Muons for study and research in condensed matter
Muon Spin Rotation/Relaxation

Prof. Elvezio Morenzoni
Laboratory for Muon Spin Spectroscopy
Paul Scherrer Institut
µSR in the world

Facilities under study in South Corea, China, US

Most intense source with unique instruments
Polarized positive muons: Magnetic microprobes of matter
\[ N_{e^+}(t) = B_G + N_0 \exp\left(-t / \tau_\mu\right) \left[ 1 + A_0 P(t) \right] \]

- **Precession frequency** → Value of local magnetic field at muon site
  \[ \omega = \gamma_\mu B_{loc} \]

- Damping (Relaxation rate) → Field width, fluctuations
- Frequency spectrum → field distributions
- Amplitude → magn. /pm/sc fractions
Why muons?

- Study of local magnetic, superconducting, electronic properties (material science but also applications in soft matter, chemistry)

- Simple magnetic probe (spin $\frac{1}{2}$)

- Local and very sensitive probe (large magnetic moment, 100% initial polarization)

Particularly suitable for:
- Very weak effects, small moment magnetism $\sim 10^{-3} \mu_B/\text{Atom}$
- Random magnetism (e.g. spin glasses), short range order
- Superconductivity

- Phase inhomogeneities, coexistence/competition of order parameters

- No restrictions in choice of materials to be studied (solid, liquid, gas, )

- Dynamics: spins, moments, local currents fluctuations:
  Fluctuation time window: $10^{-5} < t < 10^{-11}$ s
Generation of polarized muons ($\mu^+$)

2.2 mA $\simeq$ 1.4 $10^{16}$ Protons/sec with 600 MeV

$p + C \rightarrow \pi^+ \pi^- p n \ldots$

$\sim 10^7 - 10^8 \mu^+/sec$

100 % pol.

$\sim 4$ MeV
generally used for “bulk” condensed matter studies
For thin film studies: eV-30 keV
Muon Instruments at PSI: SµS (Swiss Muon Source)

**High Field µSR**, 9.5 T, 20 mK

**LEM**
Low-energy muon beam and instrument, tunable energy (0.5-30 keV, µ⁺), thin-film, near-surface and multi-layer studies (1-300 nm)

- 0.3 T, 2.5 K

**DOLLY**
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (µ⁺)

- 0.5 T, 2 K (0.25K)

**GPS**
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (µ⁺)

- 0.6 T, 1.8 K

**Shared Beam Surface Muon Facility**
(Muon On REquest)

**LTF**
Low Temperature Facility
Muon energy: 4.2 MeV (µ⁺)

- 3 T, 20 mK - 4 K

**GPD**
General Purpose Decay Channel Instrument
Muon energy: 5 - 60 MeV (µ⁺ or µ⁻)

- 0.5 T, 300 mK, 2.8 GPa

**LEM**
Low-energy muon beam and instrument, tunable energy (0.5-30 keV, µ⁺), thin-film, near-surface and multi-layer studies (1-300 nm)

- 0.3 T, 2.5 K

**DOLLY**
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (µ⁺)

- 0.5 T, 2 K (0.25K)

**GPS**
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (µ⁺)

- 0.6 T, 1.8 K

**Shared Beam Surface Muon Facility**
(Muon On REquest)

**LTF**
Low Temperature Facility
Muon energy: 4.2 MeV (µ⁺)

- 3 T, 20 mK - 4 K

**GPD**
General Purpose Decay Channel Instrument
Muon energy: 5 - 60 MeV (µ⁺ or µ⁻)

- 0.5 T, 300 mK, 2.8 GPa
Research at the SµS

- Magnetic materials
  - Molecular magnets
  - Cobaltites
  - Manganites
  - Heavy Fermions
  - Intermetallic compounds with d- and f-elements

- Semiconductors
  - Magnetic sm
  - Organic sm

- Thin films
  - Multilayers
  - Oxides
  - Spin Valves
  - FM/SC
  - AF/SC

- Low dimensional magnets
  - Spin liquids, ices, glasses

- Superconductors
  - Cuprates
  - Iron Based
  - Low T_c

- Chemistry, Soft matter
  - Free radicals
  - Liquid crystals

- Material Science
  - Multiferroics
  - Battery materials
Microscopic magnetometry

\[ B_{\text{ext}} = 0 \]

\[(C_{13}H_{23}O_{2}NO)_{2}\]

Organic antiferromagnet

\[ P(t) = a_L(t) + a_T e^{-\lambda t} \cos(2\pi \nu \mu t) \]

\[ \lambda = \frac{1}{T} \quad \text{relaxation rate, [\mu s}^{-1}] \text{ or [MHz]} \]

\[ S. \text{Blundell et al., Physica B (2000)} \]
Vortex state: microscopic properties

Vortex state

Meissner state

Normal state

Flux line lattice

\[ \kappa \equiv \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}} \]

Temperature \( T_c \)
Vortex state: microscopic properties

- Characteristic lengths: magnetic penetration depth $\lambda$, coherence length
- SC order parameter
- Structure of vortex lattice
- Vortex dynamics
- Classification of superconductors

![Diagram of vortex state](image)
Classification of superconductors

\[ T_c \text{ versus } \sigma \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}, \text{ Uemura plot} \]


Fe based sc

- LaFeAsO$_{1-x}$F$_x$
- NdFeAsO$_{1-x}$F$_x$
- SmFeAsO$_{1-x}$F$_x$
- CeFeAsO$_{1-x}$F$_x$
- FeSe$_{1-x}$
- LiFeAs
- Ba$_{1-x}$K$_x$Fe$_2$As$_2$
- Fe$_{1+y}$Se$_{1-x}$Te$_x$
Phase diagrams


E. Wiesenmayer et al., PRL 107, 237001 (2011)

M. Bendele et al., PRL 104, 087003 (2010)

R. Khasanov et al., PRB 80, 14051(R) (2009)

M. Bendele et al., PRB 82, 212504 (2010)
Nanoscale coexistence of superconductivity and magnetism

Resistivity: (Superconductivity)  
Magnetization: (Ferromagnetism)

\[ \mu \text{SR:} \]

\[ T = 5.3 \text{ K} \]

\[ T = 48 \text{ K} \]

Structure:


Dynamics: freezing of fluctuations

LaMnO$_3$: $T \rightarrow T_N$

Spin fluctuations slow down approaching the transition

YBa$_2$Cu$_3$O$_{6+x}$

Freezing of hole spins

Other intrinsic spin dynamics ...
OR persistent spin dynamics

Persistent dynamics at very low temperatures
Muon as sensitive tracer in soft matter

Phase transition in liquid crystals by dopant addition:

resonance lines
OR in buried layers: Magnetic multilayers (ML)

Ferromagnet | Normal Metal | Ferromagnet
Oscillating polarization of conduction electrons

Critical spanning vectors in Ag:

Fe/Ag/Fe Implantation profile of 3 keV muons.

OR probe very thin layers: a few Unit Cells thick

Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices

A. Boris et al., Science (2011)

LaNiO₃/LaAlO₃ Superlattices
OR study new devices

Operational Spin Valve
With organic organic Semiconducting spacer
Alq3: $\text{C}_{27}\text{H}_{18}\text{N}_3\text{O}_3\text{Al}$

Spin Diffusion length $\leftrightarrow$ Magnetoresistance

Contact and information

Physics with Muons: from Atomic physics to Condensed Matter physics, 6 CP
Lecture course 402-0770-00L  (ETH-Zürich)
Lecture course PHY 432  (Univ. Zürich)
Thursday 9-11, starting FHS: Thursday 20.2.2013  (Exercises 11-12)
Lecture script: http://people.web.psi.ch/morenzoni

Muon Spin Spectroscopy, 9 CP
Prakticum 402-0549-BSL  and MSL
Monday 3.6.2013-Friday 7.6.2013 or by arrangement

Semester/Summer Works
Bachelor/Master/PhD:  Muons, neutrons, macroscopic techniques  
(transport, magnetization..), characterization (XRD, ..)

elvezio.morenzoni@psi.ch  or morenzoni@ethz.ch
http://lmu.web.psi.ch/