Singlet-triplet spin qubit in a magnetic QD

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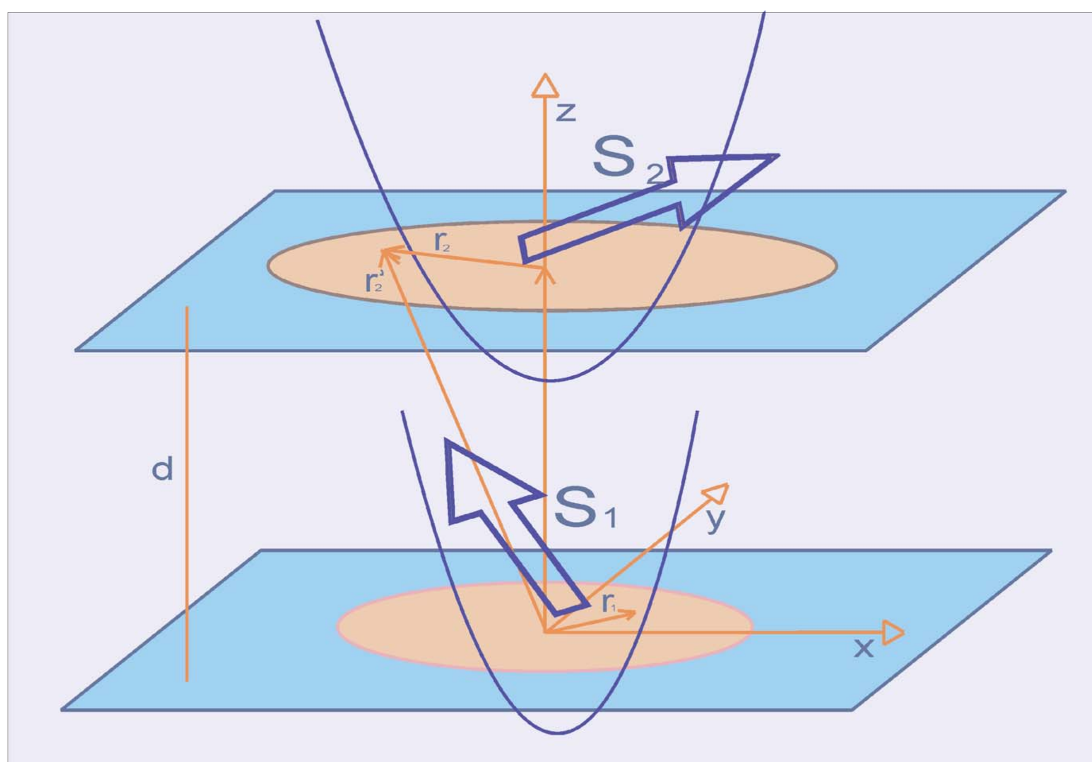
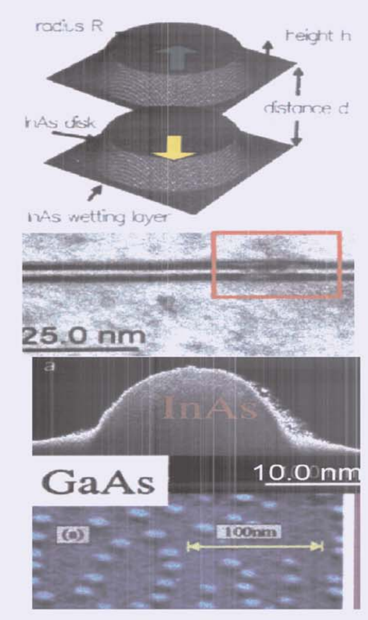
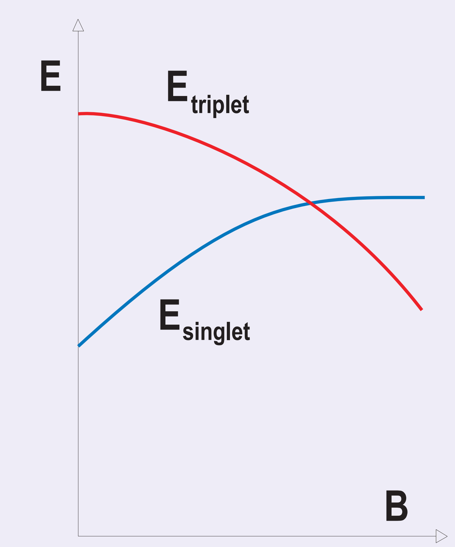
Spin-qubits and gates in QDs

- advantage: long decoherence time is expected
- disadvantage: slow single-qubit operations
- realization: single spin – H QD (DiVincenzo et al.)
- singlet-triplet transition in He QD (Jacak et al.)
- in MQDs (QD in a diluted magnetic medium) a strong Weiss field enhances Pauli term: large giromagnetic factor and removed degeneracy of the triplet state

SINGLET-TRIPLET qubit in He MQD







$$H = (\mathbf{p}_1+e/c\mathbf{A})^2/2m_1^* + (\mathbf{p}_2+e/c\mathbf{A})^2/2m_2^* + \omega_1 \mathbf{r}_1^2 + \omega_2 \mathbf{r}_2^2 + e^2/\varepsilon|\mathbf{r}_2-\mathbf{r}_1| + g_1\mu_B \mathbf{S}_1\bullet\mathbf{B} + g_2\mu_B \mathbf{S}_2\bullet\mathbf{B}$$

$$\Downarrow$$

$$H = g_1\mu_B \mathbf{S}_1\bullet\mathbf{B} + g_2\mu_B \mathbf{S}_2\bullet\mathbf{B} + J\,\mathbf{S}_1\bullet\mathbf{S}_2$$

$$J = E_{triplet} - E_{singlet}$$

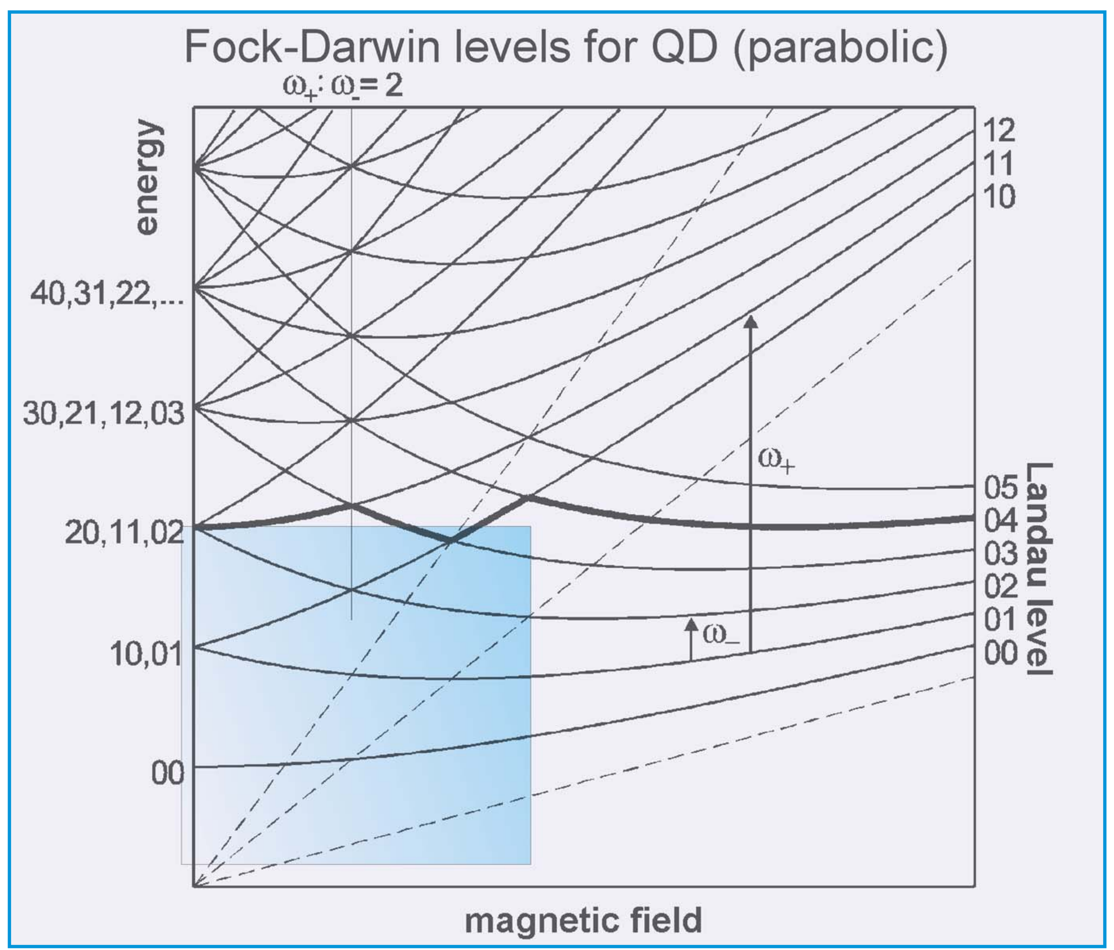
CNOT= $e^{i\pi S^z_1} e^{-i\pi S^z_2} U^{1/2} e^{i\pi S^z_1} U^{1/2}$

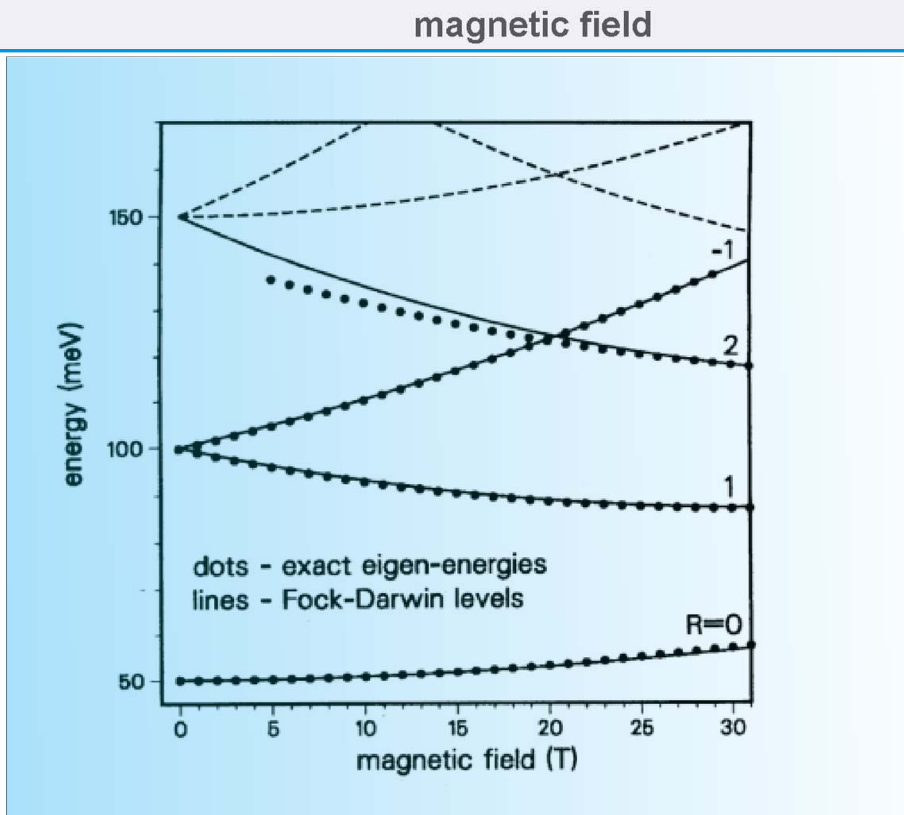
$U = Te^{i\int H dt}$

$\int J dt = \pi$

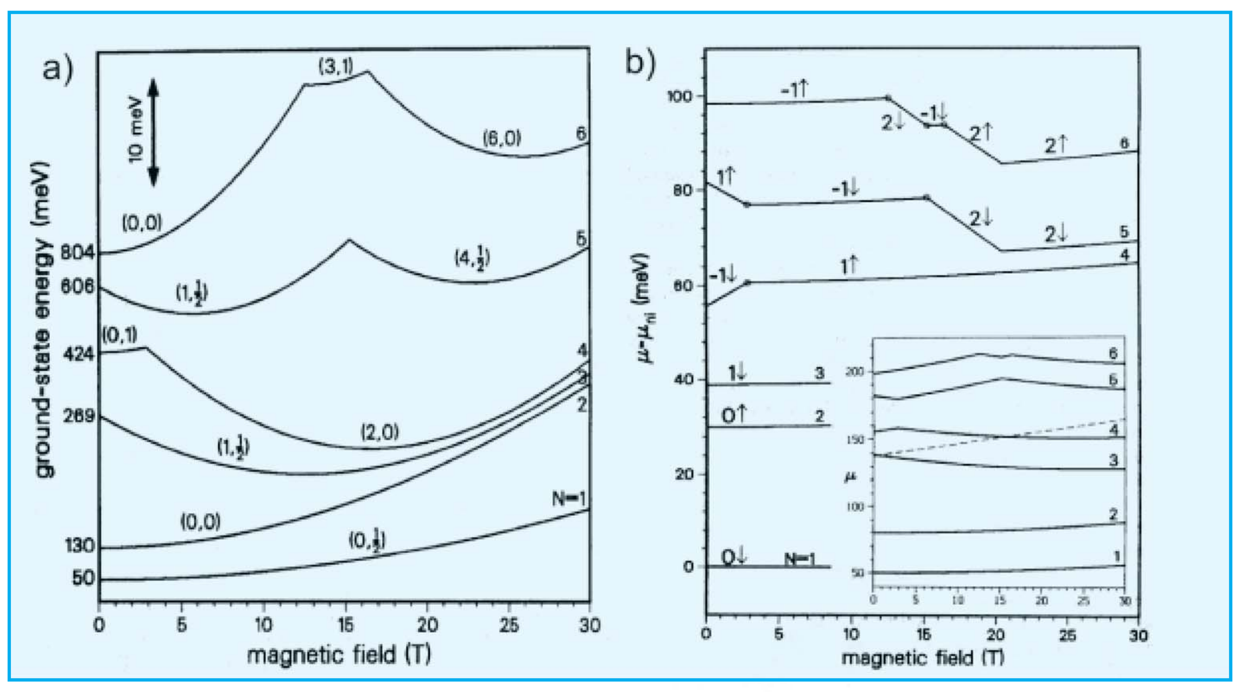
(DiVincenzo et al. 1998)

Single-electron picture



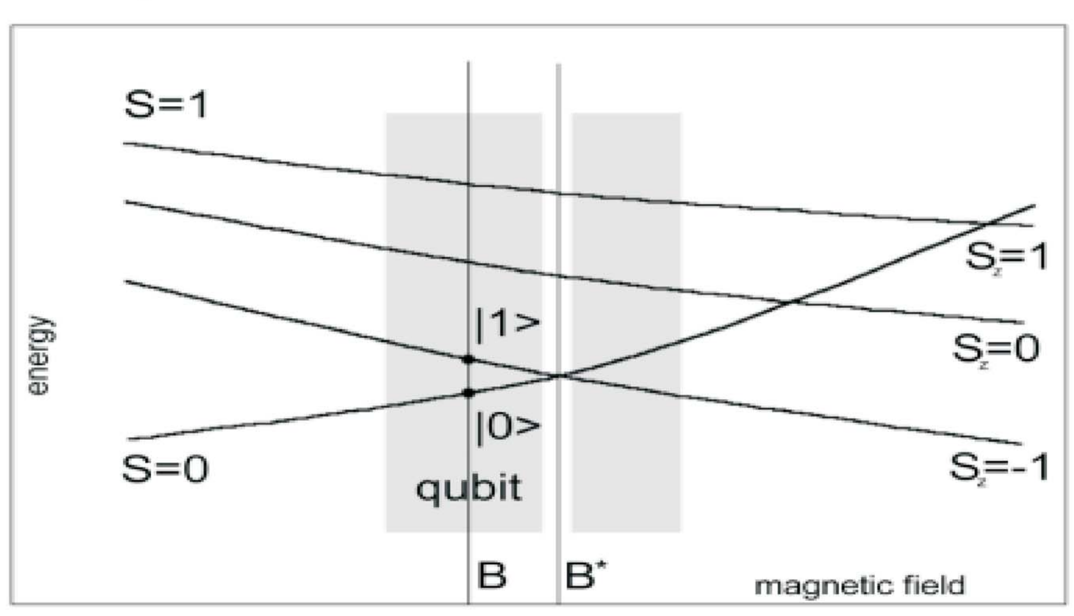


Comparison of single-electron levels of lens-shaped QD (d=18nm, h=4.4nm) with Fock-Darwin levels (parabolic)



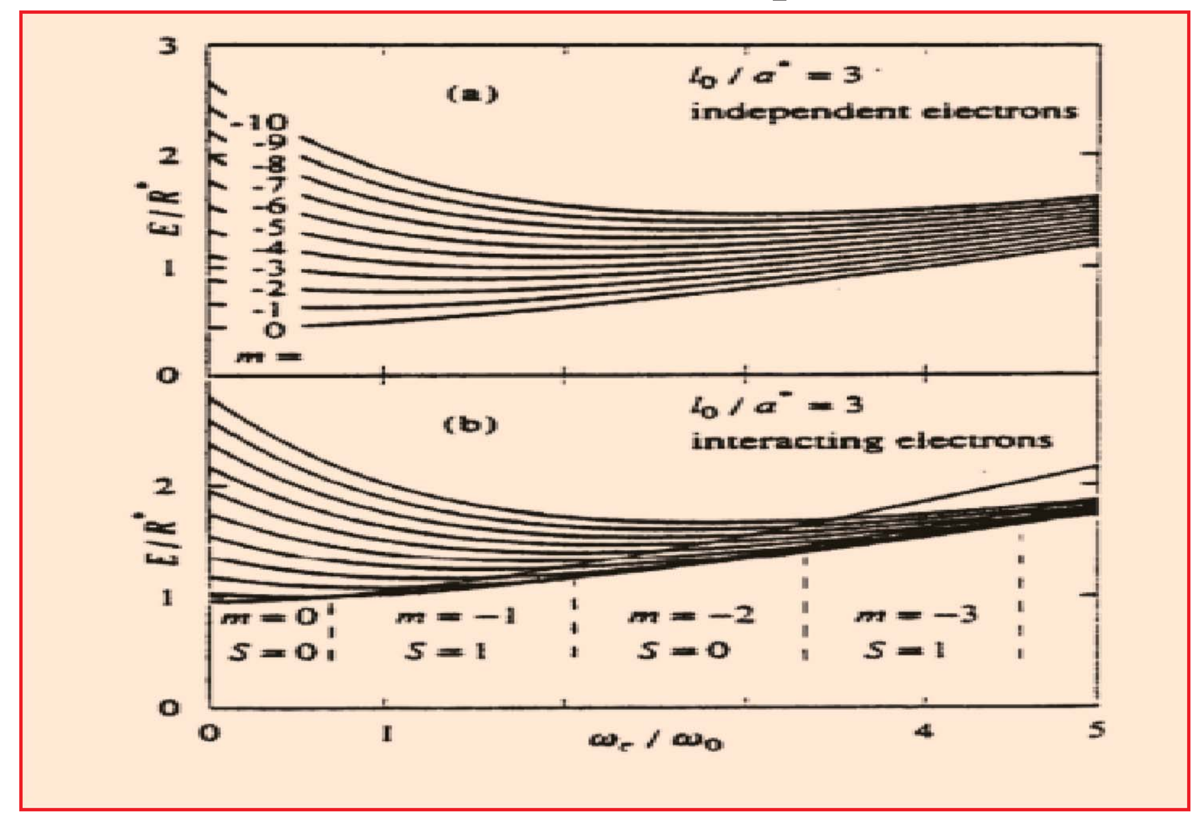
Ground state energy for N=1-6 electrons in QD, numbers (L, S) - left; L and S of single particle states - right; difference of chem. potential for interacting and noninteracting electrons - inset; (exact diag. Wojs PRB, 96)

Singlet-triplet qubit in He MQD

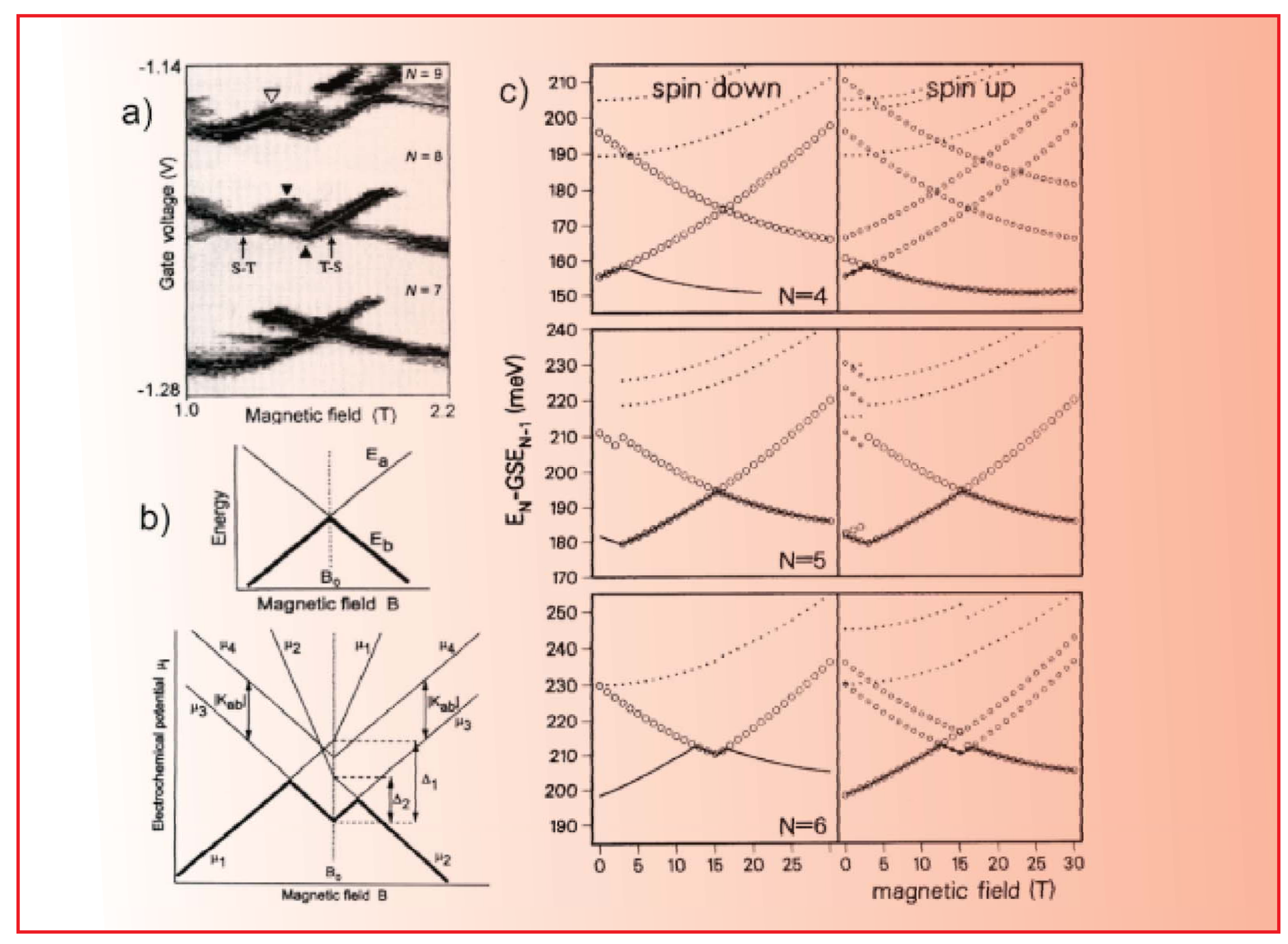


Rabi oscillations can be achieved even in the intersection point in a static inhomogeneous magnetic field (steering by magnetic field shift)

Multi-electron picture



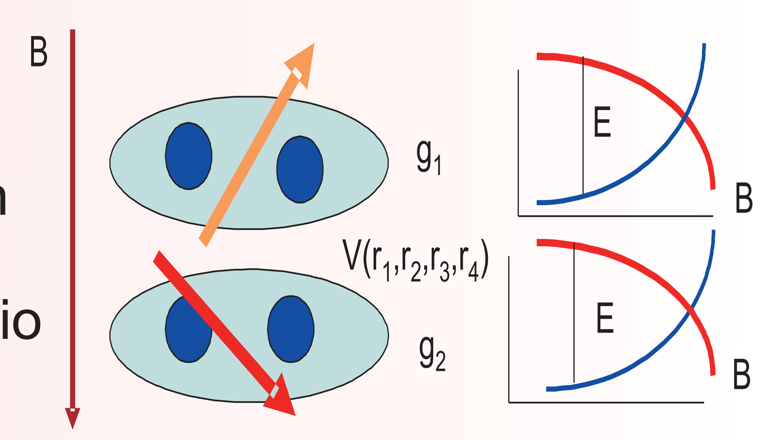
Intersection of singlet and triplet states in He QD (Wagner et al. PRB, 92)



Singlet-triplet transition (N>4) observed experimentally by Tarucha et al (PRL, 2000) and its simplified model for the last shell - left; similar transition theoretically via exact diagonalization (Wojs PRB, 96; Jacak et al. Springer, 98)

Arrangement of gate on 2 He MQDs

One can consider e.g. a vertical pair of He QDs – the Coulomb interaction *V* can be treated as small or large only by comparison with the singlet-triplet qubit energy separation*E*, which can be changed in a wide region by the magnetic field shift. Thus the ratio *V/E* can 'switch' on and off qubits interaction on demand.



Rabi oscillations

Out of the singlet-triplet intersection point

$\vec{B}(\vec{r},t)\quad \vec{B}(\vec{r})e^{i\quad t}\quad hc;\quad \vec{B}(\vec{r})\quad (\vec{B}e^{i\vec{k}\vec{r}},0,0);$

$|0\rangle\quad s;\quad |1\rangle\quad t;\quad \langle 1|w|0\rangle\quad 0;$

$w\quad (B\quad \vec{k}\quad \vec{R})(\hat{s}_{1x}\quad \hat{s}_{2x})\quad \vec{k}\quad (\hat{s}_{1x}\quad \hat{s}_{2x});$

$\sqrt{\ ^2/4\quad |w_{10}|^2/\hbar^2};\qquad \frac{E_t\quad E_s}{\hbar}$

At the intersection point – 2-dim degenerated space

$\vec{B}(\vec{r})\quad V;\quad \langle 1|V|0\rangle\quad 0;$

$E\quad (V_{00}\quad V_{11}\quad \hbar\quad);\quad \hbar\quad \sqrt{(V_{00}\quad V_{11})^2\quad 4|V_{10}|^2};$

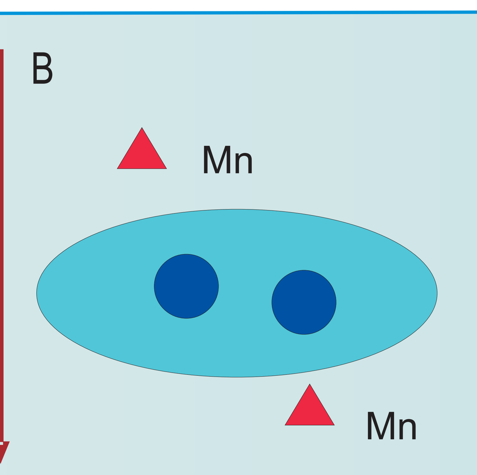
transition probability:

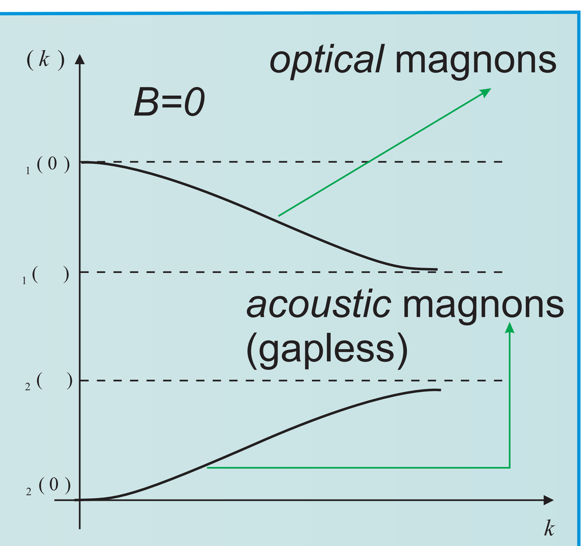
$w_{10}\quad 2\frac{|V_{10}|^2}{\hbar\quad ^2}\ 1\quad \cos(\quad t)$

Static field gives Rabi osc. only at intersection point; addressing each qubit via distinct *g*-factors in layers

Magnetic QD - towards estimation of spin decoherence due to spin waves

QD placed in a diluted magnetic semiconductor medium (e.g. $Ga_{1-x}Mn_xAs$ or $Zn_{1-x}Mn_xAs$) - large *g* factor and strong Weiss field remove the degeneracy of the triplet state





Two spin subsystems (magnetic admixtures and holes)

elementary excitations in two spin subsystems of admixtures and carriers - spin waves

Randomization of Mn admixtures

intrinsic inhomogeneity of the magnetic field

averaging over all possible distributions of admixtures in the description of the interaction of spin waves with structural fluctuations of the admixtures concentration

$$F_s(\vec{R}_1,\ldots,\vec{R}_s)\quad \frac{V}{N}^s\ \frac{N}{N_i}^s \quad \ldots \quad \vec{R}_1\quad \vec{R}_{l_1}\ \ldots\ \vec{R}_s\quad \vec{R}_{l_s}$$

probability that admixtures are placed in given points of the space (transition to a continual model)

Modeling of randomization - binary distribution function and structural factor

$$g(\vec{r})\quad 1\quad \frac{V_0}{(2\quad)^3}\quad d^3k[a(\vec{k})\quad 1]e^{i\vec{k}\vec{r}}$$

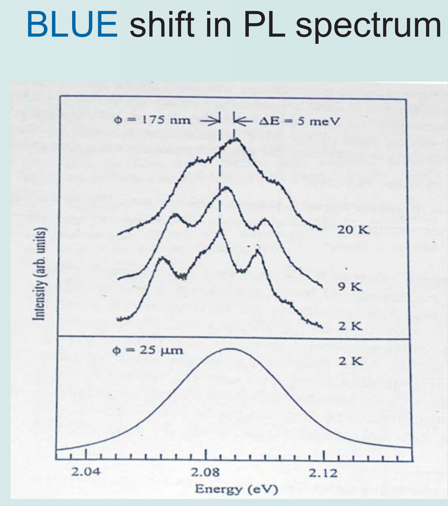
One can consider X exciton in a MQD

$$\hat{H}\quad \hat{H}_{ex}\quad \hat{H}^{ex\ Mn}_{(s)\mathrm{int}}\quad \hat{H}^{ex\ h}_{(s)\mathrm{int}}\quad \hat{H}_{(s)Mn}\quad \hat{H}_h\quad \hat{H}^{h\ Mn}_{(s)\mathrm{int}}$$

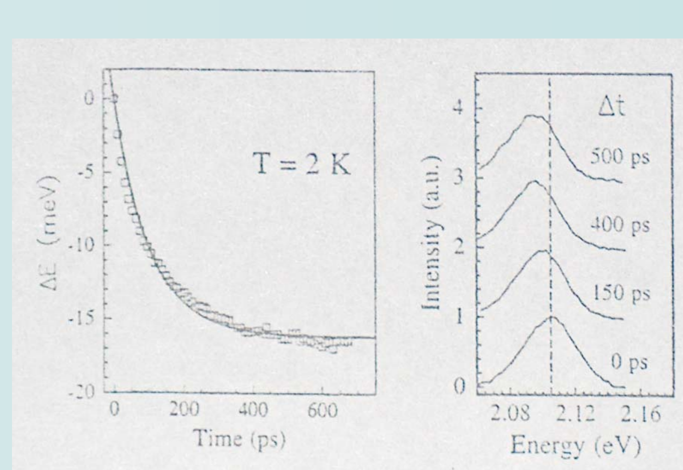
Diagonalization of last three terms provides a description of the magnetic medium (ferromagnetic diluted semiconductor) with two types of spin waves (Holstein-Primakov method)

Further diagonalization of the full Hamiltonian provides the information on formation magneto-polaron i.e. dressing of spin degrees of freedom of e-h pair with magnons - methods of causal Green function for estimation of fidelity

BLUE shift in PL spectrum



PL spectra for CdSe/Zn(Mn)S



Formation of magneto-polaron in MQD

Bacher, Forchel et al 2002

Similarly, as dressing of orbital degrees of freedom with phonons results in the decoherence (polaron dephasing mostly due to LA phonos), one can expect the decoherence of spin degrees of freedom (spin of e and of h in a MQD) due to dressing with magnons; the most important property for dephasing is the dispersion - a squared one for magnons it is not as convenient as that of LA phonons and will give a similar time scale of dephasing as LO for orbital degrees of freedom - i.e. several hundreds of ps - well confirmed by experiments