Optical control of spin-spin interaction in doped semiconductors

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Quantum Control of two spins

Neutral donors

\[|\Psi\rangle = a(t)|↑↑⟩ + b(t)|↑↓⟩ + c(t)|↓↑⟩ + d(t)|↓↓⟩\]

• Control Hamiltonian

\[H = H_0 + H_C(t, \sigma_1, \sigma_2, \ldots)\]
Optical RKKY

Conduction band

Si

Valence band

$\hbar \omega$

$E_{\text{Gap}} (\text{GaAs})$

Itinerant excitons mediate the interaction

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

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

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

- Change from ferro to antiferro
- Bound states.
Dynamics of quantum control

Dynamics of entanglement
Effect of decoherence: radiative recombination

Initial State
\[ |\uparrow\downarrow\rangle = \frac{|S\rangle + |T,0\rangle}{\sqrt{2}} \]

Follow the dynamics by numerical integration of the Liouville Equation
\[ \frac{d\rho}{dt} = -i[H,\rho] + L\{\rho\} \]
Decoherence
Off-resonant excitation

\[ \rho \] after a Gaussian pulse
\[ \Gamma = 0 \text{ meV} \]
\[ \Gamma = 0.3 \text{ meV} \] (Radiative Recombination)

\[ \psi \sim \frac{|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle}{\sqrt{2}} \]

Optical generation of entanglement!

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

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

ZnSe:Mn

Light-induced ferromagnetism

Mean Field approach

\[ k_B T_c = \frac{S(S + 1)}{3} J_{\text{ORKKYY}}[\Omega] \]
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 \quad J \sim \left( \frac{\Omega}{\Lambda} \right)^2 R y^* \frac{e^{-2R/\kappa}}{R/\kappa},

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

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

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

\Omega = \text{Rabi energy}

\Lambda = \text{energy in dot}

\delta = \text{detuning}

R = \text{interdot distance}
Excitonic effects

\[ F_{1s,1s}(q) = \int d\mathbf{r} e^{-i\frac{m_h q \cdot \mathbf{r}}{M}} \left| \Psi_{1s}(\mathbf{r}) \right|^2 \]

\[ J_{1s1s}^d(R) = \frac{\left| \Omega(t) \right|^2}{16} j_1^d j_2^d \frac{1}{\Delta^3} \left| \Psi_{1s}(0) \right|^2 \int \frac{d^d q}{(2\pi)^d} \frac{e^{-i\mathbf{q} \cdot \mathbf{R}}}{1 + (\lambda_M q)^2} \left| F_{1s,1s}(q) \right|^2 \]
The central dot mediates an indirect RKKY-like spin-spin interaction between the lateral dots.
Dynamic Spin-Stark shift

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

SPIN STRUCTURE:

\[ -4J_{12}(S^1 \cdot s)(S^2 \cdot s) - 4J_{12}(S^2 \cdot s)(S^1 \cdot s) = -2J_{12}(S^1 \cdot S^2) \]
Quantum Well

$m^*_{e} = 0.07\, \text{m}, \quad m^*_{h} = 0.5\, \text{m}, \quad \xi = 300\, \text{Å} \quad \text{Ry}^* = 10\, \text{meV} \quad a_B^* = 100\, \text{Å}

Exponential decay of the interaction

$$K = \frac{\hbar}{\sqrt{2M_X\delta}}$$
Assuming $J_{kk'}=J_{v_k v_{k'}}$

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

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

**A**: effective magnetic field. Needs circular polarization

**B**: Heisenberg term

**C**: Dzialoshinski-Moriya. Needs circular polarization + asymmetric coupling
Optical Spin-Stark Shift

\[ \delta + \Omega = J \]

Initial State

\[ |\uparrow\downarrow\rangle = \frac{|S\rangle + |T,0\rangle}{\sqrt{2}} \]
Radiative Recombination
(b) resonance

\[ \Gamma = 0 \text{ meV} \]

\[ \Gamma = 0.3 \text{ meV} \]

\( \delta = 1 \text{ meV} \)

Resonant to the \( J = 3/2 \) states

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