Introduction to μSR

μSR: muon spin rotation / relaxation / resonance

Applied* Elementary Particle Physics

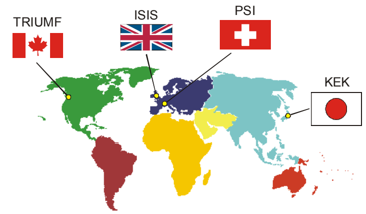
*(to basic research in Materials Science and Chemistry)

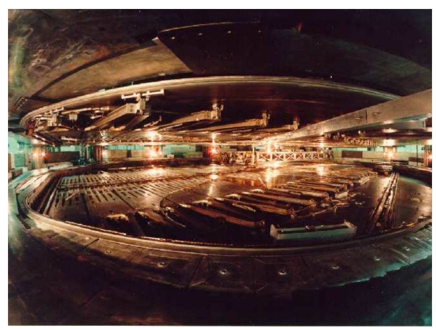
- The World's μSR Facilities
- Basic Techniques of μSR
- μSR "Toolbox" for QM
- Examples of μSR in HT_c SC

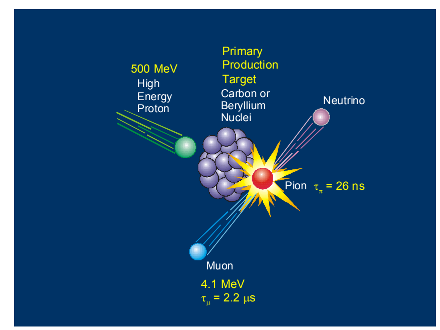
Jess H. Brewer
CIAR QM Summer School
UBC, 7 May 2008

Visit our Web site! http://musr.org

Where in the World is μSR?







Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

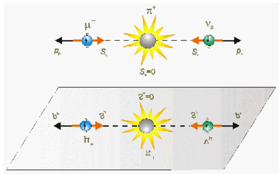
A pion **stops** in the "skin" of the primary production target.
It has zero linear momentum and zero angular momentum.

Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ.

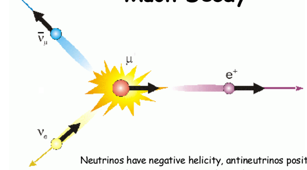
Conservation of Angular Momentum: μ^+ and ν_μ have equal and opposite spin.

Weak Interaction:
Only "left-handed" ν_μ are created.

Thus the emerging μ^+ has its spin pointing *antiparallel* to its momentum direction.

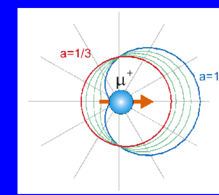


Muon Decay



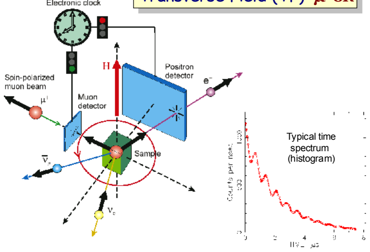
Neutrinos have negative helicity, antineutrinos positive.
An ultrarelativistic positron behaves like an antineutrino.
Thus the positron <u>tends</u> to be emitted along the muon spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

μ^+ Decay Asymmetry

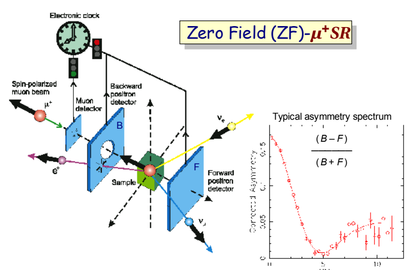


Angular distribution of positrons from μ^+ decay. The asymmetry is a = 1/3 when all positron energies are detected with equal probability.

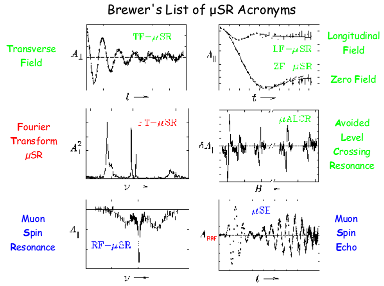
Transverse Field (TF) μ^+SR



Zero Field (ZF)-μ^+SR



Brewer's List of μSR Acronyms



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"Themes" in μ^+SR

Muonium as light Hydrogen
($Mu = \mu^+ e^-$) ($H = p^+ e^-$)

- **Mu** *vs.* **H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu** *vs.* **H in Semiconductors:**
  - Until recently, μ^+SR $\longrightarrow$ **only** data on metastable H states in semiconductors!

The Muon as a Probe

- **Probing Magnetism: unequaled sensitivity**
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. HT_cSC)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth λ
  - Coherence Length ξ

- **Quantum Diffusion:** μ^+ in metals (compare H^+); Mu in nonmetals (compare H).

μSR Toolbox for Quantum Materials

- **ZF-μSR & Static Local Magnetic Fields:**
  - Volume fraction of AF/SG order even in powder samples
  - Sensitive to very weak fields (~1 G)
  - *T*-dependence of B_{loc} $\Rightarrow$ magnetic phase diagram
- **TF-μSR & Vortex Lattice:**
  - Penetration depth $\lambda(T,H)$ $\Rightarrow$ SC phase diagram
  - Coherence length $\xi(T,H)$
  - Pinning, melting *etc.*

Motion of Muon Spins in Static Local Fields:

S_μ = Expectation value of a muon's spin direction

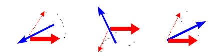
(a) All muons "see" same field B: for $B \parallel S_\mu$ nothing happens

$\omega_\mu = 2\pi\,\gamma_\mu\,|B|$

$\gamma_\mu = 135.5$ MHz/T

for $B \perp S_\mu$ Larmor precession: ω_μ

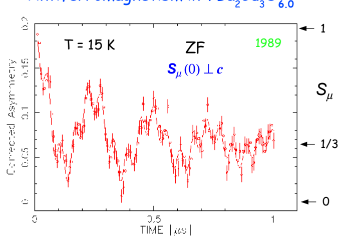
(b) All muons "see" same $|B|$ but ***random direction***:



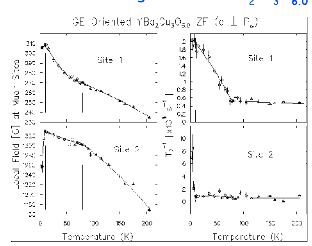
2/3 of S_μ precesses at ω_μ

1/3 of S_μ stays constant

Antiferromagnetism in $YBa_2Cu_3O_{6.0}$



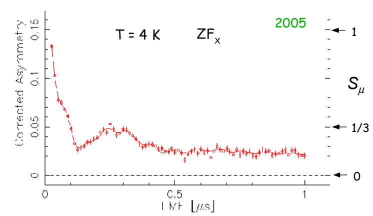
Antiferromagnetism in $YBa_2Cu_3O_{6.0}$ 1989



Two muon sites: most at Site 1 ("4 MHz site"), less at Site 2 ("18 MHz site").

Changes at 10K and 80K, cause unknown.

Magnetism in $YBa_2Cu_3O_{6.35}$



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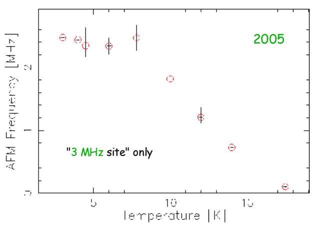
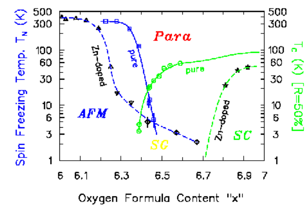


Phase Diagram of $YBa_2Cu_3O_x$ *ca.* 1990



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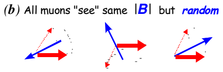
(b) All muons "see" same $|B|$ but *random direction*:



2/3 of S_μ precesses at ω_μ

1/3 of S_μ stays constant

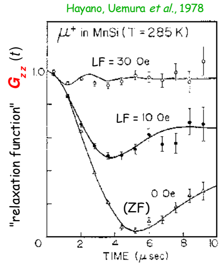
(c) Local field B *random* in *both* magnitude *and* direction:

All do not return to the same orientation at the same time

(dephasing)$\Rightarrow$ S_μ "relaxes" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

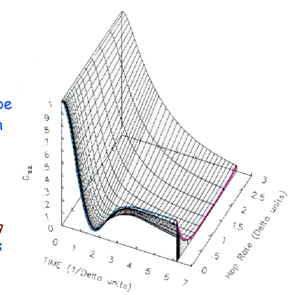
ZF-μ^+SR:

Kubo-Toyabe Relaxation due to Nuclear Dipolar Fields

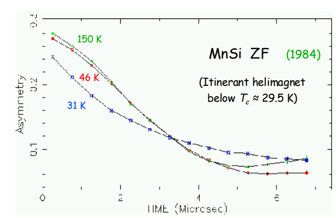


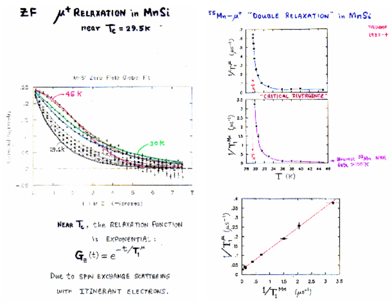
Dynamic Gaussian Kubo-Toyabe Relaxation

due to *fluctuating* local fields



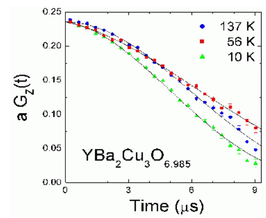
Combined Nuclear Dipolar and Paramagnetic Relaxation





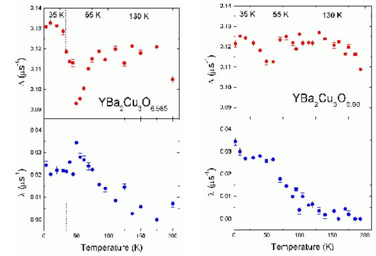
Nuclear Dipolar × "Other" Relaxation

2001



Nuclear Dipolar × "Other" Relaxation

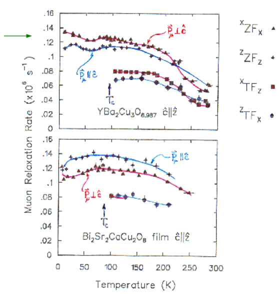
2002



"Anyon" Search

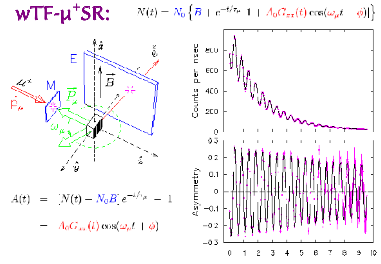
(1990)

found similar "dips" in the dipolar relaxation rate around 50K.



wTF-μ^+SR:

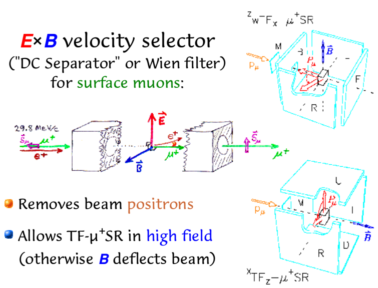
$$N(t) = N_0\left\{B + e^{-t/\tau_\mu}\left[1 + A_0 G_{xx}(t)\cos(\omega_\mu t + \phi)\right]\right\}$$



$$A(t) = [N(t) - N_0 B]\, e^{t/\tau_\mu} - 1$$
$$= A_0 G_{xx}(t)\cos(\omega_\mu t + \phi)$$

$E \times B$ velocity selector

("DC Separator" or Wien filter)
for surface muons:



- Removes beam positrons
- Allows TF-μ^+SR in high field (otherwise B deflects beam)

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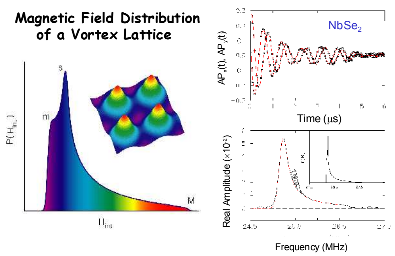

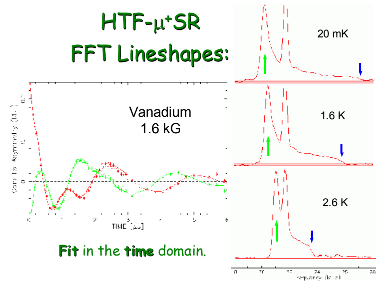

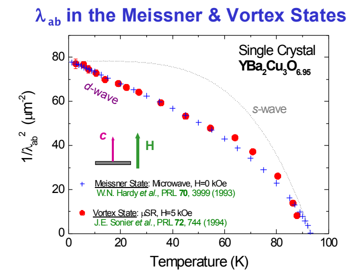

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