NMR and µSR

two complementary *bulk* and *local* probes!

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µSR stands for Muon spin Rotation, Relaxation, Resonance, Research or what have you. The intention of the mnemonic acronym is to draw attention to the analogy with NMR and ESR, the range of whose applications is well-known.

Yamazaki, Nagamine, Crowe, Brewer 1974

Outline

1. Basic principles of µSR
2. µSR in transverse field: shifts, vortex state in SC
3. Zero and Longitudinal field µSR
   - detection of frozen magnetism (LRO, SG)
   - spin dynamics: $T_1$

1. Complementarity between µSR and NMR
2. More .. (low energy muons, µSR in strong fields)

µSR: milestones

V. F. Hess & C. D. Anderson
Nobel Prize Physics 1936

Lee & Yang
Nobel Prize Physics 1957

J. Brewer
Yamazaki Prize, 2011

Y. Uemura
Yamazaki Prize, 2005

E. Morenzoni
Yamazaki Prize, 2008
Basic principles of μSR

μSR: some key features

- Positive charge $\mu^+$, finite lifetime $\tau_\mu = 2.2$ μs
- $S_\mu = 1/2$. No quadrupolar effect
- $\mu_p = 3.2 \mu_p, \gamma_\mu / 2\pi = 135.5$ MHz/T
- $m_\mu = 1/9 m_p$: Possible diffusion of the muon: $T > 150-200$ K
- Implantation in all materials.
- 100% spin polarized probe
- Material and temperature independent sensitivity.
- Bulk probe (200 μm penetration, 150 mg/cm²).
- Implantation in one well-defined (or several) site(s): O-$\mu^+$, 0.1 nm bond in oxides
- Diluted probe
- Local probe -> determination of magnetic volume fractions

S.J. Blundell, cond-mat/0207699

μSR technique

A high energy proton... 
... hits a carbon nucleus... 
... creates a pion... 
... pion decays into a muon (and neutrino)... 
... muon is implanted in the material being studied... 
... it stays there for 2 microseconds... 
... before decaying into... 
... a positron (and B neutrino)... 

Muon production

- Muons produced via pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Muons 100% spin polarized, speed~c/4, K.E.~4 MeV.

(see S.J. Blundell, Contemp. Phys. 40, 175 (1999))
Muons do not diffract or reflect! They stop in the sample at about 10-100 µm from the surface.

Muon production and decay

• Muons produced via pion decay:
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

• Muons 100% spin polarized, speed \( \sim c/4 \), K.E. \( \sim 4 \text{ MeV} \).

• Muon decays into a positron:
  \[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

• Positron decay is asymmetric with respect to the initial muon-spin polarization because of parity violation (weak interaction)

(see S.J. Blundell, Contemp. Phys. 40, 175 (1999))
Transverse Field $\mu$SR

Transverse Field $\mu$SR $\sim$ NMR

What can you measure with TF $\mu$SR?

- Shift measurement: ‘local’ susceptibility
- Vortex physics in type II supraconductors
  - field distribution, penetration length...

$N(t) = N_0 \exp(-t/\tau_\mu) \{1 + S(t)\}$

$A(t) = A_0 G(t) \cos (\gamma_\mu B_\mu t + \phi)$

- $A_0$: phase separation
- $G(t)$: field distribution (static)
- $B_\mu$: susceptibility
- magnetism
Transverse Field $\mu$SR: Knight shift

TF$\mu$SR: vortex lattice in type II superconductors


TF$\mu$SR: vortex lattice in type II superconductors

J. Sonier et al., Review of Modern Physics, 72, 769 (2000)
TFµSR in type II SC: using simple gaussian fits

Vortex phases in layered superconductors

μSR in zero (and longitudinal) field
STATIC Case

What can you measure with ZF µSR?

- Magnetic freezing (long range order, spin glass)
- Absence of magnetic order
- Spin dynamics $T_1$ (longitudinal field)

Which sensitivity?

**ZFµSR: ordered phases (F, AF, SDW)**

$$P_z(t) = \cos^2 \theta + \sin^2 \theta \cos\gamma \mu Bt$$

Well defined internal field: static LRO

**ZFµSR: ordered phases (F, AF, SDW)**

$$P_z(t) = \cos^2 \theta + \sin^2 \theta \cos\gamma \mu Bt; \ < \cos^2 \theta > = 1/3$$

Polycrystal
ZFµSR: ordered phase SDW

\[ \text{ZFµSR: ordered phases (F, AF, SDW)} \]

- Commensurate order
- Several phases

\[ \text{x = 0.5: Magnetic phases in Na}_x\text{CoO}_2 \]

\[ \text{ZFµSR: ordered phases (F, AF, SDW)} \]

\[ \text{Phases x = 0.5: the « cascade »} \]

\[ P. \text{Mendels et al., Phys. Rev. Lett (2005)} \]

\[ M. \text{Foo et al., Phys. Rev. Lett (2004)} \]
Kubo-Toyabe

\[ G(t) = \cos^2 \theta + \sin^2 \theta \cos(\gamma_\mu Bt) \]

B is randomly oriented

\[ G(t) = \frac{1}{3} + \frac{2}{3} \cos(\gamma_\mu Bt) \]

B is distributed

\[ G(t) = \frac{1}{3} + \frac{2}{3} e^{-\Delta^2 t^2 / 2(1 - \Delta^2 t^2)} \]

ZFµSR: spin glass


LF µSR: spin glass

LF µSR: spin glass

static Lorentzian relaxation
ZFμSR: weak frozen magnetism


δB_{loc}~0.5 G
Frozen moment ~0.05μB

μSR in zero (and longitudinal) field
DYNAMICS Case

ZFμSR: weak frozen magnetism

relaxation arises from small "static" nuclear fields
upper limit of a frozen moment for Cu^{2+}, if any: 6x10^{-4} μB

No order or frozen disorder down to 50 mK despite J=180 K!

LF μSR: spin dynamics, T_1

Decoupling is different for dynamic and static cases

P. Mendels et al., PRL 98, 077204 (2007)


Complementarity between μSR and NMR

- Both probes are bulk, local probes: integrate over q; same formalism
- Difference through (i) the coupling to the environment
  (ii) the time window, the field range
  (iii) sample details

NMR/μSR: a comparative summary

<table>
<thead>
<tr>
<th></th>
<th>μSR</th>
<th>NMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which sample?</td>
<td>All, easy</td>
<td>Many...needs time</td>
</tr>
<tr>
<td>Time window</td>
<td>Few ns...20 µs</td>
<td>10 µs...mn</td>
</tr>
<tr>
<td>Location/coupling</td>
<td>Interstitial, where??</td>
<td>At. Site, hyperfine</td>
</tr>
<tr>
<td></td>
<td>0.1 T/ µB</td>
<td>0.1 T - 10 T/ µB</td>
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<tr>
<td>Sensitivity</td>
<td>Magnetic transitions</td>
<td>Magnetic susceptibilities</td>
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<tr>
<td></td>
<td>Small moments</td>
<td>Whole sample?</td>
</tr>
<tr>
<td></td>
<td>Background</td>
<td></td>
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<tr>
<td>Temperature range</td>
<td>10 mK - 800 K</td>
<td>10 mK - 1000 K</td>
</tr>
<tr>
<td>Field range</td>
<td>0 - 6...9 T</td>
<td>1 - 45 T</td>
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<tr>
<td>Dynamics</td>
<td>Fast dynamics</td>
<td>Slow dynamics</td>
</tr>
<tr>
<td>Intrinsic drawback</td>
<td>Additional charge and moment</td>
<td>r.f. field needed, field needed</td>
</tr>
<tr>
<td></td>
<td>Tuning of the probe</td>
<td></td>
</tr>
</tbody>
</table>

Think and select the best: μSR, a front tool but...
From NMR technique: time window

Orders of magnitude NMR vs µSR

- Local field 10 - 100 times larger in NMR
- \( \gamma \) 10 times smaller in NMR
- Time window start 1000 times larger in NMR
- Time window end infty in NMR

One example: fast fluctuations

\[ \frac{1}{T_1} = (\gamma B)^2 \tau \]

- Coupling
- Time window

µ*: smaller couplings, shorter times

Comparison

- Static magnetism: freezing and superconductivity
  - i. Phase diagrams: ordered, glassiness: µSR
  - ii. Weak frozen moments: µSR
  - iii. Superconductivity: µSR
  - iv. Coexistence between magnetism and...superconductivity
    NMR is more local

- Measurement of local susceptibility: NMR
- Dynamics: « fast » relaxation, gapped phases: both
- Field-induced magnetism: low field versus very high field: µSR vs NMR
- « Nano »physics: 10 nm - 100 nm scale physics
- Impact of the muon on physics

µSR: direct comparison, easiness to track transitions, ZF (zero = nuclear field)

Coexistence between magnetism and superconductivity

LaFeAsO\(_{1-x}\)F\(_x\)

\( T_g \), \( T_n \), \( T_C \) from...µSR

H. Luetkens et al., Nat. Mat. 2009

NMR: more local (scalar coupling vs dipolar - long range)
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Spin glasses (2): dynamics

- NMR

- µSR

Also study of critical exponents at magnetic transitions

µ⁺: smaller couplings, shorter times. NMR wipe-out
Frustrated magnets: spin liquid like states

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Advantage of small « residual » fields and H-indep sensitivity

NMR in High Magnetic Fields

\[ H_{\text{max}} = 35 \text{ Tesla (steady, 24 MW)} \]

Magnet and non-magnetic phases of a quantum spin liquid

μSR in Small Magnetic Fields

\[ \Delta B/B = 700 \text{ ppm within 1 cm}^3 \text{ sphere (radius = 6.2 mm)} \]

Time fluctuations can be stabilized by NMR spin-lock at room T
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Do μ⁺ impact the physics?

- μ⁺ is an added charge!

Crystal field levels in rare earth compound PrNi₅

Feyerhem, 1995

- μ⁺ deposits energy!

Open issues
Plateaus of relaxation in frustrated magnets.
Exciting monopoles in spin ice

S. Blundell et al., arXiv

A marginal case, then physically interesting!
More $\mu$SR (LEM, strong field..)

Low Energy Muons: PSI

Sample environment: LF now

E. Morenzoni: 2nd Yamazaki Prize

Low Energy Muons: PSI

Penetration length in supraconductors (Meissner)

E. Morenzoni: 2nd Yamazaki Prize

Penetration length in supraconductors (Meissner)

Self-layered structure (Fe vacancies)

References

Introductory articles
2. μSR brochure by J.E. Sonier (2002)
   http://musr.ca/intro/musr/muSRBrochure.pdf

Textbooks

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