

- A novel PL feature: (D_{hi} , D_{low})



- A mechanism to understand it



- Characteristic energies

- Spin splitting at full gas polarization -- **Hole-hole interactions !**
- X^+ destabilization ----- **Binding energy !**
- Hole gas excitation ----- **Nature of the excitation ?**

- Quantitative understanding:
would need some more work from the theory side ...