All in a spin – An introduction to muon spectroscopy

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ISIS Muon Group
Plan

1. An Introduction to Muons
2. The $\mu$SR technique
3. The ISIS $\mu$SR Facility
4. Condensed matter studies with muons
5. Muons elsewhere in the world
1. An Introduction to Muons

‘Who ordered that?!’

I.I. Rabi, Physics Nobel prize winner, 1944
Cosmic rays

- Discovered 1912 - Victor Hess (Nobel Prize 1936)
- 87% protons, 12% He, 1% heavier nuclei
Discovery of the muon

Carl Anderson - Caltech
1936 Nobel prize for discovery of positron

1937, with Seth Neddermeyer - charged particle 200 x electron mass - the muon

Carl Anderson and Seth Neddermeyer with cloud chamber
courtesy Caltech Archives
Physics at the farm: discovery of the muon.
Muons in cosmic rays

Muons - average energy 4 GeV.
For muons E>1 GeV, flux is 1 cm$^{-2}$ min$^{-2}$
So - we get hit by ~1 muon s$^{-1}$!
Muons:

- fundamental, charged particles
- heavy electrons
- spin 1/2
- magnetic moment $3.2 \times m_p$
- mass $0.11 \times m_p$

- produced from pion decays
- lifetime $2.2 \mu s$
- decay into a positron (+ $2\nu$)
The life of a muon
2. The $\mu$SR technique
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

Result: a fully spin-polarised muon beam

\[ \pi^+ \text{ at rest, } l=0 \]
Muon death

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \]

Positrons emitted preferentially in muon spin direction
Muon death

\[ W(\theta) = 1 + a \cos \theta \]

Fig. 1 Angular distribution of positrons for asymmetry parameters 1 and \( \frac{1}{3} \)
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,‡ Leon M. Lederman, and Marcel Weinrich

Physics Department, Nesci Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York
It seems possible that polarised positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei, atoms and interatomic regions.

Garwin et al., Phys Rev 1957

The muon technique was born!

$\mu$SR . . . muon spin rotation, relaxation and resonance - or just muon spin research
Monitor the positron distribution to infer the muons’ polarisation after implantation. Learn about the muons’ local environment or the muon behaviour itself.

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

4 MeV muons are 100% spin polarised

Decay, lifetime 2.2\(\mu s\)

\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

we detect decay positrons

The positrons are preferentially emitted in muon spin direction

High energy protons (800 MeV at ISIS) collide with carbon nuclei, producing pions

Implantation, (stopped in \(\sim1\) mm water)

Muons interact with local magnetic environment

The \(\mu\)SR technique
The \( \mu \)SR technique

\[ \text{\textquoteleft asymmetry\textquoteright} = \frac{N_A(t) - N_B(t)}{N_A(t) + N_B(t)} \]

- non-relaxing polarisation
- relaxing polarisation

\[ \text{magnetic field} \]

\[ \text{detector A} \]

\[ \text{detector B} \]

\[ \text{muons} \]

\[ \text{time (\( \mu \)s)} \]

\[ \text{asymmetry} \]
The $\mu$SR technique

‘Transverse’ field

$B_x > 0$

asymmetry = $\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = a_0 G_x(t) \cos(\omega t)$
The $\mu$SR technique

$R_z(t) = \frac{F(t) - B(t)}{F(t) + B(t)} = a_o G_z(t)$
The $\mu$SR technique

- Precessing polarisation
- Precessing and relaxing polarisation
- Relaxing signal

Detector A

Detector B

Time (ms)
The $\mu$SR technique

Zero or ‘longitudinal’ field

$$\text{asymmetry} = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = a_0 G_Z(t)$$

Kadono et al., PRB 1989

Blundell, J. Phys C, 1999
3. The ISIS Muon Facility
The Rutherford Appleton Laboratory

The ISIS Facility
The ISIS Facility

ISIS
Spallation neutron source
800 MeV proton beam
Neutrons produced for 25 instruments
7 muon experimental areas
2000 users/yr
~800 experiments/yr
~500 publications/yr
Muons at ISIS

- **Kicker**: feeds muons to three instruments
- **Separator**: removes contaminant particles
- **Dipole steering magnet**
- **Quadrupole focusing magnet**
- **Muon production target**
- **800 MeV proton beam**
- **To neutron target**

**Components**:
- **DEVA**
- **MuSR**
- **EMU**
Muons at ISIS

- **EMU**
  - Fields: 0G - 5 T
  - Temperatures: 30 mK - 1500 K
  - Pressure: up to 6.4 kbar
  - + and - muons

- **MuSR**

- **ARGUS**

- **HiFi**
  - Gas/liquid samples
  - Pulsed stimuli, e.g. light, E/B-fields, RF

![MUONS AT ISIS](image)
4. Science with muons
• Muons as passive probes in superconductivity, magnetism, molecular dynamics, charge transport.

• Muons as active probes: proton analogues in semiconductors, proton conductors, light particle diffusion, etc.
Magnetism

CeRu$_2$Al$_{10}$

Magnetism

CeRu$_2$Al$_{10}$

CeRu$_2$Al$_{10}$

Magnetism

Sr$_3$ZnRhO$_6$

Magnetism

Sr$_3$ZnRhO$_6$

Magnetism

Example URu$_2$Si$_2$

**Neutron scattering:**
F. Bourdarot et al., condmat/0312206

![Graph showing temperature vs. magnetic field for URu$_2$Si$_2$](image)

**Muon Spin Rotation:**

![Graph showing AF volume fraction vs. temperature for URu$_2$Si$_2$](image)

**Phase separation in magnetic and non-magnetic volumes**

Only the combination of neutron and muon data allows the correct interpretation of the data.
Frustrated magnetism

Geometrical frustration: anti-ferromagnetism, spins cannot all be satisfied.

Pyrochlore compounds: Corner-sharing tetrahedra lead to geometrical frustration.

The $\mu$SR technique:
- is highly sensitive to local fields,
- is able to characterise the timescale of local field fluctuations,
- is well suited to the investigation of compounds which do not display long-range magnetic correlations,
- requires no application of external fields.
Frustrated magnetism

First order transition in the spin dynamics of geometrically frustrated Yb$_2$Ti$_2$O$_7$

J Hodges et al, PRL 88 (2002) 077204

- First order transition at 0.24 K is not to long (or short) range order, but is a change in the Yb$^{3+}$ fluctuation rate.
- Neutron diffraction, Mossbauer and $\mu$SR used.
Complementary

- neutron scattering
- Mossbauer
- %SR
- NMR
- ac susceptibility
- remanence

log (fluctuation rate), s^{-1}
Superconductors

- Interplay of superconductivity and magnetism;
- Flux lattice studies;
- Measurement of fundamental superconducting parameters
Investigation of Vortex Behavior in the Organic Superconductor \( \kappa-(BEDT-TTF)_2\text{Cu(SCN)}_2 \) Using Muon Spin Rotation

*Lee et al, PRL 1997*

\[ T_c = 10.4 \text{ K} \]

Highly anisotropic

Measurements at 1.8K
Breakdown of 3D order with B and T

\[ p(B) \text{ vs. } B - \langle B \rangle \text{ for 2.5 mT and 40 mT} \]
Superconductors

Lu$_2$Fe$_3$Si$_5$

![Graph showing the susceptibility vs. temperature for Lu$_2$Fe$_3$Si$_5$ with $T_c = 6.1$ K and $\mu_0 H = 2$ mT.](image-url)
\[ \frac{\lambda^{-2}(T, \Delta_{0,i})}{\lambda^{-2}(0, \Delta_{0,i})} = 1 + \frac{1}{\pi} \int_{0}^{2\pi} \int_{\Delta(T,\varphi)}^{\infty} \left( \frac{\partial f}{\partial E} \right) \frac{EdEd\varphi}{\sqrt{E^2 - \Delta_i(T, \varphi)^2}}, \]

\[ \frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = \omega_1 \frac{\lambda^{-2}(T, \Delta_{0,1})}{\lambda^{-2}(0, \Delta_{0,1})} + \omega_2 \frac{\lambda^{-2}(T, \Delta_{0,2})}{\lambda^{-2}(0, \Delta_{0,2})}, \]

For \( s+s \)-wave
\[ \Delta_{0,i}/k_B T_c = 1.76(6) \]
\[ \Delta_{0,2}/k_B T_c = 0.40(1) \]
\[ \omega_1 = 0.35 \]

LaRhSi$_3$

Superconductors
LaNiC$_2$

$T_c = 2.7$ K 

$\Delta C/\gamma T_c = 1.26$ c.f. (BCS: 1.43)

Note no inversion centre.

C.f. CePt$_3$Si $^{(1)}$, Li$_2$Pt$_3$B & Li$_2$Pd$_3$B $^{(2)}$, ...

$^{(1)}$ Bauer et al. PRL’04 $^{(2)}$ Yuan et al. PRL’06

Superconductors

ZFμSR on LaNiC$_2$

\[ G_z(t) = A_0 \left( \frac{1}{3} + \frac{2}{3} (1 - \sigma^2 t^2) \exp \left( -\frac{\sigma^2 t^2}{2} \right) \right) \exp(-\lambda t) + A_{bckgrd} \]

Nuclear contribution

Electronic contribution

Hillier et al PRL 102 117007 (2009)
Relaxation due to electronic moments

Moment size
\[ \sim 0.1\text{G} \quad (\sim 0.01\mu_B) \]

Spontaneous, quasi-static fields appearing at \( T_c \) ⇒ superconducting state breaks time-reversal symmetry

Hillier et al PRL 102 117007 (2009)
### Superconductors

<table>
<thead>
<tr>
<th>SO(3)xC$_{2v}$</th>
<th>Gap function (unitary)</th>
<th>Gap function (non-unitary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1A_1$</td>
<td>(\Delta(k) = 1)</td>
<td></td>
</tr>
<tr>
<td>$^1A_2$</td>
<td>(\Delta(k) = k_xk_y)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>breaks only (U(1) \times SO(3))</td>
</tr>
<tr>
<td>$^1B_1$</td>
<td>(\Delta(k) = k_xk_z)</td>
<td></td>
</tr>
<tr>
<td>$^1B_2$</td>
<td>(\Delta(k) = k_yk_z)</td>
<td></td>
</tr>
<tr>
<td>$^3A_1$</td>
<td>(d(k) = (0,0,1)k_z)</td>
<td>(d(k) = (1,i,0)k_z)</td>
</tr>
<tr>
<td>$^3A_2$</td>
<td>(d(k) = (0,0,1)k_xk_yk_z)</td>
<td>(d(k) = (1,i,0)k_xk_yk_z)</td>
</tr>
<tr>
<td>$^3B_1$</td>
<td>(d(k) = (0,0,1)k_x)</td>
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</tr>
</tbody>
</table>

* C.f. Li$_2$Pd$_3$B & Li$_2$Pt$_3$B, H. Q. Yuan et al. PRL’06

Hillier *et al.* *PRL* **102** 117007 (2009)
‘Muonium’ (Mu): light hydrogen atom

Mass: \( m_{\text{Mu}} = 1/9 m_{\text{H}} \)
Bohr radius: \( a_{\text{Mu}} = 1.004 a_{\text{H}} \)
Ionisation potential: \( I_{\text{Mu}} = 0.996 I_{\text{H}} \)
Chemical behaviour very similar - dynamics different

$$\begin{align*}
2S_{1/2} & \quad \text{F=0, 1}\quad 560 \text{ MHz} \\
2P_{1/2} & \quad \text{F=0, 1}\quad 190 \text{ MHz} \\
1S_{1/2} & \quad \text{F=0}\quad 4.5 \text{ GHz} \\
\end{align*}$$
Silicon: two muon species exist at low temperatures.

$\mu_T$: Cage-centred, isotropic, mobile

$\mu_{BC}$: Bond centred, axially symmetric, immobile

$\text{Si}_{80}\text{Ge}_{20}$

*King et al., J. Phys C 2005*
CdS: II-VI semiconductor

- Hyperfine parameter $10^{-4}$ of vacuum value
- Extended wavefunction
- Ionises at 22 K
- **Shallow donor state**
  *Gil et al, PRL 1999*
Experimental Confirmation of the Predicted Shallow Donor Hydrogen State in Zinc Oxide

S. F. J. Cox,1,2 E. A. Davis,3 S. P. Cottrell,1 P. J. C. King,1 J. S. Lord,1 J. M. Gil,4 H. V. Alberto,4 R. C. Vilão,4 J. Piroto Duarte,4 N. Ayres de Campos,4 A. Weidinger,5 R. L. Lichti,6 and S. J. C. Irvine7

1ISIS Facility, Rutherford Appleton Laboratory, Chilton OX11 0QX, United Kingdom
Organic Spintronics

Small molecule semiconductors used in molecular electronic devices such as:

- Spin valves
- OLEDs
- FETs

FIG. 1. (Color online) Molecular structures of (a) TIPS-pentacene, (b) rubrene, and (c) GaQ3 (Refs. 13, 14, and 22–24). Hydrogen has been omitted for clarity.
Organic Spintronics

ALC resonance gives a sensitive measure of the electron spin relaxation (eSR)

T dependence of the eSR is governed by intramolecular vibrational modes

Vibration-modulated spin-orbit coupling emerges as the dominant spin relaxation mechanism in this type of system (rather than hyperfine interaction)
Alan Drew from QMUL has been awarded 1.5MEuros European Research Council grant to develop the HiFi muon spectrometer.

By installing a powerful laser system on to the existing HIFI instrument – the ability to perform muon experiments enhanced by a laser in magnetic fields as high as 5T is not available anywhere else.

This research has potential impact in fields ranging from green energy production to biology and medicine.

Transport system installed and first beam Dec. First experiments already completed
Commissioning experiment on Silicon

- Site exchange conversion induces relaxation: \( \text{Mu}_T^0 \rightarrow \text{Mu}_{BC}^0 \)

n-type Si: well-studied system
Ionic conduction

Li diffusion constant determined from the fluctuation rate

\[ D_{Li} = \sum_{i=1}^{n} \frac{1}{N_i} Z_{\nu,i} s_i^2 \nu, \]

Fit to a dynamic Gaussian KT function

\[ A_0 P_{LF}(t) = A_{KT} G^{DGKT}(\Delta, \nu, t, H_{LF}) + A_{BG} \]

Molecular fluctuation rate extracted from muon depolarisation

Large increase at solid-nematic phase transition.

Motion is consistent with rotation of the whole molecule.

Molecular dynamics in a nematic liquid crystal probed by muons; BW Lovett et al, PRB 63 (2000) 054204.
For PPV, intrachain diffusion is phonon-limited, metallic-style; interchain diffusion is thermally-assisted.

Muon-spin relaxation study of charge carrier dynamics in the conducting polymer PPV, SJ Blundell et al, Synth Met. 119 (2001) 205
Partitioning of co-surfactants

Surfactant

DHTAC

Co-surfactant

2-phenylethanol

- Fragrances
- Food additives
- Drug delivery

Surfactants can form bilayers, micelles, vesicles, etc.
Partitioning of co-surfactants

40 mM Phenylethanol in DHTAC

Δ₁

Δ₀

75 °C
65 °C
55 °C
45 °C
35 °C
25 °C

μ adducts of phenylethanol

Scheuermann et al. PCCP 2002, 4, 1510
Researchers at Vanderbilt University used RIKEN-RAL facility to investigate effects of muons on state-of-the-art microelectronic memories.

Collaborators from industry including Marvell Semiconductors, Cisco Systems, and Texas Instruments.

Muon-induced data errors clearly observed in multiple devices.

Results will support investigation into error rates of commercial electronics.

Recently tested electronics for CERN.

Bias dependence of muon-induced single event upsets in 28 nm static random access memories
Sierawski, B.D.; et al Reliability Physics Symposium, 2014 IEEE International
DOI: 10.1109/IRPS.2014.6860585 (2014) p 2B.2.1 - 2B.2.5
We can use negative muons finding the active component
μSR facilities

- Japan: JPARC
- Canada: TRIUMF
- UK: ISIS
- Switzerland: PSI
μSR facilities

PSI, Switzerland

To Spallation Neutron Source (SINQ)

DOLLY

πE1

decay channel, $\mu^+$ and $\mu^-$

$E = 15 - 60$ MeV

LEMS 2004

low-energy $\mu^+$ (LEM)

$0.5 - 30$ keV

GPD

ALC: LEM, until 2003

Target E

πE2

πE3

μE1

Target M

πM1

πM3

πE5

surface muon beam, $\mu^+$

$E = 0.1 - 4.2$ MeV

Proton Beam

To Nucleon Area (NA)

GPS

LTF

Science & Technology Facilities Council

ISIS
**μSR facilities**

**Pulsed (e.g. ISIS, J-PARC)**
- Bursts of muons, ~50 Hz
- Low intrinsic background
- Weak relaxations, slow precession
- No fundamental rate limit
- Big detector arrays
- *Pulsed environments*

**Continuous (e.g. PSI, TRIUMF)**
- Single muons
- Higher intrinsic background
- Fast relaxations, rapid precession
- Data rates limited
- Small, compact detector arrays
- *PSI: low energy muons for surface studies, + pressure*
6. Summary

"You're not allowed to use the sprinkler system to keep your audience awake."
MUONS:

- Versatile probes of magnetic, superconducting, molecular systems
- Analogues of protons/hydrogen in semiconductors
- Complementary to other techniques ISIS / PSI / J-PARC all have n and μ facilities
- Around 60 groups from 20 countries using ISIS muons
- Further details:

www.isis.stfc.ac.uk/groups/muons/