Muon Spin Spectroscopy

Using the Positive Muon to Probe Matter

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Muon and Muonium Properties

Negative muon μ^-	a heavy electron (mass = 207 m_e)
	τ = 2.2 μs in vacuum …
	… less in matter because of nuclear capture
	spin $I = \frac{1}{2}$
Positive muon μ^+	a light proton (mass = 0.11 m_p)
	τ = 2.2 μs in vacuum *and* matter
	spin $I = \frac{1}{2}$

Muonium $Mu = \mu^+e^-$	a light hydrogen atom	$Mu^+ = \mu^+$
	Ionization Energy = 13.54 eV	H: 13.60 eV
	Bohr Radius = 0.532 Å	H: 0.529 Å

The Periodic Table — Chemistry Department Quilt

http://www.sfu.ca/chemistry/news/pt_quilt/index.htm

The Simplest Atom

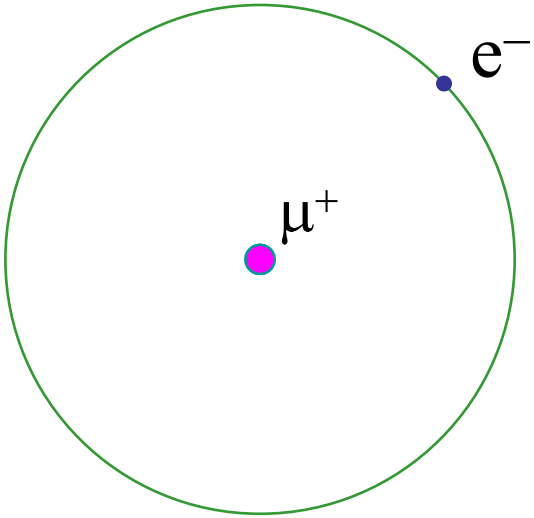
Muonium — a light isotope of hydrogen

$$\text{Mu} \equiv \mu^+ e^-$$

The properties of a single electron atom are determined by the reduced mass

$$\frac{1}{m_r} = \frac{1}{m_N} + \frac{1}{m_e} \approx \frac{1}{m_e}$$

i.e. $m_r \approx m_e$



reduced mass of Mu = 0.995 m_r(H)

ionization potential = 13.539 eV

Bohr radius = 0.532 Å

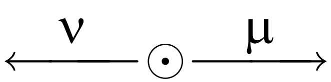
Pions Decay to Give Muons

At TRIUMF, pions are produced by bombardment of a Be or C production target with 500 MeV protons. We take the positive pions, which decay to positive muons:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

τ = 26 ns

In the pion rest frame:



Momentum is conserved: $\overrightarrow{p_\mu} = -\overrightarrow{p_\nu}$

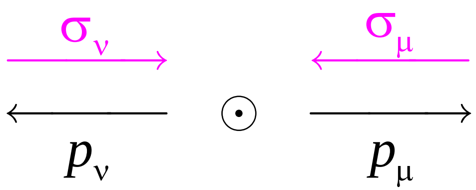
Spin is conserved: $\overrightarrow{\sigma_\mu} = -\overrightarrow{\sigma_\nu}$

Spin and momentum are related through helicity:

$$\hat{h} = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma}.\vec{p}|} \qquad \hat{h}\psi = \pm 1\psi$$

For the neutrino, *h* = -1, i.e. the spin and momentum are anti-parallel.

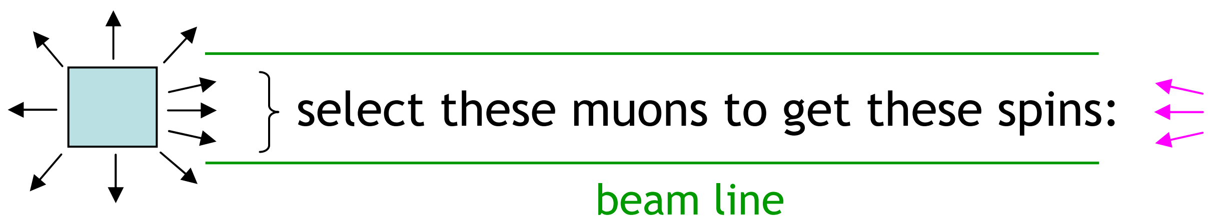
Therefore, muons are produced with σ and *p* anti-parallel.



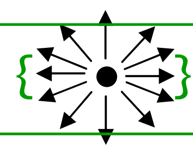
Muon Beams are Spin Polarized

There are two commonly used types of muon beam:

Surface Muon Beams collect and transport muons which are created from the decay of pions at or near the surface of the pion production target.



Decay Muon Beams collect muons from pions which decay in flight.

In the π rest frame only backward  and forward muons are transported.

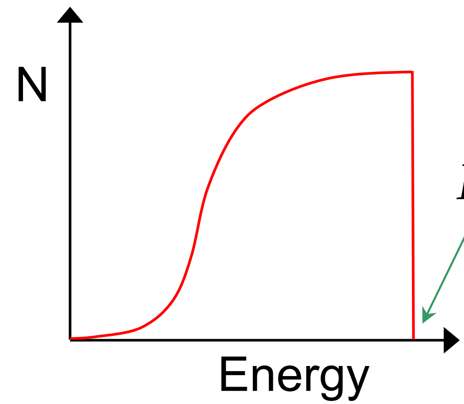
In the laboratory frame, both momentum bites travel in the forward direction.

The forward (momentum) muons (p~180 MeV/c) have backward spin;
the backward muons (p~80 MeV/c) have forward spin.

Muon Decay

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad \tau = 2.2\ \mu s$$

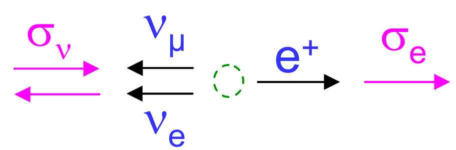
The 3 particle decay results in a spectrum of positron energies.



$$E_{max} = \tfrac{1}{2} m_\mu = 52.8\ \text{MeV}$$

The spatial distribution of positrons is asymmetric and depends on the muon spin polarization.

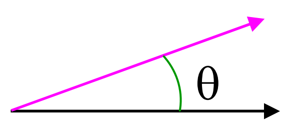
Consider the decay pattern which results in the maximum positron energy:



The e⁺ is emitted in the direction of the muon spin at the moment of decay.

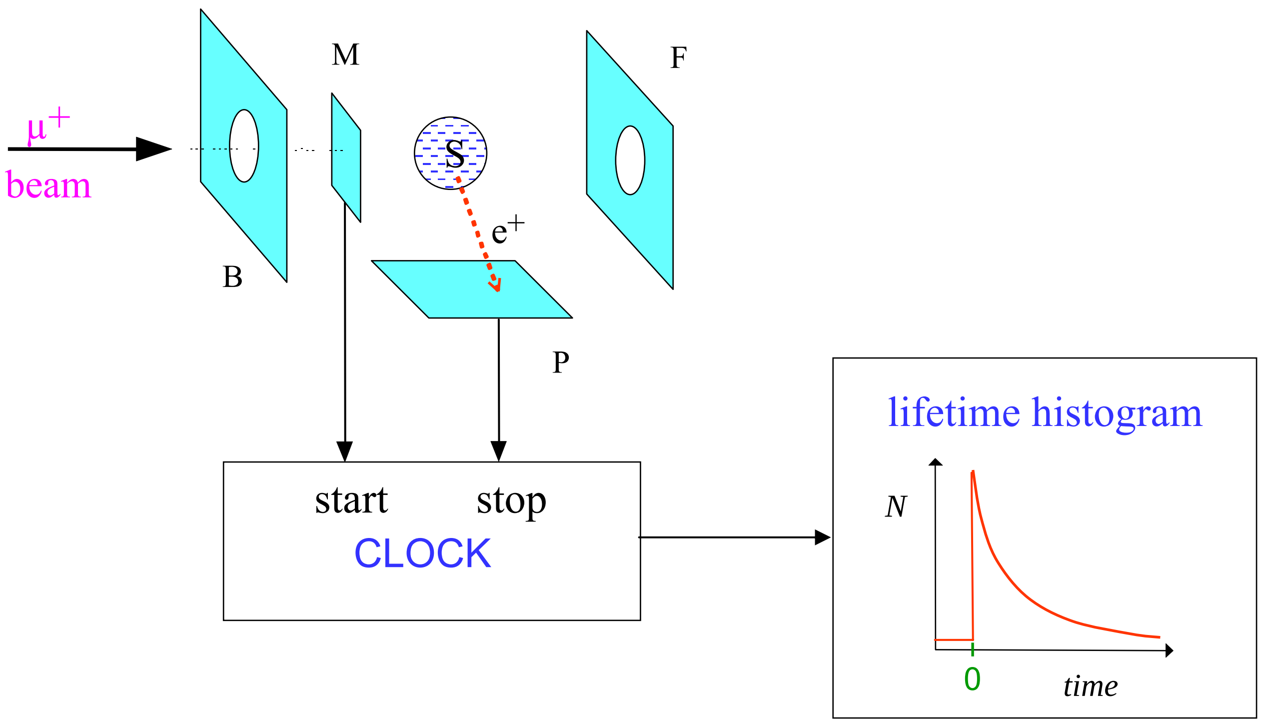
More generally,

$$\frac{dN(E,\theta)}{dE\, d\Omega} = C\left[1 + D(E)\cos\theta\right]$$



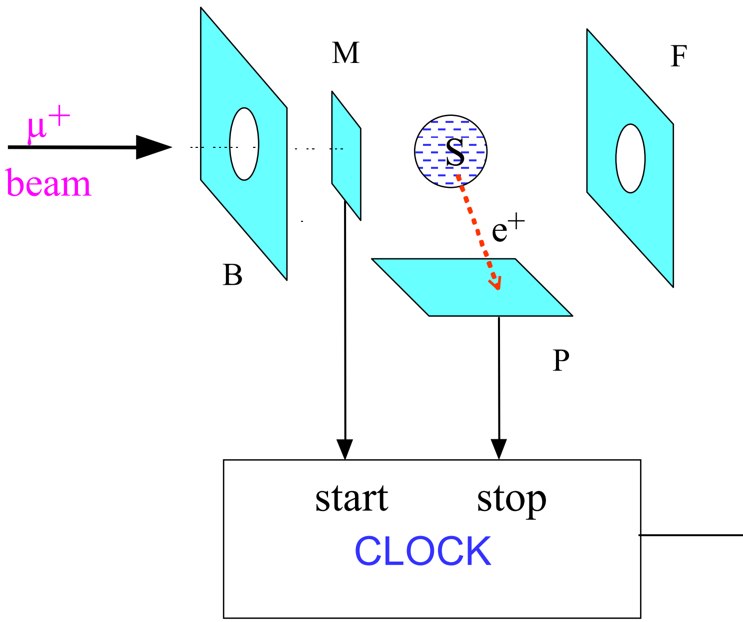
The Muon Lifetime Experiment

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad \tau = 2.2\ \mu s$$

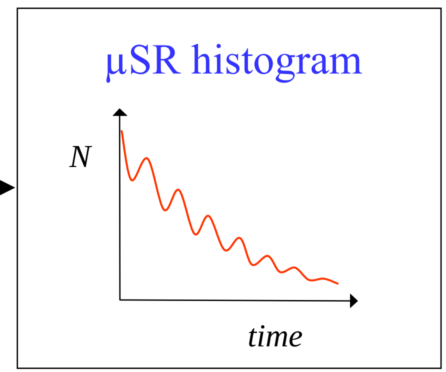


$$N = N_0\, e^{-t/\tau} + \text{background}$$

Muon Spin Rotation, μSR

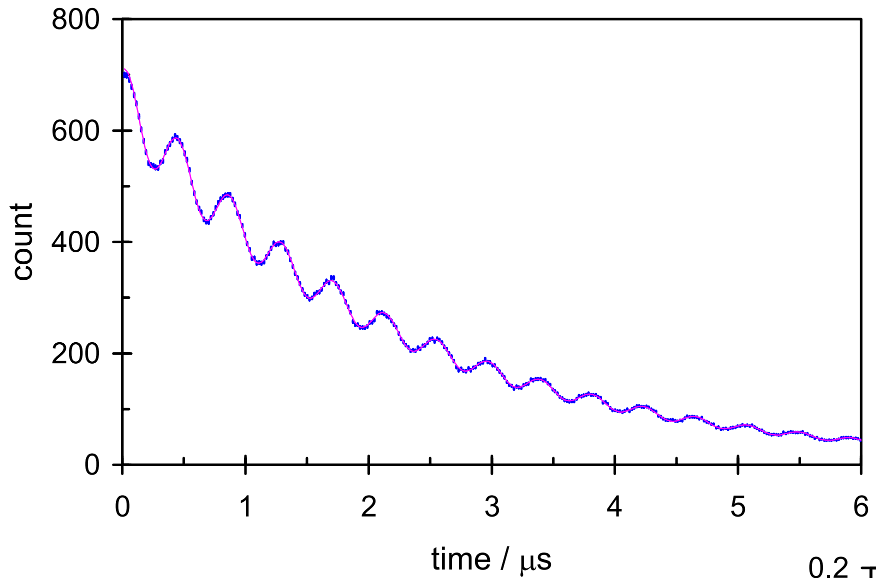


Apply a magnetic field perpendicular to the initial spin direction.



$$N = N_0\, e^{-t/\tau}\left[1 + aP(t)\cos(\omega t + \phi)\right] + \text{background}$$

The μSR Histogram

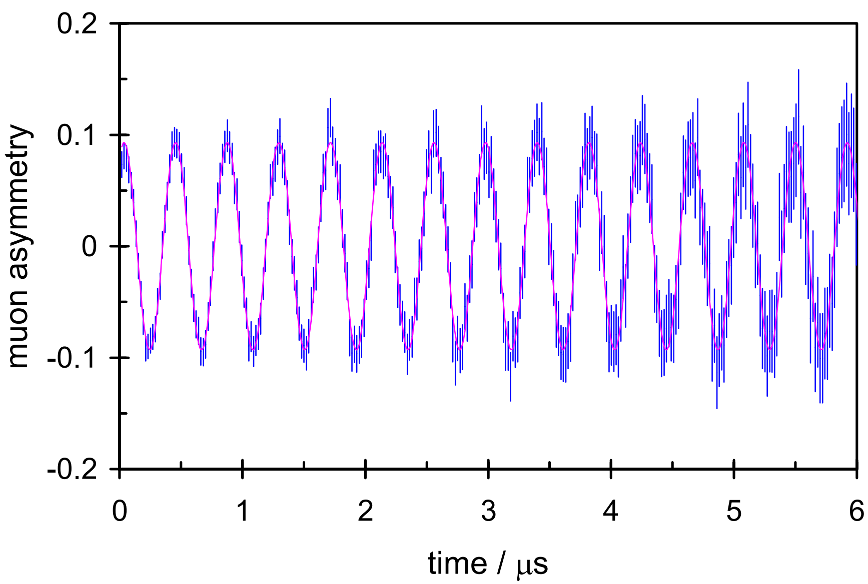


$$N_0 e^{-t/\tau}\left[1 + aP(t)\cos(\omega t + \phi)\right] + B$$

Subtract the constant background and divide out the exponential decay …

… to get the muon asymmetry, which represents the time dependence of the muon spin polarization.

$$aP(t)\cos(\omega t + \phi)$$

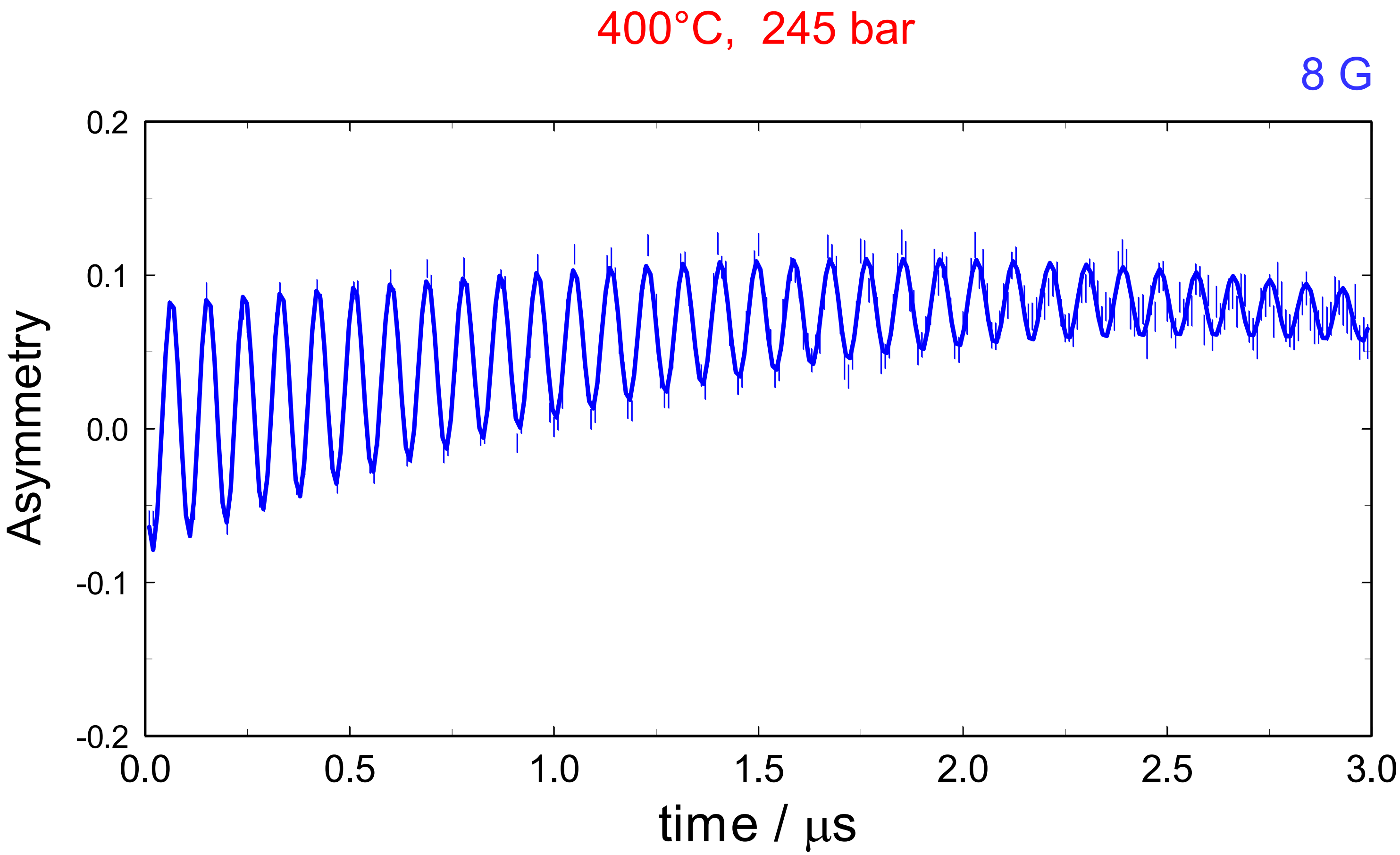


μSR: Muon Spectroscopy

Muon Spin Rotation

- spin polarized muon beam
- muons are implanted in the sample
- muons decay: $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$ $\tau = 2.2\ \mu s$
- angular distribution of e^+ has maximum in muon spin direction
- precession of muon spins in transverse magnetic field
- equivalent to free induction decay in pulsed NMR or ESR

Muonium in supercritical water

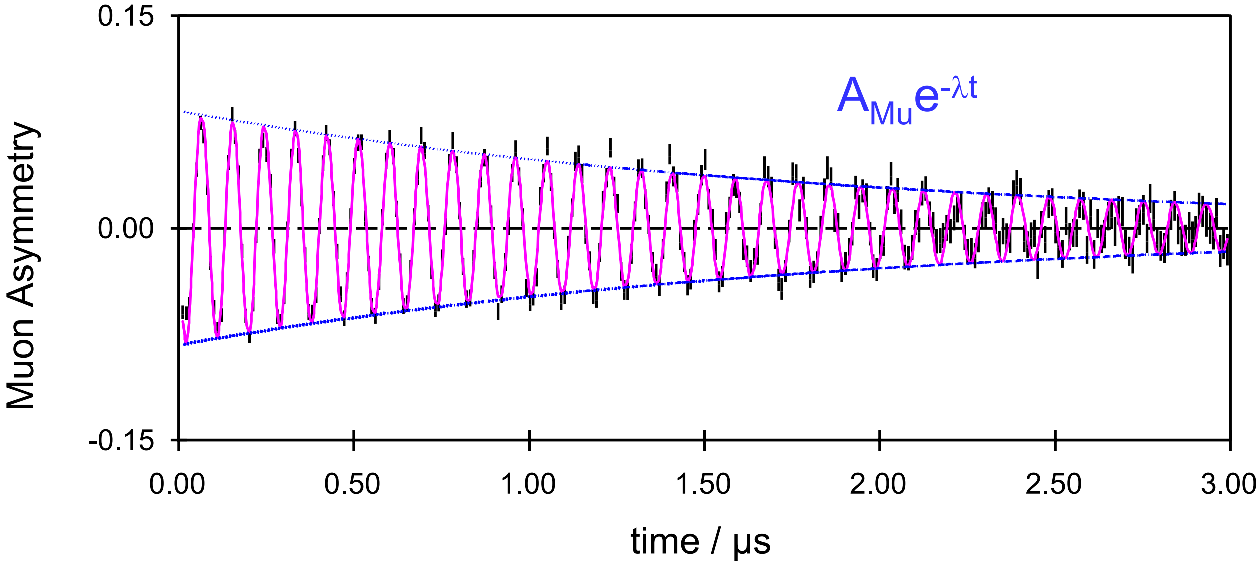


Percival, Brodovitch, Ghandi et al., Phys. Chem. Chem. Phys. 1 (1999) 4999

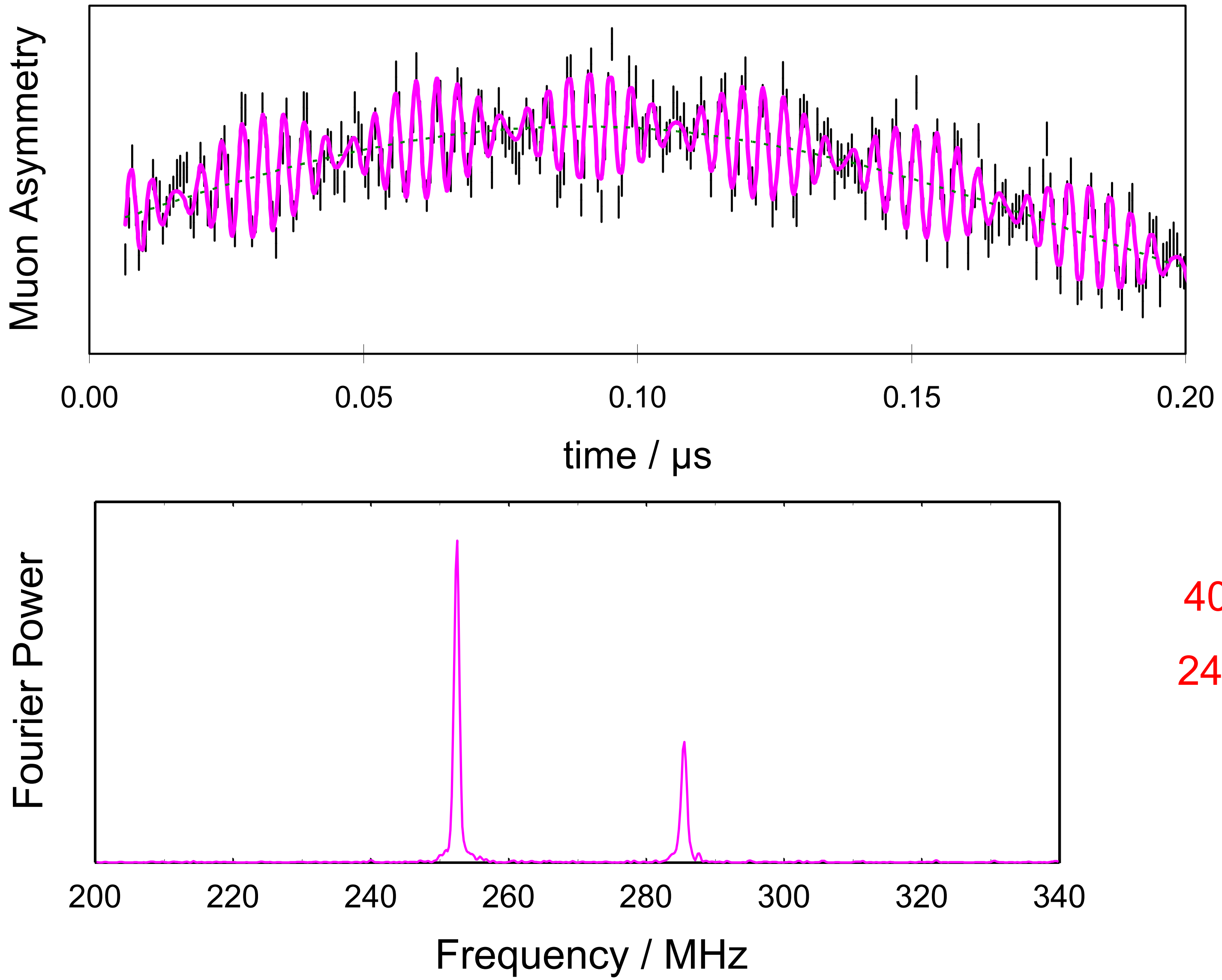
Muonium in supercritical water

400°C, 245 bar, 8 G

Diamagnetic signal subtracted



Muonium in supercritical water at 196 G

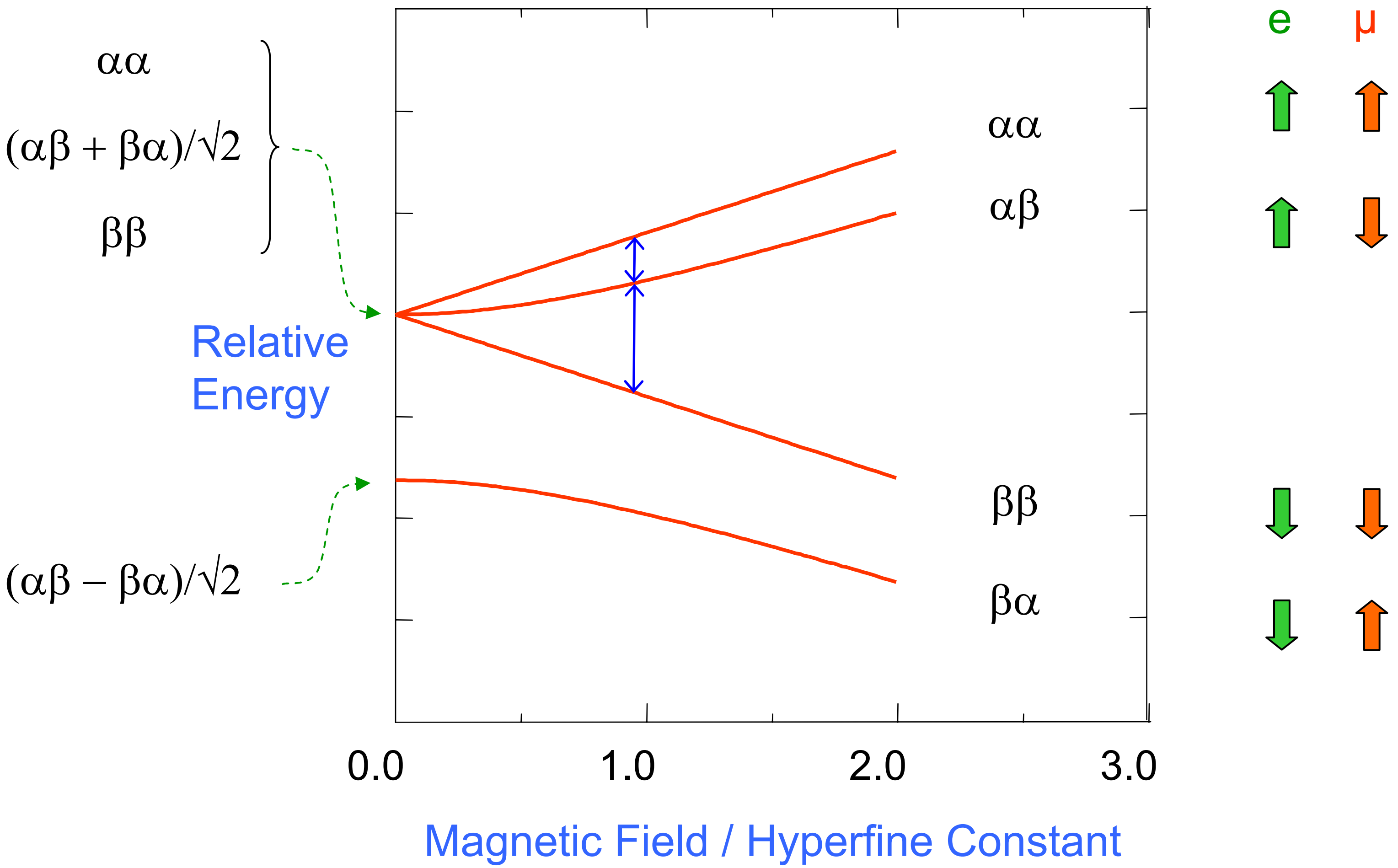


400°C

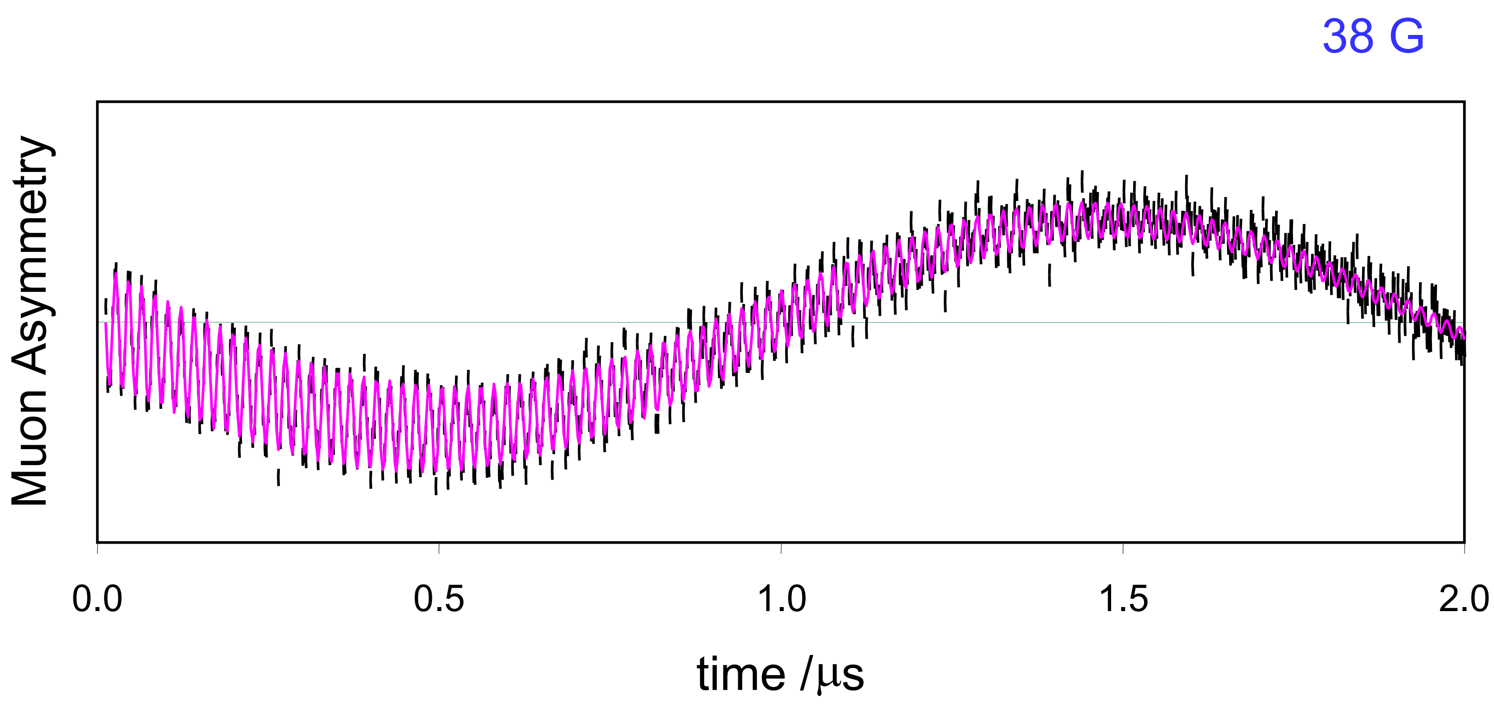
245 bar

Energy levels of a two spin-½ system

Breit-Rabi diagram



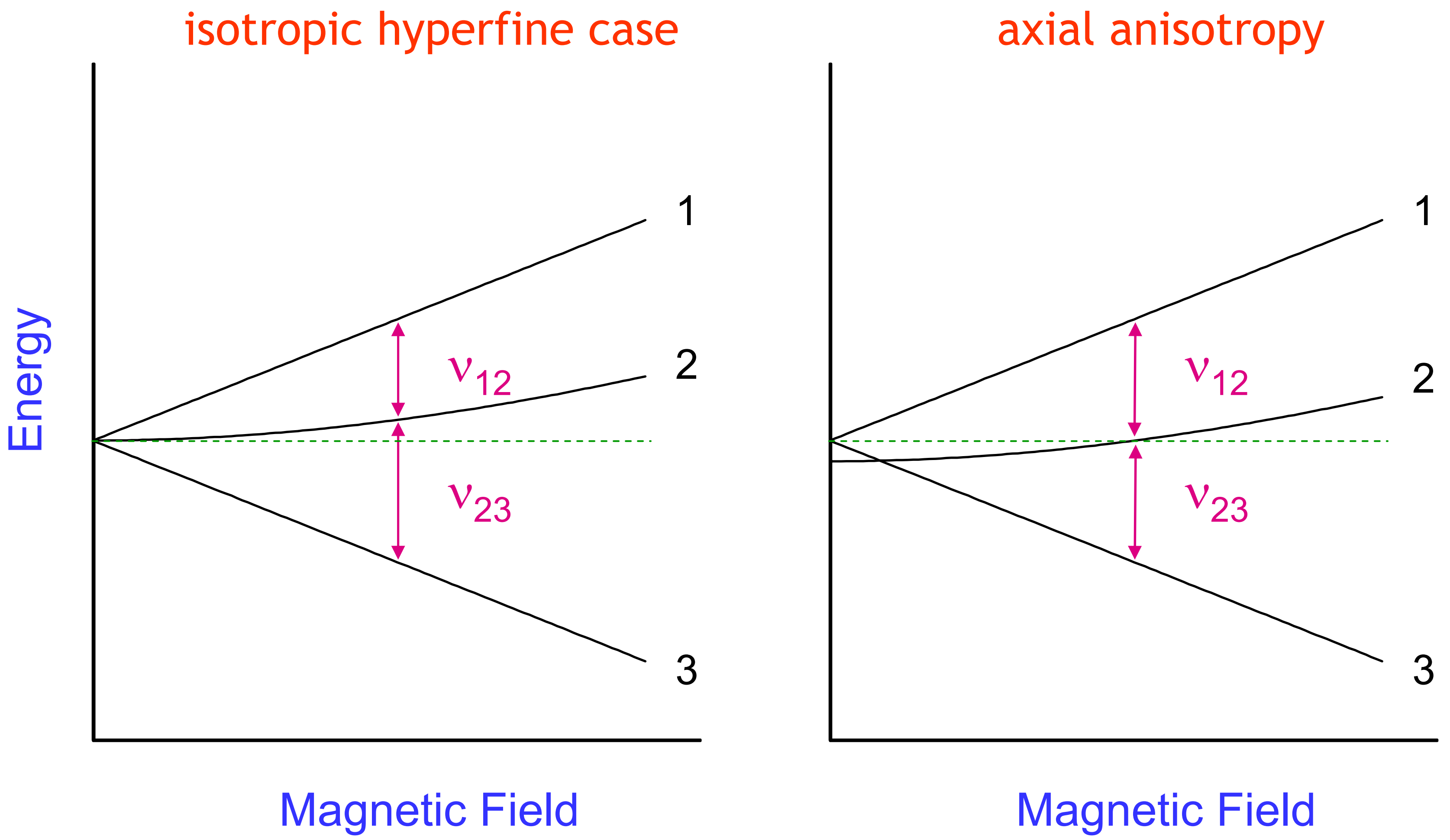
Muon spin precession in D_2O crystal at 227 K



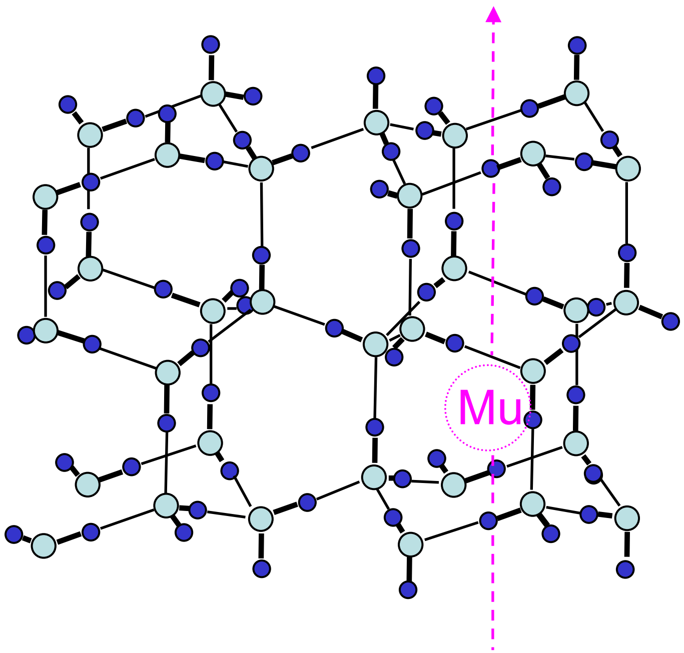
The high frequency precession is due to "triplet" (F=1) muonium.

The low frequency is due to muons in diamagnetic environments, such as MuOD and $MuOD_2^+$

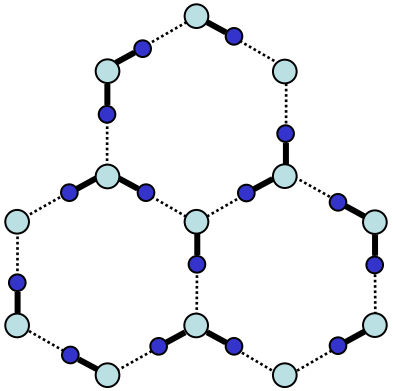
Muonium precession frequencies in low magnetic field



Muonium diffuses along the c-axis channels of ice-Ih



side view



view along *c* channel

μSR: Muon spectroscopic methods

Common features:

- spin polarized muon beam
- muons are implanted in the sample
- muons decay: $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_\varepsilon$ $\tau = 2.2\ \mu s$
- angular distribution of e+ has maximum in muon spin direction

Muon Spin Rotation μSR (TF-μSR)

- precession of muon spins in transverse magnetic field
- equivalent to free induction decay in pulsed NMR or ESR

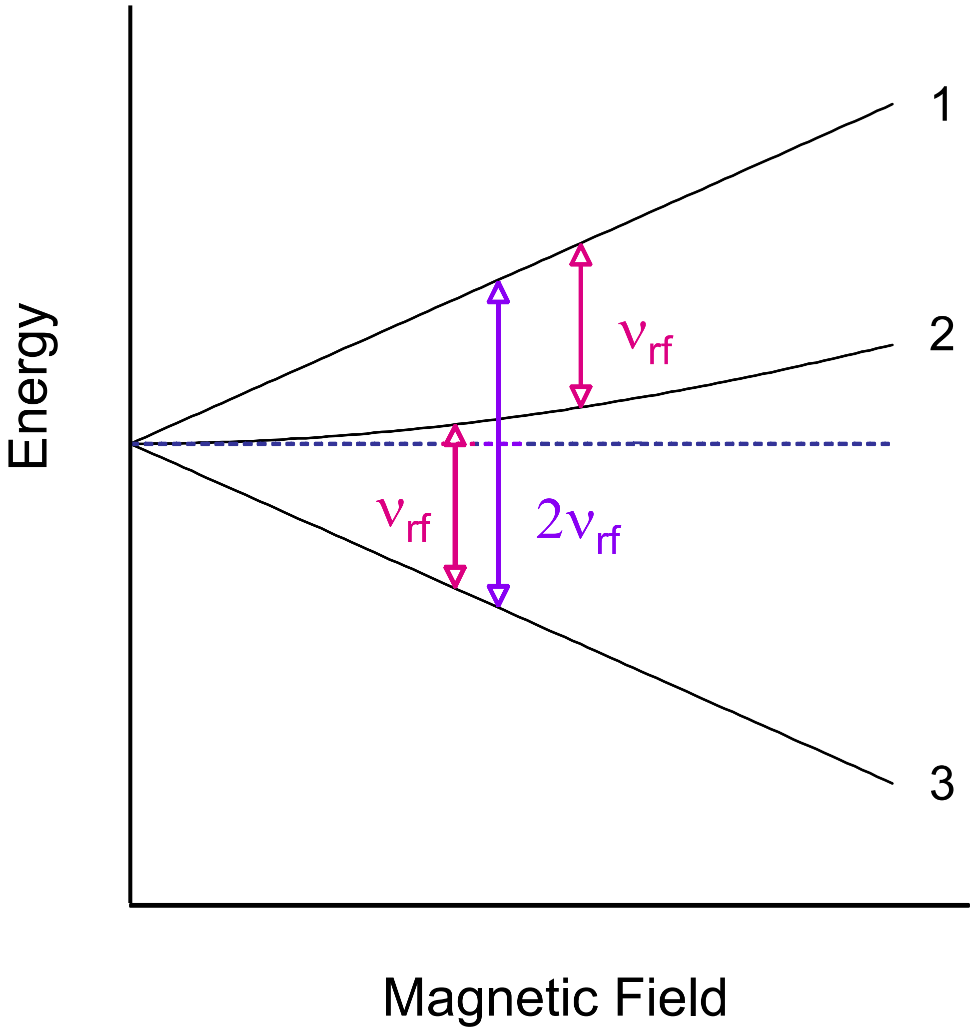
Muon Spin Resonance RF-μSR

- muon spin polarization *along* magnetic field
- transitions induced by rf field as in conventional NMR

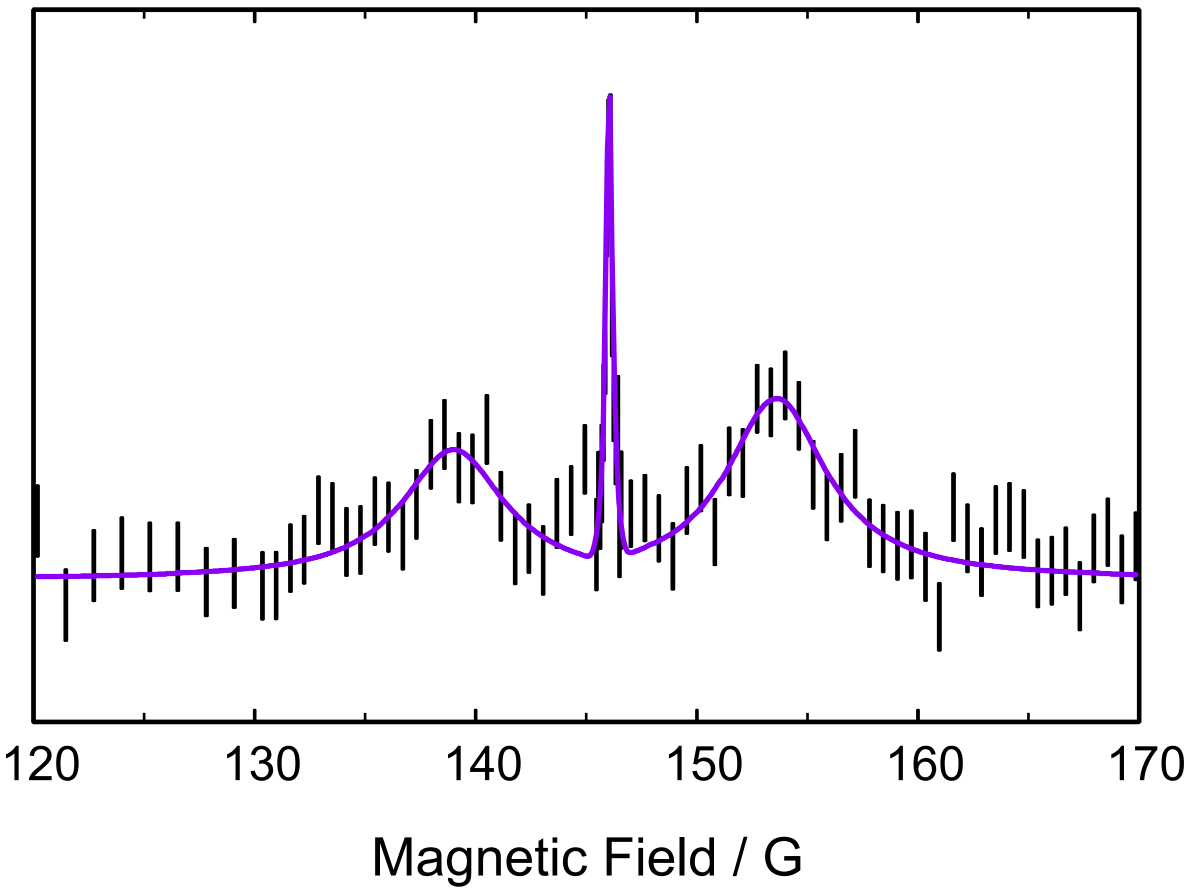
Muon Level Crossing Resonance μLCR (ALCR)

- mixing of spin levels causes *avoided* level crossing
- polarization is lost at magnetic fields where level crossing occurs

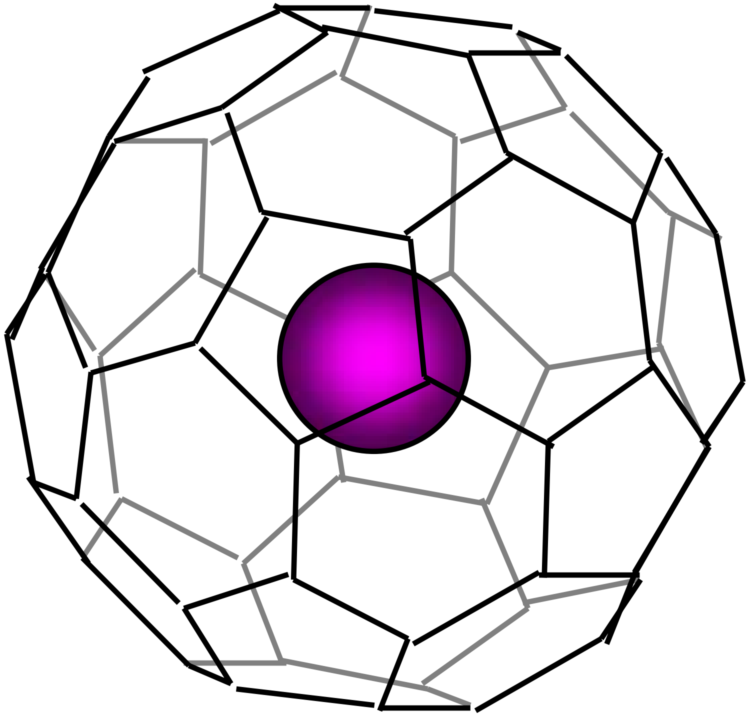
RF Transitions in Muonium at Low Magnetic Field



RFμSR Spectrum of Mu@C_{60} in C_{60} Powder

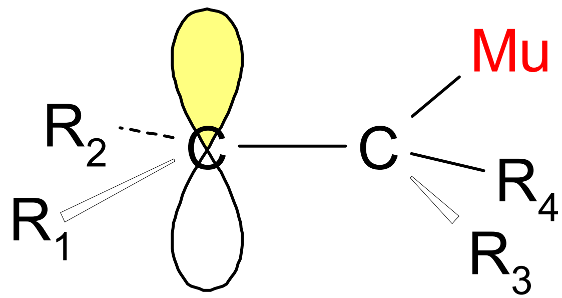


Endohedral Muonium $Mu@C_{60}$



Muonium in a universe of its own

Muoniated free radicals



μSR:

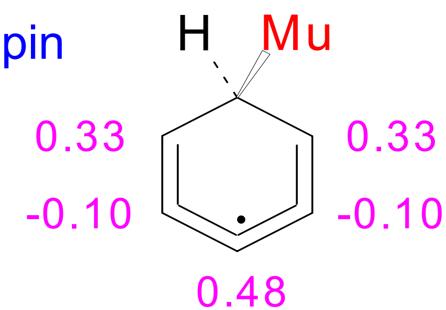
precession frequencies ⇒ muon hyperfine coupling

μLCR:

resonance fields ⇒ other nuclear hyperfine couplings

hyperfine couplings ⇒ distribution of unpaired electron spin

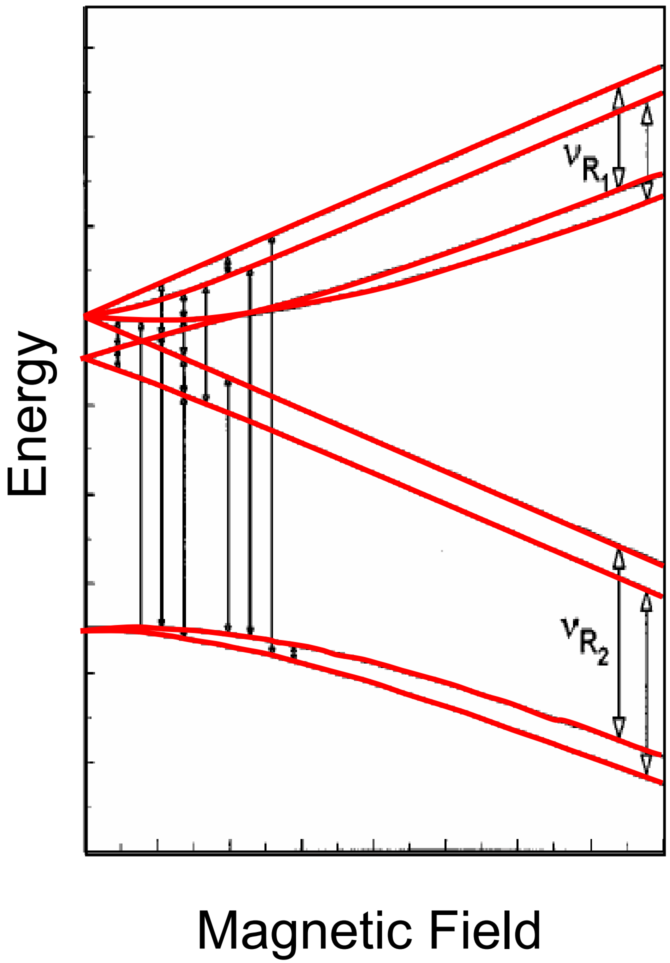
e.g. cyclohexadienyl

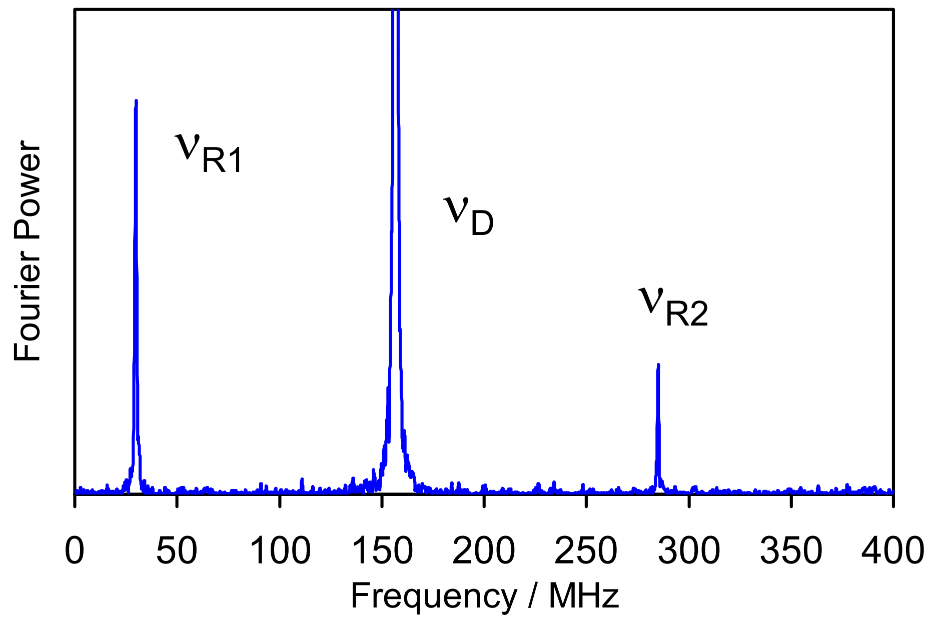


Temperature dependence of hyperfine couplings

⇒ intramolecular motion

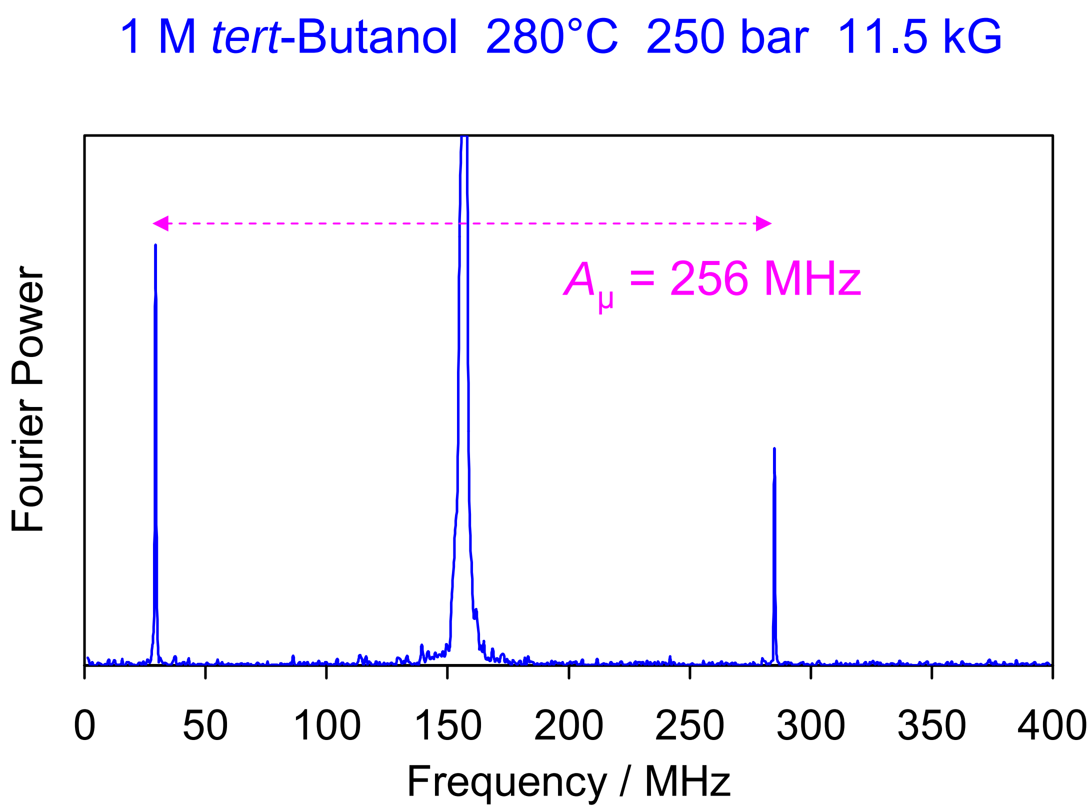
Transverse field muon spin rotation of radicals

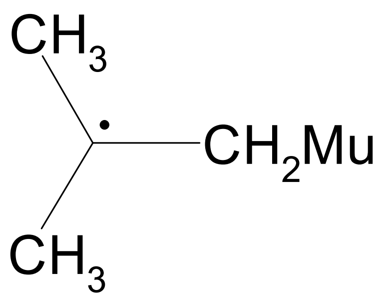




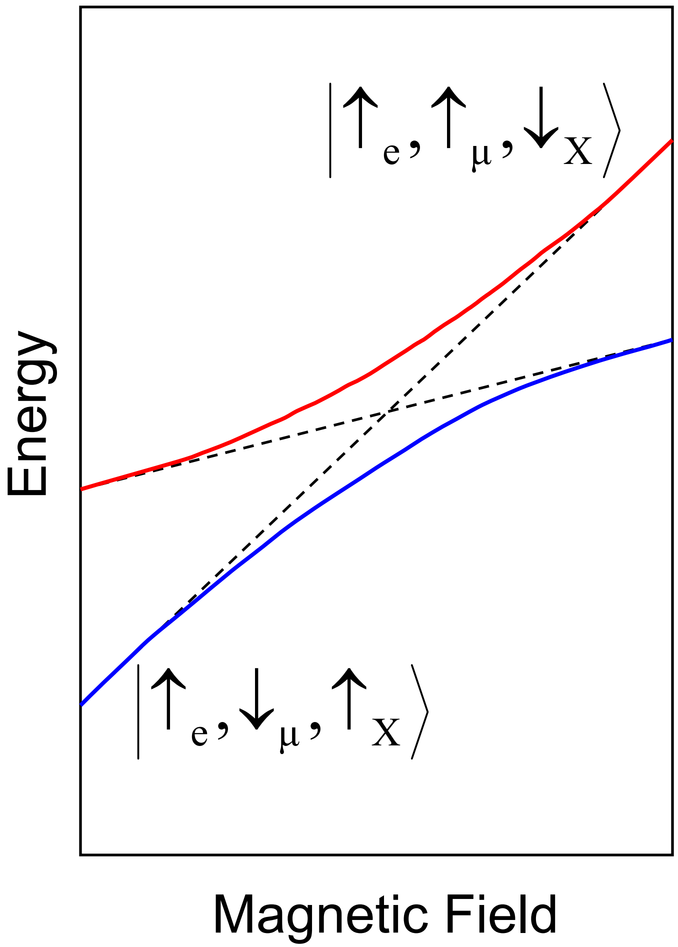
$$A_\mu = \nu_{R2} - \nu_{R1}$$

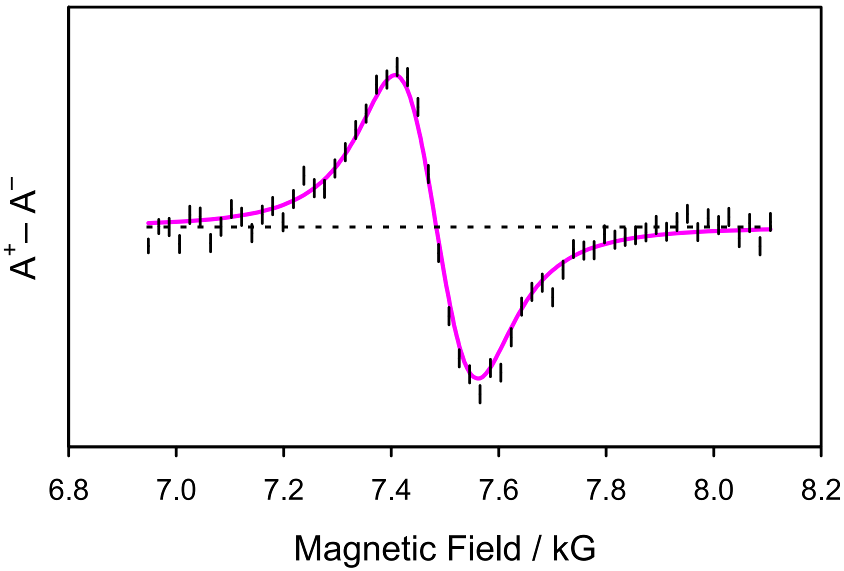
Fourier power μSR spectrum of tert-butyl





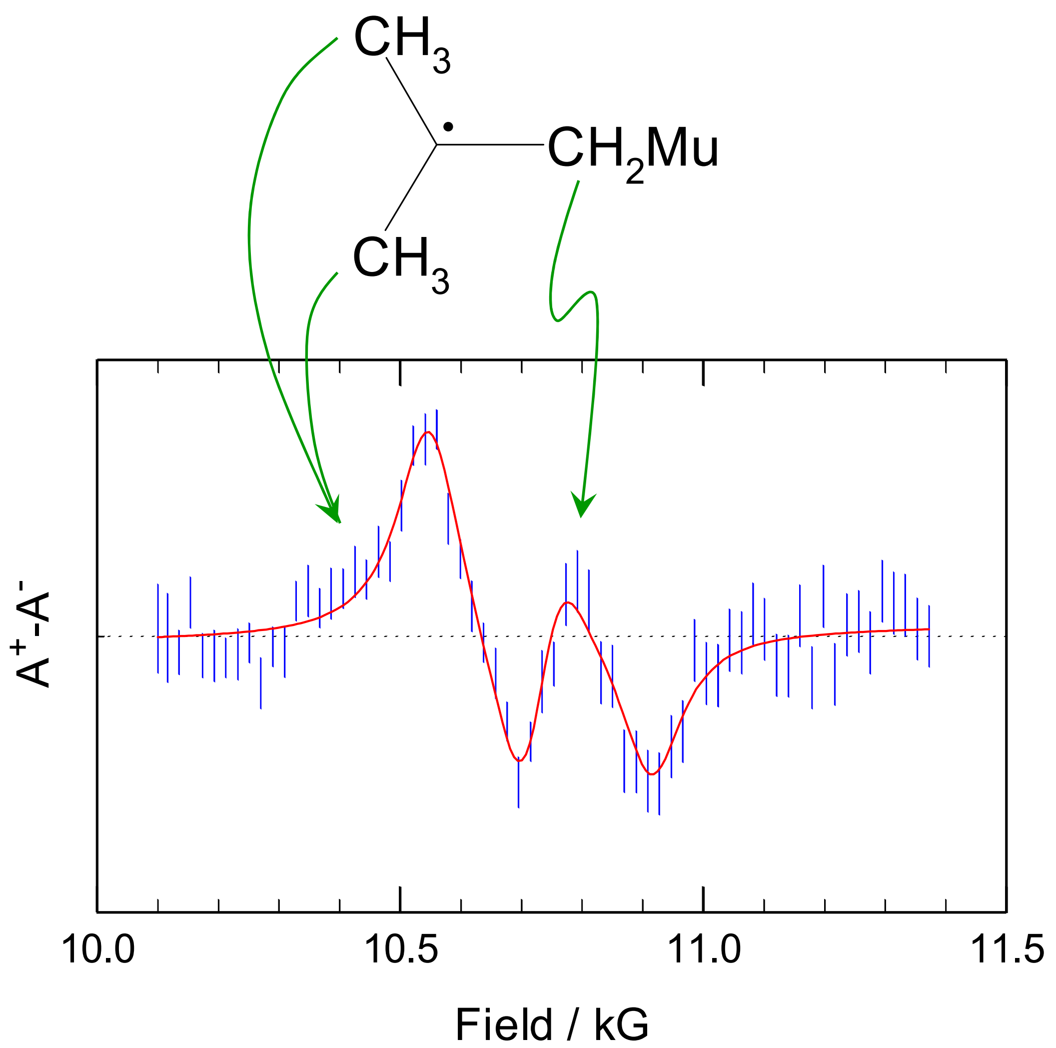
Avoided Muon Level Crossing Resonance





$$B_{res} \approx \frac{1}{2} \frac{A_\mu - A_X}{\gamma_\mu - \gamma_X}$$

tert-Butyl radical in water

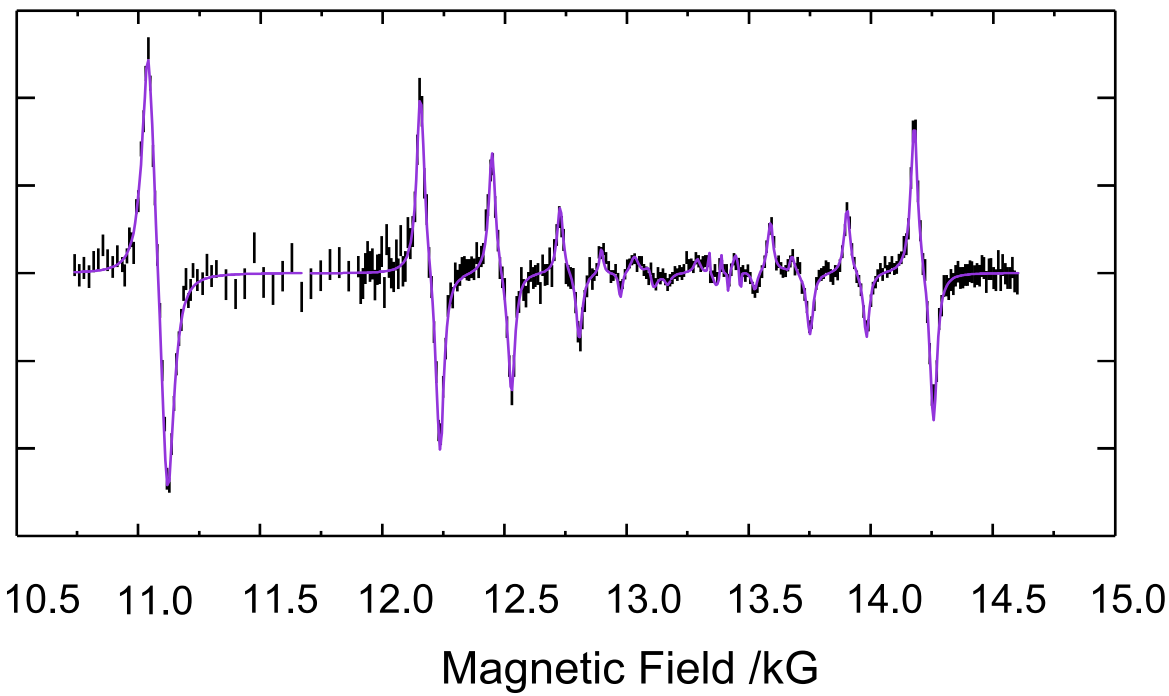


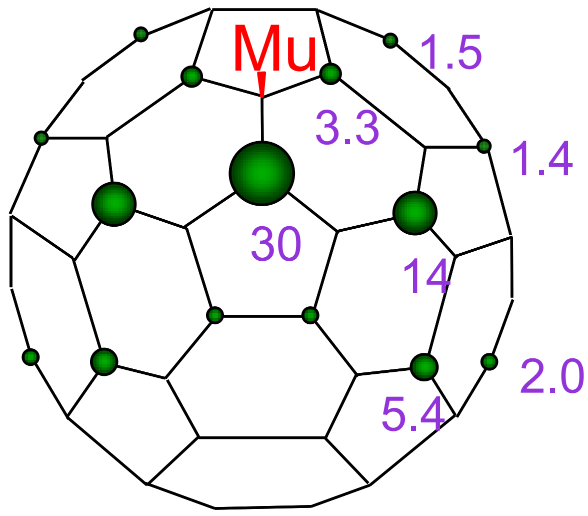
200°C

250 bar

Hyperfine constants are used to map unpaired spin in radicals

$Mu^{13}C_{60}$ Avoided Level Crossing Resonance





% Unpaired Spin Density

Percival, Addison-Jones, Brodovitch, Ji, et al., Chem. Phys. Lett., 245 (1995) 90

H atoms and free radicals in liquids

H is the simplest atom

$\Rightarrow$ fundamental chemistry

H is a constituent of water, hydrocarbons, carbohydrates

$\Rightarrow$ essential chemistry

Chemically speaking, Mu $\equiv$ H

We study Mu as a substitute for H

because it is similar: tracer, spin label

because it is different : isotope effects

Muonium Chemistry — areas of application

Muonium (caged)	Mu as probe of local environment Fixed cage: fullerenes, silsesquioxanes partial: ice transient: water
Kinetics	How fast does it go? in gases: reaction dynamics liquids: solvent effects; diffusion vs. activation control
Structure (needs e-spin)	Where does it end up? Free radicals: unpaired spin distribution
Mechanism	How does it get there? Identification of radical products Transfer of muon polarization
Dynamics intramolecular intermolecular	Nature is floppy! Temperature dependence of hyperfine constants LCR lineshape analysis

Further Reading

http://www.sfu.ca/chemistry/news/pt_quilt/index.htm

http://musr.org/cmms.php

http://musr.org/intro/musr/muSRBrochure.pdf