μSR - Muon spin rotation, relaxation and resonance

The muon is an extremely sensitive probe (~ 10^{-3} μ_B) for static and fluctuating magnetic fields and field distributions (spin 1/2 , no quadrupole interaction) in condensed matter.

- Muon and its properties
- Muon production and muon beams
- Muon interaction with matter
- Technical details of μSR experiments
- Areas of μSR applications

Some Bibliography on µSR

Books

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

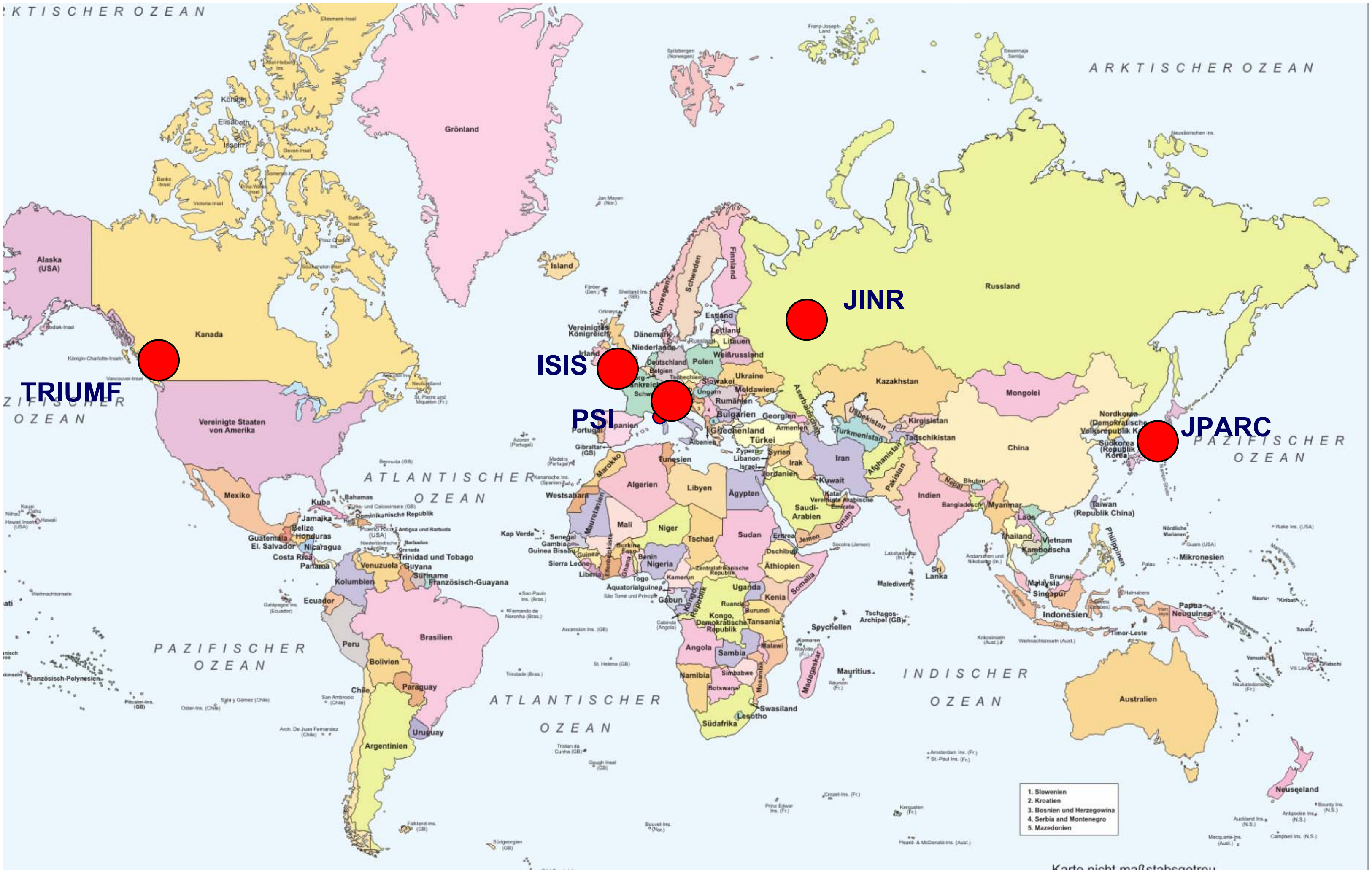
Reviews

- http://inac.cea.fr/Pisp/pierre.dalmas-de-reotier/introduction muSR.pdf
- http://musr.ca/intro/musr/muSRBrochure.pdf

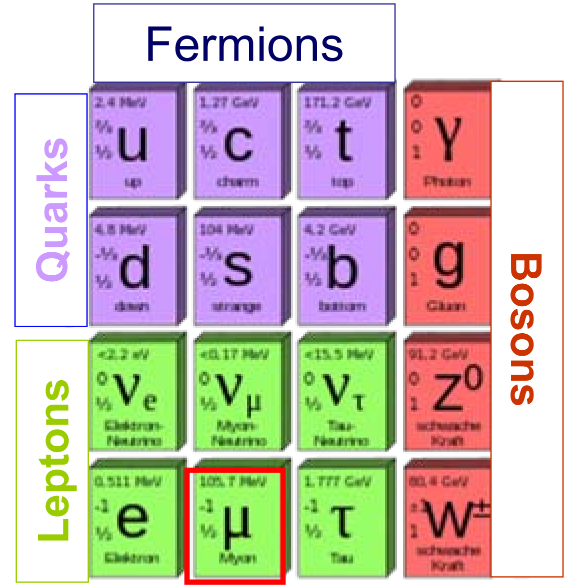
Web sites:

The TRIUMF µSR User Facility *http://musr.triumf.ca/*
Paul Scherrer Institut (PSI) Laboratory for Muon Spin Spectroscopy *http://lmu.web.psi.ch/*
The ISIS Pulsed Muon Facility *http://www.isis.rl.ac.uk/muons/*
KEK Meson Science Laboratory *http://msl-www.kek.jp/*
The RIKEN-RAL Muon Facility *http://nectar.nd.rl.ac.uk/~rikenral/*
High Intensity Proton Accelerator Facility *http://jkj.tokai.jaeri.go.jp/*

Global Muon Facilities



Muon Properties

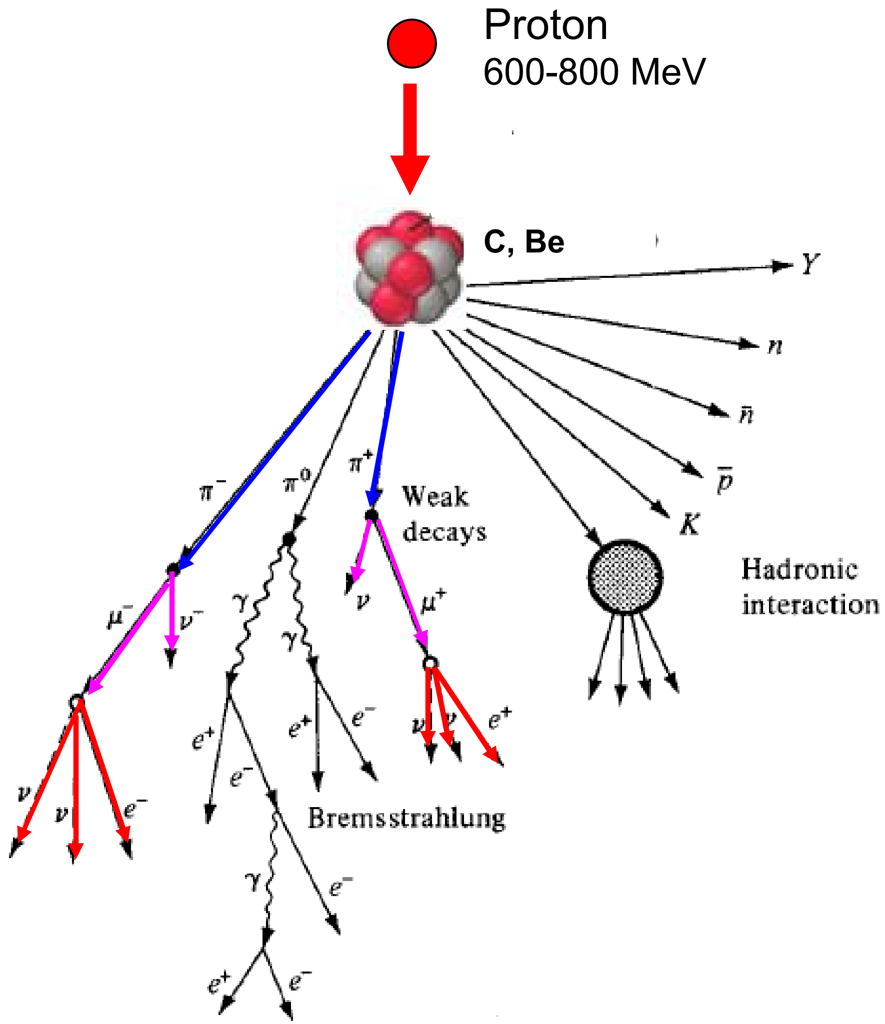


Leptons and **quarks** are the basic building blocks of matter, i.e., they are seen as the "elementary particles". There are six leptons in the present structure, the electron, muon and tau particles and their associated neutrinos.

Particle/ antiparticle	Spin	Charge	Mass	Magnetic moment	lifetime (μs) (free particle)
muon/ antimuon	1/2	-/+ e	105.7 MeV **$207\ m_e$** **$0.11\ m_p$**	$3.18\ \mu_p$	2.19
electron/ positron	1/2	-/+ e	511 keV m_e	$657\ \mu_p$	stable
Proton/ antiproton	1/2	+/- e	938 MeV $m_p = 1836\ m_e$	μ_p ($1{,}410\ 606 \cdot 10^{-26}$ J/T)	Stable (>10^{33} a)

A positive muon μ+ can be considered as an unstable light isotope of hydrogen (0.11 mp), a negative muon μ- as an unstable heavy electron (207 me)

Muon production



Protons of 600 to 800 MeV kinetic energy interact with protons or neutrons of the nuclei of a light element target (typically graphite) to produce pions (π+) as intermediate particles .

$$p + p \rightarrow \pi^+ + p + n$$
$$p + n \rightarrow \pi^- + p + p$$

Pions are unstable (lifetime 26 ns) and decay into muons (and neutrinos):

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

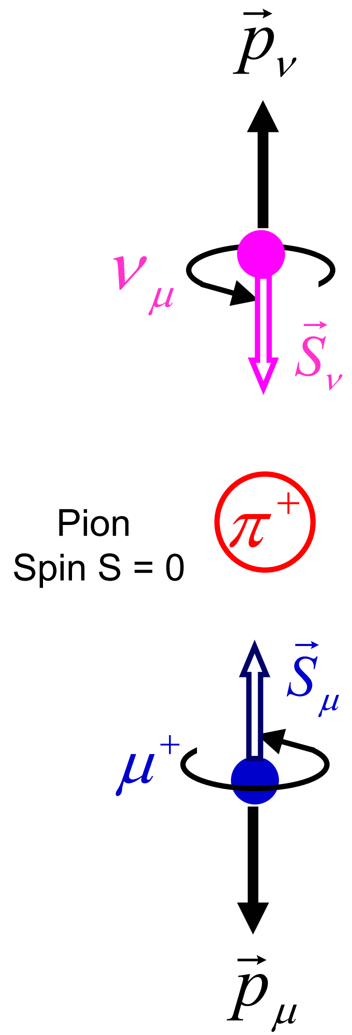
Muons are unstable (free particle lifetime 2.197 μs) and decay into electrons/positrons and neutrinos

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

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

For π at rest: $\mathbf{E_{kin}(\mu) = 4.12\ MeV}$

Muon polarization and decay kinematics



The neutrino of the weak interaction decay

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

has helicity – 1, i.e. its spin is opposite to the momentum

Momentum conservation of the pion decay at rest leads to **opposite momenta of muon and neutrino**. Since the pion has spin 0, **the fermions μ+ and ν_μ have opposite spins**.

As a consequence, the muon beam is **polarized**, i.e. the muon spin is **opposite to the momentum**

Kinematics of pion decay at rest:

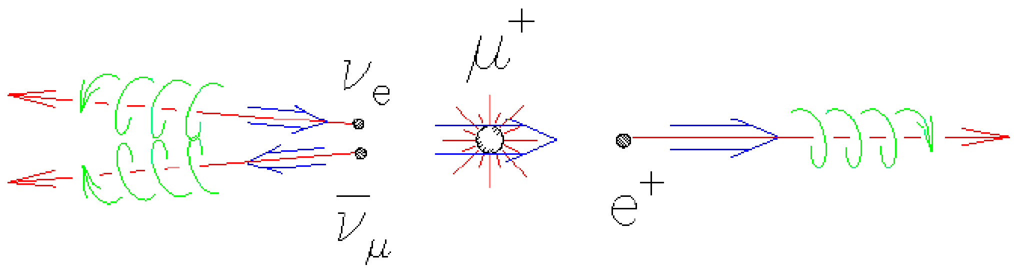
Energy and momentum conservation result in:

μ momentum: p = 29.79 MeV/c
μ kinetic energy: E = 4.12 MeV

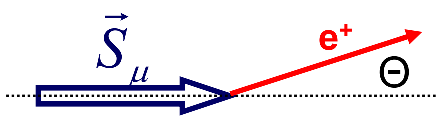
Muon polarization and correlation with the positron trajectory

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

Due to the parity violation of the muon decay, the muon emits a fast positron (electron) **preferentially along the direction of its spin**.

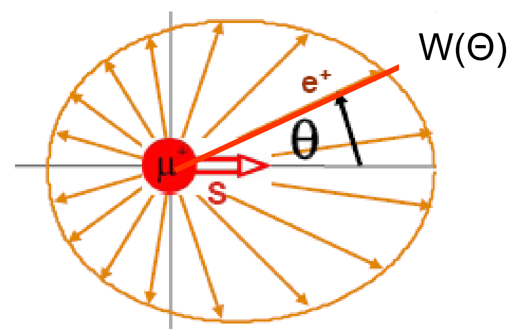


The positron emission probability is given by:



$$W(\Theta)d\Theta \propto (1 + a(E)\cos(\Theta))d\Theta$$

$$Energy\ average:\ \overline{a(E)} = 1/3$$

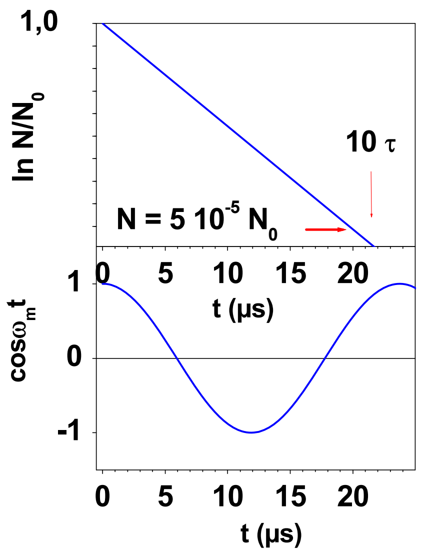


This anisotropic emission (*polarisation*) constitutes the basis for the μSR technique.

As muon spin and positron direction are correlated, detection of the positron carries information on the orientation of the muon spin at the time of decay, *similar to pertubed γγ-angular correlations (PAC).*

The muon as a probe of magnetic fields in condensed matter

Assume: At least one Larmor precession fits into the observation time window **Δt = 20 μs** (~ 10 muon life times)



τ = 2.19 μs
μ_μ = 4.8 10^{-26} J/T
μ_p = 1.4 10^{-26} J/T

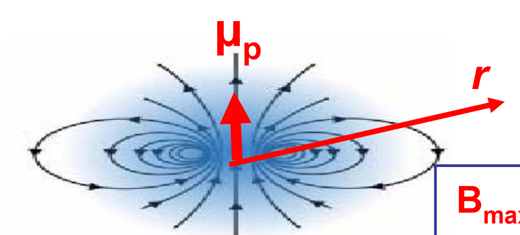
The corresponding Larmor frequency:

$$\upsilon_\mu = \frac{\mu_\mu}{h} B = \frac{1}{T} = \frac{1}{2} 10^6\, s^{-1} \approx 5 \cdot 10^4 s^{-1}$$

The lower limit of a magnetic field to be detected by μSR

$$B \geq 5 \cdot 10^4 s^{-1} \frac{h}{\mu_\mu} \approx 0.7\ mT \approx 7\ Gauss$$

For comparison: the dipolar field of a **proton**



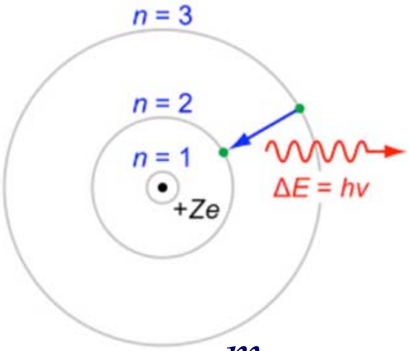
B_{max} ~ 7 G @ 2 Å

$$B_{dip} = \frac{\mu_0}{4\pi} \frac{3\vec{r} \cdot (\vec{\mu} \cdot \vec{r}) - \vec{\mu} \cdot \vec{r}}{r^5}$$

Because its the long life time (= long observation time window) the muon is an extremely sensitive probe (~ 0.001 μ_B) for static and fluctuating magnetic fields and field distributions in condensed matter

Muons in matter

The negative muon μ-



μ- behaves as a ***heavy electron*** and is easily captured into the atomic orbitals.

Because it is "heavy", the μ- quickly cascades to the atomic 1s ground state in close proximity to host nuclei, producing **muonic X-rays.**

$$r_n(\mu) = n^2 \frac{m_e}{m_\mu} a_0$$

$$a_0 = 0.5 \times 10^{-10} m$$

$$r_1(\mu) \approx 10^{-12} m$$

The significant overlap between muon and nuclear wave functions can result in *nuclear capture.* The measured mean lifetime of μ- in matter is considerably shorter than that of μ+ due to capture by nuclei.

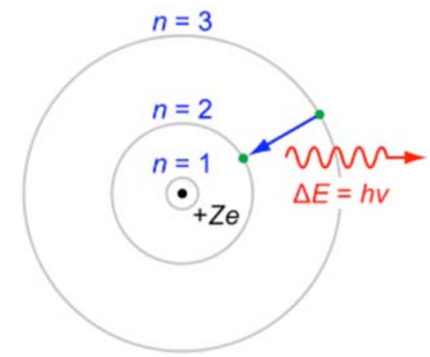
μ+ in anything ~2 μs
μ- in C: ~ 2 μs
μ- in Pb: ~ 0.07 μs
R (Pb) ~ 0.7 10^{-12} m

Because of reduced polarization and shorter lifetime , μ^- SR is used only in selected cases for solid state studies.

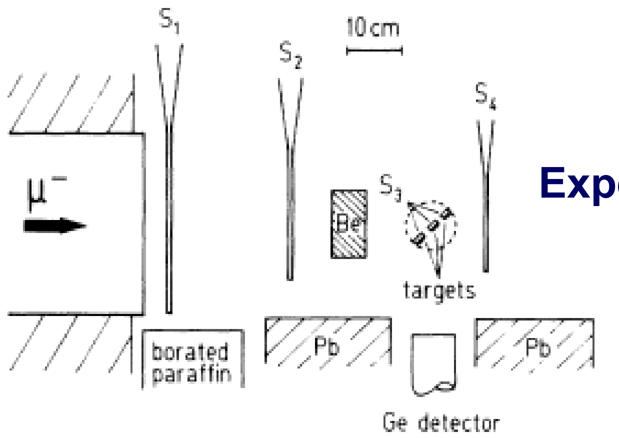
Negative muons are, however, of great interest in nuclear physics

X-rays of muonic atoms

Muonic X-rays provide valuable information on nuclear charge distributions and nuclear deformation parameters: Quadrupole splitting of muonic X-rays yield **absolute values of nuclear quadrupole moments**



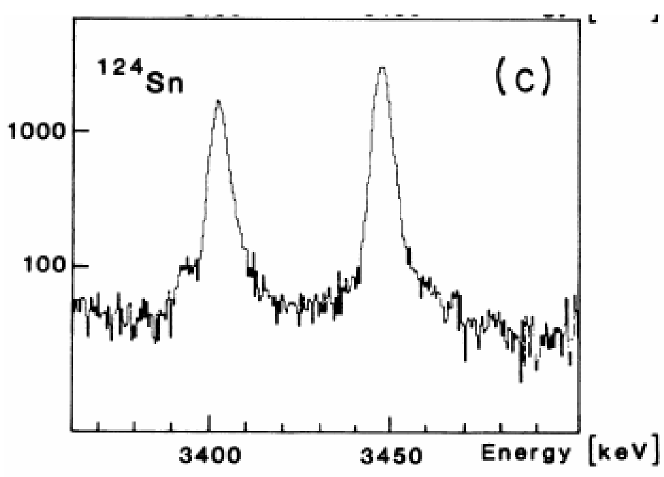
C. Piller et al., PRC 42, 182



Experimental set-up

$$E_n(\mu) \propto \frac{m_\mu}{m_e}\frac{1}{n^2}$$

$$r_n(\mu) = n^2 \frac{m_e}{m_\mu} a_0$$



Prompt muonic x-ray spectra showing the $2p_{1/2}$-1s and the $2p_{3/2}$-1s transitions in ^{124}Sn

Muons in matter

The positive muon μ^+

In crystallines solids the μ+ is *repelled* by the charge of the host nuclei but in a molecular gas or liquid μ+ is *attracted* to the electron cloud around the host molecules.

In a solid μ+ generally comes to rest at an **interstitial site** of high symmetry between the lattice ions, where it exists in a diamagnetic state as a "quasi-free„ probe.
However, in oxides the μ+ may localize near an oxygen atom, forming a μ-O bond similar to an OH "hydrogen" bond.

Muonium **(Mu ≡ μ+e-)**

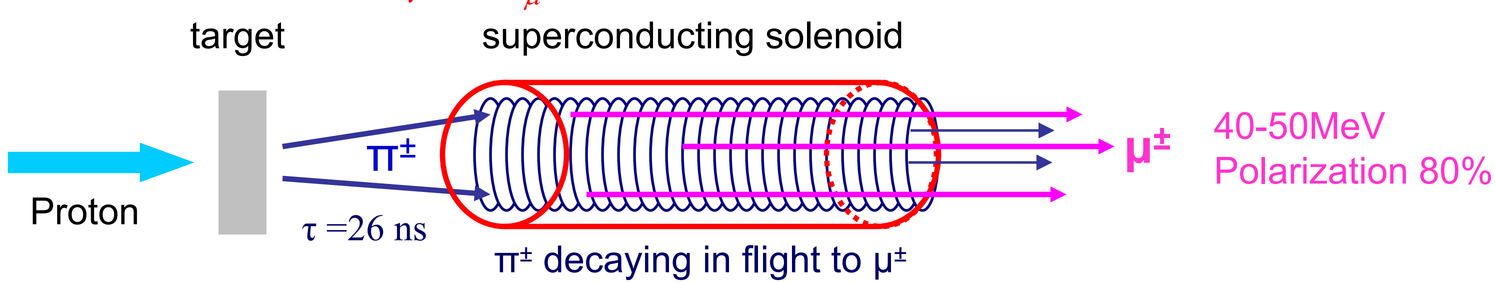
In certain materials (*e.g.* semiconductors) a μ+ can pick up an electron to form muonium which has almost the same Bohr radius and ionization potential, but a mass 9 times smaller than hydrogen (H ≡ p+e-).

Different types of muon beams

I. High-energy beams (available at PSI, TRIUMF, J-PARC and RIKEN-RAL)

Pions escaping the production target at high energies are collected over a certain solid angle and directed on to a decay section consisting of a long superconducting solenoid with a field of several Tesla. If the pion momentum is not too high, a large fraction of the pions will have decayed before they reach the end of the solenoid.

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$



Advantage: Homogeneous implantation of the muons into **large sample volumes**. Such beams are also used to study specimens inside of recipients, e.g. samples inside pressure cells.

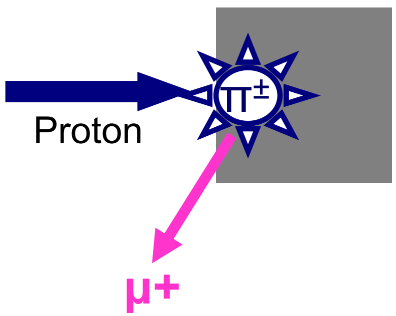
Different types of muon beams

II. Surface (or Arizona) μ^+ beams

(available at PSI,TRIUMF, J-PARC, ISIS and RIKEN-RAL).

Used for the investigation of relatively thin samples

Muons arising from pions slowing down in the production target and decaying **at rest** near the target surface



Ideally monochromatic muons,

- 100 % polarized
- kinetic energy of 4.1 MeV →
- small range in matter of ~ 180 mg/cm^2.

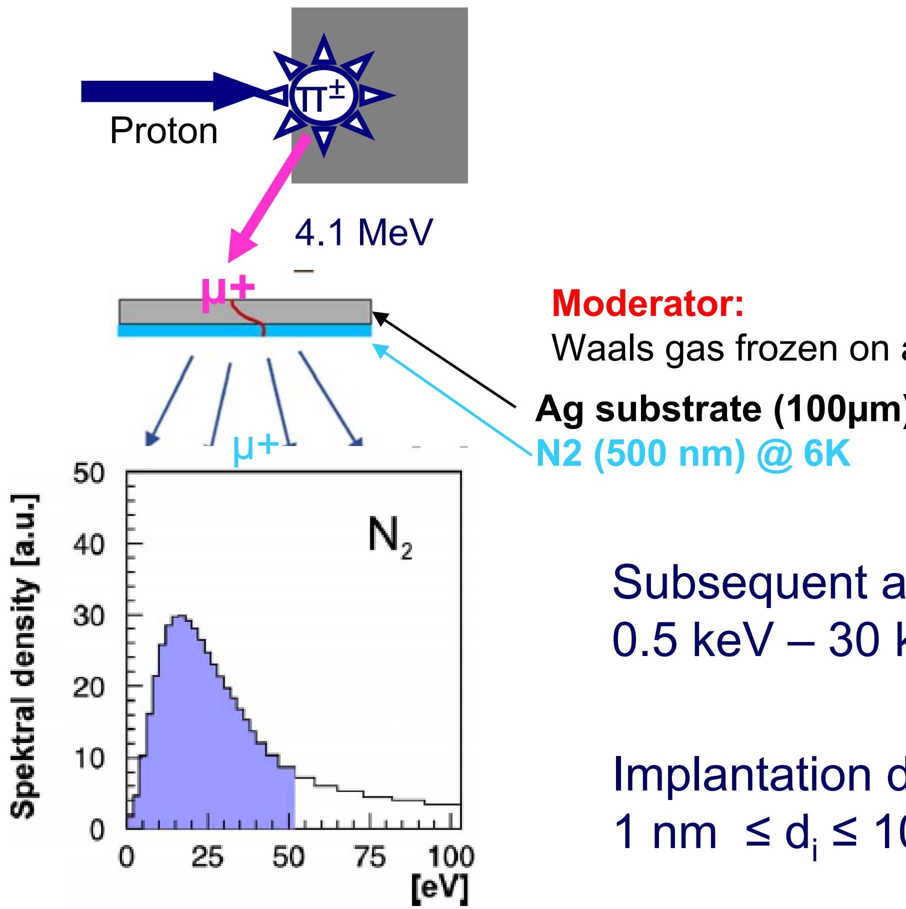
Works only for positive pions, because a negative pion stopping in the production target almost always undergoes nuclear capture from low-lying orbitals of pionic atoms (replacing an electron) before it has a chance to decay.

Different types of muon beams

III. Low-energy muon beams Surface

(available at PSI, projected at J-PARC, and RIKEN-RAL).

Moderation of Arizona beams



Subsequent acceleration to 0.5 keV – 30 keV

Implantation depth:
1 nm $\leq d_i \leq 10^2$-10^3 nm

The mechnism of muon moderation

4 MeV ≤ E_μ ≤ 10-50 keV: energy loss by ionization processes

E_μ ≤ 10 keV: energy loss by charge-exchange processes

E_μ < 50 eV

Solid Ar, N2, … are broad band isolators ⟶

Suppression of electronic energy loss for $E_\mu \approx E_{gap}$

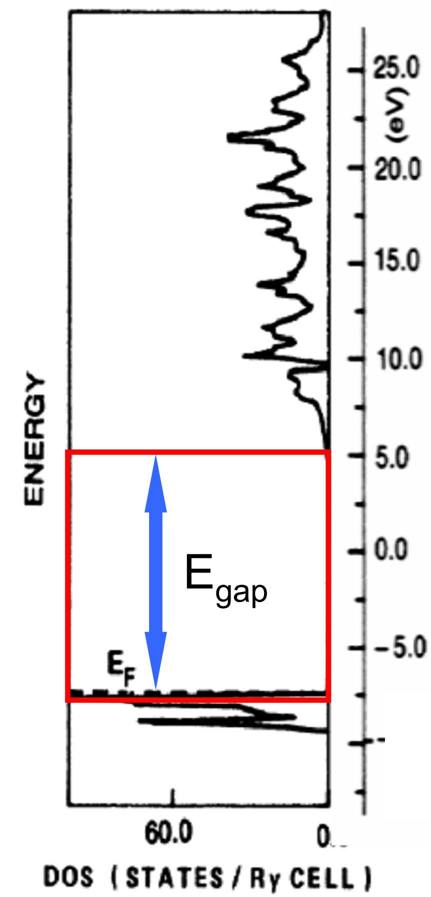
no efficient inelastic energy loss channels available ⟶

Epithermal muons can move through the solid

without efficient energy loss ⟶ **escape depth of up to 100 nm.**

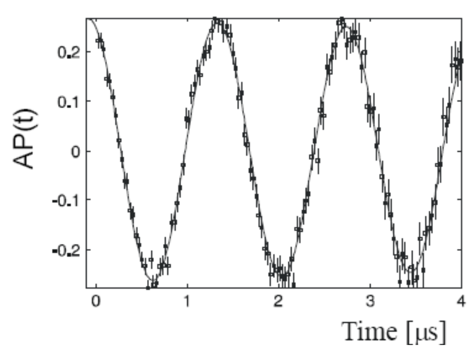
Moderation efficiency: $N_{epi}/N_{4MeV} \approx 10^{-4} – 10^{-5}$

Density of states of solid Ar



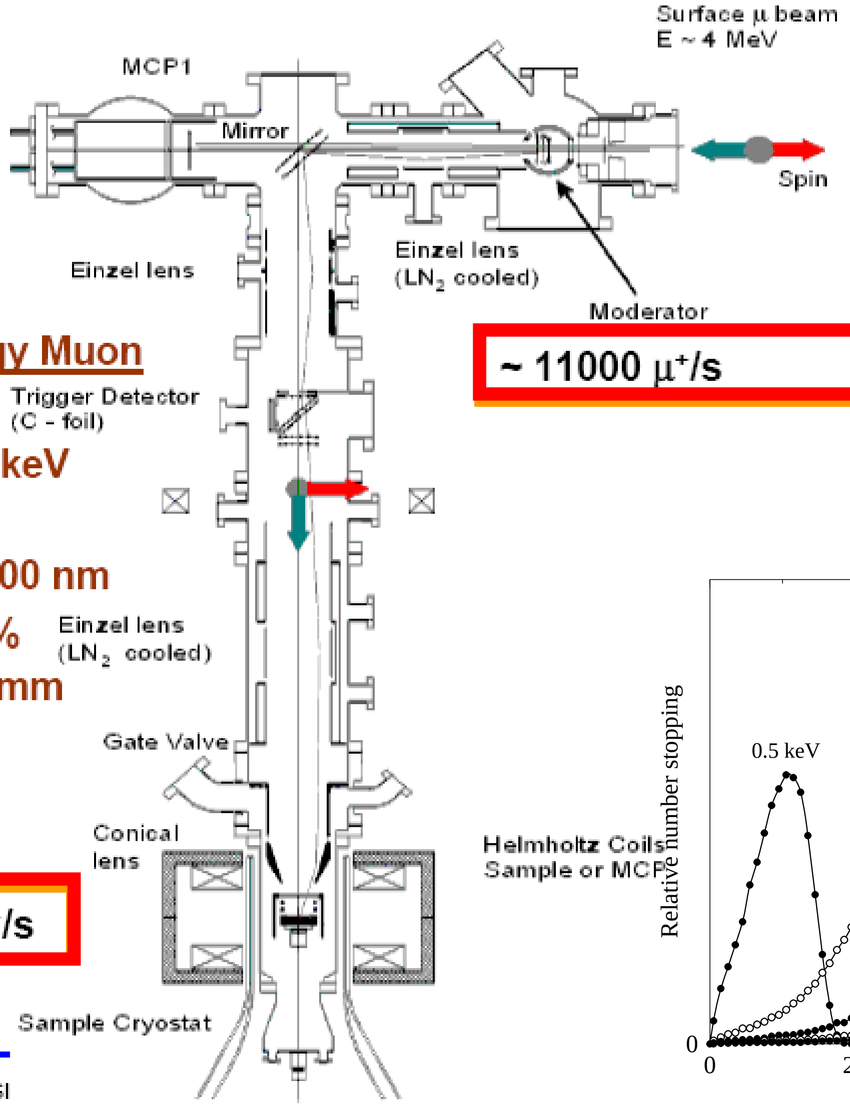
IMPORTANT:

μSR of epithemal μ+



The polarization survives moderation

Low energy μ⁺ beam at Paul Scherrer Institute



~1.9 •10^8 μ$^+$/s from new μE4 beam line

~ 11000 μ$^+$/s

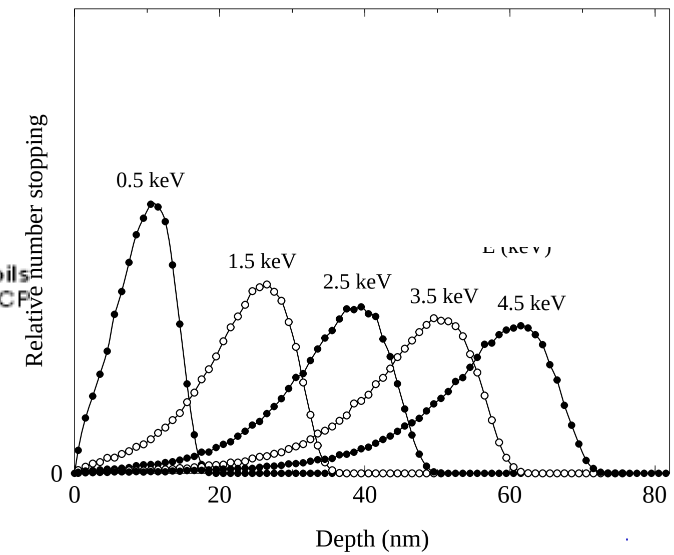
~ 4500 μ$^+$/s

- UHV system (~10^{-10} mbar)
- Electrostatic transport, focussing and energy selection.
- All transport elements LN$_2$ cooled

Polarized Low Energy Muon Beam

Energy:	0.5-30 keV
ΔE:	400 eV
Depth:	~ 1 – 200 nm
Polarization	~ 100 %
Beam Spot:	10-20 mm

Paul Scherrer Institut • 5232 Villigen PSI



μSR Introduction / June 2010 / E. Morenzoni

Tunable energy range : 0.5 -30 keV; Implantation depth: 1 nm ≤ d_i ≤ 10^2-10^3 nm

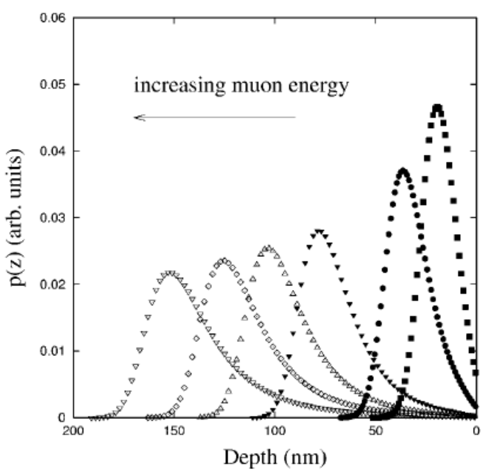
Profile of the Magnetic Field beneath the Surface of a High-Tc Superconductor with a few nm Resolution

T. J. Jackson et al, PRL 84 (2000) 4958

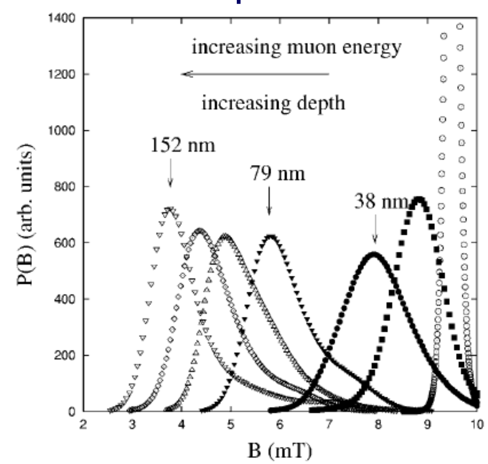
Thin film of $YBa_2Cu_3O_{7-\delta}$ (YBCO) at $T < T_C$ (~ 90 K)

Muons were implanted at depths from 20–150 nm by varying the energy of the incident muons from 3–30 keV

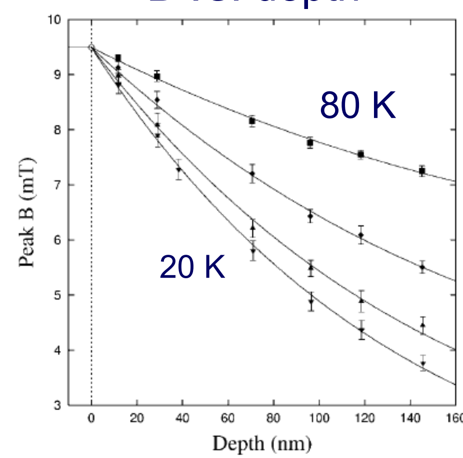
Implantation profiles



Field profiles

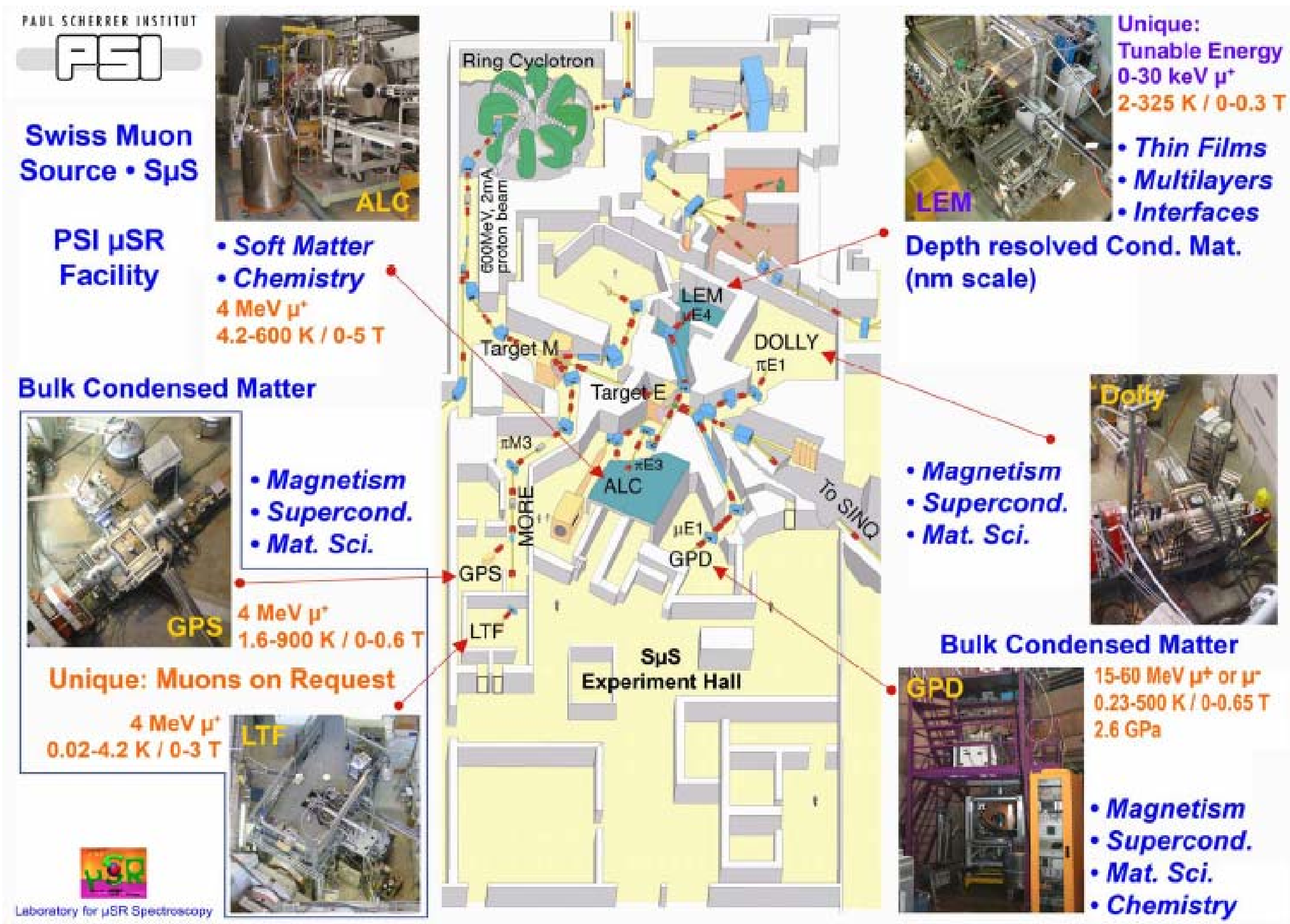


B *vs*. depth



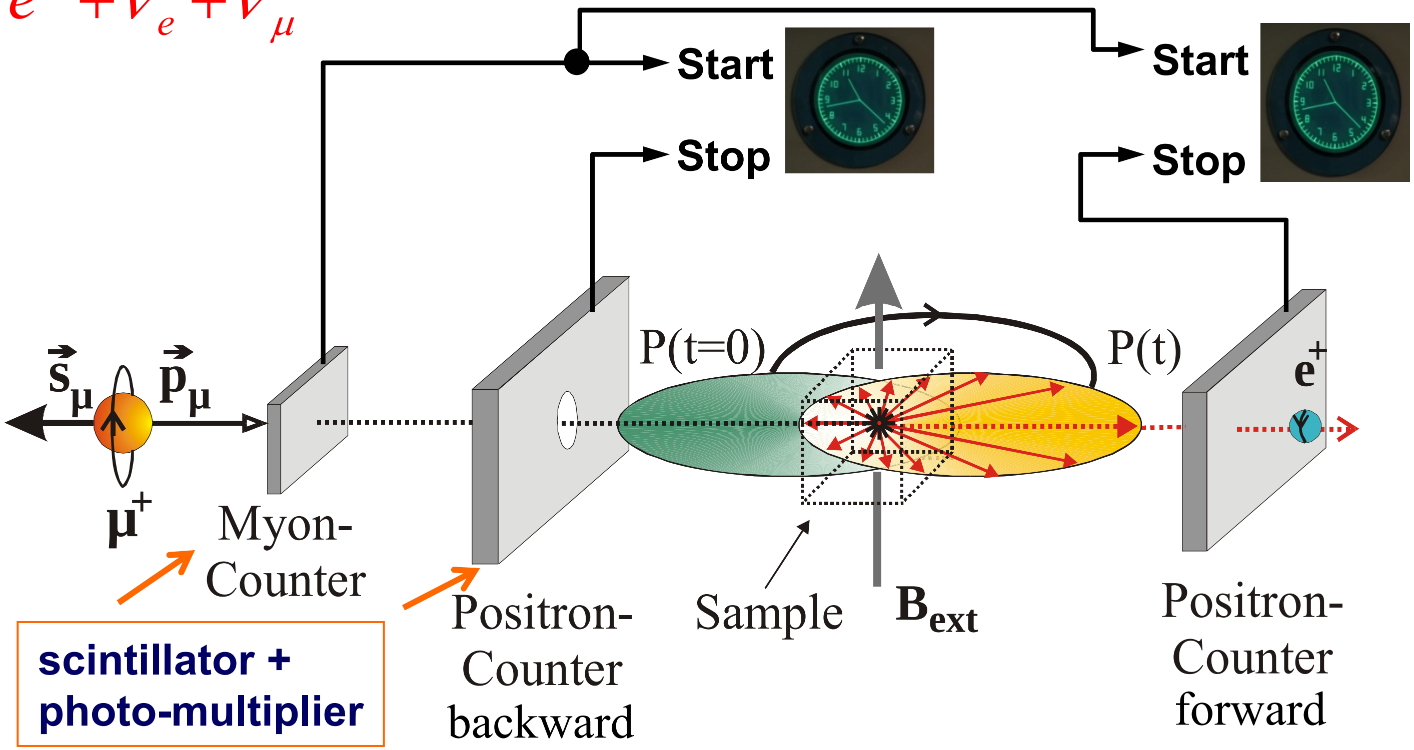
Muon beams at SμS – Swiss Muon Source

- **High energy beam (15-60 MeV μ+ or μ-)** for bulk matter studies
- **Surface (Arizona) beam (4 MeV μ+)** – Magnetism, superconductivity, soft matter,chemistry in relatively thin samples
- **Low-energy muon beam (0-30 keV μ+)** – Thin films, multilayers, interfaces on a nm scale



Principle of a Muon-Spin-Rotation (μSR) experiment

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

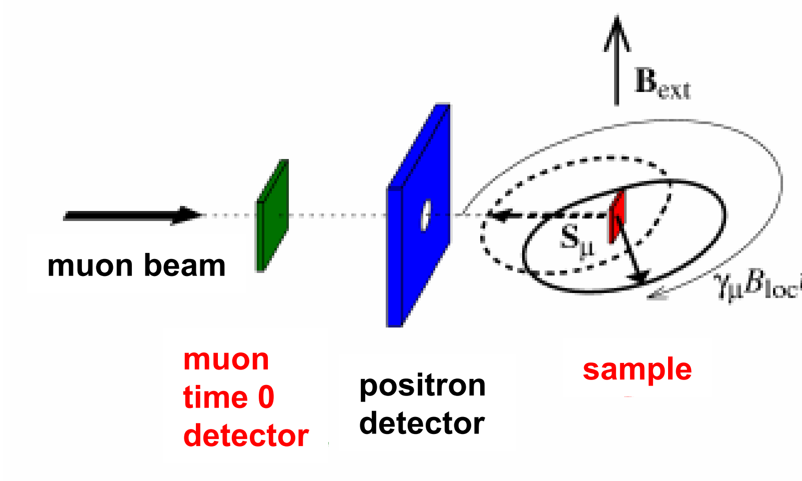


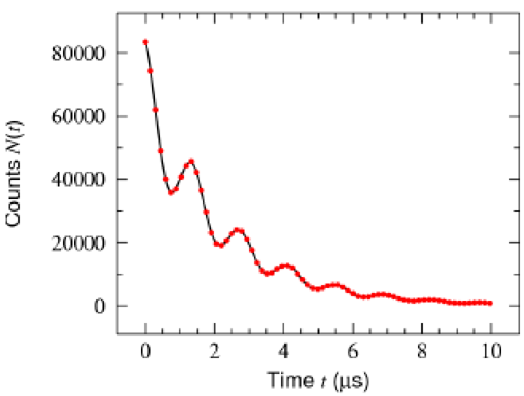
Scheuermann *et al.*, VCI 2007, 19.02.2007

3 possibilities :

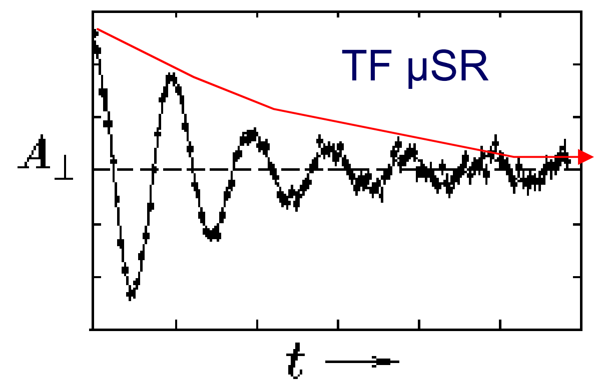
- **TF μSR (transverse field)** – Knight shift measurements, penetration depth (superconductivity)
- **LF μSR (longitudinal field)** – spin dynamics (different time scales than neutron scattering
- **ZF μSR (zero field)** – weak magnetism, search for magnetic ordering

Transverse field (TF) μSR geometry





$$A(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



Damping due to
- static field distribution
- dynamic interaction

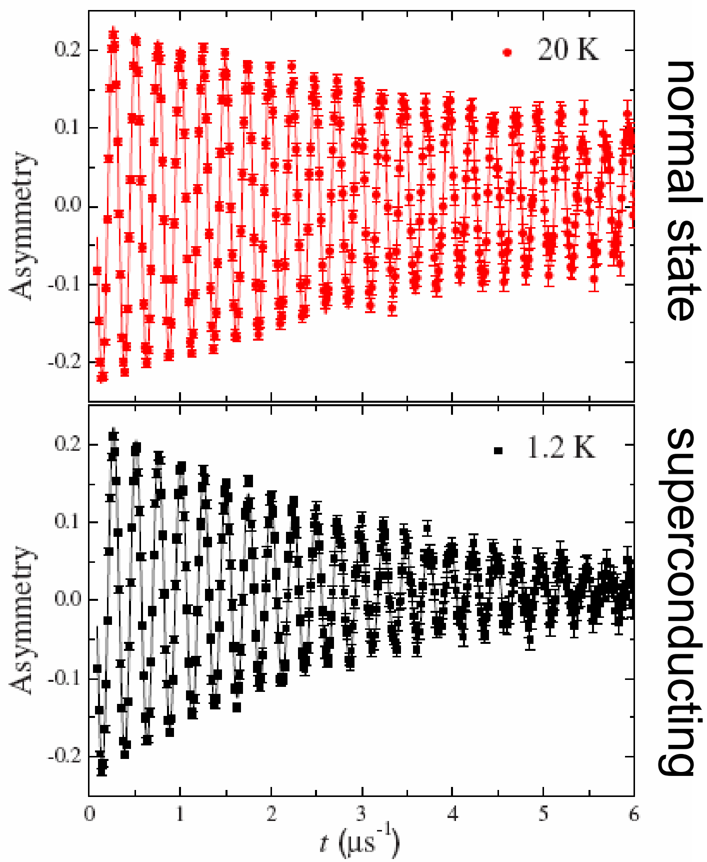
Larmor precession

$$A_0 P(t) = A_0 \left[\frac{1}{3} e^{-\lambda_L t} + \frac{2}{3} e^{-\lambda_T t} \cos(\gamma_\mu B t)\right]$$

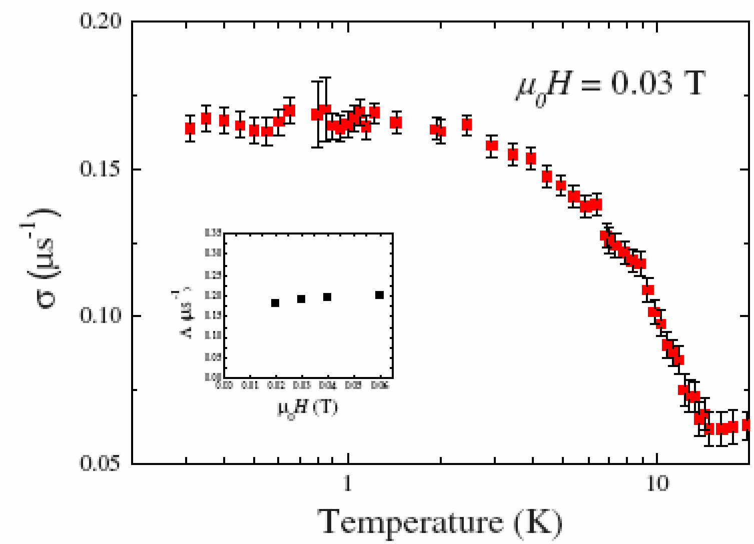
Muon-spin-spectroscopy study of superconducting $FeTe_{0.5}Se_{0.5}$ (T_c= 14.4 K)

P. K. Biswas et al., PRB **81**, 092510 (2010)

TF-μSR spectra

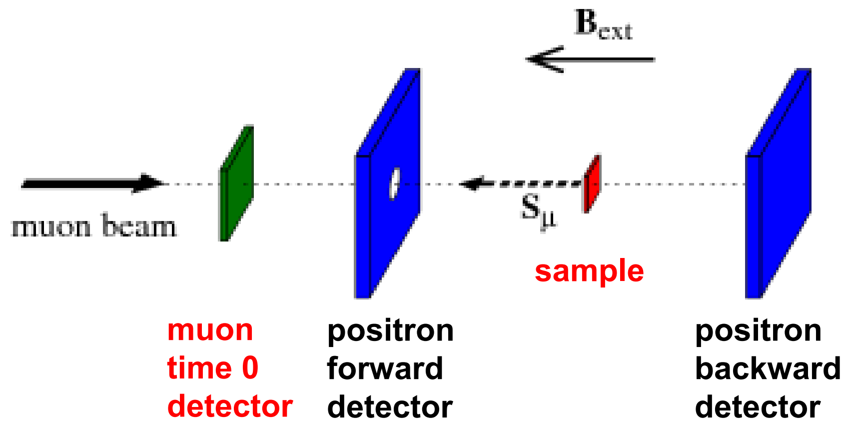


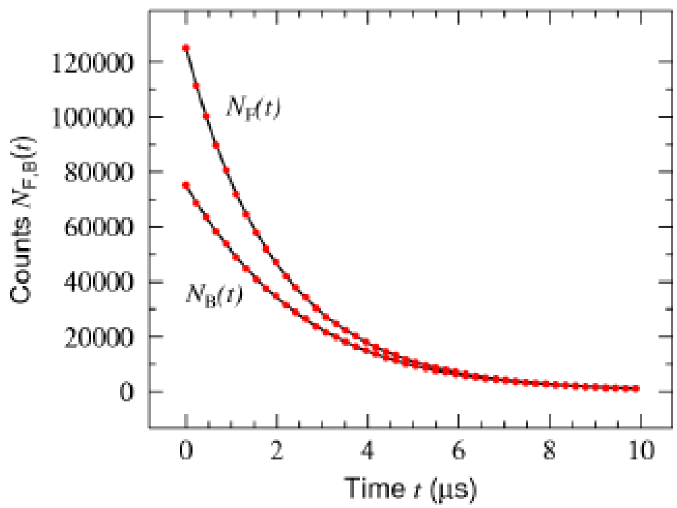
Gaussian depolarization rate

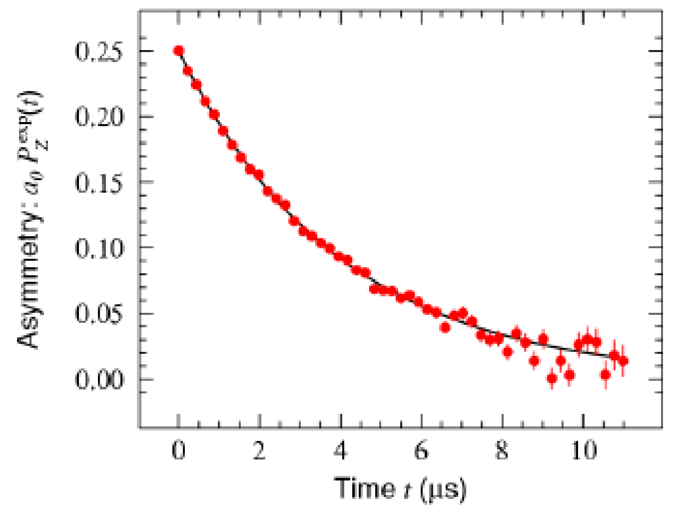


The relaxation rate increases below T_C due to the **inhomogeneous field distribution** of the flux-line lattice →
Information on the London penetration depth

Zero and longitudinal field μSR geometry



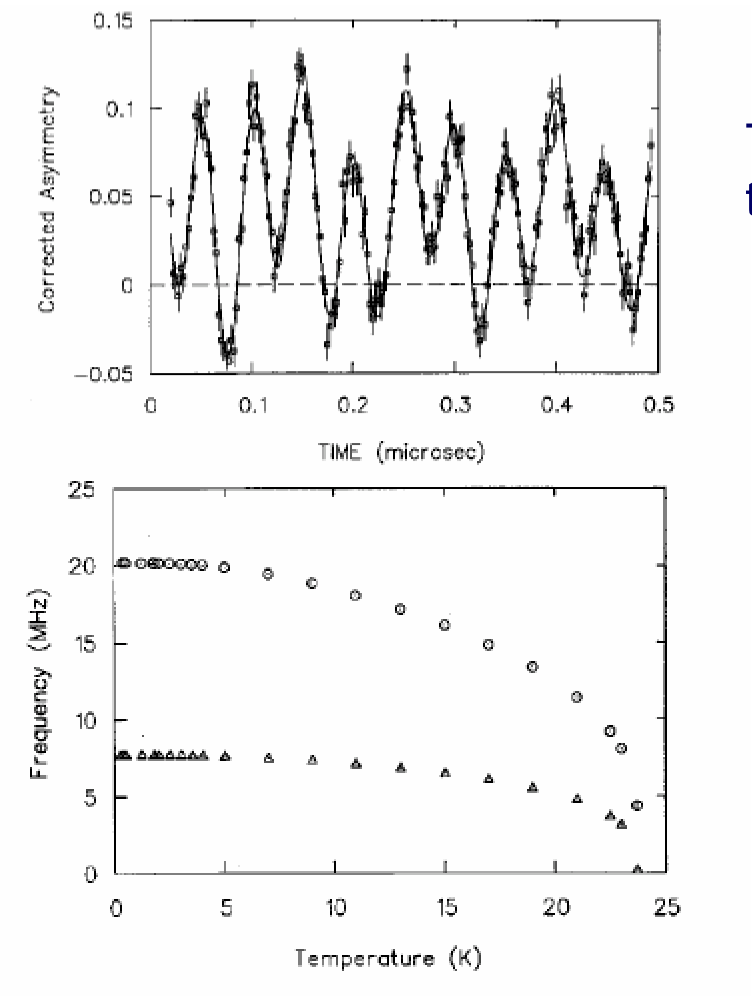




ZF-μSR is a very sensitive method of detecting **weak internal magnetism**, that arises due to ordered magnetic moments, or **random fields that are static or fluctuating with time.**

ZF-μSR provided the first evidence for static magnetic order in the undoped parent compound La2CuO4. Since then μSR has played a major role in determining magnetic phase diagrams, particularly in high-*Tc* and heavy-fermion systems.

An example of ZF μSR spectra: μ+ in antiferromagnetic CaV_3O_7



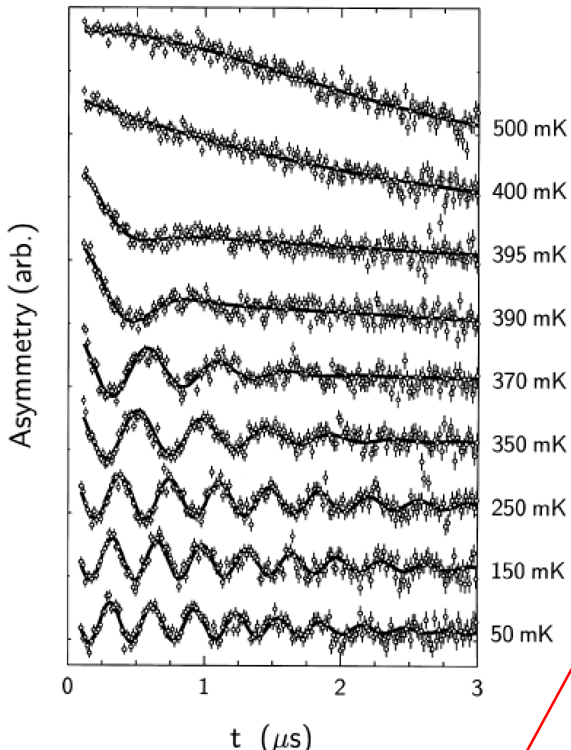
Two precession signals corresponding to two different muon sites

The local field is a consequence of the AF order of the V moments.

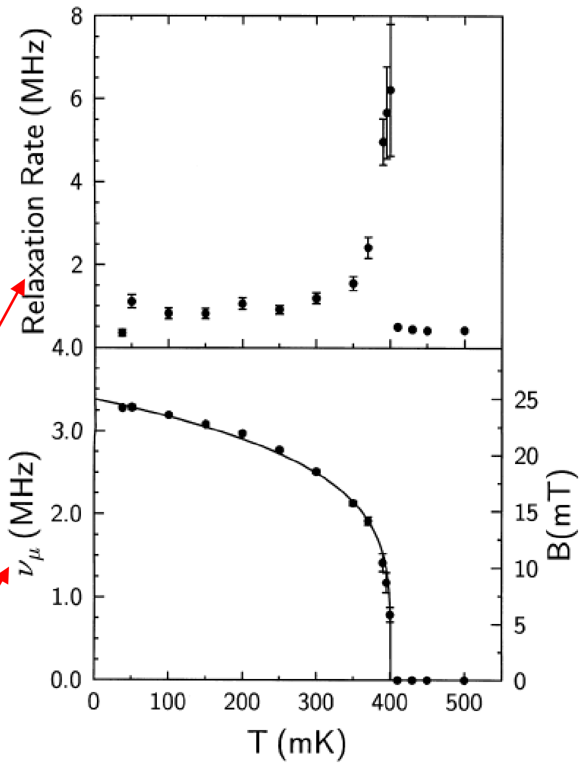
The magnetization curves

ZF- μSR and ordered organic ferromagnets and antiferromagnets

Antiferromagnetic Tanol suberate $(C_{13}H_{23}O_2NO)_2$



Raw μSR data measured on tanol suberate in zero magnetic field.



Temperature dependence of the relaxation rate and frequency of the muon-spin precession.

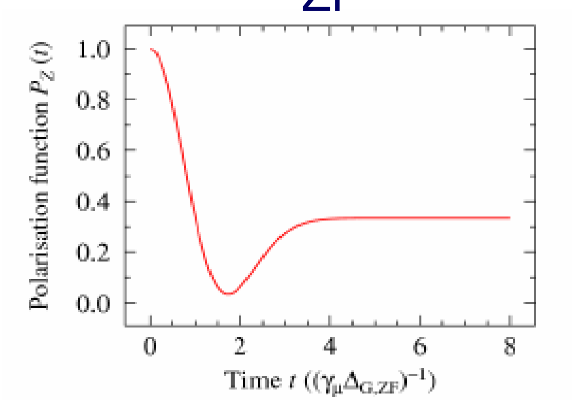
$$P(t) = a_L(t) + a_T e^{-\lambda t} \cos(2\pi\nu_\mu)$$

S.J. Blundell et al. / Physica B 289}290 (2000) 115-118

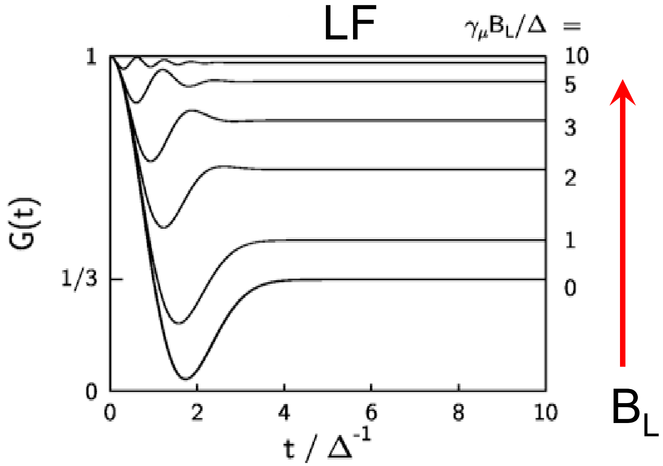
Spectra of static field distributions in ZF- and LF- geometry

Kubo Toyabe functions for
static Gaussian field distribution - width Δ

ZF

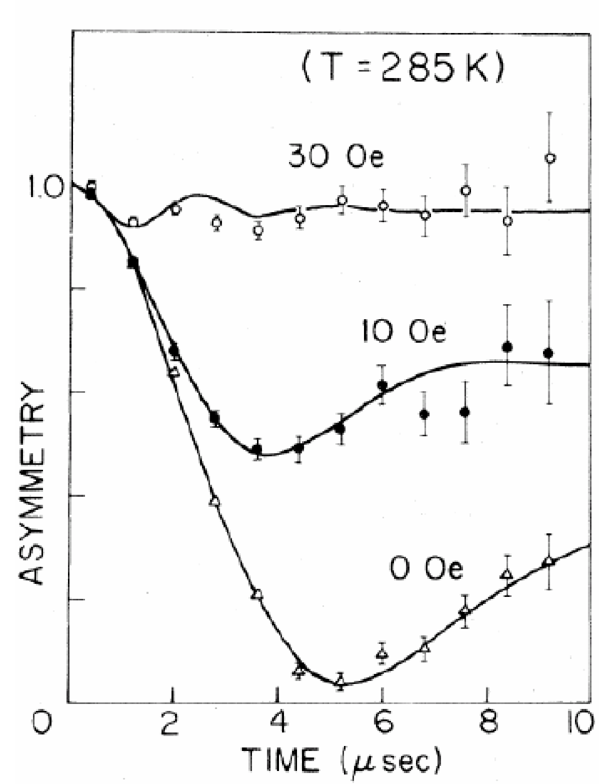


LF



The longitudinal field decouples the spins from the field distribution

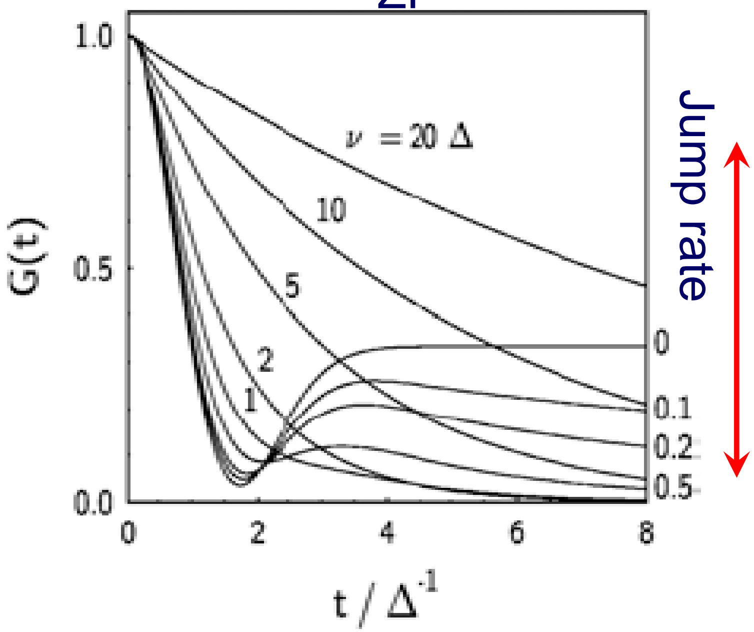
An example: Muon spin relaxation and longitudinal field-decoupling in the paramagnetic phase of MnSi (R.S. Hayano et al.,Phys. Rev **B20,** 850 (1979)).



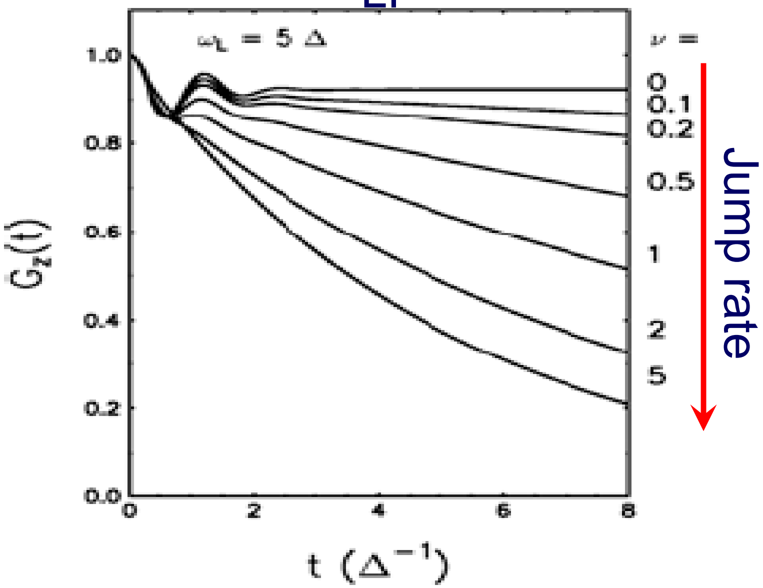
In this case the local field is produced mainly by the Mn nuclear moments.

The effect of dynamics in ZF, LF -and TF-geometry

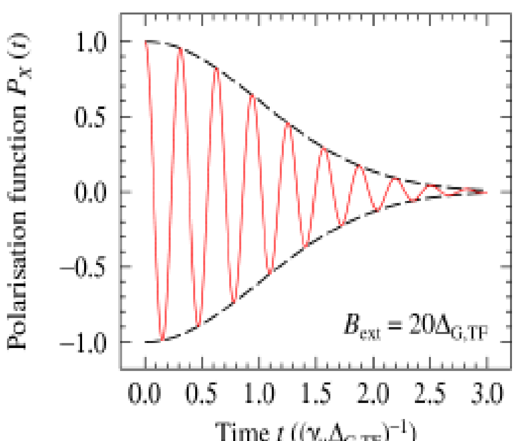
ZF



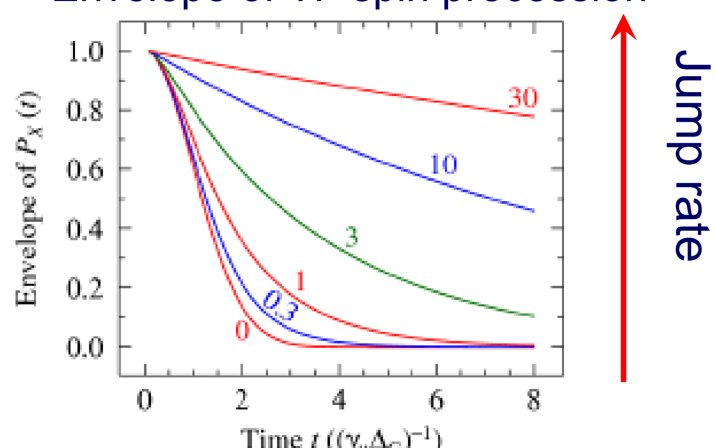
LF



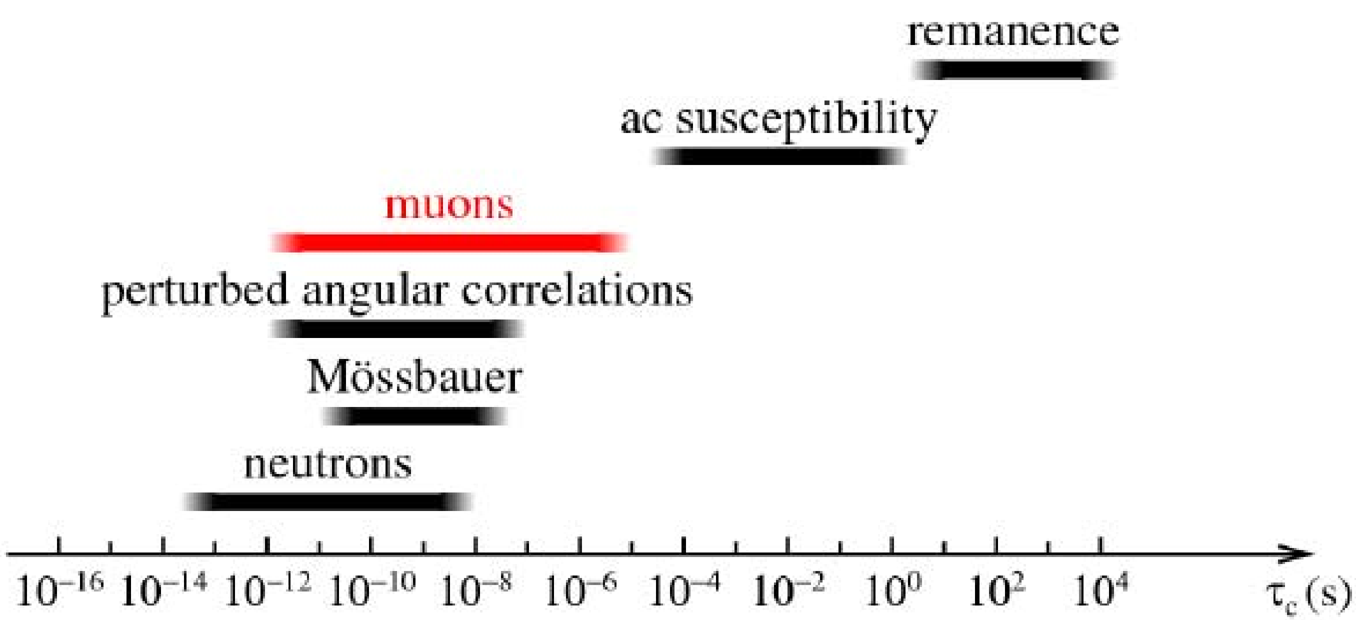
TF



Envelope of TF spin precession



The dynamical ranges of different techniques



Areas of μSR applications

Magnetic Systems

Magnetically Ordered Systems
Spin-Glass Systems
Frustrated Spin Systems
Colossal Magnetoresistance
Low-Dimensional Systems
Heavy Fermion Systems
Quasicrystals
Molecular Magnets & Clusters

Superconductors

Magnetic Phases & Phase Separation
Weak Magnetism
Characteristic Length Scales
Pairing Properties

Transport

Quantum Diffusion
Electron Transport in Non-Metals
Conducting Polymers

Semiconductors

Chemistry

Chemical Reaction Kinetics and H Isotopes
Free Radical Systems

Biological Applications