TRIUMF

Introduction to μSR

μSR: muon spin Rotation Relaxation Resonance

Applied* Elementary Particle Physics

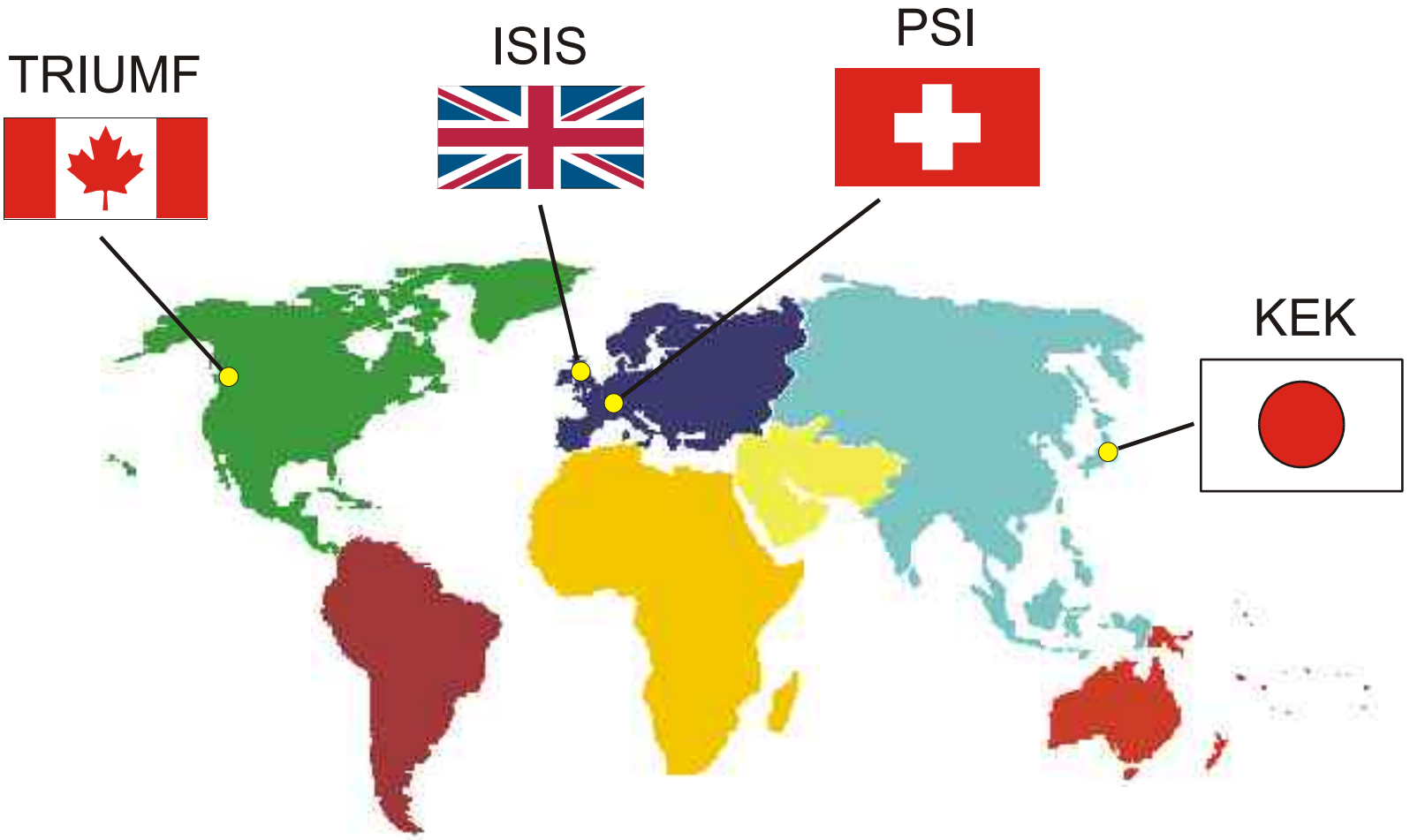
*(to basic research in Materials Science and Chemistry)

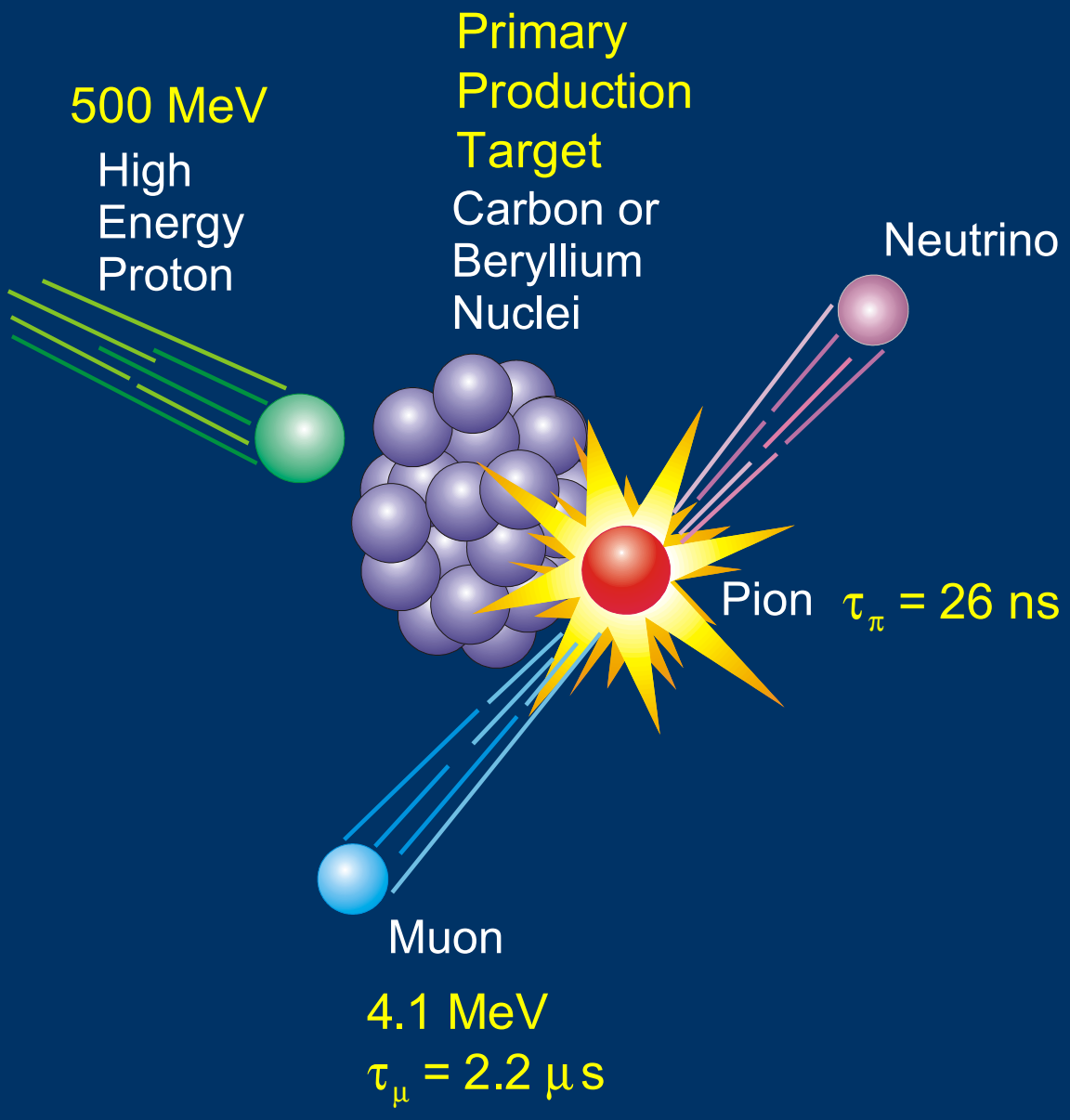
- The World's μSR Facilities
- Basic Techniques of μSR
- Applications of μSR
- Research Opportunities in μSR

Jess H. Brewer
UNBC, 26 March 2004

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

Where in the World is μSR?




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

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

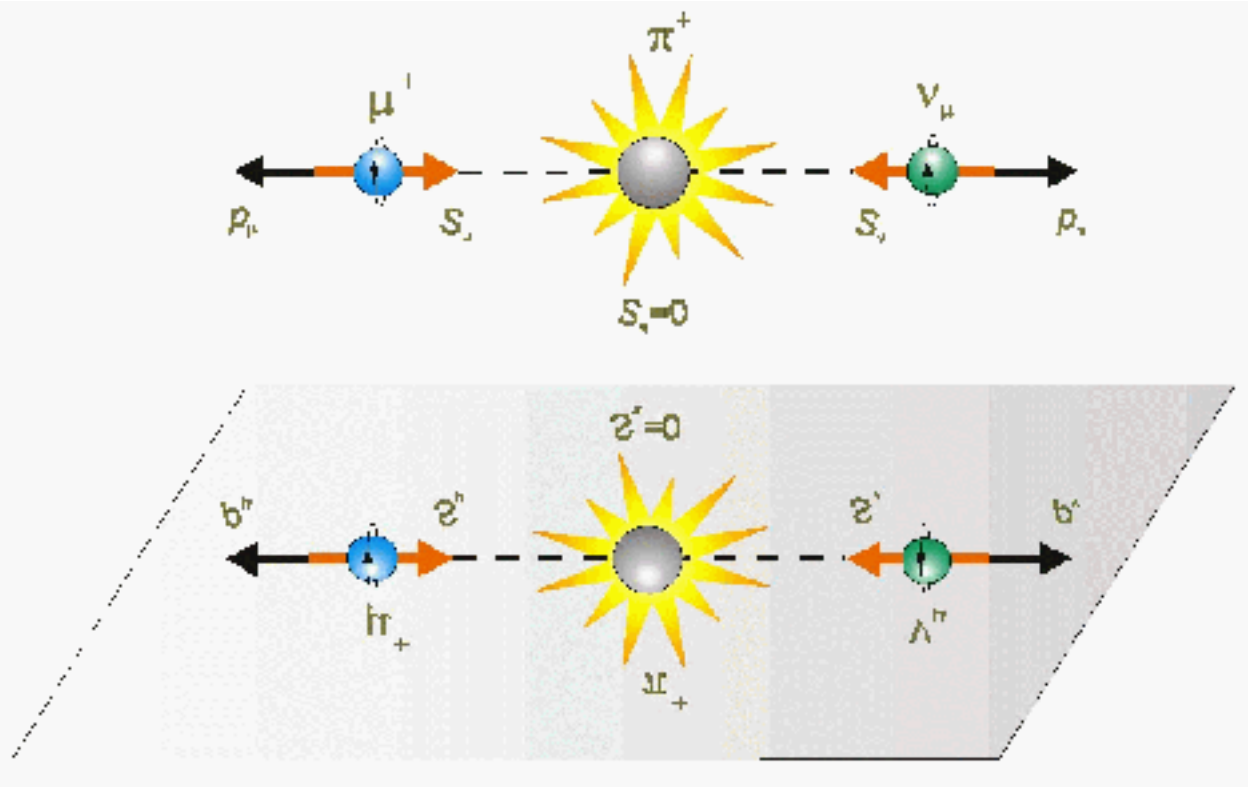
A pion **stops** in the "skin" of the primary production target.
It has zero linear momentum and zero angular momentum.

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

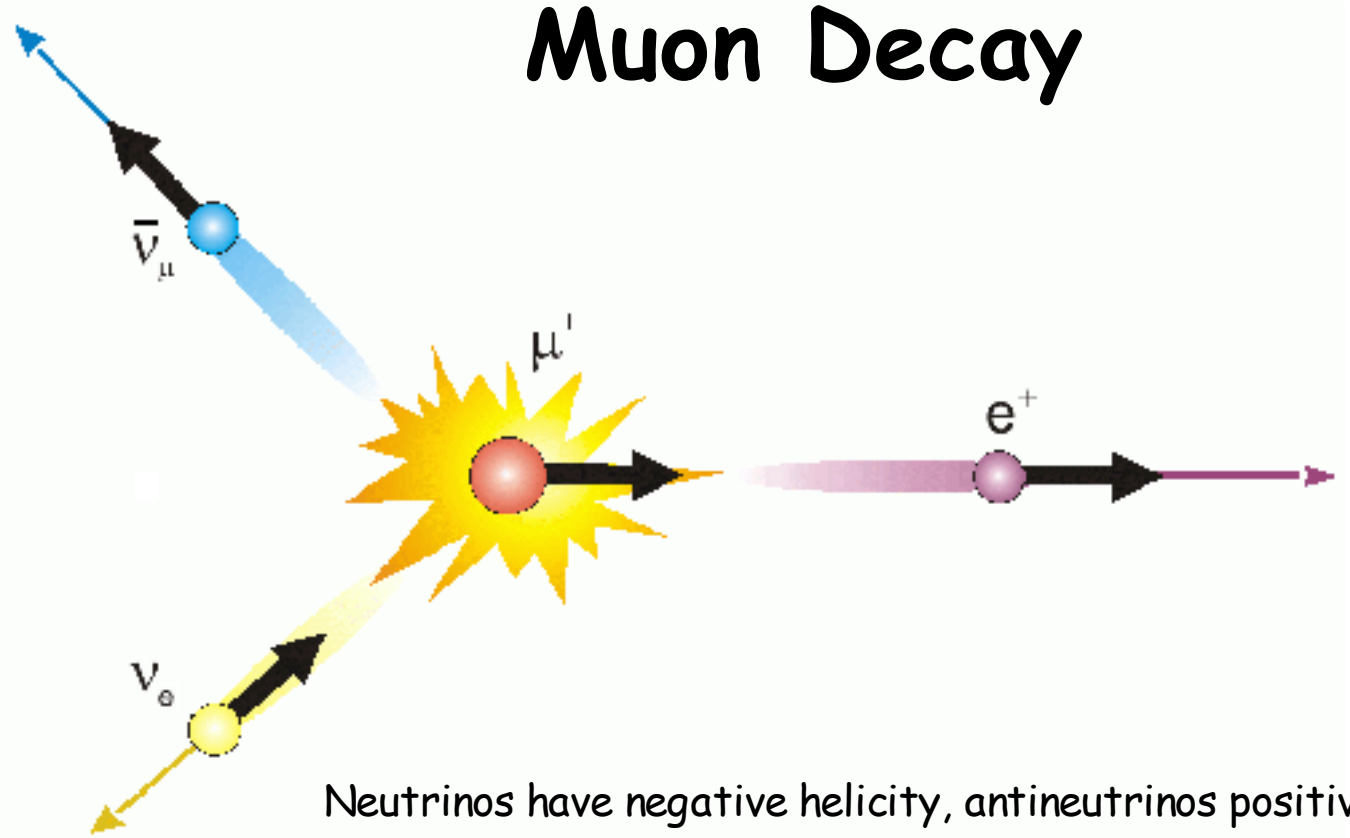
Conservation of Angular Momentum: μ^+ and ν_μ have equal and opposite spin.

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

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

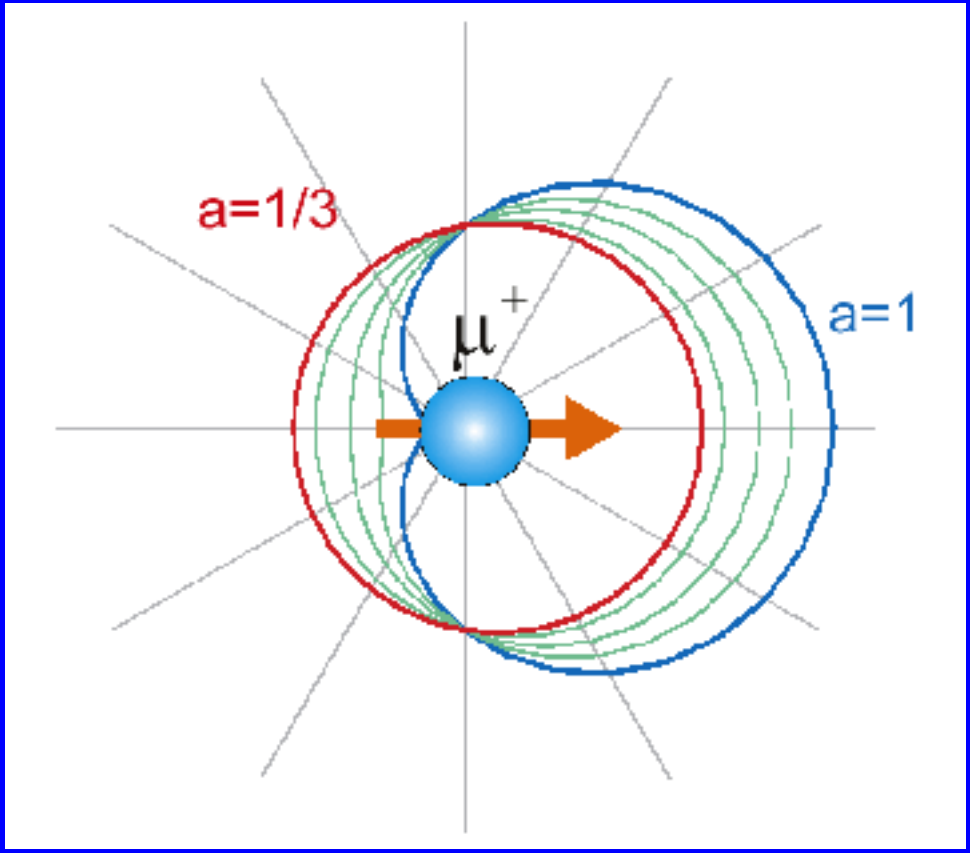


Muon Decay



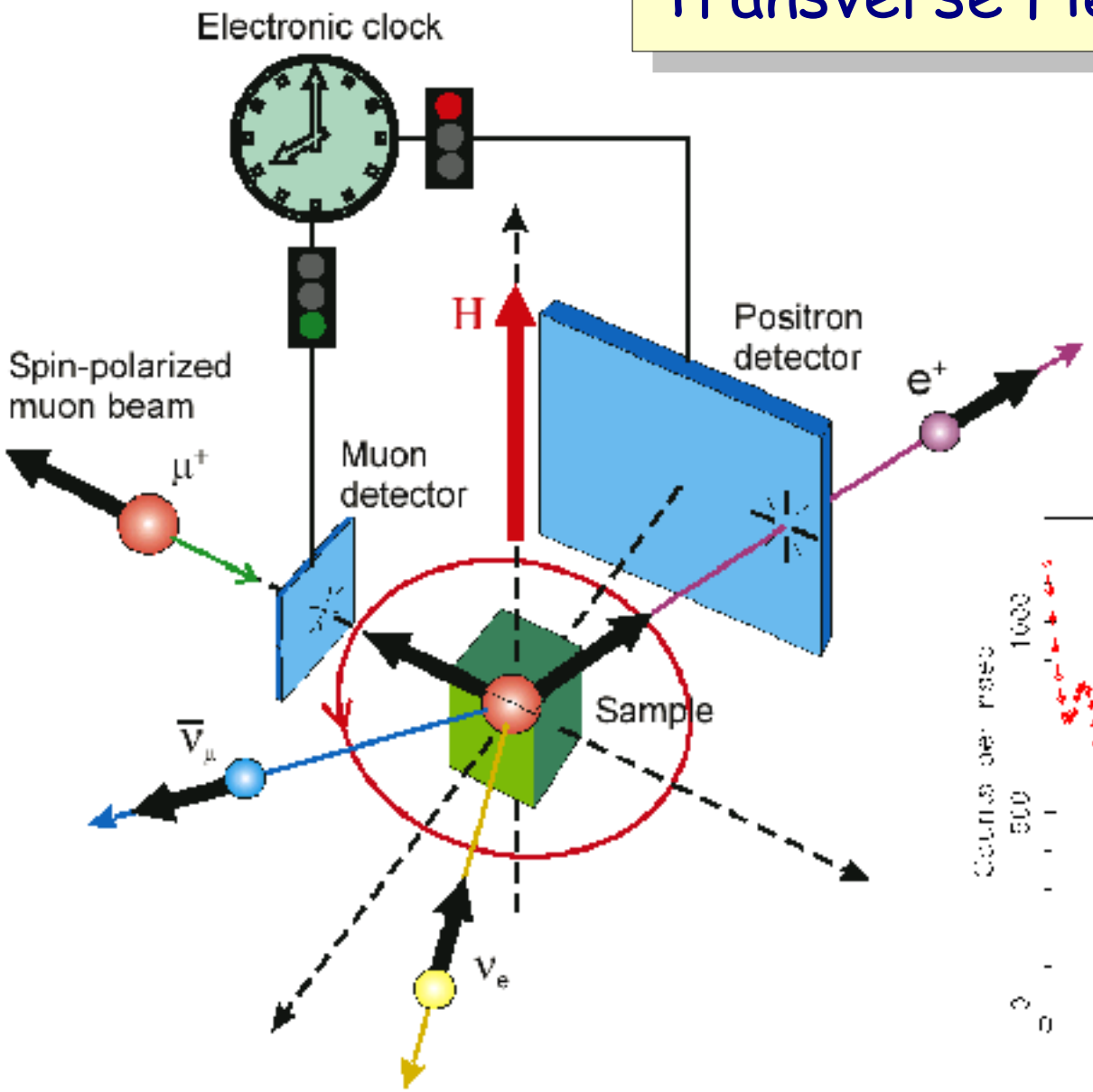
Neutrinos have negative helicity, antineutrinos positive.
An ultrarelativistic positron behaves like an antineutrino.
Thus the positron tends to be emitted along the muon spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

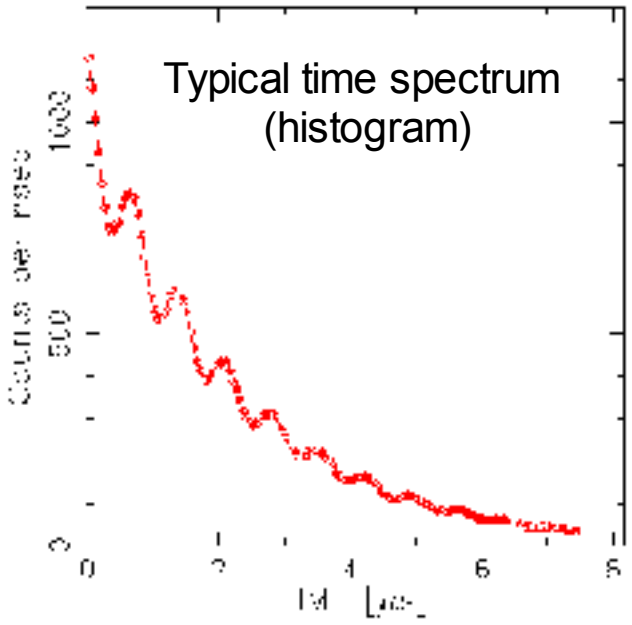
μ^+ Decay Asymmetry



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

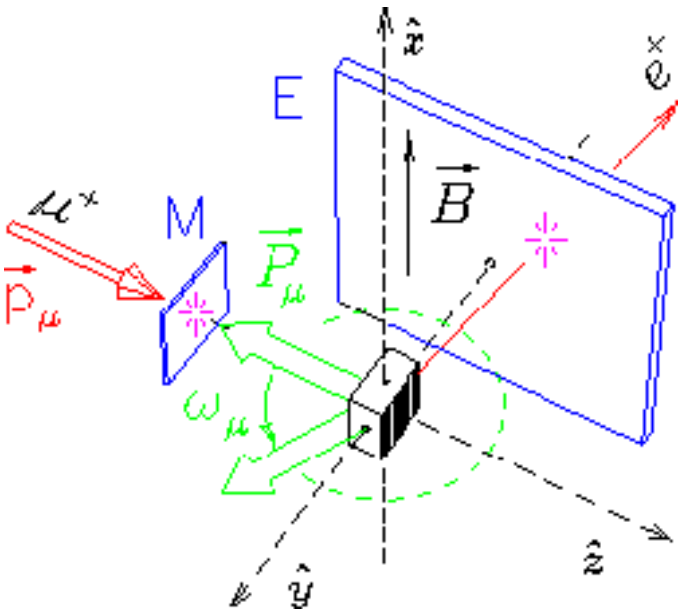
Transverse Field (TF)-μSR



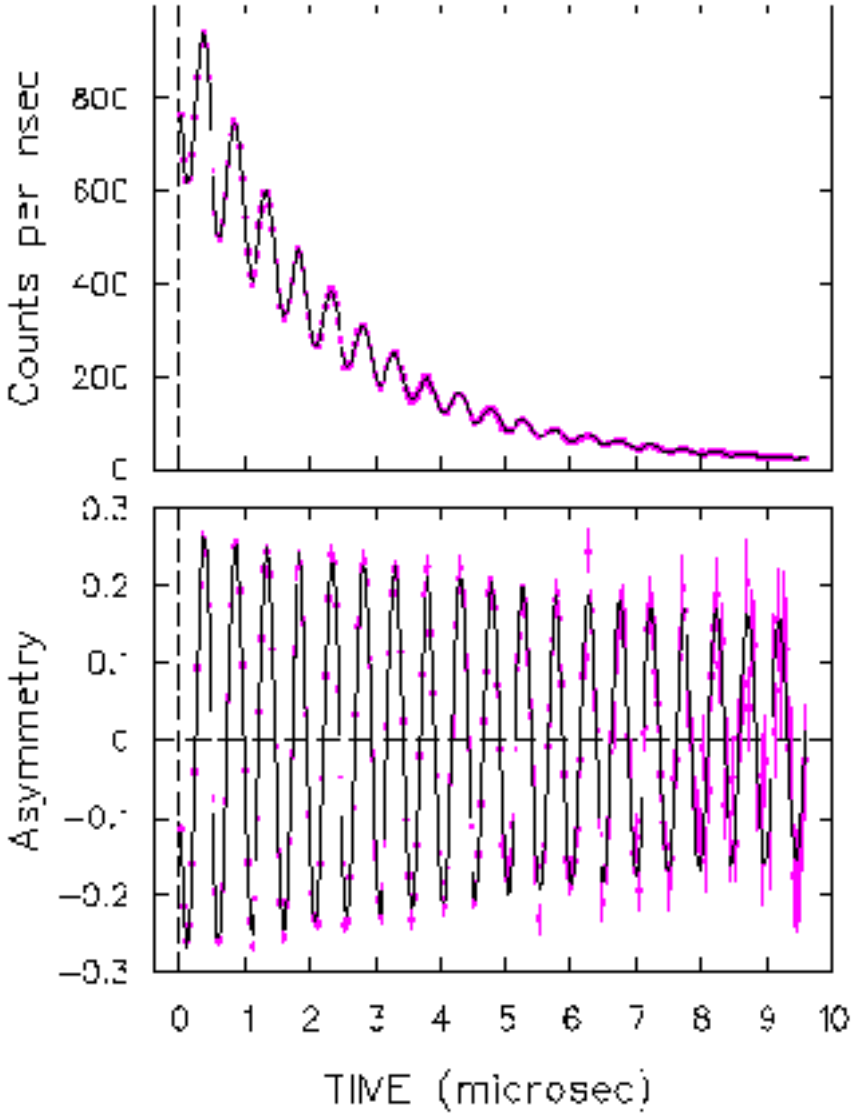


wTF-μ^+SR:

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



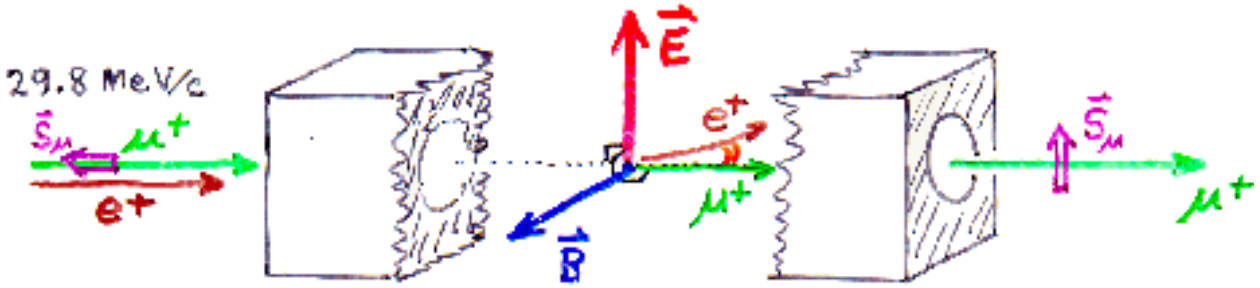
$$A(t) = [N(t) - N_0 B] e^{-t/\tau_\mu} = A_0 G_{xx}(t) \cos(\omega_\mu t - \phi)$$



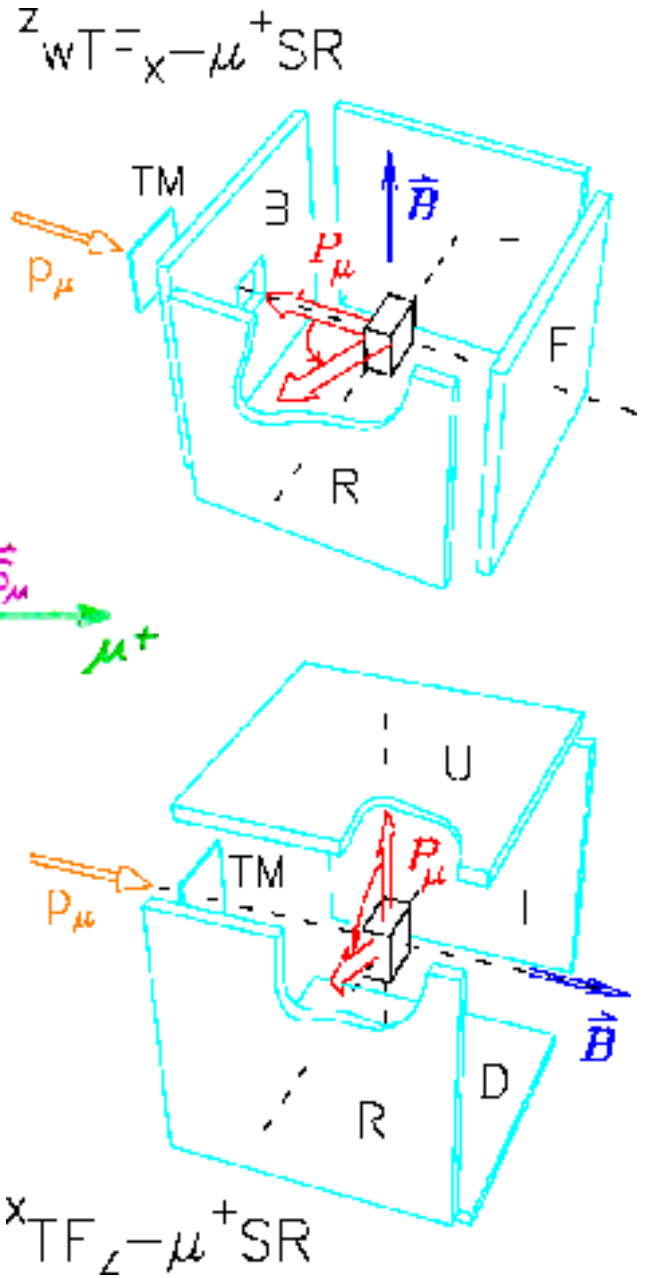
E*×*B velocity selector

("DC Separator" or Wien filter)

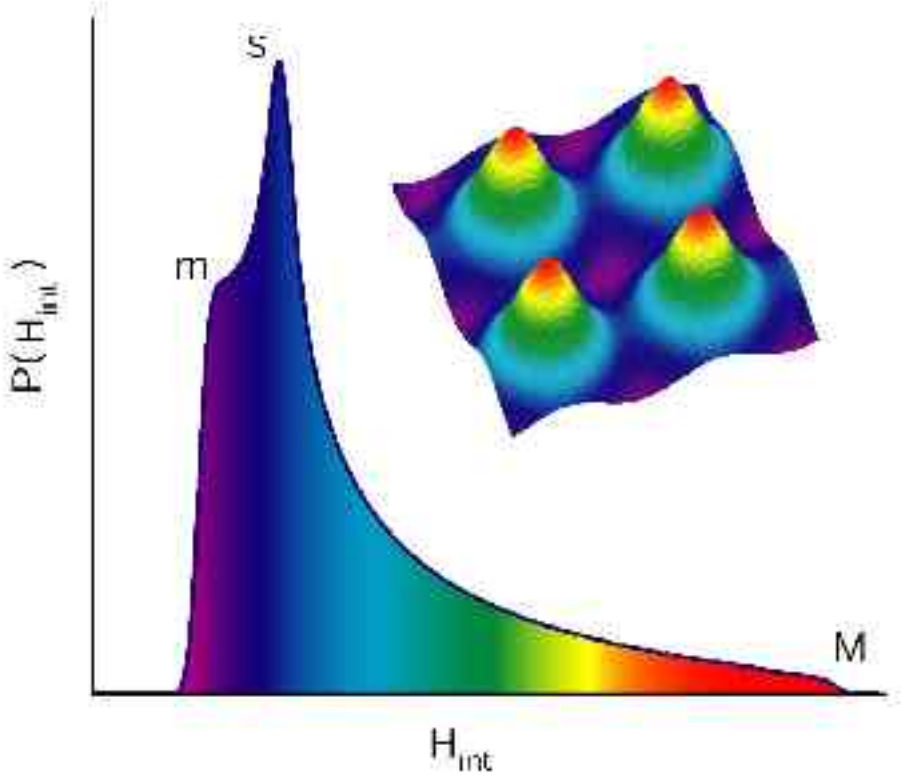
for surface muons:

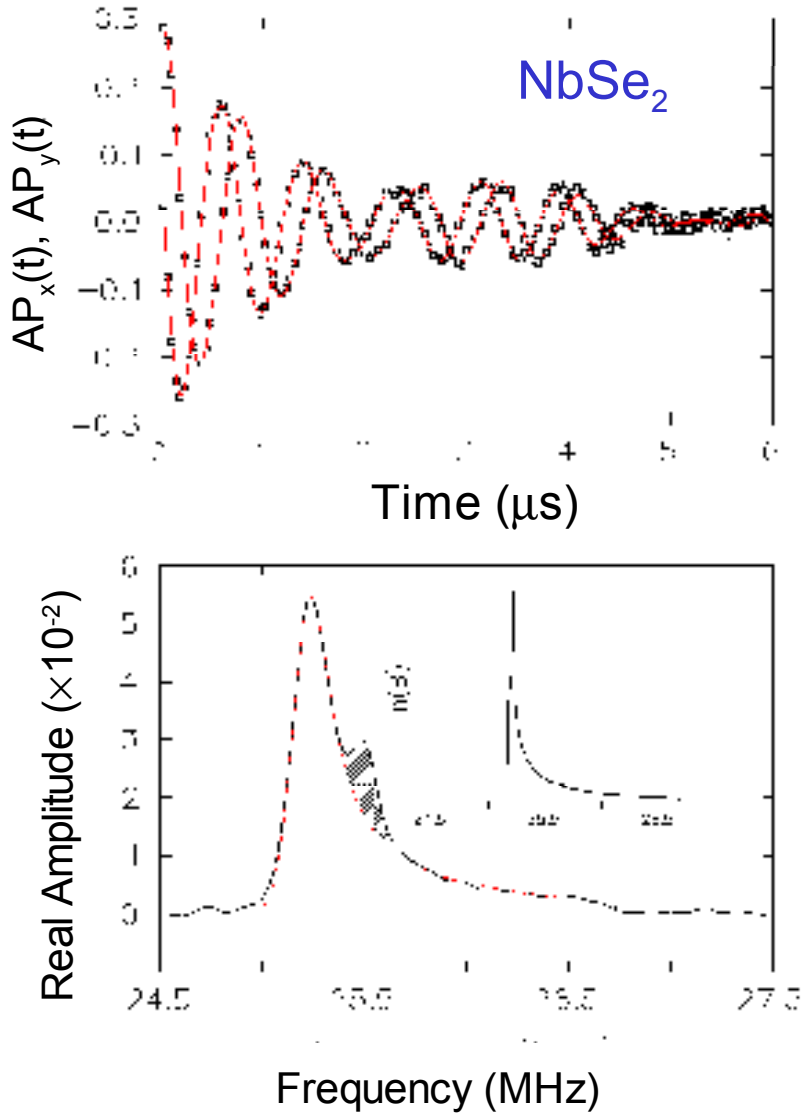


- Removes beam positrons
- Allows TF-μ^+SR in high field (otherwise ***B*** deflects beam)

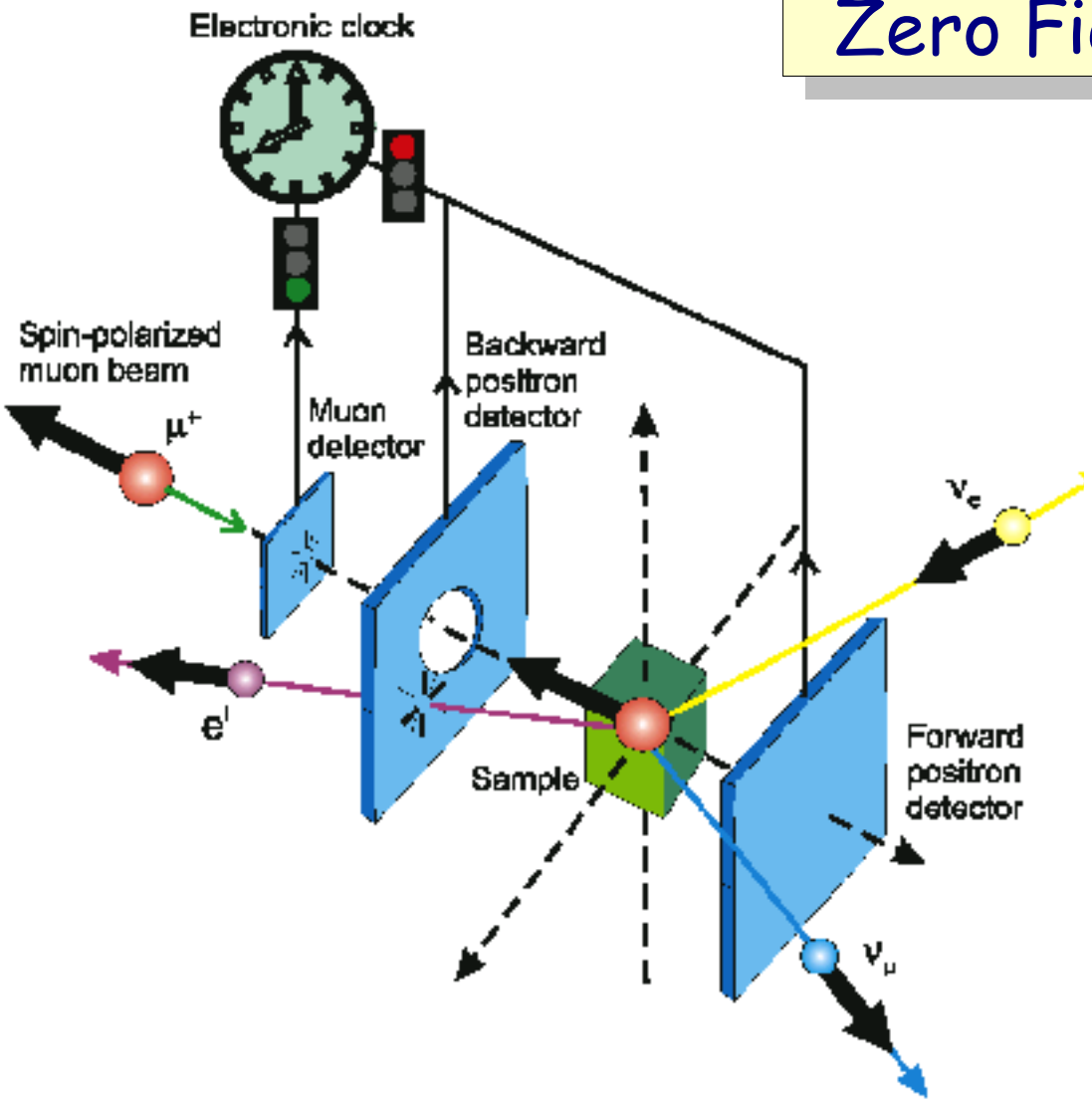


Magnetic Field Distribution of a Vortex Lattice

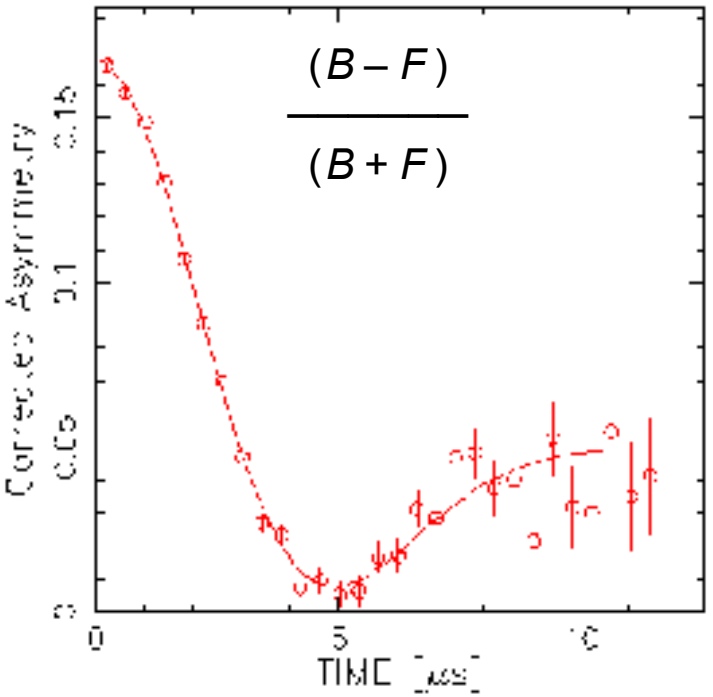




Zero Field (ZF)-μSR



Typical asymmetry spectrum



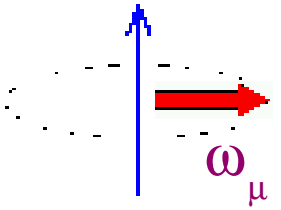
Motion of Muon Spins in Static Local Fields:

$\vec{S}_\mu$ = Expectation value of one muon's spin direction

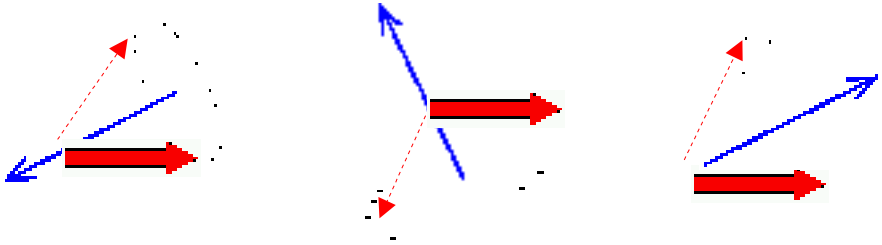
(a) All muons "see" same field $\vec{B}$: → for $\vec{B} \parallel \vec{S}_\mu$ nothing happens

$\omega_\mu = 2\pi \gamma_\mu |\vec{B}|$ for $\vec{B} \perp \vec{S}_\mu$ Larmor precession:

$\gamma_\mu = 135.5$ MHz/T



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



2/3 of $\vec{S}_\mu$ precesses at ω_μ

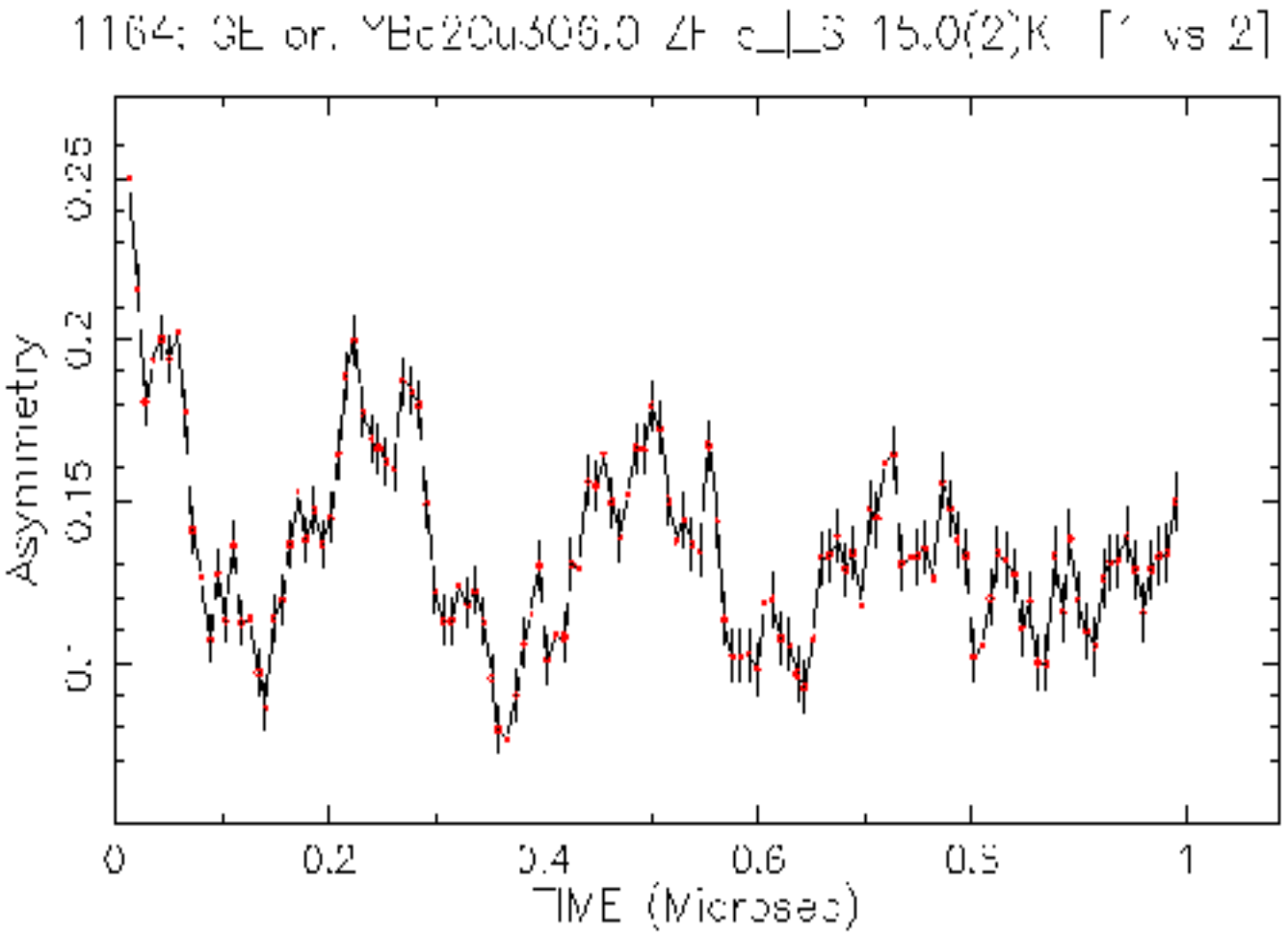
1/3 of $\vec{S}_\mu$ stays constant

(c) Local field $\vec{B}$ **random** in **both** magnitude **and** direction:

All → do not return to the same orientation at the same time (dephasing) $\Rightarrow$ $\vec{S}_\mu$ "relaxes" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

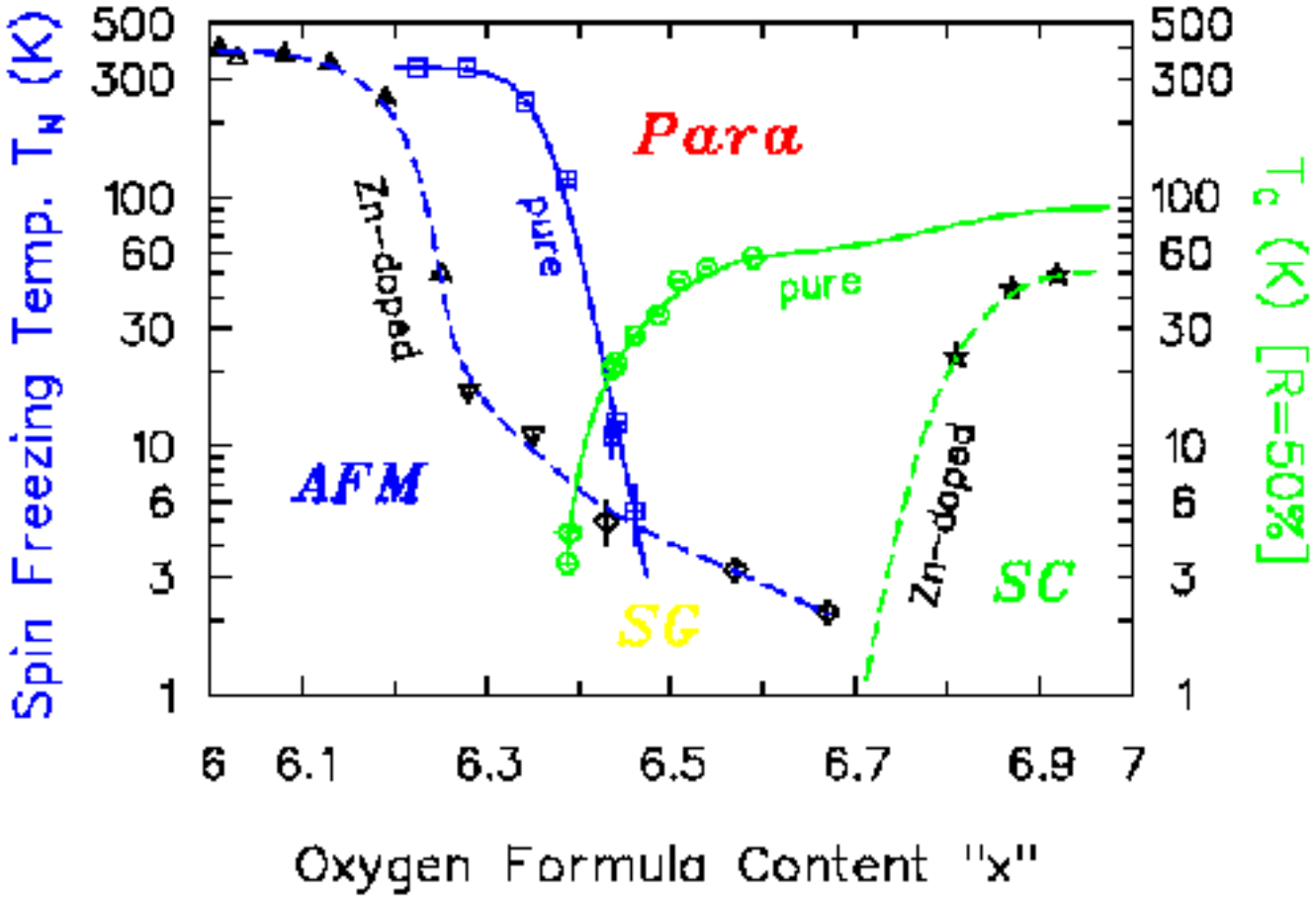
Antiferromagnetism in $YBa_2Cu_3O_{6.0}$

1989



Phase Diagram of $YBa_2Cu_3O_x$

ca. 1990



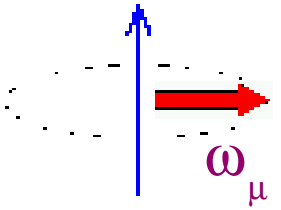
Motion of Muon Spins in Static Local Fields:

$\vec{S}_\mu$ = Expectation value of one muon's spin direction

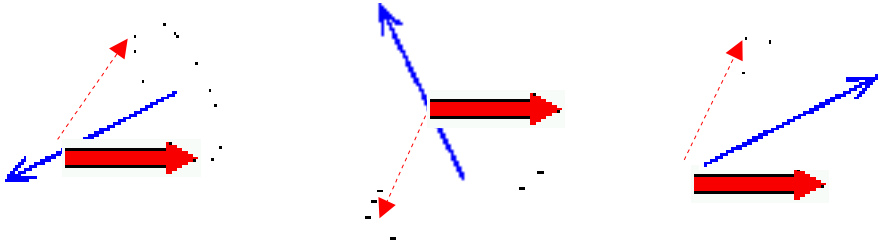
(a) All muons "see" same field $\vec{B}$: → for $\vec{B} \parallel \vec{S}_\mu$ nothing happens

$\omega_\mu = 2\pi \gamma_\mu |\vec{B}|$ for $\vec{B} \perp \vec{S}_\mu$ Larmor precession:

$\gamma_\mu = 135.5$ MHz/T



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



2/3 of $\vec{S}_\mu$ precesses at ω_μ

1/3 of $\vec{S}_\mu$ stays constant

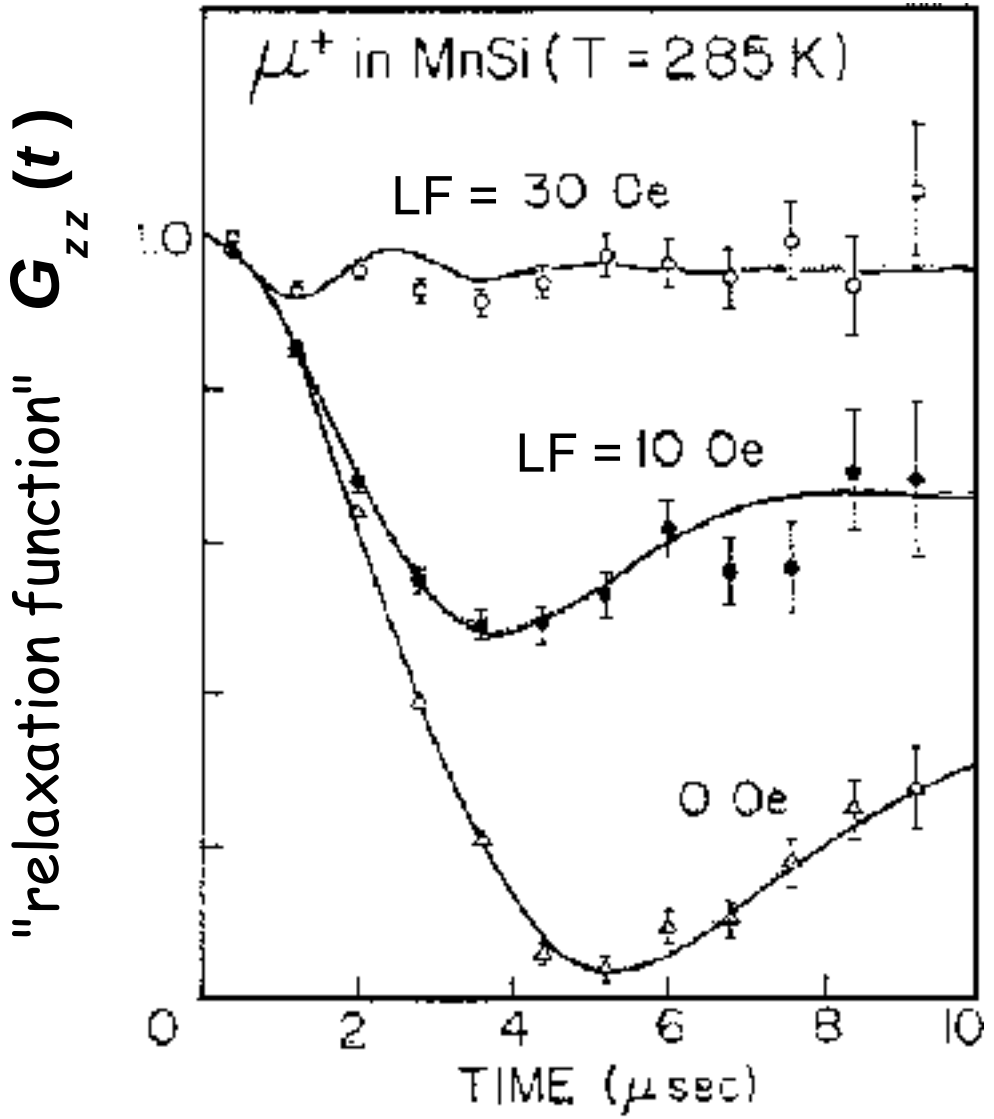
(c) Local field $\vec{B}$ **random** in **both** magnitude **and** direction:

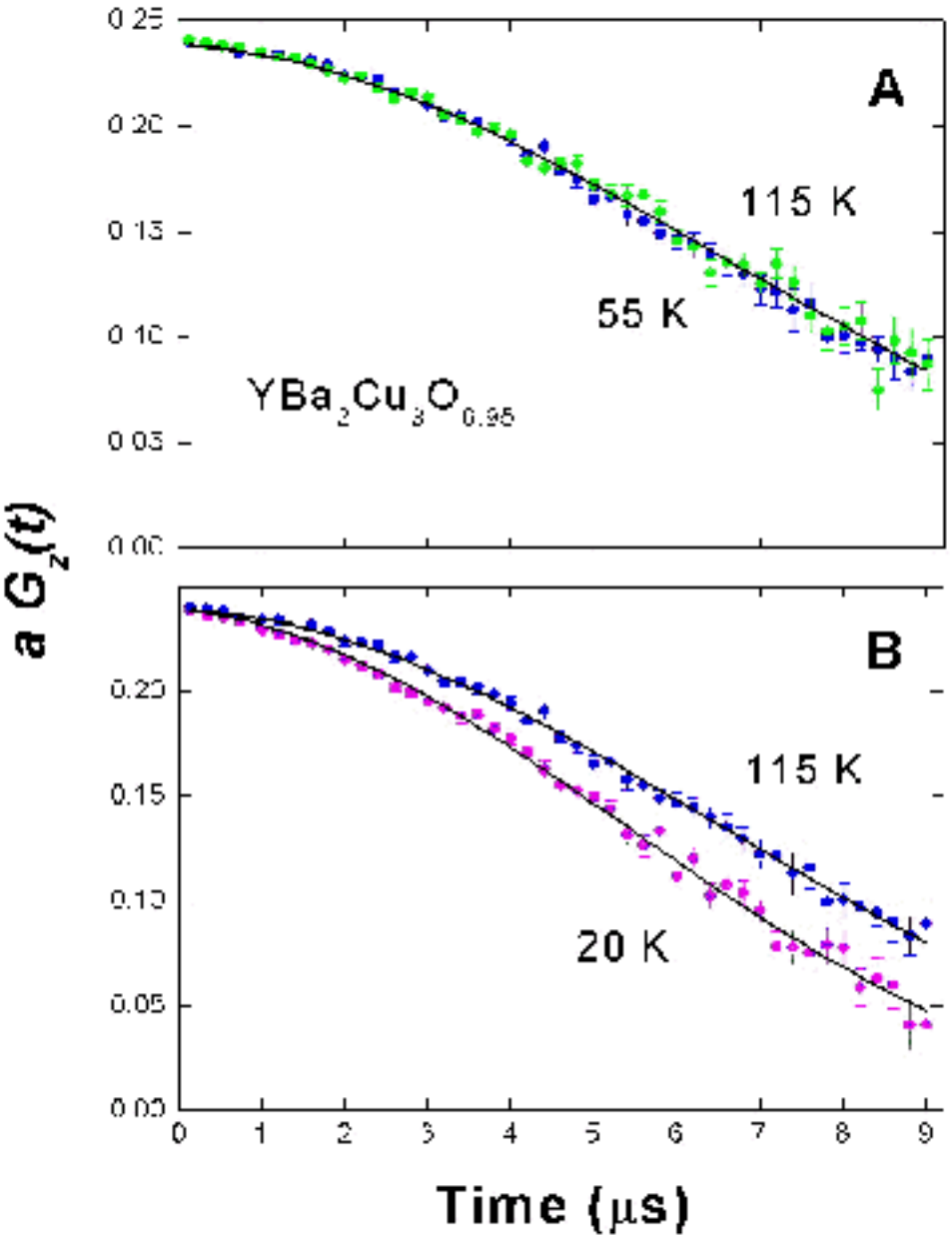
All → do not return to the same orientation at the same time (dephasing) $\Rightarrow$ $\vec{S}_\mu$ "relaxes" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

ZF-μ^+SR:

Kubo-Toyabe Relaxation due to Nuclear Dipolar Fields

Hayano, Uemura et al., 1978



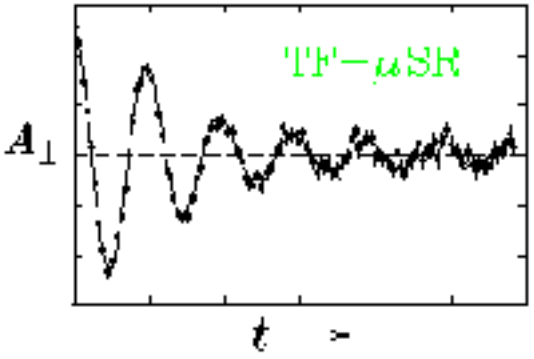


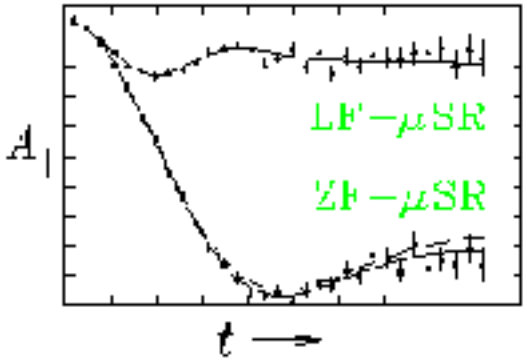
Sonier *et al.*, Science **292**, 1692 (2001)

"Extra" Magnetism at low ***T*** in $YBa_2Cu_3O_{6.95}$

Brewer's List of μSR Acronyms

Transverse Field

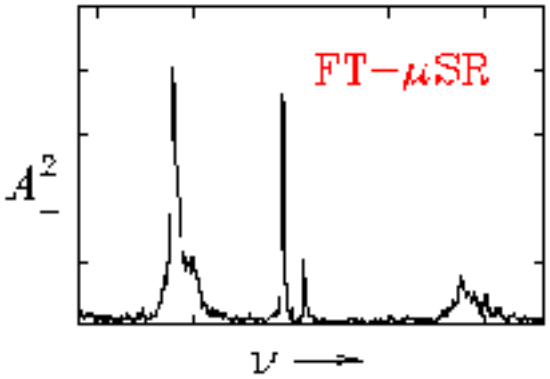


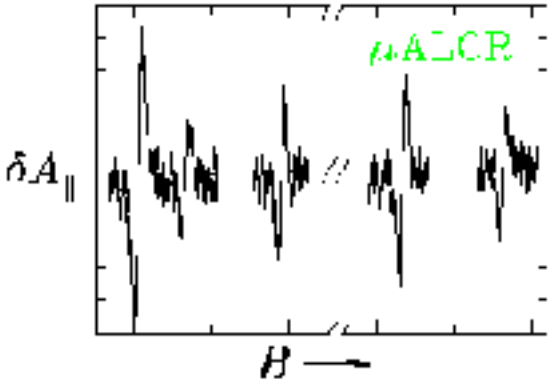


Longitudinal Field

Zero Field

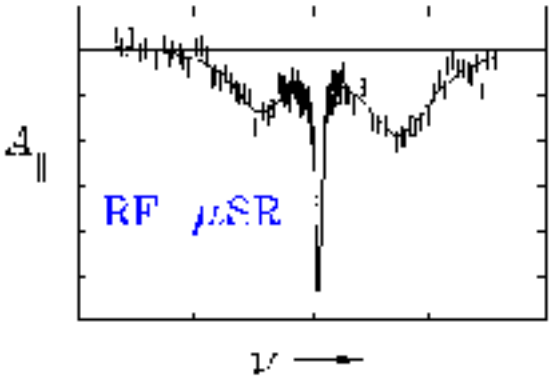
Fourier Transform μSR

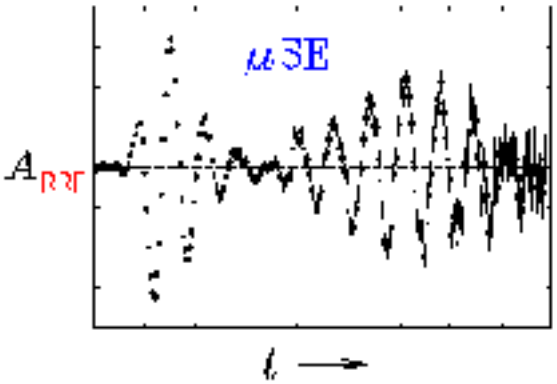




Avoided Level Crossing Resonance

Muon Spin Resonance





Muon Spin Echo

"Themes" in μ^+SR

Muonium as light Hydrogen

(Mu = μ^+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).

End of Introduction!

Ask Questions?

Take a break?

Vote on Part II:

(1) $\mu^- SR$

(2) TF-$\mu^+ SR$ in Superconductors: Vortex Lattice

(3) ZF-$\mu^+ SR$ in Superconductors: Magnetism

(4) μ^+ and Muonium States in Nonmetals

(5) Nothing (end early)