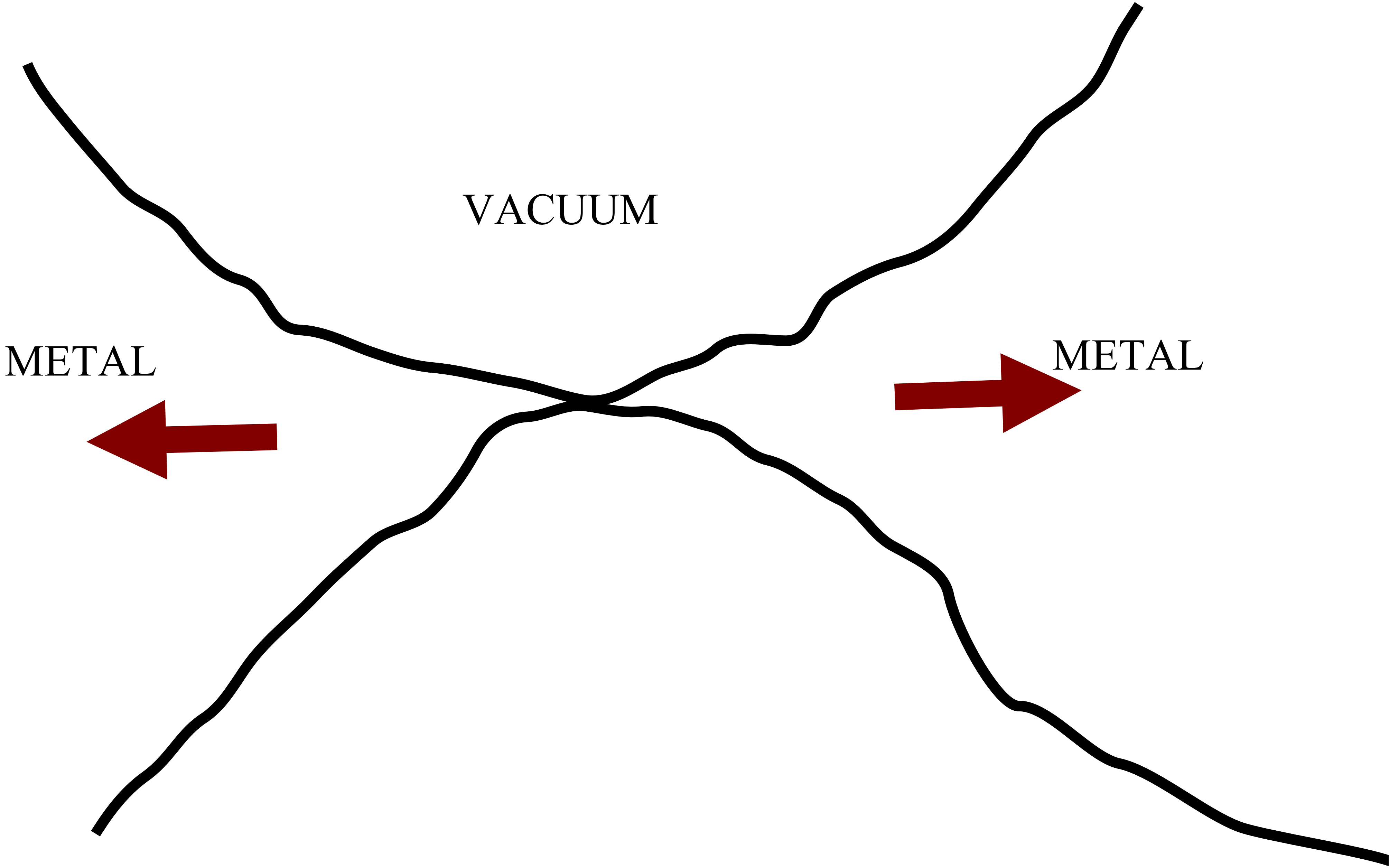
PHYSICS OF METAL NANOCONTACTS

E. Tosatti

SISSA
ICTP
CNR Democritos
Trieste
tosatti@sissa.it

ICTP Nanocollege, Hanoi, December 2009

MAKING AND BREAKING METAL-METAL CONTACTS


VACUUM
METAL
METAL

Rodrigues et al. (2000)

METAL NANOCONTACTS

(Au)

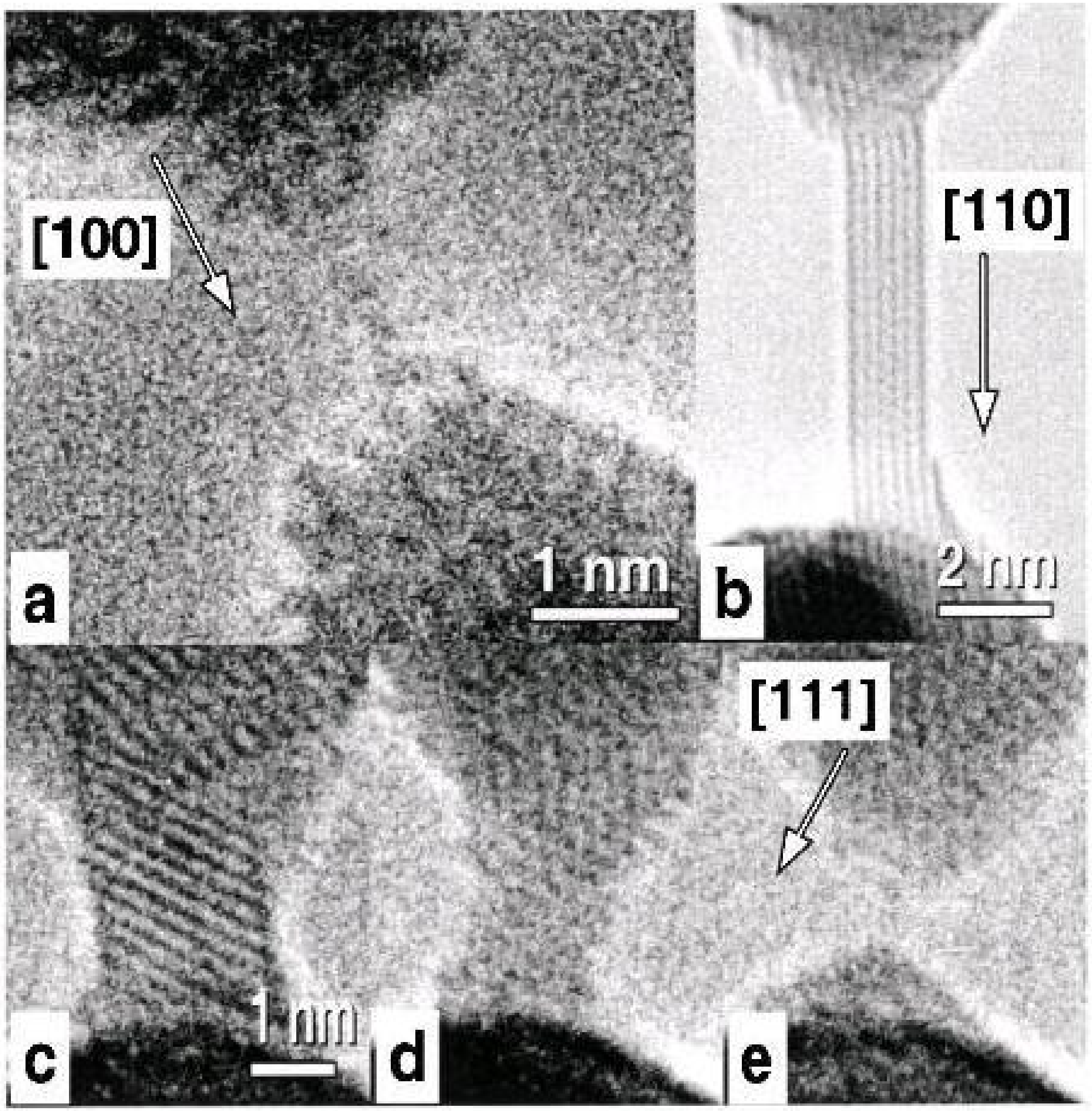
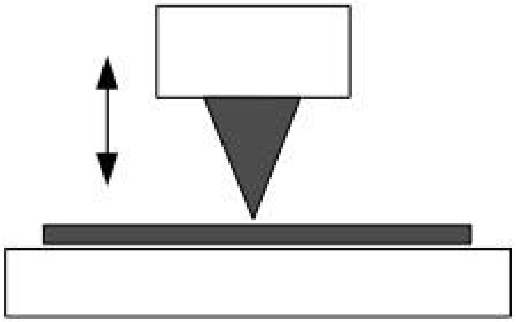


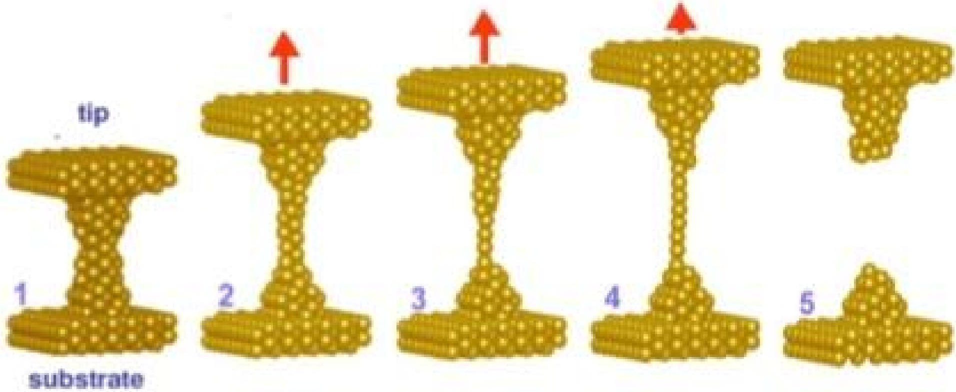
FIG. 2. HRTEM images of gold NWs; atomic positions appear dark. (a) [100] atom-chain NW; (b) rodlike [110] NW; (c)–(e) temporal evolution of a NW formed when the apexes are sliding: 0, 17:12, and 24:15 min, respectively.

Fabrication of atomic-size contacts

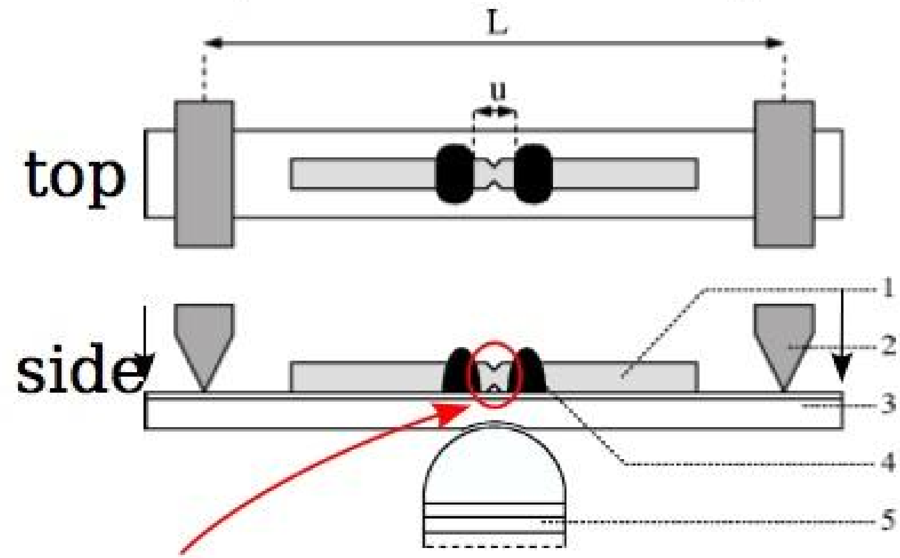
scanning tunneling microscope (STM)



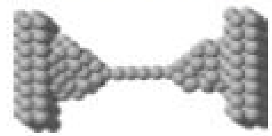
Simulation of the breaking of
Au nanocontact



mechanically controllable break junction



down to atomic chain



1 - notched wire
2 - fixed counter supports
3 - bending beam
4 - drops of epoxy adhesive
5 - stacked piezo element

N. Agraït *et al.*, Phys. Repts. 377, 81 (2003)

METAL NANOCONTACTS

1. STRUCTURE? EVOLUTION IN TIME?

2. CONDUCTANCE?

3. MAGNETISM? WHAT EFFECT ON CONDUCTANCE?

4. NANOMAGNETISM IN A NONMAGNETIC METAL CONTACT?

5. KONDO: A MANY-BODY EFFECT IN A NANOCONTACT

COMPUTATIONAL METHODS

--(S) CLASSICAL (MOLECULAR DYNAMICS) SIMULATION OF NANOWIRES AND NANOCONTACT STRUCTURE + BREAKING

--(S) AB INITIO DENSITY FUNCTIONAL ELECTRONIC STRUCTURE CALCULATIONS . CODES: MOSTLY PWSCF (QUANTUM ESPRESSO). EX-CORREL. FUNCTIONALS: LDA, GGA, (LDA+U)

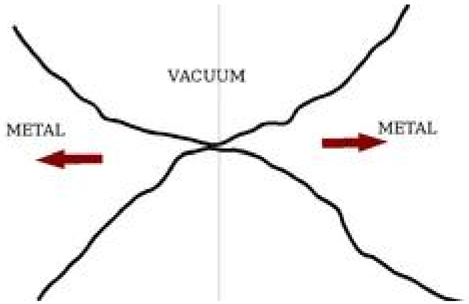
-- BALLISTIC CONDUCTANCE CALCULATIONS: IHM-CHOI METHOD (COMPLEX BAND STRUCTURE, PLANE WAVES) GENERALIZED TO ULTRASOFT PSEUDOPOTENTIALS. (SPIN-ORBIT INTERACTION INCLUDED: EFFECTS ON SPIN + ORBITAL NANOMAGNETISM, CONDUCTANCE)

-- MANY BODY METHODS (NUMERICAL RENORMALIZATION GROUP) FOR KONDO EFFECT IN TRANSITION METAL ATOMIC NANOCONTACTS (in progress)

STRUCTURE

TIME SCALES IN THE STRUCTURAL EVOLUTION OF NANOCONTACTS

τ_1. FAST PLASTIC FLOW AND THINNING



τ_2. QUASI-EQUILIBRIUM LONG LIVED (MAGIC) “NANOWIRE” STRUCTURES

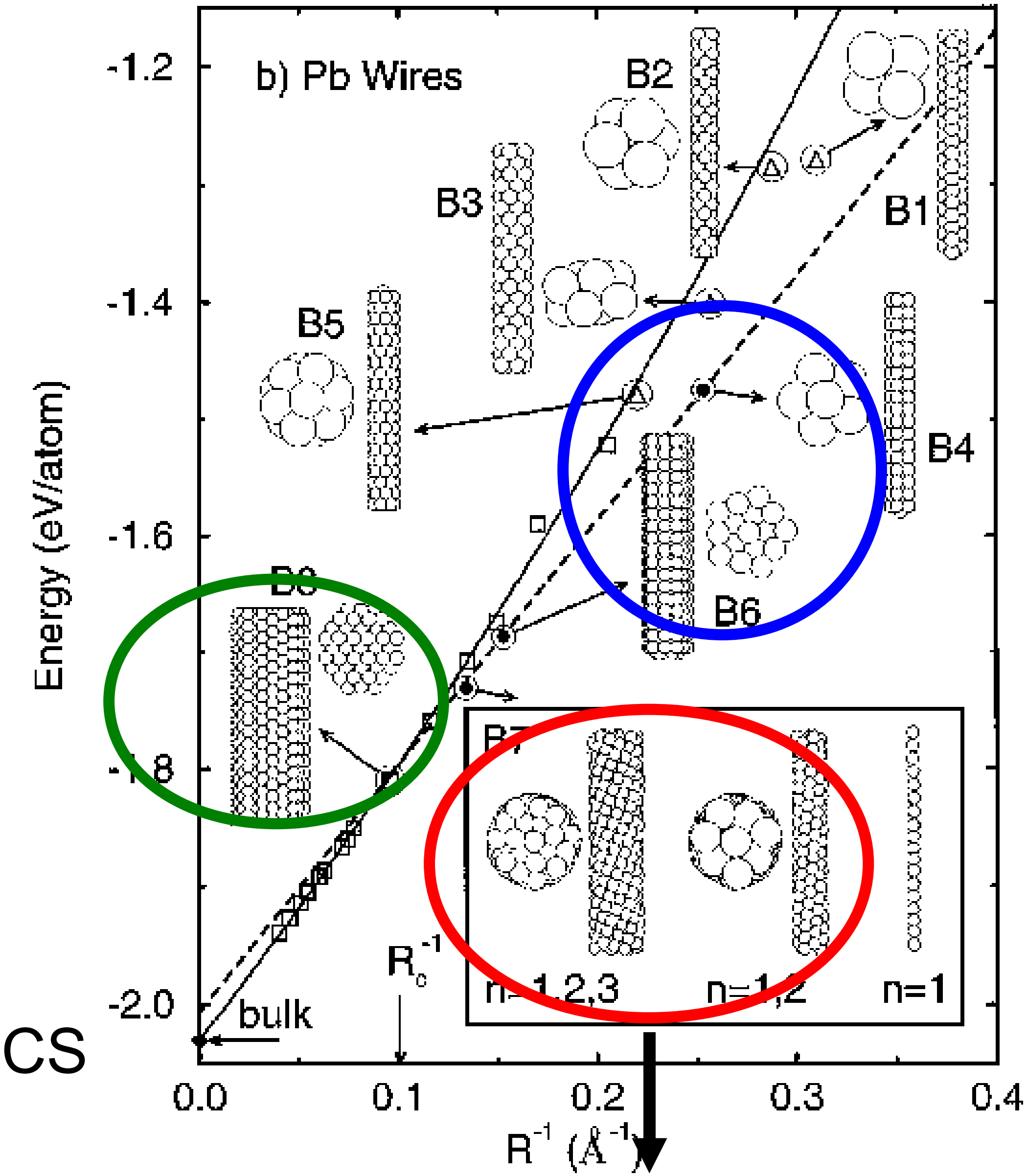
τ_3. FINAL BREAKING

IDEAL ULTRATHIN NANOWIRES (THEORY): EXPECT NEW OPTIMALLY PACKED STRUCTURES

CRYSTALLINE,
ICOSAHEDRAL,
HELICAL

GULSEREN ERCOLESSI, TOSATTI, PRL 80, 3775 (1998)

METHOD: MOLECULAR DYNAMICS SIMULATIONS. POTENTIAL: EMPIRICAL MANY BODY FORCES (ERCOLESSI, ONG (1992))



COAXIAL “WEIRD NANOWIRES”

EXPERIMENT: Au

Takayanagi et al (2000)

MAGIC GOLD

NANOWIRES

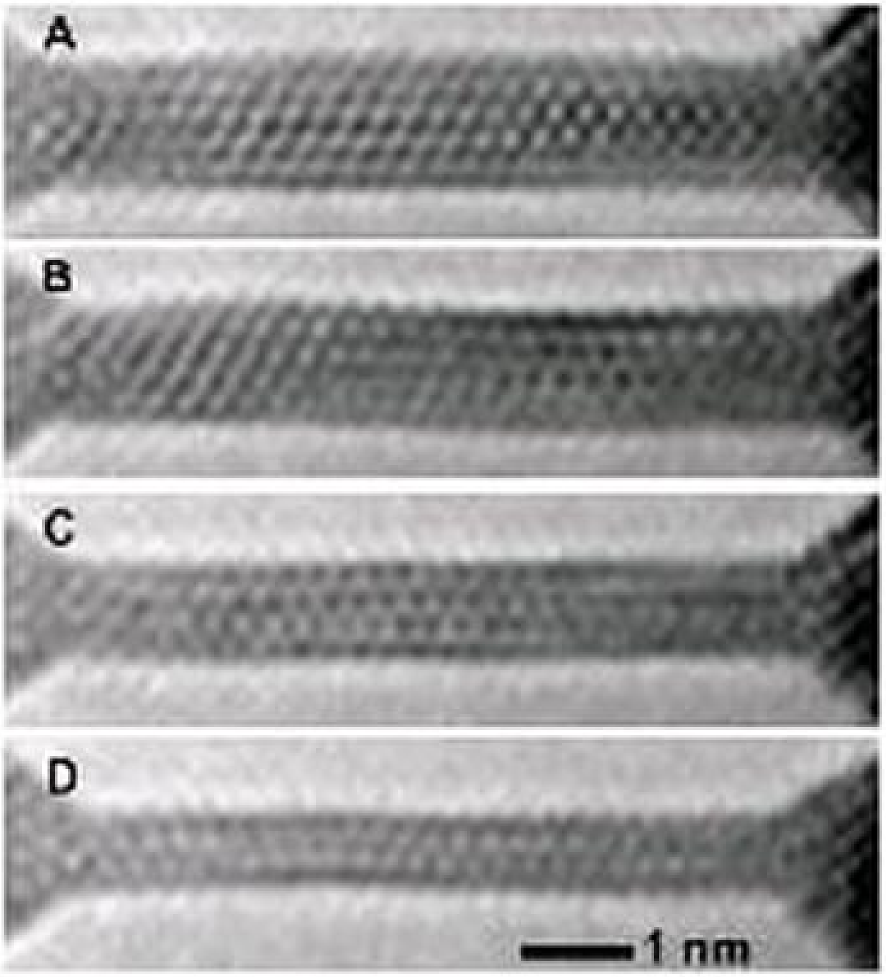


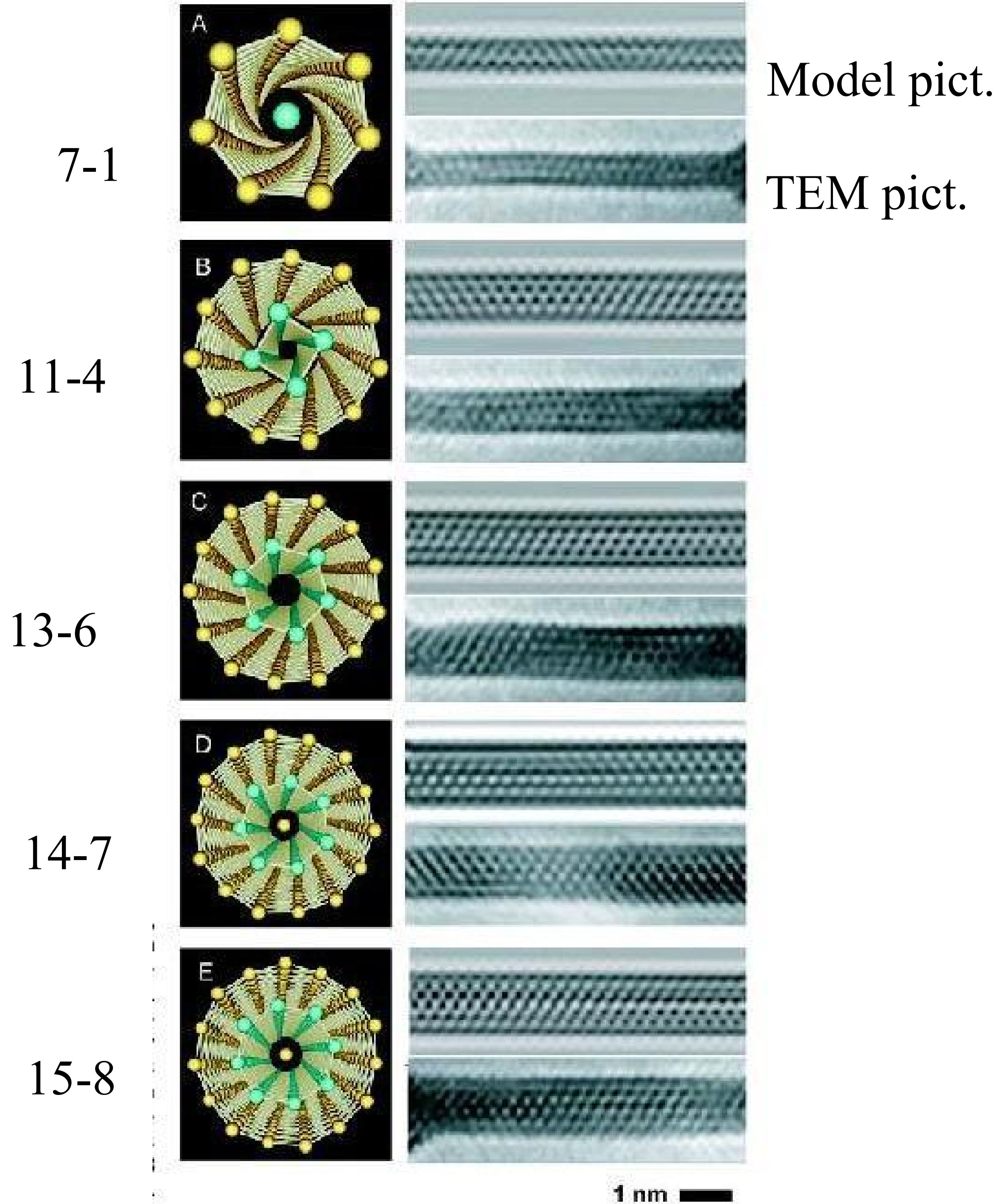
Fig. 1. TEM images of stable gold nanowires observed during one thinning process. The diameters of the wires in (A), (B), (C), and (D) are 1.3, 1.1, 0.8, and 0.6 nm, respectively. The dark dots represent positions of atoms projected on the image plane. The dark dots are aligned on atom rows along the wire axis. These wire images are wavy, particularly in (D).

Au: TEM RESULTS ANALYSED

Takayanagi et al (2000)

HELICAL!?

ΔN = 7 !?



AB INITIO THEORY OF
MAGIC NANOWIRE STRUCTURES:
CALCULATE (AND MINIMIZE) WHAT?

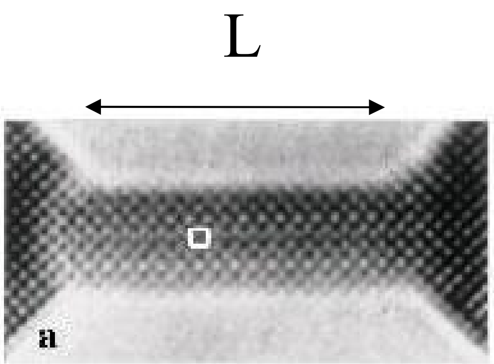
MAGIC NANOWIRES = MINIMA OF
FREE ENERGY F? **NO:**

-- F (N)/N decreases as N grows: wires should

thicken…. but they thin down!!

THE CONCEPT OF STRING TENSION

-- Reason: wires are tip-suspended, do not



$$f = \frac{F - \mu N}{L}$$

Tosatti et al
Science 291, 288 (2001)

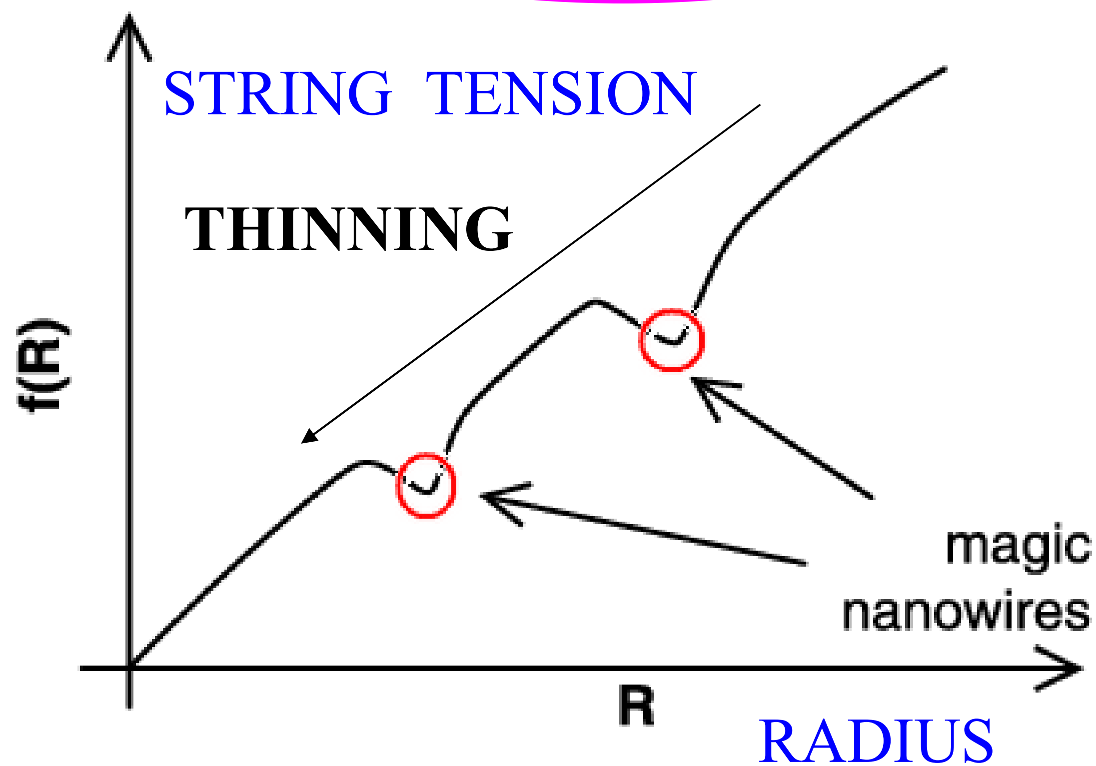


Fig. 1. String tension of a tip-suspended nanowire as a function of radius (schematic). Local minima signal long-lived magic nanowires. The wire disappears ($R = 0$) at true equilibrium.

ATOMS ESCAPE TO LEADS

MAGIC NANOWIRES: AB INITIO THEORY

(Science 291,288(2001))

$$f = \frac{F - \mu N}{L}$$

1. BUILD CRUDE WIRE MODEL USING EMPIRICAL FORCES, MOLECULAR DYNAMICS

2. OPTIMIZE STRUCTURE BY FIRST PRINCIPLES DENSITY FUNCTIONAL CALCULATIONS

3. OBTAIN F (= E AT T=0) AND L OF OPTIMAL ZERO STRESS STRUCTURE

4. μ = BULK COHESIVE ENERGY (CALC. SEPARATELY)

5. CALCULATE STRING TENSION f, REOPTIMIZE IN PRESENCE OF STRESS UNTIL SELFCONSISTENT

6. BUILD ANOTHER WIRE MODEL, ETC

MULTISHELL COAXIAL NANOWIRE MODELS

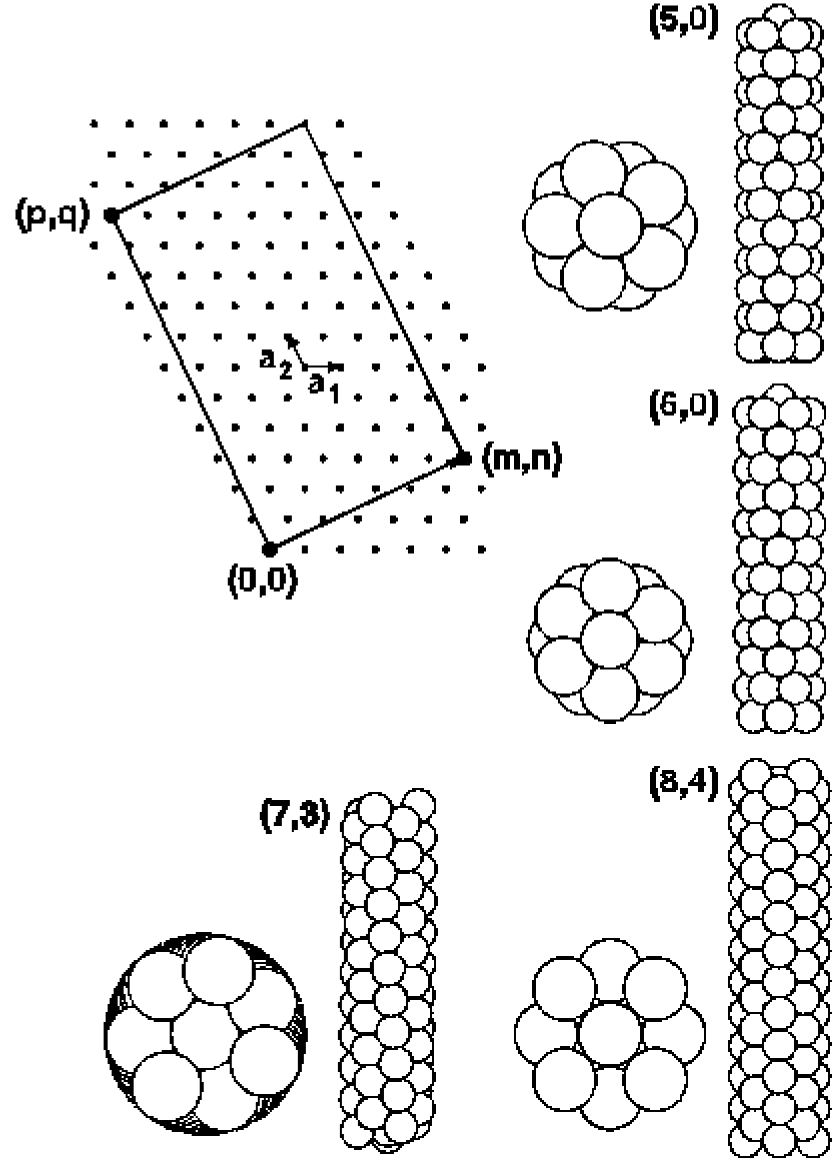
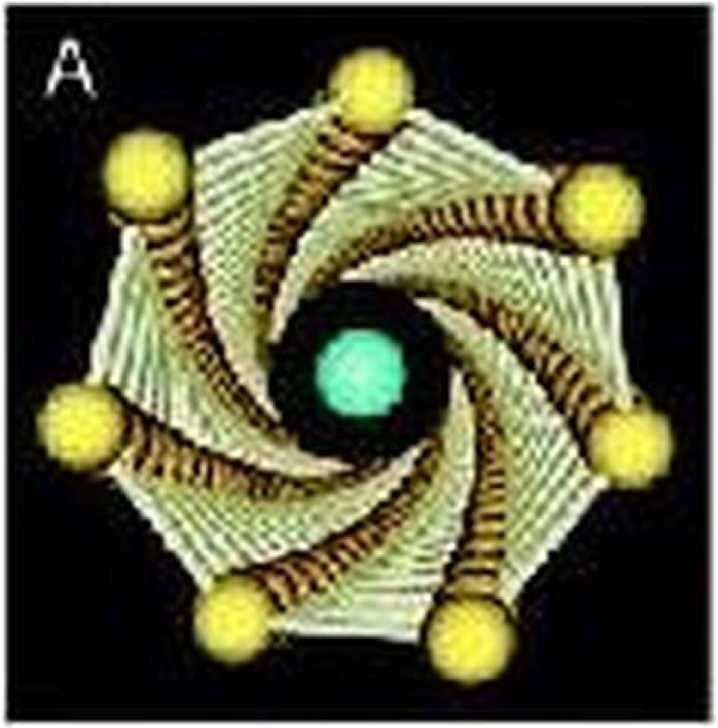
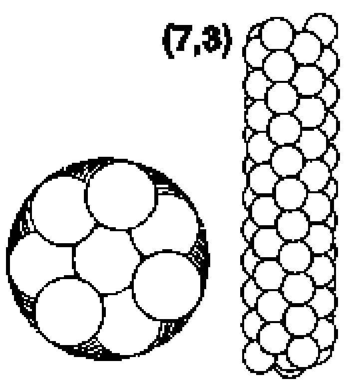


Fig. 2. Cylindrical folding of a triangular lattice for an (*m*, *n*) tube, with views of several coaxial tube nanowires. Each atom is pictured as a sphere of atomic radius. The (7, 3) gold nanowire (note its chirality) was reported to be magic in (*3*).



(7,3)



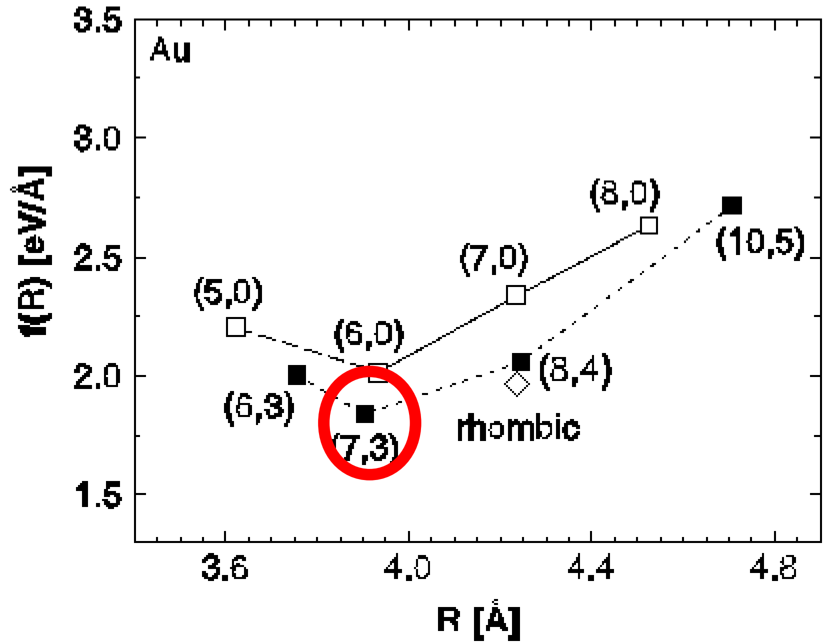


Fig. 3. Calculated (22) string tension (1 eV/Å = 1.6 nN) of tip-suspended gold nanowires at zero temperature (only the largest and smallest *n* values are shown). The minimum demonstrates why the (7, 3) nanowire is magic. The calculations were carried out for infinite tip-free wires, with structure relaxed to minimize string tension (Eq. 1), starting from initial wire geometries obtained by Voter's potential; μ(Au) = −4.401 eV was obtained from a separate bulk calculation.

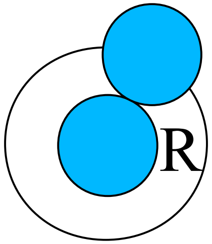
Science 291,288(2001)

WHY **HELICAL?**

$$f = \frac{F - \mu N}{L}$$

→ **HELICAL** TUBE NARROWER AND **LONGER!**

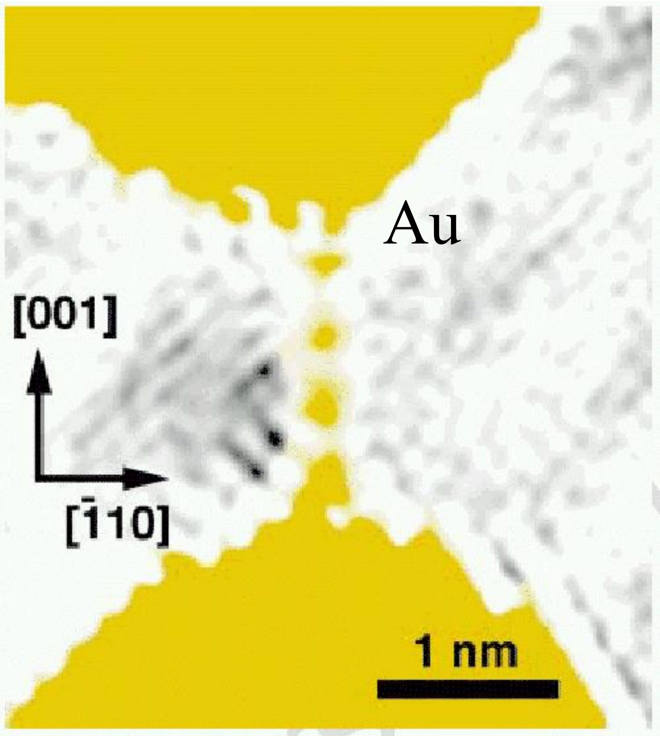
WHY **ΔN = 7**?

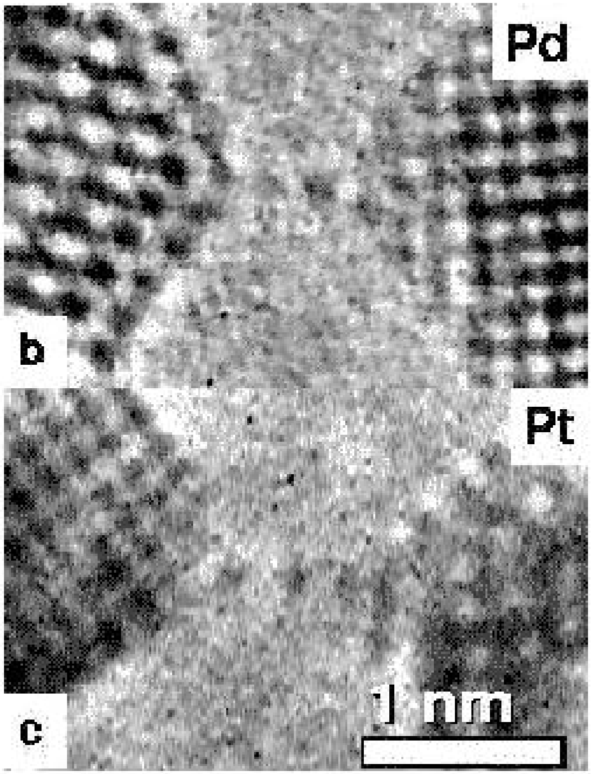


→ $2\pi(2R) < \Delta N(2R)$ → **ΔN=7!**

Monatomic nanowires

TEM = transmission electron microscope

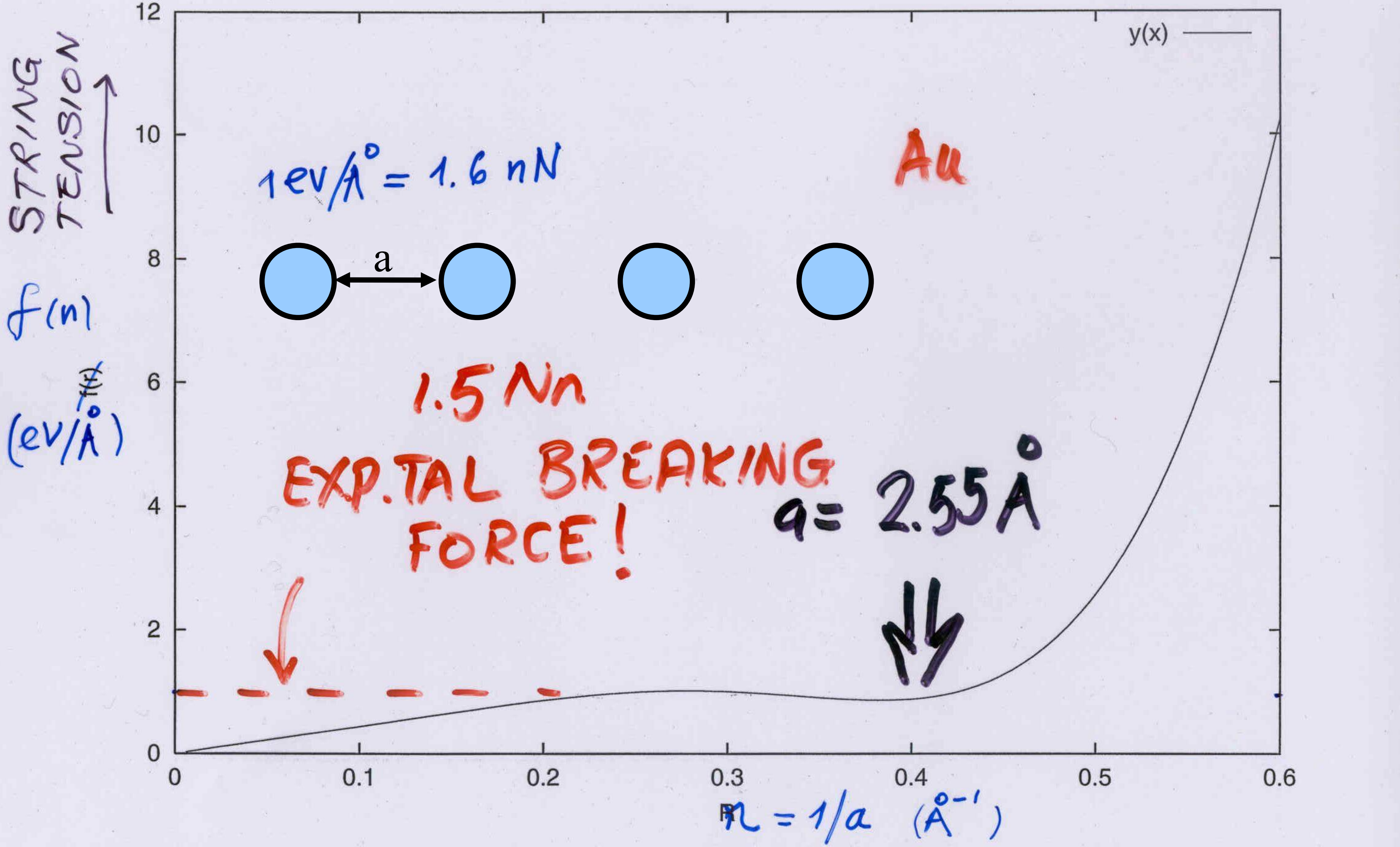




Ohnishi et al., Nature 395, 780 (1998)

Rodrigues et al., Phys. Rev. Lett, 91, 096801 (2003)

Monatomic wires are **magic** too!

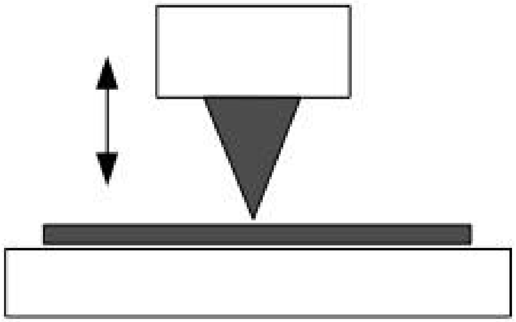


E.T., Sol. State Comm. 135, 610 (2005)

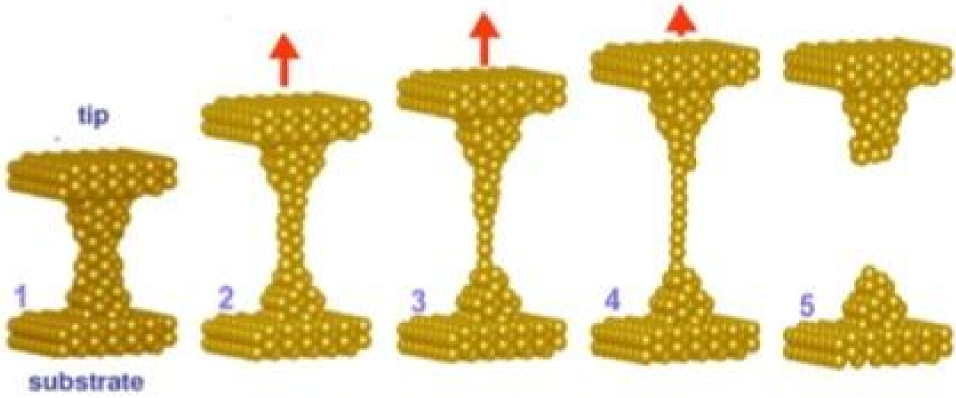
CONDUCTANCE

Fabrication of atomic-size contacts

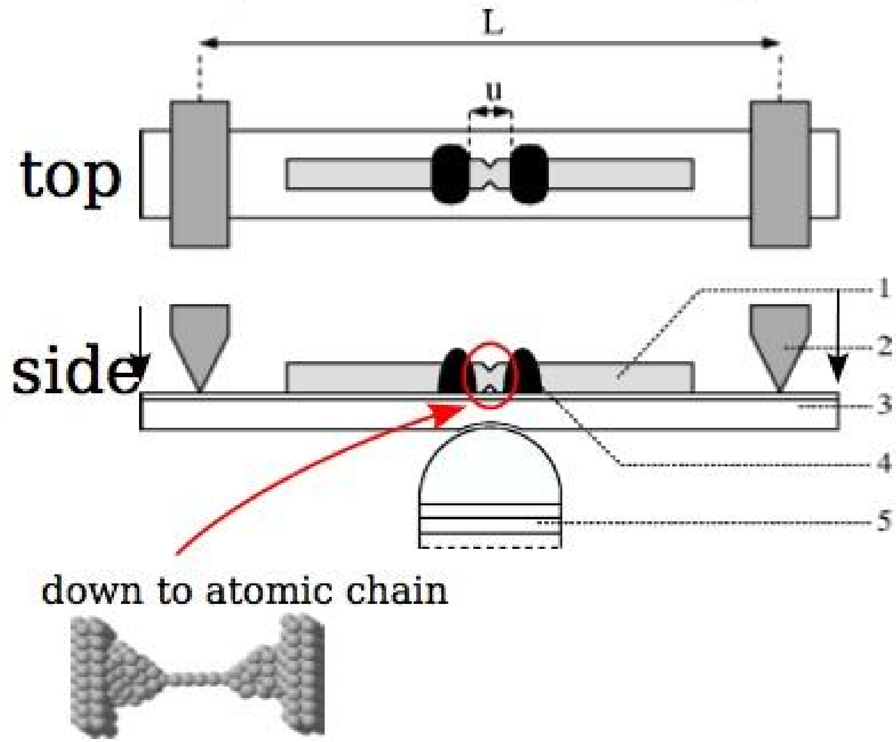
scanning tunneling microscope (STM)



Simulation of the breaking of Au nanocontact



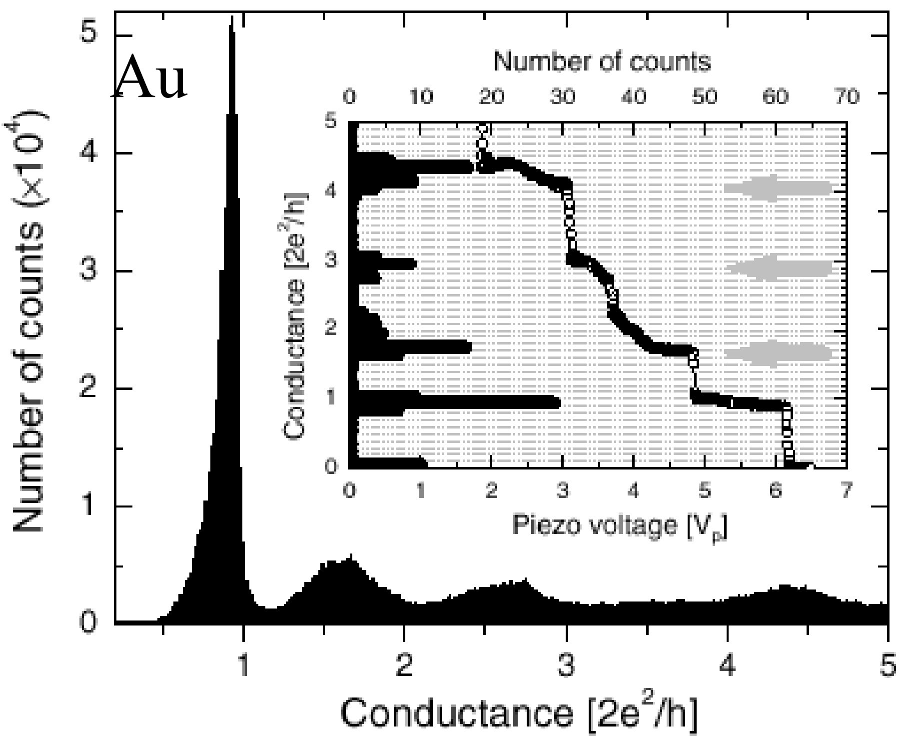
mechanically controllable break junction

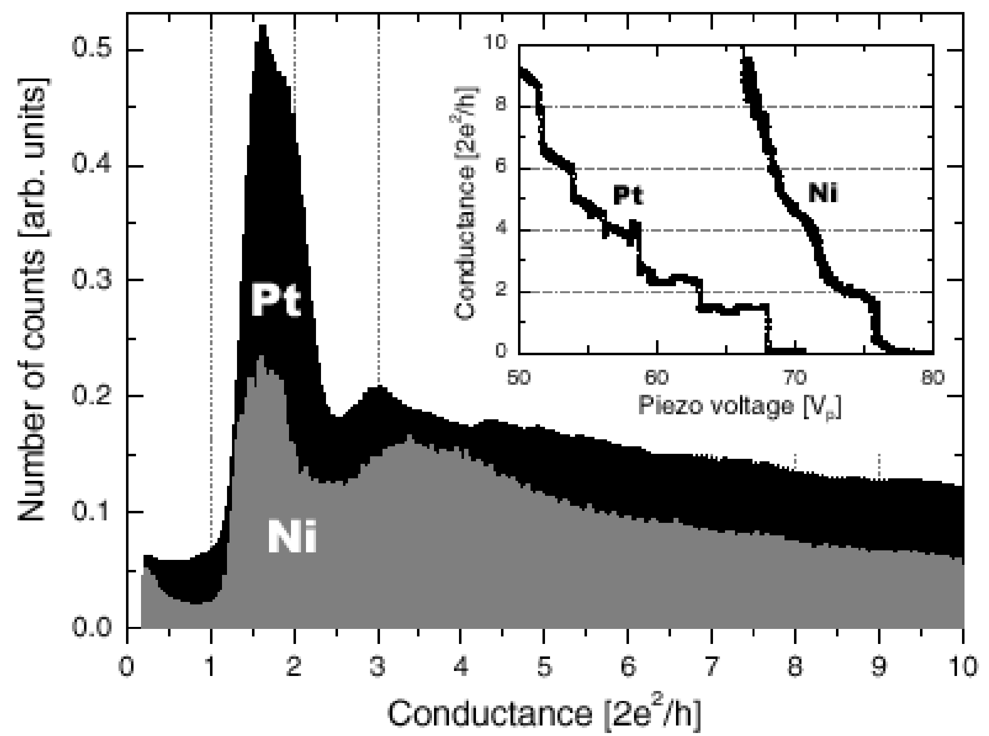


1 - notched wire
2 - fixed counter supports
3 - bending beam
4 - drops of epoxy adhesive
5 - stacked piezo element

N. Agraït *et al.*, Phys. Repts. 377, 81 (2003)

Break junction conductance histograms: quantization

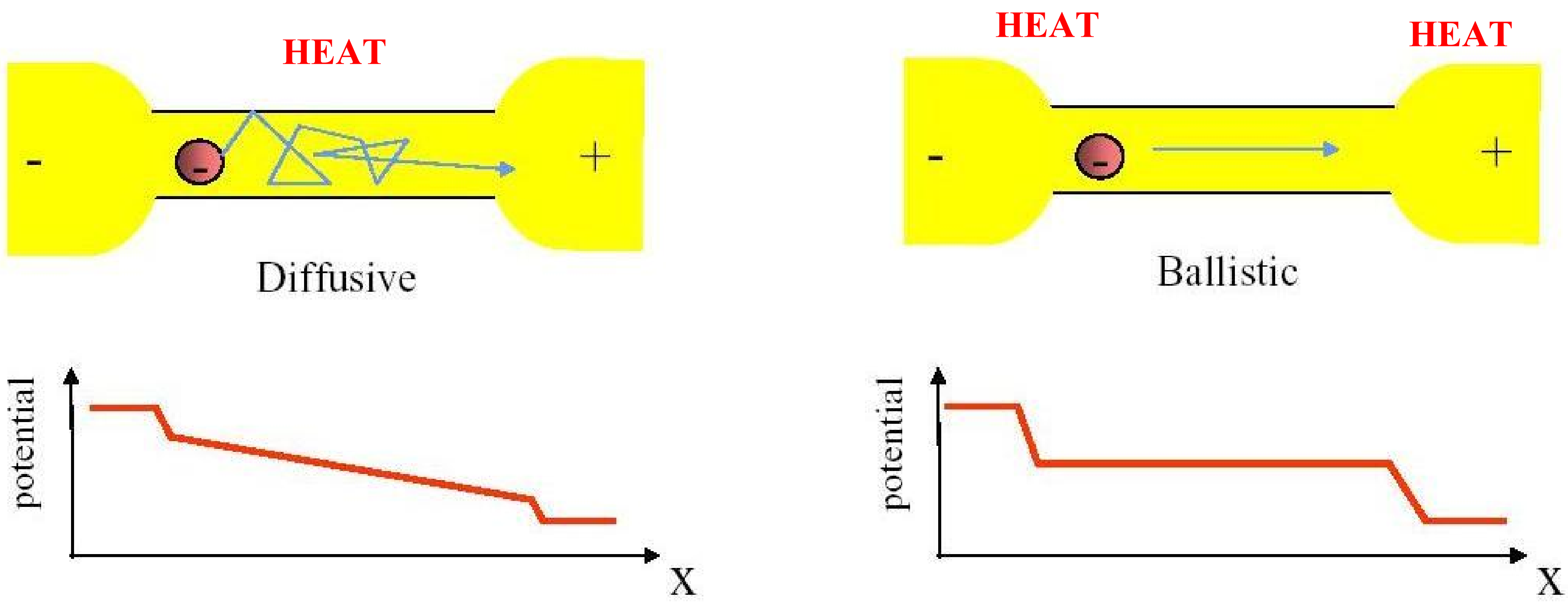




A. I. Yanson, Ph.D. Thesis, 2001

$$G_0 = 2e^2/h = (12.9\ \mathrm{K\Omega})^{-1}$$

Ballistic Electron Transport



Ohmic Conductor

$$R = \rho L/A$$

Quantum Transport

$$R = h/2e^2N$$

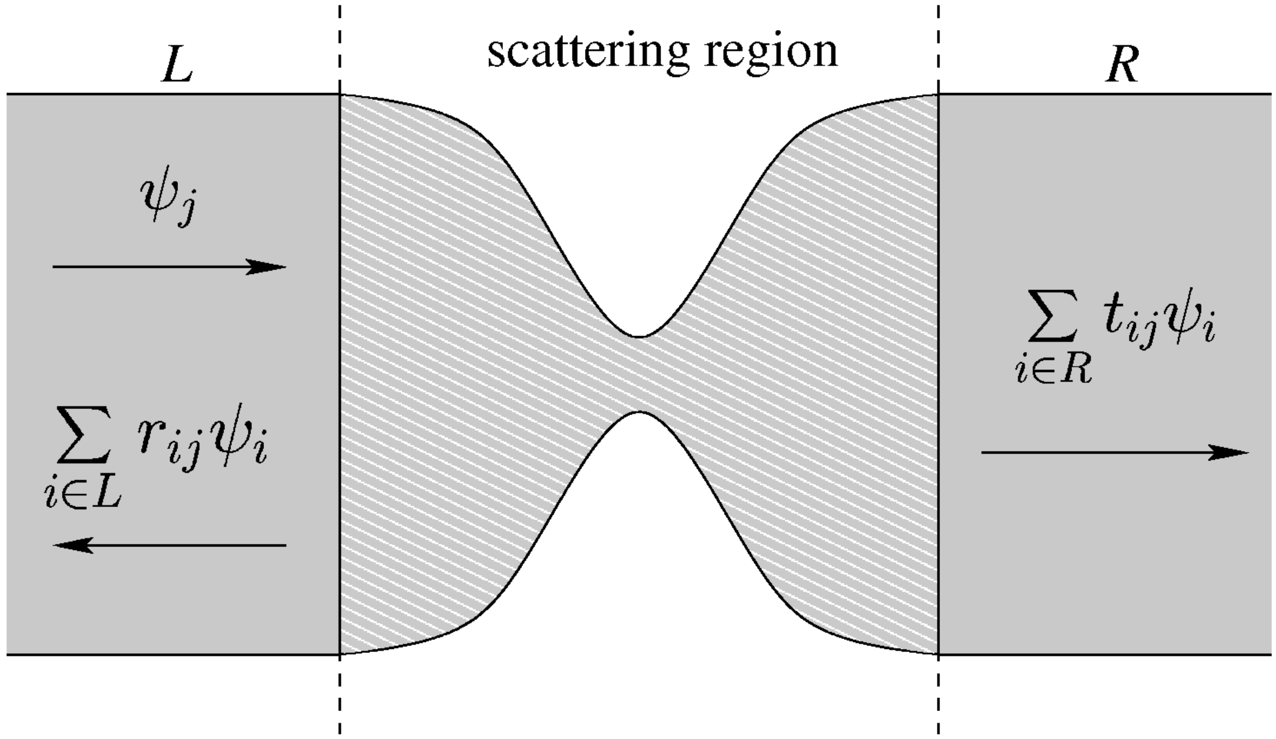
(Figure from B. Altshuler)

Ballistic conductance

Landauer-Buttiker formula for ballistic conductance:

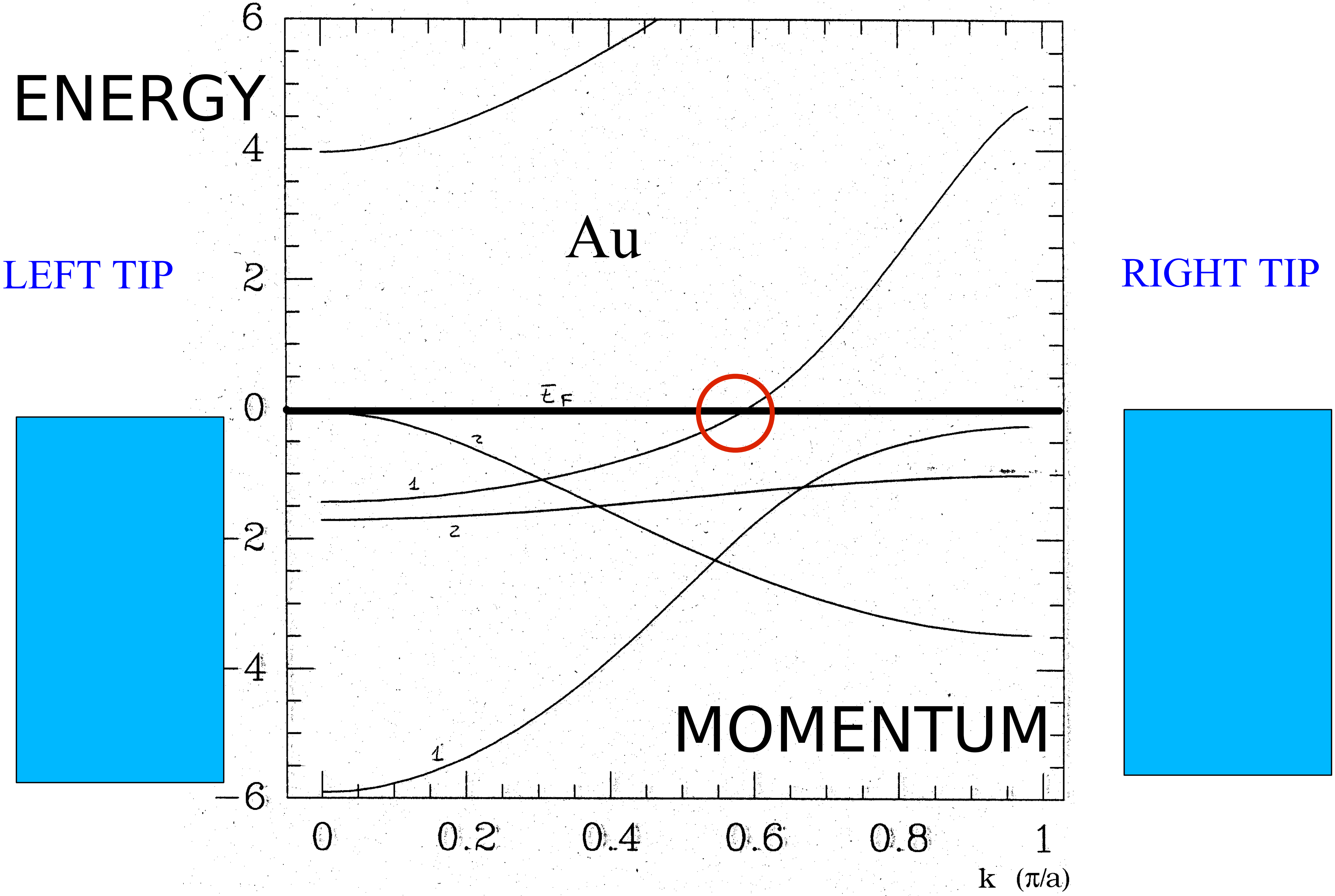
$$G = \frac{e^2}{h}\mathrm{Tr}[T^+T],$$

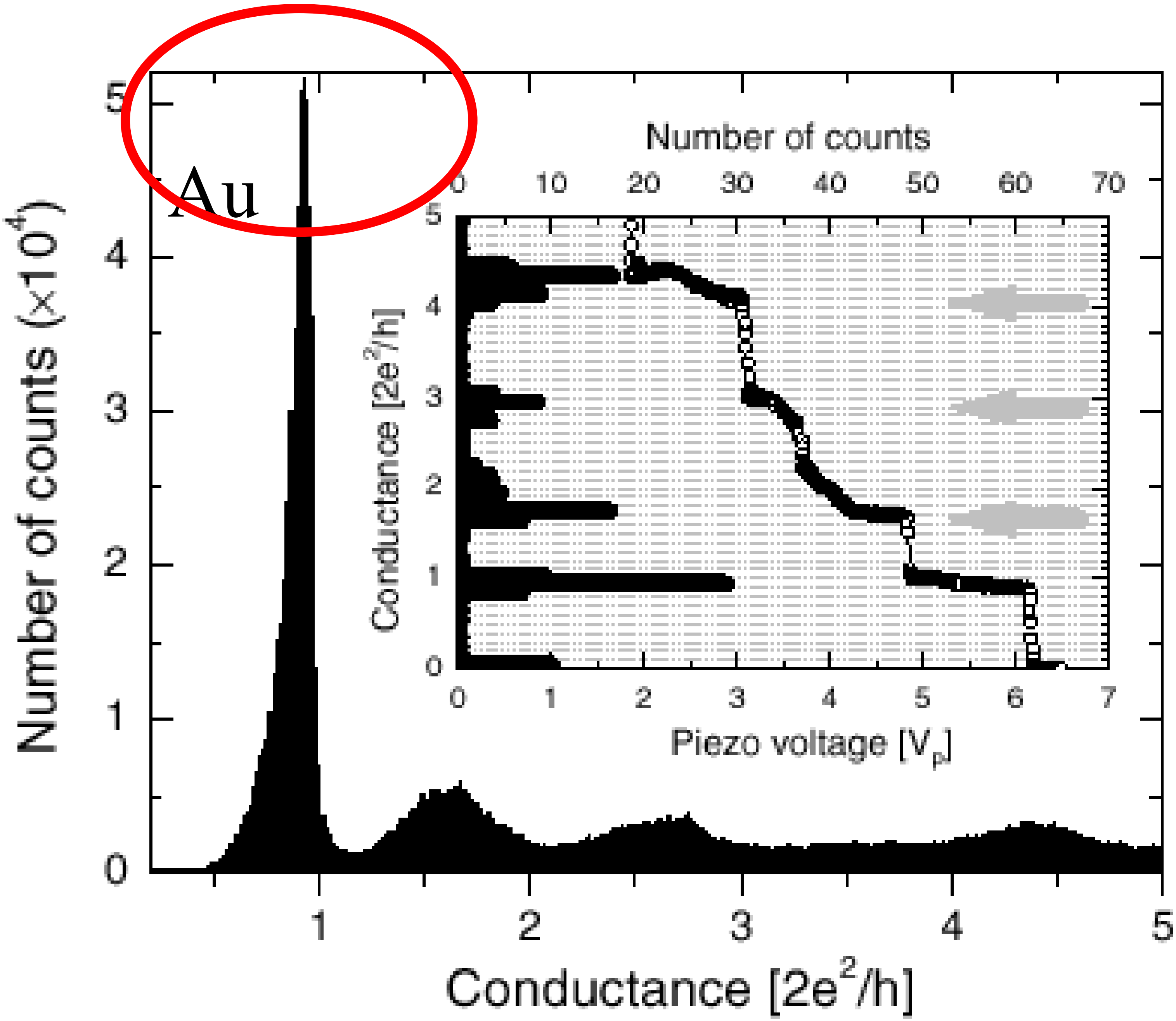
$$T_{ij} = \sqrt{\frac{I_i}{I_j}}\; t_{ij}$$



$$G < G_{MAX} = (e^2/h)\,(N_{UP} + N_{DOWN})$$

MONATOMIC Au CHAIN





A. I. Yanson, Ph.D. Thesis, 2001

COMPUTATIONAL APPROACH

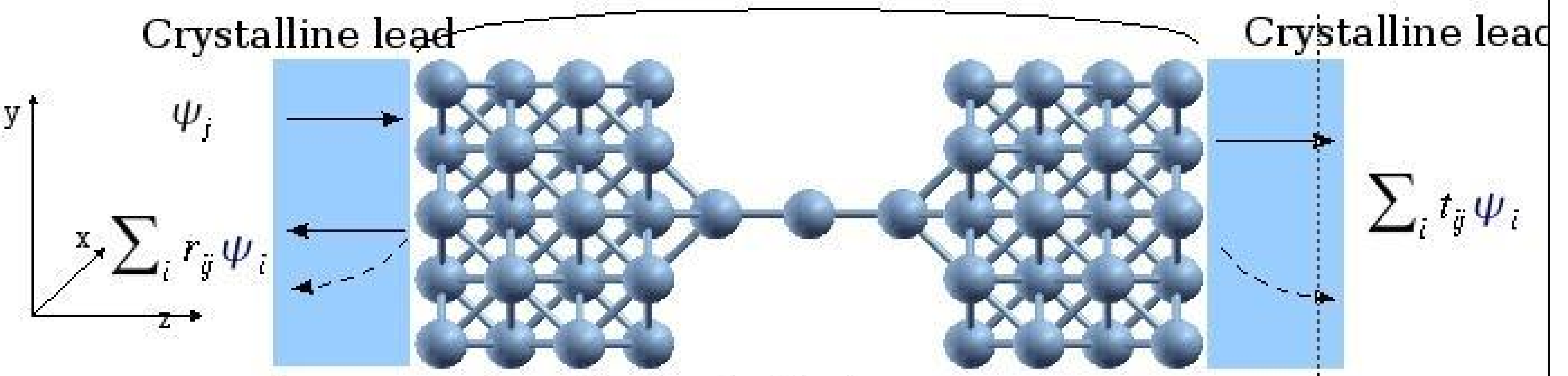
-- ELECTRONIC STRUCTURE CALCULATIONS: DENSITY FUNCTIONAL THEORY (DFT).

-- BALLISTIC CONDUCTANCE (LANDAUER) CALCULATIONS: COMPLEX BAND STRUCTURE (PLANE WAVES, ULTRASOFT PSEUDOPOTENTIALS, SPIN-ORBIT EFFECTS INCLUDED)

www.QUANTUM-ESPRESSO.org

SMOGUNOV, DAL CORSO, ET, PRB 70, 045417 (2004); PRB 73, 075418 (2006); PRB 78, 014423 (2008); [but also Mertig et al, Bluegel et al, Bagrets et al, Sanvito et al, Tsymbal et al, Barreteau et al, Brandbyge et al, Di Ventra et al, Todorov et al...

Ballistic conductance calculation



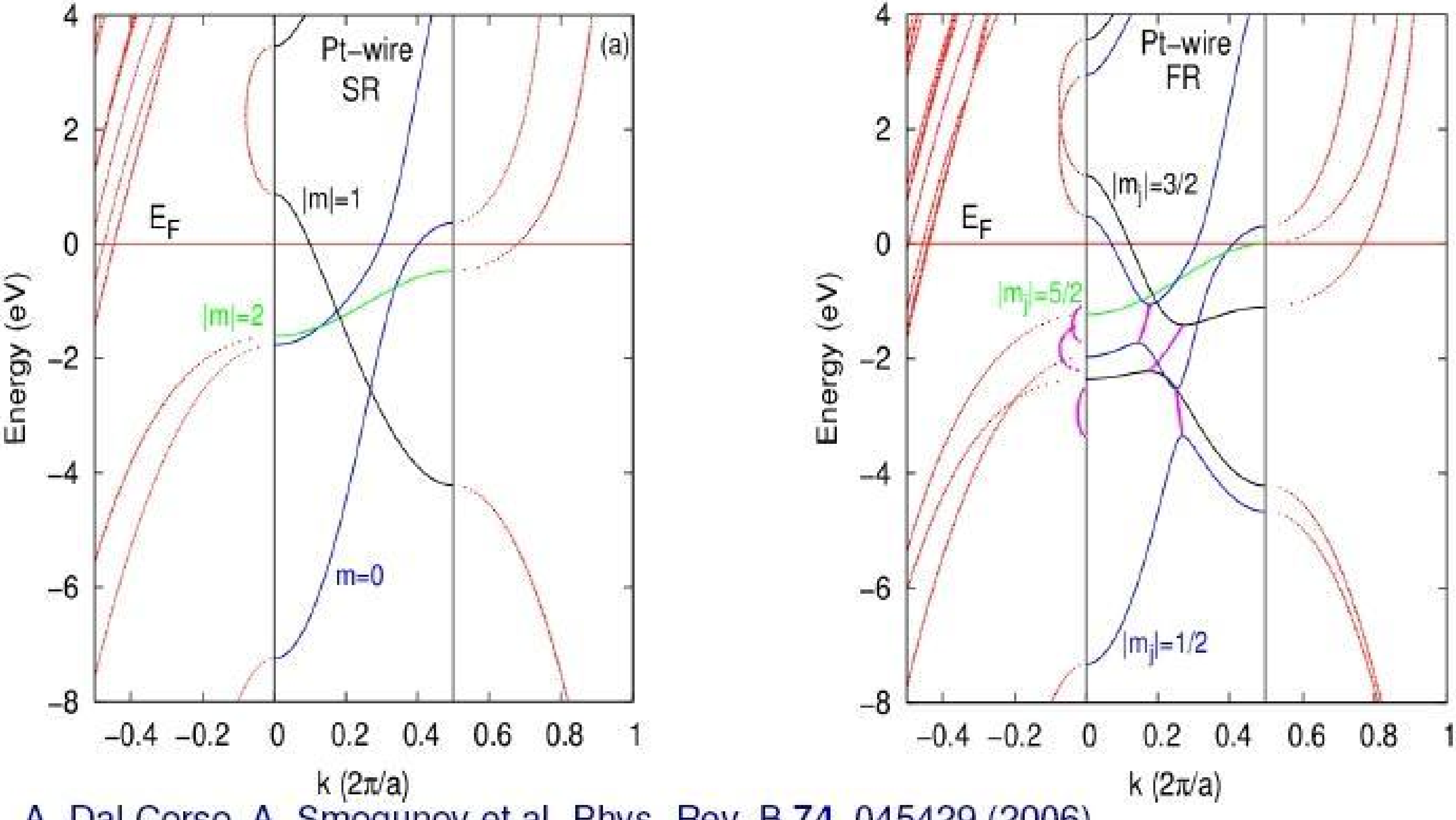
- Given the potential in the leads, find propagating (solid) and *evanescent* (dashed) states ψ_i making up the so-called *complex band structure* of the lead.
- Given s.c. potential in scattering region, construct the scattering states for each propagating wave ψ_j and find t_{ij} and r_{ij} by simple wavefunction matching
- WFs are expanded in plane waves in the *XY* plane and in the real space in the *Z*

Landauer-Büttiker formula (at zero temperature): $I = \frac{e}{h} \int_{\mu_R}^{\mu_L} T(E)\, dE$

where the total transmission $T = \sum_{ij} |t_{ij}|^2$

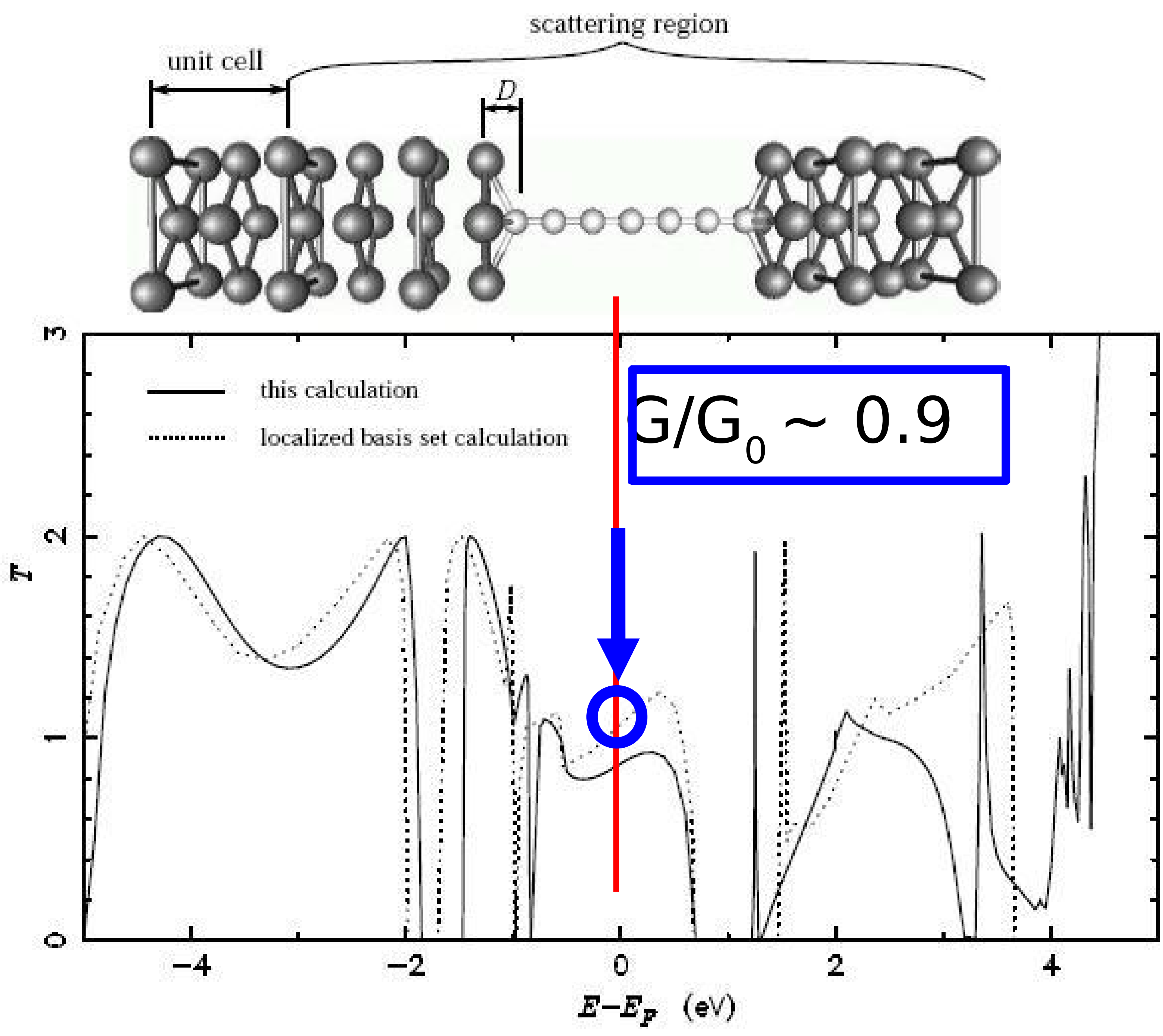
For infinitesimal voltage, $\mu_L - \mu_R = e\,\delta V$, $G = \frac{I}{\delta V} = \frac{e^2}{h} T(E_F)$.

Complex bands of a Pt monatomic wire



A. Dal Corso, A. Smogunov et al. Phys. Rev. B **74**, 045429 (2006).

TEST CASE



scattering region
unit cell
D
this calculation
localized basis set calculation
G/G0 ~ 0.9
T
0
1
2
3
−4
−2
0
2
4
E−EF (eV)

MAGNETISM

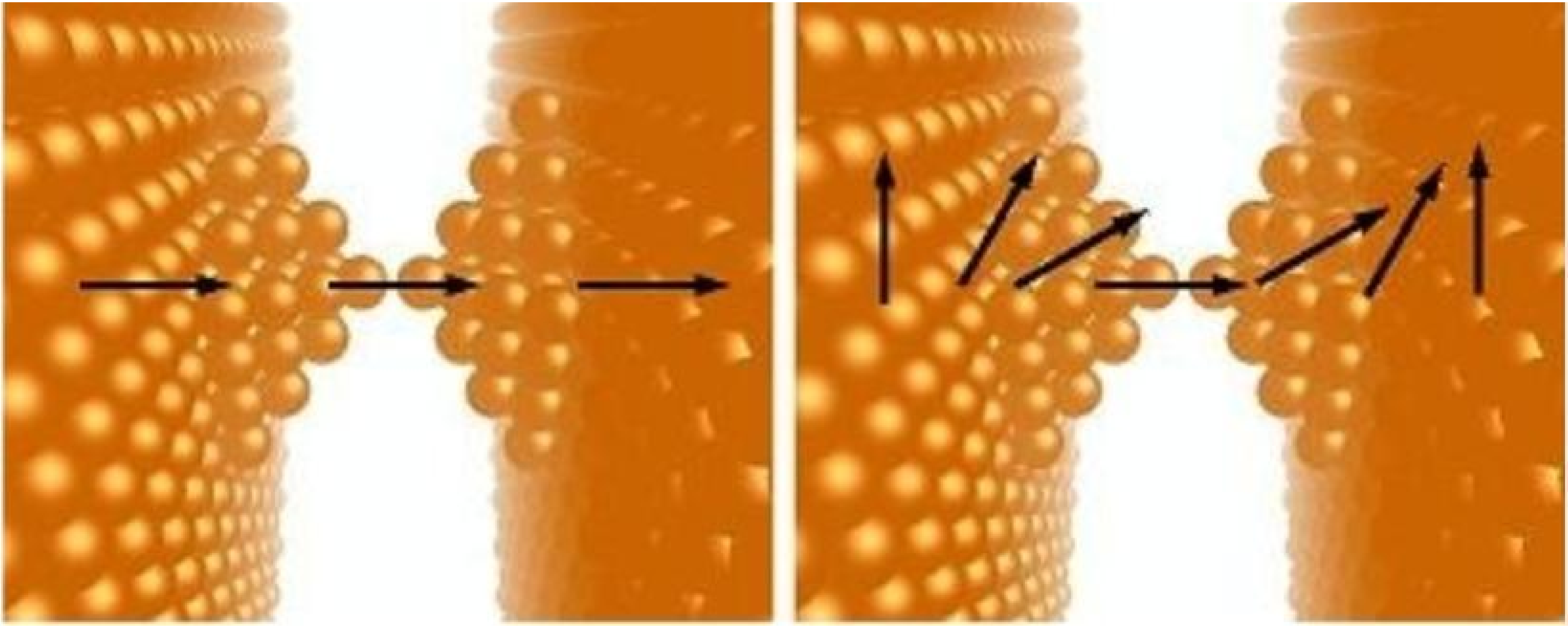
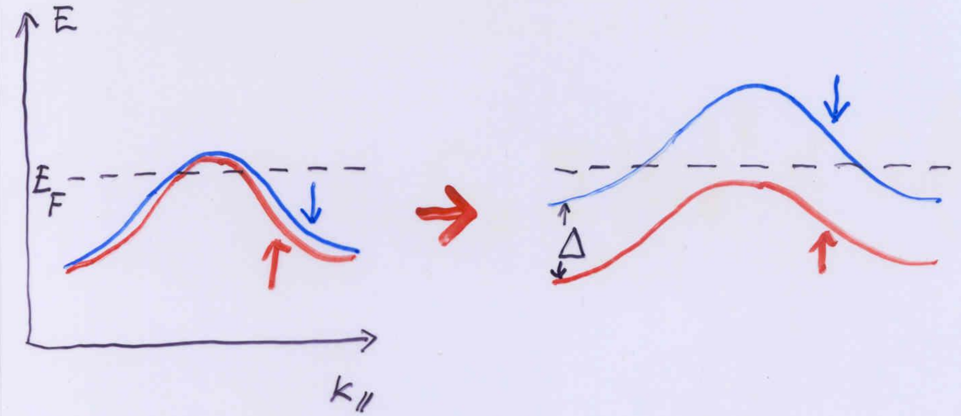


image from (Autes et al 2008)

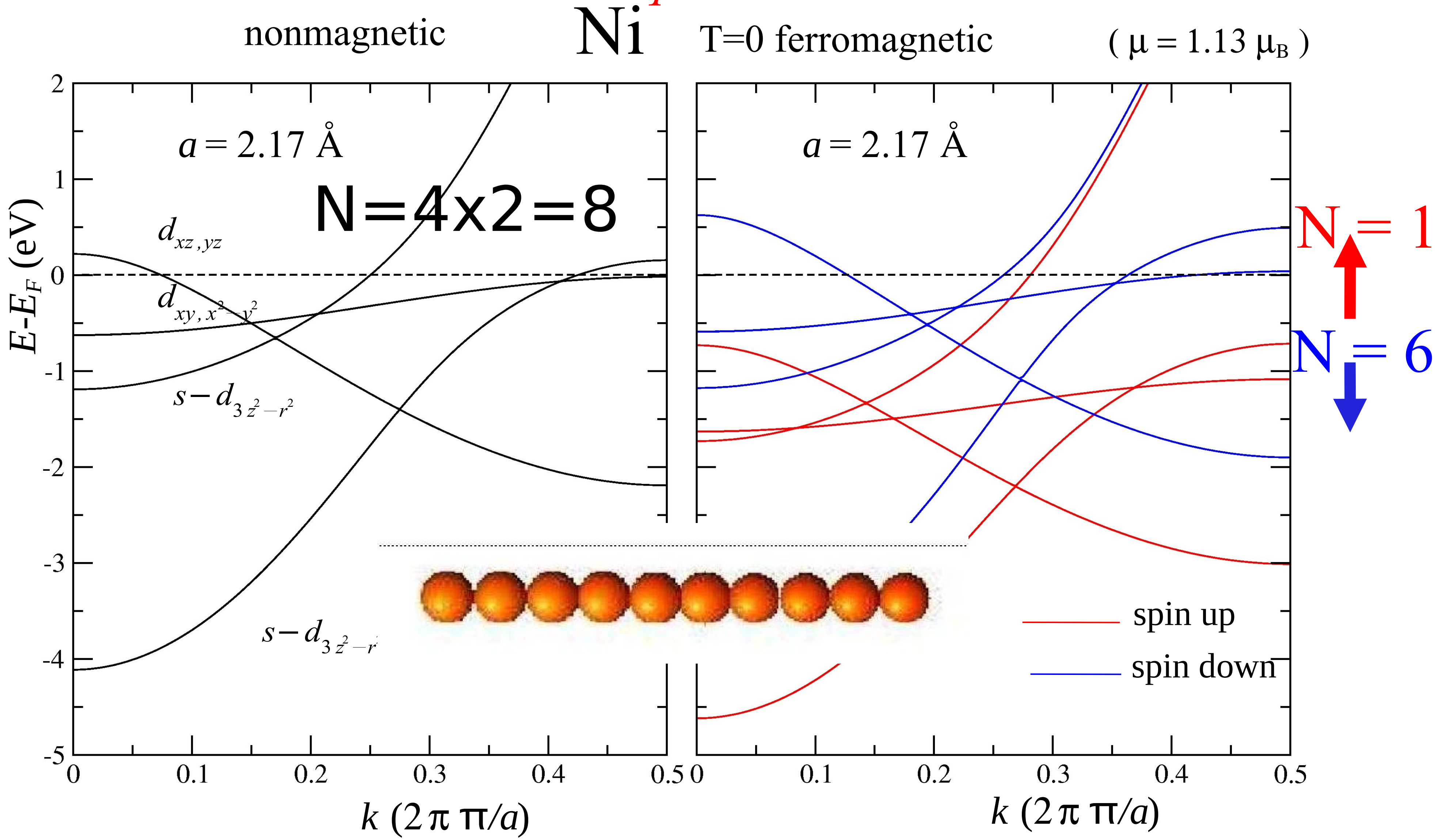
HOW **MAGNETISM** INFLUENCES BALLISTIC **CONDUCTANCE**



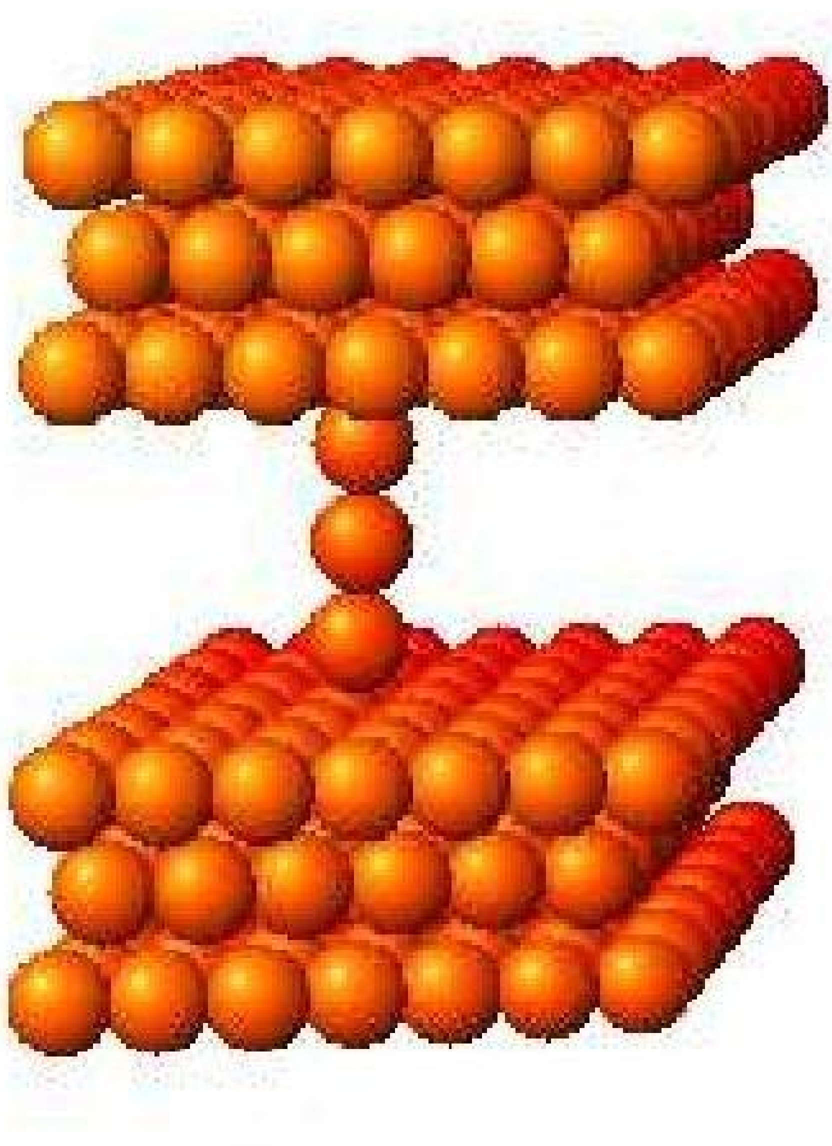
$$\frac{G}{2e^2/h} = \sum_{i\sigma} |t_{i\sigma}|^2 \lesssim N_\uparrow + N_\downarrow$$

$$G_{MAG} < G_{NON\ MAG} \qquad E = E_F$$

Electronic structure of monatomic infinite Ni wire at equilibrium



CONDUCTANCE CALCULATIONS
NICKEL NANOCONTACT



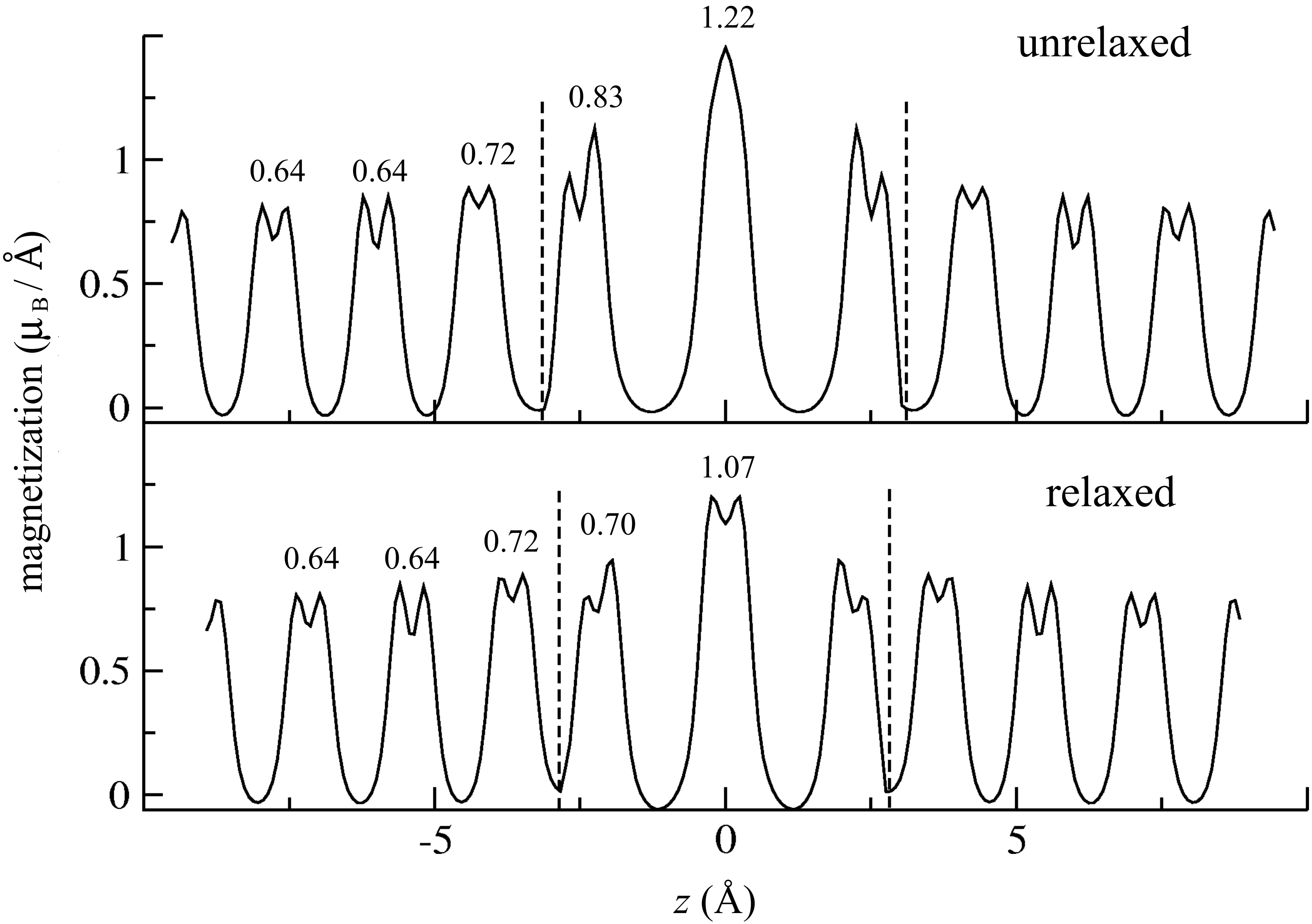
A) ab-initio electronic structure
(local spin density)

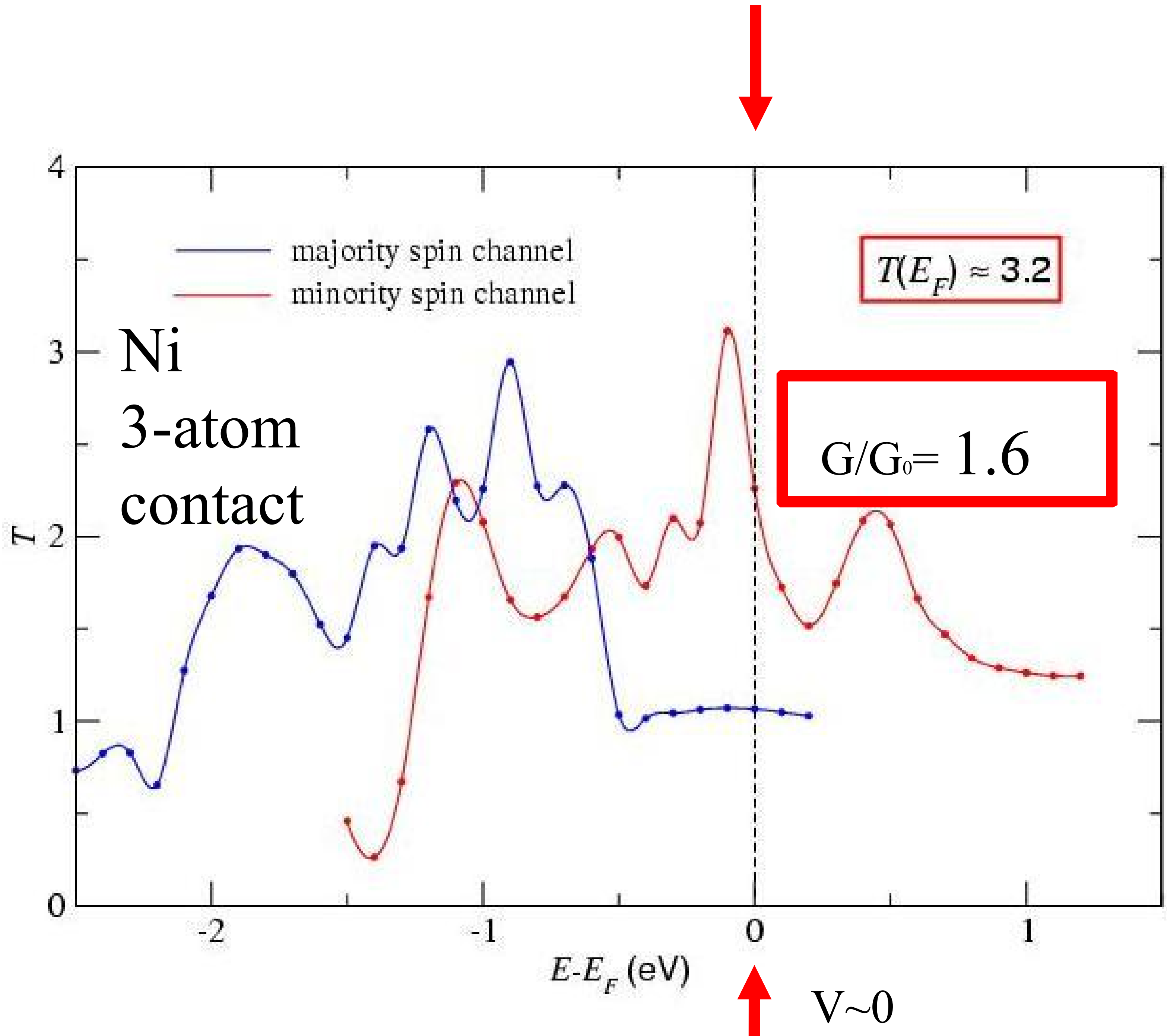
B) calculate transmission T(E)

C) ballistic conductance
$G/G_0 = 0.5\, T(E_F)$

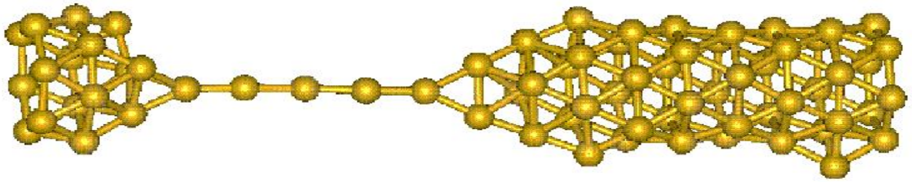
SMOGUNOV, DAL CORSO, ET
PRB 70, 045417 (2004)

Magnetization along the wire direction in the 3-atom Ni nanocontact





A. Smogunov et al (2004)



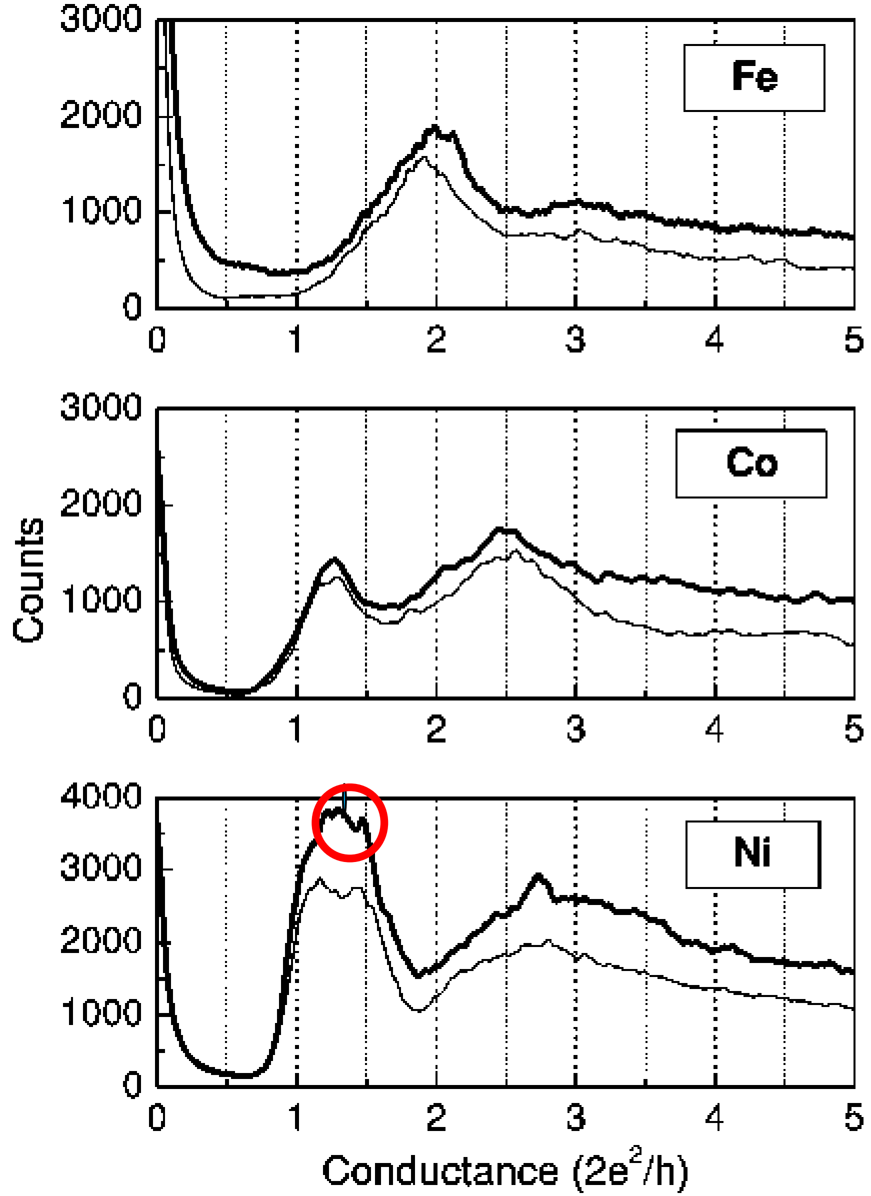
transport

s electrons

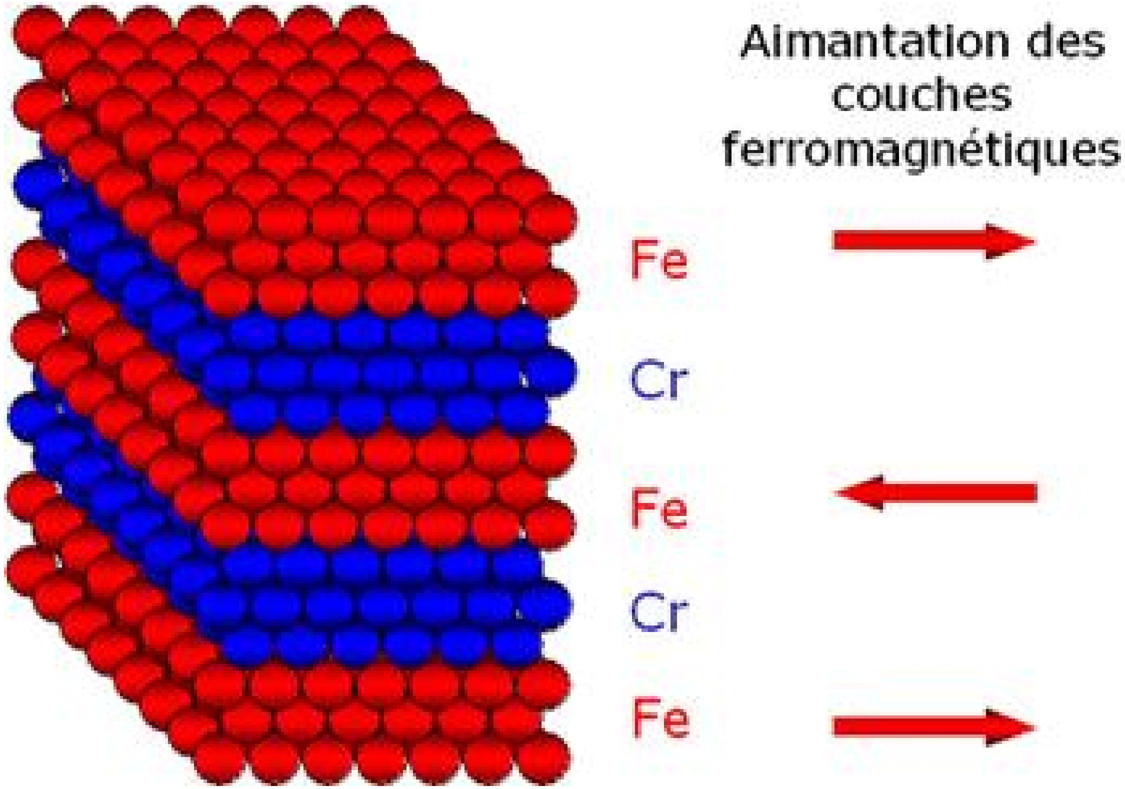
d electrons

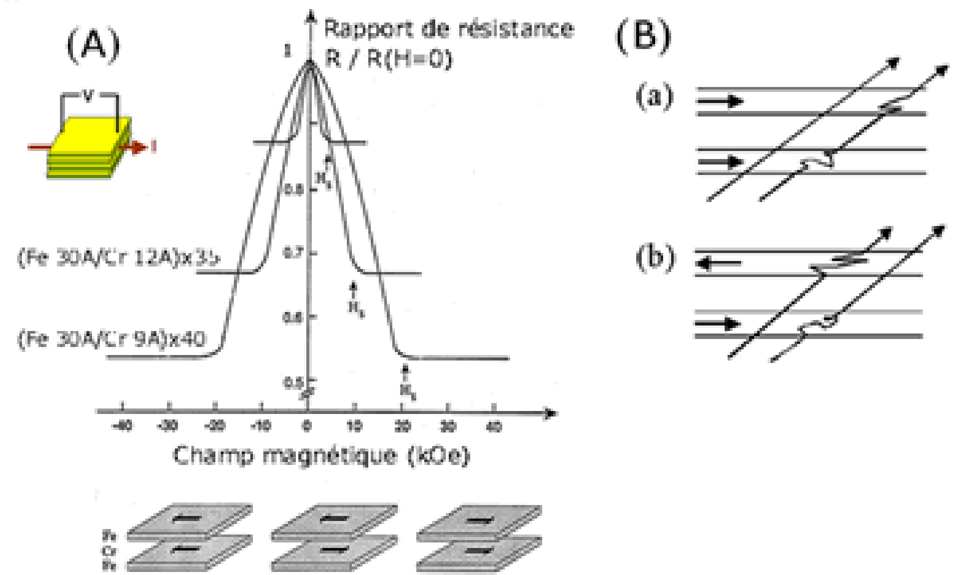
UNTIEDT, DEKKER, DJUKIC, AND VAN RUITENBEEK (2004)

T= 4.2 K



“SPINTRONICS”

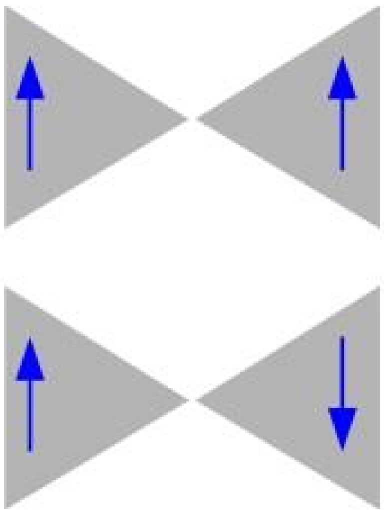




FERT

GRUENBERG

MAGNETORESISTANCE EFFECTS AT NANOCONTACTS

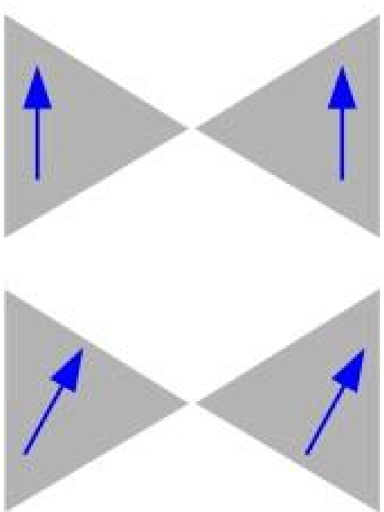


ballistic magnetoresistance (BMR)

$$\mathbf{BMR} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}}$$

Fe: BMR ~ 20-70%

M. Viret et al., PRB 66, 220401 (2002)



ballistic anisotropic magnetoresistance (BAMR)

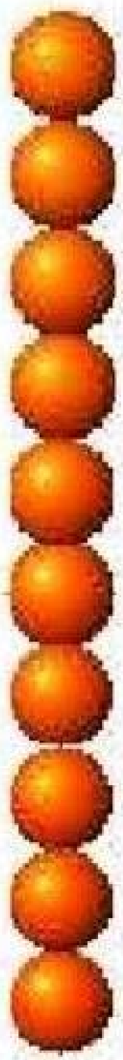
$$\mathbf{BAMR} = \frac{G_{\perp} - G_{\parallel}}{G_{\parallel}}$$

Fe : BAMR ~ 20%

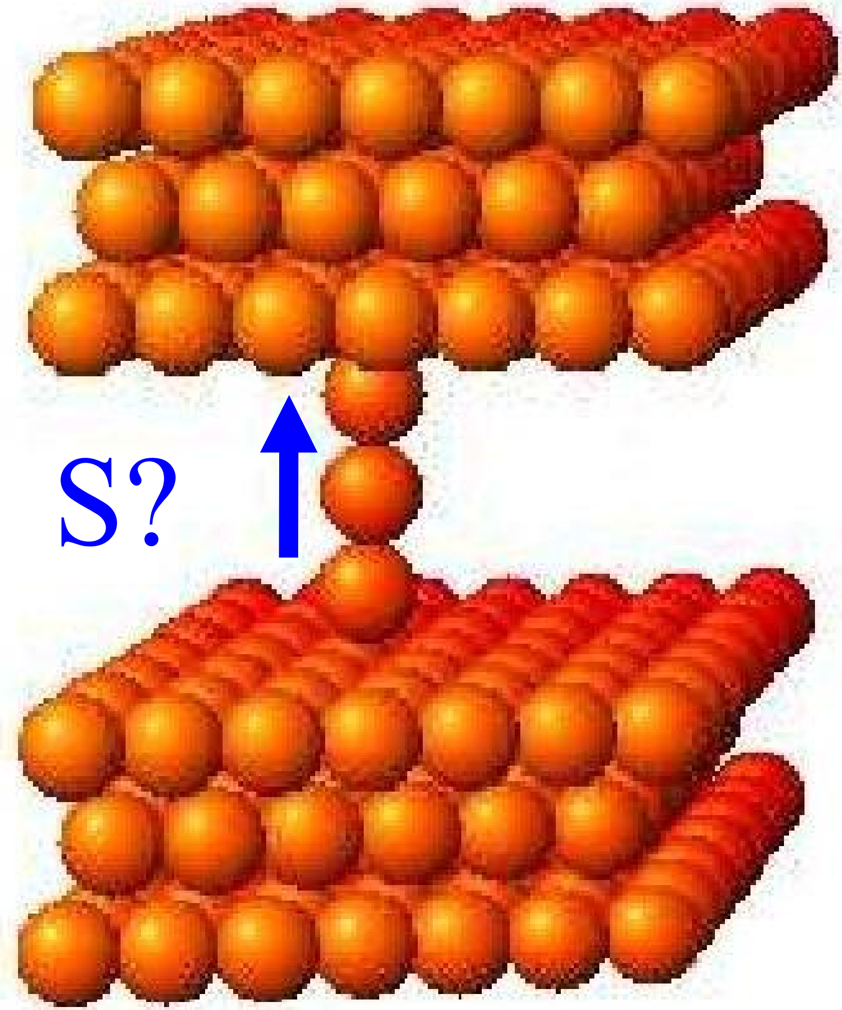
M. Viret et al., Eur. Phys. J. B 51, 1 (2006)

NANOMAGNETISM AT CONTACTS? (speculative)

CAN THIS BE LOCALLY MAGNETIC (AT T=0)?
WHAT IS THE EFFECT ON CONDUCTANCE?



Pt, Pd, ...

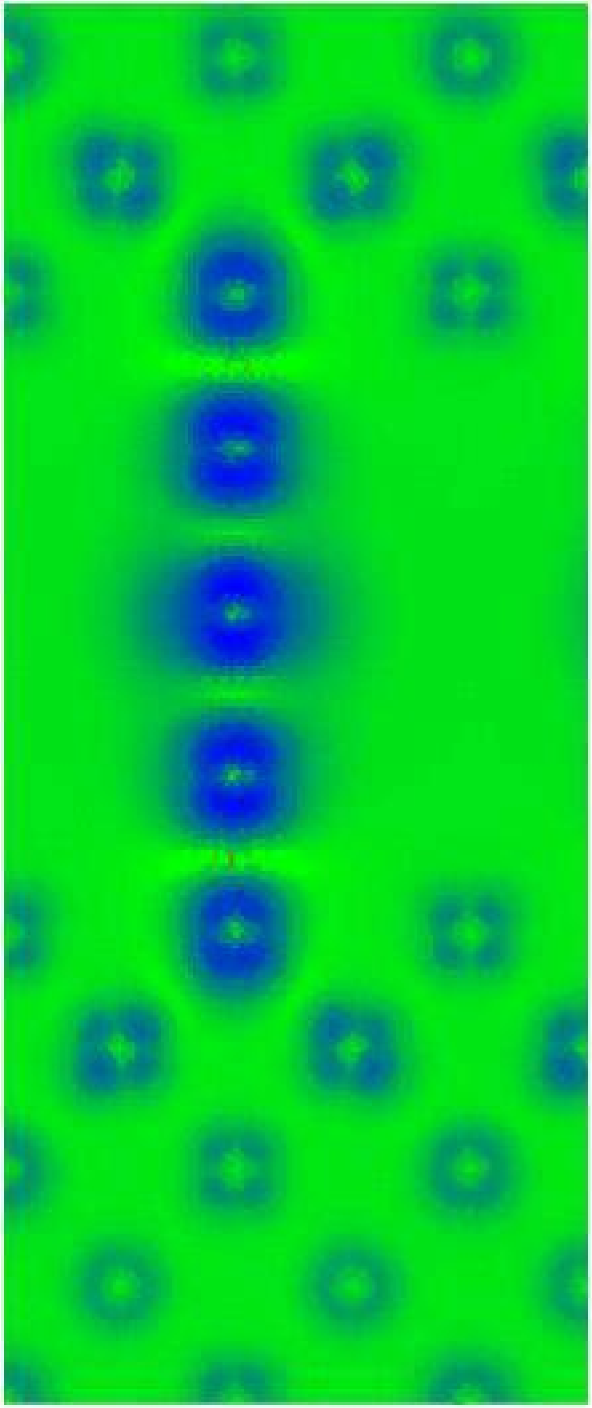


Magnetization
of Pd
3 atom
contact

0.19 μ_B

0.31 μ_B

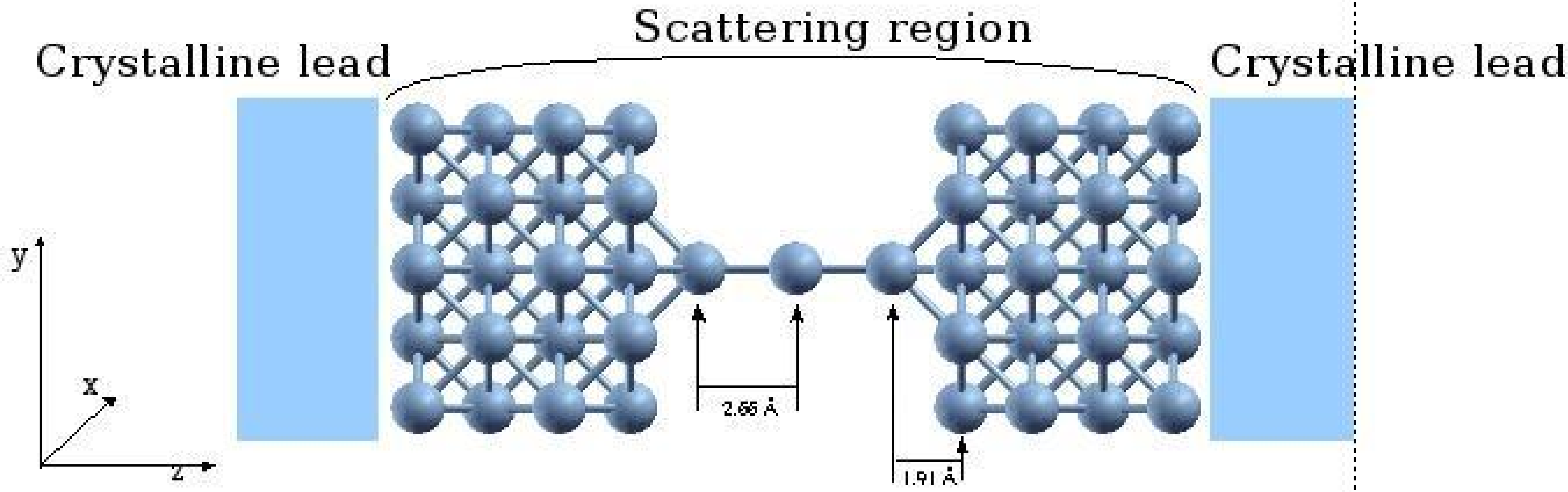
0.19 μ_B



P. Gava et al (2005)

CAUTION: A VERY WEAK EFFECT!

MODEL Pt NANOCONTACT

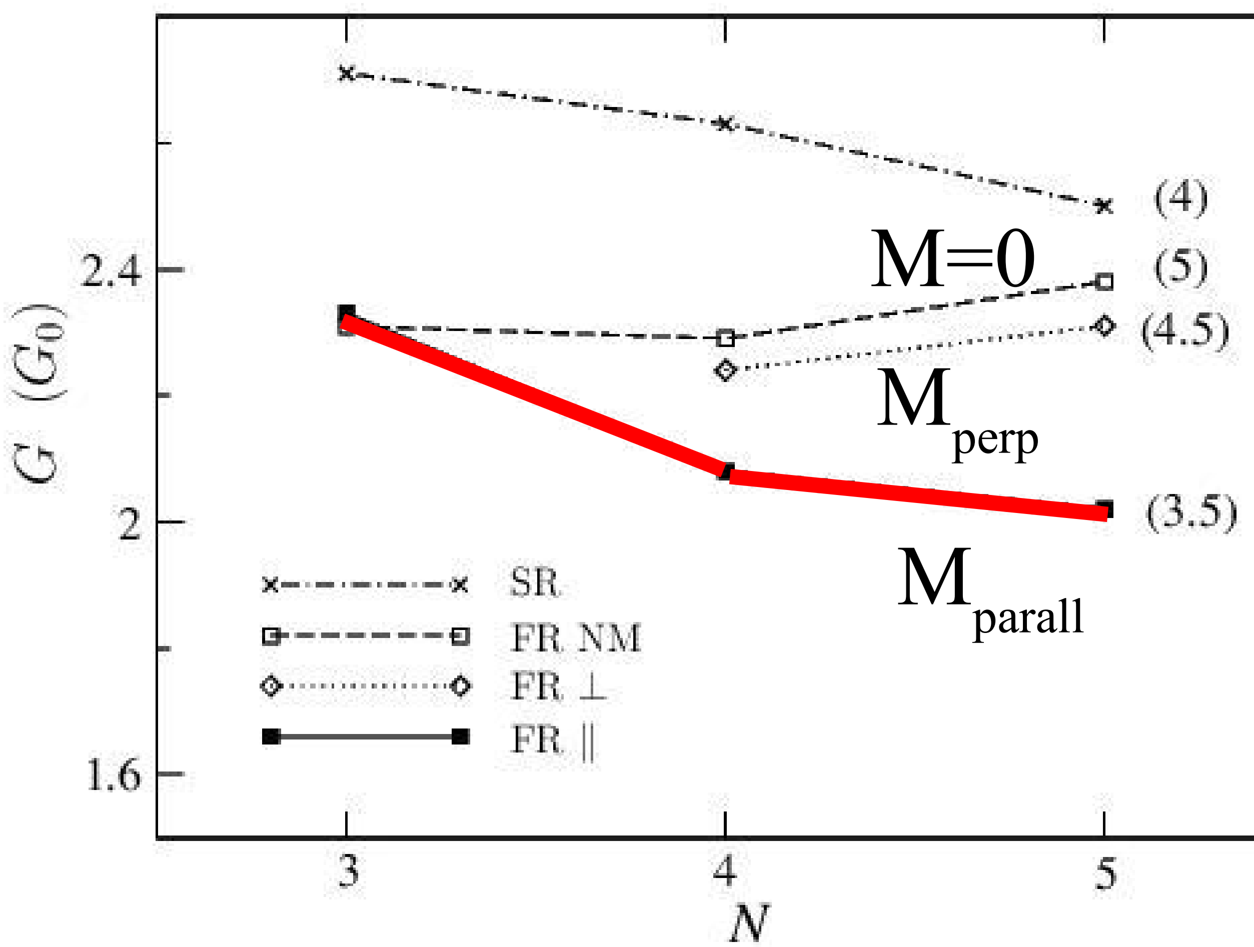


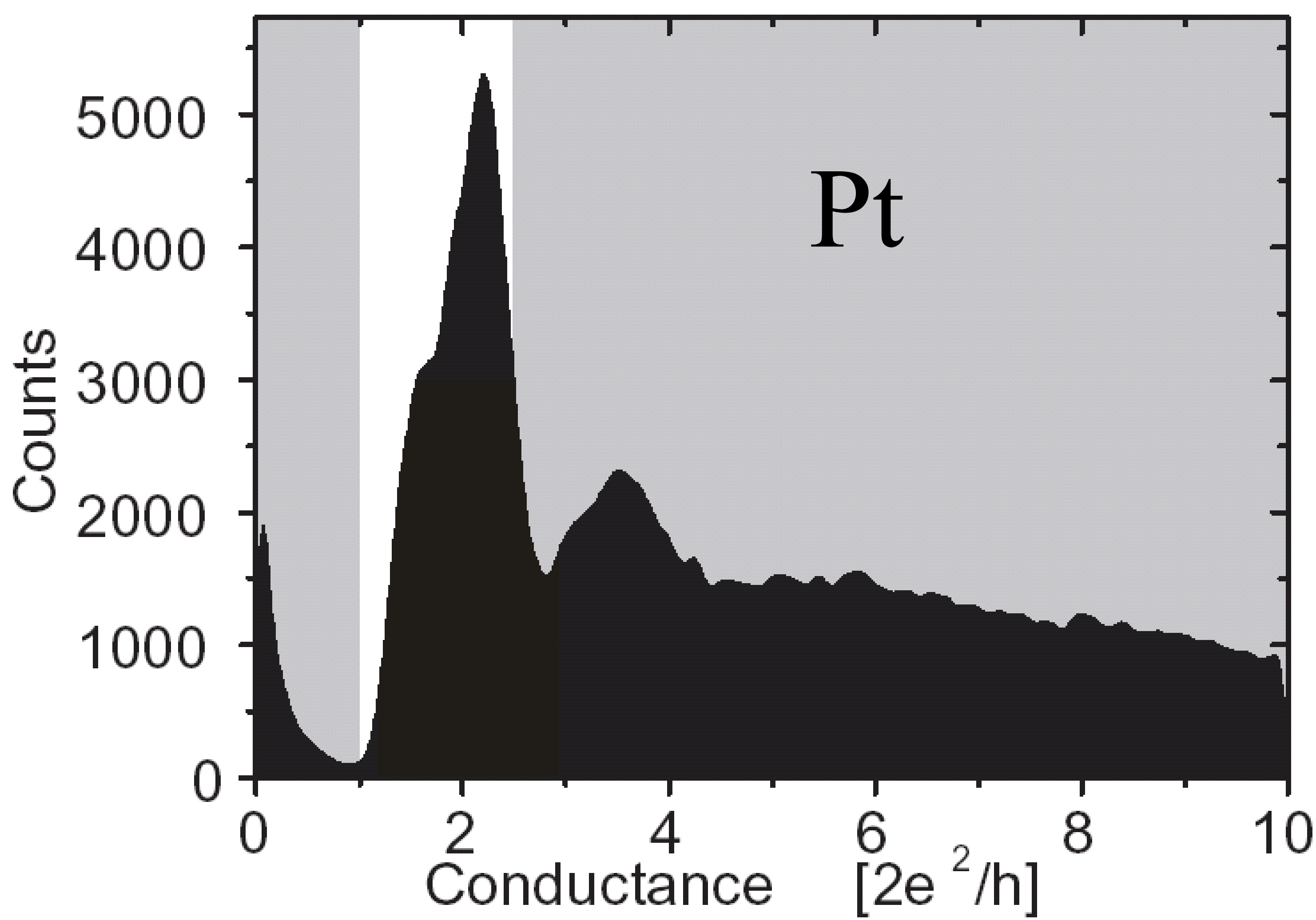
SMOGUNOV DAL CORSO, TOSATTI et al PRB 78, 014423 (2008)

- $(2\sqrt{2}\times 2\sqrt{2})$ periodicity in xy plane (8 atoms per layer)
- 7 crystalline layers in z direction simulate bulk leads
- total transmission averaged over 2D BZ (perp. to wire):

$$T(E)=\sum_{IBZ} w_{k_\parallel} T(k_\parallel, E), \quad \sum_{IBZ} w_{k_\parallel}=1$$

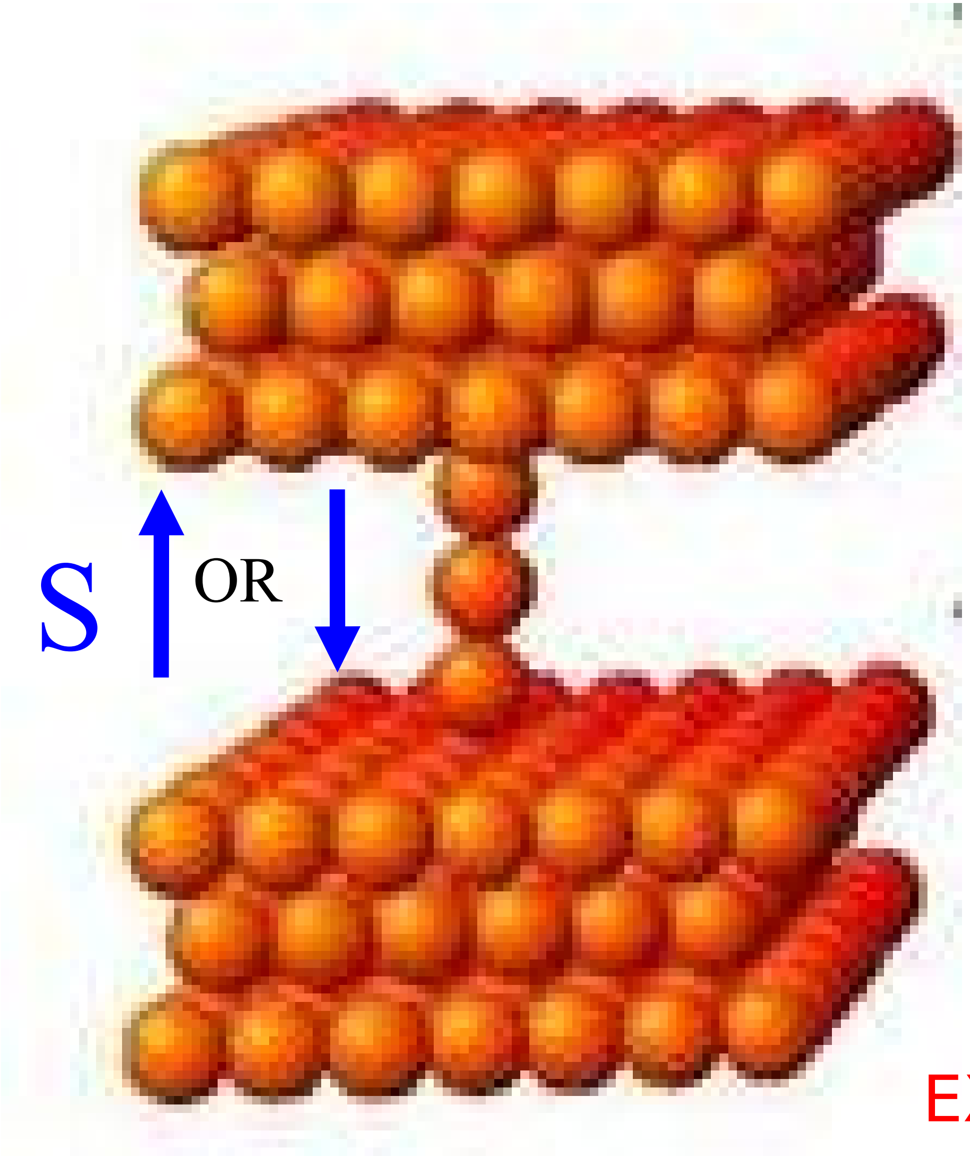
BALLISTIC CONDUCTANCE OF AN N-ATOM Pt NANOWIRE, Pt TIPS





SMIT et al, 2001

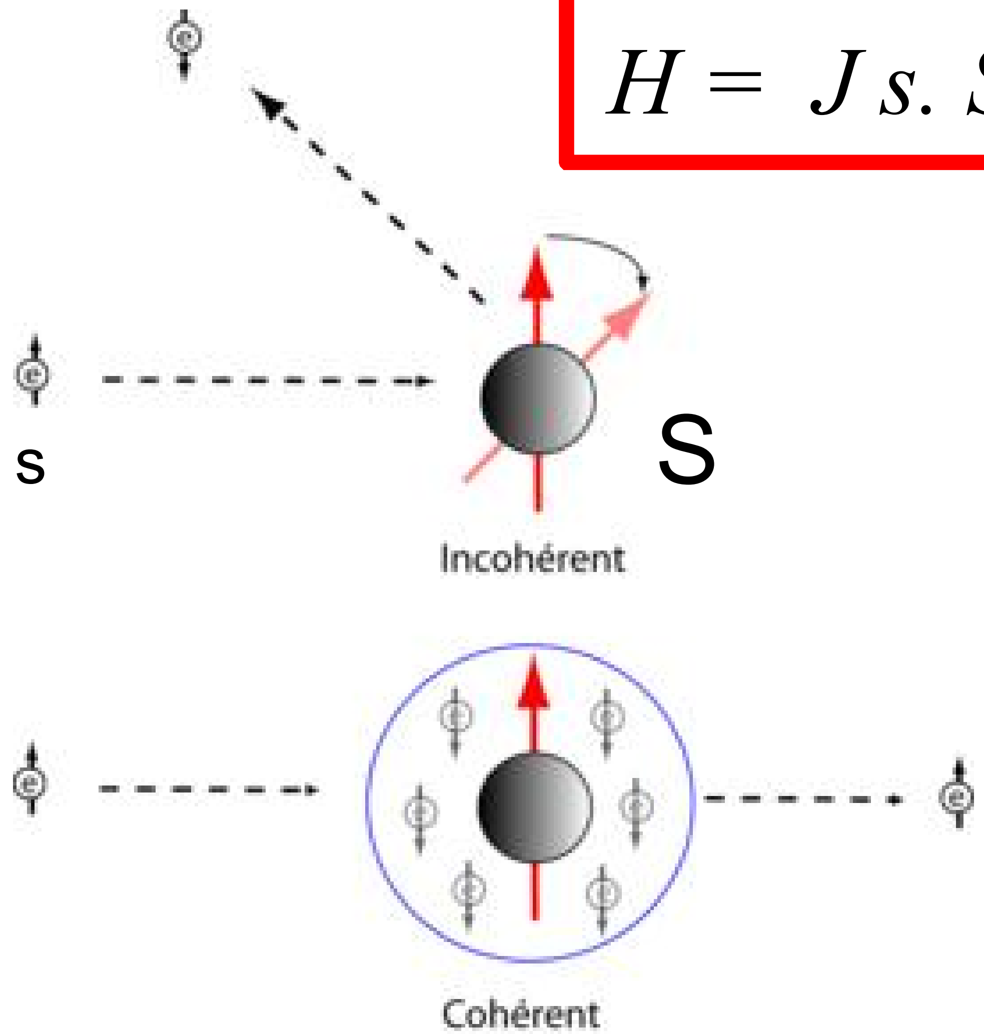
SPECULATION:
TIP-SUSPENDED Pt NANOWIRE:
AN ISING – LIKE NANOMAGNET



EXPERIMENT?

KONDO EFFECT

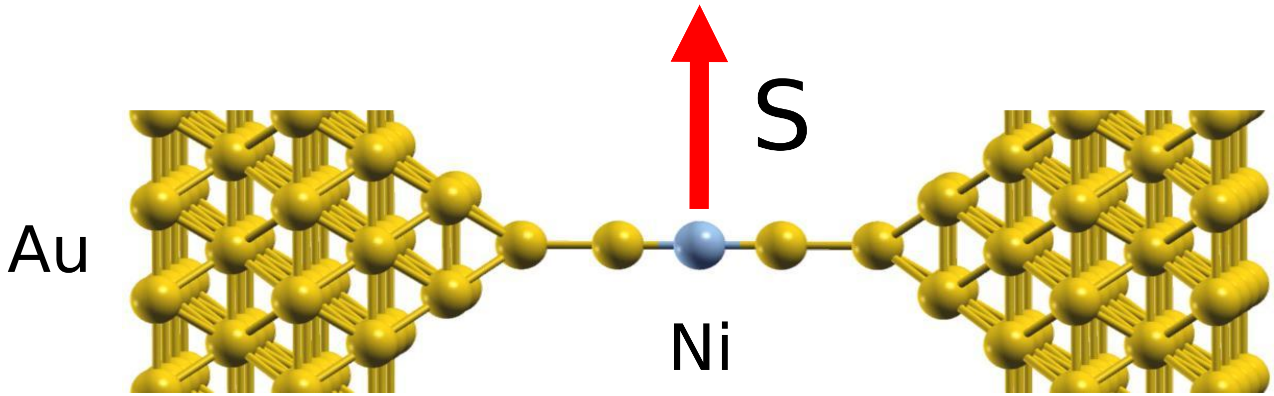
$$H = J\, s.\, S \qquad J > 0$$

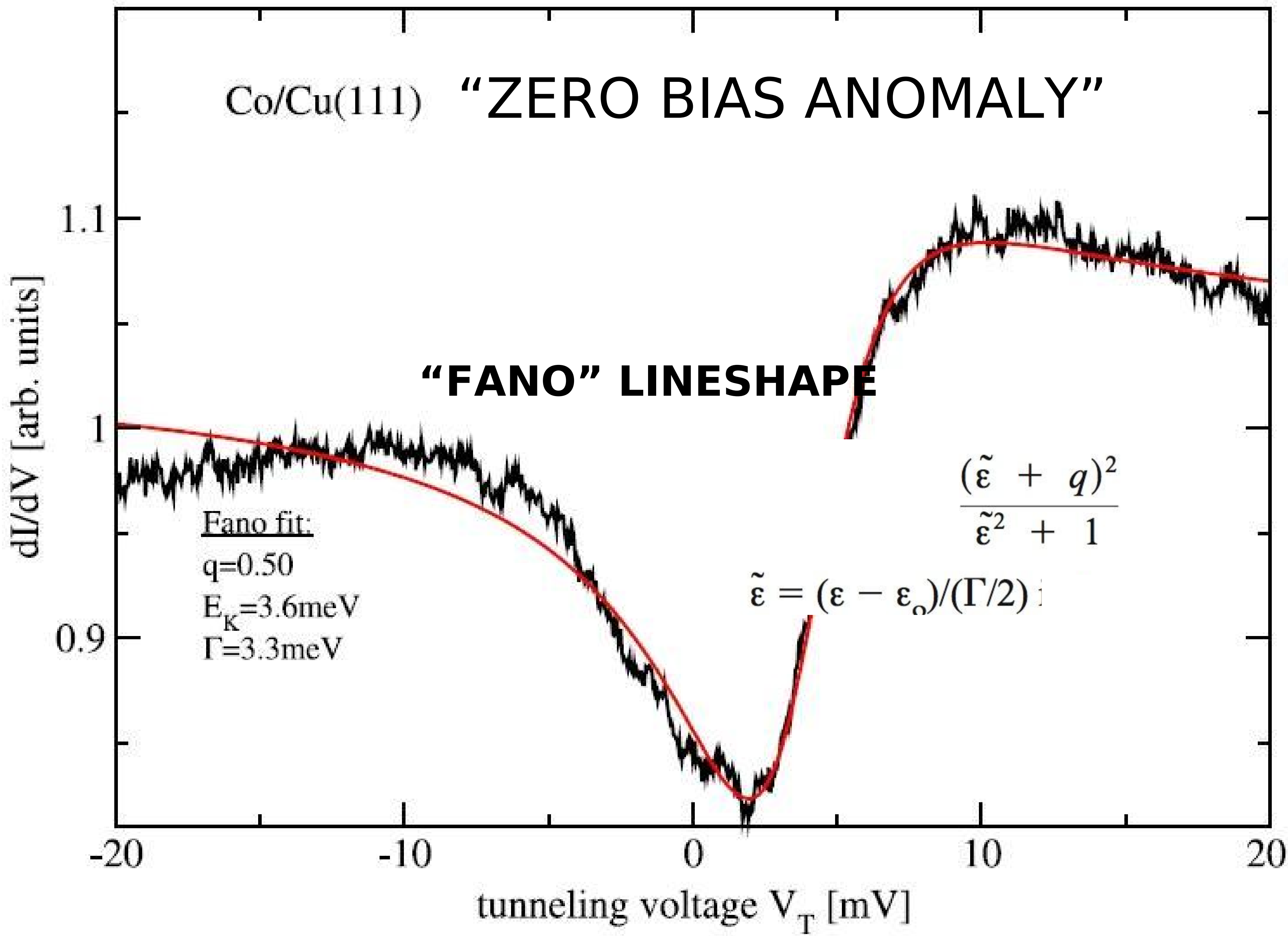


SCREENING

Jun Kondo

MAGNETIC IMPURITY IN A NONMAGNETIC METAL NANOCONTACT

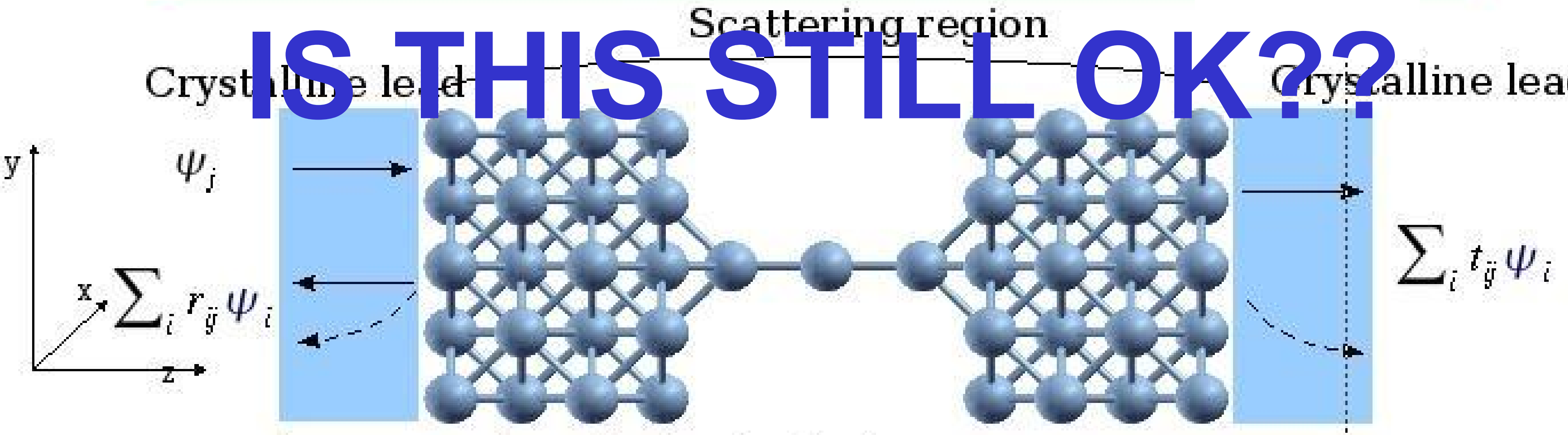




Co/Cu(111)
“ZERO BIAS ANOMALY”
“FANO” LINESHAPE
$\frac{(\tilde{\varepsilon} + q)^2}{\tilde{\varepsilon}^2 + 1}$
$\tilde{\varepsilon} = (\varepsilon - \varepsilon_o)/(\Gamma/2)$
Fano fit:
q=0.50
E_K=3.6meV
Γ=3.3meV
1.1
1
0.9
-20
-10
0
10
20
dI/dV [arb. units]
tunneling voltage V_T [mV]

Ballistic conductance calculation

IS THIS STILL OK??



- Given the potential in the leads, find propagating (solid) and *evanescent* (dashed) states ψ_i making up the so-called *complex band structure* of the lead.
- Given s.c. potential in scattering region, construct the scattering states for each propagating wave ψ_j and find t_{ij} and r_{ij} by simple wavefunction matching
- WFs are expanded in plane waves in the XY plane and in the real space in the Z

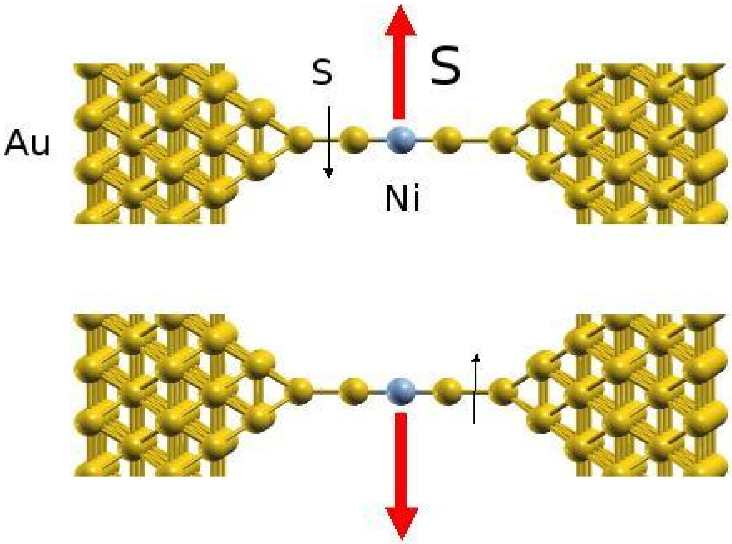
Landauer-Büttiker formula (at zero temperature): $I = \frac{e}{h}\int_{\mu_R}^{\mu_L} T(E)\,dE$

NO!!

where the total transmission $T = \sum_{ij} |t_{ij}|^2$

For infinitesimal voltage, $\mu_L - \mu_R = e\,\delta V$, $G = \frac{I}{\delta V} = \frac{e^2}{h} T(E_F)$.

MANY BODY EFFECT

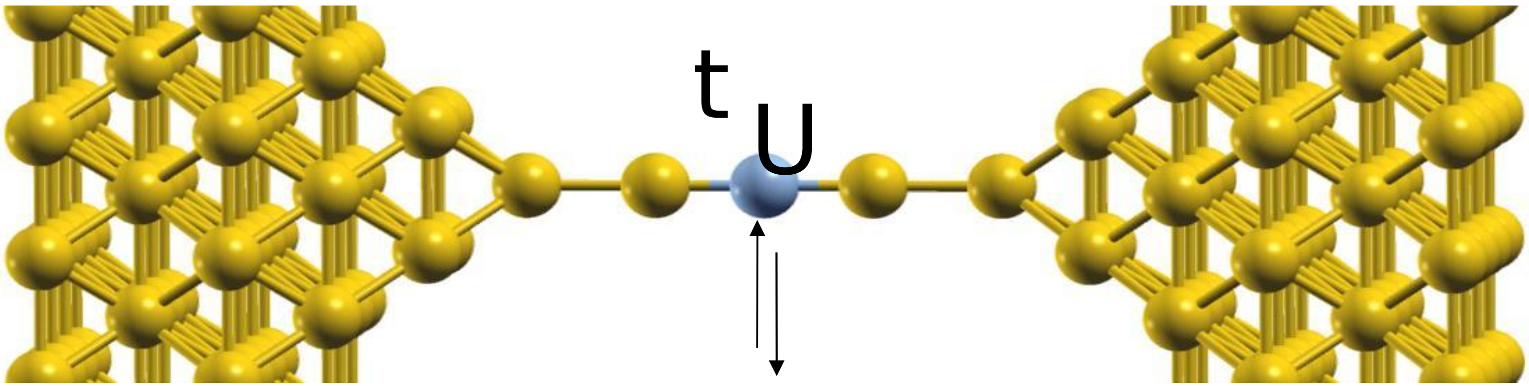


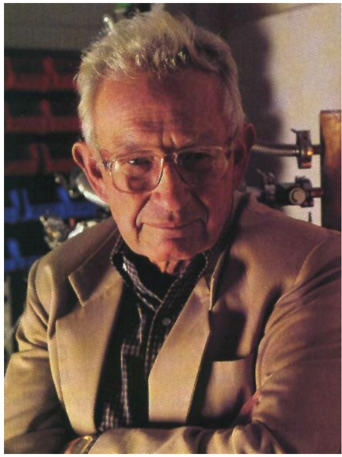
t

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}}\, c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{\sqrt{\Omega}} \left(V_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} d_{\sigma} + \mathrm{H.c.} \right)$$

$$+ \epsilon_d n_d + \frac{U}{2} \left(n_d - 1 \right)^2 ,$$

ANDERSON MODEL

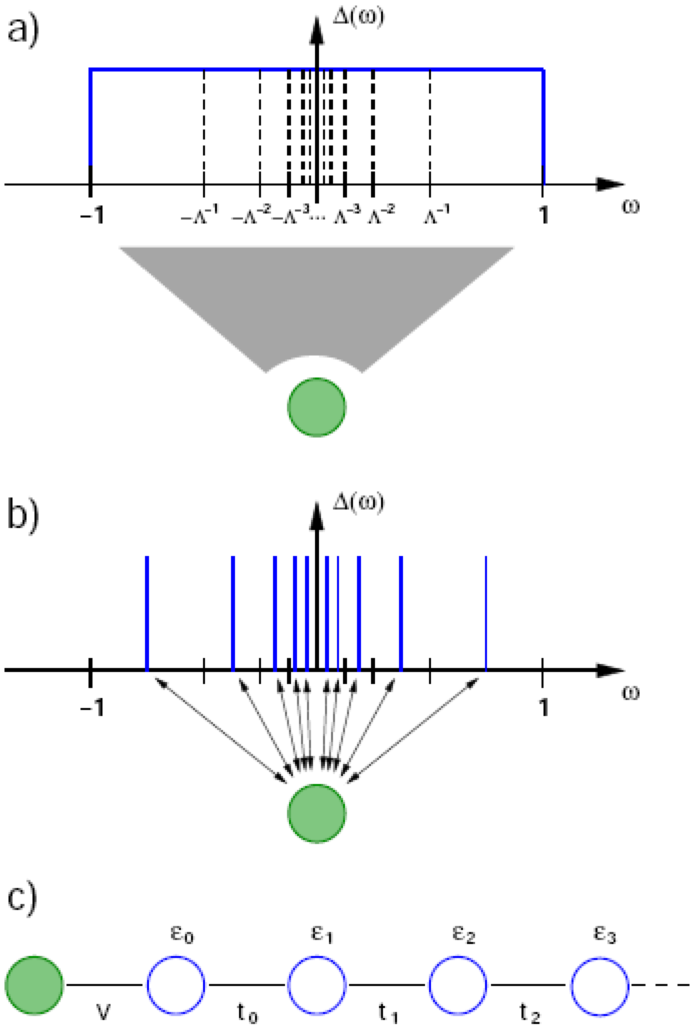


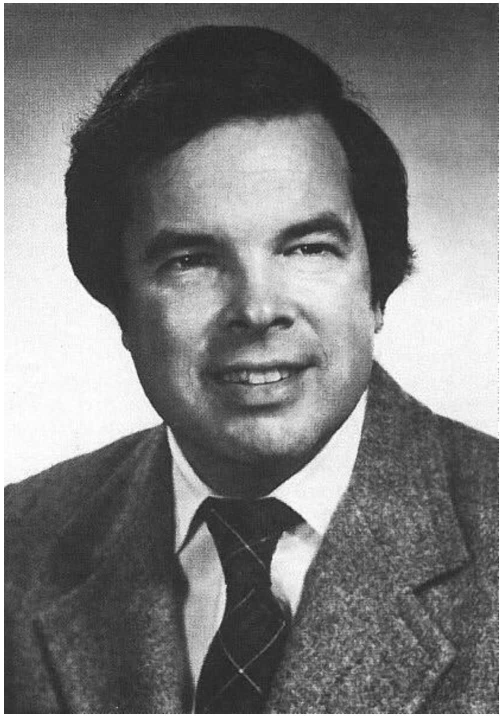


SOLVED BY e.g., NUMERICAL RENORMALIZATION GROUP

NUMERICAL RENORMALIZATION GROUP

R. BULLA et al (2008)





Ken Wilson

$$G = e^2/h \sum_\sigma \sin^2(\delta_{e\sigma} - \delta_{o\sigma})$$

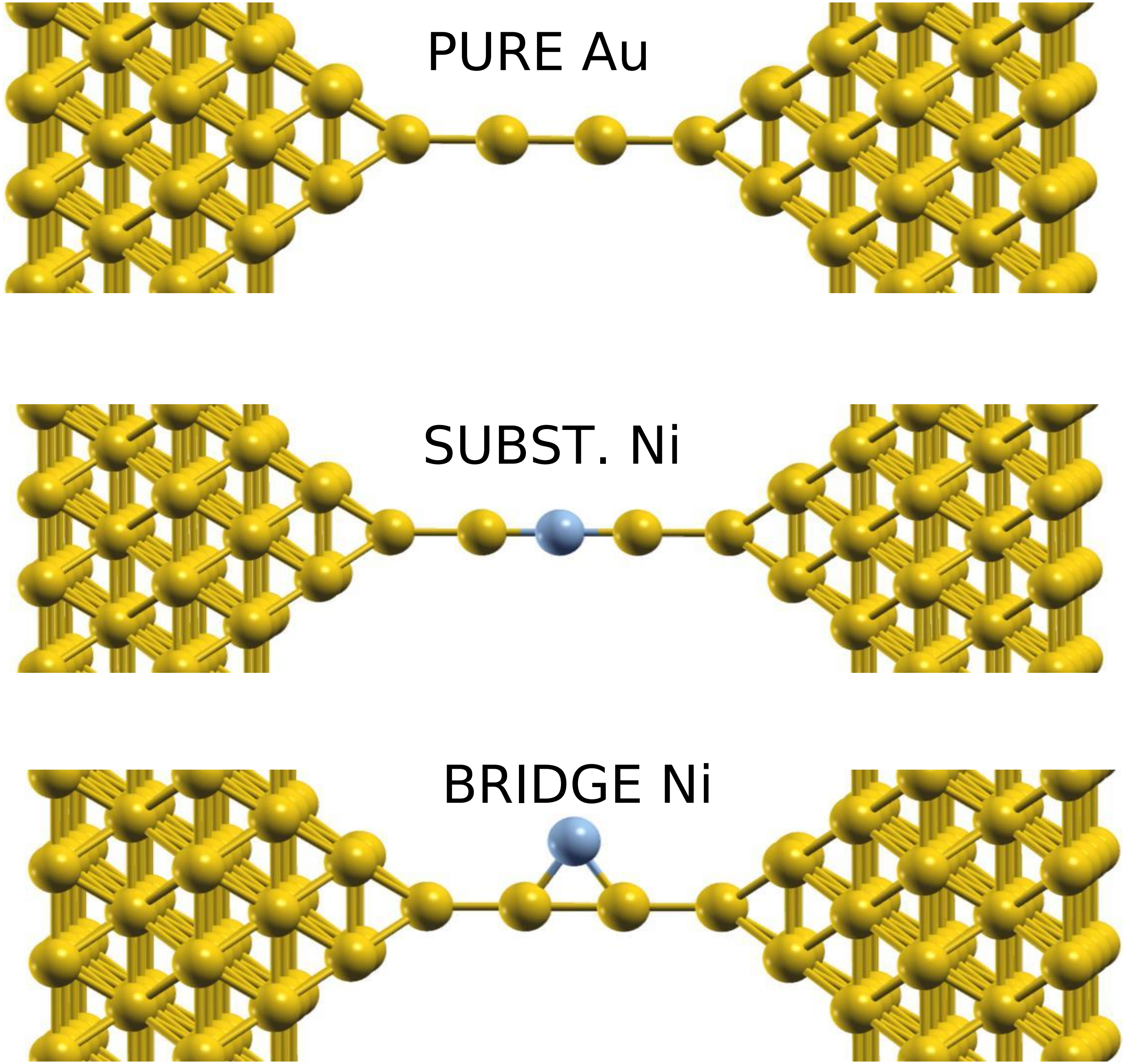
“DFT + NRG” STRATEGY

1. DFT ELECTRONIC STRUCTURE CALCULATION:
   - -- IDENTIFY NATURE, SYMMETRY OF COND. CHANNELS
   - -- MAGNETIZATION, SPIN OF IMPURITY
   - -- SYMMETRY OF FILLED + EMPTY MAGNETIC ORBITALS
   - -- EXTRACT SCATTERING PHASE SHIFTS OF CONDUCTION ELECTRONS FOR EACH SYMMETRY& BOTH SPINS

2. BUILD GENERALIZED ANDERSON MODELS, INCLUDING ALL SCATTERING SYMMETRY CHANNELS
   - -- ADJUST PARAMETERS OF ANDERSON MODEL TO CLOSELY REPRODUCE DFT PHASE SHIFTS WITHIN HARTEE-FOCK APPROX.

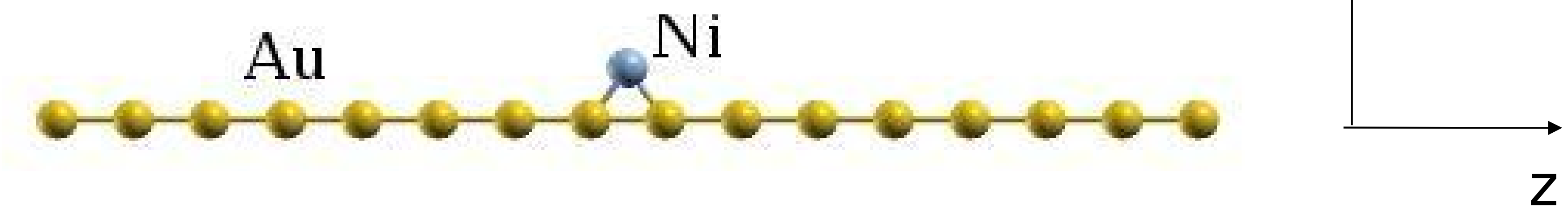
3. SOLVE ANDERSON MODEL WITH e.g.,NUMERICAL RENORMALIZATION GROUP (NRG) TO OBTAIN SPECTRAL DENSITY, CONDUCTANCE.

TEST CASE: Au-Ni NANOCONTACT



DFT ELECTRONIC STRUCTURE CALCULATIONS

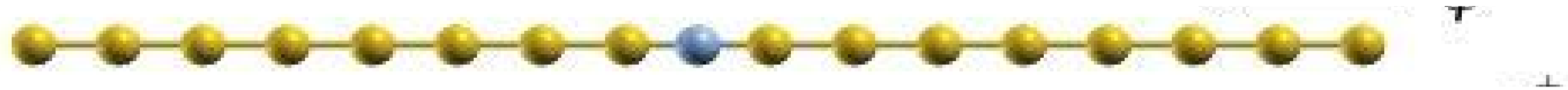
BRIDGE



E_{ad} = 3.22 eV, magn.= 1.3-1.0 μ_B

Y. MIURA et al. PRB (2008); R. MAZZARELLO et al (2009)

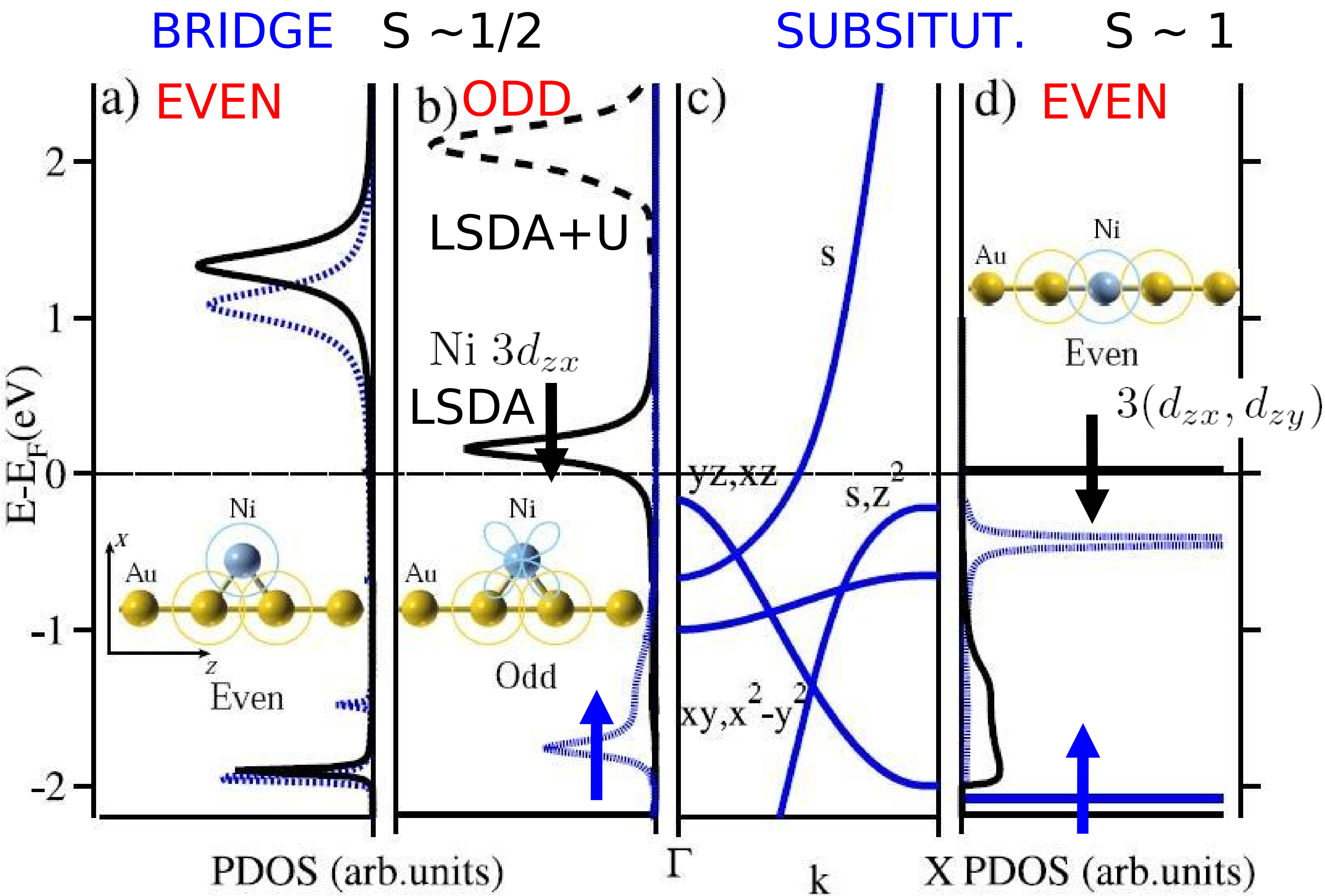
SUBSTITUTIONAL



E_{ad} = 2.32 eV, magn.= 1.9-2.0 μ_B

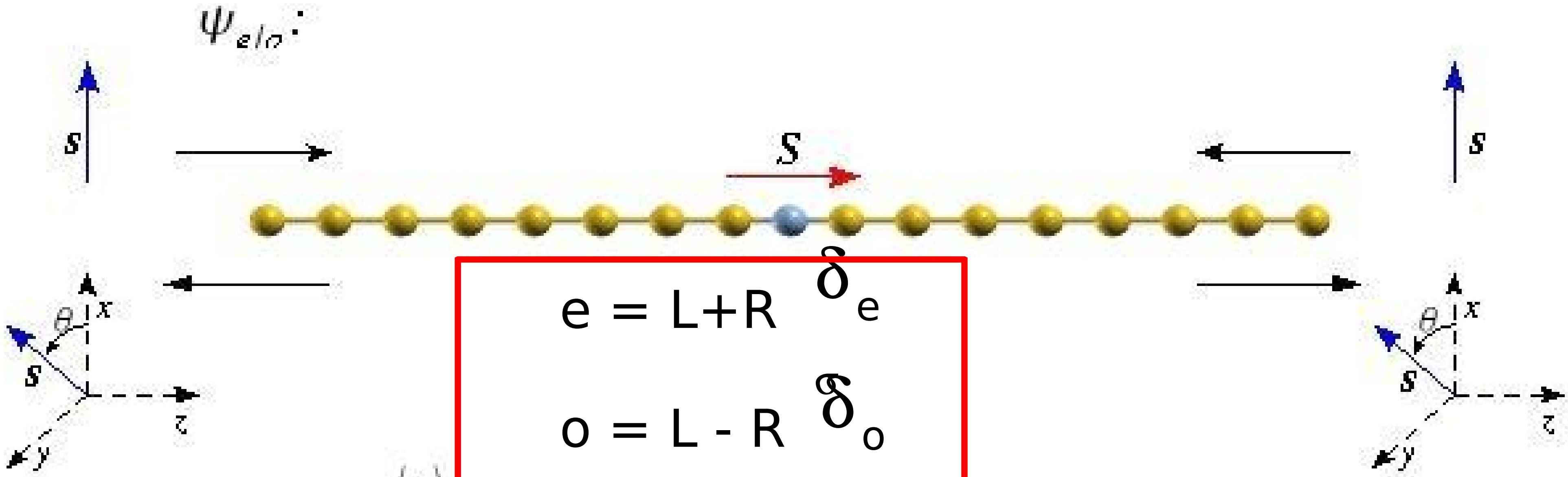
REFLECTION SYMMETRY: EVEN, ODD RELATIVE TO Ni

DFT CALCULATION: Ni SPIN DEPENDS ON GEOMETRY



CALCULATE IMPURITY PHASE SHIFTS BY SPIN ROTATION ANGLE

$\psi_{e/o}$:



e = L+R δ_e

o = L - R δ_o

Incoming wave = $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$, *polarized in the x direction*

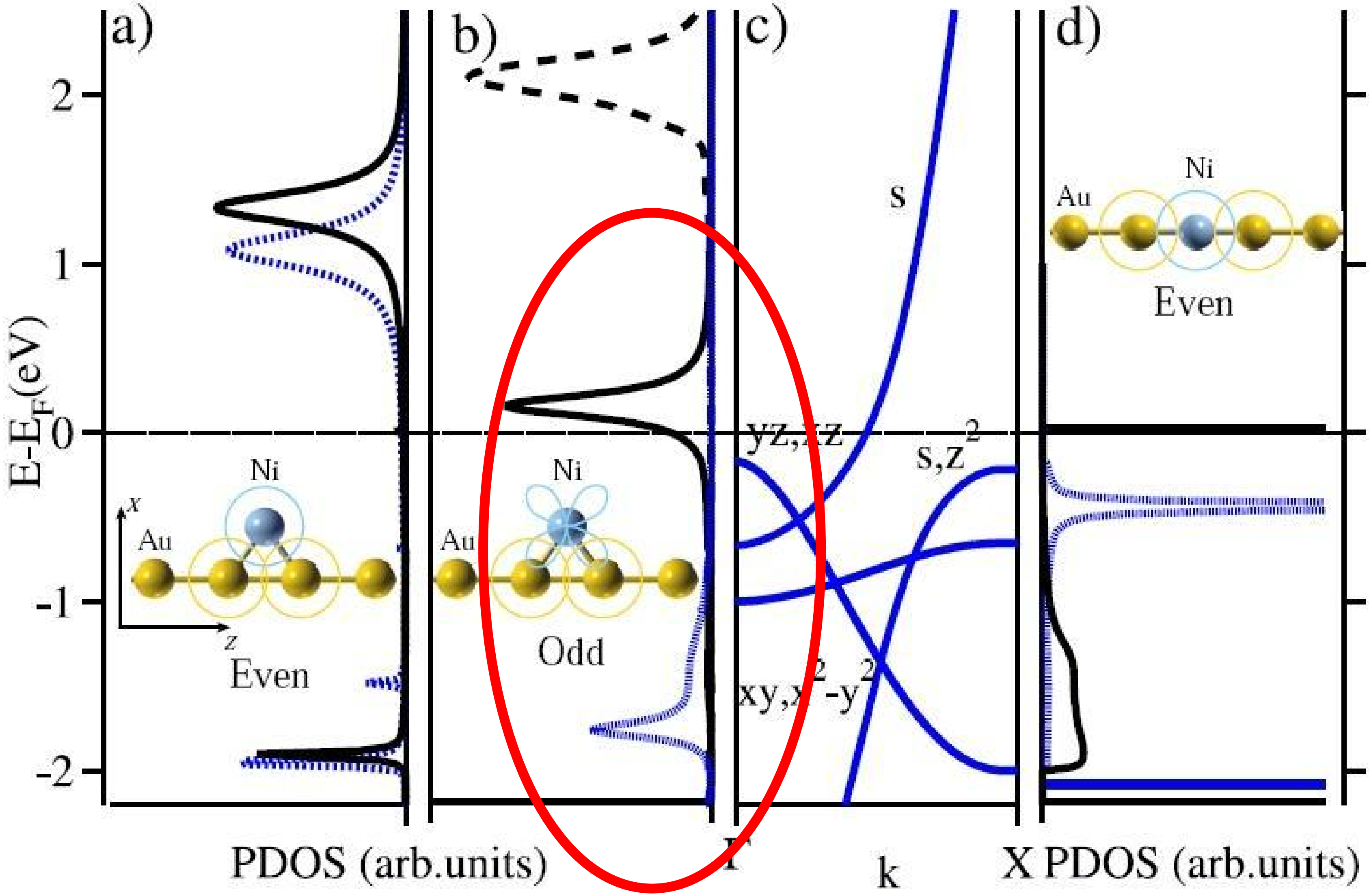
$$\textbf{Outgoing wave} = \begin{pmatrix} e^{2i\delta^{\uparrow}_{e/o}} \\ e^{2i\delta^{\downarrow}_{e/o}} \end{pmatrix} = e^{i(\delta^{\uparrow}_{e/o}+\delta^{\downarrow}_{e/o})} \begin{pmatrix} e^{i(\delta^{\uparrow}_{e/o}-\delta^{\downarrow}_{e/o})} \\ e^{-i(\delta^{\uparrow}_{e/o}-\delta^{\downarrow}_{e/o})} \end{pmatrix} \sim e^{-i\frac{\sigma_z}{2}2(\delta^{\uparrow}_{e/o}-\delta^{\downarrow}_{e/o})} \begin{pmatrix} 1 \\ 1 \end{pmatrix},$$

rotation on the angle $\theta = 2(\delta^{\downarrow}_{e/o} - \delta^{\uparrow}_{e/o})$ *around the z axis*

Simple model Kondo-like hamiltonian: $H = -\frac{d}{dx^2} + J\,\delta(x)\,S_z \cdot s_z$ → $\theta > 0$, if $J > 0$ (coupling antiferro); $\theta < 0$, if $J < 0$ (coupling ferro)

	$\delta^{\uparrow}_{e/o}$	$\delta^{\downarrow}_{e/o}$	$\theta_{e/o}$	Coupling
Bridge	1.16/0.96	1.02/1.52	-16° / +64°	F/AF
Subst.	0.74/1.19	0.62/1.13	-14° / -7°	F/F

-- ONLY ONE CASE (Bridge, odd) WHERE COUPLING IS AF
REASON : IN MOST CASES SPIN IS A SPECTATOR

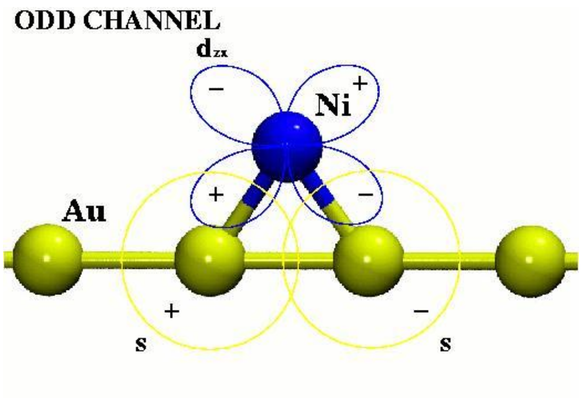


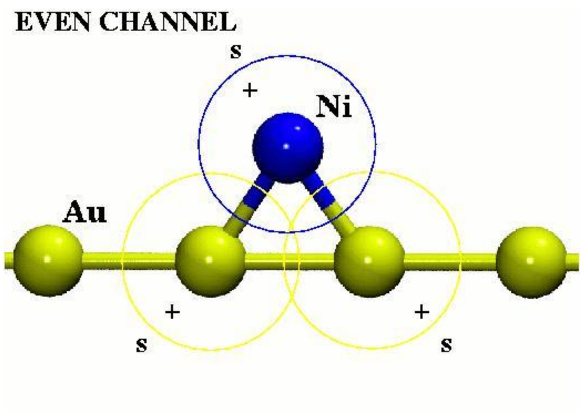
BRIDGE Ni

$\delta_{eup} - \boldsymbol{\delta}_{edown} > 0$ ferro, small

$\delta_{oup} - \boldsymbol{\delta}_{odown} << 0$ antiferro, large

EXTENDED ANDERSON MODEL





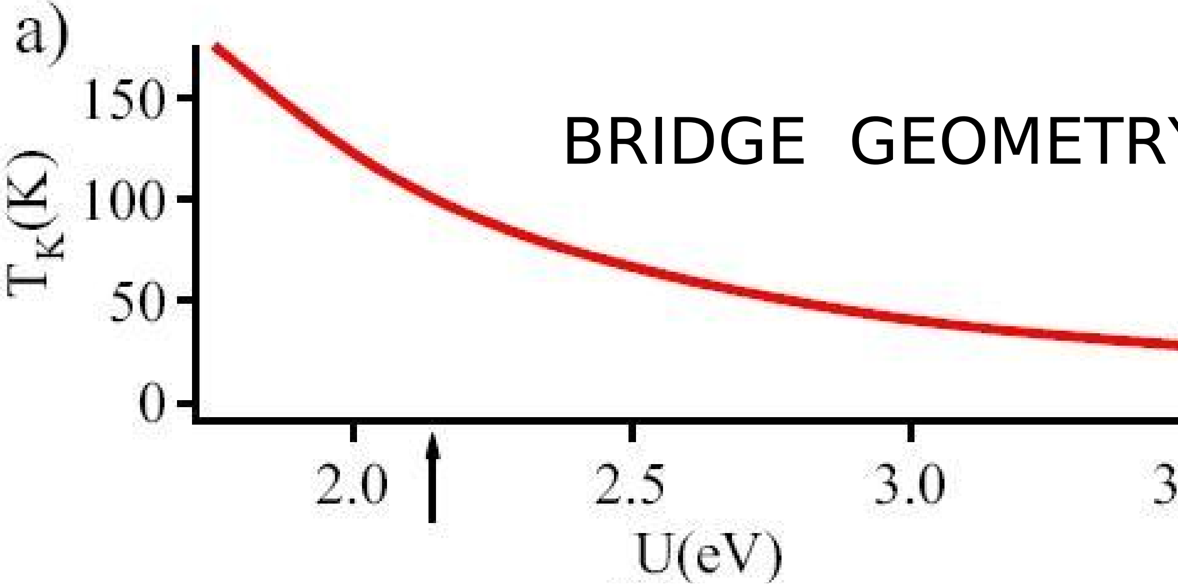
$$H = -\frac{1}{2}\sum_{a=R,L}\sum_{n\geq 1,\sigma}\left(c^\dagger_{na\sigma}c_{n+1a\sigma} + H.c.\right) - \frac{t}{2}\sum_{\sigma}\left(c^\dagger_{1R\sigma}c_{1L\sigma} + H.c.\right)$$

$$+V_e\sum_{\sigma}\left[\left(c^\dagger_{1R\sigma} + c^\dagger_{1L\sigma}\right)d_{e\sigma} + H.c.\right] + V_o\sum_{\sigma}\left[\left(c^\dagger_{1L\sigma} - c^\dagger_{1R\sigma}\right)d_{o\sigma} + H.c.\right]$$

$$+\sum_{p=e,o}\epsilon_p\, n_p + \frac{U}{2}\left(n_o - 1\right)^2,$$

	Bridge (eV)	Substitutional (eV)
ϵ_e	0	0
Γ_e	3	3
ϵ_o	-1.5	-2.1
Γ_o	0.25	–
U	2.2 (3.5*)	2.12
J_H	0.3	0.2
δ	0.38 rad	–

Angle (rad)	Bridge DFT (HF-AIM)	Subst. DFT (HF-AIM)
θ_e	-0.28 (-0.28)	-0.19 (-0.19)
θ_o	1.10 (1.17)	-0.12 (-0.00)



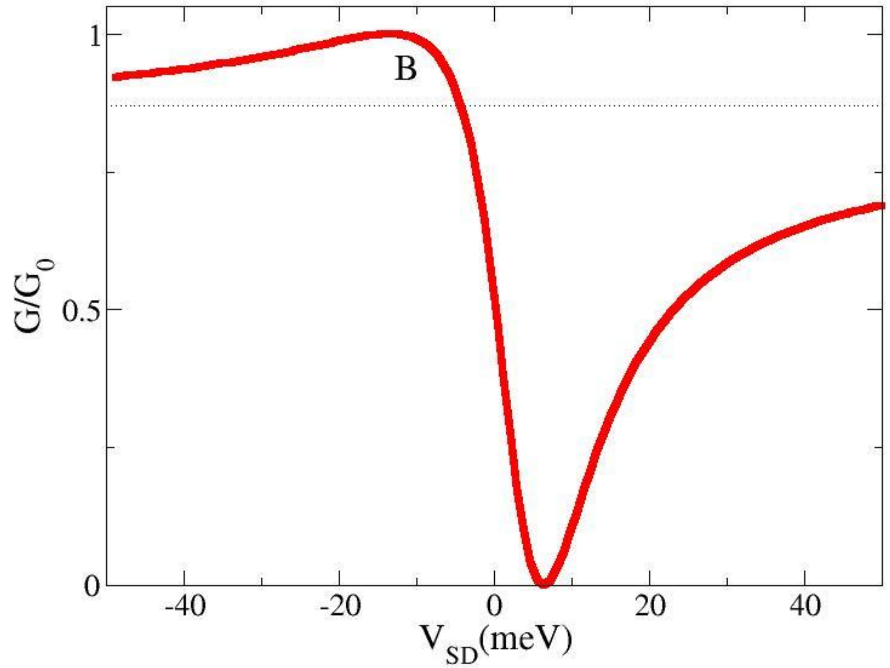
BRIDGE GEOMETRY

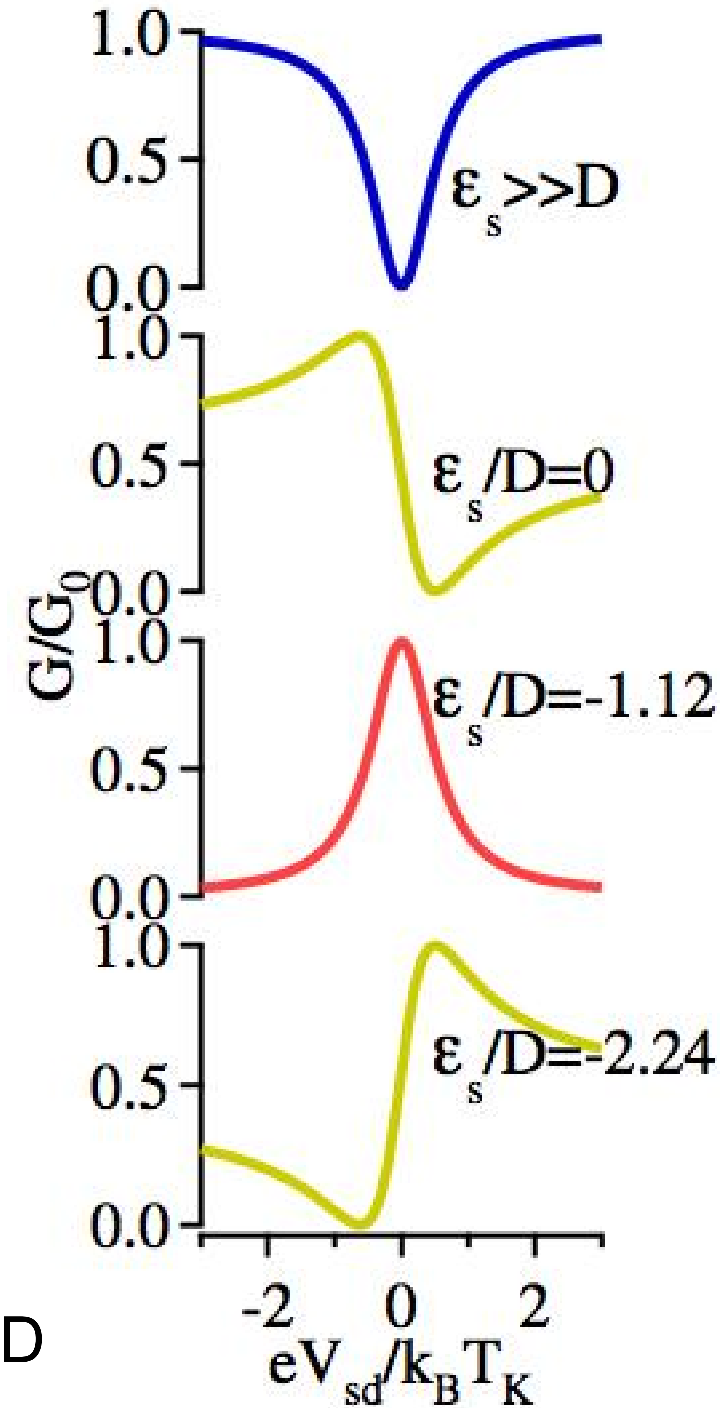
KONDO TEMPERATURE CONTROLLED BY HUBBARD U

BRIDGE GEOMETRY

DIFFERENTIAL CONDUCTANCE

$\varepsilon_s/D = -0.4$

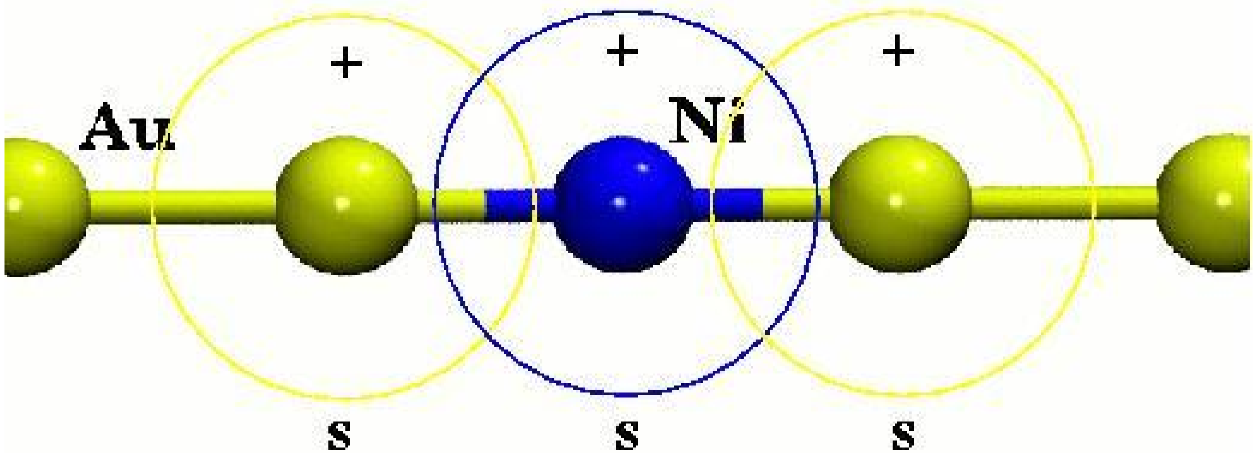




FANO INTERFERENCE CONTROLLED BY s CHANNEL ENERGY POSITION

SUBSTITUTIONAL Ni

SPIN 1 IS SPECTATOR,
COUPLING IS "FERRO"

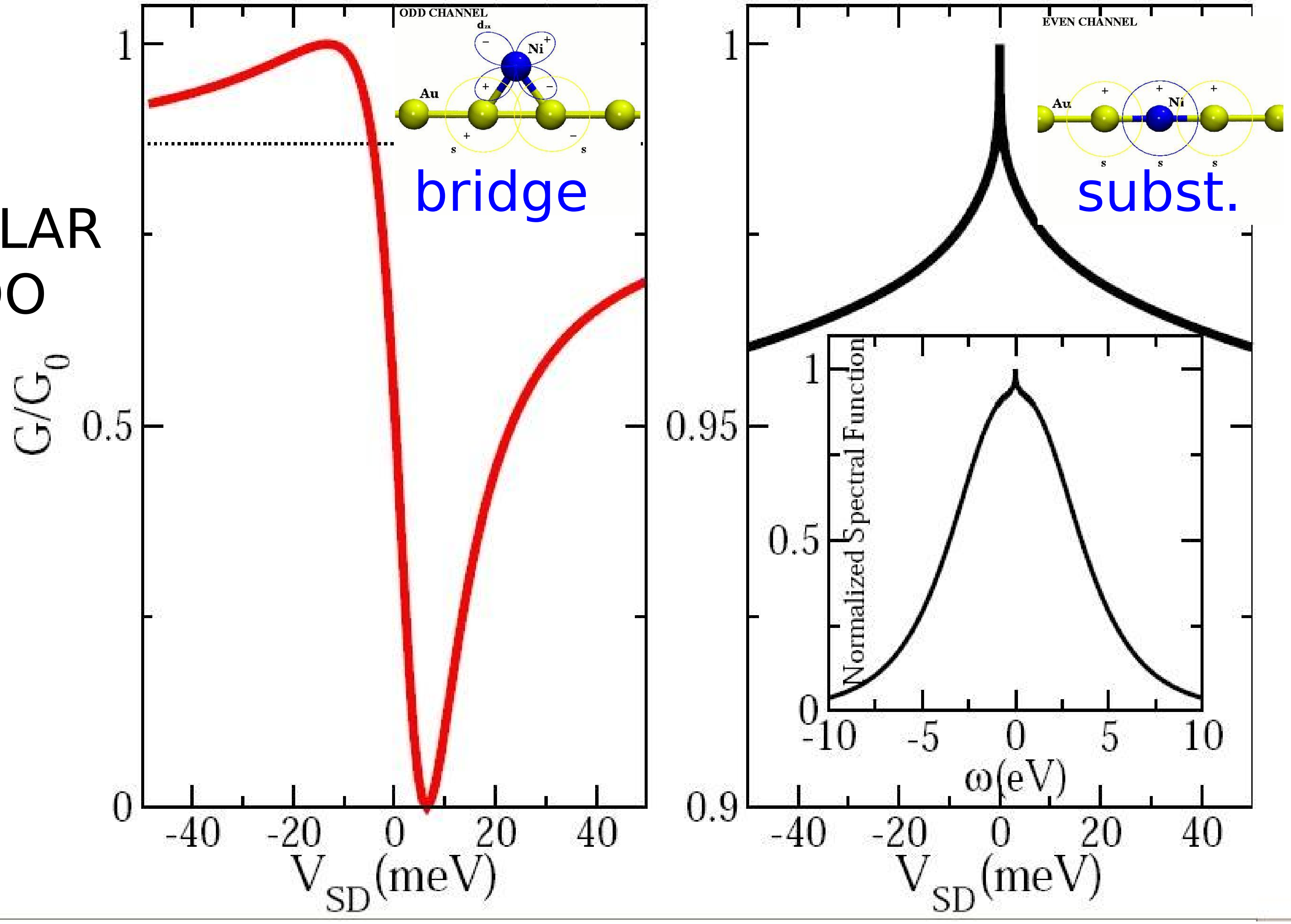


$$
\begin{aligned}
H \quad = \quad & \sum_{kp\sigma} \epsilon_{pk}\, c^{\dagger}_{kp\sigma} c^{\dagger}_{kp\sigma} + \sum_{k\sigma} V_{ks} \left(c^{\dagger}_{ke\sigma} s^{\dagger}_{\sigma} + H.c. \right. \\
& + \sum_{\sigma} \epsilon_s\, s^{\dagger}_{\sigma} s^{\dagger}_{\sigma} + \sum_{\sigma\alpha} \epsilon_{\alpha}\, d^{\dagger}_{\alpha\sigma} d^{\dagger}_{\alpha\sigma} + \\
& U \sum_{\alpha} n_{\alpha\uparrow} n_{\alpha\downarrow} + J_H \vec{S}_s \cdot \vec{S}_{d_\alpha}
\end{aligned}
$$

$J_H < 0$

PREDICT GEOMETRY-DEPENDENT KONDO EFFECTS, DIFFERENT ZERO_BIAS CONDUCTANCE ANOMALIES

REGULAR KONDO



“FERRO”-KONDO (sketch)

Experiment?

CONCLUSIONS

UNSUSPECTEDLY RICH PHYSICS AT NANOCONTACTS

QUASI-EQUILIBRIUM MAGIC NANOWIRES

BALLISTIC CONDUCTANCE AND MAGNETISM

LOCAL CONTACT MAGNETISM IN Pt, Pd?

KONDO EFFECT ACROSS MAGNETIC IMPURITIES
CALCULABLE IN ATOMISTIC DETAIL

SOME GENERAL REFERENCES (mainly experimental)

-- METAL NANOCONTACTS, BREAK JUNCTIONS

N. Agrait et al, Physics Reports 377, 81 (2003)

-- MAGNETISM AND CONDUCTANCE

Various articles by M. Viret, and by A. Fert

-- KONDO EFFECT AND ZERO BIAS CONDUCTANCE ANOMALIES IN ATOMIC NANOCONTACTS

See, e.g., M. Ternes et al, J. Phys.-Cond. Matt. 21 , 053001 (2009).

SOME WORK DONE IN TRIESTE

O. Gulseren et al , Phys. Rev. Lett.80, 3775 (1998)

E. Tosatti et al., Science 289, 561 (2000)

A. Smogunov et al. Surface Science 507, 609 (2002)

A. Delin, E. T. , Phys. Rev. B 68, 1444434 (2003)

A. Delin, et al , Phys. Rev. Lett. 92, 057201 (2004)

A. Smogunov, et al Phys. Rev. B 70, 045417 (2004)

M. Wierzbowska, et al, Phys. Rev. B 72, 035439 (2006)

A. Smogunov, et al Phys. Rev. B 73, 075418 (2006)

A. Smogunov, et al Nature Nanotech. 3, 22 (2008)

A. Smogunov, et al Phys. Rev. B78, 014423 (2008)

Y. Miura, et al., Phys. Rev. B78, 05412 (2008)

P. Lucignano et al, Phys. Rev. B78, 155418 (2008).

THANKS TO MY COLLABORATORS

P. Baruselli (Trieste)

A. Dal Corso (Trieste)

A. Delin (Stockholm)

M. Fabrizio (Trieste)

P. Gentile (Salerno)

P.Lucignano (Trieste/Naples

R.Mazzarello (Trieste)

G. Sclauzero (Trieste)

A. Smogunov (Trieste)

R. Weht (Buenos Aires)

hD & Postdoctoral openings in SISSA : phd@sissa.it, tosatti@sissa.i

END OF PART 1