Coulomb correlations in wide bandgap semiconductors

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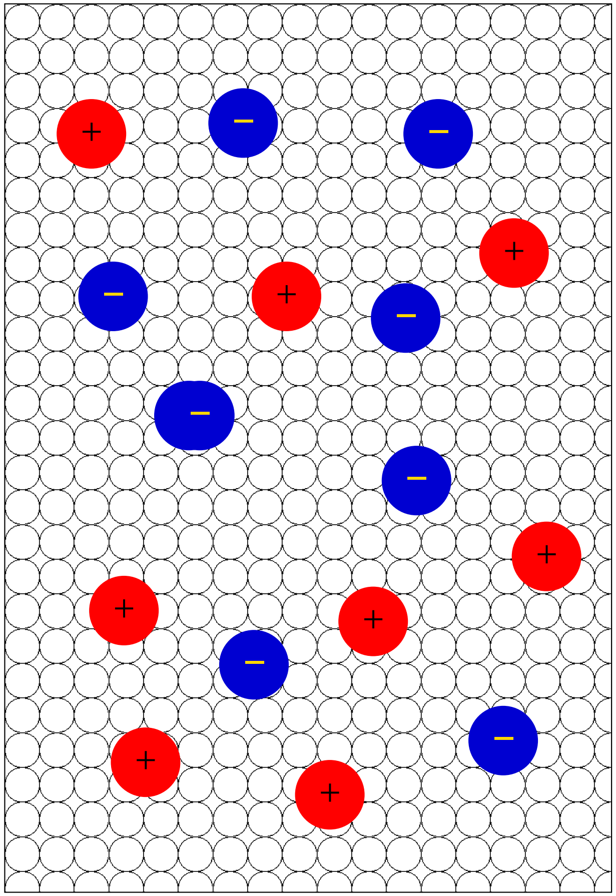
What do I mean by correlation?

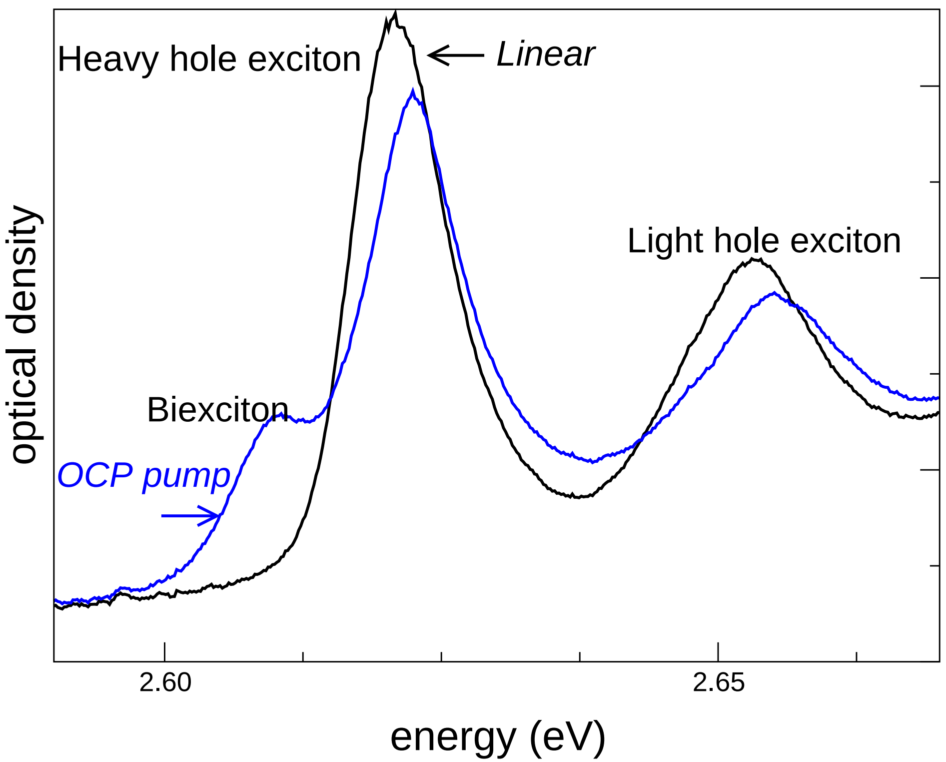
In an excited semiconductor the electrons and holes interact via the Coulomb and exchange interactions.

When this is strong enough their motion is *correlated*



Optical properties and correlation

Absorption spectrum strongly modified by the Coulomb interaction between electrons and holes.



Excitons are Hydrogen-like, bound electron–hole pairs which lower their energy by correlating their motion via the Coulomb attraction.

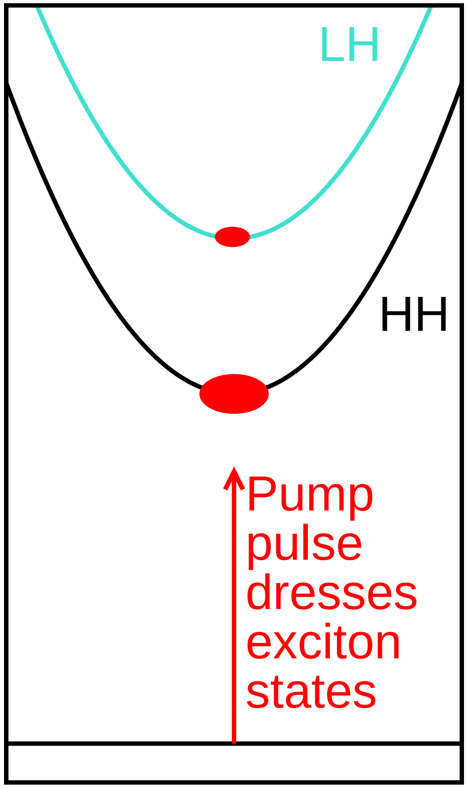
Biexcitons are pairs of excitons likewise bound as a four particle molecule.

Overview

- Non-resonant pumping
  - Experiment & Samples
  - Influence of the light hole band
- Resonant pumping
  - Second Born approximation
  - T-matrix approach
  - Comparison with experiment
- Conclusions

Non-resonant pumping

- The line width and shift of the exciton absorption peak in semiconductor quantum wells are two of the key signatures used to probe Coulomb correlations.



- By pumping well below the HH exciton we can study the influence of the LH on the correlations.

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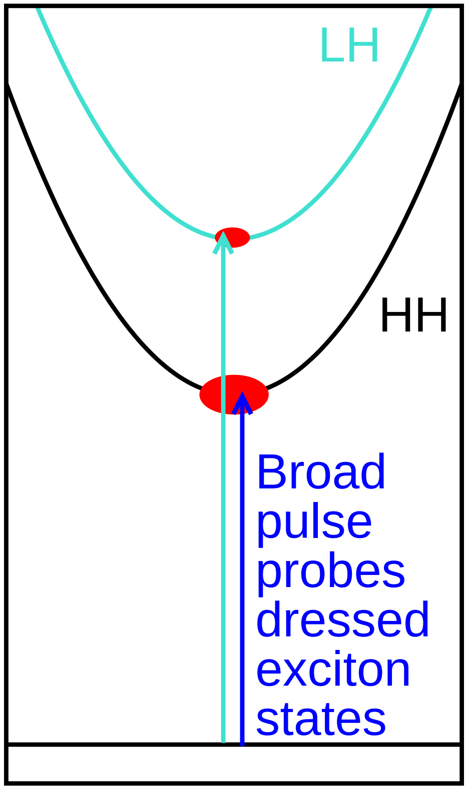

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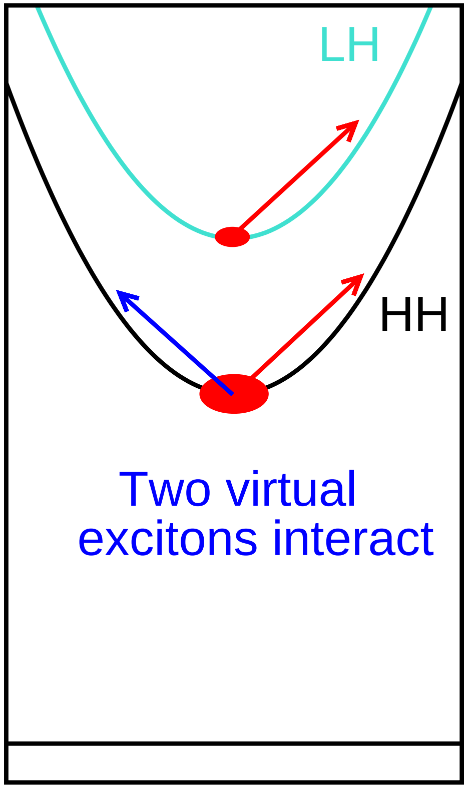

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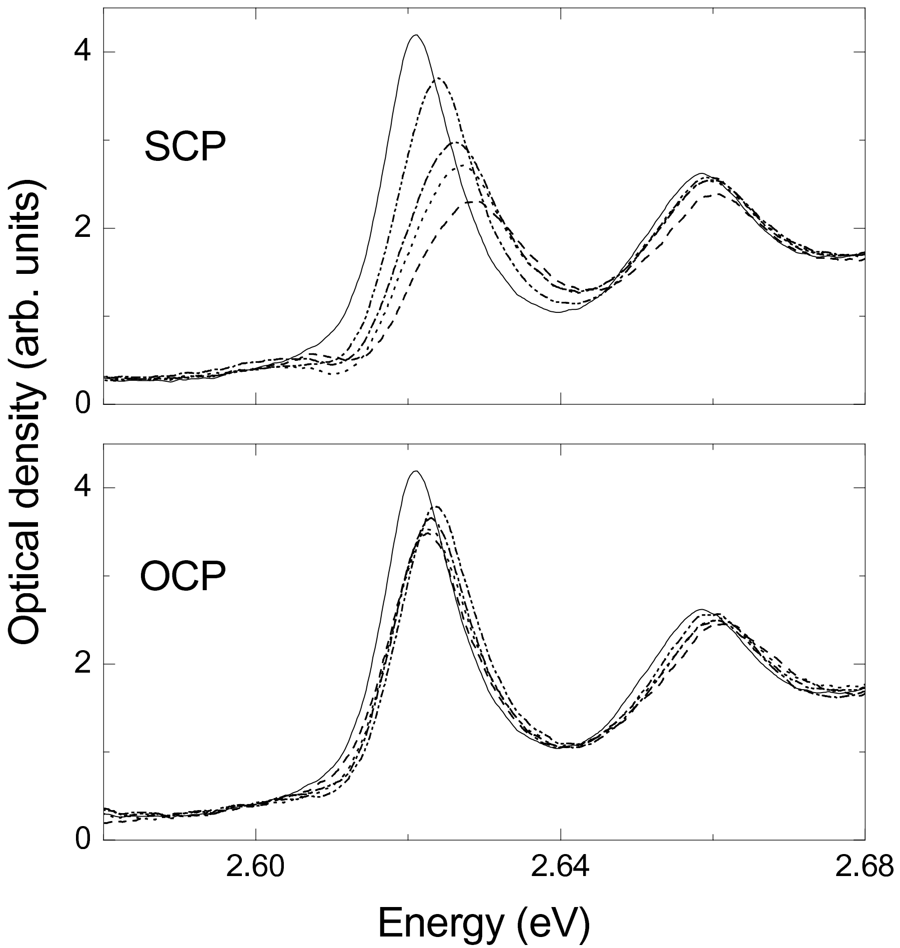
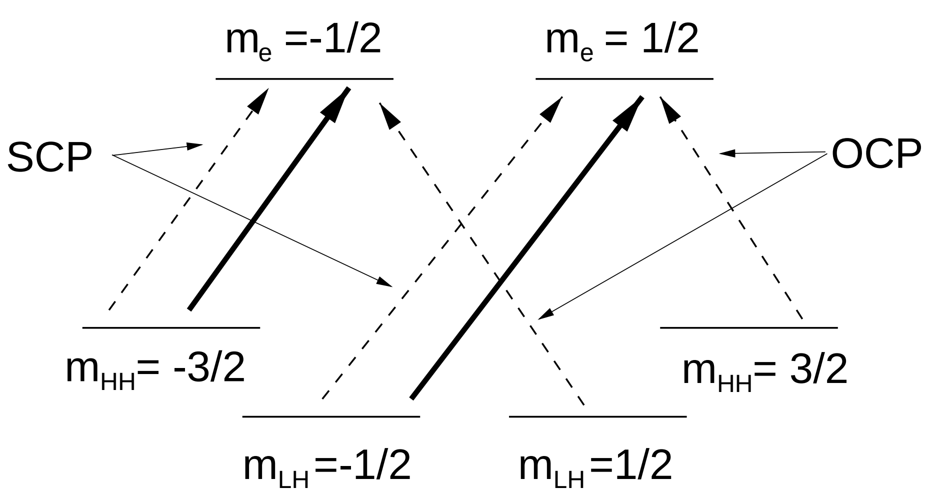
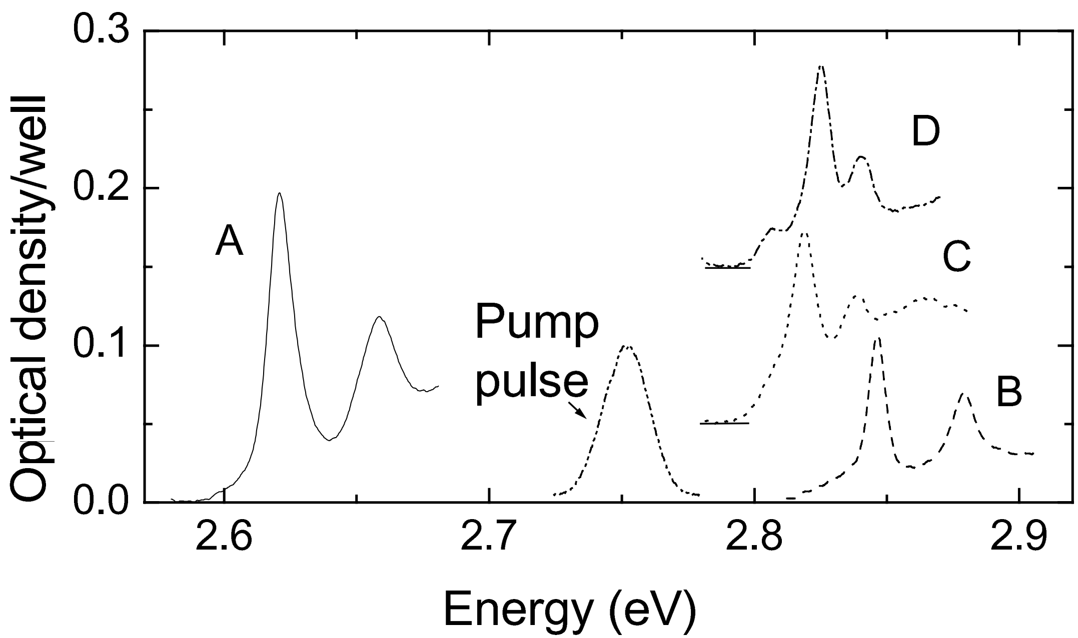
Detuning Dependence



Detunings: 36-71 meV, T=10K

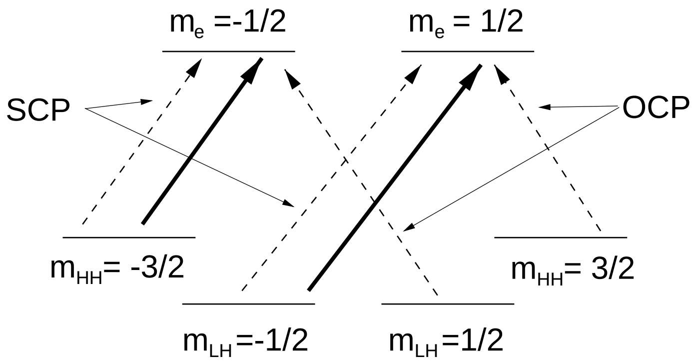


ZnSe-based QW samples

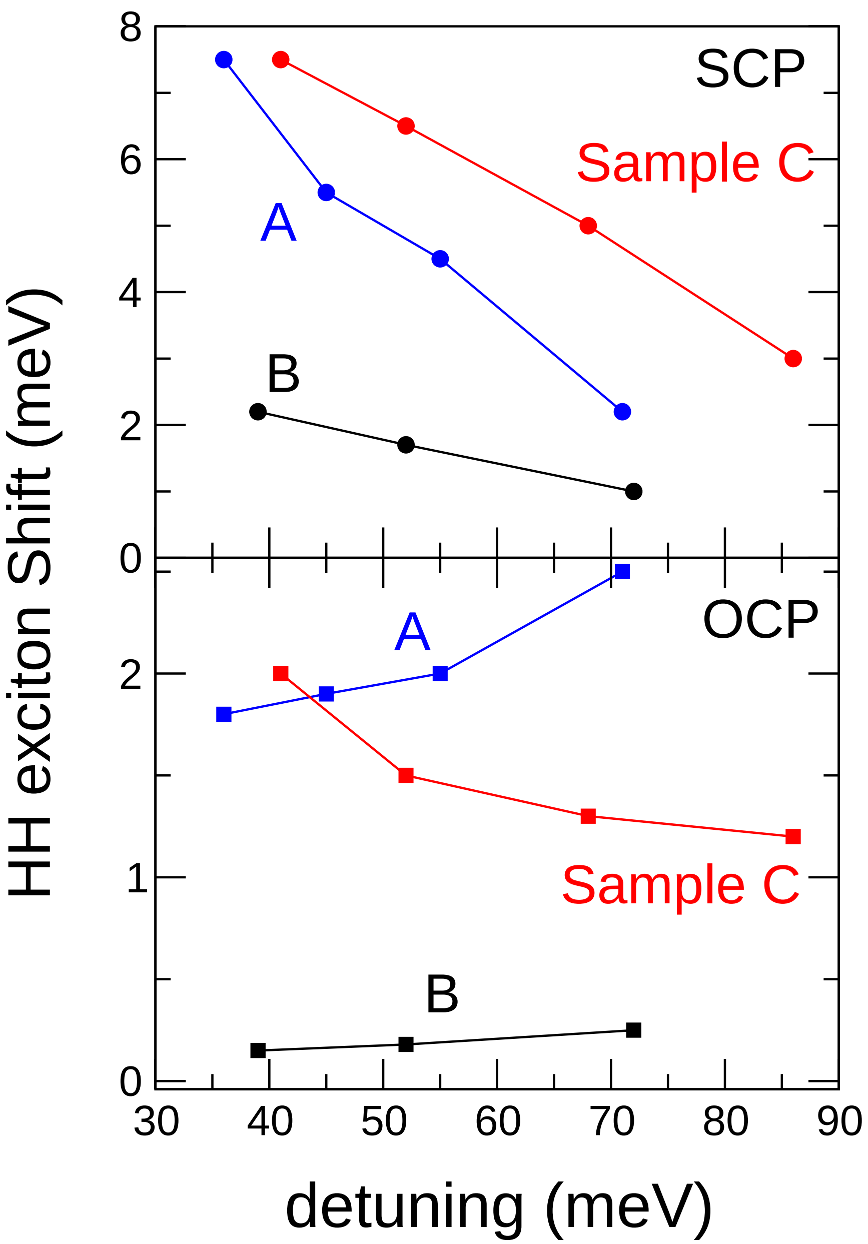


	Structure	width	HH-LH splitting	Detuning	Ratio
A	(Zn,Cd)Se/ZnSe	4 nm	36 meV	36-71 meV	1.0-2.0
B	ZnSe/ZnMgSSe	5 nm	33 meV	39-73 meV	1.2-2.2
C	ZnSe/MgS	10 nm	20 meV	41-86 meV	2.0-4.2
D	ZnSe/MgS	11 nm	16 meV	42-79 meV	2.6-4.9

In different samples...



SCP: Reduced Pauli blocking for larger detuning



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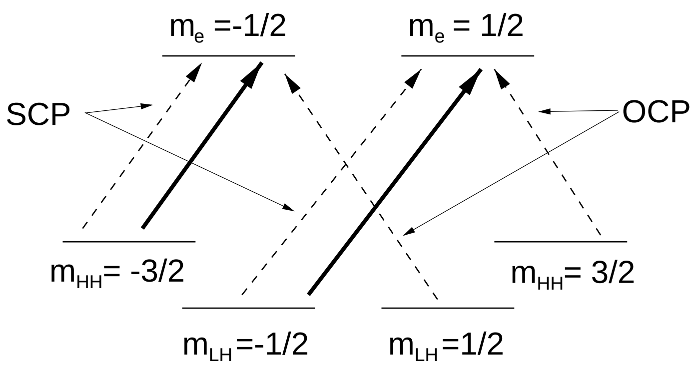
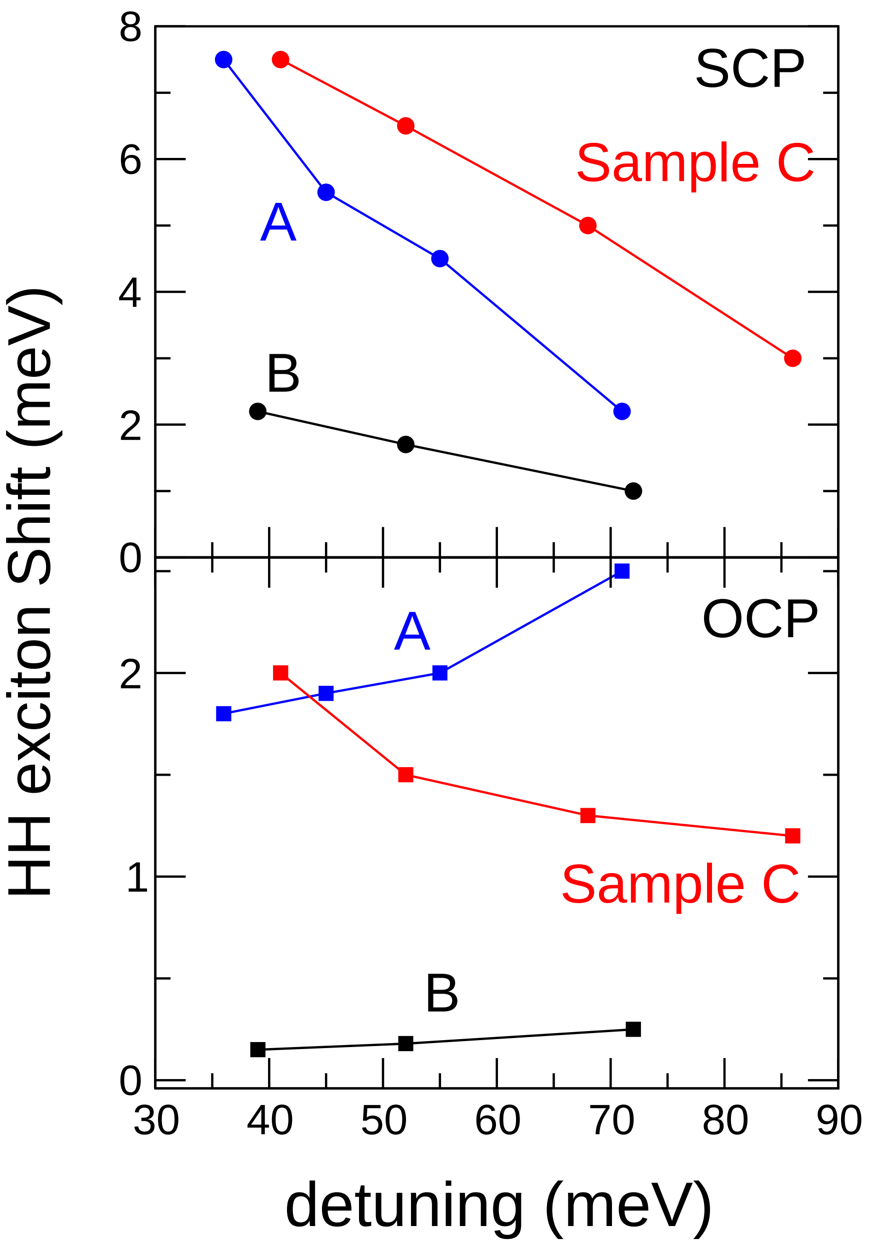


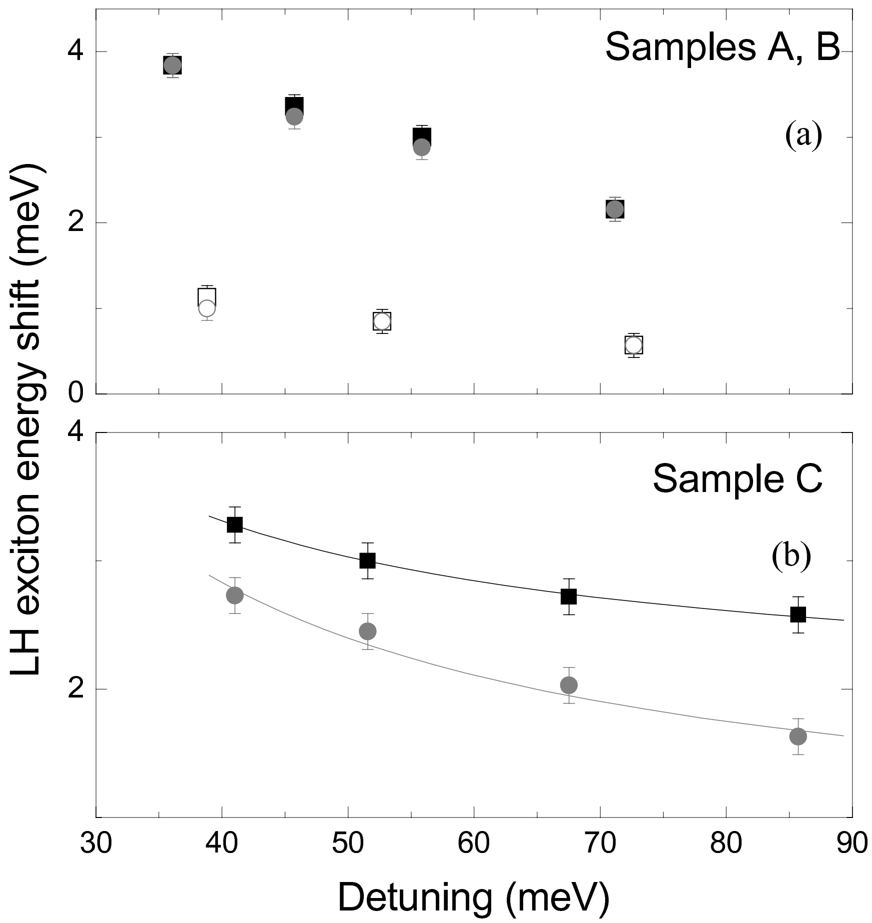
SCP: Reduced Pauli blocking for larger detuning

OCP: Reduced Pauli blocking over-compensated by red shift from LH correlations. (Brick et al PRB 64 75323 2001).



Light Hole Stark shifts

- Stronger LH Stark shift in OCP in samples with large ratios - selection rules



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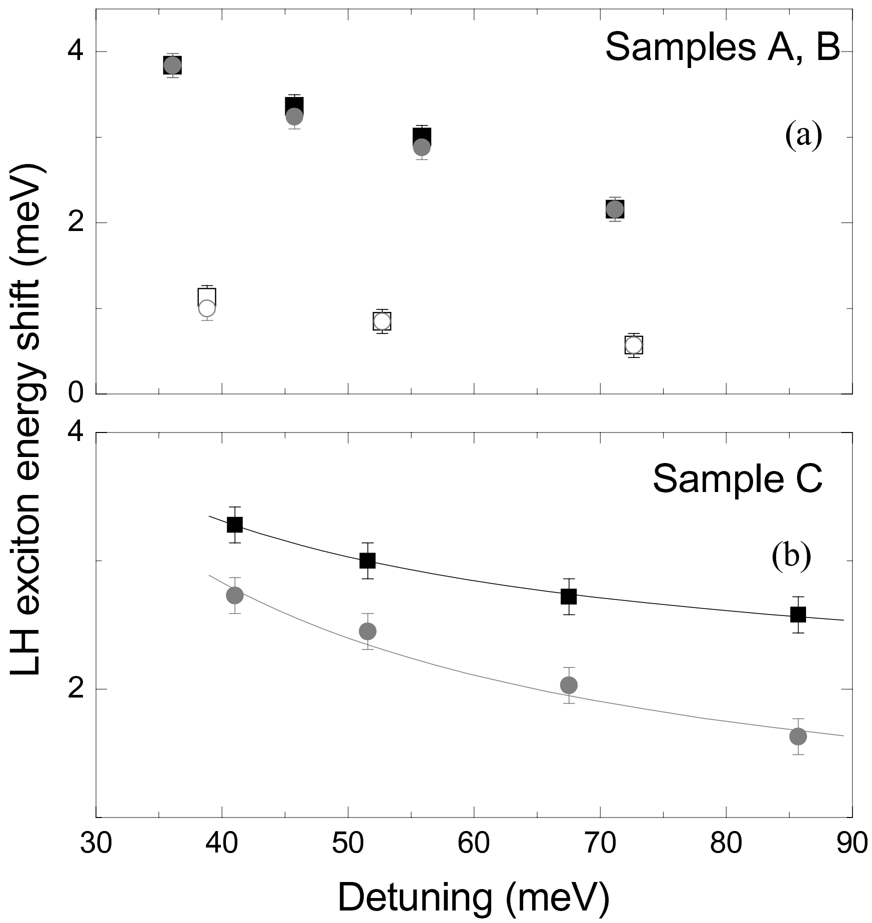
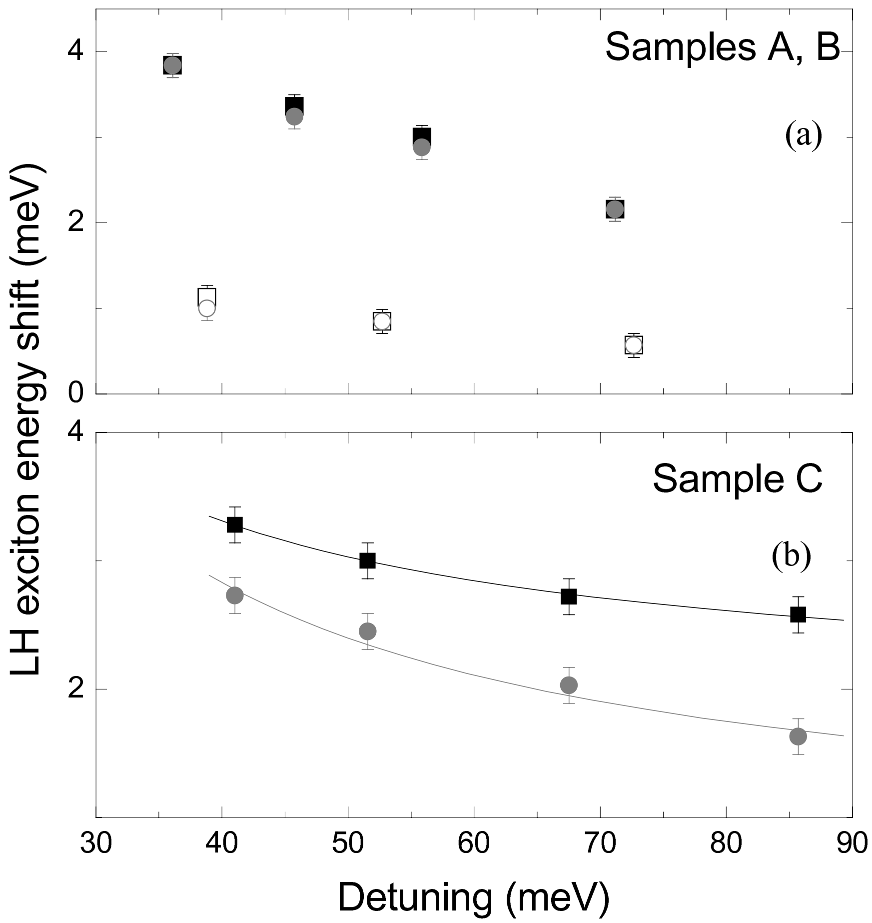
- LH Stark shift is identical in samples with small ratios.



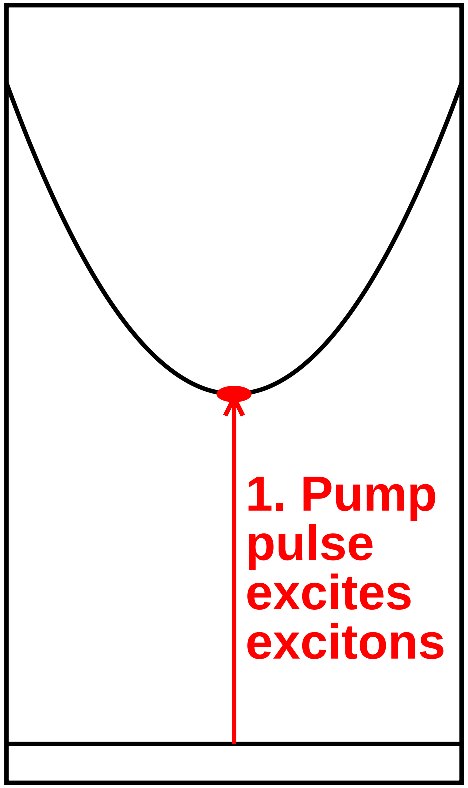
Light Hole Stark shifts

- Stronger LH Stark shift in OCP in samples with large ratios - selection rules
- LH Stark shift is identical in samples with small ratios.
- This is beyond current theory as HH is not perturbation.



Resonant pumping

- The line width and shift of the exciton absorption peak in semiconductor quantum wells are two of the key signatures used to probe Coulomb correlations.



- We study the case where a population of excitons has been created by resonant excitation (i.e. they have essentially zero centre-of-mass momentum.)

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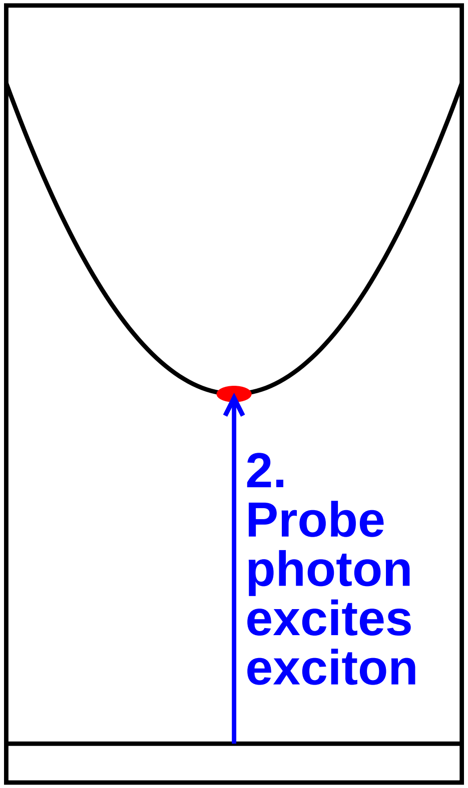

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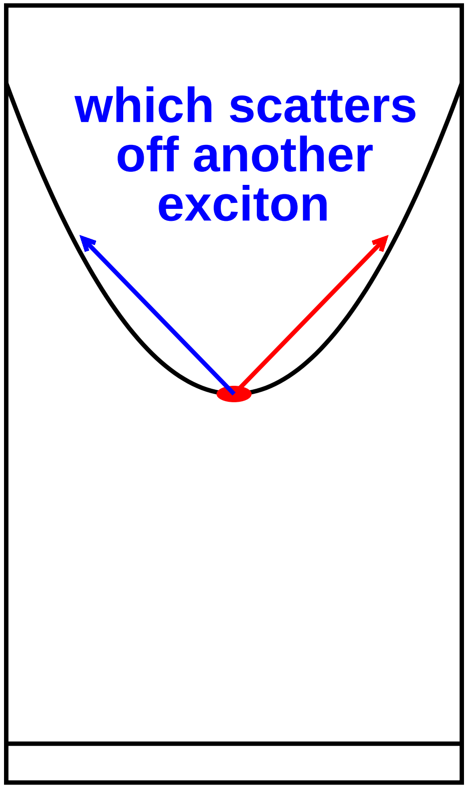

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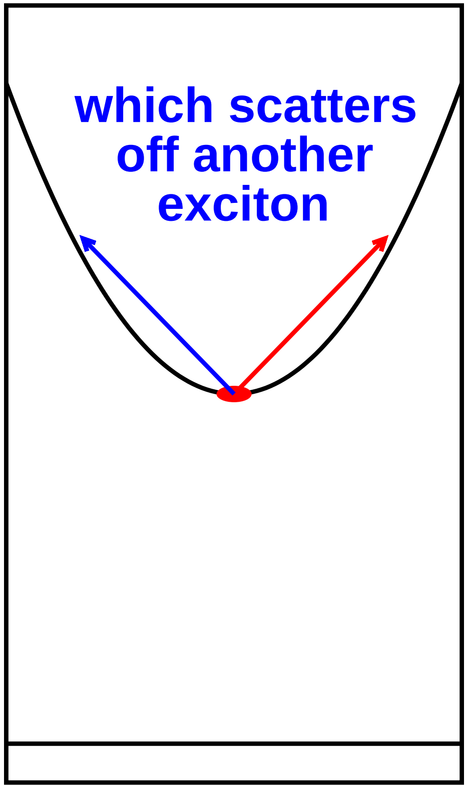
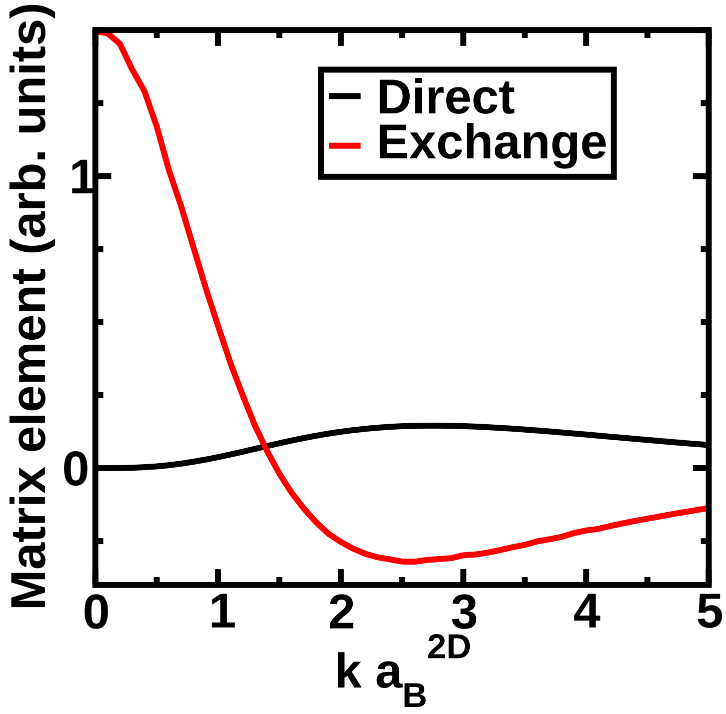


- We study the case where a population of excitons has been created by resonant excitation (i.e. they have essentially zero centre-of-mass momentum.)
- If a low density of excitons is present, the exciton line width and shift are dominated by exciton-exciton scattering.

Exciton-Exciton Coulomb Matrix elements

At low exciton momenta, the scattering matrix elements are dominated by scattering events involving electron or hole exchange:



Self-consistent Born approximation

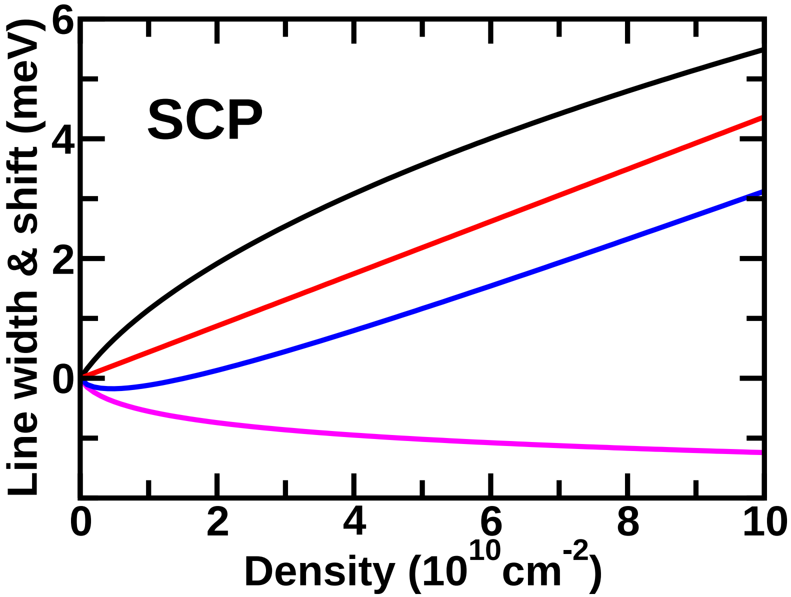
- The Line width, Γ, and shift, Δ, are given by (Boldt *et al*, PSSb **130**, 675):

$$\Gamma = N \sum_{\mathbf{Q}} |V(0,0,\mathbf{Q})|^2 \frac{2\Gamma}{\left(\frac{\hbar^2 Q^2}{M}\right)^2 + 4\Gamma^2}$$

$$\Delta = N \left(V(0,0,0) - \frac{1}{2} \sum_{\mathbf{Q}} \frac{|V(0,0,\mathbf{Q})|^2 \frac{\hbar^2 Q^2}{M}}{\left(\frac{\hbar^2 Q^2}{M}\right)^2 + 4\Gamma^2} \right)$$

  - $V(\mathbf{k}, \mathbf{k}', \mathbf{q})$ is the scattering matrix element for two excitons of momentum $\mathbf{k}, \mathbf{k}'$ and momentum transfer $\mathbf{q}$ (Ciuti *et al*, PRB **58**, 7926).
  - N is the number of excitons.
- The line width Γ is found self-consistently.

Self-consistent Born approximation - results



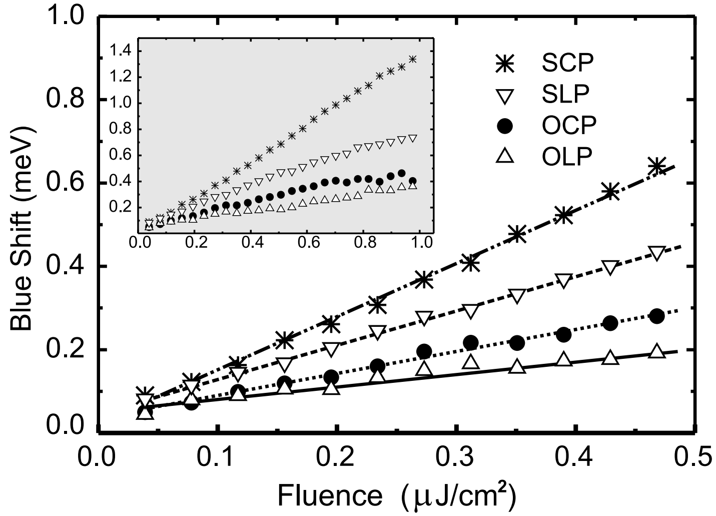
Line width

First order shift (Schmitt-Rink *et al*, PRB **32**, 6601)

Total shift

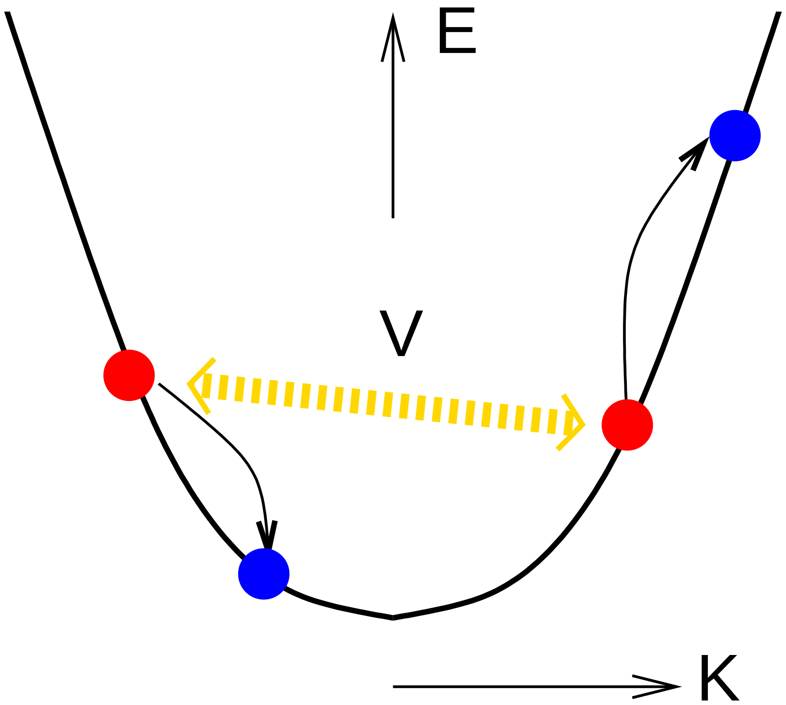
Second order shift

- Experiment: Wachter *et al*, PRB **65**, 205314
- Shift linear with fluence and to the blue



T-matrix Approach

- The T-matrix, $T(\mathbf{k}, \mathbf{k}', \mathbf{q})$, contains the exciton-exciton scattering to infinite order.



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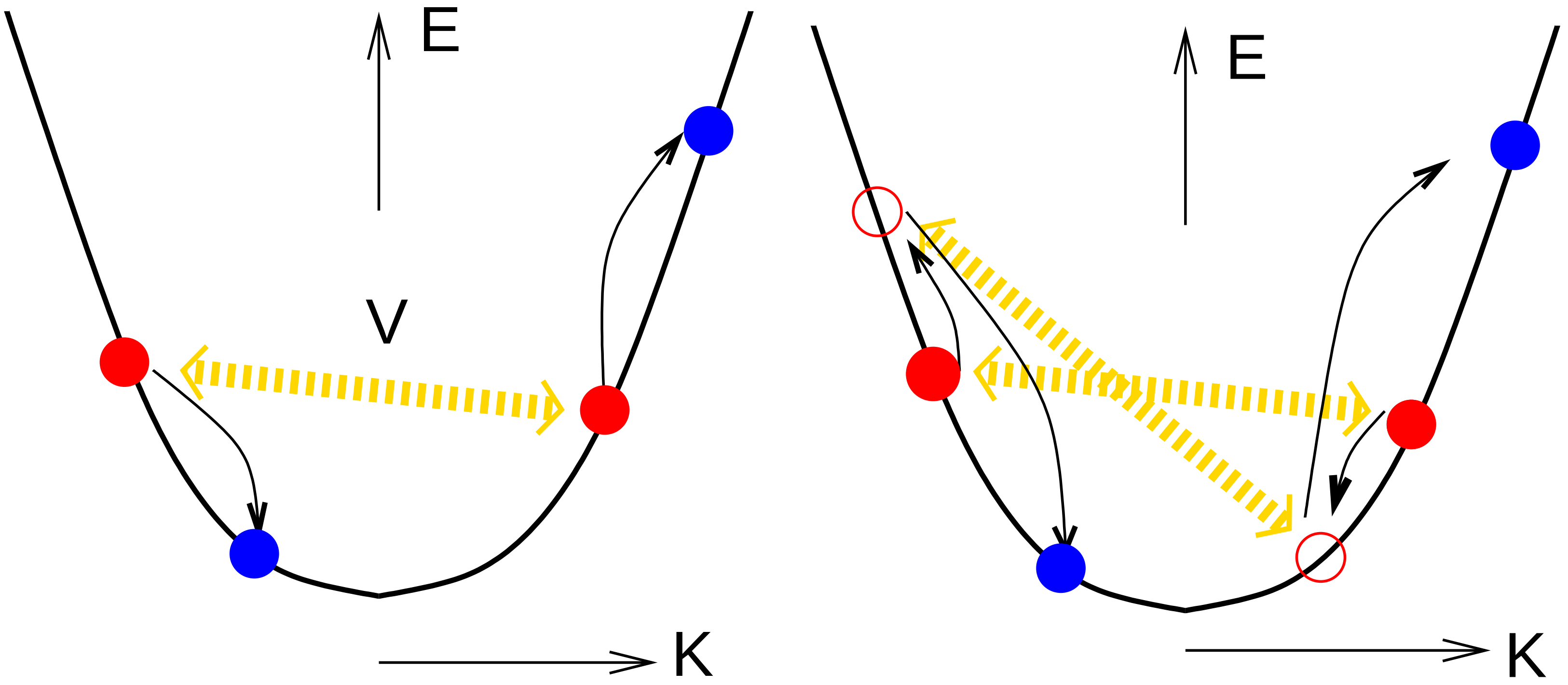

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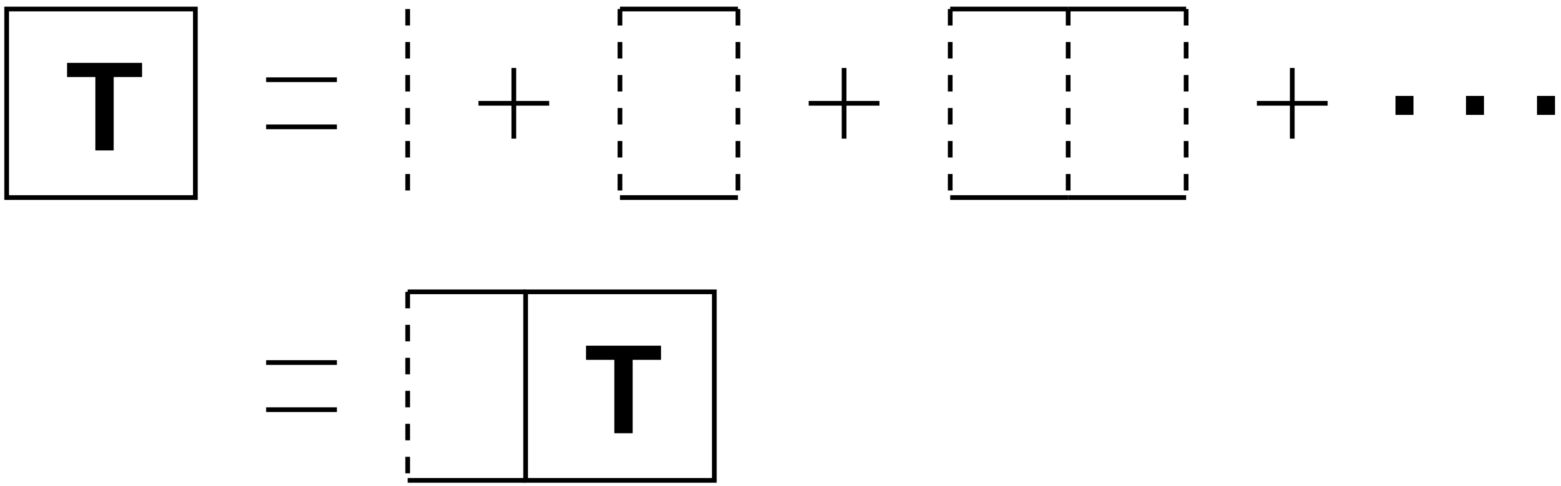

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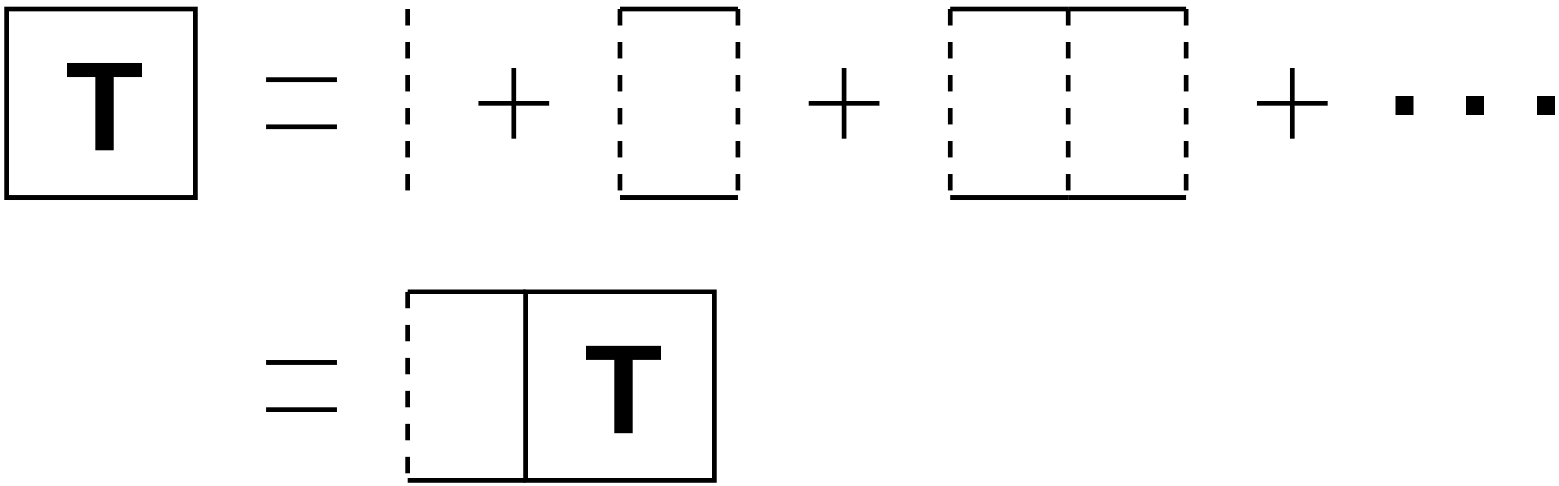


$$\begin{aligned} \color{red}{T(\mathbf{k},\mathbf{k}',\mathbf{q})} &= V(\mathbf{k},\mathbf{k}',\mathbf{q}) \\ &+ \sum_{\mathbf{Q}} \frac{\frac{1}{2}V(\mathbf{k}+\mathbf{Q},\mathbf{k}'-\mathbf{Q},\mathbf{q}-\mathbf{Q})\ \color{red}{T(\mathbf{k},\mathbf{k}',\mathbf{Q})}}{-\frac{\hbar^2 Q^2}{M}+2i\Gamma} \end{aligned}$$

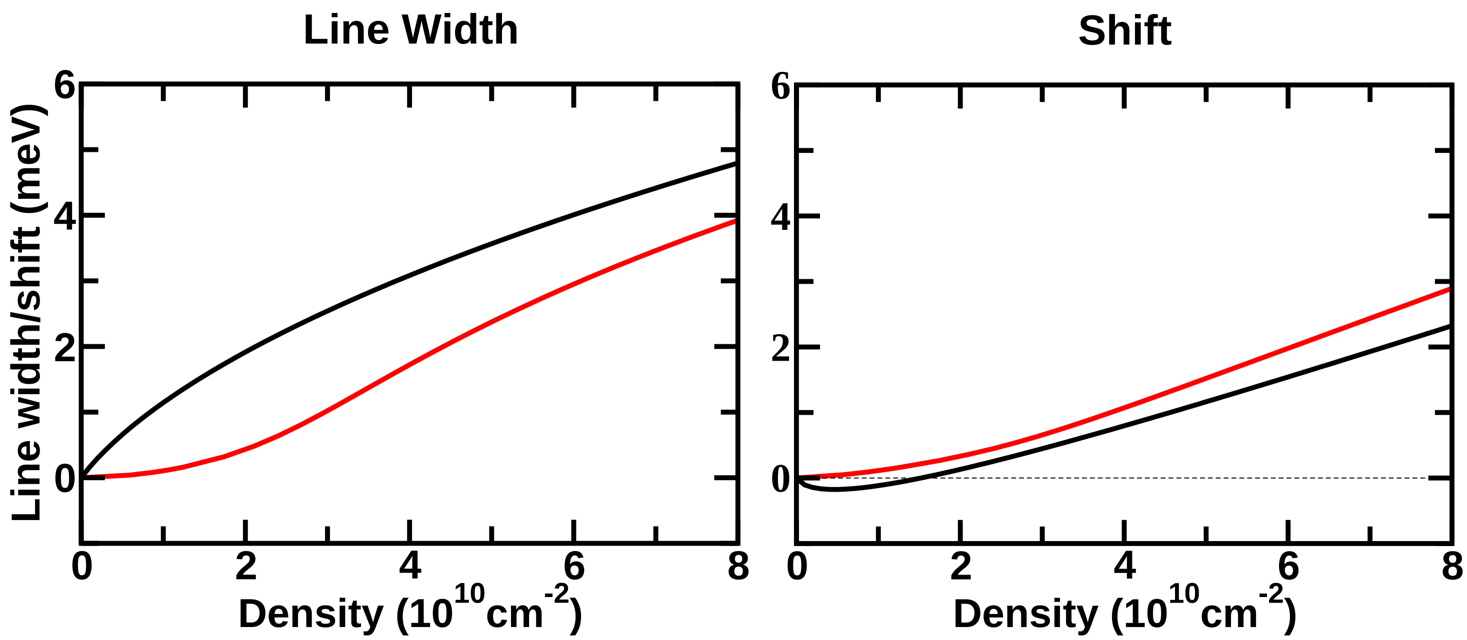
T-matrix: equations

- The T-matrix, $T(\mathbf{k},\mathbf{k}',\mathbf{q})$, contains the exciton-exciton scattering to infinite order.

$$\Gamma = N \sum_{\mathbf{Q}} |T(0,0,\mathbf{Q})|^2 \frac{2\Gamma}{\left(\frac{\hbar^2 Q^2}{M}\right)^2 + 4\Gamma^2}$$

$$\Delta = N \, \mathrm{Re}\left[T(0,0,0)\right]$$

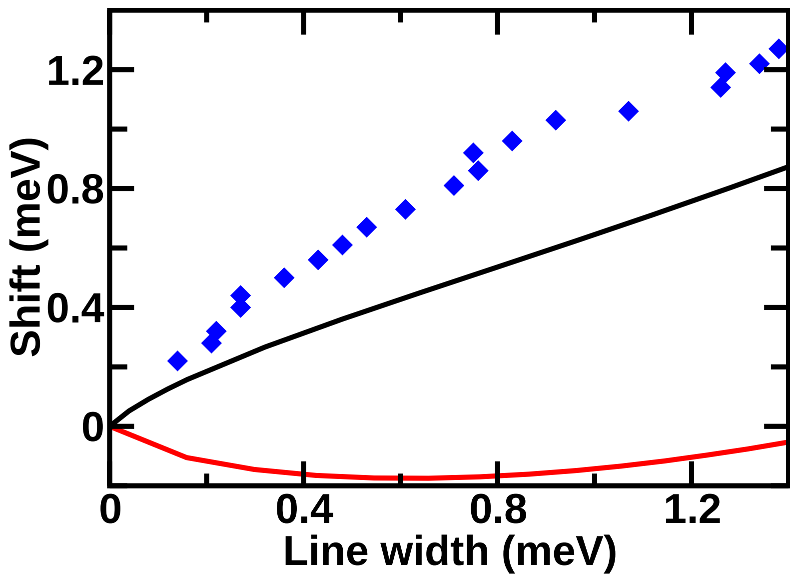
T-matrix: results



- Self-consistent Born approximation, T-matrix
- The dependence of the line width on density is not sublinear in the T-matrix calculation.
- The infinite order T-matrix removes the anomalous red shift at low densities.

T-matrix: comparison with experiment

- It is difficult to compare the density dependence with experiment due to uncertainties in the carrier density.
- This may be eliminated by plotting directly shift against line width (Wachter *et al*, PRB **65**, 205314).



Experiment

T-matrix calcs

Self-consistent Born calcs.

Summary

- Non-resonant Pumping
  - HH OCP Stark shift depends on HH-LH splitting
  - LH Stark shift - theory opportunity
- Resonant Pumping
  - We have calculated the width and shift of the exciton absorption peak in semiconductor quantum wells due to exciton-exciton scattering.
  - An infinite order T-matrix calculation gives no anomalous red shift.
  - We have fitted experimental plots of shift against line width for SCP polarisation.
  - Calculating the T-matrix for other polarisation configurations is significantly more involved.

... and thanks to ...

Collaborators

- Non-resonant Pumping
  - G. Papageorgiou, A. Kar - Expts, HW
  - C. Bradford, K. Prior - samples, HW
- Resonant Pumping
  - S. Wachter, H. Kalt - Uni Karlsruhe
  - C. Dent - Theory, HW
  - K. Ohkawa, D.Hommel - samples, Uni Bremen

Temperature dependence