Spin-dependent Coupling of Charged Quantum Dot Excitons with Continuum States

Bernhard Urbaszek

LNMO, INSA de Toulouse, FRANCE

Brian D. Gerardot and Pierre M. Petroff

Materials Department and QUEST, University of California, Santa Barbara, USA

OUTLINE

Introduction

- quantum dots and the wetting layer
- creation of highly charged excitons
- exchange effects

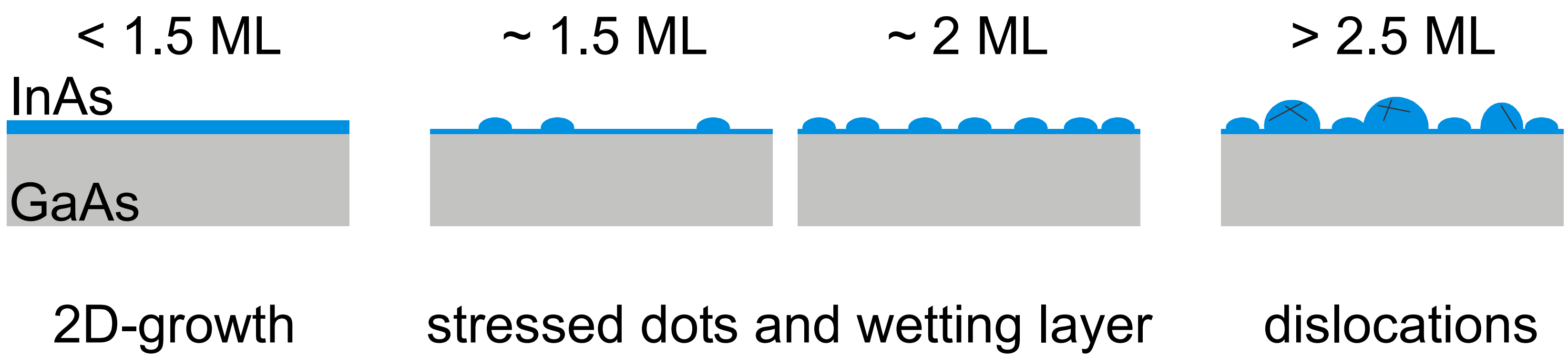
Magnetic Field Dependence

- Zeeman and diamagnetic contributions
- hybridisation of discrete and continuum states

Temperature Dependence

- PL line broadening mechanisms
- X^{3-} : sharper lines at higher T

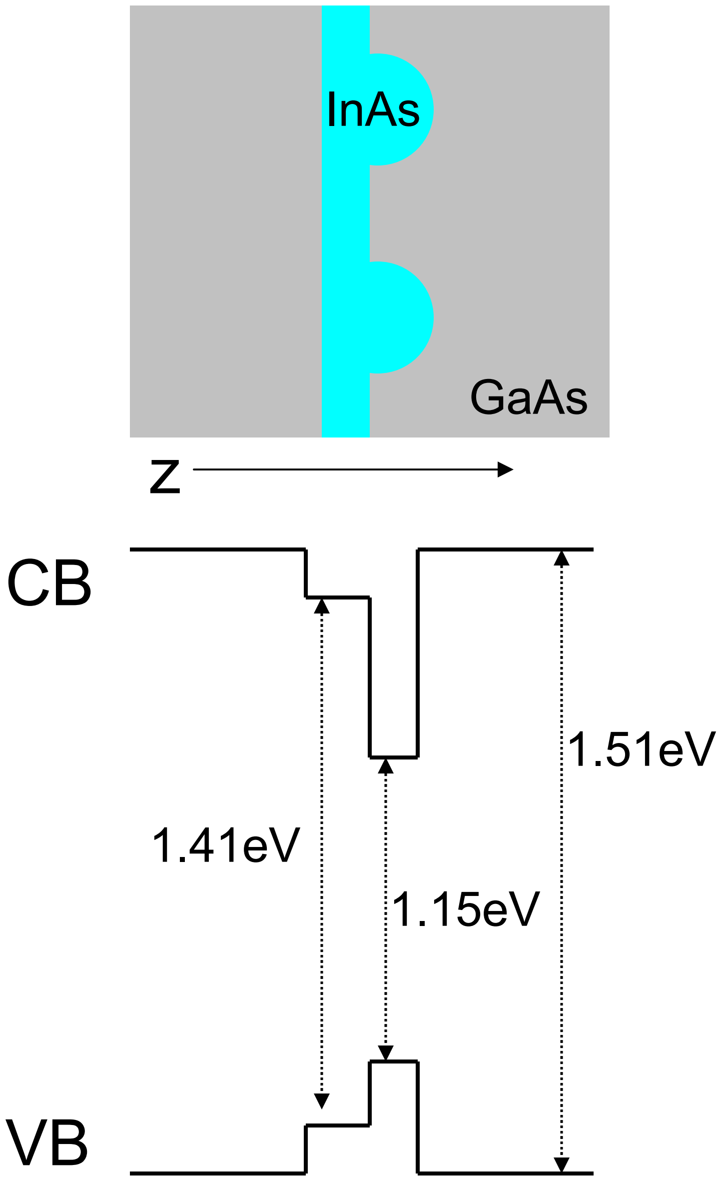
Stranski-Krastanow growth



quantum dot formation through self-assembly:

band gap: $E_G(GaAs) > E_G(InAs)$
lattice constants: $a_0(InAs) > a_0(GaAs)$

Quantum Dots and the Wetting Layer



deeply confined dot states:
'artificial atom model'

excited dot states:

continuum states in PLE

Toda *et al* PRL 1999

model: crossed transitions WL-dot

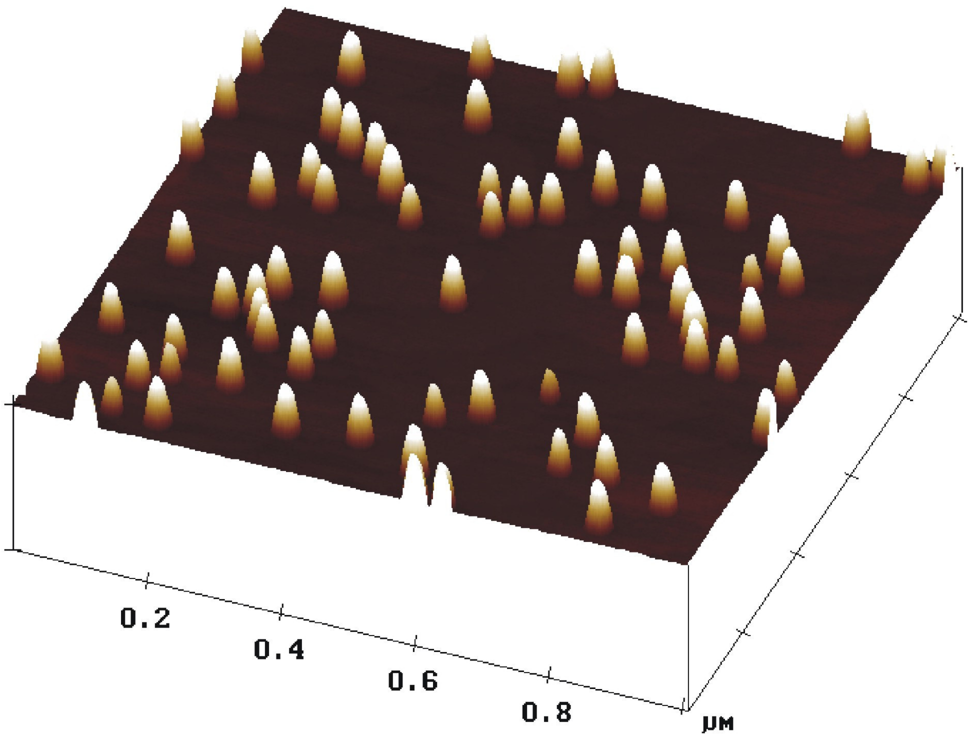
A. Vasanelli *et al,* PRL 2002

C. Kammerer *et al*, PRL 2001

R. Oulton *et al*, PRB 2003 …

Samples: InAs dots on GaAs

Atomic Force Microscopy Image



height ~ 6 nm

diameter ~ 20 nm

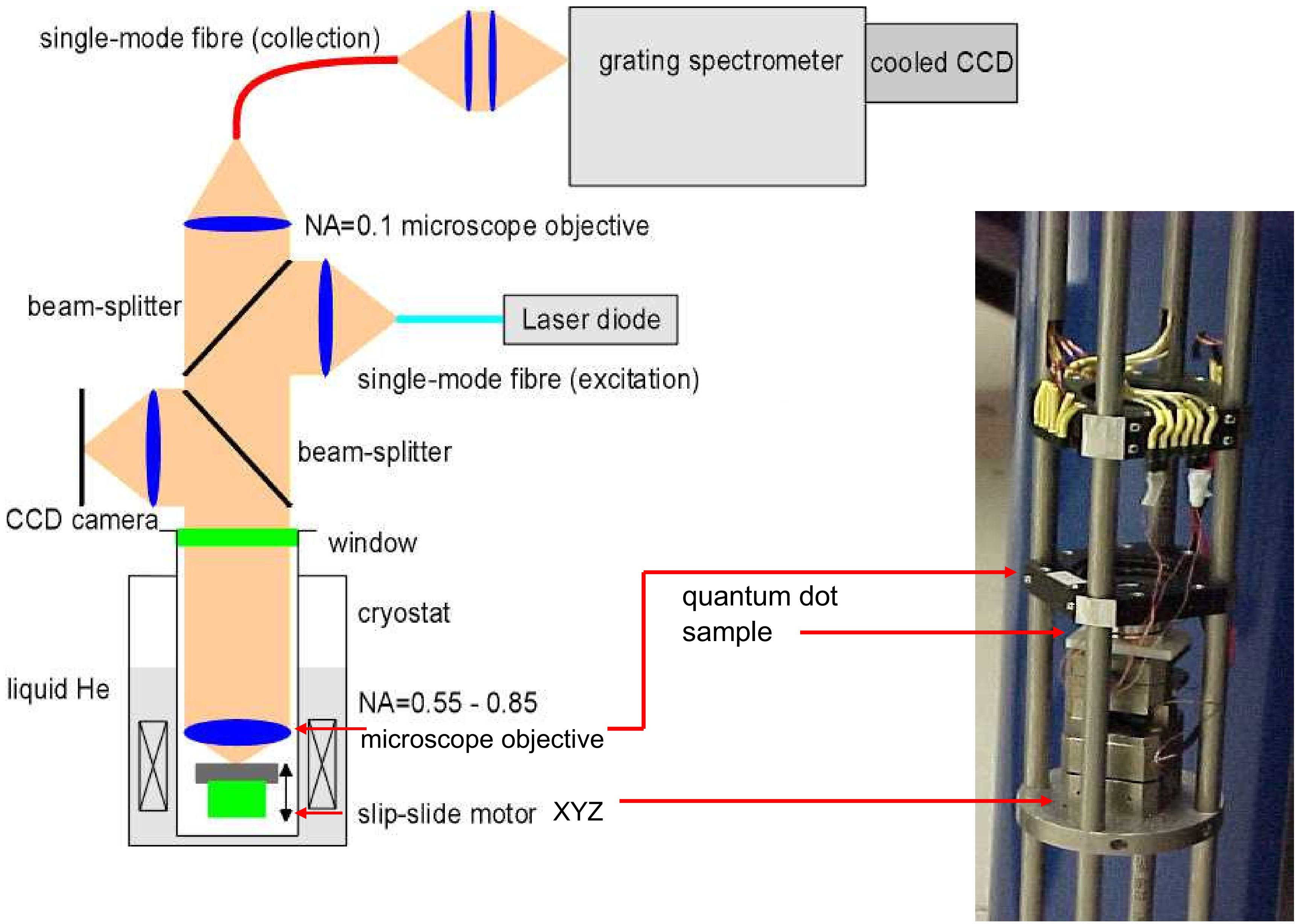
density ~ 10^{10} cm^{-2} (smaller for single dot PL)

fluctuations ~ 10%

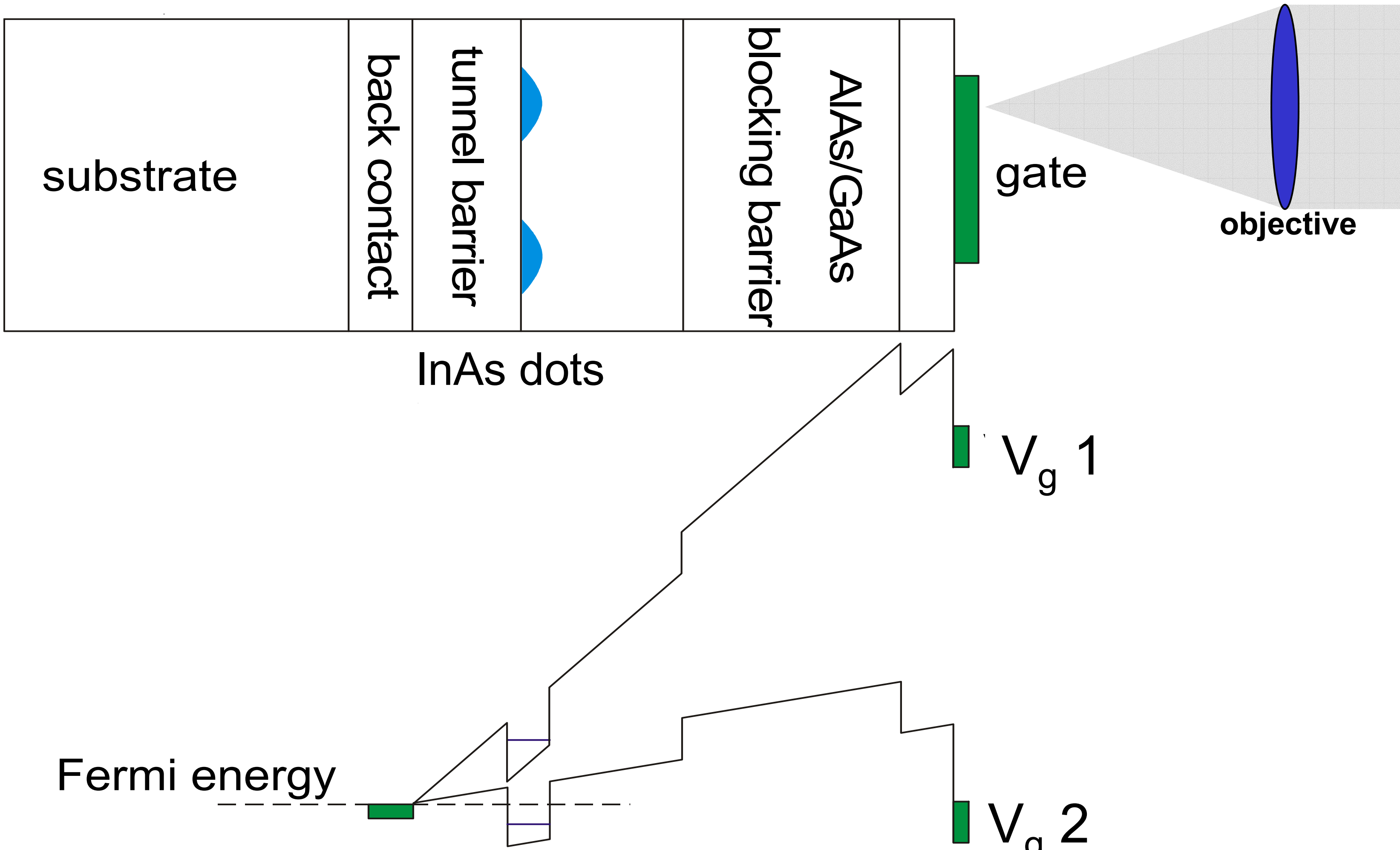
Group of P.M.Petroff,

Santa Barbara

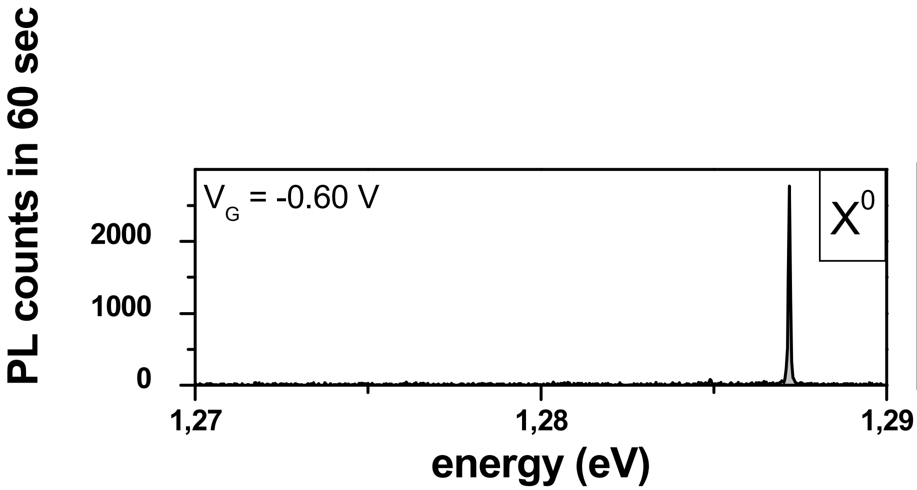
PL spectroscopy: confocal microscope set-up

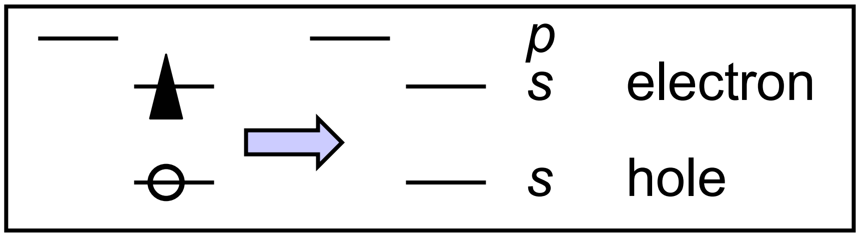


Charge Tuneable Quantum Dots

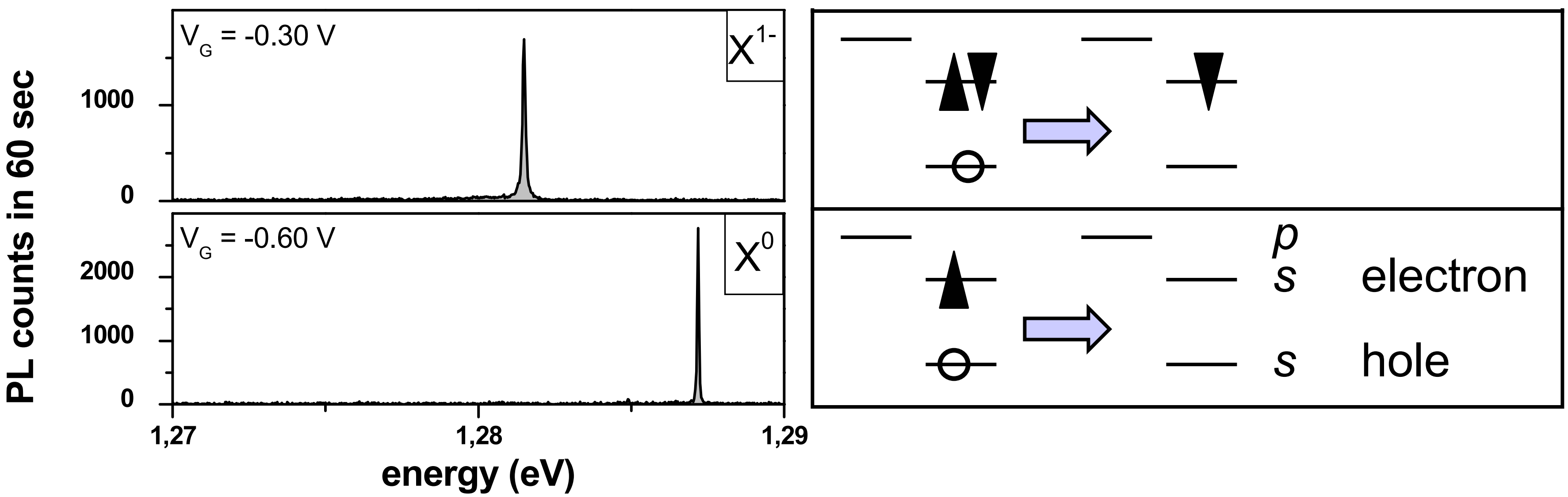


Single Dot PL *vs* Gate Voltage V_G

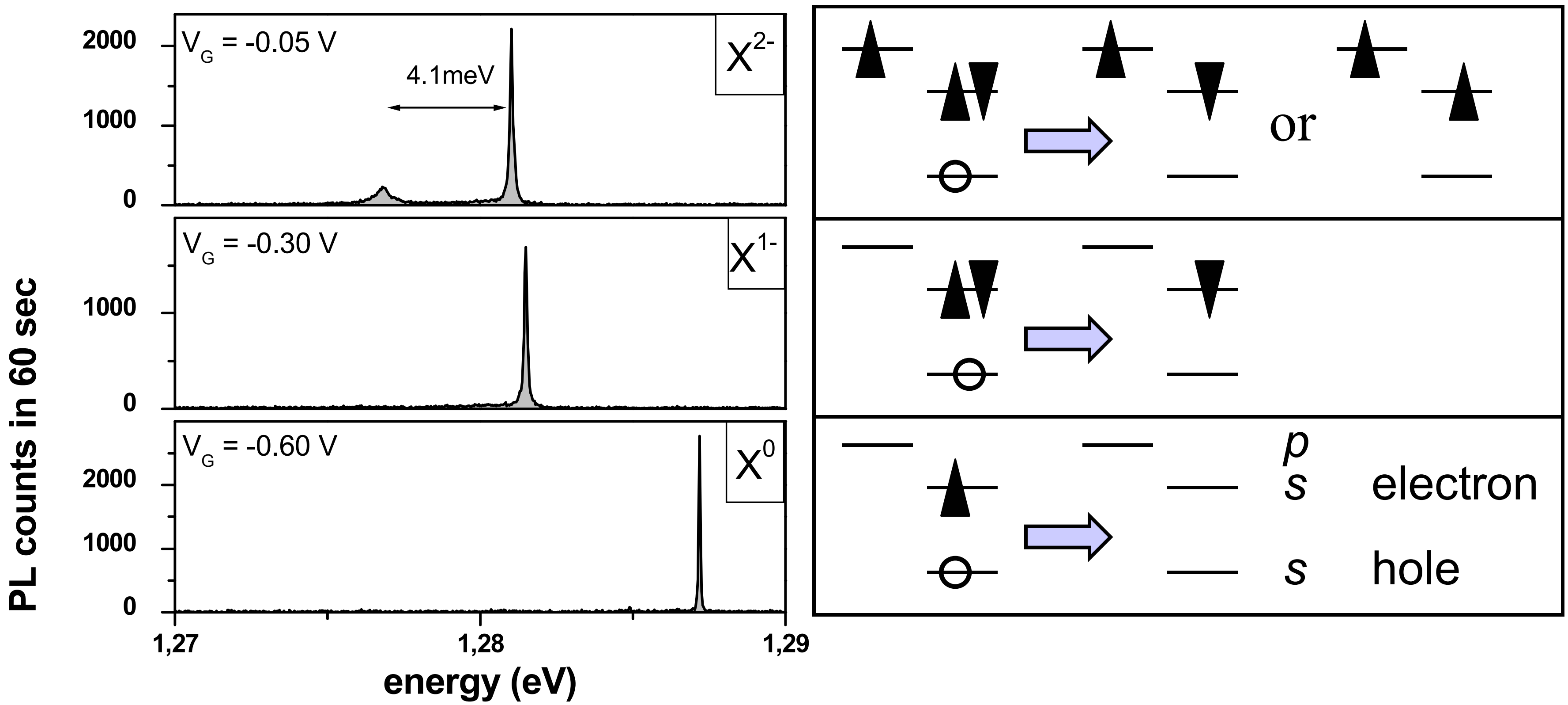




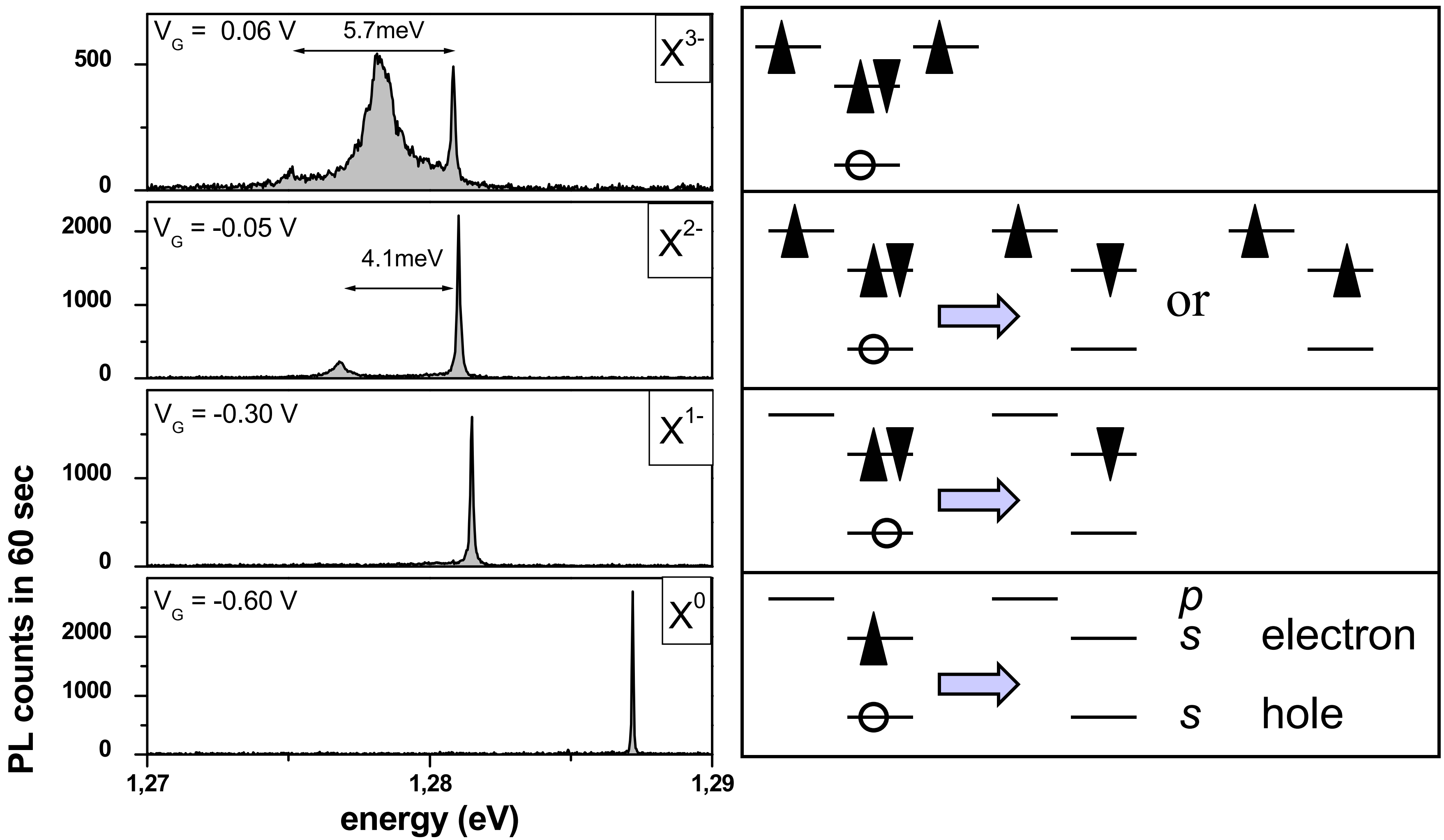
Single Dot PL *vs* Gate Voltage V_G



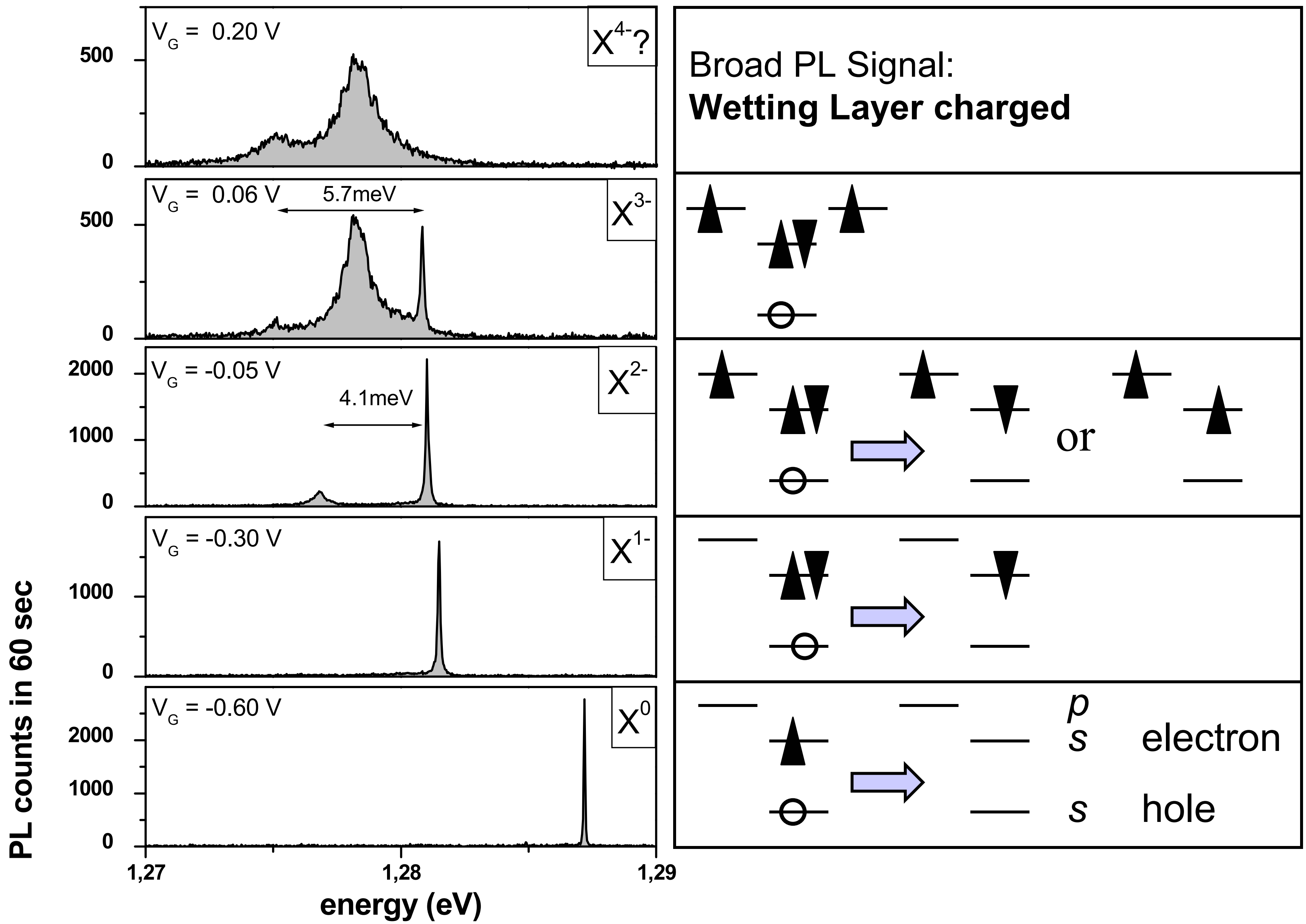
Single Dot PL *vs* Gate Voltage V_G



Single Dot PL *vs* Gate Voltage V_G

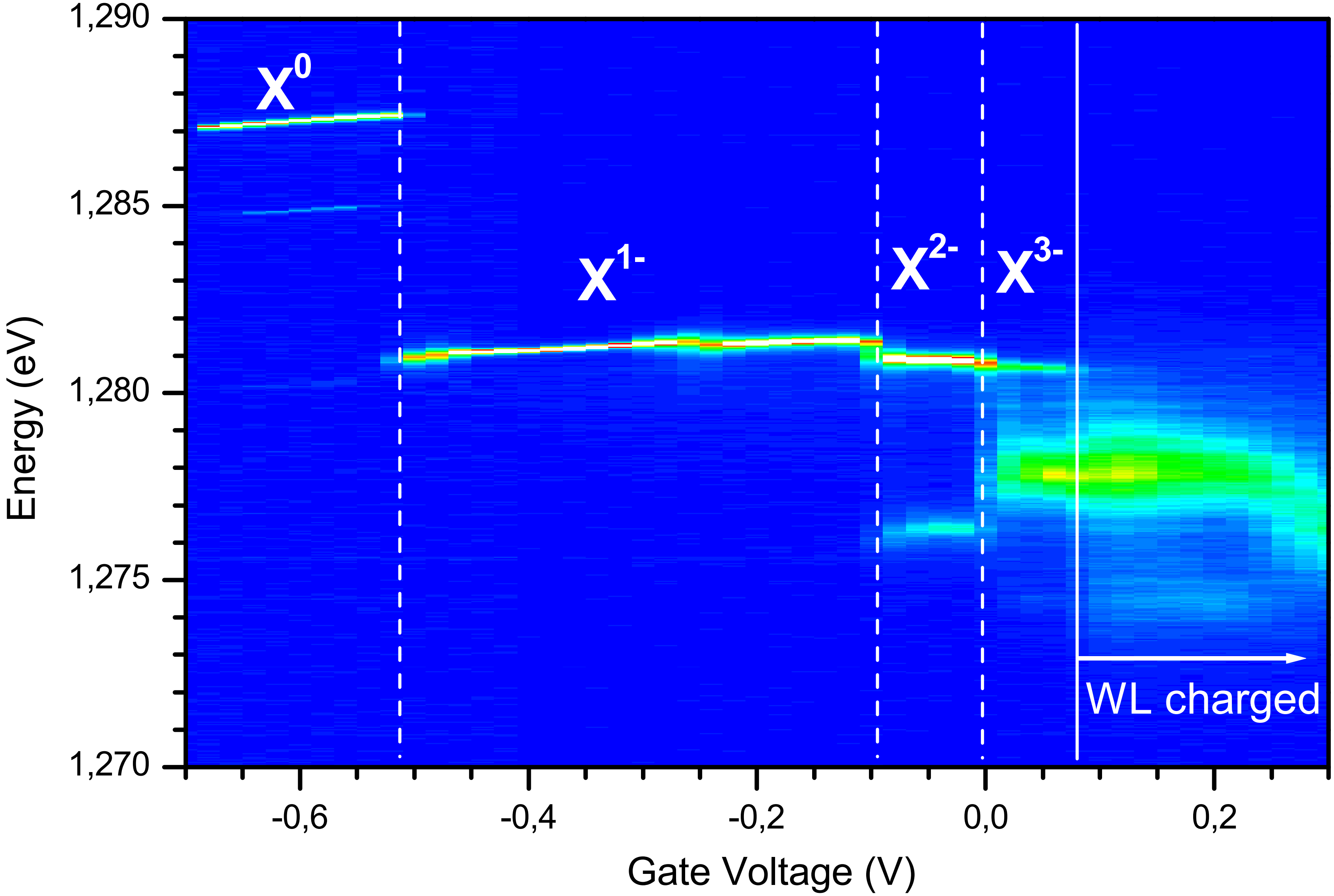


Single Dot PL *vs* Gate Voltage V_G

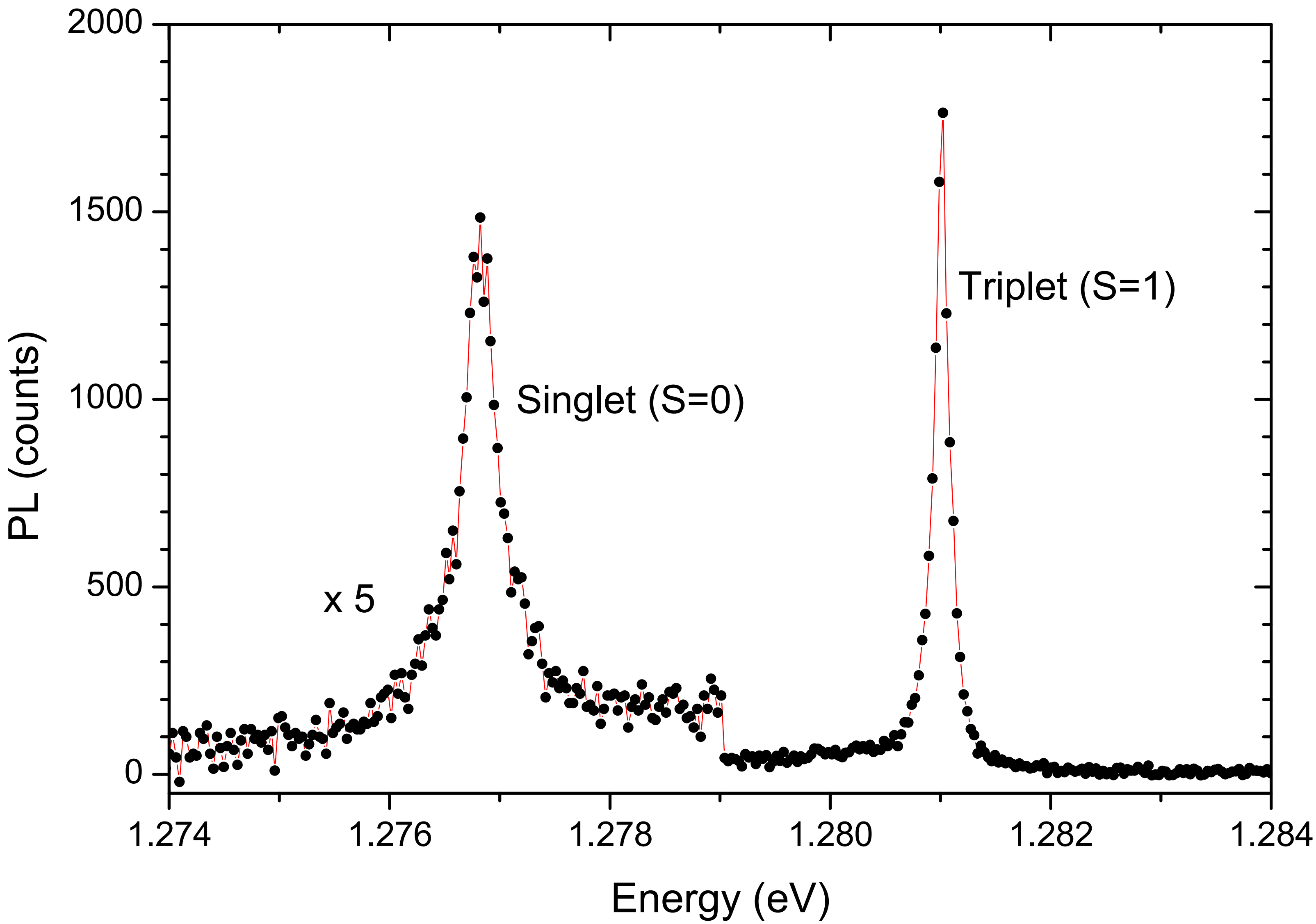


Single Dot PL *vs* Gate Voltage V_G

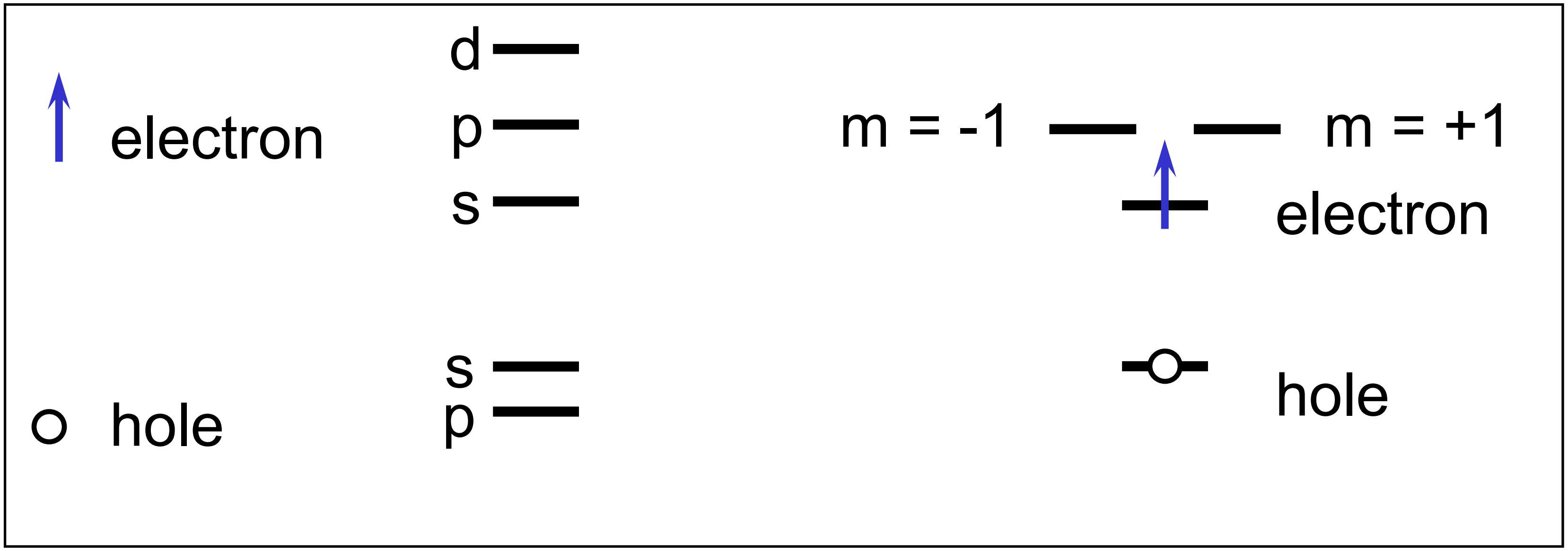
R.J. Warburton *et al*, Nature 405, 926 (2000)
B.Urbaszek *et al*, Phys. Rev. Lett. 90, 247403 (2003)

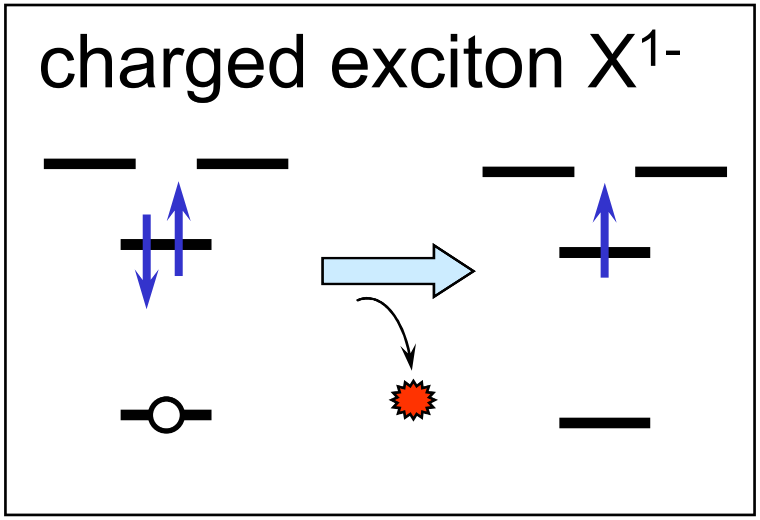


X^{2-} SINGLET - TRIPLET SPLITTING

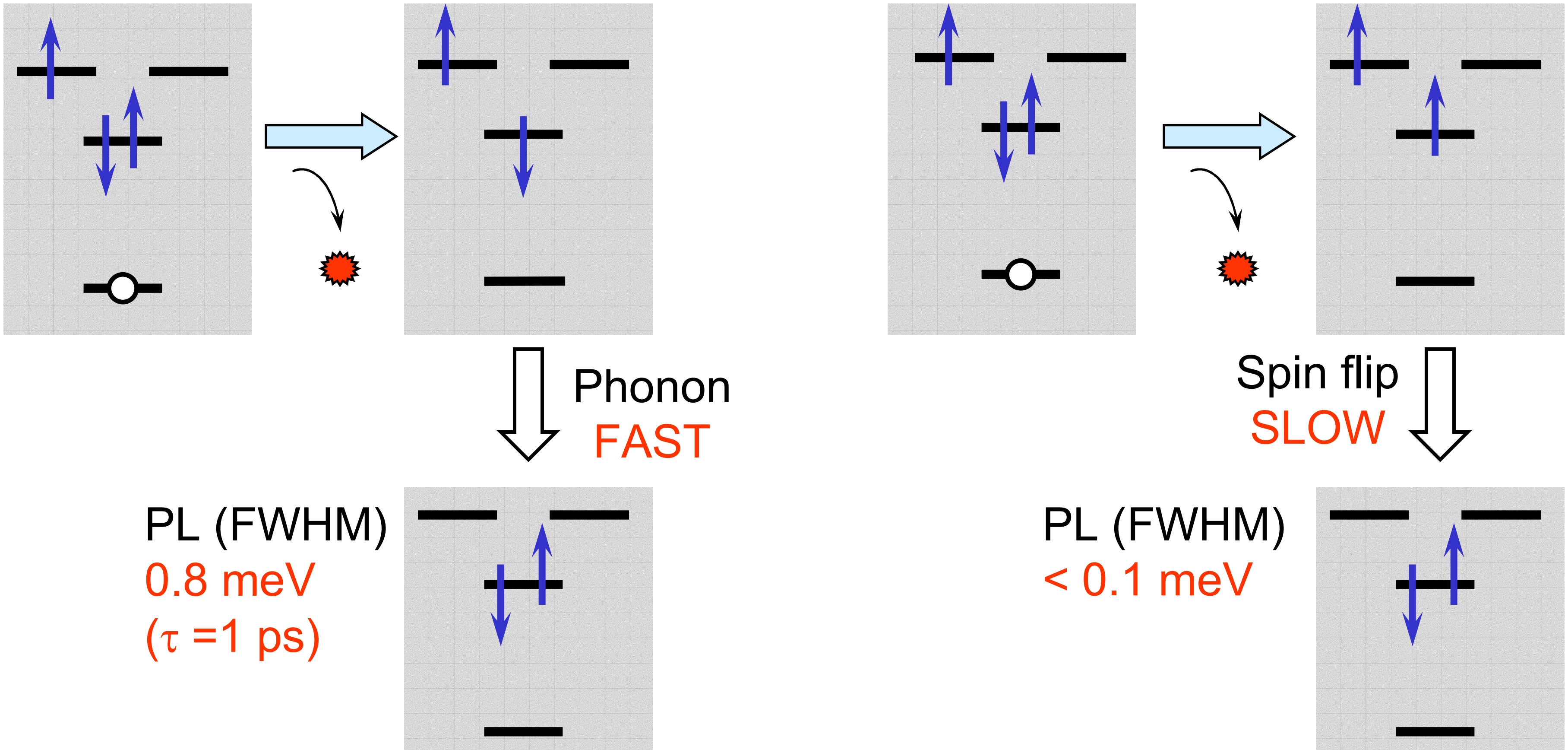


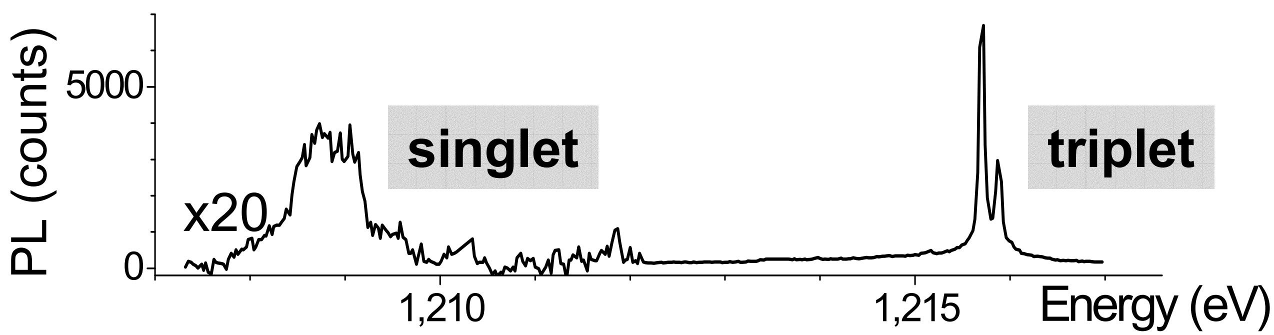
LEVEL STRUCTURE





X^{2-} RELAXATION





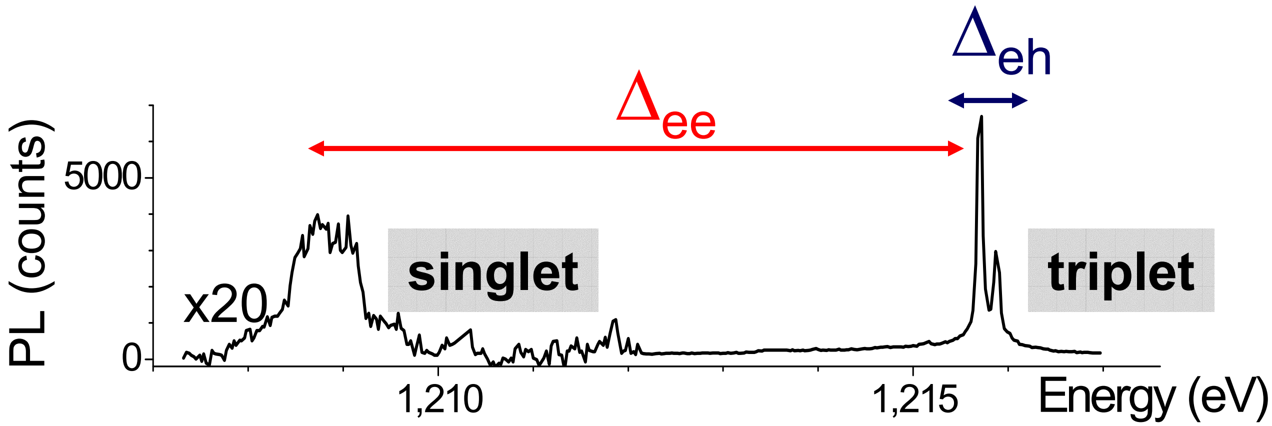
X^{2-} Exchange Effects

X^{2-} initial State : *electron-hole Exchange*

fine structure Δ_{eh}~ 0.2meV

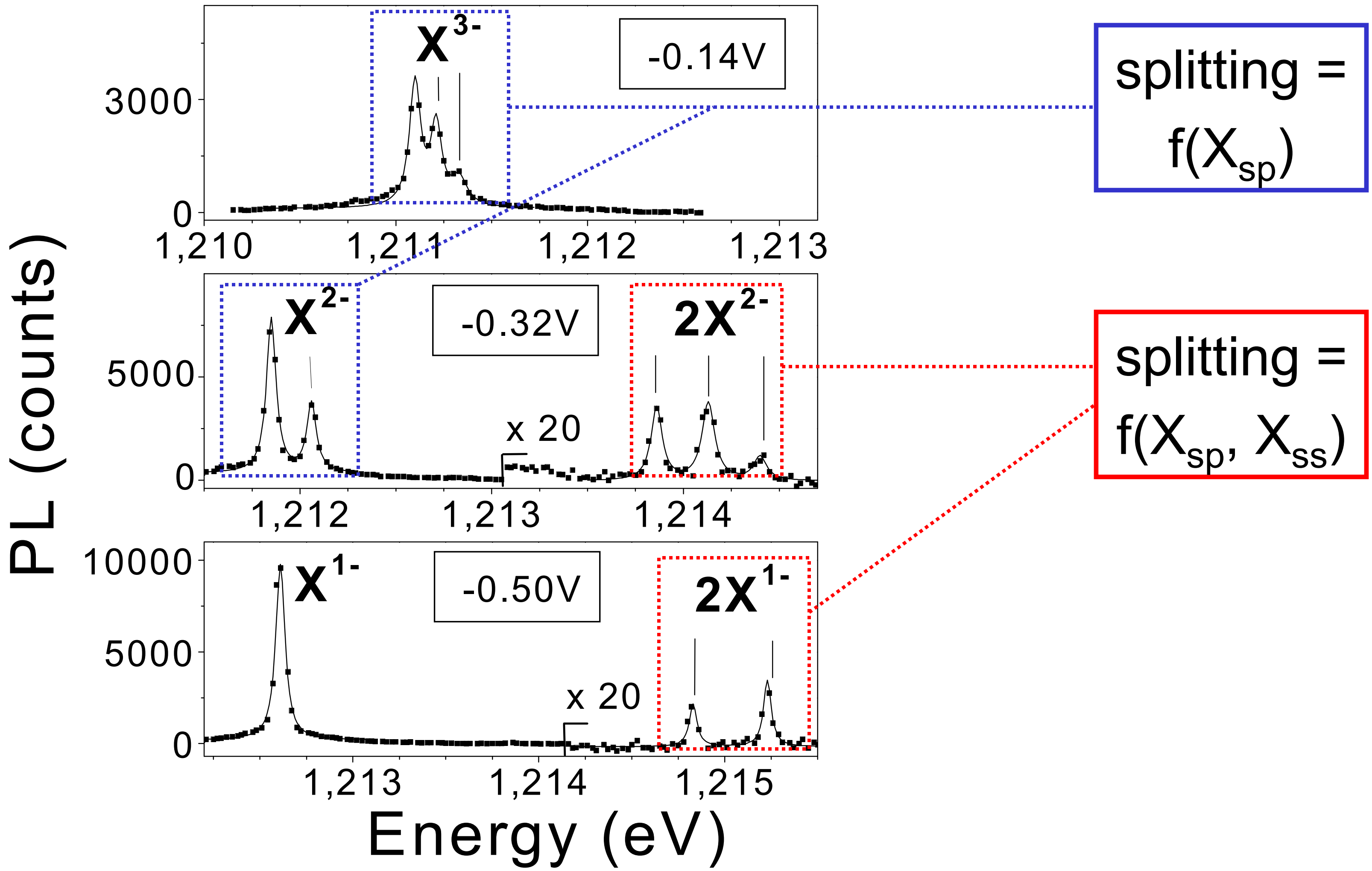
X^{2-} final State : *electron-electron Exchange*

splitting Δ_{ee}~ 5meV



electron-hole fine structure of dot no. 1

B.Urbaszek *et al*, Phys. Rev. Lett. 90, 247403 (2003)



OUTLINE

Introduction

- quantum dots and the wetting layer
- creation of highly charged excitons
- exchange effects

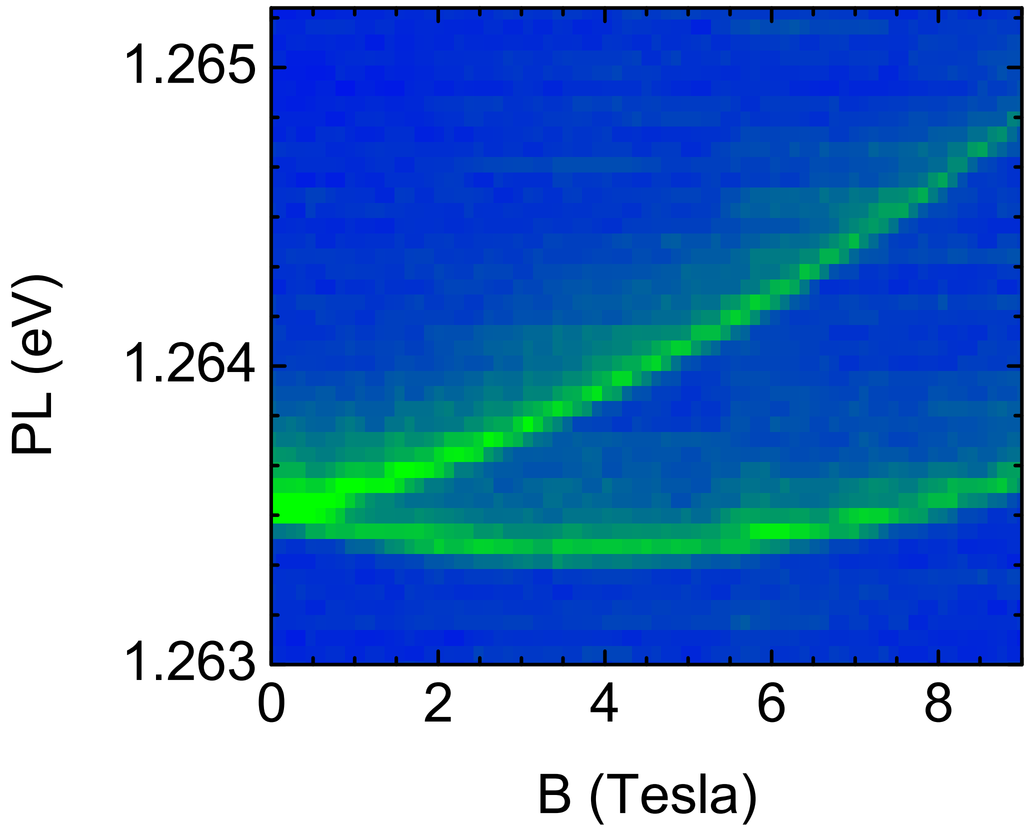
Magnetic Field Dependence

- Zeeman and diamagnetic contributions
- hybridisation of discrete and continuum states

Temperature Dependence

- PL line broadening mechanisms
- X^{3-} : sharper lines at higher T

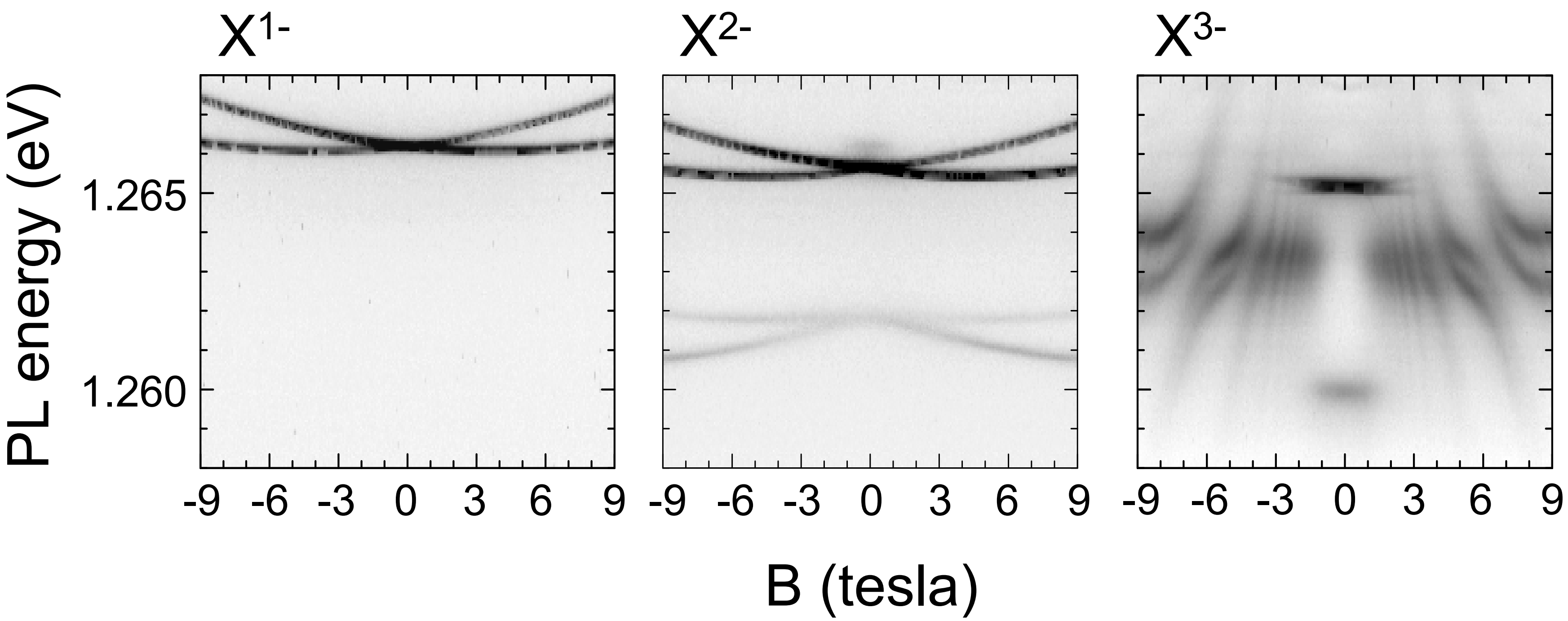
MAGNETIC DISPERSION OF X^1:



- Zeeman effect: splitting linear in B
- diamagnetic shift: quadratic in B

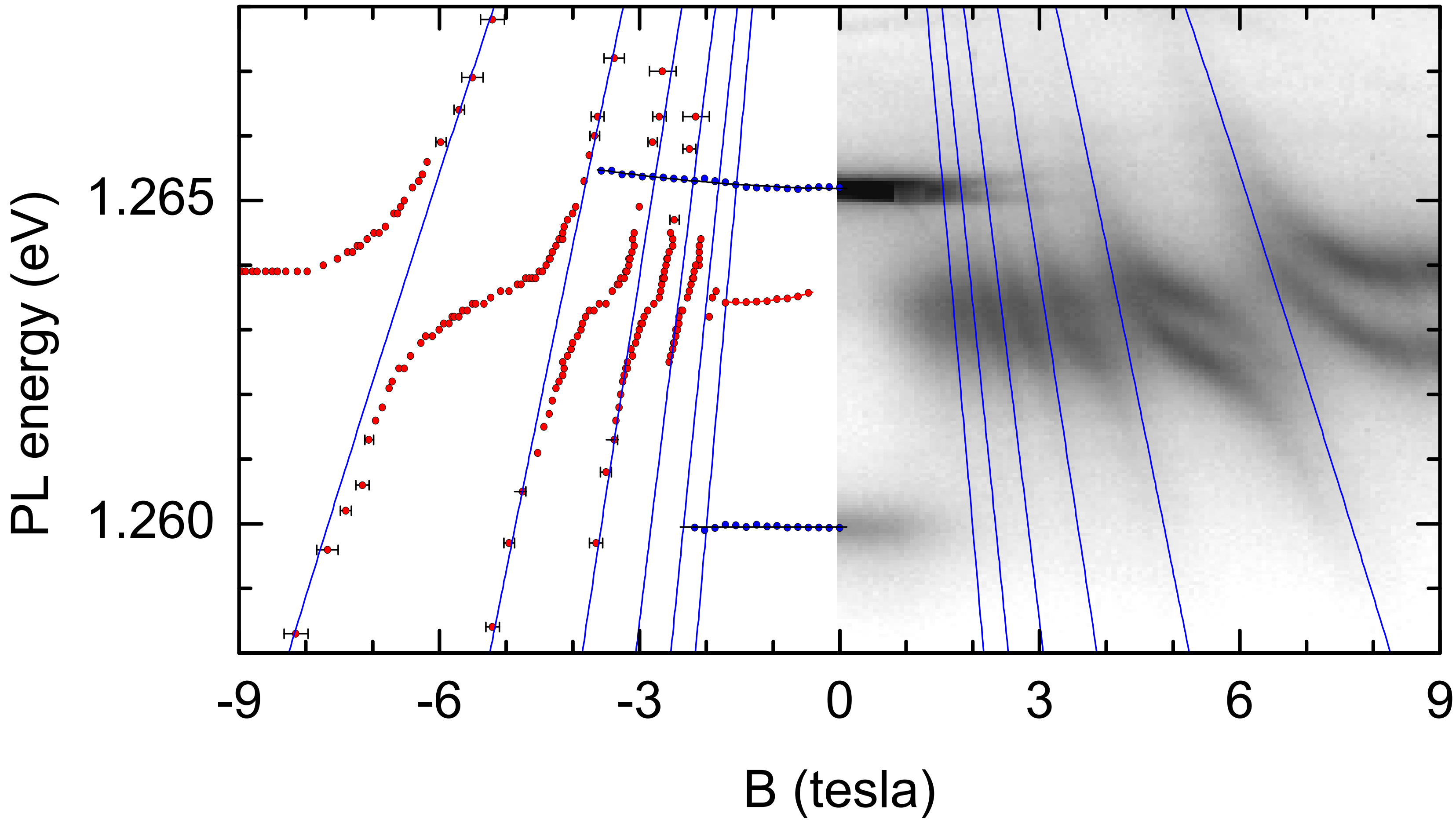
C. Schulhauser *et al.,* Phys. Rev. B **66**, 193303 (2002)

MAGNETIC DISPERSION

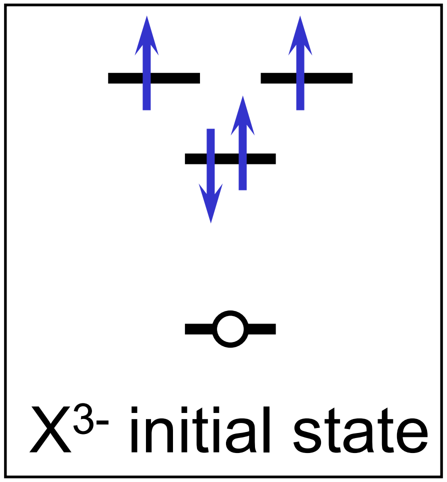


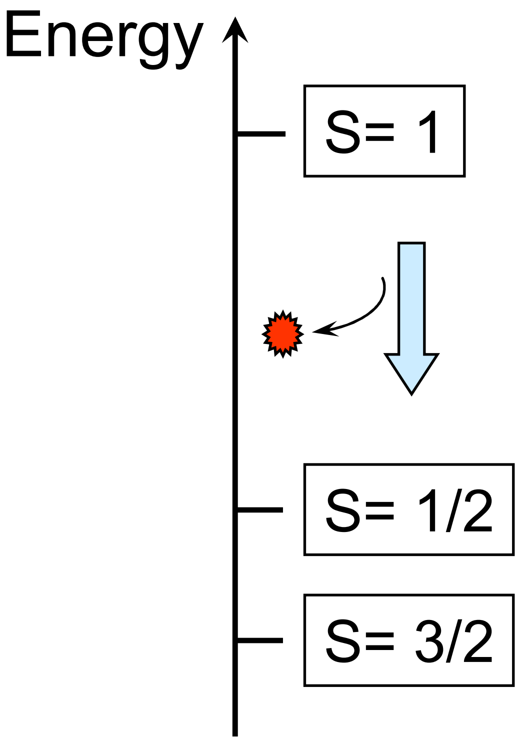
K. Karrai, *et al,* Nature **427**, 135 (2004)

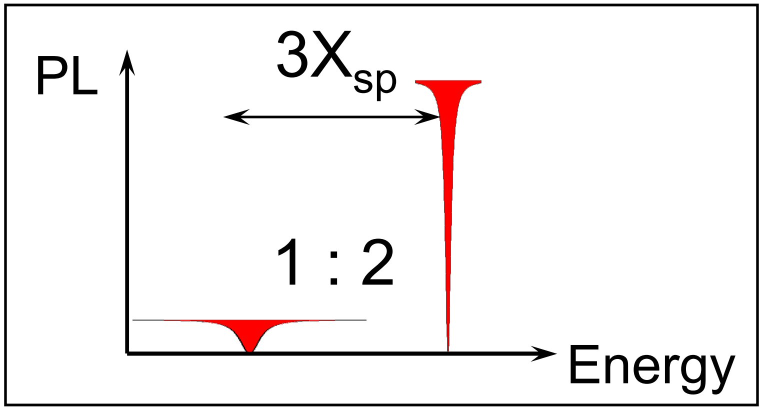
X^{3-} in a Magnetic Field



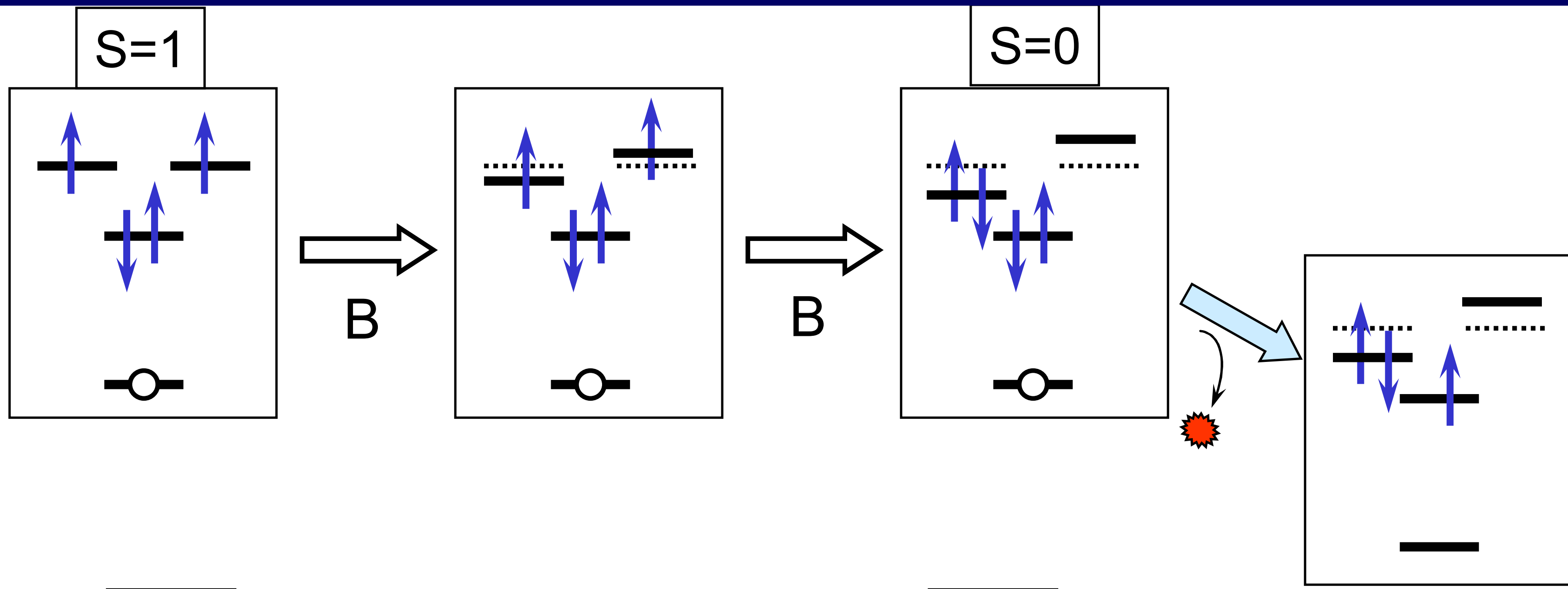
X^{3-} AND THE EXCHANGE INTERACTION

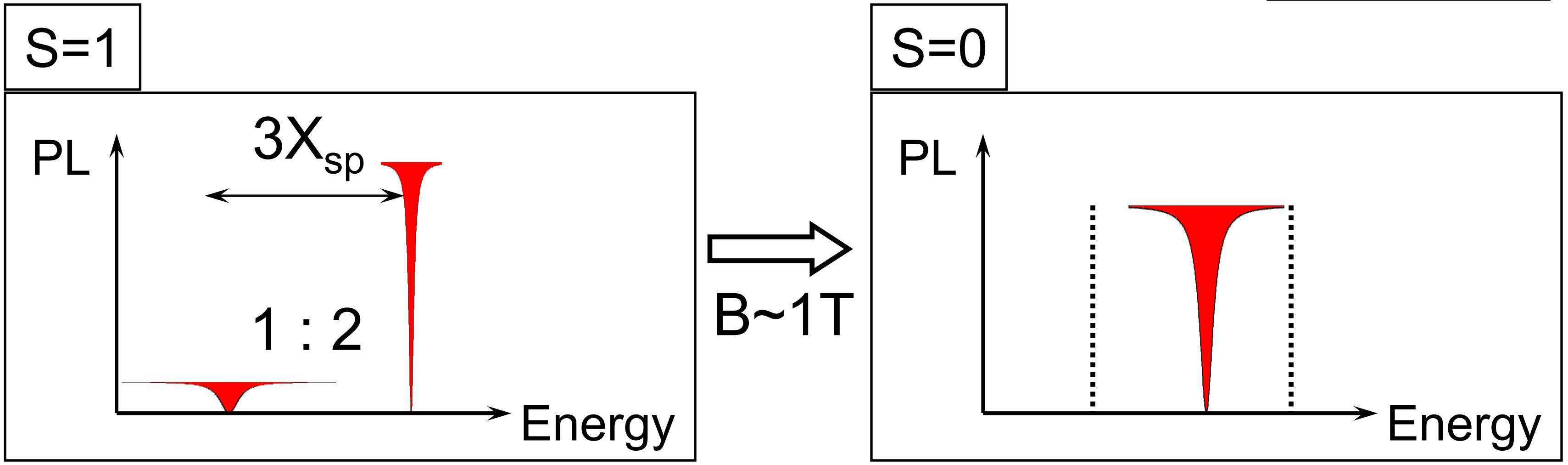




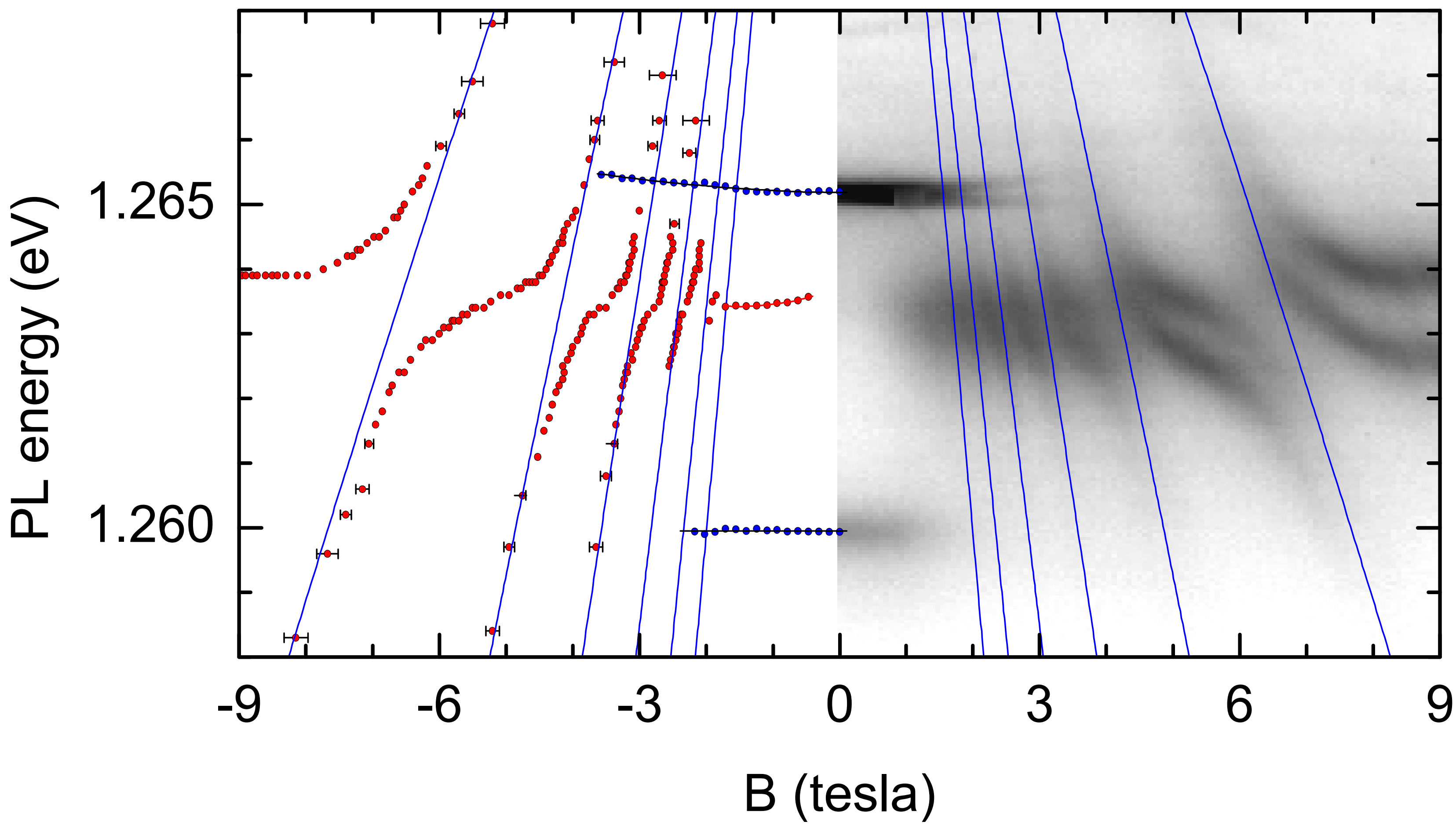


X^{3-} in a Magnetic Field

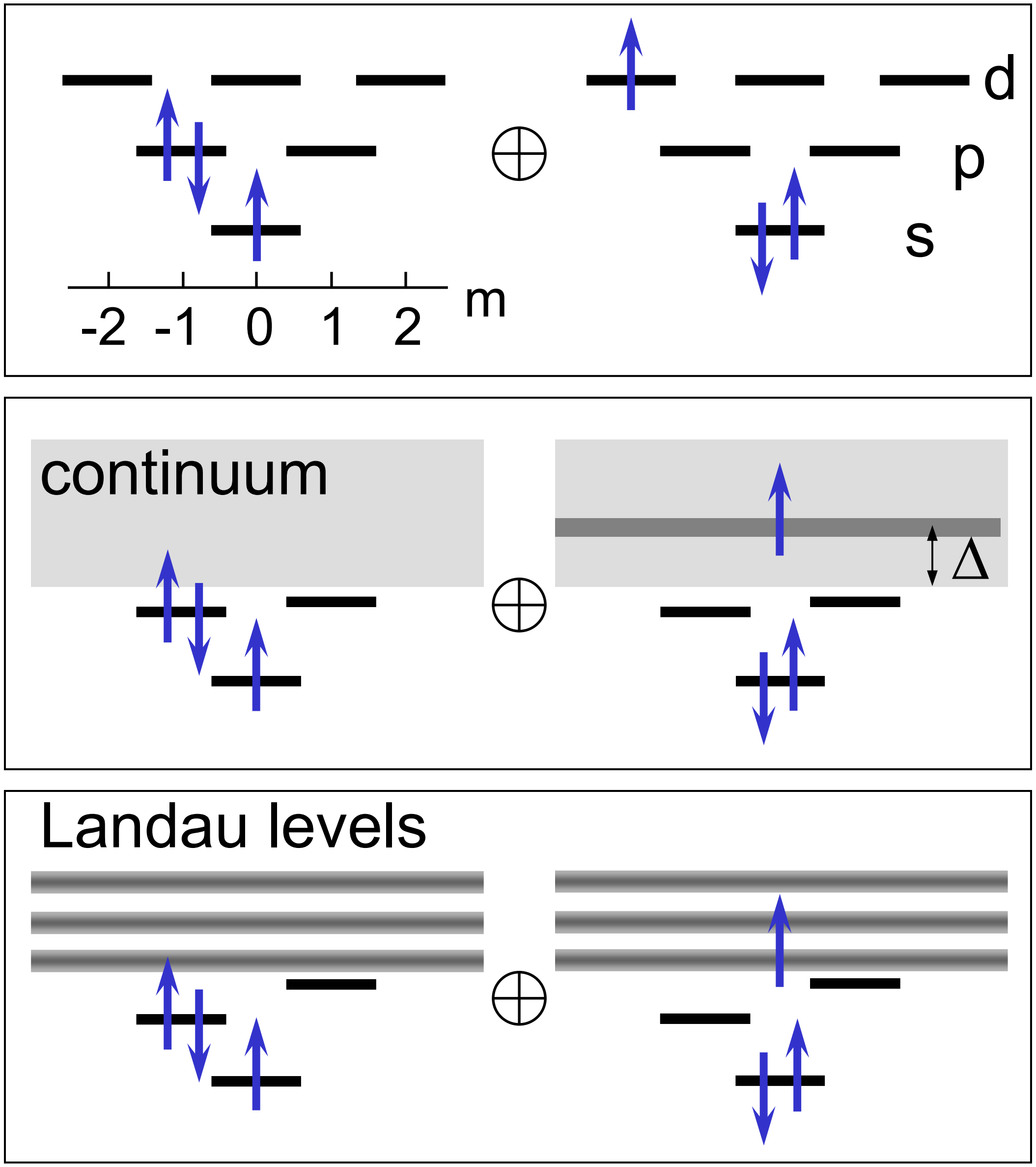


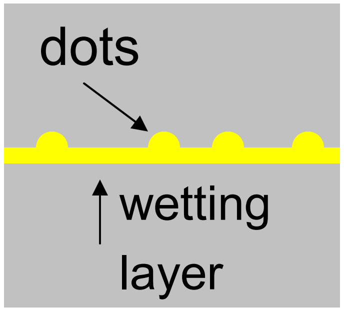


X^{3-} in a Magnetic Field

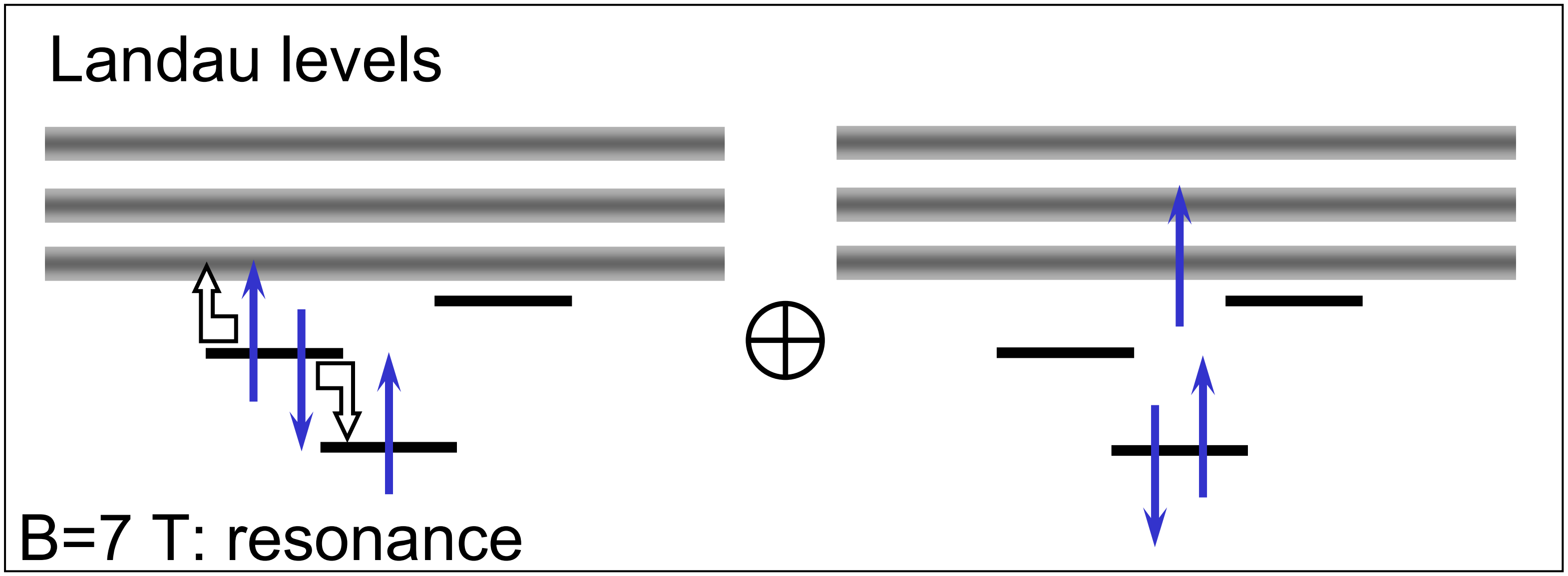


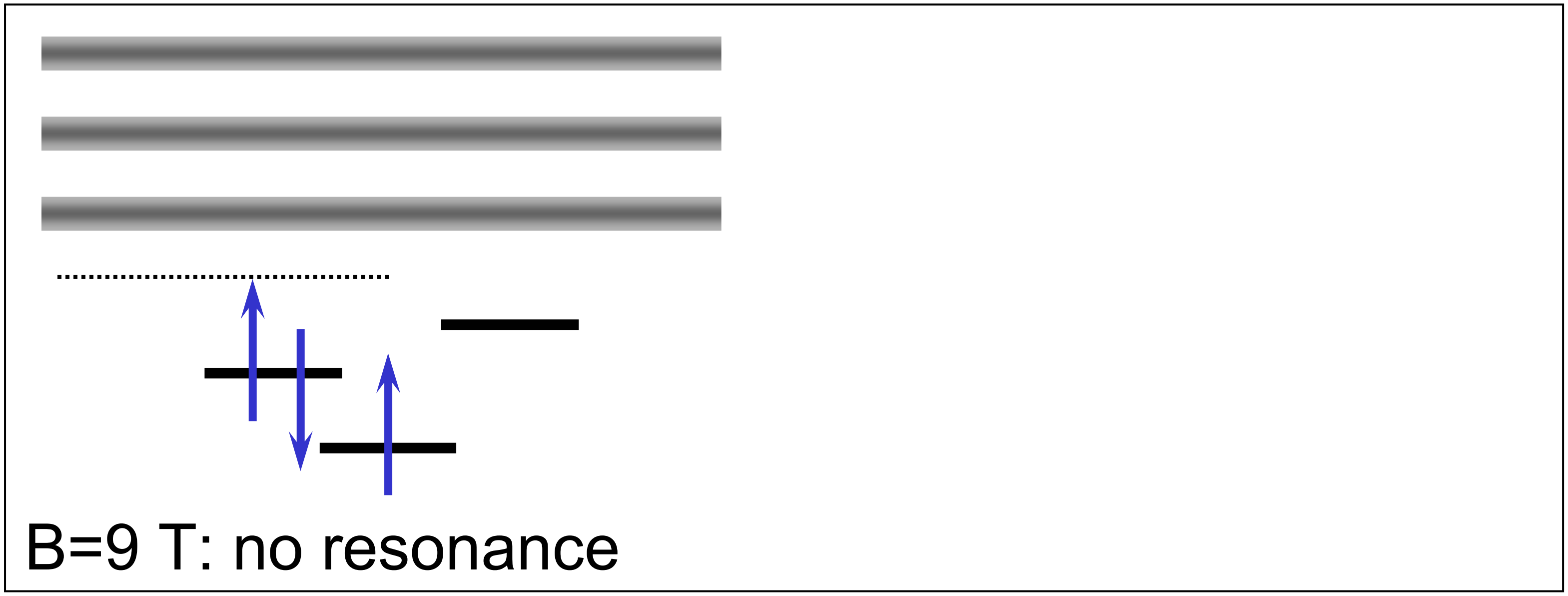
CONFIGURATION MIXING IN THE X^{3-} FINAL STATE



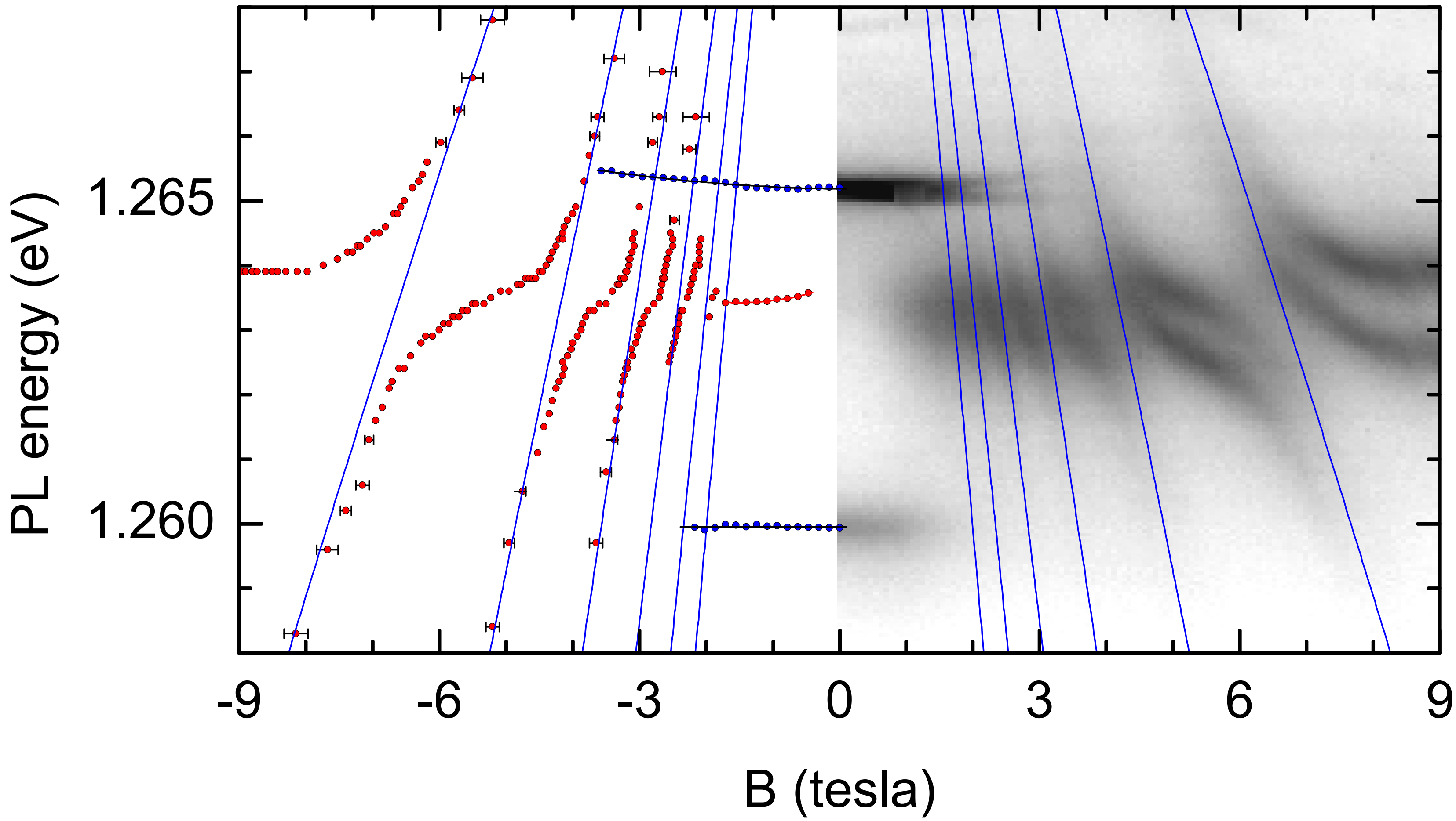


CONFIGURATION MIXING IN THE X^{3-} FINAL STATE





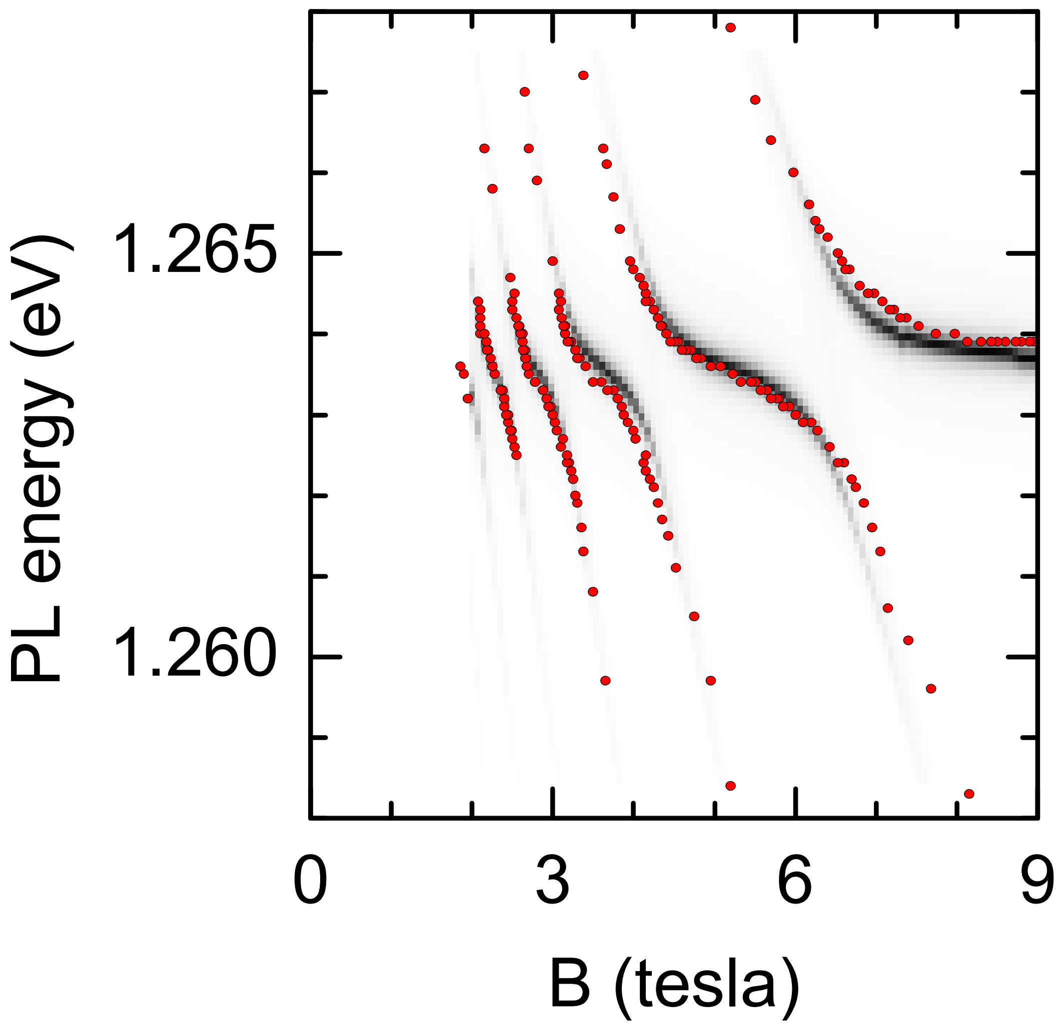
X^{3-} in a Magnetic Field



Our interpretation: **interaction with Landau levels**

1. asymptotes at anti-crossing: linear function of B
2. same zero field energy for all asymptotes

ANDERSON HAMILTONIAN MODEL



Collaboration:

A.O. Govorov

K. Karrai, *et al.,* Nature **427**, 135 (2004)

Summary: MAGNETIC FIELD Dependence

X^0 and X^{1-}

- **diamagnetic shift:**
  quadratic in magnetic field *B*
- **spin Zeeman effect:**
  splitting linear in *B*

⇨ localised excitons

X^{2-}

- for **singlet** and **triplet**:
  diamagnetic shift and
  Zeeman splitting

X^{3-}

B < 1 T

Zeeman splitting

B ≈ 1 T

two low field lines **collapse**:

⇨ single, broad line

B > 1 T

series of oscillations/ anticrossings

interaction with Landau levels in the wetting layer

OUTLINE

Introduction

- quantum dots and the wetting layer
- creation of highly charged excitons
- exchange effects

Magnetic Field Dependence

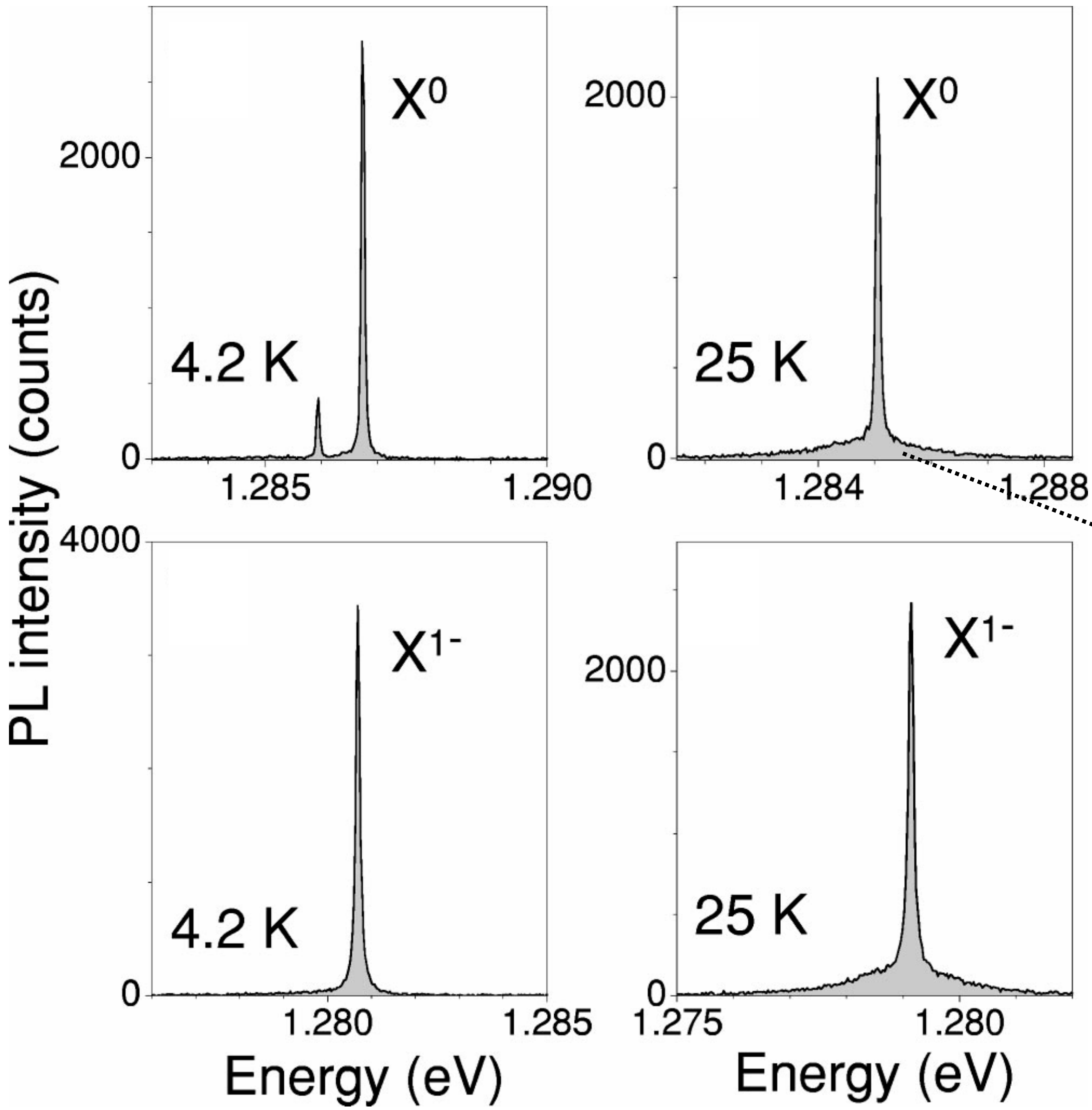
- Zeeman and diamagnetic contributions
- hybridisation of discrete and continuum states

Temperature Dependence

- PL line broadening mechanisms
- X^{3-} : sharper lines at higher T

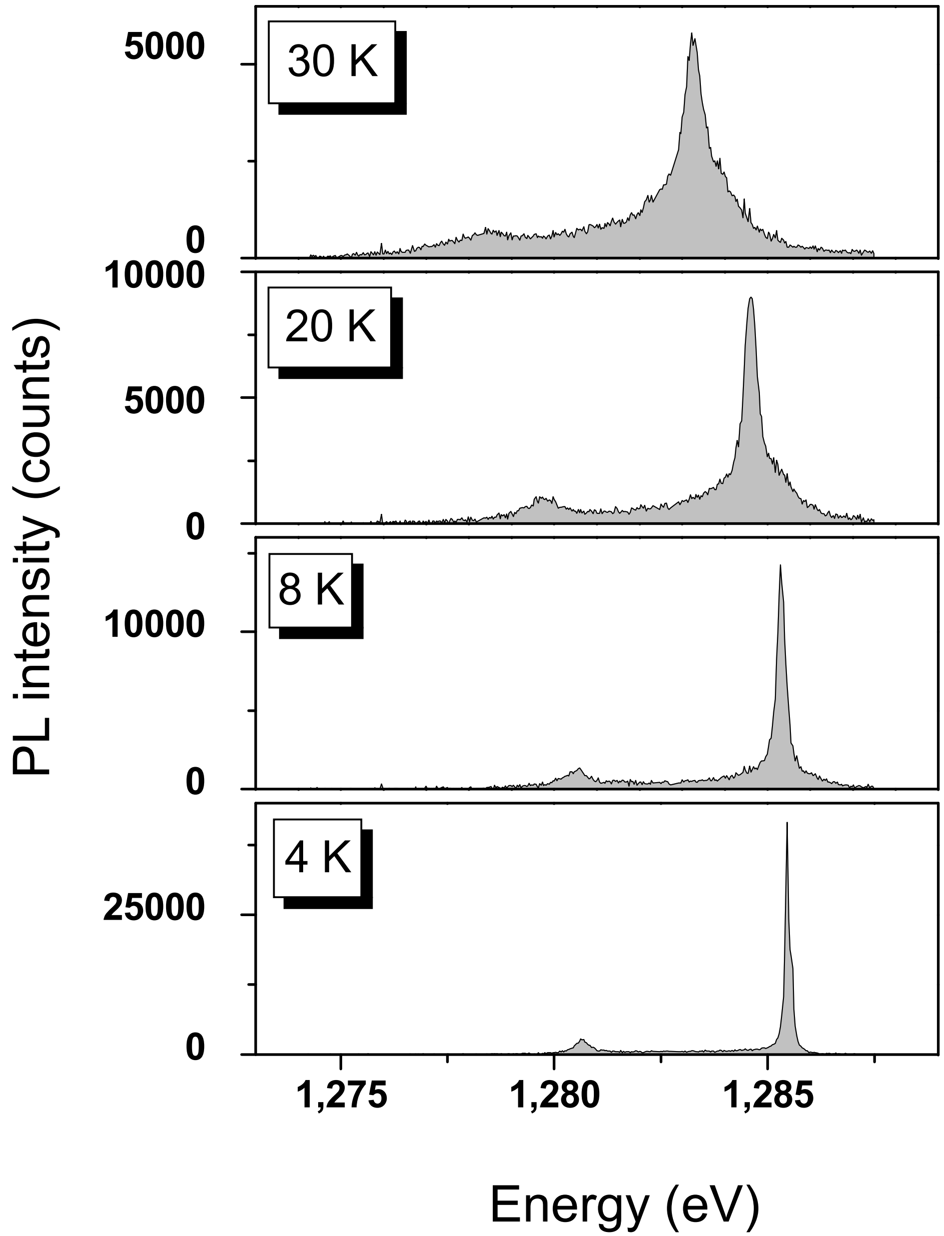
Temperature Dependent PL: X^0, X^{1-}

B. Urbaszek *et al*, Phys. Rev. B 69, 035304 (2004)

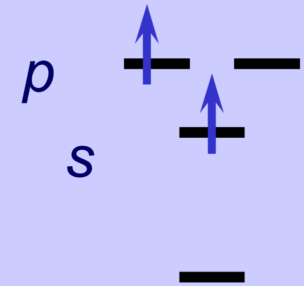


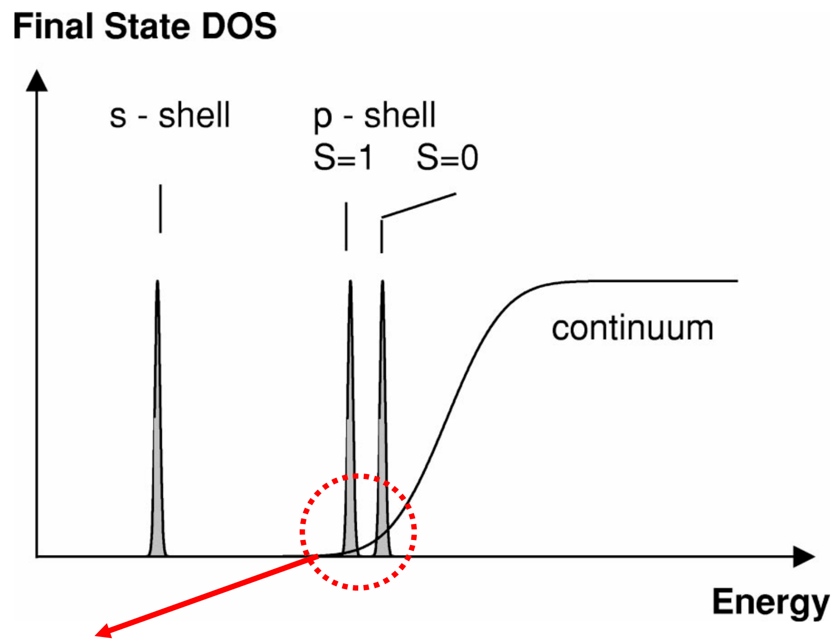
due to Exciton-
acoustic phonon coupling
L. Besombes *et al*,
Phys. Rev. B 63 (2001) 155307

Temperature Dependent PL: X^{2-}



X^{2-} final state

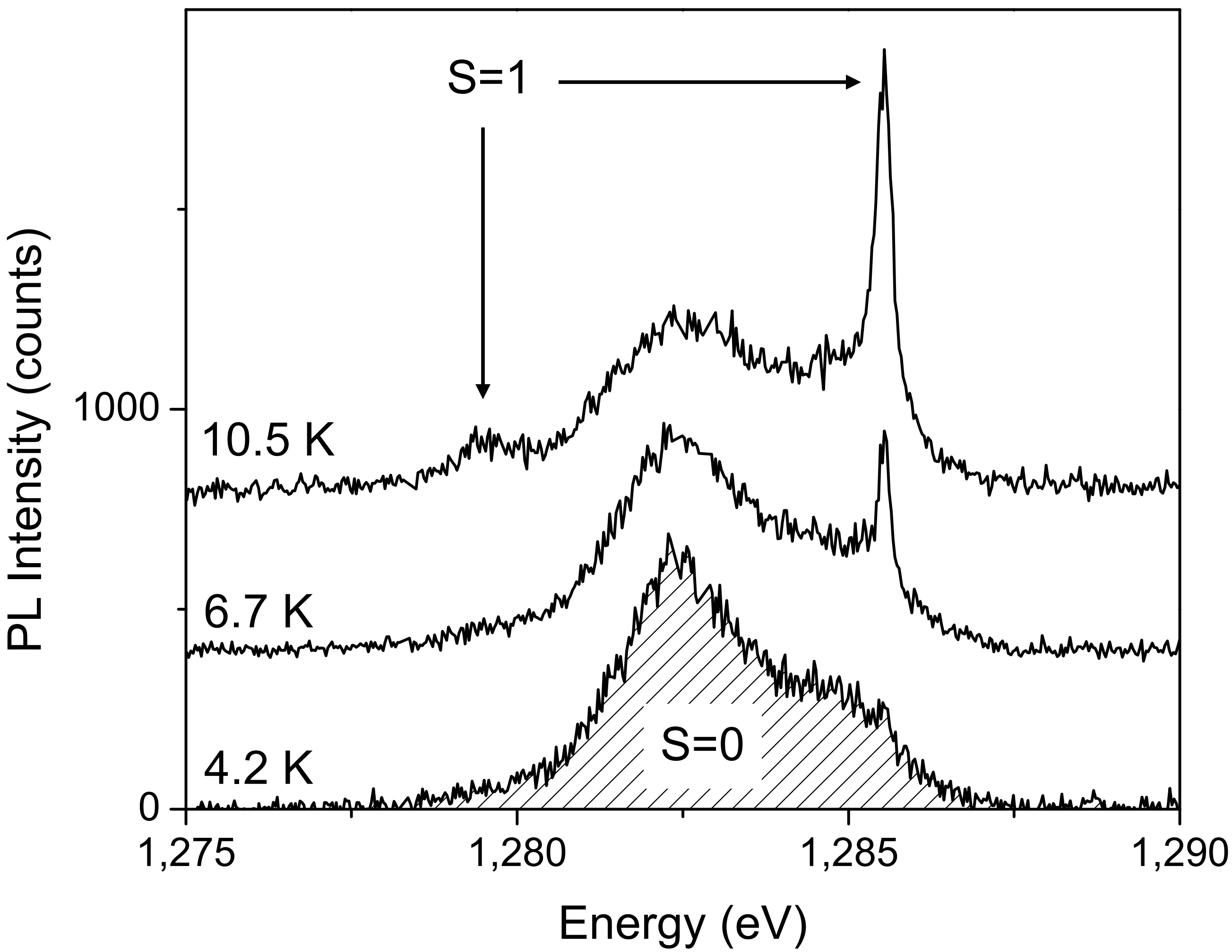




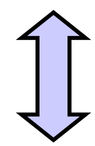
overlap enables **strong interaction with acoustic phonons** in final state

strong broadening

Temperature Dependent PL: X^{3-}

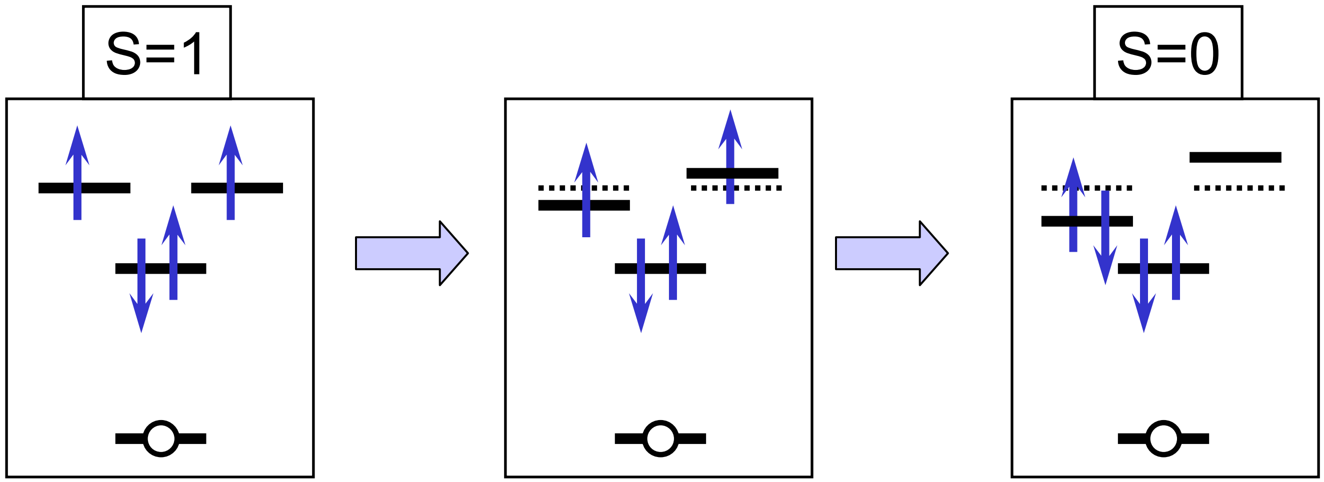


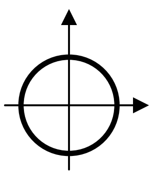
thermally occupied
S=1 initial state
sharp transition



broad transition
S=0 initial state

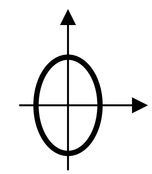
X^{3-} and Dot Anisotropy

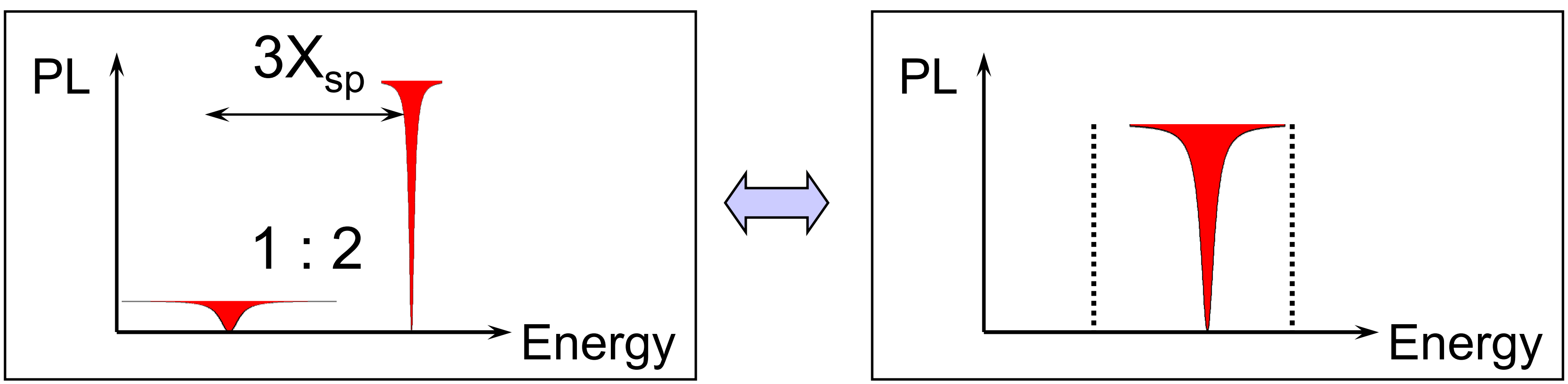




isotropic dot …

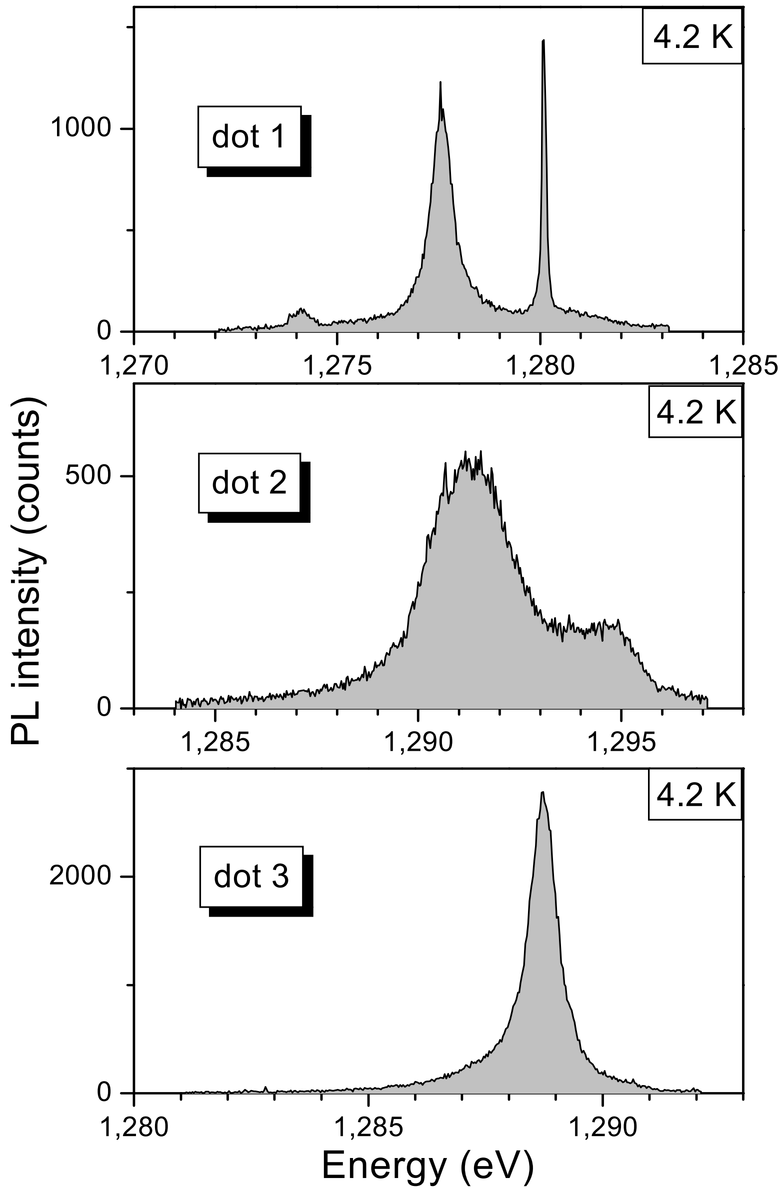
… anisotropic dot



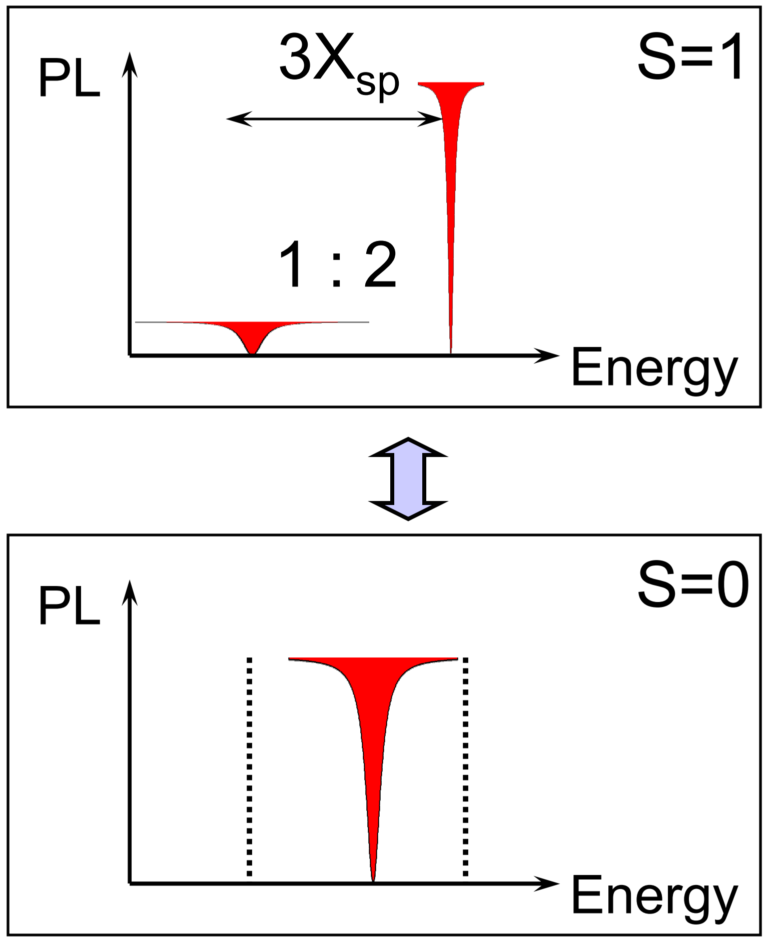


Temperature Dependent PL: X^{3-}

experiment



theory



Summary: TEMPERATURE Dependence

X^0 and X^{1-}

T=4.2K

linewidth X^0 and X^{1-} = n×10μeV

lineshape: Lorentzian

T=30K

linewidth: ↑ by a few μeV

lineshape: *non*-Lorentzian

due to exciton-phonon coupling

X^{2-}

T=4.2…30K

linewidth increases rapidly :

⇨ *enhanced scattering with acoustic phonons*

X^{3-}

T=4.2K

Broad transition of spin S=0 state

T=6.7K

sharp line emerges

(+broader partner at lower energy)

⇩

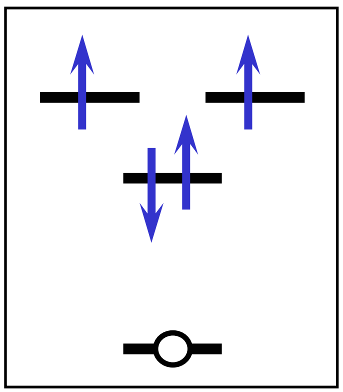
*spin **S=1** state thermally occupied*

MODEL: Why is the X^{3-} special ?

as a function of
- applied magnetic field
- occupation of the wetting layer with electrons
- dot anisotropy ?

Creation of:

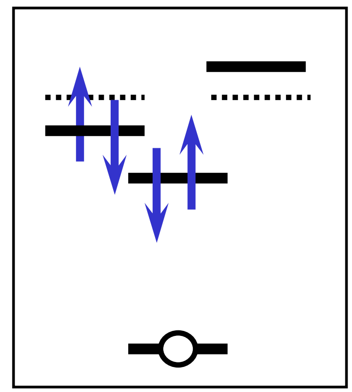
S=1 initial state



no coupling to continuum states

or

S=0 initial state



coupling to continuum states

The main difference: