Perspectives of the Muon

Francis Pratt

ISIS Muon Group

Outline of Lecture

- Key properties of the muon
- High energy particle physics perspective
- Radiation physics/chemistry perspective
- Condensed matter physics perspective
- Magnetic resonance perspective
- Chemistry perspective
- Computational science perspective
- μSR experiment perspective

Key Properties of the Muon

Discovered in 1936 by Carl David Anderson and Seth Neddermeyer in California

They used cloud chambers to study cosmic rays

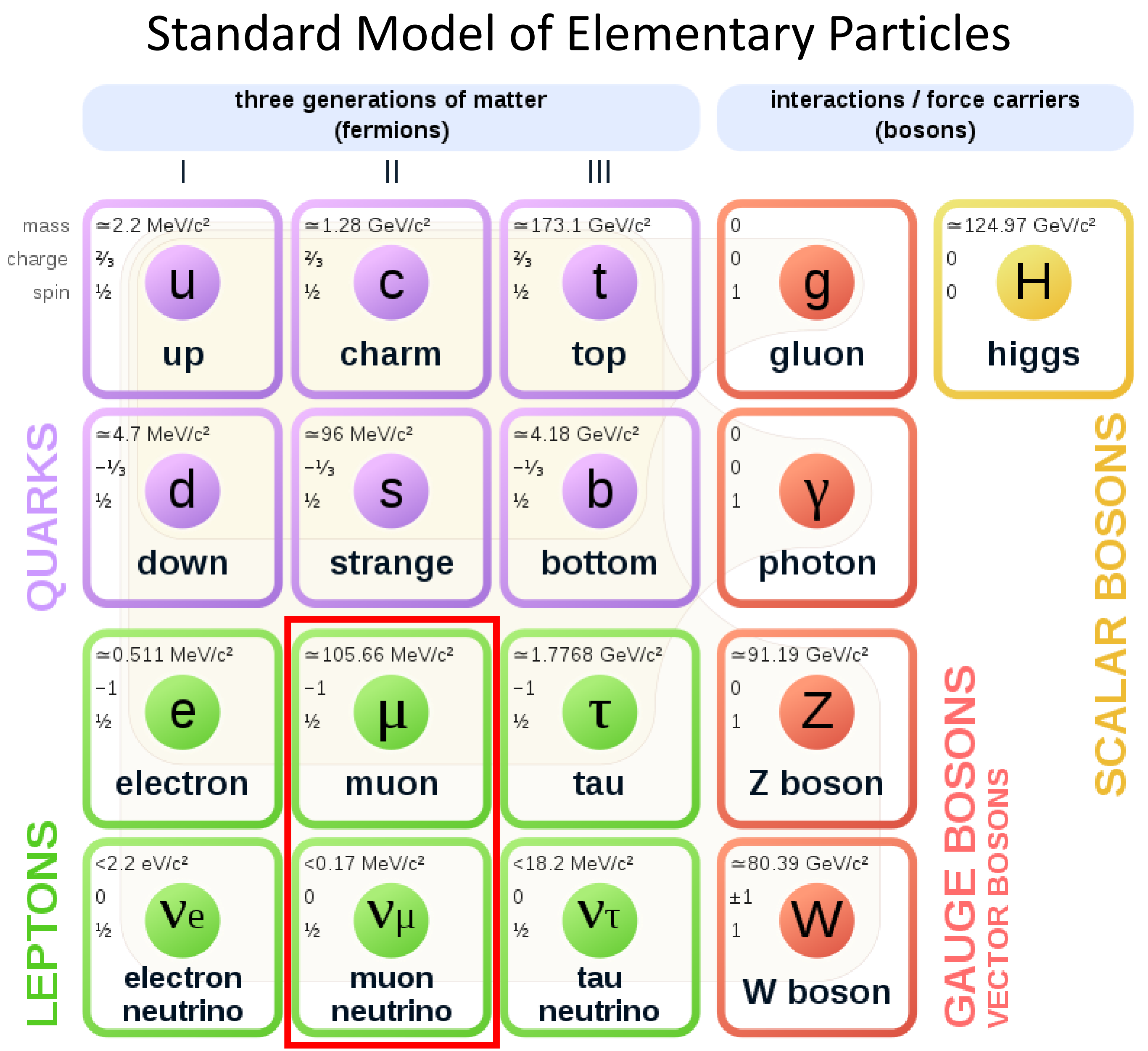
Carl David Anderson received a Physics Nobel prize the same year for his discovery of the positron using the same technique

Muon: an unstable charged particle
200 times heavier than the electron

“Who ever ordered ***that*** ?”

Isidor Isaac Rabi, 1944 Physics Nobel Laureate, commenting after the discovery of the muon

Key Properties of the Muon



Key Properties of the Muon

Comparison with the more familiar particles: electrons and protons

	Spin	Mass	Magnetic moment	Charge	Lifetime	Character	Magnetic resonance technique
e	½	m_e	657 μ_p	-e	∞	electron	ESR
μ	**½**	**207 m_e**	**3.18 μ_p**	**+e** *-e*	**2.2 μs** < 2.2 μs	**'light proton'** *'heavy electron'*	**μ^+ SR** *μ^- SR*
p	½	1836 m_e	μ_p	+e	∞	proton	NMR

Key Properties of the Muon

The standard muon decay process produces a positron or electron and two neutrinos:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

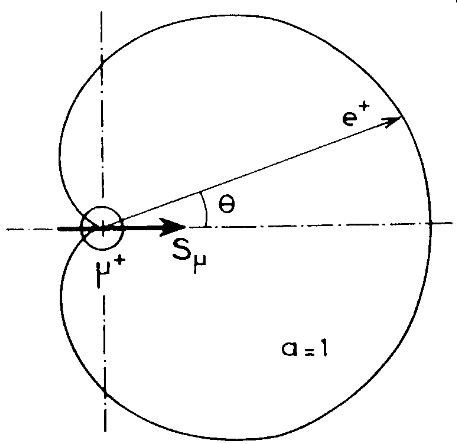
The muon decay is a result of the weak nuclear force

→ Slow decay rate

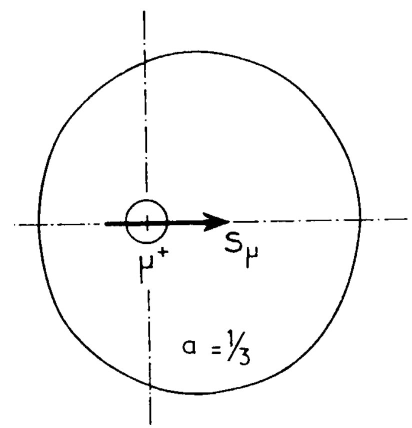
→ Asymmetric positron/electron emission from parity-symmetry violation

Taking a positive muon

$W(\theta) = 1 + a \cos\theta$



at the maximum positron energy



averaged over all positron energies

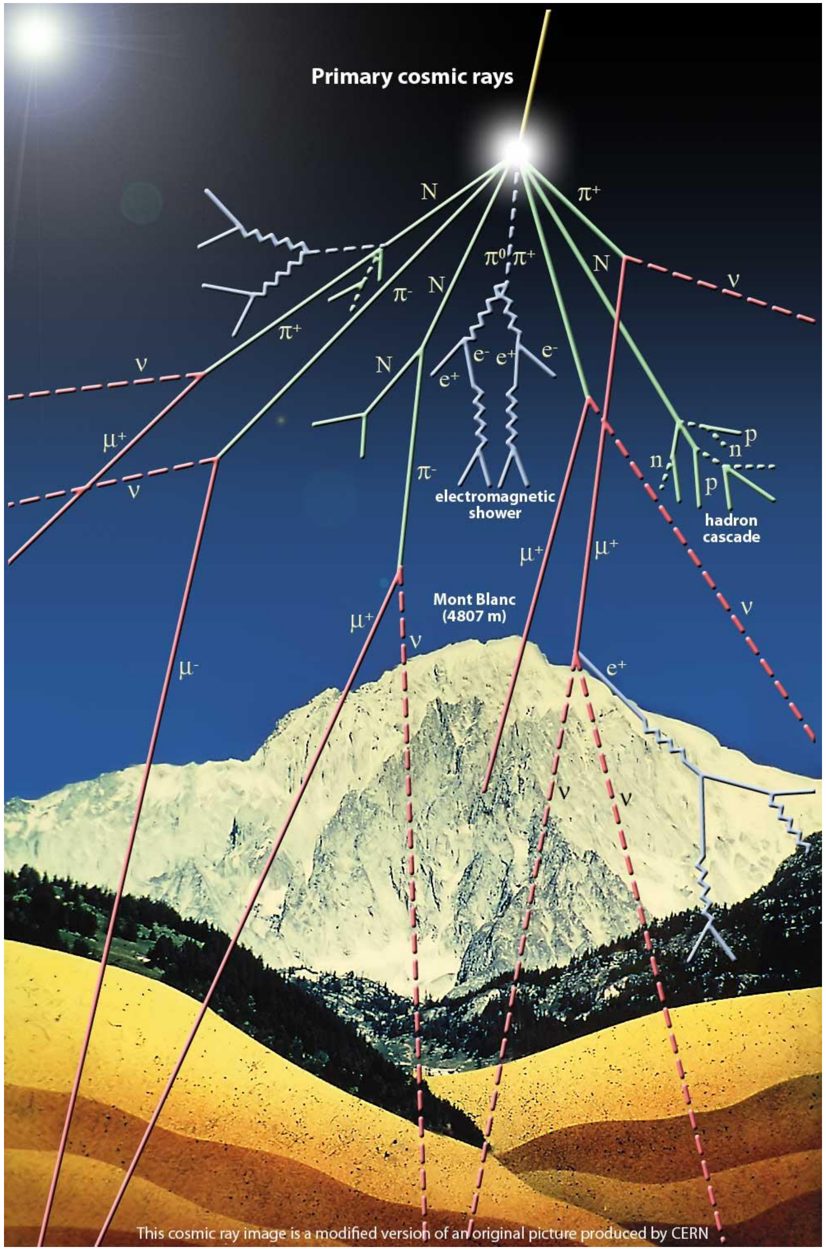
High Energy Particle Physics Perspective

Cosmic rays provided the first source of high energy particles

Primary cosmic rays are high energy protons and atomic nuclei mainly from outside the solar system

In the upper atmosphere the primary cosmic rays produce showers of secondary particles including muons, with a large number of the muons reaching the surface of the Earth

Muons played a significant role in the early development of particle physics



High Energy Particle Physics Perspective

Muons provided the first experimental proof of ***relativistic time dilation***

Rossi and Hall (1941)

They measured the survival probability of cosmic ray muons between Echo Lake (3240m) and Denver (1616m):

momentum 440 to 580 MeV/c	0.70
momentum > 580 MeV/c	0.88

Slower decay rate for higher momentum
as predicted by relativity

Their estimate of the muon lifetime before time dilation effects was 2.4(3) μs

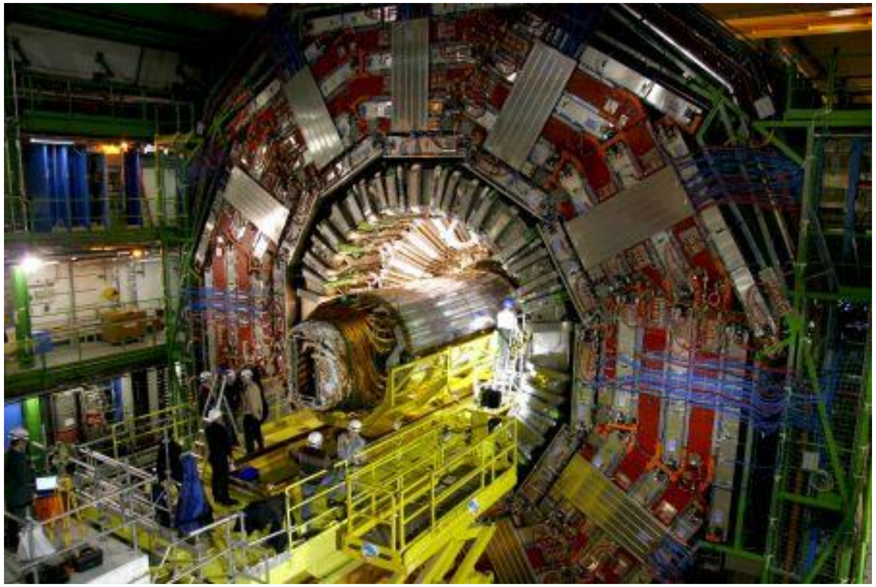
B. Rossi and D.B. Hall, Phys. Rev. 59, 223 (1941)

Echo Lake 3240 m

Denver 1616 m

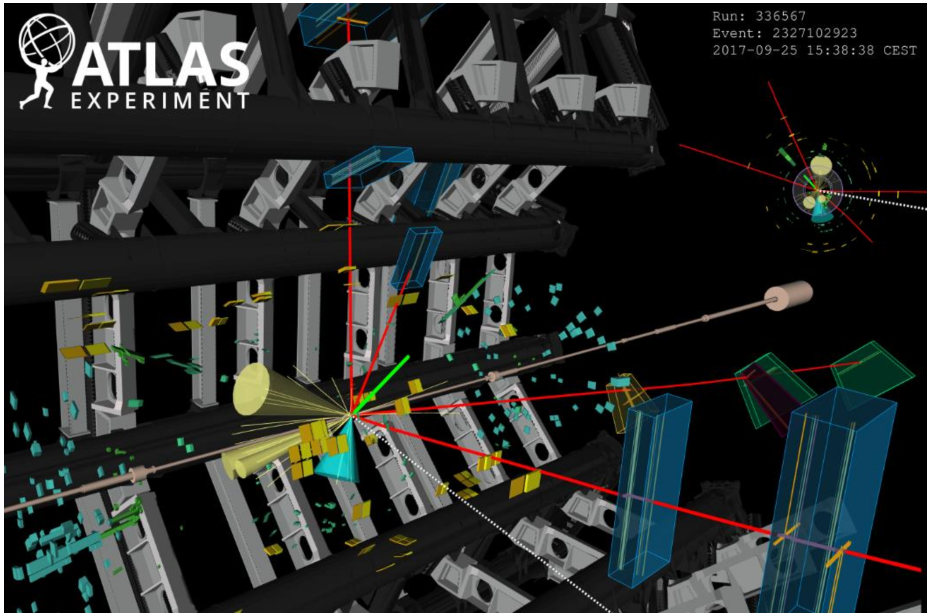
High Energy Particle Physics Perspective

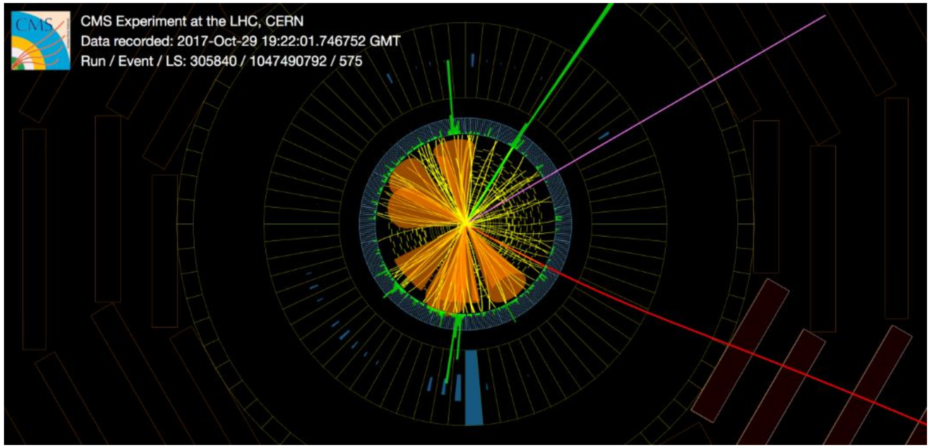
Large Hadron Collider at CERN: the muon tracking detectors Atlas and CMS are used to study the Higgs



The LHC-CMS ‘Compact Muon Solenoid’

Higgs decay events (muon tracks in red)





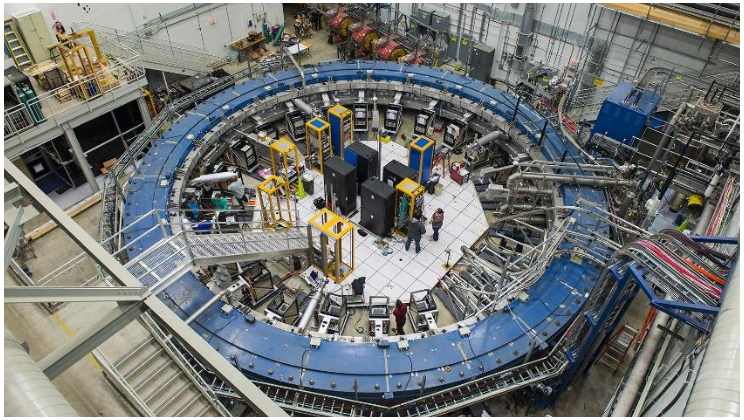
High Energy Particle Physics Perspective

High precision muon *g* - 2 experiments to test QED and the standard model

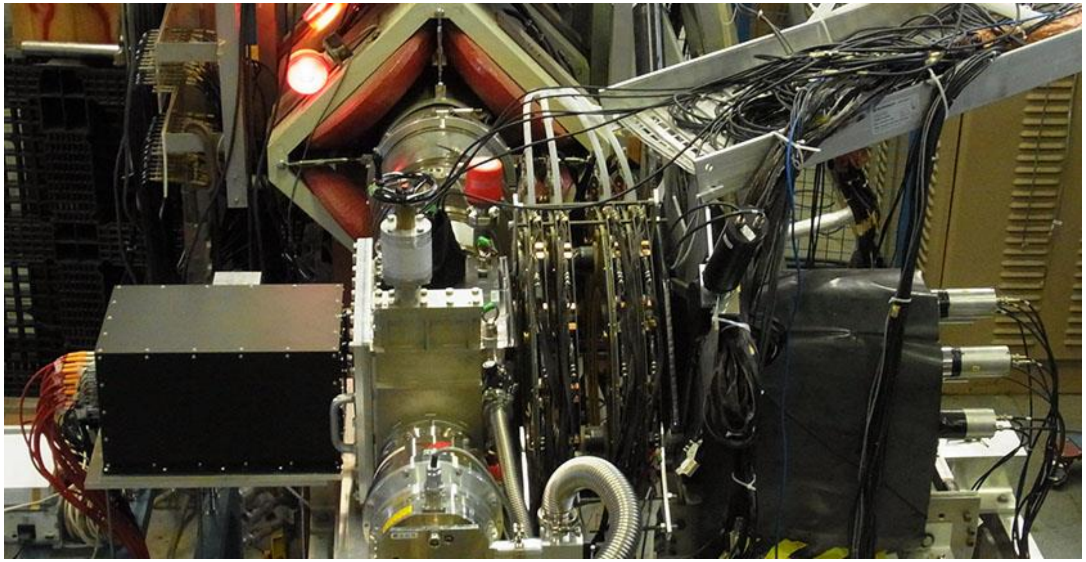
Currently 3 -4 σ deviation between theory and experiment for the muon gyromagnetic ratio - no new discoveries from LHC are able to explain this difference

New experiments:

Fermilab in the USA
(now taking data)



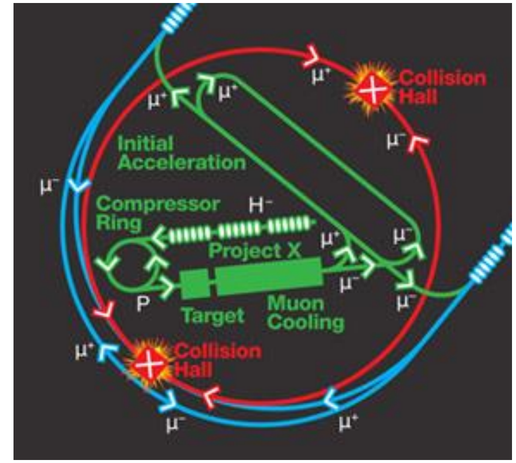
J-PARC in Japan
(building up)



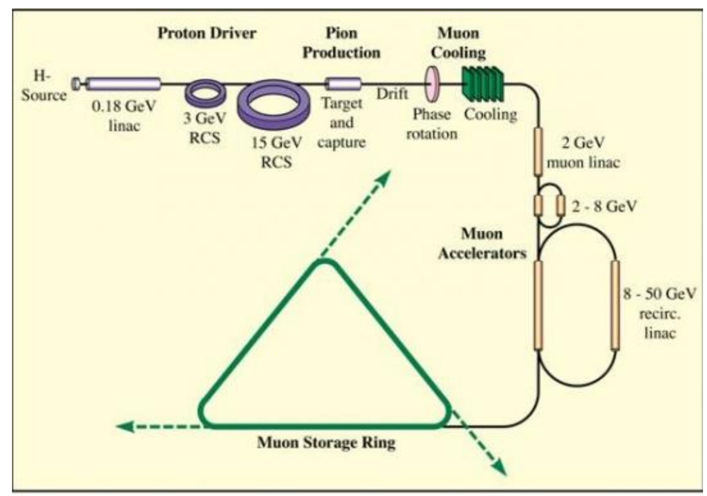
High Energy Particle Physics Perspective

Plans being developed for future high intensity muon sources:

1) Muon colliders
   (to reach higher energy concentration than LHC)



2) Neutrino factories
   (to send neutrino beams to neutrino detectors such as Super-Kamiokande in Japan and Gran Sasso in Italy)

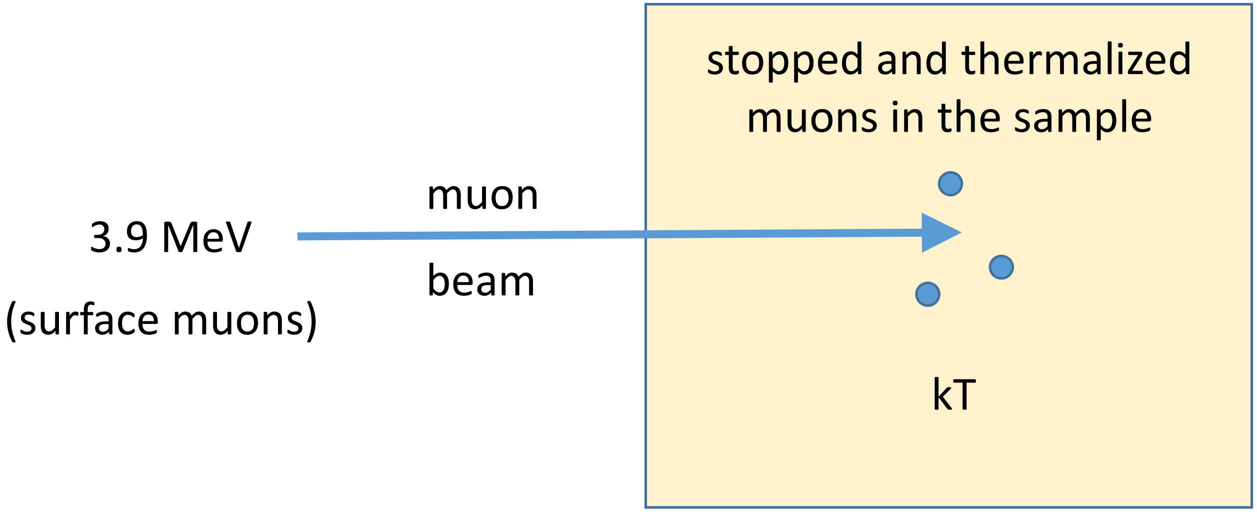


Neutrino Factory at RAL

Both of these require muon storage rings

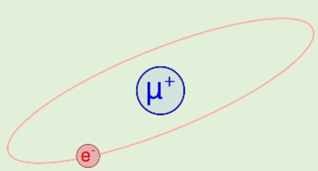
Focus on high energy muons

Radiation Physics/Chemistry Perspective



Muonium (Mu)
muon analogue
of the H atom

$Mu = \mu^+ + e^-$



Diamagnetic
Final States

e.g.

μ^+ (Mu^+)

Mu^-

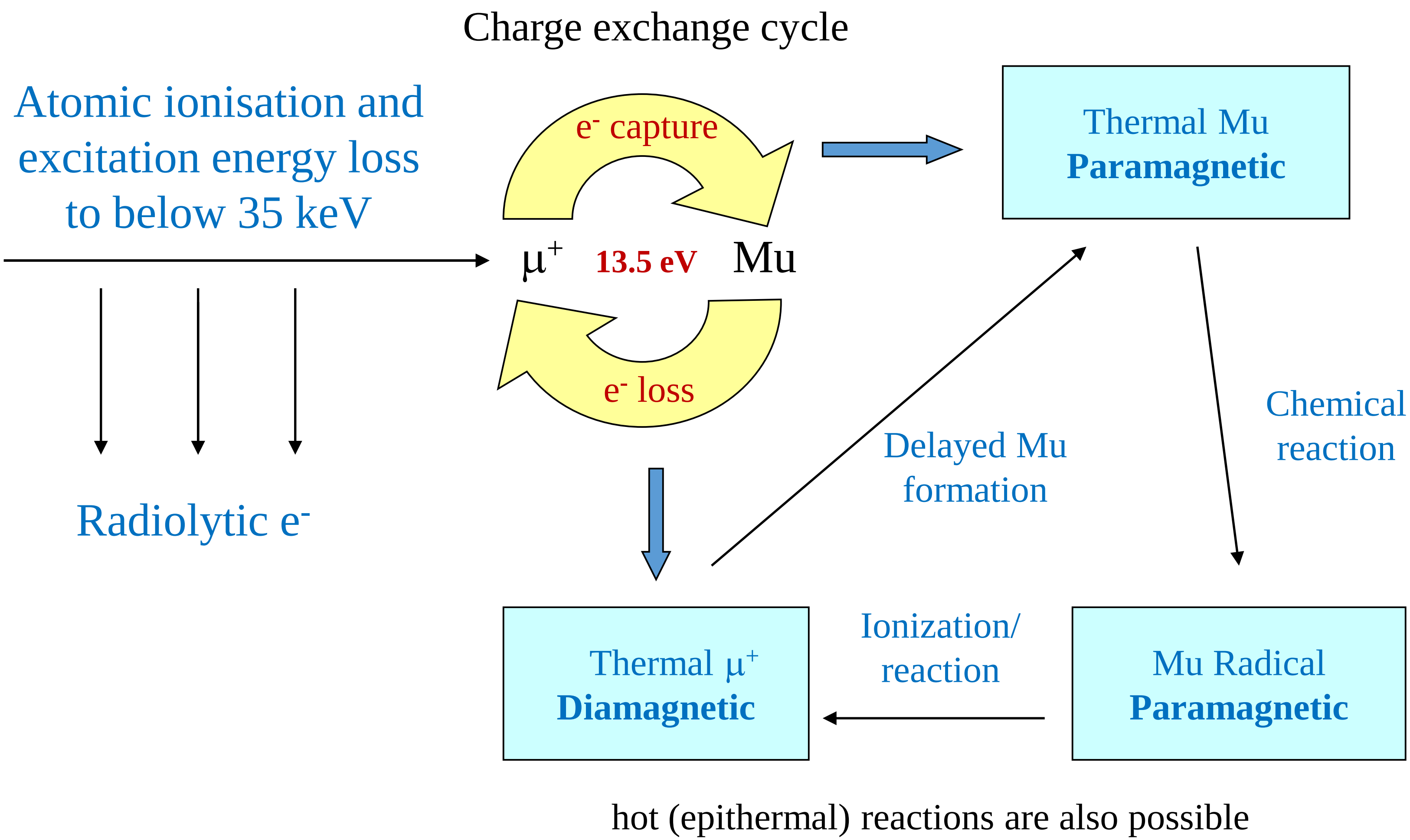
Paramagnetic
Final States

e.g.

$Mu^\bullet$

$Mu\text{-}R^\bullet$

Radiation Physics/Chemistry Perspective



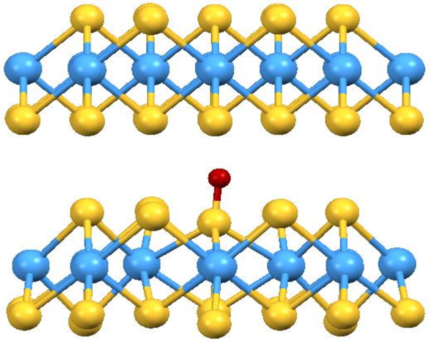
The thermalisation occurs on a ns time scale and preserves the 100% muon polarisation

Condensed Matter Physics Perspective

Thermalised muons acting as local probes of static and dynamic magnetism

Static magnetism:

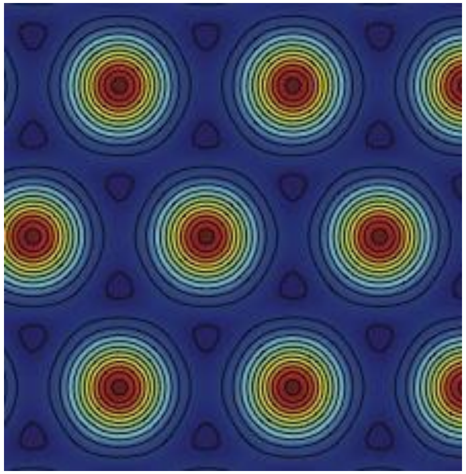
1) Muon as a local probe with a limited set of well-defined sites



data analysed in terms of specific sites

complementary site calculations to aid the analysis

2) Muon as a statistical sampling probe



superconducting vortex lattices

magnetic systems with a large cell
and many stopping sites

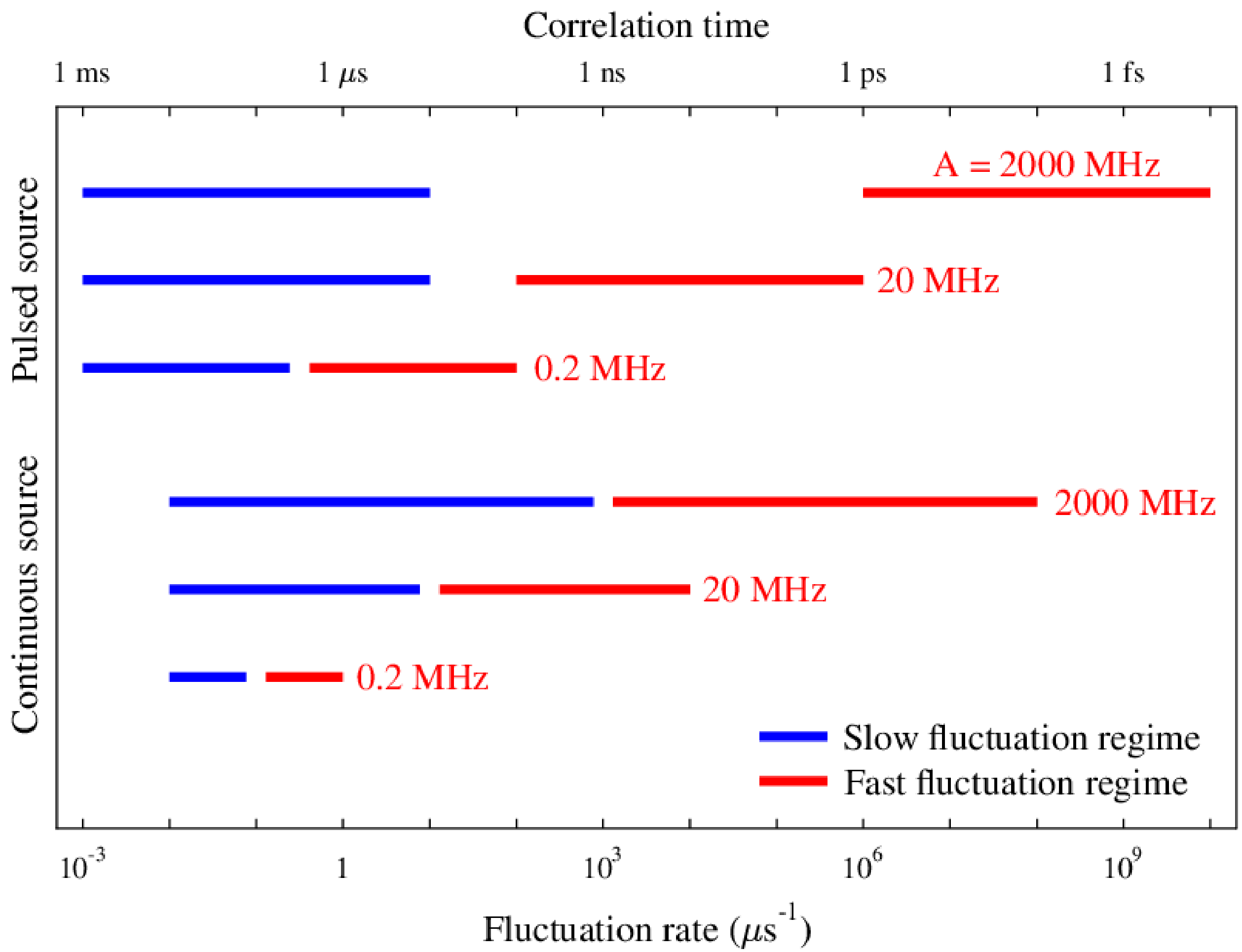
systems with a high degree of disorder

quantum delocalised systems

Condensed Matter Physics Perspective

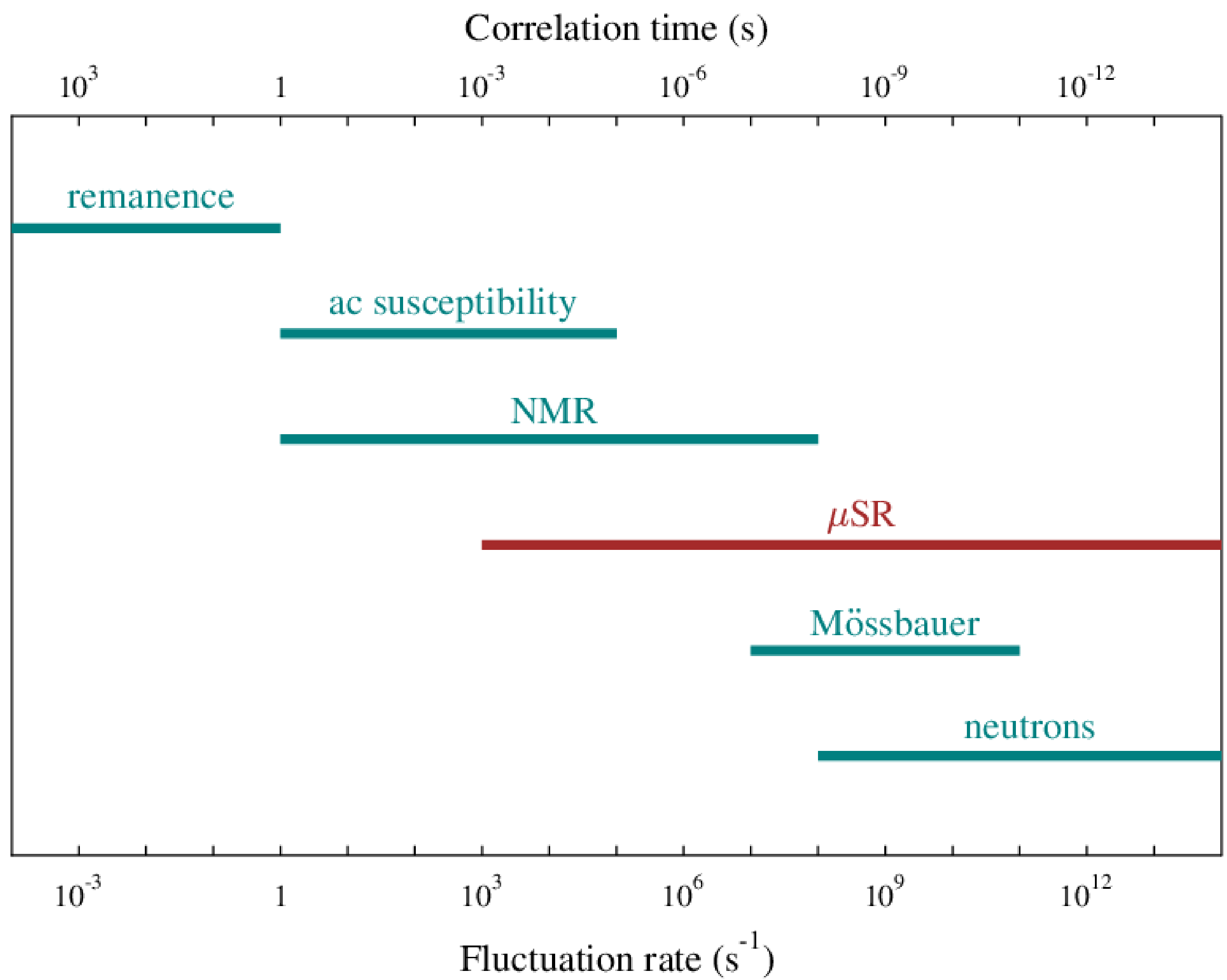
Sensitivity to dynamics:

Depends on the strength of the magnetic coupling A and the characteristics of the muon source



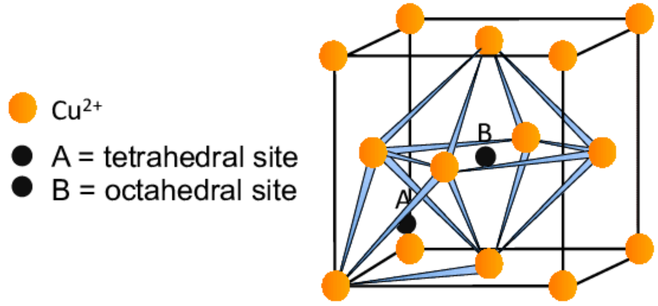
Condensed Matter Physics Perspective

μSR dynamics compared with other techniques:



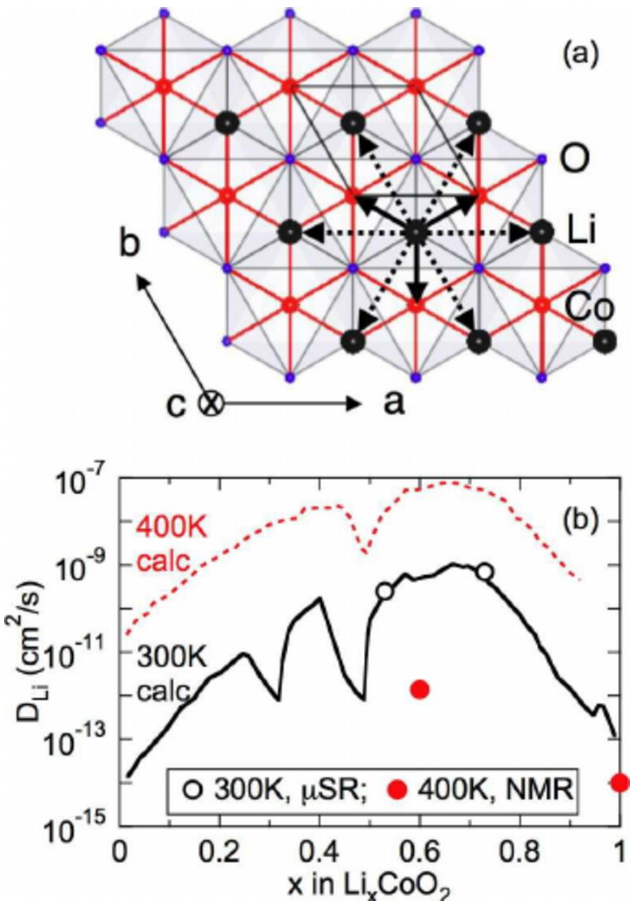
Condensed Matter Physics Perspective

Dynamics from ionic motion:



Muon motion as an analogue of hydrogen motion, e.g. in Cu

Motion of other ions can be studied if the muon is relatively immobile, e.g. Li in battery materials



J. Sugiyama et al, Phys. Rev. Lett. 103, 147601 (2009)

Condensed Matter Physics Perspective

Benefits of μSR versus bulk magnetic studies:

Volume-averaged Probe:

immune to low concentration impurity phases

phase segregated samples can easy be identified

Good Sensitivity to antiferromagnetism

Measurements possible in zero applied field

Condensed Matter Physics Perspective

<u>Other Key Features of μSR</u>

High sensitivity: very small moments can be detected, 0.01 μ_B or less
e.g. when searching for breaking of time-reversal symmetry in superconductors

No need to apply an external magnetic field

No need to align a sample array when making ZF studies

Excellent compatibility with very low temperatures, since both incoming muon and outgoing positrons easily penetrate the walls and windows of cryostats

Magnetic Resonance Perspective

	Spin	Mass	Magnetic moment	Charge	Lifetime	Character	Magnetic resonance technique
e	½	m_e	657 μ_p	-e	∞	electron	ESR
μ	**½**	**207 m_e**	**3.18 μ_p**	**+e**	**2.2 μs**	**'light proton'**	**μ^+ SR**
p	½	1836 m_e	μ_p	+e	∞	proton	NMR

μ^+SR as a more sensitive version of ^{1}H-NMR

Magnetic Resonance Perspective

Advantages of μSR over NMR

100% spin polarisation for the muon compared to very weak polarisation for NMR nuclei

The muon has a larger gyromagnetic ratio than any nucleus

No need for specific nuclear isotopes, muons can be implanted in anything

Full field range available for measurements from ZF up to 10 T

Easy sample set-up and measurement (if you have access to a muon source)

Compatible with low temperature sample environments (e.g. helium dilution refrigerators)

Potential access to a very wide range of correlation times

Magnetic Resonance Perspective

<u>Disadvantages of μSR compared to NMR</u>

The muon lifetime limits the potential for spin manipulation by RF methods

The muon stopping sites need to be determined to fully interpret the data

There will be some perturbation of the system under study by the presence of the muon

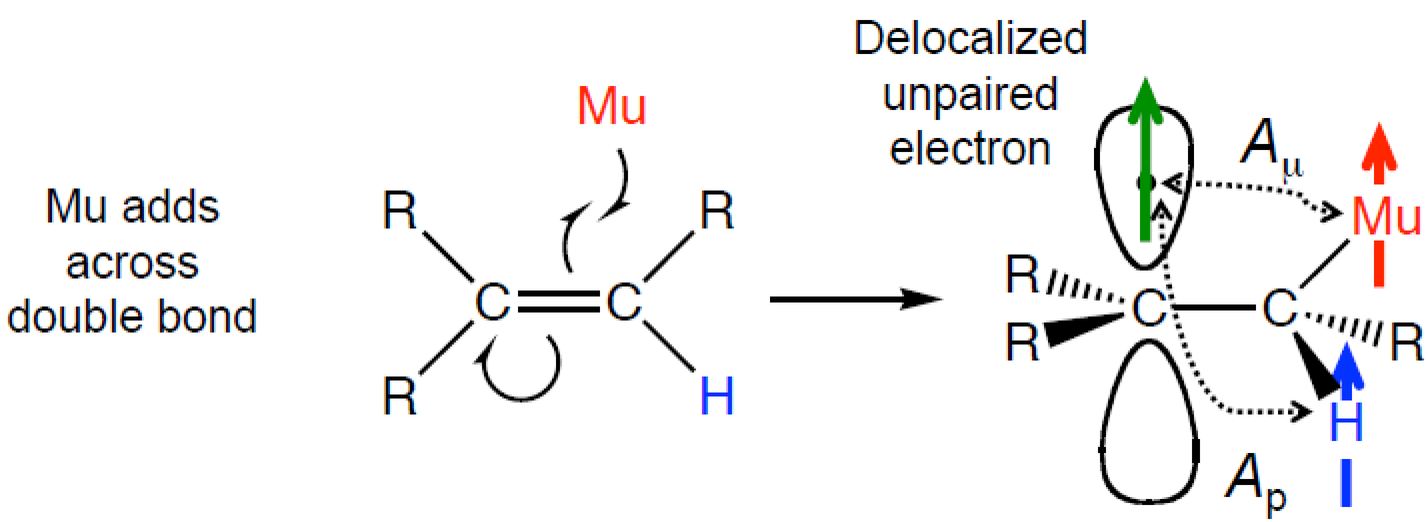
Larger sample mass is needed

Chemistry Perspective

The H atom is the simplest free radical and is highly reactive

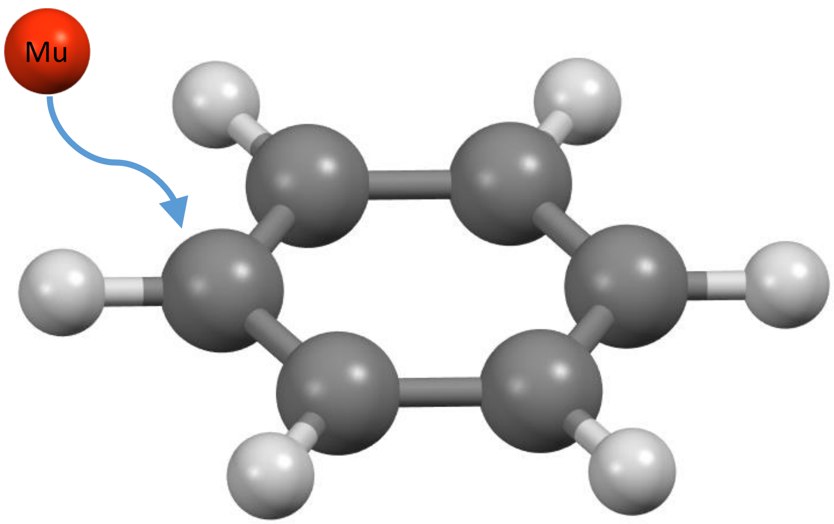
In chemical terms muonium provides a radioactively labelled light isotope of H

Studying Mu allows the time dependence of its chemical reactions to be studied

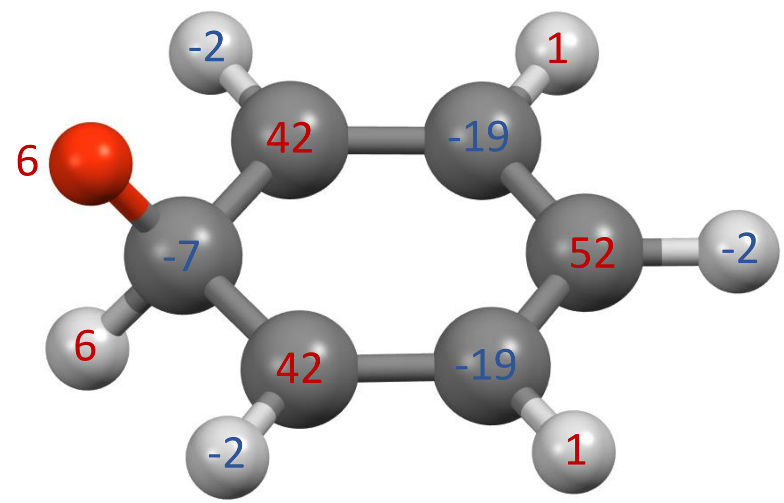


Chemistry Perspective

Addition of Mu to a benzene molecule to form a radical:



Distribution of spin density (%)

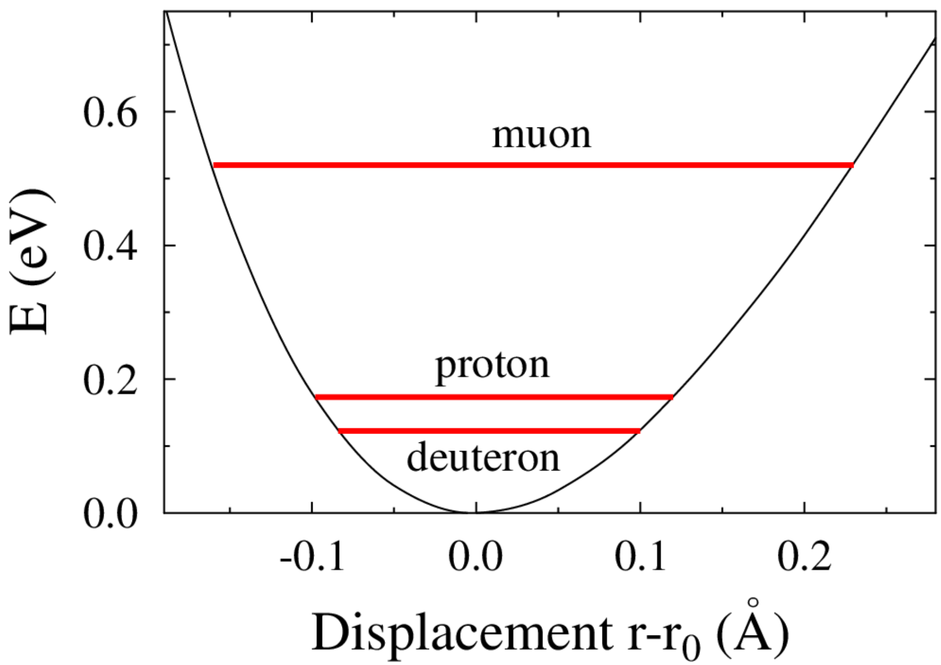


Chemistry Perspective

The isotopic sequence D, H can be extended to D, H, Mu

The low mass of Mu leads to large quantum zero point energy so that Mu probes upper reaches of the interatomic potential energy surface (PES) and can test reaction theory

Vibrational excitation (e.g. with a laser) takes the muon even higher up the PES (3 × higher)

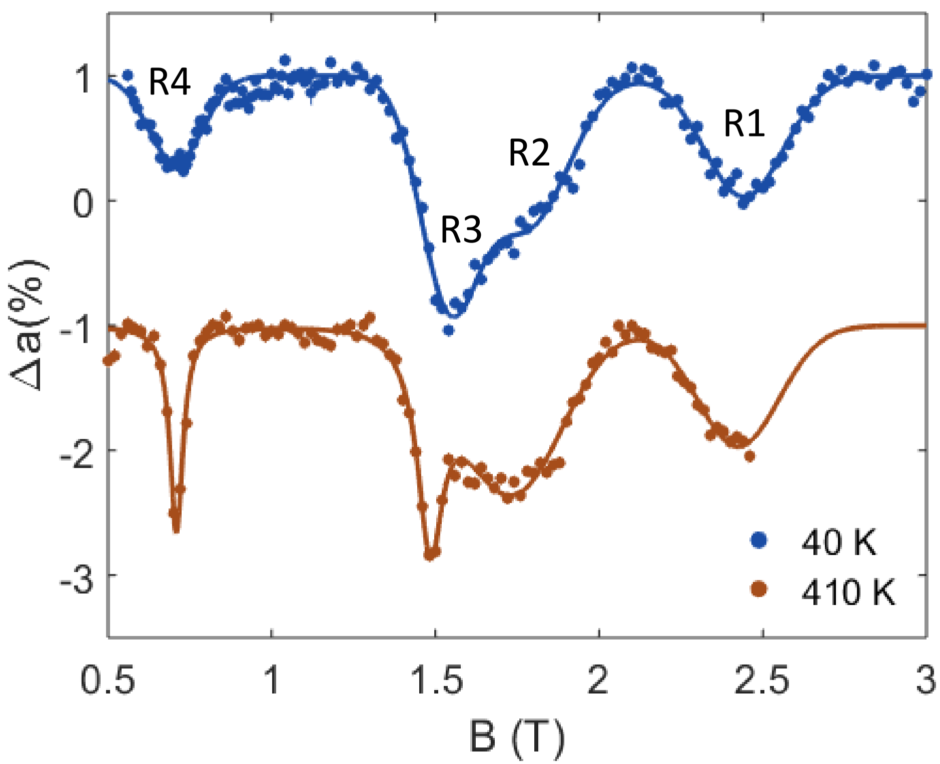


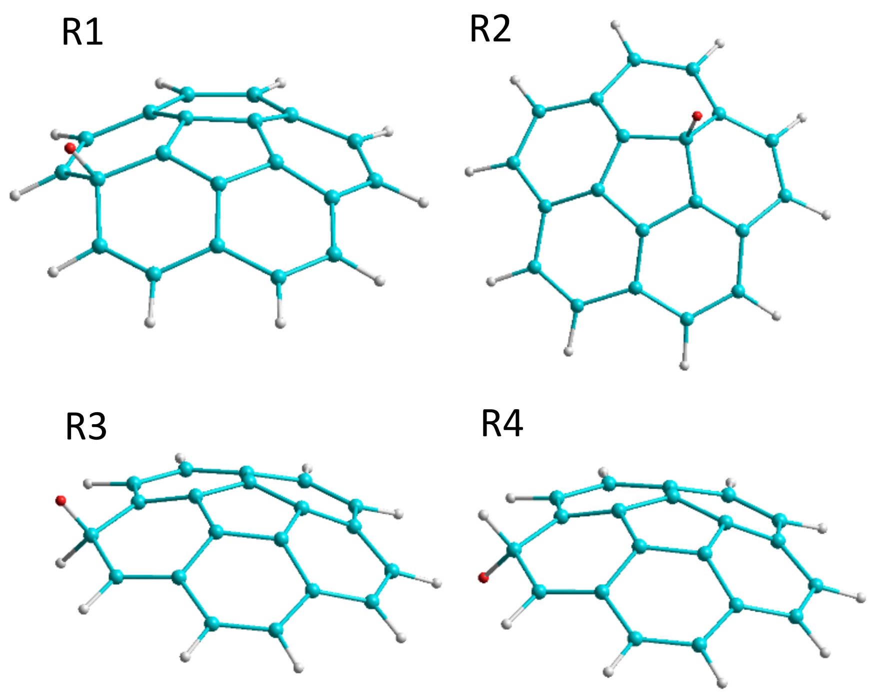
Chemistry Perspective

Spectroscopic study of muoniated radicals gives information about the molecular spin distribution, molecular environment and molecular dynamics

The main spectroscopic technique is called Avoided Level Crossing (ALC)

ALC spectrum for Corannulene

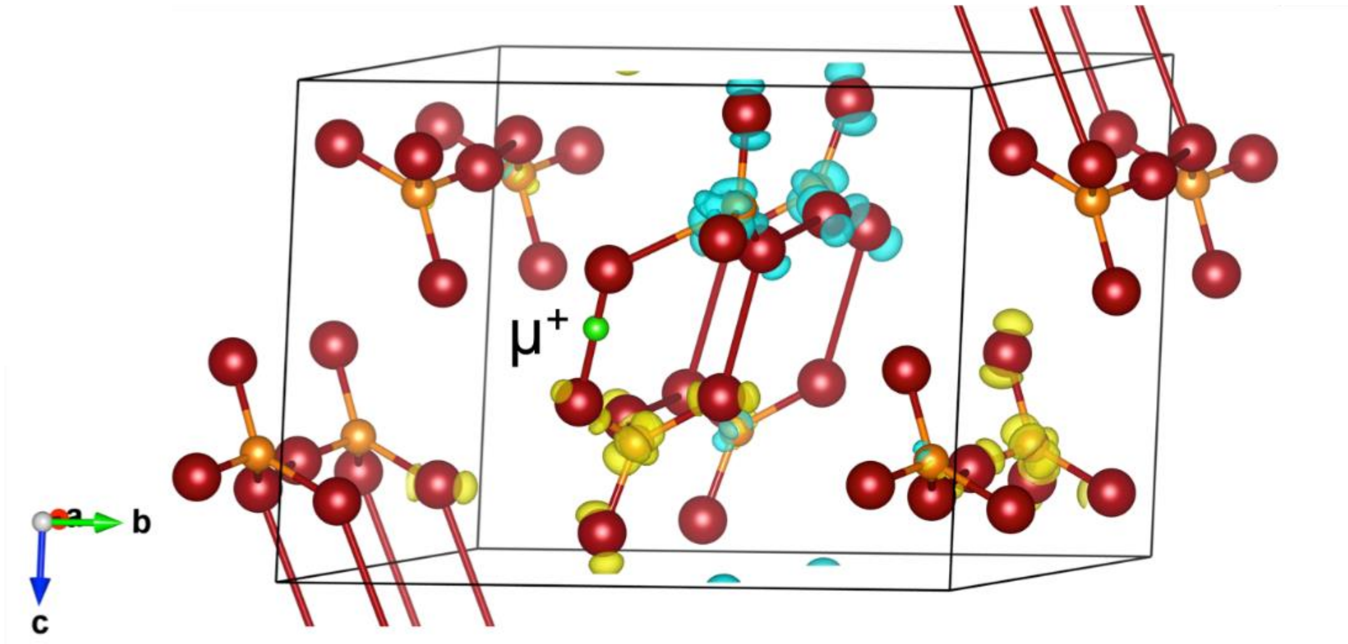




M. Gaboardi et al, Carbon (2019)

Computational Science Perspective

The implanted muon problem is a variation on the hydrogen interstitial defect problem



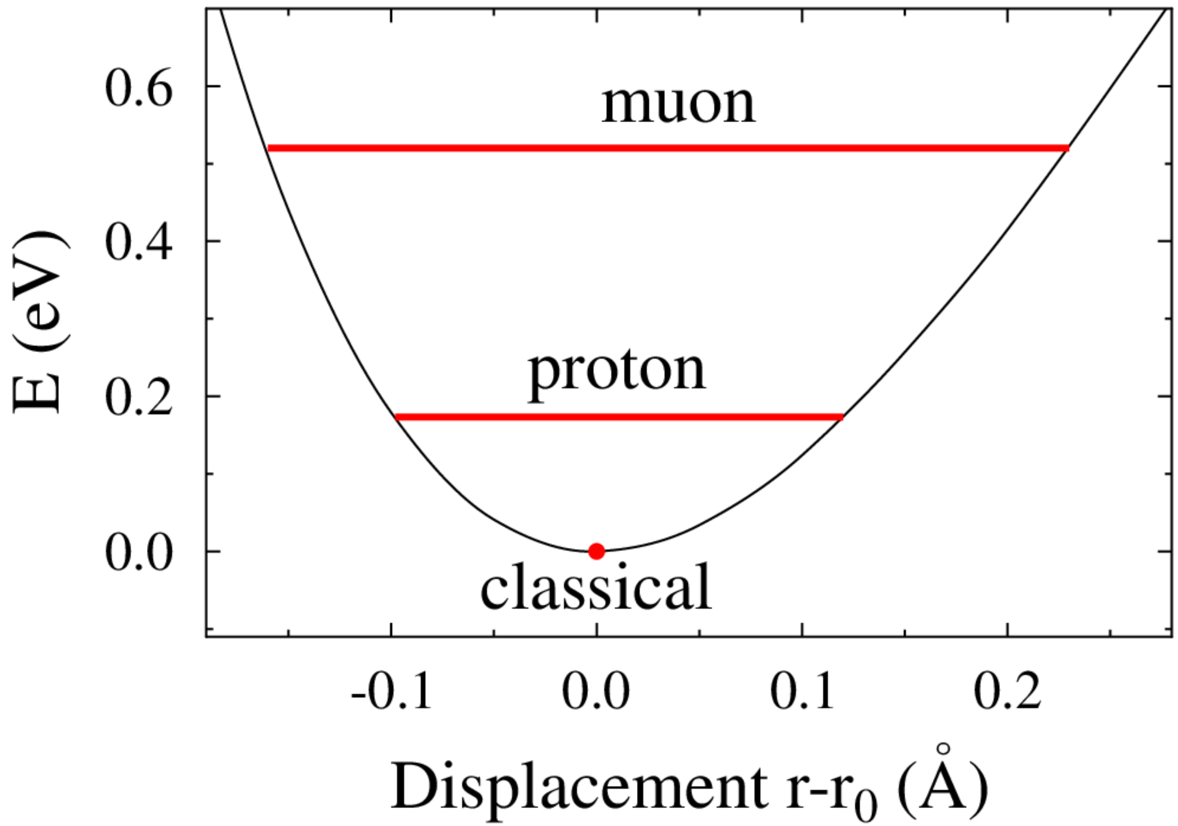
T. Lancaster et al, New J. Phys. 20, 103002 (2018)

Computational methods such as Density Functional Theory (DFT) can be used to calculate the structure of the interstitial muon defect including the surrounding atomic relaxation

Computational Science Perspective

Extra challenge from the strong quantum character of the muon

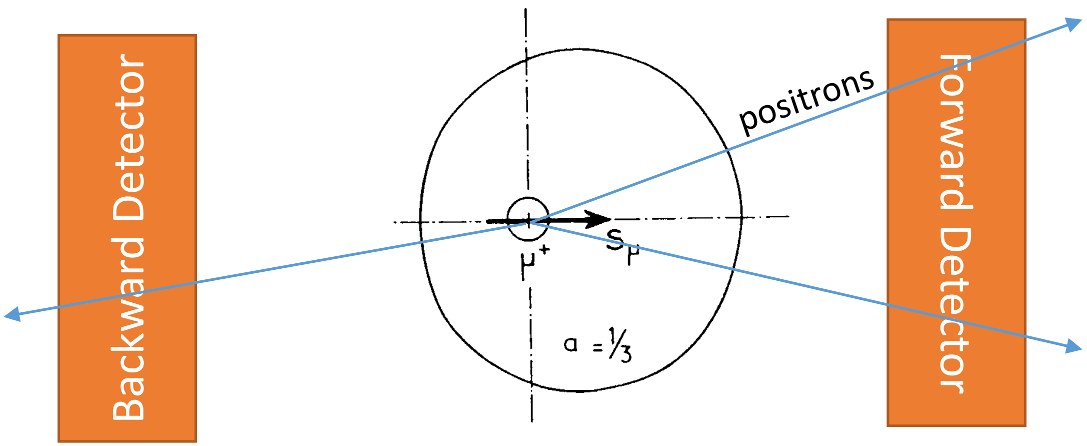
Standard computational methods such as DFT give the classical site



μSR Experiment Perspective

<u>Muon Spectrometer</u>

A muon spectrometer has an array of positron detectors placed around the sample to detect the asymmetry



$W(\theta) = 1 + a \cos \theta$

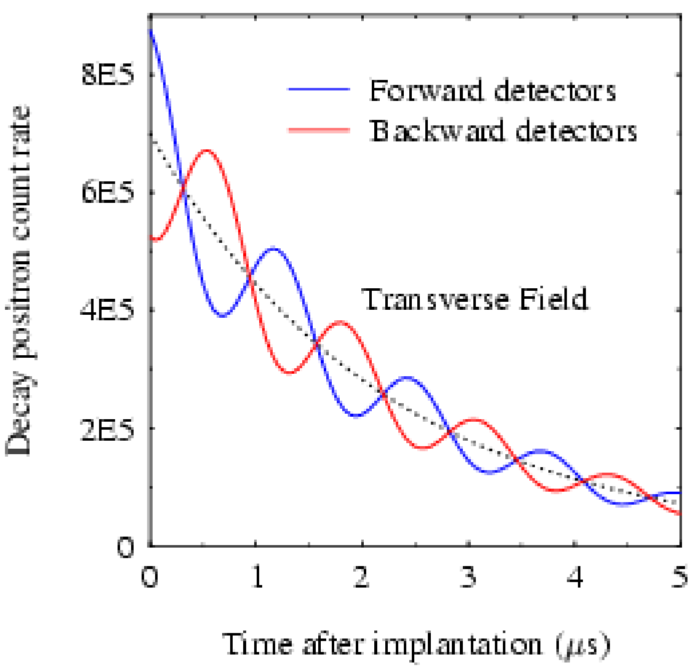
The signal for detector *d* in a transverse magnetic field takes the form:

$$N^d(t) = N_0^d \exp(-t/\tau_\mu) \, [1 + a_0 \, P_x^d(t)]$$

where a_0 is the initial asymmetry and $P_x^d(t)$ is the oscillatory polarisation function

$$P_x^d(t) = \cos(\phi_d + \gamma_\mu B_{TF} t) \, G_x(t)$$

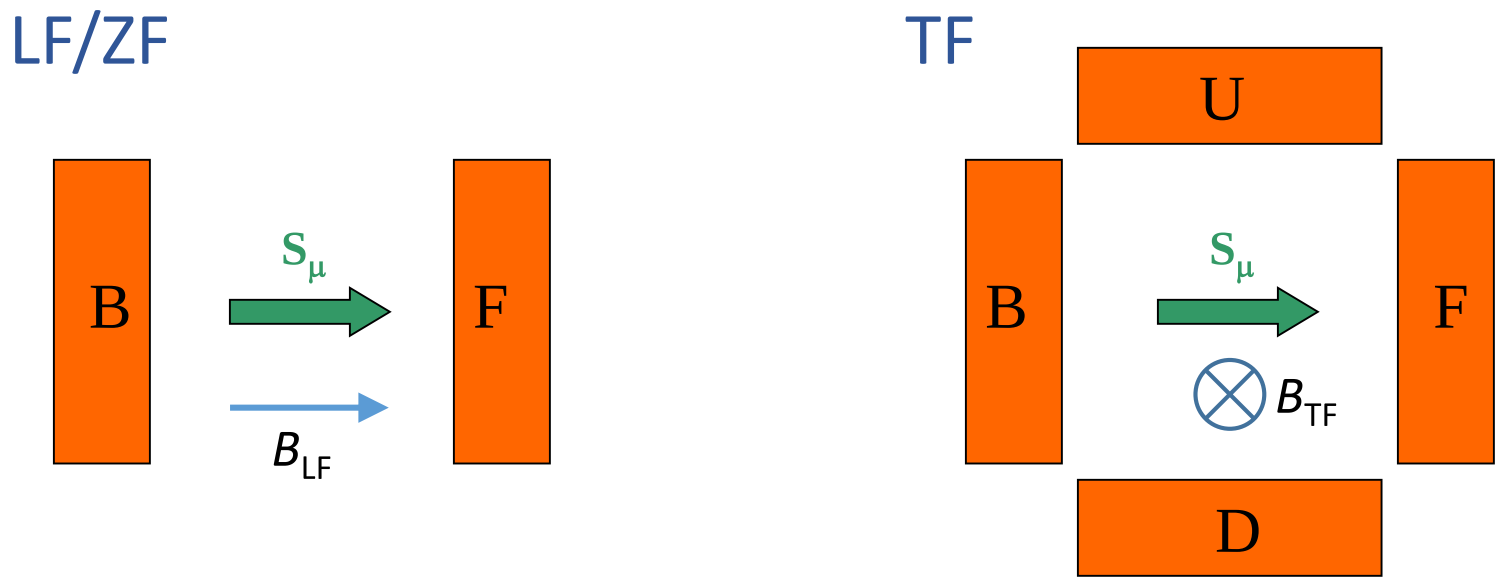
where ϕ_d is the detector phase and $G_x(t)$ is the transverse relaxation function



μSR Experiment Perspective

<u>The Muon Instrument</u>

Configuration of detectors and magnetic fields



Note that F and B detectors are defined logically in terms of the initial spin direction

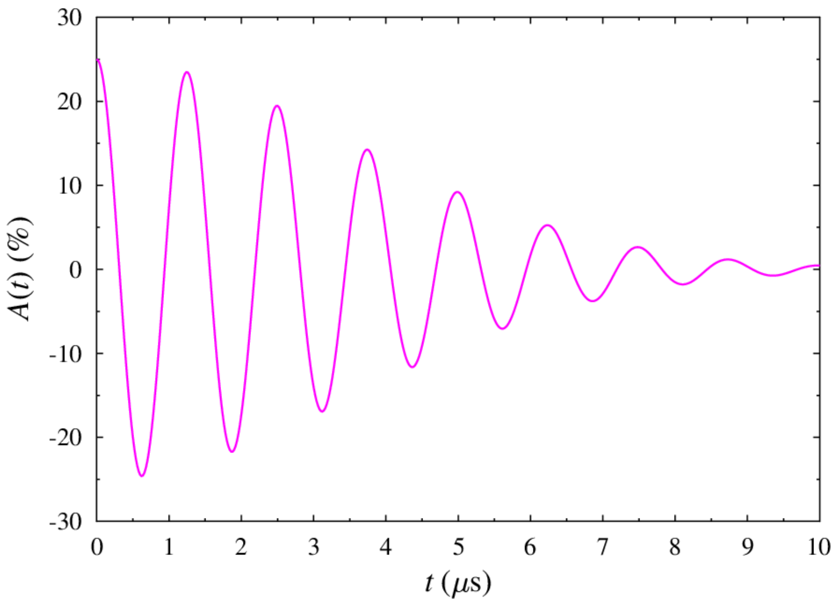
Instruments often define their detector names in terms of the physical beam geometry

μSR Experiment Perspective

It is convenient to normalise out the muon decay by working with antiphase detector pairs

$$A(t) = a_0 P_{FB}(t) = [N_F(t) - \alpha N_B(t)] / [N_F(t) + \alpha N_B(t)]$$

here α is a calibration factor to correct for any imbalance in the *F* and *B* detectors



TF Mode

$$A(t)/a_0 = G_x(t) \cos(\gamma_\mu B_{TF} t)$$

$G_x(t)$ is the transverse relaxation function

ZF/LF Mode

$$A(t)/a_0 = G_z(t)$$

$G_z(t)$ is the longitudinal relaxation function

Muon spectroscopy involves measuring $A(t)$ and analysing it in terms of $G_x(t)$ and $G_z(t)$

Summary

- Muons and particle physics: a rich history and continued current relevance
- Muons can easily be implanted into materials to provide a local spin probe
- Extremely wide range of application for muon spectroscopy
- Many advantages of muons over other experimental techniques
- Relatively easy to obtain μSR data on samples of interest, but…
- Data analysis and interpretation often needs a range of knowledge and skills
- Hence this School, whose purpose is to help with this process…

And finally…

Back to Isidor Rabi for some last words

Did you ask a good question today?

(Isidor Rabi's mother)