Measurement of spin polarisation using transport spectroscopic techniques

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Spin polarisation in ferromagnets: Positive and Negative spin polarisation

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Magnitude+sign: **The Meservey Tedrow Technique**

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Measuring the magnitude: **Point contact Andreev Reflection**

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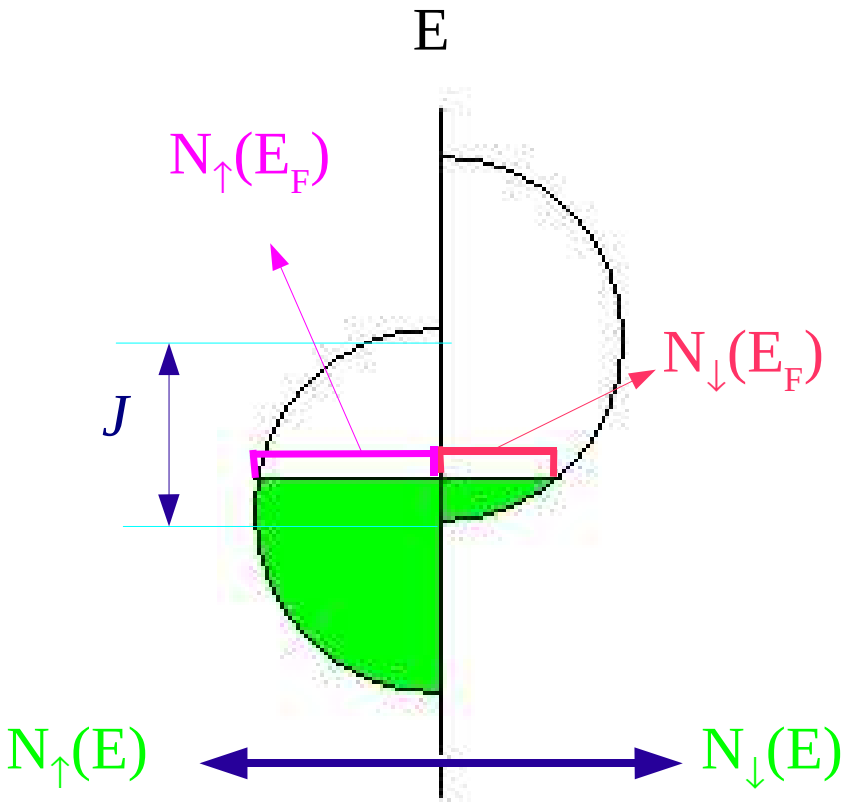
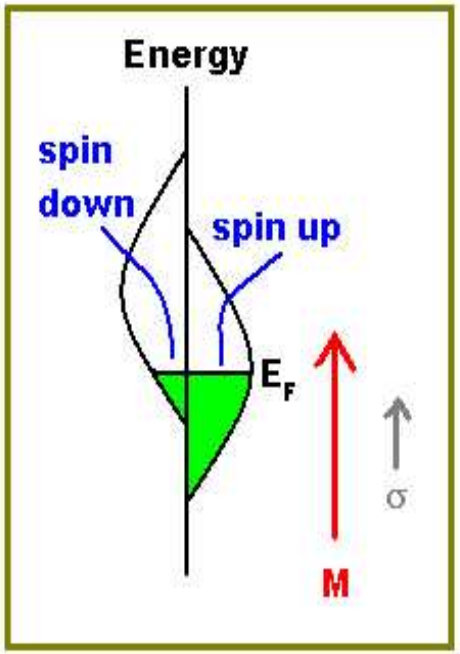
Positive or negative? **Ferromagnetic tunnel junctions**

Spin polarisation in ferromagnets

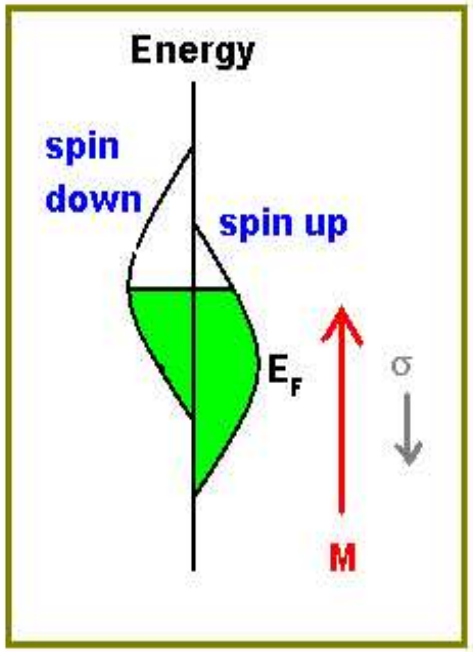


$$P = \frac{N_{\uparrow}(E_F) - N_{\downarrow}(E_F)}{N_{\uparrow}(E_F) + N_{\downarrow}(E_F)}$$

Positive and negative spin polarisation



Majority spin carrier
Ferromagnet



Minority spin carrier
Ferromagnet

P>0

Most known ferromagnets

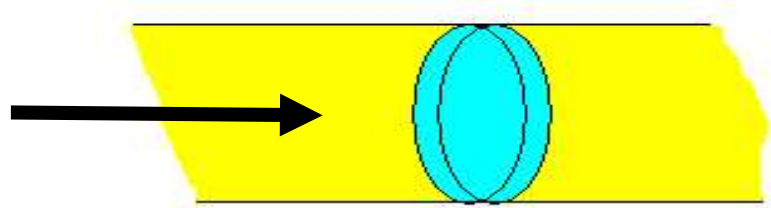
P<0

Very few: $SrRuO_3$, Fe_3O_4

Transport spin polarisation: **Ballistic limit**

l>>a

$$Net\,Flux(\sigma) = \langle N(E_F) v_F \rangle = \int_{S_{F,\sigma}} N(E_F, k) v_{F\hat{n}}(k) d^2 k$$



$$P_t = \frac{J(\uparrow) - J(\downarrow)}{J(\uparrow) + J(\downarrow)} = \frac{\langle N_\uparrow v_{F\uparrow} \rangle - \langle N_\downarrow v_{F\downarrow} \rangle}{\langle N_\uparrow v_{F\uparrow} \rangle + \langle N_\downarrow v_{F\downarrow} \rangle}$$

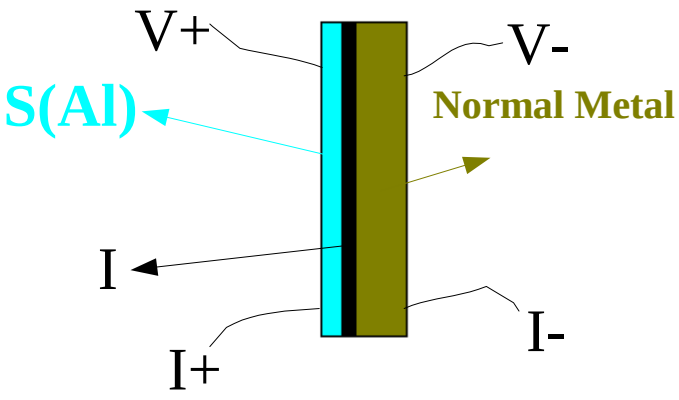
Transport spin polarisation: **Diffusive limit**

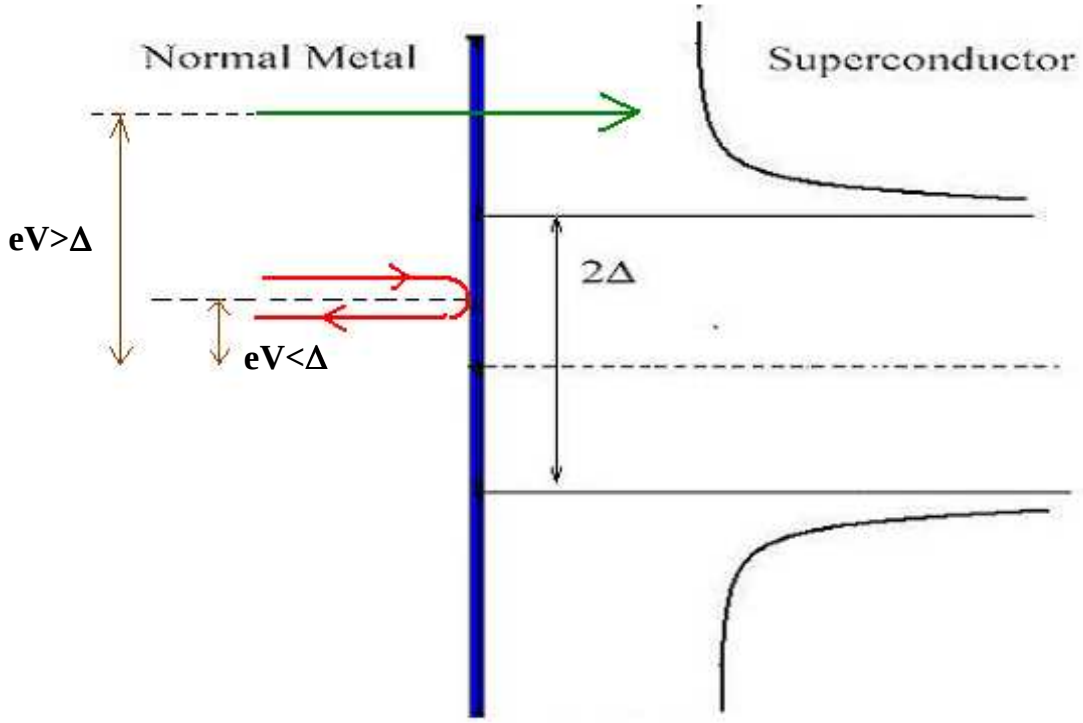
l<<a

$$P_t = \frac{J(\uparrow) - J(\downarrow)}{J(\uparrow) + J(\downarrow)} = \frac{\langle N_\uparrow v_{F\uparrow}^2 \rangle - \langle N_\downarrow v_{F\downarrow}^2 \rangle}{\langle N_\uparrow v_{F\uparrow}^2 \rangle + \langle N_\downarrow v_{F\downarrow}^2 \rangle}$$

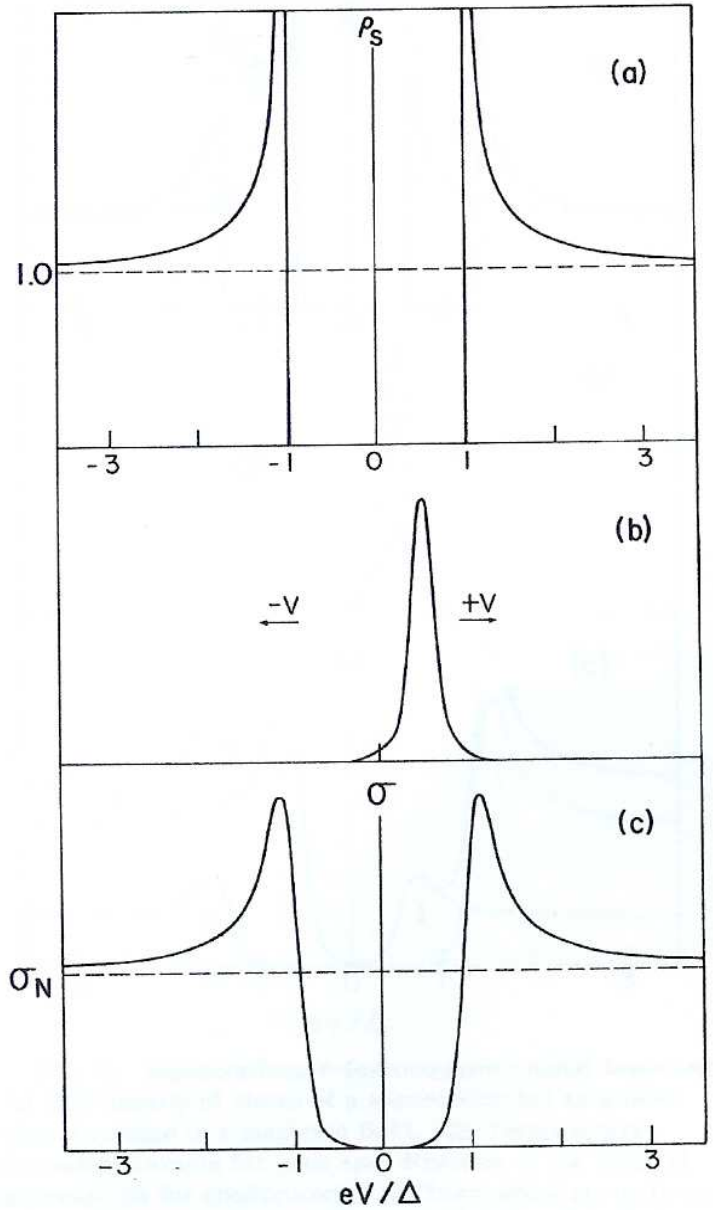
How to Define and Calculate the Degree of Spin Polarization in Ferromagnets
I. I. Mazin
Phys. Rev. Lett. **83**, 1427-1430 (1999)

Meservey Tedrow Technique (P_t)



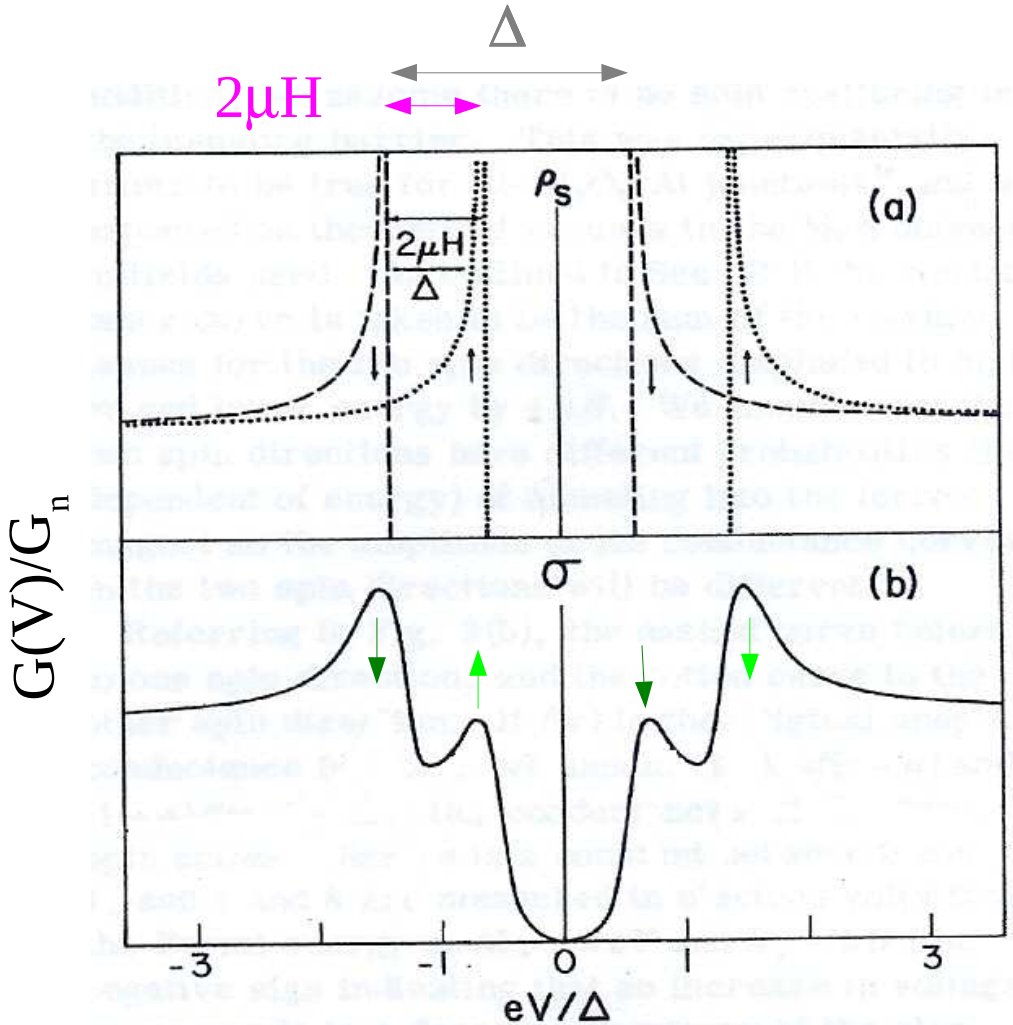


Insulating spacer

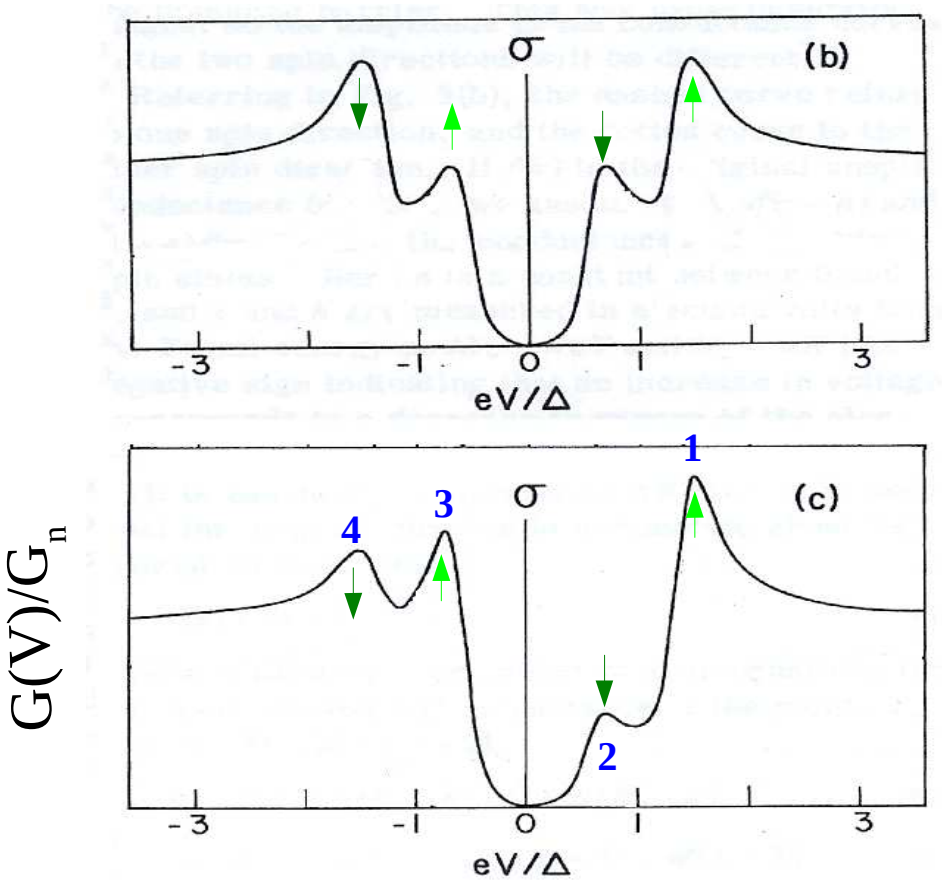


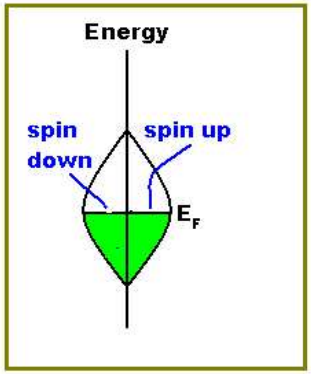
Meservey Tedrow Technique

$$N_s(E) = N_{s\uparrow}(E)+N_{s\downarrow}(E)$$
$$= (1/2)\{N_s(E+\mu H)+N_s(E-\mu H)\}$$



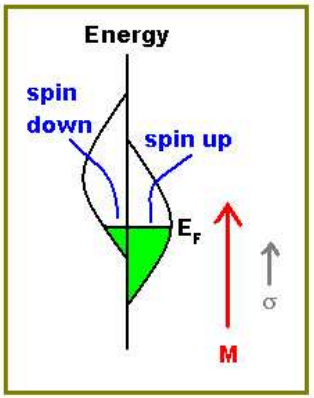
Ferromagnet/Insulator/Superconductor





Non-magtic metal

$$N_{\uparrow}(E_F)=N_{s\downarrow}(E_F)$$



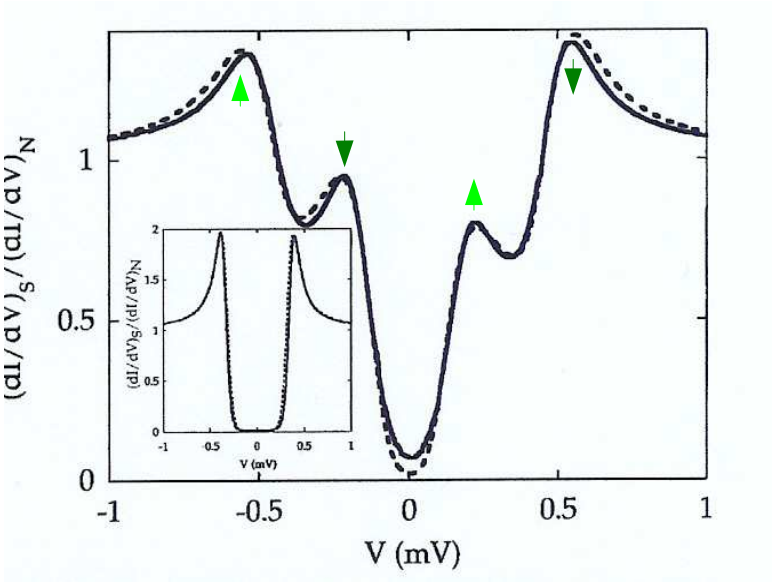
Majority spin carrier Ferromagnet

$$N_{\uparrow}(E_F)>N_{s\downarrow}(E_F)$$

$$P_t=2a-1$$

$$a=\frac{\sigma_4-\sigma_2}{\sigma_4-\sigma_2+\sigma_1-\sigma_3}$$

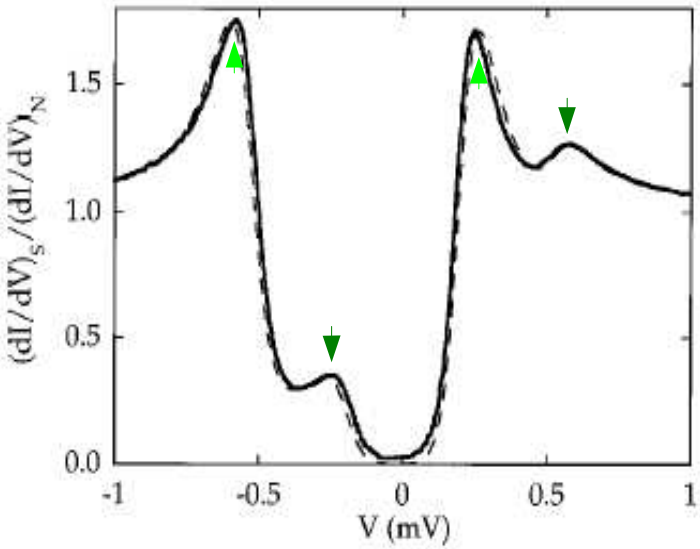
$SrRuO_3$



H=3T

P_t= -10%

$La_{2/3}Sr_{1/3}MnO_3$



H=3T

P_t=72%

Advantage

The sign and the magnitude of spin polarisation is determined from a single measurement.

Drawbacks

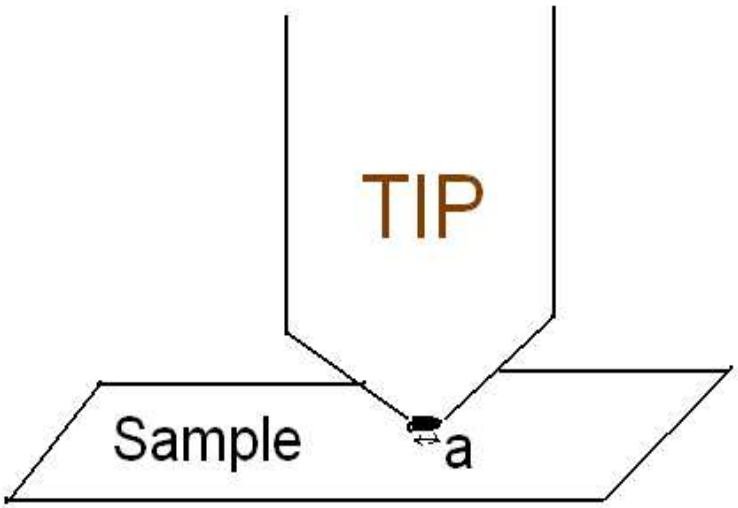
Requires a superconductor with low spin orbit coupling.
Al: Requires measurement below 1K

The magnitude of the spin polarisation is sensitive to the spin diffusion length in the insulating spacer.

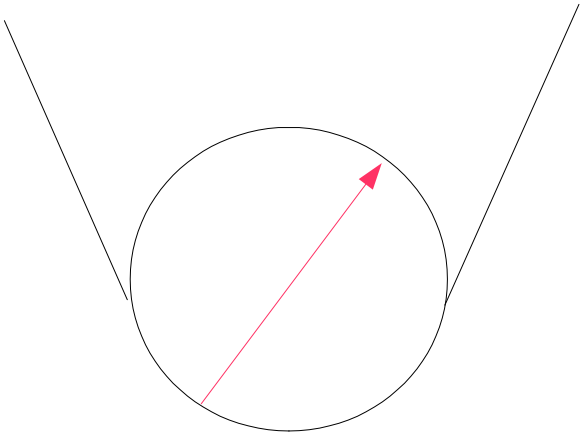
Non uniform current densities when the ferromagnet has large resistivity causes problems in the analysis.

Tedious process: requires fabrication of high quality tunnel junctions.

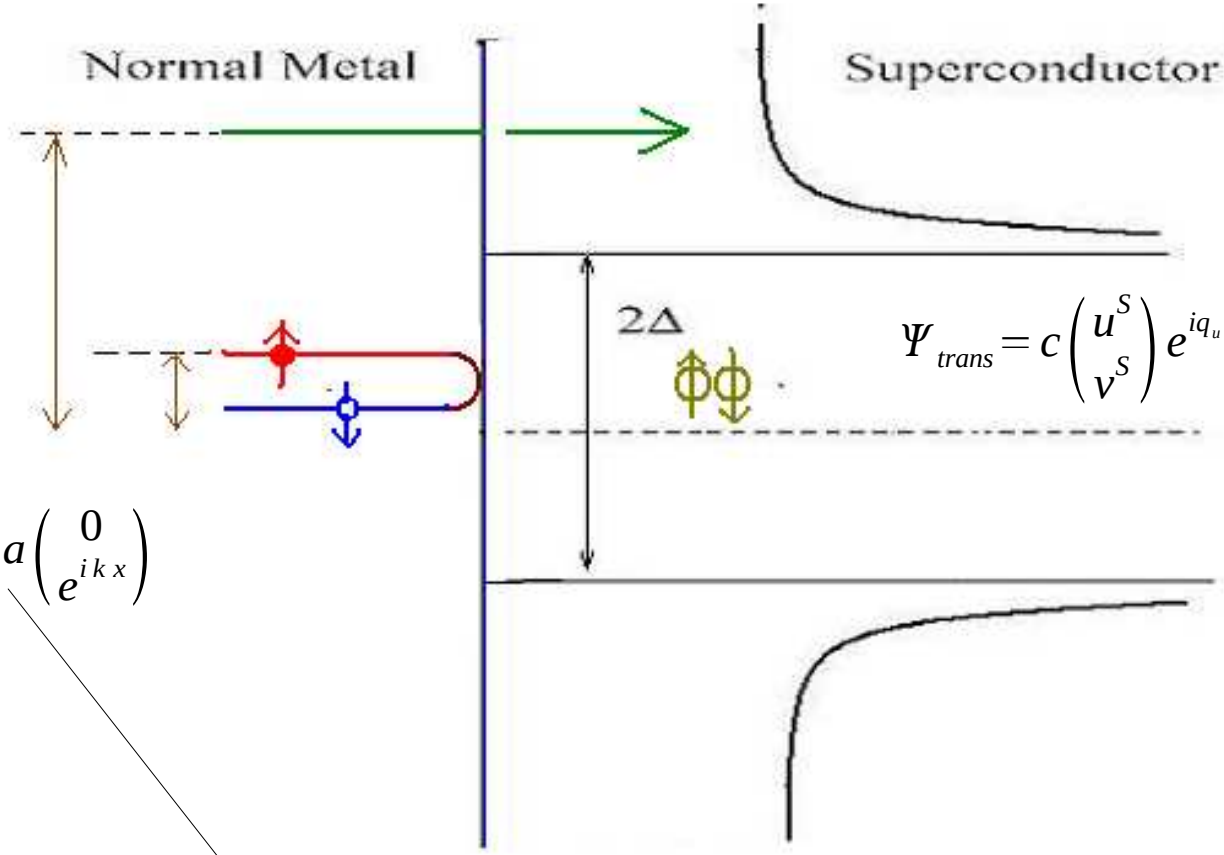
Point Contact Andreev Reflection



$l >> a$



The electron accelerates freely within a spherical volume of diameter a around the point contact.



$$\Psi_{inc} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ikx}$$

$$\Psi_{trans} = c \begin{pmatrix} u^S \\ v^S \end{pmatrix} e^{iq_u x} + d \begin{pmatrix} v^S \\ u^S \end{pmatrix} e^{-iq_v x}$$

$$\Psi_{refl} = b \begin{pmatrix} e^{-ikx} \\ 0 \end{pmatrix} + a \begin{pmatrix} 0 \\ e^{ikx} \end{pmatrix}$$

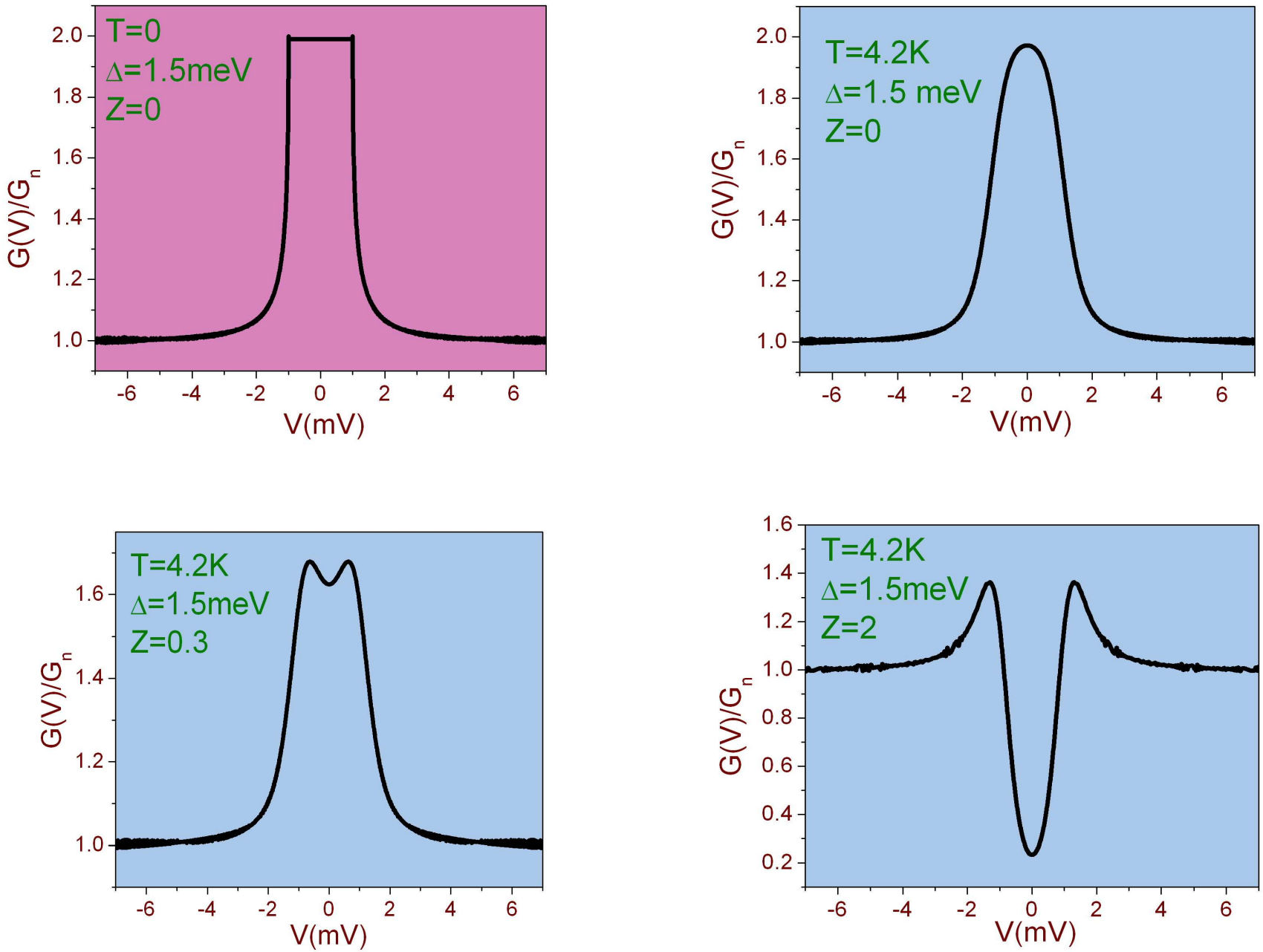
Normal reflection

Andreev reflection

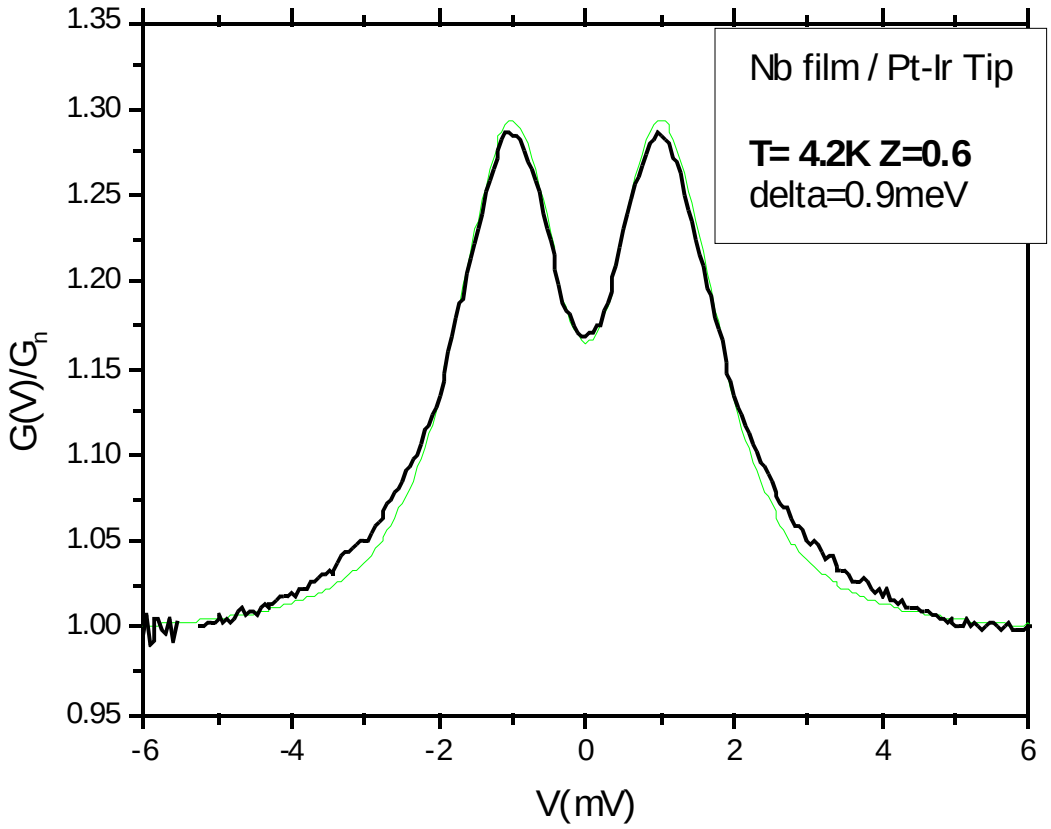
$$V(x) = V_0 \delta(x) \qquad Z = V_0 / \hbar v_F$$

$$\Psi_n(x=0) = \Psi_s(x=0)$$

$$\Psi_s'(x=0) - \Psi_n'(x=0) = \frac{2mV}{\hbar^2} \Psi(x=0)$$

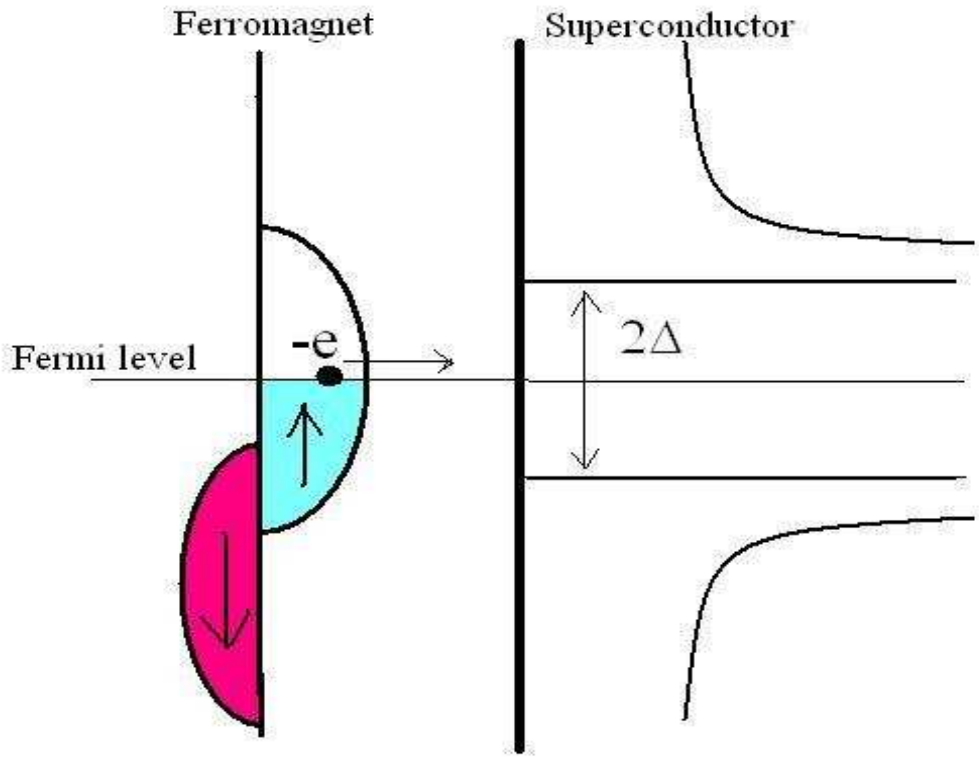

T=0
Δ=1.5meV
Z=0
T=4.2K
Δ=1.5 meV
Z=0
T=4.2K
Δ=1.5meV
Z=0.3
T=4.2K
Δ=1.5meV
Z=2
G(V)/G_n
V(mV)

Nb film/Platinum-Iridium tip



Z=0.6

Andreev reflection across a ferromagnet/superconductor interface



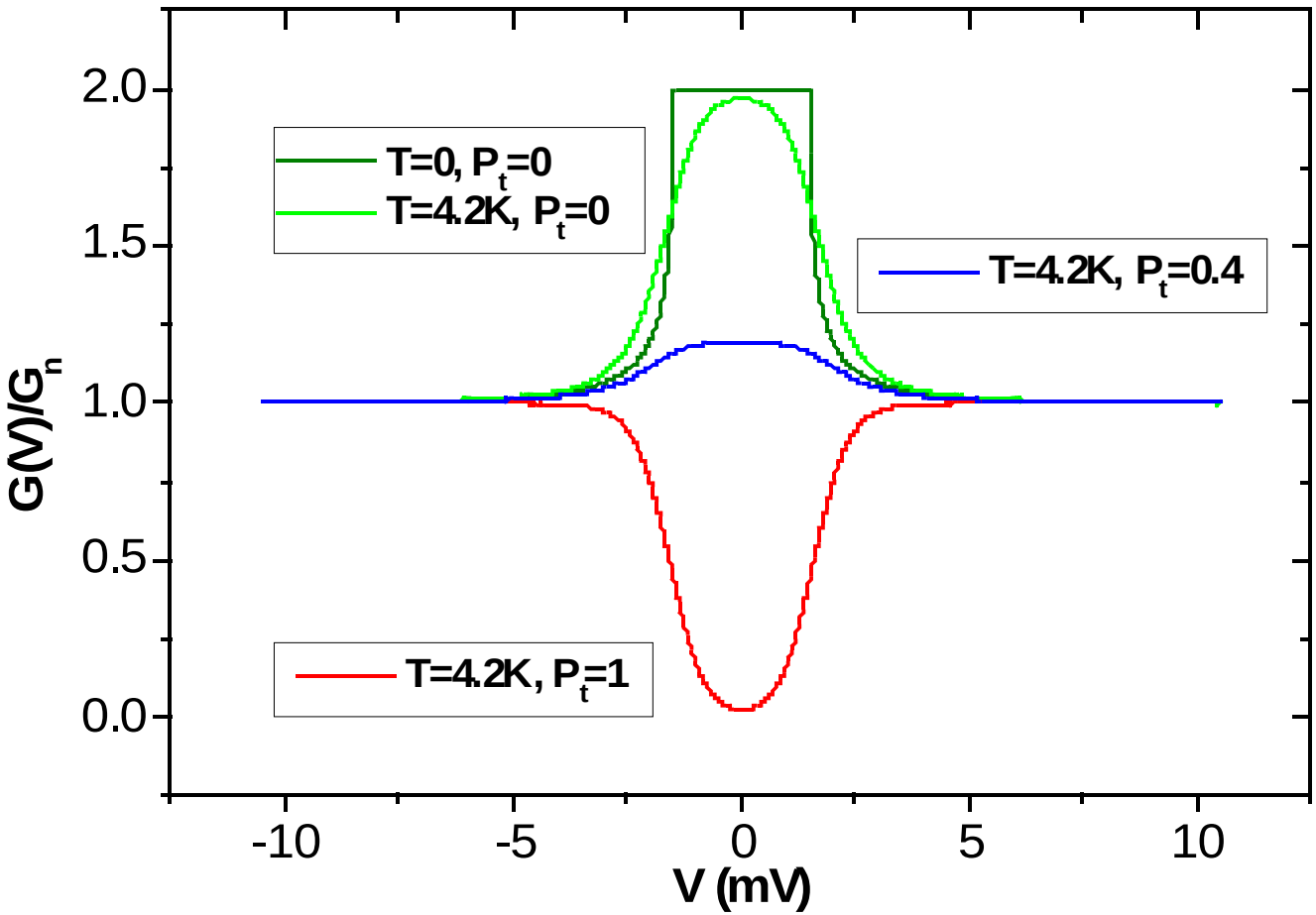
$$\Psi_{inc} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ikx}$$

$$\Psi_{refl} = b \begin{pmatrix} e^{-ikx} \\ 0 \end{pmatrix} + a \begin{pmatrix} 0 \\ e^{\kappa x} \end{pmatrix}$$

Evanescent wave

$$\Psi_{trans} = c \begin{pmatrix} u^S \\ v^S \end{pmatrix} e^{iq_u x} + d \begin{pmatrix} v^S \\ u^S \end{pmatrix} e^{-iq_v x}$$

Ferromagnet/superconductor interface



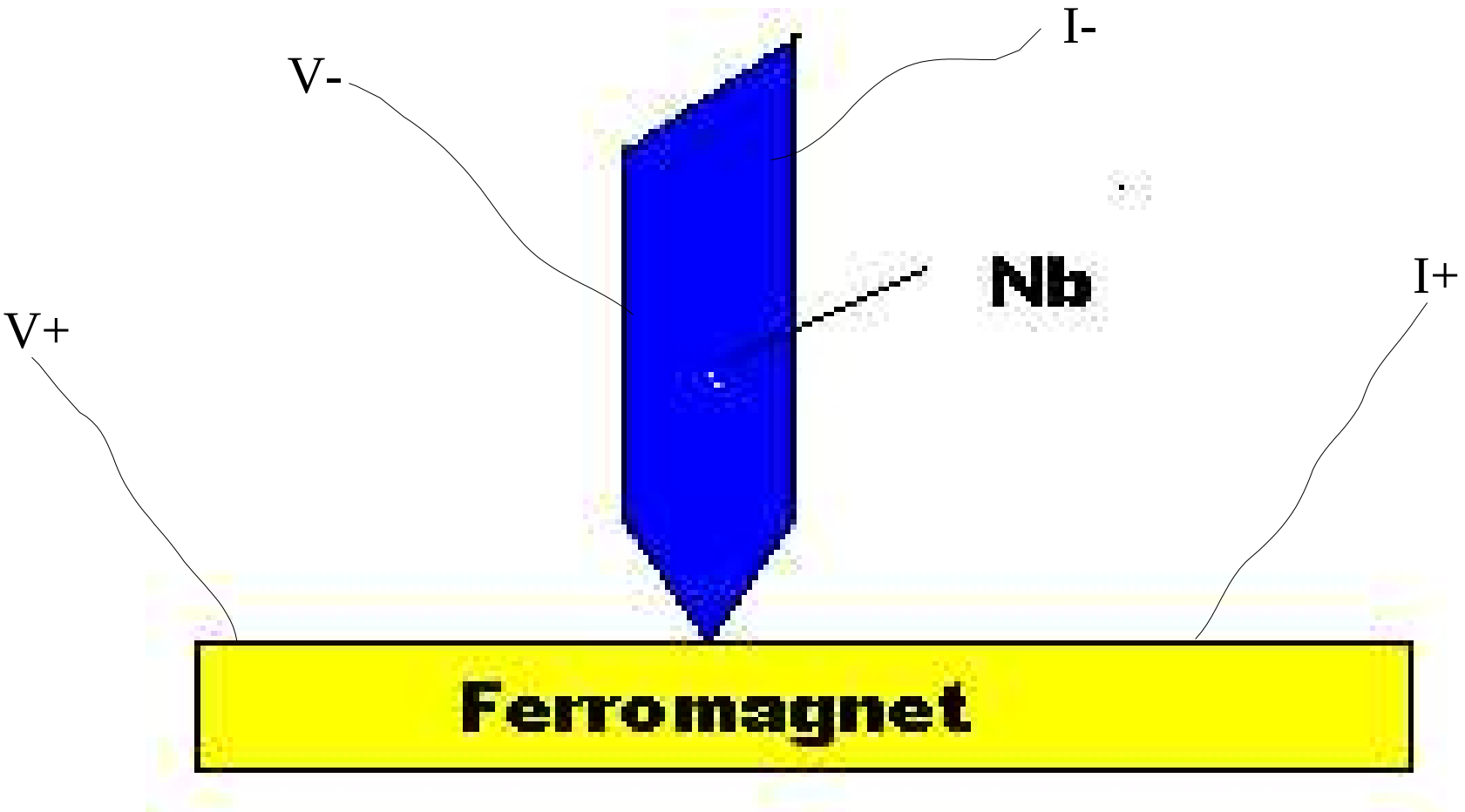
For finite P_t

$$I=I_u(1-P_t)+I_p P_t$$

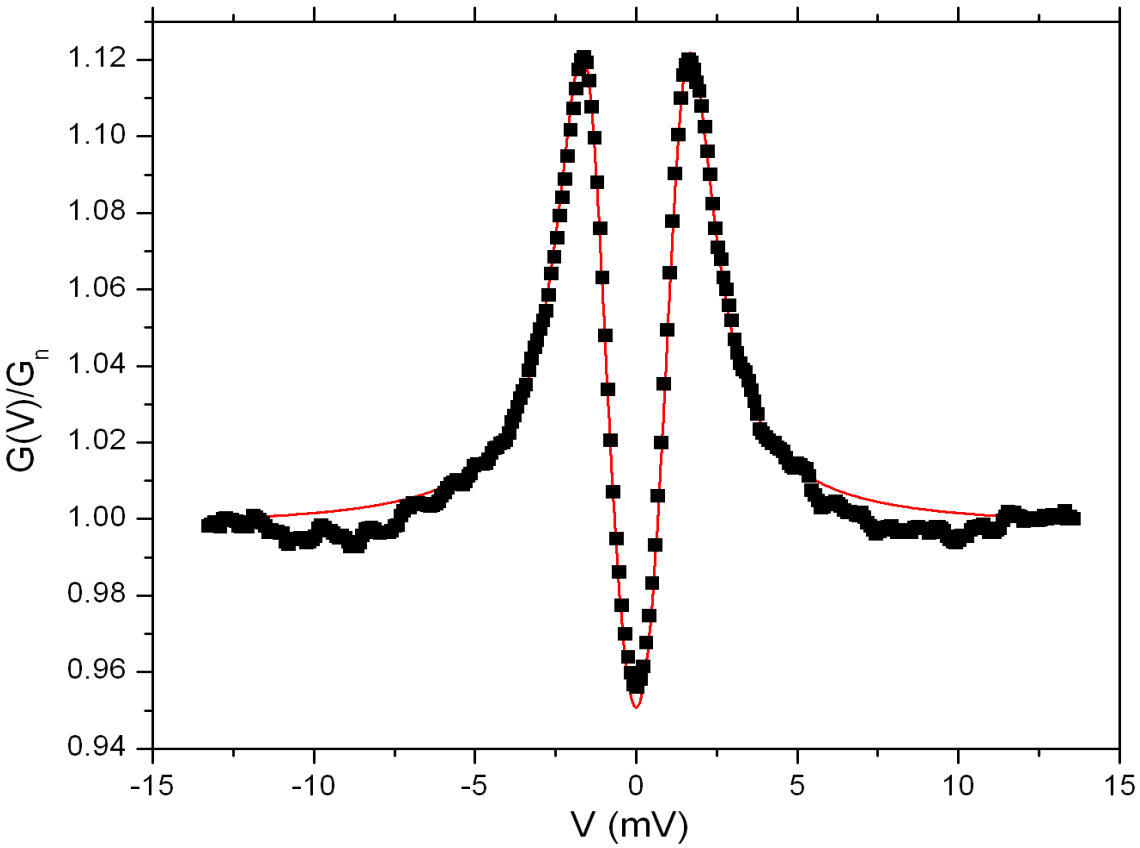
Point contact setup

$I=I_{dc}+I_{ac}\sin(\omega t)$ $\quad$ $V=V_{dc}+V_{ac}\sin(\omega t)$

$$G(V_{dc}) \approx \frac{I_{ac}}{V_{ac}}$$



Spin polarisation of Iron



T=3.5K

Δ=1.5 meV

Z=0.28

P_t=0.43

Transport spin polarisation $SrRuO_3$

4d ferromagnet with T_c~160K.

M_s=1.6μ_B/Ru

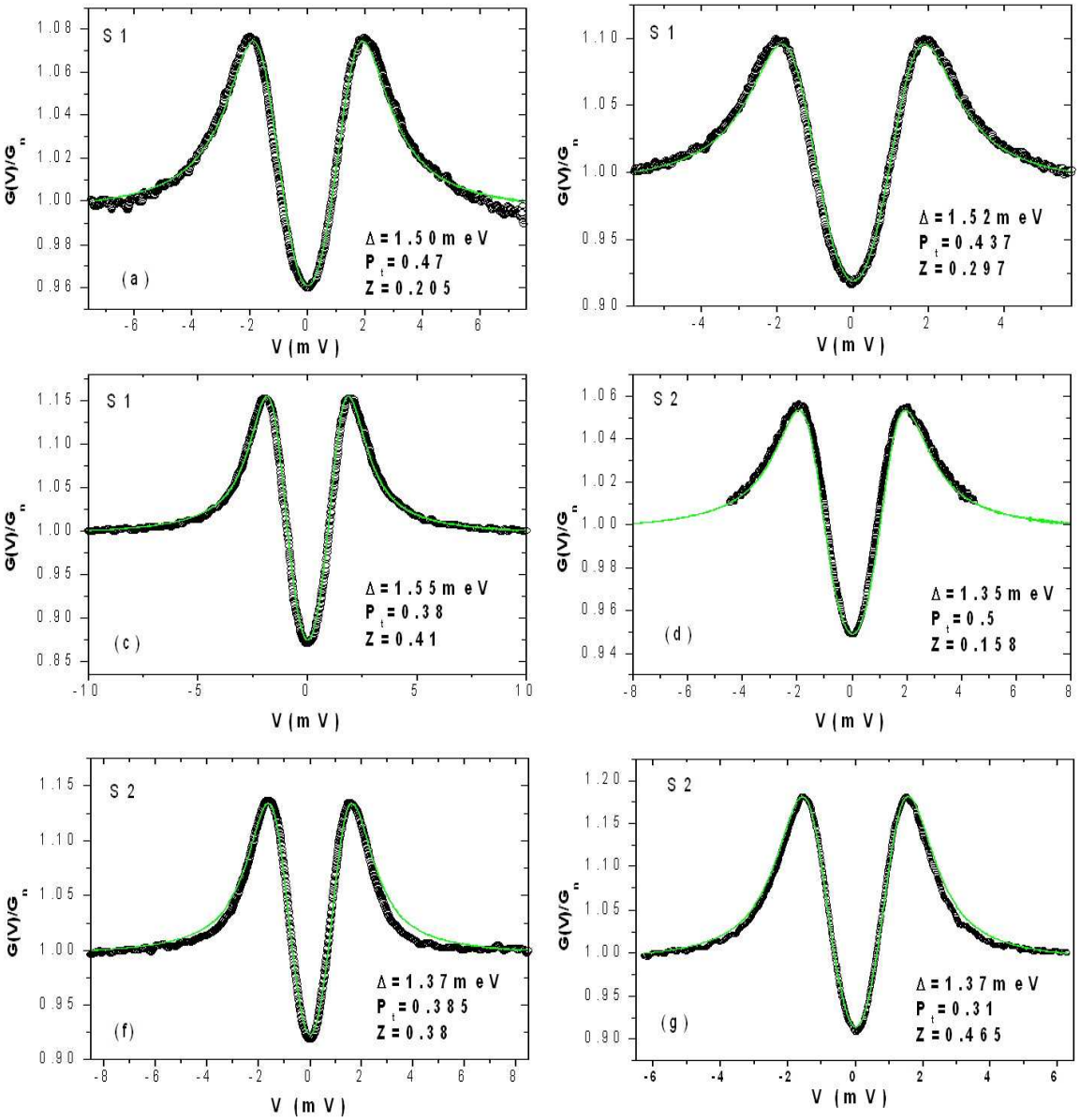
1. Clean system with large mean free path: ~ 400Å ⇒ Easy to realise a ballistic limit in point contact.

2. One of the very few oxide ferromagnets where quantum oscillations could be observed.

3. P~0.091-0.2 $\boxed{N_\downarrow(E_F) \approx N_\uparrow(E_F)}$

4. $\boxed{v_{F\downarrow} >> v_{F\uparrow}}$

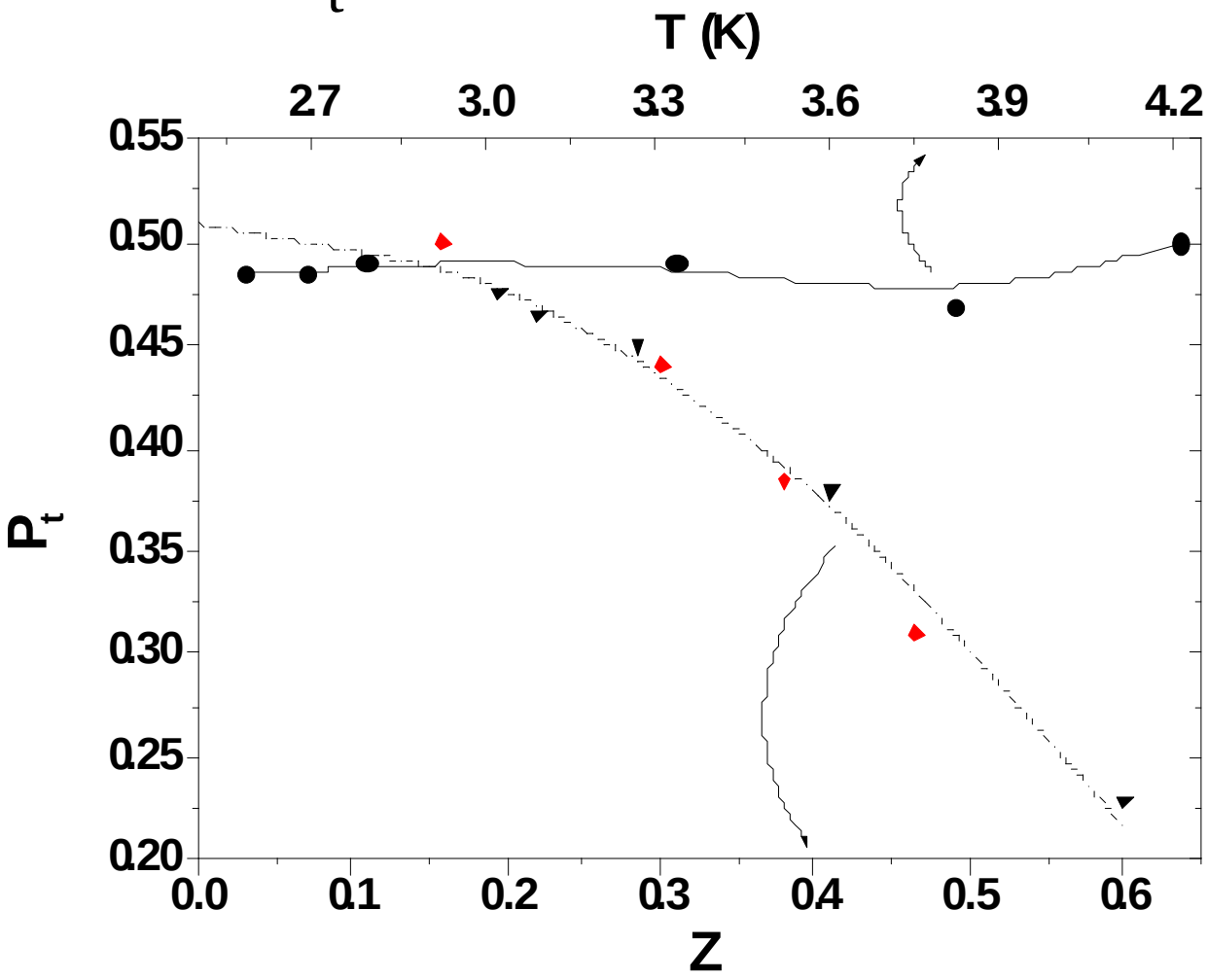
$SrRuO_3$



Fitting parameters

Δ, Z, P_t

P_t as a function of Z



$|P_t|$=0.51±0.02

Phys. Rev. B **67**, 020411 (2003)

Advantages

Simple easy to do.

No artefact associated with spacer layer.

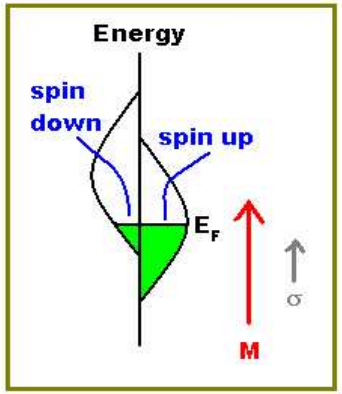
Disadvantages

Only magnitude, no sign.

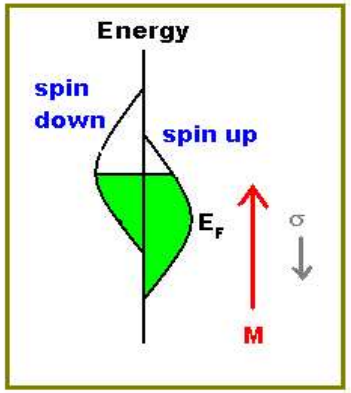
Ballistic contact essential: Cannot measure on ferromagnets with short mean free paths

Cannot measure on samples with high resistivity

Sign of spin polarisation: Ferromagnetic tunnel junction



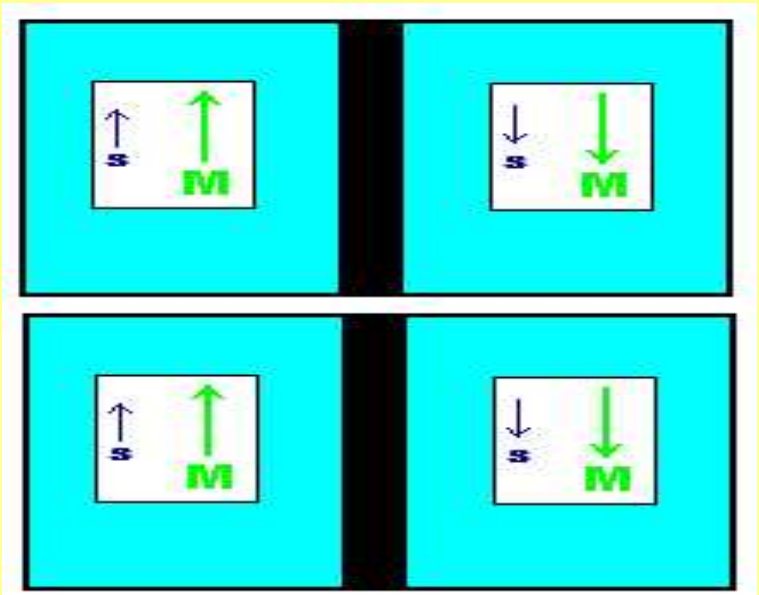
Majority spin carrier
Ferromagnet



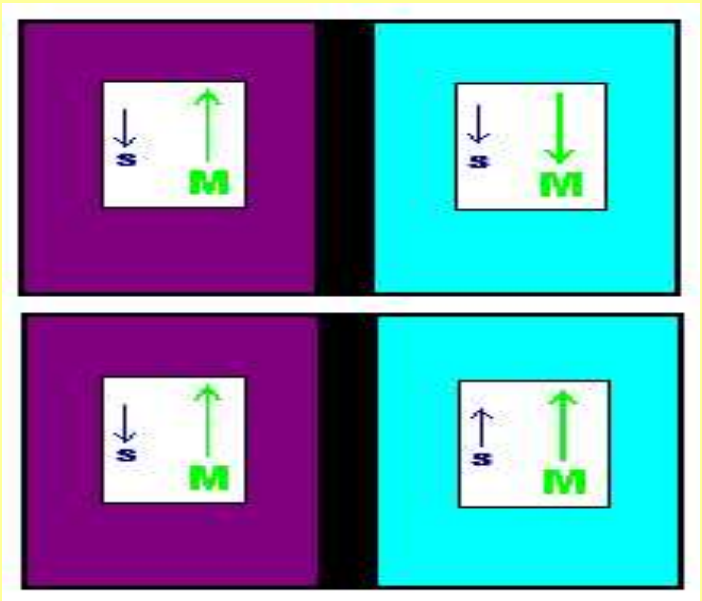
Minority spin carrier
Ferromagnet

H=0

H≠0

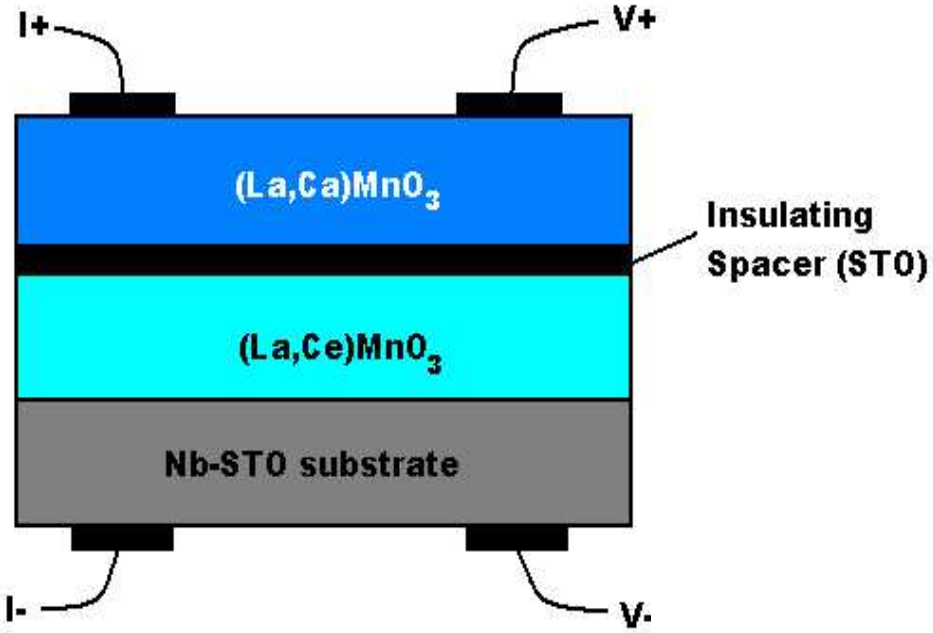


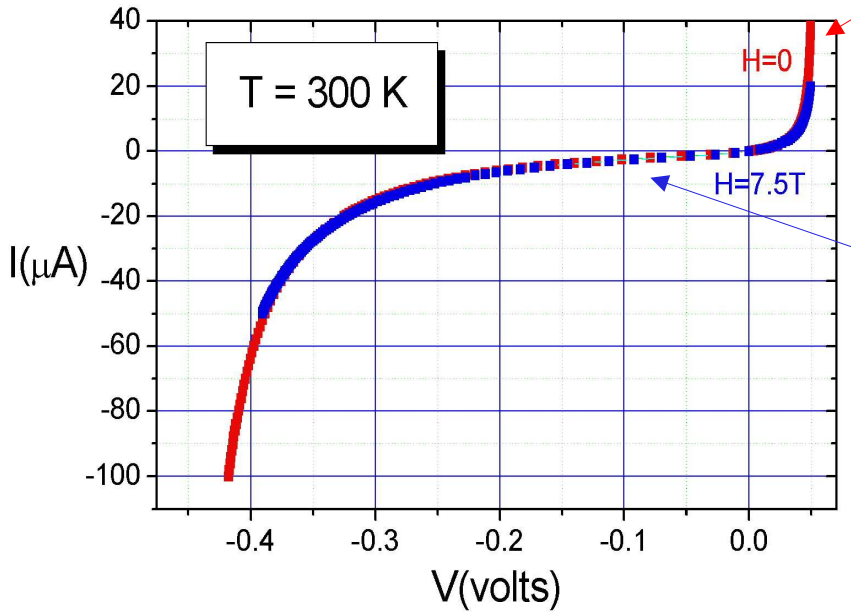
R(H)<R(H=0)



R(H)>R(H=0)

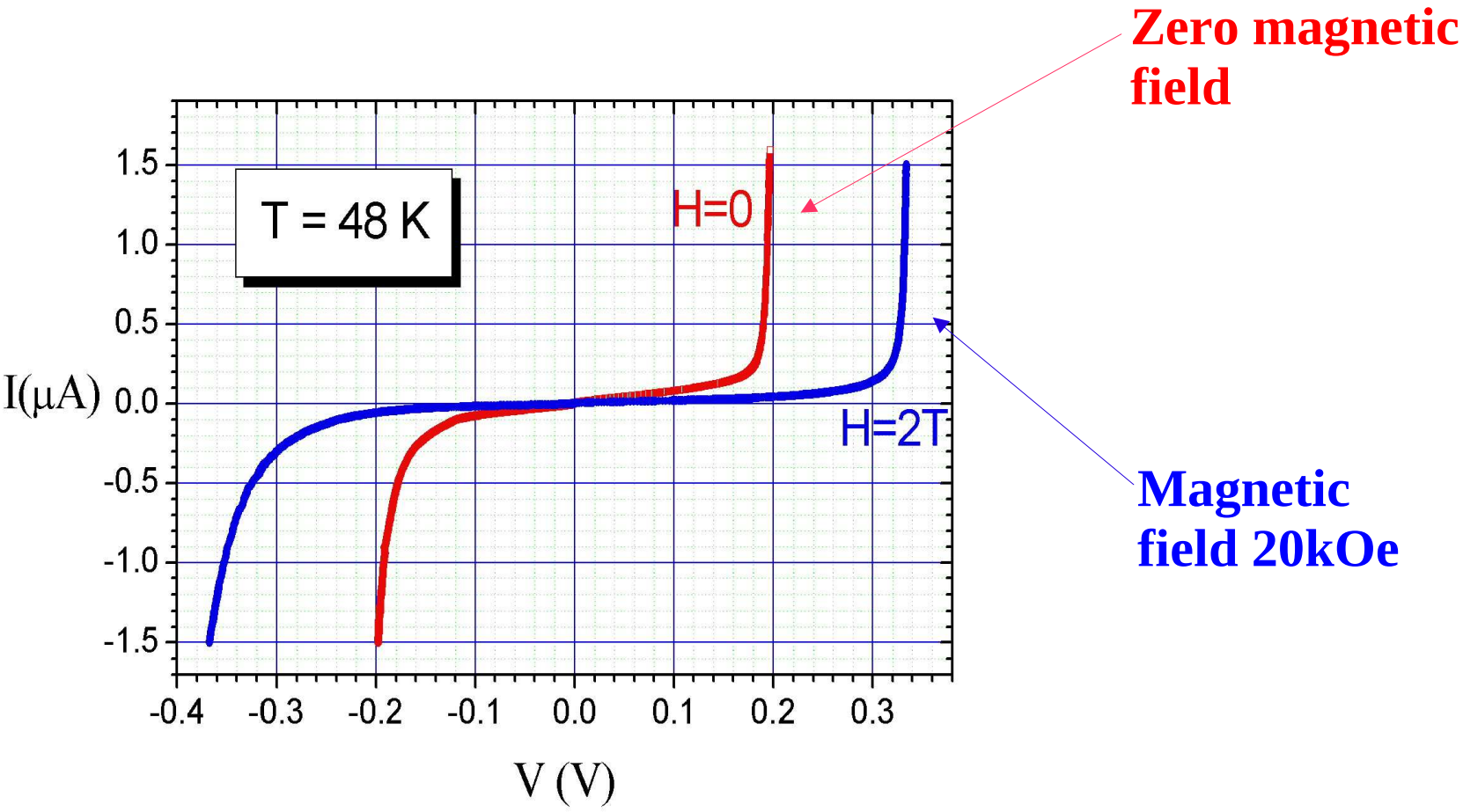
Negative spin polarisation in $La_{0.7}Ce_{0.3}MnO_3$





Zero magnetic field

Magnetic field 75kOe



Negative spin polarisation in La0.7Ce0.3MnO3

Phys. Rev. Lett. **90**, 017202 (2003)

Techniques available for measuring spin polarisation

Magnitude: **Point contact Andreev Reflection**
Sign: **Ferromagnetic tunnel junctions**

Future developments

Sign+Magnitude: **Meservey Tedrow Technique**

Further Thoughts

Tunneling magnetoresistance and Meservey Tedrow type measurements using STM