Muons for time-dependent studies in magnetism

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Content:

Introduction: muon properties; history.

μSR method: muon beams; sample environment;

Muons for solid state physics & examples.

In a few words:

Polarized muons (S=1/2) are implanted into the sample

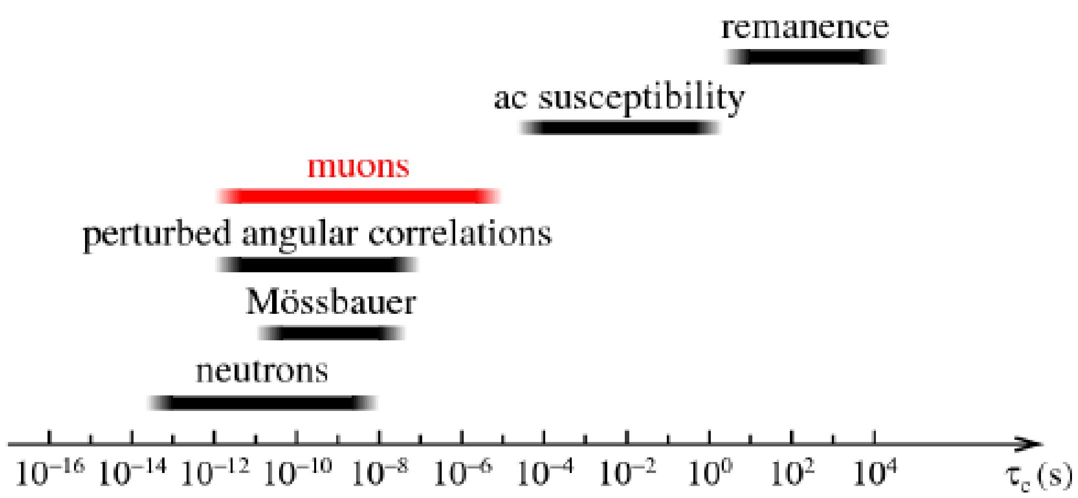
The spin of the muon precesses around the local magnetic field

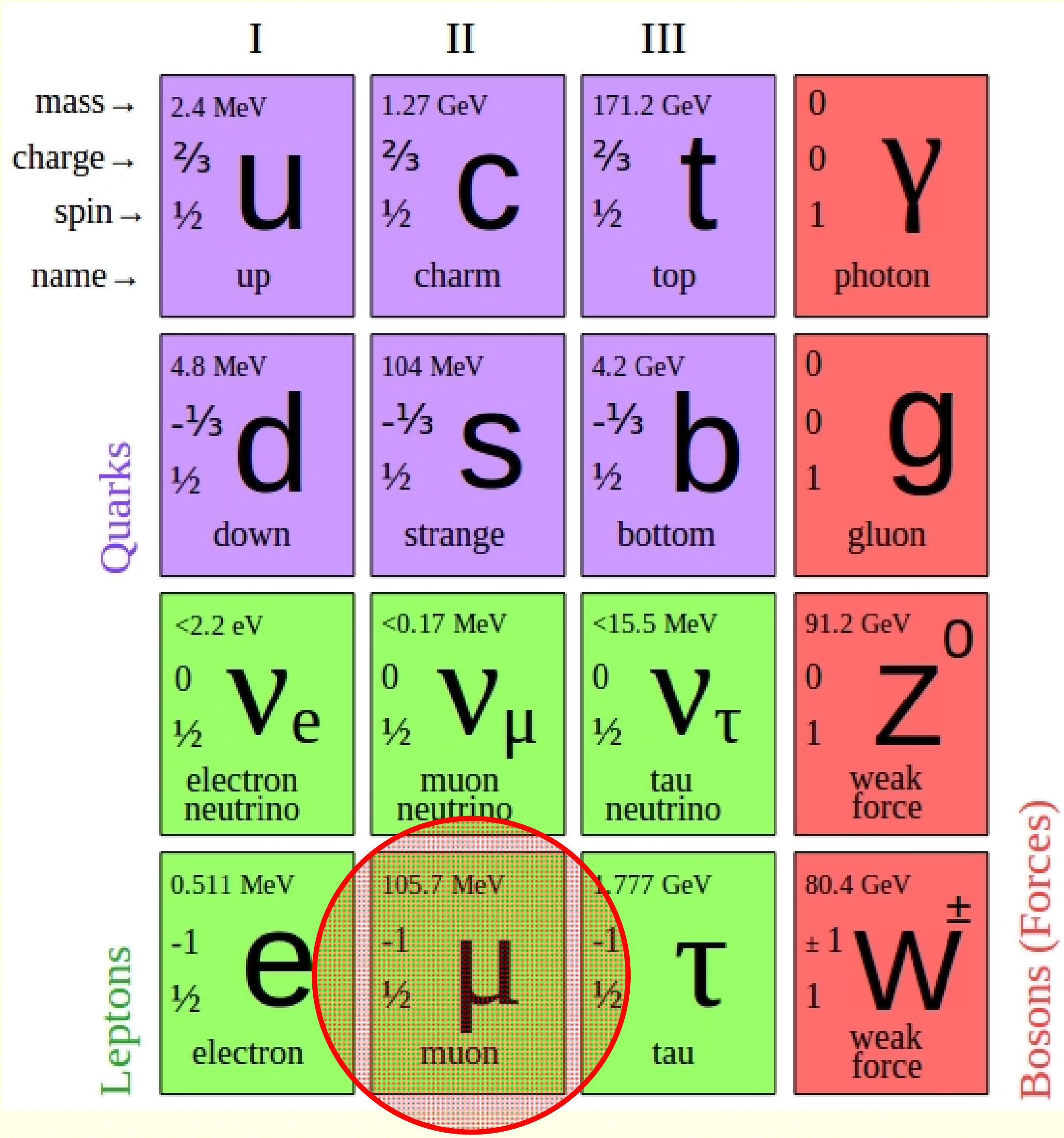
The muons decay (2.2 μs) by emitting a positron preferentially along the spin direction.

The positrons are counted/recorded in hystograms along certain directions = the μSR spectra = the physics of your sample.

It belongs to the family of NMR, EPR, PAC, neutron scattering and Mossbauer experimental methods.

Comparison of dynamical ranges accessible to different techniques




I
II
III
mass →
charge →
spin →
name →
2.4 MeV
⅔
½
u
up
1.27 GeV
⅔
½
c
charm
171.2 GeV
⅔
½
t
top
0
0
1
γ
photon
4.8 MeV
-⅓
½
d
down
104 MeV
-⅓
½
s
strange
4.2 GeV
-⅓
½
b
bottom
0
0
1
g
gluon
Quarks
<2.2 eV
0
½
νe
electron neutrino
<0.17 MeV
0
½
νμ
muon neutrino
<15.5 MeV
0
½
ντ
tau neutrino
91.2 GeV
0
1
Z0
weak force
0.511 MeV
-1
½
e
electron
105.7 MeV
-1
½
μ
muon
1.777 GeV
-1
½
τ
tau
80.4 GeV
±1
1
W±
weak force
Leptons
Bosons (Forces)

-Small magnetic probe. Spin: 1/2, Mass: m_μ = 206.7682838(54) m_e = 0.1126095269(29) m_p

- Charge: +-e

- Muon beam 100% polarized → possibility to perform ZF measurements

- Can be implanted in all type of samples

- Gyromagnetic ratio: $\gamma_\mu = 2\pi \times 13.553882$ (±0.2 ppm) kHz/Gauss → senses weak magnetism.

- Allows independent determination of the magnetic volume and of magnetic moment.

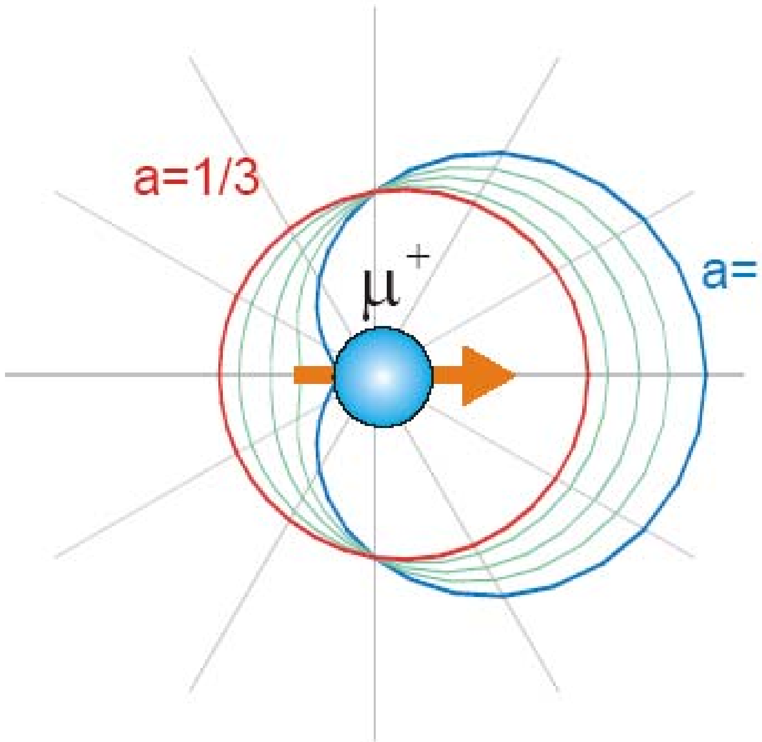
- Possibility to detect disordered magnetism (spin glass) or short range magnetism.

How ?

The muon decay into an electron and two neutrinos after an average lifetime of τ_μ = 2.19703(4) μs:

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu}_\mu$

The decay is highly anisotropic.



Angular distribution of the positrons from the muon decay: $W(E,\theta) = 1 + a(E)\cos(\theta)$. When all positron energies E are sampled with equal probability the asymmetry parameter has the value $a = 1/3$ (red curve).

Muon, positron, neutrino

How do we cook muons?

Origin: cosmic rays; accelerators

Muons: from pions;

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\tau_{\pi+}$ = 26.03 ns)

Pions: from protons

$p + p \rightarrow p + n + \pi+$

$p + n \rightarrow n + n + \pi+$

Muon, positron, neutrino, cosmic ray, pion, proton, neutron

Let's go back to beginning of the XX'th century (1911):

Keywords are: radioactivity, radiation, cosmic rays.

1911: Wilson invents the cloud chamber

? What are the cosmic rays?

? What do we find if we smash the nucleus, and how we can do that?

Nuclear physics starts its development.

Scientist had ideas to check/verify and started to have tools to do that.

Muon, positron, neutrino, ~~cosmic ray~~, pion, proton, neutron

1919: Rutherford discovers the proton.

This was the first reported nuclear reaction, $^{14}N + \alpha \rightarrow {}^{17}O + p$.

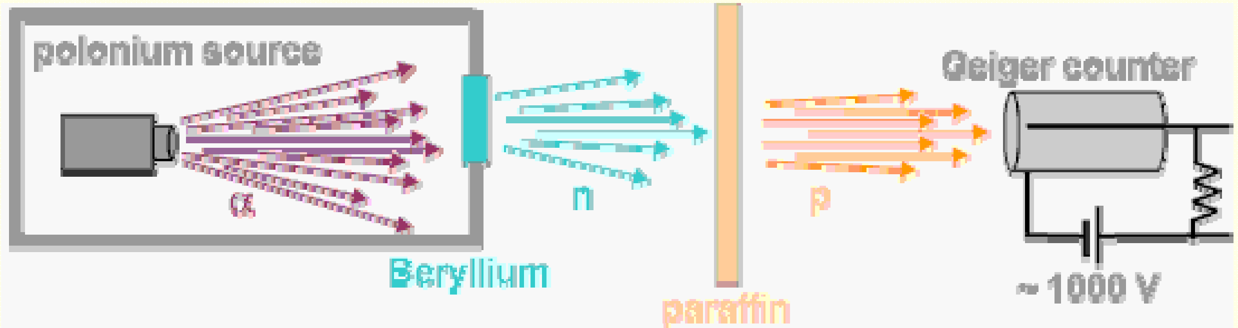
The hydrogen nucleus is therefore present in other nuclei as an elementary particle, which Rutherford named the proton.

Up to about 1930 it was presumed that the fundamental particles were protons and electrons but that required that somehow a number of electrons were bound in the nucleus to partially cancel the charge of A protons (the atomic mass number A of nuclei is a bit more than twice the atomic number Z for most atoms and essentially all the mass of the atom is concentrated in the relatively tiny nucleus).

1931: James Chadwick (NP 1935) discovers the neutron.

Picked up where Rutherford left off with more scattering experiments…

Performed a series of scattering experiments with α-particles

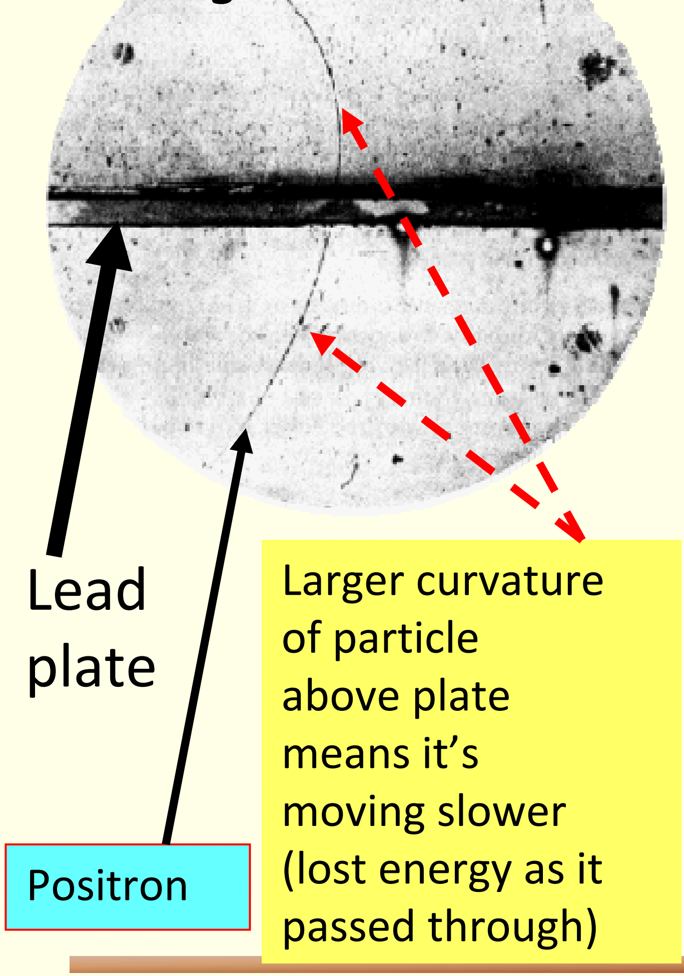


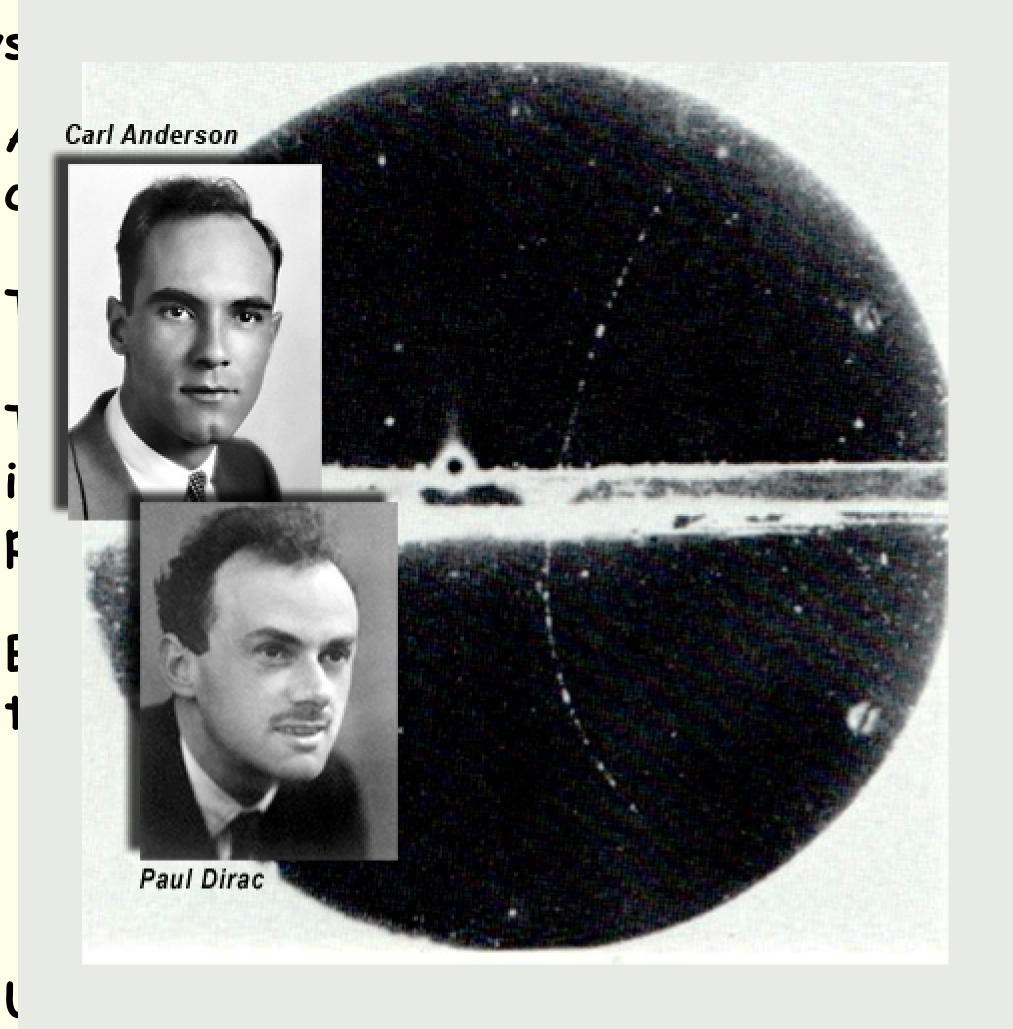
Applying energy and momentum conservation he found that the mass of this new object was ~1.15 times that of the proton mass.

Chadwick postulated that the emergent radiation was from a new, neutral particle, the neutron.

$$^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

1932: Carl Anderson (NP1937) discovers the positron (predicted by Dirac in 1928): in cosmic rays ... d in a magnetic field



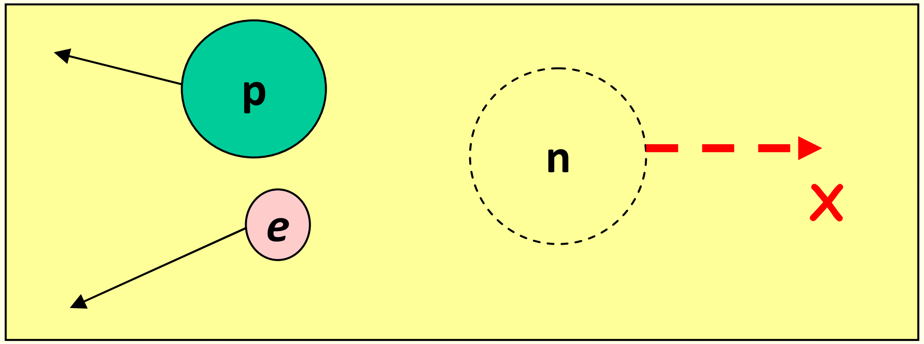


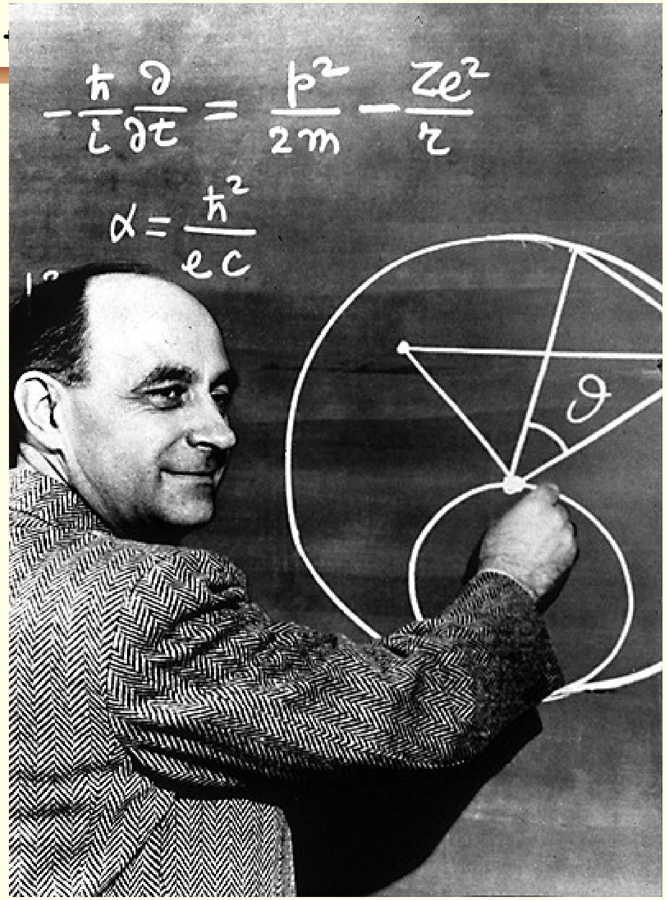
... traveled, it can be deduced it's not a proton.

1934: Enrico Fermi (NP 1938)

To account for the "unseen" momentum in the reaction (decay):

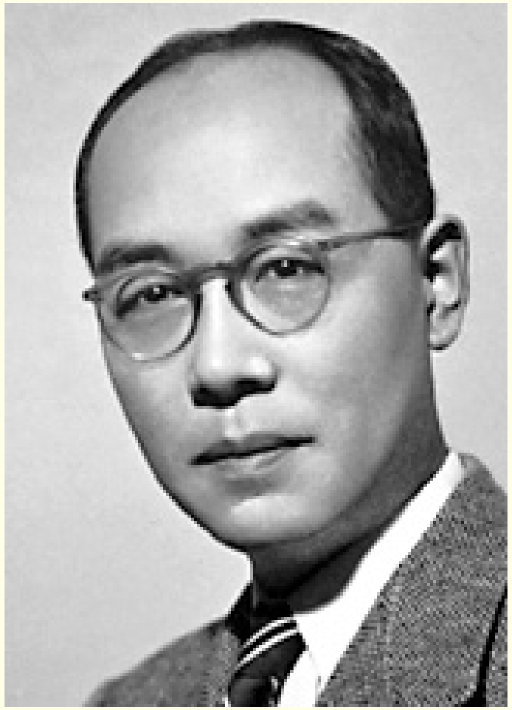
$$n \rightarrow p + e^- + X$$





Fermi proposed that the unseen momentum (X) was carried off by a particle dubbed the *neutrino* (ν), discovered in 1956. (means "*little neutral one*")

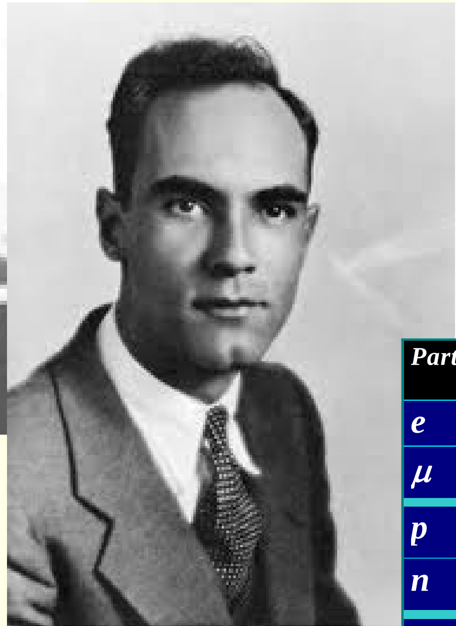
1935: Yukawa (NP 1949) predicts the existemce of a particle who mediates the strong interaction (later called pion). He estimated its mass to be around 0.1 GeV.



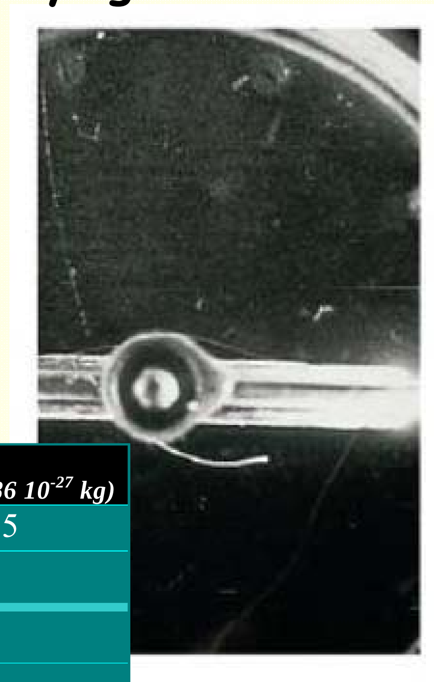
Yukawa theory predicted that the negative mesotron should be easily captured around the positively charged atomic nucleus and absorbed by the strong force before they could decay.

1936: Seth Neddermeyer and Carl Anderson discover the muon (mesotron): mass between that of the electron (x 200) and proton (/10)

Penetrating cosmic ray tracks with unit charge but mass in between electron and proton (first seen in 1930 but misinterpreted as ultra-high-energy electrons obeying new laws of physics).



Is this the Yukawa particle?



Particle	Electric charge ($x\ 1.6\ 10^{-19}$ C)	Mass (GeV=$x\ 1.86\ 10^{-27}$ kg)
e	-1	0.0005
μ	-1	0.106
p	$+1$	0.938
n	0	0.940
γ	0	0

Muon, ~~positron~~, ~~neutrino~~, ~~cosmic ray~~, pion, ~~proton~~, ~~neutron~~

Yes, it was, for some years ...

It was the mass that caused the muon to be confused with the pion.

1947: Marcello Conversi, Ettore Pancini & Oreste Piccioni:

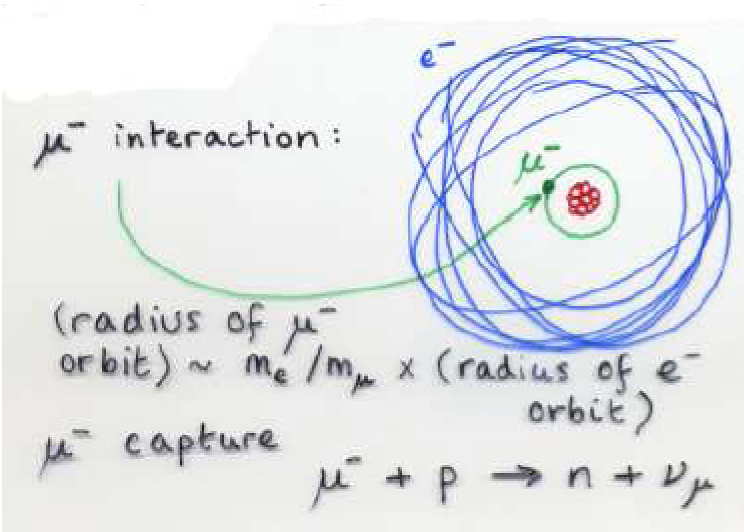
show that the mesotron decays and measure its lifetime.

Targets: Iron; Carbon, …

Results of the experiment to implant cosmic ray muons in matter and measure their lifetime:

μ^+ in anything 2 μs
μ^- in C 2 μs
μ^- in Pb 0.07 μs

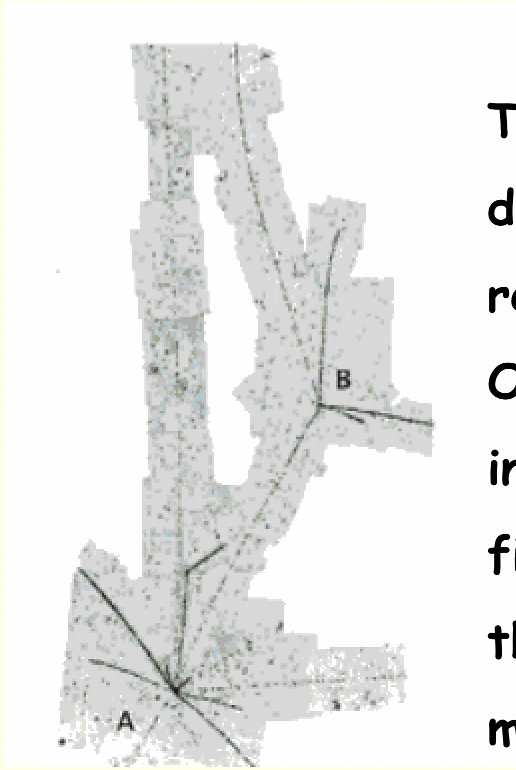
hence, <u>mesotrons (muons) are not interacting strongly enough to be Yukawa's particle!</u>



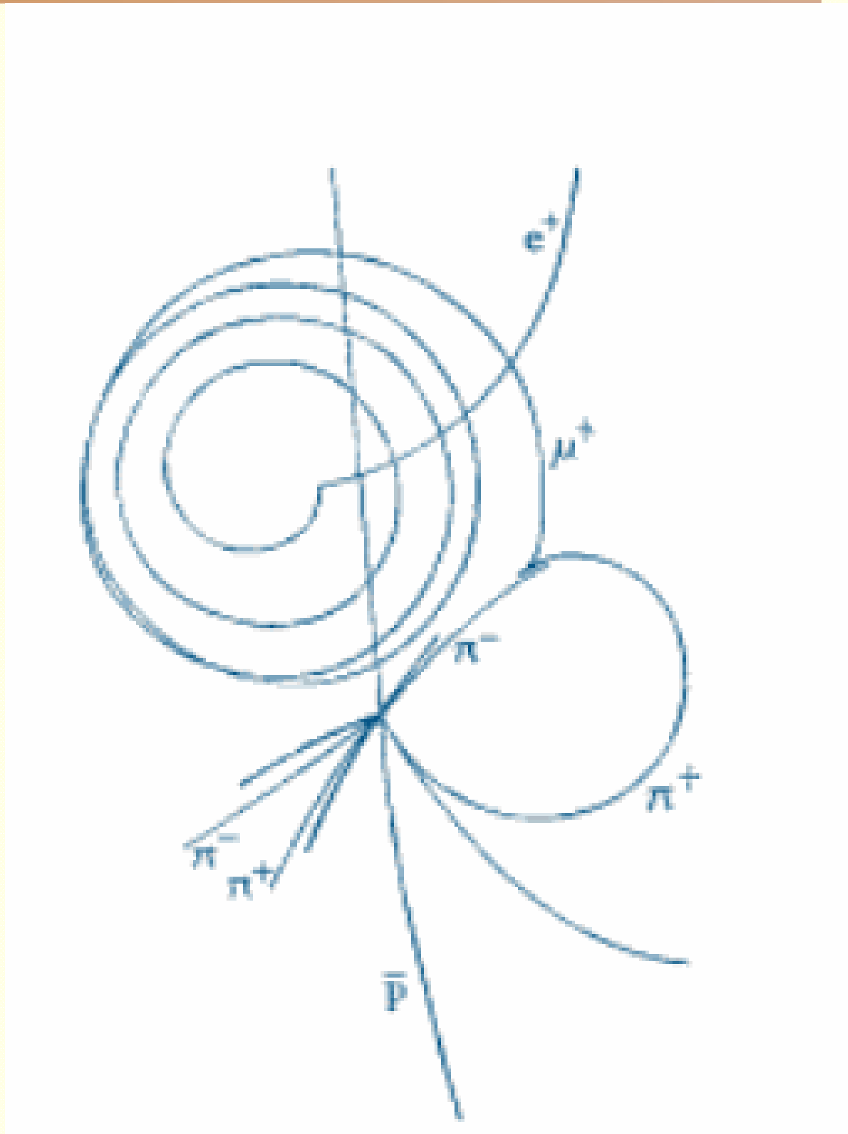
Reason for μ^- interaction: μ^- capture

(radius of μ^- orbit is ~ (m_e/m_μ) x radius of e^- orbit)
so the μ^- occupies an orbit close to the nucleus, and sees the full +Ze charge on nucleus)

1947: Cecil Powell (NP 1950) discovers the pion in cosmic rays captured in photographic emulsion (Peak du Midi, french Alps)



The birth (A) and death of a pion, recorded by Lattes, Occhialini and Powell in 1947, one of the first observations of the creation of a muon. AB=0.11 mm.



Muon, ~~**positron**~~, ~~**neutrino**~~, ~~**cosmic ray**~~, **pion**, ~~**proton**~~, ~~**neutron**~~

ALL THE INGREDIENTS HAVE BEEN DISCOVERED

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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(Received January 15, 1957)

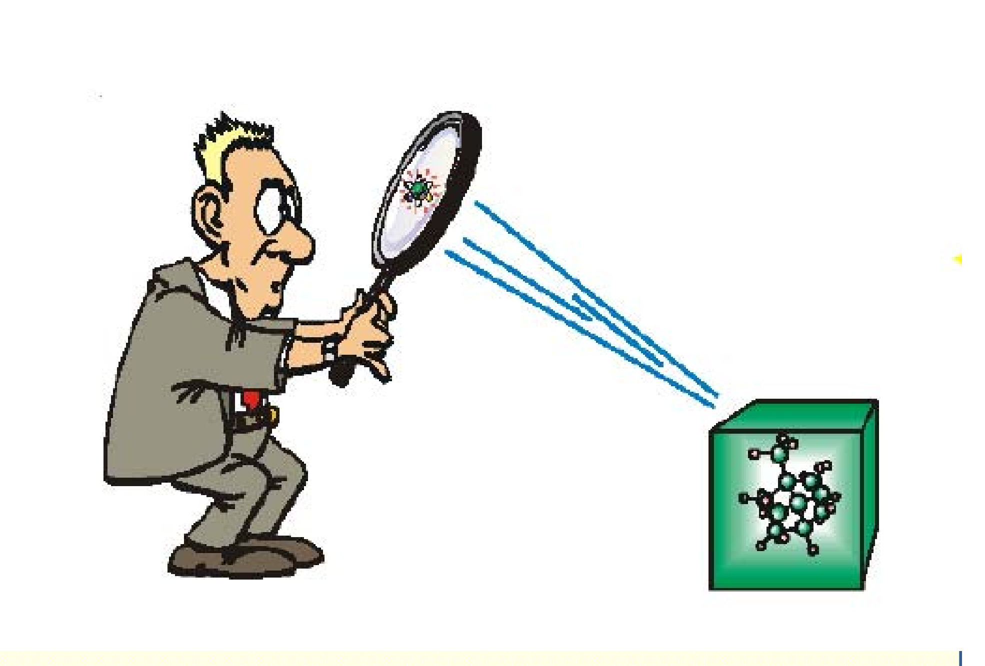
It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

What to do with muons ?

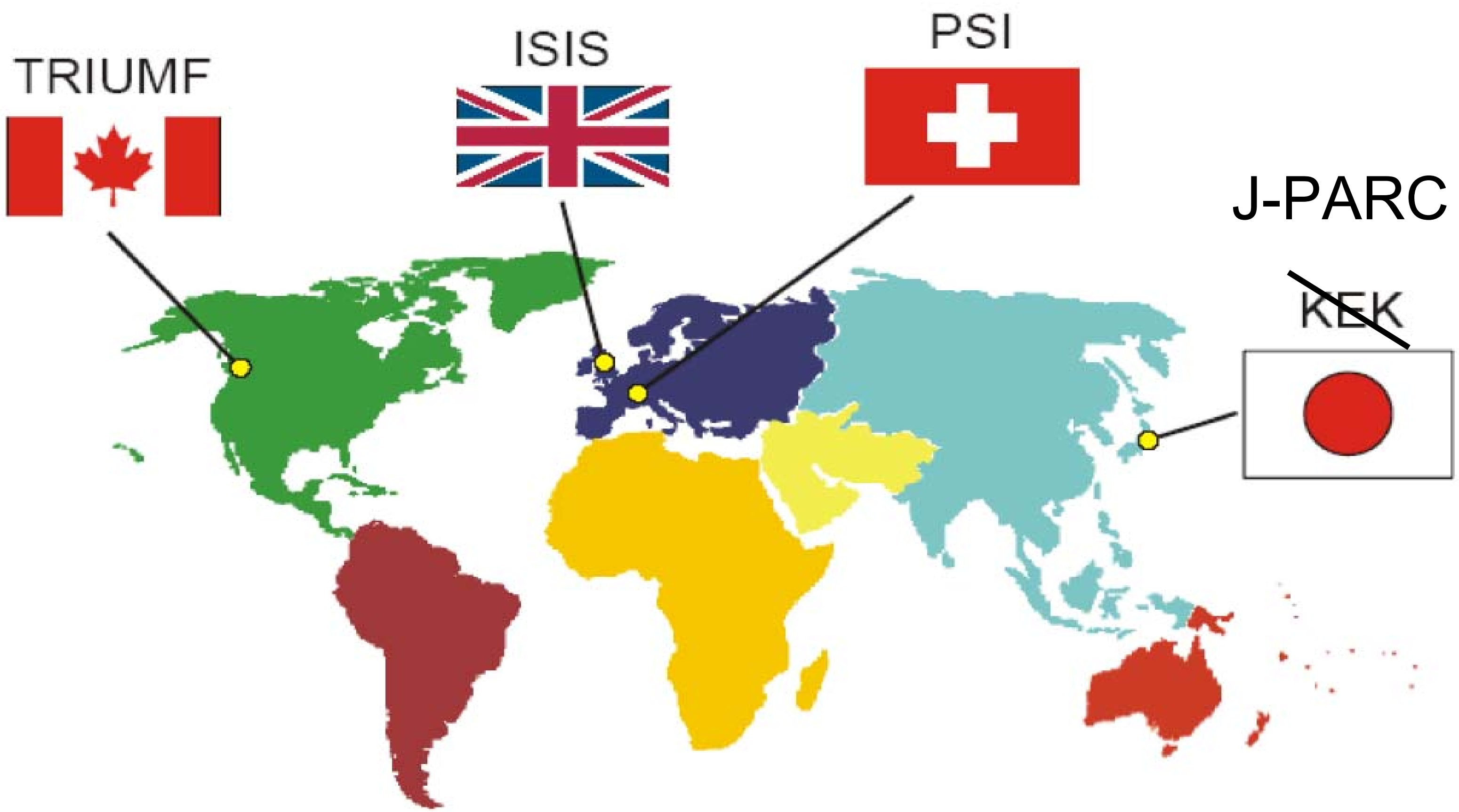
Probe the magnetic field inside matter at a microscopic level in order to have an insight into its magnetic and electronic properties: local fields, field distributions and dynamics.

Exploit the analogy with protons

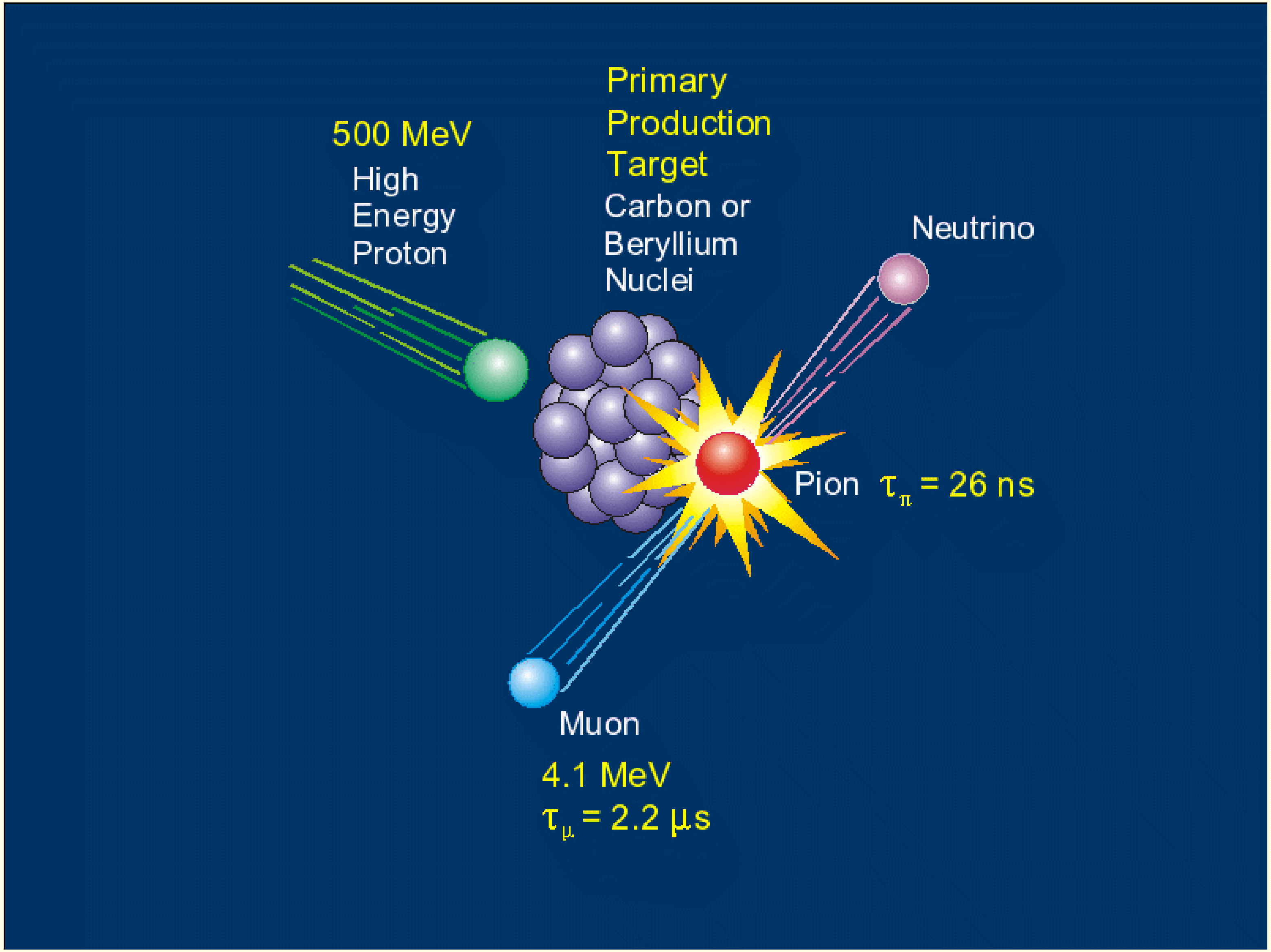
- Diffusion in metals
- A model for hydrogen in semiconductors and dielectrics
- Muonium chemistry – isotope effects
- A spin label for organic radicals – molecular dynamics

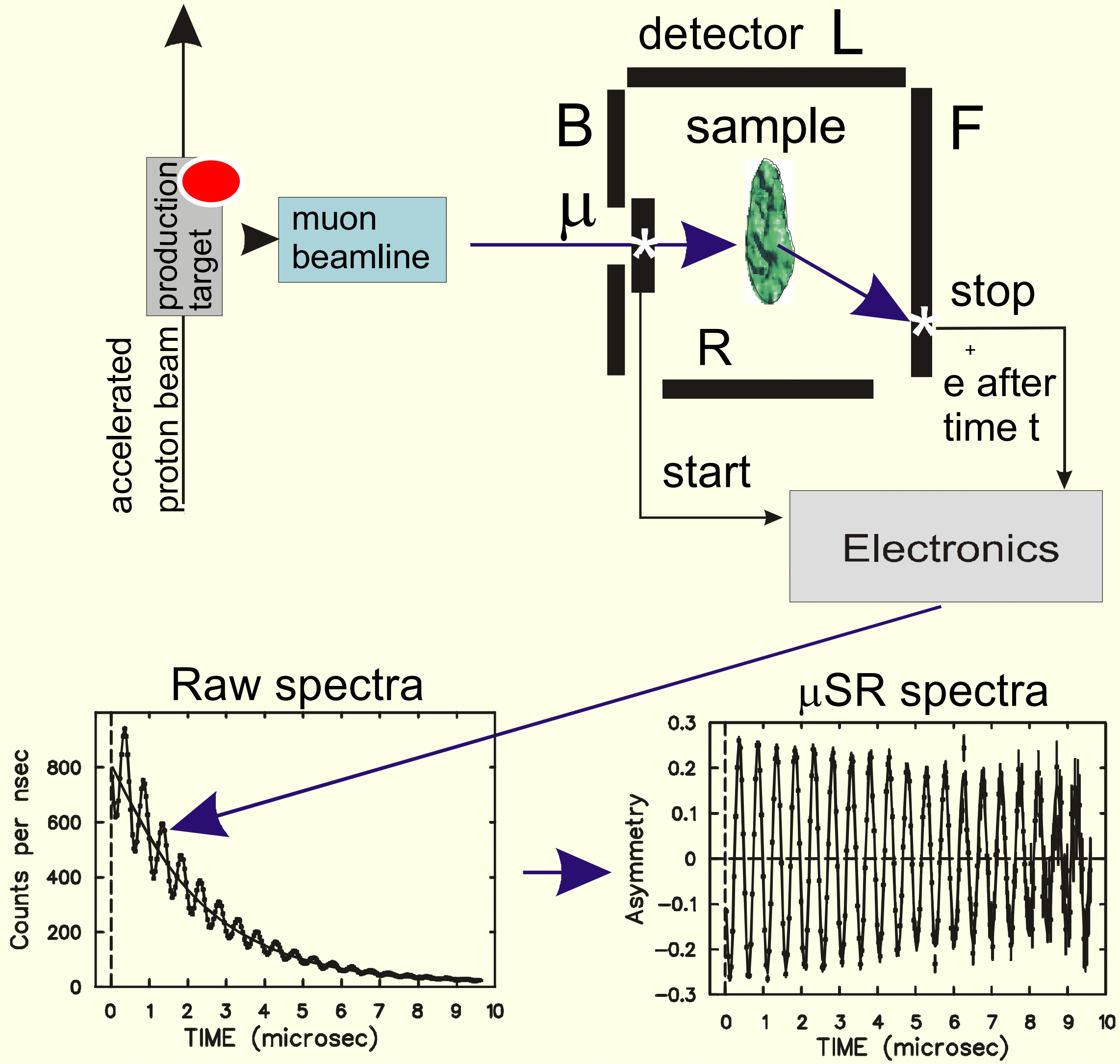


And where?



μSR facilities of the world.


500 MeV
High
Energy
Proton
Primary
Production
Target
Carbon or
Beryllium
Nuclei
Neutrino
Pion τ_{π} = 26 ns
Muon
4.1 MeV
τ_{μ} = 2.2 μs

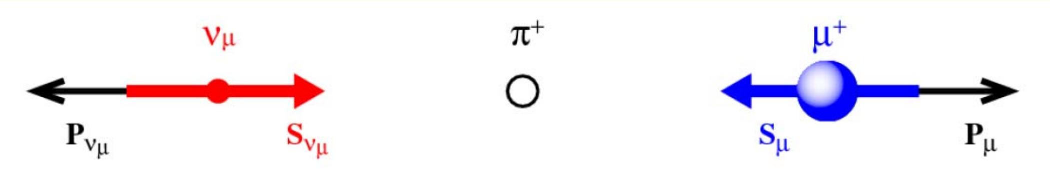


detector L
B
sample
F
μ
muon
beamline
production
target
accelerated
proton beam
stop
R
e+ after
time t
start
Electronics
Raw spectra
μSR spectra
Counts per nsec
Asymmetry
TIME (microsec)
TIME (microsec)

Production of a beam of polarised muons:

- Consider pions decaying at rest,
- since the pion is spinless and the neutrino helicity is −1

(i.e. its spin and linear momentum are antiparallel), conservation of linear and angular momenta dictates:



One can have a muon beam which is 100% polarized, with $S\mu$ antiparallel to $P\mu$.

Such a beam is called a surface muon beam (Arizona beaam).

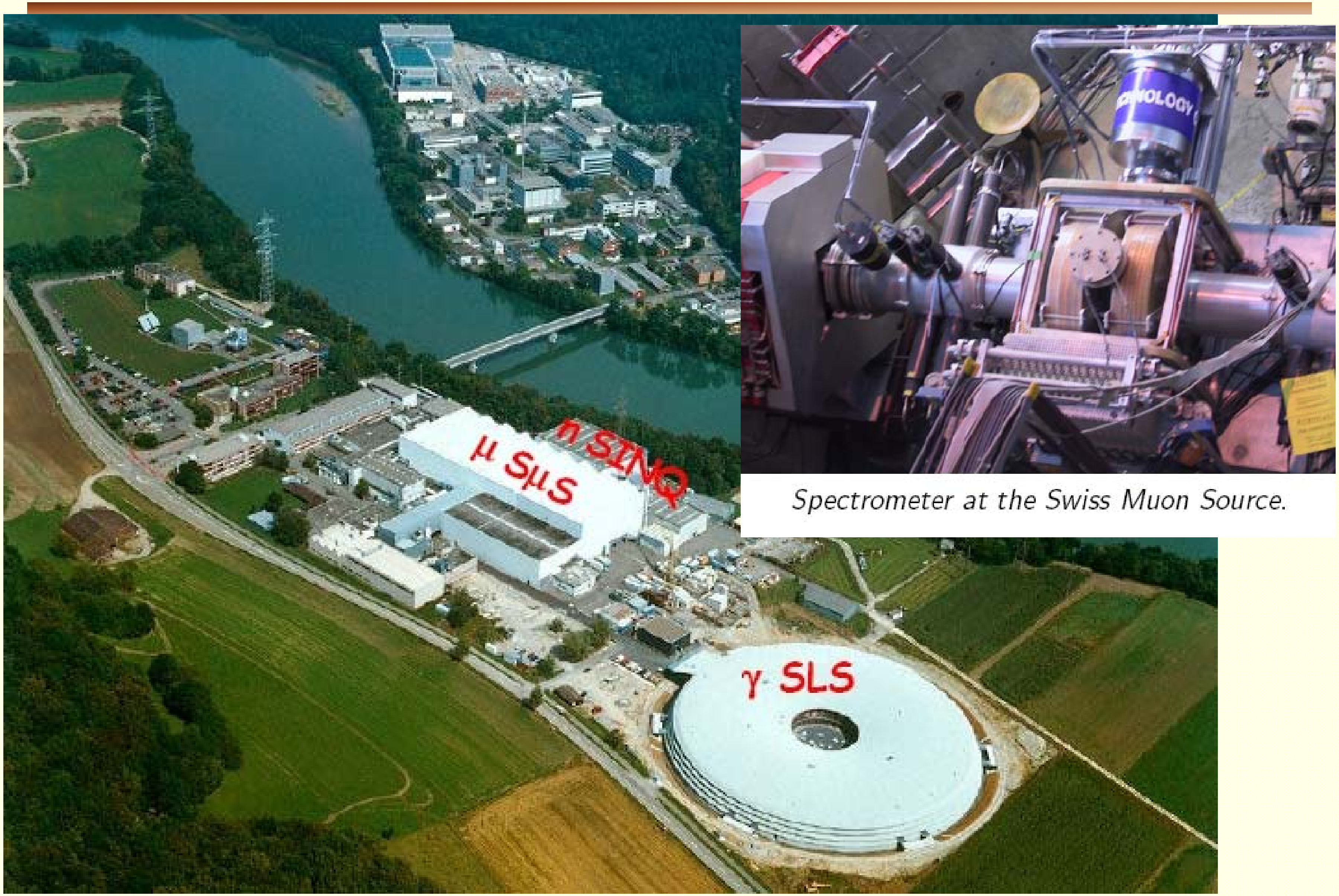
Muon kinetic energy: $E\mu$ = 4.12 MeV.

Function of the beam momentum:

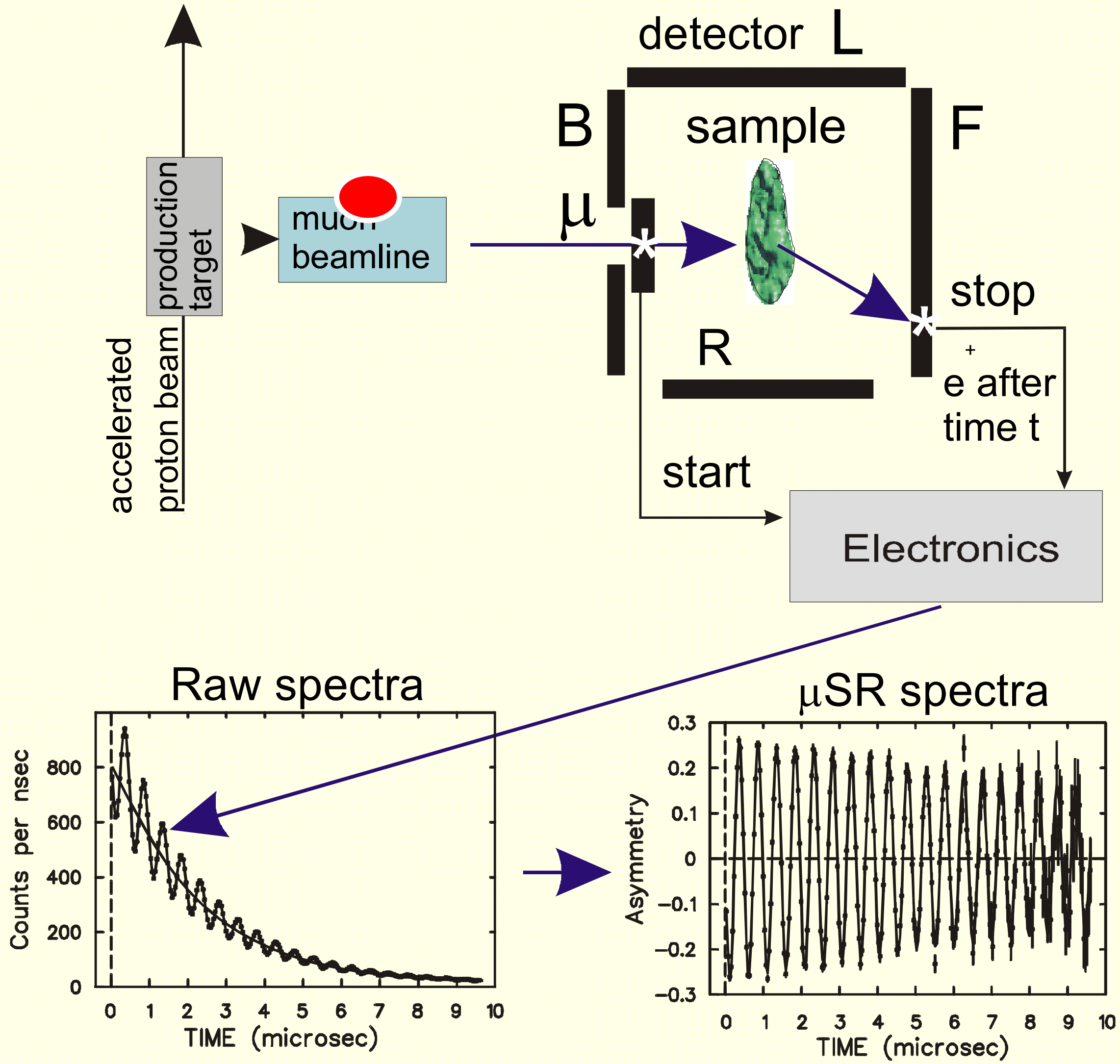
- Arizona (200 mg/cm^2) (from pions decaying at rest)
- High energy (samples inside containers, p-cells) – (from pions decaying in flight)
- Low energy (surfaces, interfaces, multilayers)

Function of the time structure:

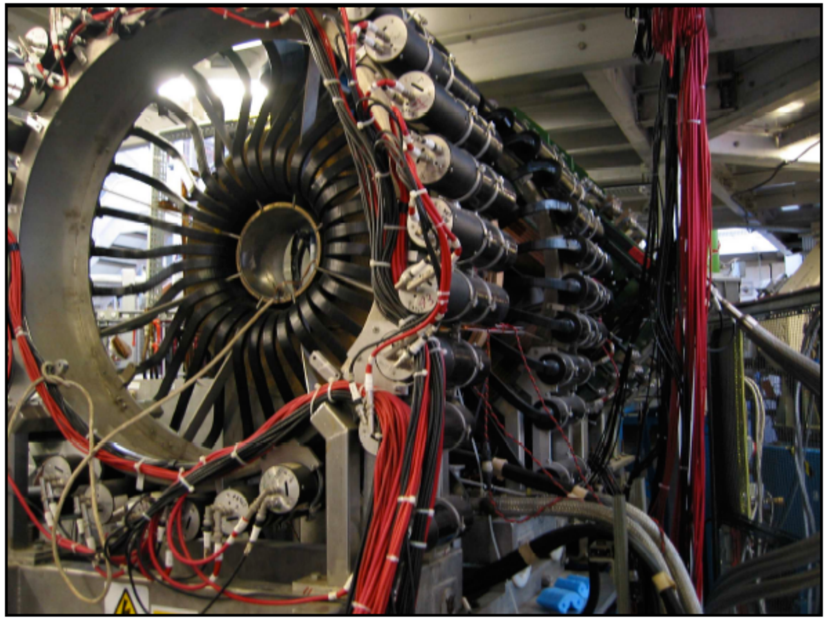
- Continuous (PSI and TRIUMF)
- Pulsed (ISIS and J-PARC)



Spectrometer at the Swiss Muon Source.



accelerated
proton beam
production
target
muon
beamline
detector L
B
F
sample
μ
stop
R
e+ after
time t
start
Electronics
Raw spectra
Counts per nsec
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10
TIME (microsec)
μSR spectra
Asymmetry
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0 1 2 3 4 5 6 7 8 9 10
TIME (microsec)



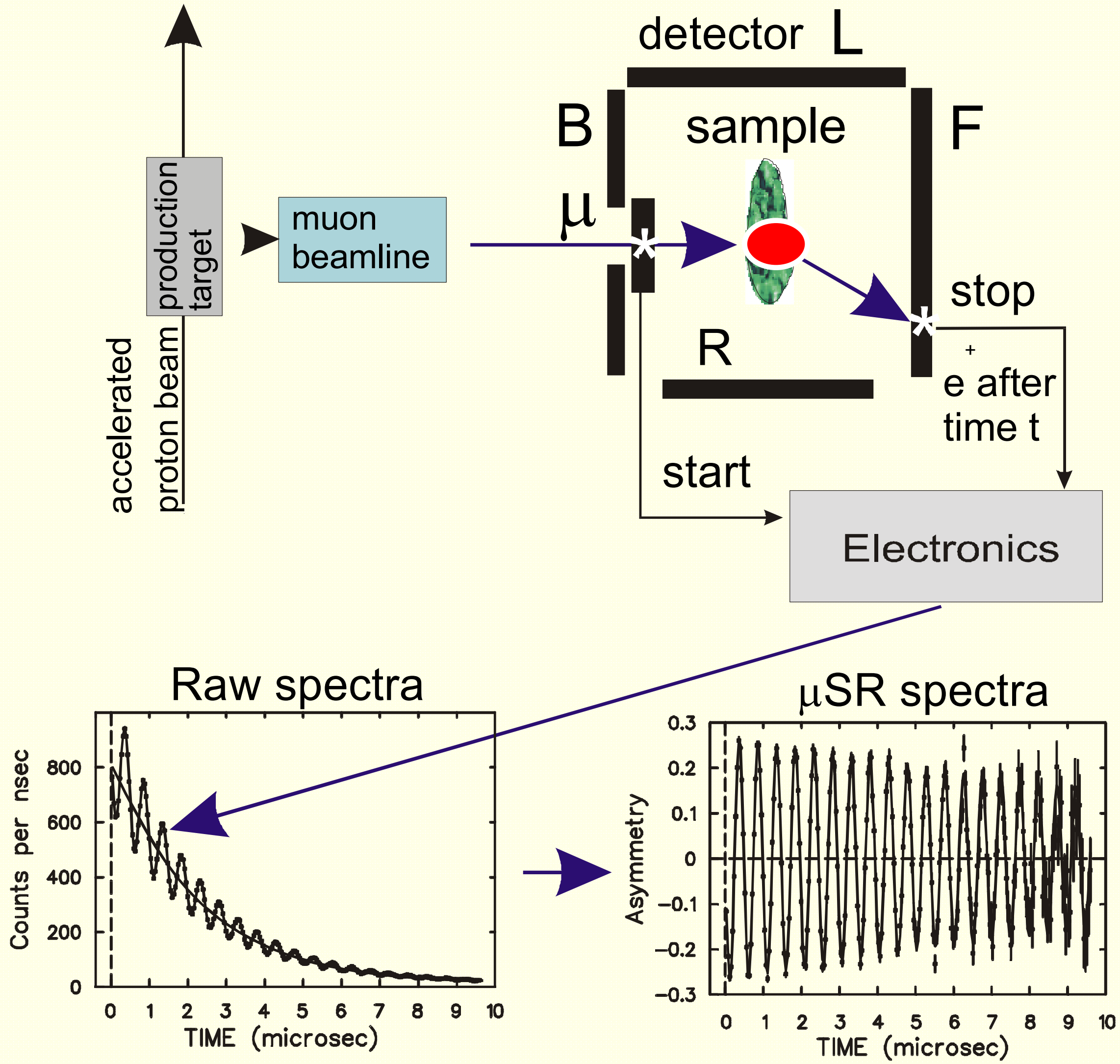

Experiments at the ISIS
muon facility

Muon implantation, thermalisation and localisation.

For decreasing kinetic energy of the muon:

- Inelastic scattering of the muon involving Coulomb interaction through atomic excitations and ionisations.
- $\mu+$ picks up an electron to form a muonium atom Mu (i.e. a $\mu+$-$e-$ bound state) and releases it many times.
- Last stage of thermalisation through collisions between Mu and atoms in the sample
- Eventually, dissociation of Mu into $\mu+$ and a free $e-$, in most cases. Exceptions are semiconductors, molecular materials. . .
- This process takes place in 10^{-10} - 10^{-9} s.
- No loss of muon polarisation during thermalisation.

Limited radiation damages: relatively few implanted $\mu+$ (108).
Muons finally localise in interstitial crystallographic sites.
Implantation range for 4.12 MeV muons: 0.1 to 1 mm, depending on material density.

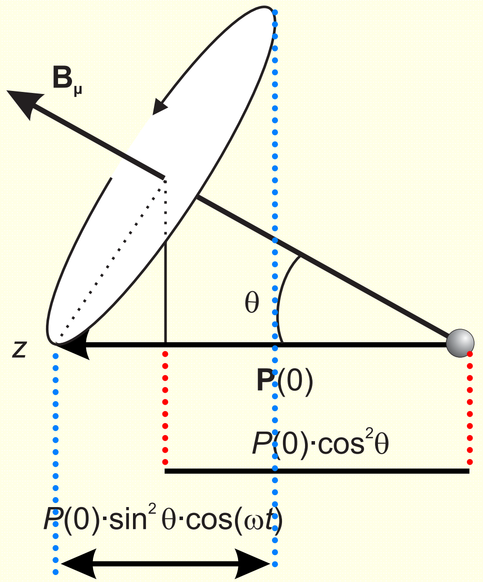


detector L
B
sample
F
μ
muon beamline
production target
accelerated proton beam
stop
R
+
e after time t
start
Electronics
Raw spectra
Counts per nsec
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10
TIME (microsec)
μSR spectra
Asymmetry
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
0 1 2 3 4 5 6 7 8 9 10
TIME (microsec)

The ideal case: muons sense an internal magnetic field (delta function) at their stopping site.

with $\nu_\mu = \frac{\omega_\mu}{2\pi} = \frac{\gamma_\mu}{2\pi} B_\mu$

$\omega_\mu \rightarrow$ $B_\mu \propto M$
order parameter:(sublattice) magnetizatio



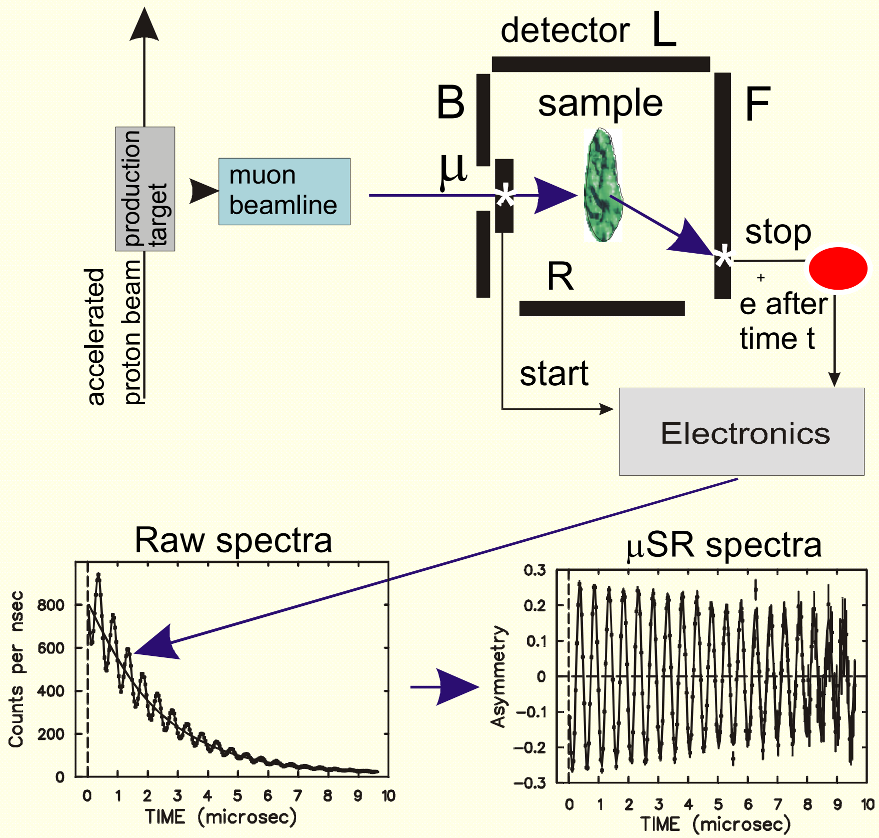
μSR works with FM order
as well as with AFM order !!
(except for the special case where B_μ = 0

Simple case of single-domain single crystal with one type of muon site and looking at the time evolution along z (and $P(0)$ = 1):

$$P_z(t) = \cos^2\theta + \sin^2\theta \cdot \cos(\omega_\mu t)$$

More general case:

$$\frac{\mathrm{d}\mathbf{S}_\mu(t)}{\mathrm{d}t} = \gamma_\mu \mathbf{S}_\mu(t) \times \mathbf{B}_{\mathrm{loc}}(t).$$



If the sample exhibits phase separation

$$AP_r(t) = \sum_i A_i P_{ir}(t)$$

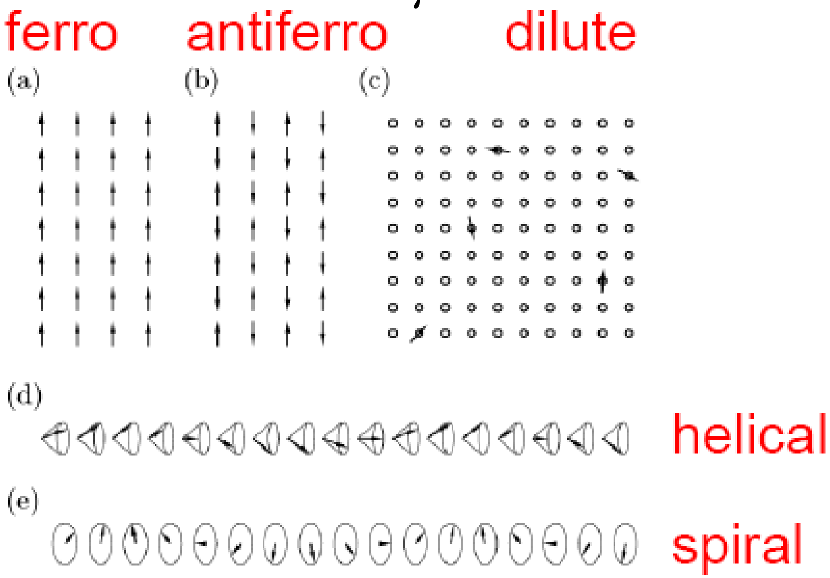
$$N_{e^+}(t) = B + \frac{N_0}{\tau_\mu} \exp\left(-t/\tau_\mu\right)\left[1 + AP_r(t)\right]$$

The result that you obtain, $AP_r(t)$, depends on the:

- physics of your sample,
- quality of your sample,
- quality of your experiment.

Relaxation functions:

$$N_{e^+}(t) = B + \frac{N_0}{\tau_\mu}\exp(-t/\tau_\mu)[1 + AP_r(t)]$$



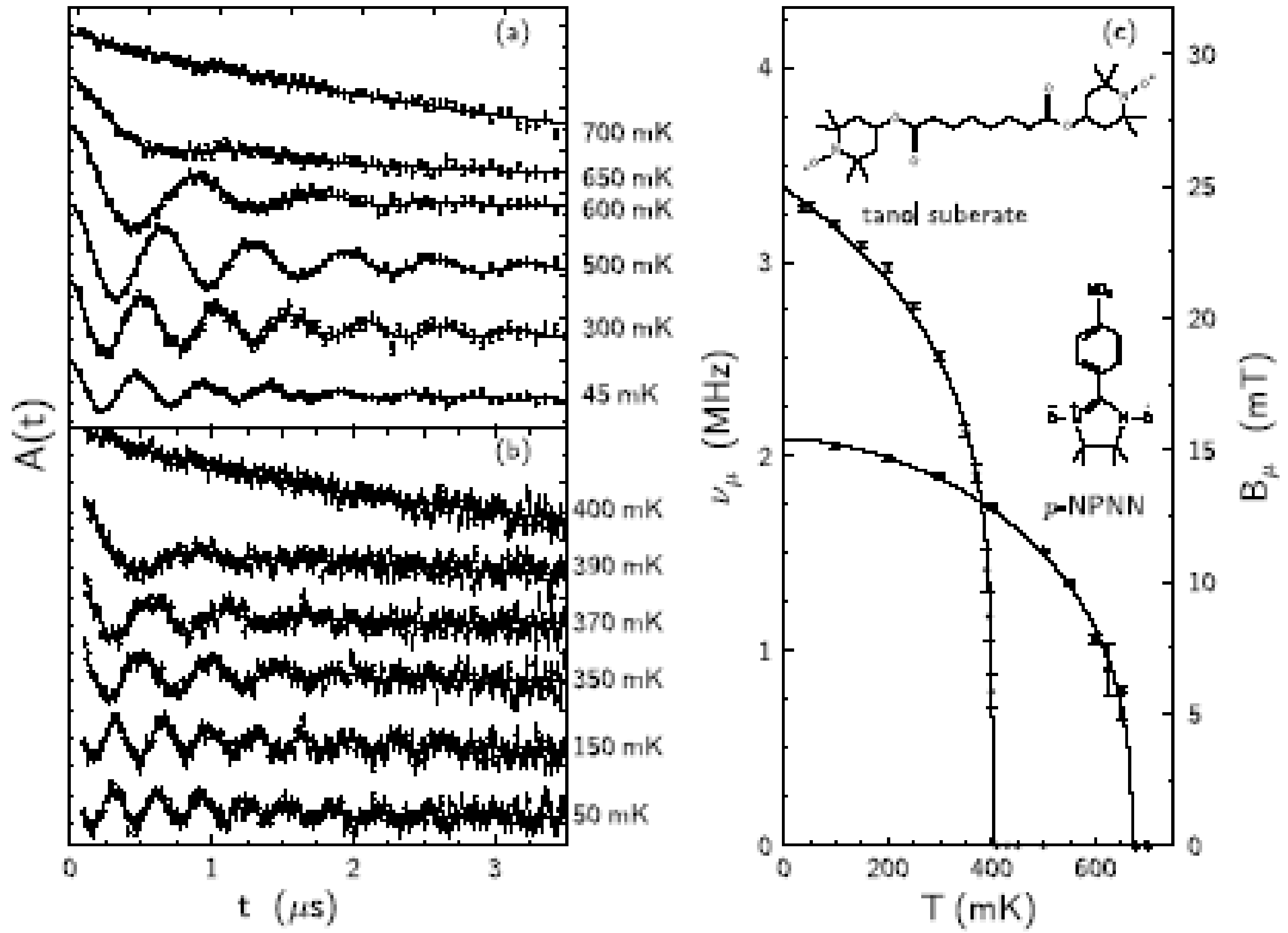
- nuclear moments
- electronic moments

- static moments
- fluctuating moments

- various spin structures
- spin glasses (randomness)
- variety of field distributions

dedicated $P_r(t)$ for each problem

Example.



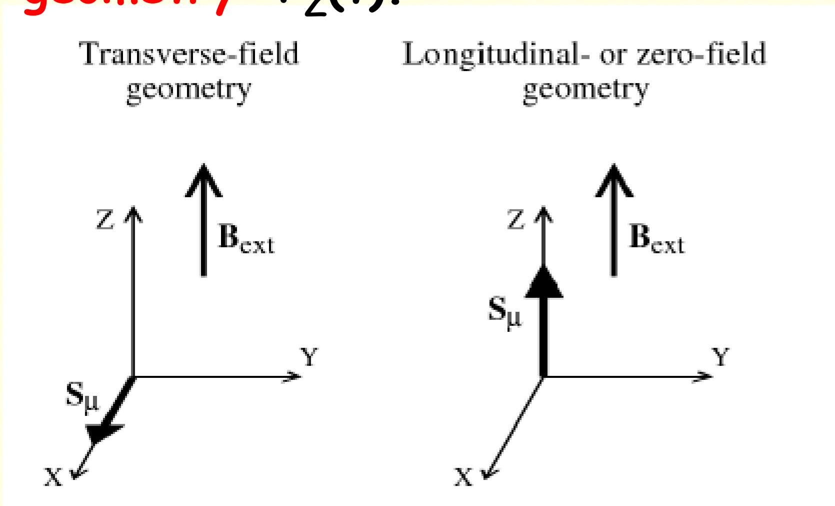
P-NPNN: Ferromagnet & Tanol suberate: Antiferromagnet [from S.J. Blundell and F.L. Pratt, J. Phys.: Condens. Matter 16 (2004) R771]

$P_r(t)$: $P_X(t)$ and $P_Z(t)$ (ZF and TF geometries)

- The primary purpose of a μSR experiment is to determine the evolution of the polarization of the implanted muons.
- The polarization is defined as the average over the muon ensemble of the muon normalized magnetic moment or spin.
- In fact, only the projection of the polarization along a direction is measured. This is the direction of the positron detector.

TF geometry: $P_X(t)$; LF or ZF geometry: $P_Z(t)$.

The muon momentum is, in both cases, || z

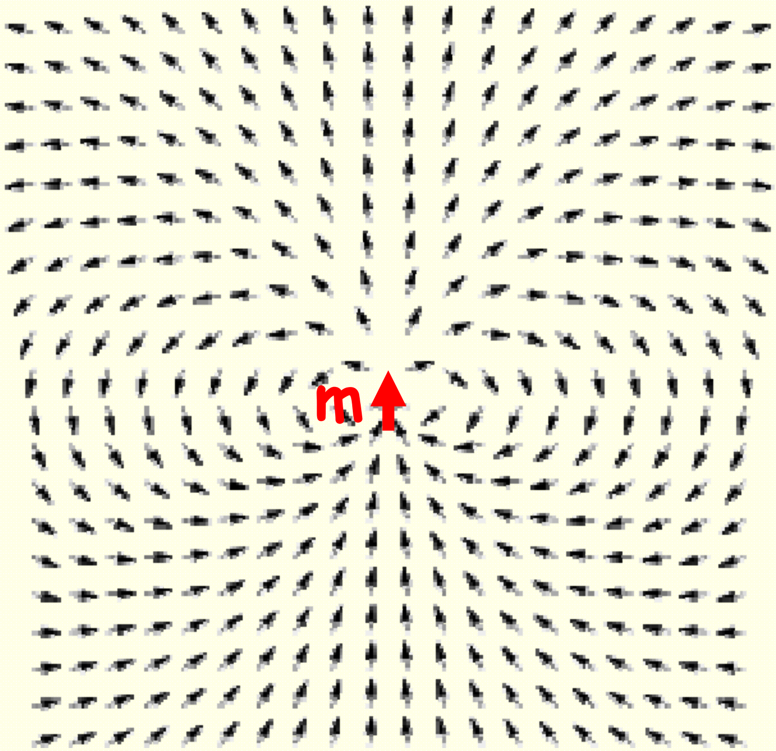


For the Zero-Field geometry:
(only internal fields)

$$\mathbf{B}_\mu = \mathbf{B}_{dip} + \mathbf{B}_c$$

<u>Hyperfine contact field</u>: due to the electron spin density at the muon site

<u>Dipolar field</u>: depends on muon site and direction of $\mathbf{m}$



$$\mathbf{B}_{dip} = \sum_i \frac{1}{r_i^3}\left[\frac{(3\mathbf{m}_i \cdot \mathbf{r}_i)}{r_i^2}\mathbf{r}_i - \mathbf{m}_i\right]$$

$B_{dip} \sim m/r^3$

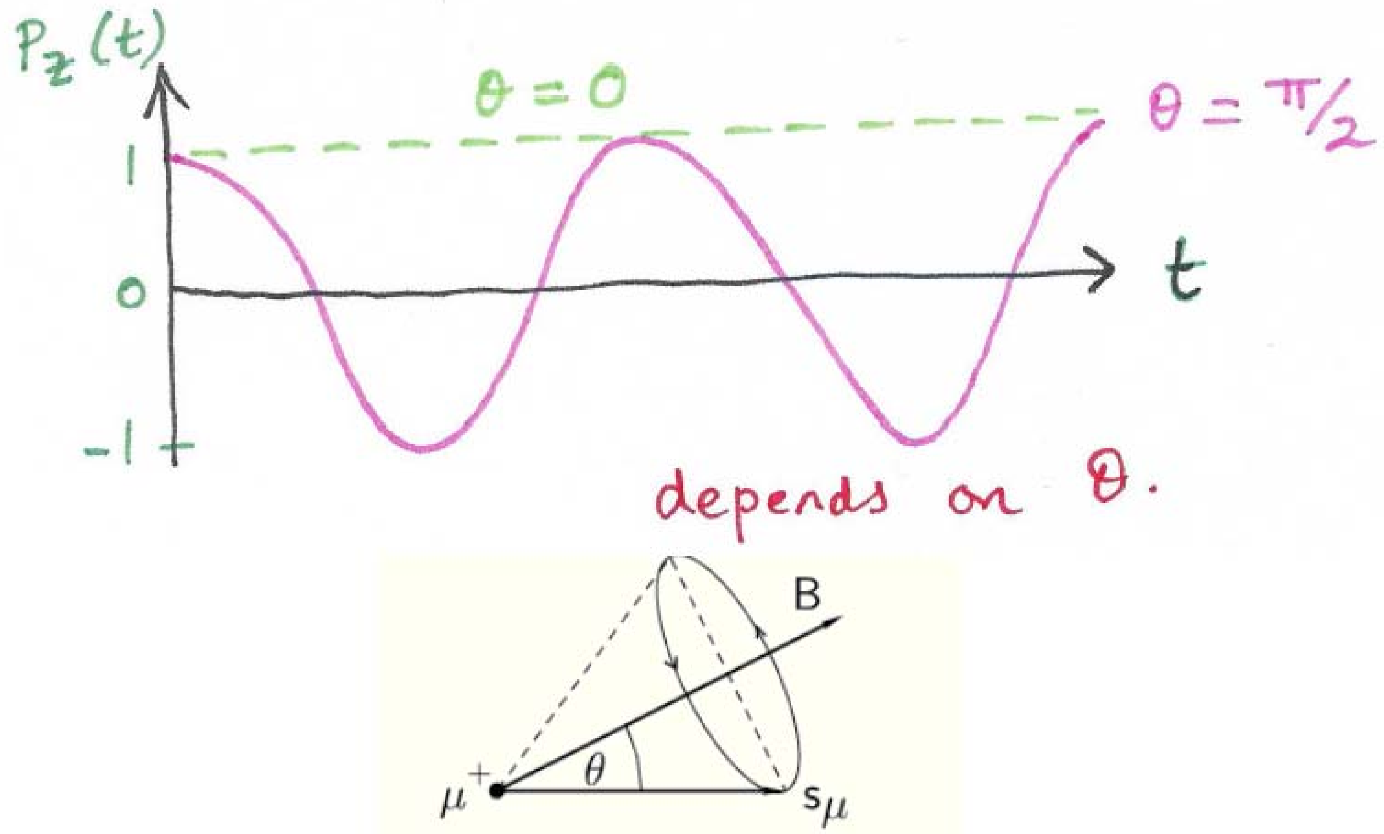
For $m = 1\ \mu_B$ and $r = 1$ Å $\longrightarrow B_{dip} \sim 1$ T

➡ static moments as low as 0.001 μ_B can be detected by μSR

$$1\ \text{mT} \cdot \gamma_\mu/(2\pi) \approx 0.14\ \text{MHz}$$

Spin precession

$$P_z(t) = \cos^2\theta + \sin^2\theta \cos\left[\gamma_\mu B t\right]$$



Hyperfine Interactions 85 (1994) 245–250 245

STUDY OF SPIN DYNAMICS IN $NdRh_2Si_2$ CRYSTALS BY μSR RELAXATION MEASUREMENTS

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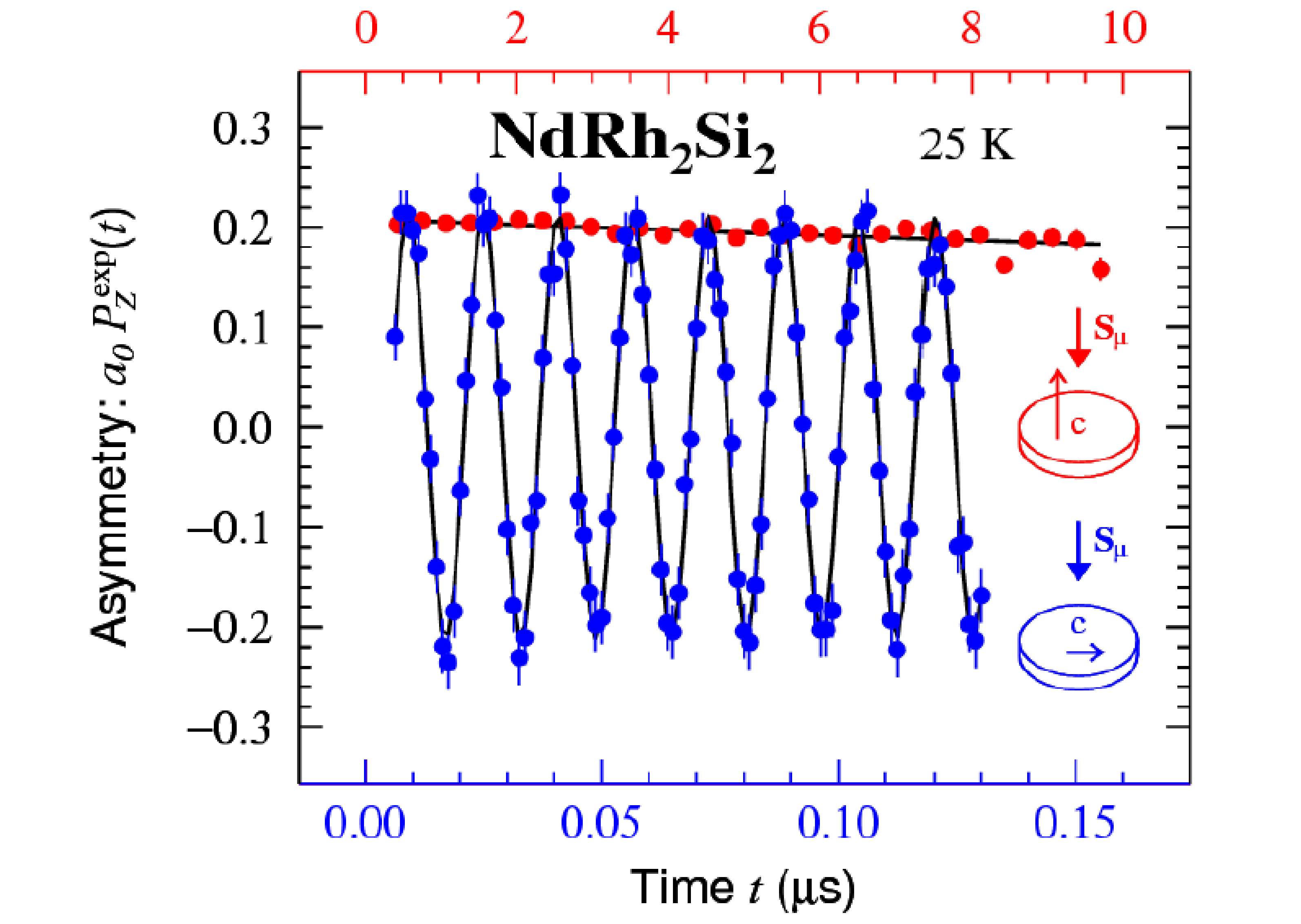
We have studied by zero-field and longitudinal field μSR measurements the uniaxial antiferromagnetic intermetallics $NdRh_2Si_2$. The measurements have been performed on single crystals. Our data show that the magnetic field at the muon site is parallel to the c axis. Below the Neel temperature T_N the spin-lattice relaxation is driven by a two magnon process. In the paramagnetic region near T_N we observe, a critical divergence of the damping rate.



NdRh2Si2
25 K
Asymmetry: $a_0 P_Z^{exp}(t)$
Time t (μs)
0 2 4 6 8 10
0.00 0.05 0.10 0.15
0.3 0.2 0.1 0.0 −0.1 −0.2 −0.3
S_μ
c
S_μ
c

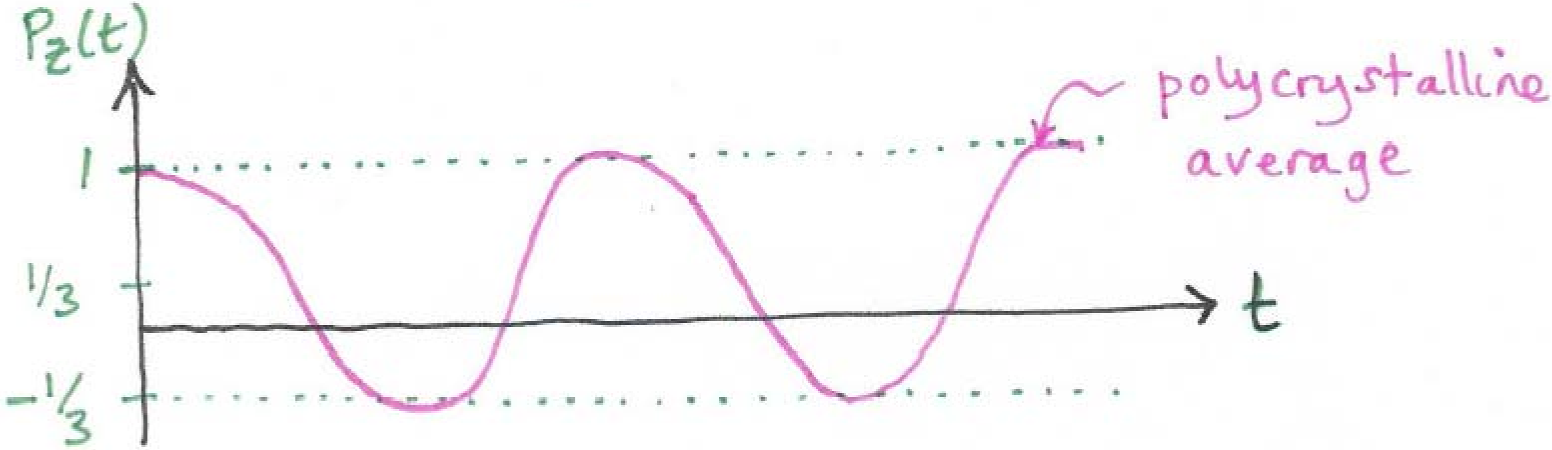
Polycrystalline sample

Angular averages: $\langle \cos^2\theta \rangle = \frac{1}{3}$

$\langle \sin^2\theta \rangle = \frac{2}{3}$

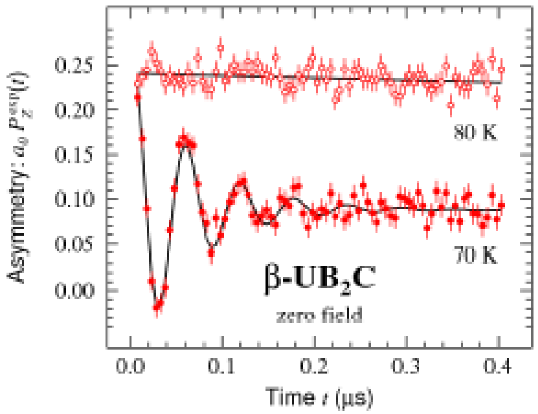
average taken over a sphere

$$\therefore \quad P_z(t) = \frac{1}{3} + \frac{2}{3}\cos\left[\gamma_\mu B t\right]$$

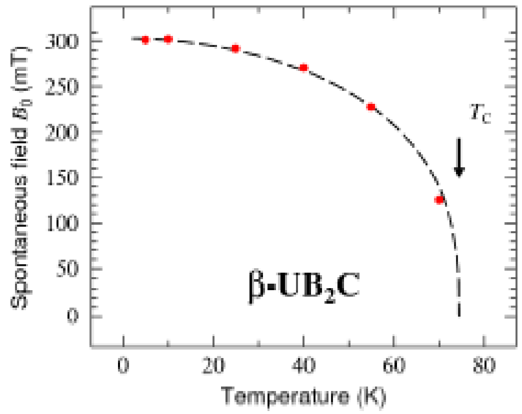


Magnetic phase transition in a polycrystal

Actually, one needs to take into account broadening and/or dynamics:



μSR spectra: a magnetic transition at $T_C = 74.5$ K.



Temperature dependence of B_0.

Above T_C,

$$P_Z(t) = \exp(-\lambda_Z t).$$

Below T_C,

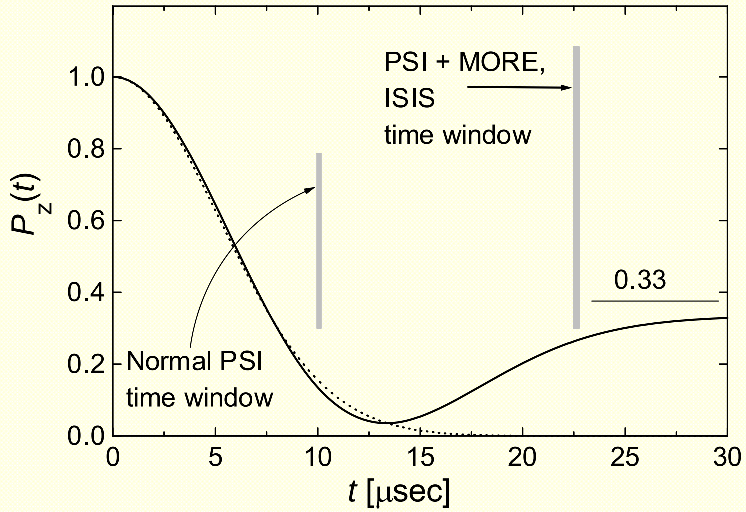
$$P_Z(t) = \frac{1}{3}\exp(-\lambda_Z t) + \frac{2}{3}\exp(-\lambda_X t)\cos(\omega_\mu t).$$

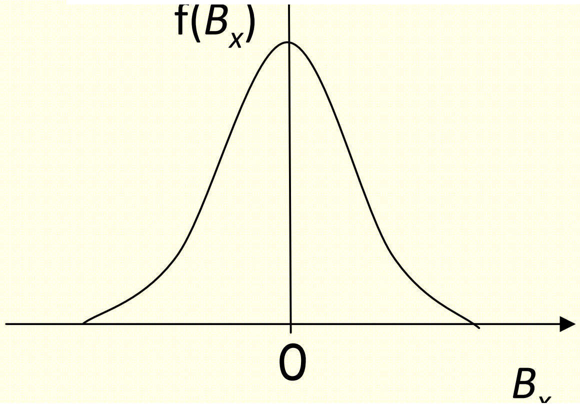
The spontaneous field is $B_0 = \omega_\mu/\gamma_\mu$.

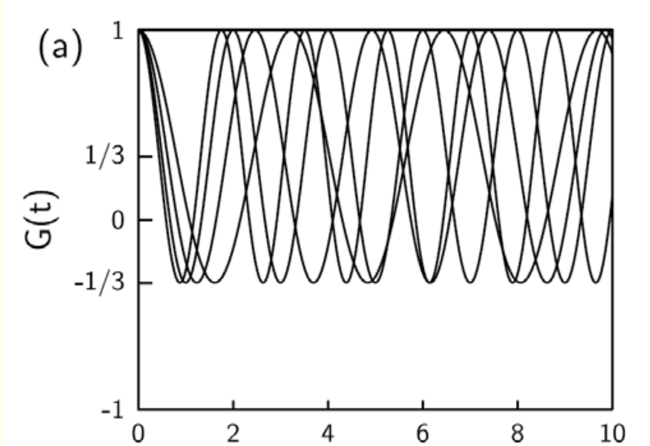
Static isotropic Gaussian magnetic field distribution with zero average

Gaussian KUBO-TOYABE (KT) relaxation function

$$\frac{1}{\sqrt{2\pi}\Delta}\times\exp\left(-B_i^2/2\Delta^2\right) \qquad (i = x, y, z))$$

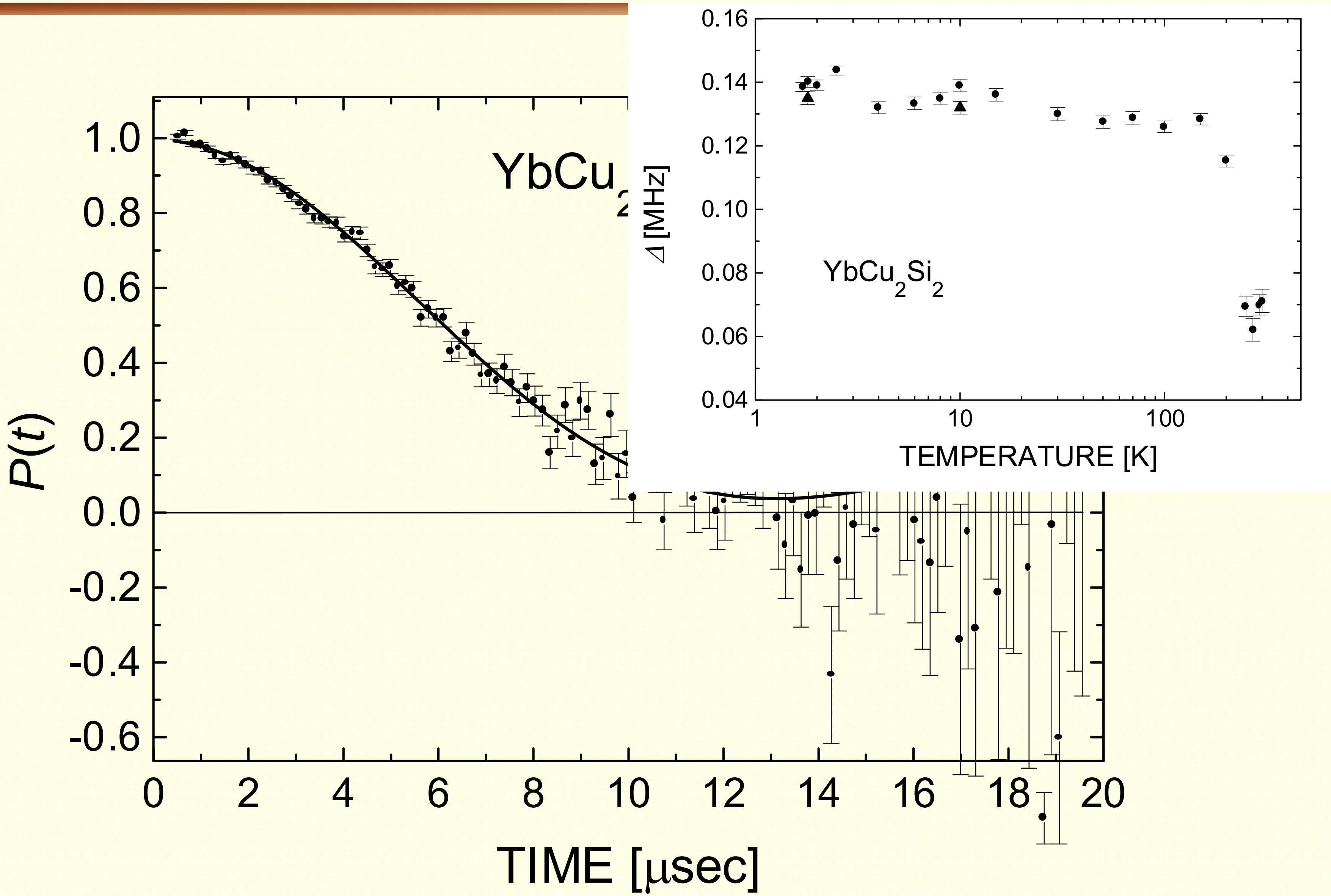






$$P_z(t) = \int f\left(\boldsymbol{B}_\mu\right)[\cos^2\theta + \sin^2\theta\cos\omega t]\,\mathrm{d}^3 B_\mu$$

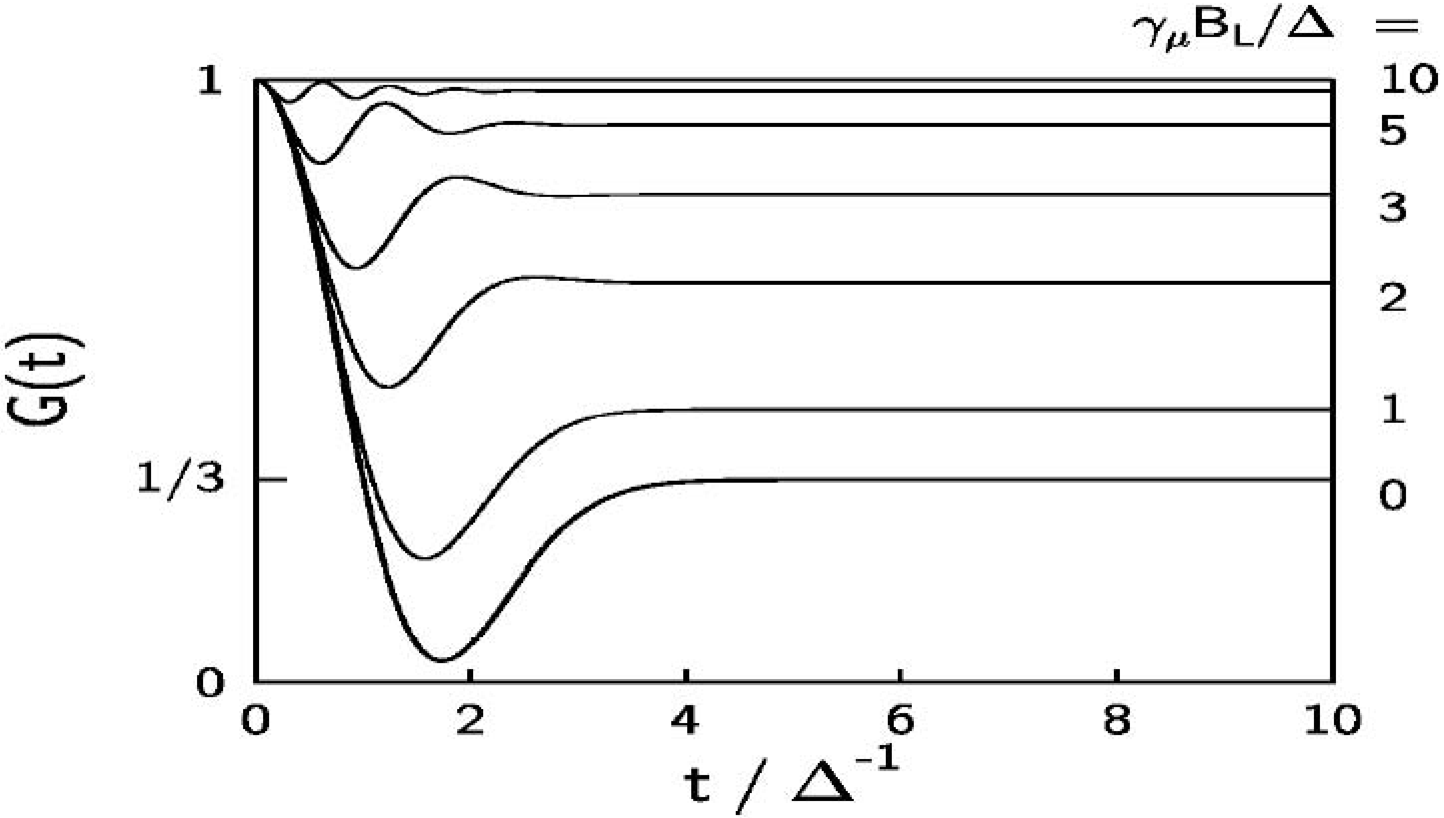
$$P_z(t) = \frac{1}{3} + \frac{2}{3}\left(1 - \Delta^2 t^2\right)\cdot\exp\left(-\frac{\Delta^2 t^2}{2}\right)$$

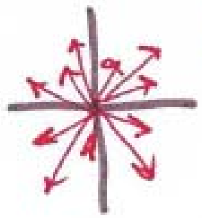


YbCu
P(t)
TIME [μsec]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
2
4
6
8
10
12
14
16
18
20
YbCu$_2$Si$_2$
Δ [MHz]
TEMPERATURE [K]
0.16
0.14
0.12
0.10
0.08
0.06
0.04
1
10
100

Apply a longitudinal field:

see a recovery of the K-T function!

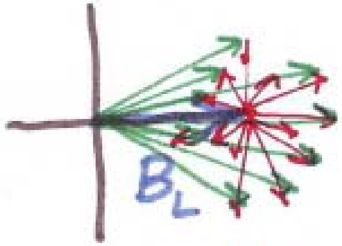




- random fields in all directions

  ~ 1/3 parallel or antiparallel to the muon-spin

  ~ 2/3 perpendicular ⇒ depolarize on a time ~ $1/\Delta$



- now add a longitudinal component

  boosts the $\frac{1}{3}$ fraction along z

$$P_z(t) = \langle \cos^2\theta \rangle + \langle \sin^2\theta \cdot \cos \gamma_\mu B t \rangle$$

BOOSTED   "RINGS" at $\sim \gamma_\mu B_L$.

Analytical calculation:

$$P(B_x) = \frac{\gamma_\mu}{(2\pi)^{1/2}\Delta} e^{-\gamma_\mu^2 B_x^2/2\Delta^2}$$

$$P(B_y) = \frac{\gamma_\mu}{(2\pi)^{1/2}\Delta} e^{-\gamma_\mu^2 B_y^2/2\Delta^2}$$

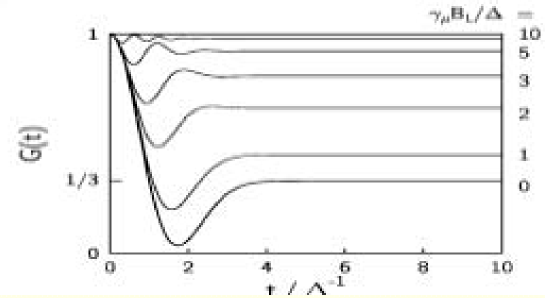
$$P(B_z) = \frac{\gamma_\mu}{(2\pi)^{1/2}\Delta} e^{-\gamma_\mu^2 (B_z - B_L)^2/2\Delta^2}$$

Gaussian distribution with offset

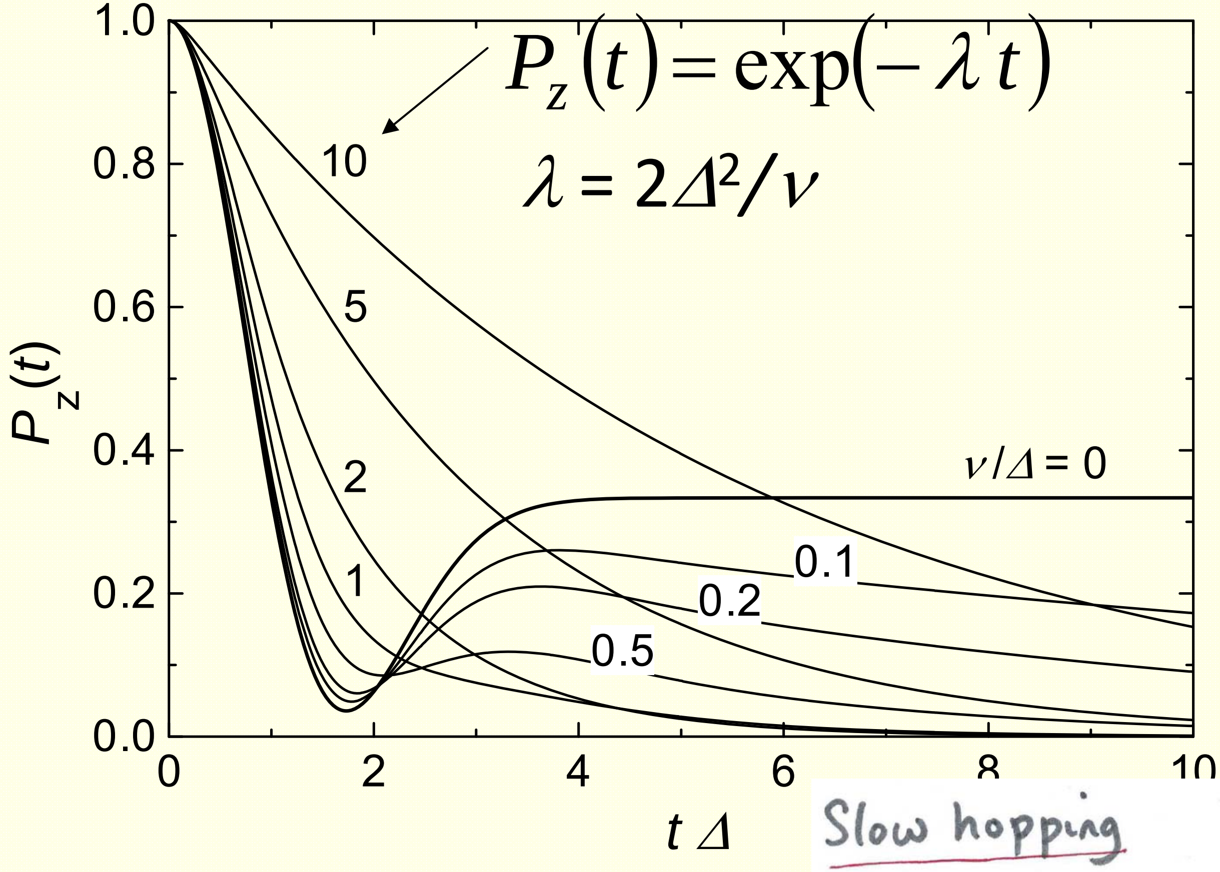
$$P_z(t) = \int d^3B \left[\cos^2\theta + \sin^2\theta \cos(\gamma_\mu B t)\right] P(B_x)P(B_y)P(B_z)$$

$$\Rightarrow \boxed{P_z(t) = 1 - \frac{2\Delta^2}{(\gamma_\mu B_L)^2}\left(1 - e^{-\frac{1}{2}\Delta^2 t^2}\cos \gamma_\mu B_L t\right) + \frac{2\Delta^4}{(\gamma_\mu B_L)^3}\int_0^t e^{-\frac{1}{2}\Delta^2\tau^2} \sin \gamma_\mu B_L \tau \, d\tau}$$

LONGITUDINAL-FIELD KUBO TOYABE FUNCTION

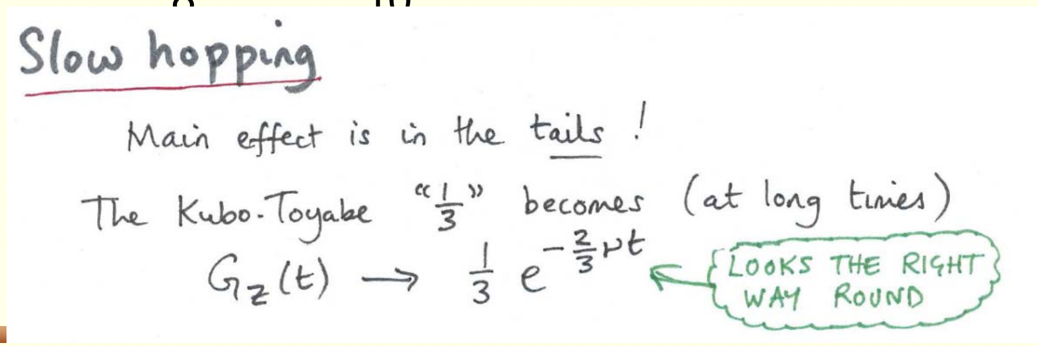


KT: Switch on the dynamics

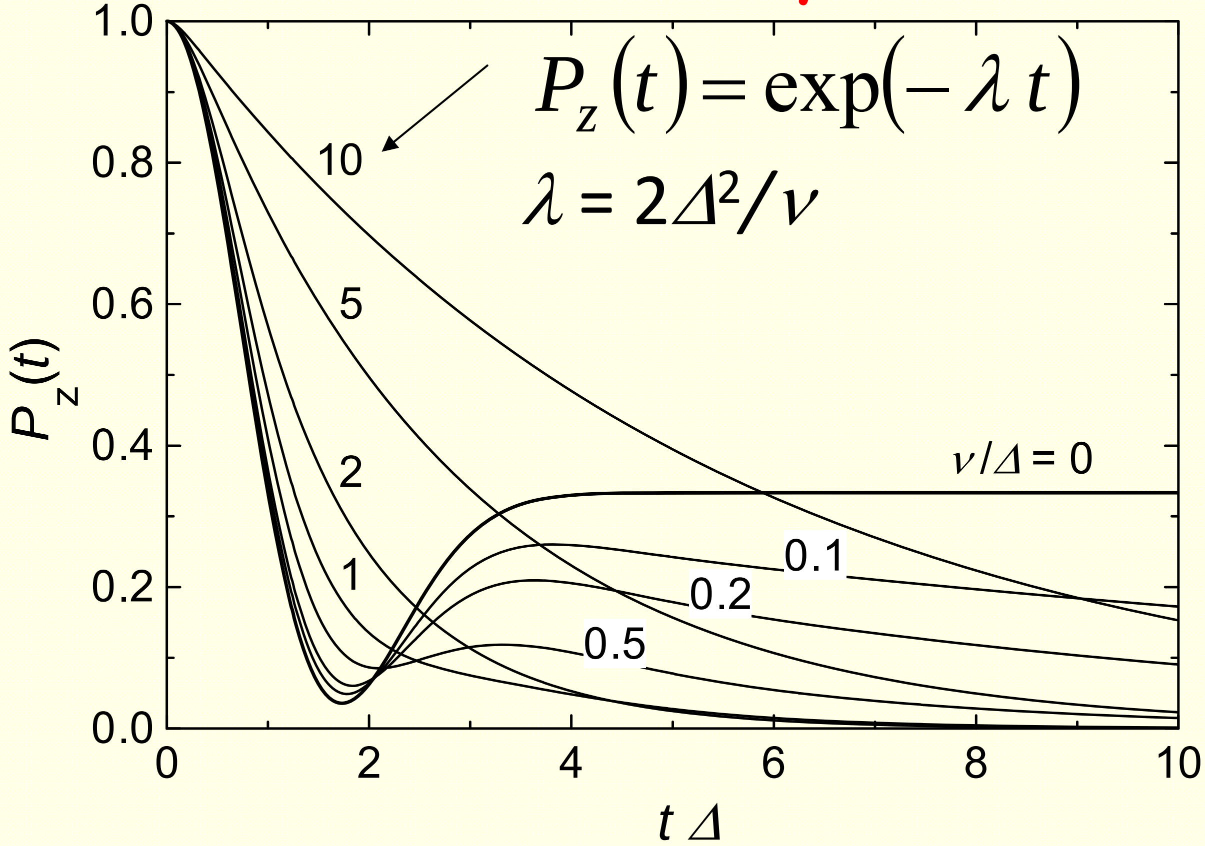


Jumps with a characteristic frequency ν. Between jumps, KT. Initial and final state are not correlated.

No analitical form, only numerical integration and some approximations



KT: Switch on the dynamics



! An exponential relaxation exp(-λt) is an indication that there might be some dynamics in the system.

To be sure: Longitudinal field μSR; decoupling

= > apply a longitudinal field B>10 Δ/γ

$$\lambda = \frac{2\Delta^2\tau_0}{1+\omega^2\tau_0{}^2}$$

In the fast fluctuation regime: no LF dependence of λ

$$\lambda = 2\Delta^2/\nu$$

Hyperfine Interactions 85 (1994) 245–250 245

STUDY OF SPIN DYNAMICS IN $NdRh_2Si_2$ CRYSTALS BY μSR RELAXATION MEASUREMENTS

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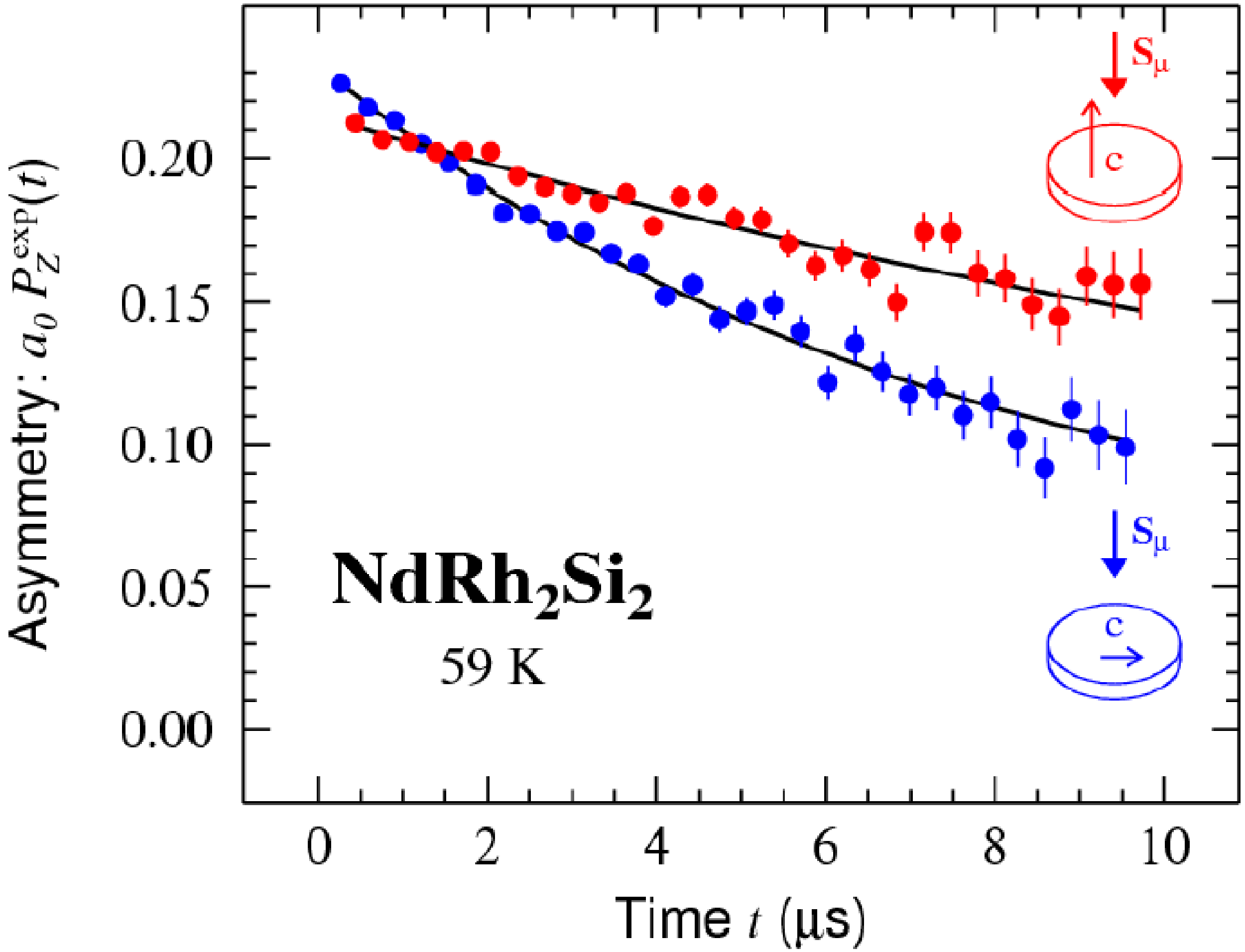
We have studied by zero-field and longitudinal field μSR measurements the uniaxial antiferromagnetic intermetallics $NdRh_2Si_2$. The measurements have been performed on single crystals. Our data show that the magnetic field at the muon site is parallel to the c axis. Below the Néel temperature T_N the spin-lattice relaxation is driven by a two magnon process. In the paramagnetic region near T_N we observe, a critical divergence of the damping rate.



S_μ
c
S_μ
c
0.20
0.15
0.10
0.05
0.00
Asymmetry: $a_0 P_Z^{\exp}(t)$
0
2
4
6
8
10
Time t (μs)
$NdRh_2Si_2$
59 K

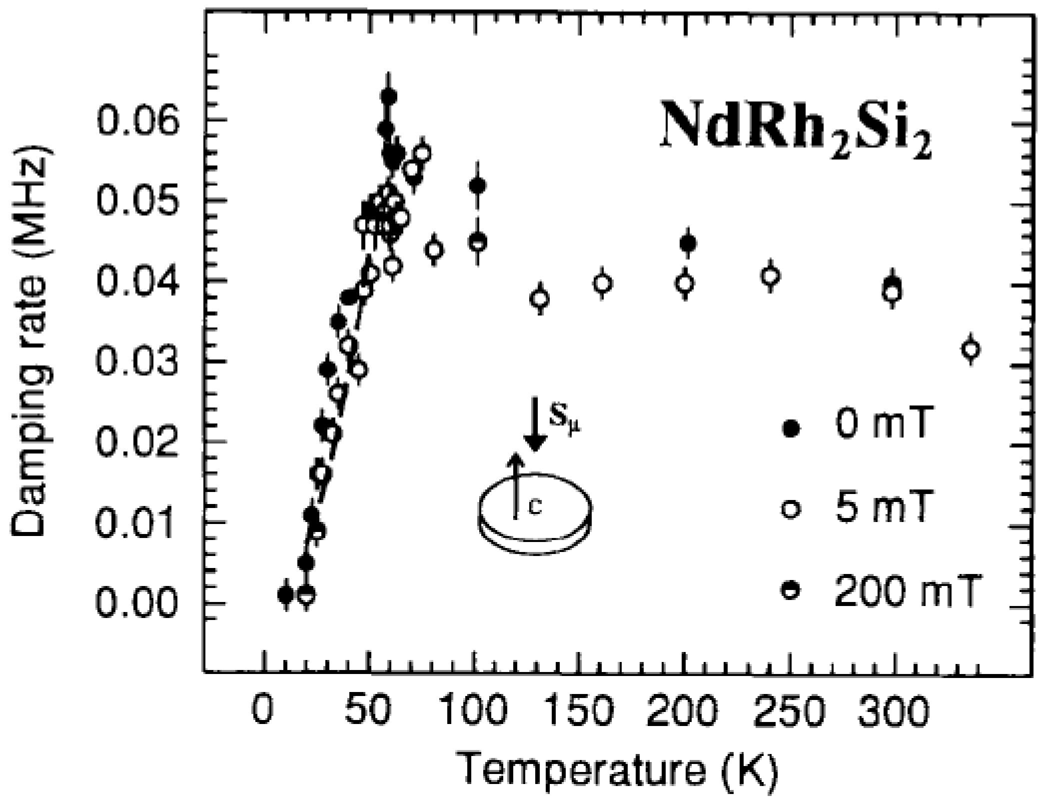


Fig. 1. Temperature dependence of the damping rate measured on a single crystal of $NdRh_2Si_2$. The initial muon beam polarisation is parallel to the c axis. The dashed line gives the prediction for a quadratic temperature dependence of the damping rate in the ordered state.

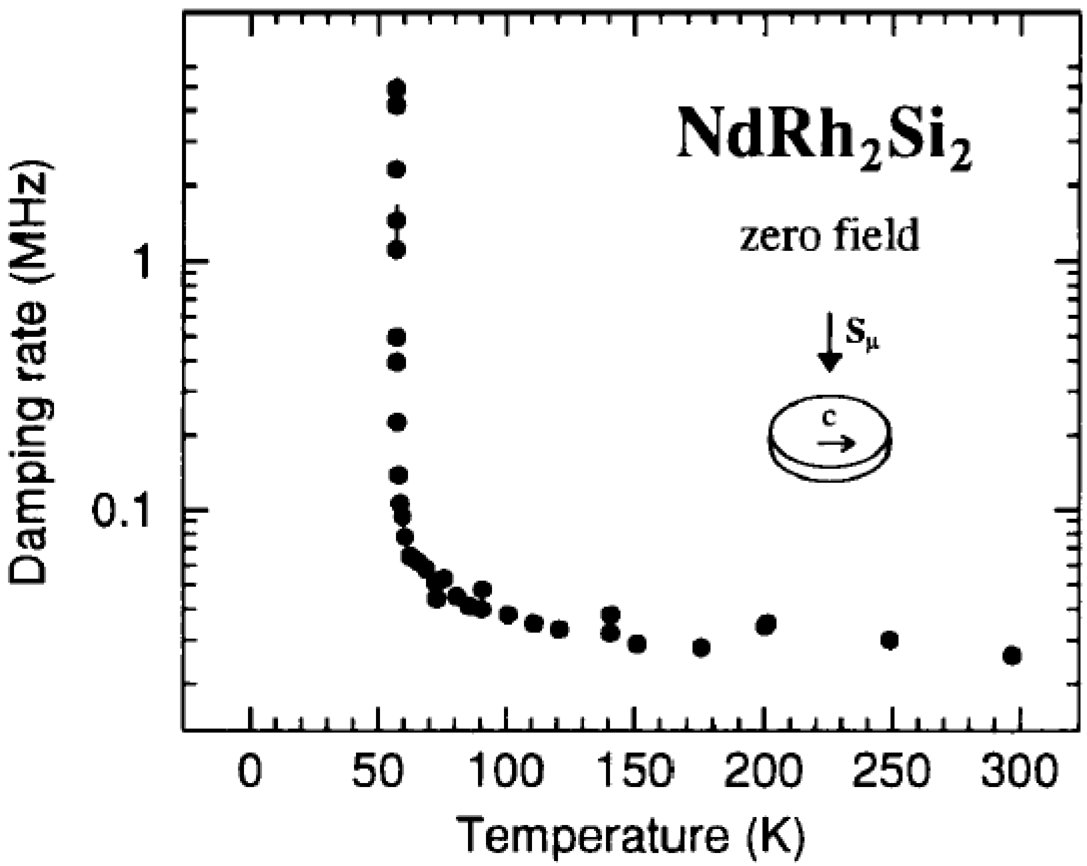
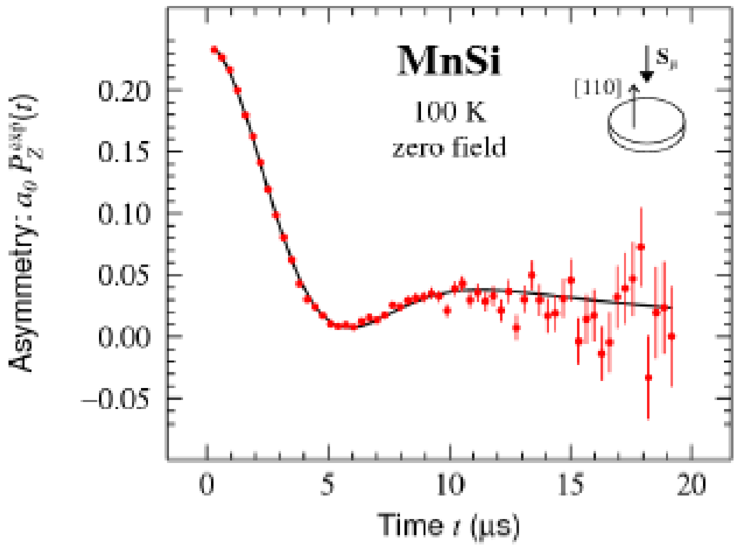


Fig. 2. Temperature dependence of the damping rate measured on a single crystal of $NdRh_2Si_2$. The initial muon beam polarisation is perpendicular to the c axis.

μSR response in a paramagnetic phase

The case of MnSi

A magnetic phase transition to a (nearly ferromagnetic) helimagnetic phase below $T_c \simeq 30$ K.



The sources of the magnetic field at the muon are:

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **17** (2005) L129–L135 doi:10.1088/0953-8984/17/13/L01

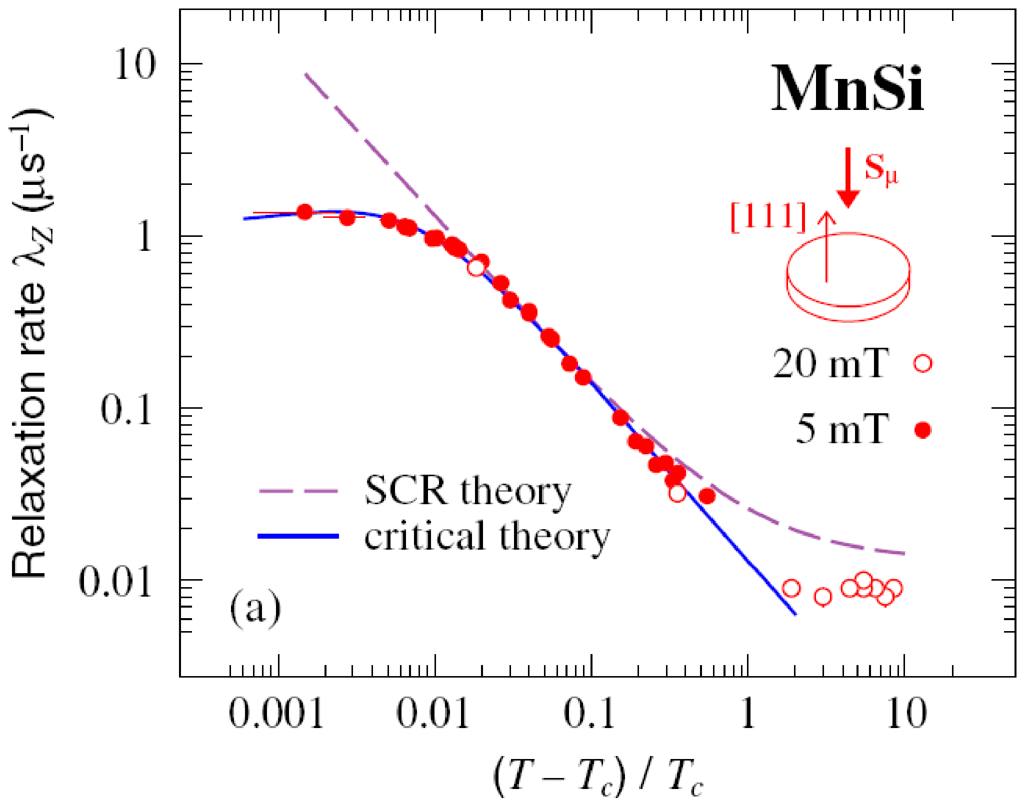
LETTER TO THE EDITOR

Testing the self-consistent renormalization theory for the description of the spin-fluctuation modes of MnSi at ambient pressure

A Yaouanc[1], P Dalmas de Réotier[1], P C M Gubbens[2], S Sakarya[2], G Lapertot[1], A D Hillier[3] and P J C King[3]

MnSi is a metallic compound which undergo a second order magnetic phase transition at $\sim$29.5 K into a helical magnetic structure characterized by a small wavevector $Q_0 = 0.035$ Å^{-1}

it is found that $\lambda_Z(T) \propto T/(T - T_N)^{1/2}$ and $\lambda_Z(T) \propto T/M_{Q_0}$ for an antiferromagnet in the paramagnetic and ordered phases respectively [10]. Hence, $\lambda_Z(T) \propto T^{1/2}$ in the high-temperature limit, i.e. λ_Z should never level off at high temperature.



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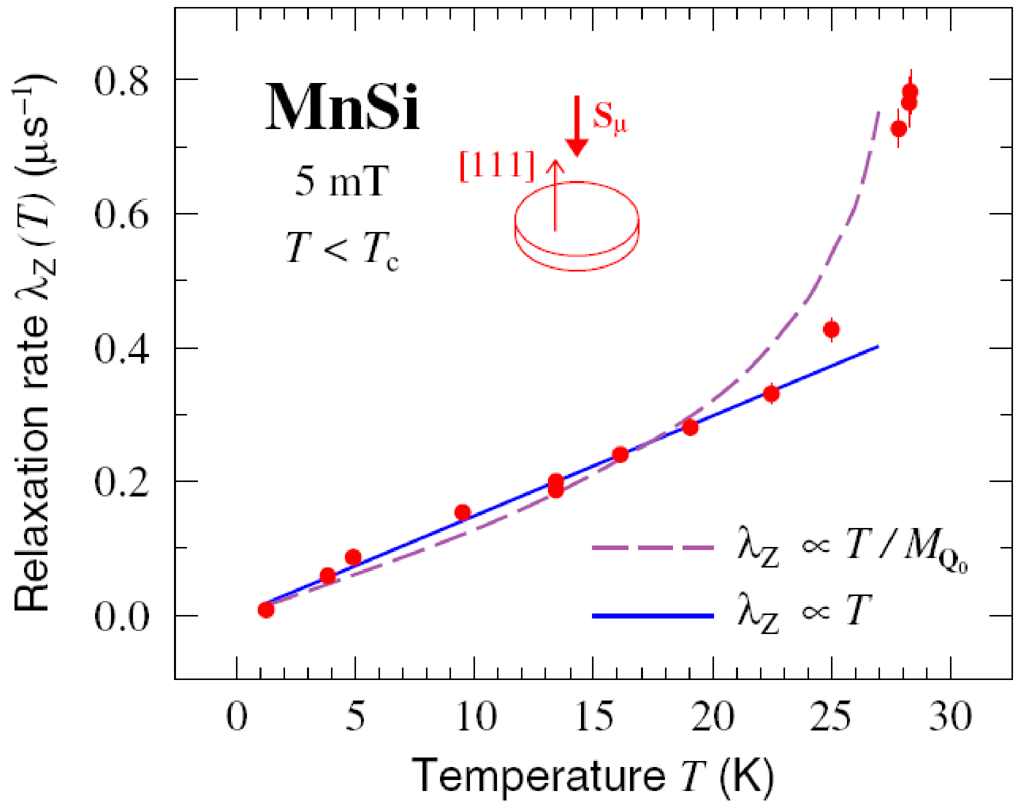
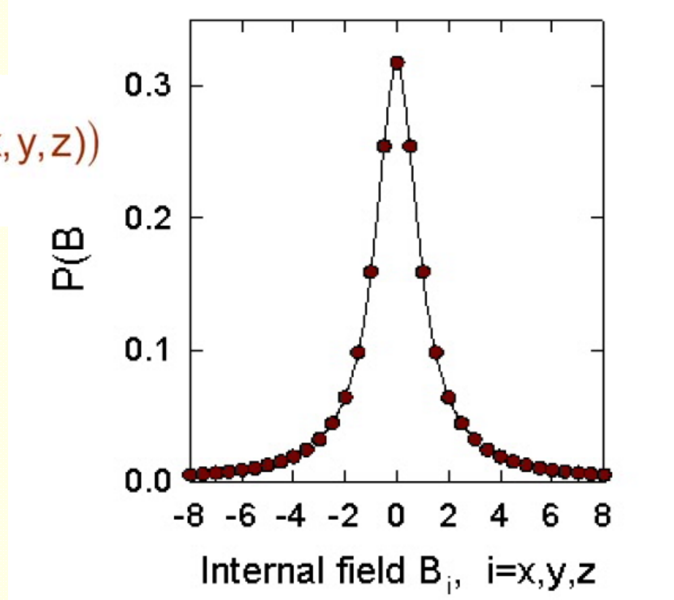


it is found that $\lambda_Z(T) \propto T/(T - T_N)^{1/2}$ and $\lambda_Z(T) \propto T/M_{Q_0}$ for an antiferromagnet in the paramagnetic and ordered phases respectively [10]. Hence, $\lambda_Z(T) \propto T^{1/2}$ in the high-temperature limit, i.e. λ_Z should never level off at high temperature.

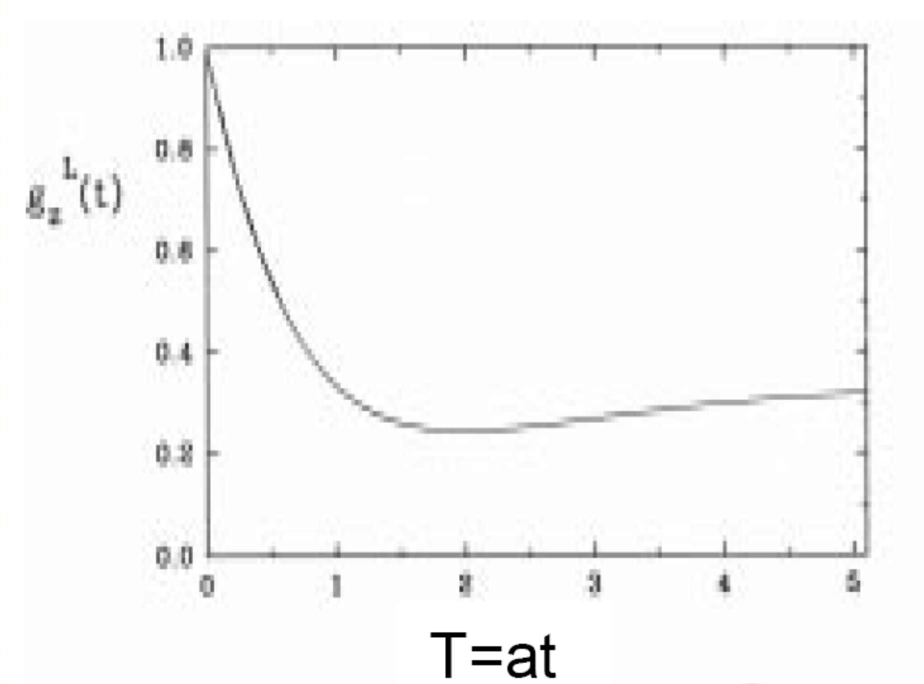
The case of the Lorentzian field distribution:

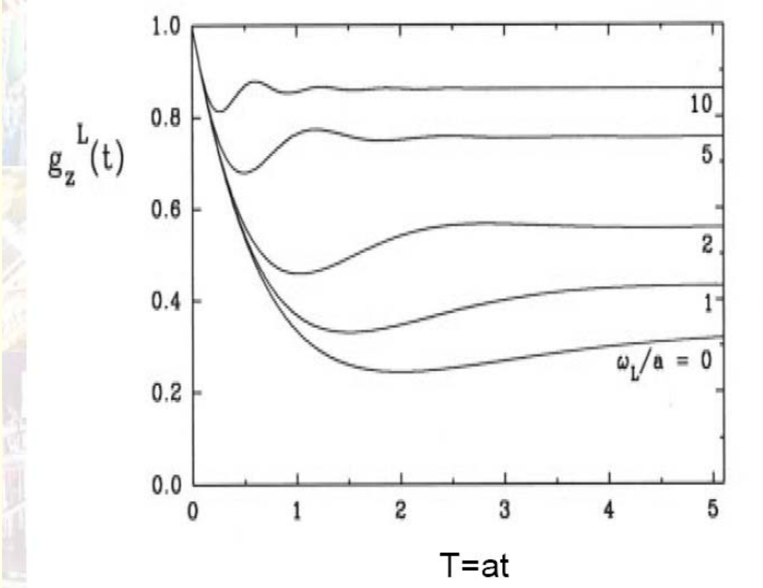
$$\frac{1}{\pi}\frac{\Lambda}{\left(\Lambda^2+B_i^2\right)} \qquad (i=x,y,z))$$



$$G_z(t)=\frac{1}{3}-\frac{2}{3}(1-at)\exp(-at)$$

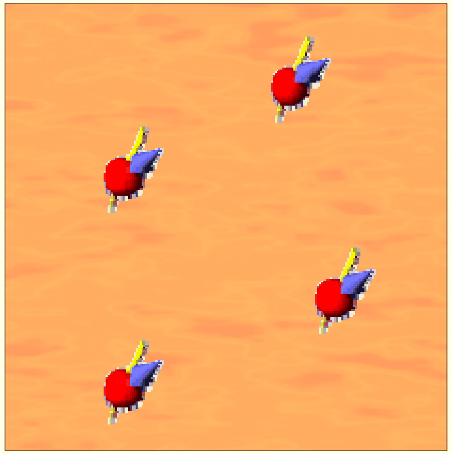
with $a=\gamma_\mu\Lambda$

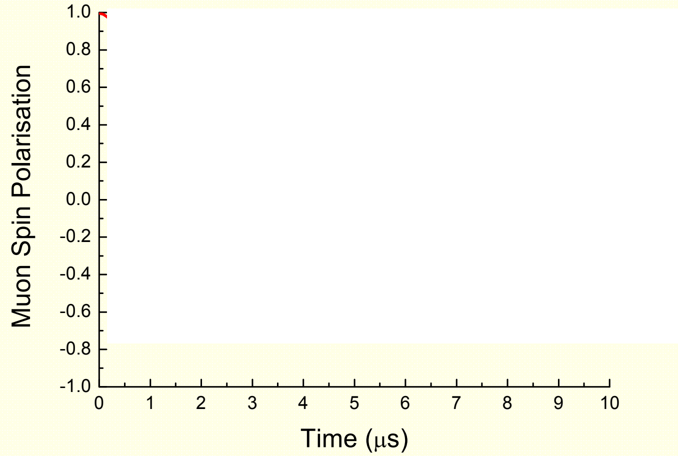




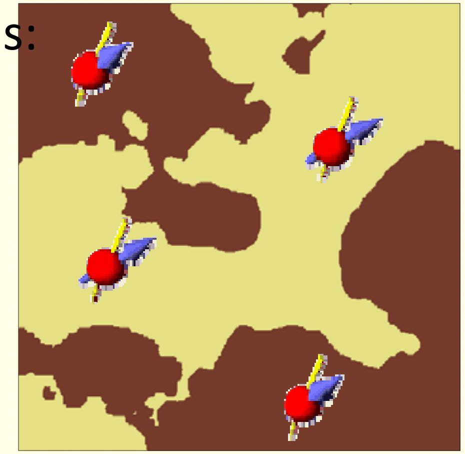
Detection of phase separation:

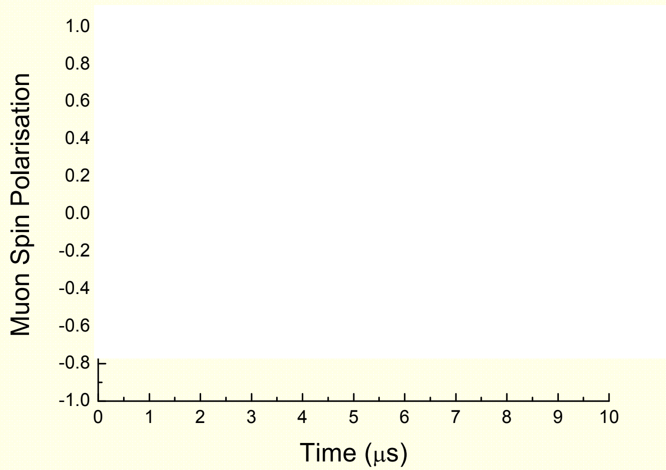
Homogeneous:





Inhomogeneous:



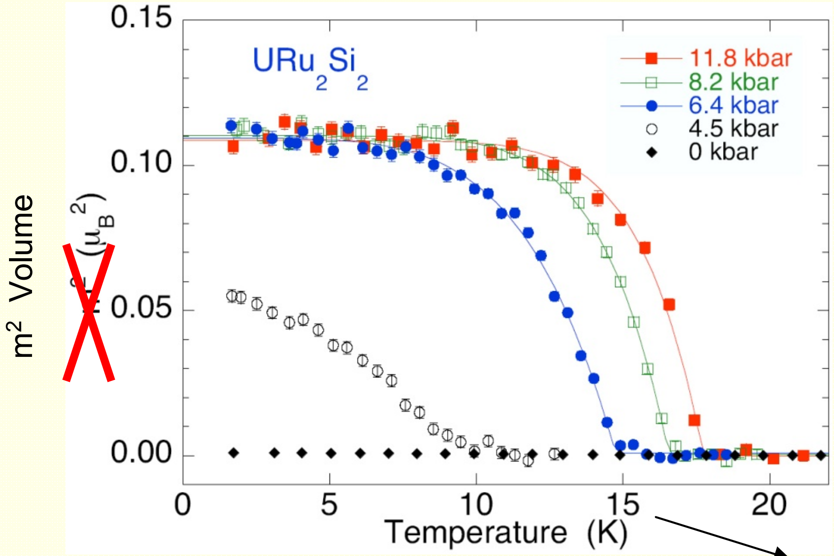


Frequency = Internal magnetic field
Amplitude = Magnetic volume fraction

Detection of phase separation:

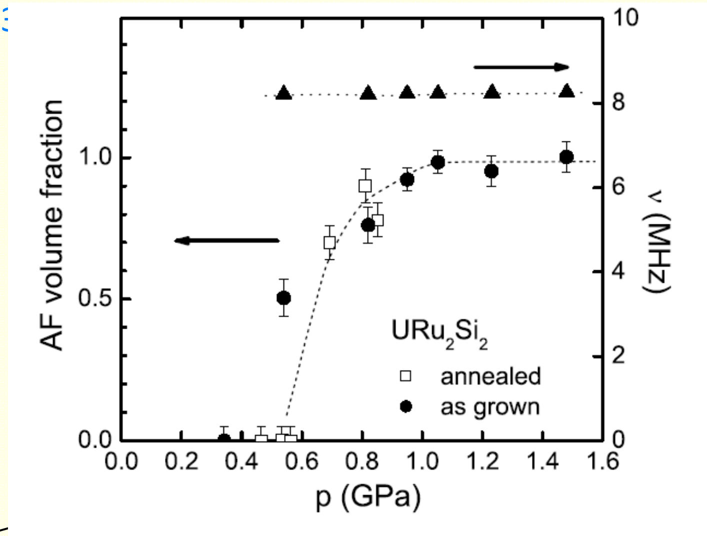
Neutron scattering

F. Bourdarot et al., condmat/0312206

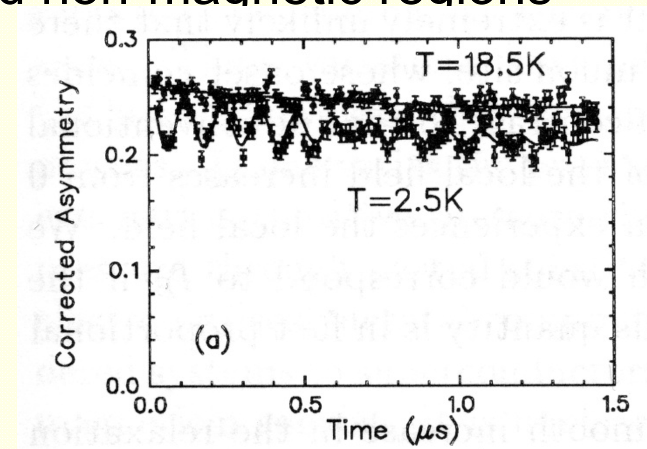


Muon Spin Rotation:

A. Amato et al., J. Phys.: Condens. Matter 16 (2004) S4403



Phase separation in magnetic und non-magnetic regions



Not only observed under pressure, but also
at ambient pressure by μSR on non-perfect crystals

G.M. Luke et al., Hyp. Inter. 85 (1994) 397.

T-p phase diagram:

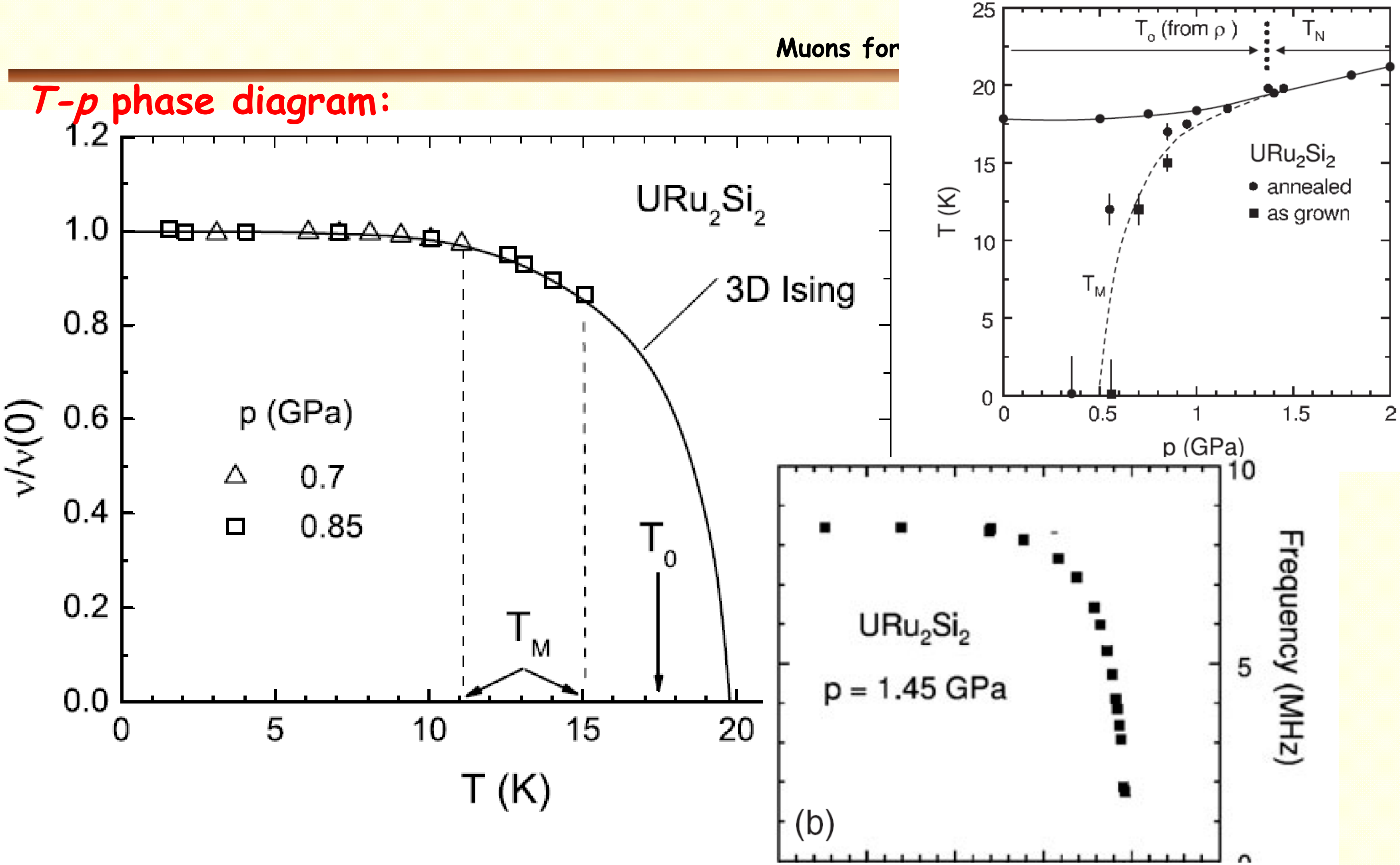


Figure 9. Temperature dependence of the spontaneous μ^+ frequency for URu_2Si_2 under pressure. Note that all the data collapse on a universal curve well described by a 3D Ising model. The different pressure measurements differ in the first-order transition temperature T_M, which increases under pressure. Note that for clarity only two different pressures are reported.

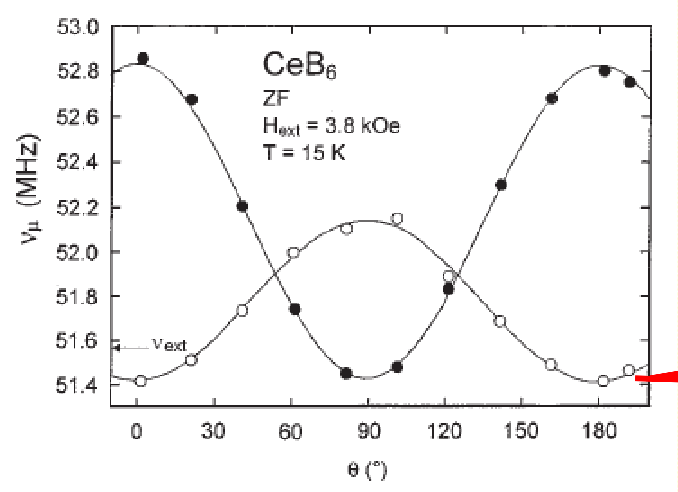
Checking of magnetic structures by μSR

Example: CeB_6 Pm-3m

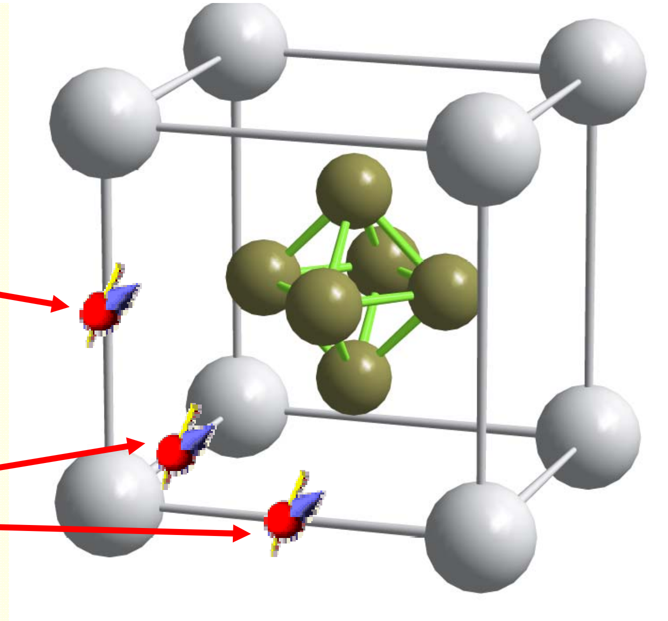
The cubic system CeB_6 (space group Pm$\bar{3}$m) orders antiferromagnetically below $T_N = 2.3$ K and shows antiferroquadrupolar ordering between 2.3 K and $T_Q = 3.2$ K [11]. The magnetic structure was found by neutron measurements to be described at 1.3 K by the wave-vectors $\boldsymbol{q}_1 = (\frac{1}{4}, \frac{1}{4}, \frac{1}{2})$ and $\boldsymbol{q}_2 = (\frac{1}{4}, \frac{1}{4}, 0)$, with a relatively small static Ce-moment of $\mu_s \simeq 0.28\mu_B$.

μSR Knight shift:

A. Amato, Rev. Mod. Phys. 69 (1997) 1119.



Field rotated in the (110) plane



3d-position

[11] J.M. Effantin et al., J. Magn. Magn. Mater. 47–48 (1985) 145.

Checking of magnetic structures by μSR

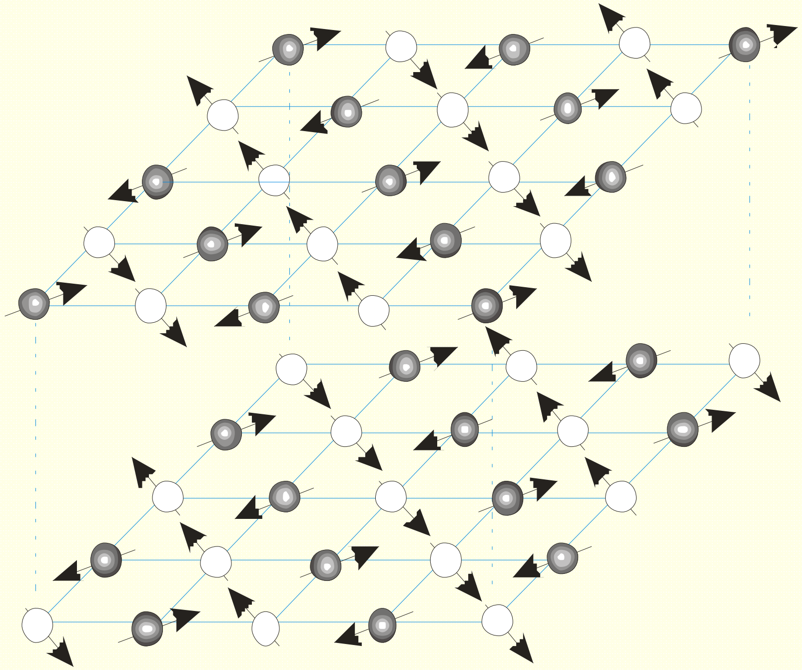
CeB_6 : Magnetic structure based on early neutron data :

$$\mathbf{S}_n = \mu\mathbf{e}_{[1,-1,0]}\cos[2\pi\mathbf{k}_1\mathbf{t}(n)] + \mu\mathbf{e}_{[1,1,0]}\cos[2\pi\mathbf{k}_1^{'}\mathbf{t}(n)]$$

with $\mu = 0.28\ \mu_B$ and

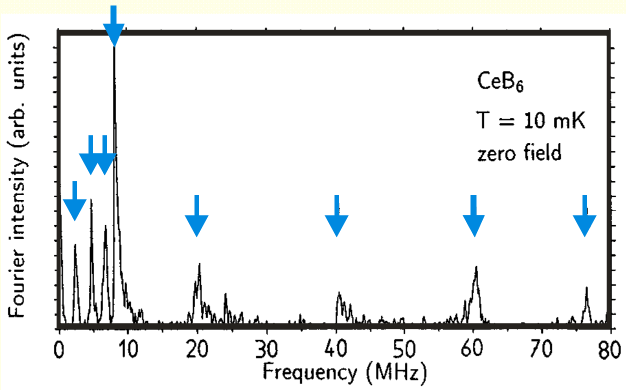
$k_1 = [1/4,1/4,0]$ and $k_1^{'} = [1/4,1/4,1/2]$

J.M. Effantin et al.,J.M.M.M. 47-48 (1985) 145



But incompatible with μSR studies:

R. Feyerherm et al., Physica B 194-196 (1994) 357.



Checking of magnetic structures by μSR

➡ Reinterpretation of neutron data:

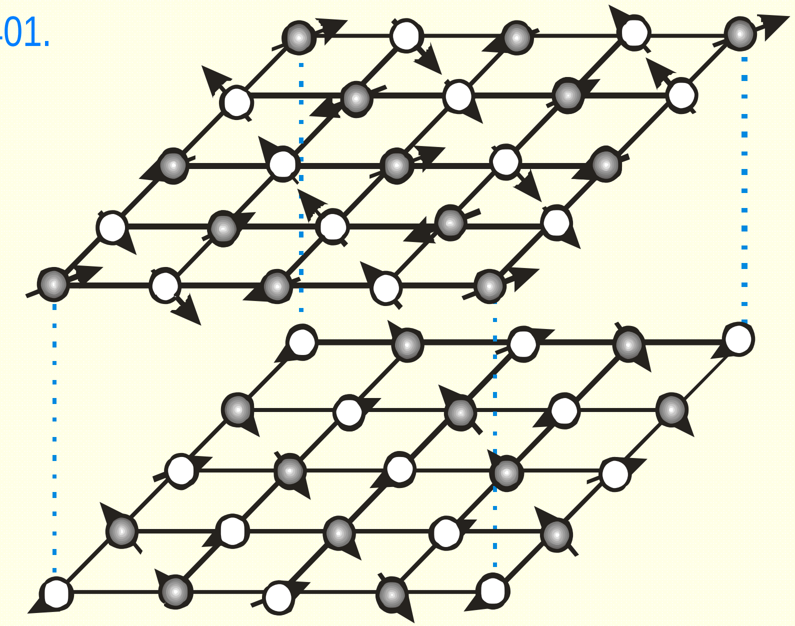
$$\mathbf{S}_n = \mu_i \mathbf{e}_{[1,-1,0]} \cos[2\pi \mathbf{k}_1 \mathbf{t}(n)] + \mu_i \mathbf{e}_{[1,-1,0]} \cos[2\pi \mathbf{k}_1^{'} \mathbf{t}(n)]$$
$$+ \mu_i \mathbf{e}_{[1,1,0]} \cos[2\pi \mathbf{k}_2 \mathbf{t}(n) + \pi/2] + \mu_i \mathbf{e}_{[1,1,0]} \cos[2\pi \mathbf{k}_2^{'} \mathbf{t}(n) - \pi/2]$$

with $k_2 = [1/4,-1/4,0]$ and $k_2' = [1/4,-1/4,1/2]$

and $\mu_i = 0.64\ \mu_B$ for z=1 + modulation

$\mu_i = 0.073\ \mu_B$ for z=0 + modulation

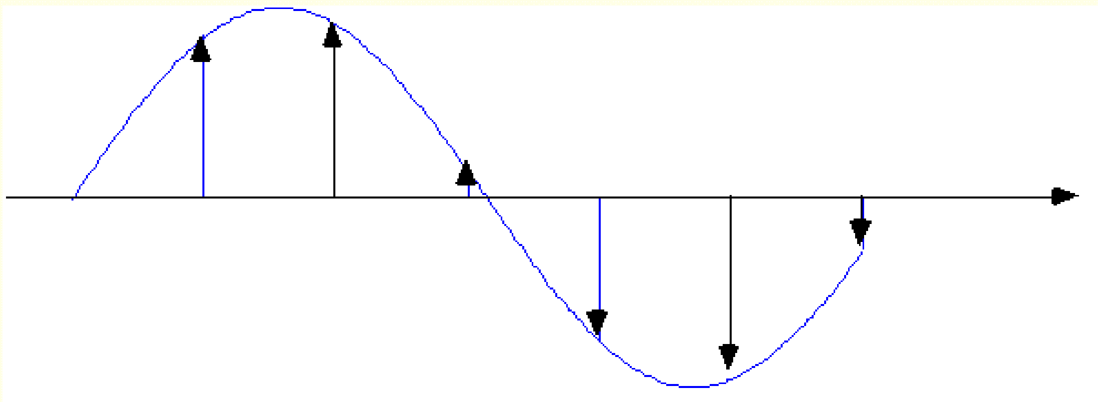
O. Zaharko, Phys. Rev. B 68 (2003) 214401.



Incommensurate magnetic structures

$$m_i = M\cos(2\pi k r_i + \phi)$$

By neutrons: For small k it may be not so easy to distinguish between commensurate and incommensurate structure



Incommensurate magnetic structures

By μSR:

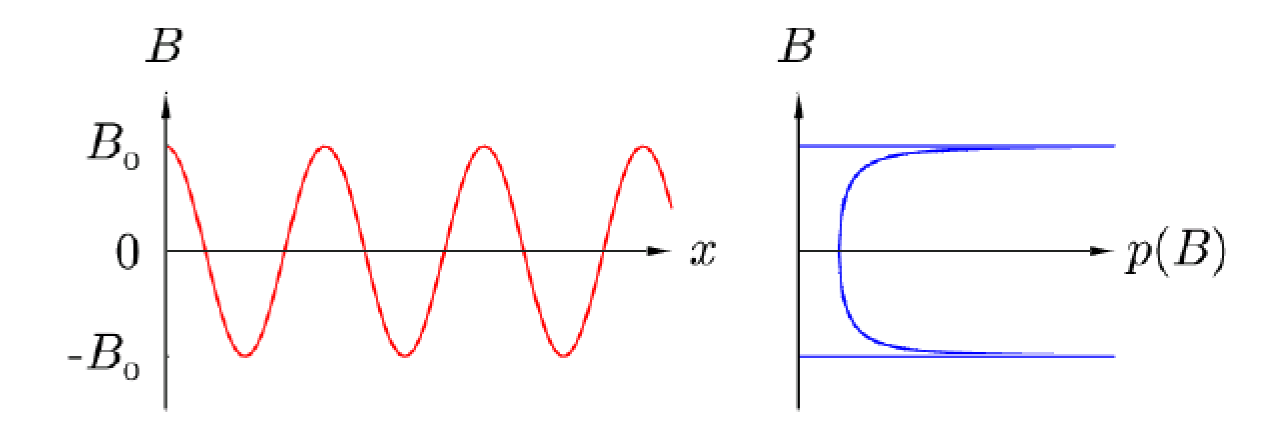
Each muon stopping site will be magnetically "unique" ($\mathbf{B}_\mu(\mathbf{r}_i) \neq \mathbf{B}_\mu(\mathbf{r}_j)$)

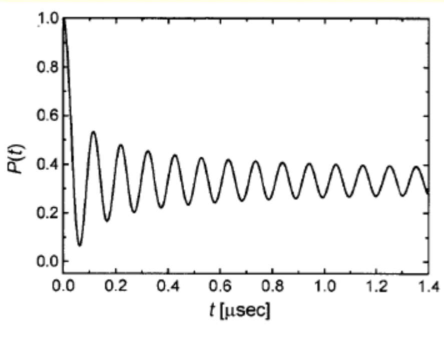
➡ wide and smooth field distribution
at crystallographically equivalent muon stopping sites

For a simple modulation, the field at the muon site usually approximated by

$$\mathbf{B}(\mathbf{r}) = \mathrm{B}_0\cos(2\pi\mathbf{k}\cdot\mathbf{r})$$

Only an approx. !!!





$$p(B) = \frac{2}{\pi}\frac{1}{\sqrt{B_0^2 - B^2}} \quad \Rightarrow \quad P(t) = \tfrac{1}{3} + \tfrac{2}{3}\int_{-B_0}^{B_0} p(B)\cos(\gamma_\mu B t)\, dB = \tfrac{1}{3} + \tfrac{2}{3} J_0(\gamma_\mu B_0 t)$$

Incommensurate magnetic structures

Assuming a magnetic structure described by

$$\mathbf{m}_i = \mathbf{M}\cos(2\pi\,\mathbf{k}\cdot\mathbf{R}_i + \varphi)$$

$$\Rightarrow \quad \mathbf{B}_{dip} = \sum_i \frac{1}{r_i^3}\left[\frac{3(\mathbf{m}_i\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^2} - \boldsymbol{m}_i\right]$$

$$\mathbf{B}_{dip} = \sum_i M\cos(2\pi\,\mathbf{k}\cdot\mathbf{R}_i + \varphi)\left[\frac{3(\mathbf{1}_M\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5} - \frac{\mathbf{1}_M}{r_i^3}\right]$$

By making the substitution $\mathbf{R}_i = (\mathbf{r}_i + \mathbf{r}_\mu)$ we get:

$$\mathbf{B}_{dip} = \cos(2\pi\,\mathbf{k}\cdot\mathbf{r}_\mu)\sum_i M\cos(2\pi\,\mathbf{k}\cdot\mathbf{r}_i + \varphi)\left[\frac{3(\mathbf{1}_M\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5} - \frac{\mathbf{1}_M}{r_i^3}\right]$$

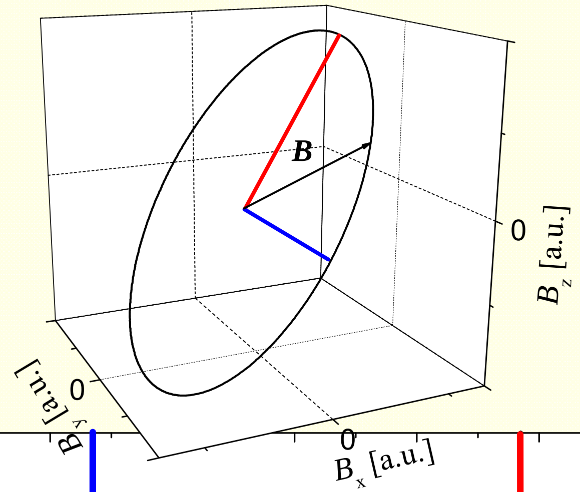
$$-\sin(2\pi\,\mathbf{k}\cdot\mathbf{r}_\mu)\sum_i M\sin(2\pi\,\mathbf{k}\cdot\mathbf{r}_i + \varphi)\left[\frac{3(\mathbf{1}_M\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5} - \frac{\mathbf{1}_M}{r_i^3}\right]$$

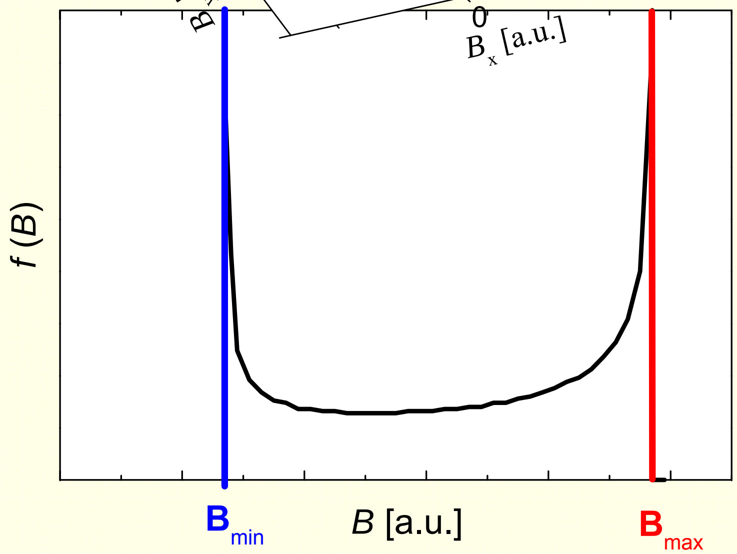
The magnetic fields at the muon site lie in a plane and define an ellipse:

$$\mathbf{B}_{dip} = \mathbf{S}_{\cos}\cdot\cos(2\pi\,\mathbf{k}\cdot\mathbf{r}_\mu) - \mathbf{S}_{\sin}\cdot\sin(2\pi\,\mathbf{k}\cdot\mathbf{r}_\mu)$$

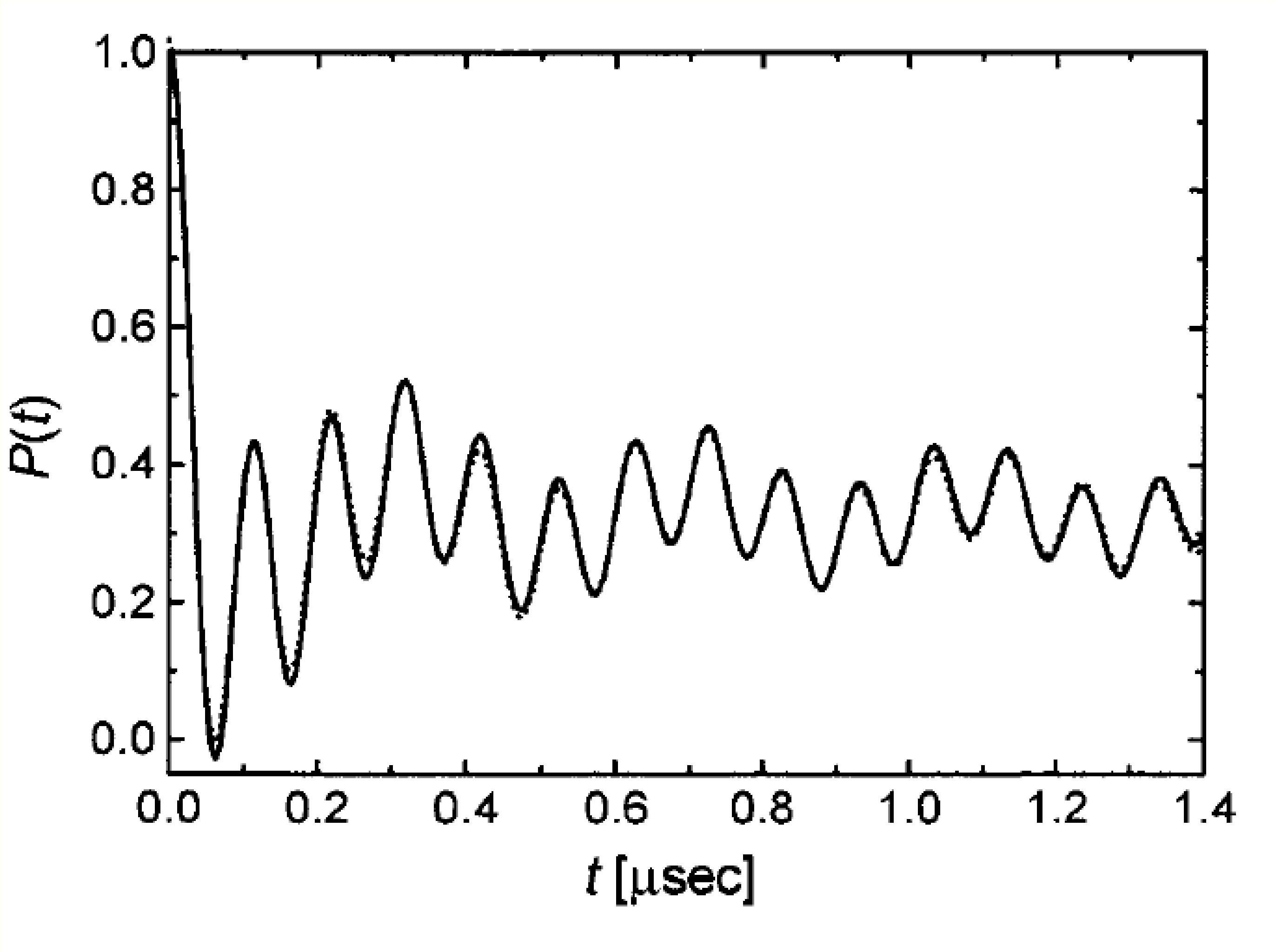
with principal axis: B_{min} and B_{max}

For an incommensurate structure, all the points of the ellipse will be reached and the field distribution given by:





$$f(B) = \frac{2}{\pi}\frac{B}{(B^2 - B_{min}^2)^{1/2}(B_{max}^2 - B^2)^{1/2}}$$

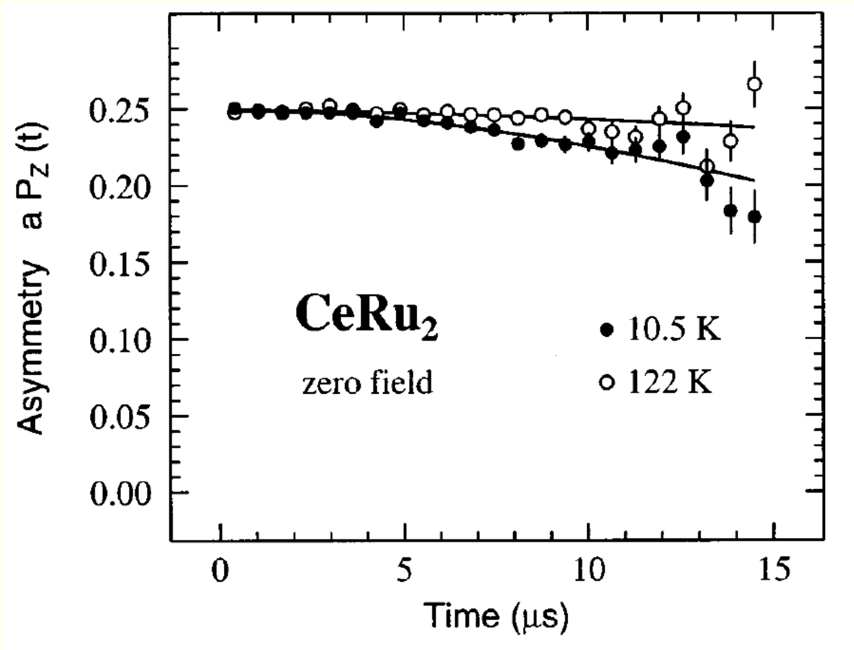

1.0
0.8
0.6
0.4
0.2
0.0
P(t)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
t [μsec]

Example sensivity

Magnetic Superconductor $CeRu_2$

A.D. Huxley et al., Phys. Rev. B 54 (1996) R9666

Magnetic state below 40K, $m_{Ce} \approx 10^{-4}\ \mu_B$



Example sensivity

Magnetic Superconductor $CeRu_2$

$CeRu_2$: A magnetic superconductor with extremely small magnetic moments

A. D. Huxley, P. Dalmas de Réotier, A. Yaouanc, D. Caplan, and M. Couach
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(Received 17 April 1996; revised manuscript received 25 July 1996)

Muon-spin-relaxation experiments and ac low-field magnetization measurements have been carried out on the superconductor $CeRu_2$. The relaxation rate of the muon-spin polarization in zero field exhibits a small but significant increase below $T_M \simeq 40$ K, which is suppressed by applying a longitudinal field. This result taken together with magnetization measurements provides definite evidence for the occurrence of static electronic magnetism involving extremely small magnetic moments. Our work shows that $CeRu_2$ is a member of a restricted family of superconducting compounds that order magnetically with extremely small magnetic moments at a temperature much higher than that at which they become superconducting.
[S0163-1829(96)51138-0]

Example sensivity

Magnetic Superconductor $CeRu_2$

Our finding is that the cubic Laves phase superconductor $CeRu_2$ condenses into a static magnetic state at a temperature $T_M \simeq 40$ K which persists into the superconducting state below $T_c = 6.1$ K. The evidence comes from both muon-spin-relaxation (μSR) measurements and ac susceptibility measurements on a single crystal. Our work supports the interpretation that anomalies seen in recently presented high field measurements are due to the occurrence of static magnetism at T_M.[6]

Example sensivity

Magnetic Superconductor $CeRu_2$

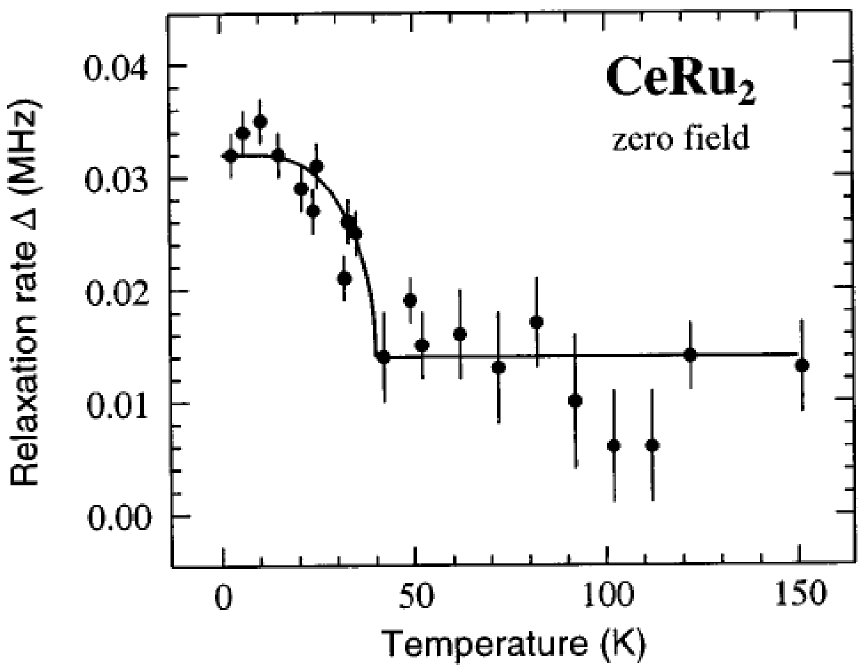

FIG. 2. Temperature dependence of the Gaussian muon-spin-relaxation rate, Δ, in $CeRu_2$ at zero field. The line is the Brillouin function prediction for a spin $S = 1/2$ and $T_M = 40$ K. This result provides evidence for the occurrence of static electronic magnetism at $T_M \simeq 40$ K.

Other fields addressed by the μSR techniques

and not mentioned here !

- Diffusion of a light interstitial particle in a crystal lattice (Brownian motion).
- Study of semiconductors: Mu is formed and it mimics a hydrogen impurity in the material. Study of its interaction with the environment.
- Physical chemistry: Mu binds to a molecule to give a spin-labelled free radical. Study of chemical reaction mechanisms.
- Study of superconductors magnetic response.
- Study of thin materials with low-energy muons.

PHYSICAL REVIEW B **66**, 054506 (2002)

Vortex motion in type-II superconductors probed by muon spin rotation and small-angle neutron scattering

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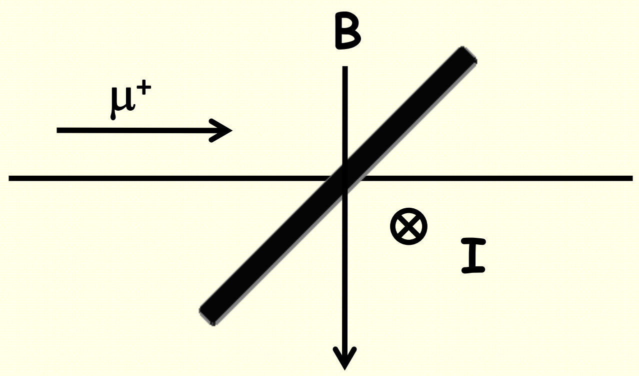
(Received 26 April 2002; published 2 August 2002)

We report muon spin rotation (μSR) measurements on the moving vortex lattice (VL) in the type-II superconductor Pb-In, backed up by small-angle neutron scattering (SANS) observations on the same sample. We observe a motional narrowing of the μSR lineshape $p(B)$ and by SANS, alignment of the VL to the direction of vortex motion. We have calculated the μSR lineshape expected with a range of orientations of the moving VL. We demonstrate how the new μSR results give information on the moving VL which is complementary and consistent with the SANS data.

DOI: 10.1103/PhysRevB.66.054506 PACS number(s): 74.60.Ge, 76.75.+i

- The shape of the field distribution gives access to the London penetration depth λ_L and to the coherence length.
- From $\lambda_L(T)$, information on the symmetry of the order parameter of the superconducting phase.

Sample: $Pb_{0.8}In_{0.2}$. **Annealed** (increases sample homogeneity and reduces bulk pinning); **sample spark-cut from the ingot and chemically polished** (remove residual traces of oxidation, resulting in a shiny surface with very low surface pinning).



B: 30 mT

I: Pulsed, up to 80 A, 20 μs wide, synchronized with the muon pulses: 80 ns long, repeating every 20 ms.

Recall: in the mixed state of a type-II superconductor, the muons are implanted at random positions in a magnetic field distribution *B(r).*

In the absence of a transport current (static VL):

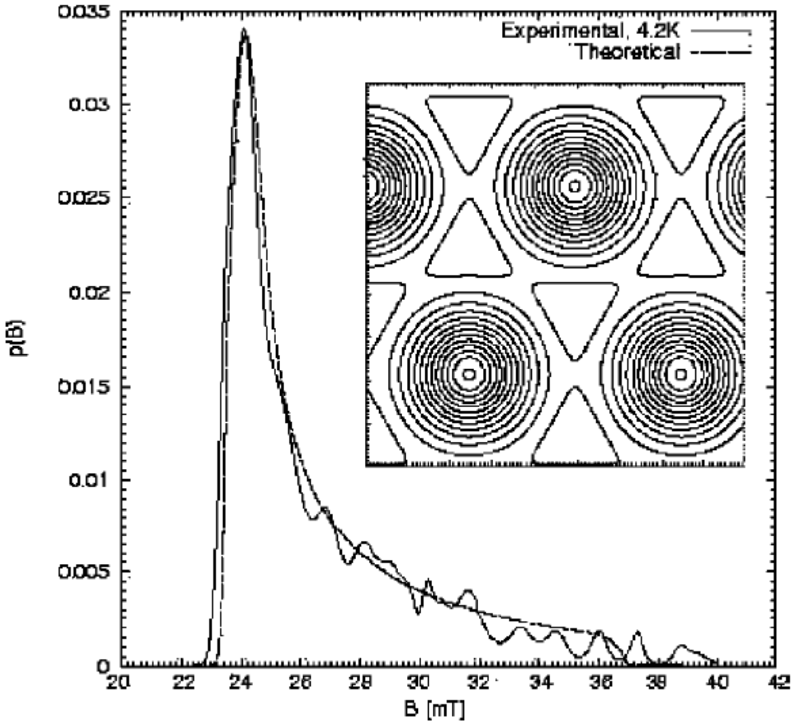


FIG. 2. Experimental and theoretical $p(B)$ line shapes corresponding to a stationary VL. The theoretical curve (dashed line) has been obtained from a solution to the full Ginzburg-Landau equations for $\kappa = 5.2$ and $b = \overline{B}/B_{c2} = 0.1$, where $B_{c2} = 270$ mT at 4.2 K, using a method developed by Brandt (Ref. 18). The value of κ was chosen to give agreement between the two line shapes. Due to finite sample magnetization, this gives $\overline{B} \sim 27$ mT for an applied field of 30 mT.

In the presence of a transport current (dynamic VL):

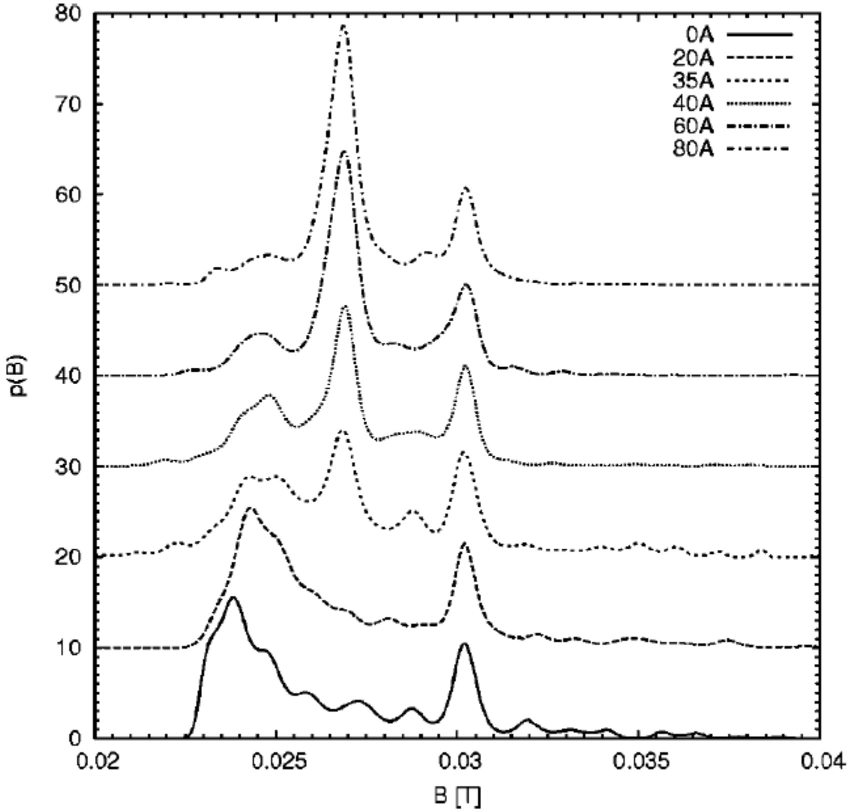
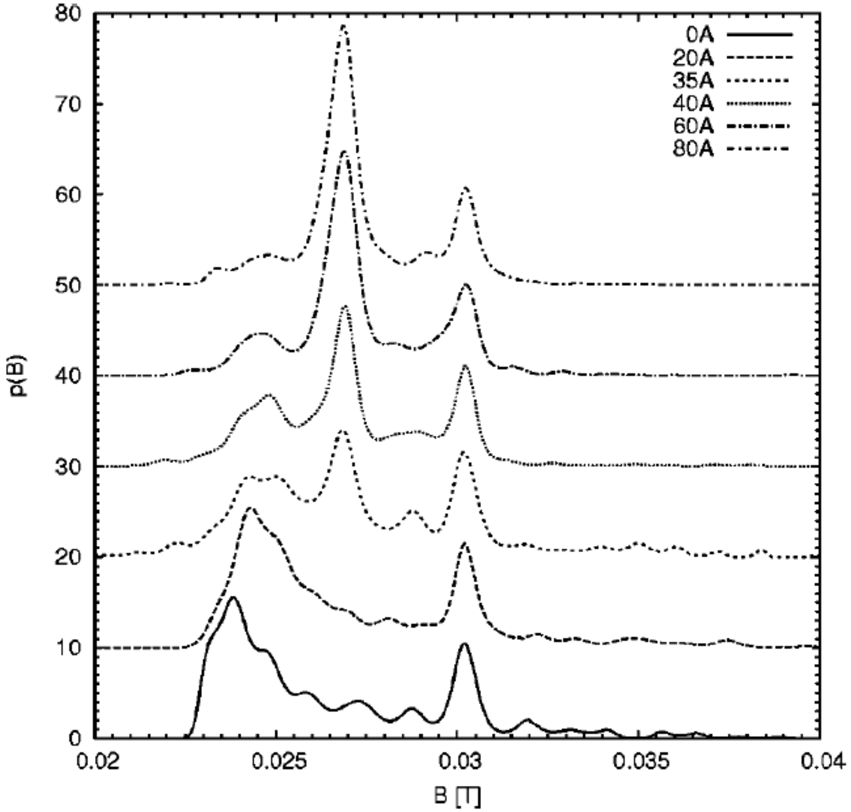


FIG. 3. Maximum entropy-fitted μSR $p(B)$ line shapes for a range of applied currents at 30 mT and 4.2 K. The peak at approximately 30 mT arises from muons stopping in the sample cryostat. This background peak has been subtracted from the data shown in Fig. 2.



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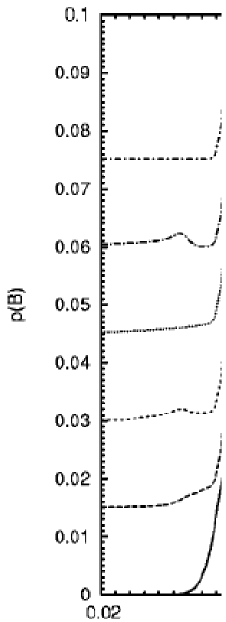


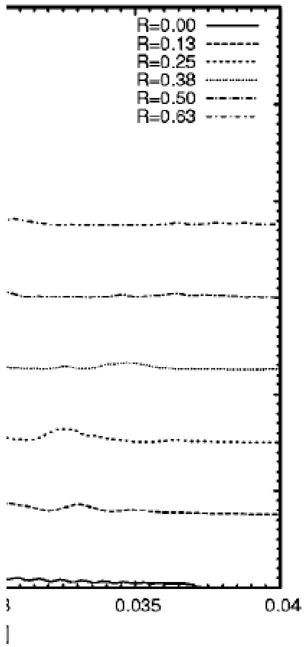


FIG. 4. Calculate
moves as a whole alc
single orientation. Small "side-band" peaks are due to modulation of the muon precession frequency.

oving VL, assuming a uni-
f the VL present, each mov-
ing as a whole with a well-defined velocity.

Advantages of μSR

- Implanted nuclear probe:
  little pertubation to the system,
  no requirement in the presence of isotopes.
- Full polarisation of the probe, including in zero field and at any temperature
- Extremely high sensitivity:
  detection of decay of (almost) all muons,
  detection of small magnetic field (large γ_μ).
- Only magnetic fields are probed.
  No sensitivity to electric fields.
- Local probe: independent determination of magnetic moment and magnetic volume fraction

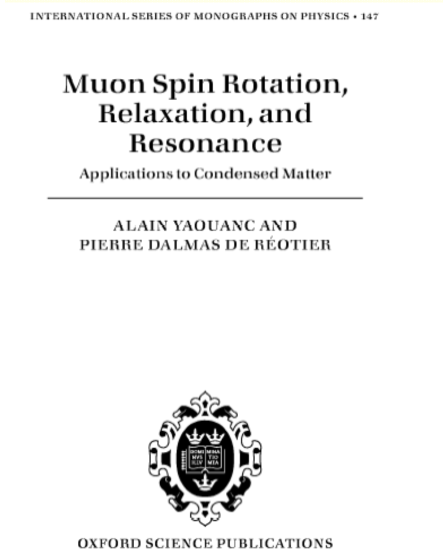
Bibliography

Introductory articles

- μSR brochure by J.E. Sonier (2002) http://musr.ca/intro/musr/muSRBrochure.pdf
- S.J. Blundell, *Spin-Polarized Muons in Condensed Matter Physics*, Contemporary Physics 40, 175 (1999)

Books

- A. Yaouanc and P. Dalmas de Réotier, *Muon Spin Rotation, Relaxation and Resonance: Applications to Condensed Matter*, (Oxford University Press, Oxford, 2011)
- E. Karlsson, *Solid State Phenomena, As Seen by Muons, Protons, And Excited Nuclei*, (Clarendon, Oxford 1995)
- A. Schenck, *Muon Spin Rotation Spectroscopy*, (Adam Hilger, Bristol, 1985)



I have used also slides from:
S. Blundell , A. Yaouanc, P. Dalmas de Reotier, R. Cywinski.
I thank them here.

Positive muons in matter probe their local environment either directly or through a captured electron.

Comparison of dynamical ranges accessible to different techniques