From Discovery to Innovation...

NANOSPINTRONICS WITH QUANTUM DOTS

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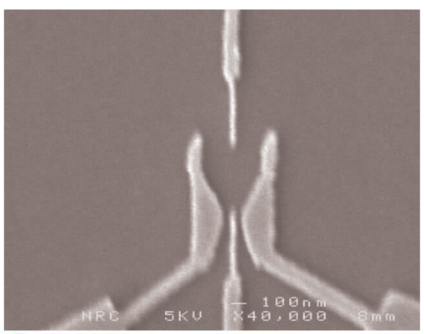
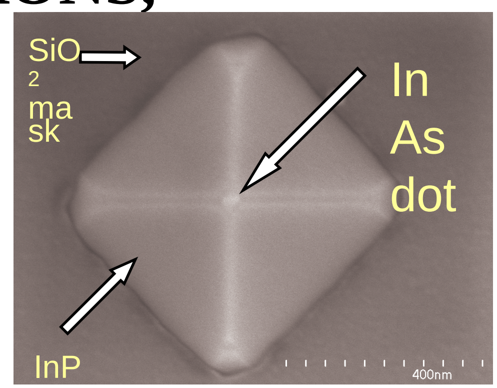
OTTAWA, K1AOR6,CANADA

CONTROLLING SPINS, ELECTRONS, AND PHOTONS AT THE NANOSCALE





NANOSPINTRONICS

OUTLINE

SPIN IN LATERAL GATED DOTS

SPIN BLOCKADE SPECTROSCOPY
SINGLE SPIN TRANSISTOR
SPIN-ORBIT INTERACTION

SELF-ASSEMBLED DOTS

THEORETICAL CHALLENGES
SPIN-ORBIT INTERACTION

QUANTUM DOTS WITH MAGNETIC IONS

CARRIER MEDIATED Mn-Mn INTERACTION

NRC · CNRC

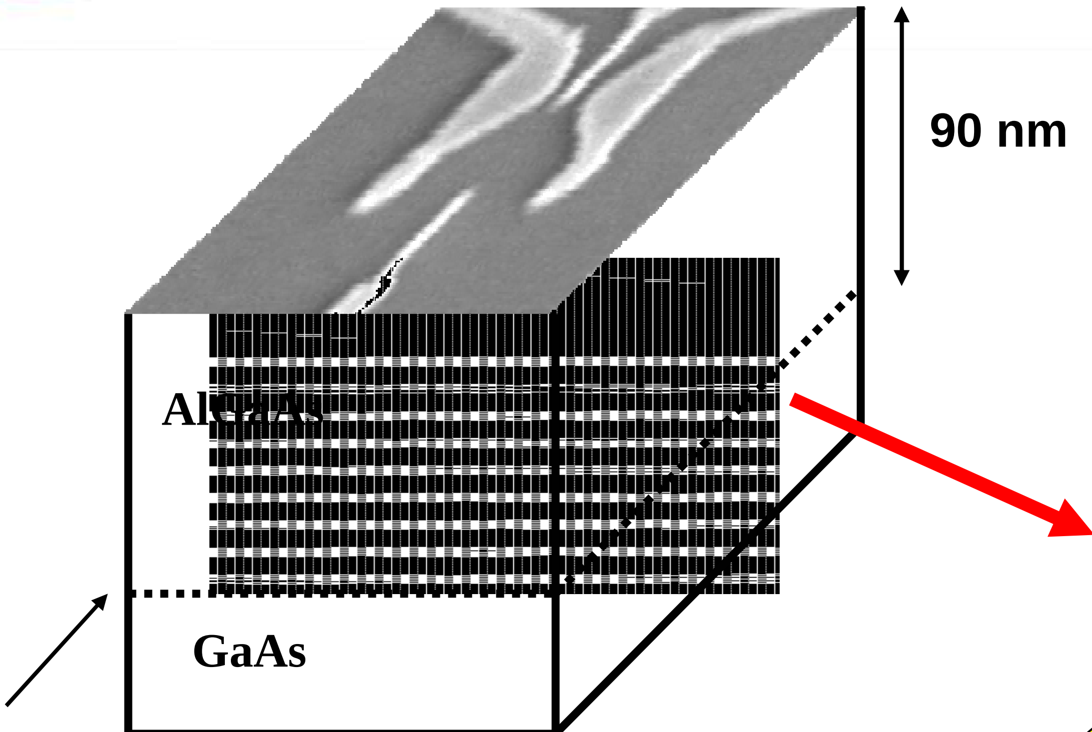
NANOSPINTRONICS

TOWARD SINGLE SPIN ELECTRONICS

SINGLE SPIN TRANSISTOR

NRC · CNRC

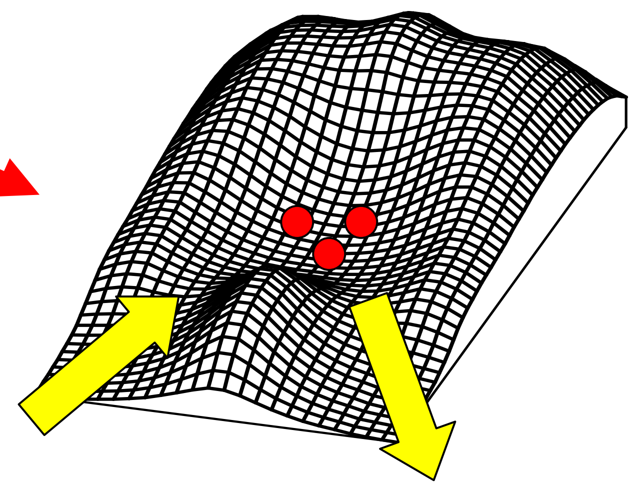
CONTROL OF ELECTRONS ON NANOSCALE



LOCALIZING CONTROLLED NUMBER OF ELECTRONS 1-100

2D electron gas at GaAs/AlGaAs

SOURCE



DRAIN

A.Sachrajda,M.Ciorga,PH
Phys.Rev.B 2000

POTENTIAL ENERGY LANDSCAPE

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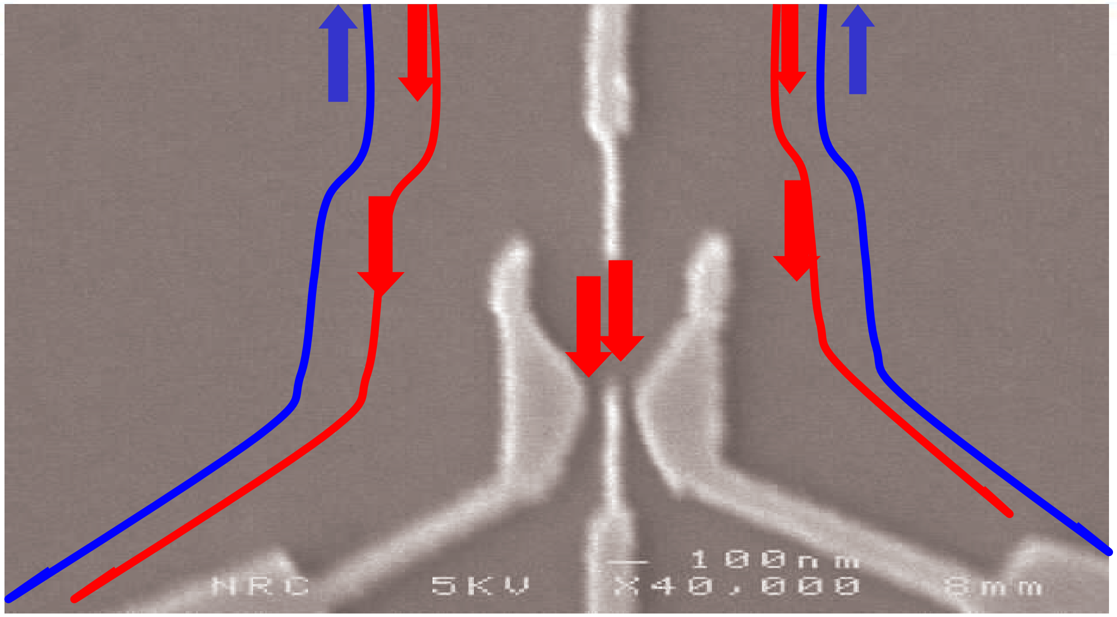
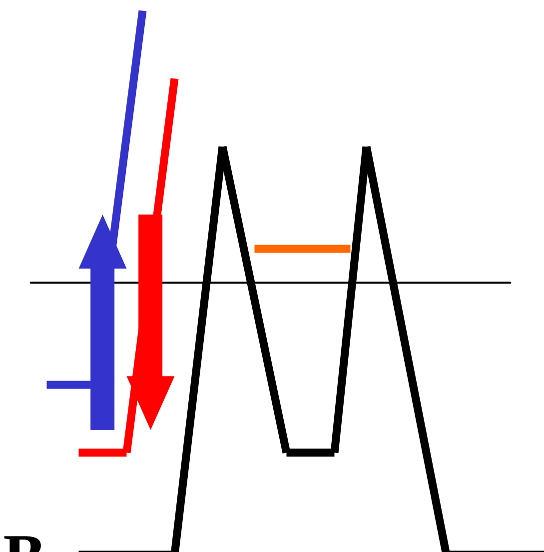
NANO SPINTRONICS
CONTROL AT SINGLE SPIN LEVEL



Sachrajda,Ciorga,PH
IMS NRC



Electron droplet:

control over electron numbers Ne

spin polarized injection/detection in small B

spin blockade spectroscopy

Nano-spintronics or single-spin-tronics

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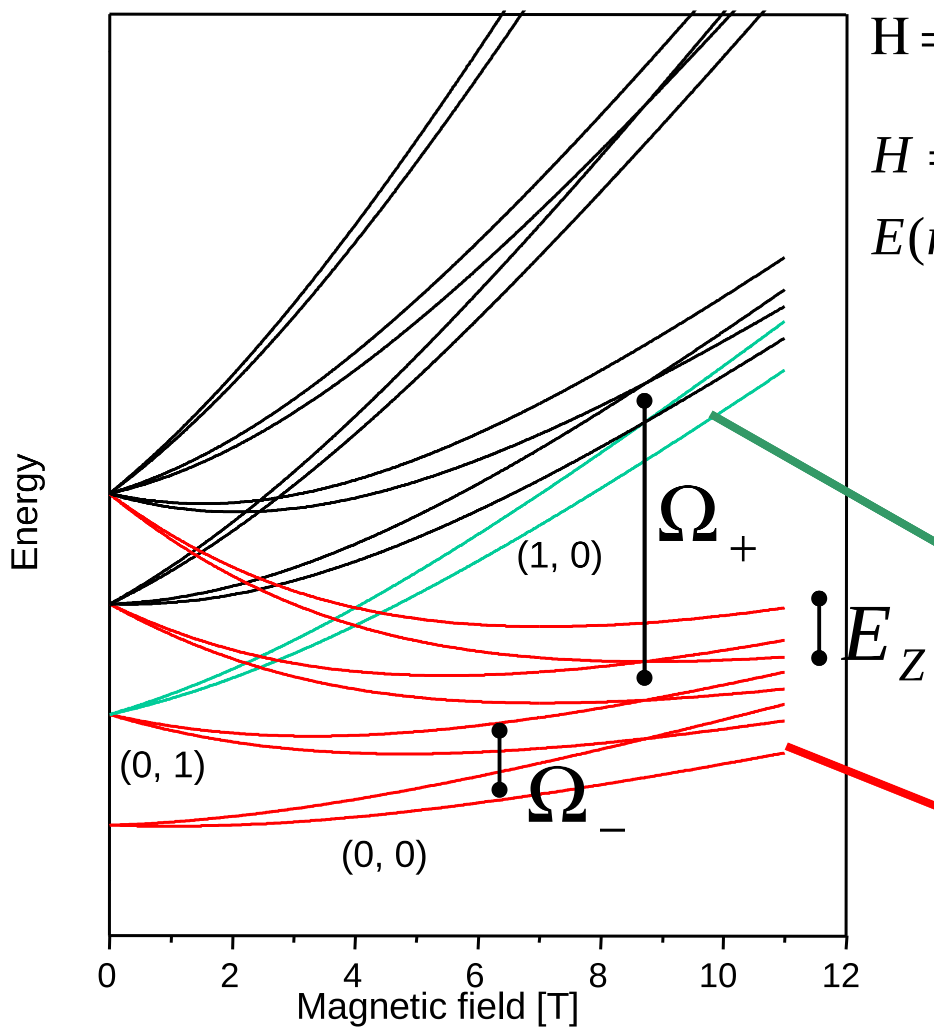
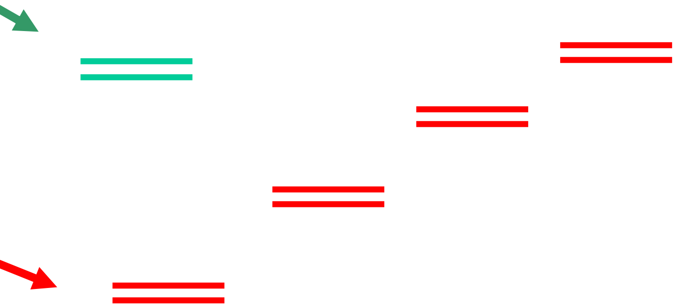
NANO SPINTRONICS
QDOT SINGLE PARTICLE SPECTRUM

$$H = \frac{(p - eA/c)^2}{2m} + \tfrac{1}{2} m\omega^2 r^2 + g\mu B\sigma$$

$$H = \Omega_-(b^+b + 1/2) + \Omega_+(a^+a + 1/2) + g\mu B\sigma$$

$$E(m,n) = \Omega_-(m + 1/2) + \Omega_+(n + 1/2) + g\mu B\sigma$$





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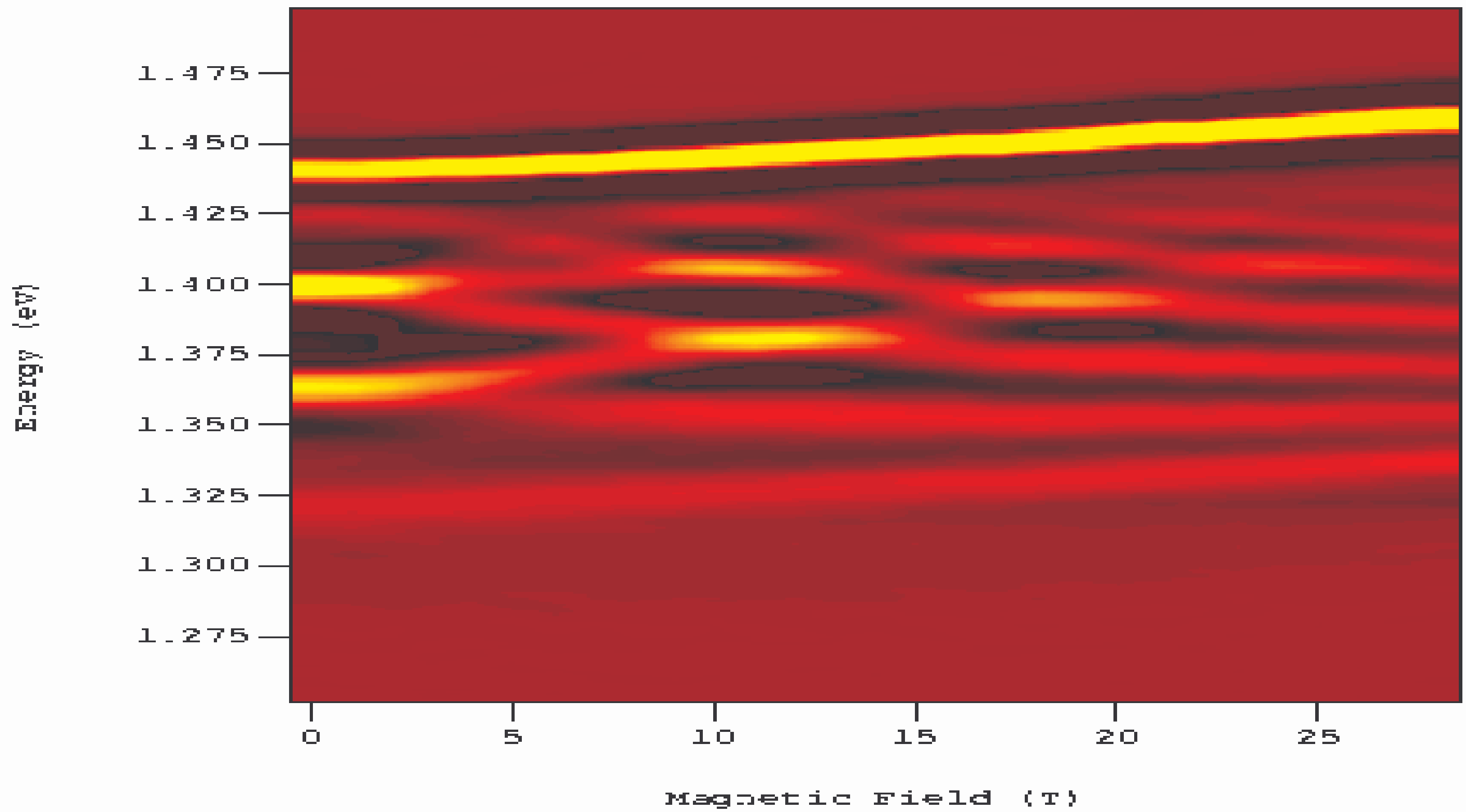
NANO SPINTRONICS
DETECTING QDOT SINGLE PARTICLE SPECTRUM



Raymond et al, PRL 2004, IMS/Grenoble/Dortmund
S.J.Cheng et al theory PRB 2004

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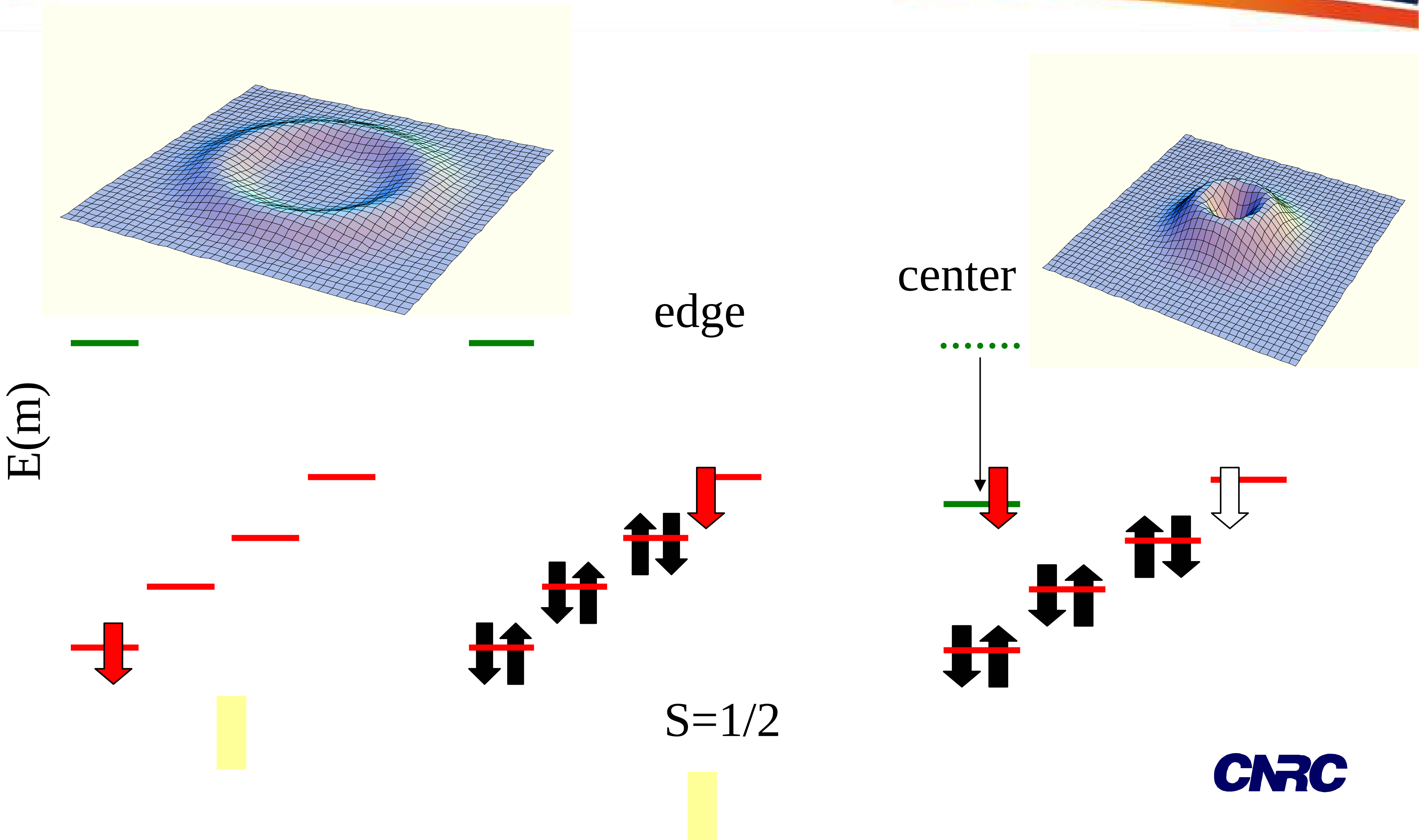
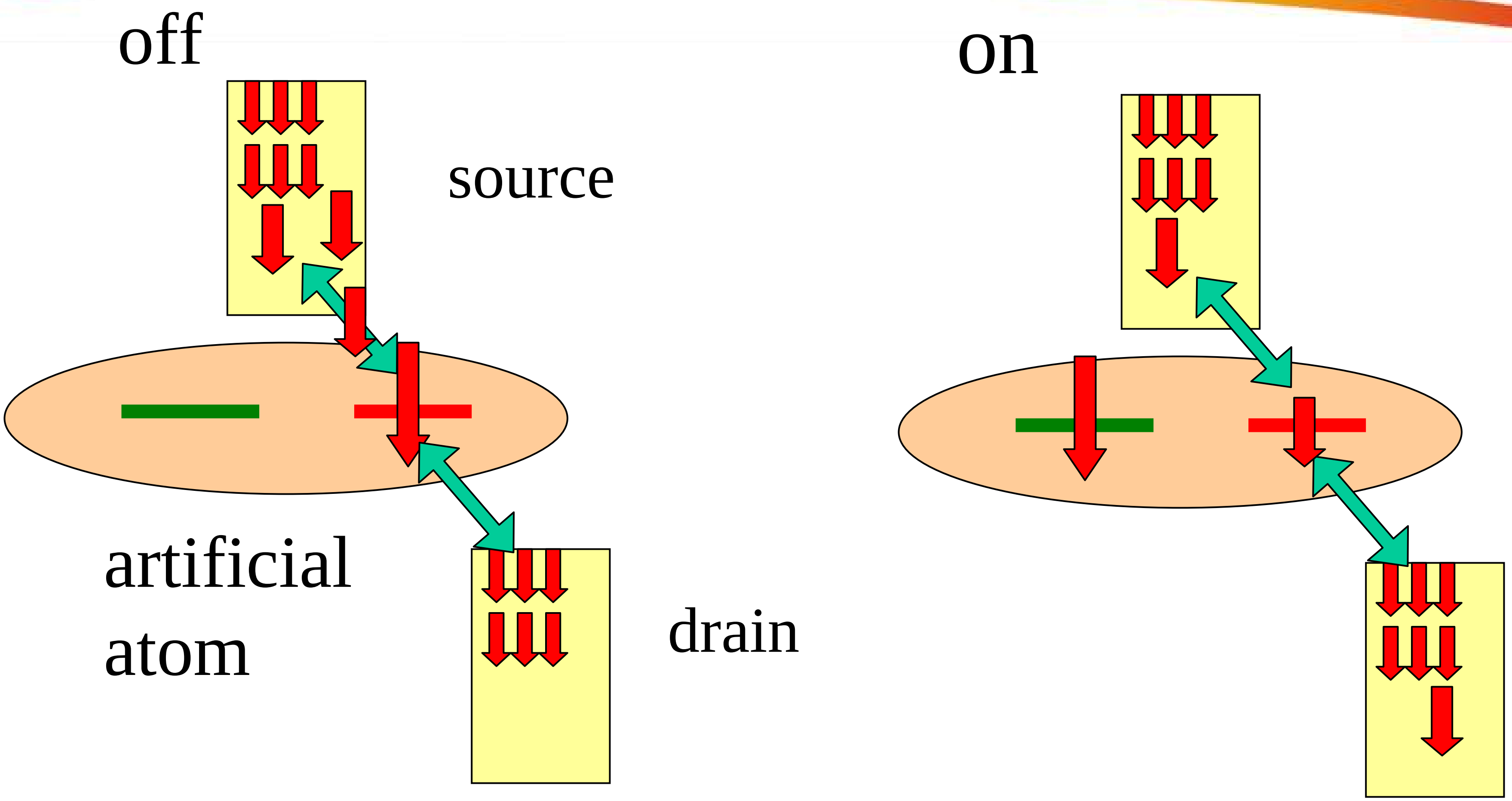
NANO SPINTRONICS
ISOLATING CONTROLLING READING SINGLE SPIN



CNRC

NANO SPINTRONICS
SINGLE SPIN TRANSISTOR



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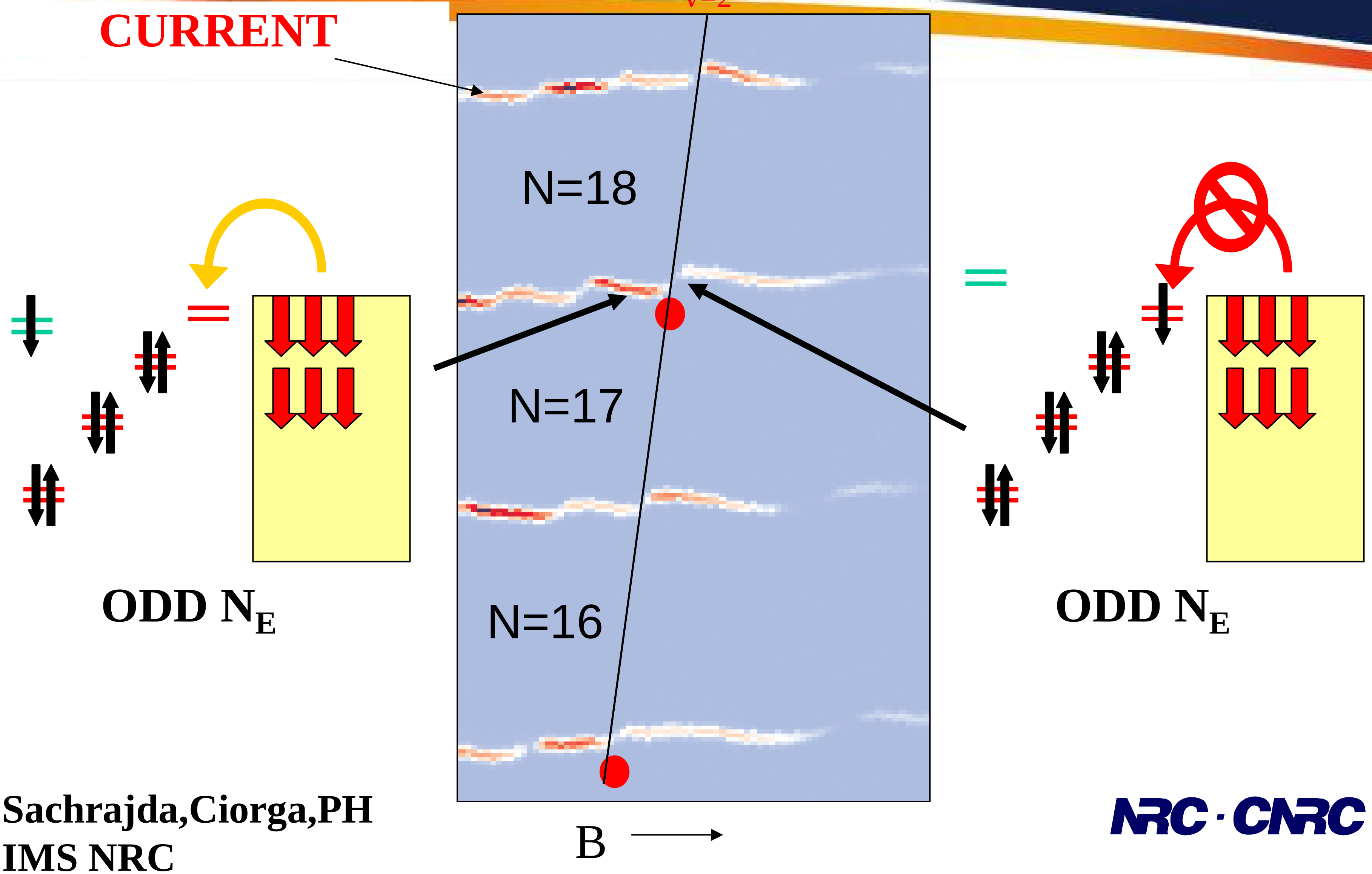
NANO SPINTRONICS
SINGLE SPIN TRANSISTOR



Sachrajda,Ciorga,PH
IMS NRC

NRC · CNRC

NANOSPINTRONICS

CONTROLLING SPIN

SPIN TEXTURES

2 ELECTRON COMPLEX:
MAGNETIC FIELD
GATE VOLTAGE
SPIN-ORBIT INTERACTION

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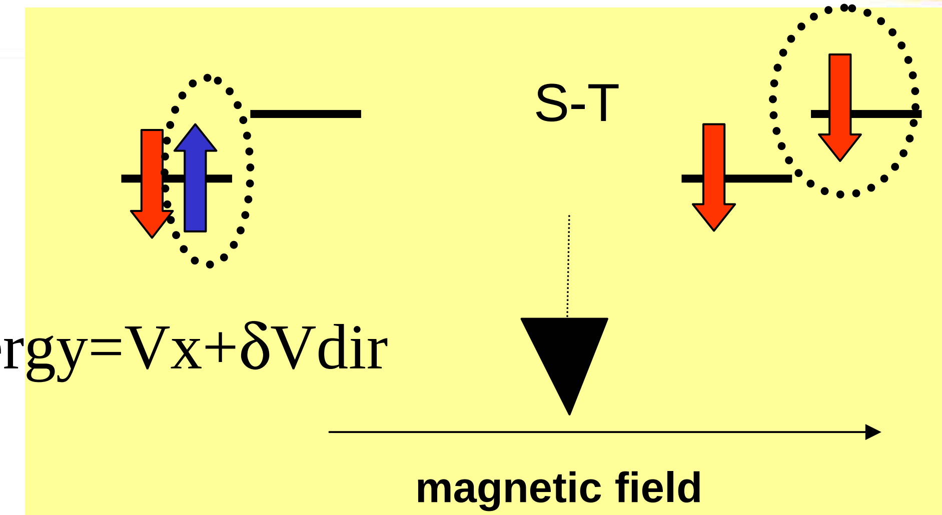
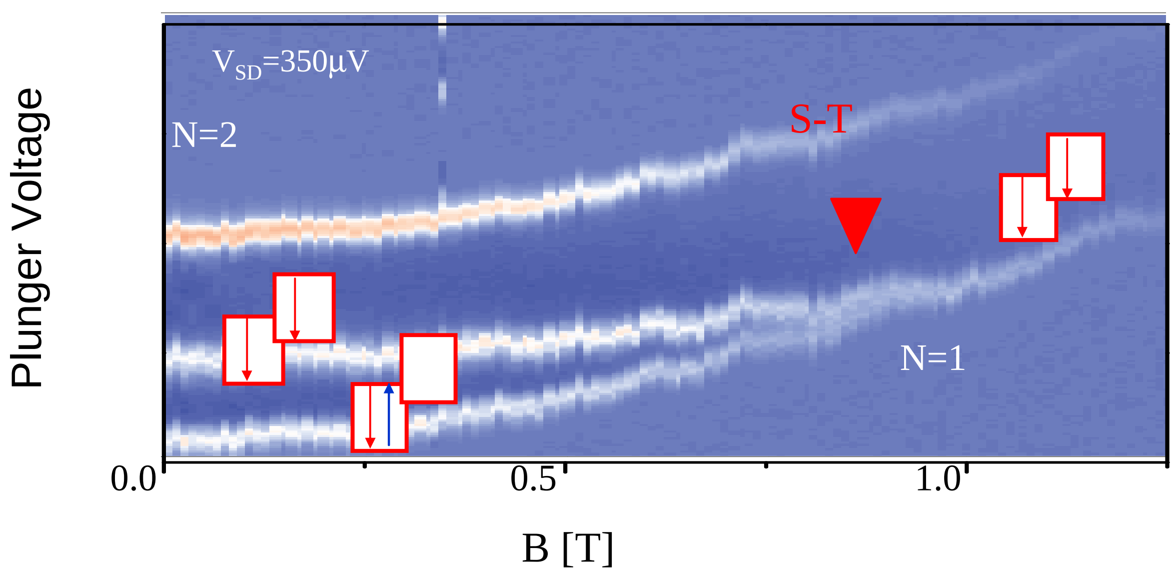
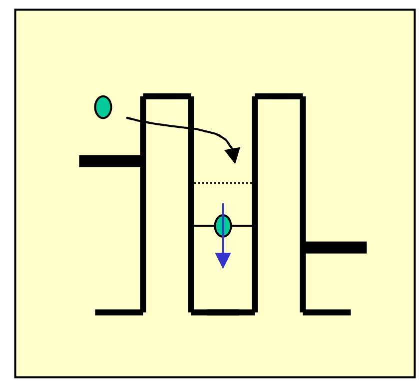
SPIN TRANSITIONS TUNED BY MAGNETIC FIELD



kinetic energy=Vx+δVdir





M.Ciorga et al. Physica E11 (2001)35

SPIN TRANSITIONS TUNED BY MAGNETIC FIELD
SPIN ORBIT INTERACTION

Dresselhaus term – lack of crystal inversion symmetry

Rashba term – lack of nanostructure inversion symmetry
(interface, electric field)

$$H_{so}^{(R)} = \alpha\left(\pi_x \sigma_y - \pi_y \sigma_x\right)$$

momentum   spin

$$\sigma_x \,|\uparrow> \,=|\downarrow>$$

$$\sigma_x \,|\downarrow\uparrow>= \quad \sigma_x \,|\uparrow\uparrow>$$

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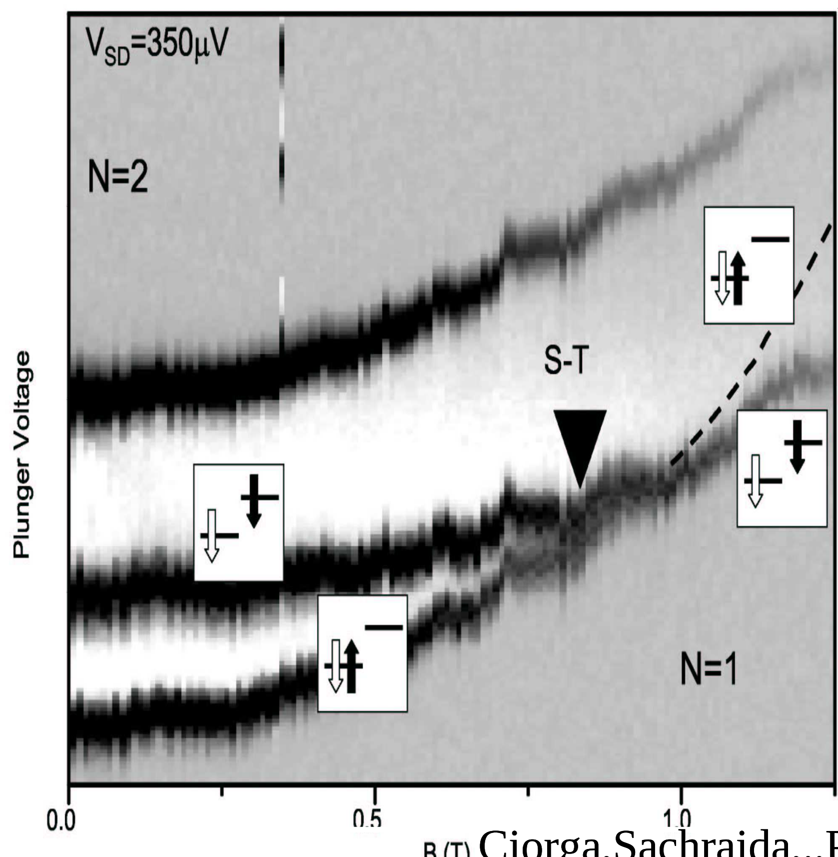
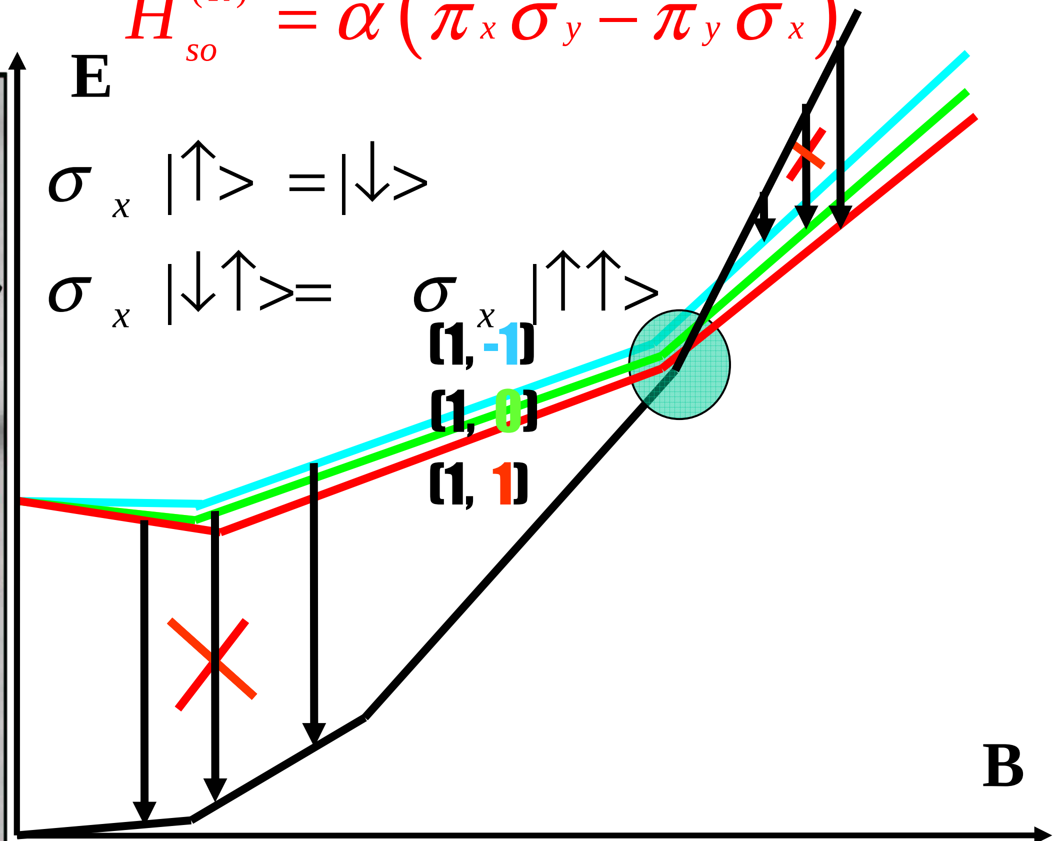
SPIN TRANSITIONS TUNED BY MAGNETIC FIELD
SPIN ORBIT INTERACTION

$$H_{so}^{(R)} = \alpha\left(\pi_x \sigma_y - \pi_y \sigma_x\right)$$



$$\sigma_x \,|\uparrow> \;= |\downarrow>$$

$$\sigma_x \,|\downarrow\uparrow> = \quad \sigma_x \,|\uparrow\uparrow>$$



Ciorga,Sachrajda,..PH, Physica E 11, 35 (2001)
Dickmann, PH, JETP (2002).
Florescu,Ciorga,Sachrajda,PH.. PHYS.E (2004), Florescu,PH,PRB2005

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NANOSPINTRONICS

TOWARD SINGLE SPIN ELECTRONICS

BUILDING
SINGLE ELECTRON SPIN DEVICES

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BUILDING
ELECTRON SPIN BASED QUANTUM COMPUTER

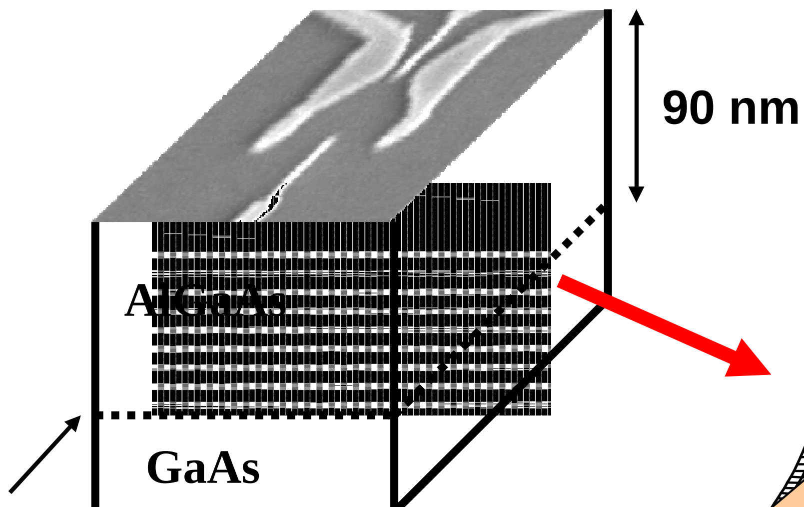
Model of QComputer : interacting qubits S

$$H = \sum \vec{S}_i \vec{B}_i + \sum \vec{S}_i J_{ij} \vec{S}_j$$

Effective qubit

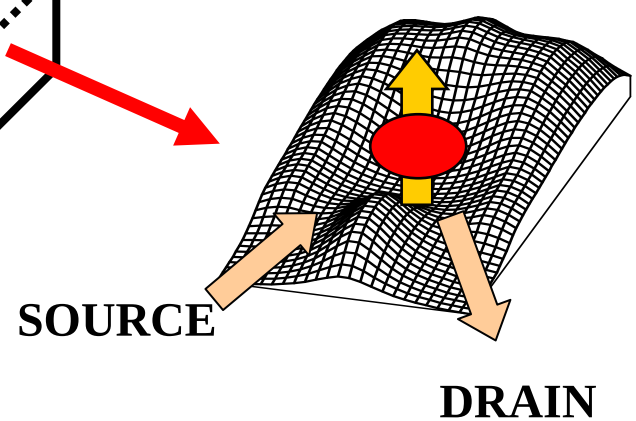
local field

tunable entanglement J



2D electron gas at GaAs/AlGaAs

LOCALISING CONTROLLED NUMBER OF ELECTRONS 1-100



A.Sachrajda

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ELECTRON SPIN BASED QUANTUM COMPUTER

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$$H = \sum \vec{S}_i \vec{B}_i + \sum \vec{S}_i J_{ij} \vec{S}_j$$

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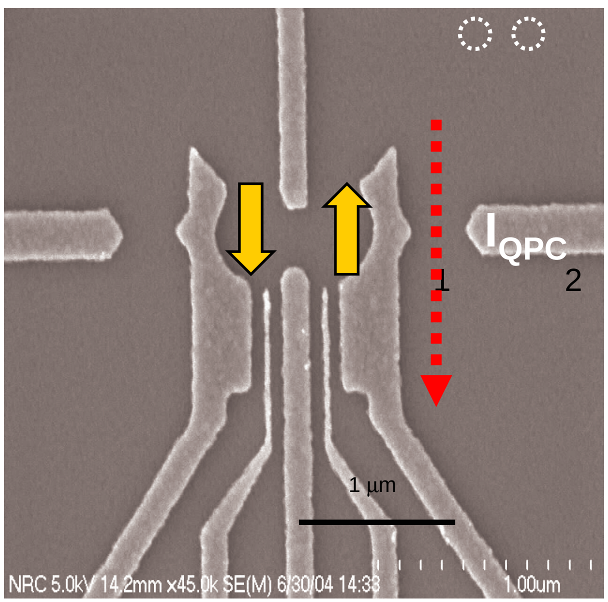

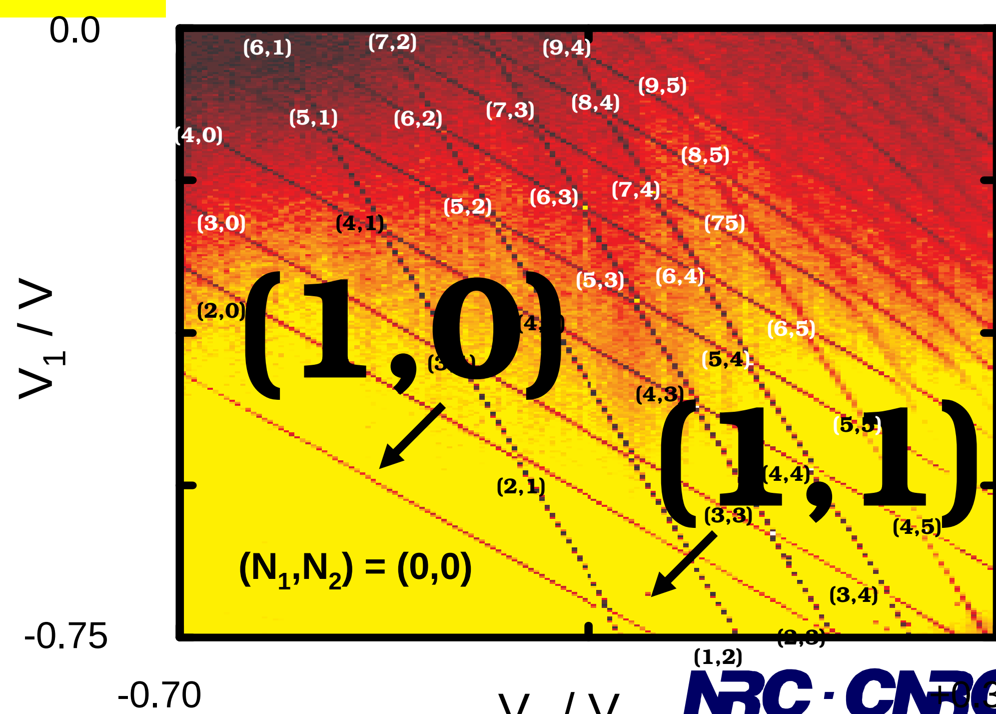

A.Sachrajda,M.Pioro-Ladriere,R.Abolfath,PH, … PRL2003,PRB2004

ELECTRON SPIN BASED QUANTUM COMPUTER

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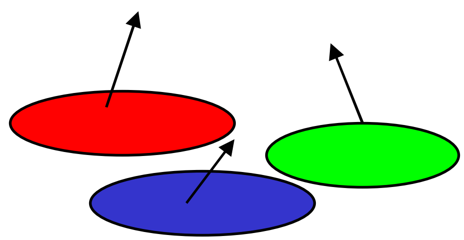
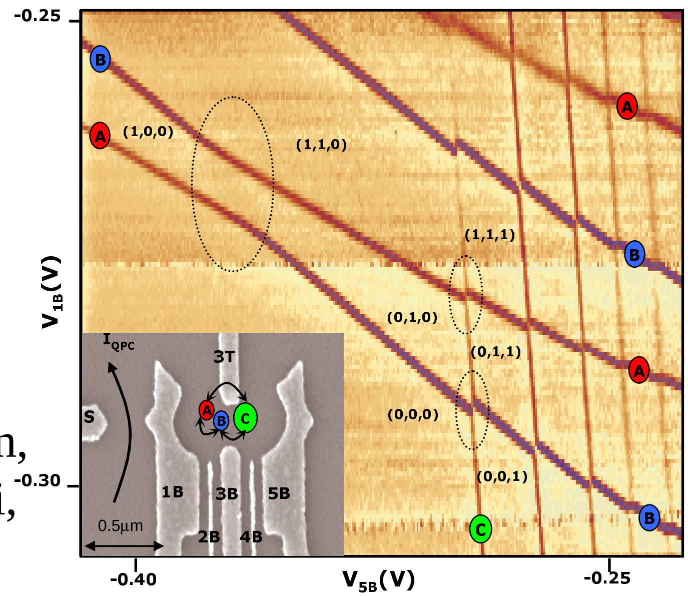
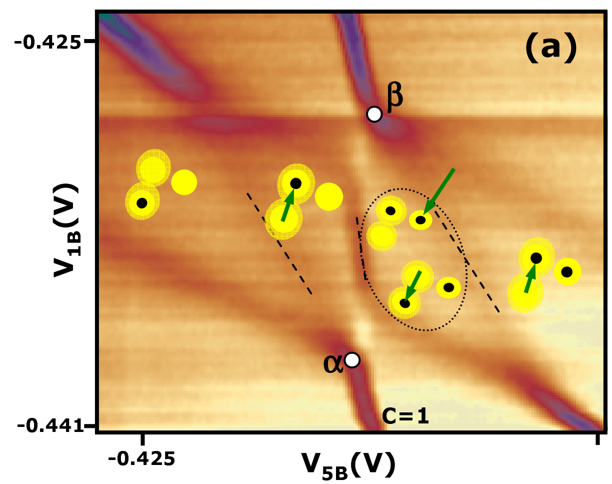




Conditional dynamics



L.Gaudreau, S.Studenikin, A.Sachrajda, P.Zawadzki, A.Kam, J.Lapointe, M.Korkusinski, P.Hawrylak

cond-mat/0601597

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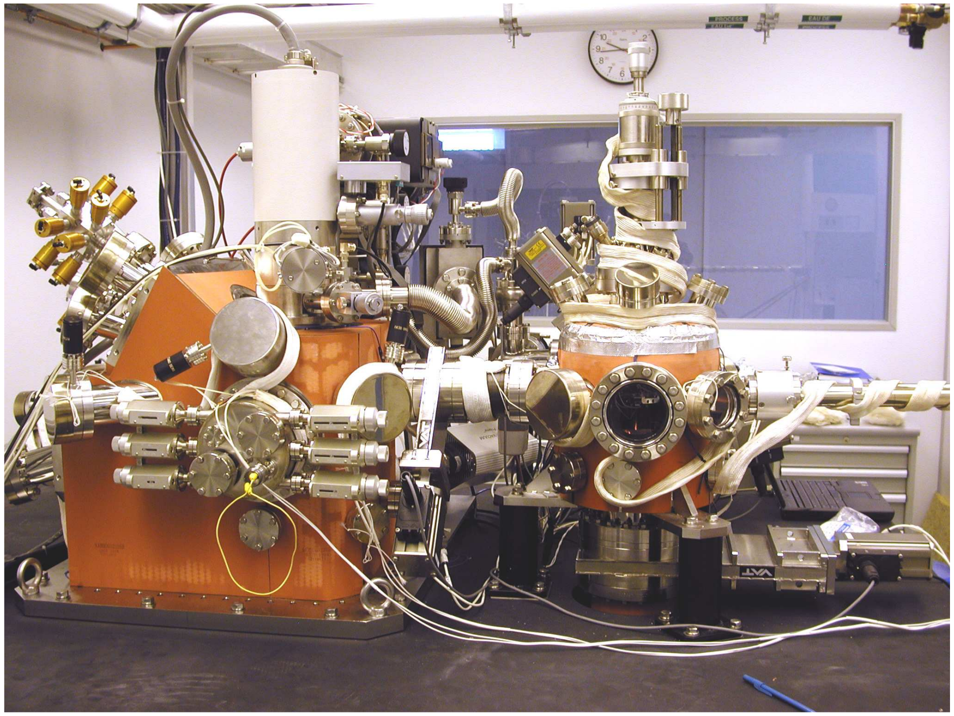
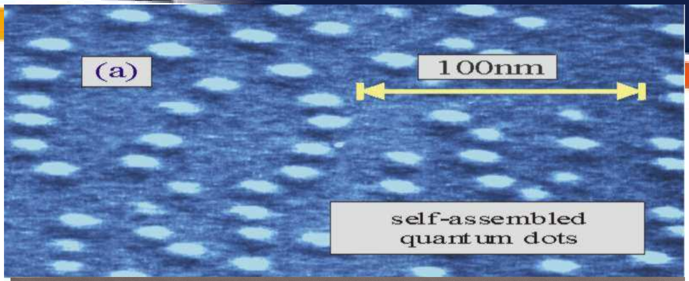
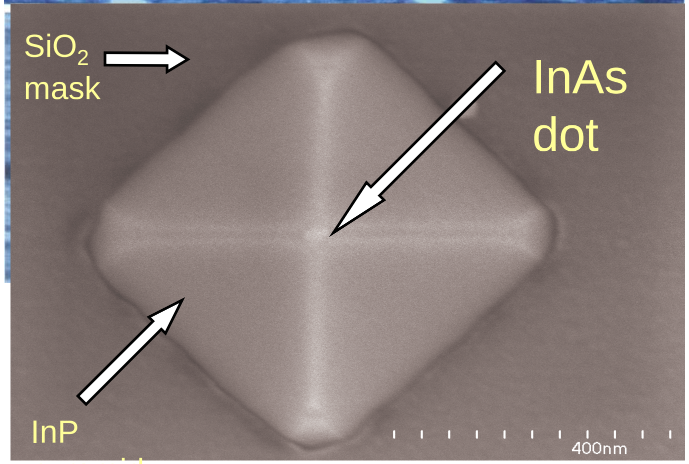
REPLACING LITHOGRAPHY WITH SELF-ASSEMBLY

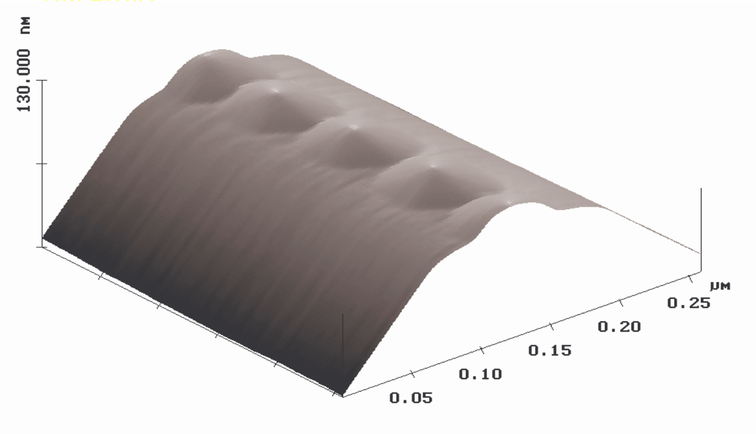
STRAIN DRIVEN
SELF-ASSEMBLY: InAs/GaAs
R.WILLIAMS, P.POOLE
DIRECTED SELF-ASSEMBLY VIA
LITHOGRAPHY: InAs/InP at 1.5μm

ARTIFICIAL ATOM FACTORY









HOW MANY ATOMS?

100*100*100=10^6

WHAT ARE THE ENERGY SCALES?

SINGLE PARTICLE GAPS – ~0.4-1.5 eV
STRAIN EFFECT (ON GAPS) – ~0.5 eV
LEVEL SPACING IN CB - ~0.05eV
LEVEL SPACING IN VB - ~0.01eV
SPLITTING OF SHELLS - ~0.001eV
FINE STRUCTURE - ~0.00001eV

INTERMIXING EFFECTS - ????????
SHAPE AND SIZE EFFECTS - ????????

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HOW MANY ATOMS?
100*100*100=10^6
WHAT ARE THE TOOLS AVAILABLE?

Configuration Interaction – 2 atoms
Density Functional - 10^2 atoms
DFT+GW+BS - 10^2 atoms+ 1 exciton
Pseudo-potential - 10^6 … excitations?
Tight binding - 10^6 … excitations?

K*P - 10^24 …. excitations?
Effective mass - 10*24 … excitations

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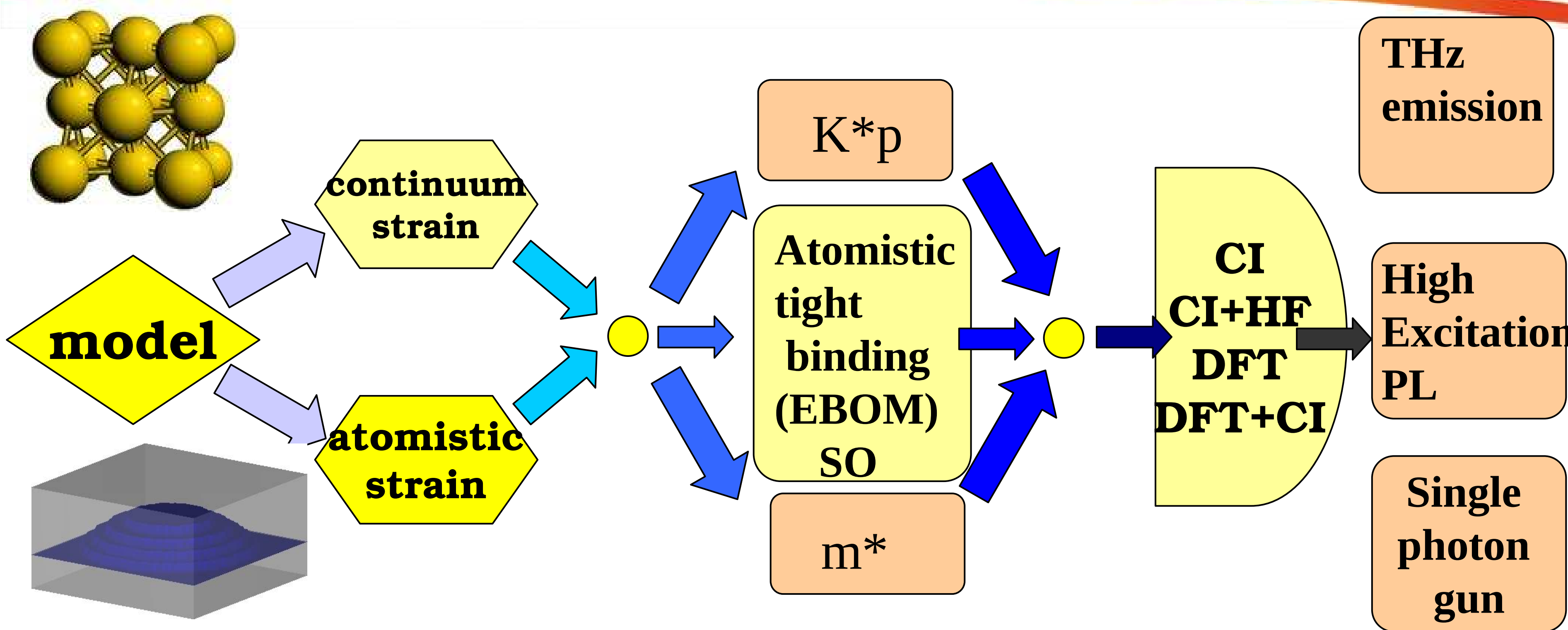
MICROSCOPIC ATOMISTIC THEORY
MILLION ATOM NANOSTRUCTURES

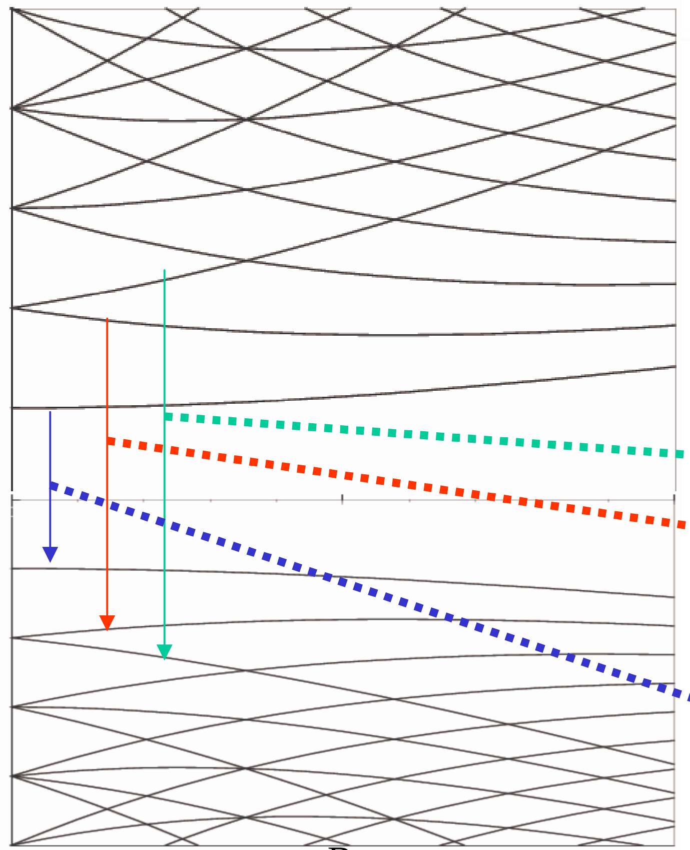


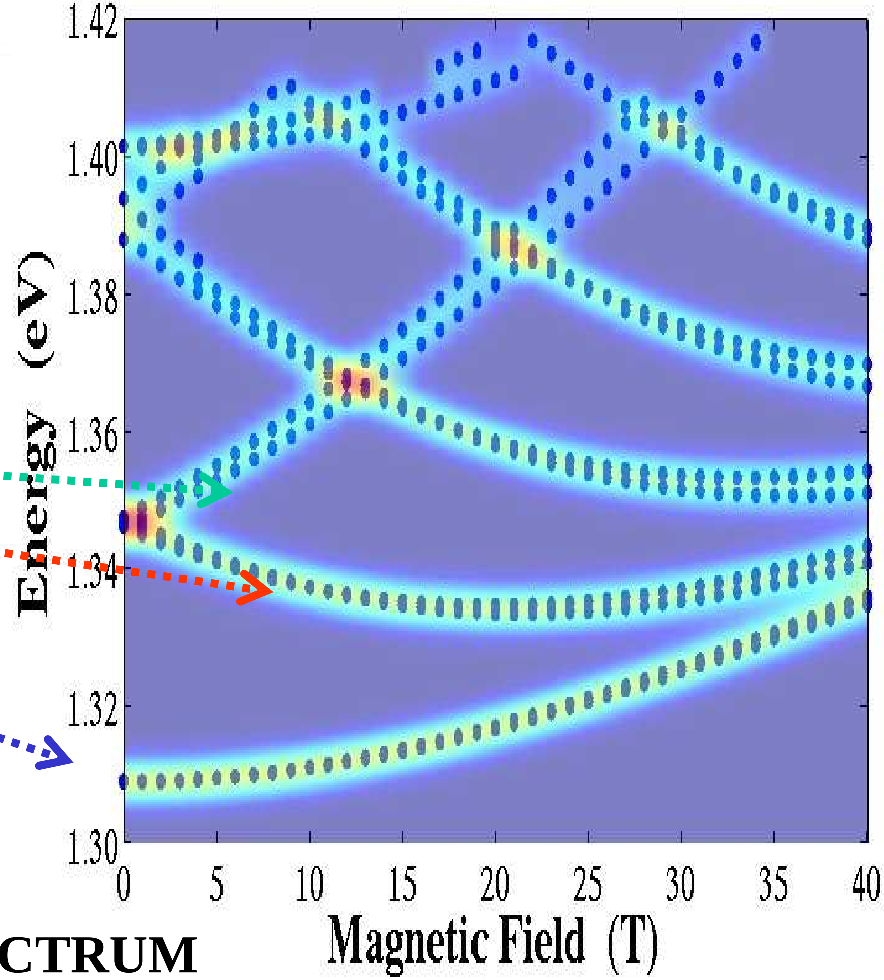
Kinetic model: Shape, composition ~ 10^9 atoms

Mechanical ~ 10^9 atoms → Electronic ~10^6 atoms → Optical ~ 10 quasipaticles

W.Sheng, M.Korkusinski, R.Abolfath,PH

DESIGNING ELECTRON-HOLE SYSTEMS: BUILDING DEGENERATE SHELLS – SIMPLE MODEL





EL-HOLE PAIR=PHOTON FD SPECTRUM

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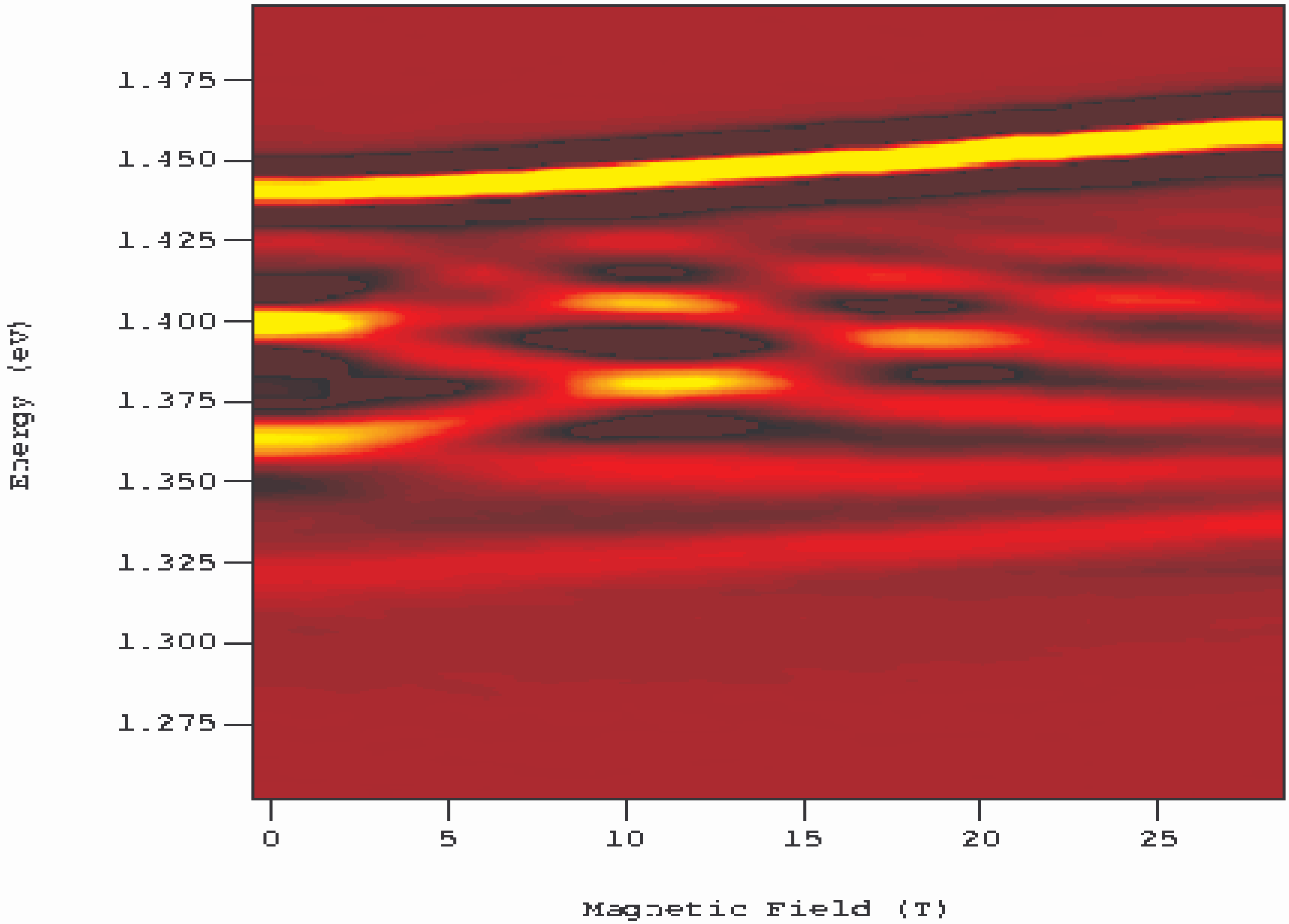
S.J.Cheng,W.Sheng,PH, PRB2004

EMISSION FROM HIGHLY EXCITED SELF-ASSEMBLED InGaAs DOTS IN HIGH MAGNETIC FIELDS In FLUSH+ANNEALING



Raymond
……
PRL 2004,
Ottawa/
Grenoble/
Dortmund

CNRC

NANO SPINTRONICS

CONTROLLING PHOTONS WITH SPINS AND VICE VERSA

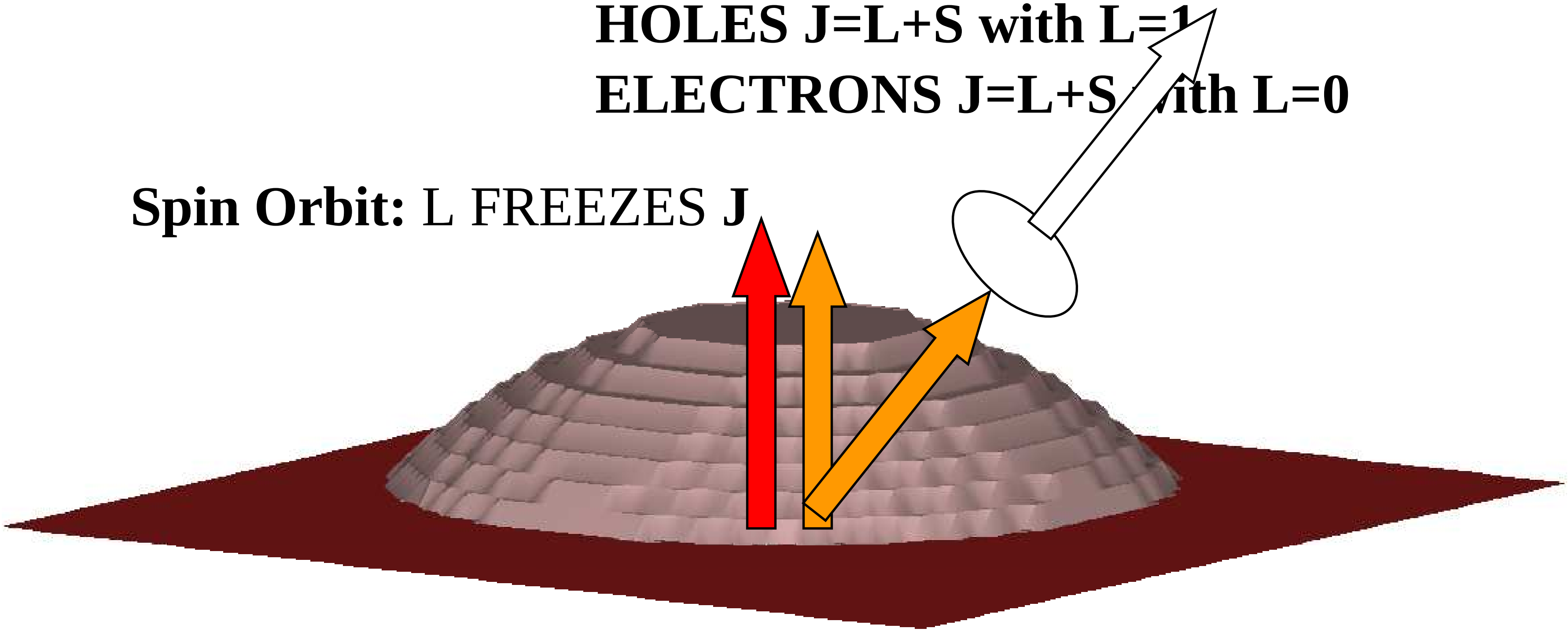
PHOTON ANGULAR MOMENTUM

L(photon) = L(initial) – L(final)

HOLES J=L+S with L=1

ELECTRONS J=L+S with L=0

Spin Orbit: L FREEZES **J**



Engineering exciton photon coupling

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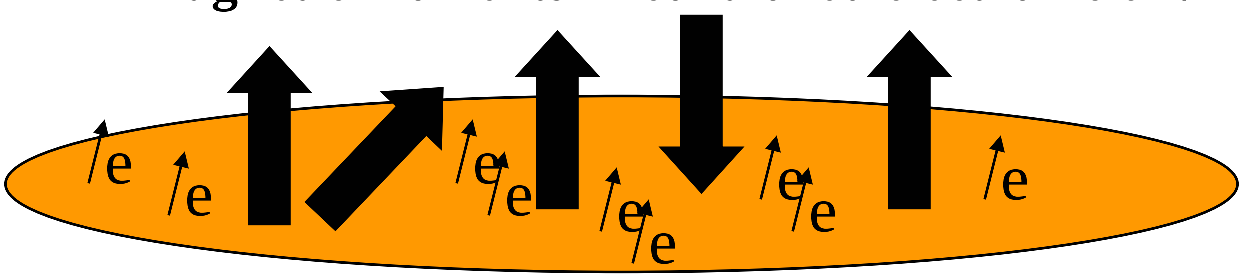
NANOSPINTRONICS

•Semiconductor quantum dots with magnetic ions

•Combining magnetic,transport and optical properties of semiconductors

•Controlling magnetism on nanoscale

•Magnetic moments in controlled electronic environement



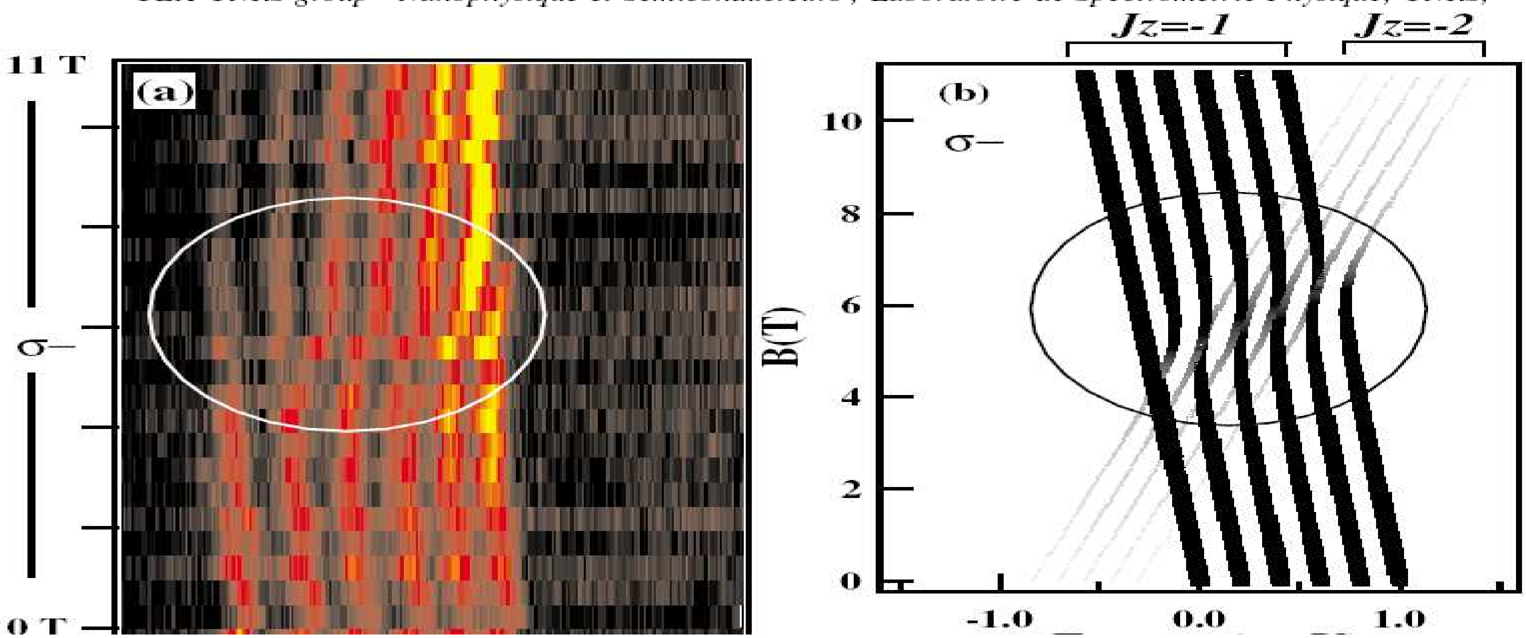
F.Qu (Uberlandia,Brasil),PH

CURRENT STATUS OF SELF-ASSEMBLY DOWN TO ONE Mn ION

VOLUME 93, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 12 NOVEMBER 2004

Probing the Spin State of a Single Magnetic Ion in an Individual Quantum Dot

L. Besombes,* Y. Léger, L. Maingault, D. Ferrand, and H. Mariette
CEA-CNRS group "Nanophysique et Semiconducteurs", Laboratoire de Spectrométrie Physique, CNRS,



Mn ion M=5/2 6 states

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MAGNETO-POLARONS IN QDOTS

PHYSICAL REVIEW B VOLUME 44, NUMBER 23 15 DECEMBER 1991-I

Tunneling in a periodic array of semimagnetic quantum dots

Pawel Hawrylak
Institute for Microstructural Sciences, National Research Council, Ottawa, Canada K1A 0R6

Marek Grabowski
Department of Physics, University of Colorado, Colorado Springs, Colorado 80933

J. J. Quinn
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996
(Received 24 June 1991)

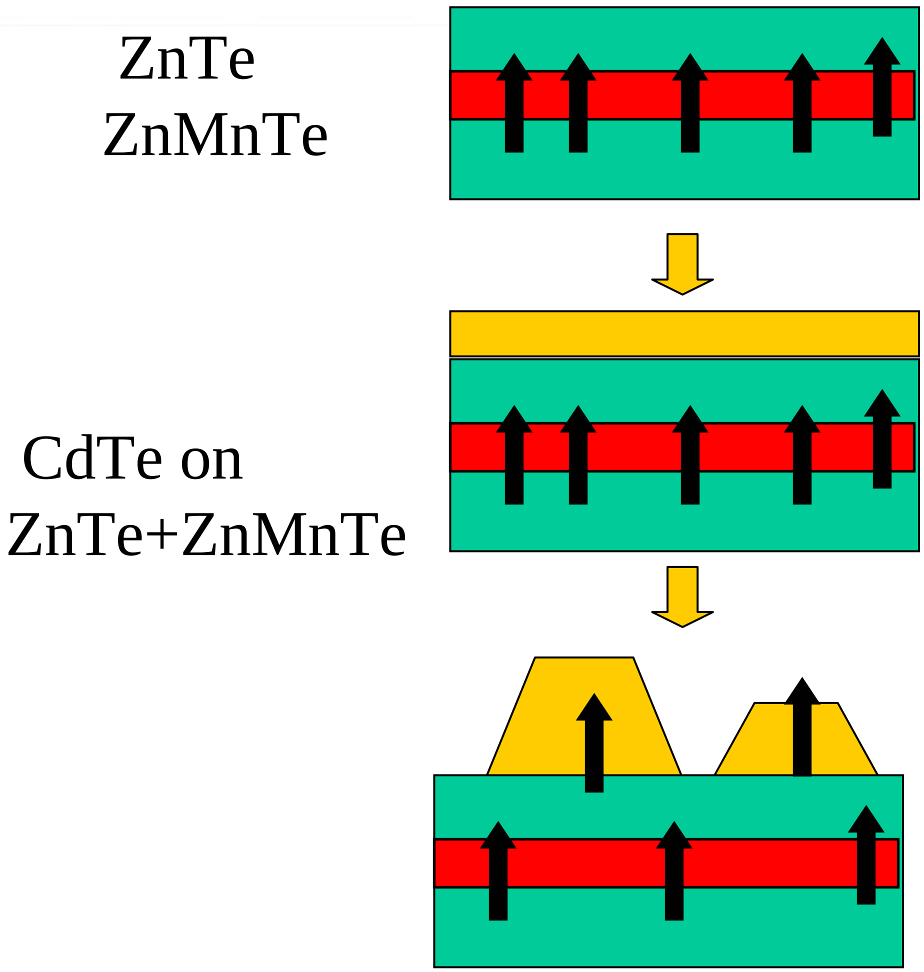
We investigate the tunneling of carriers in a quasi-one-dimensional array of semimagnetic quantum dots. The large magnetopolaron effects due to the exchange interaction of carriers with magnetic ions result in a transmission via solitonlike electronic states. The intensity-dependent transmission coefficient shows the opening of intensity-dependent gaps in the transmission spectrum.

TWO MATERIAL SYSTEMS

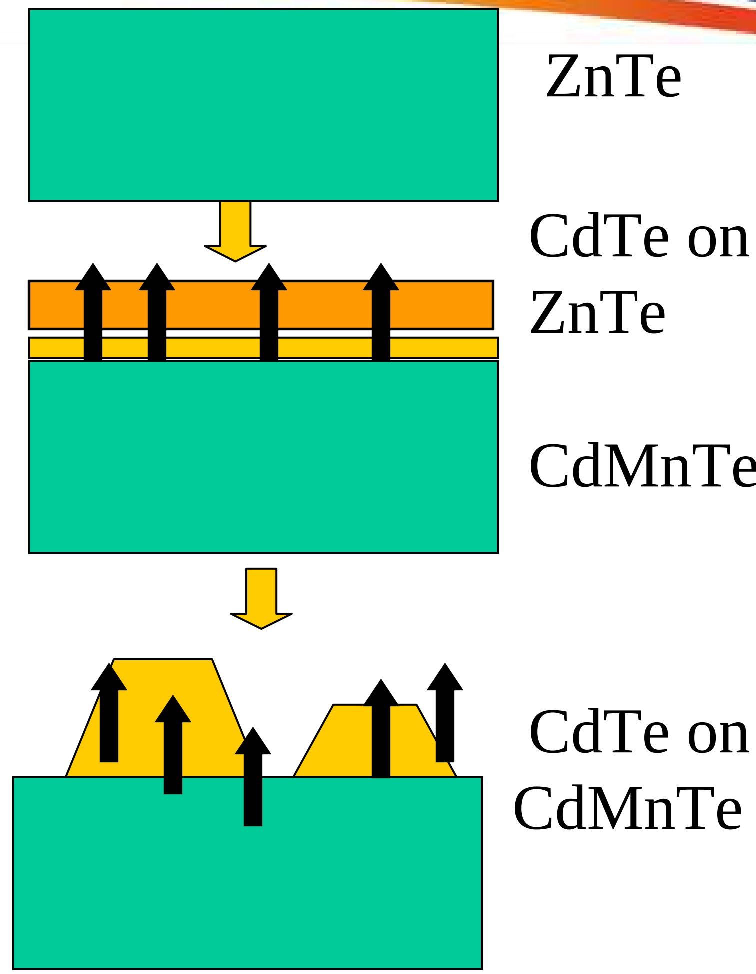
InAs/GaAs: Mn-acceptor

CdTe/ZnTe: Mn-isoelectronic impurity

CURRENT STATUS OF SELF-ASSEMBLY



Marriette Grenoble



Kossut Warsaw

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CURRENT STATUS OF SELF-ASSEMBLY

Bacher, Gould, Forchel,Yakovlev,Ossau,Molenkamp,Furdyna
Wurzburg and Notre Dame

Wojnar,Kossut,Karczewski,Dietl,Wojtowicz,Furdyna
Warsaw and Notre Dame

Besombes,Kheng,Marriette,Cibert,Kossacki,Gaj,Dietl
Warsaw and Grenoble

CARRIER MEDIATED FERROMAGNETISM ON NANOSCALE

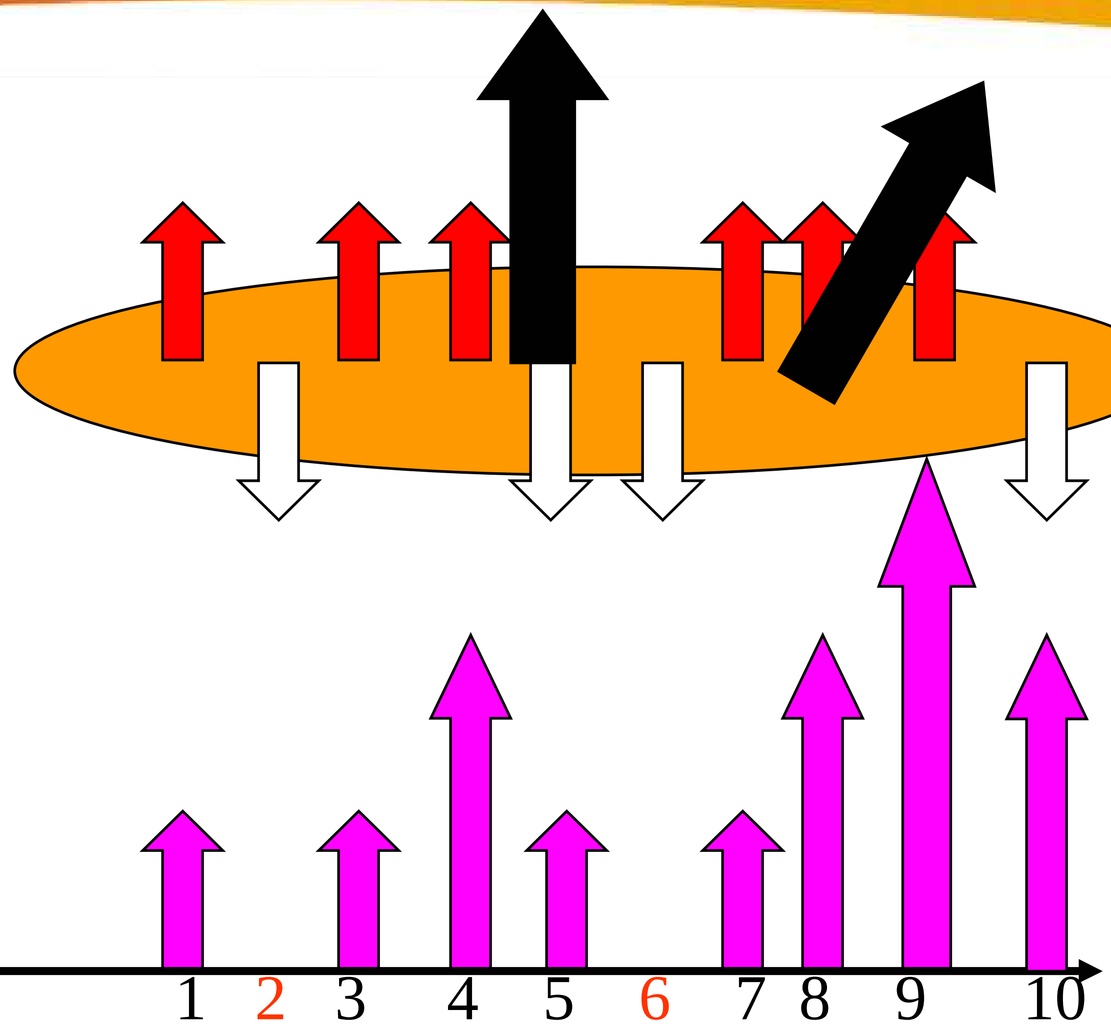
J.I.Climente,M.Korkusinski,PH,J.Planelle, PRB2005
F.Qu, PH, PRL2005
F.Qu, PH, PRL2006
Parallel work : MacDonald and co-workers
Fernandez-Rossier and Brey
Govorov and co-workers
S.J.Cheng
Efros and co-workers
……….

CARRIER MEDIATED AND CONTROLLED

Mn-Mn INTERACTION IN QDOTS

NANO SPINTRONICS

Mn IONS IN A CONTROLLED ELECTRONIC ENVIRONMENT



Loading qdot with electrons:

Qdot Degeneracies

Closed shells
Open shells

Hund's rule

Qu,PH,PRL2005

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NANO SPINTRONICS
Mn-Mn CARRIER MEDIATED INTERACTION

$$\hat{H} = g_{Mn}\mu_B B M_1^z + g_{Mn}\mu_B B M_2^z + J_{12}\vec{M}_1 \cdot \vec{M}_2$$

Mn-Mn AF interaction

$$-\sum_{i,j,I} \frac{J_{ij}(R_I)}{2} \left[(c_{i,\uparrow}^{+} c_{j,\uparrow} - c_{i,\downarrow}^{+} c_{j,\downarrow}) M_I^z + c_{i,\downarrow}^{+} c_{j,\uparrow} M_I^{+} + c_{i,\uparrow}^{+} c_{j,\downarrow} M_I^{-} \right]$$

Mn-e F interaction

$$+\sum_{i\sigma} E_{i,\sigma} c_{i,\sigma}^{+} c_{i,\sigma} + \frac{1}{2} \sum_{ijkl}^{\sigma\sigma'} \langle i, j | V_{ee} | k, l \rangle c_{i,\sigma}^{+} c_{j,\sigma'}^{+} c_{k,\sigma'} c_{l,\sigma}$$

Spin conserving scattering in effective B field of Mn

e-e interactions

Spin flip scattering

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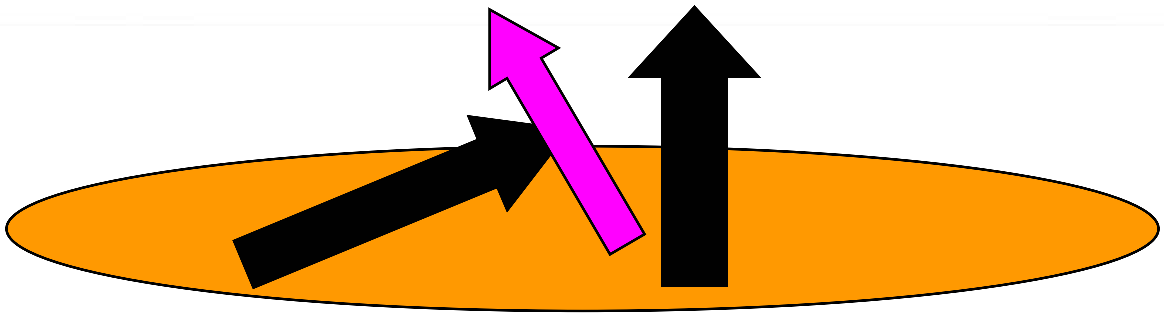
NANO SPINTRONICS
Mn-Mn CARRIER MEDIATED INTERACTION

CdTe qdot

Mn ions
M=5/2



$$|k\rangle = |i_1, i_2, \ldots, i_{N\uparrow}\rangle |j_1, j_2, \ldots, j_{N\downarrow}\rangle |M_1^z M_2^z\rangle \qquad \langle k'|H|k\rangle$$

Kondo physics, disorder, e-e interactions

NANO SPINTRONICS
ENGINEERING OF ELECTRON AND Mn ION INTERACTION

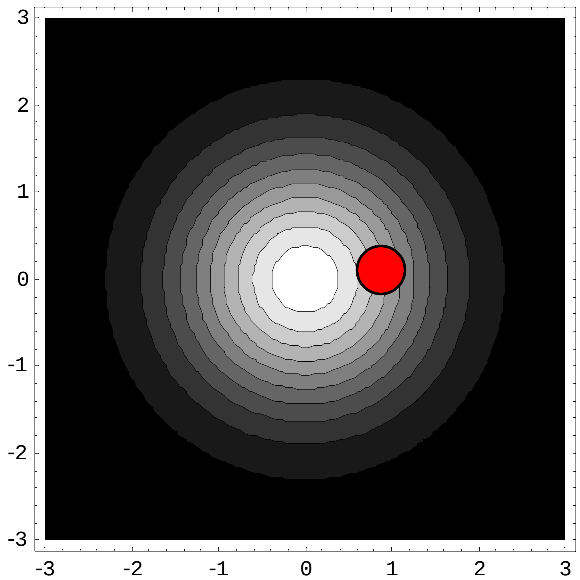
Quantum engineering of electron-Mn interaction

$$J_{ij}(R) = J_C^{2D}\ \varphi_i^*(R)\varphi_j(R)$$

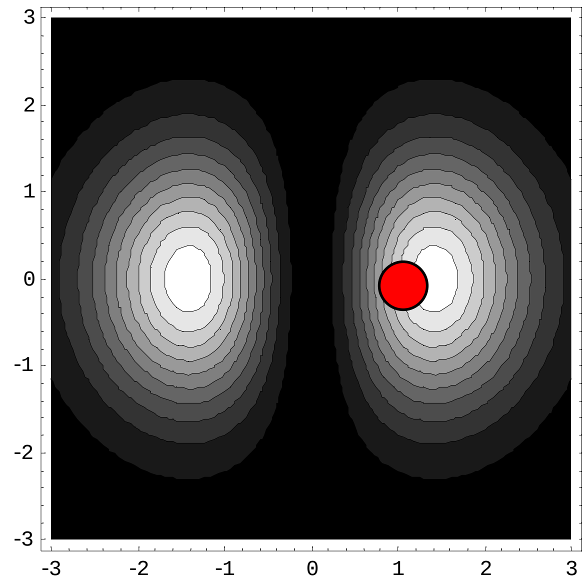
Vary size J~1/L

Vary orbitals ϕ
By varying Fermi level

S-shell



p-shell



J probes the
Wavefunction!

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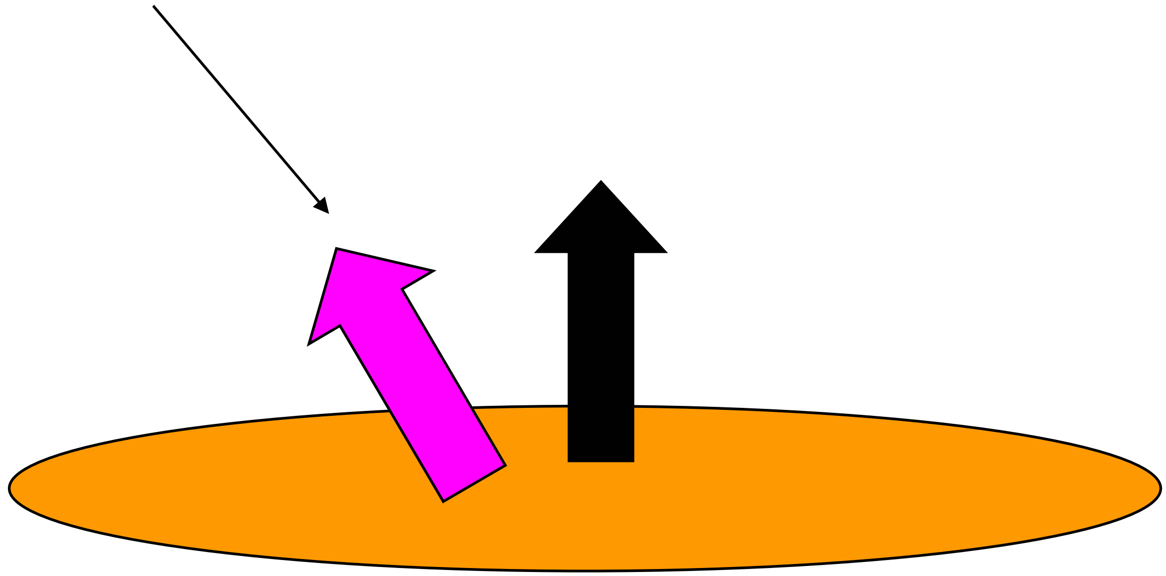
SINGLE Mn- MANY ELECTRON SPIN SYSTEM

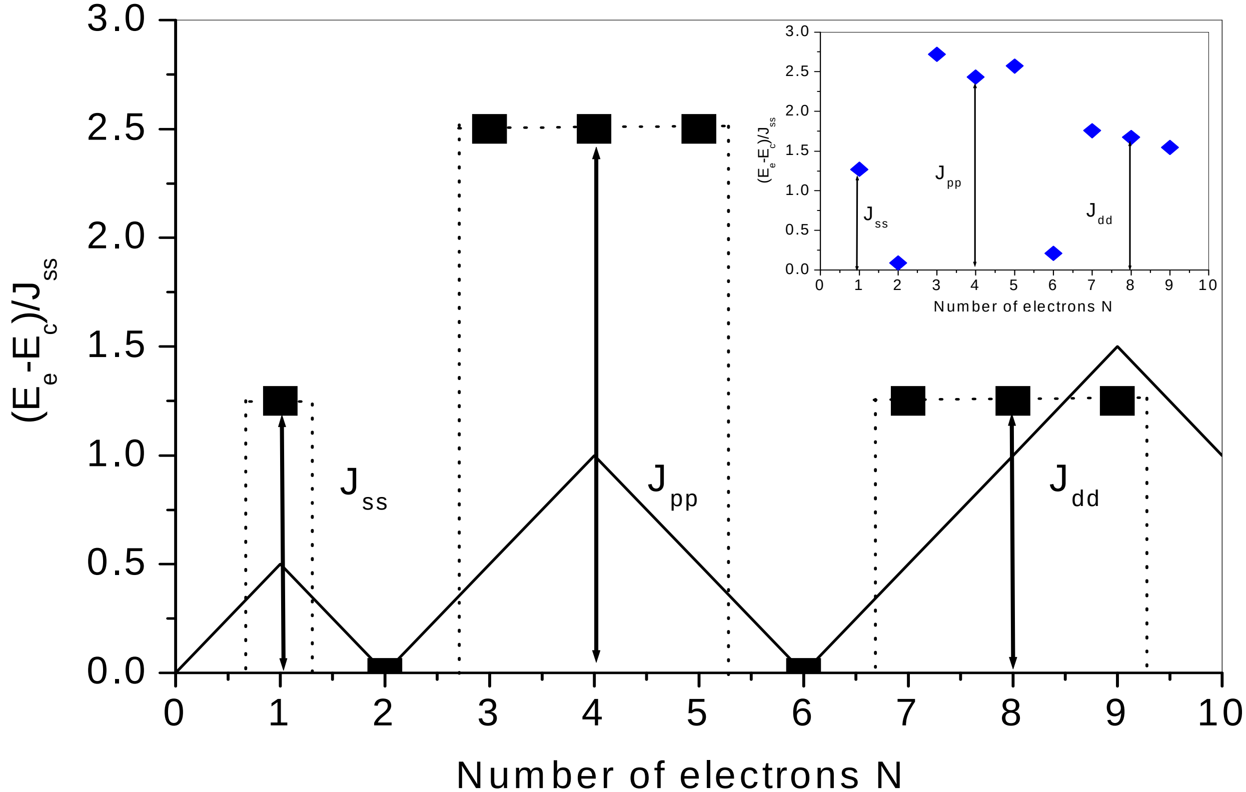
TUNABLE ELECTRON-Mn INTERACTION



NANO SPINTRONICS
Mn ION IN A COTROLLED ELECTRONIC ENVIRONMENT

$$\Delta E = J_{eff} S_{total} M$$

Tracks the total spin of electrons ?



Cancellation
of el-el interaction

Qu,PH, PRL2005

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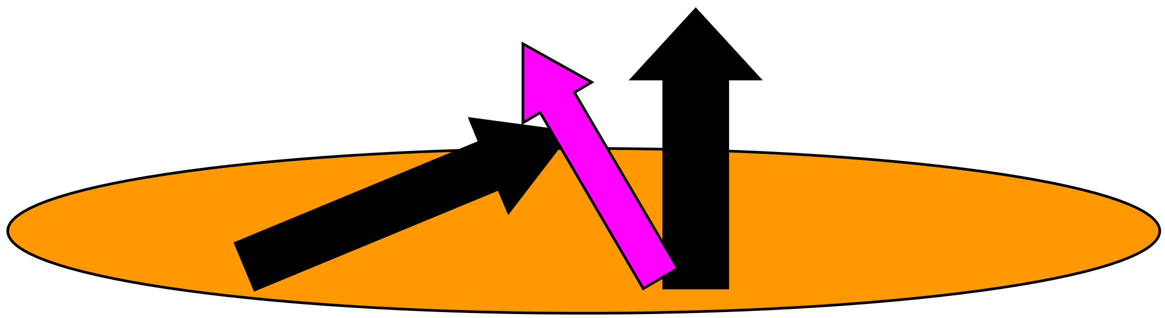
Mn-Mn CARRIER MEDIATED INTERACTION

Classifying electron mediated Mn-Mn interacion



Interacting Mn-Mn , Mn-e, and e-e system

Closed shells
Electron S=0
RKKY interaction

Strong coupling

Partially filled shells
Electron Finite spin
Magneto-polarons

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Mn-Mn CARRIER MEDIATED RKKY INTERACTION

Example filled s-shell: 2 electrons, bi-exciton

$$\hat{H} = +J_{12}\vec{M}_1 \cdot \vec{M}_2 + J_{RKKY}(R1, R2)\vec{M}_1 \cdot \vec{M}_2$$

$$J\left(\vec{R}_1, \vec{R}_2\right) = -\left(\frac{J_c^{2D}}{\pi d_0^2}\right)^2 \left(\frac{1}{4\omega_0}\right) \left\{ \alpha \vec{R}_1 \cdot \vec{R}_2 + \beta \frac{\left(\vec{R}_1 \cdot \vec{R}_2\right)^2 - \left(\vec{R}_1^{\,2} + \vec{R}_2^{\,2}\right) + 2}{4} \right\} e^{-\frac{\vec{R}_1^{\,2} + \vec{R}_2^{\,2}}{2}}$$

scaling

Scattering
To
P-shell

Scattering
To
D-shell

Carrier
confinement

Number of shells controls RKKY interaction

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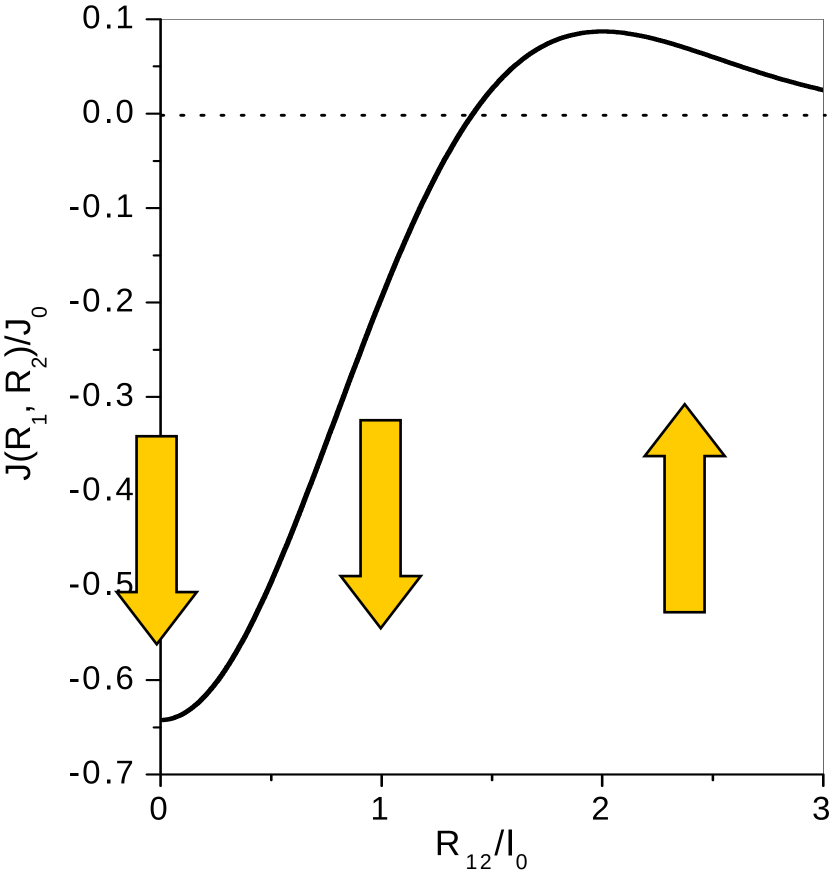
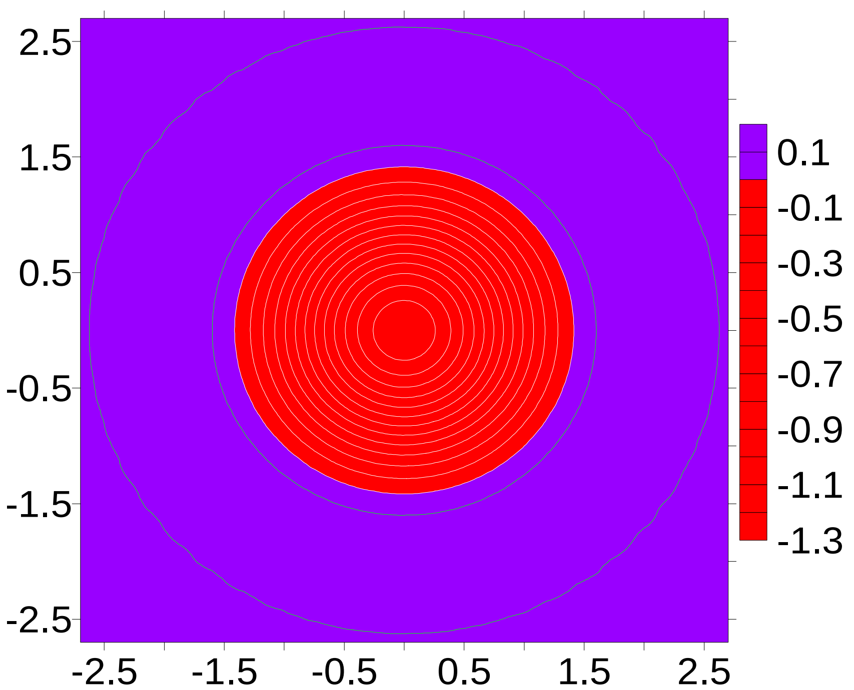
Mn-Mn CARRIER MEDIATED RKKY INTERACTION

S-shell filled





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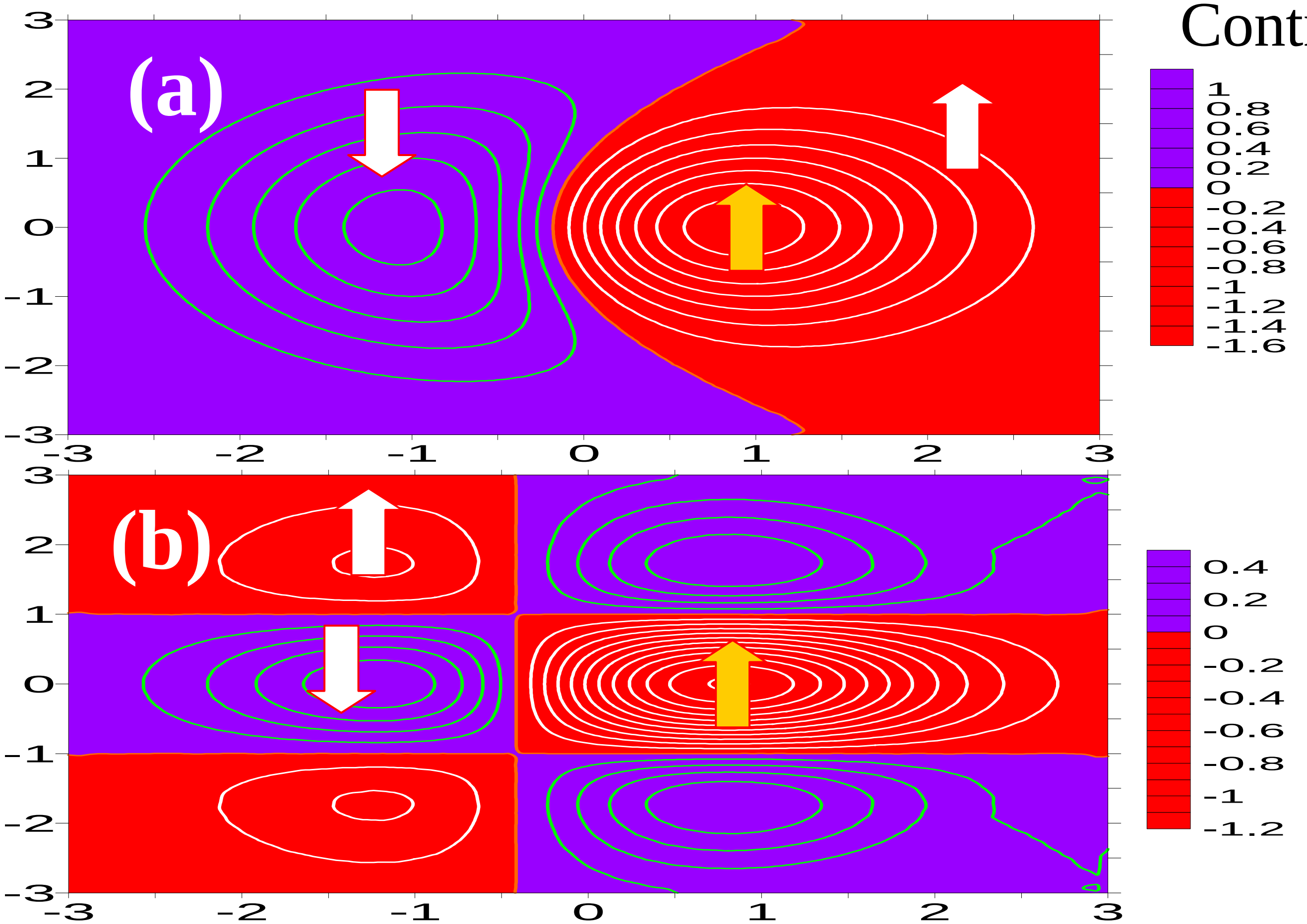
Mn-Mn CARRIER MEDIATED RKKY INTERACTION

Controlling J with Ne



S-shell filled

S and p shells filled

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Mn-Mn CARRIER MEDIATED INTERACTION

Magnetic polarons- partially filled shells

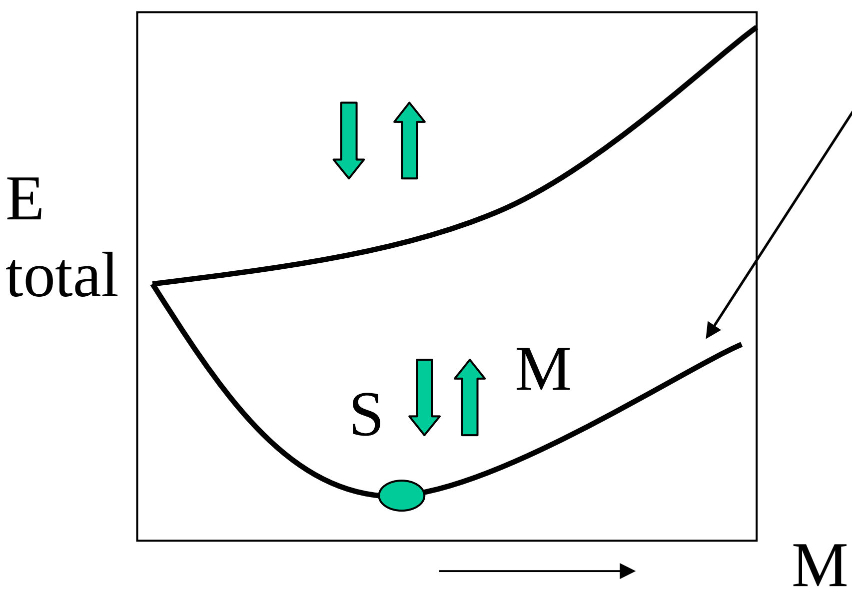
$$\vec{M} = \vec{M}_1 + \vec{M}_2$$

$$\hat{H} = \frac{J_{12}}{2}(\vec{M}^2 - \vec{M}_1^2 - \vec{M}_2^2) - \frac{J_{ss}}{2}\left[(c^+_{s,\uparrow}c_{s,\uparrow} - c^+_{s,\downarrow}c_{s,\downarrow})M^z + c^+_{s,\downarrow}c_{s,\uparrow}\, M^+ + c^+_{s,\uparrow}c_{s,\downarrow}\, M^-\right]$$

$$0 \le M \le M_1 + M_2 \qquad c^+_{s,\downarrow}\,|\,0 >| M, M^z > \qquad c^+_{s,\uparrow}\,|\,0 >| M, M^z >$$

$$E(M,+) = -(\frac{J_{ss}}{2})M + (\frac{J_{12}}{2})\left[M(M+1) - \frac{35}{2}\right]$$

Negative!



ferromagnetic (M^*=5),
canted (0<M^*<5) and
antiferromagnetic (M^*=0) GS
by adjusting the ratio δ=*Jss/J12*

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Mn-Mn CARRIER MEDIATED INTERACTION

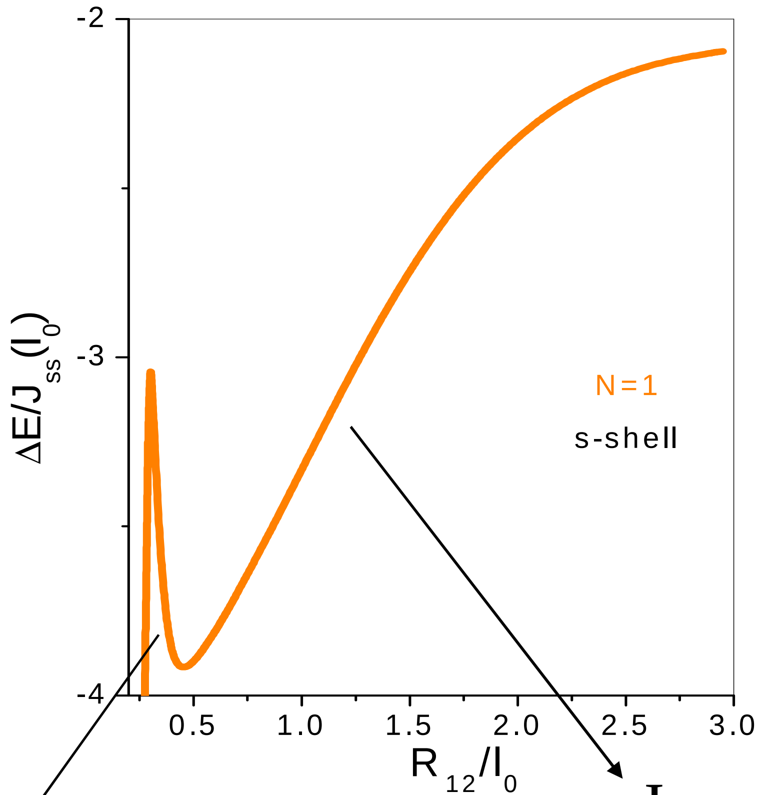
$$E(M,+) = -(\frac{J_{ss}}{2})M + (\frac{J_{12}}{2})\left[M(M+1) - \frac{35}{2}\right]$$

$$M^{*} = (\frac{J_{ss}}{J_{12}} - 1)/2$$

M=

$$E(M^{*},+) = -(\frac{J_{12}}{8})[(\frac{J_{ss}}{J_{12}} - 1)^{2} + 70]$$

Functions of R1 and R2



Jss

J12

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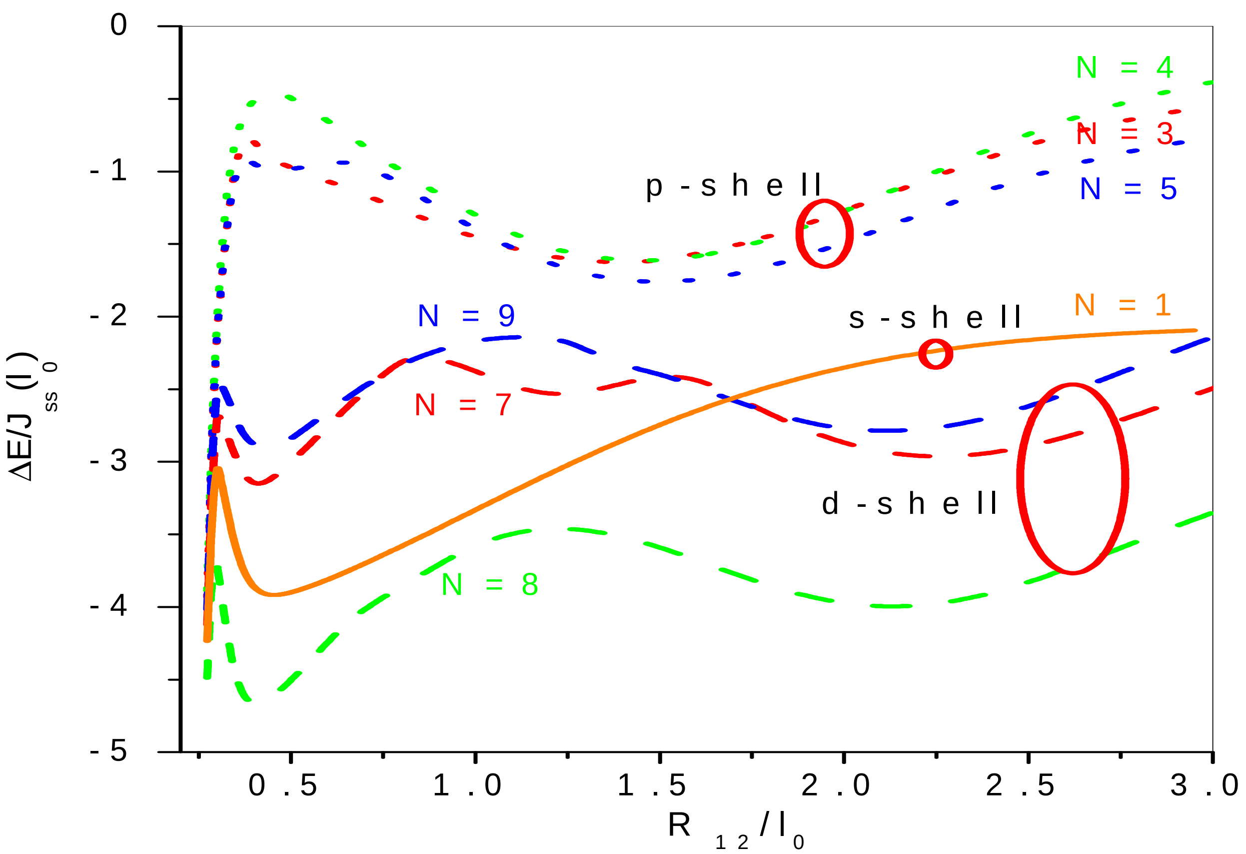
Mn-Mn CARRIER MEDIATED INTERACTION

Magneto-polarons in partially filled shells



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NANOSPINTRONICS

IMS QUANTUM INFORMATION PROJECTS: NANOELECTRONICS AND NANOPHOTONICS

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