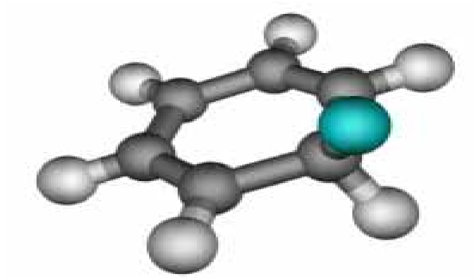
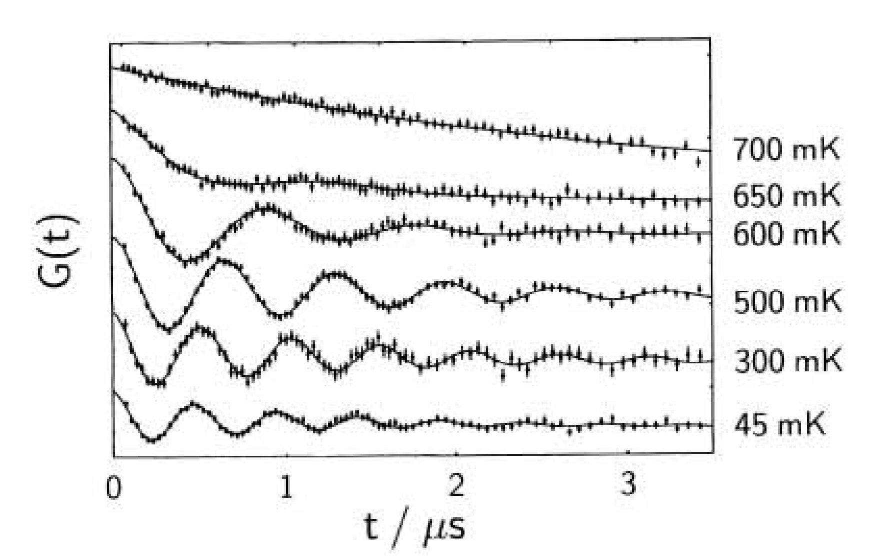
Introduction to μSR
(Steve Cox)

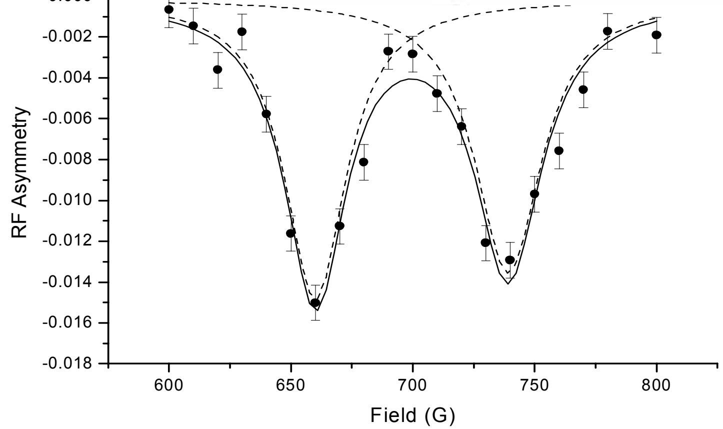
What? How? Why? Where?

μSR: Muon Spin Rotation, Relaxation, Resonance



(c.f. ESR: Electron Spin Resonance)

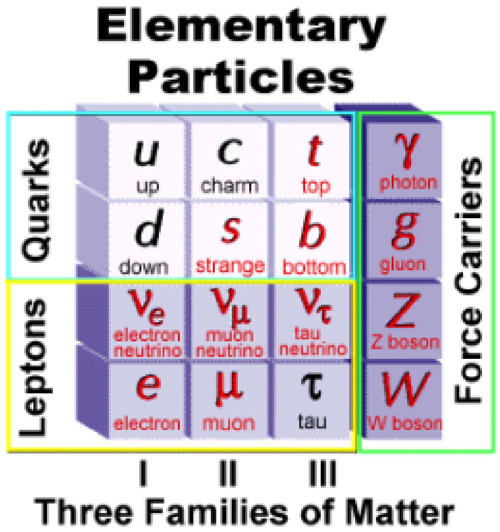


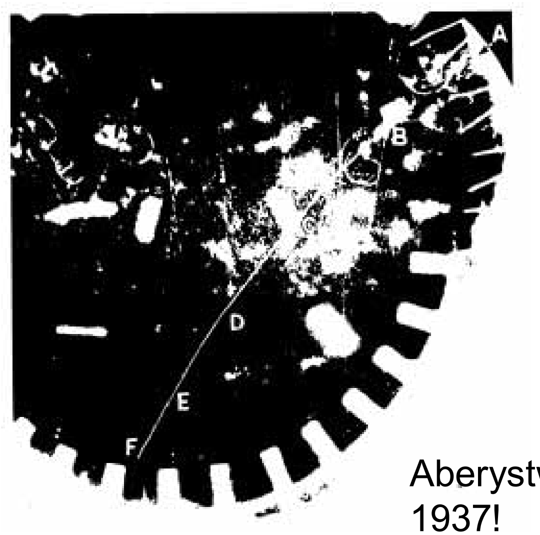


What is a muon?

1. Particle physicists' view:

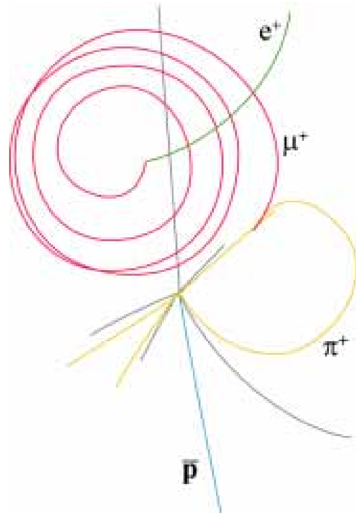
- elementary particle/antiparticle
  - a heavy positron/electron
- names a family in the Standard Model
- unstable particle
  - $\tau_{\mu} = 2.2\mu s$
  - famous for parity violation



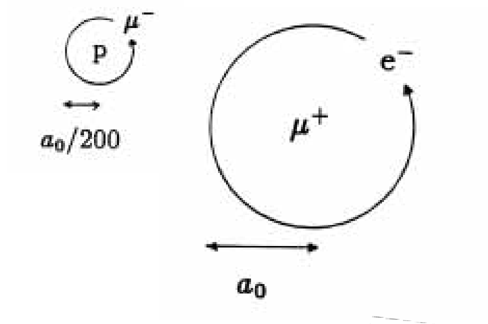


Aberystwith 1937!

CERN picture library



2. Atomic physicistsí view:



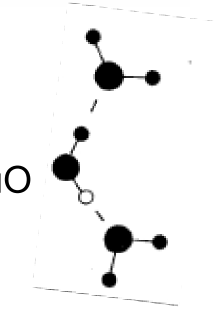
· Negative muons = heavy electrons – $m_\mu = 200 m_e$
  – substitute for orbital electrons in ìexotic atomsî
  – shields nuclear charge and promotes d-t fusion

· Positive muons form ***muonium***, Mu = $[\mu^+ e^-]$
  – the all-leptonic atom with ìpoint chargeî nucleus
  – testing ground for QED

3. Chemists' view:

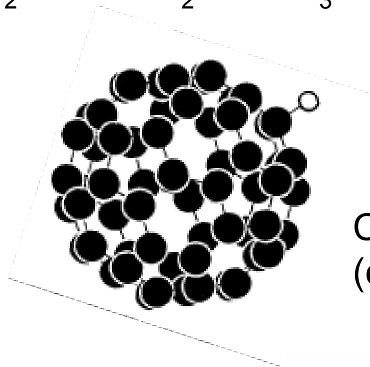
$\mu^+ \rightarrow Mu^+$ e.g. $\mu^+ + H_20 \rightarrow H_2OMu^+$

$H_2OMu^+ + H_2O \rightarrow H_3O^+ + HMuO$



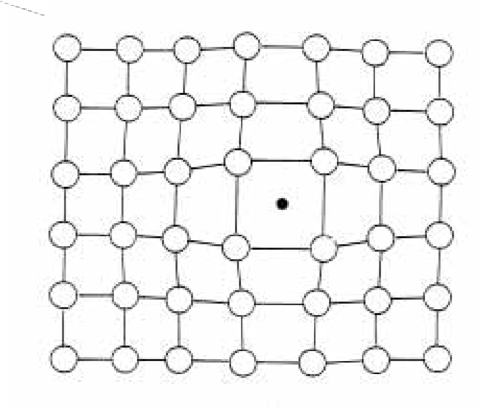
· A lightweight proton – $m_\mu = (1/9) m_p$
  – localisation vs propagation

· Muonium as a light isotope of hydrogen
  – kinetic and dynamic isotope effects



$C_{60}Mu$
(contrast $Mu@C_{60}$!)

4. Solid state physicists' view:



· A spin-Ω probe – sensitive to internal magnetic fields
· A fundamental point defect or ìtest chargeî
· The prototype light interstitial

Why use muons?

Use their spin (magnetic moment) as a magnetic probe

- Sensitive and accurate magnetometer
- Measures internal field and their variations
  (distribution in space, fluctuation in time)
- Applications in superconductivity, magnetism, conducting polymers...

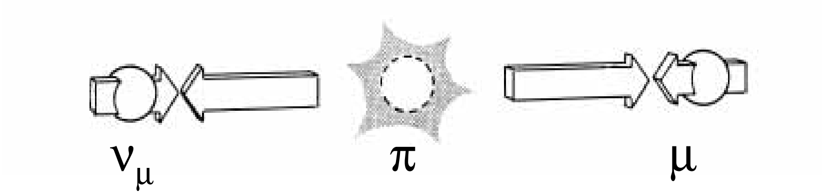
Exploit the analogy with protons

- Diffusion in metals
- A model for hydrogen in semiconductors and dielectrics
- Muonium chemistry – isotope effects
- A spin label for organic radicals – molecular dynamics

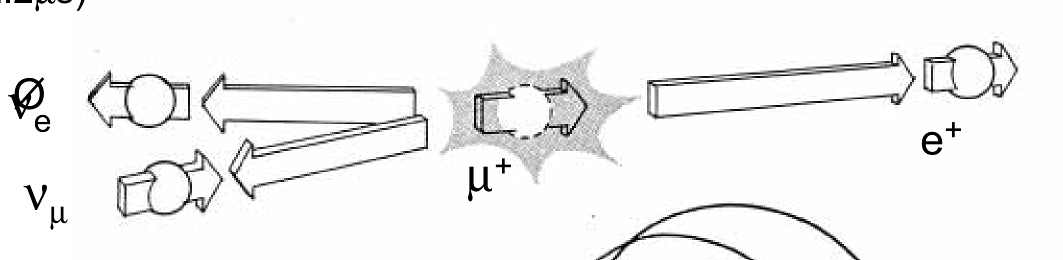
Exploit the timescale...

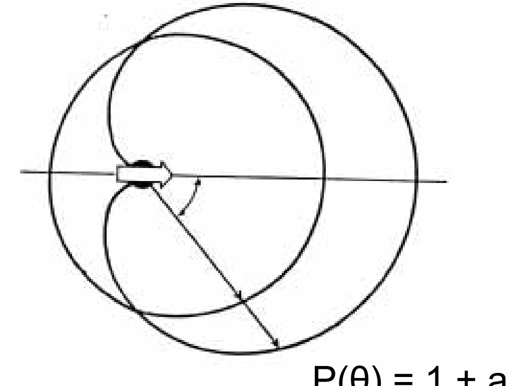
What use is a probe that lasts 2 microseconds?

Pion decay produces polarized muons:
$\pi \rightarrow \mu$ (26ns)



Asymmetry in muon decay
$\mu^+ \rightarrow e^+$ (2.2μs)

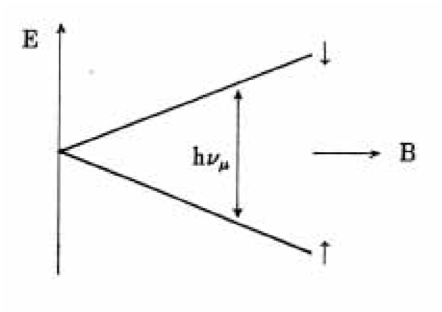


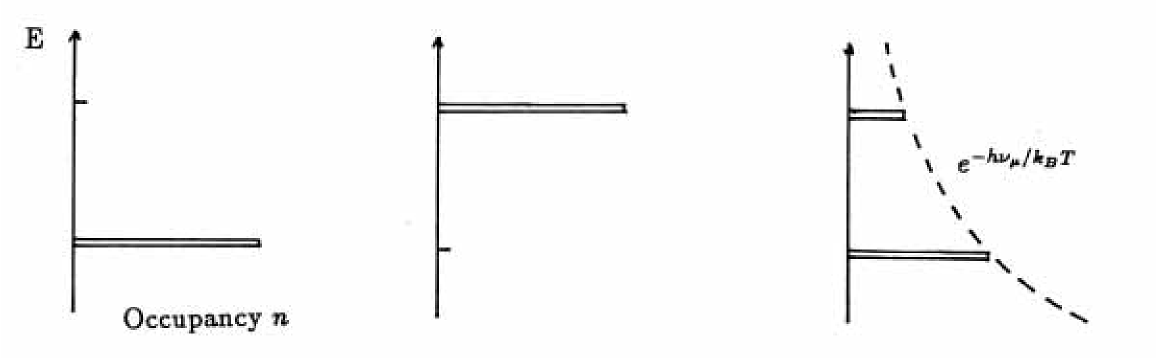


$P(\theta) = 1 + a.\cos\theta$

Timescale for dynamical studies...

Basics

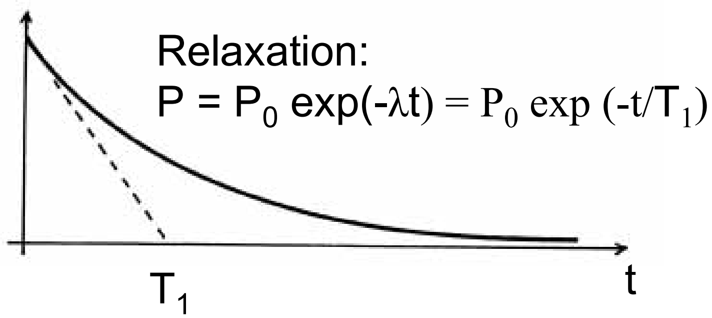




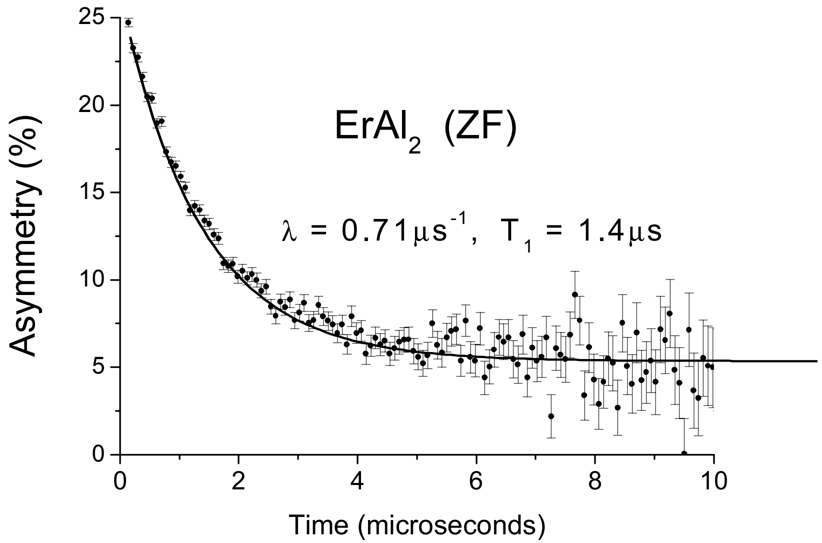
Spin states (up, down)
Zeeman energy
Larmor freq (13.6kHz/G)
Gyromagnetic ratio ($\omega = \gamma B$)

Populations (a) initial (b) Final (Boltzmann)

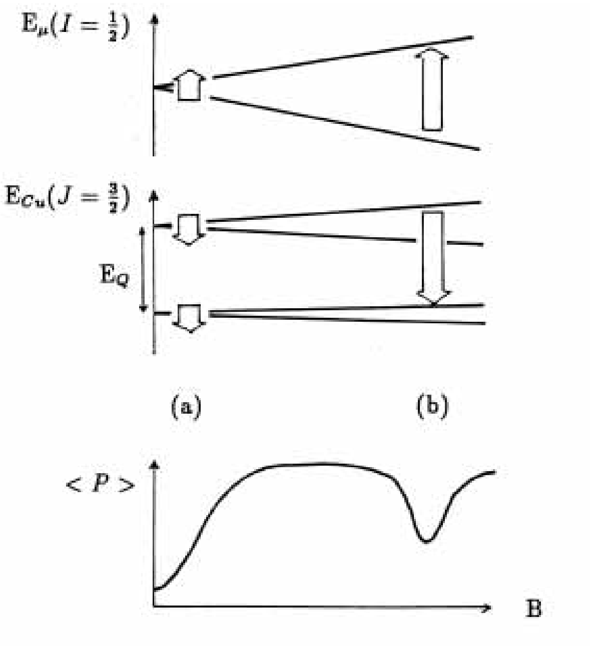
Polarization: $P = (n_\uparrow - n_\downarrow) / (n_\uparrow + n_\downarrow)$



(spin-lattice relaxation time)

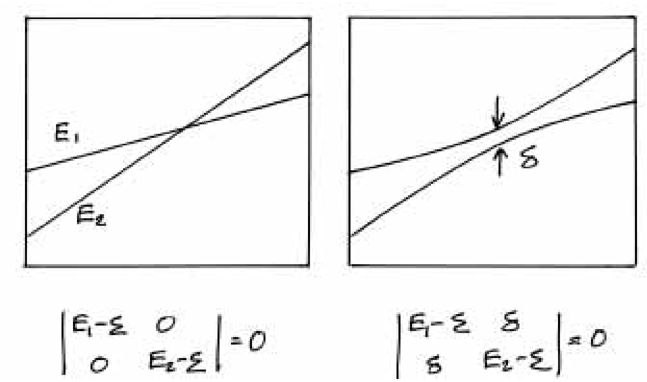


Spin-spin or cross relaxation

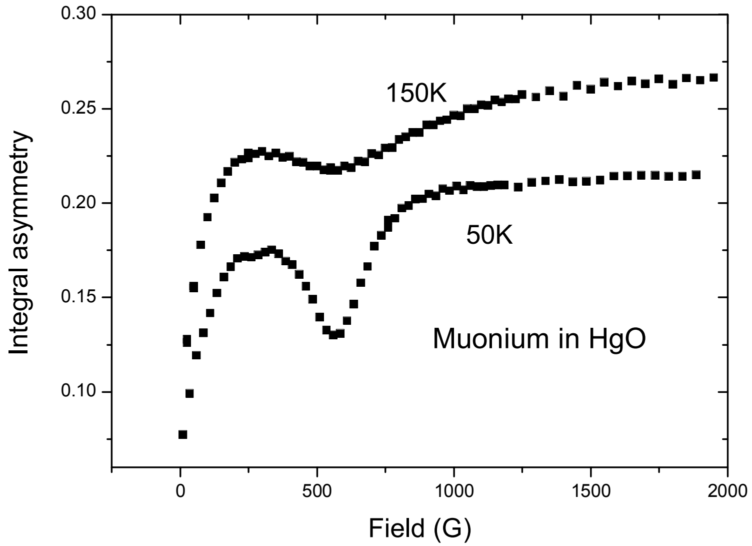


Non-resonant   Resonant

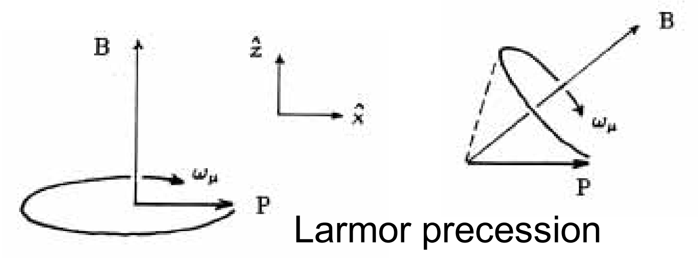
Level crossing resonance



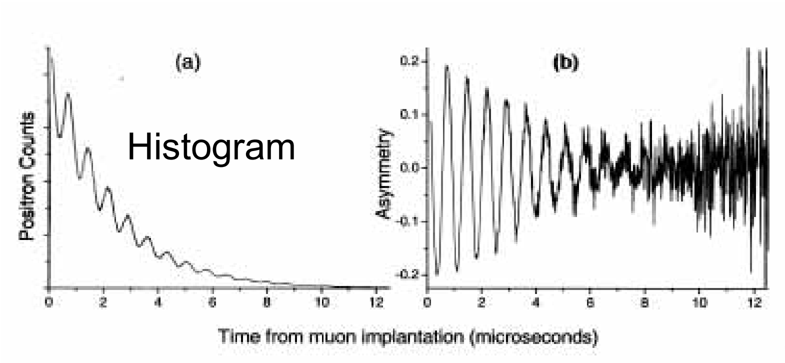
'avoided crossing'

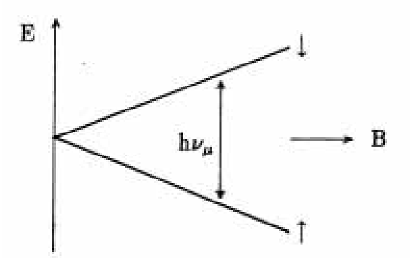


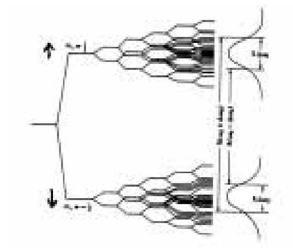
Transverse fields: muon spin rotation



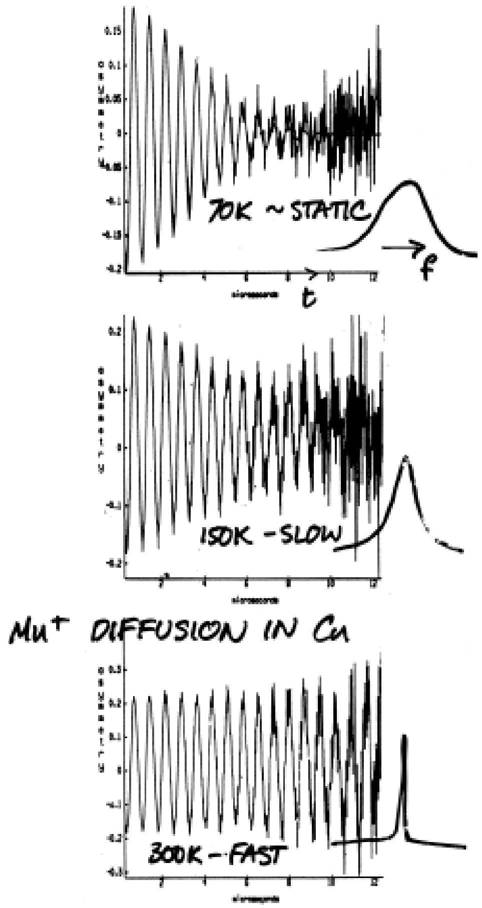
Larmor precession







Local fields: broadening



Motional narrowing

Where?