Quantum Computation with Spins and Excitons in Semiconductor Quantum Dots (Part II)

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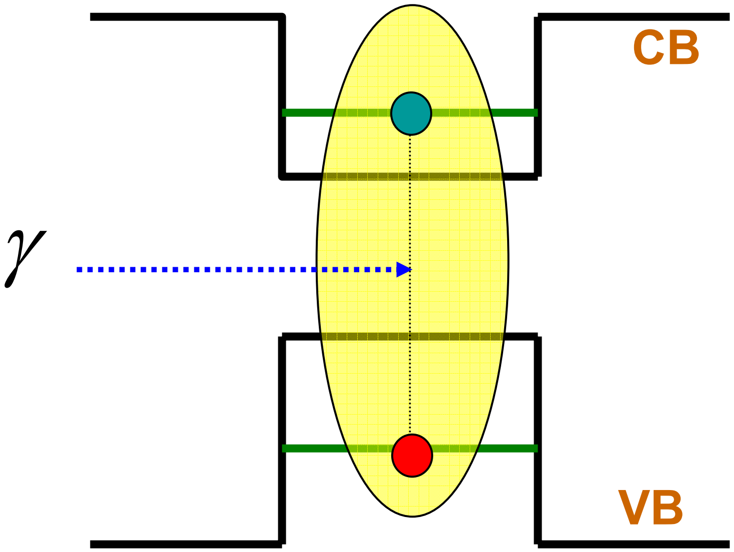
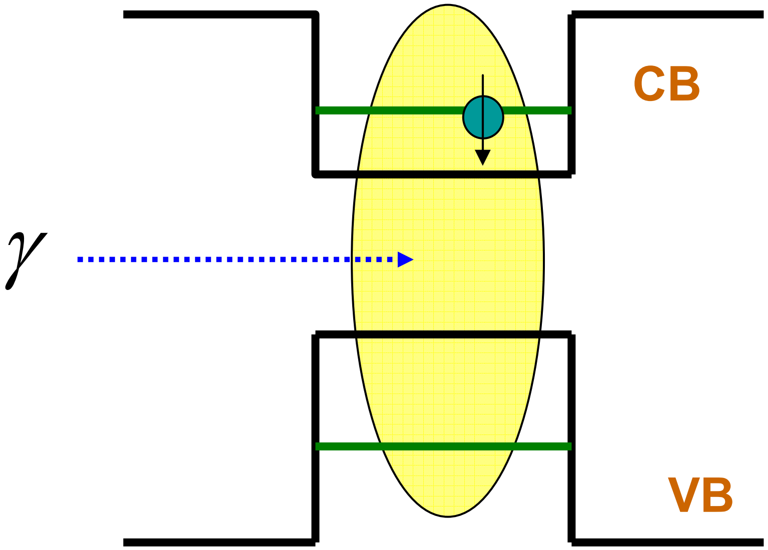
11th,14th, 15th 2008

Optics of Quantum Dots

Neutral Quantum Dot

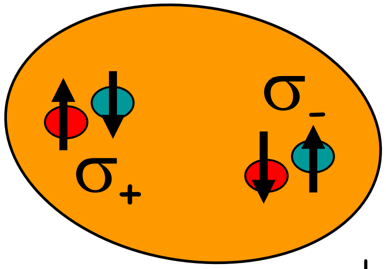


Charged Quantum Dot



Quantum Optical Control

I



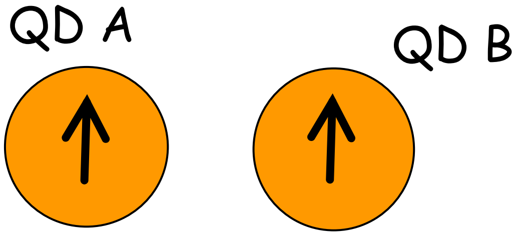
Optical control of two excitons in a single quantum dot

$$\left|\Psi\right\rangle = \alpha\left|0\right\rangle + \beta\left|+\right\rangle + \gamma\left|-\right\rangle + \delta\left|-+\right\rangle$$

Experimentally realized

Realize a two-qubit quantum computer

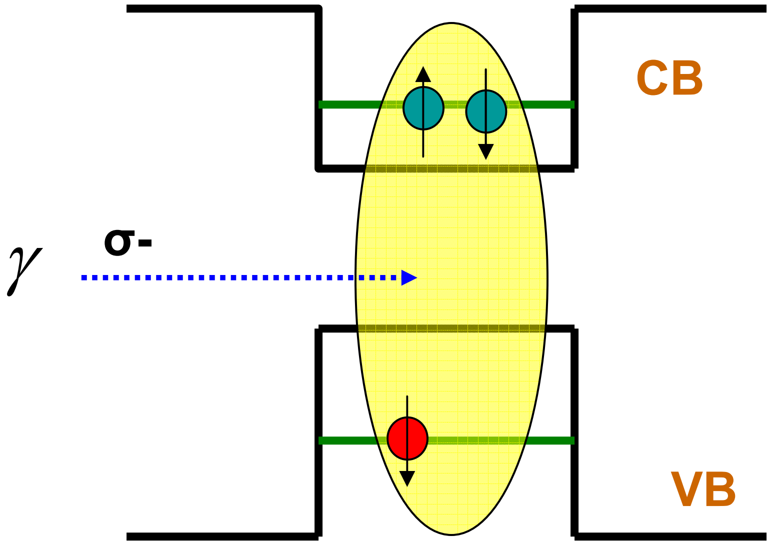
II



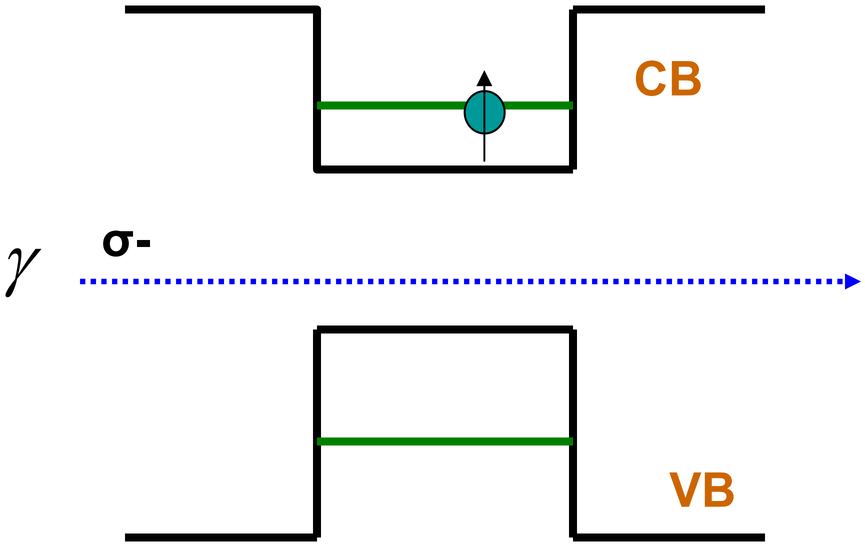
Optical control of two spins in charged dots:

$$\left|\Psi\right\rangle = \alpha\left|\downarrow\downarrow\right\rangle + \beta\left|\downarrow\uparrow\right\rangle + \gamma\left|\uparrow\downarrow\right\rangle + \delta\left|\uparrow\uparrow\right\rangle$$

Trion Selection rules in Quantum Dots

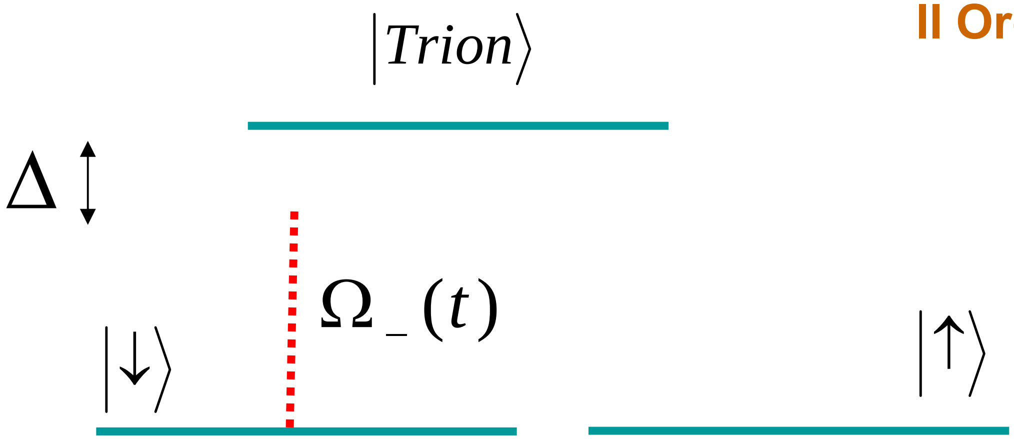


Dark



Dynamic Stark Shift

THREE LEVEL SYSTEM



II Order perturbation theory

$$\Delta E_\downarrow(t) = -\frac{\Omega_-(t)^2}{\Delta}$$

By the Adiabatic Theorem

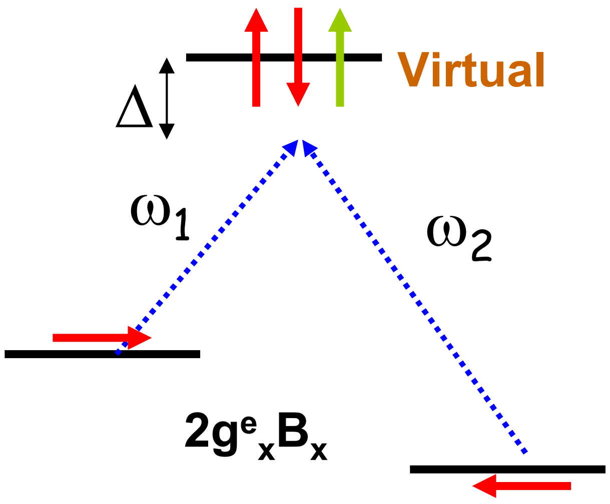
$$|\downarrow\rangle \rightarrow e^{-i\int \Delta E_\downarrow(t)dt}|\downarrow\rangle$$

Spin rotation around z

$$|\uparrow\rangle \rightarrow |\uparrow\rangle$$

Raman Transition

$$H_{RF} = \begin{array}{c} \begin{array}{ccc} |\rightarrow\rangle & |\leftarrow\rangle & |\uparrow\downarrow\Uparrow\rangle \end{array} \\ \begin{bmatrix} 0 & 0 & \Omega \\ 0 & 0 & \Omega \\ \Omega & \Omega & \Delta \end{bmatrix} \end{array}$$



Voigt configuration

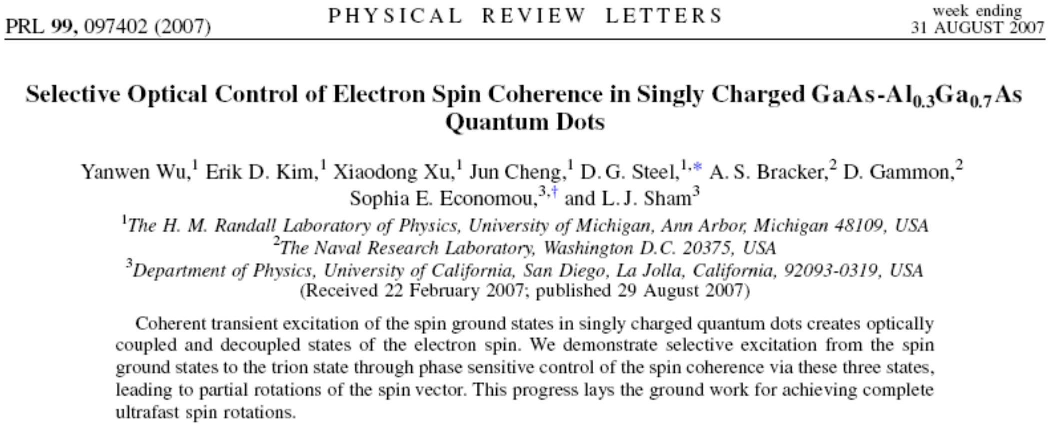
Second order perturbation theory:

$$H_{eff} = \begin{array}{c} \begin{array}{cc} |\rightarrow\rangle & |\leftarrow\rangle \end{array} \\ \begin{bmatrix} 0 & \dfrac{\Omega^2}{\Delta} \\ \dfrac{\Omega^2}{\Delta} & 0 \end{bmatrix} \end{array}$$

Effective Hamiltonian
for single spin

Pochung Chen, C. Piermarocchi, L. J. Sham, D. Gammon, and D. G. Steel, *Theory of Quantum Optical Control of Single Spin in a Quantum Dot*, Phys. Rev. B 69 075320 (2004)

Experiments



PRL 99, 097402 (2007) PHYSICAL REVIEW LETTERS week ending 31 AUGUST 2007

Selective Optical Control of Electron Spin Coherence in Singly Charged GaAs-$Al_{0.3}Ga_{0.7}As$ Quantum Dots

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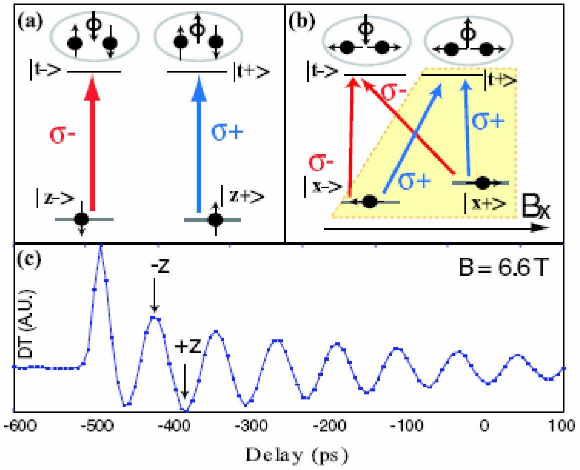
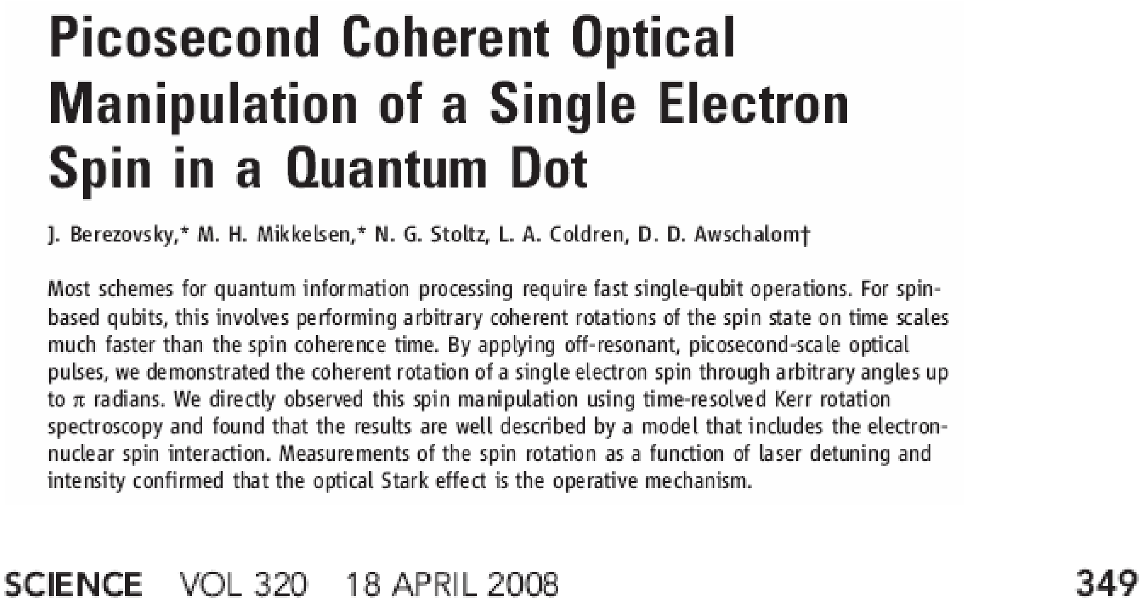
Coherent transient excitation of the spin ground states in singly charged quantum dots creates optically coupled and decoupled states of the electron spin. We demonstrate selective excitation from the spin ground states to the trion state through phase sensitive control of the spin coherence via these three states, leading to partial rotations of the spin vector. This progress lays the ground work for achieving complete ultrafast spin rotations.





Picosecond Coherent Optical Manipulation of a Single Electron Spin in a Quantum Dot

J. Berezovsky,* M. H. Mikkelsen,* N. G. Stoltz, L. A. Coldren, D. D. Awschalom†

Most schemes for quantum information processing require fast single-qubit operations. For spin-based qubits, this involves performing arbitrary coherent rotations of the spin state on time scales much faster than the spin coherence time. By applying off-resonant, picosecond-scale optical pulses, we demonstrated the coherent rotation of a single electron spin through arbitrary angles up to π radians. We directly observed this spin manipulation using time-resolved Kerr rotation spectroscopy and found that the results are well described by a model that includes the electron-nuclear spin interaction. Measurements of the spin rotation as a function of laser detuning and intensity confirmed that the optical Stark effect is the operative mechanism.

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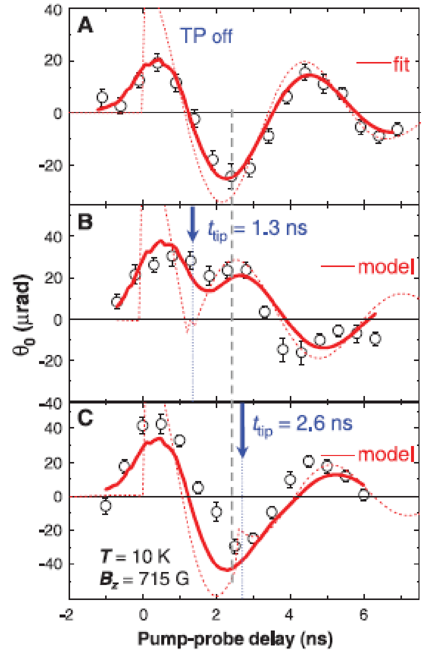
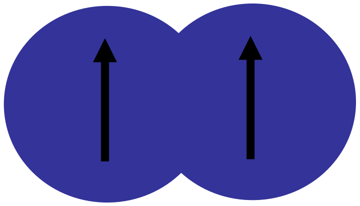
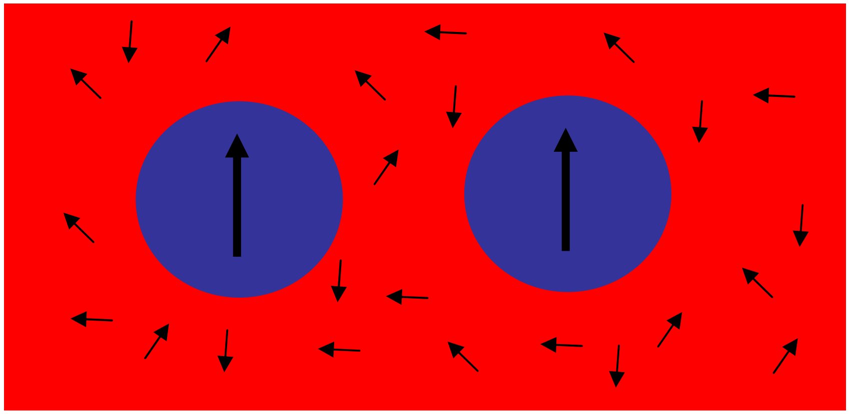


Control of ↑↑



DIRECT:

Charge distribution overlap



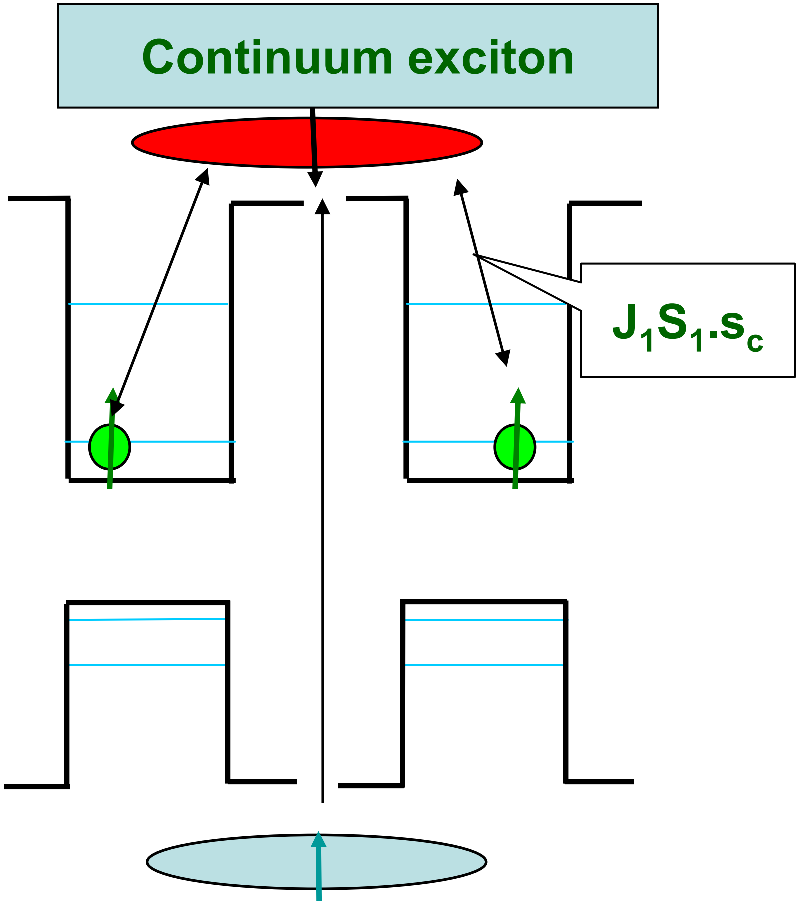
INDIRECT:

Mediated by interaction
with conduction electrons

$$H = -\frac{J^2 m^*}{4(2\pi)^3 \hbar^2} \frac{(2k_F R \cos(2k_F R) - \sin(2k_F R))}{R^4} \vec{S}_1 \cdot \vec{S}_2$$

RKKY

Quantum Dots



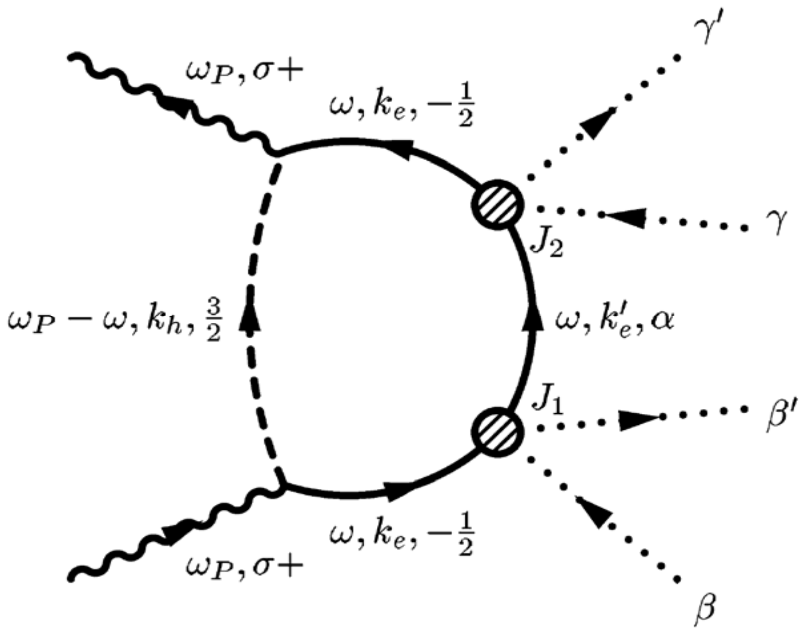
Photoexcited electron-hole pairs in the host material embedding the QDs

$$H = -J(R)S_1 \cdot S_2$$

Real Excitation
Virtual Excitation

C. Piermarocchi, P. Chen, L. J. Sham, and D. G. Steel, “Optical RKKY interaction between semiconductor quantum dots” Phys. Rev. Lett. (2002)

Optical RKKY



VIRTUAL:

$$\Delta = \varepsilon_C - \omega_P$$

SPIN STRUCTURE:

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

$$\downarrow$$

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

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

EXCHANGE:

$$j_i^d = \iint d^d\mathbf{r}\, d^d\mathbf{r}' \Psi^*(\mathbf{r}') V(\mathbf{r}'-\mathbf{r}) \Psi(\mathbf{r}) \approx I Ry^* a_B^* \xi^{d-1}$$

Dimensionality effects

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

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

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

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

Ω = Rabi energy

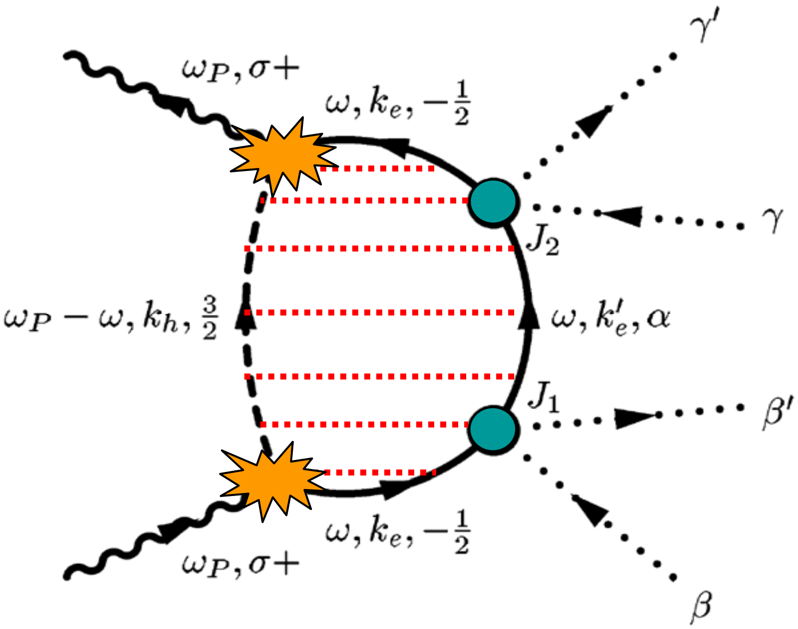
Λ = energy in dot

δ = detuning

R = interdot distance

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

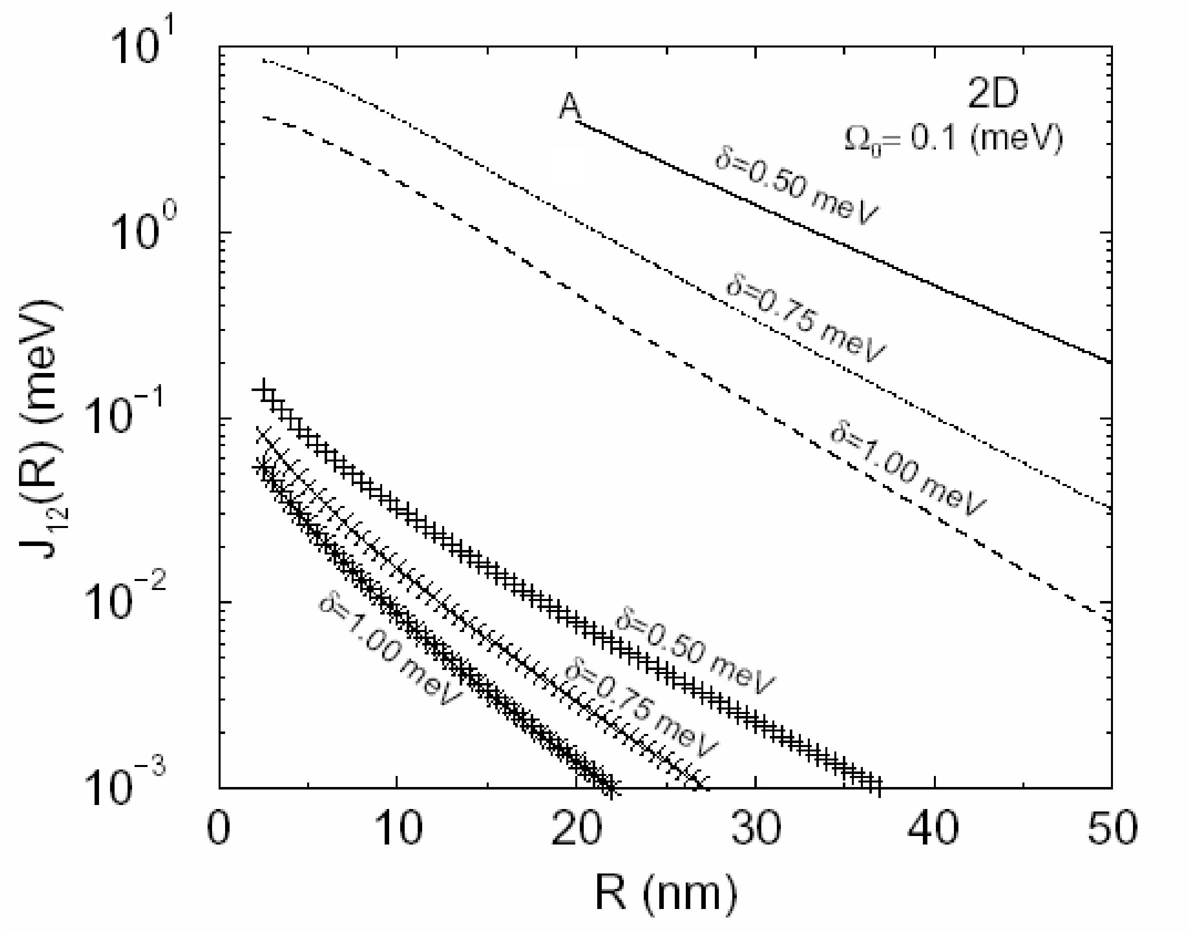
Excitonic effects



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

$$J^d_{1s12}(R) = \frac{|\Omega(t)|^2}{16} j_1^d j_2^d \frac{1}{\Delta^3} \left|\Psi_{1s}(0)\right|^2 \int \frac{d^d\mathbf{q}}{(2\pi)^d} \frac{e^{-i\mathbf{q}\cdot\mathbf{R}}}{1+(\lambda_M q)^2} \left|F_{1s,1s}(q)\right|^2$$

Numerical Calculation



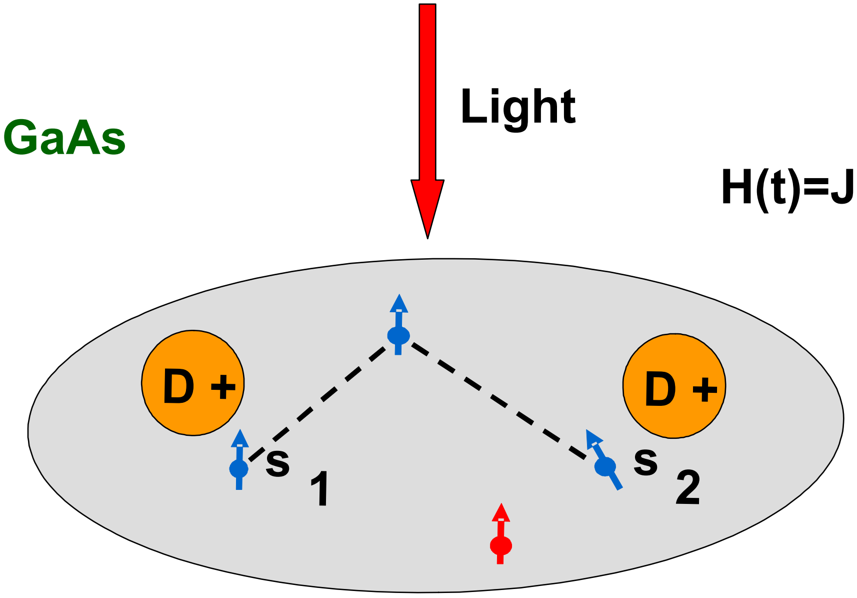
m^*_e=0.07m,
m^*_h=0.5m,
ξ=300 Å

Ry^*=10 meV
a_B^*= 100 Å

Availability of ultra-short pulses
Flexibility in the control: shaping
No leads: less decoherence

Optical RKKY with impurities

Si donors in GaAs



$H(t)=J(t)\, s_1 \cdot s_2$

Charged quantum dots replaced by diluted neutral donors
Photo-excited eh pairs mediate the RKKY interaction
Homogeneous system

Beyond ORKKY

Can we have anti-ferromagnetic coupling?

What is the effect of multiple scattering?

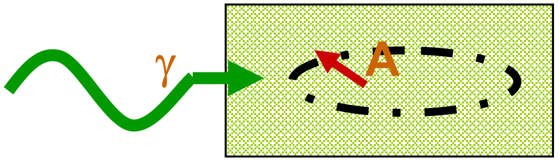
What if the exciton is bound to the impurity?

Beyond second order in the exciton-spin coupling

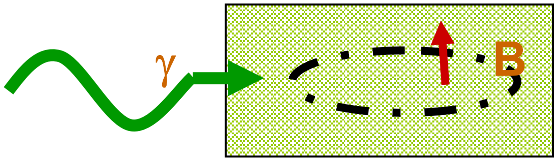
C. Piermarocchi and G. F. Quinteiro, *Coherent optical control of spin-spin interaction in doped semiconductors*, Phys. Rev. B 70, 235210 (2004)

We seek a solution in terms of T matrix equation →

$$\hat{T} = \hat{H}_1 + \hat{H}_1 \hat{G}^0 \hat{T}$$



Solution for spin A + exciton



Solution for spin B + exciton

T^A T^B

Solution for the 2 spins using

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

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

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

$$H_{eff}=B_{eff}\cdot(s^A+s^B)+J_{eff}s^A\cdot s^B$$

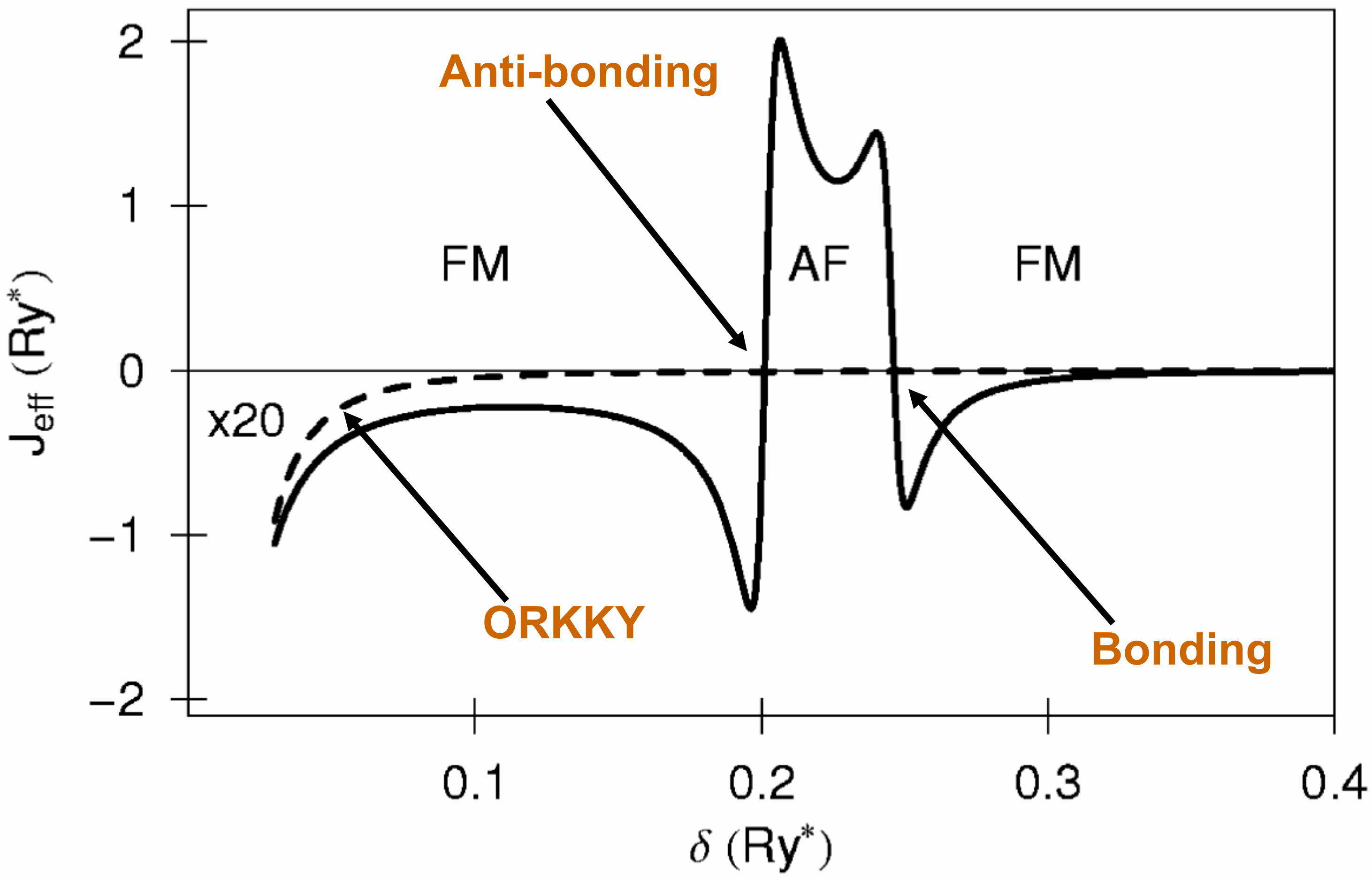
Effective magnetic field :

$$B_{eff}=\frac{|\Omega_{\sigma+}|^2-|\Omega_{\sigma-}|^2}{\delta^2}\,\frac{|\phi_{1s}|^2v_0^2J(1-JF_R^-)}{(1-JF_R^+)[1-JF_R^+(3JF_R^--2)]}\,\frac{\hat{z}}{2}$$

Heisenberg coupling:

$$J_{eff}=\frac{|\Omega_{\sigma+}|^2+|\Omega_{\sigma-}|^2}{\delta^2}\,\frac{|\phi_{1s}|^2v_0^2J^2F_R/2(1-JF_R^-)}{(1-JF_R^+)[1-JF_R^+(3JF_R^--2)][1-JF_R^-(3JF_R^+-2)]}$$

Spin-spin coupling

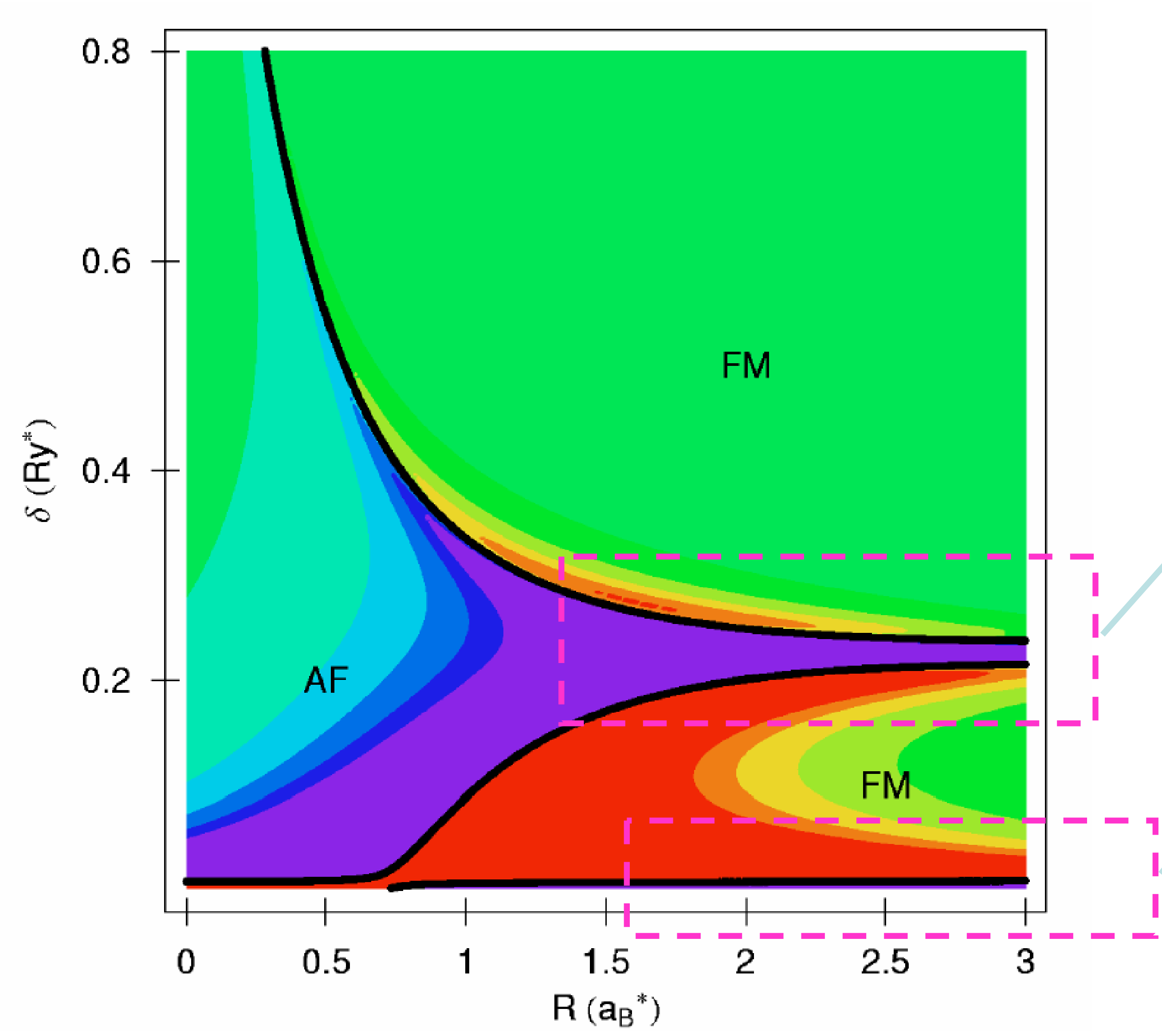


2 Si in GaAs

$R=2a_B$ (~20 nm)

1 Ry^*=5 meV

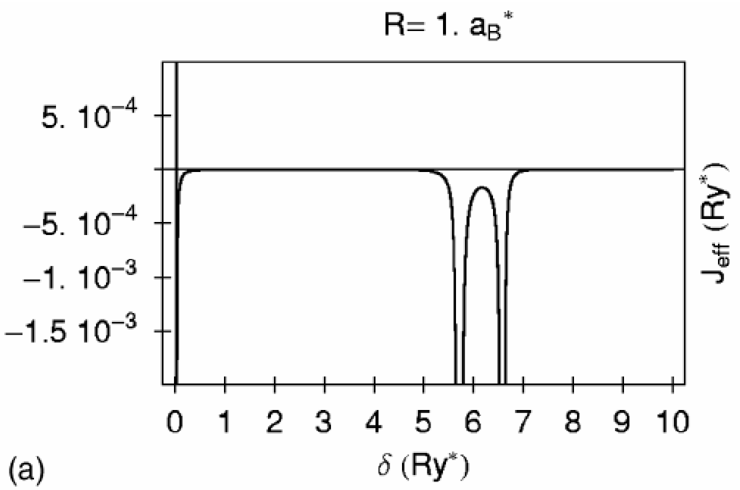
R-dependence

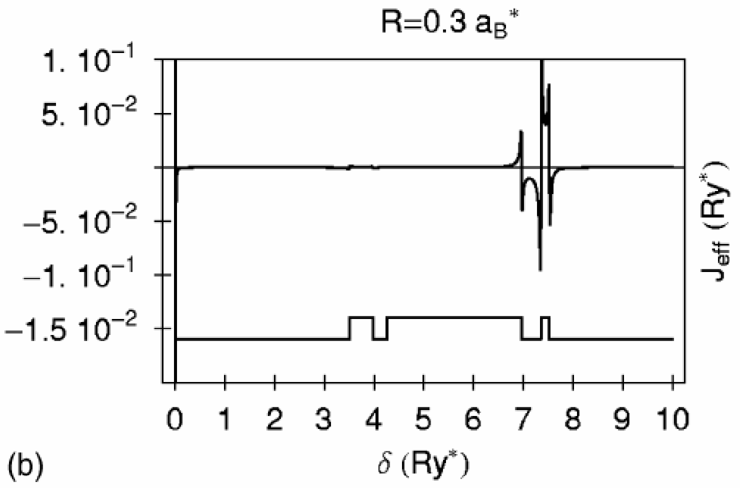


Excitons bound donors. Short range

Free excitons Long range

Deep impurities





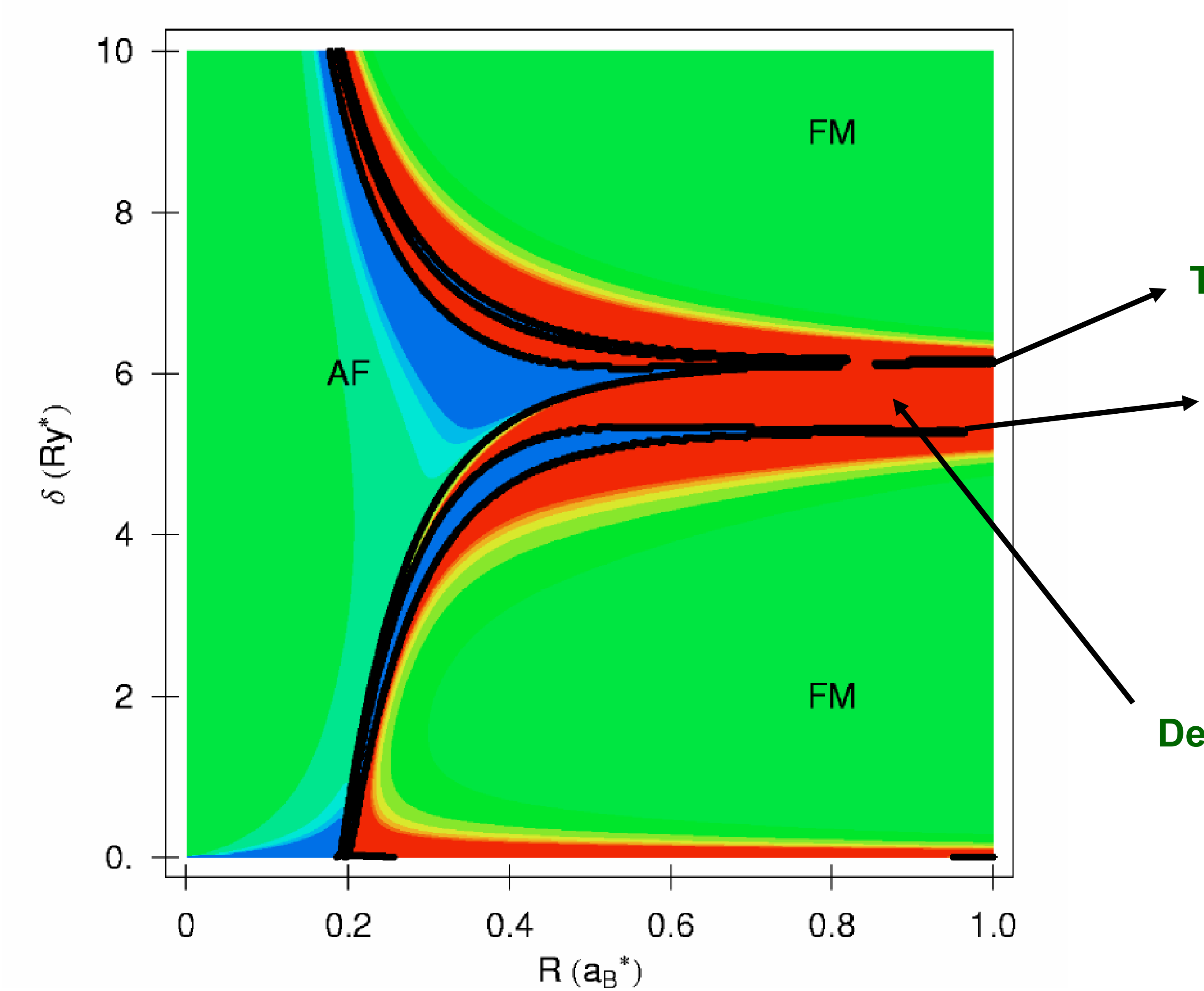
Rare earth impurities

Yb^{3+} in InP

Long decoherence for spin

Coupling with exciton by s-f exchange

R dependence InP:Yb

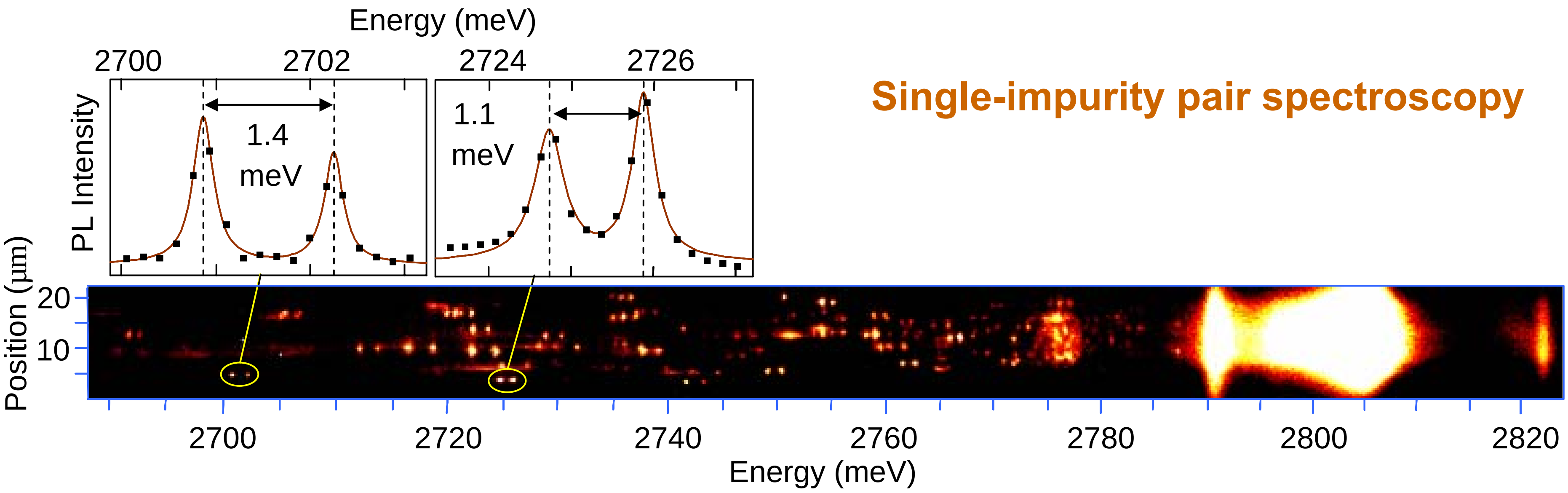


Triplet channel

Singlet channel

Deep confinement

Experiments

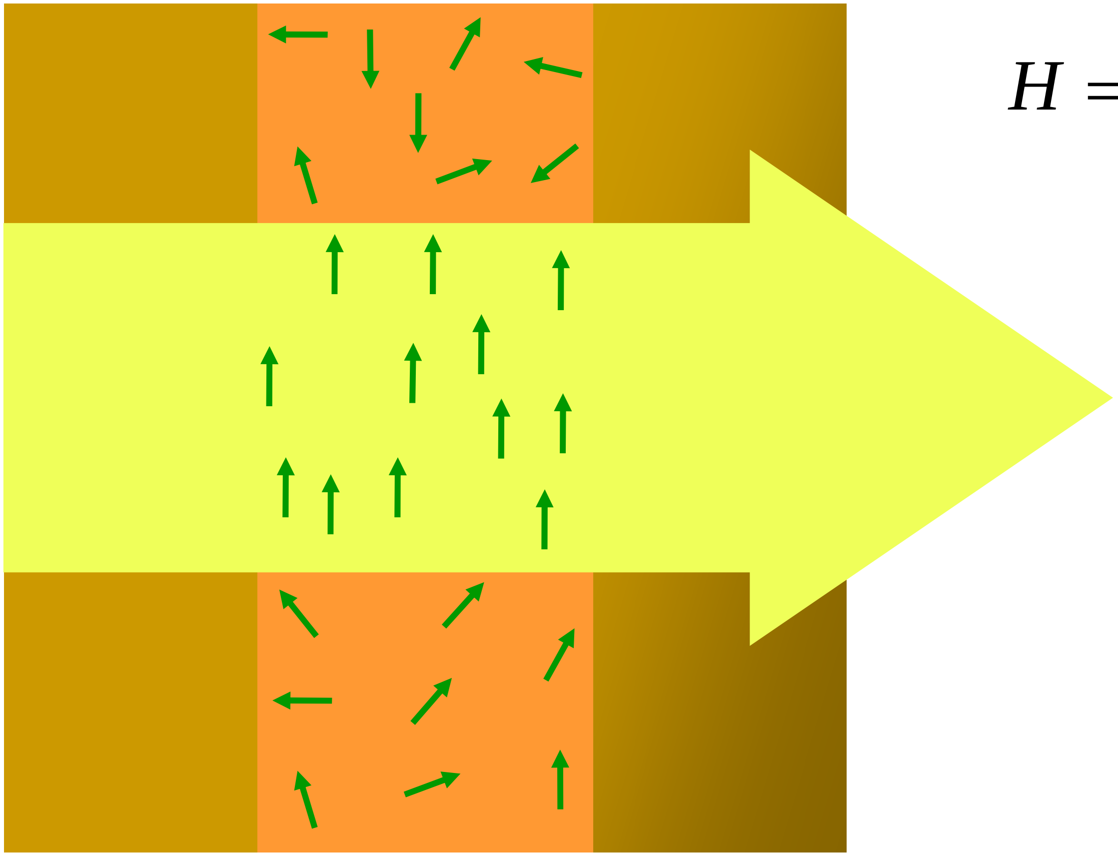


Single-impurity pair spectroscopy

Excitons bound to single Te pairs in ZnSe.
Deep isoelectronic (non magnetic)
Average separation between pairs: 1 micron

A. Muller, P. Bianucci, C. Piermarocchi, M. Fornari, I. C. Robin, R. André and C. K. Shih, *Time-resolved photoluminescence spectroscopy of individual Te impurity centers in ZnSe*, Phys. Rev. B 73, 081306 (R) (2006)

From Quantum Computing to Spintronics Materials

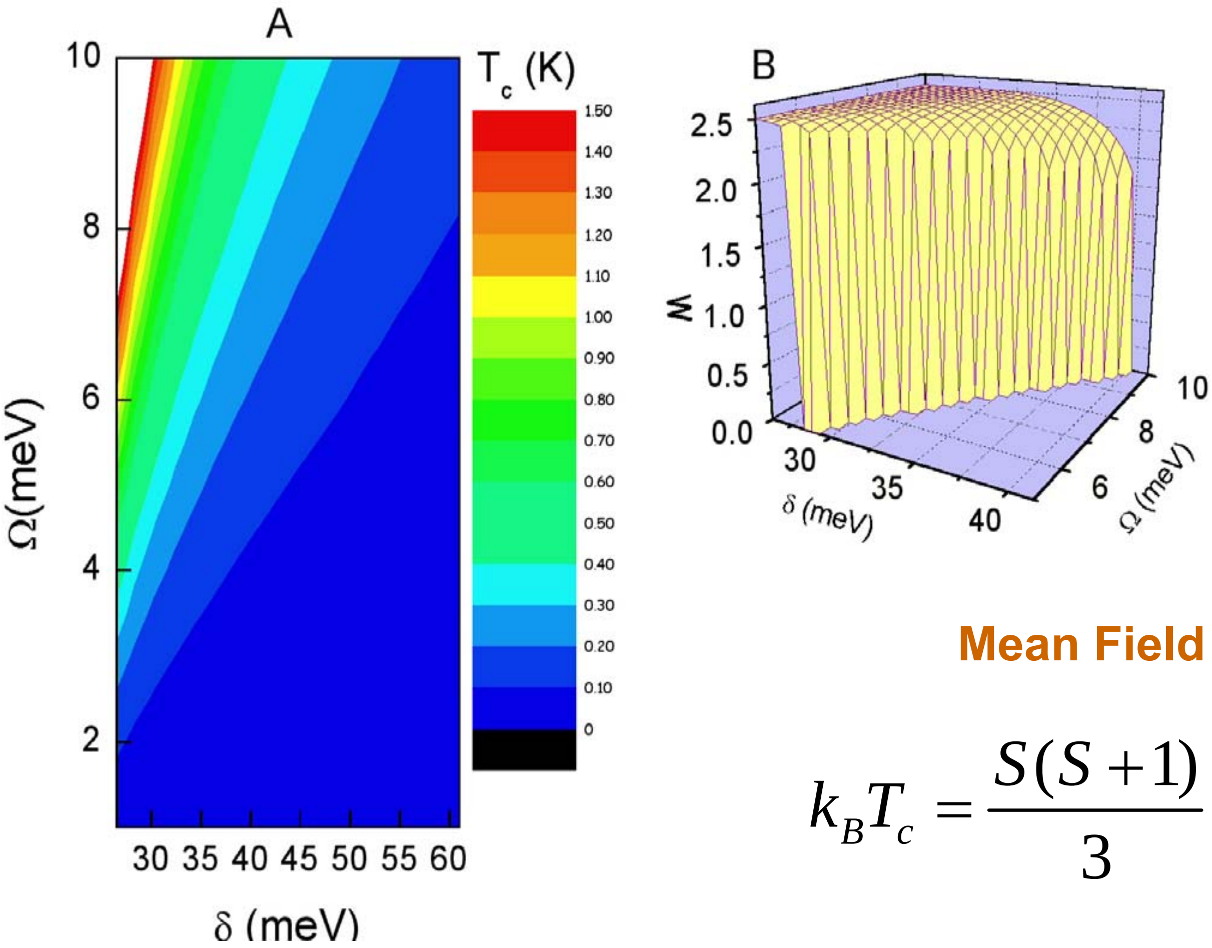


ZnSe:Mn

$$H = -J_{ORKKY}[\Omega]\sum_{ij}\vec{\sigma}_i \cdot \vec{\sigma}_j$$

Can we induce a PM/FM transition using light?

Light induced ferromagnetism



Mean Field approach

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

J. Fernández-Rossier, C. Piermarocchi, Pochung Chen, A. H. MacDonald, and L. J. Sham, *Coherently photo-induced ferromagnetism in diluted magnetic semiconductors*, Phys. Rev. Lett. 93, 127201 (2004)

Conclusions

Single spin controlled using trion resonance

Spin-spin coupling can be induced by Optical RKKY

Impurities are as good as quantum dots

Optically induced ferromagnetism