SPIN EXCITATIONS IN MODULATION-DOPED SEMIMAGNETIC QUANTUM WELLS

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Summary :

Why semimagnetic quantum wells?

Raman spectroscopy and electronic excitations in modulation doped-quantum wells

Electronic excitations in n-type modulation-doped CdMnTe quantum wells :

towards spin polarized electron gases

Collaborations :

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Why semimagnetic quantum wells?

Previous studies of spin polarized gases:
GaAs, large magnetic fields, quantum Hall effect

- C.Kallin et al., Phys.Rev.B30, 5655 (1984)

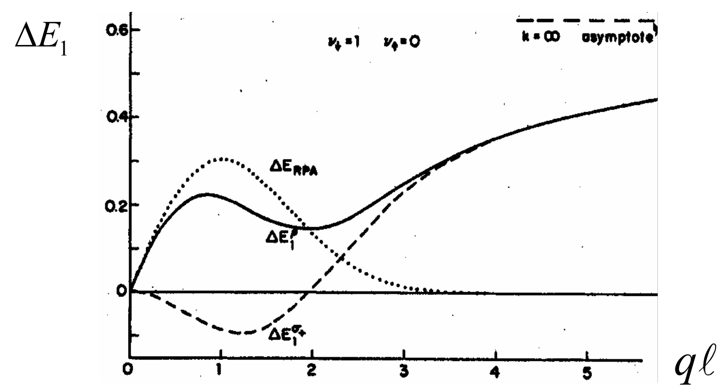
Strong Landau quantization :

$$e^2/\varepsilon\ell < \hbar\omega_c = \frac{eB}{m^*} ==> B > 10T$$

$$E_1^\rho = \hbar\omega_c + \Delta E_1^\rho(q\ell)$$

$$E_1^\sigma = \hbar\omega_c + g^*\mu_B B + \Delta E_1^\sigma(q\ell)$$

Full spin polarization : ν=1



$$\Delta E_1^\rho(q\ell) = \Delta_1 + \Delta_2(q\ell)$$

$$\Delta E_1^\rho(q\ell) = \Delta_1 + \Delta_2(q\ell) + \Delta_3(q\ell)$$

self-energy difference **exchange correction** **direct correction**
positive, non dispersive

$q\ell = 0$ **====>** $\Delta_2(q\ell) \rightarrow -\Delta_1$ $\Delta_3(q\ell) \rightarrow 0$

exact cancellation of 3 many-body corrections
Kohn's theorem (W.Kohn, Phys.Rev.123, 1242, 1961)
➔ no information on many body physics

$q\ell \approx 1$ **====> maximum corrections**

q = 1.6x10^5 cm^{-1} ===> $\ell \cong 60nm$ **<====> B ≅ 0.2T**

B ≅ 10T ===> $q\ell \approx .02$

➔ difficult to access experimentally

wavevector relaxation due to disorder
(M.A. Erikson, A. Pinczuk et al PRL 82, 2163, 1999)

Giant Zeeman effect in quantum wells with diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$

magnetic quantum well :

$Cd_{1-x}Mn_xTe$ $x \cong 1\%$ $d \cong$ 10-15nm

band gap$\cong$ 1.6eV effective mass in conduction band $\cong$ 0.1

non magnetic barriers:

$Cd_{1-y}Mg_yTe$ $y \cong$ 15-20%

modulation doping:

iodine spacer layer $\cong$ 20 nm

electronic density : $n \cong 2\text{-}3\times10^{11}$ cm^{-2}

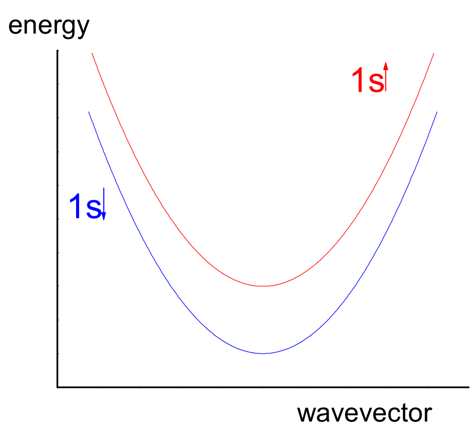
➔ very similar to GaAs/GaAlAs but magnetic ! ! !

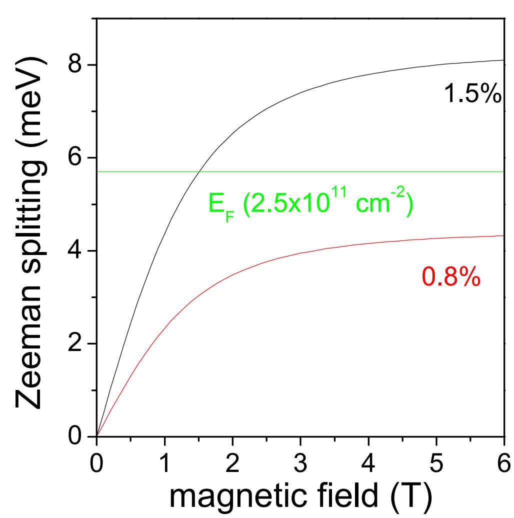
exchange interaction between :

localized electrons on substituted Mn^{2+} ions

and conduction electrons

➔ ZEEMAN GIANT EFFECT: $Z = g^* \mu_B B + \alpha \left\langle S_z^{Mn} \right\rangle (B,T)$

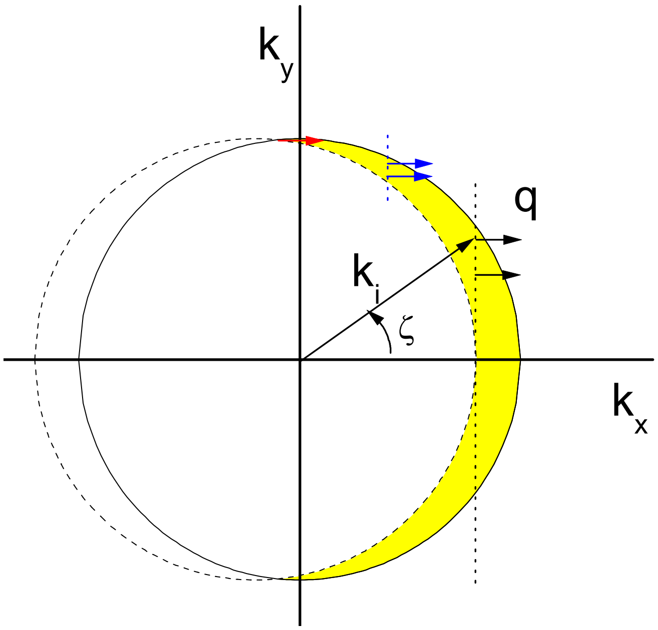




a novel system to study spin polarized electron gases:

- **charge and spin excitations**
- **single particle and collective excitations**

spectrum of intraband excitations

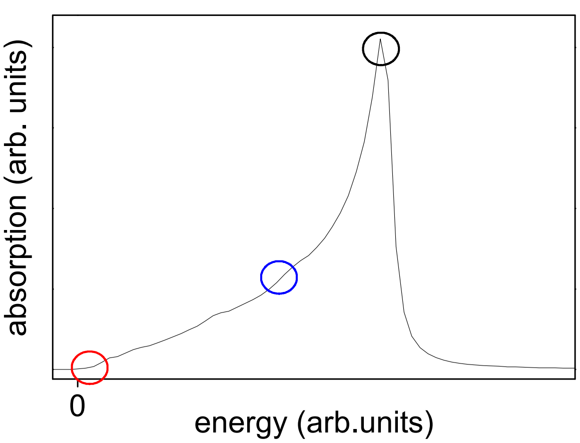


$$\Delta E = E(\vec{k}+\vec{q}) - E(\vec{k})$$

$$= \frac{\hbar^2}{2m^*}(2kq\cos\zeta + q^2)$$

$$= \frac{\hbar^2 q}{m^*}(k\cos\zeta + q/2)$$

$$= f(k\cos\varsigma)$$



Energy at peak intensity :

$$\Delta E = \frac{\hbar^2 q}{m^*}(k_F - q/2) \approx \hbar v_F q$$

$$\frac{q(\approx 10\mu m^{-1})}{k_F(\approx 200\mu m^{-1})} \cong 1/20$$

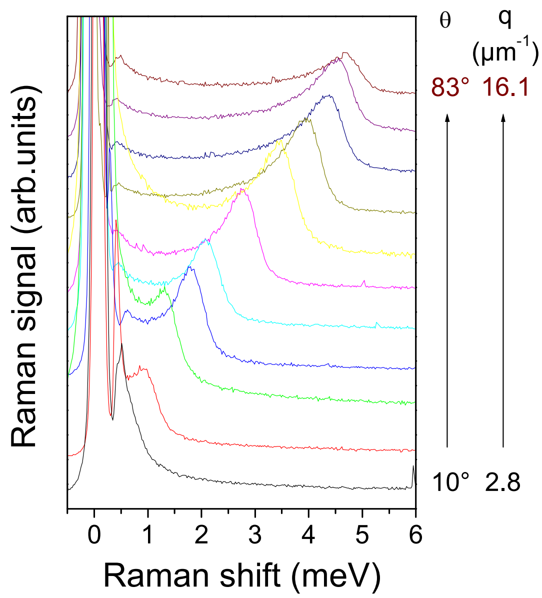
measure of angular dispersion

➔

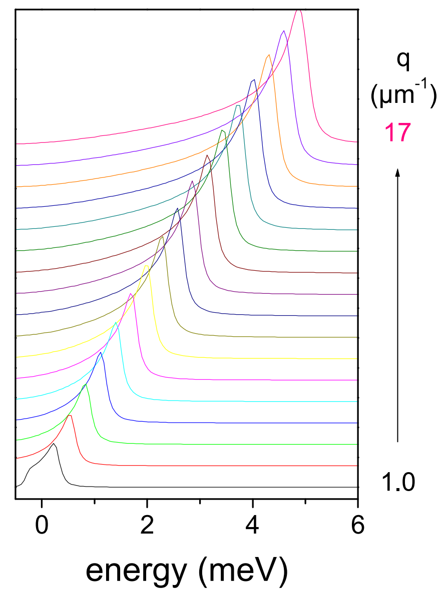
Fermi velocity

Fermi velocity

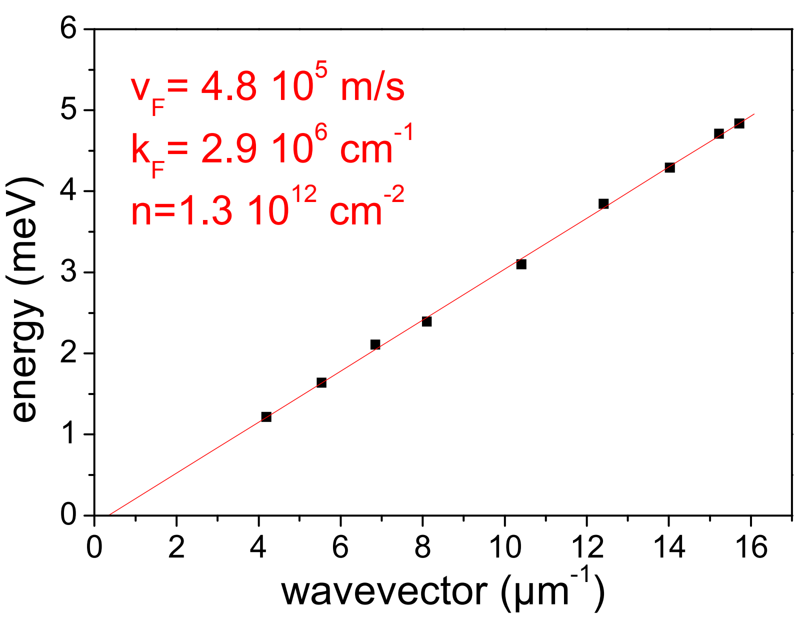
experiment



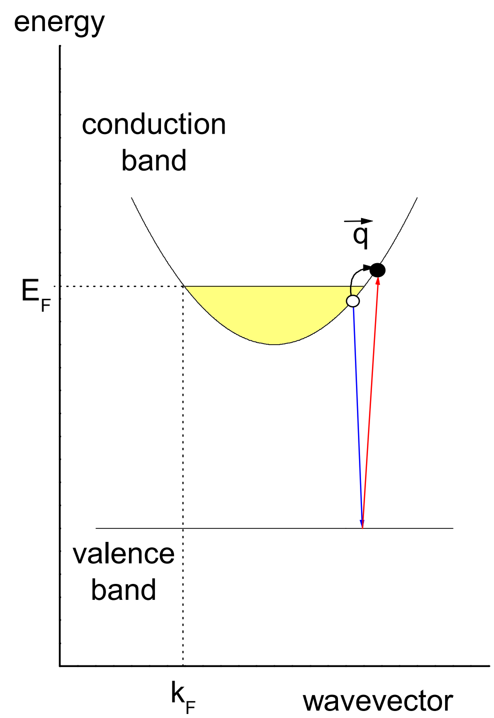
Theory



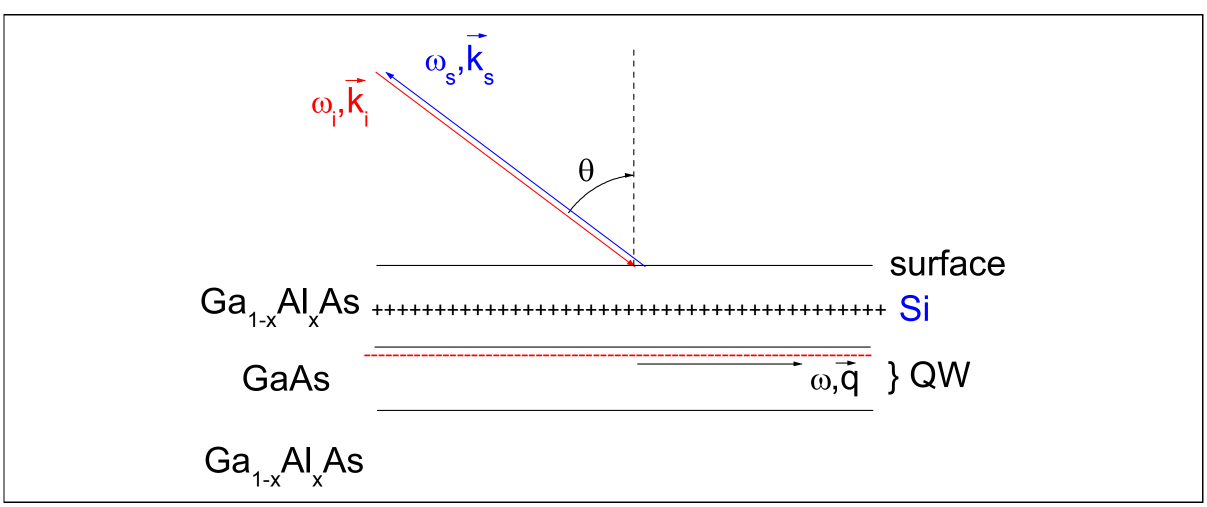
$$v_F = \frac{\hbar k_F}{m^*}$$



electronic Raman scattering



$$\omega_i = \omega_s + \omega \quad ; \quad \vec{k}_i = \vec{k}_s + \vec{q} \;\Rightarrow\; q \cong \frac{4\pi}{\lambda}\sin\theta \approx 10\ \ \mu m^{-1}$$



electronic Raman tensor

dipolar electric approximation at second order:

$$R_{\alpha\beta} \approx \sum_{V} \frac{\langle \beta | \vec{p} \bullet \vec{e}_2 | V \rangle \langle V | \vec{p} \bullet \vec{e}_1 | \alpha \rangle}{\omega_G - \omega_1}$$

1) numerators ===> selection rules

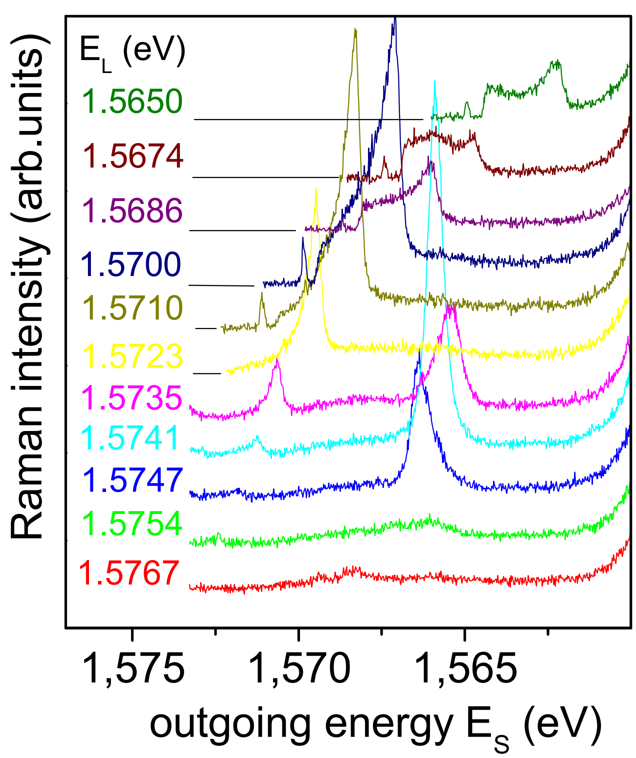
spin-orbit coupling in valence band

$|\alpha\rangle, |\beta\rangle = |1s \uparrow\rangle$ or $|1s \downarrow\rangle$ $\qquad |V\rangle = \alpha |X + iY \downarrow\rangle + \beta |Z \uparrow\rangle$

α,β same spin	**<====>**	**parallel polarisations**
α,β opposite spins	**<====>**	**crossed polarisations**

2) denominators ===> resonances

low temperature, high mobilities

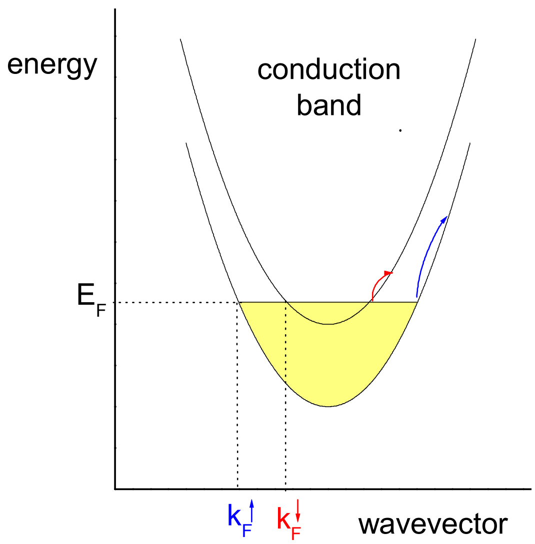


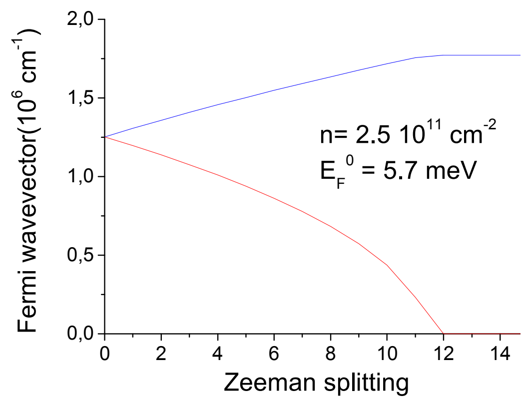
spin excitations in semimagnetic quantum wells

B ≠ 0 ➔ 4 different spin excitations

B// QW plane ➔ no Landau quantization

1) spin conserving excitations

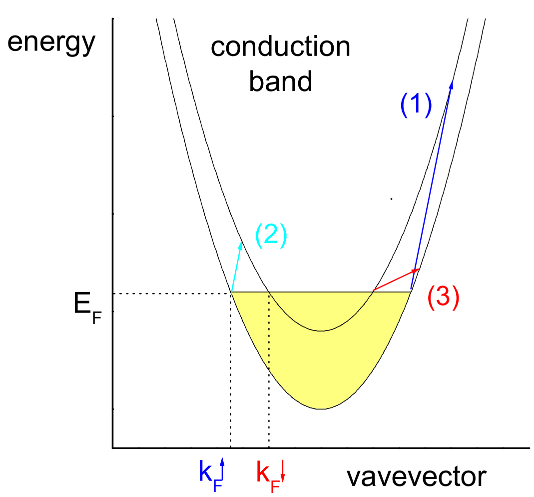


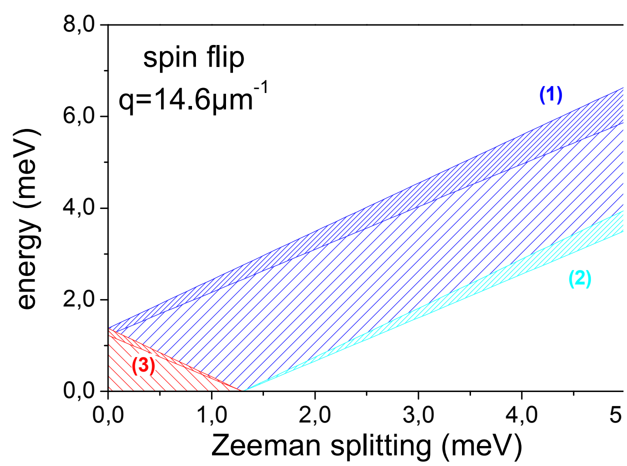


$$k_F^\uparrow \neq k_F^\downarrow$$

full or partial spin polarization

2) spin flip excitations



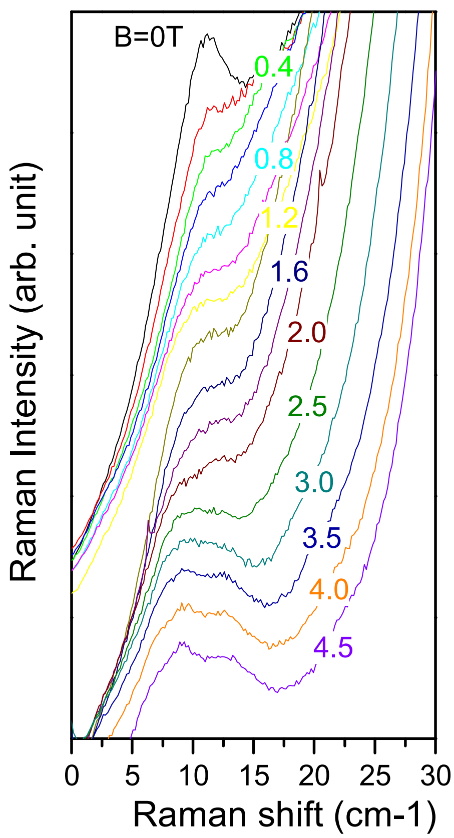


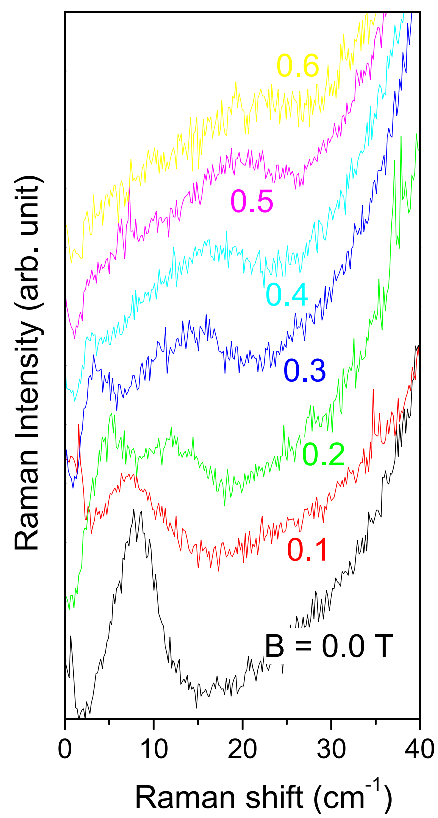
$$k_F^\uparrow - k_F^\downarrow \leq q$$

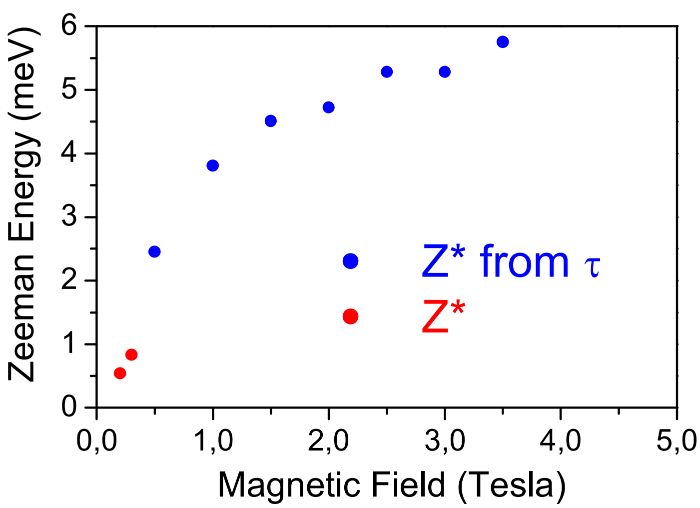
experimental results

- **x(Mn) = 1.6%** **first observation of spin flip excitations**
  PRL 91, 086802 (2003)
- **x(Mn) = 0.8%**

Spin conserving **Spin flip**

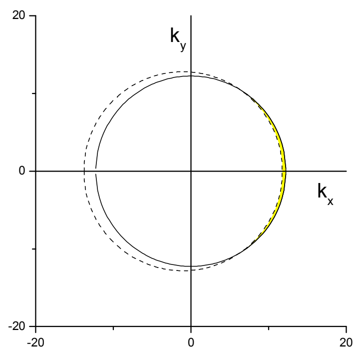


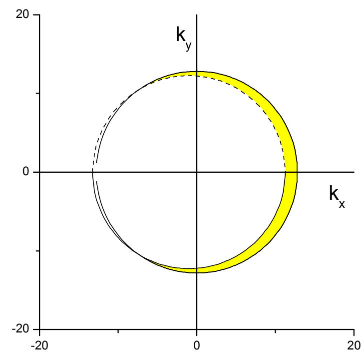


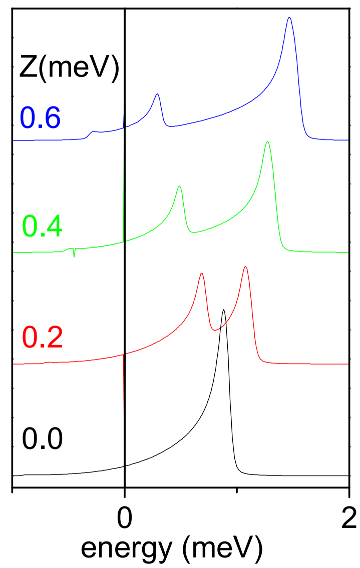


crossed polarization : spin flip

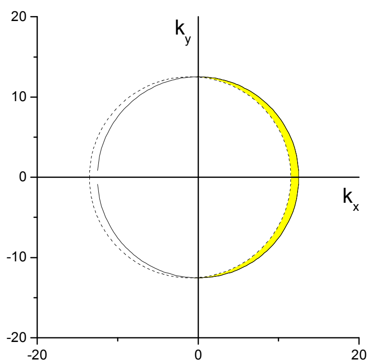
Small fields

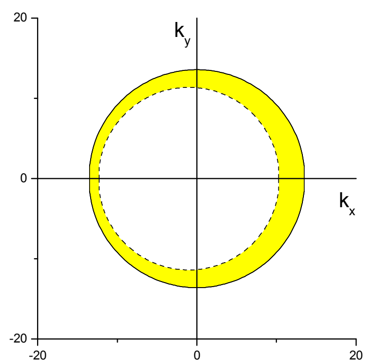


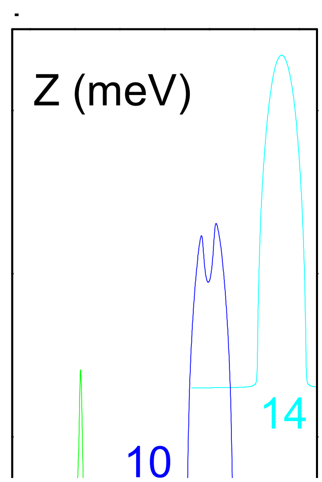


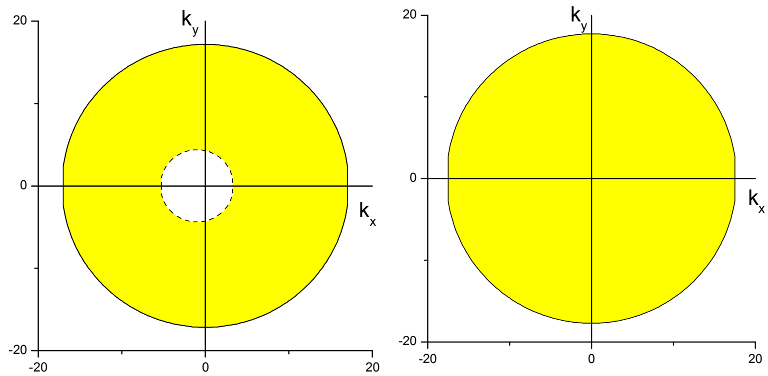


Larger fields









20
0
-20
-20
0
20
k
y
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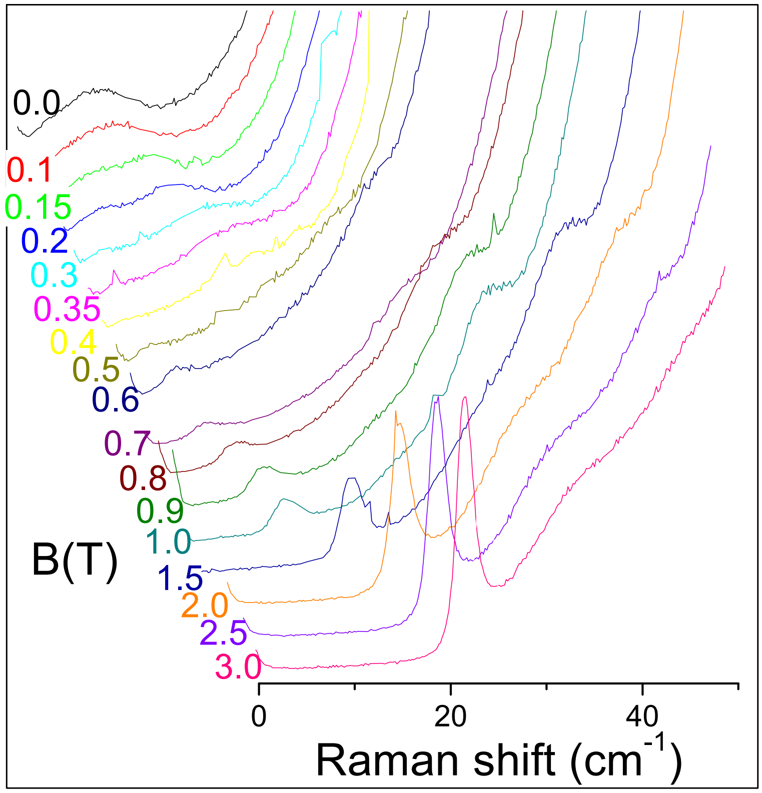
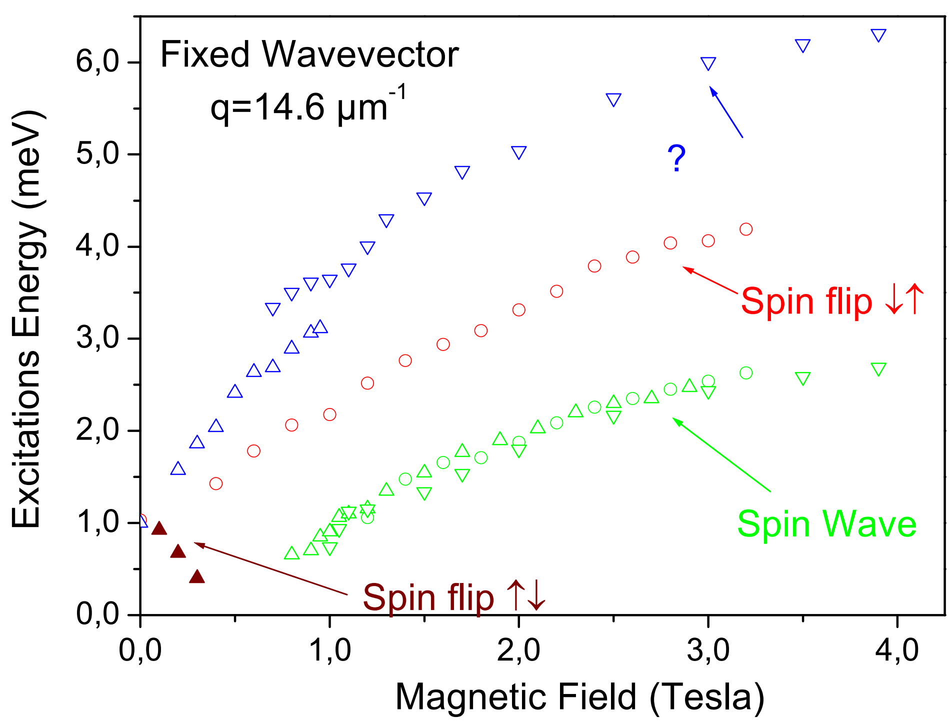
20
0
-20
-20
0
20
k
y
k
x

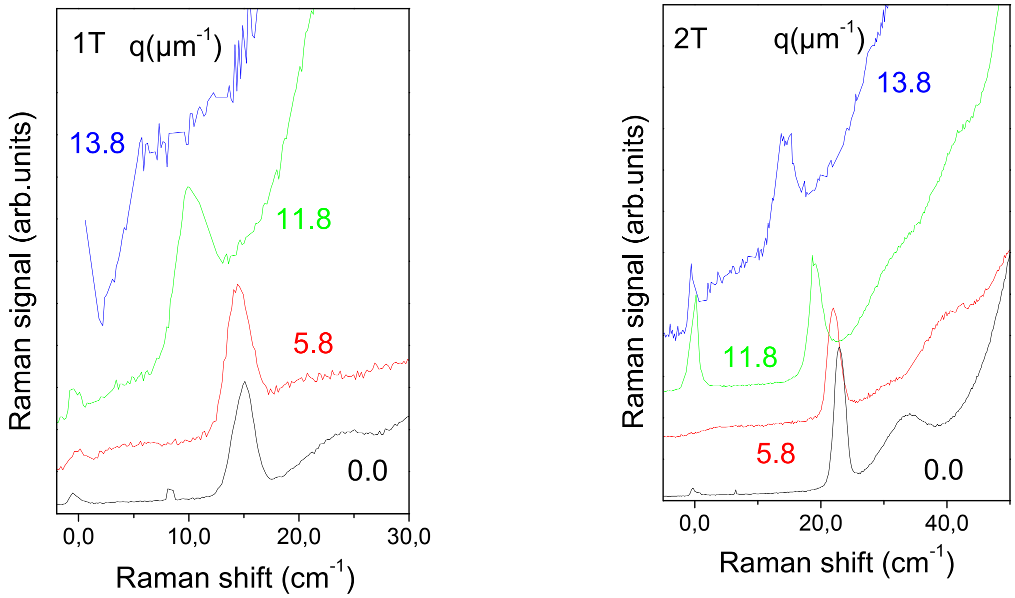
experimental results: larger fields

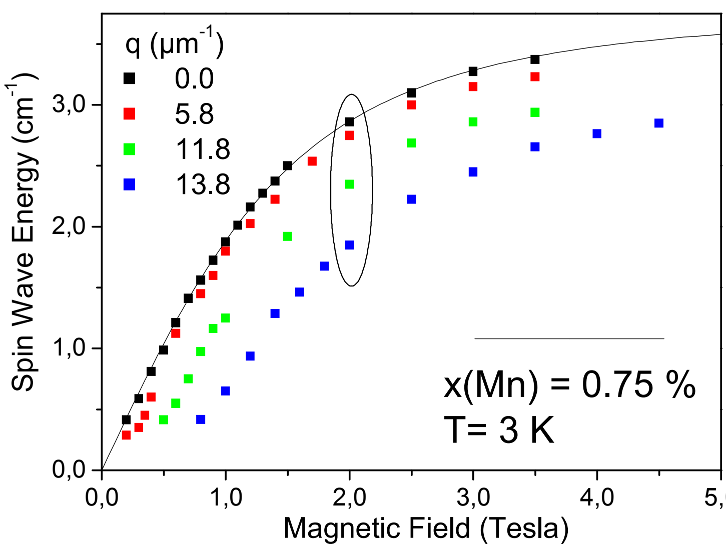




in plane dispersions

low energy line





===> Brillouin function at q=0 (Kohn's theorem)

- **spin flip collective excitation**
- **bare Zeeman splitting Z**

collective excitations in spin polarized electron gases

qualitative description:

4 degrees of freedom: fluctuations (in space and time) of:

- **particle densities: $\rho\uparrow$ and $\rho\downarrow$**
- **spin flip densities: ρ_+ and ρ_-**

➔ four collective modes in general

1) no spin polarization

- **charge density : $\rho\uparrow + \rho\downarrow$ ➔ plasmon**
- **spin density : $\rho\uparrow - \rho\downarrow$ ≡ spin flip (symmetry)**

➔ two collective modes

1) full spin polarization: two independent degrees

- **charge $\rho\downarrow$ and spin flip ρ_+**

➔ two collective modes

2) **partial spin polarization**

charge density and spin density no longer decoupled!

quantitative description:

without interaction : $\mathrm{Im}(P(q,\omega))$

with interaction : $\mathrm{Im}(\Pi(q,\omega))$

$$\Pi(q,\omega) = \frac{P(q,\omega)}{1 - v(q)P(q,\omega)}$$

interaction potential in the RPA :

$$v(q) = \frac{2\pi e^2}{\varepsilon q}$$

exchange correlation in spin polarized electron gases

- A.K.Rajagopal, Phys.Rev.B 17, 2980 (1978) — 3D
- J.C.Ryan, Phys.Rev.B 43, 4499 (1991) — 2D, exchange
- K.S.Yi, J.J.Quinn Phys.Rev. 54, 13398 (1996) — linear response
- J.Moreno et al. Phys.Rev.B 68, 195210 (2003) — G factors
- P.Gori-Giorgi et al. Phys.Rev.B 69, 041103 (2004) — correlations

$$s = n\uparrow - n\downarrow = \frac{2m^*}{\pi\hbar^2} Z^*$$

$$\Pi(q,\omega,s) = \begin{pmatrix} \Pi_{00}(q,\omega,s) & \Pi_{03} & 0 & 0 \\ \Pi_{30} & \Pi_{33} & 0 & 0 \\ 0 & 0 & \Pi_{\uparrow\downarrow} & 0 \\ 0 & 0 & 0 & \Pi_{\downarrow\uparrow} \end{pmatrix}$$

spin flip :

$$\Pi_{\uparrow\downarrow} = \frac{P_{\uparrow\downarrow}}{1 - 2G^{(2)}_{xc\times} P_{\uparrow\downarrow}}$$

spin + charge fluctuations:

$$\Pi_{00} = \left\{ P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - 4G^{(2)}_{xc//} P_{\uparrow\uparrow} P_{\downarrow\downarrow} \right\} / D$$

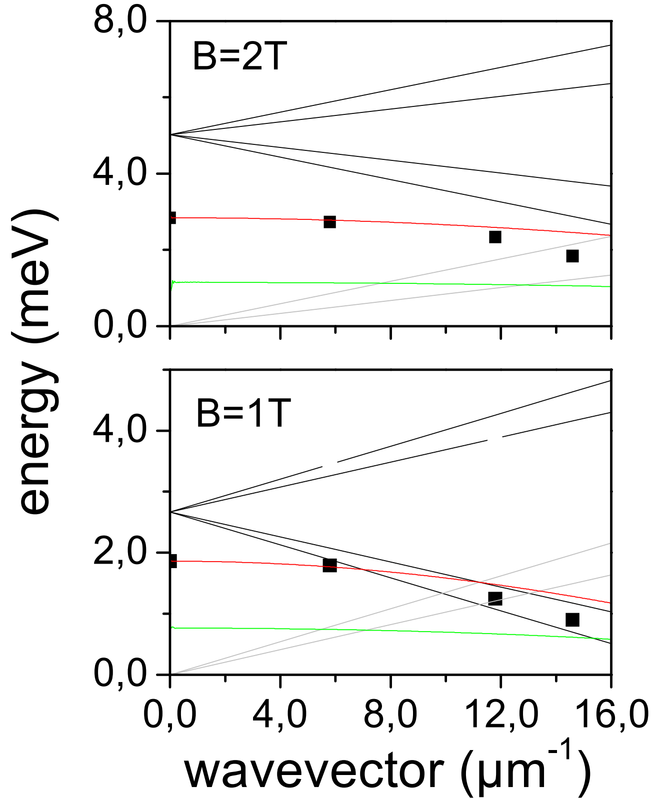
$$\Pi_{33} = \left\{ P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - 4(V_c + G^{(2)}_{xc//}) P_{\uparrow\uparrow} P_{\downarrow\downarrow} \right\} / D$$

$$\Pi_{03} = \Pi_{30} = \left\{ P_{\uparrow\uparrow} - P_{\downarrow\downarrow} + 4G^{(1)}_{xc} P_{\uparrow\uparrow} P_{\downarrow\downarrow} \right\} / D$$

$G^{(1)}_{xc}$, $G^{(2)}_{xc//}$, $G^{(2)}_{xc\times}$: **coulomb matrix elements**

in-plane dispersion

r_s=1.7



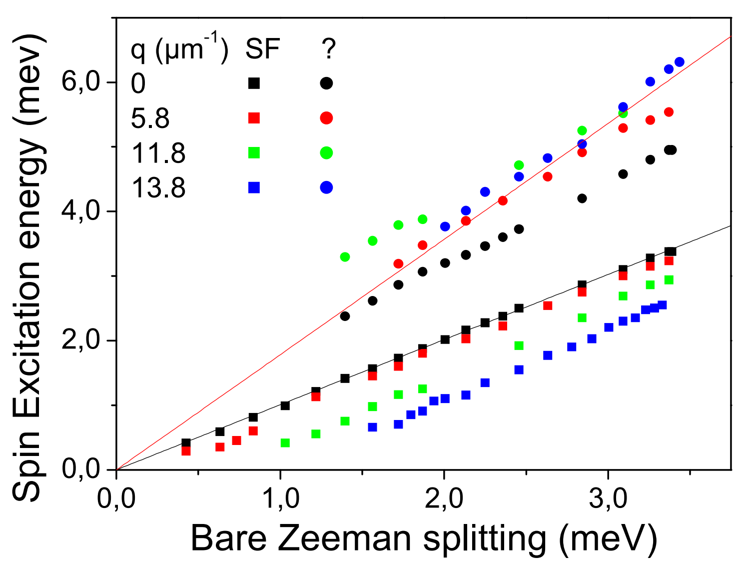
B=2T

Z=2.84 Z*=5.04
τ = 0.255

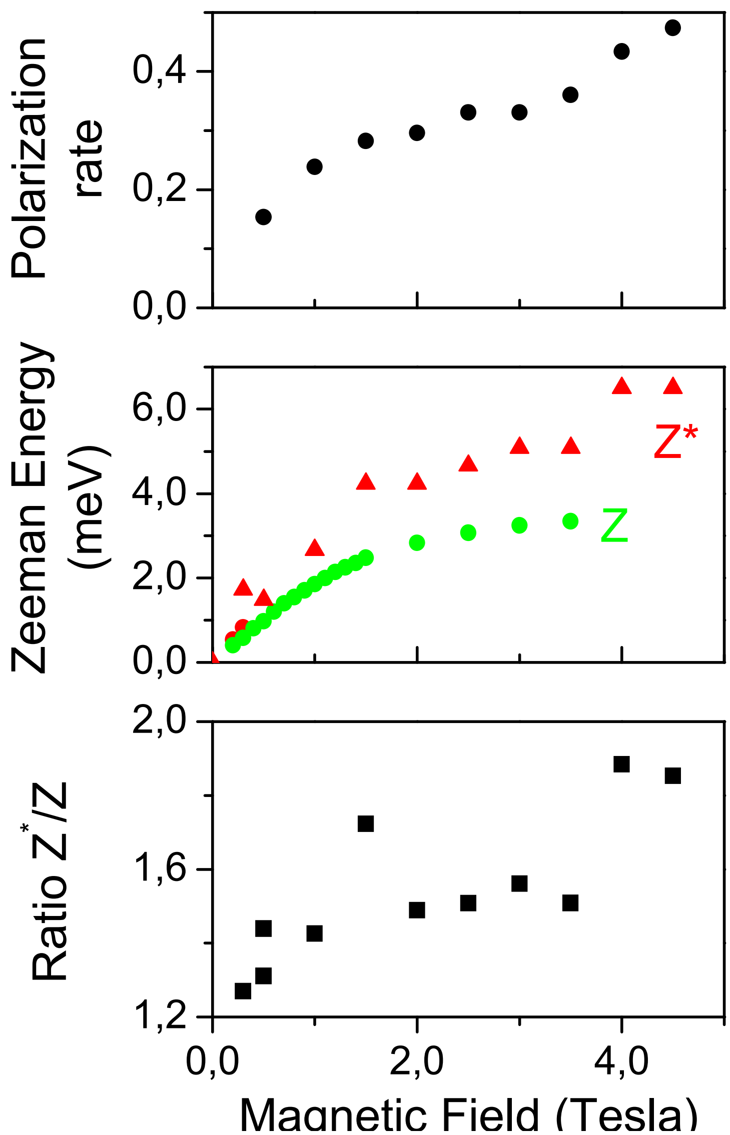
B=1T

Z=1.86 Z*=3.26
τ = 0.166

high energy line?



Comparison Z / Z*



quantitative determination of exchange corrections

Conclusion

Electronic Raman scattering

➔ detailed spectroscopy of spin levels

➔ single particle and collective excitations

Full description in paramagnetic n-doped CdMnTe

Low energy spin wave with negative dispersion
= Spin flip collective excitation

High energy spin wave with positive dispersion:
= Spin density fluctuation in polarized gases?

Quantitative determination of dispersions

➔ theories of exchange-correlation in polarized electron systems

Extension to ferromagnetic systems:

CdMnTe dopé p ?

Others?