μSR

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ISU Physics-590B 01 March 2019

What is μSR?

μSR is one of a group of nuclear precession probes used to study condensed matter systems.

As a *time domain* (rather than energy domain) measurement, it is best suited to systems in which the local fields are small.

(Reminder: Mössbauer spectroscopy is an *energy domain* measurement.)

What is μS**R**?

Depending on who you ask, the "R" stands for:

- Rotation
- Resonance
- Relaxation

The majority of actual experiments involve watching the muon precess while the polarisation decays, so, *none of the above*.

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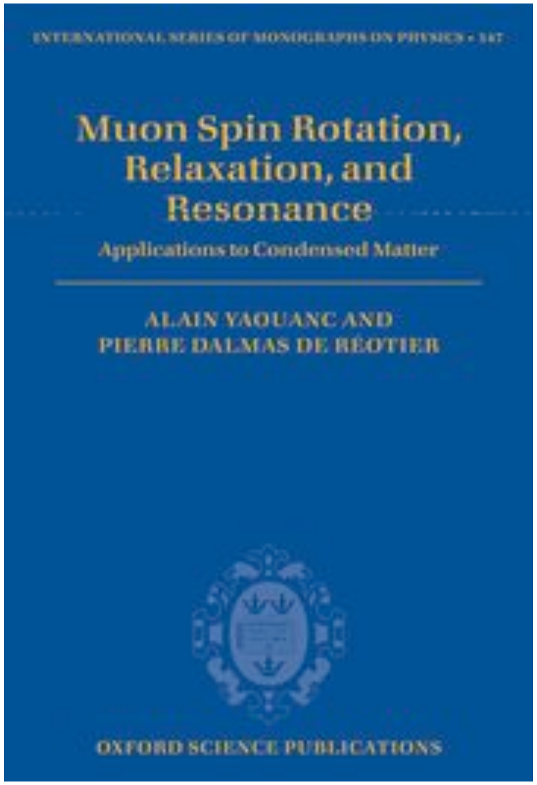
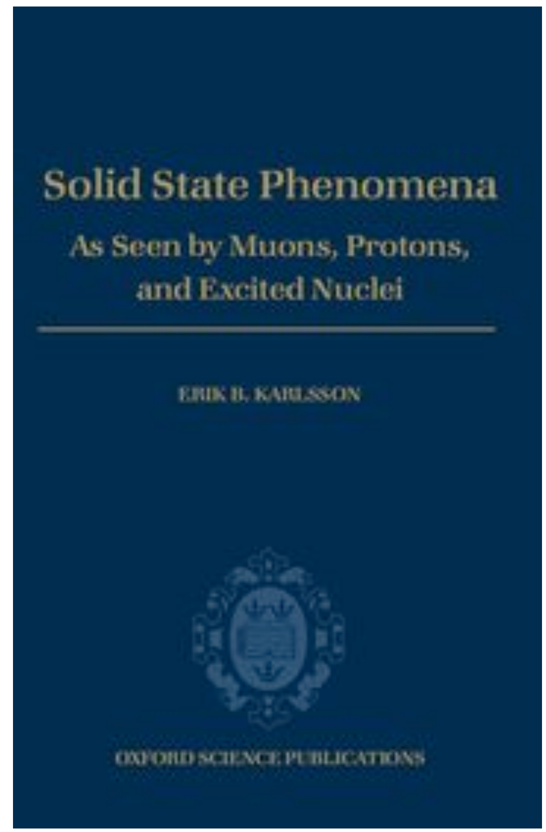
Two useful books



Muon Spin Rotation, Relaxation, and Resonance
Alain Yaouanc and Pierre Dalmas de Reotier



Solid State Phenomena
As Seen by Muons, Protons, and Excited Nuclei
Erik B. Karlsson

What is a muon?

The muon is a lepton (fundamental particle) and along with its lighter (electron) and heavier (tau) cousins, and their associated neutrinos they form a family of particles that interact via the weak force (and EM).

Muons are produced primarily through the decay of pions and are a major component of cosmic rays, with 3-4 passing through the top of your head every second.

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How are they made?

Whack 500MeV protons into a light-element target (graphite is a favourite choice) to make pions and “arrange” for them to come to rest near the surface of the target.

The pions fall apart almost immediately (26ns) emitting 4MeV muons:

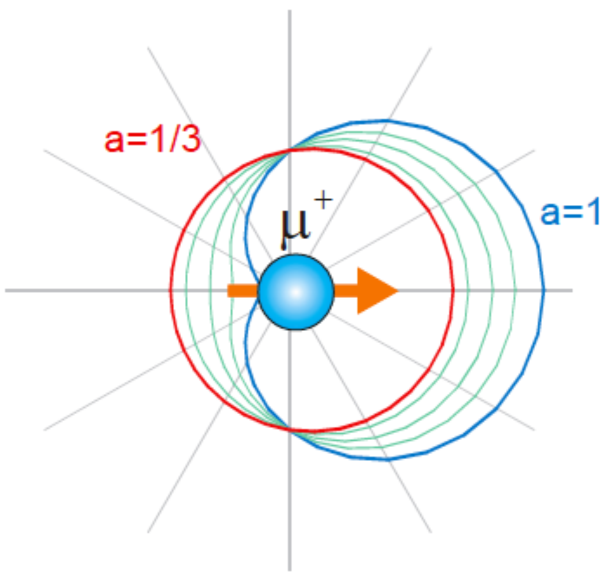
$$\pi^+ \longrightarrow \mu^+ + \bar{\nu}_\mu$$

Thanks to the maximal parity violation in the weak decay, the muons are perfectly spin polarised opposite to their momenta.

The muons are collected, isolated from other decay products and delivered to the target where they decay (2.2μs) by emitting a rather energetic (up to 52MeV) positron:

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

The decay positron is emitted preferentially in the direction of the muon moment.



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

$$a(52\text{MeV}) = 1$$

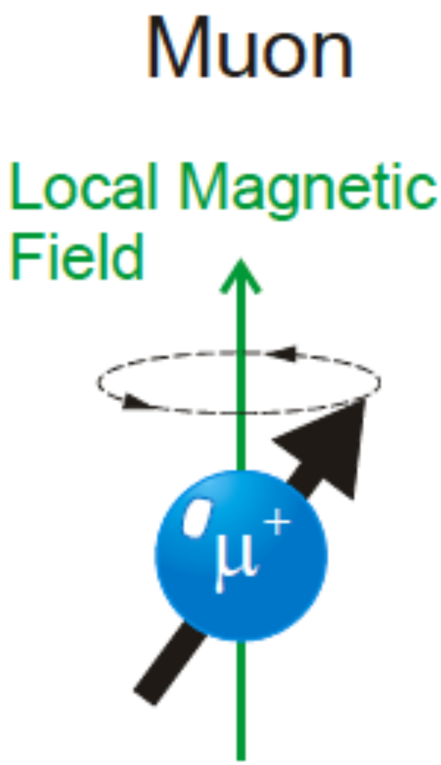
$$a(26\text{MeV}) = ⅓$$

The experiment…

We know which way the muon moment was pointing when it arrived (backwards) and by measuring which way the positron goes when the muon decays, we can know which way the muon moment was pointing when it decayed.

Why would the moment direction change?

Larmor precession



Put a magnetic moment in a field and it will precess.

Neutron: 29.16 MHz/T
Proton: 42.58 MHz/T
Muon: 135.53 MHz/T

So, if we can measure the precession frequency then we can know the field seen by the muon.

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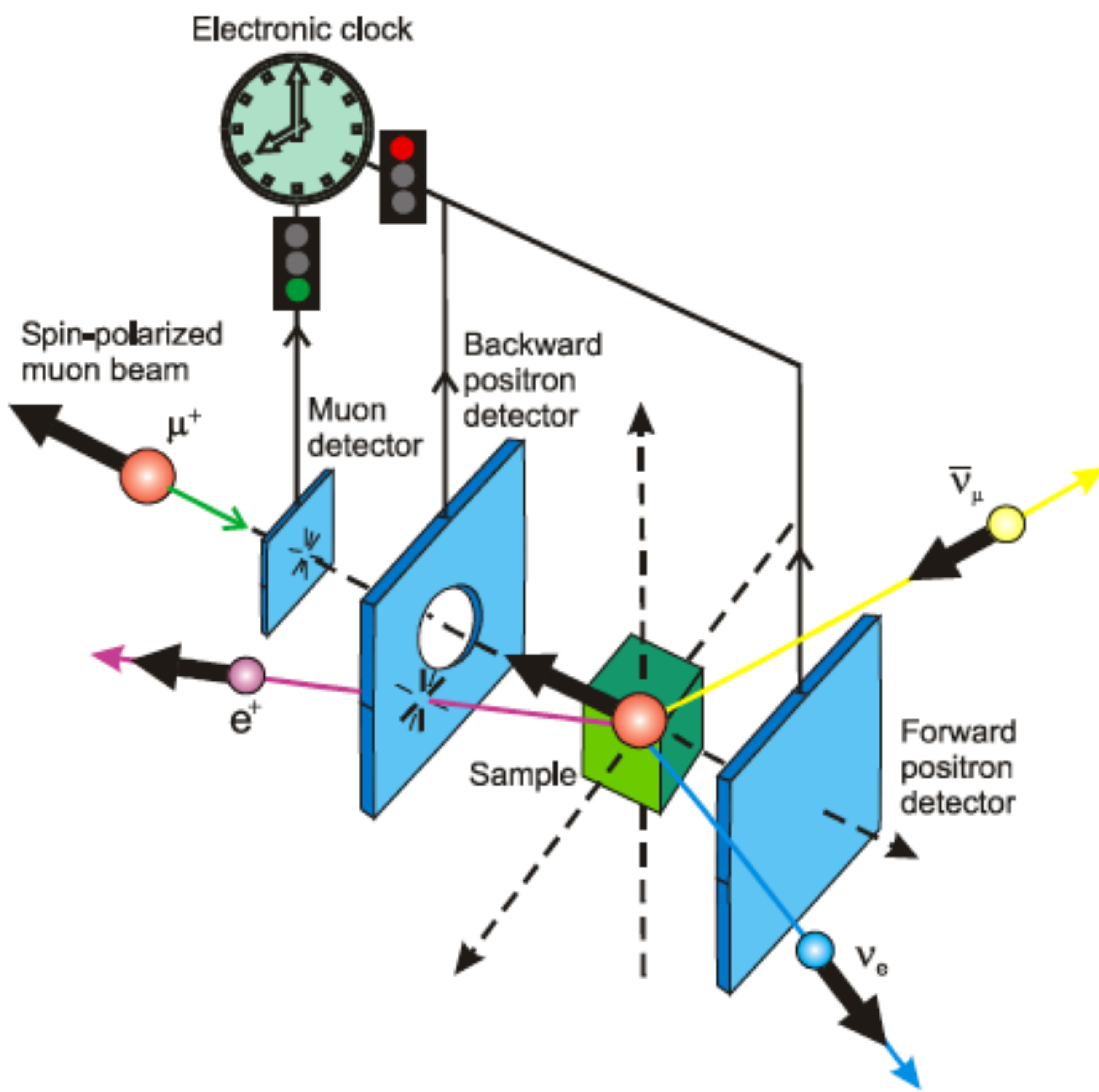
Mechanics


Electronic clock
Spin-polarized muon beam
μ^+
Muon detector
Backward positron detector
$\bar{\nu}_\mu$
e^+
Sample
Forward positron detector
ν_e

CW process (TRIUMF)

- Wait for a muon to hit the arrival detector. **Start** the clock.
- Prompt hit on forward (F) detector ⇒ **Veto** (muon did not stop in the sample)
- Wait for a hit in either the F or B detectors. **Stop** the clock.
- Record time and which detector was hit.
- If you get a second arrival hit before you see an exit hit ⇒ **Veto** (two muons in the sample)
- If you do not get an exit hit within 10 (you choose) muon lifetimes ⇒ **Veto** (the positron missed your detectors)

Pulsed process (ISIS)

- Pulse of ~1000 muons all arrive together (~50ns wide)
- Wait for the misses to pass through.
- Record times and which detectors are hit as the muons decay.
- Wait for the next pulse (50Hz)

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Facilities

CW:
TRIUMF (CANADA)
PSI (Switzerland)

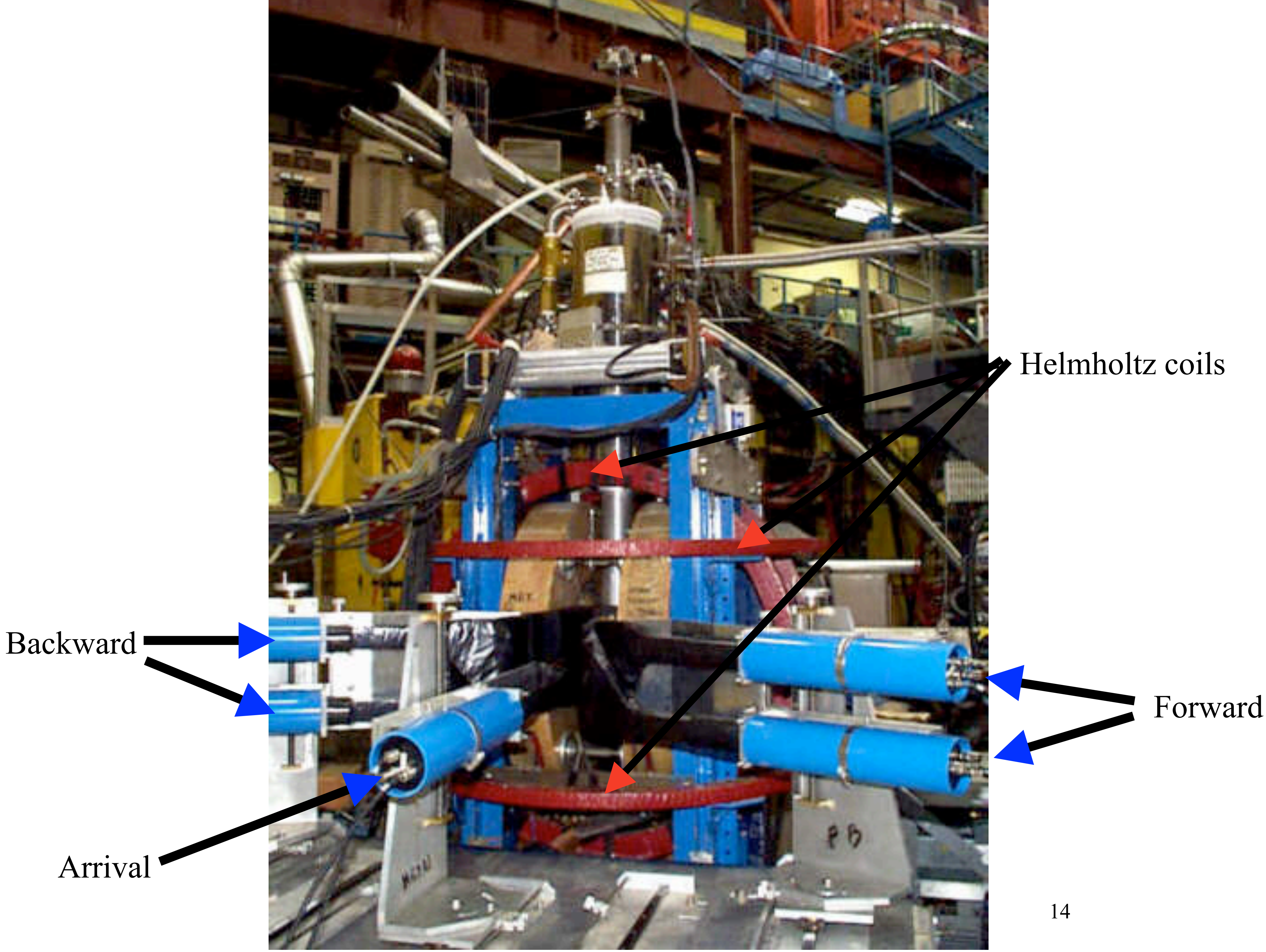
Strengths:
Time resolution <1ns
Early time data

Weaknesses:
Low data rates
Poor backgrounds
Limited long-time data

Pulsed
ISIS (England)

Strengths:
High data rates
Clean backgrounds
Great long-time data

Weaknesses:
Very limited time resolution (50-100ns)
No early time data



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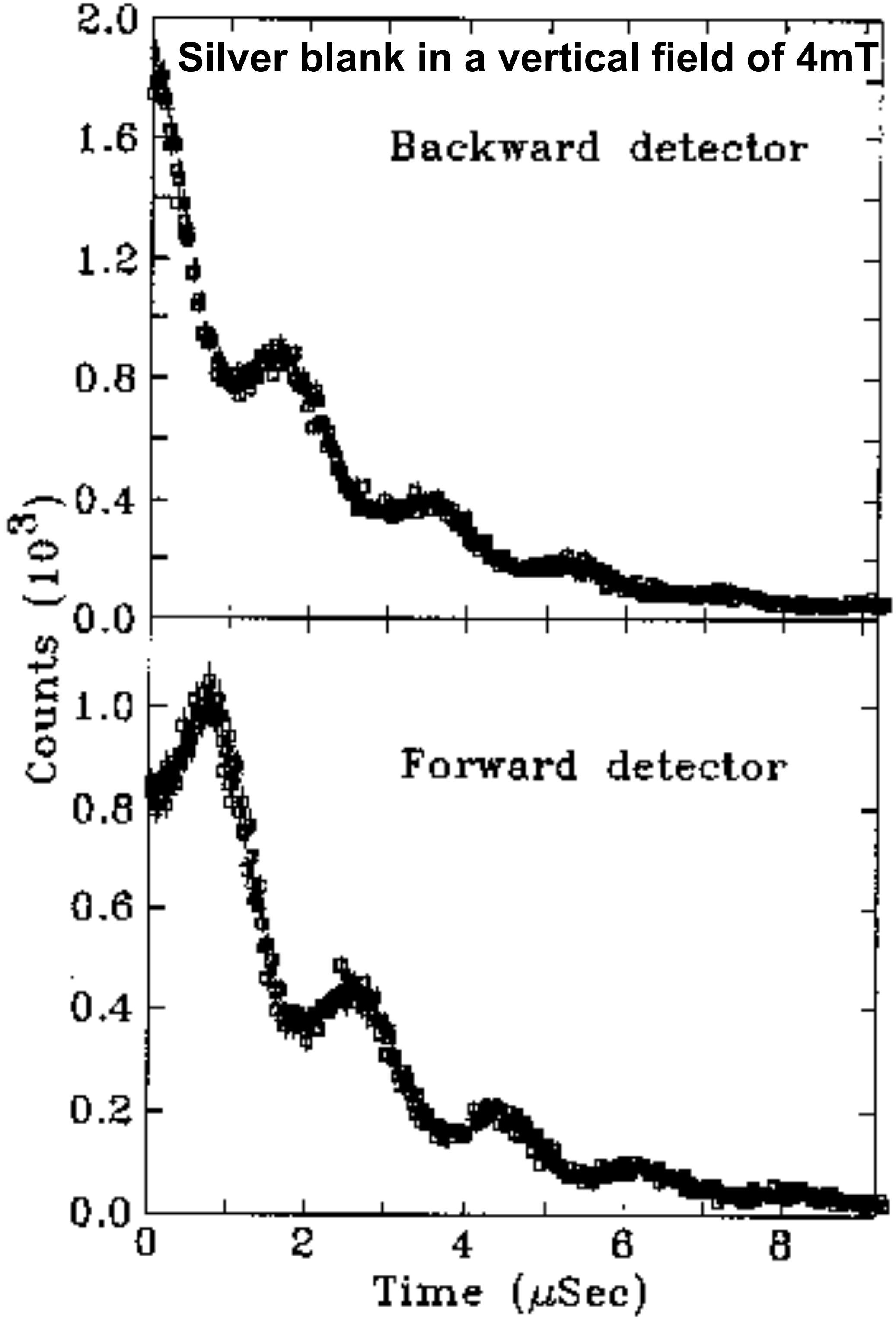

The precession is apparent, but the signal is dominated by the decay of the muons.

We scale this out by forming the “asymmetry”:

$$(F - B)/(F + B)$$

This is the difference between the two detectors normalised to the total signal.

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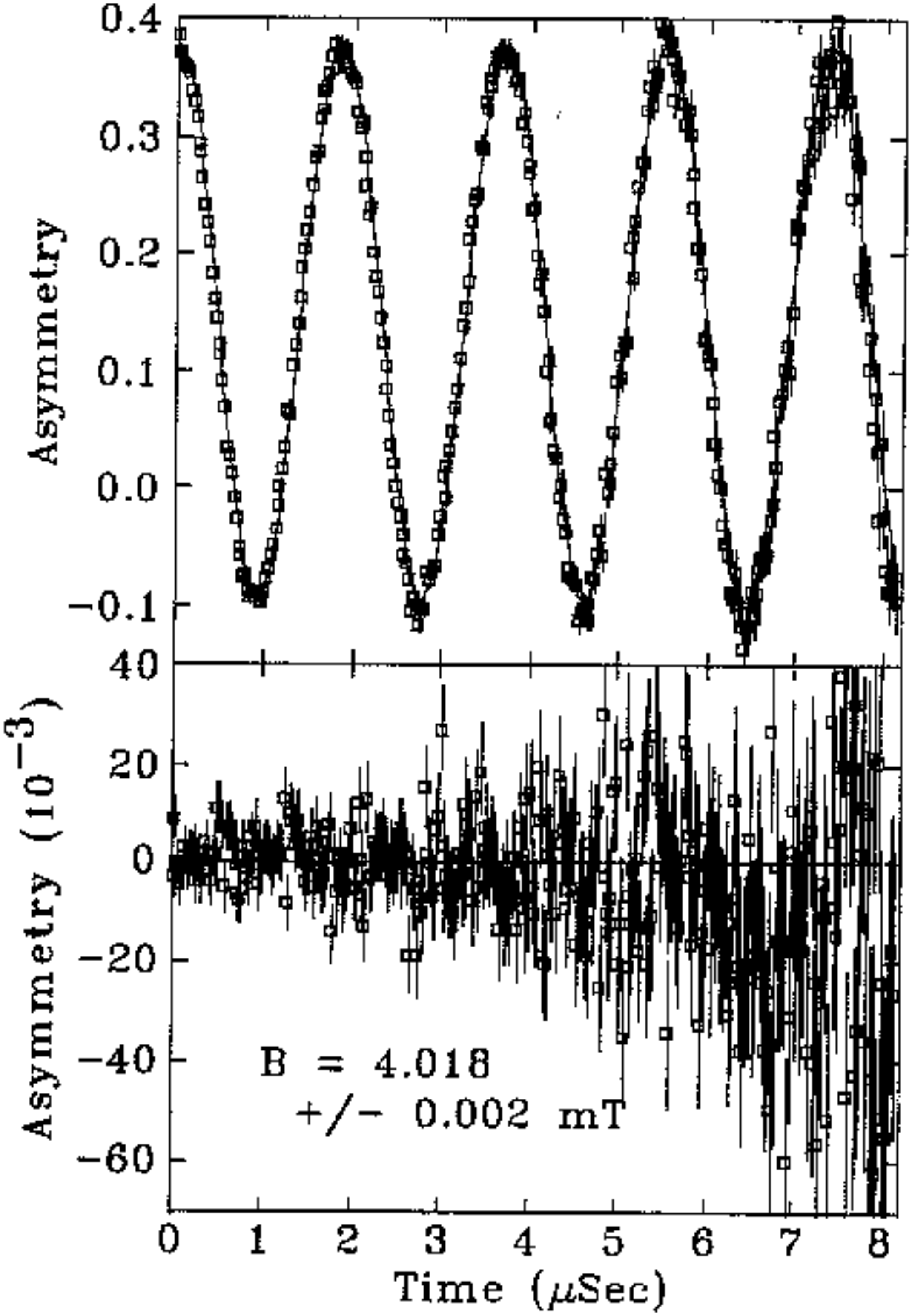
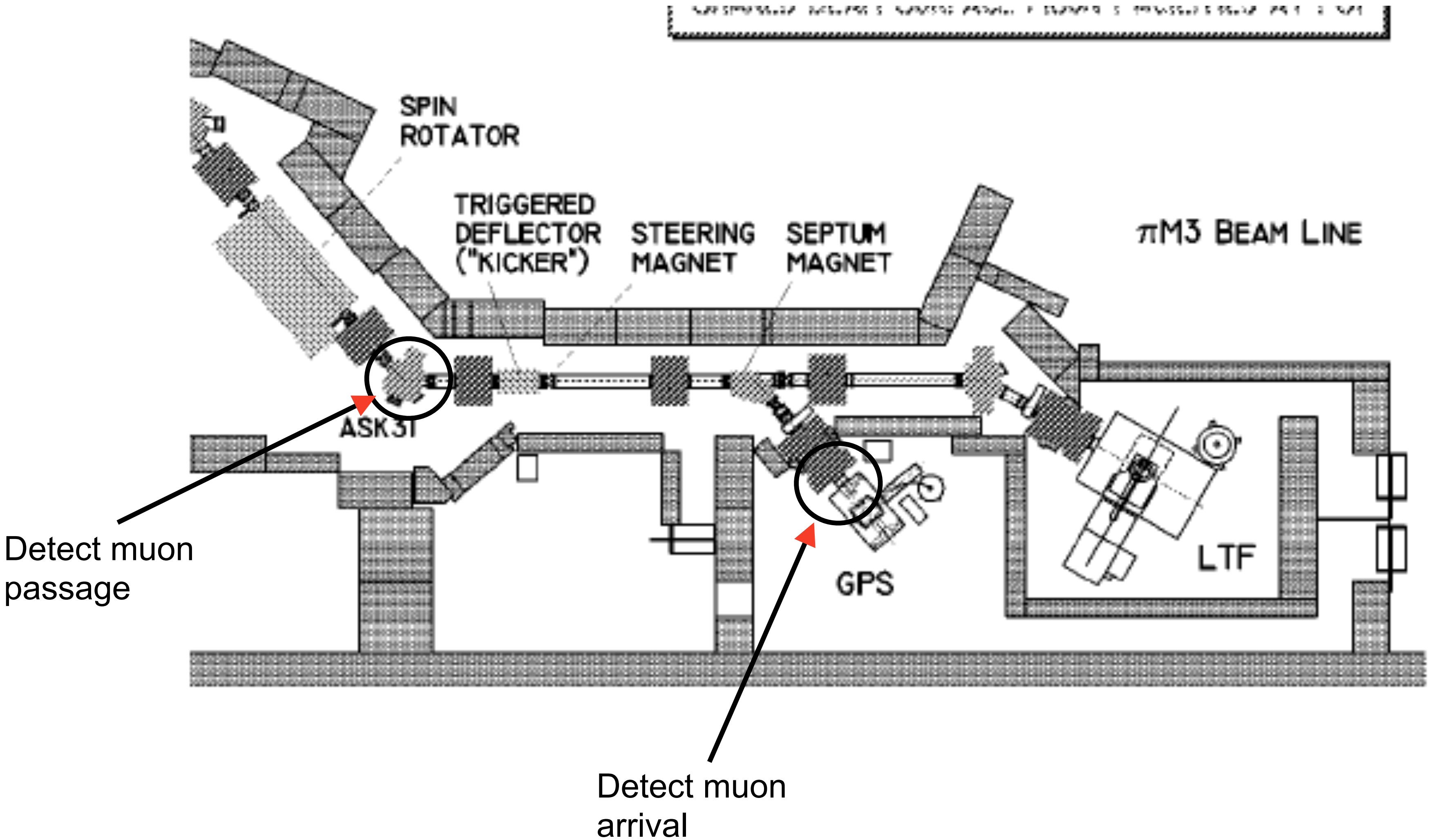


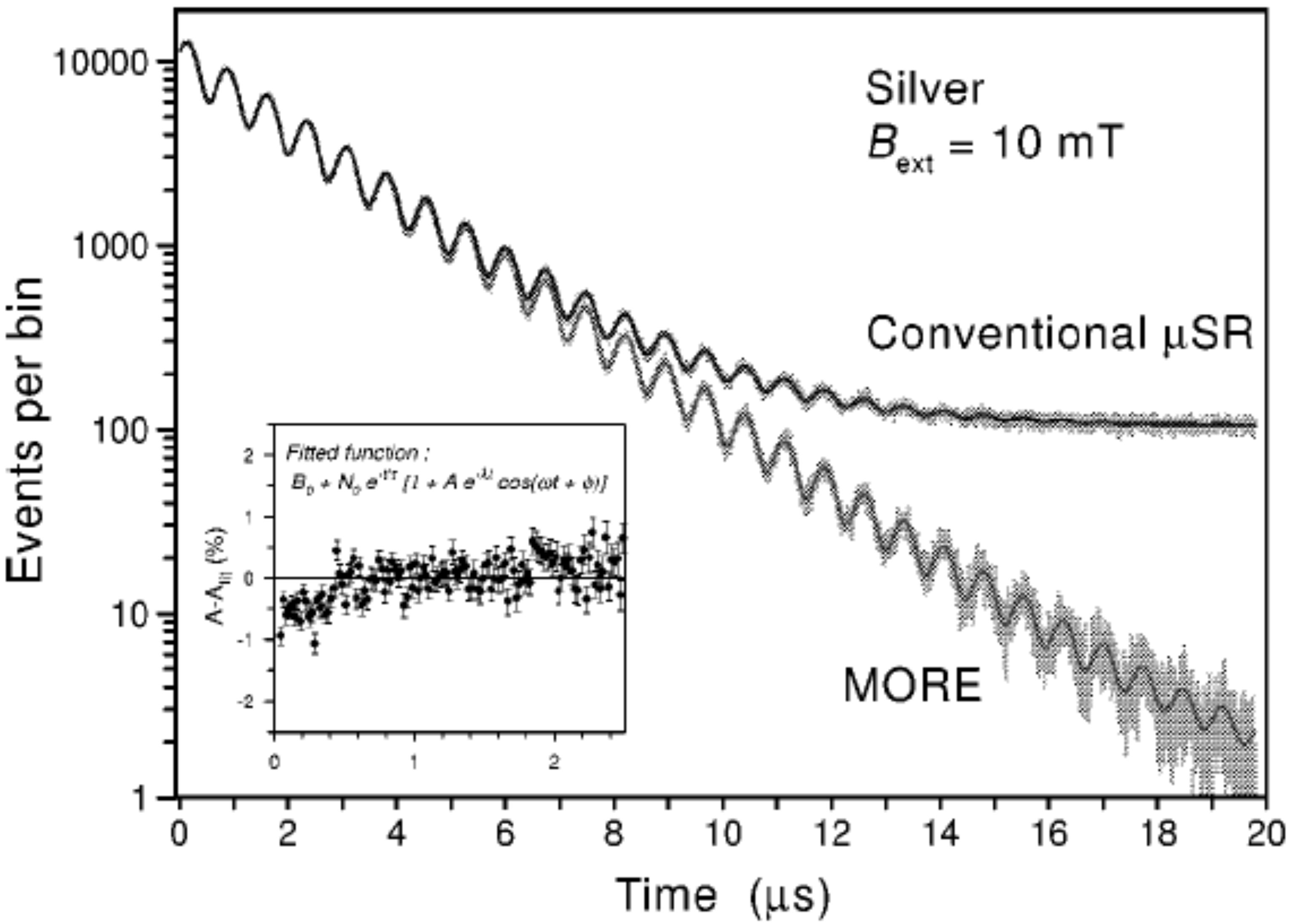
Signal is now a nice sinusoid, but…

- A is not symmetric about zero (detector efficiencies are not perfectly matched).
- The errors blow up at late times (no muons left).
- Background is not flat.

Muons on request (MORE)



Hyperfine Interactions 120/121 (1999) 575–578



	Convent.	MORE	MORE	μSR
Trigger	none	ASK31	GPS	50 Hz
B_0/N_0 (10^{-5})	660	6.3	8.7	$\sim$1
Time resol. (ns)	1	1	1	80
Event rate $(10^6/\mathrm{h})$	12	3.2	20	10–20

What can muons tell you?

- They can detect *weak* magnetism (they can even see the effects of nuclear moments).
- They are *volume-quantitative*. If your sample has inhomogeneous order, the volume fractions can be measured.
- Muons are sensitive to magnetic fluctuations so they can be used to probe *dynamics*.

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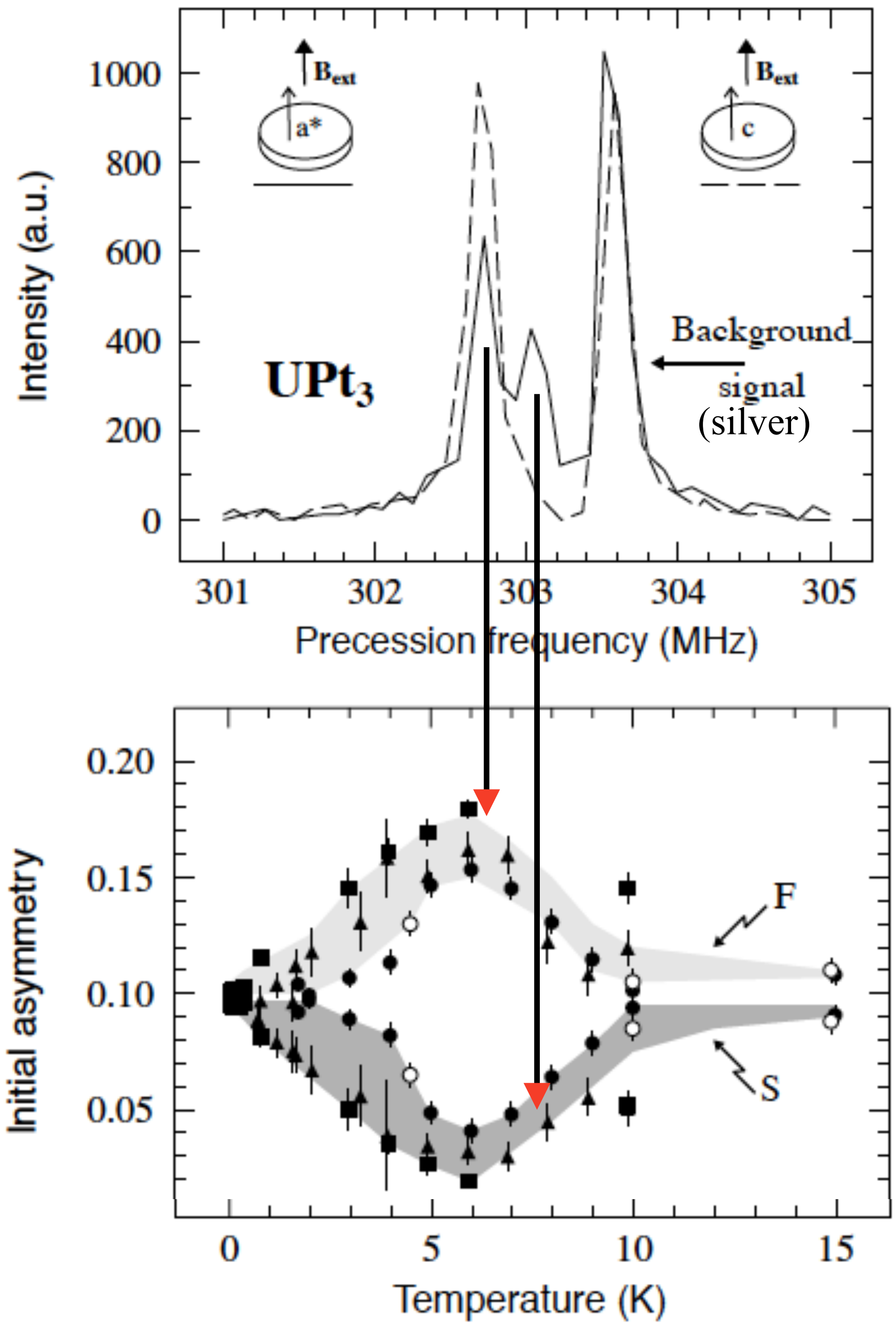
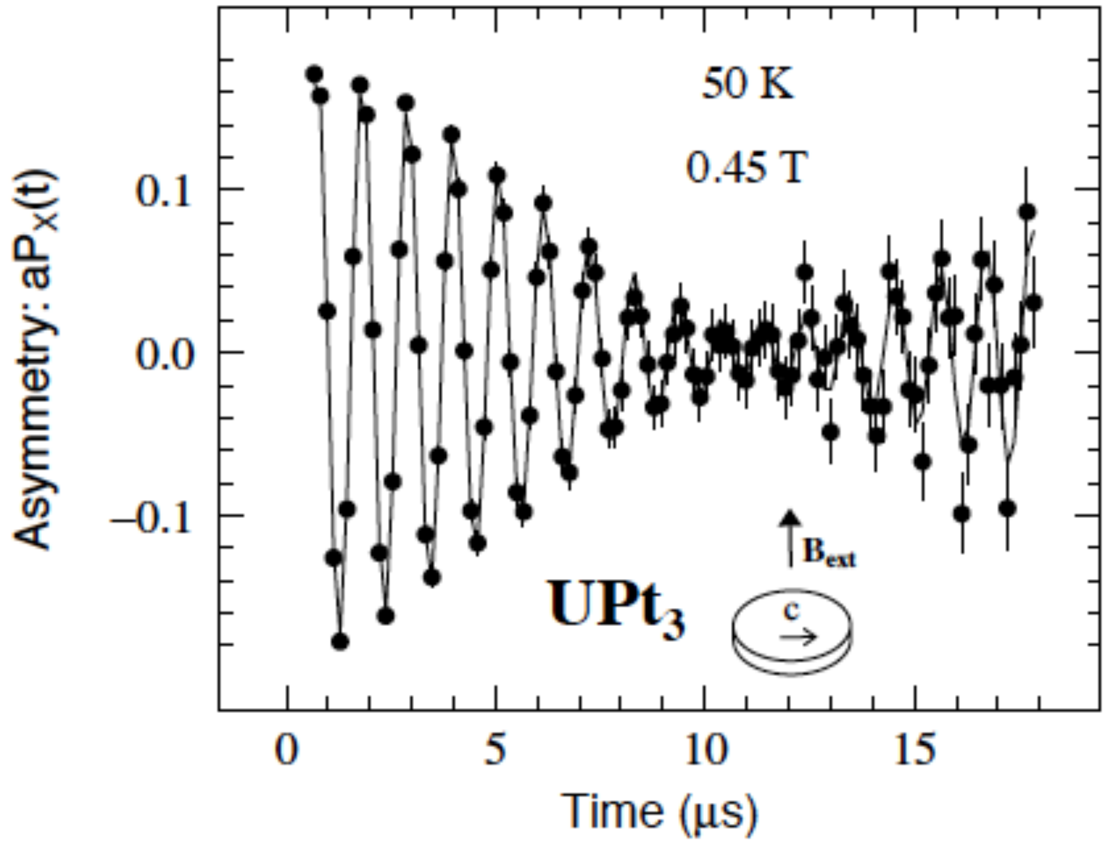
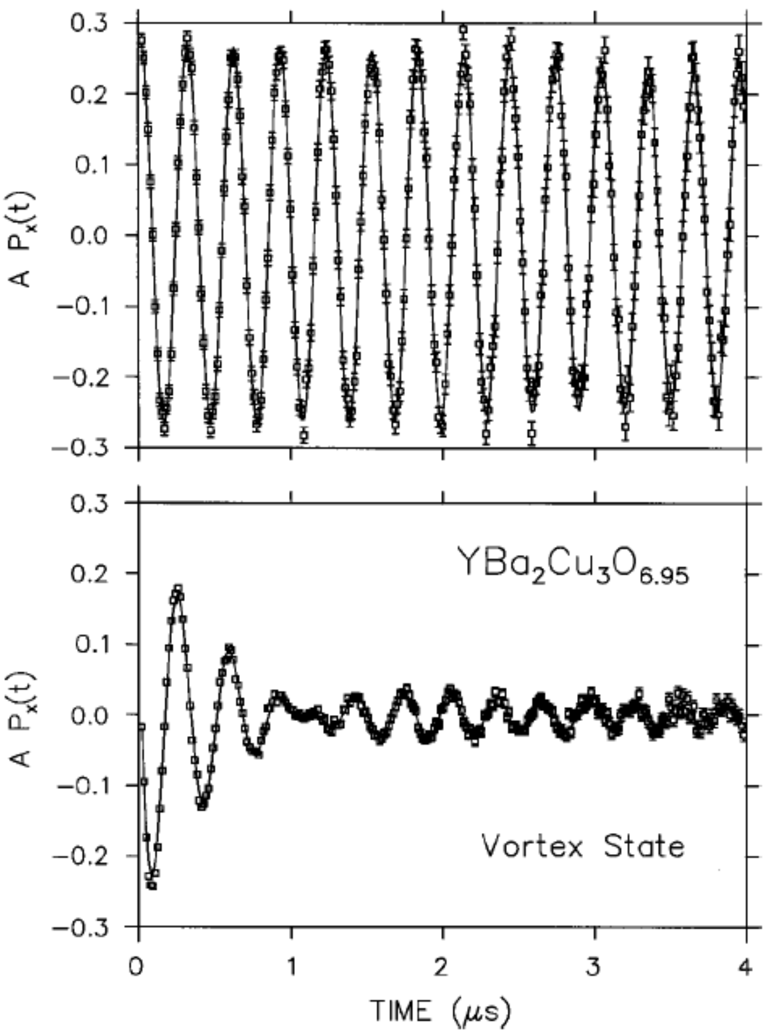
UPt3 (a heavy fermion superconductor)

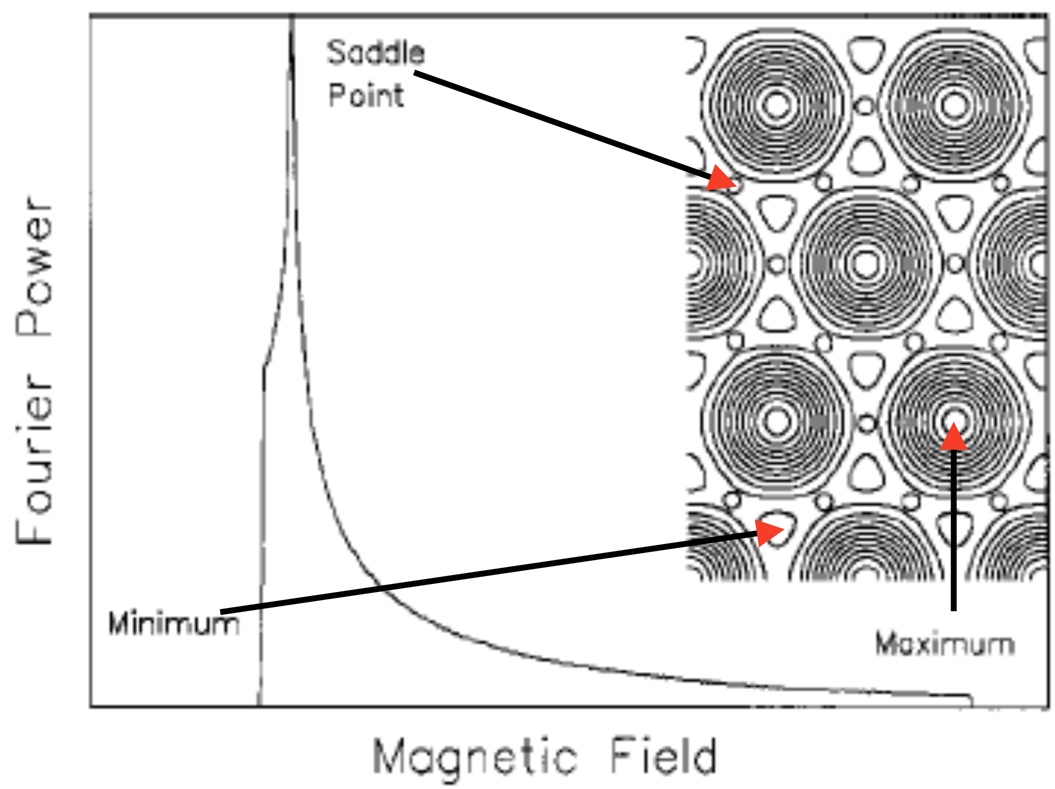




A. Yaouanc *et al.* PRL **84** (2000) p2702

Type-2 superconductors

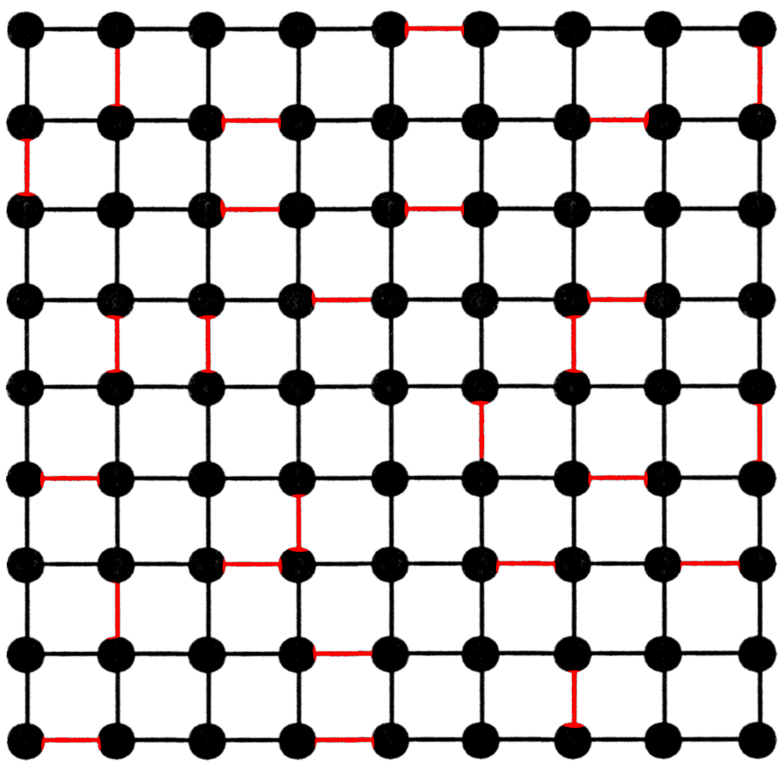


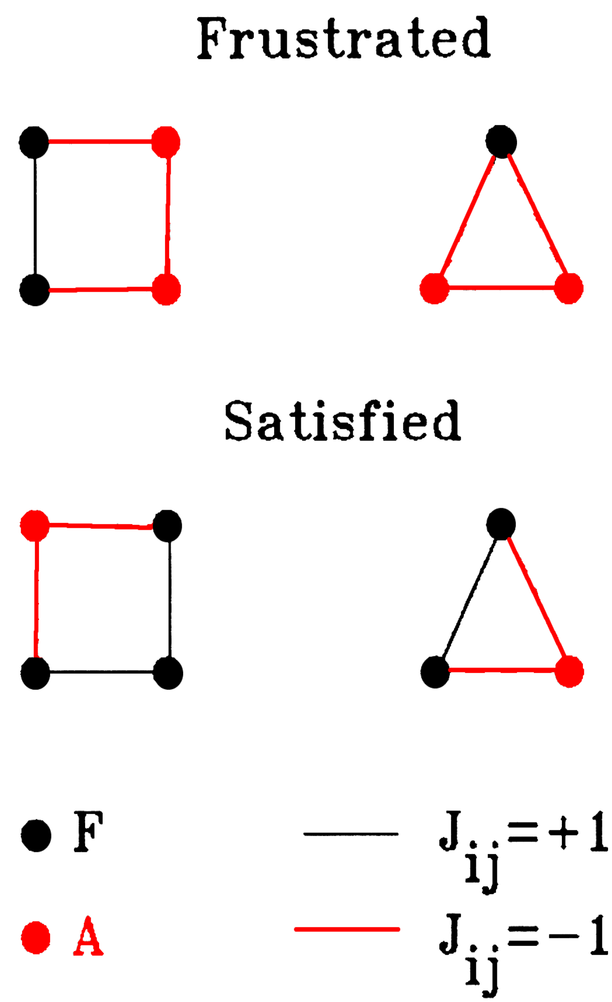


J.E. Sonier *et al.* Rev.Mod.Phys. **72** (2000) 769

Dynamics in frustrated systems

What happens when you take a ferromagnet and randomly replace some of the bonds with antiferromagnetic ones?





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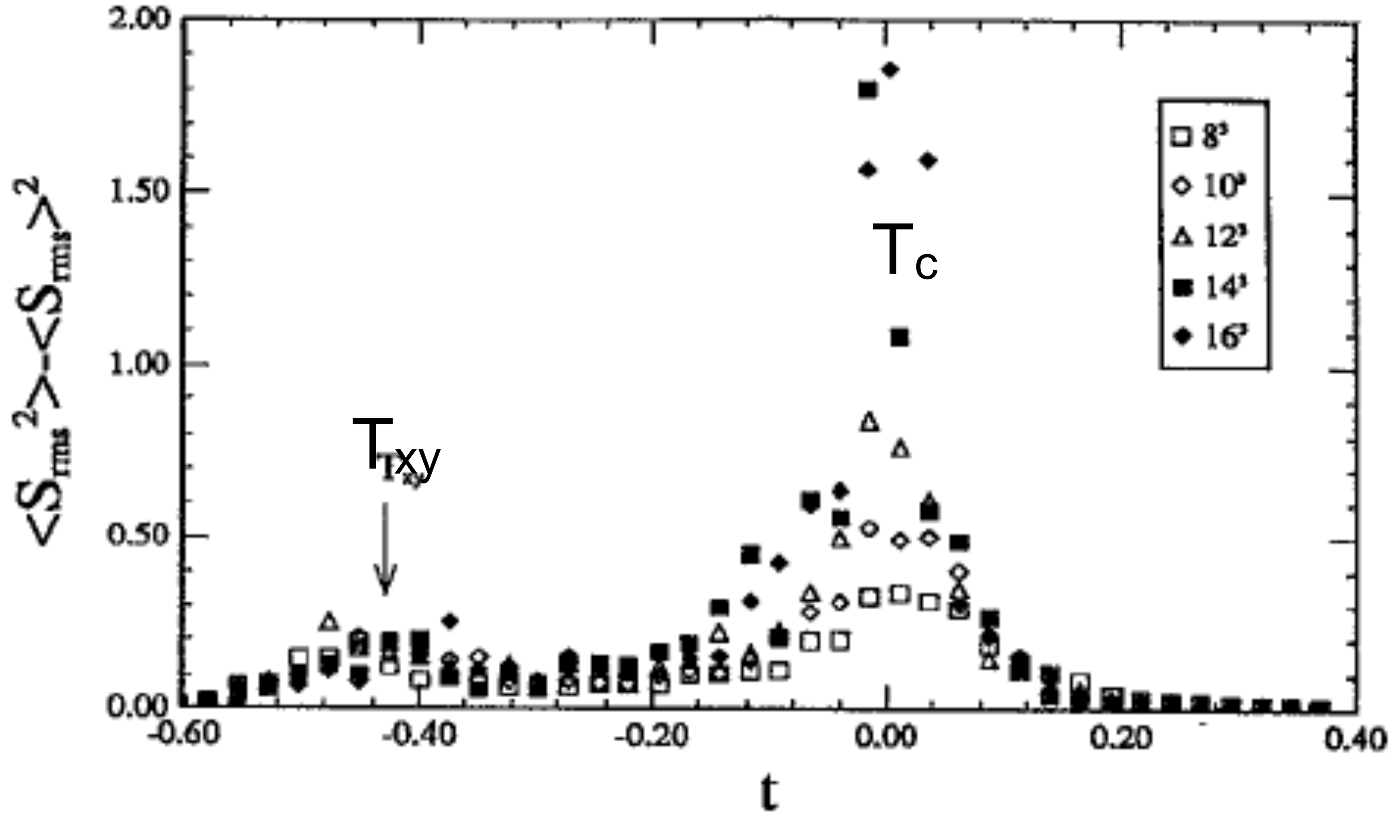
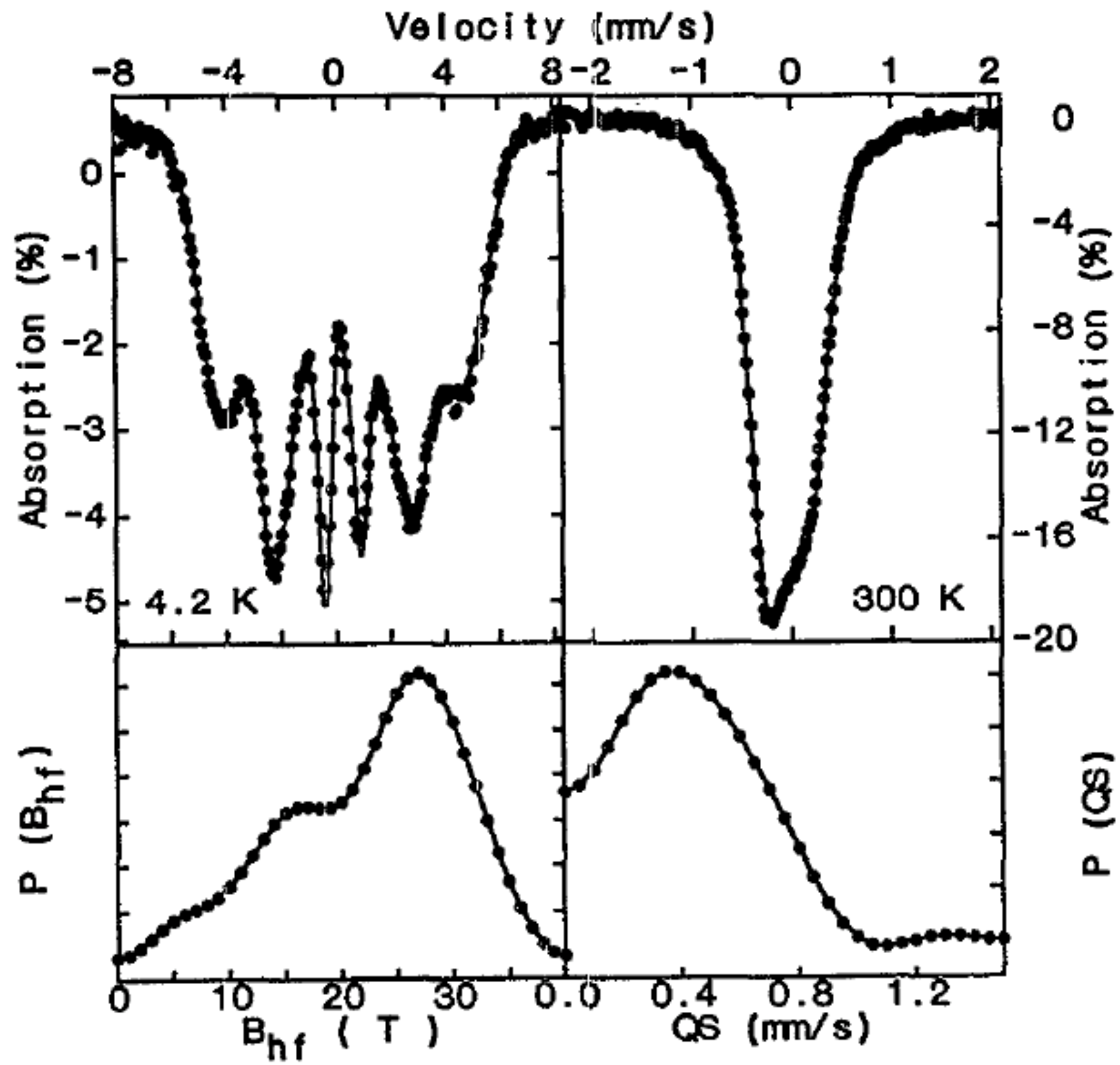
You get *two* magnetic transitions



The fluctuations associated with T_{xy} occur *within* the ferromagnetic phase established at T_c

J.R. Thomson *et al.*
PRB **45** (1991) 3129

Amorphous materials exhibit a distribution of parameters



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μSR in disordered materials

Dynamic relaxation forms:

$$A_d = A_o \exp(-\lambda t)$$

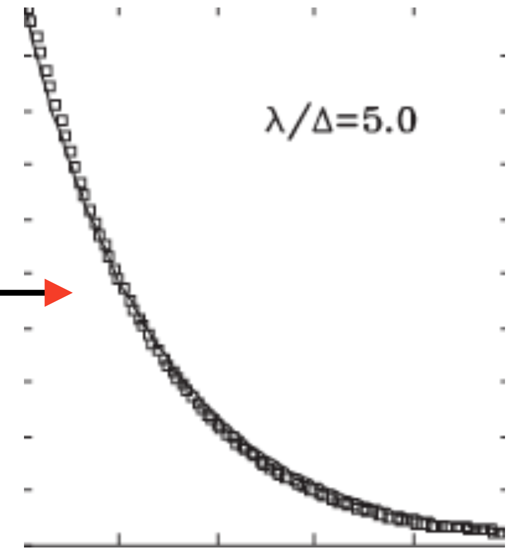
Static (Kubo-Toyabe) form:

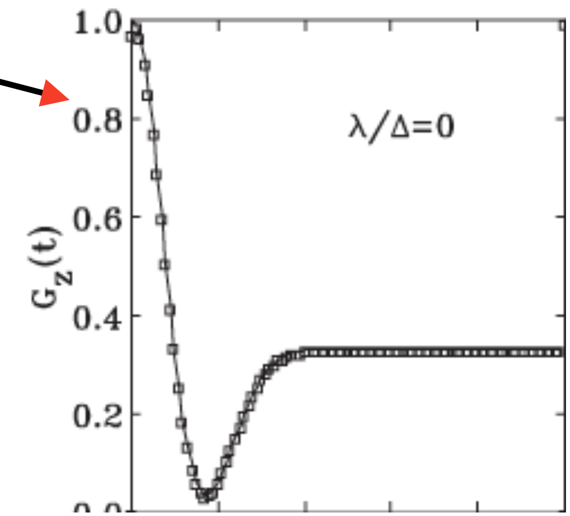
$$G_z^G(\Delta, t) \; = \; \frac{1}{3} + \frac{2}{3}\left(1 - (\Delta t)^2\right)\exp\left(-\frac{(\Delta t)^2}{2}\right)$$

Δ/γ_μ is the rms field.

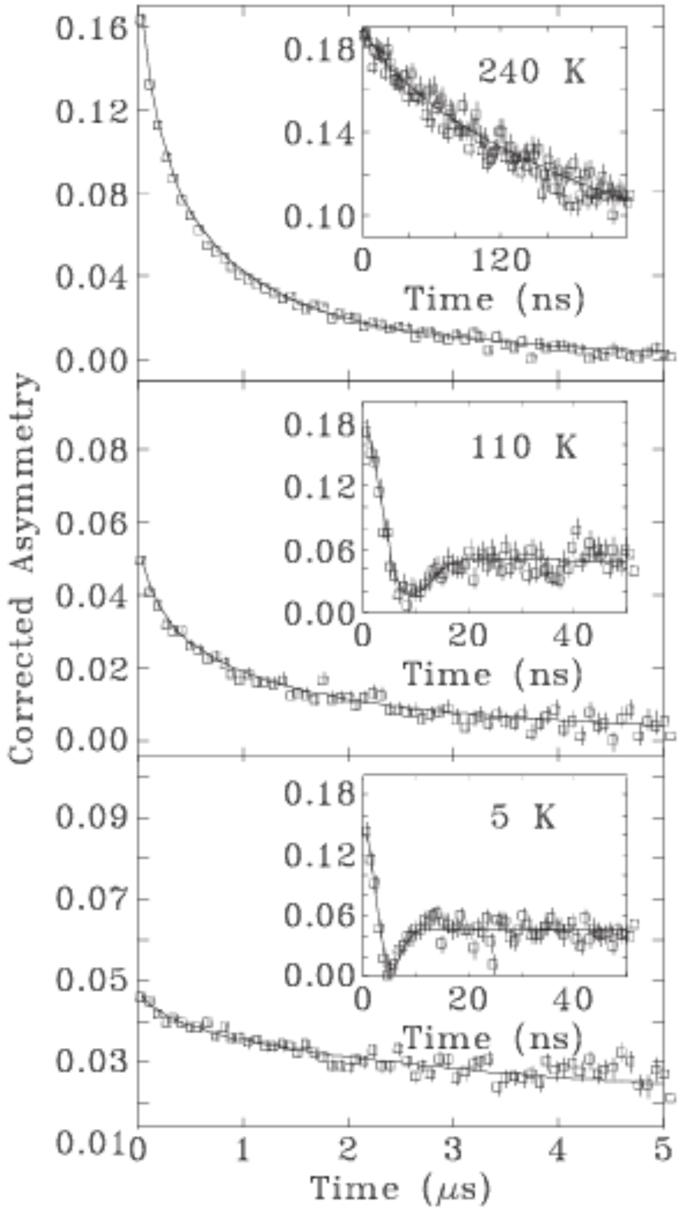
If both are present, and $f_L \gg \lambda$

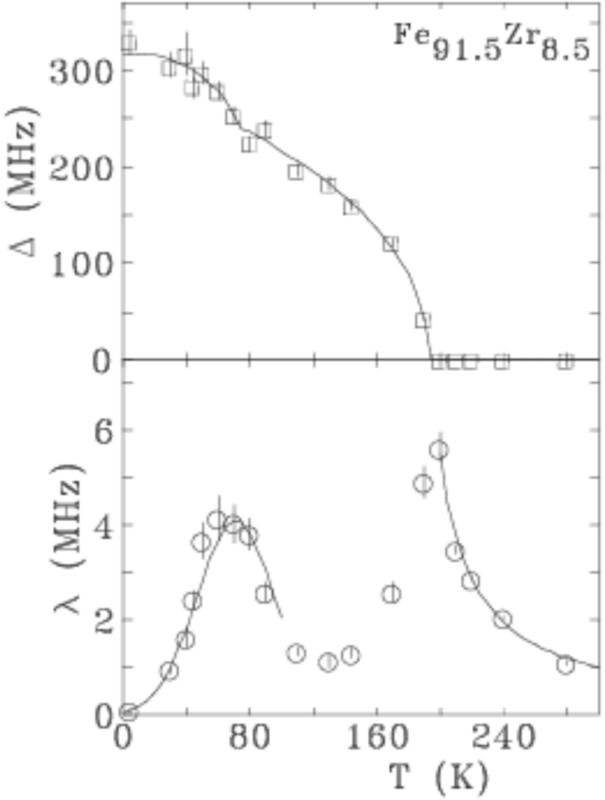
$$A = A_d * G_z^G.$$

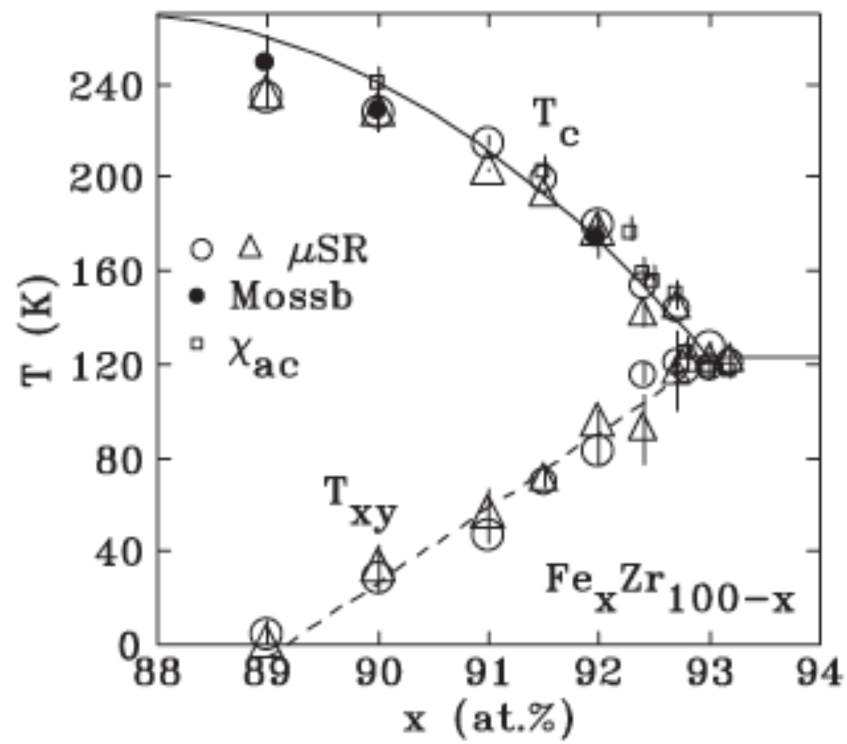


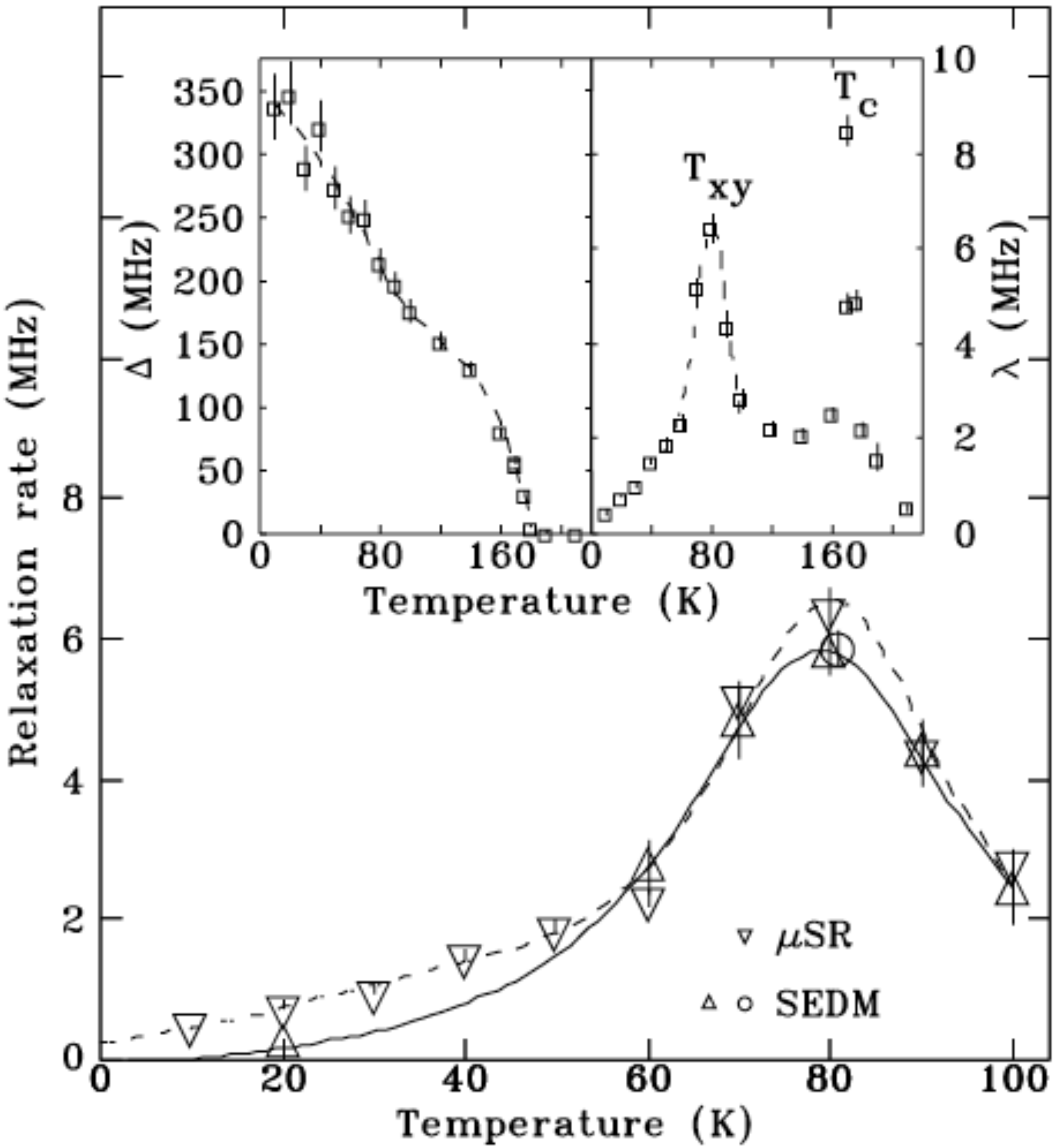


D H Ryan[1], J van Lierop[2] and J M Cadogan
J. Phys.: Condens. Matter 16 (2004) S4619–S4638


Corrected Asymmetry
240 K
Time (ns)
110 K
Time (ns)
5 K
Time (ns)
Time (μs)


$Fe_{91.5}Zr_{8.5}$
Δ (MHz)
λ (MHz)
T (K)


T_c
○ △ μSR
● Mossb
□ χ_{ac}
T_{xy}
Fe_xZr_{100-x}
T (K)
x (at.%)



Relaxation rate (MHz)
Temperature (K)
μSR
SEDM
Δ (MHz)
λ (MHz)
T_xy
T_c

μSR A summary

Advantages:

- Works with any magnetic material
- Sensitive to weak magnetic fields
- Volume quantitative
- Can be used in zero applied field
- Works in relatively large magnetic fields
- Sensitive to dynamics

Limitations:

- Generally need large (few gram) samples
- Limited availability of facilities
- Tends to be a limited/ specialised field
- Analysis, except in trivial cases, can be complex
- Where did the muon land?
- Did the muon change anything?

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