NMR Probe for Electrons in Semiconductor Mesoscopic Structures

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Discussions:

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References:

- N. Cooper and V. T., Phys. Rev. B 77 (2008)
- V. T. and N. Cooper, J. Phys. Cond. Matt. 20 (2008)
- K. Dhochak and V. T., Phys. Rev. Lett. 103 (2009)

Outline

Strongly correlated electron systems:
Overview

Problem:
How to detect the electronic state in nanoscale structures.

Two examples where the usual methods don't work.

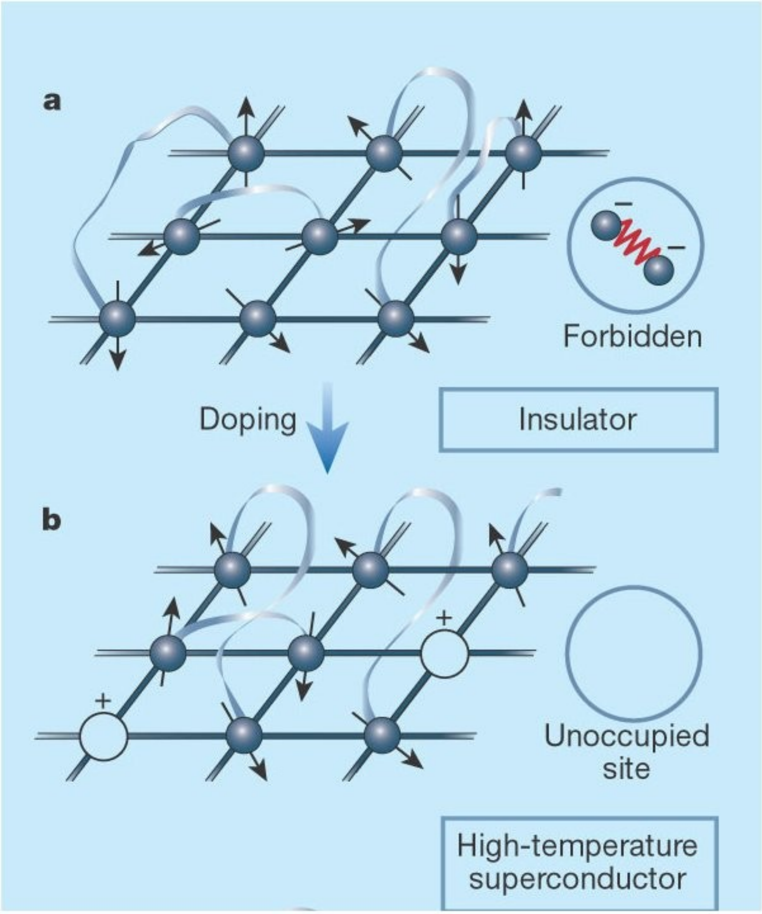
Solution:
We showed NMR techniques can be very useful in such circumstances.

Strongly Correlated Electron Systems

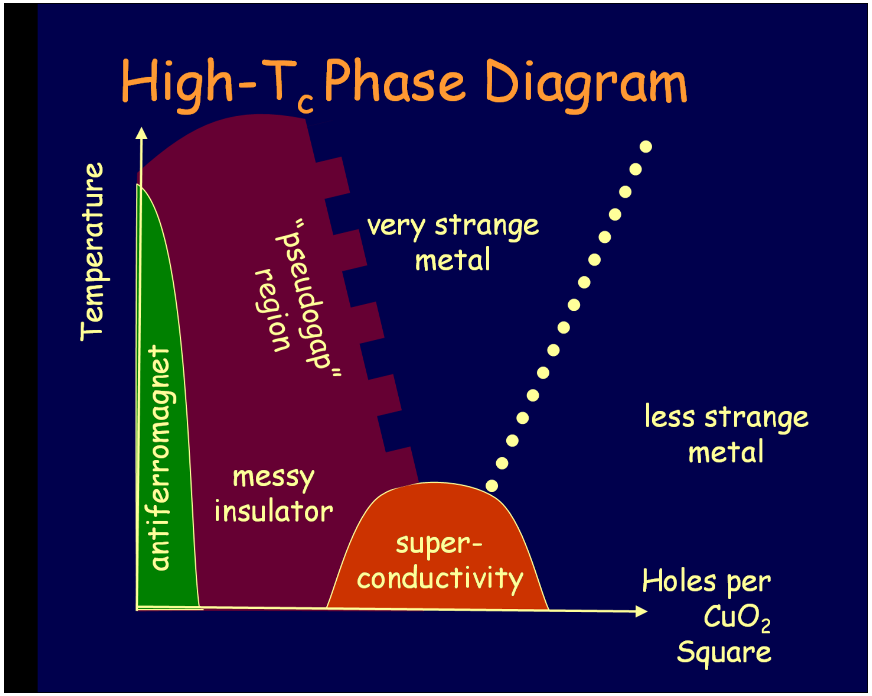
Mutual interaction of electrons dominates their kinetic energies giving rise to surprisingly rich physics.

High-T_c superconductors: strong correlation in bulk

Berdnoz, Müller (1986)

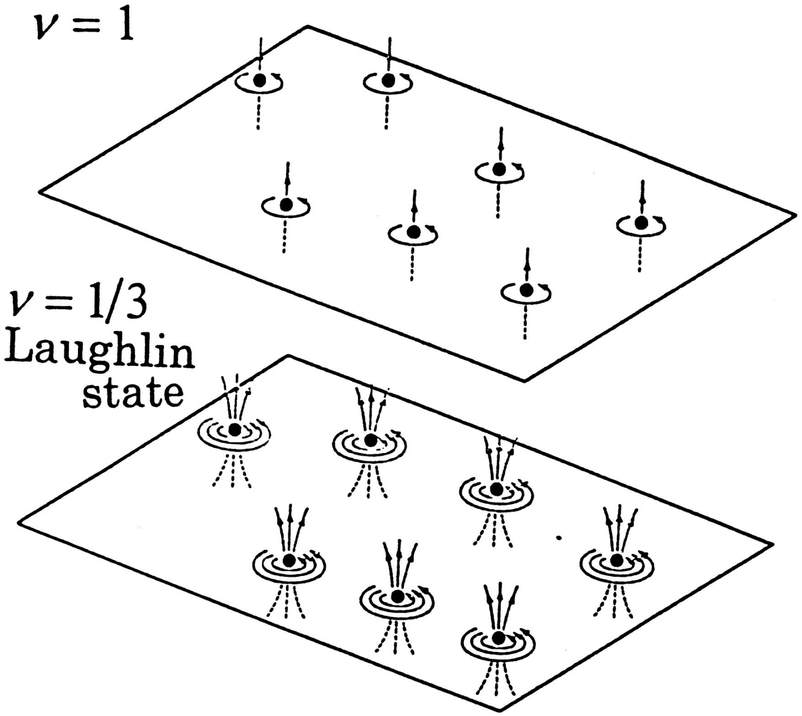


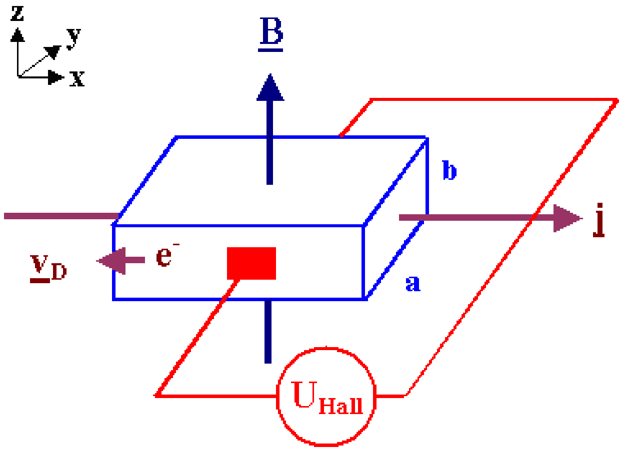
Superconductivity upon doping some of the best insulators in the world
-- Mott insulators

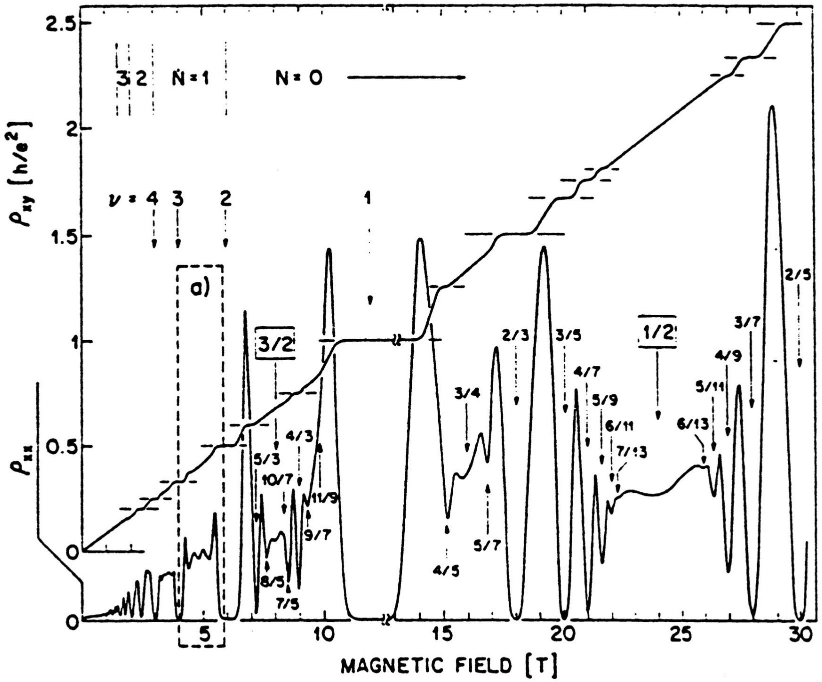


Fractional quantum Hall effect – strong correlation on the nanoscale

Tsui, Stormer, Gossard (1982); Laughlin (1983); Jain (1989)







Strongly interacting electrons + Magnetic field = Weakly interacting Composite Fermions

Problem

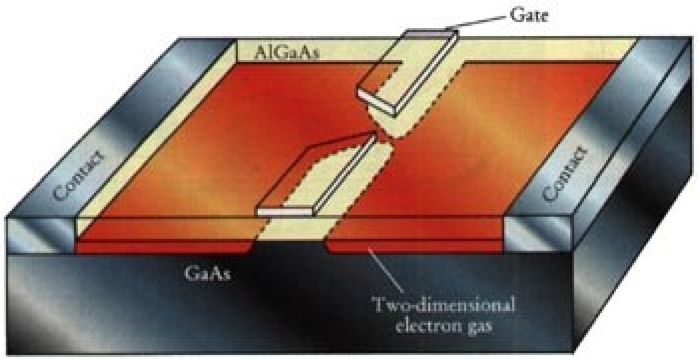
Unearthing the strongly correlated electron state in nanoscale devices is not easy:

(a) Small size hinders the use of bulk probes

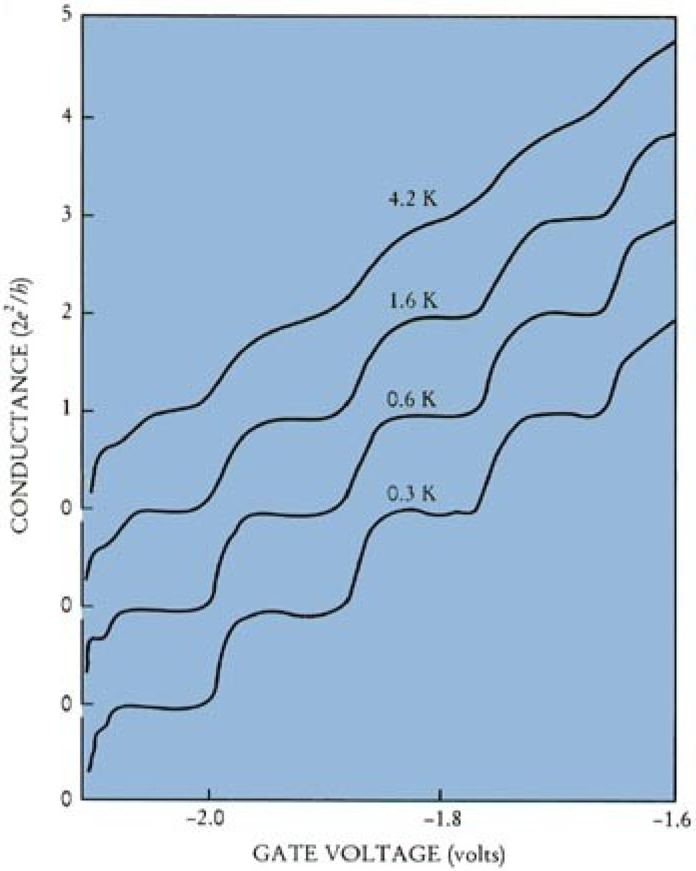
(b) Resistance measurement – the commonly employed probe does not always give clear answers

I. Electrons in quantum point-contacts (QPC)

Van Wees *et al.*, Delft group (1988)
Wharam *et al.*, Cambridge group (1988)



A QPC device

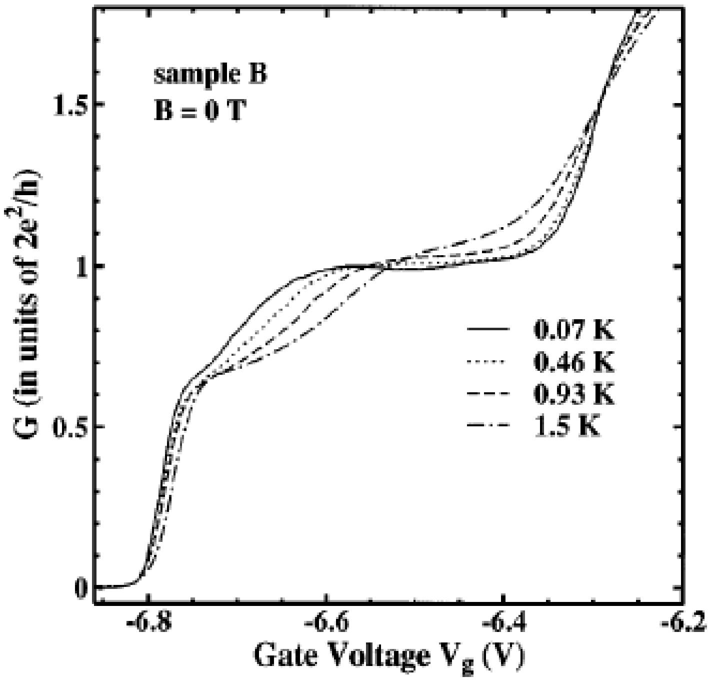


A QPC acts as a waveguide for electrons.

I. 0.7 effect – strongly correlated electrons in QPCs

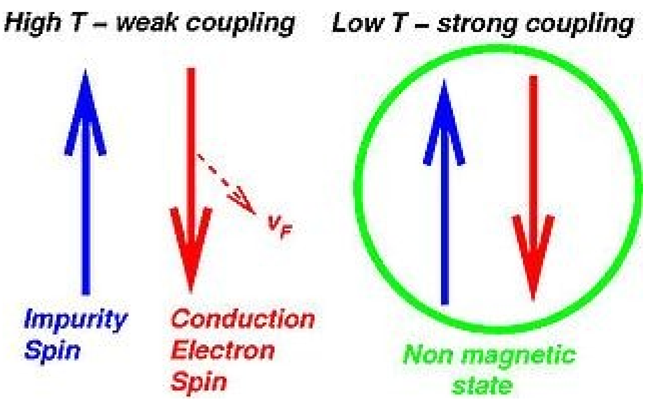
Thomas *et al.*, Cambridge group (1996)

The 0.7 conductance anomaly in quantum point-contact devices is an unresolved mystery more than 10 years after discovery.

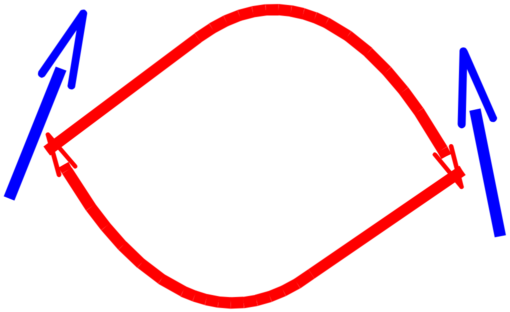


- Cannot be explained by assuming non-interacting electrons.
- Presently **three** serious contending scenarios – each substantially explains observed transport properties.
- Three scenarios: Are we seeing a spontaneous spin-splitting or a Kondo effect or a spin-incoherent Luttinger liquid (SILL)?

II. Kondo and RKKY effects in nanoscale devices



Impurity screening by conduction electrons - Kondo effect



Impurity interaction through conduction electrons - RKKY

Jeong *et al.*, Science (2001)

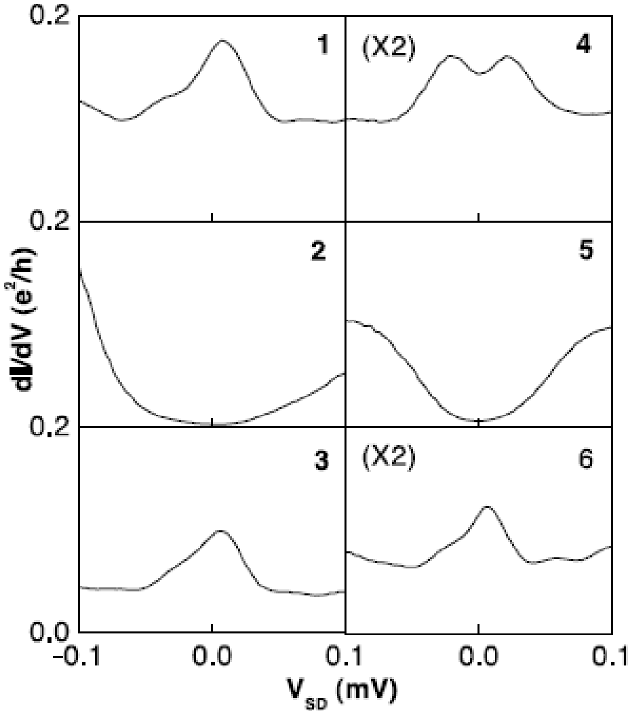


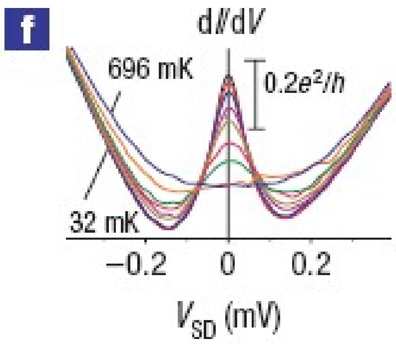
Fig. 3. Differential conductance traces from 1 to 6 in Fig. 2 B. Trace 4 and 6 are magnified by a factor of 2. The occurrence of Kondo resonance peaks is well contrasted. The periodicity is consistent with the diagram in Fig. 2A. A unique feature of the Kondo resonance peaks is their spitting, as compared with the single peaks from single dots (e.g., Fig. 1B).

Competition of Kondo and RKKY

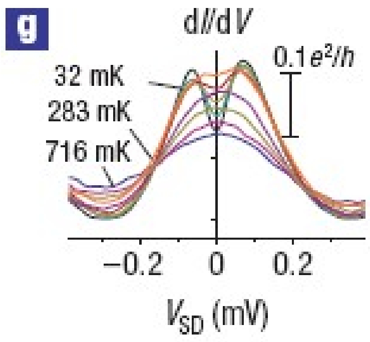
II. Kondo lattice scenario in 2D semiconductor heterostructures

Spontaneous formation of a 2D Kondo lattice in a semiconductor heterostructure has been proposed recently.
Can we rely on the usual probe (resistance measurement)?

Kondo ZBA?



RKKY-split ZBA?



- Observation of alternating splitting and merging of Zero Bias Anomaly – Kondo lattice?
- Two-impurity or few-impurity picture also leads to same result. Need additional handle.

C. Siegert *et al*. Nature Phys. (2007);
Cambridge and IISc groups.

Proposed Solution

We showed that a suitably-adapted NMR probe can help unearth the strongly correlated electron state.

I. 0.7 effect in QPC devices

Resistive detection of nuclear polarisation

N. Cooper and V. T., PRB (2008)

Non-interacting electrons:

$$H=\sum_{s,k,\sigma}\left[\epsilon_s+\frac{\hbar^2k^2}{2m}+\frac{\sigma}{2}g\mu_B B\right]c^+_{sk\sigma}c_{sk\sigma}+A_s\sum_i \boldsymbol{I}_i\cdot\boldsymbol{s}(\boldsymbol{R}_i)$$

$$\epsilon_s=\hbar\omega_y(s+1/2)$$

Overhauser shift: $Z_e=g\mu_B B+A_s n_{nuc}\langle I^z\rangle$

Conductance: $G(Z_e)=\frac{e^2}{h}\sum_{s,\sigma}f(\epsilon_s+\sigma Z_e/2)$

Exchange-enhanced spin-splitting scenario

Wang & Berggren (1996), Bruus et al. (2001),
Spivak & Zhou (2000)

Phenomenological model: $Z_{eff} = Z_e + \gamma n$ [D. Reilly et al., PRB (2005)]

$$T_1^{-1} = \Gamma_0 \int_{\hbar\omega_y/2+|Z_e|/2}^{\infty} \frac{f(\epsilon)[1-f(\epsilon)]}{\sqrt{(\epsilon-\hbar\omega_y/2)^2-(Z_e/2)^2}}\, d\epsilon$$

$$\Gamma_0 = \frac{2\pi A_s^2 m}{\hbar^3 w_y^2 w_z^2}$$

[N. Cooper and V. T. (2008)]

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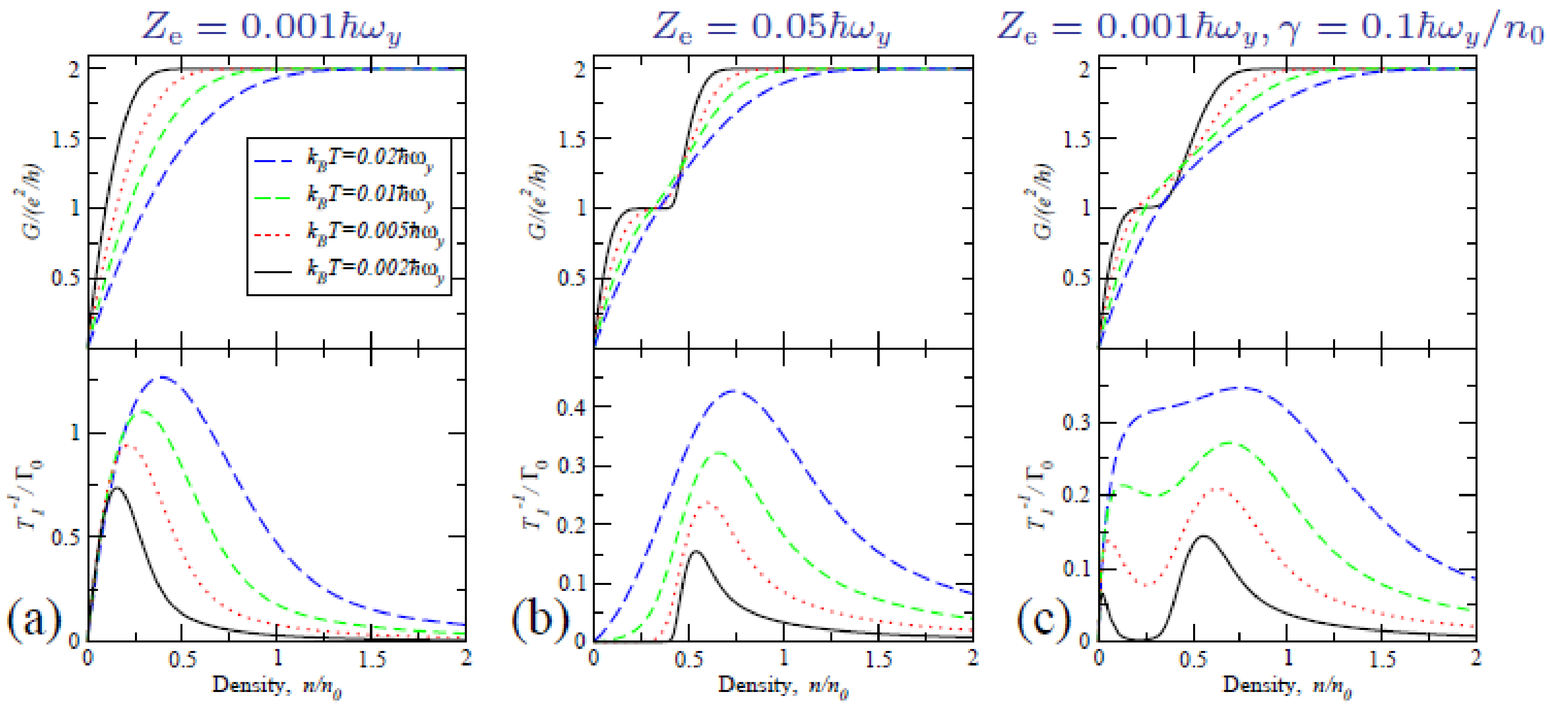
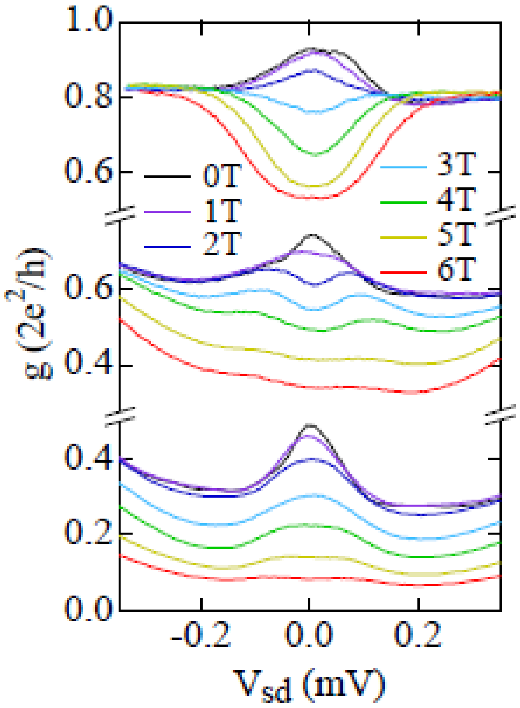


$n_0 = \sqrt{m\omega_y/\pi\hbar}$

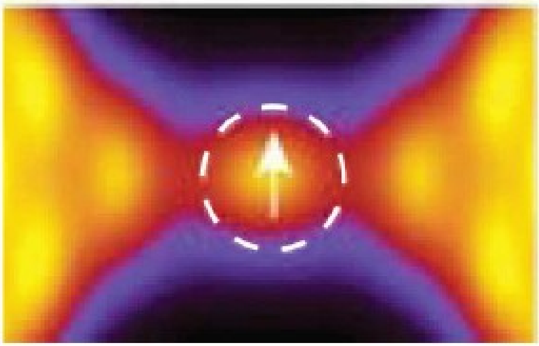
Double peak structure indicates exchange enhanced spin splitting

Kondo scenario

Cronenwett et al., PRL (2002)



Meir, Hirose, Wingreen, PRL (2002)
Rejec & Meir, Nature (2006)



Nuclear spin relaxation in QPC is dominated by coupling to the impurity spin:

$$T_1^{-1} = k_B T \left(\frac{A_d}{\hbar g_s \mu_B} \right)^2 \Im \left. \frac{\chi^{+-}(\omega)}{\omega} \right|_{\omega \to 0}$$

$$A_d \sim \frac{A_s}{w_x w_y w_z}$$

. . . Kondo scenario

High temperature (weak coupling) limit $T \gg T_K \sim \epsilon_F \exp[1/J\nu]$

$$T_1^{-1} = 2\frac{A_d^2 S(S+1)}{3\pi\hbar(k_B T)[J\nu]^2}$$

[Götze & Wölfle, JLTP (1975)]

Low temperature (local Fermi liquid) limit $T \ll T_K \sim \epsilon_F \exp[1/J\nu]$

$$T_1^{-1} = \frac{2\pi(k_B T)A_d^2}{\hbar(g_s\mu_B)^4}\chi_{imp}^2$$

[Shiba, Prog. Theor. Phys. (1975)]

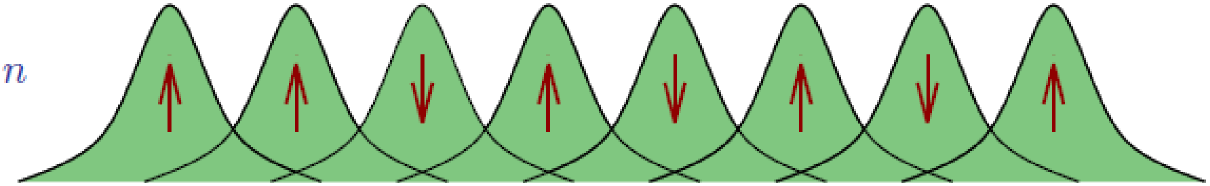
χ_{imp} - Kondo impurity susceptibility

Kondo impurity is characterised by non-monotonic temperature dependence.

Spin-incoherent Luttinger liquid (SILL)

[Matveev, PRL (2004)]

$$\frac{\hbar^2 n^2}{m} \ll \frac{e^2}{\epsilon} n$$



$$G \approx \frac{e^2}{h}$$

$$J_{ex} \ll k_B T \ll \epsilon_F$$

Temperature high compared to inter-electron exchange interaction

Low energy spin-flip excitations of a spin chain with lattice constant *1/n*, gap J_{ex} and high temperature:

$$T_1^{-1} \sim \Gamma_{SILL} = \frac{A_s^2 n^2}{\hbar w_x^2 w_y^2 J_{ex}} \quad \Rightarrow \quad \frac{\Gamma_{SILL}}{\Gamma_0} \sim \frac{\epsilon_F}{J_{ex}} \gg 1$$

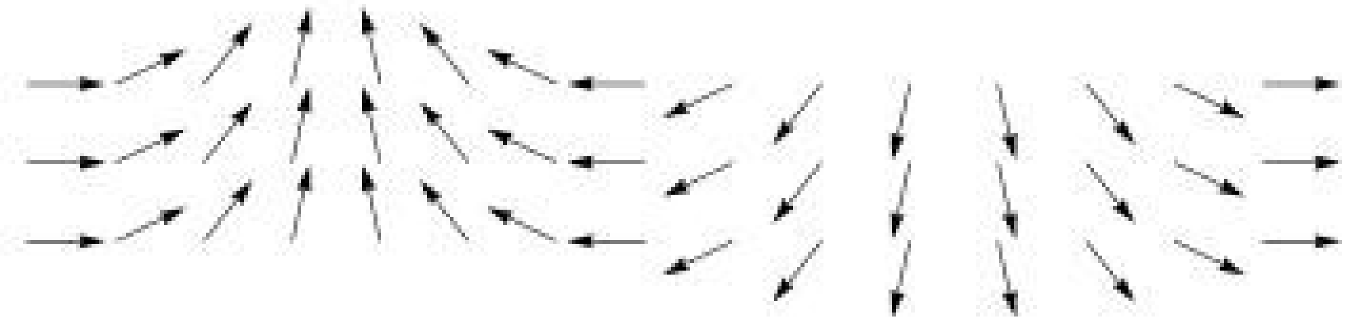
The SILL is characterised by weak temperature dependence.

II. Probing magnetic order in a 2D electron gas

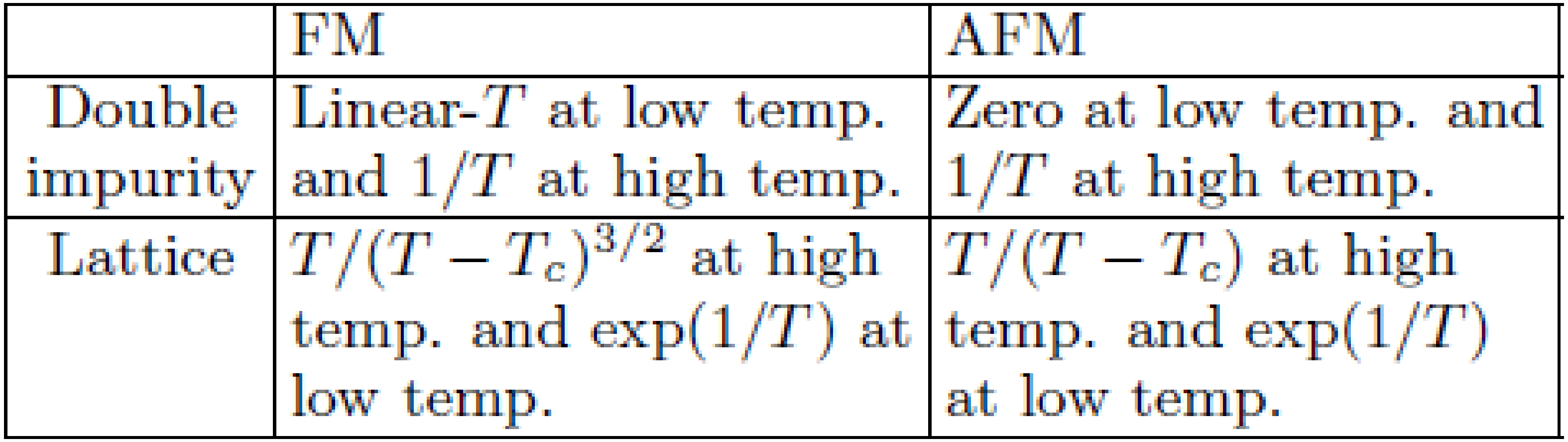
K. Dhochak and V. T., Phys. Rev. Lett. (2009)

Exploit the main physical difference

Low energy (long wavelength) magnetic excitations are possible.



Results



	FM	AFM
Double impurity	Linear-T at low temp. and $1/T$ at high temp.	Zero at low temp. and $1/T$ at high temp.
Lattice	$T/(T-T_c)^{3/2}$ at high temp. and $\exp(1/T)$ at low temp.	$T/(T-T_c)$ at high temp. and $\exp(1/T)$ at low temp.

Summary

- NMR can provide an additional handle for probing the electronic state in mesoscopic devices – transport measurements are not always reliable.

- Quantum point contact: NMR shows qualitative differences for the three proposed scenarios – density dependent spin-splitting, Kondo effect and spin-incoherent Luttinger liquid.

- 2D electron gas: NMR can distinguish between a double impurity picture and a Kondo lattice picture. In comparison zero bias anomaly signatures are the same.