Muons in Chemistry Training School 2018

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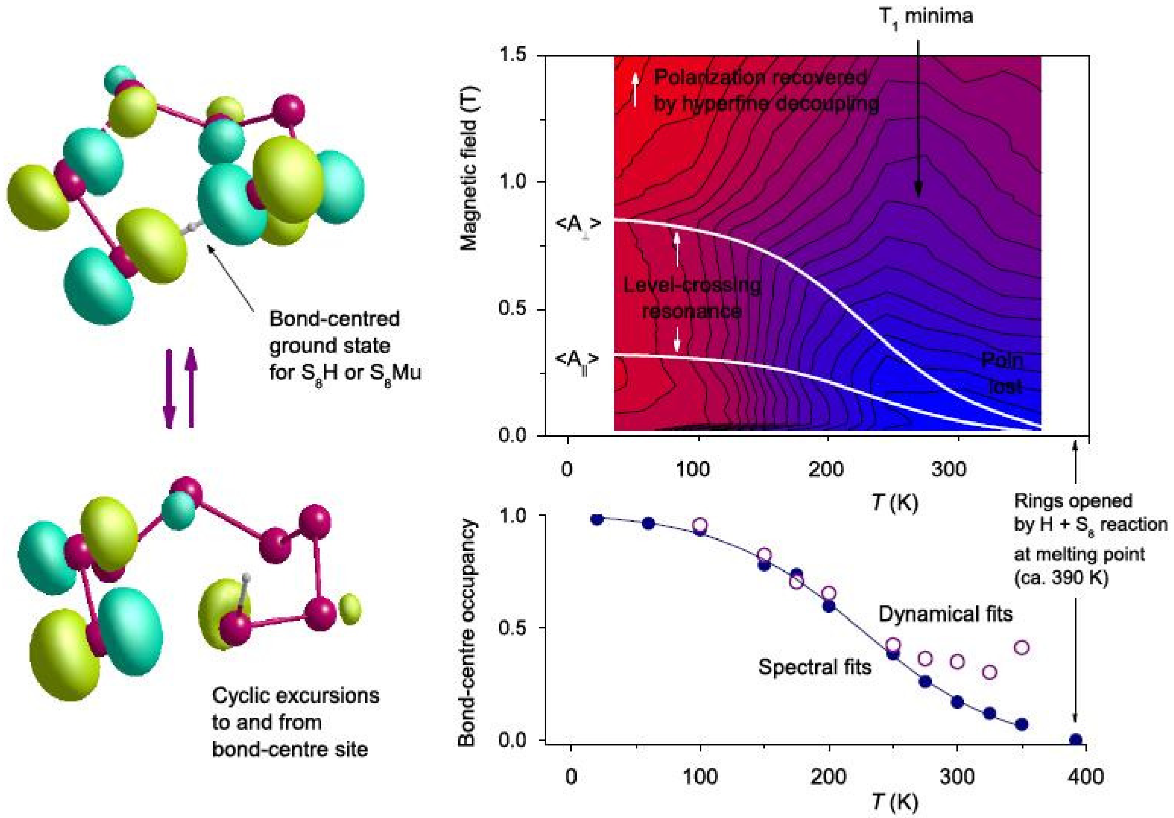
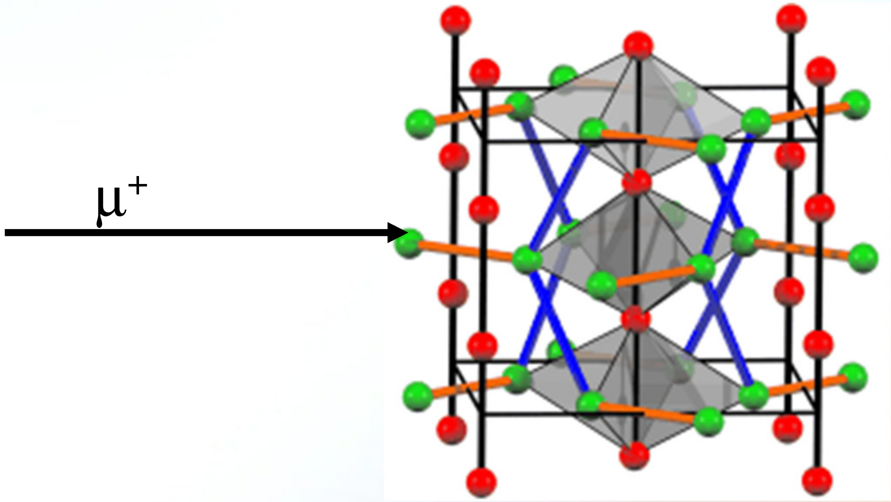
Why use muons?

- Extrinsic probe (Mu^+, $Mu^\bullet$, muoniated radical)
- Intrinsic interest
- Framing of the chemical problem
- Rationale
  - Muon as a light isotope of hydrogen
  - Magnetic moment
- Structure, dynamics and kinetics



S F J Cox *et al* 2011 *J. Phys.: Condens. Matter* **23** 315801
doi:10.1088/0953-8984/23/31/315801

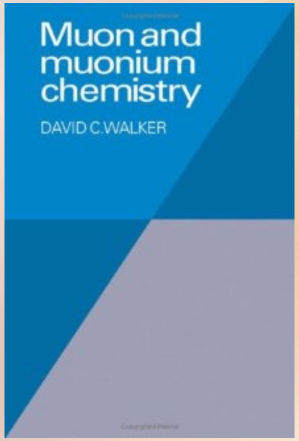
What happens?



Mu^+	diamagnetic
$\mathrm{Mu}^\bullet$	paramagnetic
$\mathrm{RMu}^\bullet$	paramagnetic

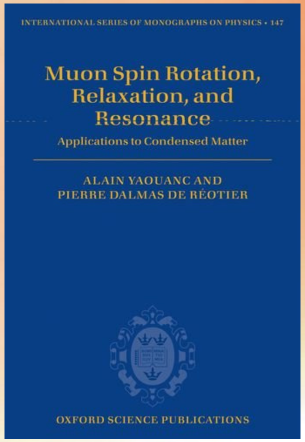
Muons in Chemistry

- Kinetic isotope effect in radical reactions
  - low mass of the muonium as an isotope of hydrogen,
- Observation of hydrogen atom processes
- Probing the local magnetic environment
- Muons as an exotic particle.



Muon and muonium chemistry

DAVID C.WALKER



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Muon Spin Rotation, Relaxation, and Resonance

Applications to Condensed Matter

ALAIN YAOUANC AND
PIERRE DALMAS DE RÉOTIER

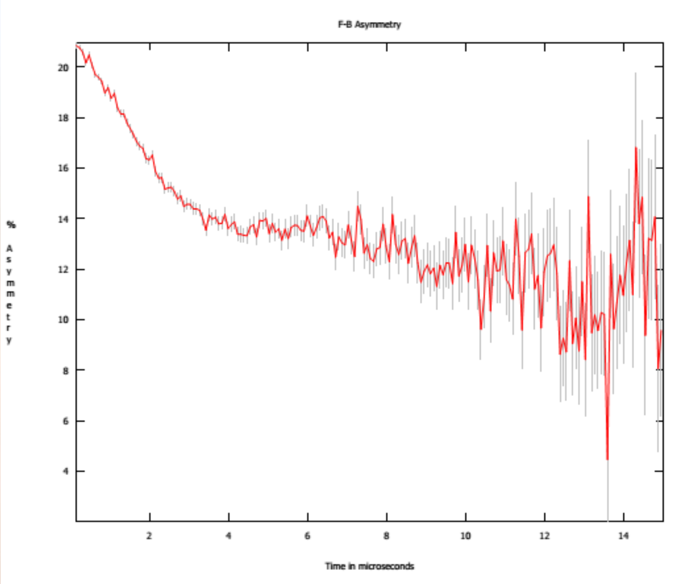
OXFORD SCIENCE PUBLICATIONS

New directions

- Surface studies
- Soft matter
- Combination experiments
    - Electric fields
    - Laser irradiation
- Extreme environments

What can be determined?

- Nature of the muon species
  - Mu^+, $Mu^\bullet$, muoniated radical
- Number of species
- Functional form of the decay
- Decay constant
- Hyperfine coupling constants
  - $Mu^\bullet$, muoniated radical



μ^+ implanted into $Zr(H_2PO_4)(PO_4).2H_2O$ at 10 K in zero external magnetic field

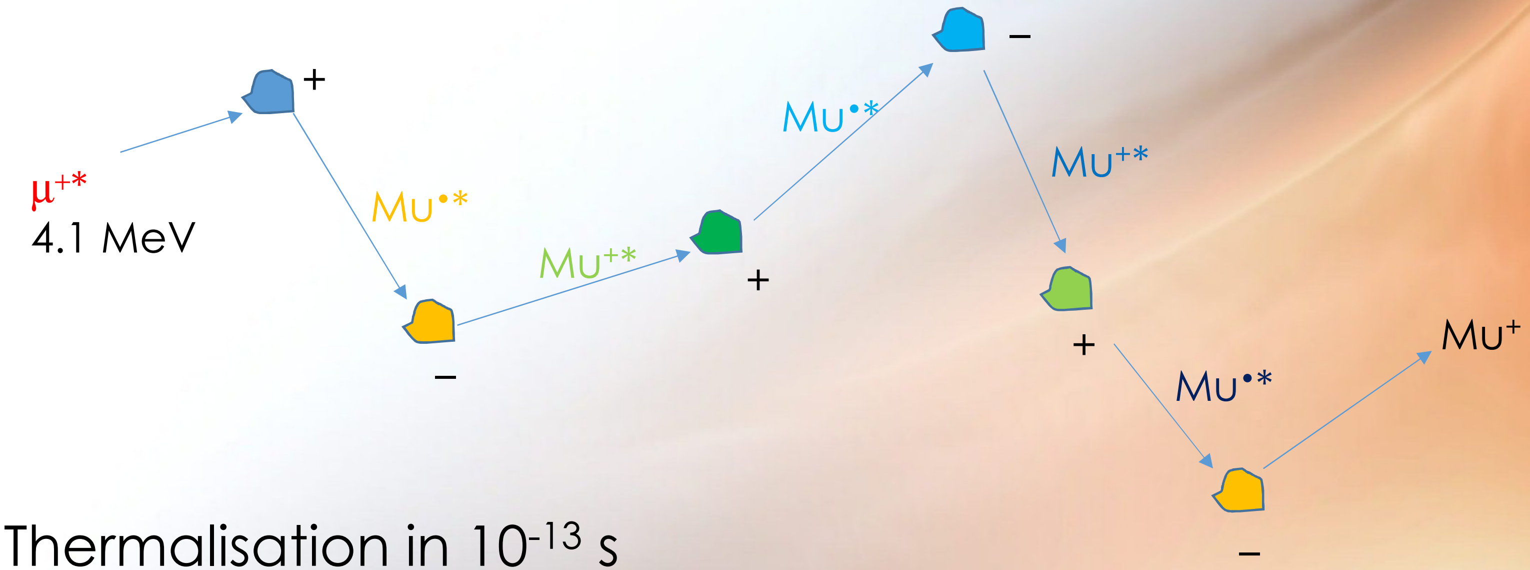
Diamagnetic Muons

Illustrative example

- Sample: $Zr(H_2PO_4)(PO_4).2H_2O$
- Aim: study dynamics of implanted muon
- Expectation, diamagnetic muon
  - Insulator
  - Chemistry of similar systems
  - Bare Mu^+, trapped near O
  - Abstraction reaction, MuOH
  - Muon decay determined by field from local nuclear magnetic moments

Muon thermalisation

- But do we really know $\mathrm{Mu}^{\bullet}$ wont be formed?



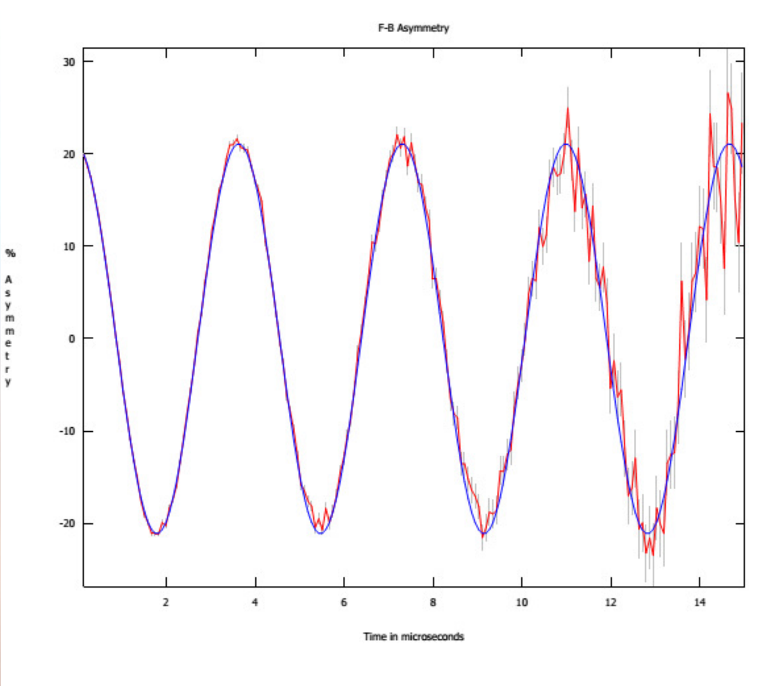
Thermalisation in 10^{-13} s
Observation > 10^{-7} s

Check the asymmetry

Calibrate using Ag
Transverse field, 2 mT, 20 G

Fit to rotation frequency

$a_0 = 21.1\%$
0.271 MHz



Sample 20 G transverse field

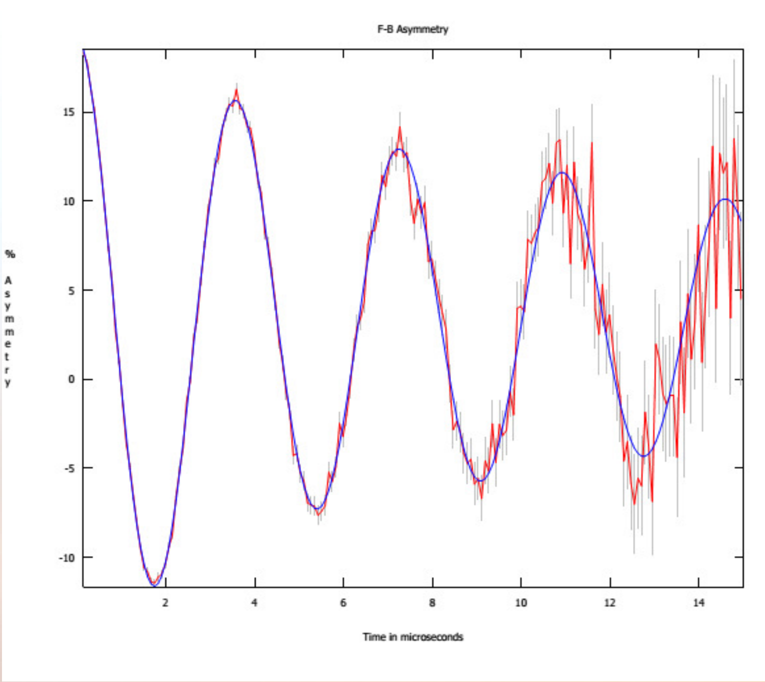
Transverse field, 20 G

Fit to rotation frequency
with Gaussian decay
Two components required

a_0 (1) = 16.23%
0.272 MHz
$\sigma = 0.04\ \mu s^{-1}$

a_0 (T) = 21.8%

a_0 (2) = 5.55%
0.276 MHz
$\sigma = 0.283\ \mu s^{-1}$



μ^+ implanted into $Zr(H_2PO_4)(PO_4).2H_2O$
at 10 K in 2 mT transverse magnetic field

Check the asymmetry

- Full asymmetry
- Rotation frequency typical of diamagnetic muon
- $P_D = 1.0$
- No evidence for muonium – repolarisation, $P_M = 0.0$
- No evidence for a “missing” fraction, $P_L = 0.0$
  - Hyperfine oscillations during thermalisation
  - Depolarising encounter with paramagnetic species (e_s^-)

Can we use the rotation frequency?

- Would be equivalent to the NMR chemical shift
- Severely limited by the muon lifetime

$\tau_{Mu} = 2.2\ \mu s$

Lifetime and energy uncertainty

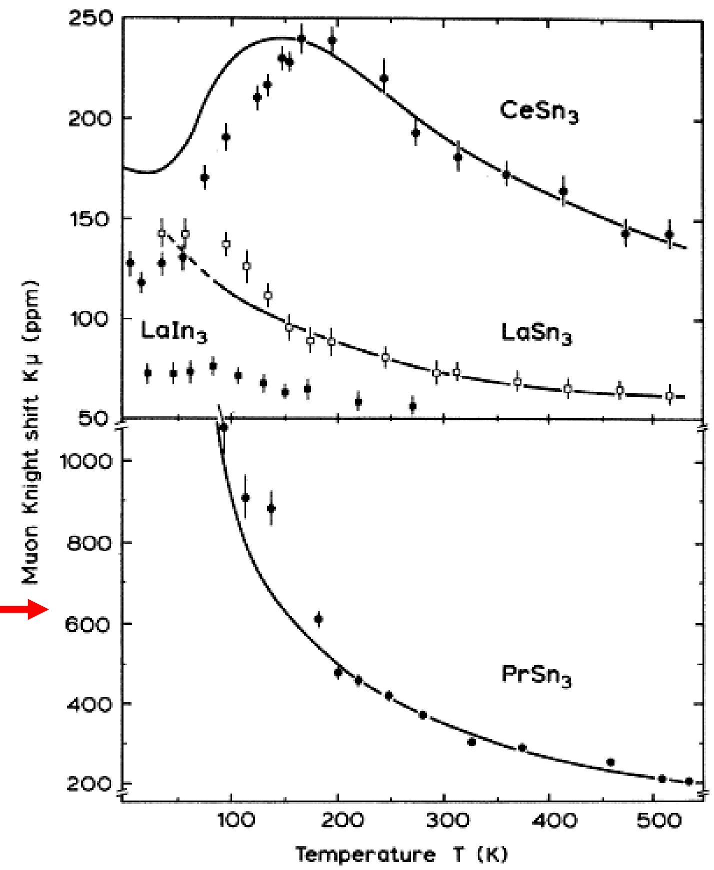
$$\delta E \cdot \tau_{Mu} \approx \mathrm{h} \qquad \delta E = h\delta\nu$$

$$\Delta\nu = \frac{10^6}{(2\pi \times 2.2)} = 0.072\ \mathrm{MHz}$$

Typical ^{1}H chemical shifts ~ 10^{-5} MHz

Muon Knight Shift

- Change in muon frequency caused by hyperfine coupling to metallic conduction electrons
- Density of states at the Fermi Level



Size of shift in ppm

How can we tell diamagnetic muons apart?

- Not through the rotation frequency!
- Size of local nuclear dipolar field
  - Obtain from the relaxation time constant
  - Propose structural model based on chemistry
  - Search crystal structure
- Evidence for two sites
  - Two different relaxation rates
  - Origin of multiple sites?

Zero-field MuSR

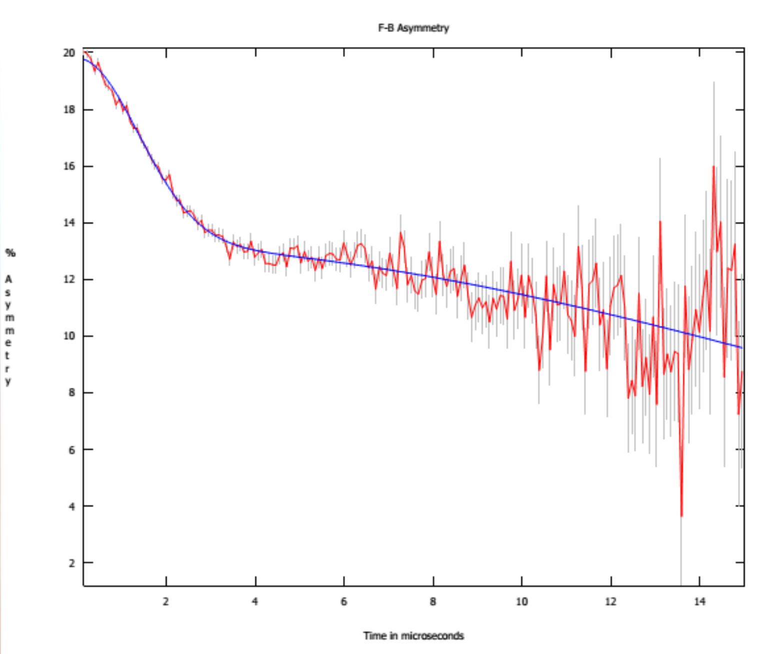
Sensitive to slow muon diffusion

Fit to Gaussian decay
Two components required

a_0 (1) = 13.25%
σ = 0.038 μs $^{-1}$

a_0 (2) = 6.56%
σ = 0.522 μs $^{-1}$

Low temperature, no dynamics
Values for σ reflect local nuclear dipolar field

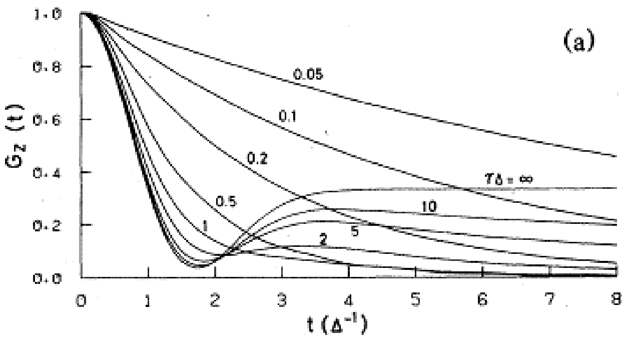


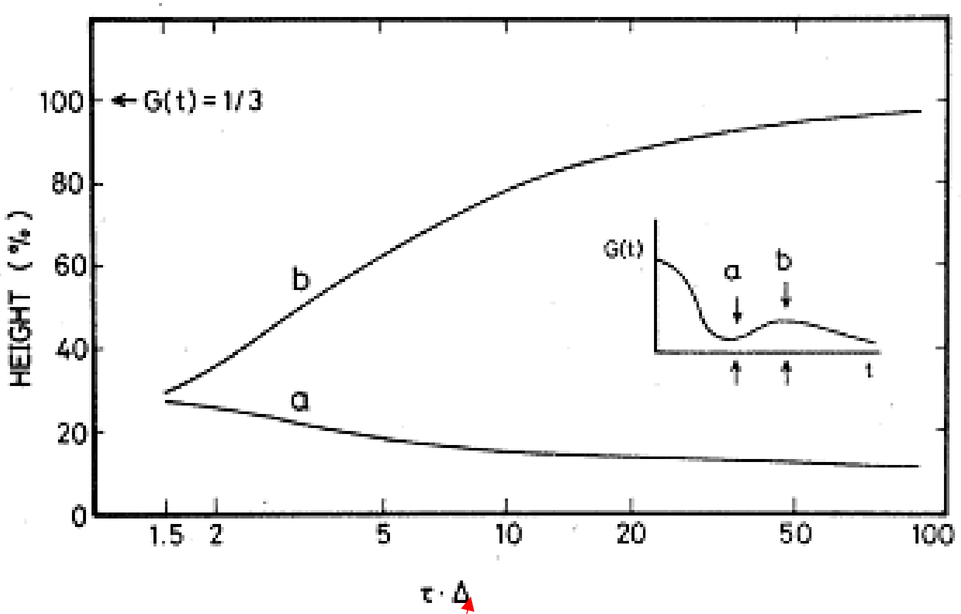
μ^+ implanted into $Zr(H_2PO_4)(PO_4).2H_2O$ at 10 K in zero external magnetic field

Kubo-Toyabe function

$$G(t) = \tfrac{1}{3} + \tfrac{2}{3}\left(1-\Delta^2 t^2\right)\exp\left(-\Delta^2 t^2/2\right)$$

Height of recovery sensitive to correlation time





Width of static distribution

Zero-field MuSR

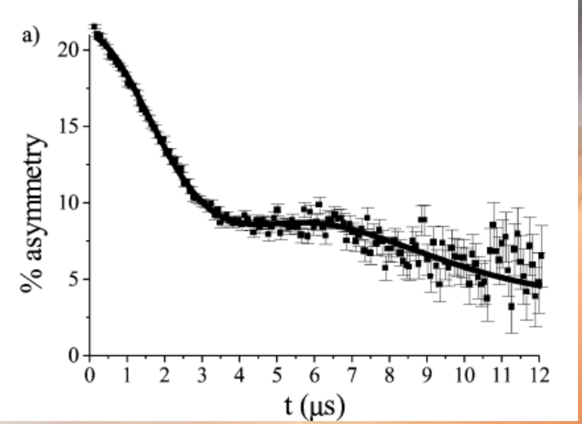
Fit to Gaussian Kubo-Toyabe decay
Two components required

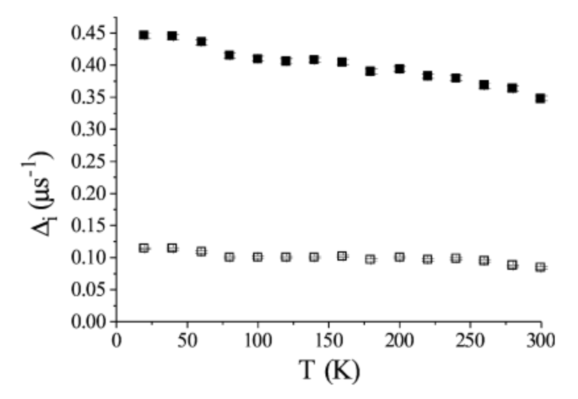
a_0 (1) ~ 10.5%
$\Delta = 0.12 \pm 0.005\ \mu s^{-1}$

a_0 (2) ~ 10.5%
$\Delta = 0.45 \pm 0.004\ \mu s^{-1}$

Little temperature dependence

Consistent with low proton conductivity
$10^{-3} – 10^{-4}$ S m^{-1} at 20° C





Evidence from $Zr(H_2PO_4)(PO_4)$

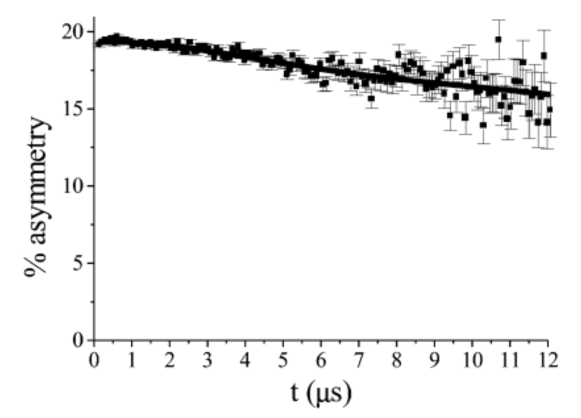
Fit to Gaussian Kubo-Toyabe decay
Two components required

a_0 (1) ~ 17.9%
$\Delta = 0.03 \pm 0.001\ \mu s^{-1}$

a_0 (2) ~ 1.5%
$\Delta = 0.202 \pm 0.01\ \mu s^{-1}$

Loss of faster decaying component
Associated with muon addition to H_2O

Slow decaying, Mu trapped by O-P



μ^+ implanted into $Zr(H_2PO_4)(PO_4)$ at 260 K in zero external magnetic field

Interpretation of Δ

- Model reactions in ice

$$H_2O + \mu^+ = H_2OMu^+$$
$$H_2OMu^+ + L = HOMu + LH^+$$

- Hydrated crystals
  - Gypsum, 300 K HOMu
  - Oxalic acid dihydrate, H_2OMu^+

Calculation of Δ

- Related to the second moment, M_2

$$M_2 = 2\Delta^2$$

$$M_2 = \frac{4}{3}\left(\frac{\mu_0}{4\pi}\right)^2 \gamma_S^2 \gamma_{Mu}^2 S(S+1) \sum_j r_j^{-6}$$

- Assume a substitution reaction
- Use H positions from neutron diffraction crystal structure

Calculation of Δ

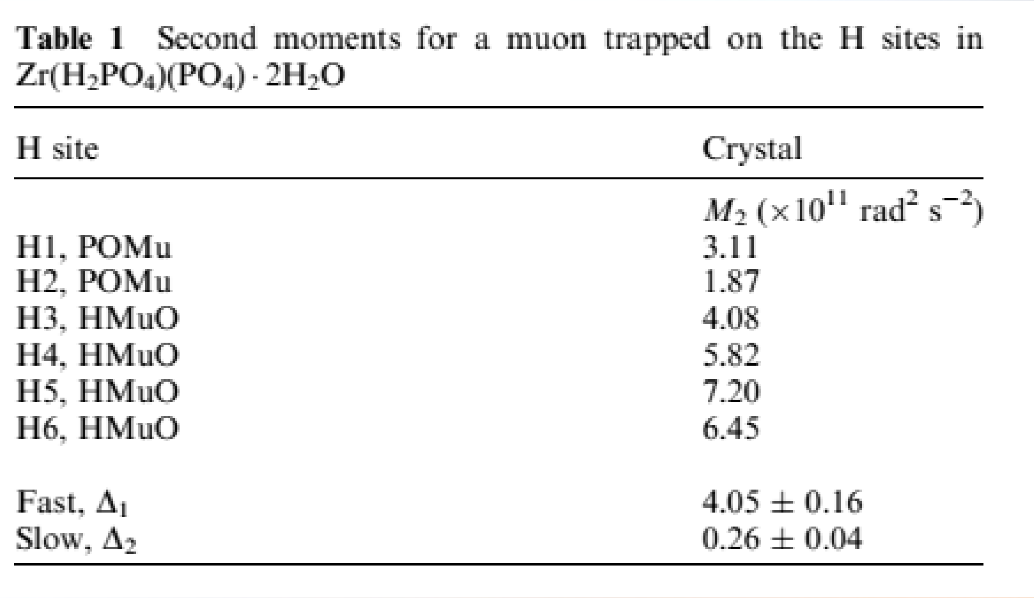


Table 1 Second moments for a muon trapped on the H sites in $Zr(H_2PO_4)(PO_4)\cdot 2H_2O$

H site	Crystal
	M_2 ($\times 10^{11}$ $rad^2\ s^{-2}$)
H1, POMu	3.11
H2, POMu	1.87
H3, HMuO	4.08
H4, HMuO	5.82
H5, HMuO	7.20
H6, HMuO	6.45
Fast, Δ_1	4.05 ± 0.16
Slow, Δ_2	0.26 ± 0.04

Isolated H_2OMu^+ $M_2 > 5.5 \times 10^{11}$ rad^2s^{-2}

Summary

- Diamagnetic muons, full asymmetry in any magnetic field
- Rotation frequency of 271 kHz in 2 mT (20 G) transverse field
- Relaxation rate from fit to time domain data
- Choose functional form e.g. gaussian, lorentzian on the basis of best fit χ^2
- Low temperature relaxation rate to assign muon site through M_2
- Temperature dependence indicative of muon dynamics

Muonium and muoniated radicals

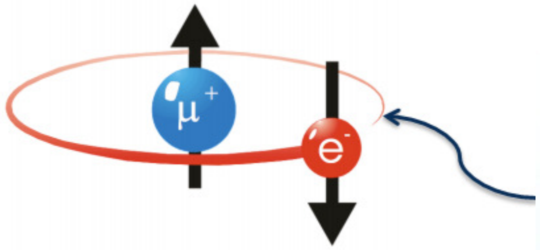
Muonium and muoniated radicals

- Paramagnetic: unpaired electron
- Strength of coupling between muon and electron given by the Hyperfine coupling constant

Isotropic hyperfine coupling	$A_X = \left(\frac{\mu_0 h}{3\pi}\right)\gamma_e \gamma_X \left\|\psi(0)\right\|^2$	Unpaired electron density at nucleus Transmitted through bonds
Anisotropic hyperfine coupling	$D_X = \left(\frac{\mu_0 \gamma_e \gamma_X h}{4\pi}\right)\left\langle \frac{1-3\cos^2\theta}{r^3} \right\rangle$	Dipole-dipole Through space Averages to zero in solution

Order of 10-100's MHz

Muonium



Muonium, Mu$^\bullet$ (IUPAC)
μ^+, e^-

$A_\mu = 4.463$ GHz

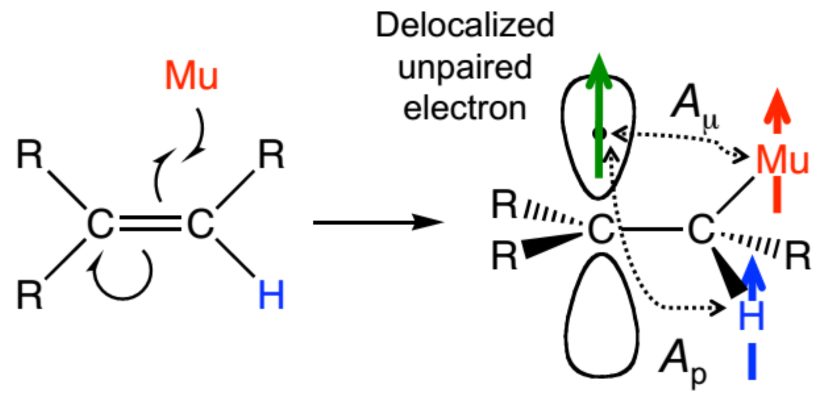
Reactive chemistry similar to H$^\bullet$

Ionisation energy 13.54 eV
Bohr radius 53.2 pm

^{S}Mu and ^{T}Mu created in equal amounts
^{S}Mu rapidly depolarised – not observed

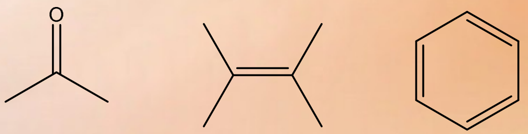
Muoniated radical

Muoniated = replacement of an H by muonium



Mu adds across
a double bond

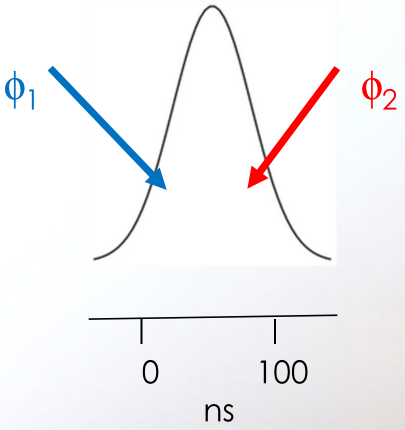
Range of hyperfine
coupling constants

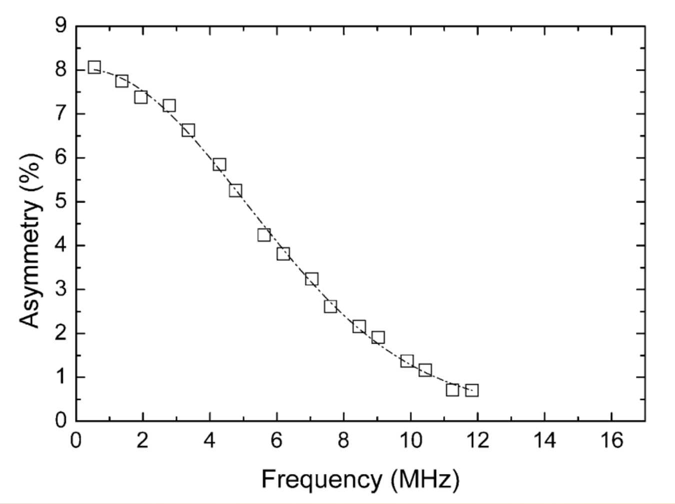


A_μ = 10 200 500 MHz

How do you know if you have a paramagnetic species?

- Full asymmetry not seen in a 2 mT TF experiment
- Finite width of muon pulse at ISIS





Triplet precession of muonium in quartz

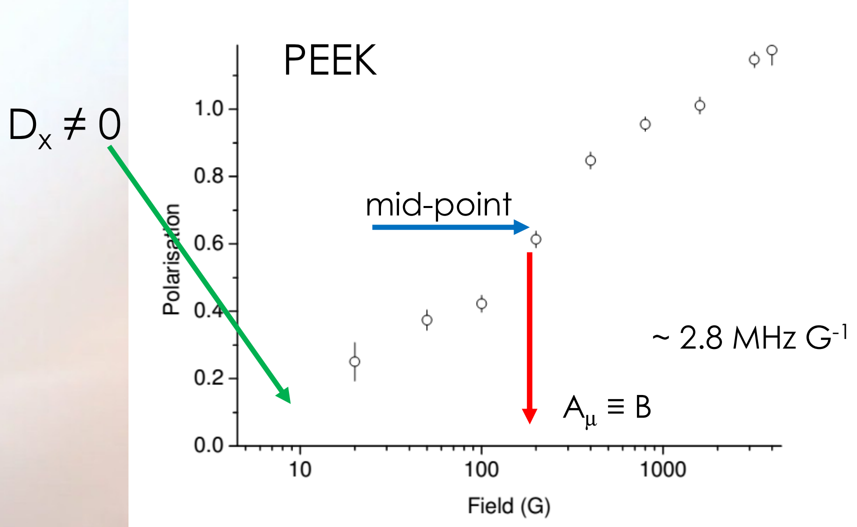
Repolarisation

- Asymmetry increases with increasing longitudinal field

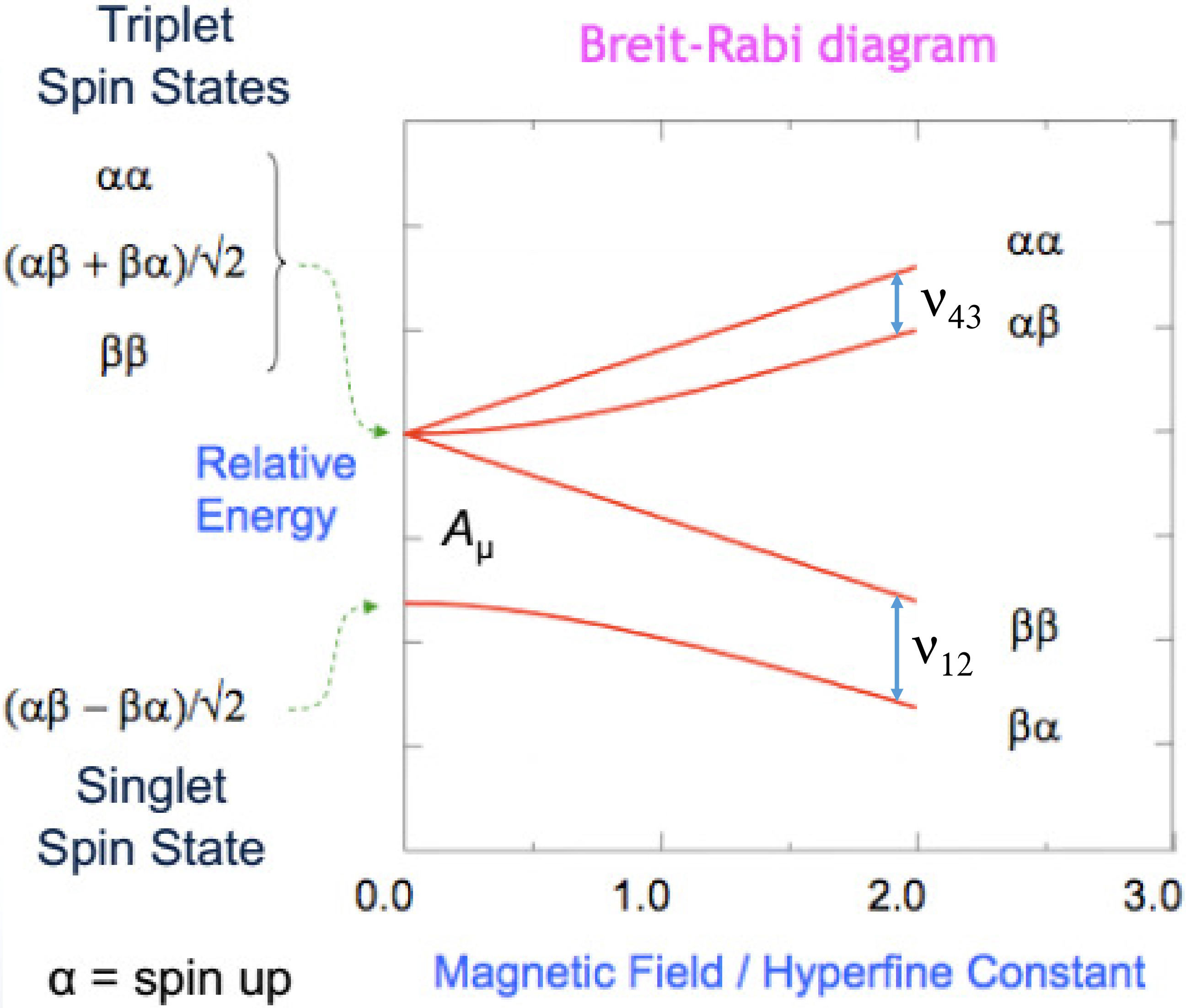
$$P = h_D + \frac{h_M}{2}\left[1 + \frac{x^2}{1 + x^2}\right]$$

$$x = \frac{(\gamma_e + \gamma_\mu)B}{2\pi} \cdot \frac{1}{A_\mu}$$

h_D = diamagnetic fraction
h_M = paramagnetic fraction
$A\mu$ (MHz)



Breit-Rabi diagram

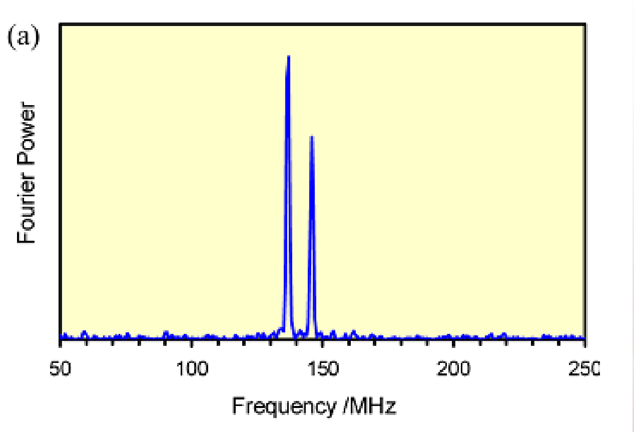


α = spin up
β = spin down

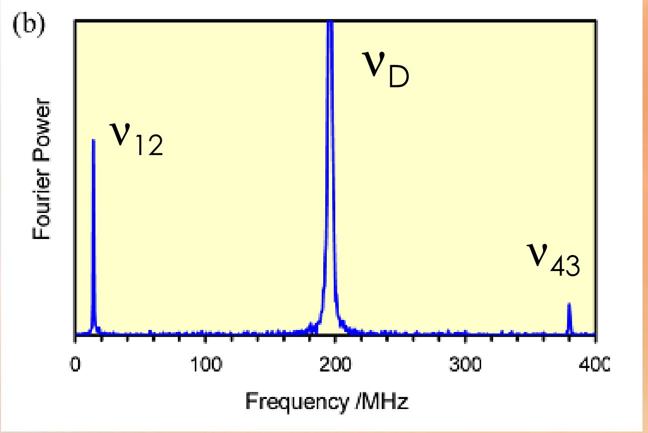
Muonium or muoniated radical?

- Muonium, large hyperfine coupling constant
  - ISIS: LF > 1 kG required for repolarisation
  - PSI/TRIUMF: High precession frequency at low TF

$$A_\mu = |\nu_{12}| + |\nu_{43}|$$



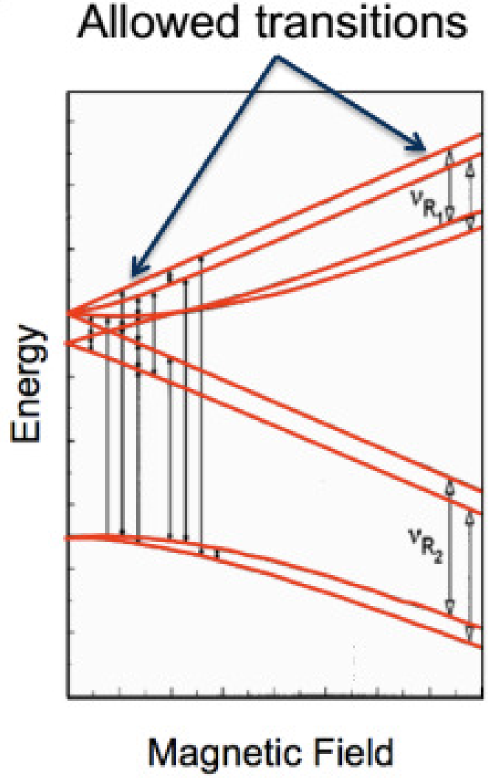
Cyclopentane hydrate -10° C in 100 G TF

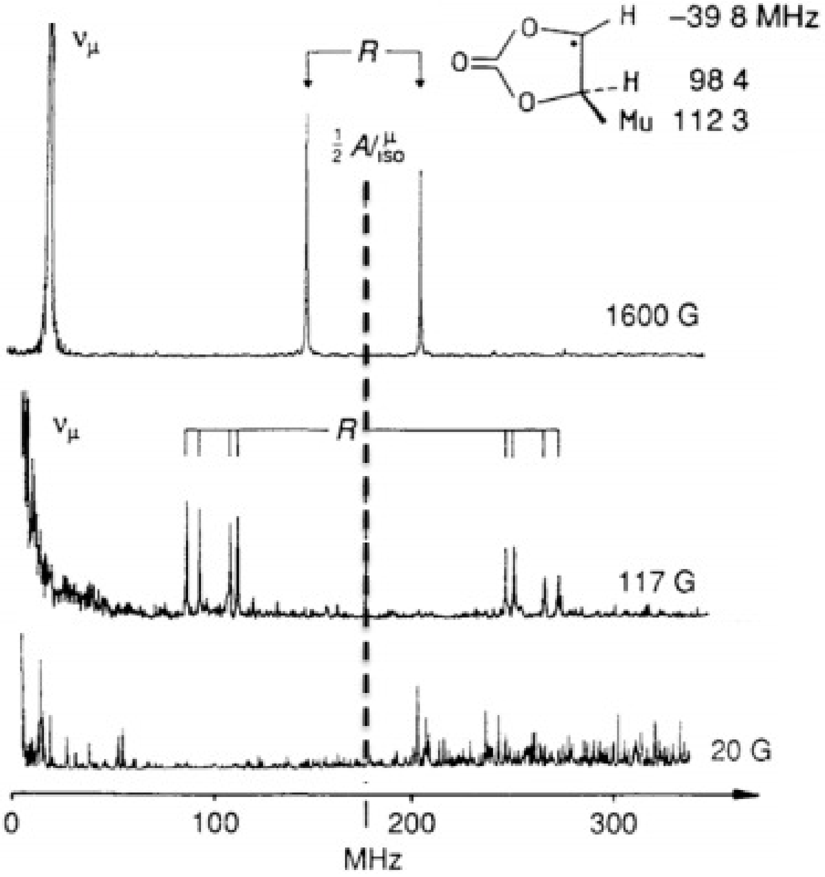


2,5 -dihydrofuran hydrate -12° C in 14.46 kG TF

Percival et al J. Phys. Chem. A 2014, 118, 1162−1167

TF-μSR of Muoniated Radicals





High field
$\nu_e > A_\mu$

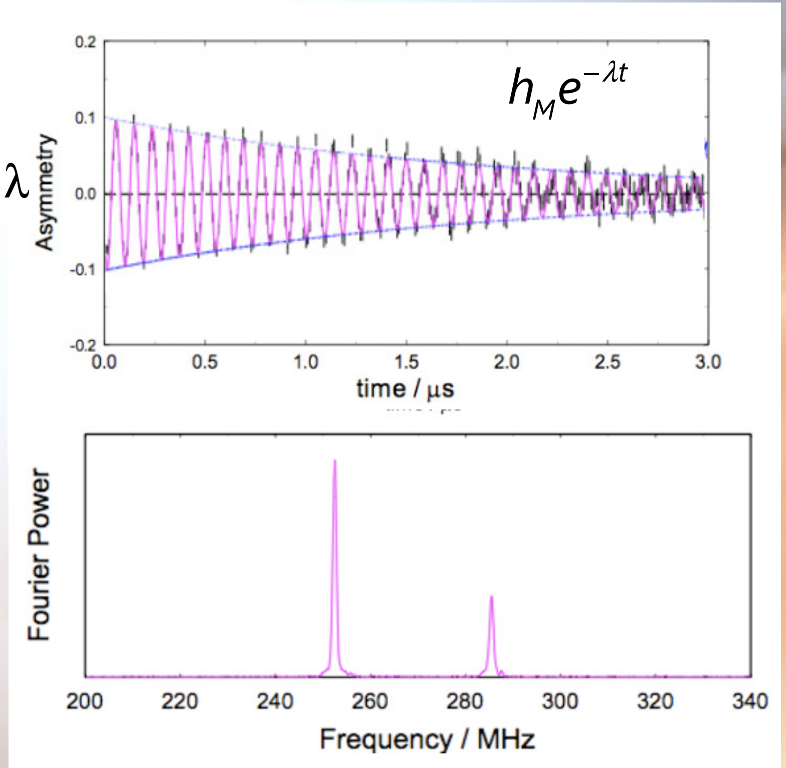
$$\nu_R = \nu_\mu \pm \frac{1}{2} A_\mu$$

Roduner *Chem. Soc. Rev.* **1993**, *29*, 337

TF-MuSR of muonium

Low field < 10 G
Obtain the relaxation rate, λ
Kinetics

Intermediate field, 250 G
Measure A_μ
(Solvent dependent)



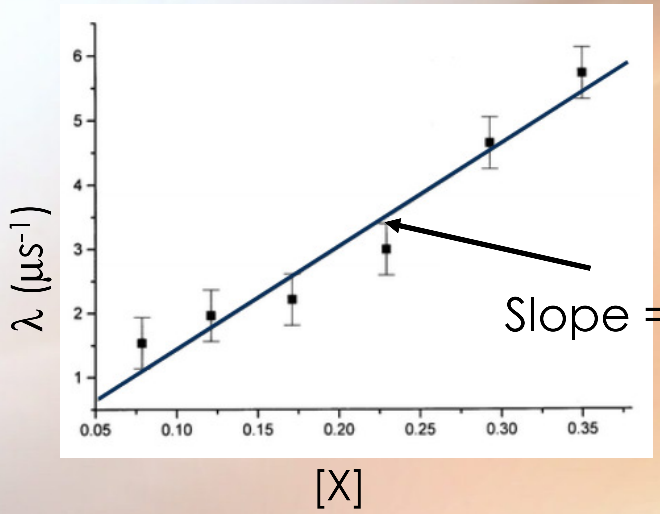
Measuring Mu• reaction rates

$$\lambda = \lambda_0 + k_{MU}[X]$$

Concentration of reactant X

Relaxation rate
In pure solvent

Pseudo 1st order
Rate constant



Slope = k_{MU} ($M^{-1}s^{-1}$)

Rate window
$10^5\ M^{-1}s^{-1} < k_{MU} < 10^{10}\ M^{-1}s^{-1}$

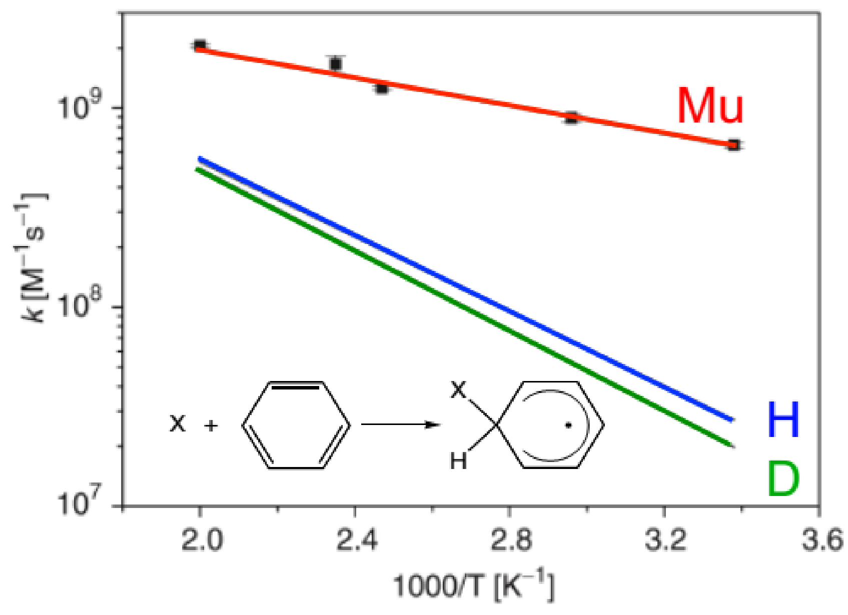
Muonium kinetics

Formation of muoniated radicals

Addition reactions
$k_{Mu} > k_H$

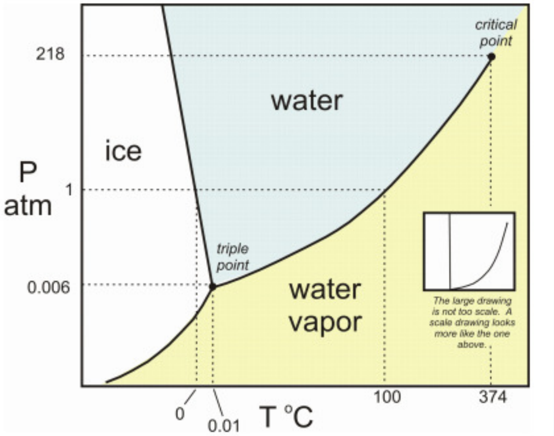
Diffusion controlled
Kinetic isotope effect

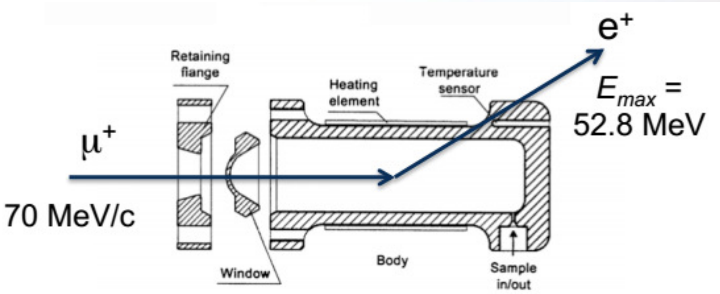
(Abstraction reactions
$H_2 + Mu^\bullet = MuH + H^\bullet$)

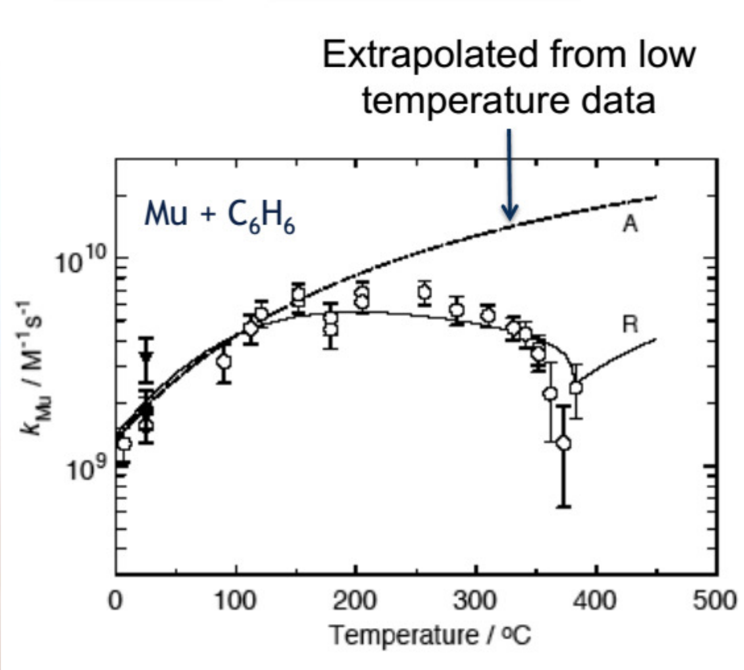


E. Roduner et al. Ber. Bunsenges. Phys. Chem. 94(1990) 1224

Extreme Environments

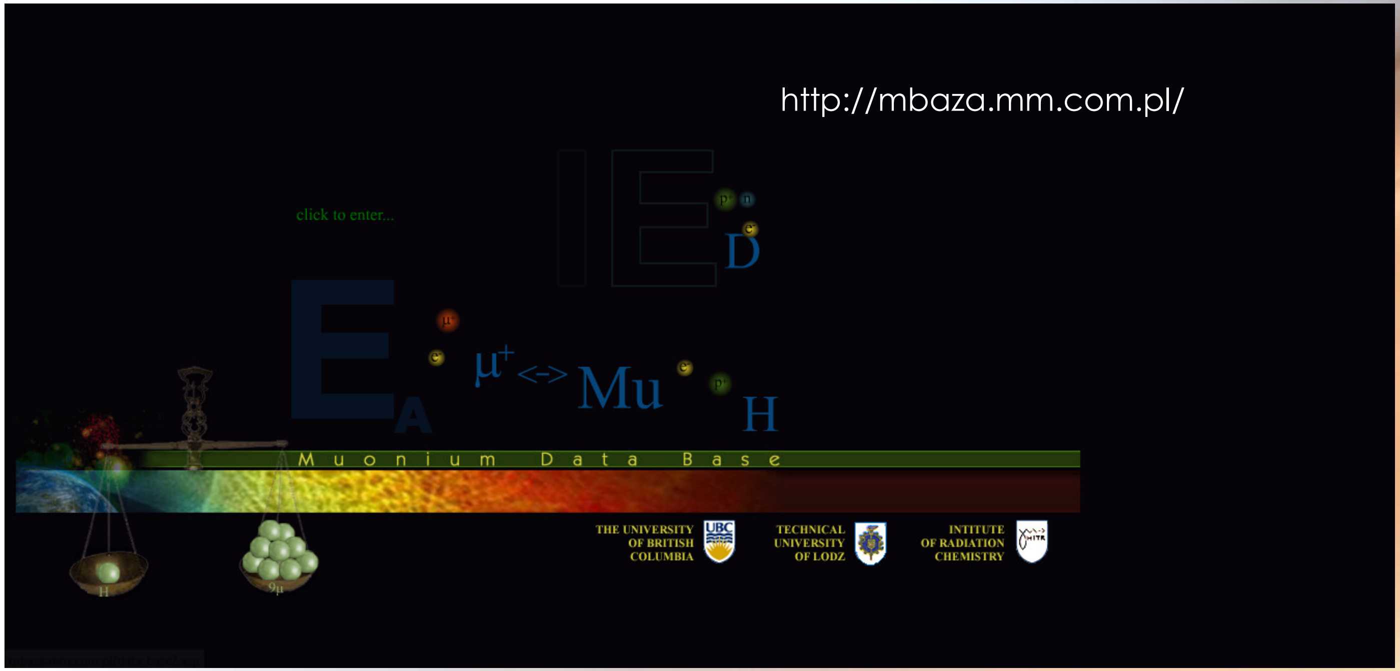






Phys. Chem. Chem. Phys., 2002, 4, 586–595

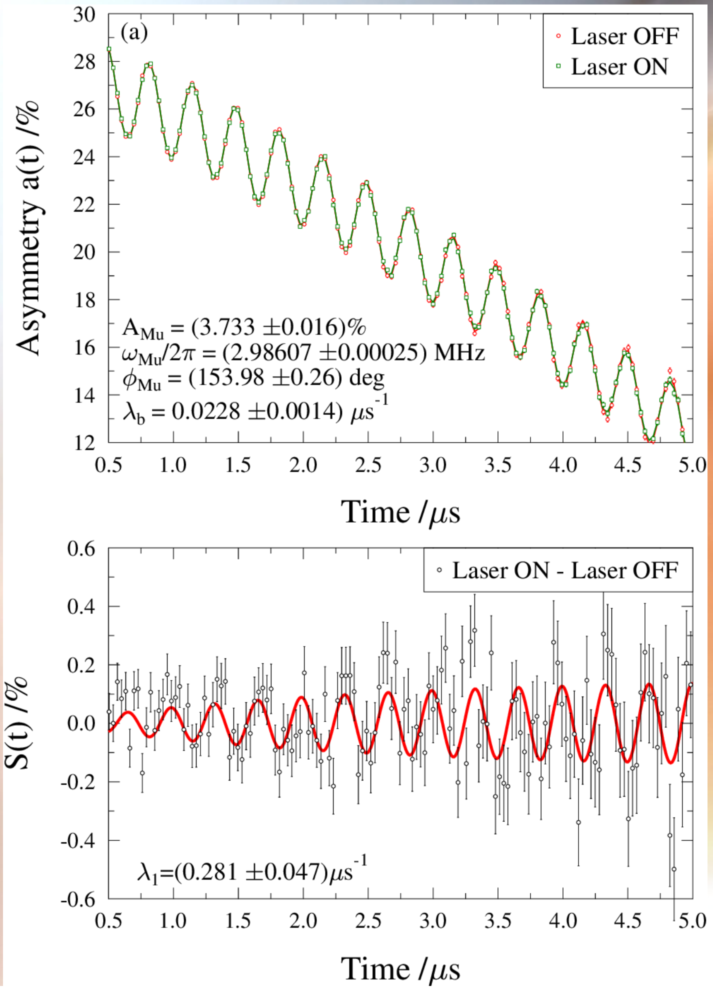
Compilation of muonium reaction rates



http://mbaza.mm.com.pl/

Combination experiments

- Combine muons with laser irradiation
- Excite H_2 to v=1
- $H_2(v=1)+Mu^\bullet$ reaction
- Explore reactivity in non-equilibrium states



Summary

- Muoniums, low asymmetry in 20 G TF and LF
- Requires > kG for LF repolarisation (ISIS)
- High precession frequency (PSI/TRIUMF)
- Kinetics (dynamics/diffusion) from excess relaxation rate
- Reacts to give muoniated radicals
- Extensive database of muonium reaction rates
- Novelty, extreme conditions of temperature and pressure

Muoniated radicals

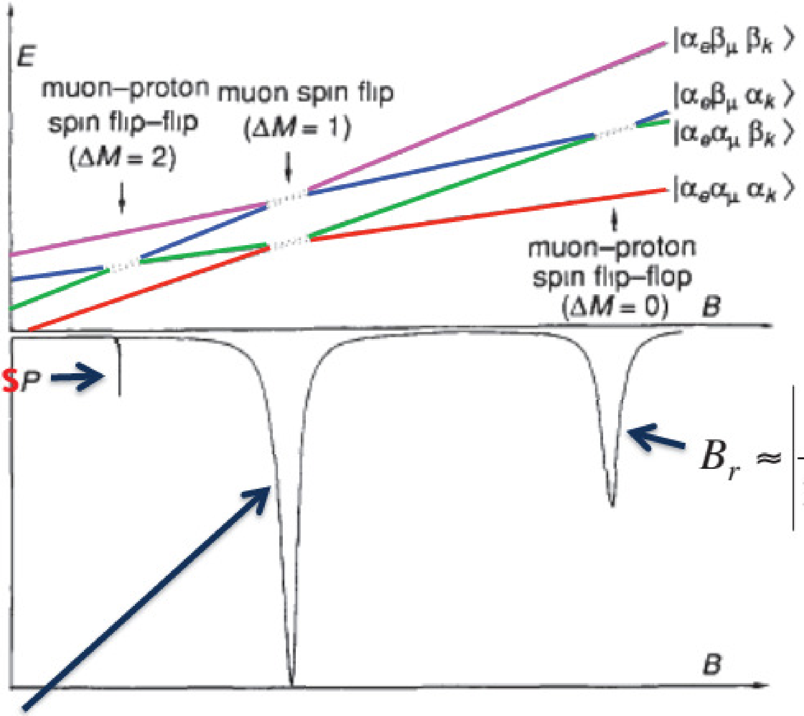
Muoniated radicals

- System chosen to generate such species
- Presence of unsaturated carbon centre
  - Intrinsic
  - Target added, benzene will give muonio cyclohexyldienyl radical
- Hyperfine coupling constants sensitive to environment
- Chemical exchange/dynamics averages hyperfine coupling constants
- Kinetics and dynamics from excess relaxation rates

Avoided Level Crossing Muon Spin Resonance Spectroscopy (ALC-μSR)

- Depolarisation when e, Mu, H energy levels would cross
- Gives A_H rather than A_μ
- Generally better signal-to-noise
  - Improved count rates
  - No dephasing problem with slow forming radicals
- Initial problem, defining range of the magnetic field swept
- Three transitions possible, $\Delta M = 0,1,2$

ALC-μSR of Muoniated Radicals



ΔM=2 Resonances

Narrow and weak.
Rarely observed.

ΔM=0 Resonances

$$B_r \approx \left| \frac{A_\mu - A_k}{2(\gamma_\mu - \gamma_k)} - \frac{A_\mu + A_k}{2\gamma_e} \right|$$

Observed in solids, liquids and gases.

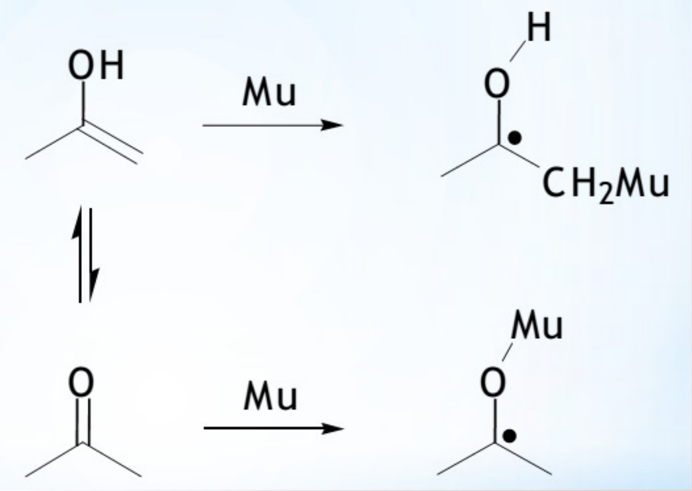
ΔM=1 Resonances

Sensitive indicator of reorientation dynamics on timescale of 20 - 50 ns.

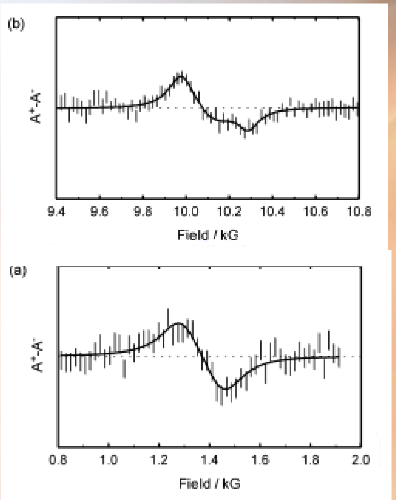
$$B_r = \left[\frac{A_\mu}{2\gamma_\mu} - \frac{A_\mu}{2\gamma_e} \right]$$

Extreme environments

Example of radical trapping to follow an equilibrium



Equilibrium in water

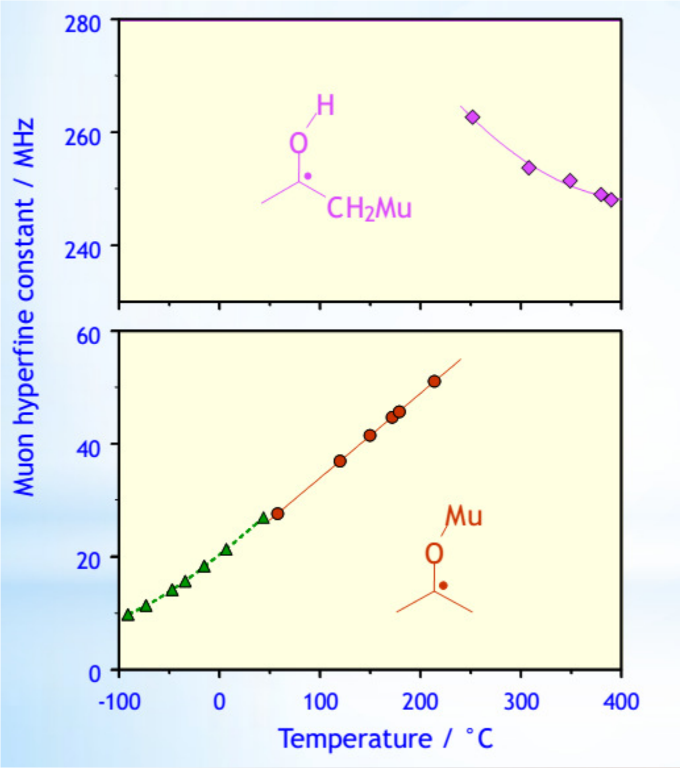


350° C
250 bar

92°
136 bar

ALC-MuSR spectra of enol and keto radicals

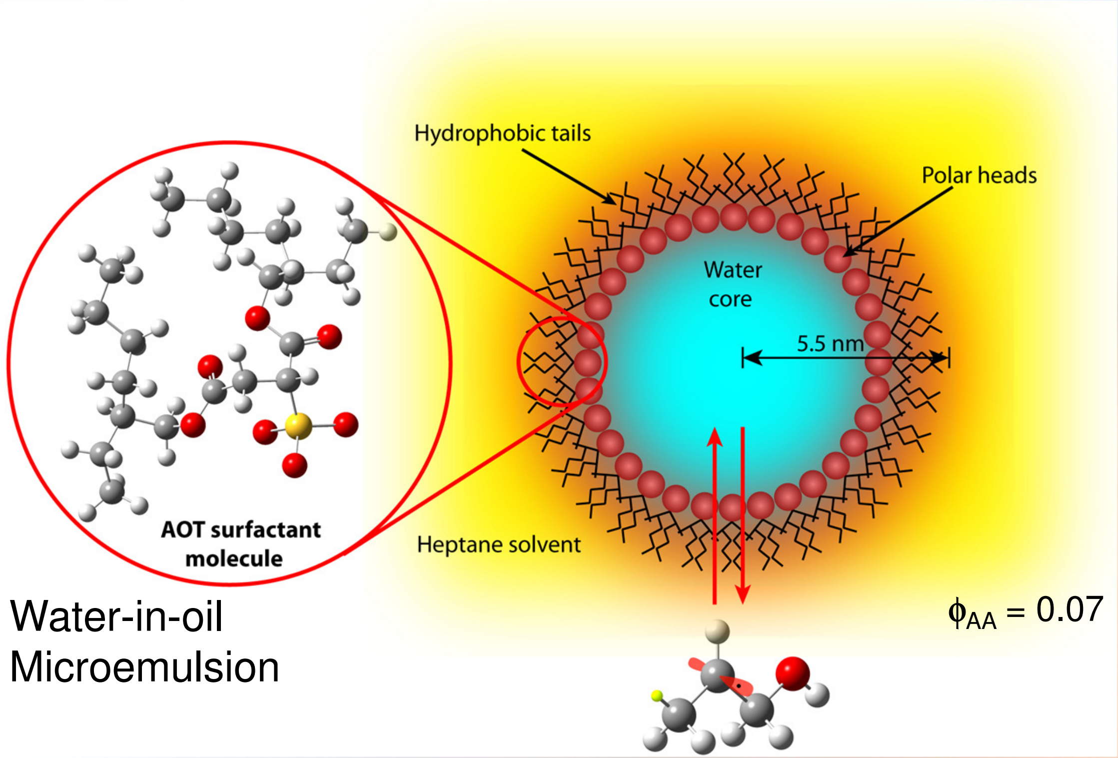
Extreme environments



Ghandi, Addison-Jones, Brodovitch, McCollum, McKenzie, and Percival, JACS 125 (2003) 9594.

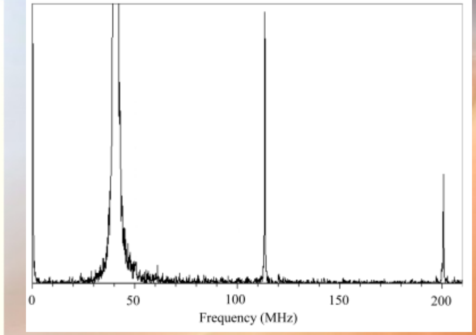
Interfacial transfer

Langmuir 2016, 32, 664-672



Water-in-oil Microemulsion

$\phi_{AA} = 0.07$

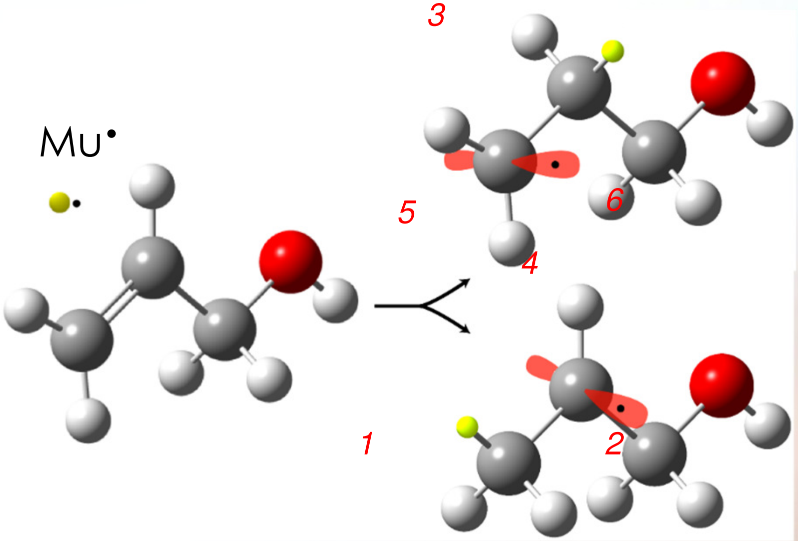


TF-MuSR of AA in microemulsion

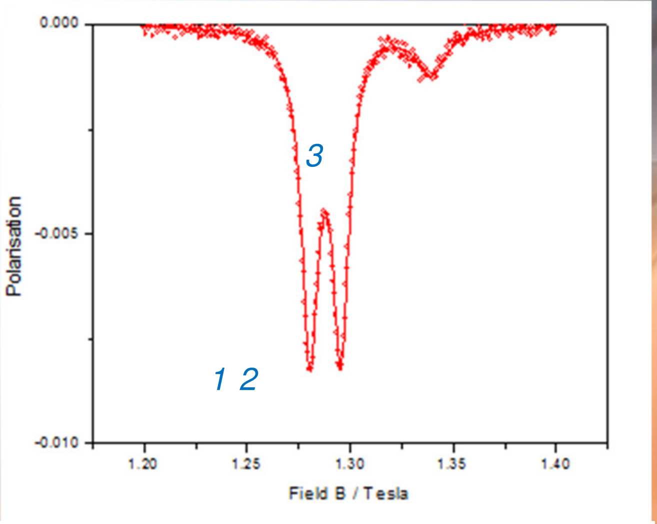
Muoniated Allyl Alcohol (AA) Radical

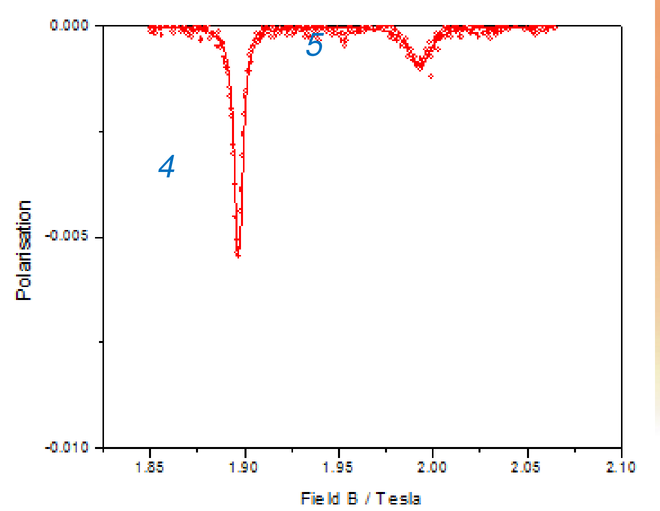
(AA is CH_2=CH-CH_2-OH)

Interfacial transfer



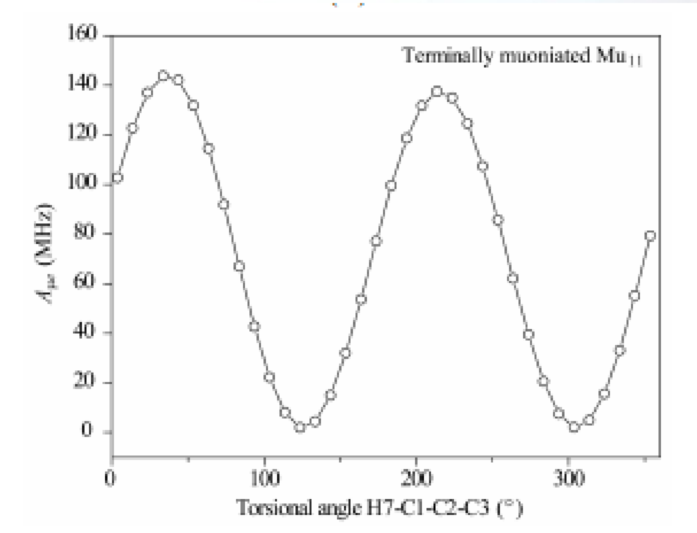
ALC-MuSR of AA in heptane

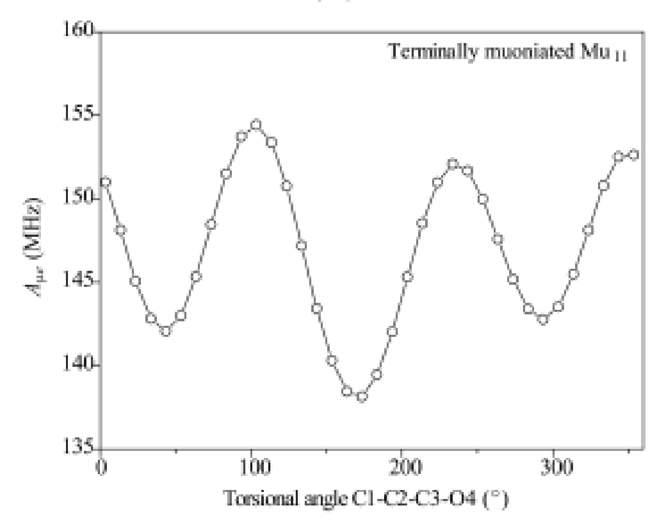




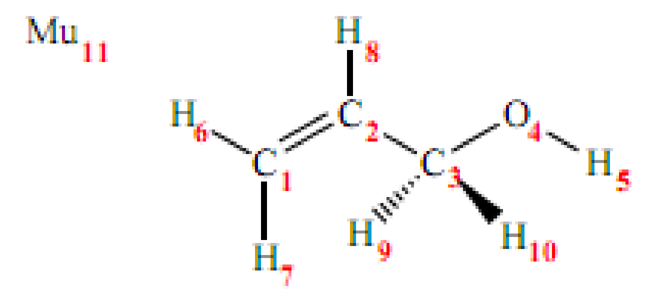
DFT calculation of hyperfine coupling constants

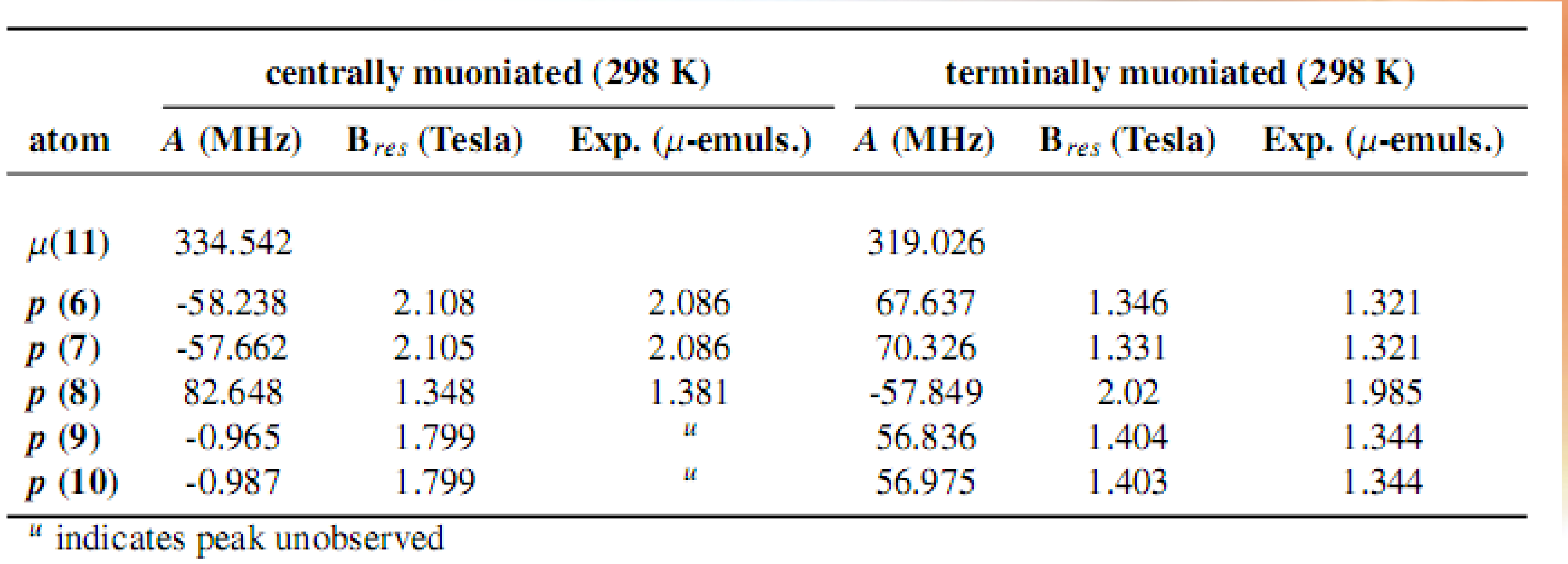
- B3LYP hydrid GGA functional : EPR-III basis set (triple zeta)
- Gaussian 03
- Gas phase calculation, averaging over two torsional oscillations ca 100 cm^{-1} required





DFT calculations

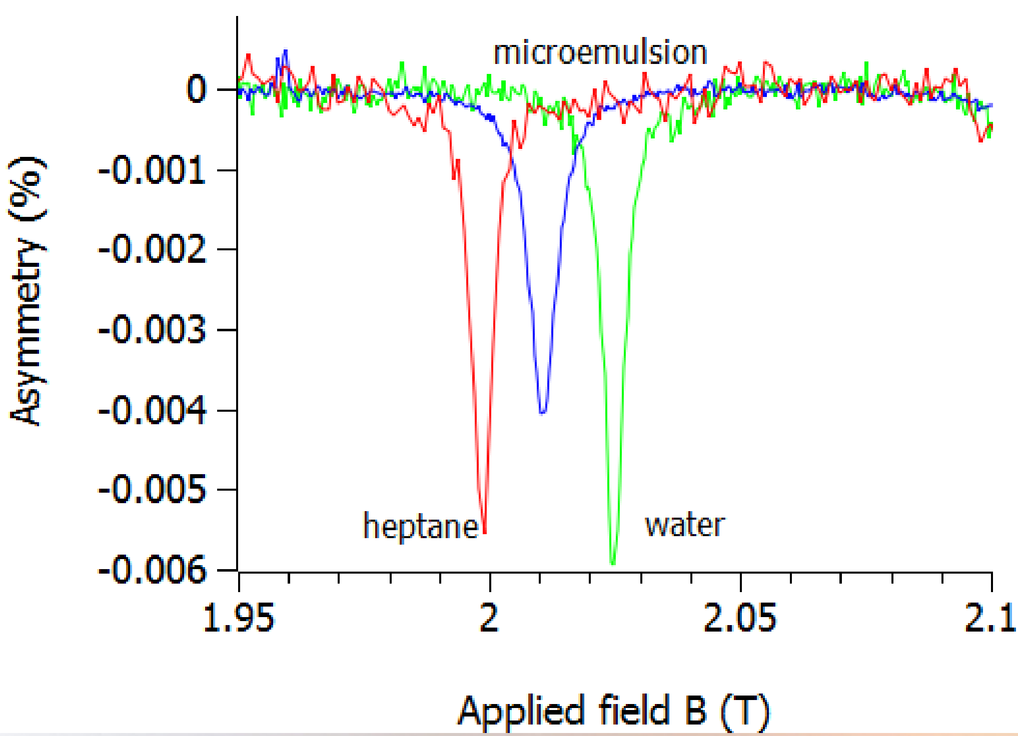




atom	centrally muoniated (298 K)			terminally muoniated (298 K)		
	A (MHz)	B_{res} (Tesla)	Exp. (μ-emuls.)	A (MHz)	B_{res} (Tesla)	Exp. (μ-emuls.)
μ(11)	334.542			319.026		
p (6)	-58.238	2.108	2.086	67.637	1.346	1.321
p (7)	-57.662	2.105	2.086	70.326	1.331	1.321
p (8)	82.648	1.348	1.381	-57.849	2.02	1.985
p (9)	-0.965	1.799	^{u}	56.836	1.404	1.344
p (10)	-0.987	1.799	^{u}	56.975	1.403	1.344

^{u} indicates peak unobserved

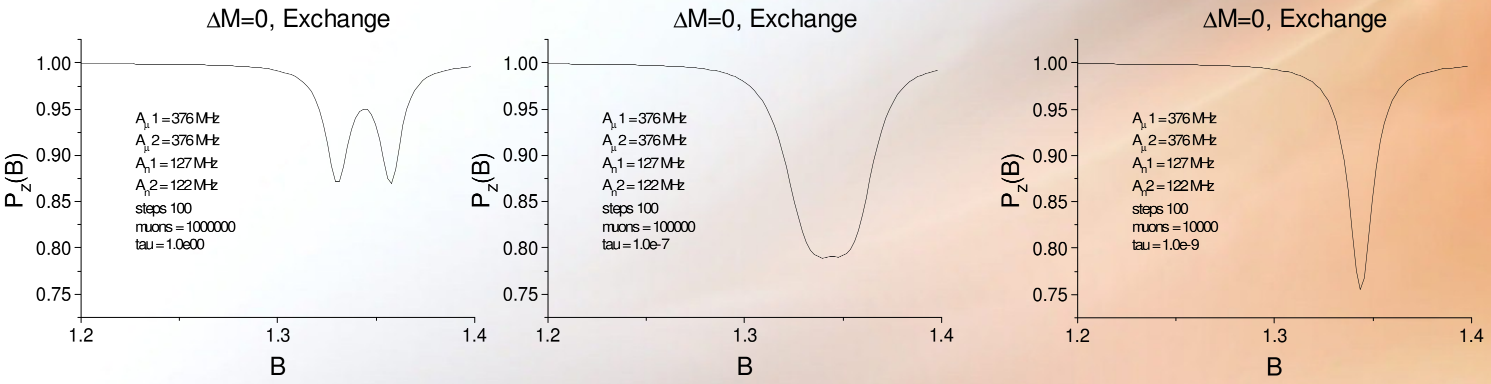
Chemical exchange



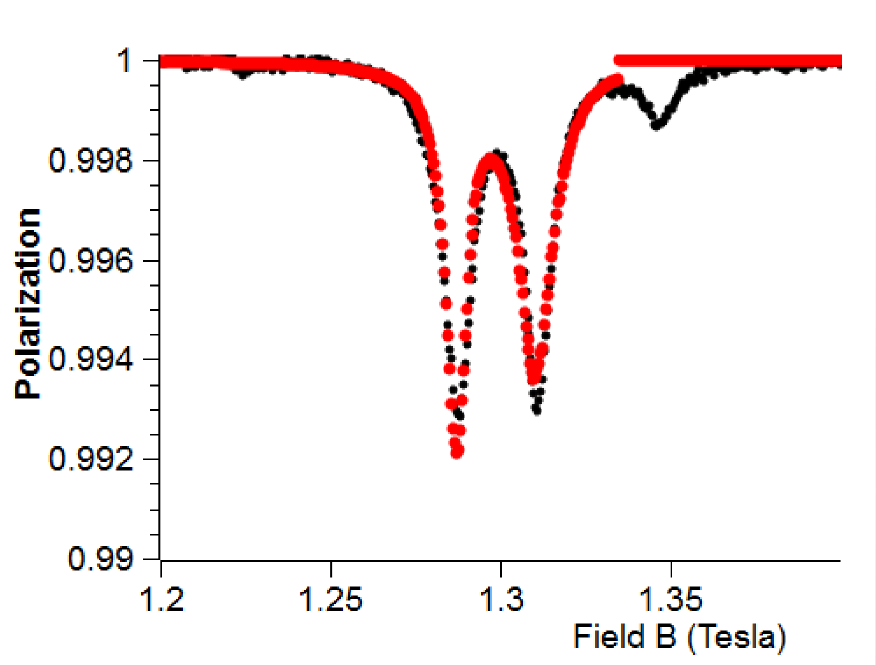
ALC-MuSR spectrum at 280 K
showing peak 4

Simulation of ALC spectra

- Monte-Carlo (Tregenna-Piggott, Roduner)
- QUANTUM (Lord)



Simulation of ALC spectrum



$\tau = 6.5 \times 10^{-9}$ s

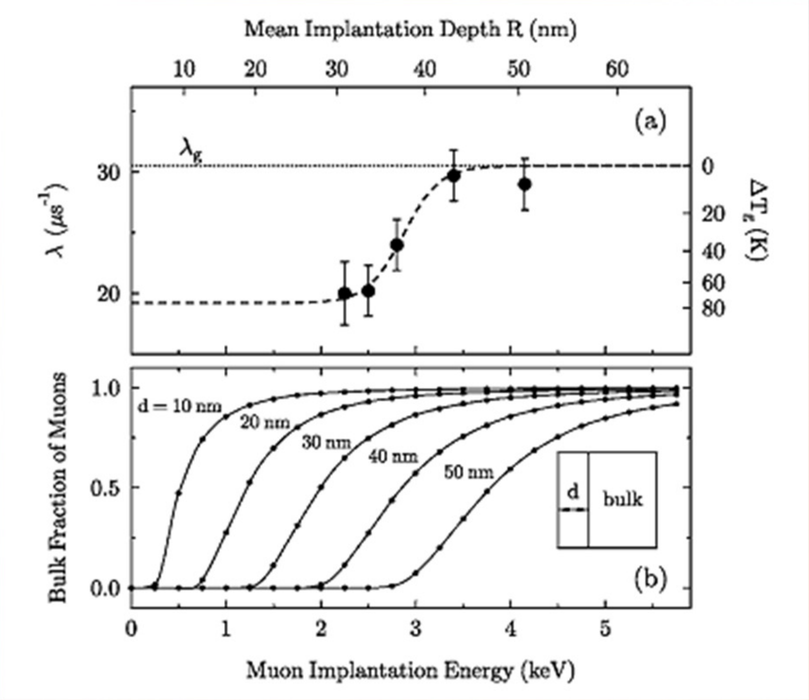
(1.53×10^{8} s^{-1})

For the process

$RMu^{\bullet}_{oil}$: Mi = {$RMu^{\bullet}_{water}$:Mi}

Surface dynamics

- Typical penetration depth, 4.1 MeV, mm’s
- Slow muons, moderator
  - Only at PSI
  - Ag foil 125 mm, layer of van der Waal gas N_2 on Ar at 20 K
- Polystyrene
  - Muniocyclohexadienyl radical
  - Bulk T_g, more static λ_g
  - Surface, more mobile



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Summary

- Muoniated radicals formed by reactions between muonium and unsaturated centres
- Intrinsic or added target molecules
- Identify through repolarisation and hyperfine coupling constant
- Monitor radical kinetics and dynamics through λ
- Hyperfine coupling constants sensitive to environment
- Location and exchange between sites
- ALC Δ_1 shapes sensitive to dynamics