Proximal magnetometry of magnetic monolayers and ultra-thin films

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Outline

• Introduction
  – LE-µSR and β-NMR and their application for magnetic monolayers and ultra-thin films
  – Some experimental results

• Numerical Calculation
  – Field distribution
  – Depth dependence

• Summary and Conclusions
Introduction:
Magnetic monolayers and ultra-thin films

- A magnetic system – monolayer, ultra thin film, islands etc.
- Insufficient stopping material to implant a local probe.
  Can we measure their magnetic properties?
Proximal magnetometry using a local probe

- Implant the probe above or below the magnetic layer.
- Measure dipolar fields from the magnetic layer.

Below is a better option

➢ The probe can be close to the magnetic layer
➢ Narrower stopping distribution
**Single Molecule Magnets**

\[
H = -DS_z^2 - g\mu_B H_z S_z
\]

\(D=0.64\ \text{K},\ S=5,\ DS^2=16\ \text{K}\)
Monolayers of Fe$_4$

STM of Monolayers of Fe$_4$

Au(111) on mica, f.a., 0.5 mM solution in CH$_2$Cl$_2$, 20 h

XMCD on Monolayers of Fe₄

XMCD on Fe₄: Bulk vs. Monolayer

$\beta$-NMR in $\text{Fe}_4$ on Si

$B_0 = 6.5 \, T$

$E = 1 \, \text{keV}$

$E = 28 \, \text{keV}$

$T = 3.2 \, \text{K}$
LE-μSR in Fe$_4$ on Au

Salman et al, arXiv:0909.4634v1
Uniformly magnetized sheet

First approximation – assume a uniformly magnetized sheet
→ Divide into annular regions
→ Integrate dipolar field contribution
→ Dipolar field is zero
Local probe perspective

\[ \vec{B}_i(\vec{r}_i) = \frac{\mu_0}{4\pi} \frac{3\vec{r}_i(\vec{\mu}_i \cdot \vec{r}_i) - \vec{\mu}_i r_i^2}{r_i^5} \]

In a LE-\(\mu\)SR or \(\beta\)-NMR we are interested in \(B_z\) only.
Local probe perspective
Dipolar field at a layer $z=z_0$

- Assume magnetic monolayer at $z=0$
- The dipolar field at $z=z_0$ is the sum of contributions from all moments.
- A spin probe samples these fields.
Field distribution sensed by the probe

- Sum contributions from all moments in $\rho_0 = aN$
- The field distribution shifts due to the finite size of $\rho_0$. 
Correction of field distribution

- Correction by taking the contribution of the rest of the monolayer.
- Outside $\rho_0 = aN$ the uniform magnetization approximation holds.

\[ M = \frac{\mu_0 M}{2\rho_0(1 + \zeta^2)^{3/2}} \quad \text{with} \quad \zeta = \frac{z}{\rho_0} \]
Corrected field distribution

$$n_{nc}(z,B) \text{ [%]}$$

$$Ba^3 [\text{TÅ}^3]$$

$$n(z,B) \text{ [%]}$$

$$Ba^3 [\text{TÅ}^3]$$

$$B_{\text{max}} \text{ [TÅ] }$$

$$a^3 [\text{TÅ}^3]$$

$$N$$

Graphs showing corrected field distribution with different values of $$N$$.
The effect of the stopping distribution

\[ L(B) = I(B) \ast \int_{z_0}^{\infty} D(z)n(z, B)dz \]

Intrinsic line + disorder

Stopping distribution
**β-NMR in Fe\textsubscript{4} on Si**

Model line:

\[ S \sim 4.7 \]

Moment on disordered triangular lattice:

- Lattice constant \( \sim 8 \text{ nm} \)
- ML - substrate \( \sim 1 \text{ nm} \)

**Graphical Data**

- Signal [a.u.]
- Frequency [kHz]

**Parameters**

- Temperature: \( T=10 \text{ K} \)
- Magnetic field: \( B=6.5 \text{ T} \)
Depth dependence of the width

- Much easier to look at the distribution width or broadening relative to the intrinsic width.
- The broadening is:
  - Proportional to the RMS of the magnetic moment.
  - Decreases like $1/z^2$
Summary and conclusions

Low energy $\mu$SR and $\beta$-NMR can be used as “proximal” magnetometers. Sensitive enough to measure monolayers of magnetic material.

- The field distribution depends on the characteristic length scale, average size of magnetic moment and distance between monolayer and substrate.

- The broadening due to a magnetic monolayer decreases like $1/z^2$ away from the monolayer and is proportional to the RMS of the magnetic moment.