Optical control of spin-spin interaction in doped semiconductors

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Quantum Optoelectronics Theory at MSU

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Collaborations

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MICHIGAN STATE UNIVERSITY

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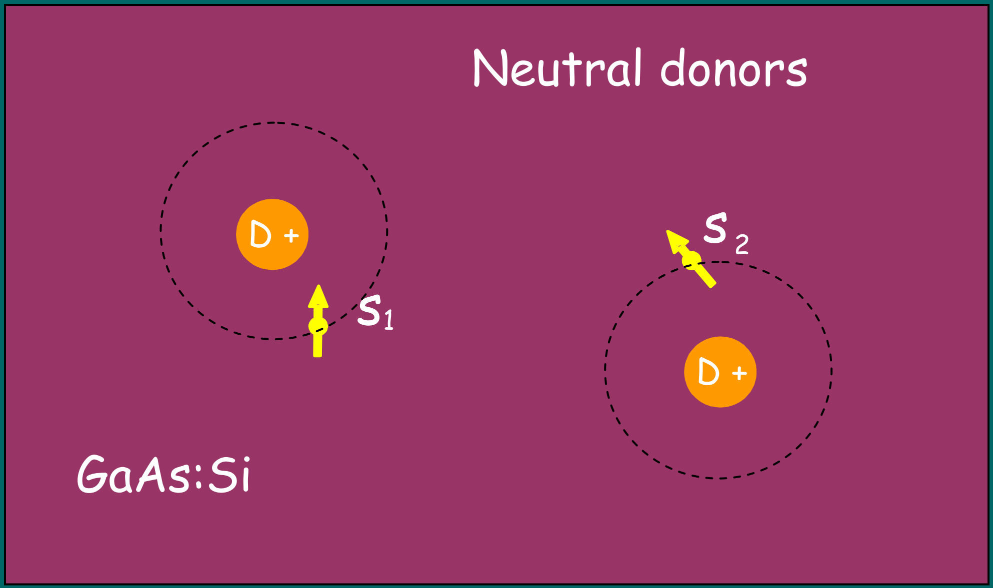
NSF

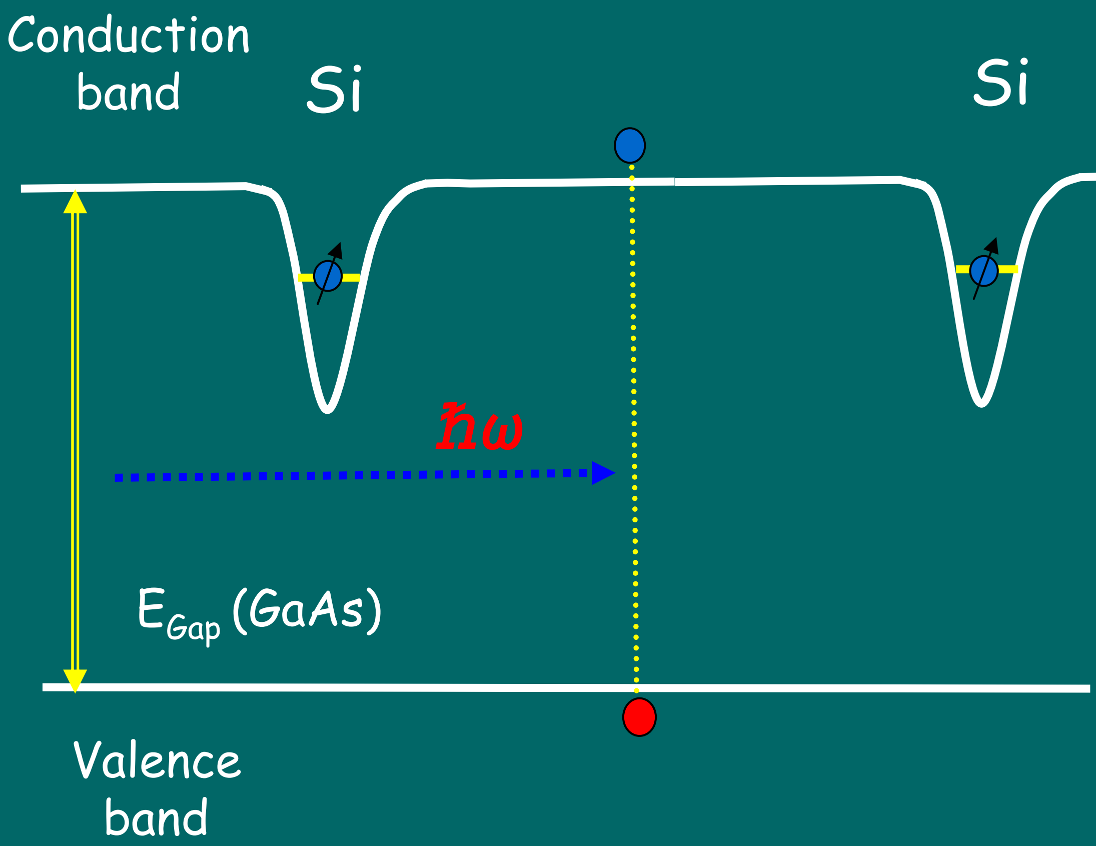
Quantum Control of two spins



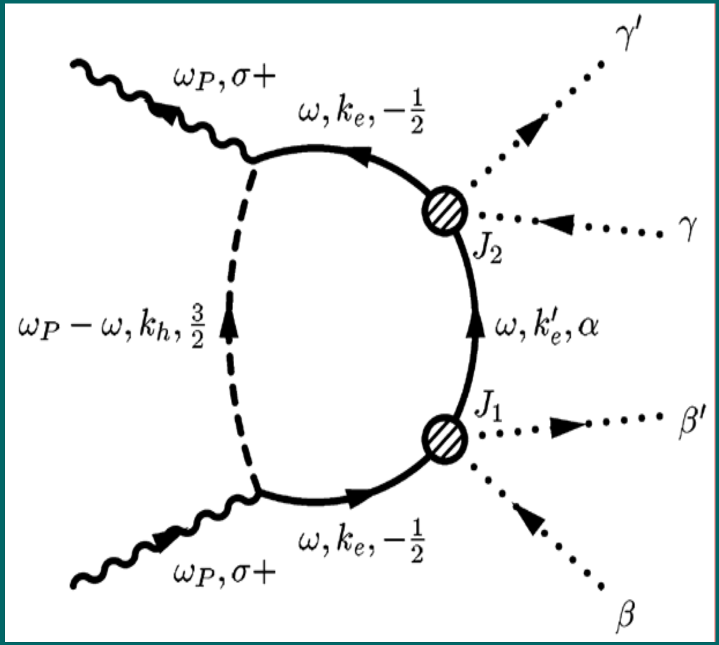
$$|\Psi\rangle = \alpha(t)|\uparrow\uparrow\rangle + \beta(t)|\uparrow\downarrow\rangle + \gamma(t)|\downarrow\uparrow\rangle + \delta(t)|\downarrow\downarrow\rangle$$

- Control Hamiltonian $H = H_0 + H_C(t, \sigma_1, \sigma_2, \ldots)$

Optical RKKY



Itinerant excitons mediate the interaction



C. Piermarocchi, P. Chen, L.J. Sham, G.D. Steel, Phys. Rev. Lett. **89** 167402 (02)

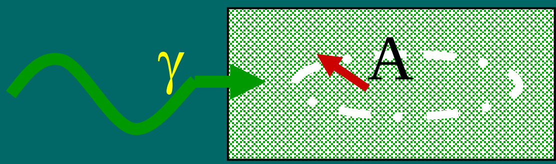
$$H = J_{eff} s_1 \cdot s_2$$

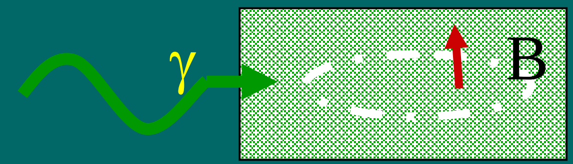
Beyond ORKKY

- Can we have Anti-ferromagnetic coupling?
- What is the effect of multiple scattering?
- What if the exciton is bound to the impurity?

Beyond second order in the exciton-spin coupling

G. F. Quinteiro and C. Piermarocchi, (to be published)



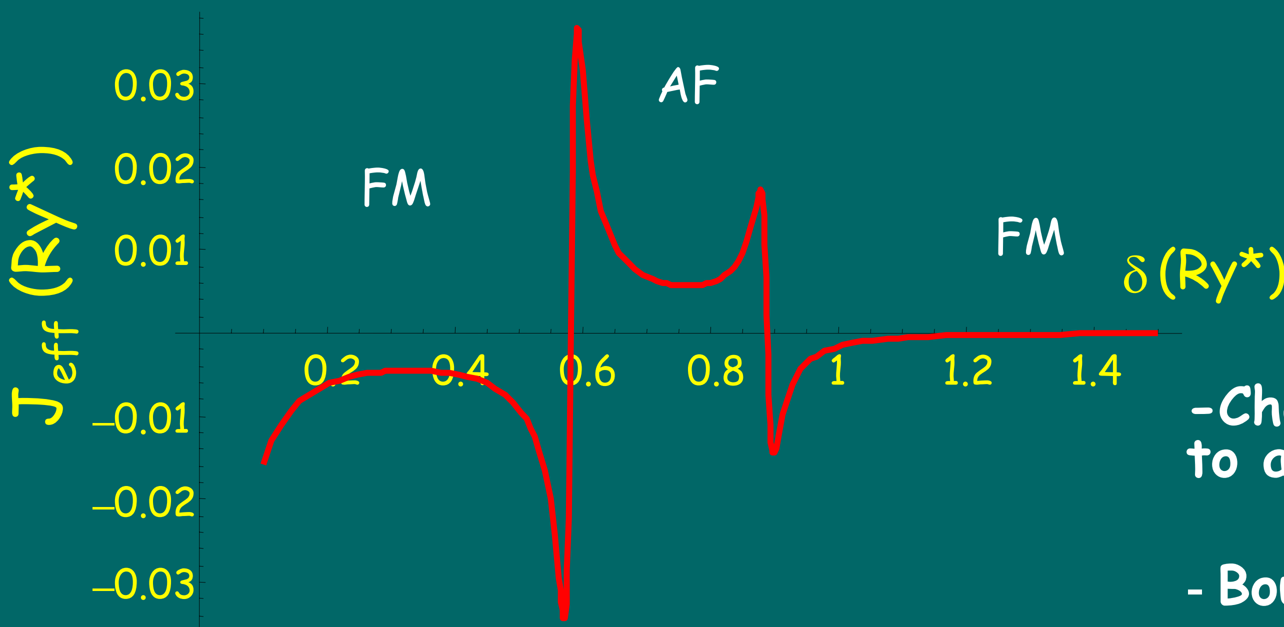


Solution for spin A + exciton

Solution for spin B + exciton

T^A T^B

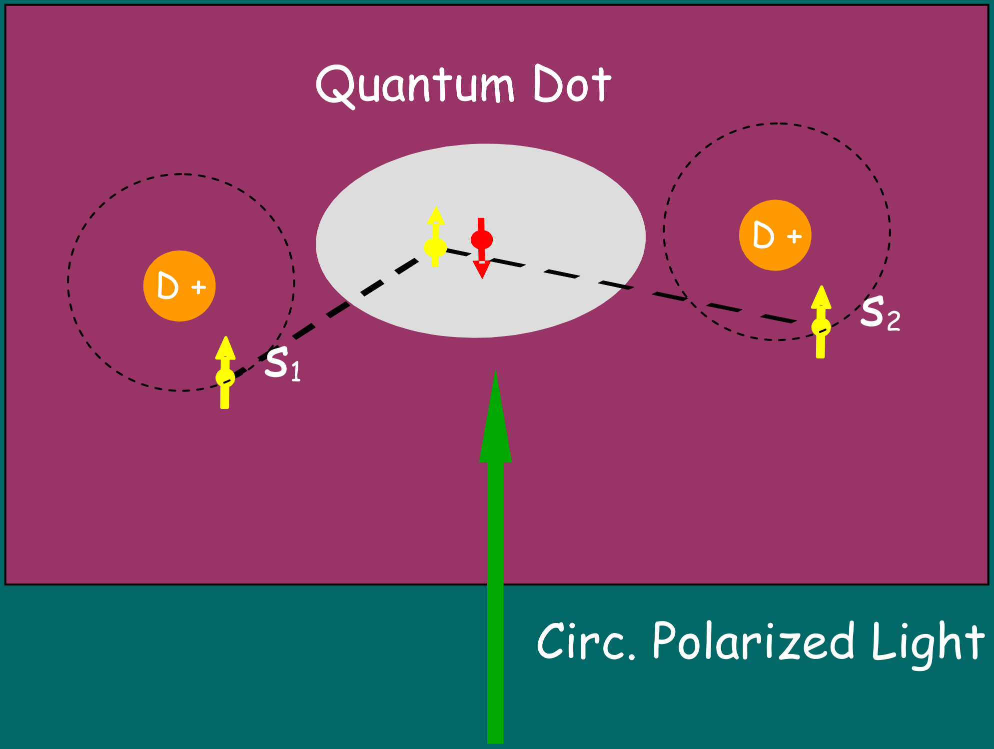
$$T = \frac{1}{1 - T^A G^0 T^B G^0} T^A [1 + G^0 T^B] + (A \rightleftarrows B)$$



-Change from ferro to antiferro

- Bound states.

Dynamics of quantum control



Initial State

$$|\uparrow\downarrow\rangle = \frac{|S\rangle + |T,0\rangle}{\sqrt{2}}$$

Follow the dynamics by numerical integration of the Liouville Equation

$$\frac{d\rho}{dt} = -i[H,\rho] + L\{\rho\}$$

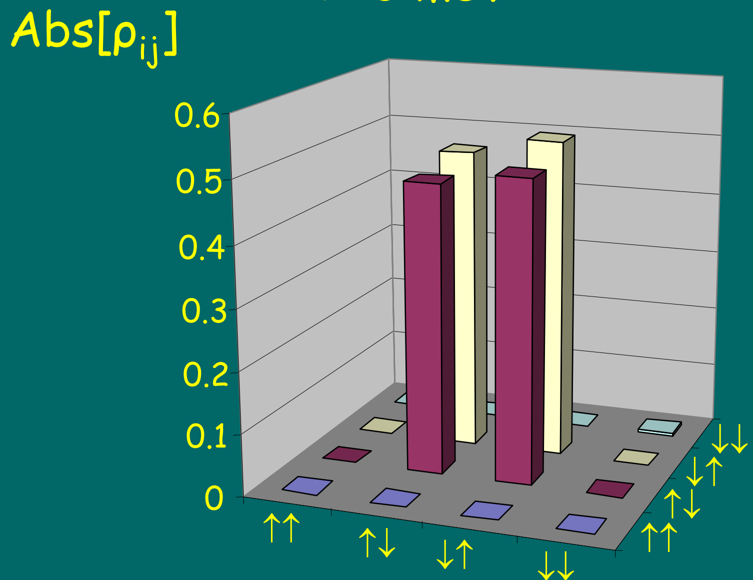
Dynamics of entanglement

Effect of decoherence: radiative recombination

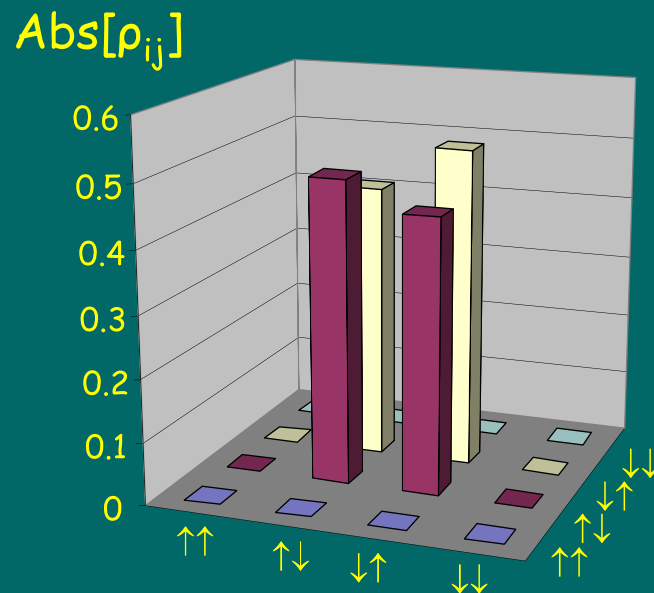
Decoherence
Off-resonant excitation

ρ after a Gaussian pulse

Γ=0 meV



Γ=0.3 meV (Radiative Recombination)

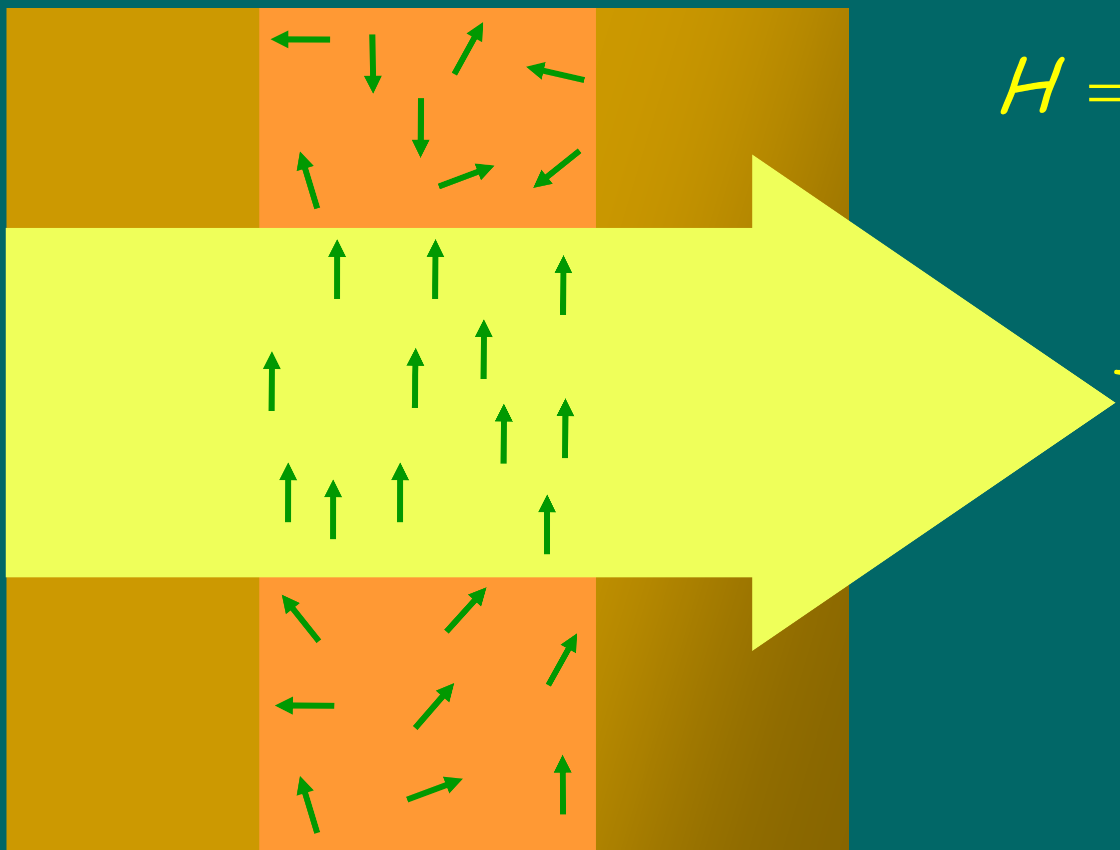


$$|\Psi\rangle \sim \frac{|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle}{\sqrt{2}}$$

Optical generation of entanglement !

J. Bao, A. V. Bragas, J. K. Furdyna, R. Merlin, Nature Mat. 2003

Light-spin thermodynamics



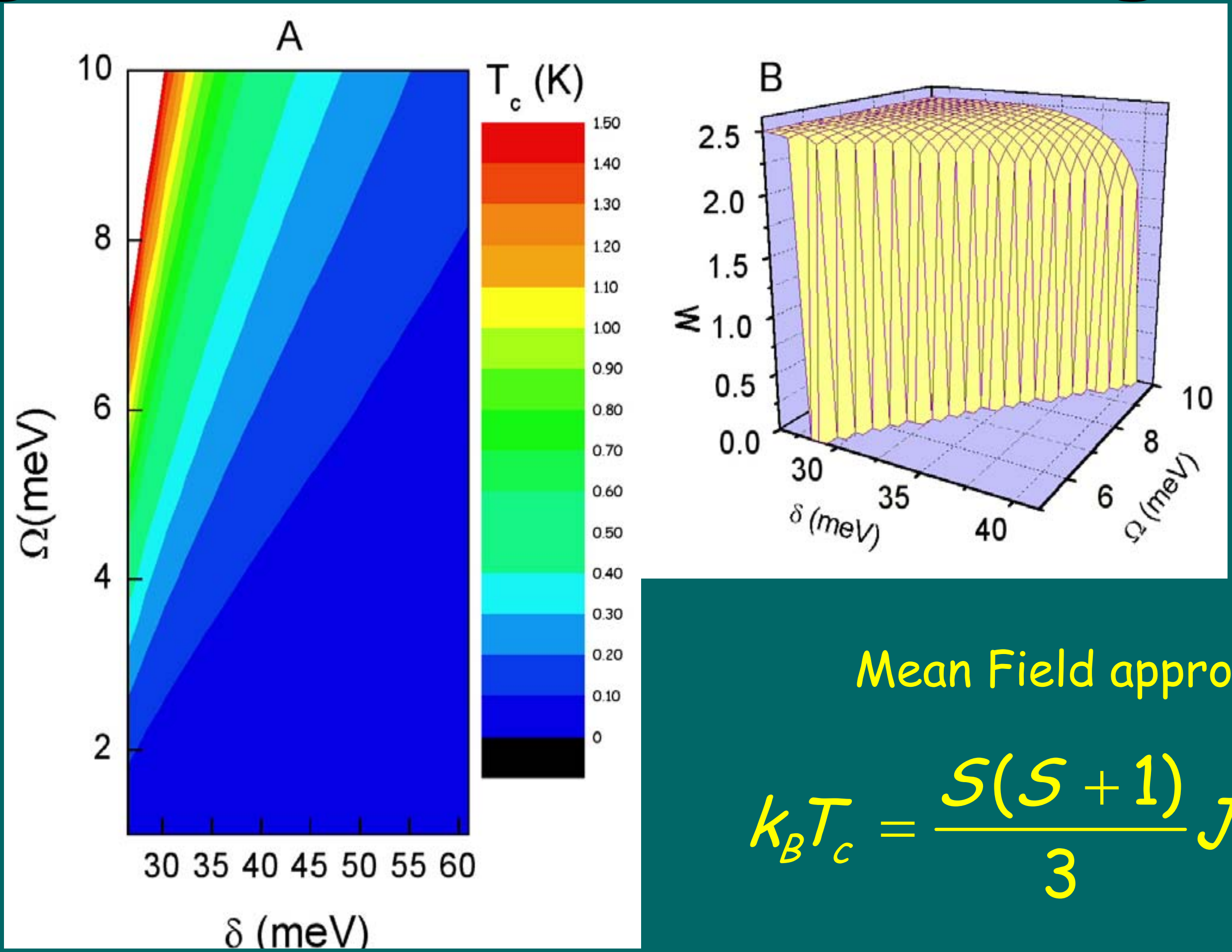
ZnSe:Mn

$$H = -J_{ORKKY}[\Omega]\sum_{ij} s_i \cdot s_j$$

Can we induce a PM/FM transition using coherent light?

J Fernandez-Rossier, C Piermarocchi, P Chen, LJ Sham, and AH MacDonald, (condmat/0312445, accepted in Phys. Rev. Lett.)

Light-induced ferromagnetism



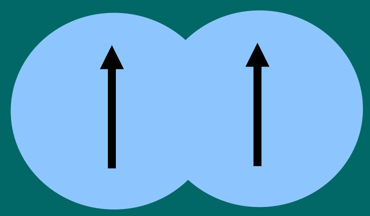
Mean Field approach

$$k_B T_c = \frac{S(S+1)}{3} J_{ORKKY}[\Omega]$$

Conclusions

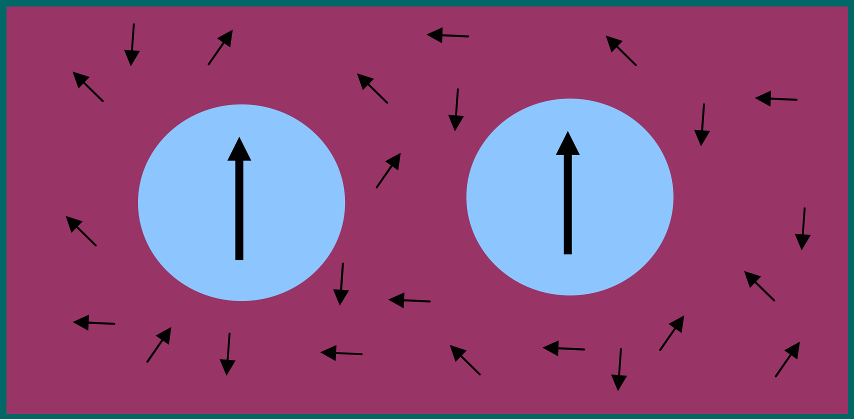
- Light can induce spin-spin interaction in a semiconductor.
- Strength, sign of the interaction are controllable.
- Dynamics and decoherence.
- Light-induced ferromagnetism.

Spin-spin interaction in Magnetism



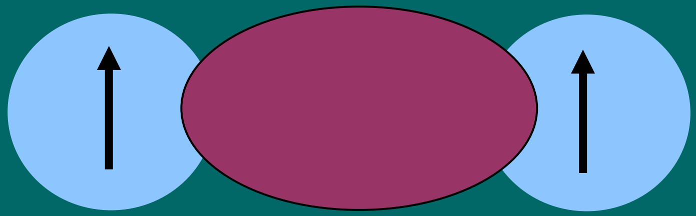
DIRECT:

Charge distribution overlap
e. g. H_2



INDIRECT:

RKKY
Ex: Gd
or
Super-exchange
Ex: $CaMnO_3$



Dimensionality effects

$$H = -2J(R)\sigma_1 \cdot \sigma_2.$$

3D $$J \sim \left(\frac{\Omega}{\Lambda}\right)^2 Ry^* \frac{e^{-2R/\kappa}}{R/\kappa},$$

2D $$J \sim \left(\frac{\Omega^2}{\Lambda\delta}\right) Ry^* e^{-2R/\kappa},$$

1D $$J \sim \left(\frac{\Omega}{\delta}\right)^2 Ry^* \left(1 + \frac{R}{\kappa}\right) e^{-2R/\kappa}.$$

Ω = Rabi energy

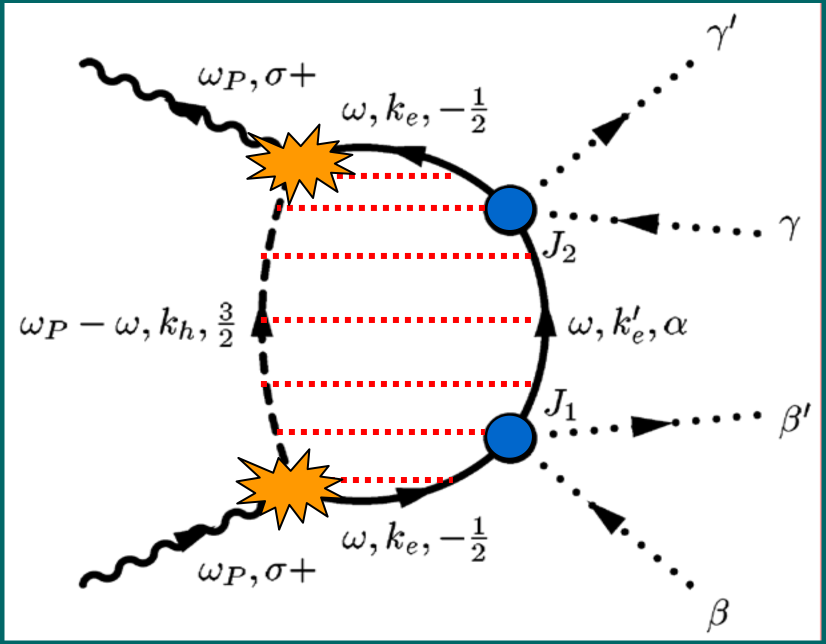
Λ = energy in dot

δ = detuning

R = interdot distance

$$\kappa = \sqrt{\frac{\hbar^2}{2m\delta}}$$

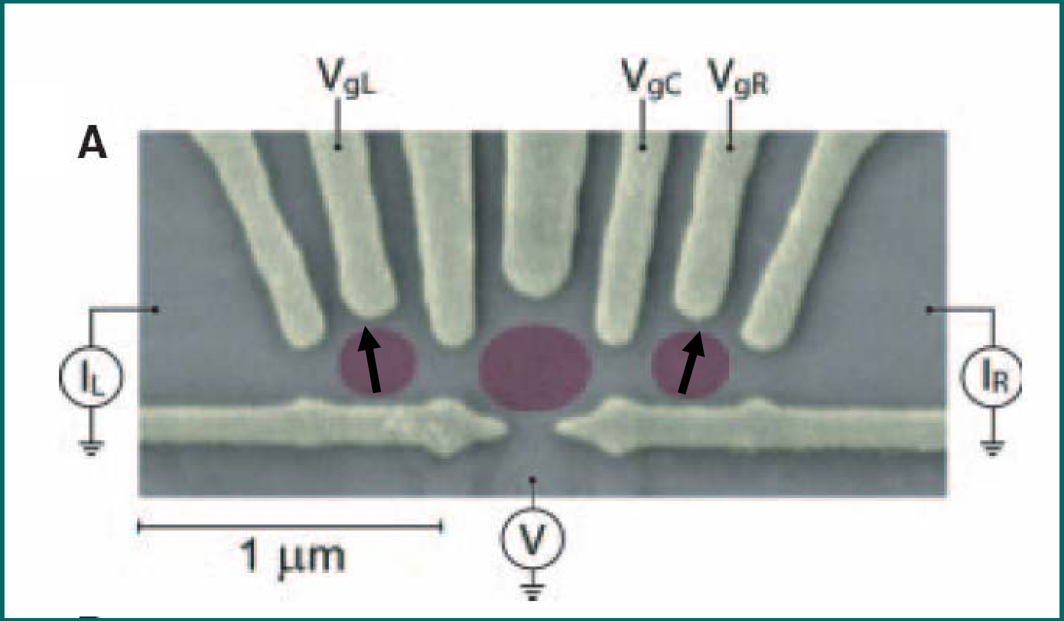
Excitonic effects



$$F_{1s,1s}(\mathbf{q}) = \int dr e^{-i\frac{m_h}{M}\mathbf{q}\cdot\mathbf{r}} \, |\Psi_{1s}(r)|^2$$

$$J^d_{1s12}(R) = \frac{|\Omega(t)|^2}{16} j^d_1 j^d_2 \frac{1}{\Delta^3} \left|\Psi_{1s}(0)\right|^2 \int \frac{d^d\mathbf{q}}{(2\pi)^d} \frac{e^{-i\mathbf{q}\cdot\mathbf{R}}}{1+(\lambda_M q)^2} \left|F_{1s,1s}(q)\right|^2$$

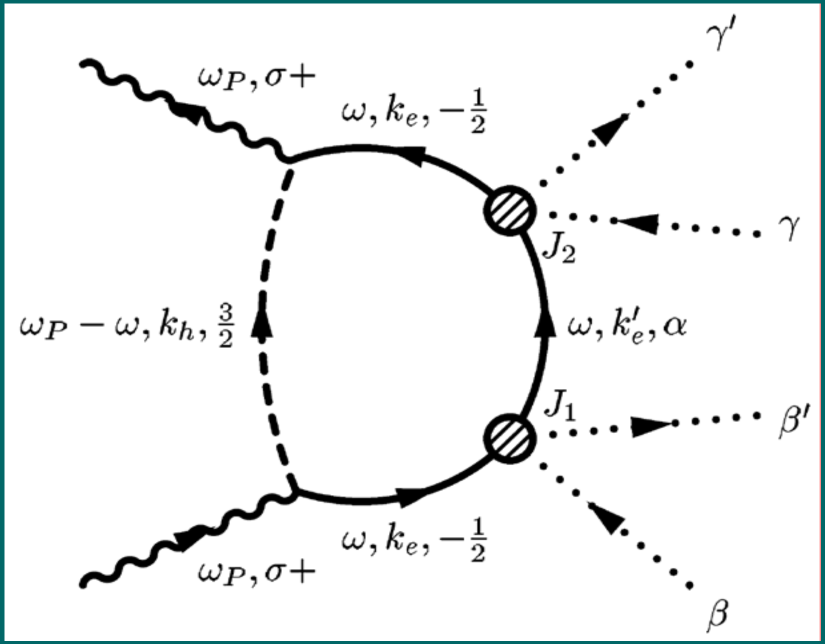
Controlled indirect spin-spin interaction in semiconductors



N.J. Craig et al.
Science April 23rd 2004

The central dot mediates an indirect RKKY-like spin-spin interaction between the lateral dots

Dynamic Spin-Stark shift



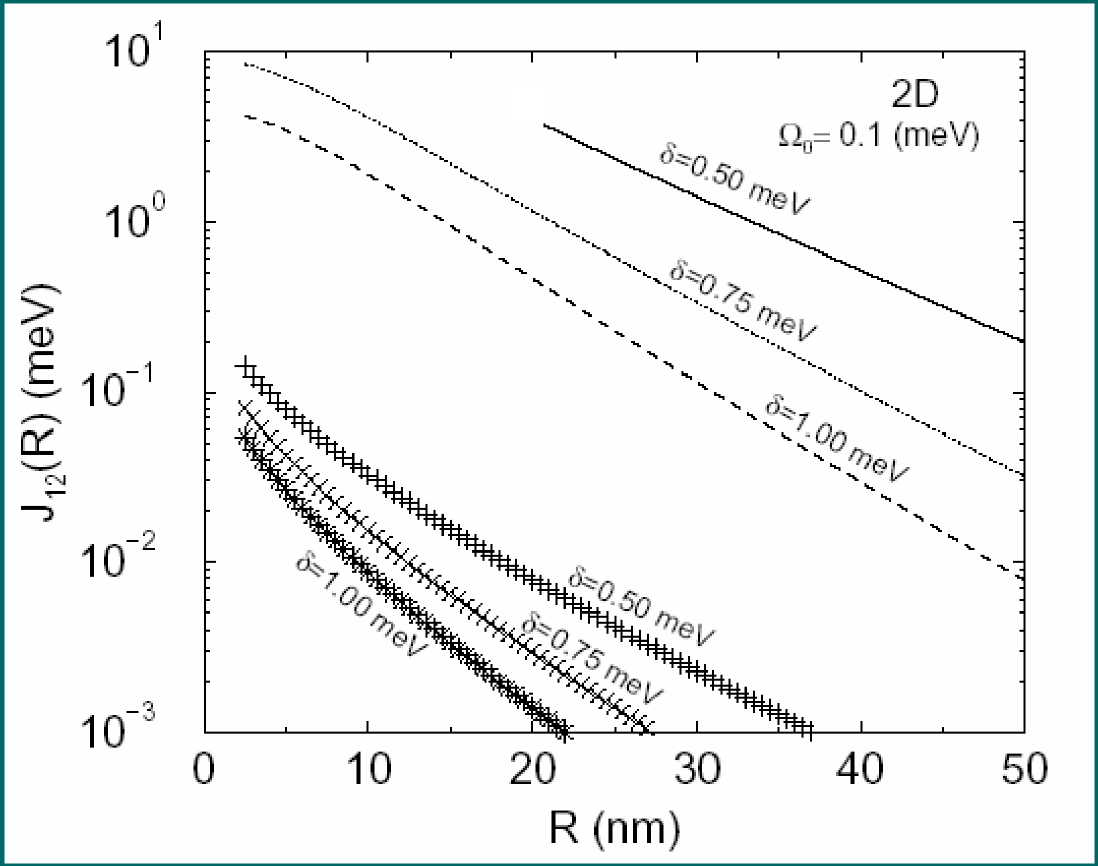
SPIN STRUCTURE:

$$-4J_{12}(S^1 \cdot s)(S^2 \cdot s) - 4J_{12}(S^2 \cdot s)(S^1 \cdot s)$$

$$= -2J_{12}(S^1 \cdot S^2)$$

$$J_{12}(R) = \frac{|\Omega(t)|^2}{16} \iint \frac{d^d k}{(2\pi)^d} \frac{d^d k'}{(2\pi)^d} \frac{j_1^d j_2^d e^{-i(k-k')R}}{\left(\Delta + \frac{k^2}{2m_h} + \frac{k^2}{2m_e}\right)^2 \left(\Delta + \frac{k^2}{2m_h} + \frac{k'^2}{2m_e}\right)}$$

Quantum Well



m^*_e=0.07m,
m^*_h=0.5m,
ξ=300 Å

Ry^*=10 meV
a_B^*= 100 Å

$$\kappa = \frac{\hbar}{\sqrt{2M_x\delta}}$$

Exponential decay of the interaction

Assuming $J_{kk'}=J\, v_k\, v_{k'}$

↳ Exact analytical solution of the effective H of two localized spins

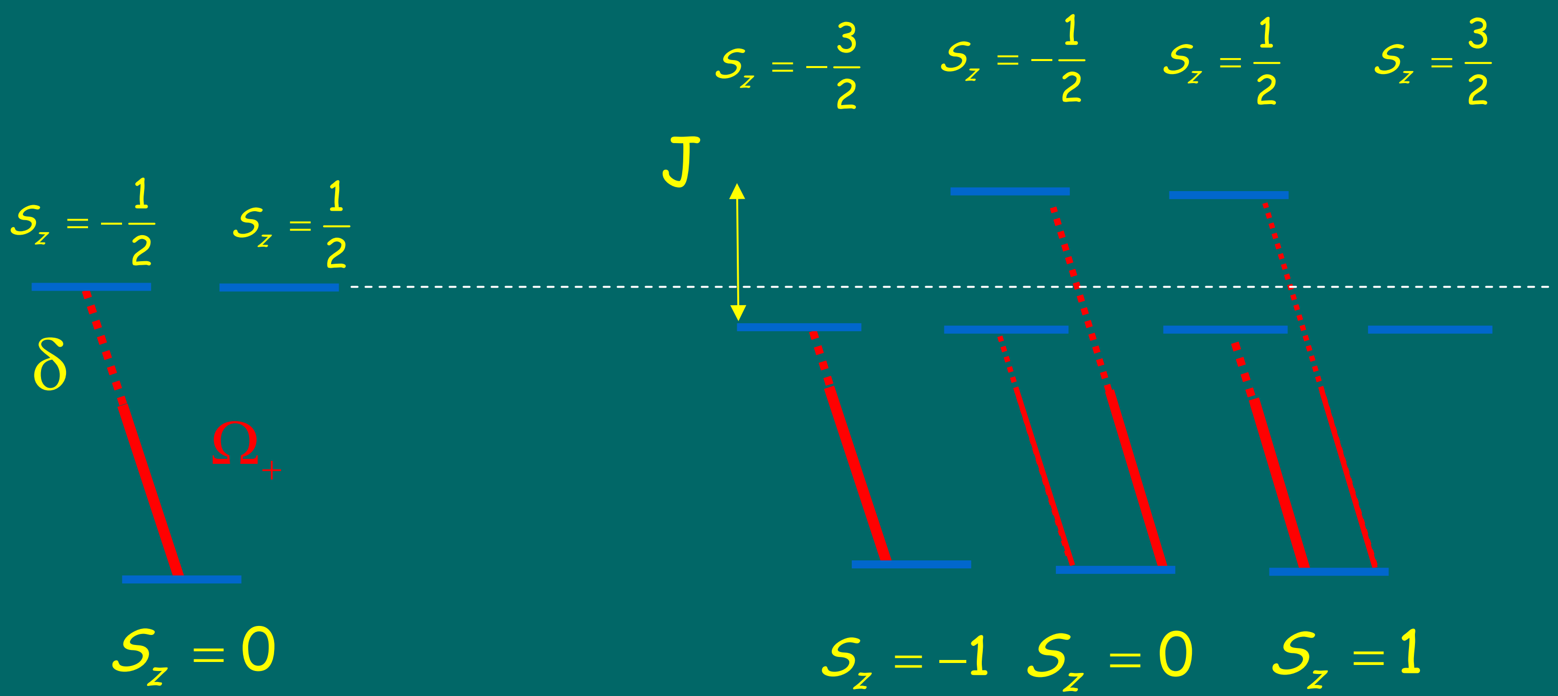
$$H_{eff}=-2\left(\frac{\Omega}{\delta}\right)^2 \left|\varphi_{1s}\right|^2 [A(s_1+s_2)\cdot s+B s_1\cdot s_2+C(s_1\times s_2)\cdot s]$$

A: effective magnetic field. Needs circular polarization

B: Heisenberg term

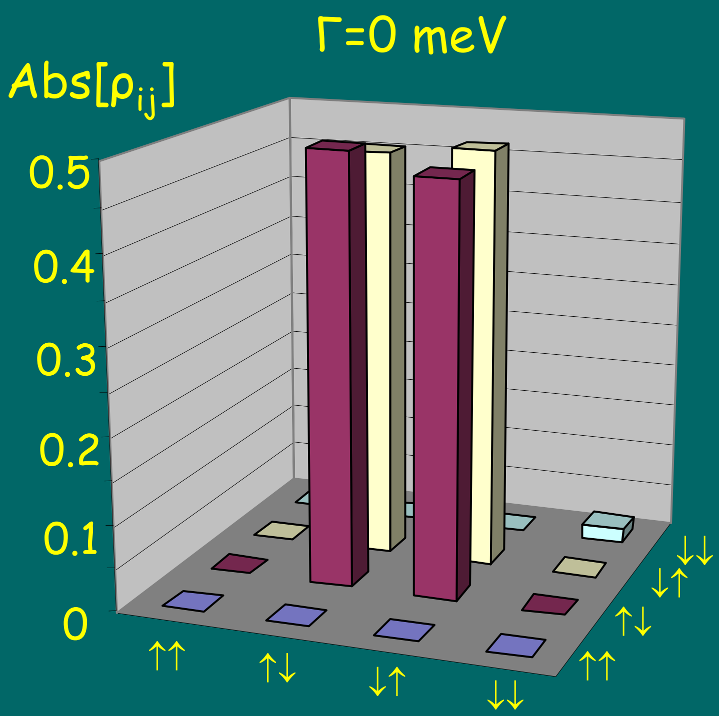
C: Dzjaloshinski-Moriya. Needs circular polarization + asymmetric coupling

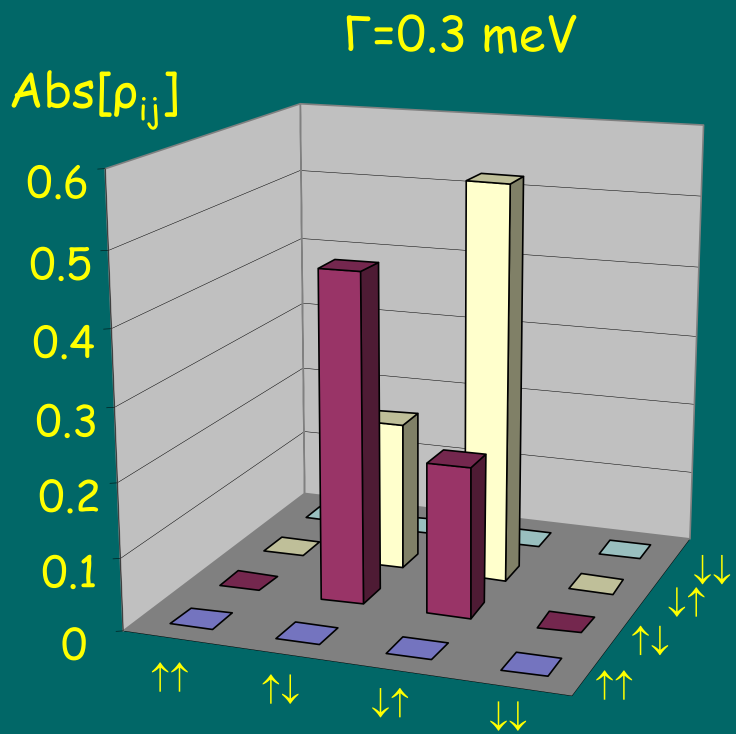
Optical Spin-Stark Shift



Initial State $$\left|\uparrow\downarrow\right\rangle = \frac{\left|S\right\rangle + \left|T,0\right\rangle}{\sqrt{2}}$$

Radiative Recombination
(b) resonance





δ=1 meV

Resonant to the J=3/2 states

Nearly thermal in the S_z=0 subspace,
but still entangled in terms of Peres criterion