Tunable Spin-Qubit Coupling Mediated by a Multielectron Quantum Dot

V. Srinivasa, H. Xu, and J.M. Taylor;PRL 114, 226803 (2015)

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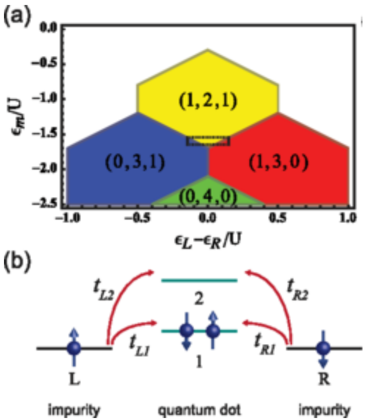
Current context

- Single spins as qubits in impurity atoms, quantum dots
- Scalable long-range coupling scheme is needed
- Mediators: optical cavities, MW resonators, floating metallic and ferromagnetic couplers, spin chains, SC systems
- Triple dot setup. Center dot-mediator of interactions.
- Effective exchange from electron cotunelling between the outer dots[1]
- Drawback-large virtual energy cost

[1] G.Platero et al., Nat. Nanotech. 8, 261 (2013)

Recent proposal

- Mediator: two-level quantum dot with two electrons.
- Spin qubits reside on single-level impurity atoms
- Related to spin qubits in quantum dots
- Multiorbital Hubbard model for the linear three site system.
- Impurities near ionization points (by gate voltages)

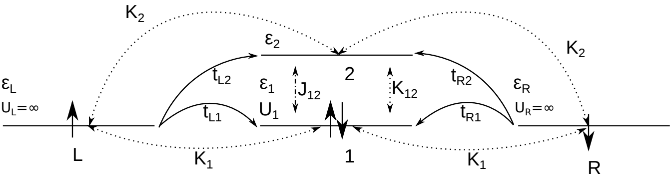


Model I

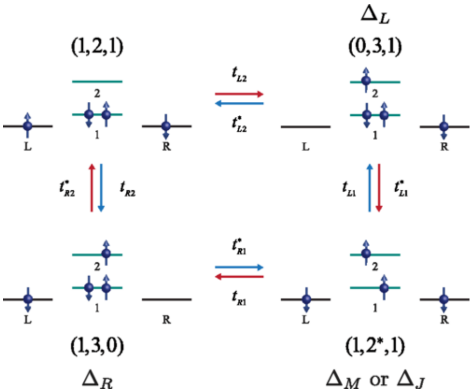
$$H_{\mathrm{hub}} = H_n + H_t$$

$$\begin{aligned} H_n &= \sum_i \epsilon_i n_i + \frac{U_i}{2} n_i(n_i - 1) + \sum_{i \neq j} \frac{K_{ij}}{2} n_i n_j + J_{12} \sum_{\sigma,\sigma'} c^\dagger_{1,\sigma} c^\dagger_{2,\sigma'} c_{1,\sigma'} c_{2,\sigma}, \\ H_t &= -\sum_{i=1,2} \sum_\sigma \left(t_{Li} c^\dagger_{i,\sigma} c_{L,\sigma} + t_{Ri} c^\dagger_{i,\sigma} c_{R,\sigma} + \mathrm{h.c.} \right) \end{aligned}$$

with $i, j = L, R, 1, 2$



Model II



- $E_0 = \epsilon_L + \epsilon_R + 2\epsilon_1 + U_1 + 4K_1$, energy of (1,2,1) states without tunneling set as an energy origin. $\Delta_{L(R)} = \epsilon_2 - \epsilon_{L(R)} + W$; $W = -2K_1 + K_2 + 2K_{12} - J_{12}$
- $\Delta_M = \epsilon_2 - \epsilon_1 + W - U_1 + K_2 - K_{12}$; $\Delta_J = \Delta_M + 2J_{12}$

Perturbative approach

- Typical values: $\Delta_i \sim 20 - 500\mu eV$; $t_{Li,Ri} \sim 1 - 10\mu eV$
- H_t perturbation to H_n
- Effective exchange coupling caused by H_t between states $|(1,2,1), S_{LR}, S_{11}\rangle$, $\left|(1,2,1), T_{LR}^{(0)}, S_{11}\right\rangle$
- $1^{st}, 3^{rd}$ order vanish. 2^{nd} identical for both states
- 4^{th} order shift $J = \delta E_T^{(4)} - \delta E_S^{(4)} = -2\left(\frac{t_{R2}^* t_{R1} t_{L1}^* t_{L2}}{\Delta_R \Delta_M \Delta_L} + c.c.\right)$
- RKKY-like interaction

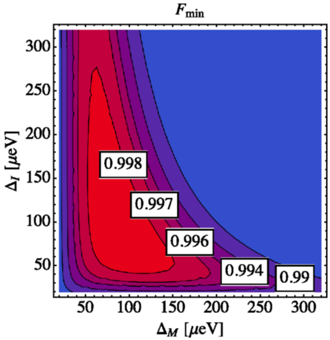
Analysis of the coupling

- $J \sim (\epsilon_2 - \epsilon_L)^{-1}$; $J \sim (\epsilon_2 - \epsilon_R)^{-1}$ those are voltage controlled detunings, highly tunable.
- No extra energy needed for double occupied virtual state as in cotunneling scenario[2]
- Efficient switch off: tuning impurities away from ioniz. point (by gate voltages)
- Nontrivial dependence on tunneling phases, interference possible
- Might result in highly spatial dependent coupling, requiring atomic scale control to implement the coupling.
- Interfacial disorder mixes valley eigenstates-supression of interference.

[2]Vandersypen et al., Nat. Nanotech. 8, 432 (2013)

Charge noise and exchange gate fidelity

- Fluctuating electric field→Fluctuating J
- Effects of classical charge noise on the detuning parameters (white noise model with Gaussian distr.)
- Fidelity-proportional to overlap betw. the states produced by ideal and actual exchange gate.
- Error correcting protocols need fidelities at least 0.98
- Results for P donors in Si



Charge noise and exchange gate fidelity II

- Typical values $J = 0.2neV$ corresp. to gate time $\tau_G \approx 5\mu s$ with fidelity $F = 0.998$
- Smaller J does not fundamentally limit the fidelity!
- Some studies suggest[3] increased robustness of this setup due to the screening of Coulomb interaction by the paired electrons already present in the dot.

[3] C.M.Marcus et al., PRL 112, 026801 (2014)

Effects of inhomogeneous g factors

- Difference in the g factor betw. the dot and and impurities couples subsp. with different total spin
- Add B in the z direction as $H_Z = \frac{\Omega_z}{2} \sum_{i=1,2} (n_{i,\uparrow} - n_{i,\downarrow}); \Omega_z \equiv \Delta g_z \mu_B B$
- Go to basis where $H_n + H_Z$ is diagonal and take H_t as a perturbation
- 1^{st} order in Ω_Z and 2^{nd} in tunneling gives correction to the exchange effective Hamiltonian
- $H_g = f_g \left(\left| T_{LR}^{(0)}, S_{11} \right\rangle \langle S_{LR}, S_{11} | + | S_{LR}, S_{11} \rangle \left\langle T_{LR}^{(0)}, S_{11} \right| \right)$
- $f_g = \frac{\Omega_z}{2} \left(\frac{|t_{L2}|^2}{\Delta_L^2} - \frac{|t_{R2}|^2}{\Delta_R^2} \right)$, possible to tune to zero

Summary

- QD with two electrons tuned to the two level regime can be used to mediate a coupling between the spin qubits, yelding and RRKY like exchange interaction with good tunability.
- Charge noise does not substantially lower the fidelity of two qubit gates. Error corrections is still possible.
- Inhomogenious g factors give zero-tunable contribution.