Introduction to

- Helicity
- Particle Physics of μSR
- The World's μSR Facilities
- Basic Techniques of μSR
- Applications of μSR

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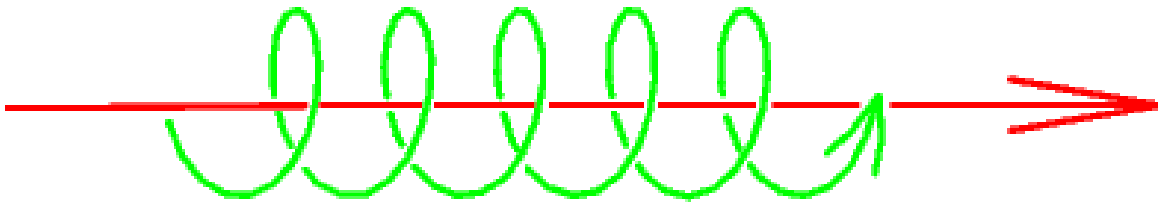
Suppose you sign up your home computer for the SETI search and the data they give you to analyze contains this message:

We of *Barnard's Star II* have been studying your Earth civilization for decades and have now deciphered your language, units of measurement and cultural conventions by watching your TV broadcasts. We would like to begin trading with Earth, but we wish to negotiate exclusively through the first person to receive this message.

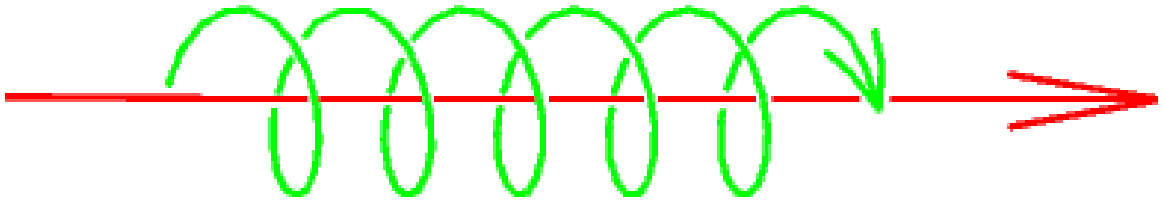
Our specialty is manufacturing metal fasteners (nuts and bolts) and we will send you a shipment to sell for us at 10% of standard Earth prices as soon as we receive your message explaining the difference between **right-handed** and **left-handed** threads.

What message would you send to land this entreprenuerial plum?



"left handed" = negative helicity

"right handed" = positive helicity



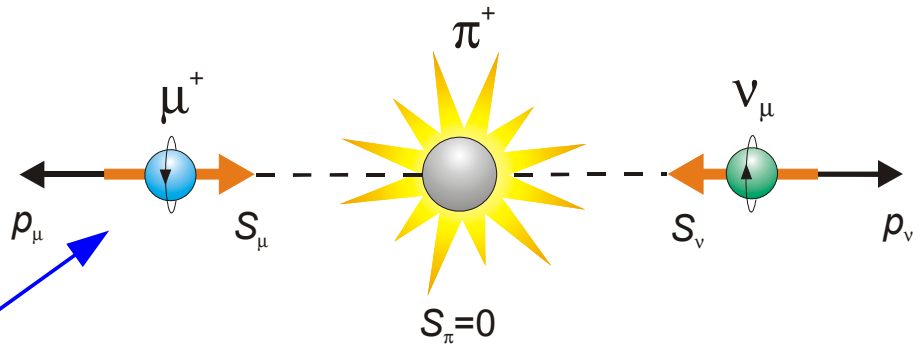
Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Some pions **stop** in the "skin" of the primary production target. They have zero linear momentum and zero angular momentum.

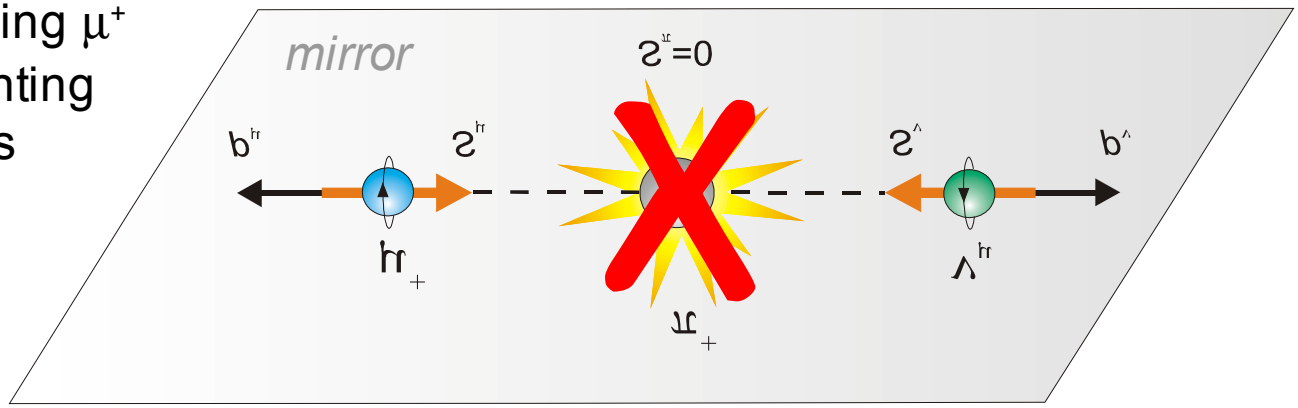
Conservation of Linear Momentum: The μ^+ is emitted with *momentum* equal & opposite to that of the ν_μ.

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

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



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



What's a **PION** ?

An unstable elementary particle
(mean lifetime $\tau_\pi \approx$ 26 ns)
made when protons hit nuclei.

"Nuclear glue" (Yukawa, 1937)

Mass intermediate between
electron and proton, hence
called a "meson".

No spin.

Three types: π^+, π^0, π^-

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

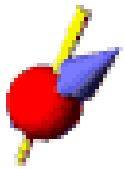
What's a **MUON** ?

A slightly more stable particle
(mean lifetime $\tau_\mu \approx$ 2.2 μs)

μ^- = "heavy electron"
($m_\mu \approx 207\ m_e$)

μ^+ = "light proton"
($m_\mu \approx m_p/9$)

Spin precesses in a magnetic field:



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

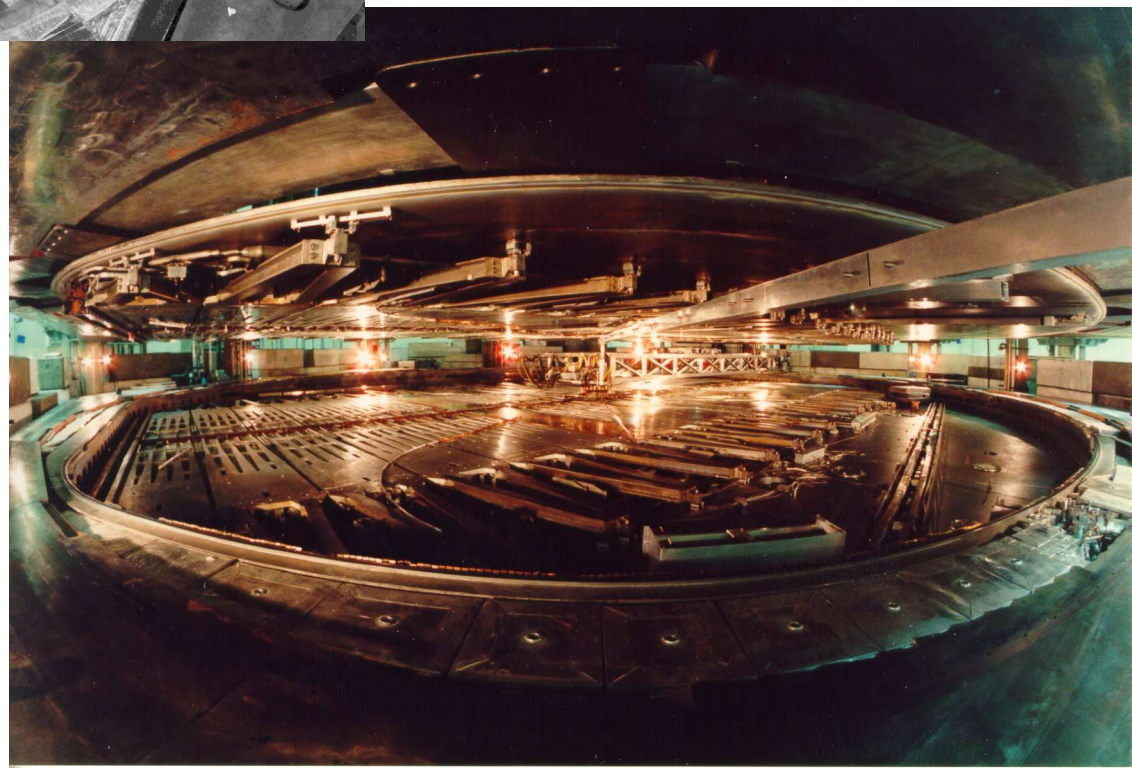
TRIUMF

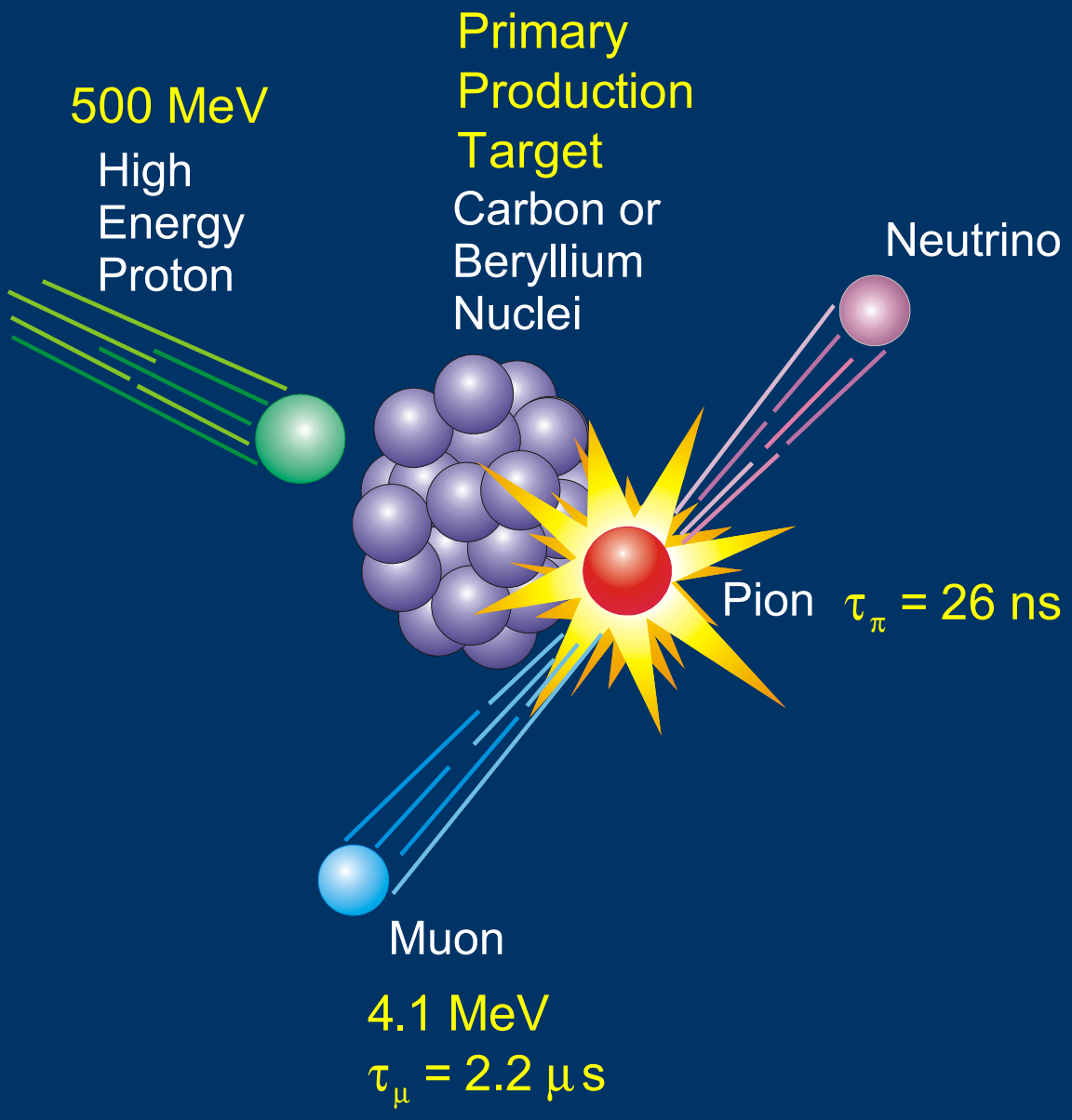
Lower half of
TRIUMF
cyclotron
magnet

1972

Inside
TRIUMF
cyclotron

today




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

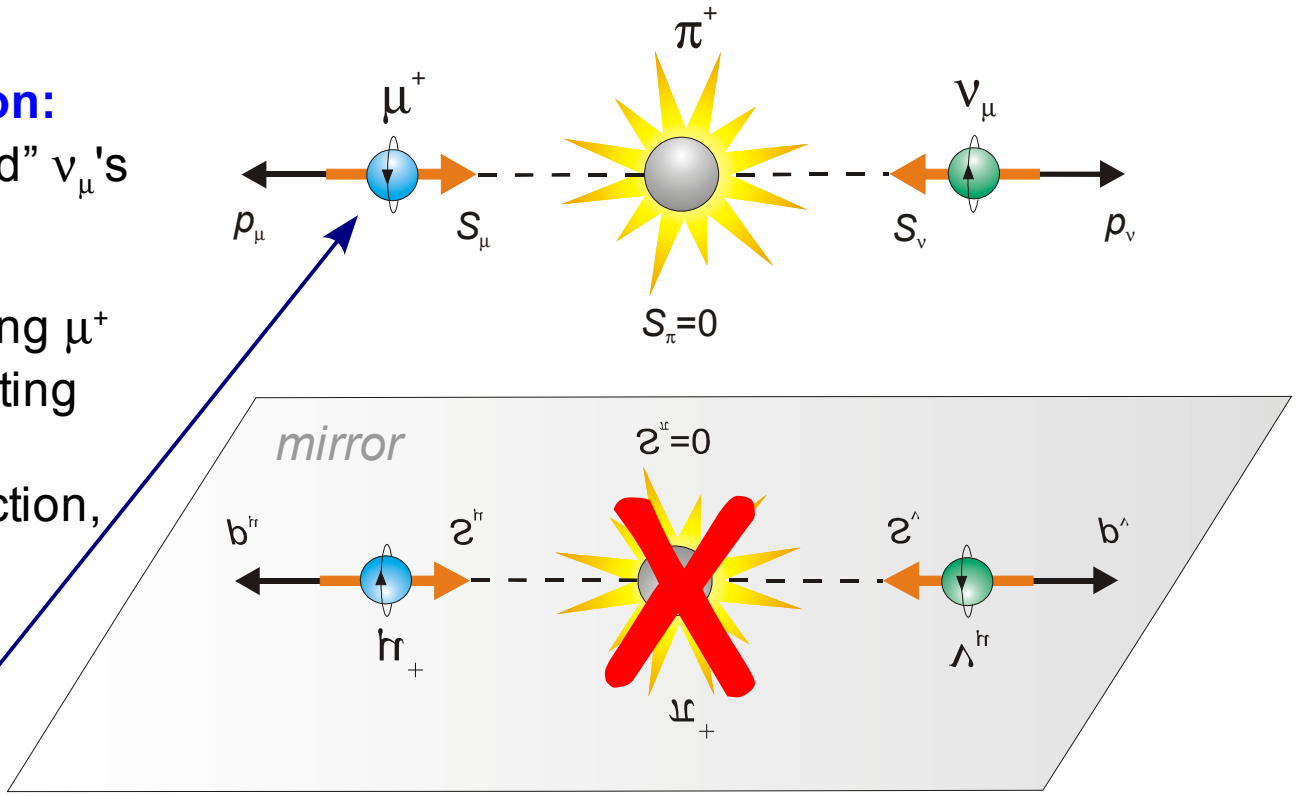
A pion **stops** in the "skin" of the primary production target.
It has zero linear momentum and zero angular momentum.

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

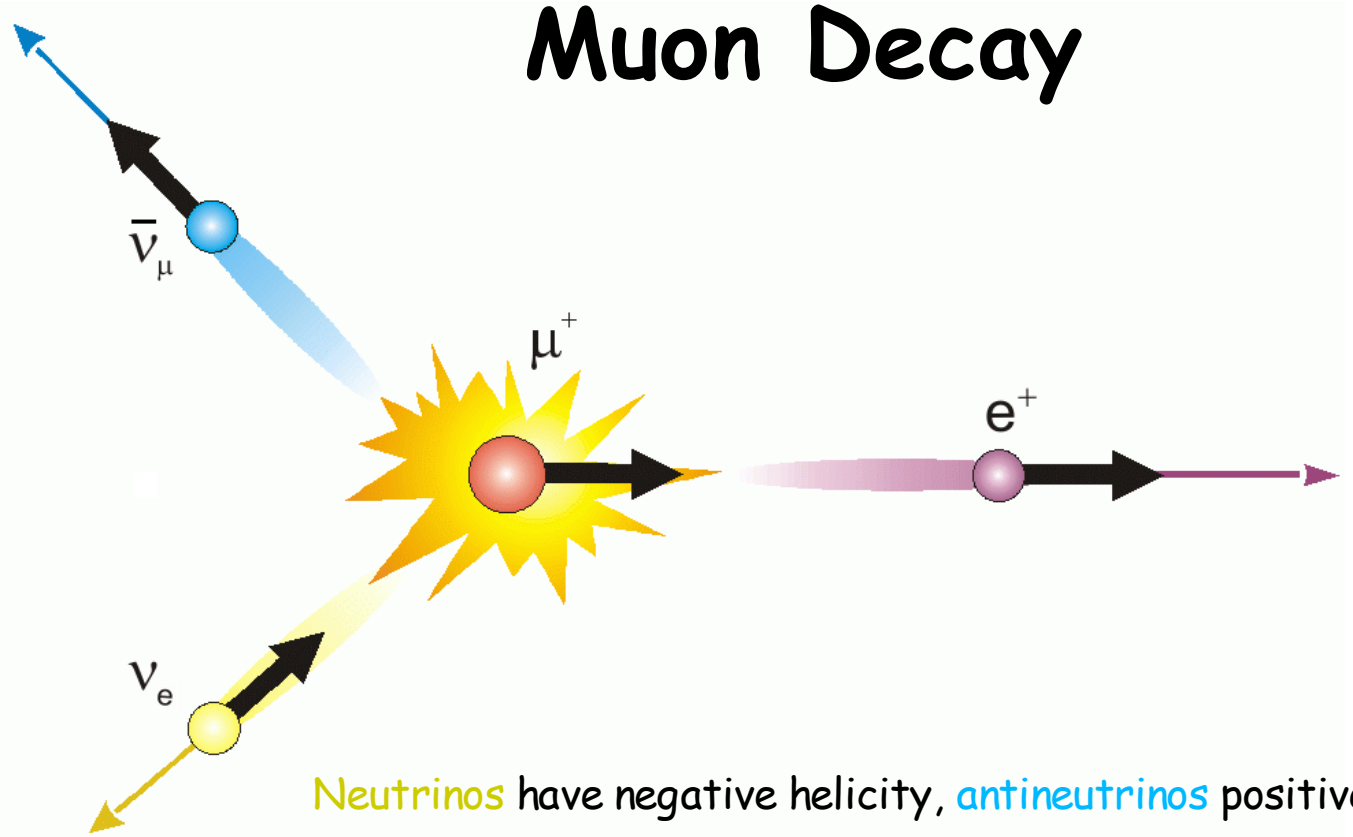
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite *spin*.

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

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

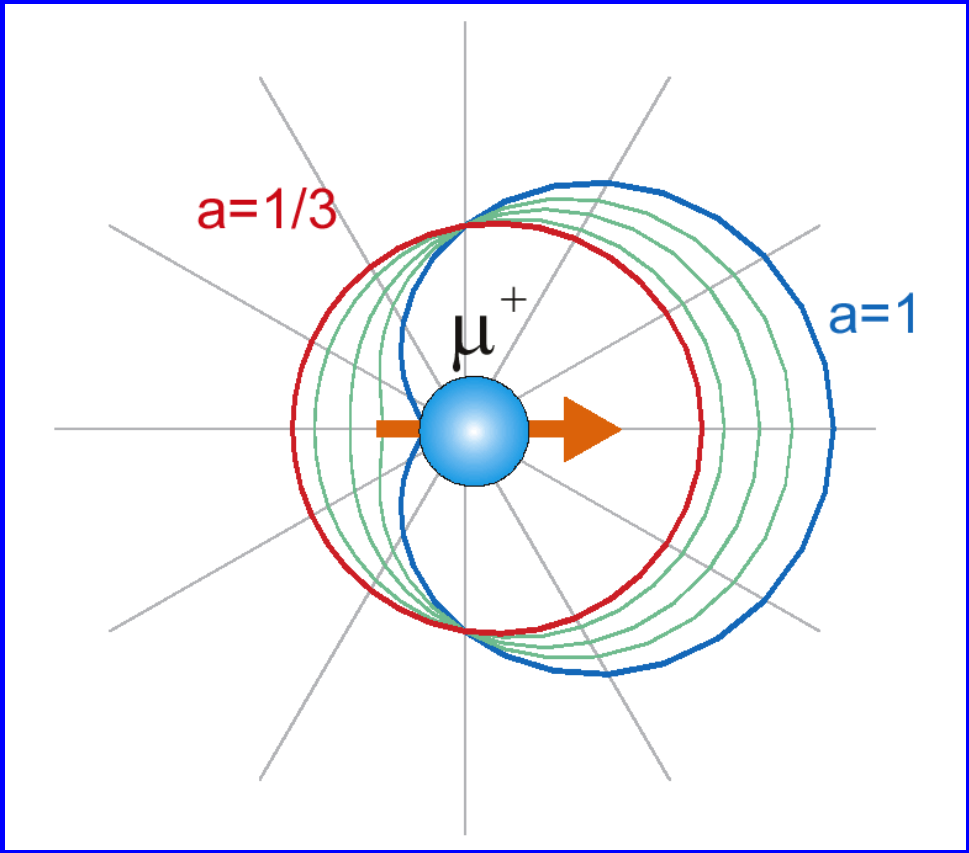


Muon Decay



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

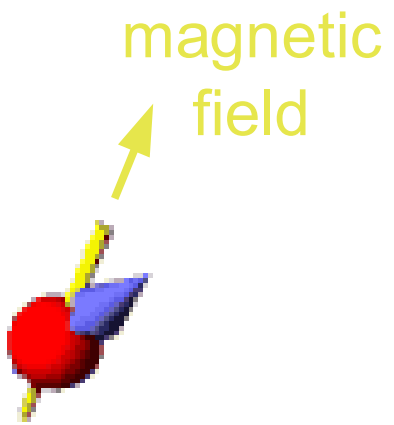


Angular distribution of positrons from μ^+-decay. The asymmetry is a = 1/3 when all positron energies are detected with equal probability.

What happens when you try to tip a top? Instead of tipping over the way you twist, it moves sideways! This is how you steer a bicycle, though you never think about it. If gravity keeps trying to tip over the top, it keeps slipping away sideways.

Many elementary particles (like protons, electrons & muons) have an intrinsic **spin** like a little top that never needs winding. When a **magnetic field** tries to tip them over, guess what we get!

This is called **precession**.



Spin Precession

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

μSR otation elaxation esonance

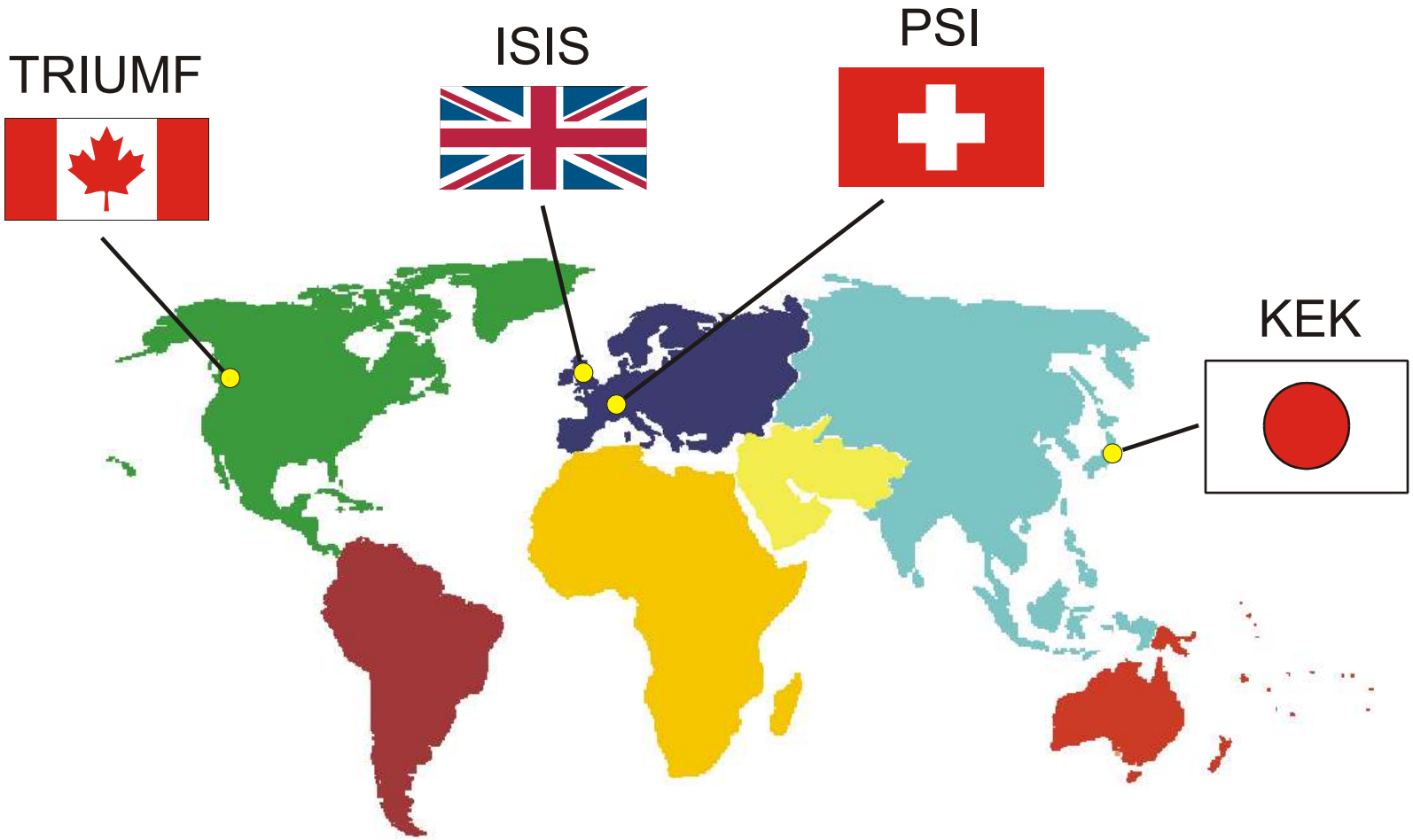
m s
u p
o i
n n

Applied*
Elementary
Particle
Physics

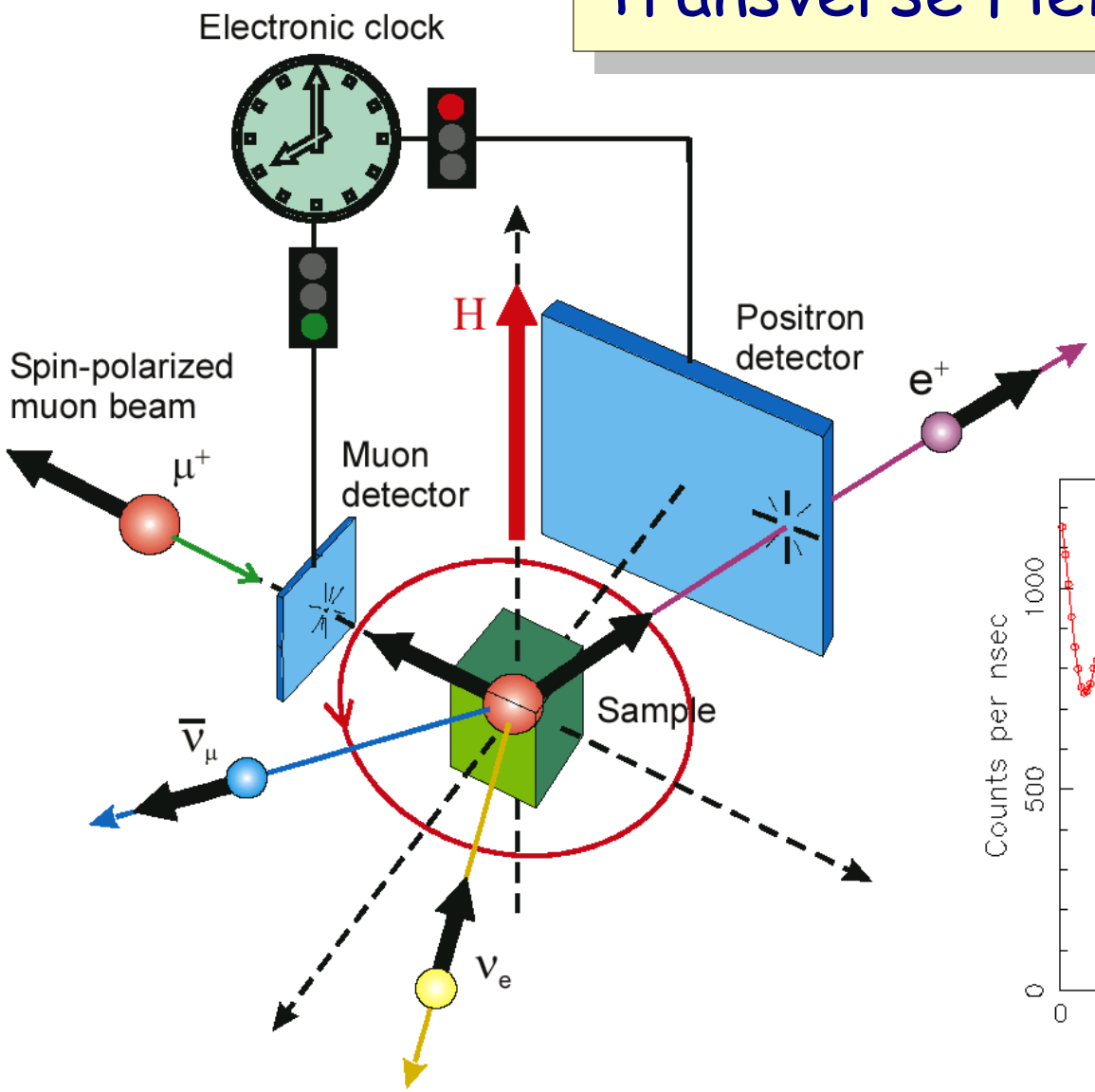
*(to basic research in Materials Science and Chemistry)

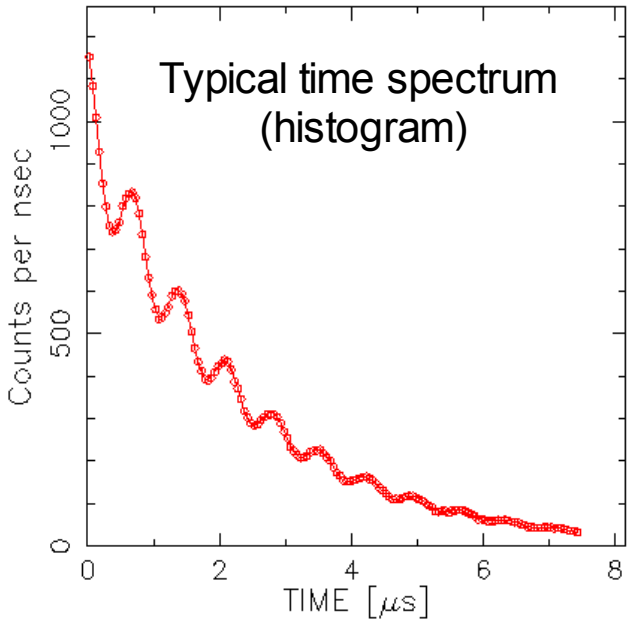
- The World's μSR Facilities
- Basic Techniques of μSR
- Applications of μSR

Where in the World is μSR?

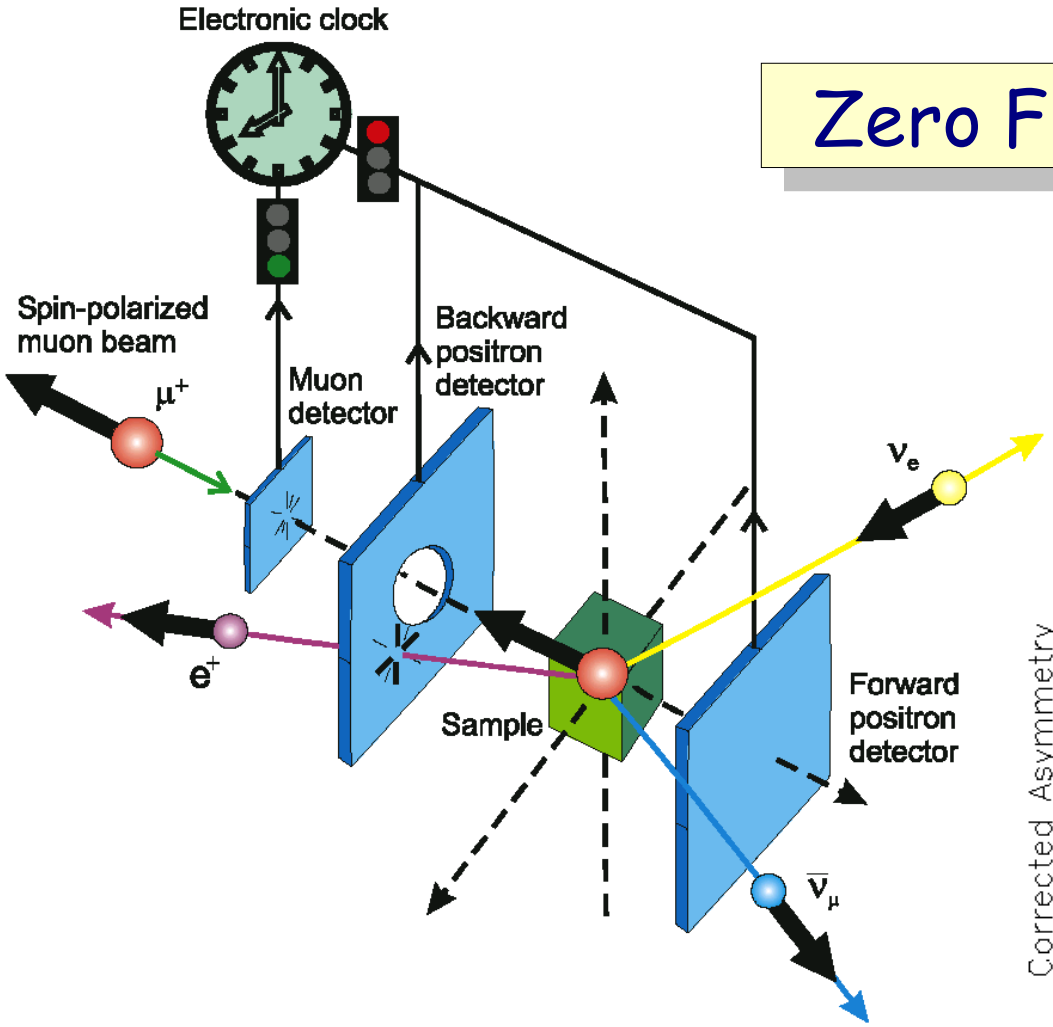


Transverse Field (TF)-μSR

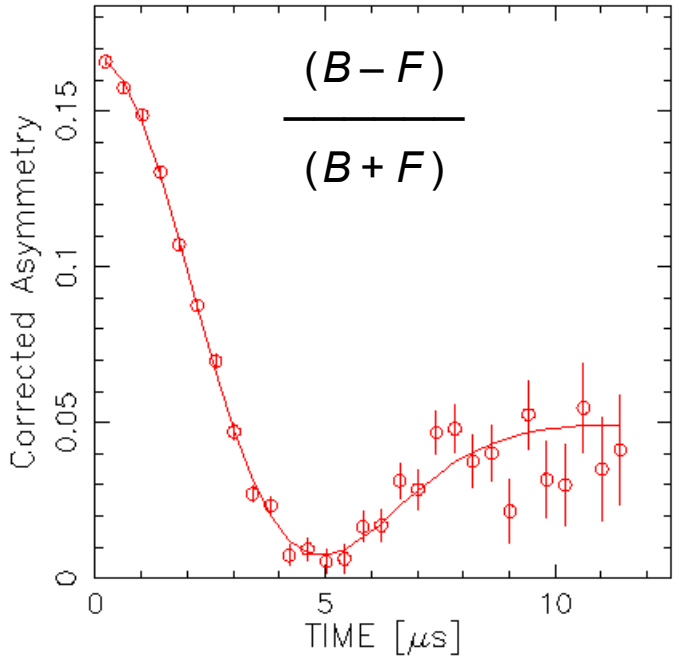




Zero Field (ZF)-μSR

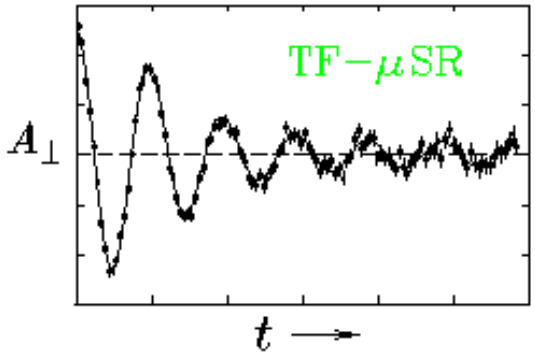


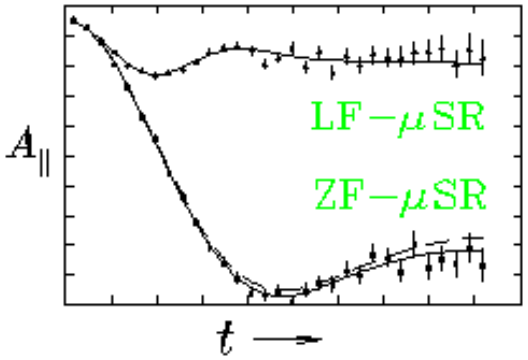
Typical asymmetry spectrum



Brewer's List of μSR Acronyms

Transverse Field

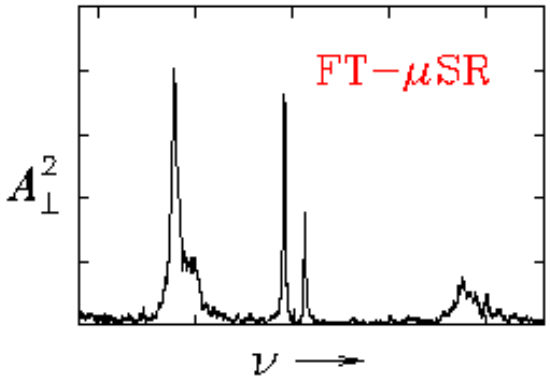


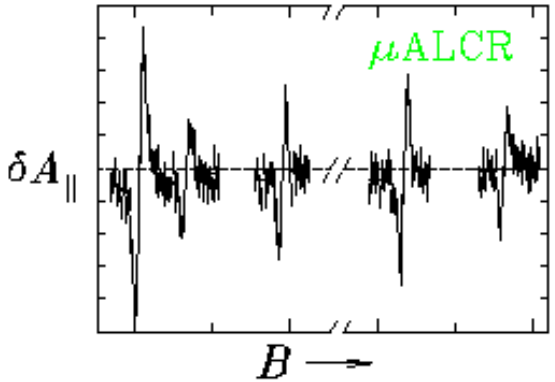


Longitudinal Field

Zero Field

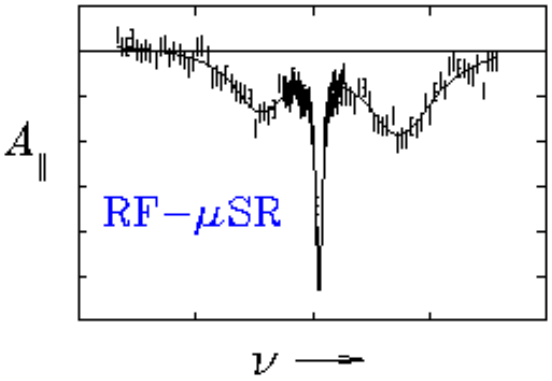
Fourier Transform μSR

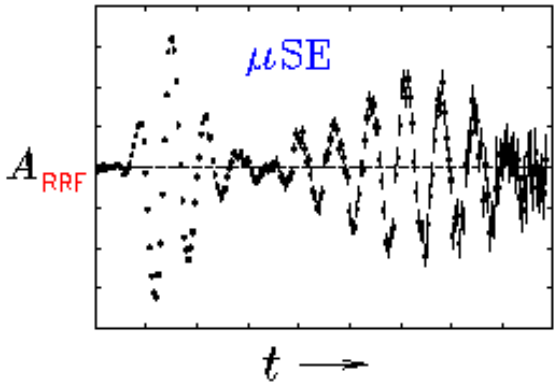




Avoided Level Crossing Resonance

Muon Spin Resonance





Muon Spin Echo

"Themes" in μSR

Muonium as light Hydrogen

(Mu = μ^+e^-) (H = p^+e^-)

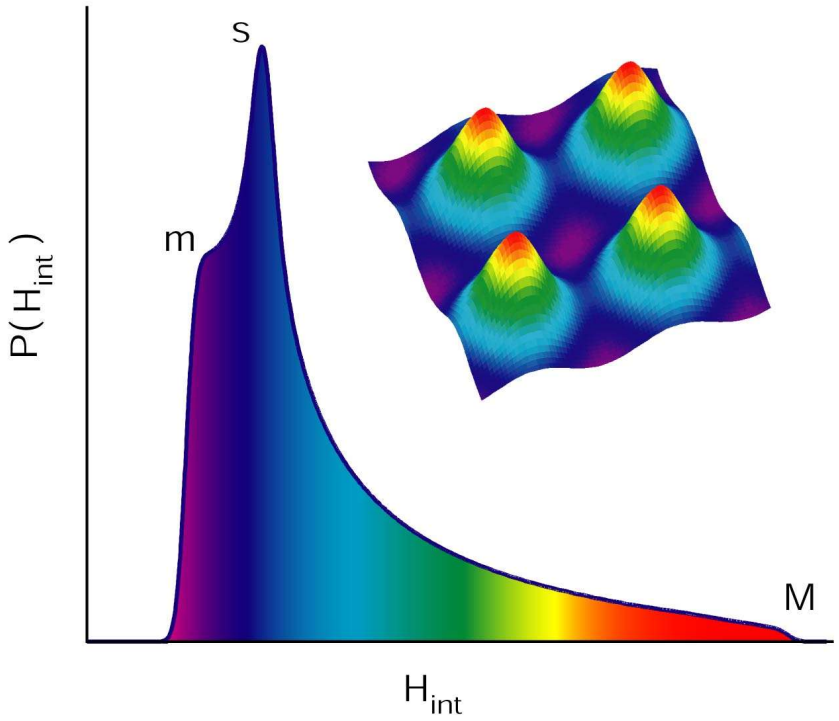
- **Mu vs. H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu vs. H in Semiconductors:**
  - Until recently, μ^+SR ⟶ **only** data on metastable H states in semiconductors!

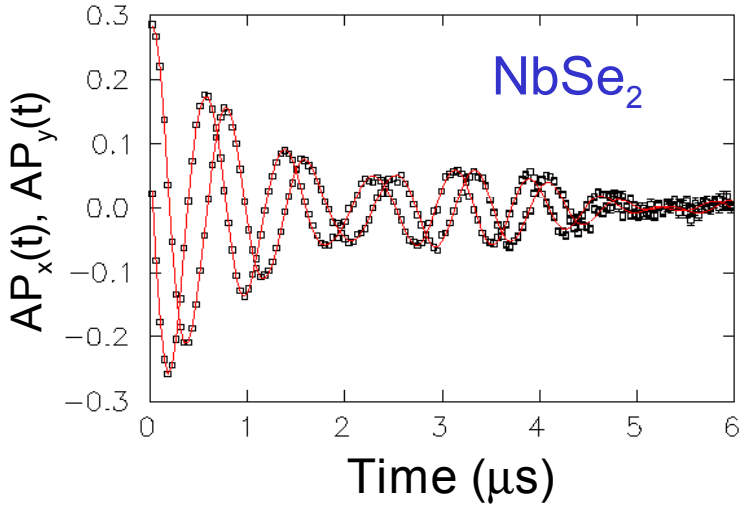
The Muon as a Probe

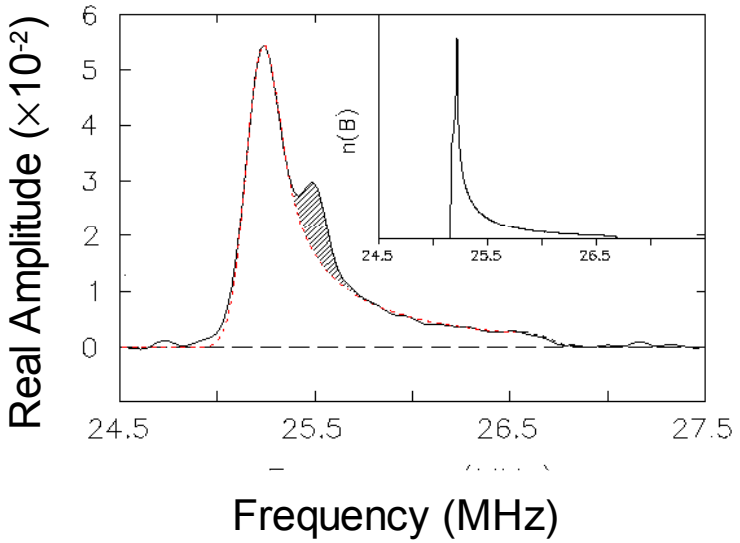
- **Probing Magnetism:** unequalled sensitivity
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. HT_cSC)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth λ
  - Coherence Length ξ

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

Magnetic Field Distribution of a Vortex Lattice







λ_{ab} in the Meissner & Vortex States