

Diluted magnetic semiconductors effects of sp-d interactions and origin of d-d interactions

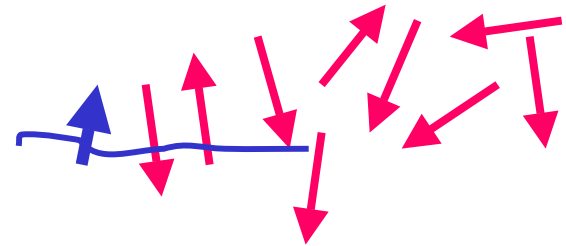
Tomasz DIETL
Lecture V Schladming'05

Outline

1. Giant spin splitting of band states

$$\hbar\omega_s = \alpha M/g\mu_B \text{ (lecture IV)}$$

2. Spin-disorder scattering



3. Bound magnetic polarons

4. Indirect d-d interactions

Effects of sp-d exchange interaction -- spin disorder scattering in DMS

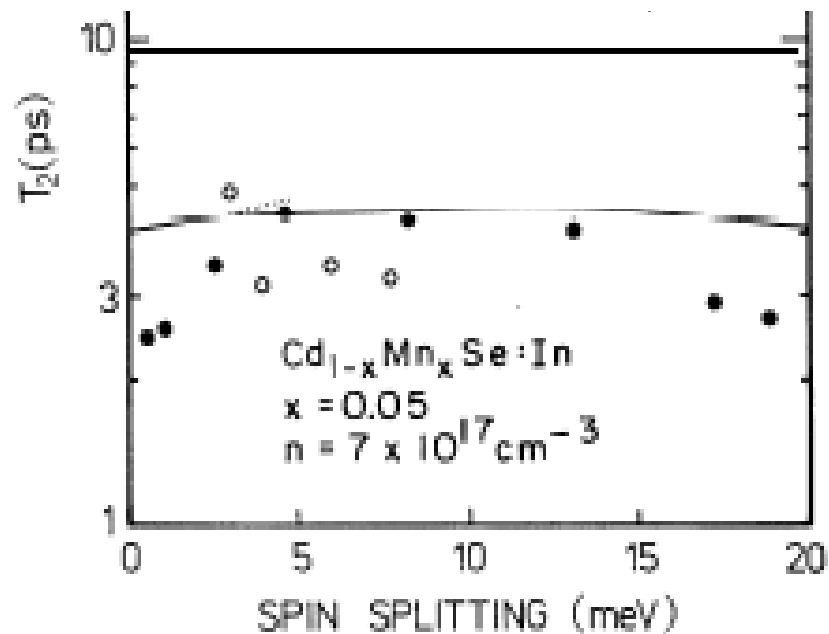
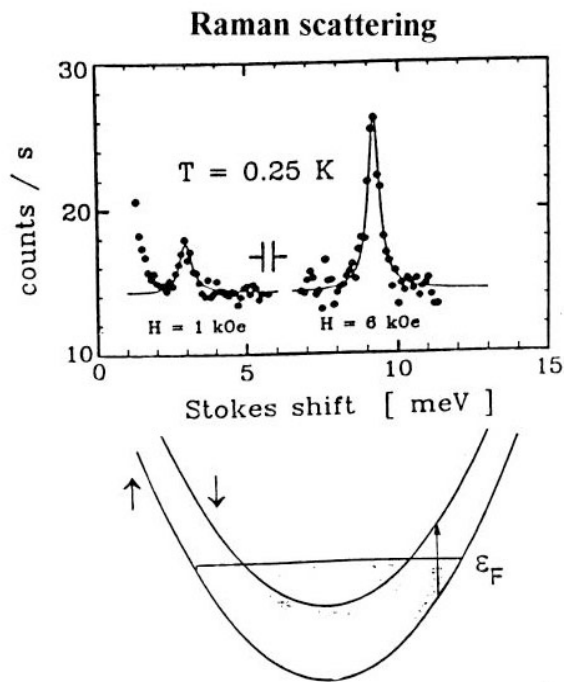
- Two sources
 - thermodynamic fluctuations
 - chemical disorder

$1/\tau \sim \alpha^2 \rho(\varepsilon_F)$ - weaker in semiconductors than in metals

determinations:

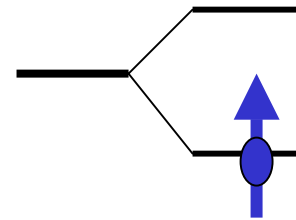
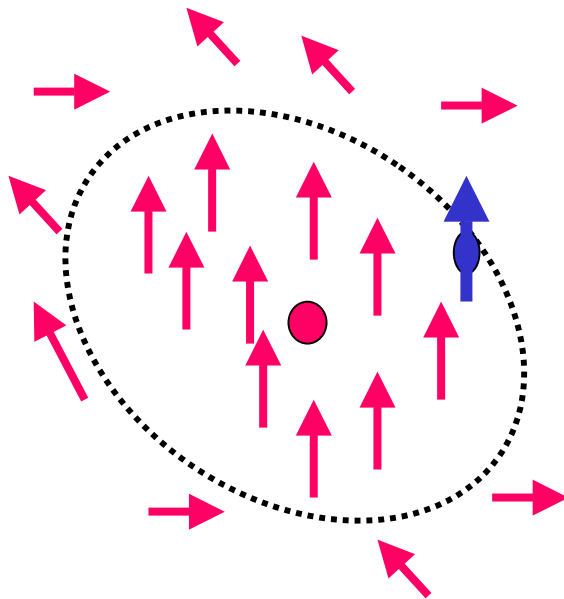
- SFRS
- quantum transport

Linewidth in spin flip Raman scattering in n-(Cd,Mn)Se



Effects of sp-d exchange interaction -- bound magnetic polaron

Donor state in DMS



Zero-field splitting

- **Two sources of local magnetization**
 - molecular field of donor electron
 - thermodynamic fluctuations

Some statistical mechanics

$$\mathcal{P}(E) = C \exp(-E/kT)$$

If states are degenerate

$$\mathcal{P}(E) = Cg(E) \exp(-E/kT)$$

$$\mathcal{P}(E) = C' \exp\{-[E - kT \ln g(E)]/kT\}$$

$$\mathcal{P}(E) = C' \exp[-\mathcal{F}(E)/kT]$$

$$\mathcal{P}[M(\mathbf{r})] = C \exp[-\mathcal{F}[M(\mathbf{r})]/kT]$$

$$\mathcal{F}[M(\mathbf{r})] = \mathcal{F}_S[M(\mathbf{r})] + \mathcal{F}_c[M(\mathbf{r})]$$

Free energy of Mn spins

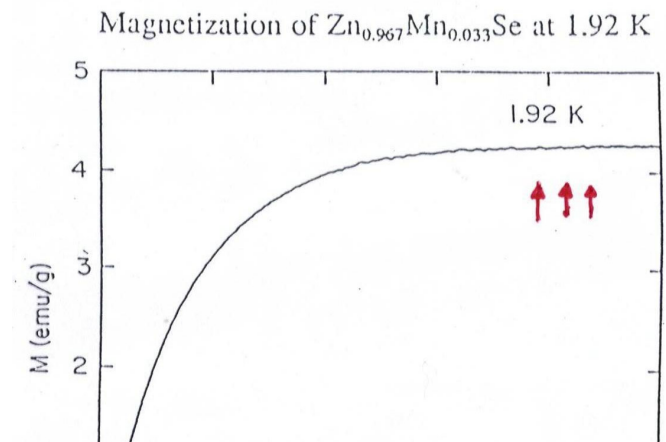
$$\mathcal{P}[M(\mathbf{r})] = C \exp[-\mathcal{F}[M(\mathbf{r})]/kT]$$

$$\mathcal{F}[M(\mathbf{r})] = \mathcal{F}_S[M(\mathbf{r})] + \mathcal{F}_c[M(\mathbf{r})]$$

$$\mathcal{F}_S[M] = \int_0^M dM_o H(M_o) \rightarrow \frac{\delta M_{\parallel}^2}{2\chi_{\parallel}} + \frac{\delta M_{\perp}^2}{2\chi_{\perp}}$$

Gaussian approx.

$$\chi_{\parallel} = \partial M_o / \partial H; \chi_{\perp} = M_o / H$$



Free energy of the electron

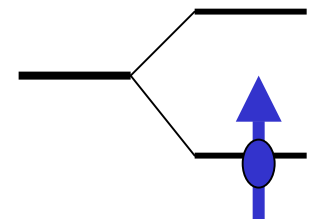
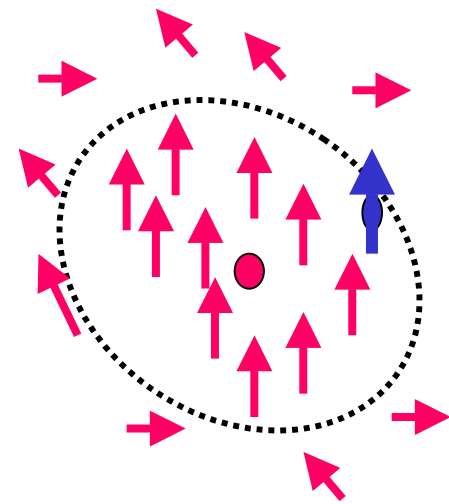
$$\mathcal{P}[M(\mathbf{r})] = C \exp[-\mathcal{F}[M(\mathbf{r})]/kT]$$

$$\mathcal{F}[M(\mathbf{r})] = \mathcal{F}_S[M(\mathbf{r})] + \mathcal{F}_c[M(\mathbf{r})]$$

$$H_{sd} = \frac{\alpha}{g\mu_B} \mathbf{s} \cdot \mathbf{M}$$

$$\Delta[M(\mathbf{r})] = \frac{\alpha}{g\mu_B} \int dr M(\mathbf{r}) |\varphi(\mathbf{r})|^2$$

$$\mathcal{F}_c[M(\mathbf{r})] = -kT \ln[2 \cosh(\Delta[M(\mathbf{r})]/2kT)]$$



Mean field approximation

$$\mathcal{P}[M(\mathbf{r})] = C \exp[-\mathcal{F}[M(\mathbf{r})]/kT]$$

$$\mathcal{F}[M(\mathbf{r})] = \mathcal{F}_S[M(\mathbf{r})] + \mathcal{F}_c[M(\mathbf{r})]$$

$$\partial\mathcal{F}[M(\mathbf{r})]/\partial M(\mathbf{r}) = 0 \implies \tilde{M}(\mathbf{r})$$

$$F = \mathcal{F}[\tilde{M}(\mathbf{r})]$$

$$\mathcal{P}[M(\mathbf{r})] = \delta[M(\mathbf{r}) - \tilde{M}(\mathbf{r})]$$

Statistical mechanics of BMP

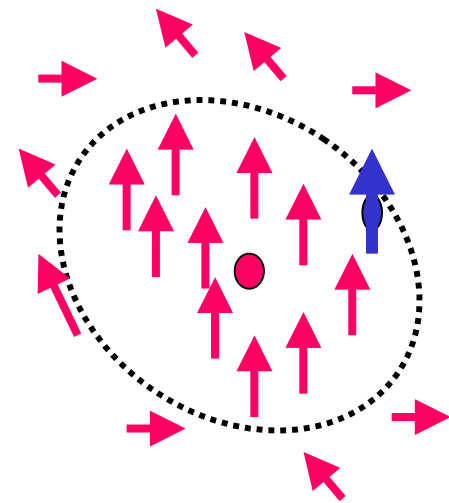
$$\mathcal{P}[M(\mathbf{r})] = C \exp[-\mathcal{F}[M(\mathbf{r})]/kT]$$

$$\mathcal{F}[M(\mathbf{r})] = \mathcal{F}_S[M(\mathbf{r})] + \mathcal{F}_c[M(\mathbf{r})]$$

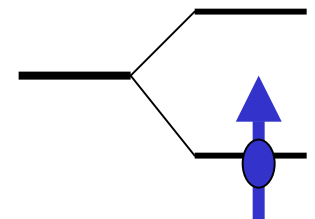
$$\mathcal{P}(\Delta) = C' \int DM(\mathbf{r}) \mathcal{P}[M(\mathbf{r})] \delta(\Delta - |\Delta[M(\mathbf{r})]|)$$

$$\mathcal{P}(\Delta) = C \Delta^2 \exp(-\Delta^2/8kT\epsilon_p) \cosh(\Delta/2kT)$$

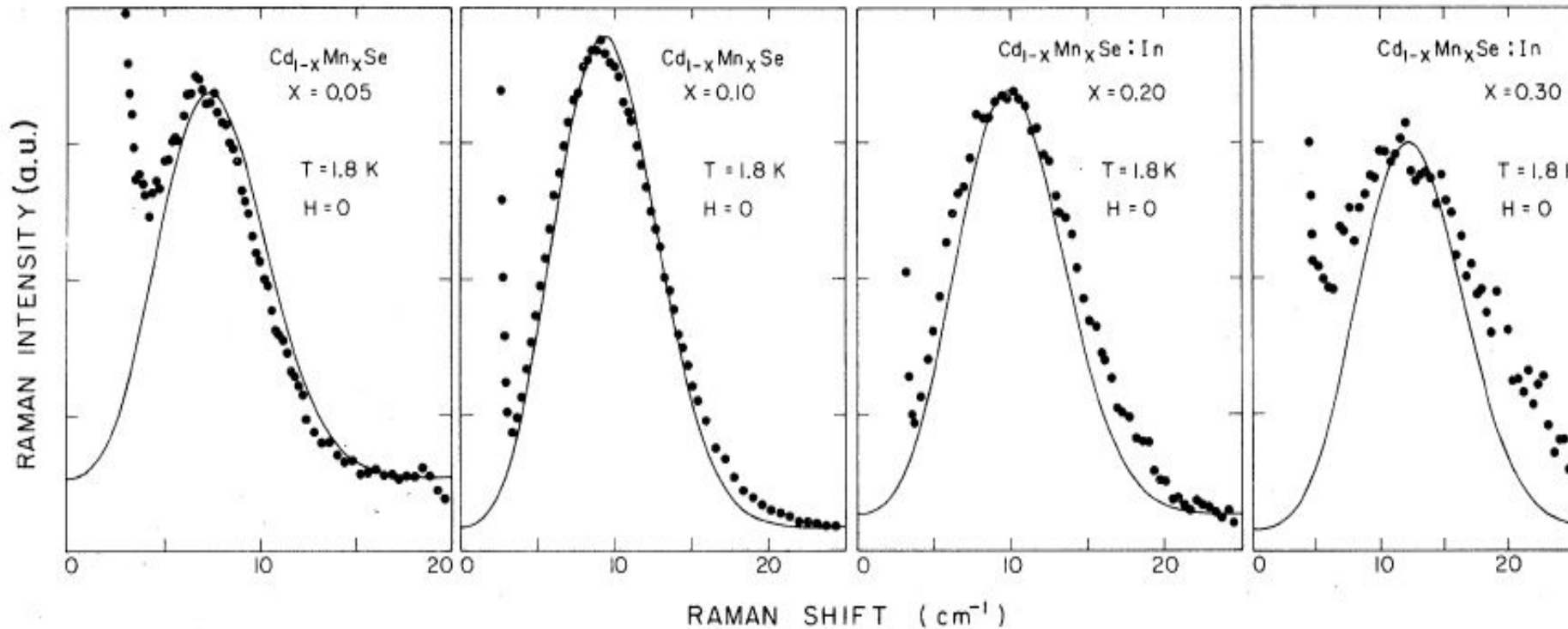
$$\epsilon_p(T, H) = \alpha^2 \chi(T, H) / 32 \pi g^2 \mu_B^2 a^3$$



$H = 0$



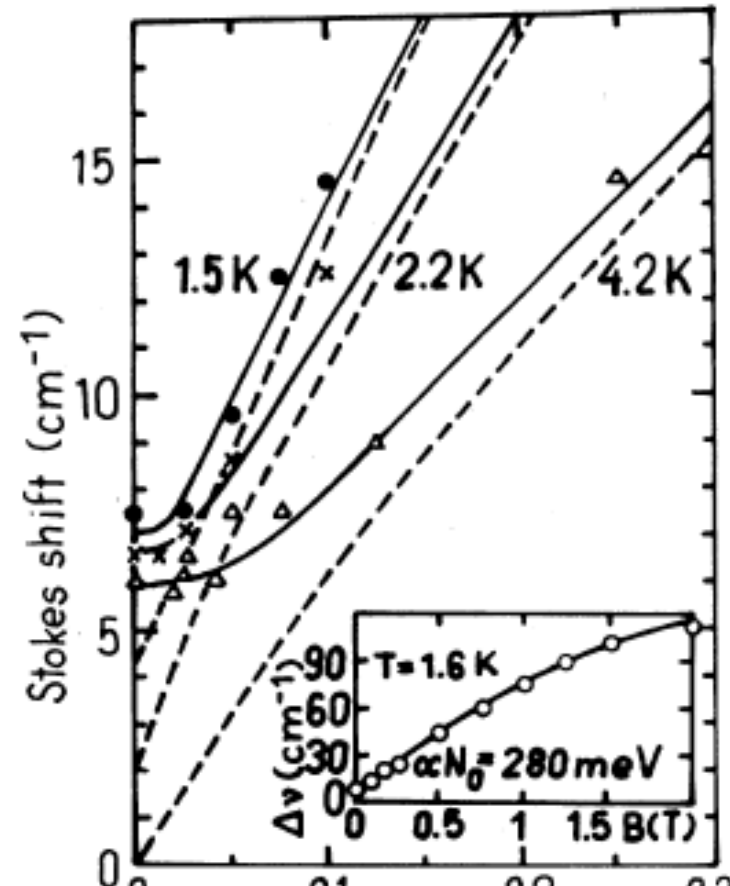
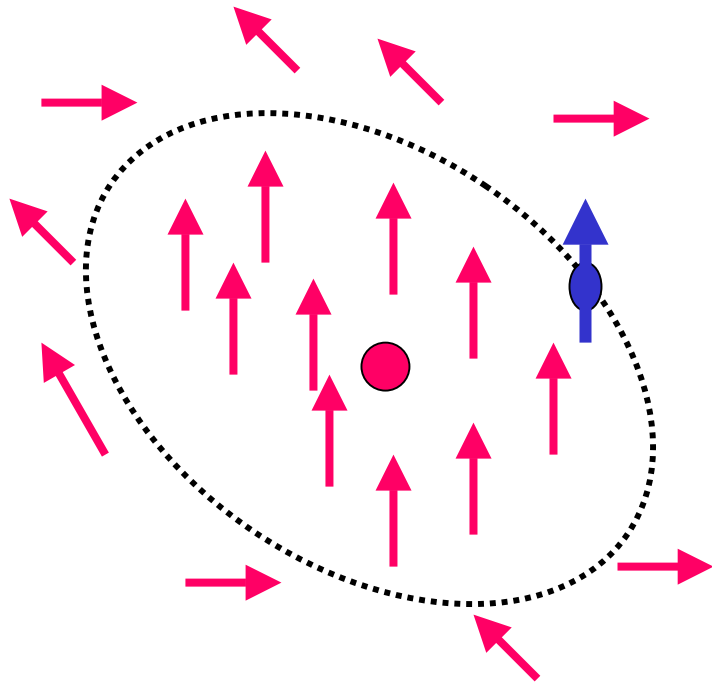
Spin-flip Raman scattering by donors



*expl. Ramdas et al., PRB'83
theory, T. D., Spalek PRL'82*

Spin flip Raman scattering in weakly n-type (Cd,Mn)Se, bound magnetic polaron

Donor state in DMS



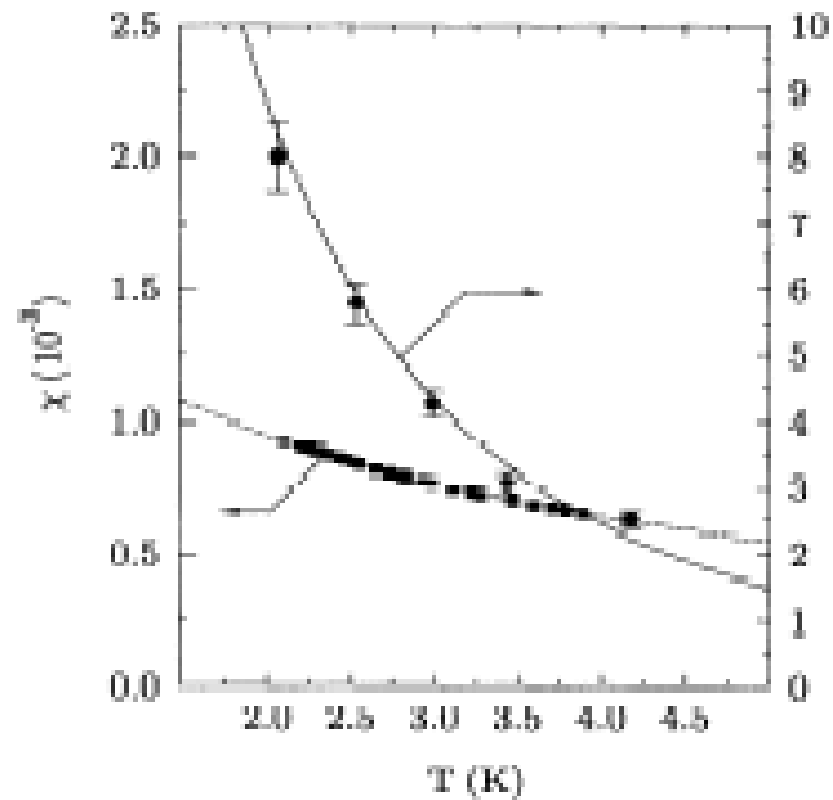
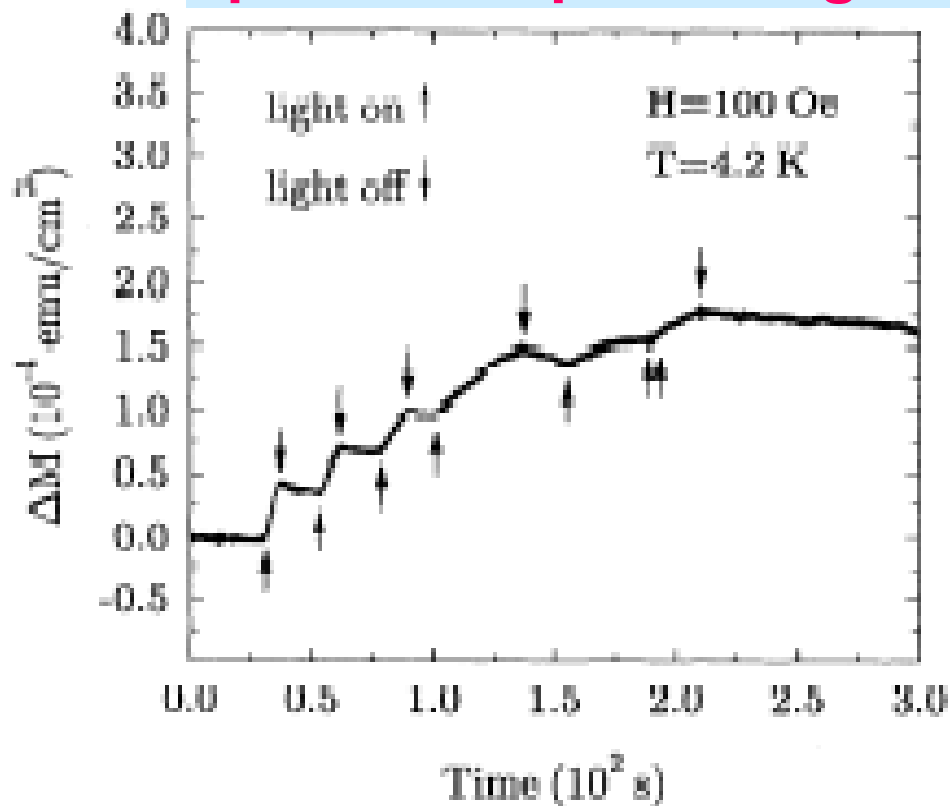
Free energy of BMP

$$F[\vec{M}(\vec{r})] = F_s[\vec{M}(\vec{r})] + \frac{\hbar^2}{2m^*a^2} - \frac{e^2}{\kappa a} - kT \ln \left\{ 2 \cosh \frac{\Delta[\vec{M}(\vec{r})]}{2kT} \right\}.$$

$$F_p = -kT \ln \left[\frac{\int DM(\mathbf{r}) \mathcal{F}[M(\mathbf{r})]}{\int DM(\mathbf{r}) \mathcal{F}_S[M(\mathbf{r})]} \right]$$

$$F_p = \frac{\hbar^2}{2m^*a^2} - \frac{e^2}{\kappa a} - \frac{\epsilon_p}{2} - kT \ln \left[2 \cosh \left(\frac{\Delta_0}{2kT} \right) + \frac{4\epsilon_p}{\Delta_0} \sinh \left(\frac{\Delta_0}{2kT} \right) \right]$$

Contribution of BMPs to magnetization -- persistent photomagnetization in (Cd,Mn)(Te,Se):In



*expl. Wojtowicz et al. PRL'93
theory, T. D., Spalek PRL'82*

Origin of d-d exchange interactions in DMS

Mechanisms of couplings between localized spins

Origin of the coupling: exchange interaction between the localized spins and band electrons, $-\beta N_o \mathbf{Ss}$

- INSULATORS**

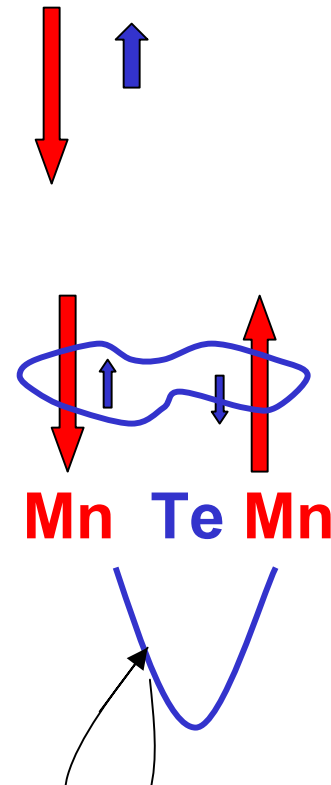
spin polarization of occupied orbitals

magnetic orbitals involved:

Kramers and Anderson superexchange

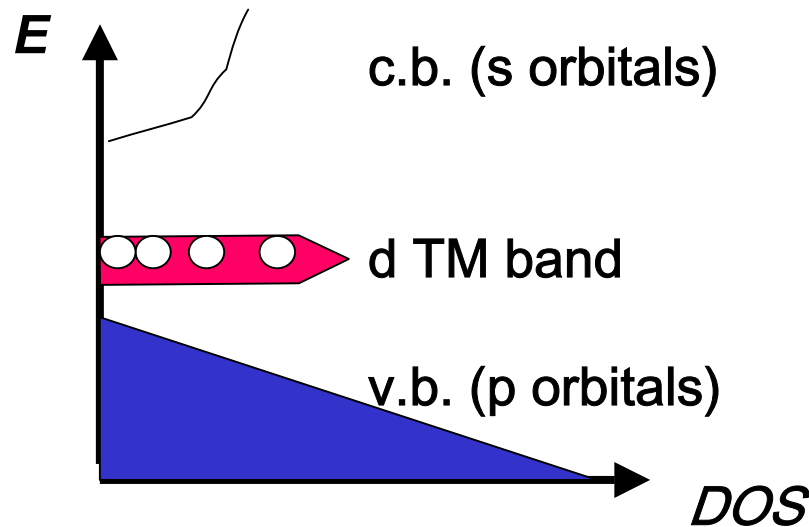
non-magnetic orbitals involved:

Bloembergen-Rowland mechanism

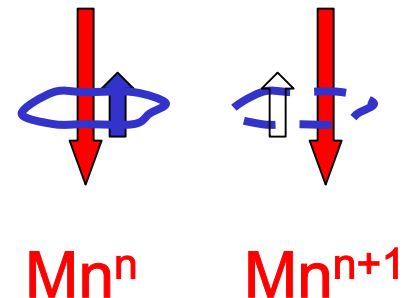


Doped materials

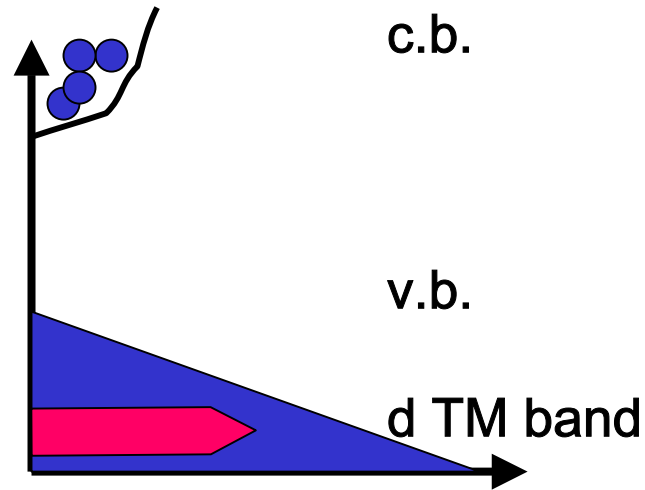
- MIXED VALENCE MATERIALS



- Zener double exchange**
possibility of hopping lowers energy

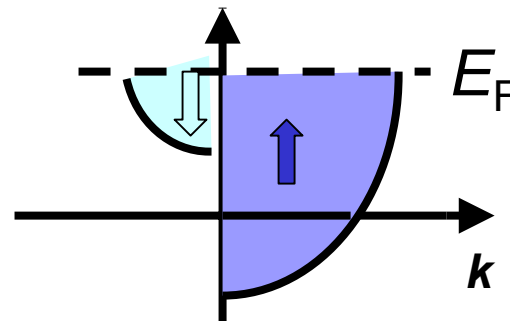
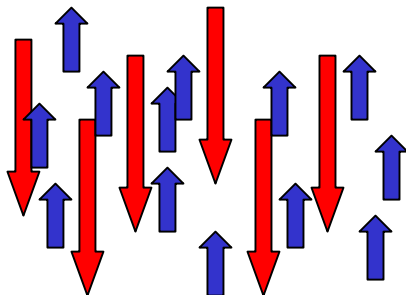


- METALS
(heavily doped semiconductors)



Zener exchange mediated by free carriers

redistribution of carriers between spin subbands lowers energy

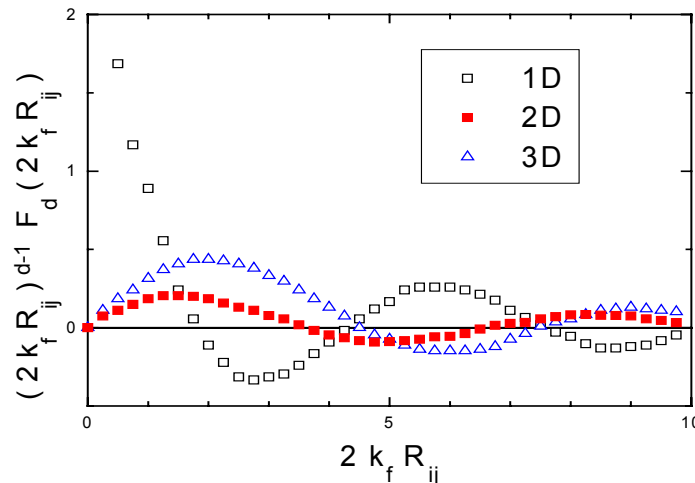
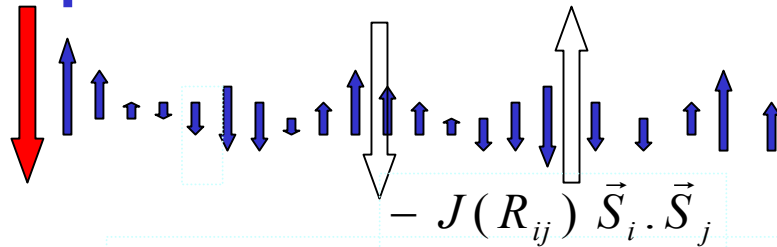


$$\hbar\omega_s = \beta N_o \langle S \rangle$$

- METALS

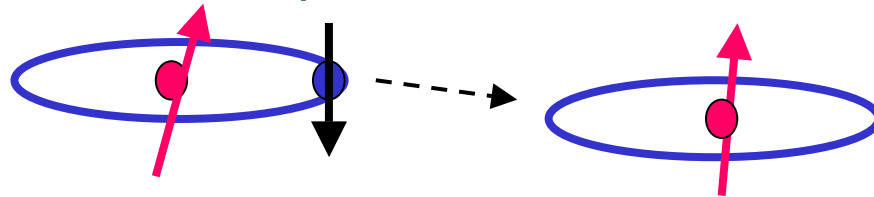
Ruderman-Kittel-Kasuya-Yosida interaction

Spin polarization of free carriers induced by a single spin



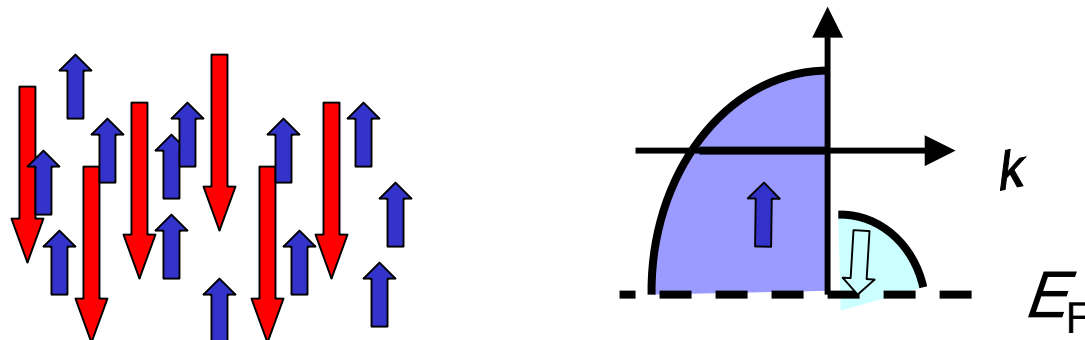
Mn-Mn exchange mediated by effective mass holes – localization issue

-- localized carriers (*Bhatt et al., Das Sarma et al., ...*)



-- delocalized carriers (Zener/RKKY model)

(*Leroux-Hugon, da Cunha Lima, ..., Dietl et al, MacDonald et al.*)



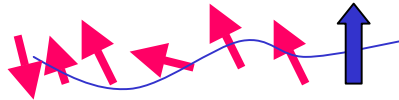
Mean-field Zener model

Which form of magnetization minimizes $F[\mathbf{M}(\mathbf{r})]$?

$$F = F_{\text{Spins}}[\mathbf{M}(\mathbf{r})] + F_{\text{carriers}}[\mathbf{M}(\mathbf{r})]$$

$F_{\text{spins}} \Leftarrow$ from $M(H)$ for undoped DMS (T_{AF} , X_{eff})

$F_{\text{carriers}} \Leftarrow$ VCA, Mol.F.A, 6x6 Luttinger model

$\mathbf{M}(\mathbf{r}) \neq 0$ for $H=0$ at $T < T_C$ 

if $\mathbf{M}(\mathbf{r})$ uniform \Rightarrow ferromagnetic order

otherwise \Rightarrow modulated magnetic structure

Making (II,Mn)VI DMSs ferromagnetic: Zener/RKKY MF model of doped DMS

$$T_C = T_{CW} = T_F - T_{AF} \leftarrow \text{superexchange}$$

$$T_F = S(S+1)x_{eff}N_oA_F\rho^{(s)}(E_F) \beta^2/12L_c^{d-3}$$

$A_F > 1$ Stoner enhancement factor

($A_F = 1$ if no carrier-carrier interaction)

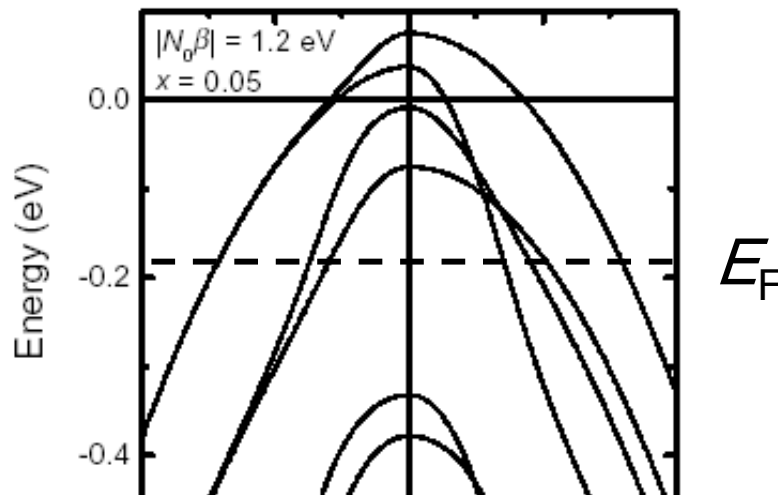
$$\rho^{(s)}(E_F) = m^*k_F^{d-2} \text{ (if no spin-orbit coupling)}$$

**$\Rightarrow T_C \sim 50$ times greater for the holes
large m^***

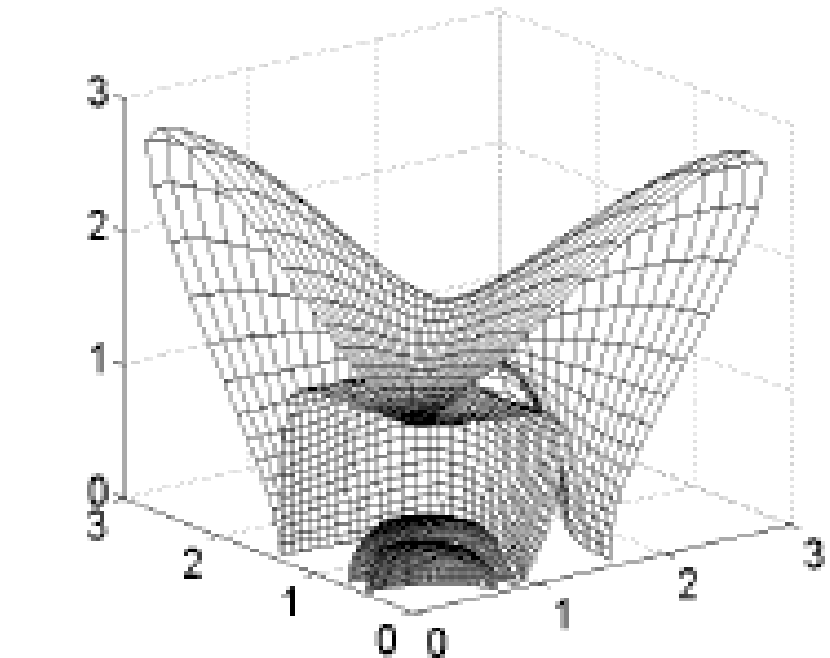
How to describe valence band structure?

Essential features:

- spin-orbit coupling
- anisotropy
- multiband character



Cross-section of the Fermi surface $M \parallel [100]$



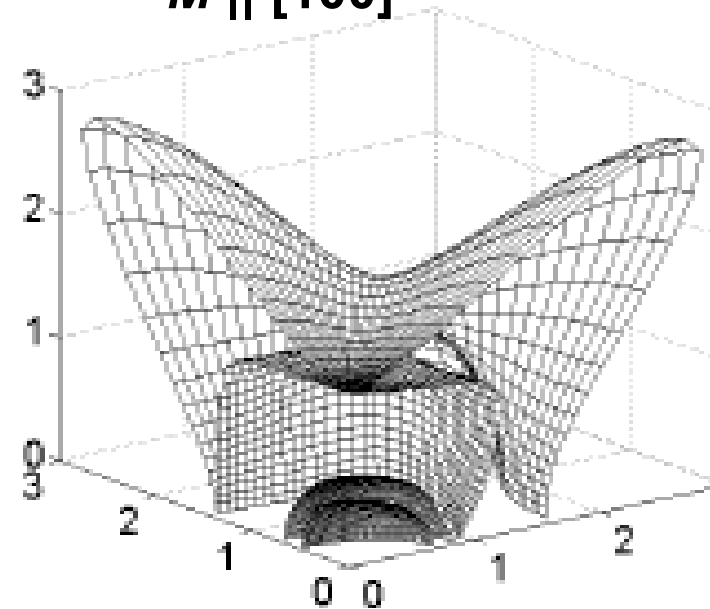
Mean Field Zener model

-- effective hamiltonian method

- *Kondo hamiltonian*

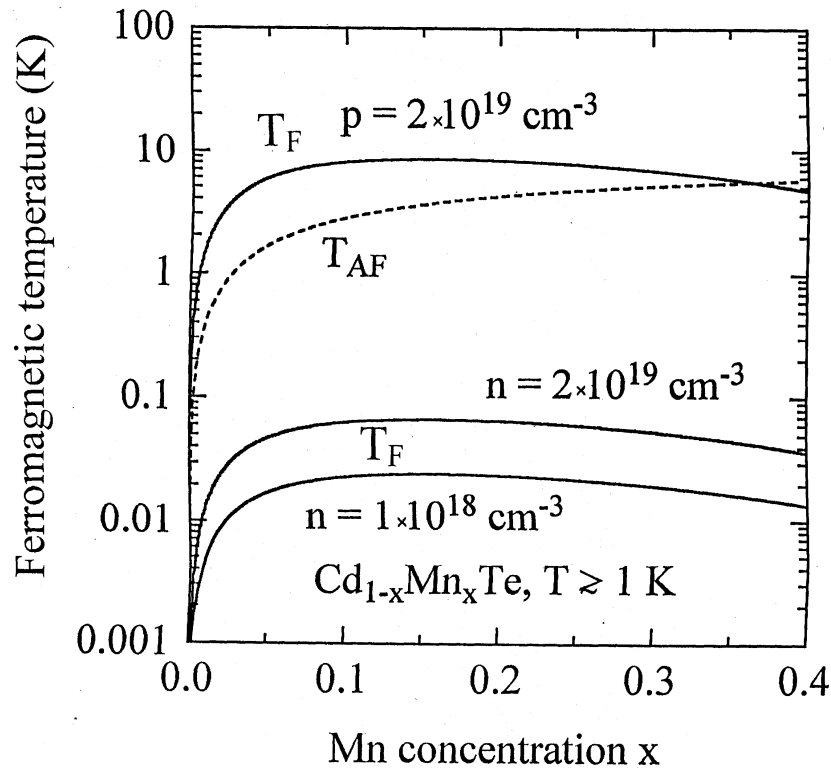
$$H = -\beta s \mathbf{S}$$
- *Luttinger-Kohn 6x6 kp effective mass hamiltonian*
- *Hole-hole exchange: Fermi liquid theory*
- *MFA + continuous medium approximation*
 $n_{\text{holes}} \ll N_{\text{spins}}, \text{ Zener} \equiv \text{RKKY}$

Cross-section of the Fermi surface
 $M \parallel [100]$

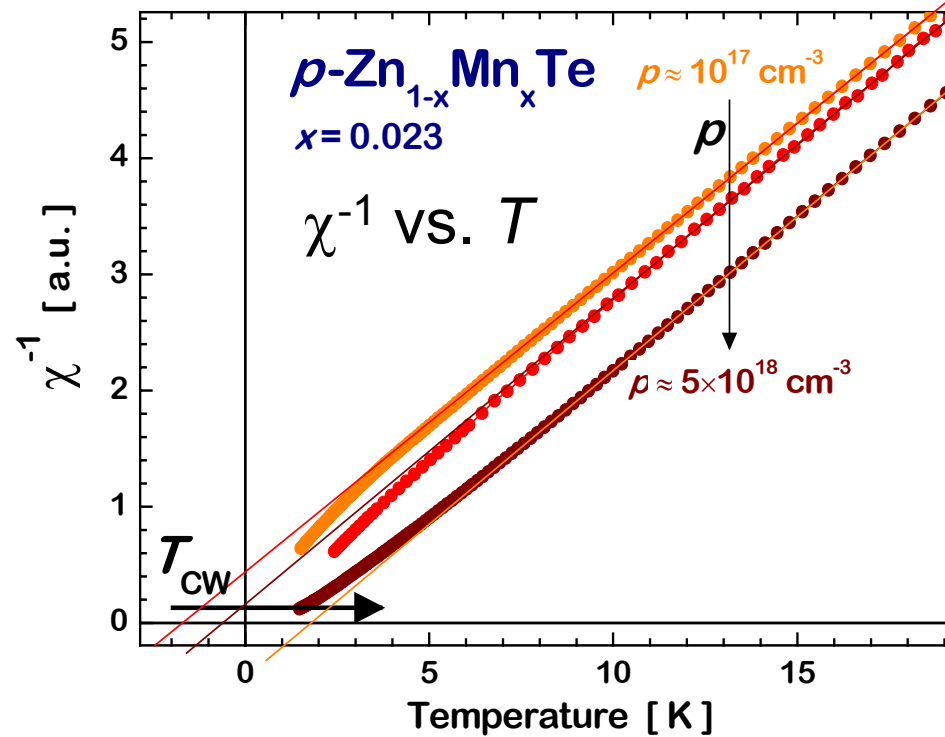


No adjustable parameters

Predictions vs. experiment

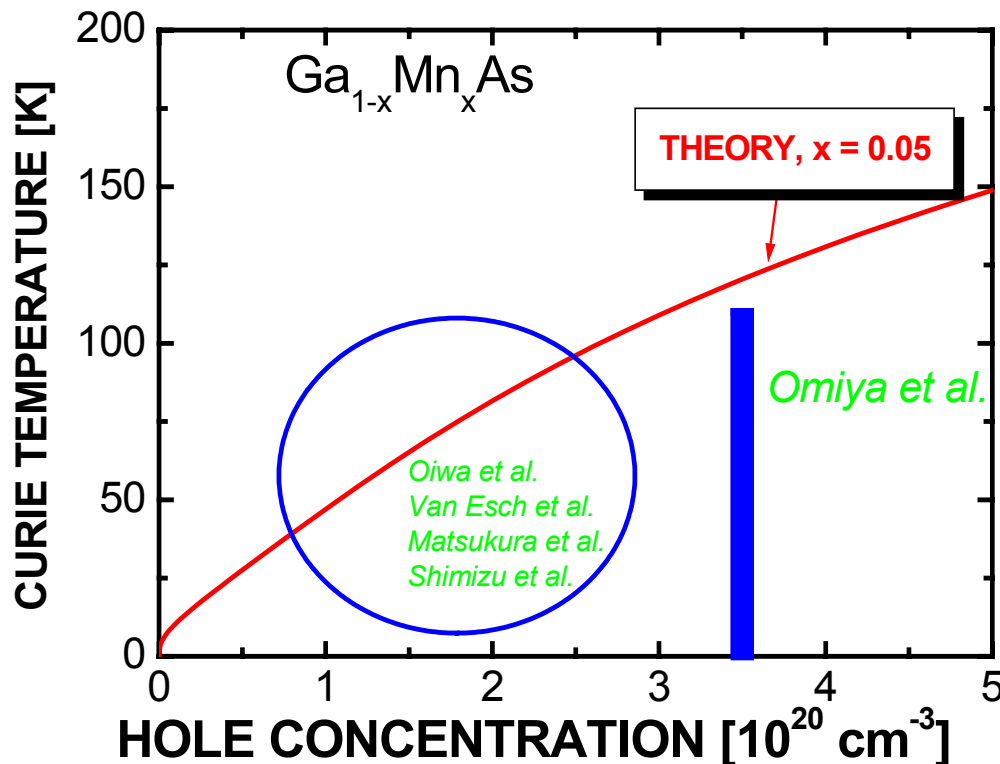


T.D. et al. PRB'97



D.Ferrand, ..., T.D. PRB'01
M.Sawicki, ..., T.D., pss'02

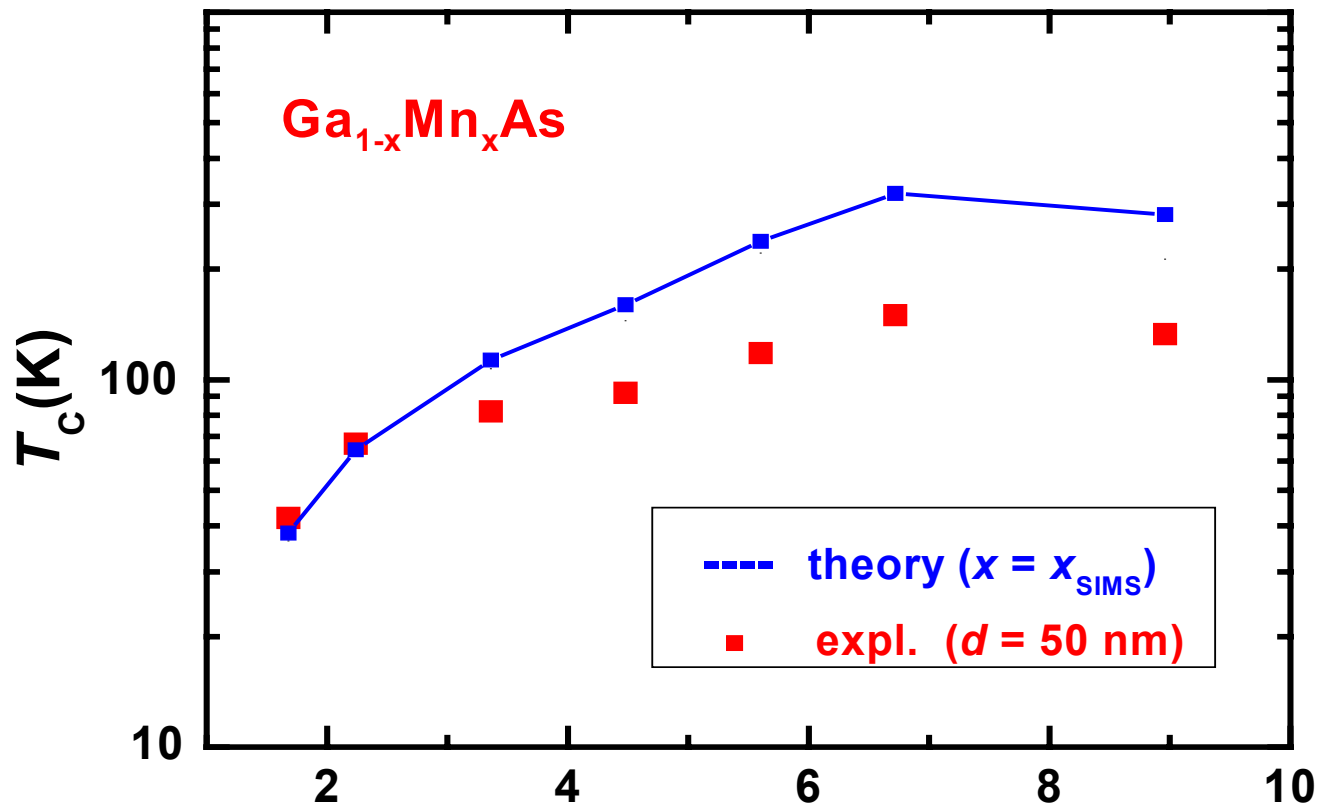
Curie temperature in p-Ga_{1-x}Mn_xAs theory vs. experiment



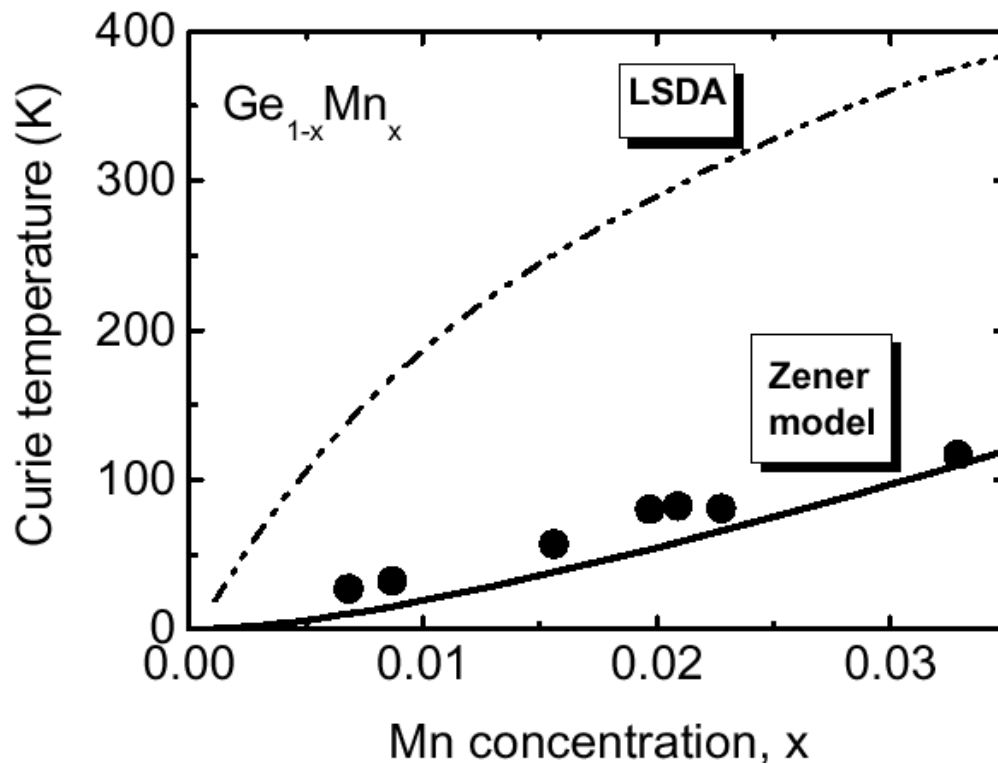
T.D. et al. PRB'01

- Anomalous Hall effect
→ p uncertain
- Omiya et al.:
27 T, 50 mK
- Theory: $T_C > 300 \text{ K}$
for $x > 0.1$
and large p
- 2003: T_C up to 170 K
(Sendai, Notre Dame,
Pen State,
Nottingham, Tokyo...)

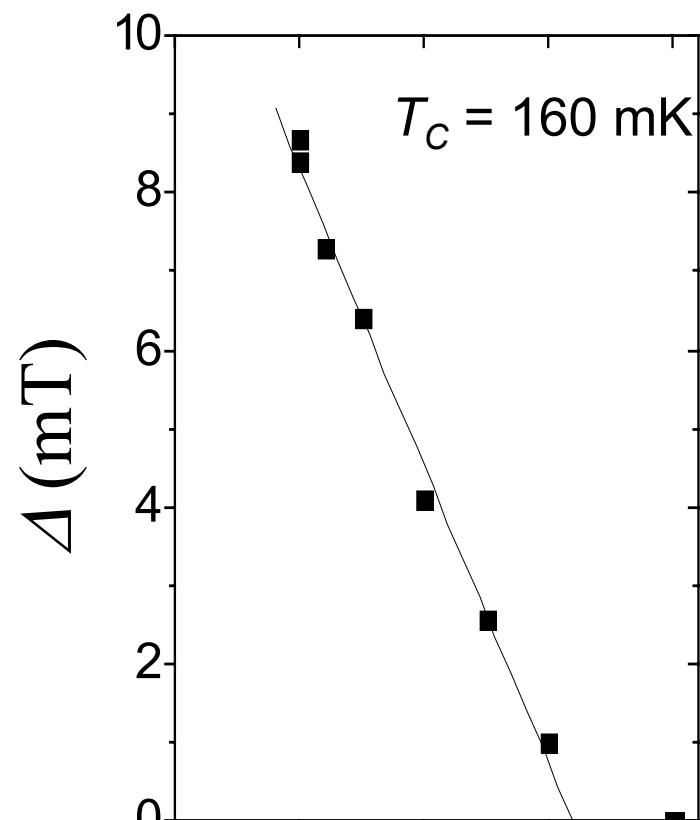
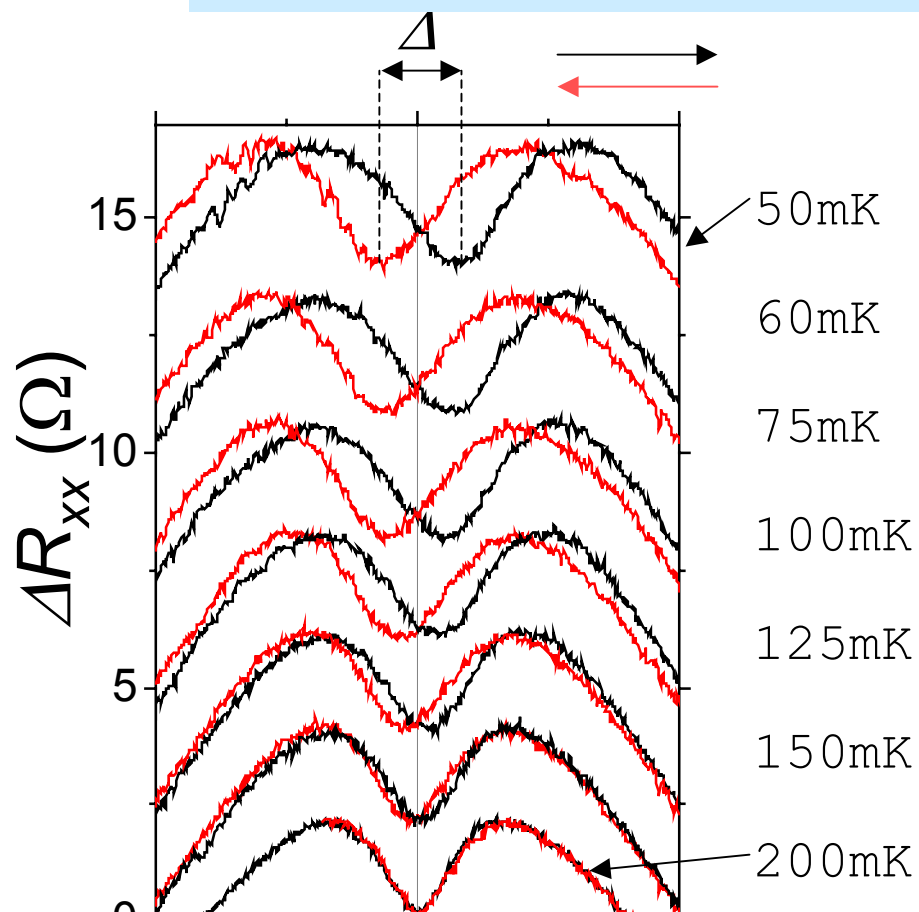
Curie temperature in p-Ga_{1-x}Mn_xAs theory and experiment



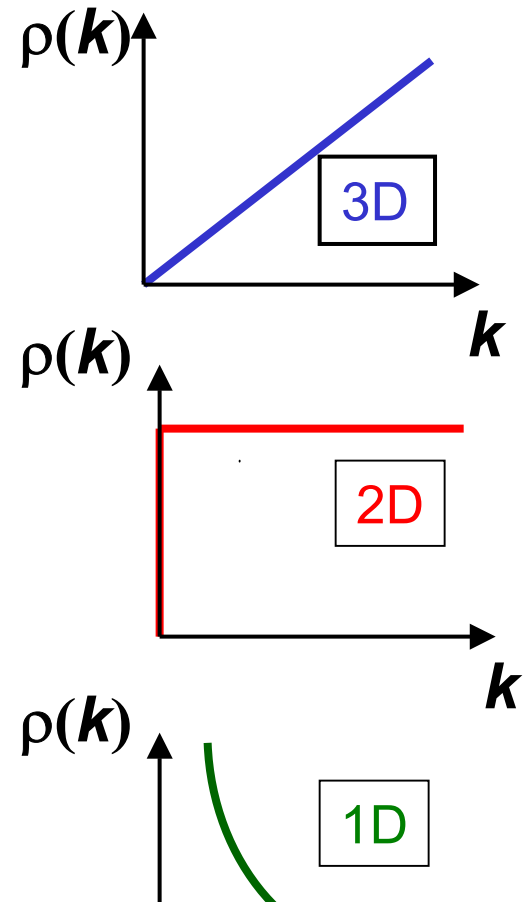
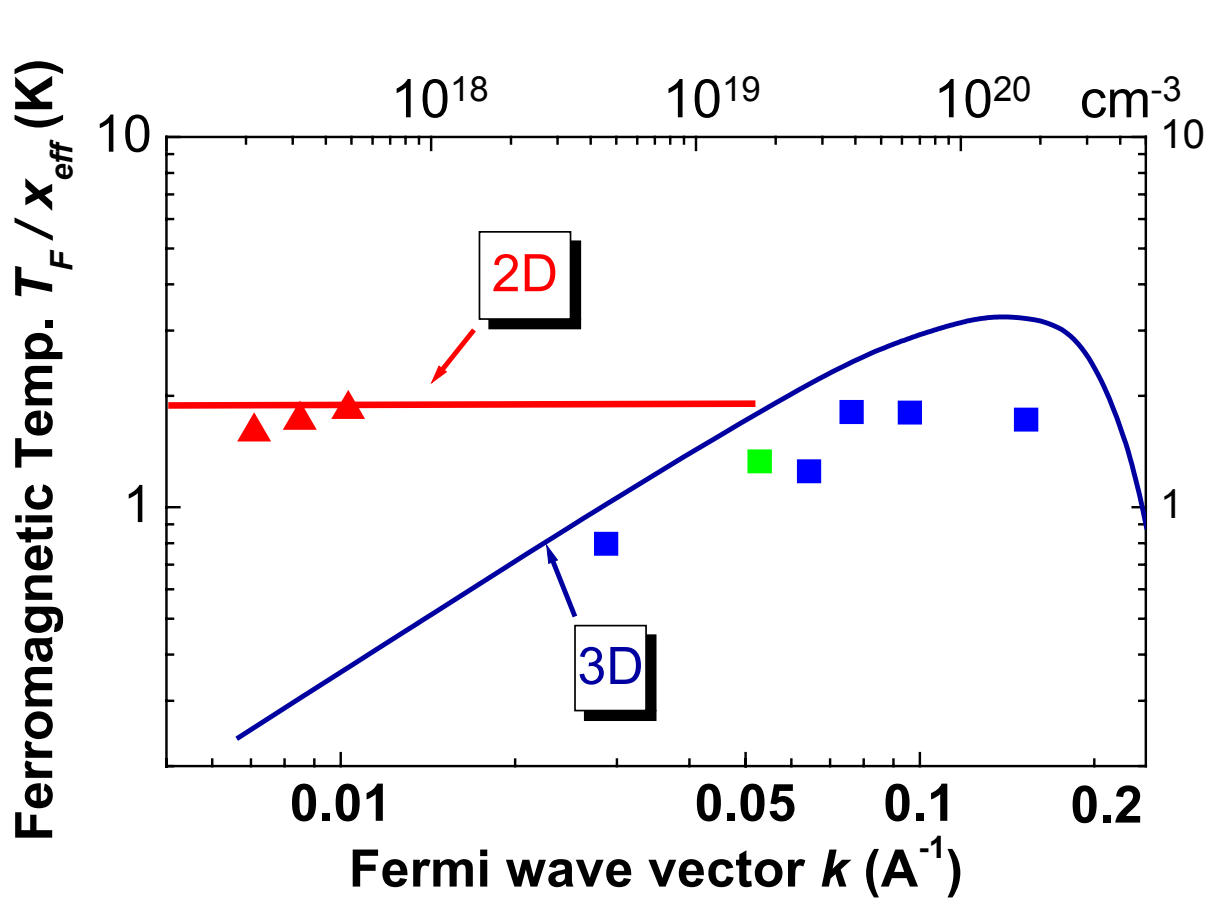
Ferromagnetism of $\text{Ge}_{1-x}\text{Mn}_x$



Magnetoresistance hysteresis $n\text{-Zn}_{1-x}\text{Mn}_x\text{O:Al}$, $x = 0.03$

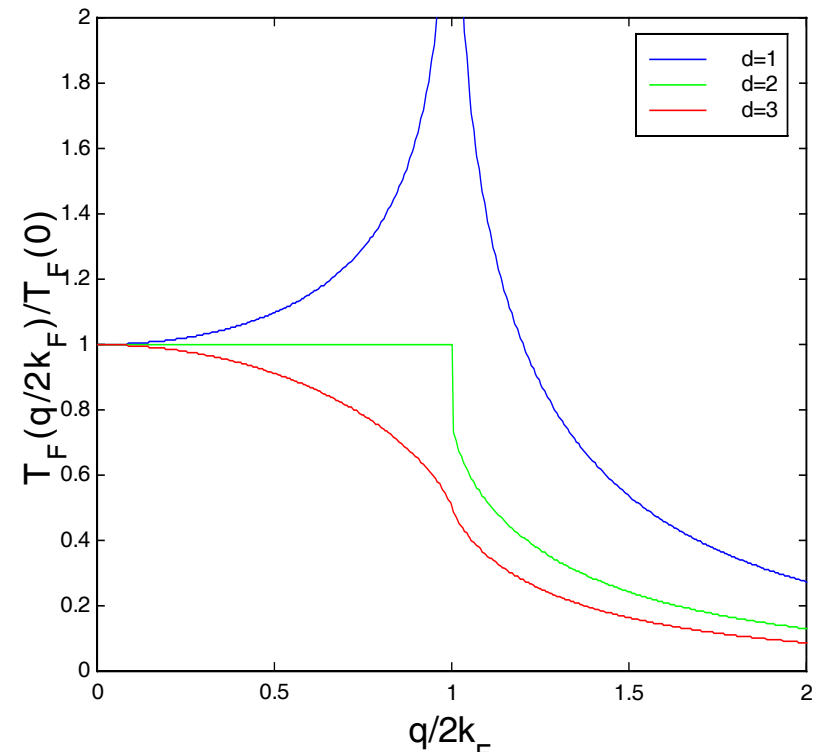


Ferromagnetic temperature in 2D p-Cd_{1-x}Mn_xTe QW and 3D Zn_{1-x}Mn_xTe:N



Effects of confinement magnetic quantum wires - expectations

1D: $T_F(q)$ has
maximum at $2k_F$
→ spin-Peierls
instability → SDW



Summary, spin-spin interactions in DMS

- DMS with no carriers: **merely antiferro superexchange**
- DMS with carriers: **ferro Zener/RKKY**
 - strong for holes
 - weak for electrons

Literature

→ DMS

TD, in: Handbook on Semiconductors, vol. 3B ed. T.S. Moss (Elsevier, Amsterdam 1994) p. 1251.

→ ferromagnetic DMS

- *F. Matsukura, H. Ohno, TD, in: Handbook of Magnetic Materials, vol. 14, Ed. K.H.J. Buschow, (Elsevier, Amsterdam 2002) p. 1*

- *TD, Semicond. Sci. Technol. 17, 377 (2002)*