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From structural distortions to weak magnetism Exploring the capabilities of β-NMR

TRIUMF – ISAC20 Symposium - 21 August 2019

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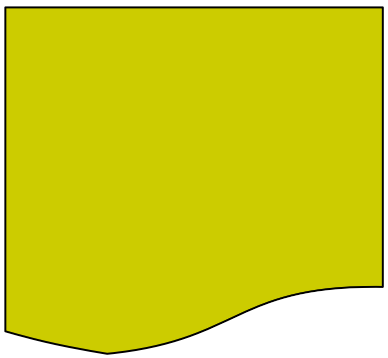
Outline

- Introduction – Why β-NMR? Unique capabilities.
- Some examples:
  - Structural transition near the surface of $SrTiO_3$
  - Week magnetism at $LaAlO_3/SrTiO_3$ interfaces
  - Tuning magnetism via interface engineering
  - Other ongoing activities
- Summary and conclusions

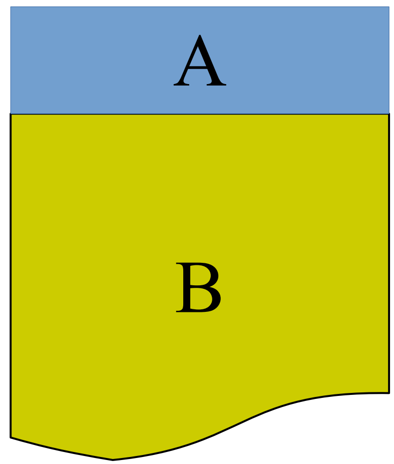
Unique capabilities and special powers of β-NMR

The low tunable implantation energy = depth resolved measurements

Near surface region



Buried interfaces

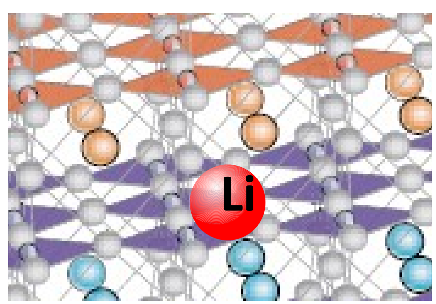


Effects of confinement

What else?

The behaviour of Li (or other probe) in materials.

Battery materials etc.

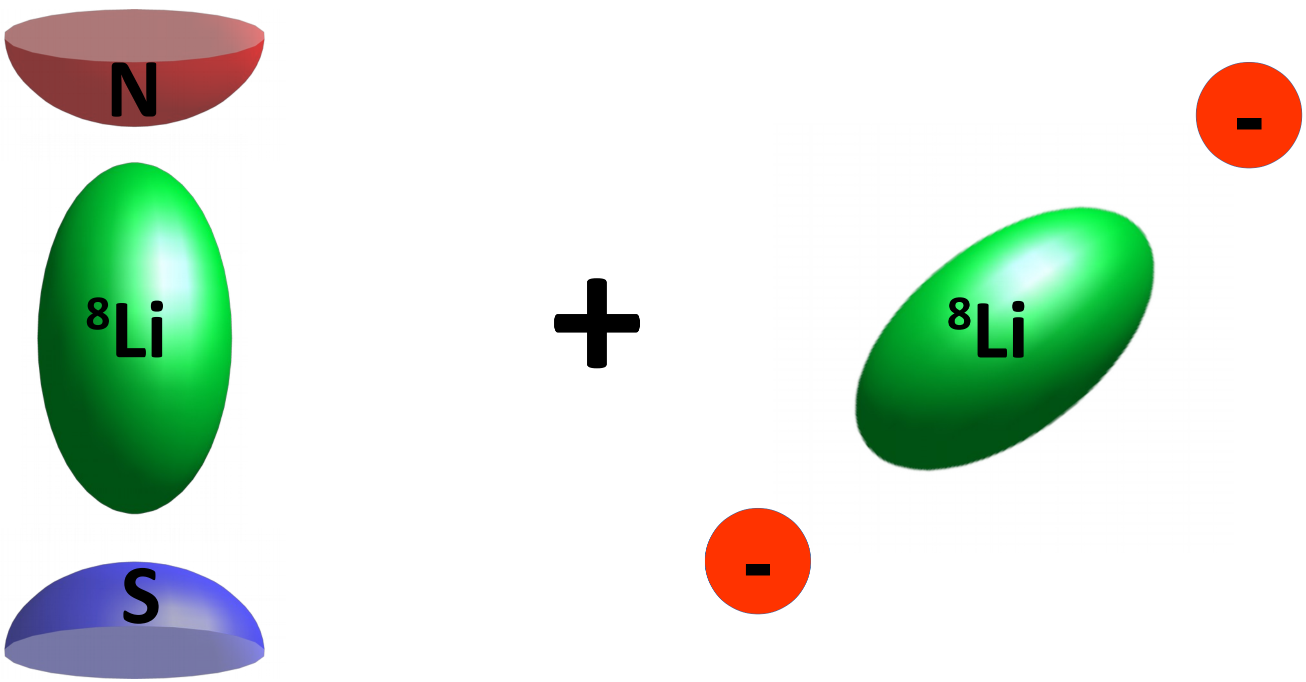


What can we study with (^{8}Li) β-NMR?

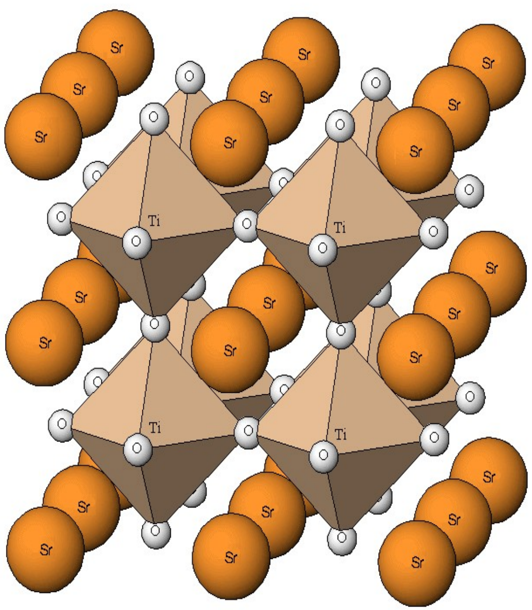
^{8}Li$^+$ with spin *I=2* (spin >1/2)

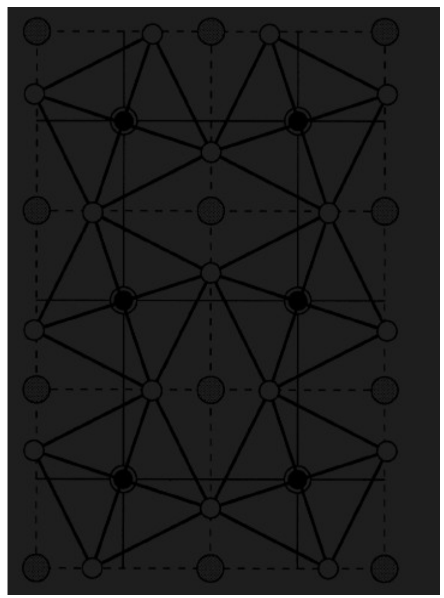
Nuclear magnetic **dipole** moment couples to magnetic fields

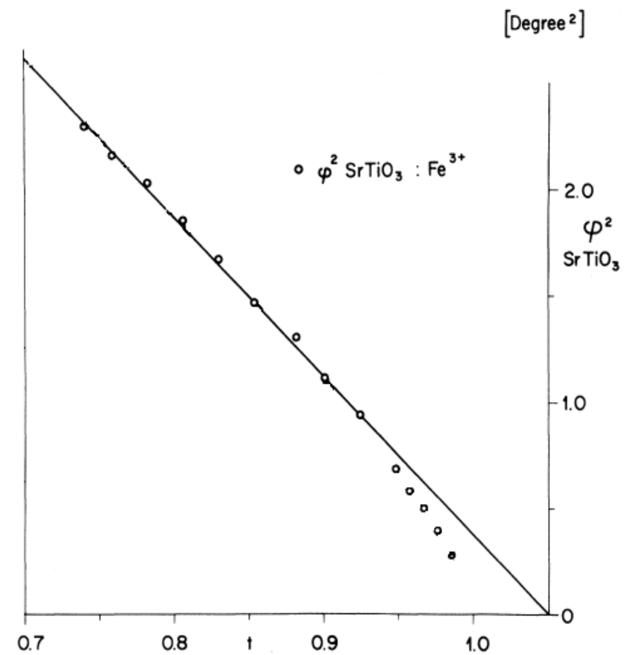
Nuclear electric **quadrupole** moment couples to electric field gradient



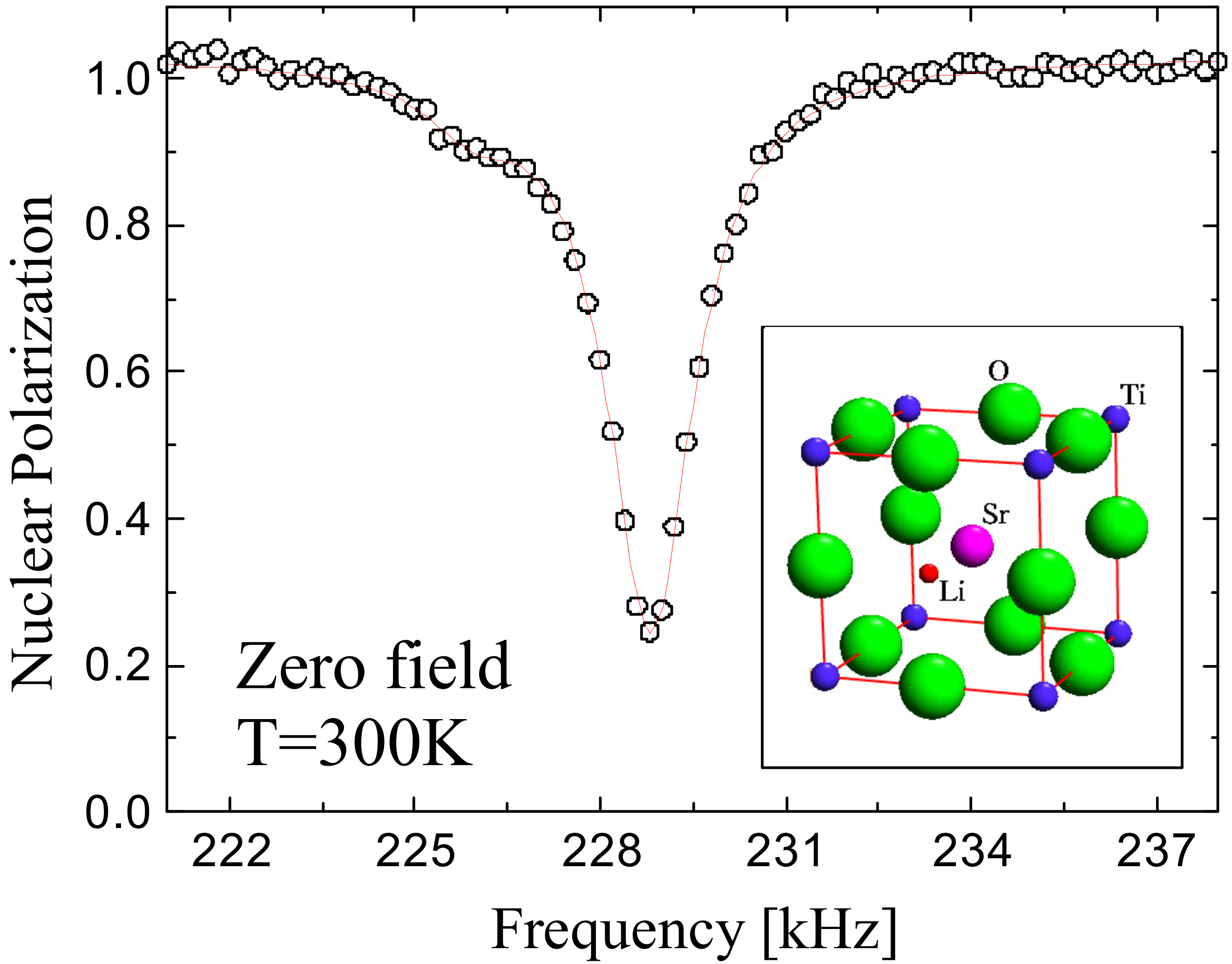
Example 1: Structural Phase Transition in $SrTiO_3$ Tc~105 K





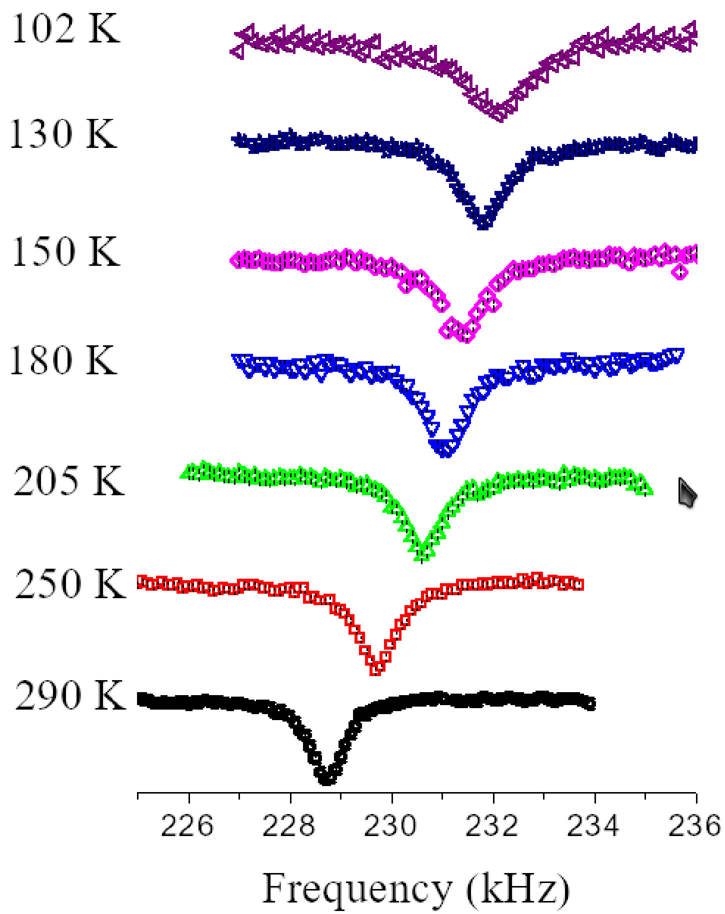


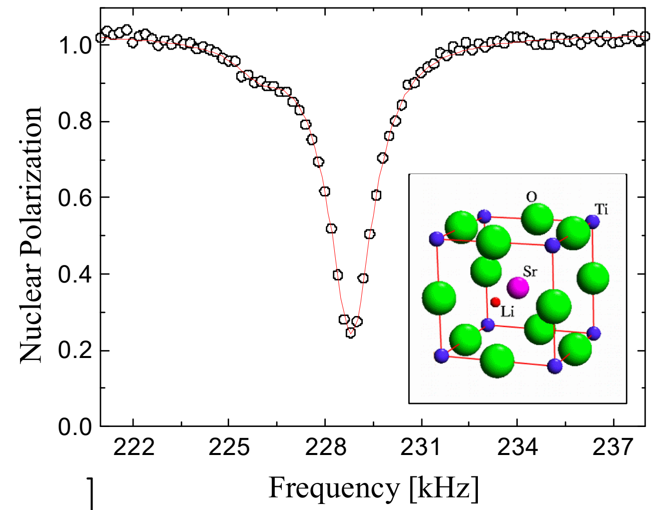
Zero Field β-NMR in $SrTiO_3$

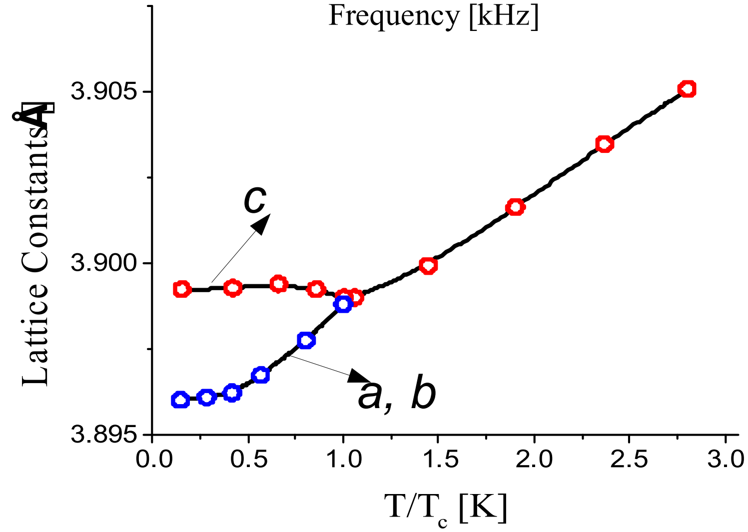


Salman et al., PRB 70, 104404 (2004)

Zero Field β-NMR in $SrTiO_3$

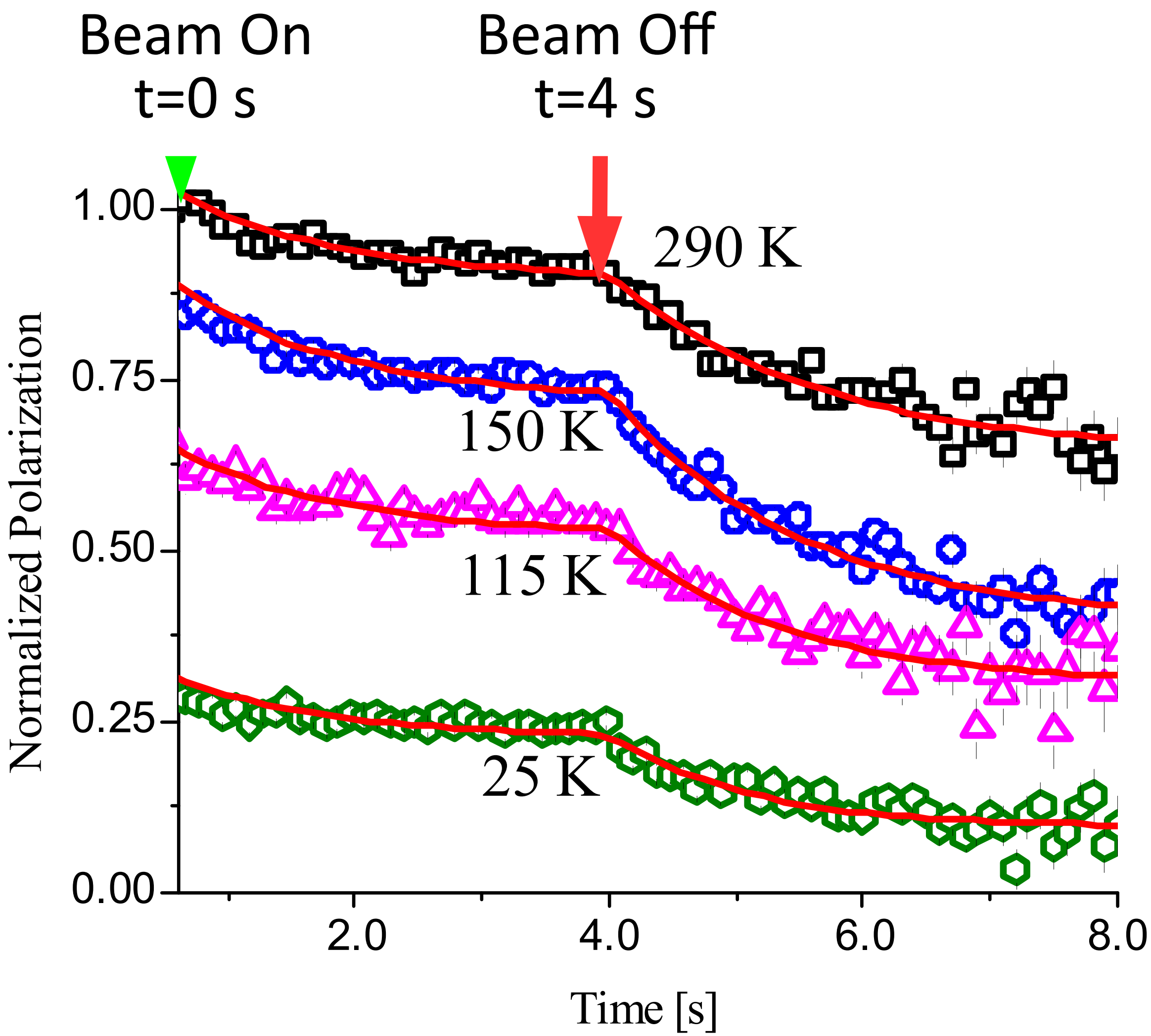






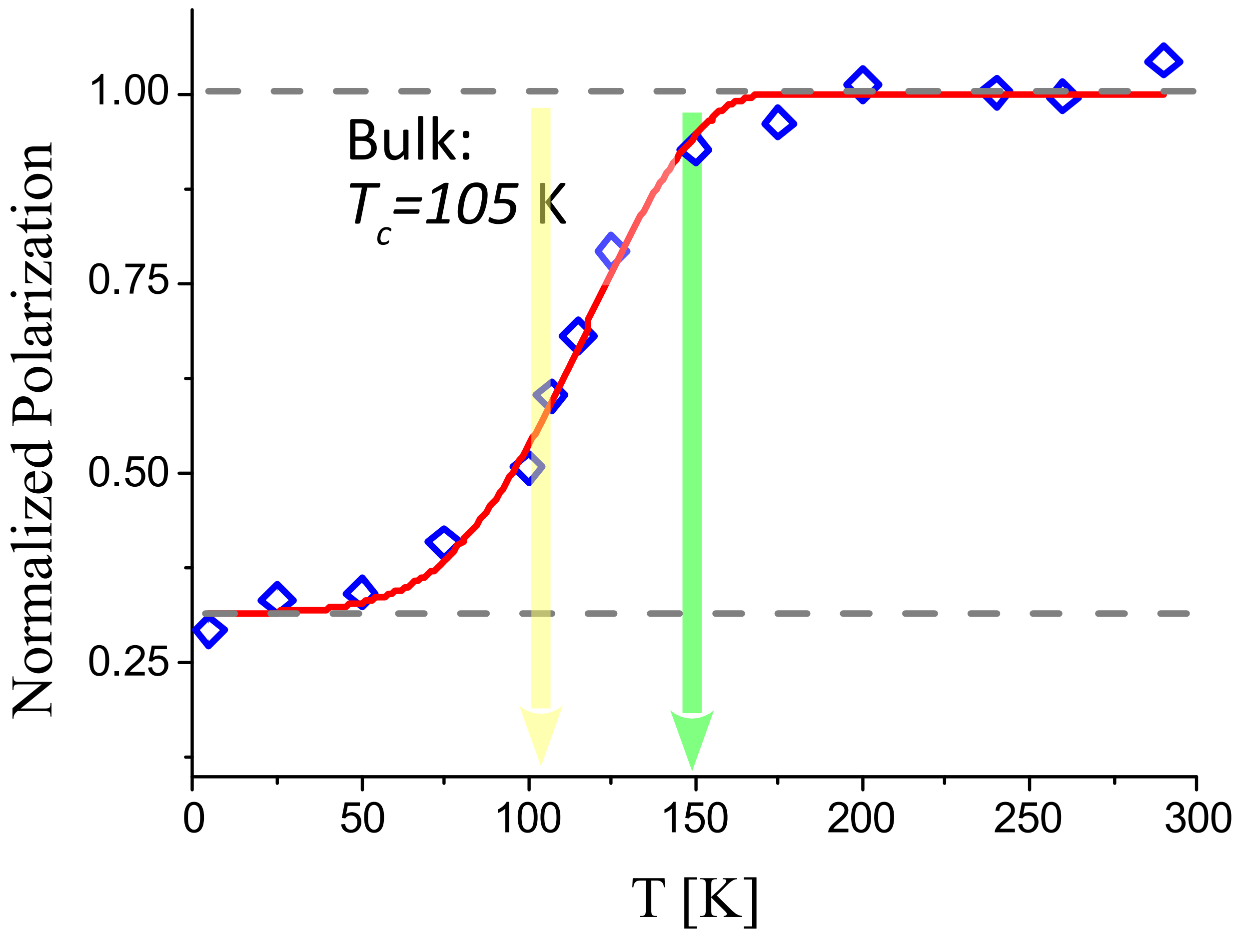
Salman et al., PRL 96, 147601 (2006)

Spin Lattice Relaxation vs. T



Salman et al., PRL 96, 147601 (2006)

Polarization Loss at T>T_c

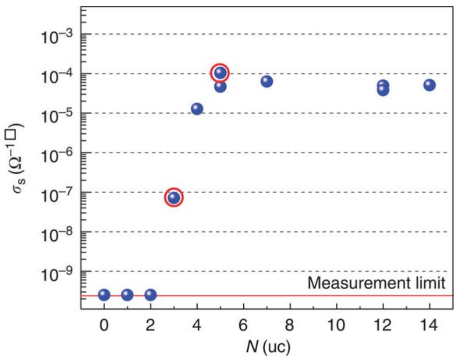


Salman et al., PRL 96, 147601 (2006)

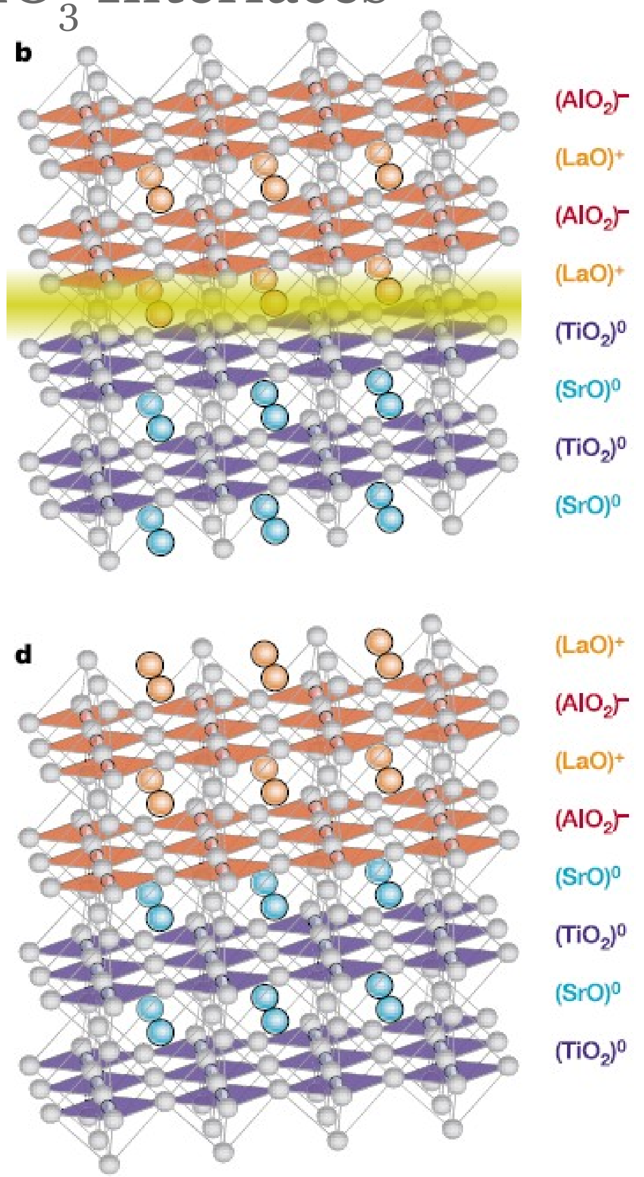
Example 2: $LaAlO_3/SrTiO_3$ Interfaces

Both $LaAlO_3$ (LAO) and $SrTiO_3$ (STO) are insulating and non-magnetic

The interface between them becomes metallic, superconducting and magnetic

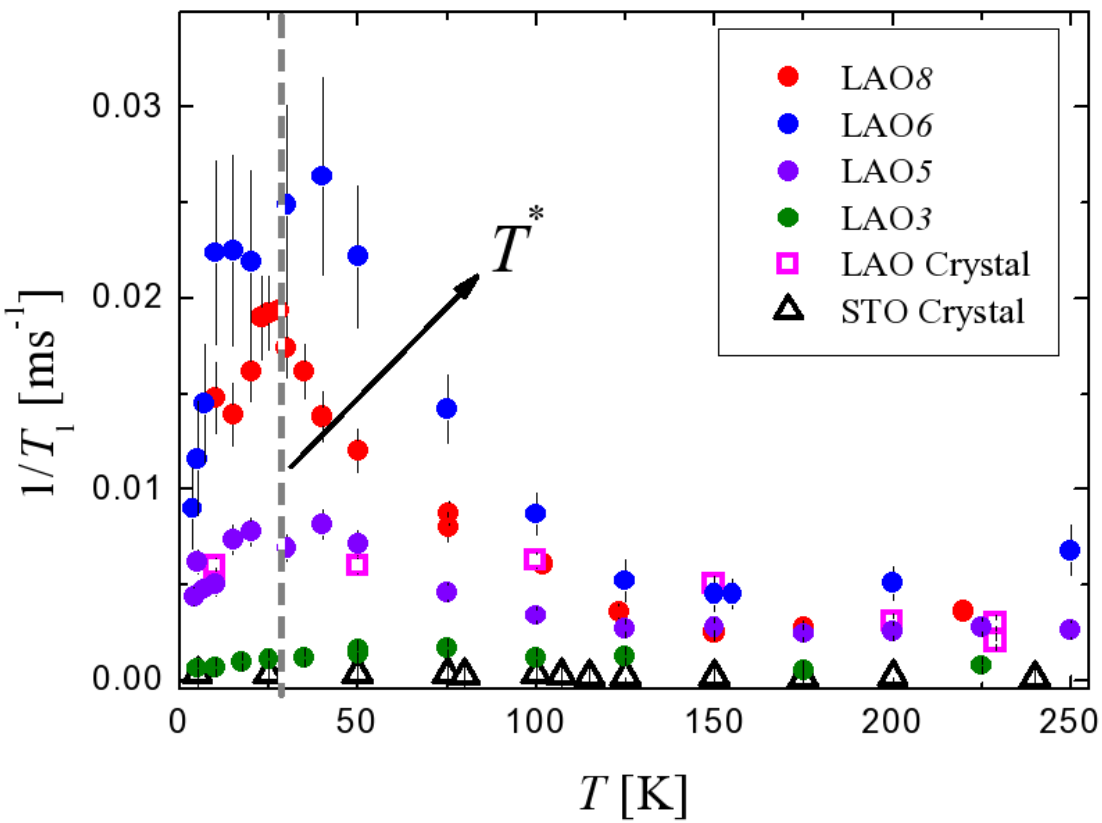


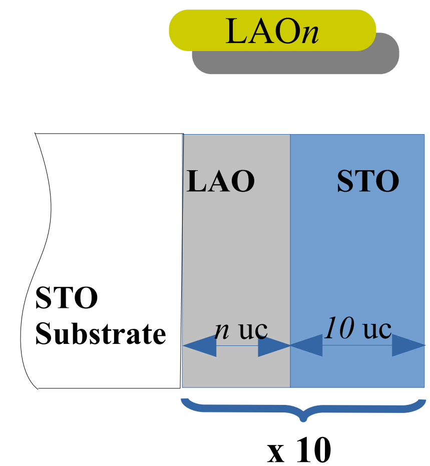
Annadi et al, Nature Commun. 4, 1838 (2013)



Ohtomo et al, Nature **427**, 423 (2004)

Relaxation rates in superlattices of LAO/STO

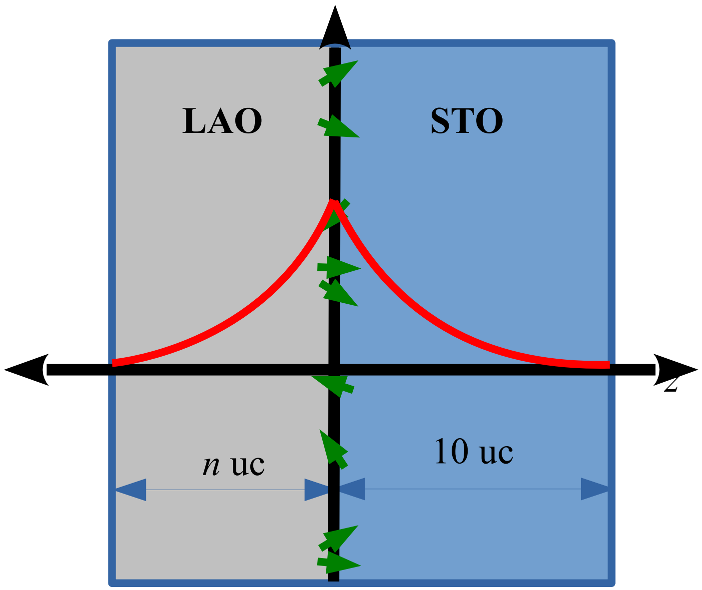




- Magnetism appears in SLs with LAO layers of 6 or larger unit cells
- Peak near the "magnetic transition", T^*~35 K.

Salman et al, Phys. Rev. Lett 109, 257207 (2012)

Density of Magnetic Moments at the Interface

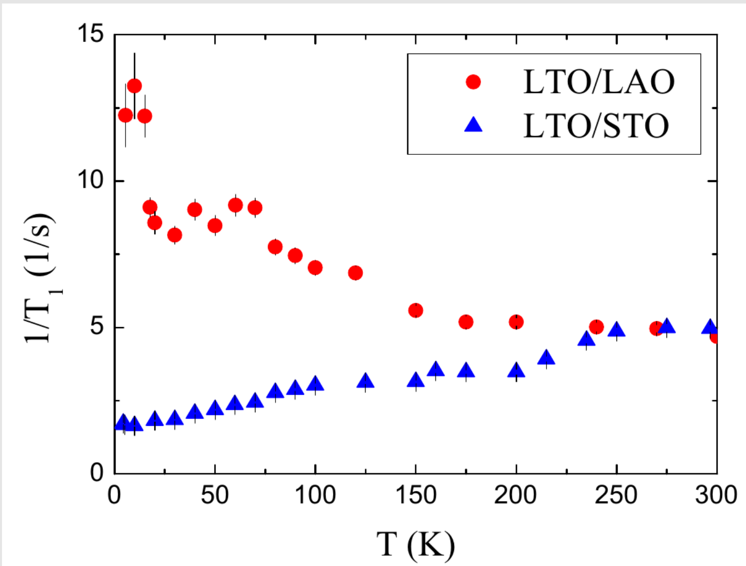


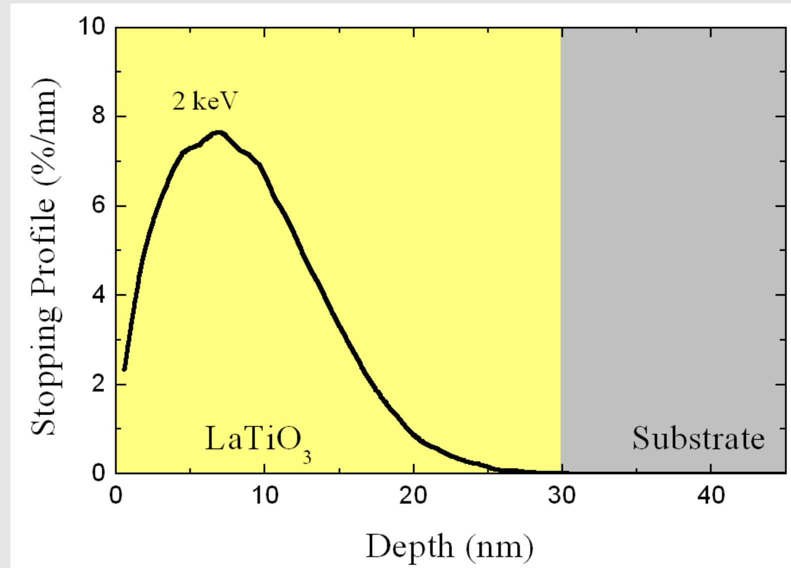
- The magnetism can be produced in superlattices.
- There is a "critical thickness" for the appearance of magnetism is 4 or 5 u.c.
- The magnetism, in both LAO*8* and LAO*6*, is associated with:

  $\mu \sim 1.8 \times 10^{-3} \mu_B$ density $\sim 1.13 \times 10^{12} \mu_B/cm^2$

- Consistent with magnetism on both interfaces: Ti_2O/LaO^+ and SrO/AlO_2^-

Example 3: Probing $LaTiO_3$/Substrate Interface with $^8Li^+$





On STO:

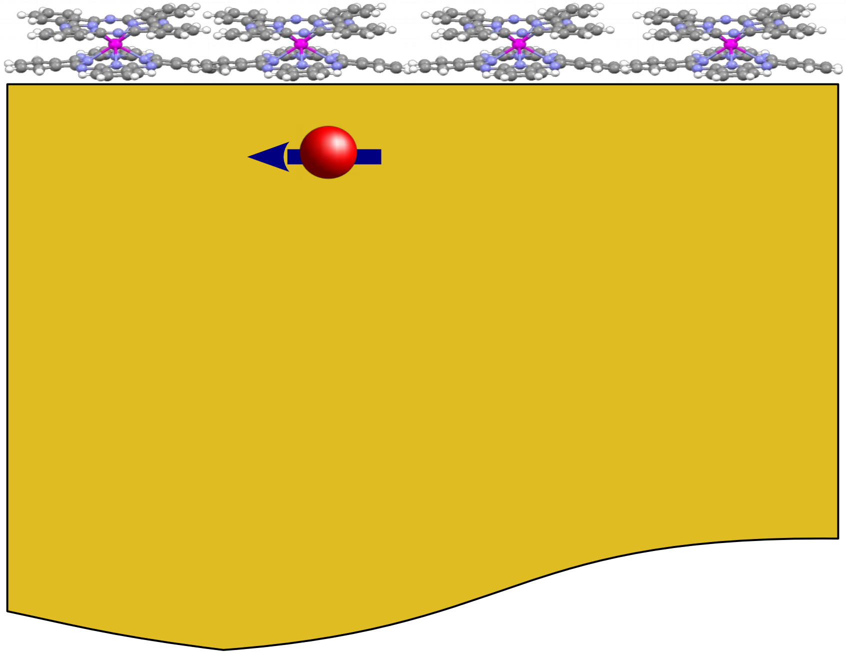
- No static magnetism.
- Linear decrease in $1/T_1$ as expected in metallic systems.

On LAO:

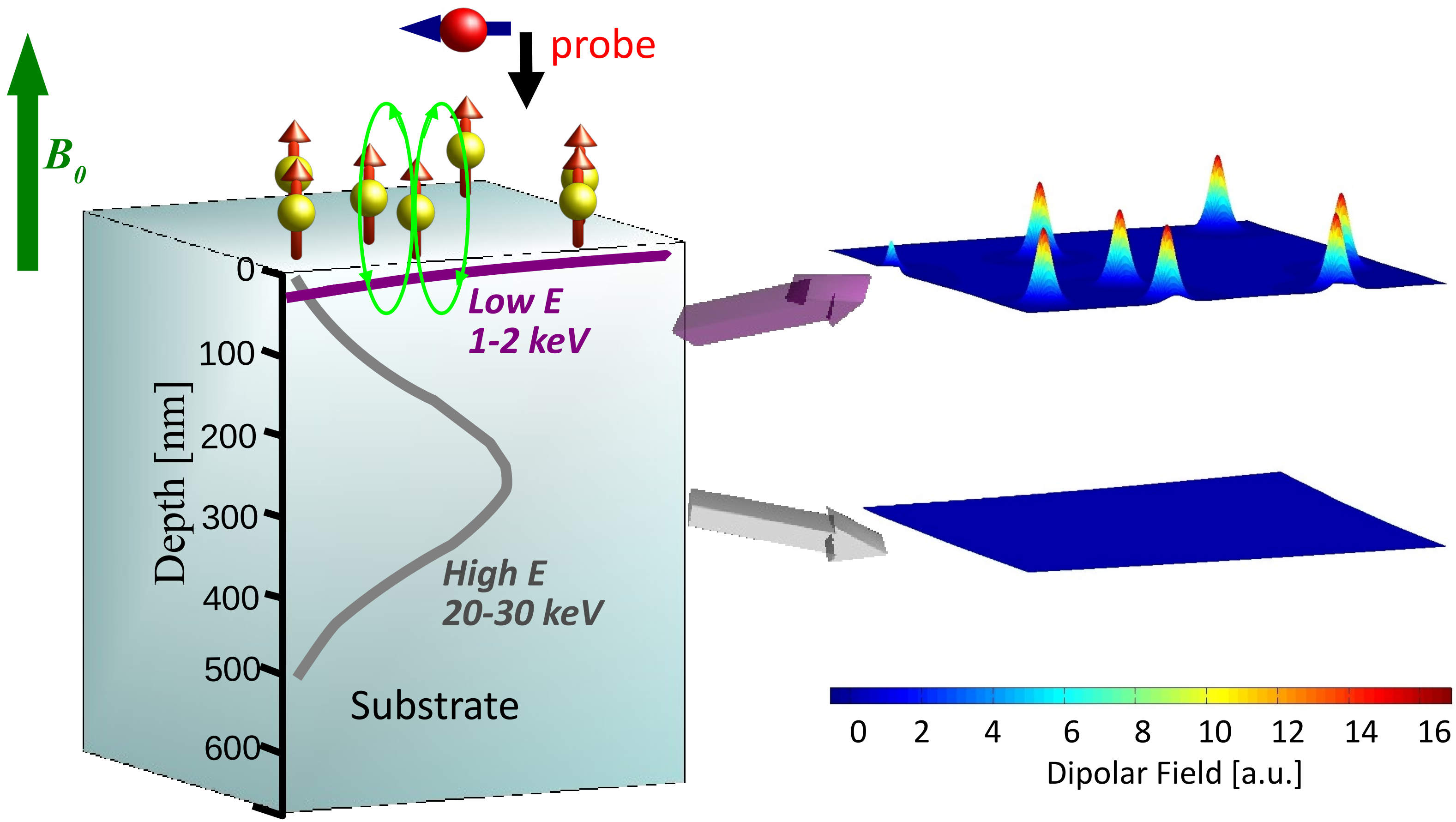
- A broad peak centred around ~75K, consistent with a magnetism.
- Another sharp increase below ~10K.

Salman et al, in preparation.

Example 4:
How to measure magnetism from a monolayer
Pushing the limit of β-NMR

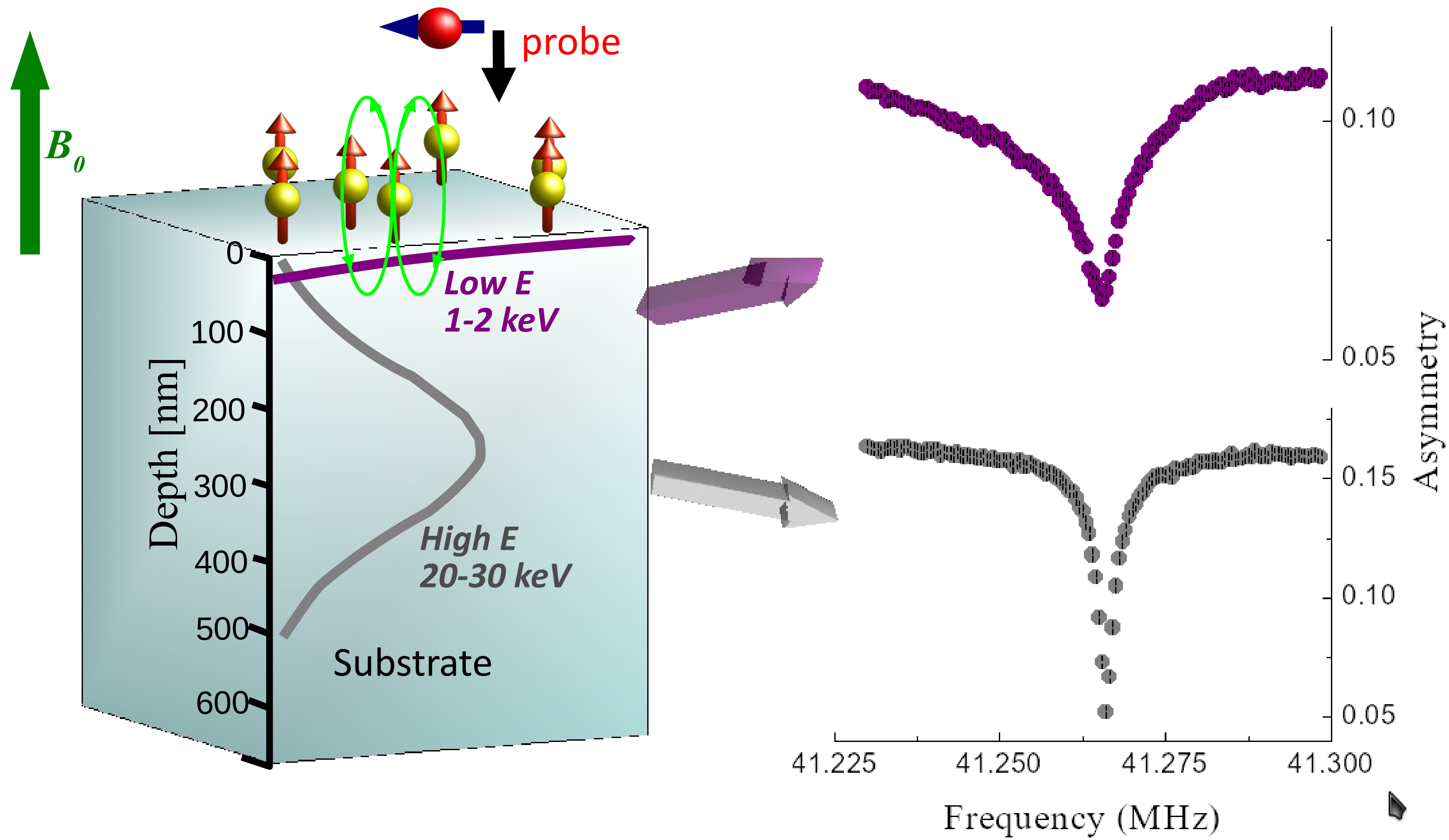


Dipolar Fields in the Substrate



Salman et al., Nano Lett. 7, 1551 (2007)

β-NMR in a monolayer of $TbPc_2$ on Si



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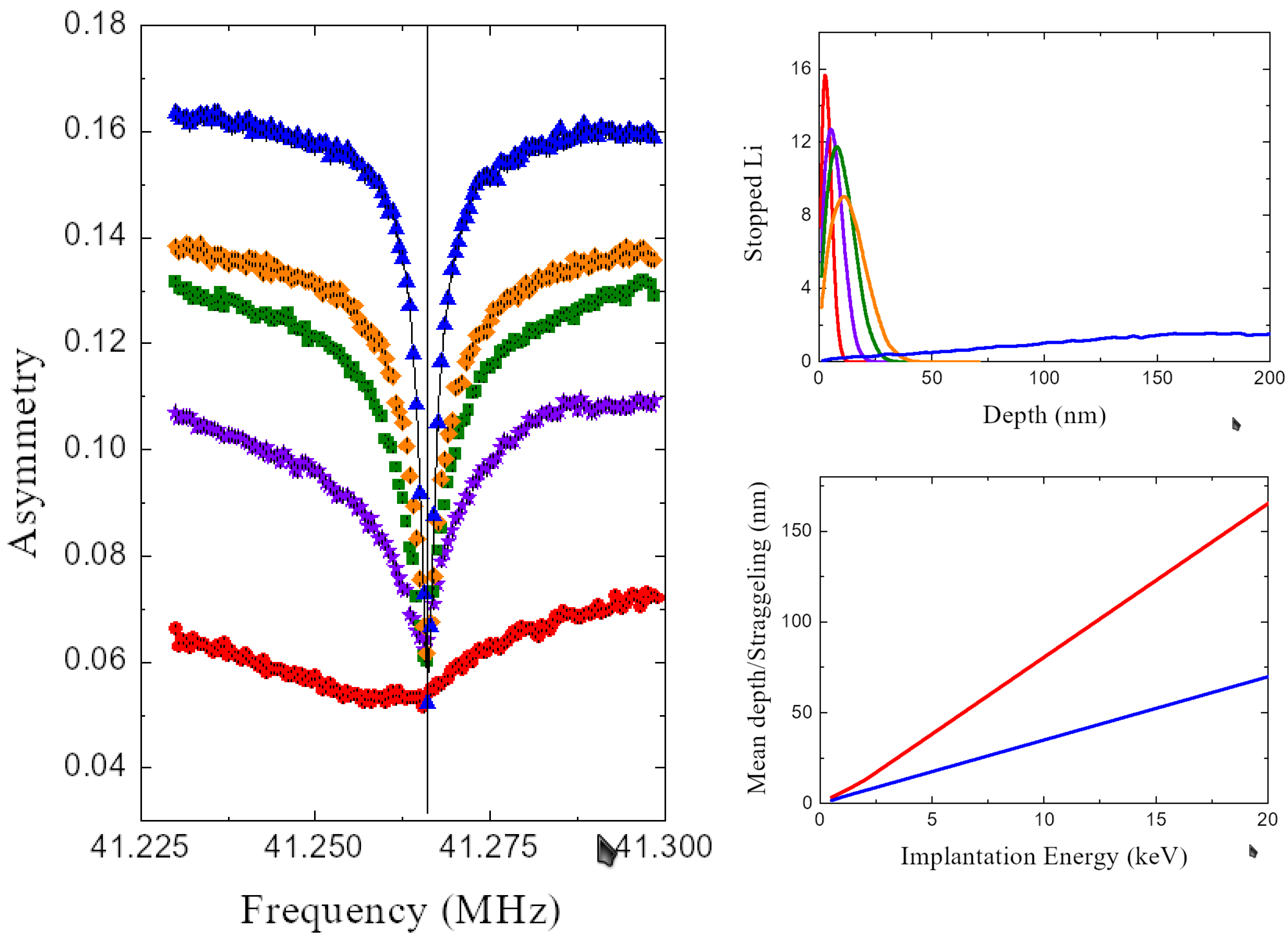

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Other ongoing projects (only partial list)

- Dirac/topological materials
  - Looking at surface/interface topological states
- Van der Waals materials, transition metal chalcogenides and 2D magnets
  - Some of these are graphene like 2D materials but with more versatile properties
- Molecular dynamics in polymers, their surfaces and interfaces
- Li diffusion in general and in Li battery materials

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Summary and Conclusions

- Low energy implanted spin probes give a powerful and unique tool to investigate thin films and interfaces, finite size effects, diffusion etc.
- Spin 1/2 probes detect magnetic properties while spin >1/2 probes can also probe structural/orbital effects.
- The most important feature are:
  - High sensitivity (films/nano-structures)
  - Depth resolved capability on nm scale
  - Access to buried interfaces

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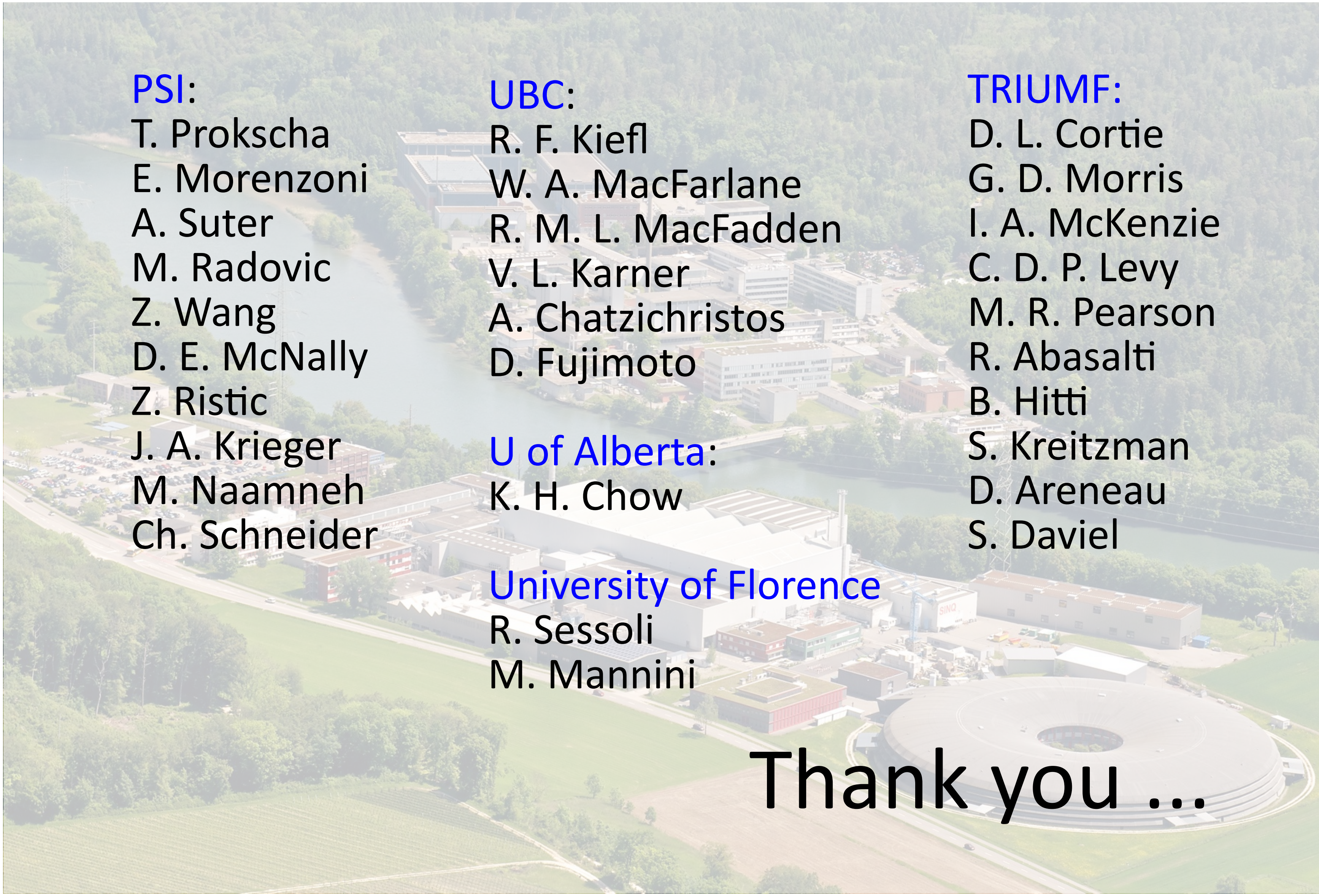

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Thank you ...

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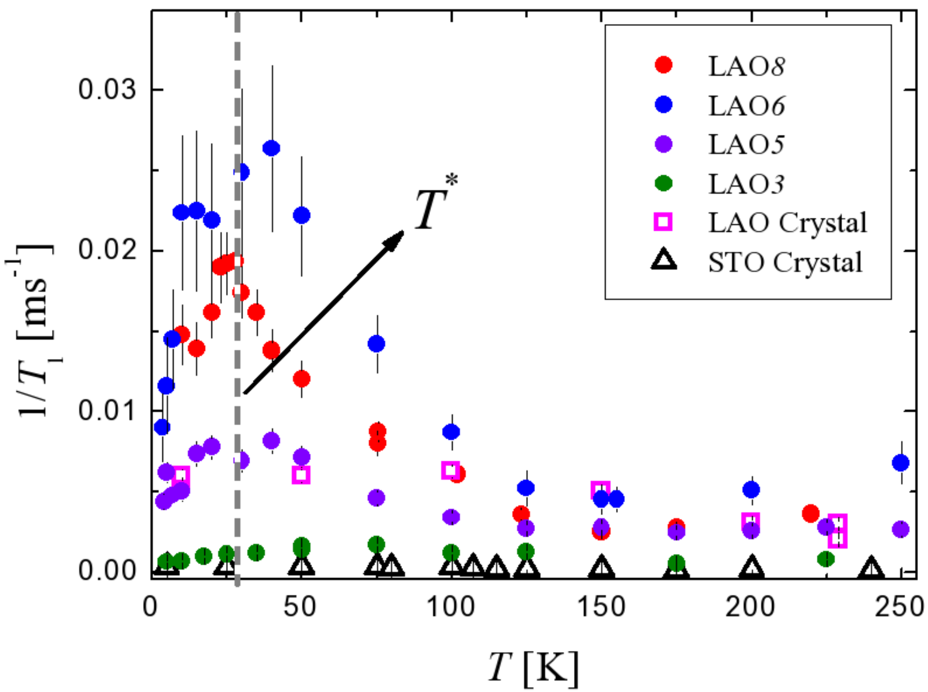
Relaxation rates in superlattices of LAO/STO



$$\frac{1}{T_1} = \frac{\gamma^2 \Delta^2 \tau_c}{1+\omega^2 \tau_c^2}$$

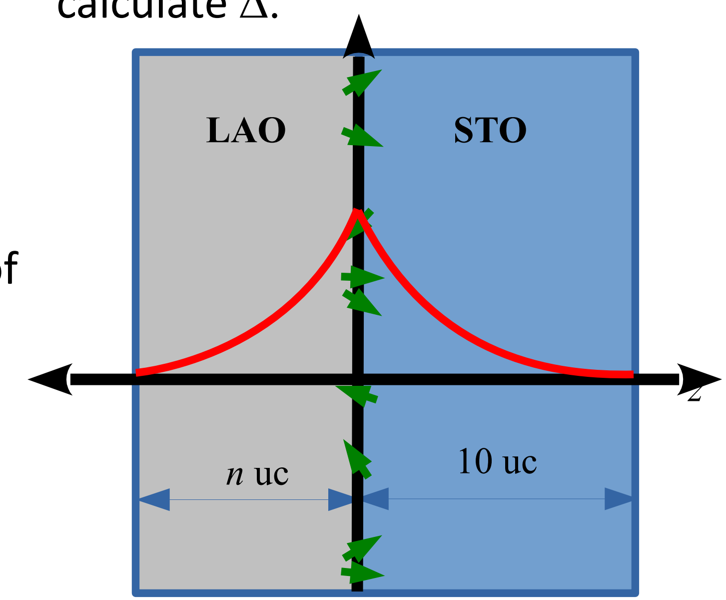
γ - gyromagnetic ratio

τ_c - correlation time

ω - probe frequency

Δ - RMS of local field

at the peak $\omega\tau_c \sim 1$ so we can calculate Δ.

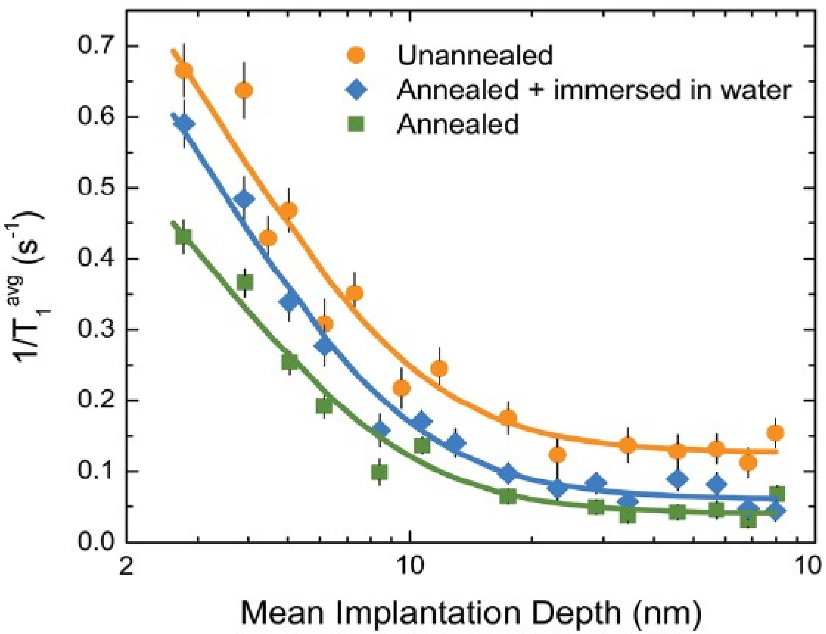


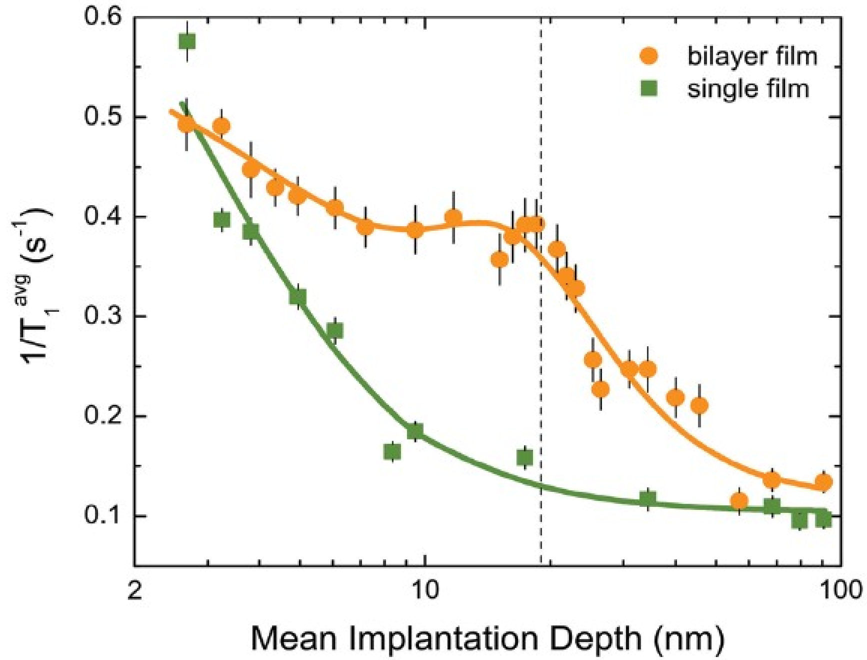
Δ can also be calculated assuming 2D arrangement of magnetic moments, μ.

From comparison of the two values of Δ we can extract μ or the density of moments.

Salman and Blundell, Physics Procedia **30**, 168 (2012)
Salman et al, Phys. Rev. Lett 109, 257207 (2012)

Molecular dynamics in PS films





I. McKenzie et al, Soft Matter, 14, 7324 (2018)