Disorder effects on spin dependent tunneling

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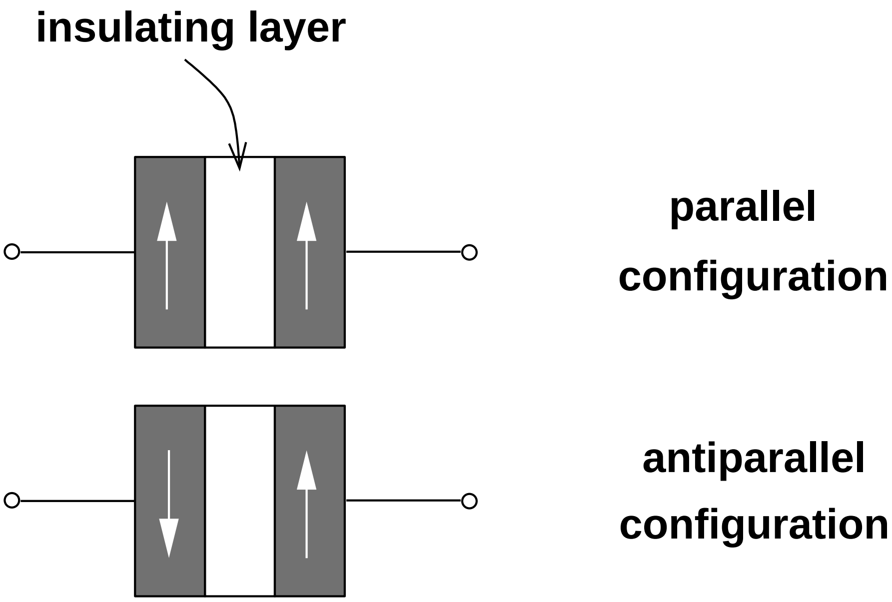
Outline of the talk

- Motivation and Definitions
- Overview of theoretical models
  - Juillière's model
  - *ab initio* calculations
  - Bratkovsky's model
  - Extension of Bratkovsky's model
- Results
  - Magnetic field dependence
  - Effect of disorder on the TMR
  - Connection to Juillière's model
- Conclusion

Tunneling magnetoresistance

The resistance of an insulating layer sandwiched between two ferromagnetic contacts depends on the alignment of the magnetization in the ferromagnets:



The resistance is *higher* in the antiparallel configuration.

The TMR ratio is defined as

$$TMR = \frac{R_{AP} - R_P}{R_P}$$

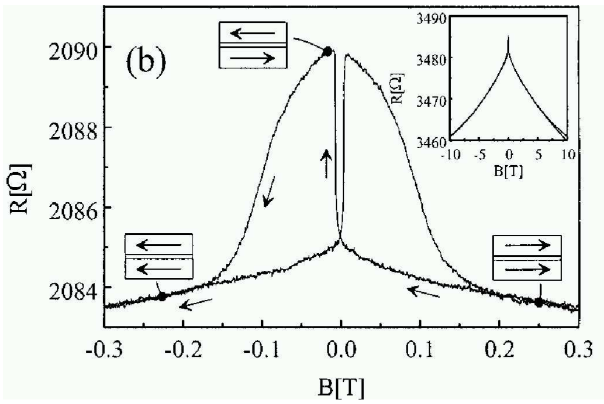
- Juillère 1975: TMR 14% at 4.2 K and small bias voltages (Ge)
- today: TMR $> 10\%$ at room temperature and higher voltages (Al_2O_3)

The TMR effect has promising applications in spin-electronics: magnetic sensors, hard disks, MRAMs

Experiments

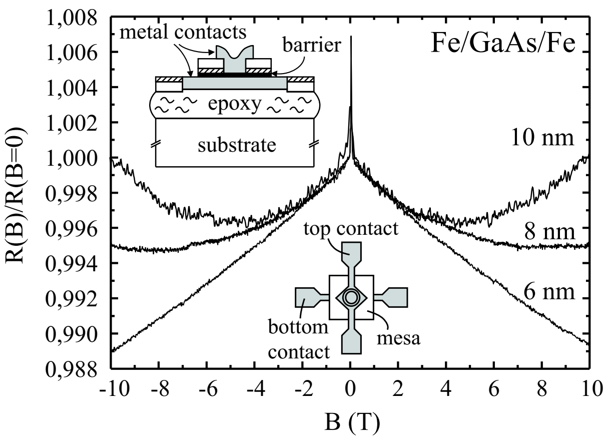
Experiments in the group of Prof. Weiss in Regensburg on Fe/GaAs/Fe tunnel junctions

➤ small TMR effect: 0.2–1.7% (band structure considerations predicted ≈ 100%!)



S. Kreuzer *et. al.*, Appl. Phys. Lett., **80**, 4582 (2002)

➤ anomalous magnetoresistance in high magnetic fields



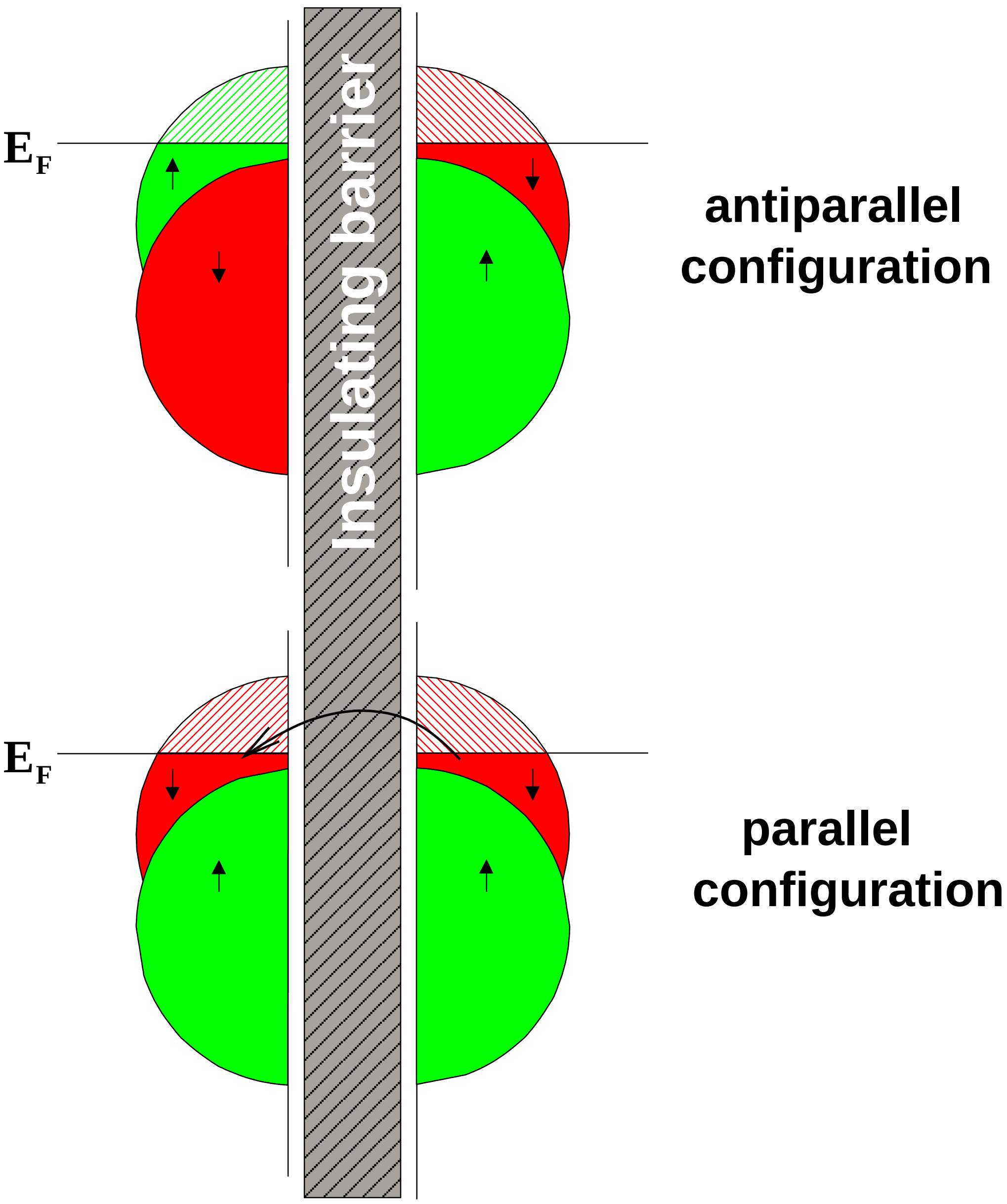
M. Zenger *et. al.*, to be published in Appl. Phys. Lett.

➜ Interdiffusion of iron atoms in GaAs barrier?

➜ Importance of spin flip scattering?

Physics behind TMR

The density of states of a magnet is different for spin up and spin down. Tunneling depends on the density of states:



Juillière's model

Physics Letters **54A**, 225(1975)

Assuming that the conductance is proportional to the DOS, the TMR ratio reads:

$$TMR = \frac{2P^2}{1 - P^2}$$

where P is the (spin) polarization of the ferromagnets:

$$P = \frac{D_\uparrow(E_\mathrm{F}) - D_\downarrow(E_\mathrm{F})}{D_\uparrow(E_\mathrm{F}) + D_\downarrow(E_\mathrm{F})}$$

- widely used to interpret experiment
- TMR ratio intrinsic property to the ferromagnetic leads
- rather useful for e.g. Al_2O_3 barriers
- however: overestimates TMR value for GaAs barrier

From a theoretical point of view:

Model is valid for the case of a very **high** and **disordered** barrier!

D. Ryndyk, unpublished

ab inito calculations

Try to model the system as detailled as possible:

- structure
- electronic properties
- relativistic effects (spin-orbit, ...)

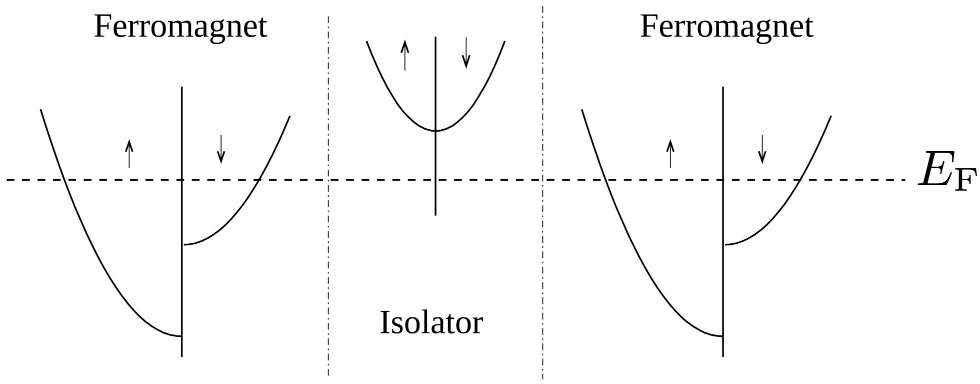
but:

- usually limited to epitaxial systems
- numerics can be difficult $\longrightarrow$ various problems
- in my opinion: results can be difficult to interpret
- Prediction for GaAs barrier: $TMR \approx$ 100%
- large TMR values arise because of *symmetries*

Bratkovsky's model

PRB **39**, 6995 (1989), PRB **56**, 2344 (1997)

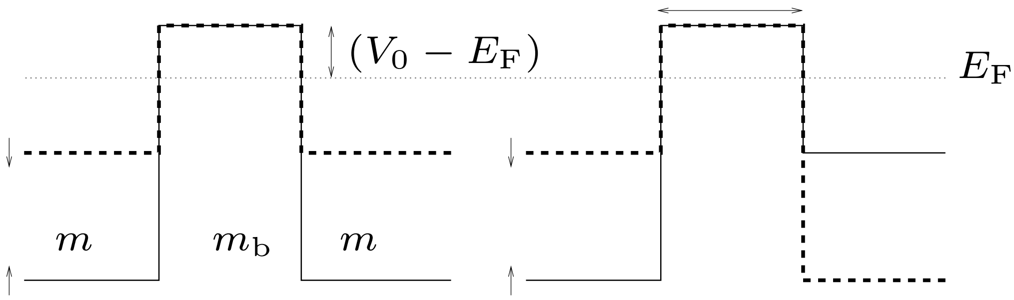
Model the system using a free electron gas description:



- ferromagnet: exchange splitting.
- different materials: different effective mass m^*.

$\Rightarrow$ "Tunneling through a step barrier"

Parallel confi guration   Antiparallel confi guration



Symmetry in the system

We consider a **clean** system

$\Rightarrow$ translational symmetry parallel to the barrier

$\Rightarrow$ conservation of parallel momentum $k_{||}$.

$\Rightarrow$ independent transport channels

Bratkovsky's model - part 2

Bratkovsky's approximations

This model can be solved exactly (numerically). But there is some useful approximation:

In the case of a **low** barrier,

- transport is essentially **one-dimensional**,
- only perpendicular incidence is transmitted.

In this limit the Juillière model holds with a **modified** Polarization P_{eff}:

$$P_{\mathrm{eff}} = P\,\frac{\kappa_0 - (m_b/m)^2 k_{\mathrm{F},\uparrow} k_{\mathrm{F},\downarrow}}{\kappa_0 + (m_b/m)^2 k_{\mathrm{F},\uparrow} k_{\mathrm{F},\downarrow}}$$

- IF the effective mass in the barrier is small compared to the electron mass $m_{\mathrm{b}} \ll m_{\mathrm{e}}$

  $\Rightarrow$ The same result as Juillière's model

  BUT: this is just a coincidence, the physics is totally different!

- Again: no quantitative agreement with experiment.

Comparison of models

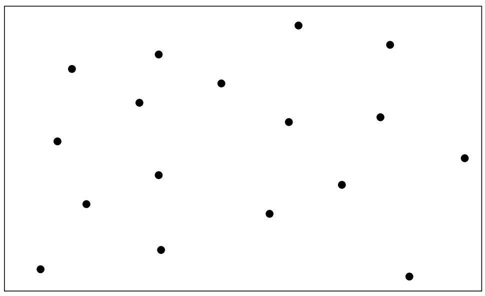
Juillière’s model	Bratkovsky’s model	*ab inito* calculations
high barrier	low barrier	any system
disordered system	clean system	epitaxial systems

- Juillière’s and Bratkovsky’s model describe contrary situations
- Juillière’s model more appropriate for oxide barriers
- Bratkovsky’s model maybe appropriate for semiconductor barriers?

Model and technique

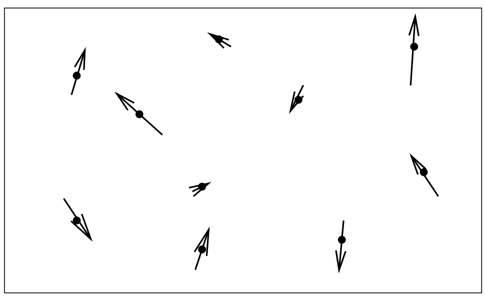
Extend Bratkovsky's model to include disorder:

- elastic disorder: δ-peaked impurities with random position and strength



$\Rightarrow$ isotropic momentum scattering

- spin-flip disorder: δ-peaked impurities with random position and a small random magnetization



$\Rightarrow$ spin-flip **and** momentum scattering

➜ model is useful to describe scattering on **magnetic** impurities (e.g. iron atoms in GaAs)

➜ not suited for magnon scattering

➜ low-bias and $T = 0$ limit

➜ conductance is now calculated numerically

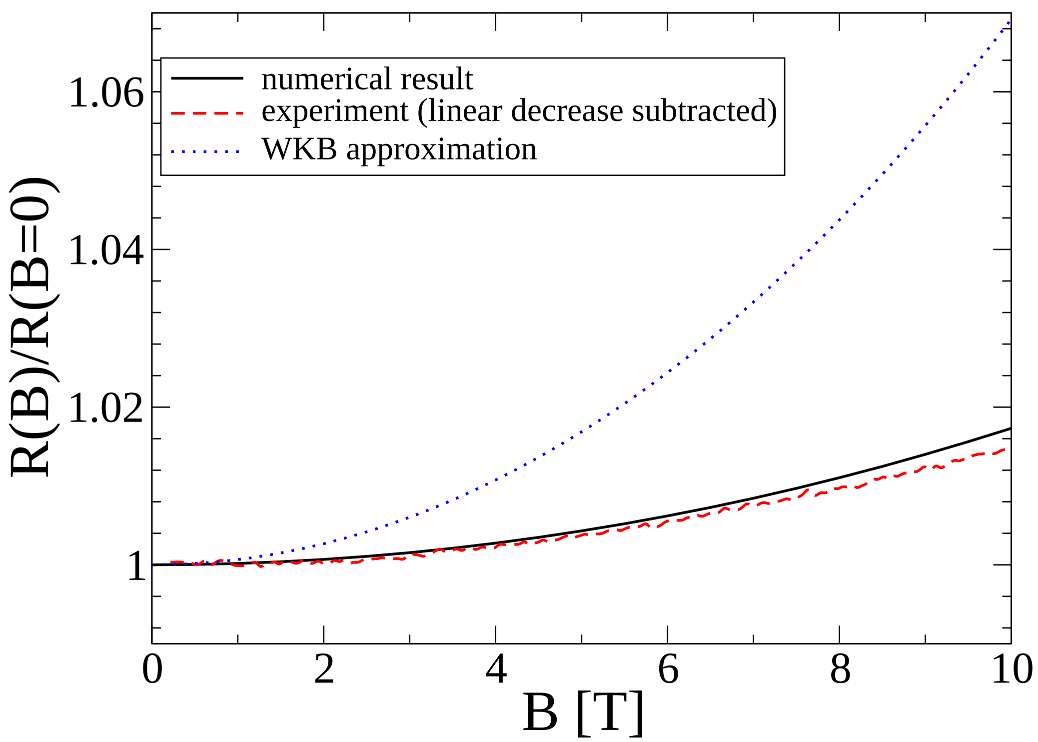
Magnetic fi eld dependence of tunnel resistance

We consider a magnetic field parallel to the tunnel barrier

- WKB approximation: quadratic increase of resistance

  (L. Eaves, in *The physics and fabrication of microstructures and microdevices*)

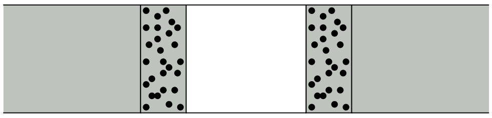
- our numerical studies show **qualitative** agreement with WKB approximation, but better **quantitative** agreement with experiment



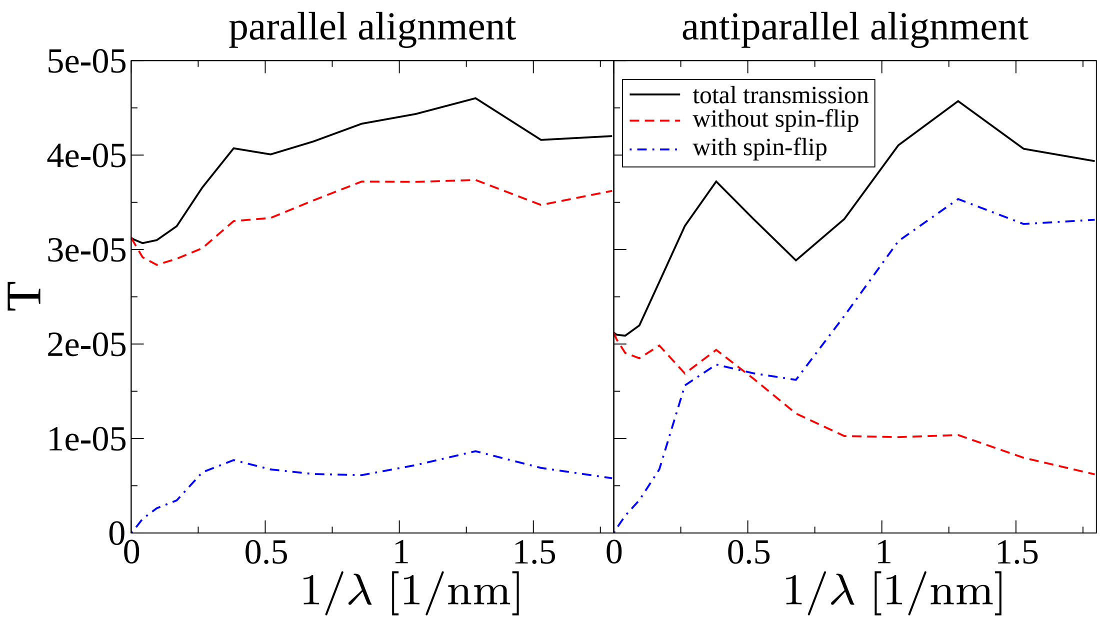
➜ simple model can capture a lot of the relevant physics.

Disorder at interface – transmission

Consider disorder only close to interface

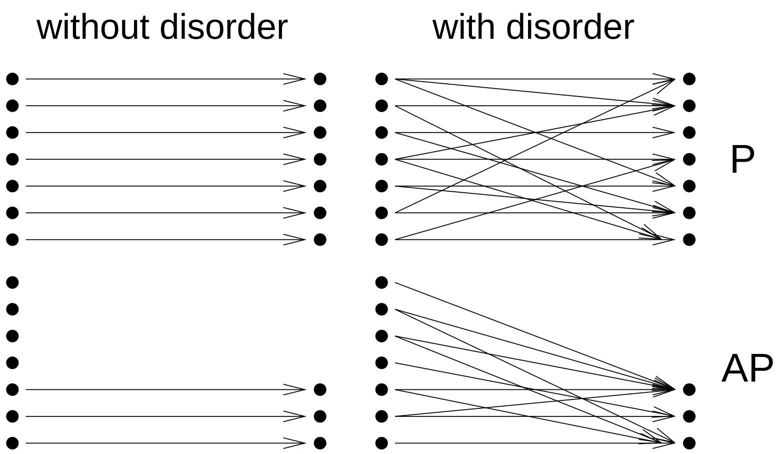


Transmission with spin-flips:



➜ overall transmission is increased

➜ disorder lifts $k_{||}$-conservation



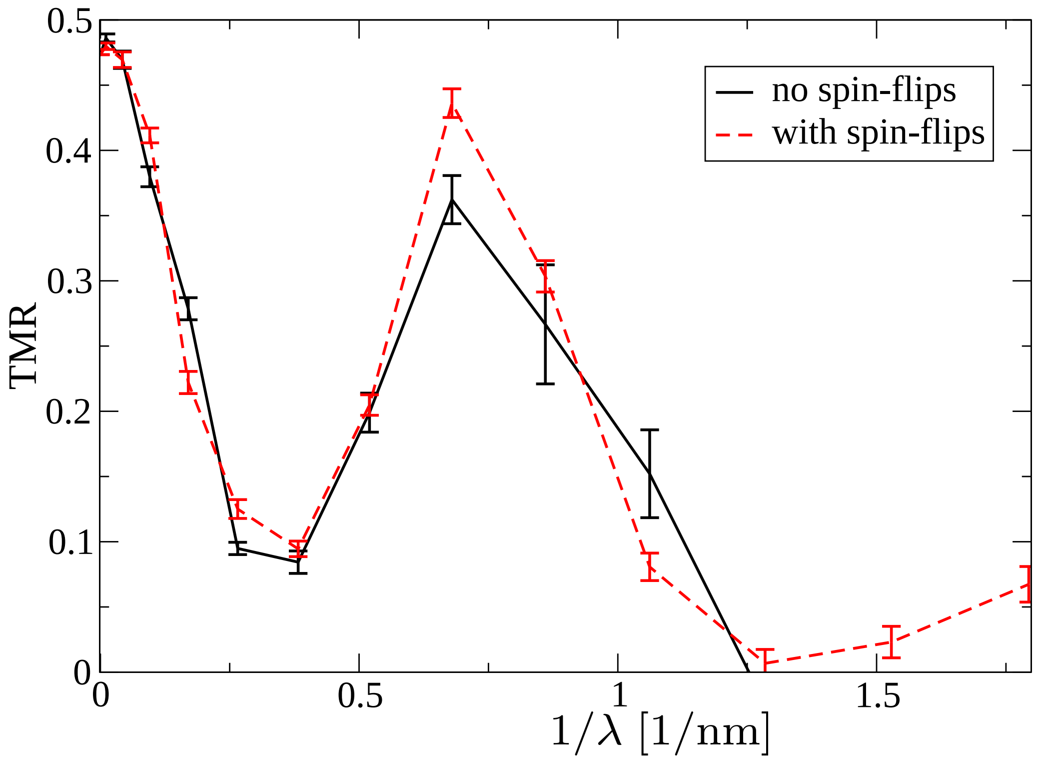
➜ increase in antiparallel case is stronger than in parallel case

$\Rightarrow$ decrease in TMR ratio

Disorder at interface – TMR ratio

Definition: $TMR = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}}$. (“optimistic” TMR ratio)

Effect of disorder on the TMR ratio:

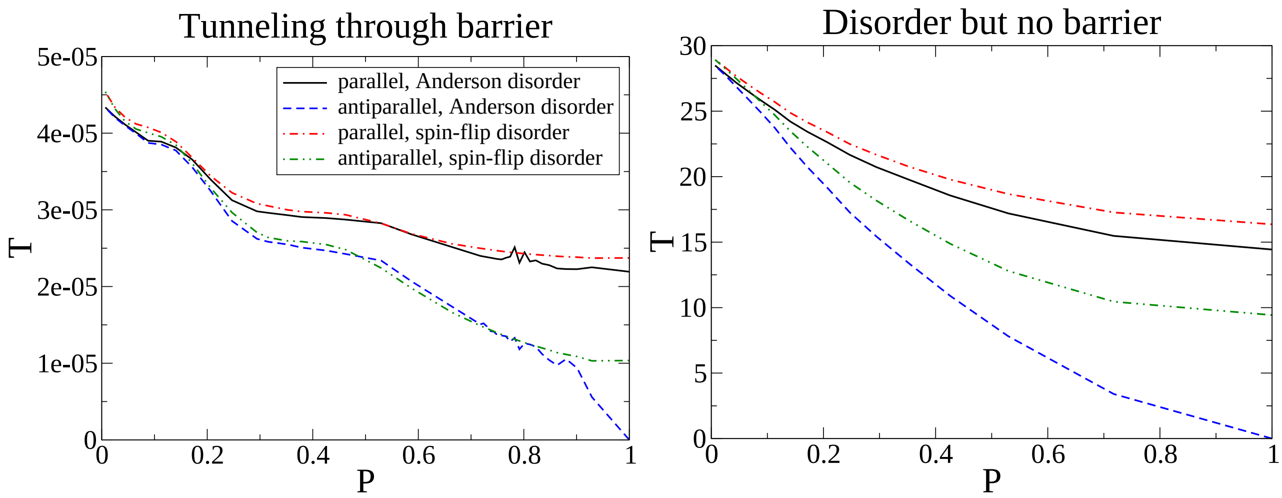


➜ disorder can decrease the TMR effect significantly

➜ almost **identical** decrease of TMR ratio for spin conserving and spin-flip scattering!

Disorder at interface – polarization dependence

Transmission in the presence of disorder depending on the spin-polarization P of the ferromagnets:



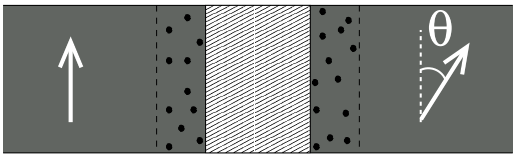
➜ similar behaviour of tunneling probability for spin-conserving and spin-flip scattering except for $P \approx 1$

➜ **but**: significant effect of spin-flips without barrier!

$\Rightarrow$ spin-flips less important because barrier acts as a quasi one-dimensional channel?

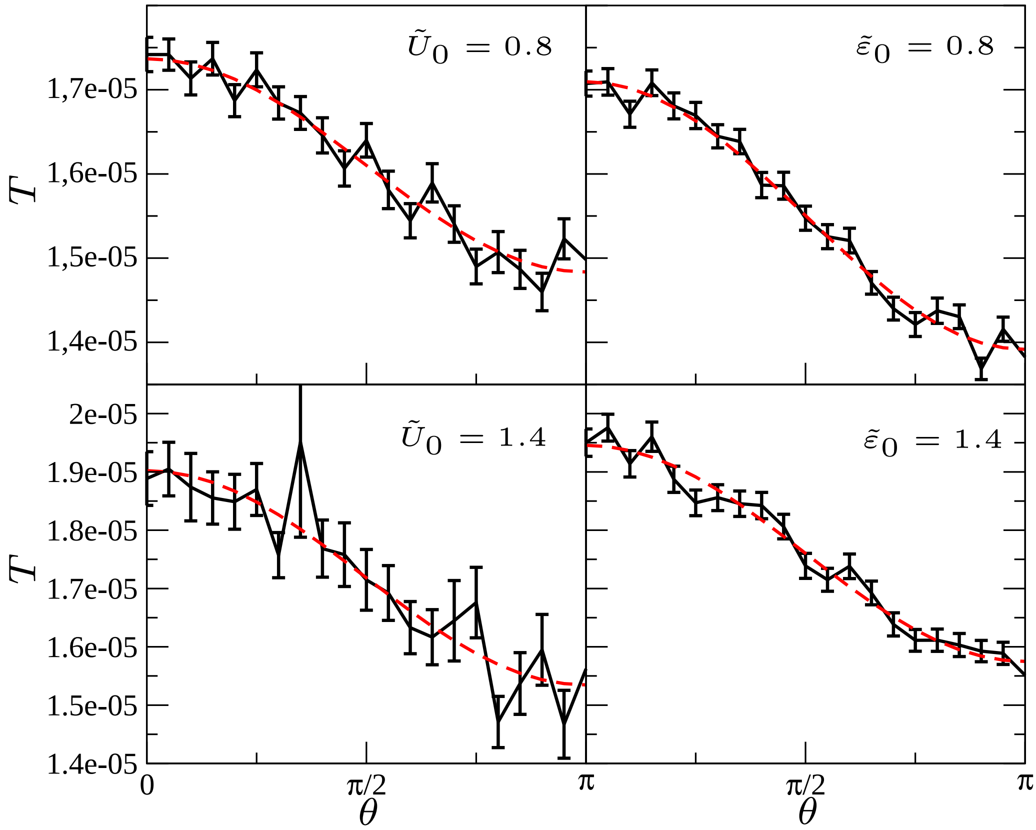
Disorder at interface – angular dependence

Dependence of transmission probability on the angle between the magnetizations in the ferromagnet with disorder:



Transmission probabilities:

no spin-flips with spin-flips



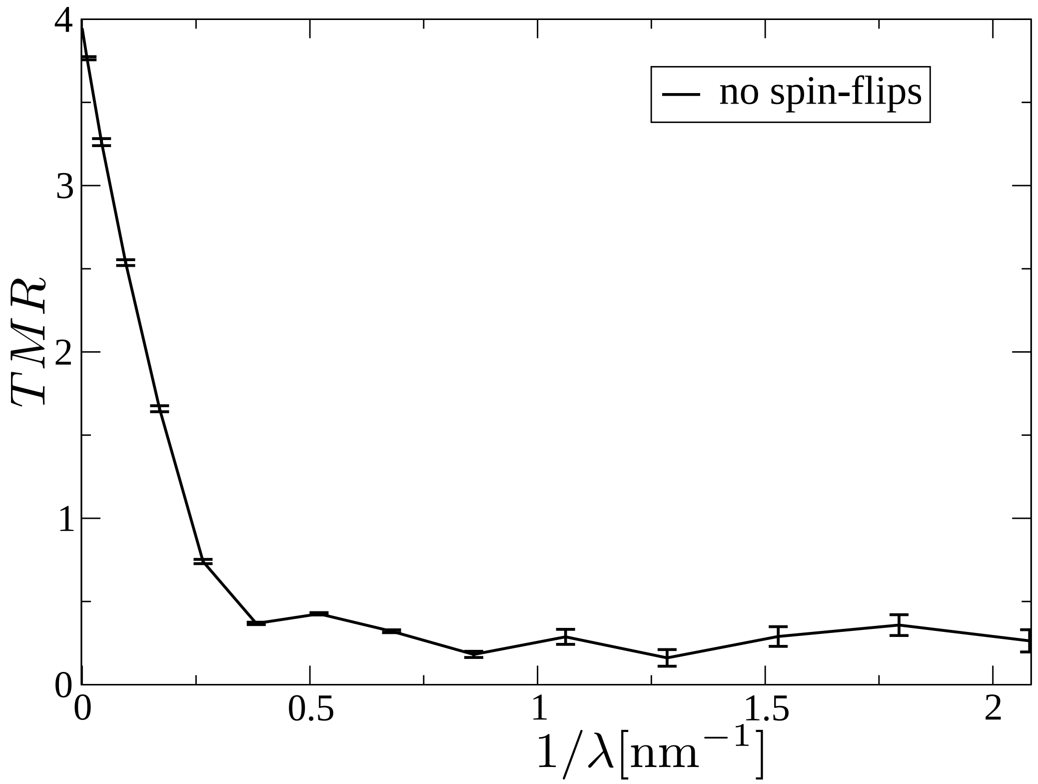
➜ angular dependence shows cos-behaviour just as in clean case, regardless of scattering

➜ “effective” (spin) polarization is decreased

What about Juillière's model?

- Juillière's model rather successful for Al_2O_3 barriers
- oxide barriers are usually amorphous $\longrightarrow$ a lot of disorder
- we just showed that disorder decreases the TMR ratio ...

Consider the case of a **very high** barrier (15 eV) and disorder at the barrier interface



➜ disorder again **reduces** TMR value drastically

➜ BUT: TMR ratio saturates at a value above 0

➜ this is consistent with Juillière's model: a finite TMR ratio for a high, disordered barrier.

Conclusions

We have shown that:

- Disorder can decrease the TMR effect significantly.
- Spin-flips have little influence on the TMR ratio if there is also momentum scattering.
- The TMR of high tunnel barriers (e.g. oxide barriers) is more robust against disorder than low barriers (e.g. semiconducting barriers)

Have we explained the experimental findings?

Maybe. Maybe not.

- The model of the system may be to simple.
- The strength of the impurities is a *parameter* in our simulations, it should be calculated from first principles.
- However: the simulations can show us *trends*:

  ➜ Although the semiconducting barrier itself is one-crystalline, having a clean interface might be crucial for such a low barrier, in contrast to the rather high oxide barriers $\Rightarrow$ contradicts our intuition!

Suggestions to the experimentalists

Unfortunately I don’t have any. But open for discussion ...