Spin Dynamics of Hole Systems

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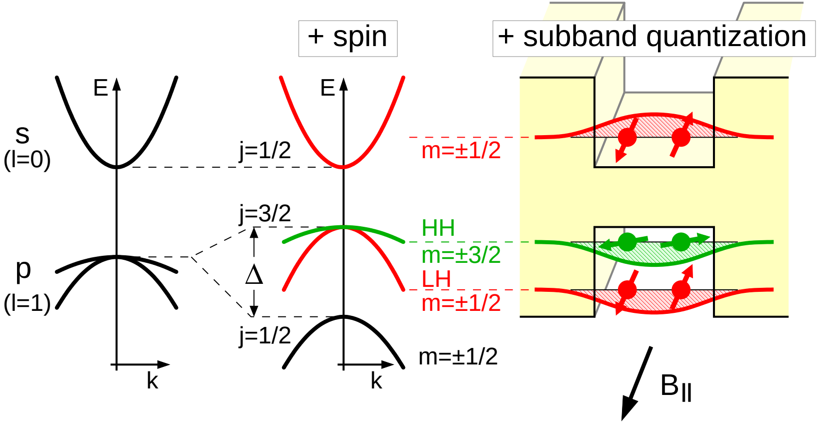
Electron versus Hole Subbands



HH states: spin orientation
fixed by subband quantization

Overview

- Charge carriers in semiconductors:

  spin-1/2 electrons versus spin-3/2 holes

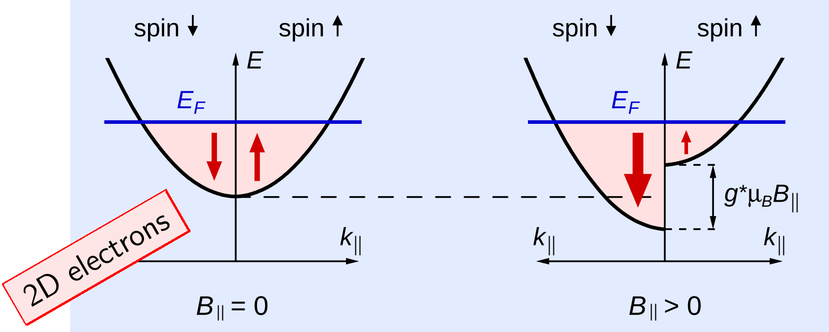
- Zeeman splitting and spin polarization
  of 2D hole systems in an in-plane magnetic field

- exchange-correlation enhancement of Zeeman splitting

- multipole expansion of spin density matrix

- spin precession of hole systems

Zeeman Energy Splitting and Spin Polarization



electron systems: fully spin polarized when $g^* \mu_B B_\parallel > E_F$

(measurement: magnetoresistance)

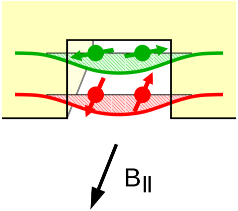
hole systems: qualitatively different from that!

Zeeman Energy Splitting of HH Systems

- frozen spin of HH states
- no Zeeman splitting linear in $B_\parallel$ $\quad (g_\parallel^* \approx 0)$

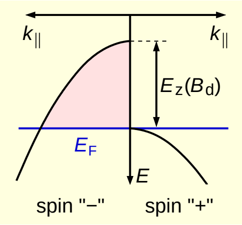
  [van Kesteren *et al.*, PRB **41**, 5283 (1990)]
- Zeeman splitting is a higher-order effect

$$\Delta E_{\mathrm{HH}} \propto \frac{B_\parallel^3}{E_{\mathrm{HH}} - E_{\mathrm{LH}}}$$



$\Rightarrow$ Zeeman splitting of HH states competes with HH-LH splitting

PRB **71**, 113307 (2005)



Depopulation of Minority HH Spin Subband due to $B_\parallel$

determined experimentally
via magnetoresistance

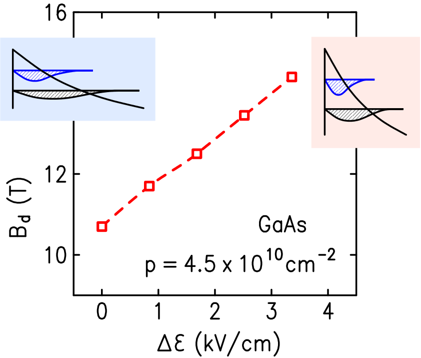
small HH-LH splitting

⇳

large Zeeman splitting

⇳

small B_d



large HH-LH splitting

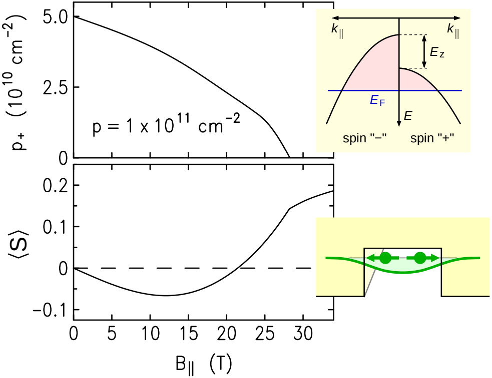
⇳

small Zeeman splitting

⇳

large B_d

Zeeman Energy Splitting versus Spin Polarization: Holes



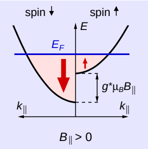
symmetric (100)
$Al_{0.3}Ga_{0.7}As$-
GaAs QW
$p = 1 \times 10^{11}\ \mathrm{cm}^{-2}$
$w = 150$ Å

Heavy hole systems:

- Zeeman energy splitting not simply related with spin polarization
- spin polarization always $\ll 1$
- sign reversal of the spin polarization at $B_\parallel > 0$

PRB 71, 113307 (2005)

Why are these experiments interesting?



– **Known for dilute electron systems**

- Spin susceptibility enhanced because of exchange-correlation

- large enhancement for
  - small densities ("dilute systems")
  - large m^* $\Rightarrow$ **use holes**

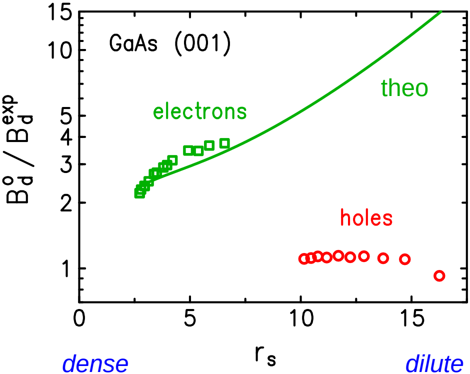
– **2D hole systems in $B_{||}$ studied experimentally by many groups**

– **Holes mediate ferromagnetism in GaMnAs**

– **Spin Hall effect in hole systems**

Spin Susceptibility of Dilute 2D Systems

enhancement of spin susceptibility



dense *dilute*

density parameter $r_s = 1/a_B^* \sqrt{\pi\, n} \propto\ m^*$

- electrons: enhanced spin susceptibility due to exchange-correlation
- holes: no enhancement despite large r_s PRB **72**, 195321 (2005)

Why is exchange-correlation in hole systems different?

Spin 1/2 Systems (Electrons):

- 2×2 spin density matrix
- 4 independent parameters: density + vector of spin polarization
- Systematic scheme: multipole expansion of spin density matrix

  $l = 0$: monopole $\equiv$ charge density

  $l = 1$: dipole $\equiv$ spin polarization

- Compare:

  Multipole expansion of Hamiltonian for spin 1/2 systems

$$\hat{H} = \underbrace{\left[\frac{p^2}{2m^*} + V(\mathbf{r})\right] \mathbb{1}_{2\times 2}} + \underbrace{\frac{g^*}{2}\mu_B\, \mathbf{B}\cdot\boldsymbol{\sigma}}$$

$l = 0$: dynamics of charge density

$l = 1$: spin polarization for $B > 0$

- Orbital and spin dynamics decoupled because wave functions factorize

Spin 3/2 Systems (Holes):

- 4×4 spin density matrix
- 16 independent parameters: $\Rightarrow$ very complex ☹

- Multipole expansion of spin density matrix

  $l = 0$: monopole $\equiv$ charge density

  $l = 1$: dipole $\equiv$ spin polarization ($B > 0$)

  $l = 2$: quadrupole $\equiv$ HH-LH splitting

  $l = 3$: octupole $\equiv$ supplement to spin polarization ($B > 0$)

  $\Rightarrow$ gauge invariant!

- compare: Hamiltonian ("Luttinger Hamiltonian")

  $l = 0$: kinetic energy + potential

  $l = 1$: Zeeman term

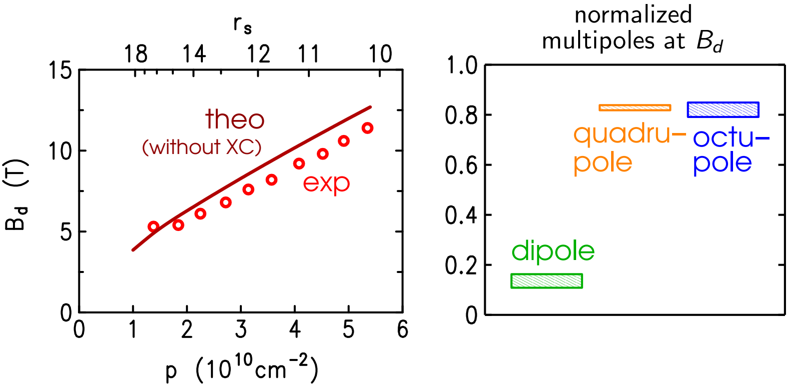
  $l = 2$: HH-LH splitting

  $l = 3$: negligible

- dynamics of multipole moments coupled,
  because wave functions cannot be factorized PRB **70**, 125301 (2004)

Spin Multipoles of 2D Hole Systems

GaAs (001) heterojunction



octupole = new degree of freedom of hole spins at $B_{\|} > 0$

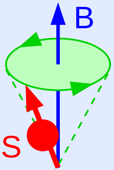
needed: exchange-correlation energy as a function of all four multipoles

Spin Precession

Electrons ($S = 1/2$):

$$\hat{H} = H_0 + \tfrac{1}{2}\,\mathbf{S}\cdot\boldsymbol{\mathcal{B}}$$

$$\frac{d\mathbf{S}}{dt} = \frac{i}{\hbar}[\hat{H}, \mathbf{S}]$$



$$\langle\dot{\mathbf{S}}\rangle = \tfrac{1}{\hbar}\,\langle\mathbf{S}\rangle \times \boldsymbol{\mathcal{B}}$$

$$\frac{d\,|\langle\mathbf{S}\rangle|}{dt} = 0$$

$\langle\mathbf{S}\rangle$ = Bloch vector

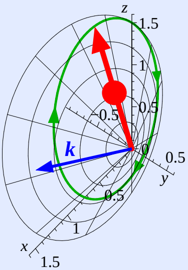
$\boldsymbol{\mathcal{B}}$ = Dresselhaus field $\boldsymbol{\mathcal{B}}(\mathbf{k})$

$\Rightarrow$ Dyakonov-Perel spin relaxation

cond-mat/0605390

Holes ($S = 3/2$):

$$\hat{H} = \hat{H}_0 + \cancel{\hat{H}_1} + \hat{H}_2 + \cancel{\hat{H}_3}$$



$\mathcal{B} = 0!$

oscillating spin polarization

$$\langle\dot{\mathbf{S}}\rangle \rightarrow \text{dipole } \mathbf{S} + \text{quadrupole } \mathbf{Q} + \text{octupole } \mathbf{O}$$

$$\frac{d\,|\langle\mathbf{S}\rangle|}{dt} \neq 0$$

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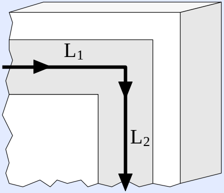
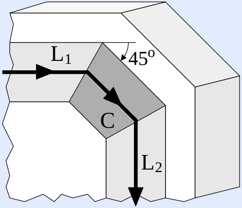
Holes Turning a Corner (B=0!)



[fabricated by Grayson *et al.*,
APL **86**, 032101 (2005)
– but as of yet only *n*-type!]



in region L_1:

$$|\mathbf{S}(t)|^2 = |\mathbf{O}(t)|^2 = 0$$

in region L_2 (ballistic regime):

$$\begin{aligned} |\mathbf{S}(t)|^2 &= 0 \\ |\mathbf{Q}(t)|^2 &= \frac{1}{16} + \frac{3}{16}\cos^2(\omega t) \\ |\mathbf{O}(t)|^2 &= \frac{3}{16}\sin^2(\omega t) \end{aligned}$$

in region C (ballistic regime):

$$\begin{aligned} |\mathbf{S}(t)|^2 &= \frac{9}{80}\sin^2(\omega t) \\ |\mathbf{Q}(t)|^2 &= \frac{1}{64} + \frac{15}{64}\cos^2(\omega t) \\ |\mathbf{O}(t)|^2 &= \frac{39}{320}\sin^2(\omega t) \end{aligned}$$

$$\omega = (E_{\mathrm{HH}} - E_{\mathrm{LH}})/\hbar$$

robust against disorder if $\omega > 1/\tau_s$

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Summary & Outlook

- Usually spin polarization of 2D holes at $B_{\|} > 0$ only small

  Sign reversal of spin polarization at $B_{\|} > 0$
- Spin density matrix of holes characterized by 4 multipoles

  Spin octupole: new degree of freedom of holes at $B_{\|} > 0$
- Usually no exchange-correlation enhancement
  of spin susceptibility of HH states
- 2DHSs on (113)GaAs: Spin susceptibility enhanced *only*
  when $B_{\|}$ does give rise to a spin polarization
- required: XC energy and spin susceptibility as a function
  of all 4 spin multipoles
- Spin precession of holes: alternating spin polarization at $B = 0$

$\Rightarrow$ Dyakonov-Perel spin relaxation of holes

See PRB **70**, 125301 (2004), PRB **71**, 113307 (2005),
PRB **72**, 195321 (2005), cond-mat/0605390