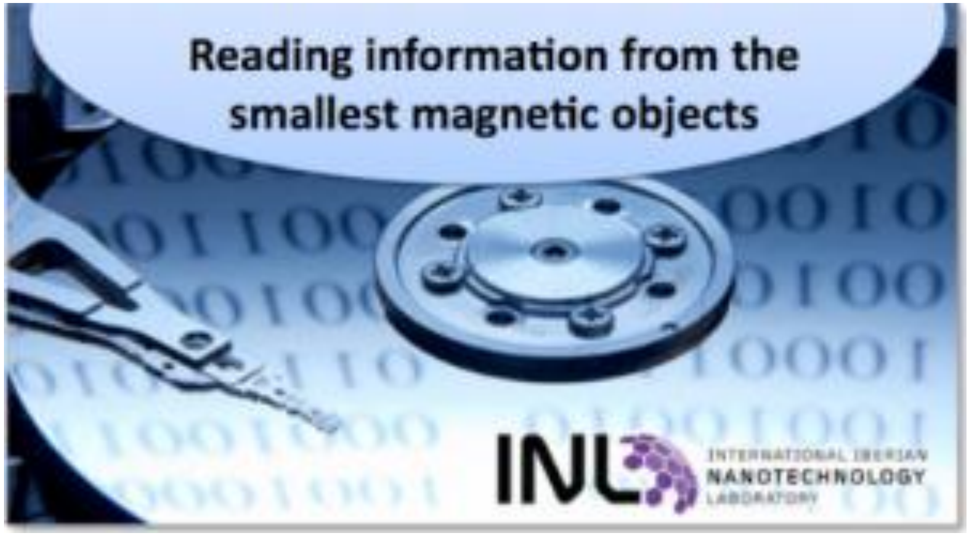
PROBING THE NUCLEAR SPIN OF A SINGLE DONOR IN SILICON NANOTRANSISTORS

F. Delgado* and J. Fernández-Rossier
*Email: fernando.delgado@inl.int



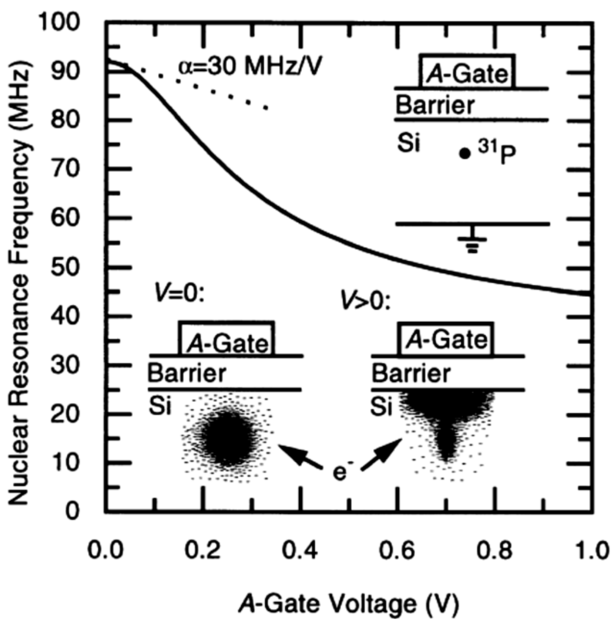
SINGLE NUCLEAR SPINS AS QUBITS

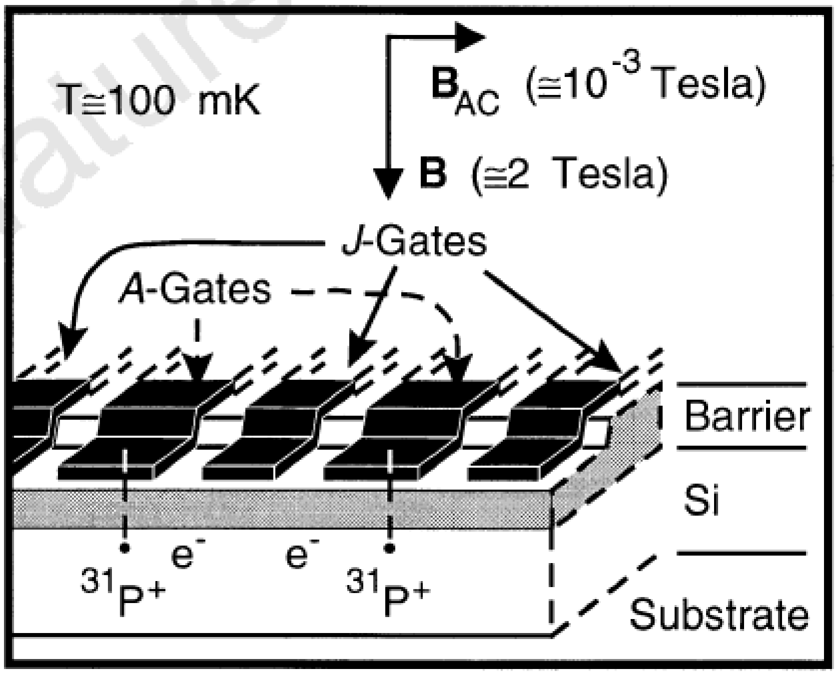
A silicon-based nuclear spin quantum computer

B. E. Kane

Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Au

From B. E. Kane, Nature (1998).





Advantages:

- High isolated qubits
- Long coherence/relaxation times (~10 ms)
- Scalable systems

DETECTION SCHEMES FOR SINGLE NUCLEAR SPINS

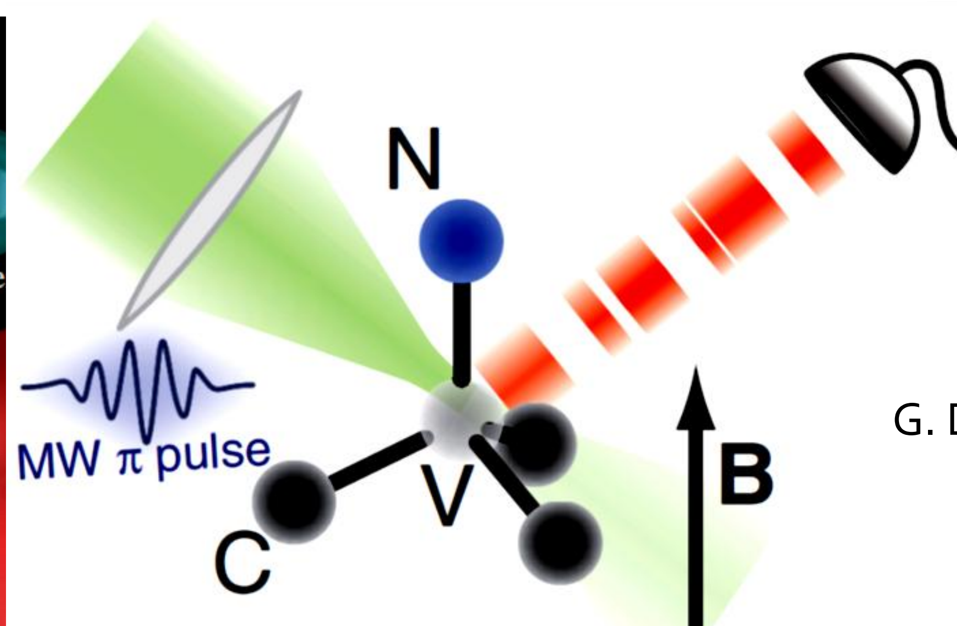
- MRFM
- OD-MR

OD-MR (Optically Detected Magnetic Resonance)

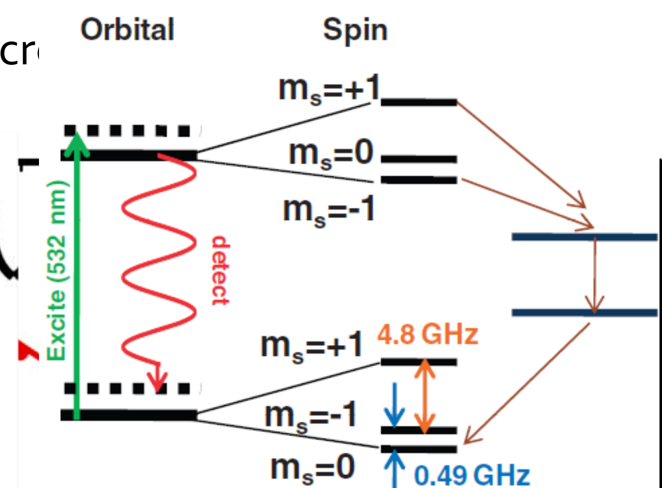
(Single nuclear spin detection)

NV centers in diamond

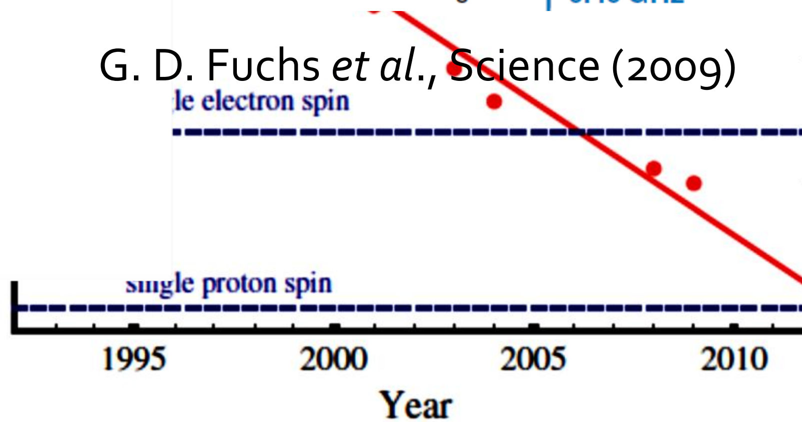
D. Rugar *et al.*, Nature (2004)



P. Neumann *et al.*, Science (2010)



G. D. Fuchs *et al.*, Science (2009)



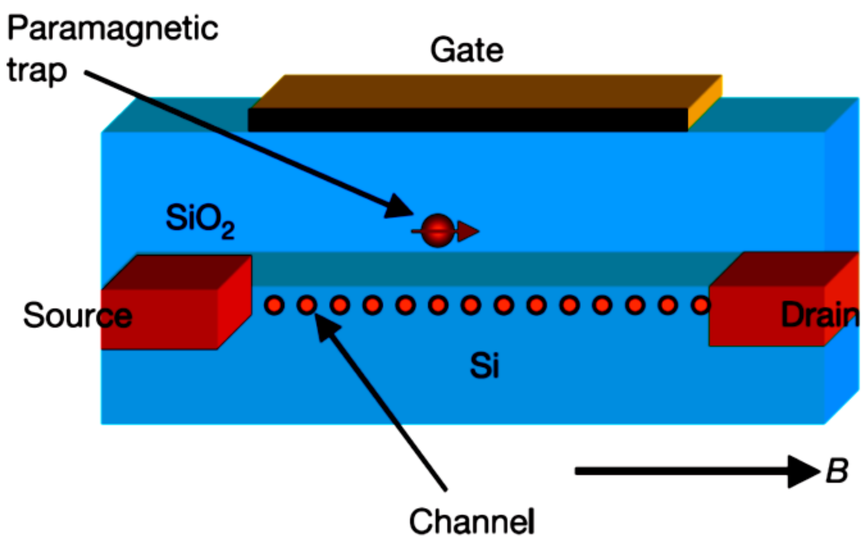
M. Poggio & C. L. Degen *et al.*, Nanotechnology (2010)

DETECTION SCHEMES FOR SINGLE NUCLEAR SPINS

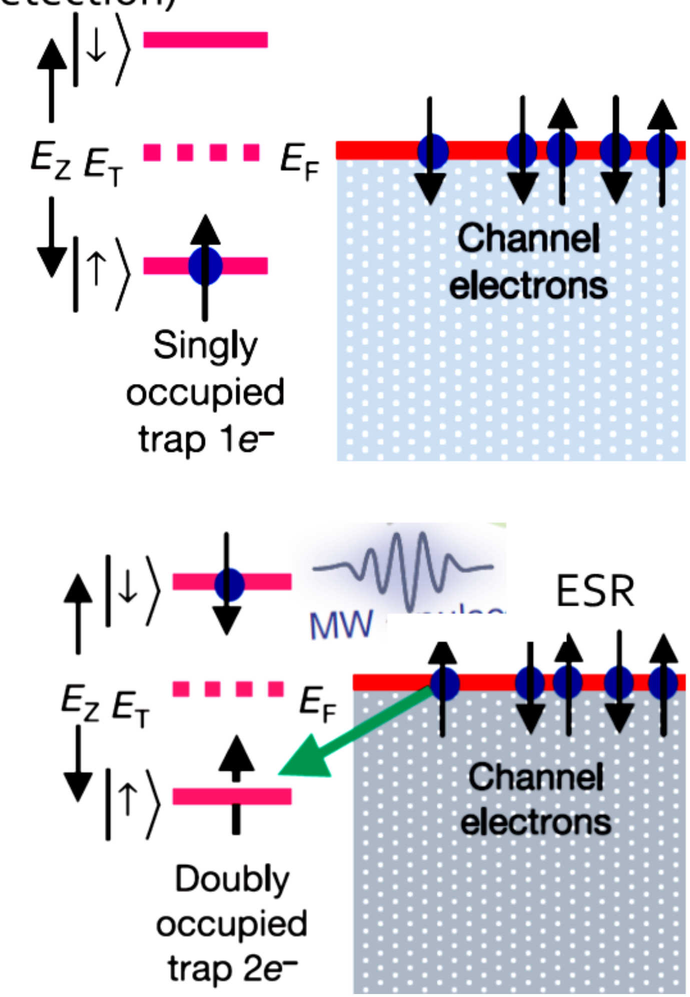
Transport- based detection

- EDMR

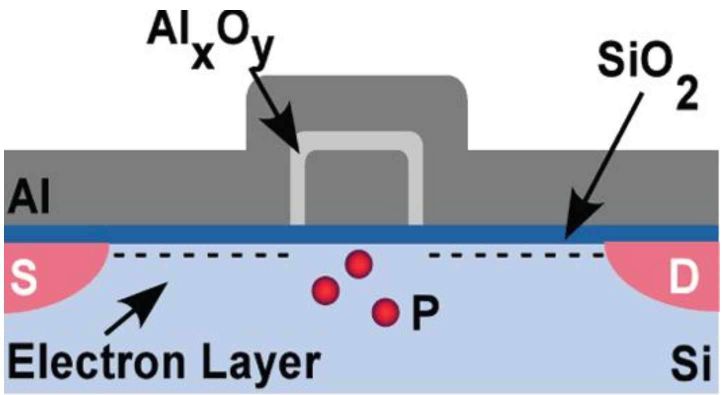
EDMR (Electrically Detected Magnetic Resonance)
(spin-to-charge conversion)
↓
(demostrated single spin detection)

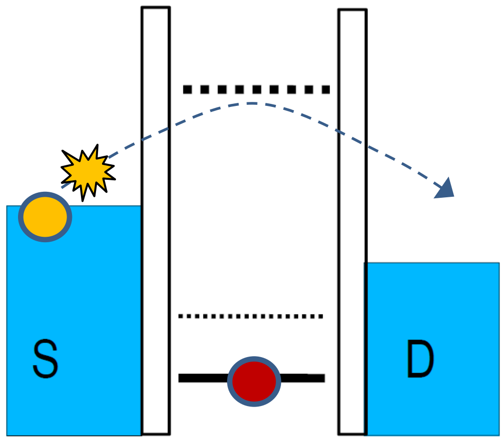


M. Xiao *et al.*, Nature(2004)



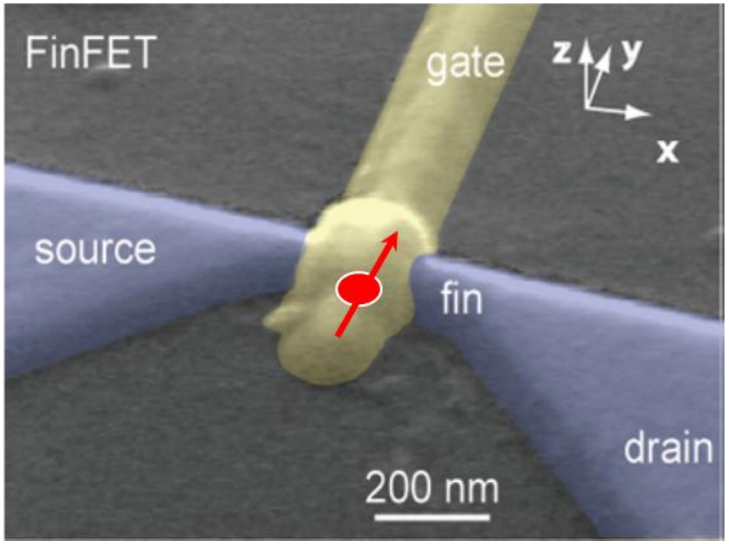
SINGLE DOPANT Si NANOTRANSISTORS

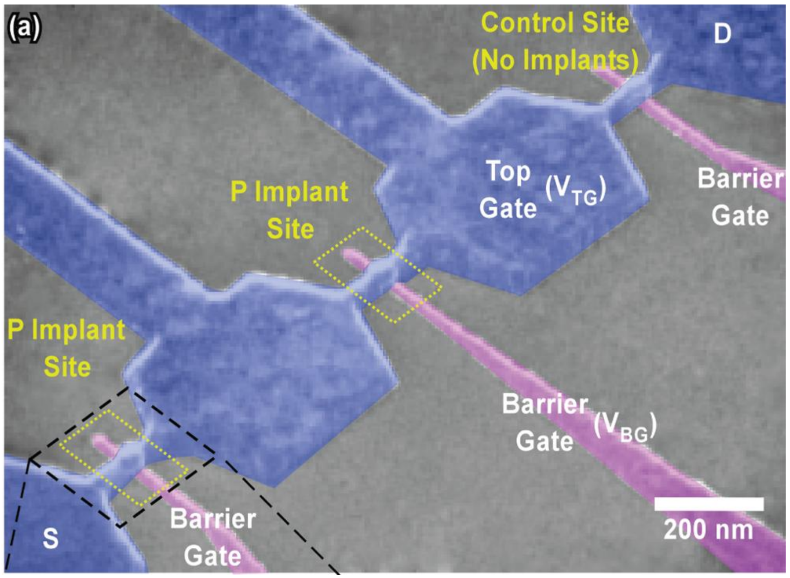




G. P. Lansbergen *et al*., Nano (2010).

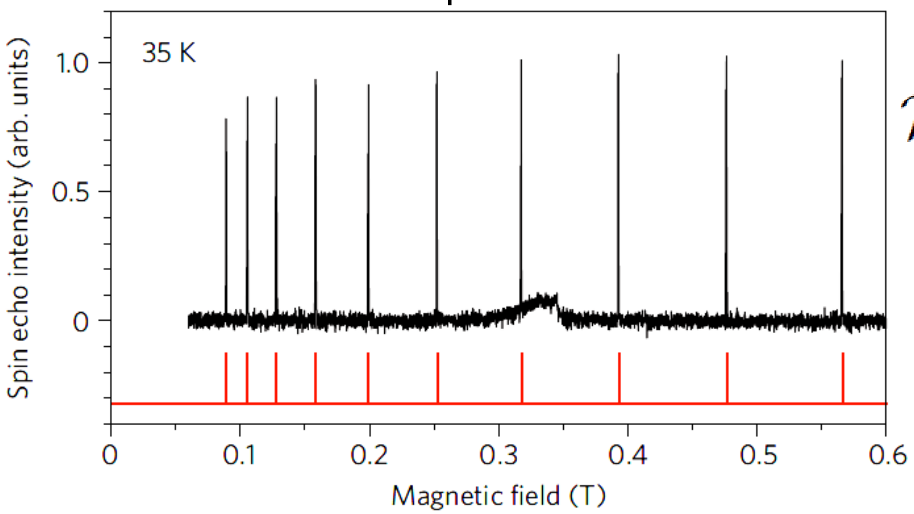
K. Yen Tan *et al*., Nano (2009).

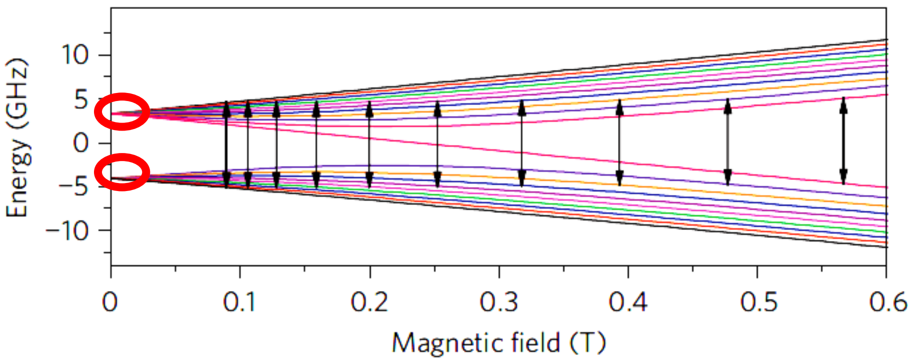




Si: ^{209}Bi SPIN SYSTEM

ESR spectrum



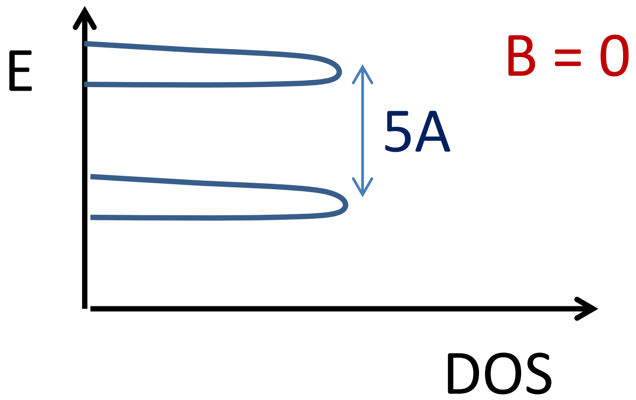


Electro-nuclear system

$$\mathcal{H}_{\text{Spin}} = A\vec{I}\cdot\vec{S} + \left(g\mu_B\vec{S} + g\mu_I\vec{I}\right).\vec{B}$$

$I = 9/2$ & $S = 1/2$ & $A = 6.1\mu eV$

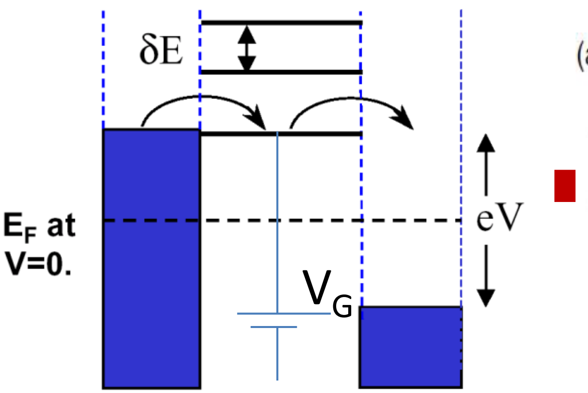
$$\vec{F} = \vec{S} + \vec{I} \longrightarrow F = 4,\ 5$$

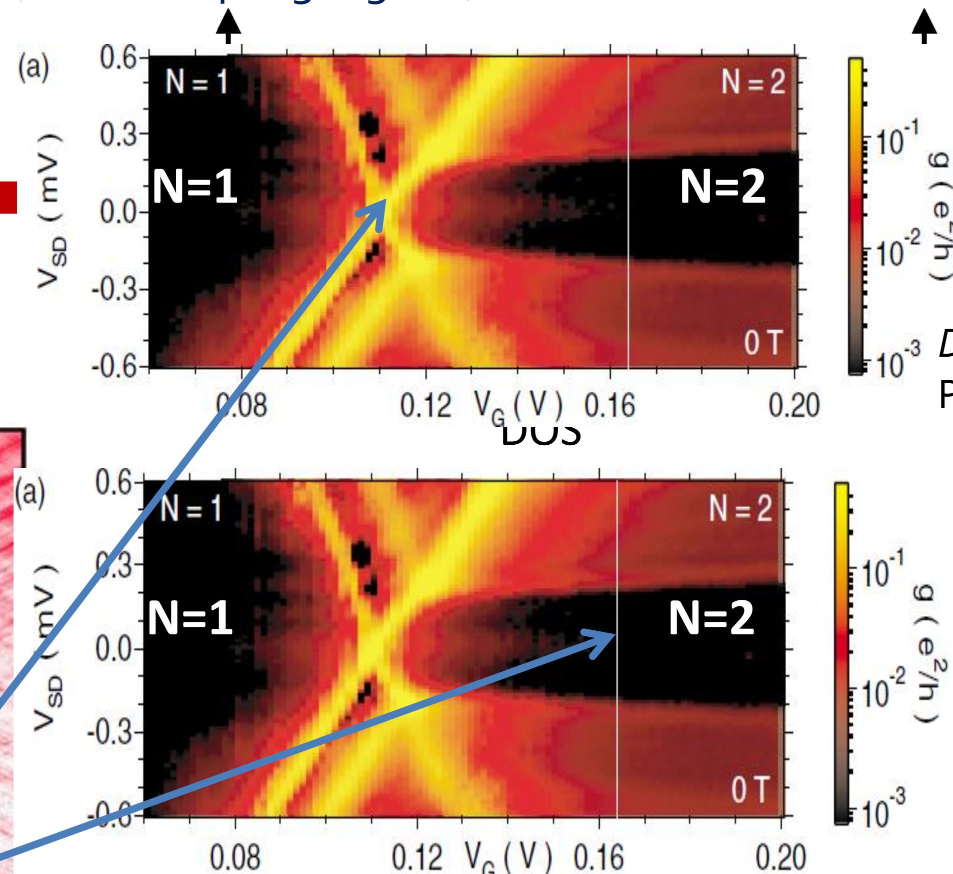


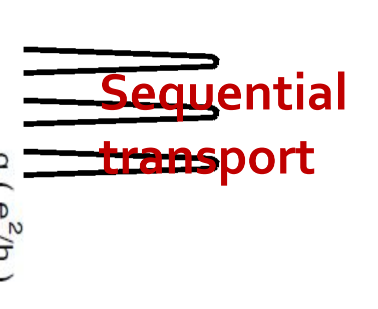
- G. W. Morley *et al.*, Nature Materials (2010)
- R. E. George *et al.*, Phys. Rev. Lett. (2010)

ELECTRONIC TRANSPORT

Coulomb blockade regime (Weak coupling regime)



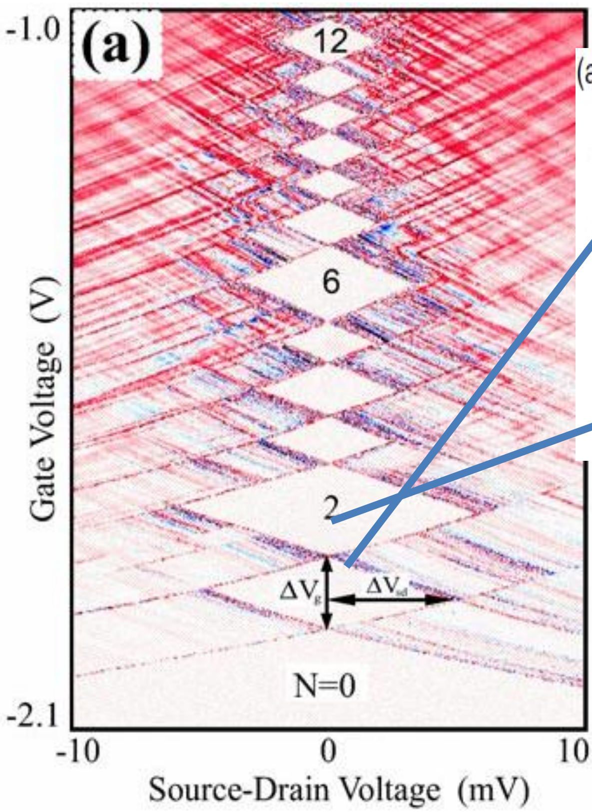




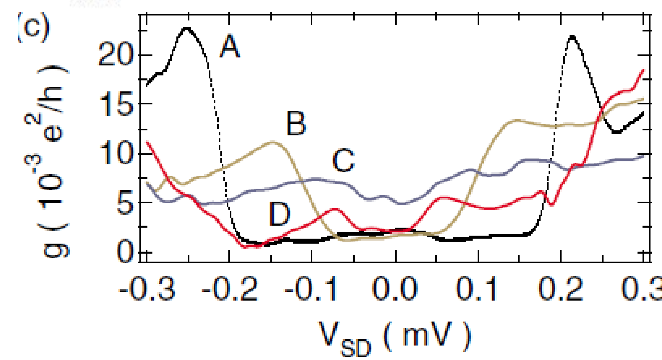
D. M. Zumbühl et al., Phys. Rev. Lett. (2004)

Cotunneling

IETS



L. P. Kouwenhoven *et al.*, Rep. Prog. Phys. (2001)



THEORETICAL TREATMENT

Total Hamiltonian

$$\mathcal{H}_T = \mathcal{H}_{Spin} + V_g \sum_\sigma n_\sigma + \mathcal{H}_S + \mathcal{H}_D + \mathcal{V}$$

Free electron reservoirs

$$\mathcal{H}_S + \mathcal{H}_D = \sum_{k\eta\sigma} \epsilon_{k\eta\sigma} c^\dagger_{k\eta\sigma} c_{k\eta\sigma}$$

Electro-nuclear spin system

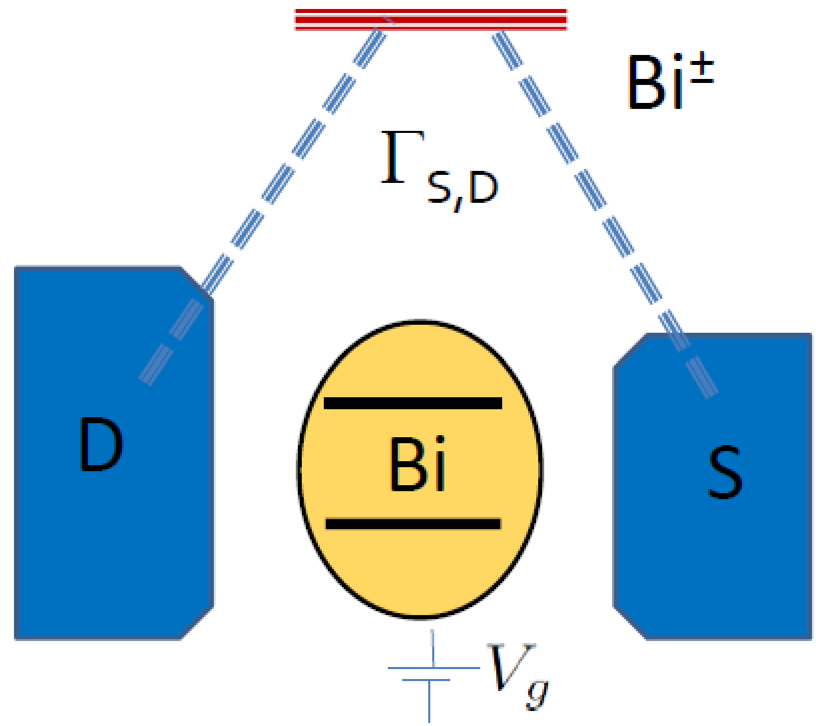
$$\mathcal{H}_{Spin} + V_g \sum_\sigma n_\sigma$$

Tunneling Hamiltonian *(Perturbation)*

- **Sequential transport** (1st order in $\mathcal{V}$)
- **Cotunneling transport** (2nd order in $\mathcal{V}$)

$$\Gamma\Gamma^{cot}_{M,M'} \propto |\langle M|\mathcal{V}_{eff}|\ldots|M'\rangle|^2$$

$$\mathcal{V}_{eff} = J\vec{s}.\vec{S} + W$$



J. Fernández-Rossier *et al*. Phys. Rev. Lett. (2007) & F. Delgado *et al*., Phys. Rev. B (2011)

THEORETICAL TREATMENT

Sequential transport

- Charge fluctuations: $Q_{Bi} = 0, 1\ e^-$

- Current

$$I^{seq} = e \sum_{\alpha_0,\alpha_1} \left(P_{\alpha_0}(V) W^{S \to Bi}_{\alpha_0,\alpha_1} - P_{\alpha_0} W^{Bi \to S}_{\alpha_1,\alpha_0} \right)$$

Non-equlibrium populations

$$\frac{dP_{\alpha_i}(V)}{dt} = 0$$ *(Steady state condition)*

P_{α_0} : Occupation probability of $0e^-$ state α_0

P_{α_1} : Occupation probability of $1e^-$ state α_1

Cotunneling transport

- Negligible charge fluctuations

$$\mathcal{V}_{eff} = J\vec{s}.\vec{S} + W$$

- Current

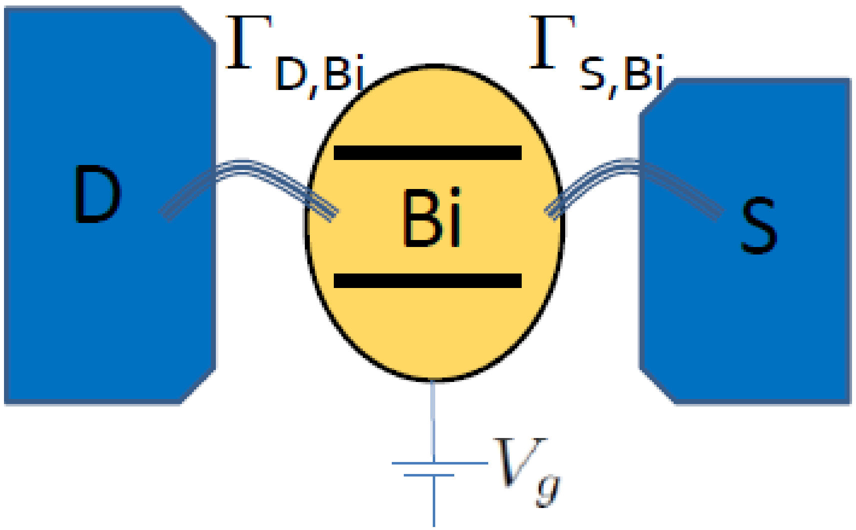
$$I^{cot} = e \sum_{M,M'} P_M(V) \left(W^{StoD}_{M,M'} - W^{D \to S}_{M,M'} \right)$$

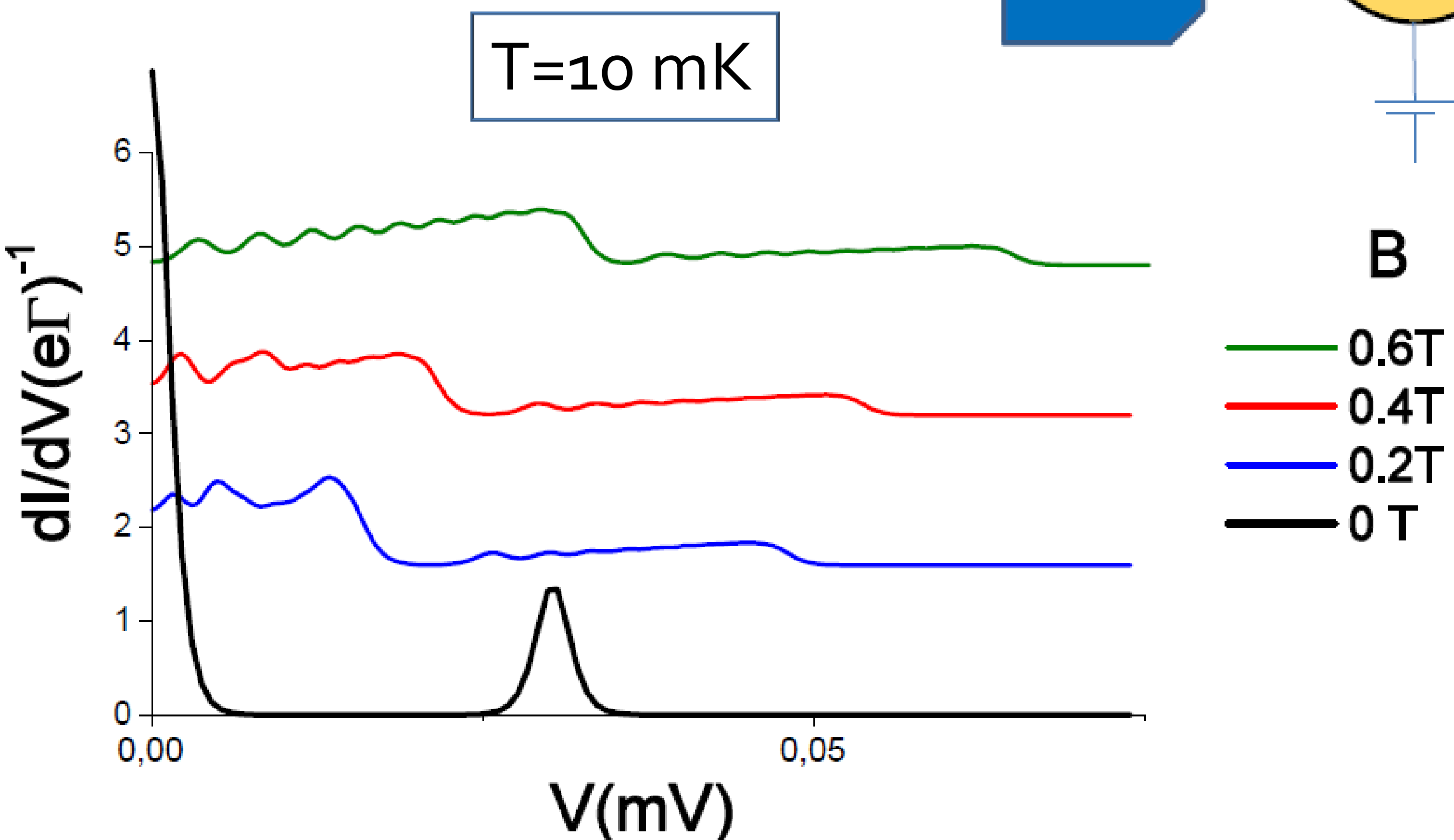
Non-equlibrium populations

$$\frac{dP_M(V)}{dt} = 0$$ *(Steady state condition)*

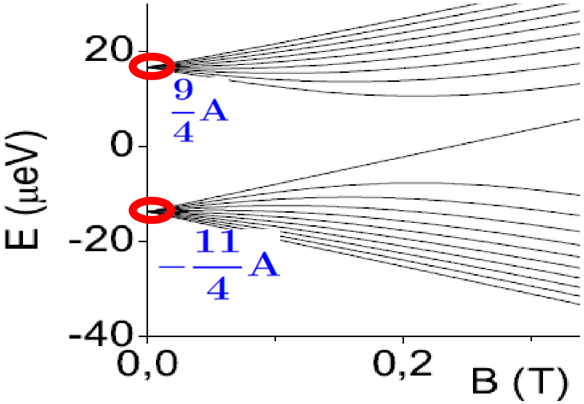
J. Fernández-Rossier *et al*. Phys. Rev. Lett. (2007) & F. Delgado *et al*., Phys. Rev. B (2011)

SEQUENTIAL TRANSPORT REGIME





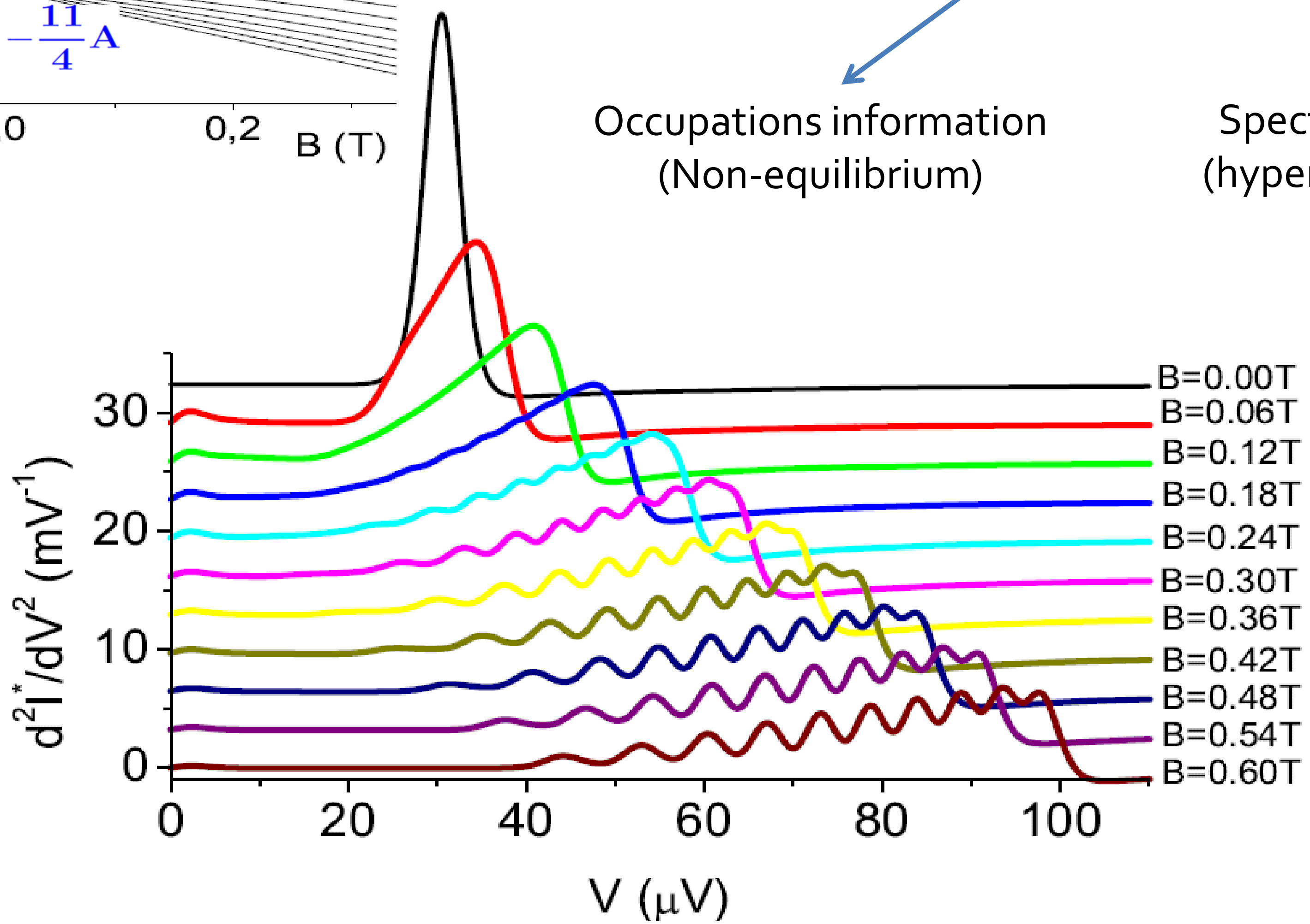
IETS: COTUNNELING REGIME



$$\frac{d^2 I}{dV^2} \propto \mathcal{S}(\omega) \equiv \sum_{M,M',a} P_M \left| \hat{S}_a^{M,M'} \right|^2 \delta\left(\hbar\omega - \Delta_{M',M}\right)$$

Occupations information (Non-equilibrium)

Spectral information (hyperfine interaction)



CONCLUSIONS

- Si:Bi nanotransistors are good candidates to probe nuclear spins due to the large hyperfine coupling in Bi ($A >> k_B T$)

- Hyperfine structure can be probed in the sequential or in the cotunneling regime

- Single nuclear spins can be probed by IETS.

INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

ACKNOWLEDGMENTS

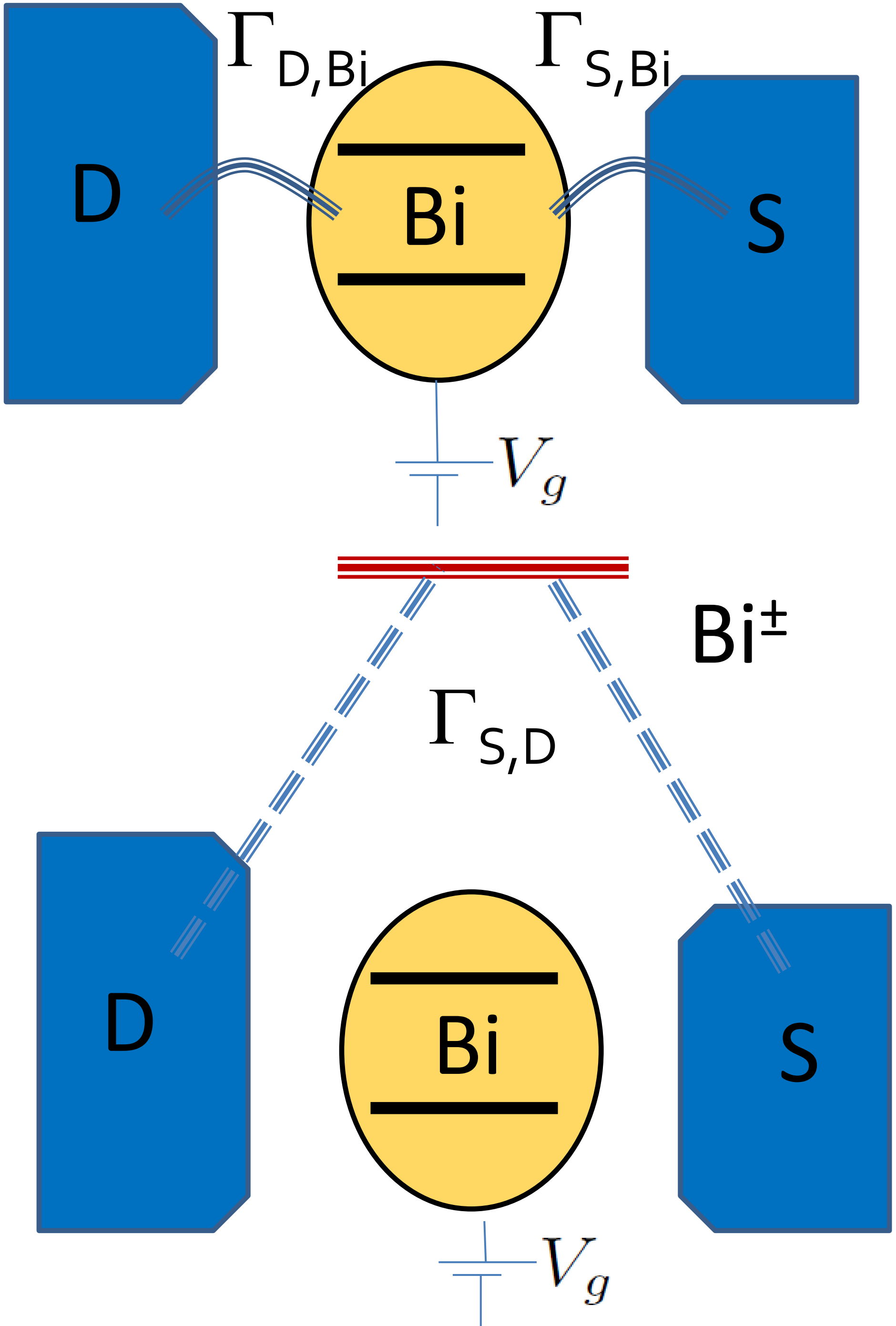
Joaquín Fernández-Rossier
INL, Braga, Portugal

With the finantial support of:
JCI-2008-01885

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

THANK YOU FOR YOUR ATTENTION !!!

Departamento de Física Aplicada
Universidad de Alicante



$\Gamma_{D,Bi}$
$\Gamma_{S,Bi}$
D
Bi
S
V_g
$Bi^{\pm}$
$\Gamma_{S,D}$
D
Bi
S
V_g