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Muons in Magnetism

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Local Magnetic Probe

The muon responds to static and dynamic local magnetic fields at the muon site with contributions from

1) Electronic spins: Dipolar and hyperfine coupling to the muon

2) Nuclear spins: Weak dipolar coupling to the muon

Magnetic dipolar coupling: $$\mathrm{B}_{\mathrm{dip}}(\mathbf{r}_\mu) = \frac{\mu_0}{4\pi}\sum_i \frac{3(\mathbf{m}_i \cdot \hat{\mathbf{r}}_{i\mu})\hat{\mathbf{r}}_{i\mu} - \mathbf{m}_i}{|\mathbf{r}_\mu - \mathbf{r}_i|^3}$$

Fermi contact hyperfine coupling: $$A = \frac{2\mu_0}{3}\gamma_\mu\gamma_e\rho(\mathbf{r}_\mu)$$

Scaling ratio electronic to nuclear:

$\mu_B / \mu_N = m_e / m_p = 1835$

What makes μSR appealing for magnetism?

- μ^+ is a local sensitive probe
- You can study weak moment system
- Can study dilute magnetism
- True ZF measurements – important for critical behaviour
  - Measure critical exponents
- Pick apart both static and dynamic magnetic behaviours
- You are looking at the MHz time range
  - AC susceptibility tends to be slower
  - Neutron scattering is faster
  - NMR varies but can be kHz

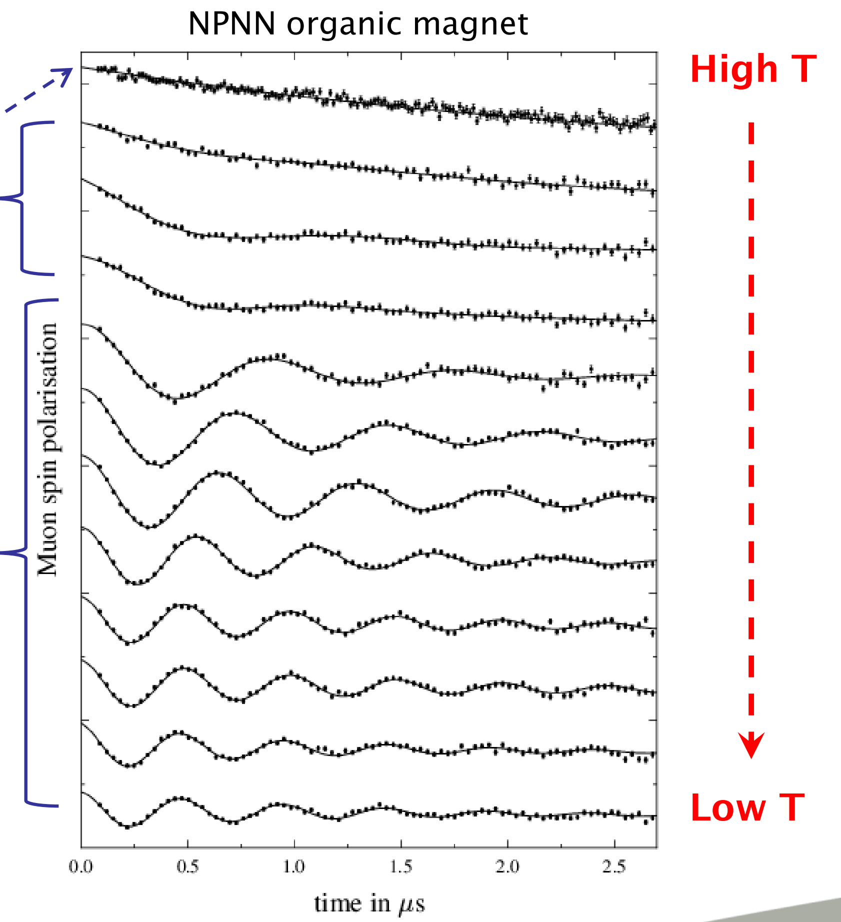
Magnetic Transitions

Characteristic regions versus temperature T

Paramagnetic ($T>T_c$): weak static nuclear moments dominate

Critical ($T\sim T_c$): electronic fluctuations plus weak static moments from both electrons and nuclei

Ordered ($T<T_c$): static electronic moments dominate

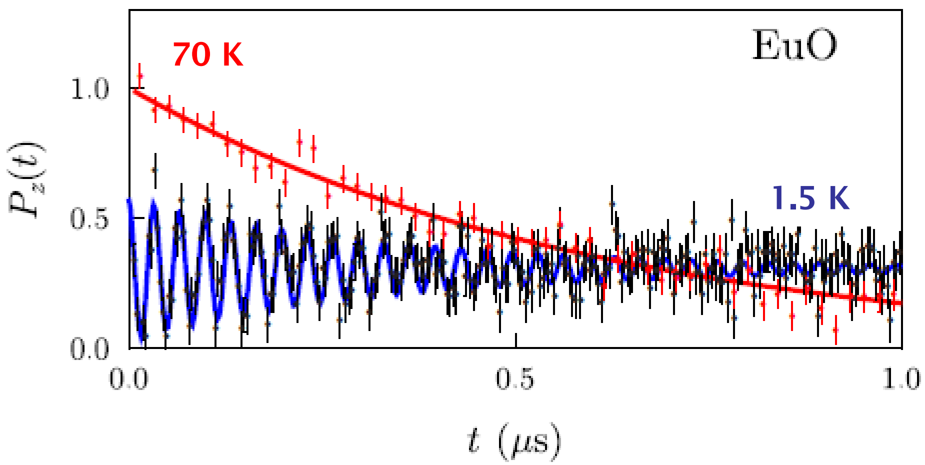


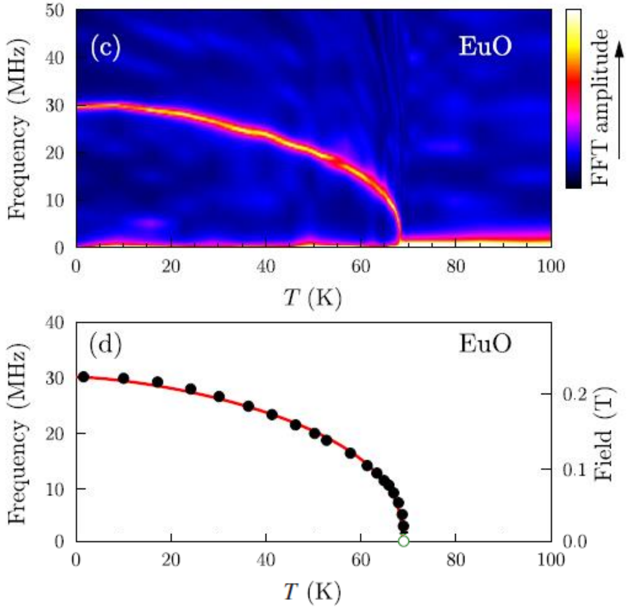
P.A. Pattenden et al,
Synth. Met. 71, 1823 (1995)

Simple Example

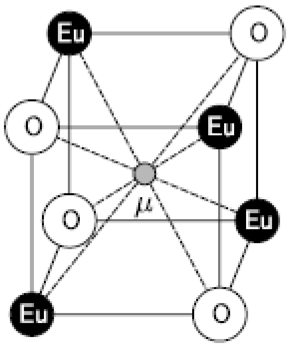
Local moment ferromagnet EuO

Nearly ideal example of a Heisenberg magnet





S.J. Blundell et al,
Phys. Rev. B 81, 092407 (2010)



Single high symmetry muon site

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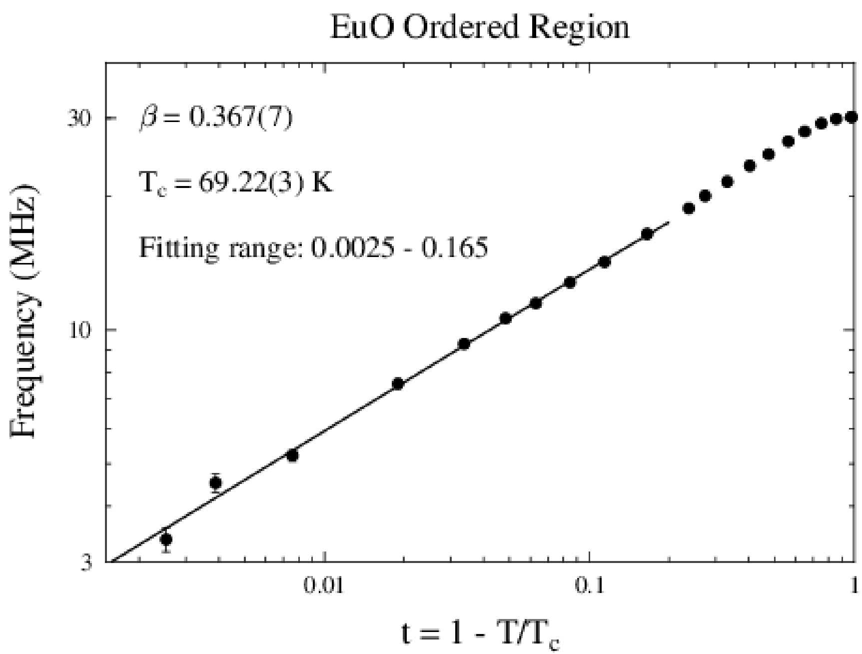
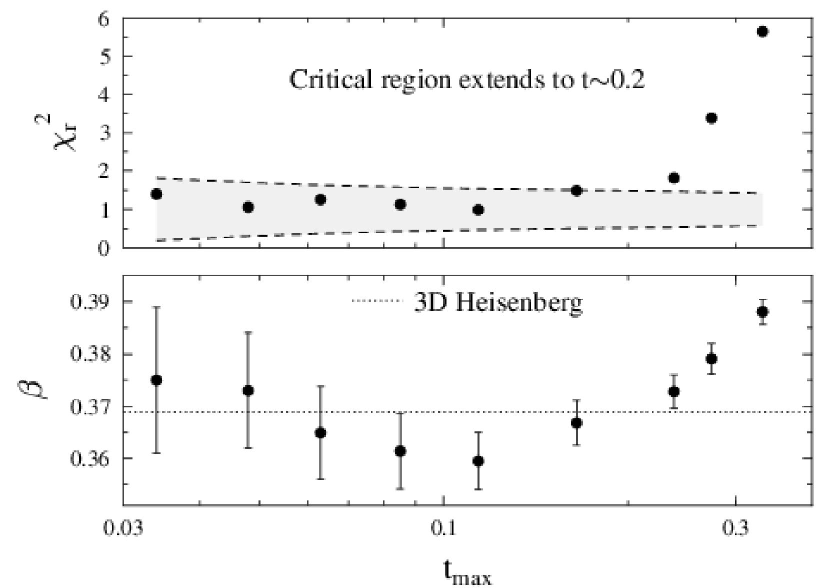
Critical Behaviour

Precession frequency scales with the magnetic order parameter M which follows the power law scaling $M \propto (T_N - T)^{\beta}$



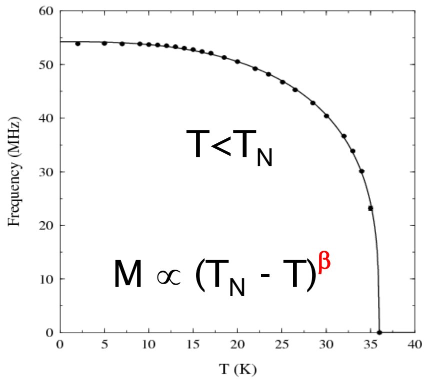


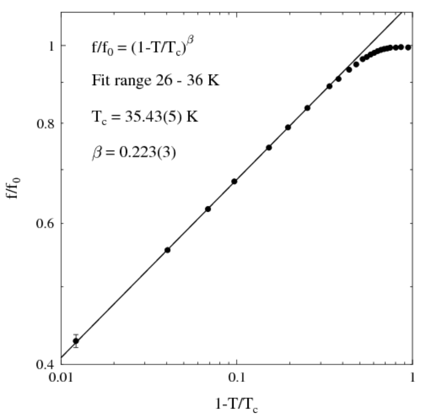
Critical exponent β reflects the 'universality class' of the system

Exponents Obtainable by μSR

Order parameter

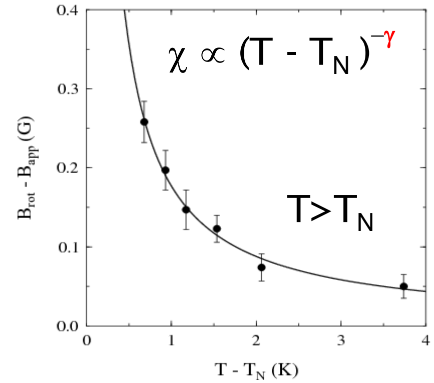
(ZF precession)

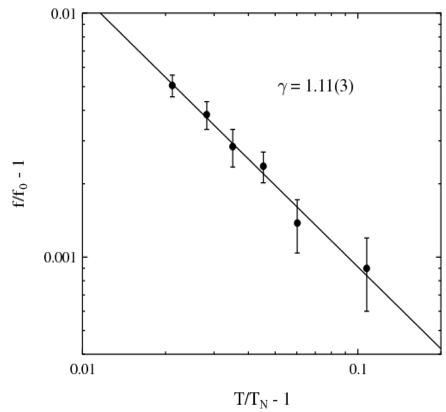




Local susceptibility

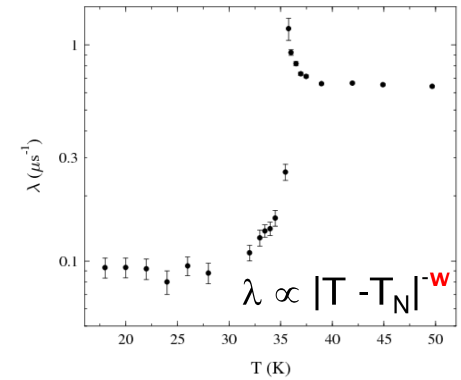
(TF frequency shift)

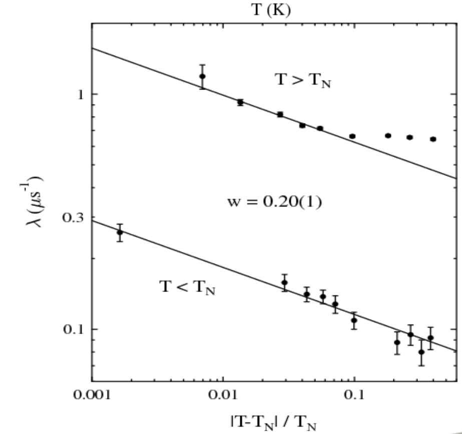




Spin correlation time

(relaxation rate)



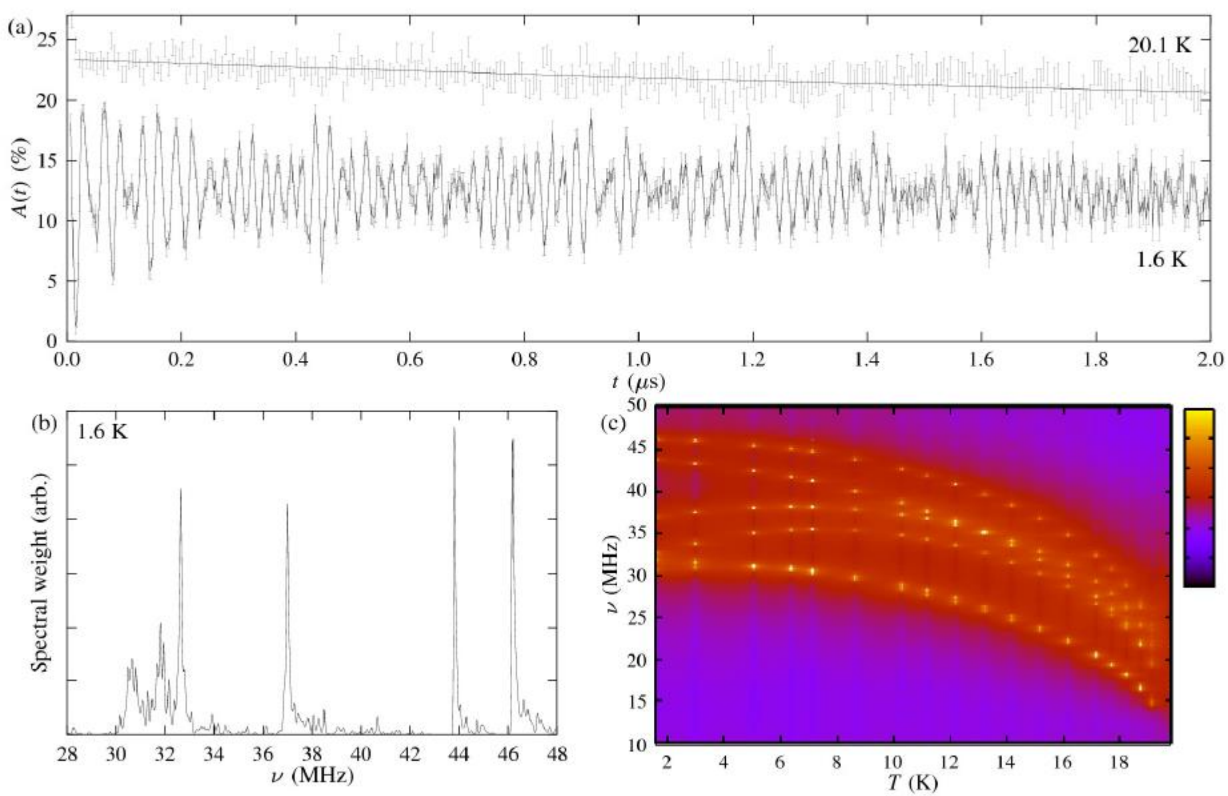


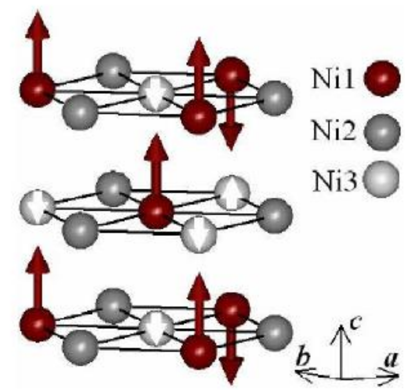
Can obtain the full critical exponents set just from μSR (in the ideal case)

F.L. Pratt et al,
Phys. Rev. Lett. 99, 017202 (2007)

Multiple Sites & Complex Order

$AgNiO_2$: a triangular lattice system with coupled charge and spin order



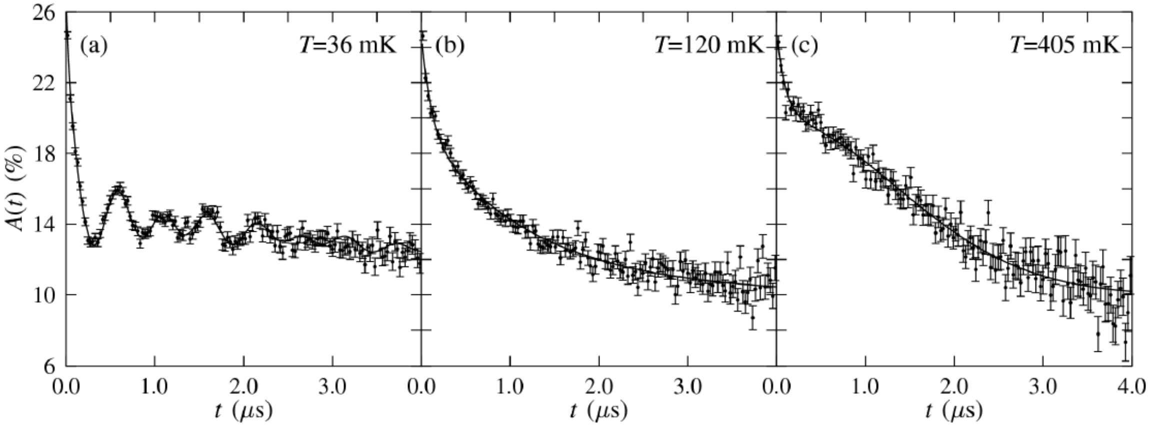


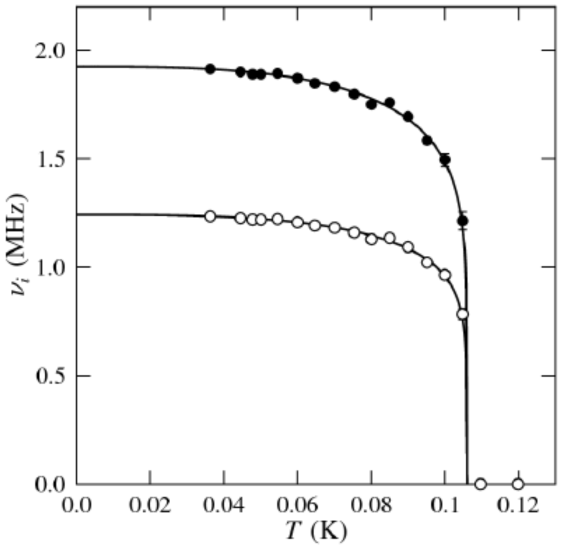
Six magnetically distinct sites

T. Lancaster et al,
Phys. Rev. Lett. 100, 017206 (2008)

Weak Moments

$Cu(NO_3)_2(pyz)$: S=1/2 Heisenberg AF spin chain





Ordered moment is 0.13 μ_B and T_N is 107 mK

T. Lancaster et al,
Phys. Rev. B 73, 020410(R) (2006)

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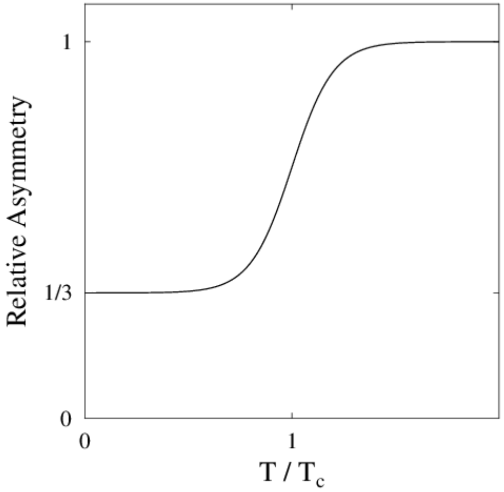
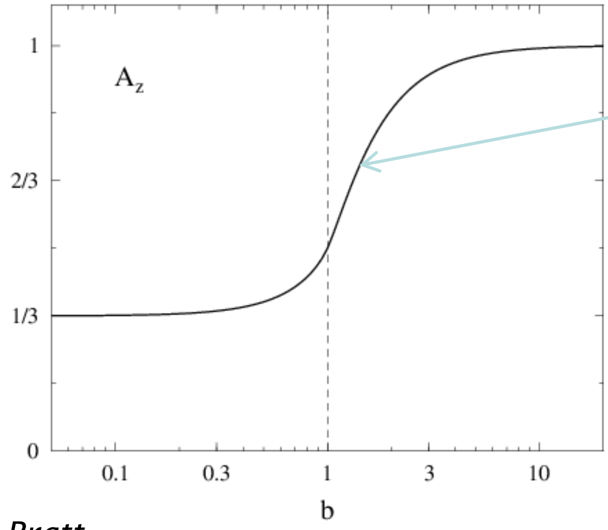
Repolarisation

For polycrystalline samples the time-averaged asymmetry drops to 1/3 when the sample is cooled into a static ordered state



This asymmetry can be recovered by applying a longitudinal field in the ordered state



$$A_z(b) = \frac{3}{4} - \frac{1}{4b^2} + \frac{(b^2-1)^2}{8b^3}\log\left|\frac{b+1}{b-1}\right|$$

$b = B / B_0$

This provides an alternative estimate of the local field B_0

F.L. Pratt
J. Phys.:Condens. Matter 19, 456207 (2007)

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Spin Dynamics

Correlation function for local field fluctuations (simple relaxation model):

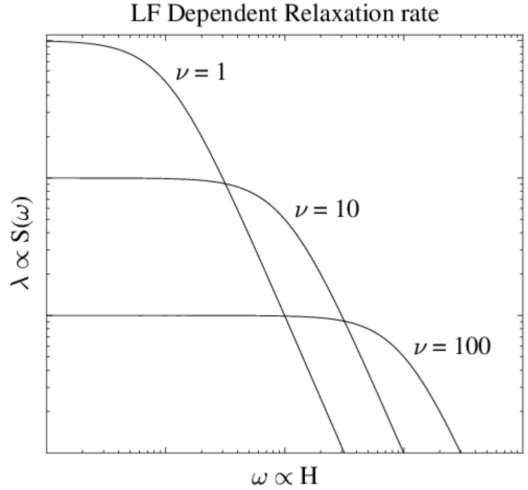
$$\Phi(t) = \frac{\langle B(t)B(0)\rangle}{\langle [B(0)]^2\rangle} = e^{-\nu t}$$

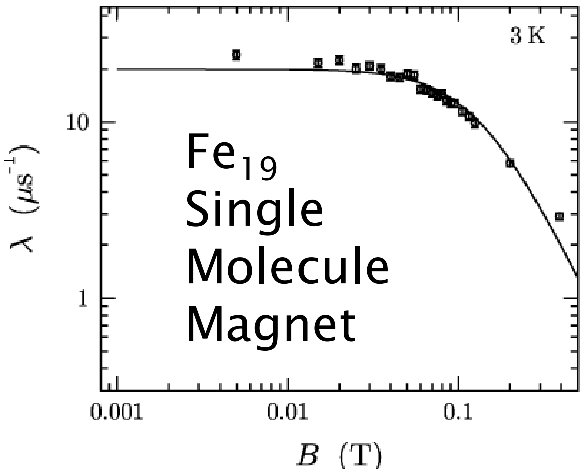
Fourier transform of $\Phi(t)$ gives spectral density $S(\omega)$

$$S(\omega) = \frac{\nu}{\nu^2+\omega^2}$$

Muon spin relaxation rate $\lambda \propto S(\omega)$, where $\omega \propto H$, the applied magnetic field

Complex relaxation processes such as spin diffusion produce different forms for $\Phi(t)$ and $S(\omega)$





S.J. Blundell et al, Physica B 326, 556 (2003)

Summary

Muon gives local probe of static and dynamic magnetic fields

Some particular strengths of μSR for magnetic studies:

- Weak magnetic phenomena
- Low temperature magnetic transitions
- Antiferromagnets
- *Weak but uniform* magnetism versus *dilute phase* magnetism