Theory of Photoluminescence at $\nu = 1$

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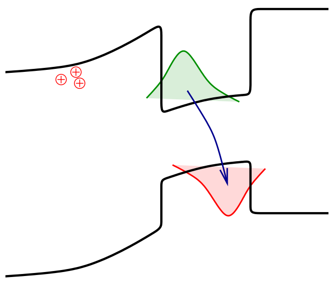
[Osborne et al., preprint (1997)]

Outline

- Introduction to photoluminescence
- Properties of the $\nu = 1$ state
- The PL discontinuity: Observations, and explanation
- “Excitonic” States: PL lineshapes
- Skyrmion-excitons & other possibilities

Introduction to Photoluminescence

Intrinsic photoluminescence (PL) of 2DEGs in GaAs quantum wells (i.e. not "extrinsic" PL).



Experiment

[Clark, Turberfield, Heiman, Goldberg...]

PL displays structure that correlates with transport features in the quantum Hall (and fractional quantum Hall) regimes.
What can it tell us about the properties of these systems?

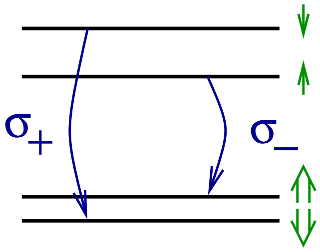
Theory

[MacDonald, Rashba, Quinn...]

Requires a knowledge of the low-energy states of a valence-band hole in an interacting electron gas.
In general a "hard" problem: exact diagonalization studies and approximate analytic approaches in the fractional QH regime leave many unanswered questions.

Experiments around $\nu = 1$ also show interesting PL features.
In particular, a strong dependence on the circular polarization.

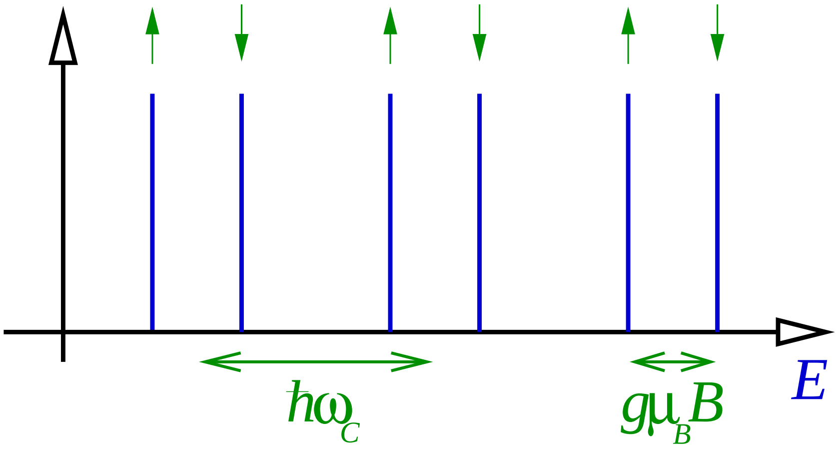
$\Longrightarrow$ PL is a spin-sensitive probe



A much simpler state to study theoretically, yet it has interesting spin-related properties (spin-waves, Skyrmions).
What are the consequences for PL?

Properties of the $\nu = 1$ state

Two-dimensional electron gas, in magnetic field B.



Filling fraction $\nu \equiv n(2\pi\ell^2)$ $\quad(\ell \equiv \sqrt{\hbar/eB})$

$+$ Interactions

Typically (GaAs) $e^2/\epsilon\ell \gg g\mu_B B$

$\Rightarrow$ Interactions are important for the spin-order.

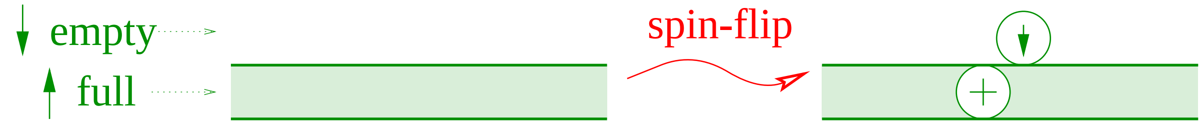
Assume: $e^2/\epsilon\ell \ll \hbar\omega_c$

The $\nu = 1$ state is "ferromagnetic": the groundstate is spin-polarized for $g \to 0$. [MacDonald et al., 1996]

Complete spin-polarization is observed in experiment. [Barrett et al., 1995; Aifer et al., 1996]

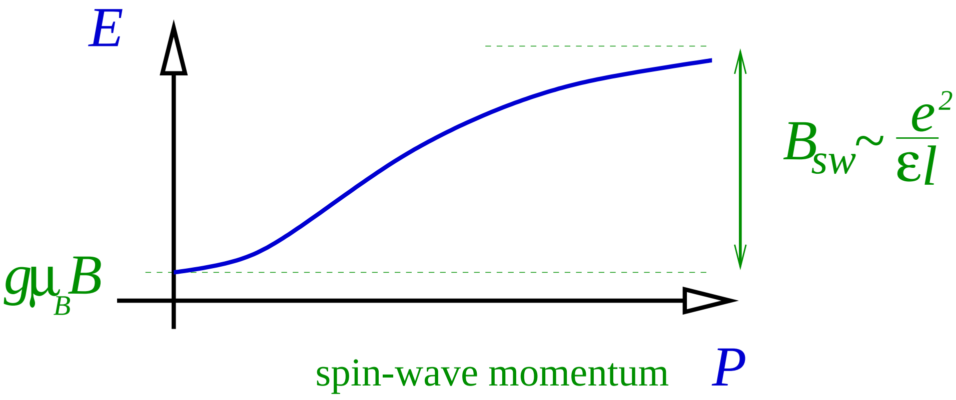
Ferromagnet $\Longrightarrow$ low-energy spin-wave excitations

[Bychkov, Iordanskii & Eliashberg, 1981; Kallin & Halperin, 1984]

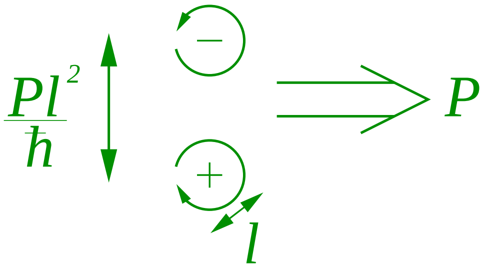


$\hbar\omega_c \gg e^2/\epsilon\ell \Longrightarrow$ spin-wave $=$ magnetic exciton

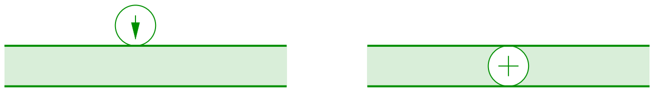
Dispersion Relation [Lerner & Lozovik, 1980]



Semiclassical Picture:



$P\ell/\hbar \to \infty \Longrightarrow$ quasielectron/quasihole pair.



$$E_{qe} + E_{qh} = g\mu_B B + B_{sw}$$

Since $g\mu_B B \ll e^2/\epsilon\ell$, it can be energetically favourable to introduce additional spin-flips.

$\Longrightarrow$ "charged spin-textures" and "Skyrmions"

[Sondhi et al., 1993]

Observations of a PL Discontinuity

[Goldberg et al., 1992; Osborne et al., 1997]

As ν is reduced through $\nu = 1$:

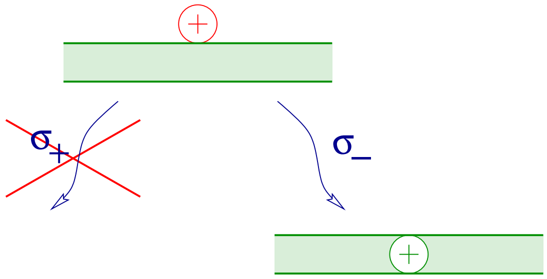
- σ_+ is quenched;
- σ_- is redshifted by $\Delta \sim 1\text{meV} \gg g\mu_B B \sim 0.1\text{meV}$
  $\Rightarrow$ interactions
- The discontinuity vanishes for small electric fields (small electron-hole separation).

An Explanation for the Discontinuity

[Muzykantskii, 1992; C.&C., 1997]

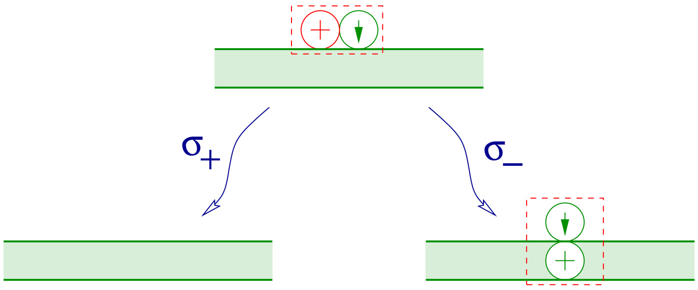
The screening properties of the 2DEG are quite different at $\nu < 1$ and $\nu > 1$. [Neglecting "Skyrmion" effects for now.]

$\nu < 1$: The quasiholes are repelled from the valence-band hole $\Rightarrow$ one can expect an initial "free-hole" state.



$$E_-^{fh} = E_{vbh} - E_{qh}$$

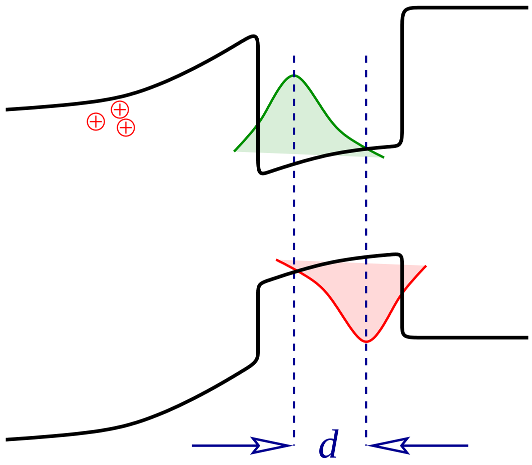
$\nu > 1$: The quasielectrons are attracted to the valence-band hole $\Rightarrow$ one can expect an initial "excitonic" state.



$$E_+^{ex} = [E_{vbh} + E_{qe} - B_{ex}]$$
$$E_-^{ex} = [E_{vbh} + E_{qe} - B_{ex}] - [E_{qe} + E_{qh} - B_{sw}]$$

As ν is reduced through $\nu = 1$:

- σ_+ will be quenched;
- σ_- will be redshifted by $B_{sw} - B_{ex}$.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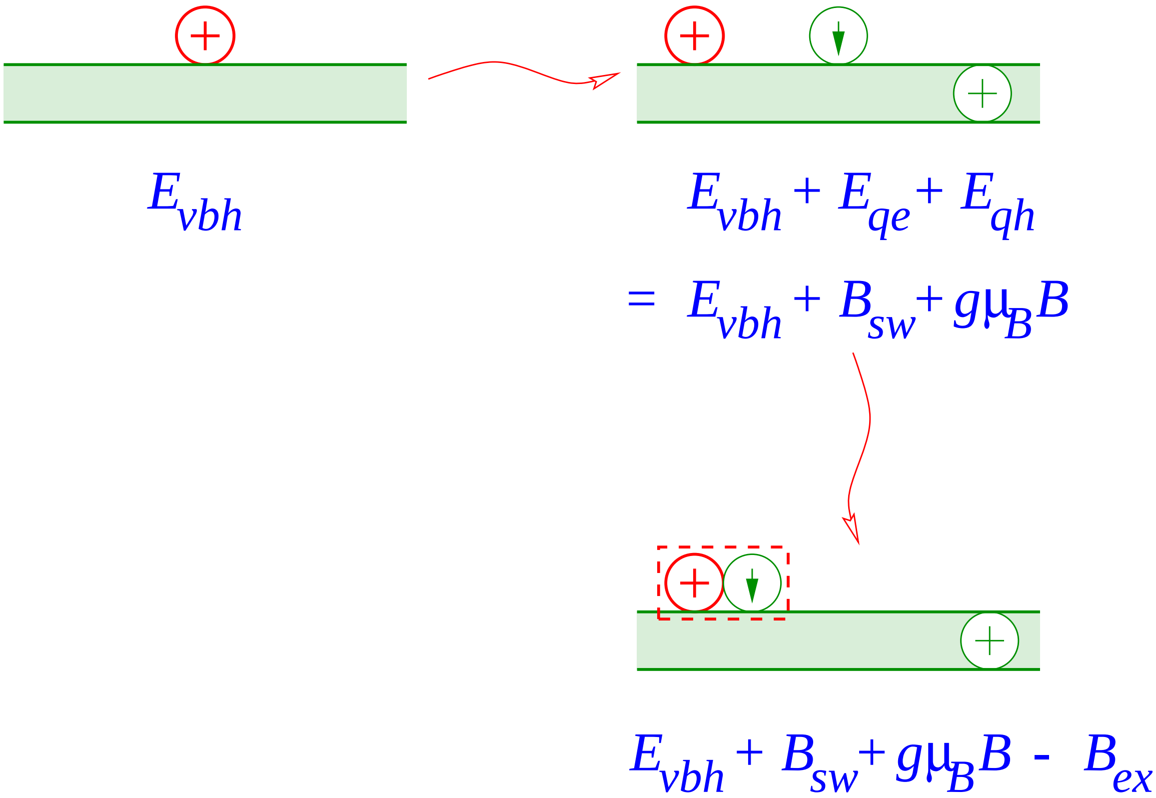
Why does the discontinuity disappear?

Consider the free-hole state:

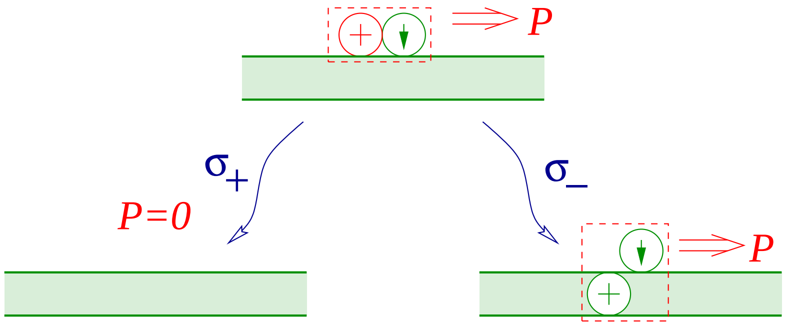


If $B_{ex} > B_{sw} + g\mu_B B$, the free-hole state is unstable to the formation of an excitonic state.
One can then expect an initial excitonic state on *both* sides of $\nu = 1$
$\Longrightarrow$ no discontinuity.

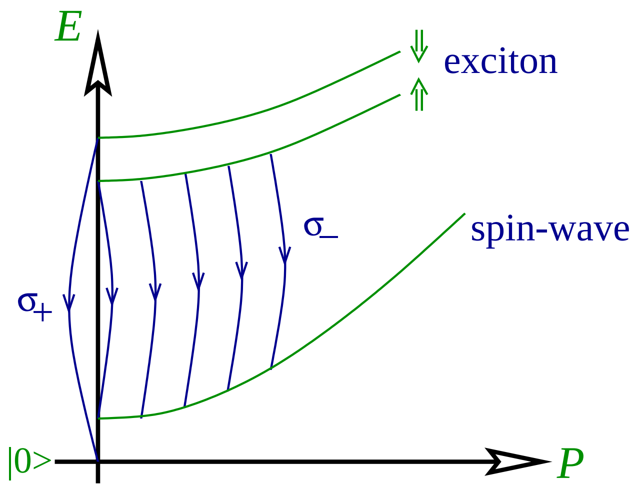
($B_{ex} > B_{sw}$ requires Landau level mixing for the electrons.)

Excitonic State: PL lineshapes

Further evidence for excitonic states is obtained from the PL lineshapes of samples showing no discontinuity. [C.&C., 1997]



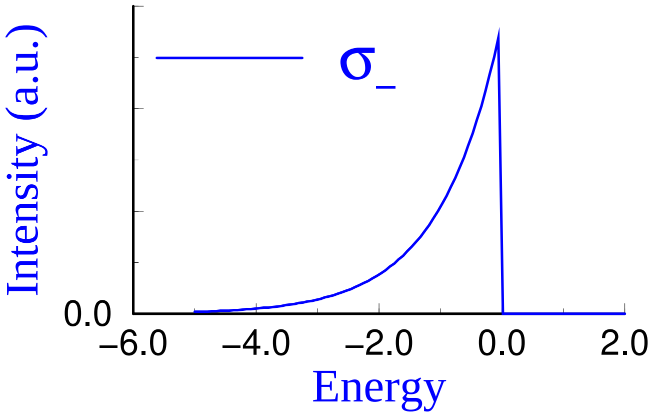
Dispersion relation and radiative transitions:



A spread of initial momenta will produce a sharp line in σ_+, but an *asymmetric* line in σ_-.

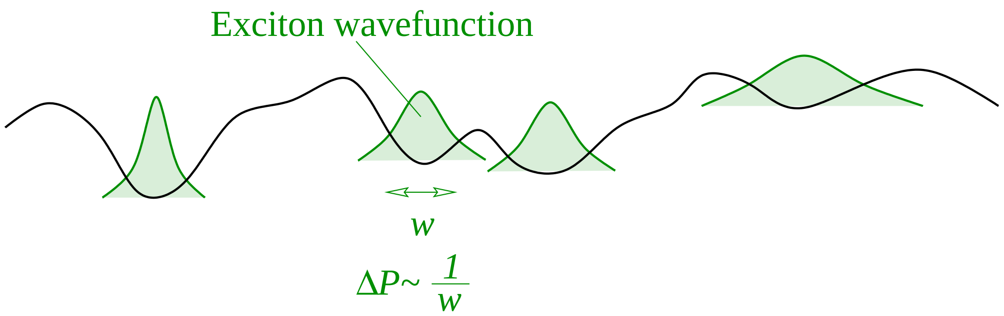
Calculation shows that $M_{ex} > M_{sw} \Rightarrow$ a broadening of σ_- to *lower* energy (spin-wave shake-up), consistent with experimental observations.

(1) No disorder: Thermal population

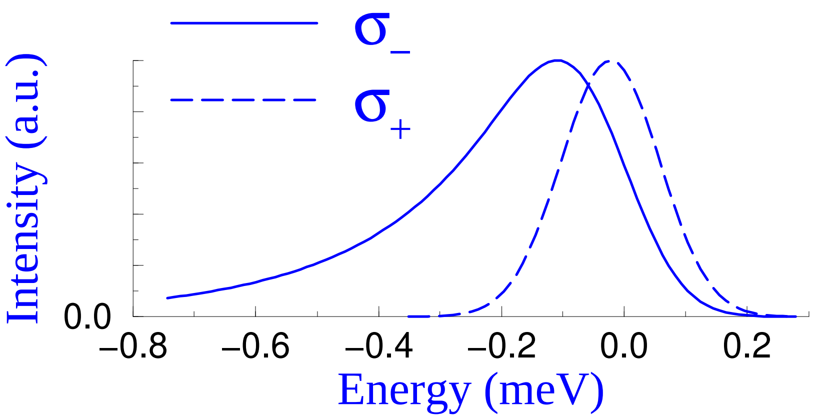


in units of $k_B T \left(\frac{M_{ex}}{M_{sw}} - 1 \right)$

(2) Long-range disorder [remote donors]



Average over the spectra from states in all minima [for the sample of Plentz et al. (1995)].



Skyrmion-excitons

Recall:

Similarly:

If the charged excitations are Skyrmions, then Skyrmion-excitons must have lower energy when $d \gg \ell$.

Numerical calculations show that the behaviour depends sensitively on the electron-hole separation, d:

- $d < 1.4\ell \Rightarrow$ the excitonic state is stable to the addition of a spin-flip even for $g \to 0$;
- $d > 1.4\ell \Rightarrow$ the excitonic state is unstable to the addition of a spin-flip for sufficiently small g $\Rightarrow$ expect a Skyrmion-exciton.

[see also Portengen et al., Nicholas et al., 1997]

The recombination of these states would lead to asymmetric line-shapes in *both* polarizations (spin-wave shake-up for both).

Indirect PL in double QW sample shows some evidence of this.

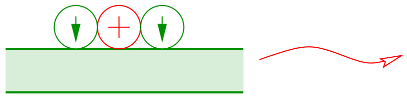
[Osborne et al., 1997]

Further possibilities

Perhaps spin-flips could bind to the "free-hole" state:

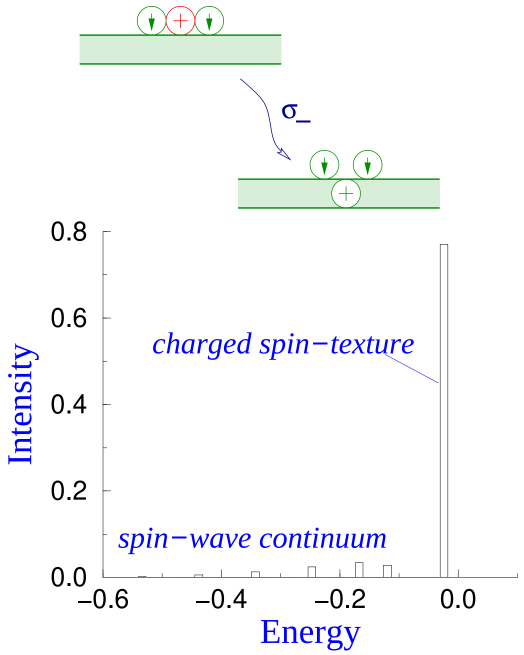
This can only occur for $d < 0.5\ell$.

Perhaps a negatively-charge excitonic state could form:



Numerical calculations show this to be bound, but the binding energy falls quickly with d.

The σ_- recombination spectrum would show a gap related to the formation energy of the spin-$3/2$ charged spin-texture.



Summary

- Intrinsic photoluminescence of GaAs quantum wells shows interesting polarization-resolved structure close to $\nu = 1$.

- The spectral discontinuity observed in samples with large electron-hole separation can be understood in terms of a transition from an excitonic state at $\nu > 1$ to a free-hole state at $\nu < 1$.

- The polarization dependences of the PL lineshapes are consistent with this explanation.

- Simple models show that other low-energy initial states could also form. Further systematic experimental investigations would be required to identify such states.