μSR: Fantasy, Fiction, Physics

The Story of

Muon Spin Rotation/Relaxation/Resonance

according to

Jess H. Brewer

Fantasy, Fiction, Physics ?

- **Fantasy**: violates the "known laws of physics"
- **Science Fiction**: possible in principle, but impractical with existing technology. (**Clarke's Law**: *"Any sufficiently advanced technology is indistinguishable from magic."*)
- **Routine Physics**: "We can do that . . ."
- **Applied Science**: The magic goes away . . .

Groups of People

- **Discoverers** of *P*-violation, who turned Fantasy to Fiction
- **Obsessors** who created μSR to test QED
- **Developers** who turn Fiction into Physics
- **Promoters** who support and encourage Developers & Users
- **Users** who apply the Developers' tools to continue the story
- **Students** who do all the hard work for the Users

Cast of Characters

in approximate order of appearance

Fantasy Era

Yukawa; Anderson; Rasetti

Science Fiction Era

Theory: Lee & Yang
Exp't: Wu; Friedman & Telegdi;
Garwin, *Lederman* & Weinrich

Frontier Era

USSR: Firsov; Nosov & Yakovleva
Ivanter & Smilga; *Gurevich*
QED: Hughes; Telegdi; *Crowe*
$\mu^+e^- \to \mu^-e^+$: Bowen & Pifer

Golden Era

SIN→PSI: *Schenck*, Kündig, Patterson,
Fischer, Kalvius, Kiefl
LAMPF: Hughes, *Heffner*, MacLaughlin
TRIUMF: Warren, *Fleming*, *Brewer*, Crowe,
Walker, Vogt, *Uemura*, Williams
KEK/BOOM: Kubo, *Yamazaki*, *Nagamine*
RAL/ISIS: Stoneham, *Cox*

Modern Era at TRIUMF

Percival, Kreitzman, Kiefl, Luke, Sonier,
MacFarlane, Uemura, Storchak, Sugiyama,
*hundreds of **Users**, dozens of **PDFs** and **Students**, **Visitors**, . . .*

Before 1956: ***Fantasy***

- 1930s: **Mistaken Identity**

  Yukawa's "nuclear glue" mesons ≠ cosmic rays
  1937 Rabi: Nuclear Magnetic Resonance

- 1940s: "**Who Ordered That**?"

  1940 Phys. Rev. Analytical Subject Index: "mesotron"
  1944 Rasetti: 1st application of **muons** to **condensed matter physics**
  1946 Bloch: Nuclear Induction (modern NMR with FID *etc.*)
  1946 Various: "two-meson" π-μ hypothesis Brewer: born
  1947 Richardson: produced π & μ at Berkeley 184 in. Cyclotron
  1949 Kuhn: *"The Structure of Scientific Revolutions"*

- 1950s: "**Particle Paradise**"

  culminating in weird results with strange particles:
  1956 Cronin, Fitch, . . . : *"τ -θ puzzle"* (neutral kaons) → ***Revolution!***

THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 1 AND 2 JULY 1 AND 15, 1944

Deflection of Mesons in Magnetized Iron

F. RASETTI
Laval University, Quebec, Canada
(Received May 8, 1944)

The deflection of mesons in a magnetized ferromagnetic medium was investigated. A beam of mesons was made to pass through 9 cm of iron, and the resulting distribution of the beam was observed. Two arrangements were employed. In the first arrangement, the deflection due to the field caused a fraction of the mesons to hit a counter placed out of line with the others. An increase of sixty percent in the number of coincidences was recorded when the iron was magnetized. In the second arrangement, all the counters were arranged in line, and the deflection due to the field caused an eight percent decrease in the number of coincidences. These results are compared with theoretical predictions deduced from the known momentum spectrum of the mesons and from the geometry of the arrangement. The observed effects agree as well as can be expected with those calculated under the assumptions that the effective vector inside the ferromagnetic medium is the induction B, and that the number of low energy mesons is correctly given by the range-momentum relation.

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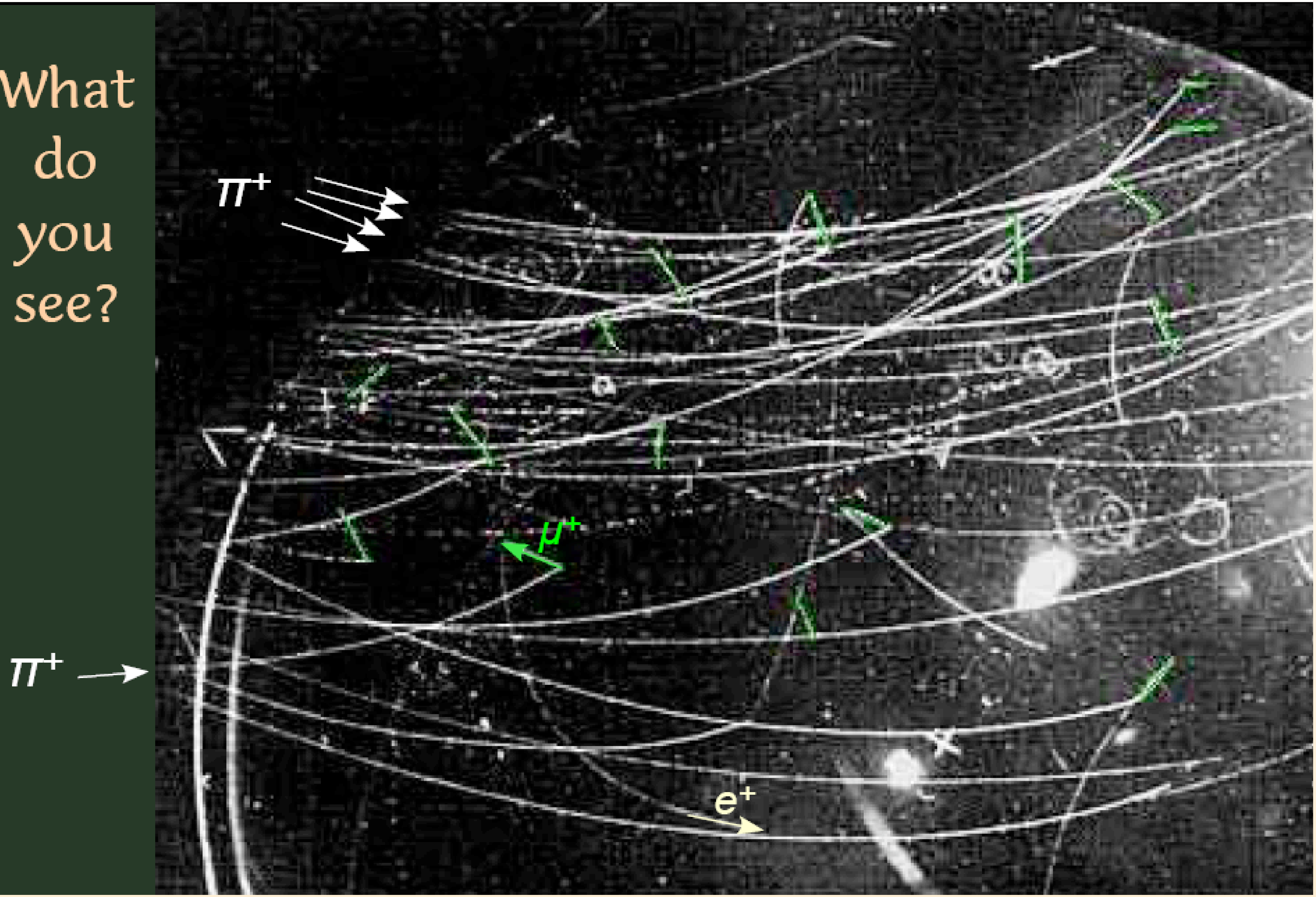
What do you see?



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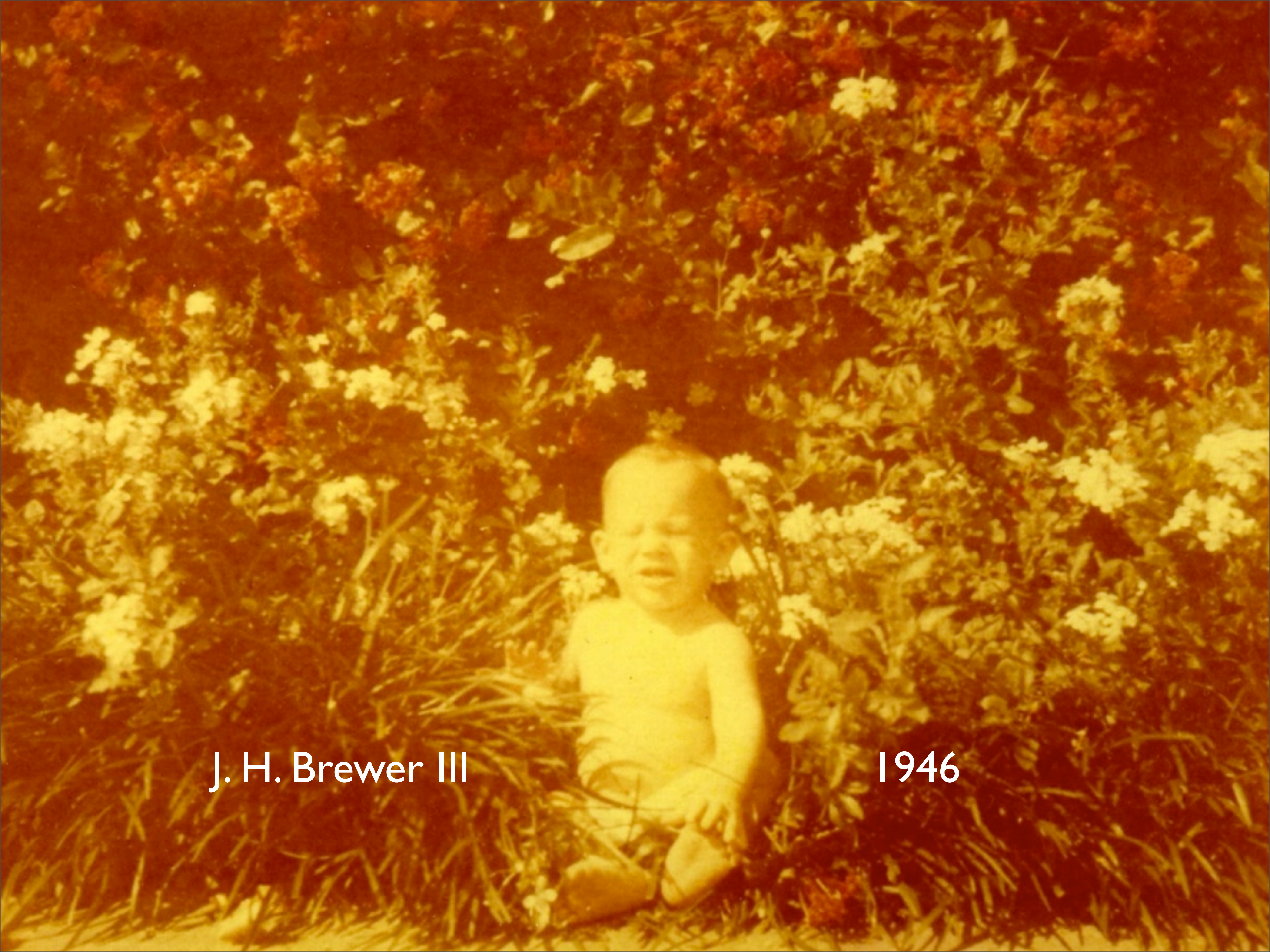

J. H. Brewer III
1946

1956-7: *Revolution*

- 1950s: "**Particle Paradise**"
  culminating in weird results with strange particles:
  1956 Cronin, Fitch, . . . : *"τ - θ puzzle"* (neutral kaons)
- 1956: Lee & Yang postulate
  ***P*-violation** in weak interactions
- 1957: Wu confirms *P*-violation in β decay;
  Friedman & Telegdi confirm *P*-violation in π-μ-*e* decay;
  so do Garwin, Lederman & Weinrich, using a prototype ***μSR*** technique.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

↓

Experimental Test of Parity Conservation in Beta Decay*

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON, *National Bureau of Standards, Washington, D. C.*
(Received January 15, 1957)

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

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ - \mu^+ - e^+$*†

JEROME I. FRIEDMAN AND V. L. TELEGDI

Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 17, 1957)

↓

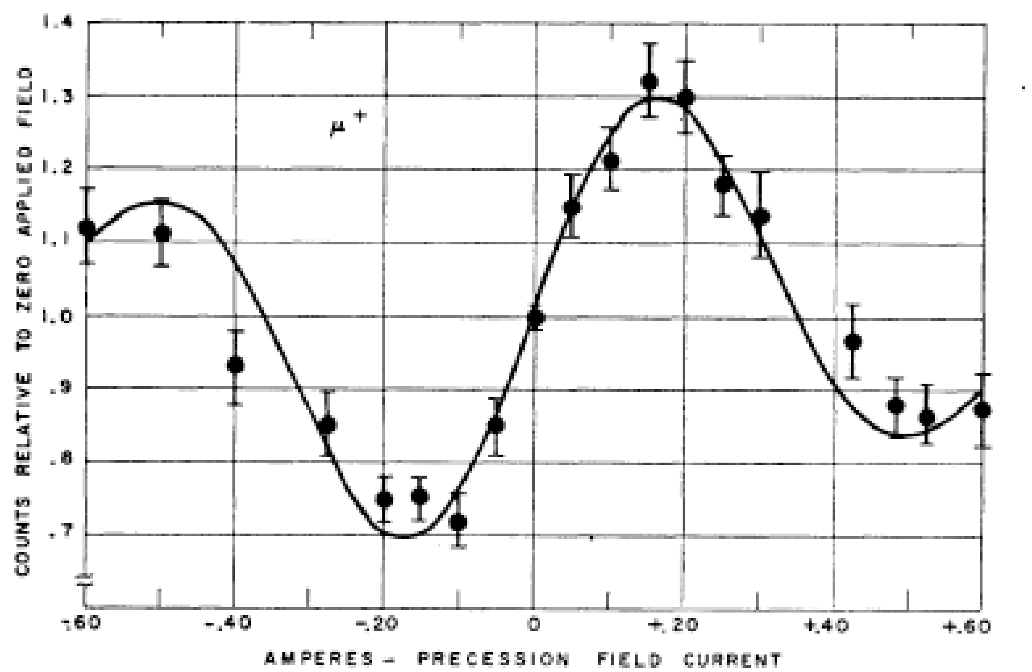


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

→

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.

So . . .

How does it work?

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.

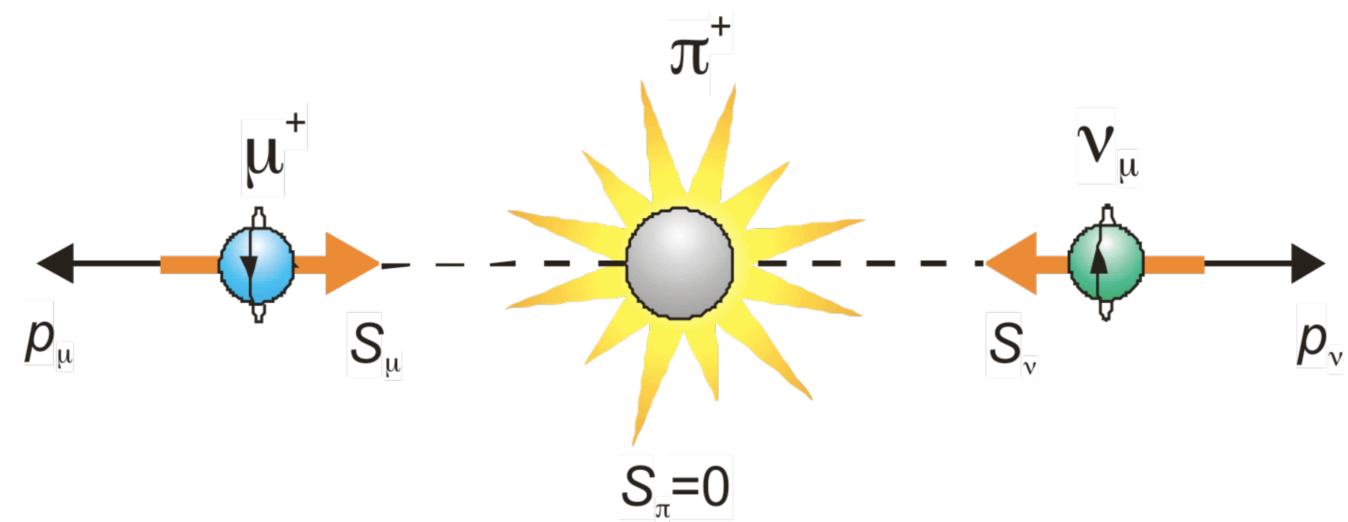
Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ.

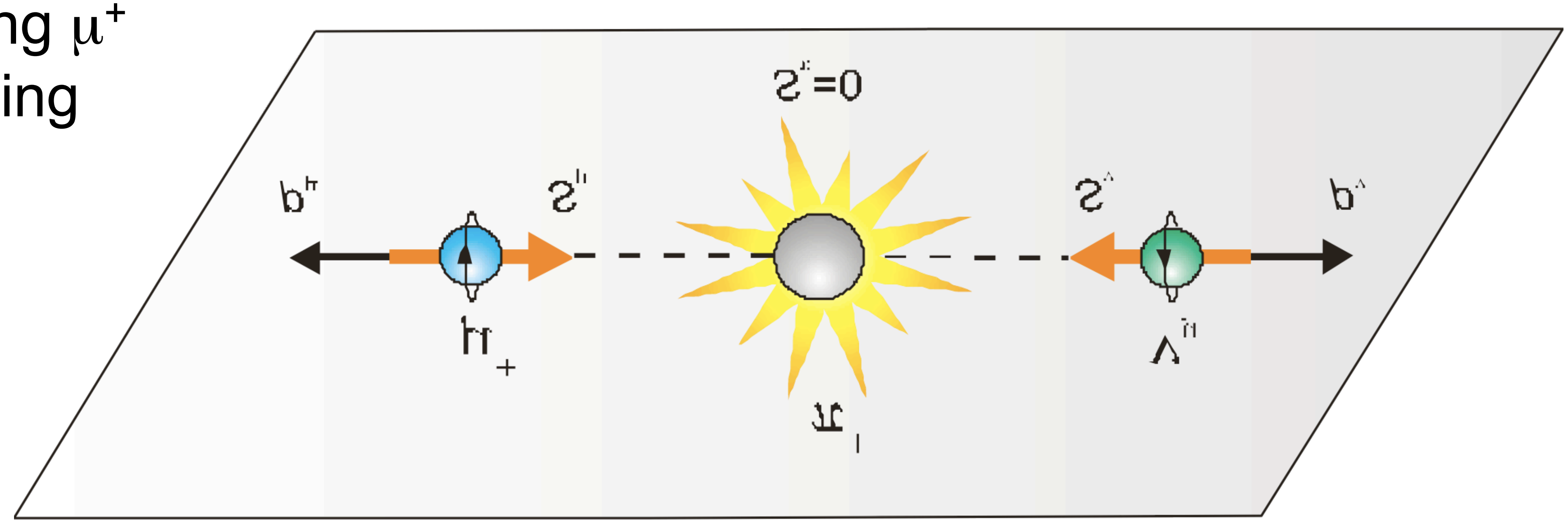
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite spin.

Weak Interaction:

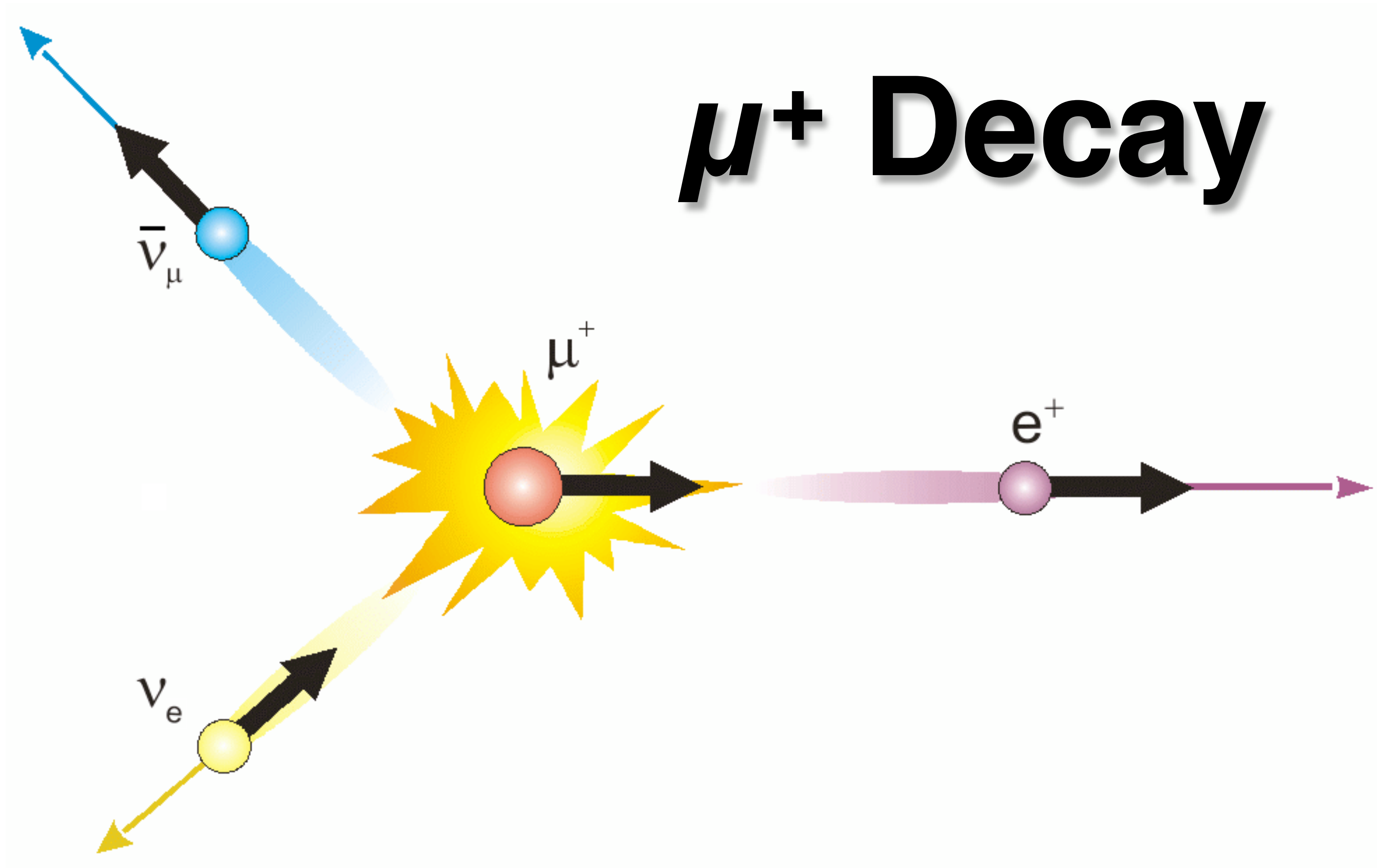
Only “left-handed” ν_μ are created.

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





μ^+ Decay

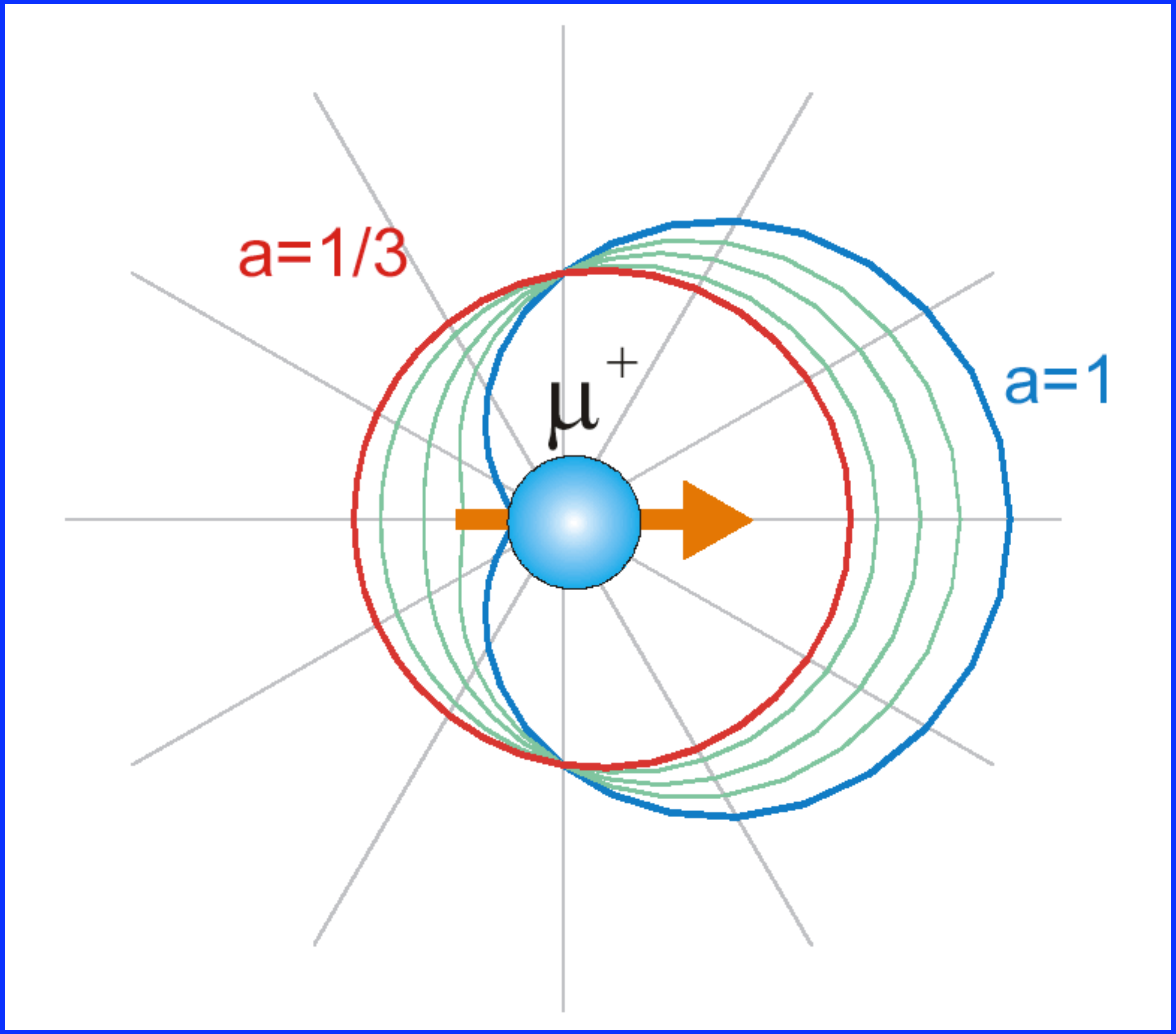


Neutrinos have negative helicity, antineutrinos positive.

An ultrarelativistic positron behaves like an antineutrino.

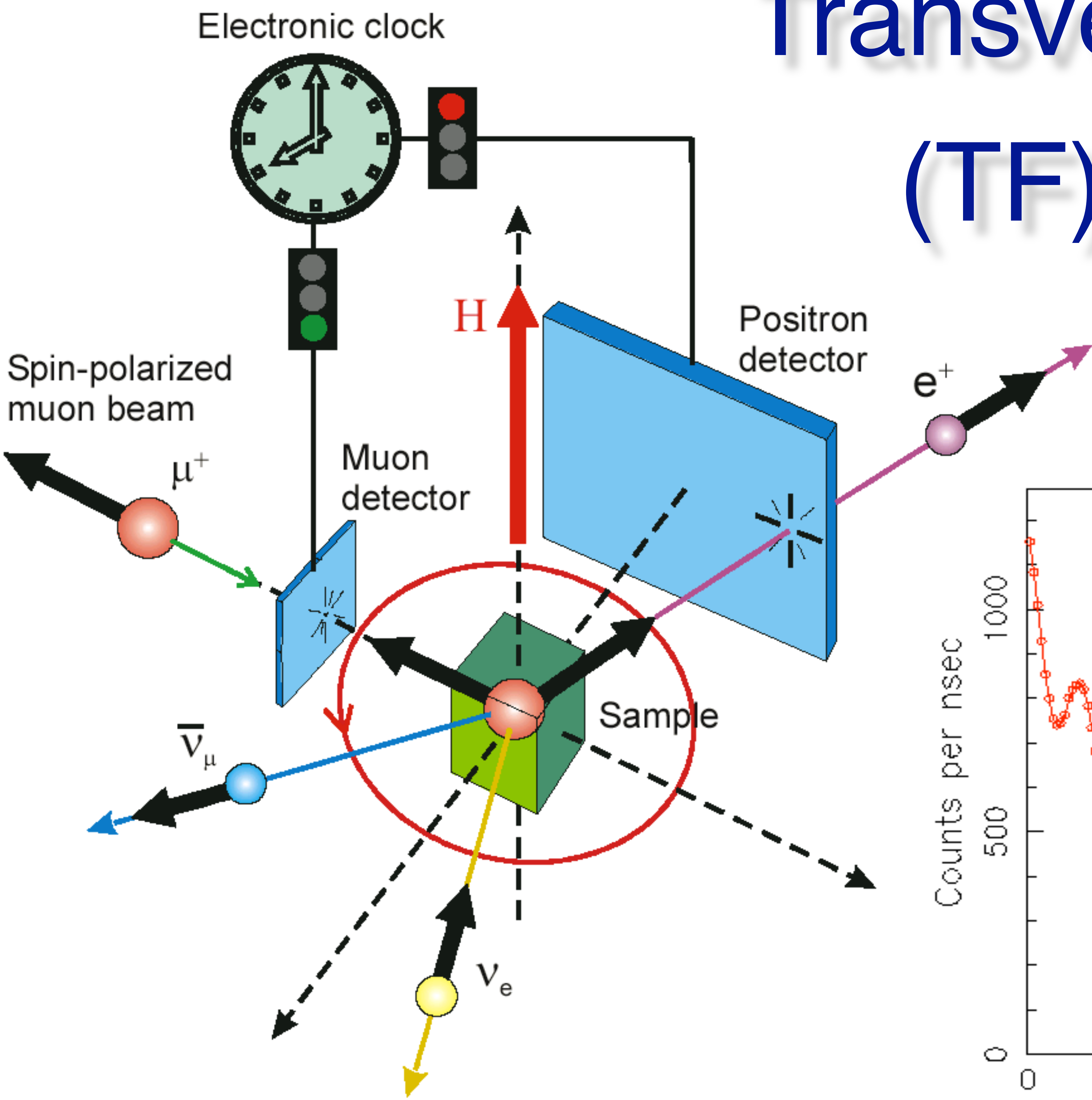
Thus the positron tends to be emitted along the μ^+ spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

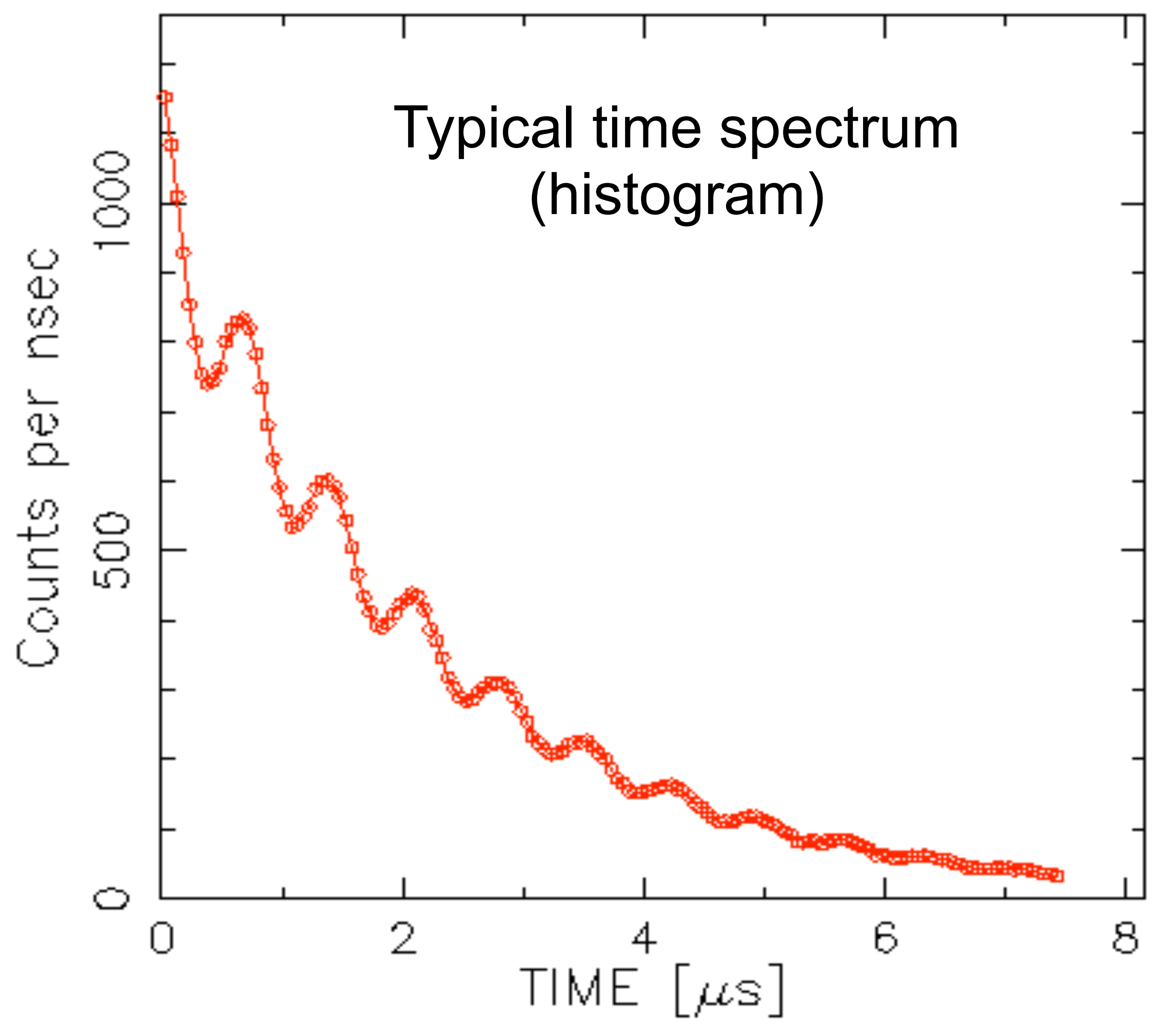
μ^+ Decay Asymmetry



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

Transverse Field (TF)-μ^+SR





1958-1973: *Science Fiction*

- 1960s: **Fundamental Physics Fun!** – *Tours de Force*

  Michel Parameters = Weak Interaction Laboratory
  Heroic **QED** tests: A_{HF}(Mu), μ_μ, $g_\mu - 2$
  All lead to *refined μSR techniques*.
  Applications: Muonium Chemistry, Semiconductors, Magnetism

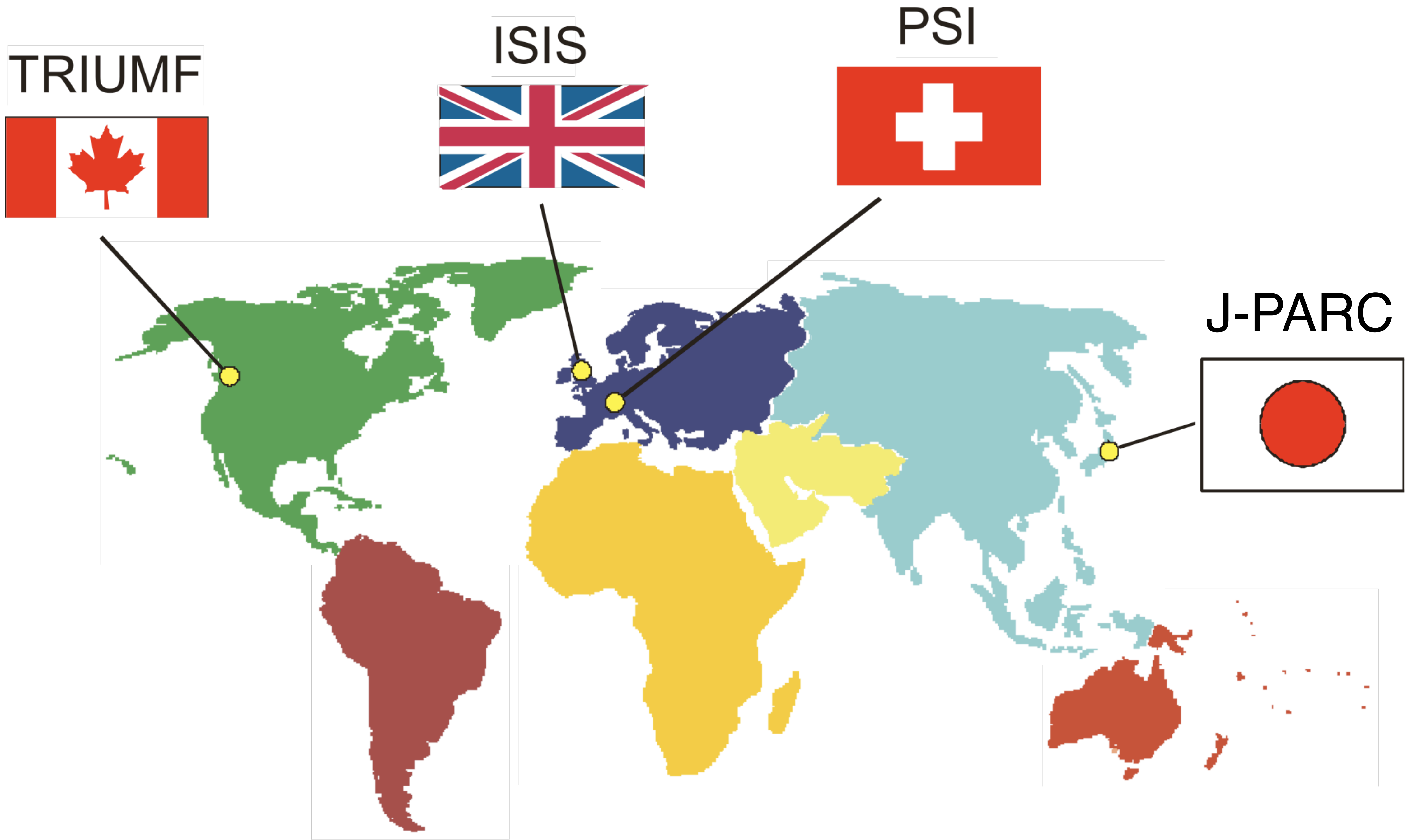
- 1967: **Brewer goes to Berkeley** – *to study Radicals*
  Rationale: a *science fiction author* needs credibility; what better credential than a Ph.D. in Physics? (But *μSR* was too much fun!)

- 1972: **Bowen & Pifer** build first Arizona/surface muon beam
  to search for for $\mu^+e^- \rightarrow \mu^-e^+$ conversion

- mid-1970s: **Meson Factories** – *Intensity Enables!*

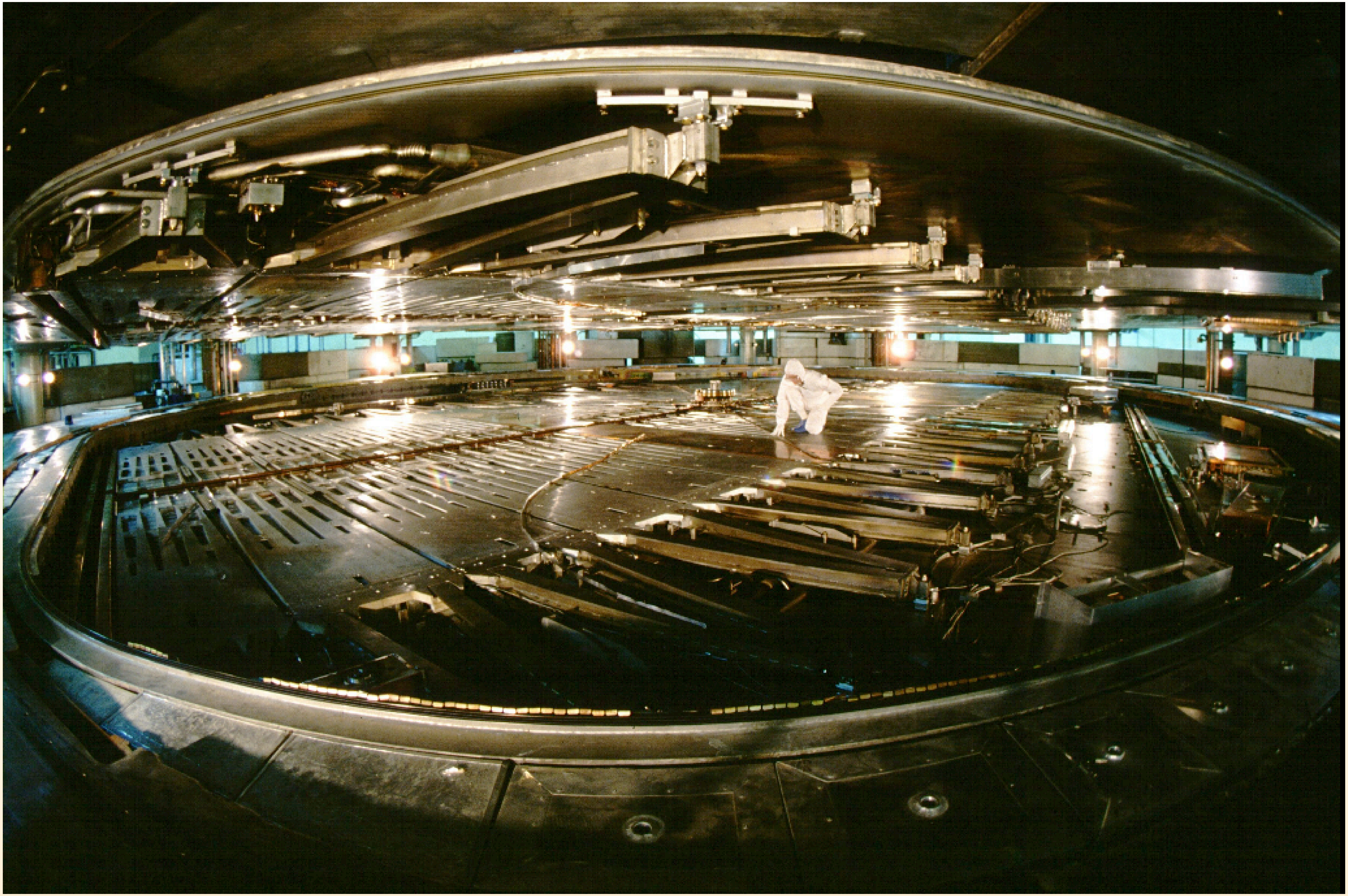
  USA: **LAMPF** (now defunct)
  Switzerland: **SIN** (now **PSI**)
  Canada: ***TRIUMF***
  UK: **RAL/ISIS**

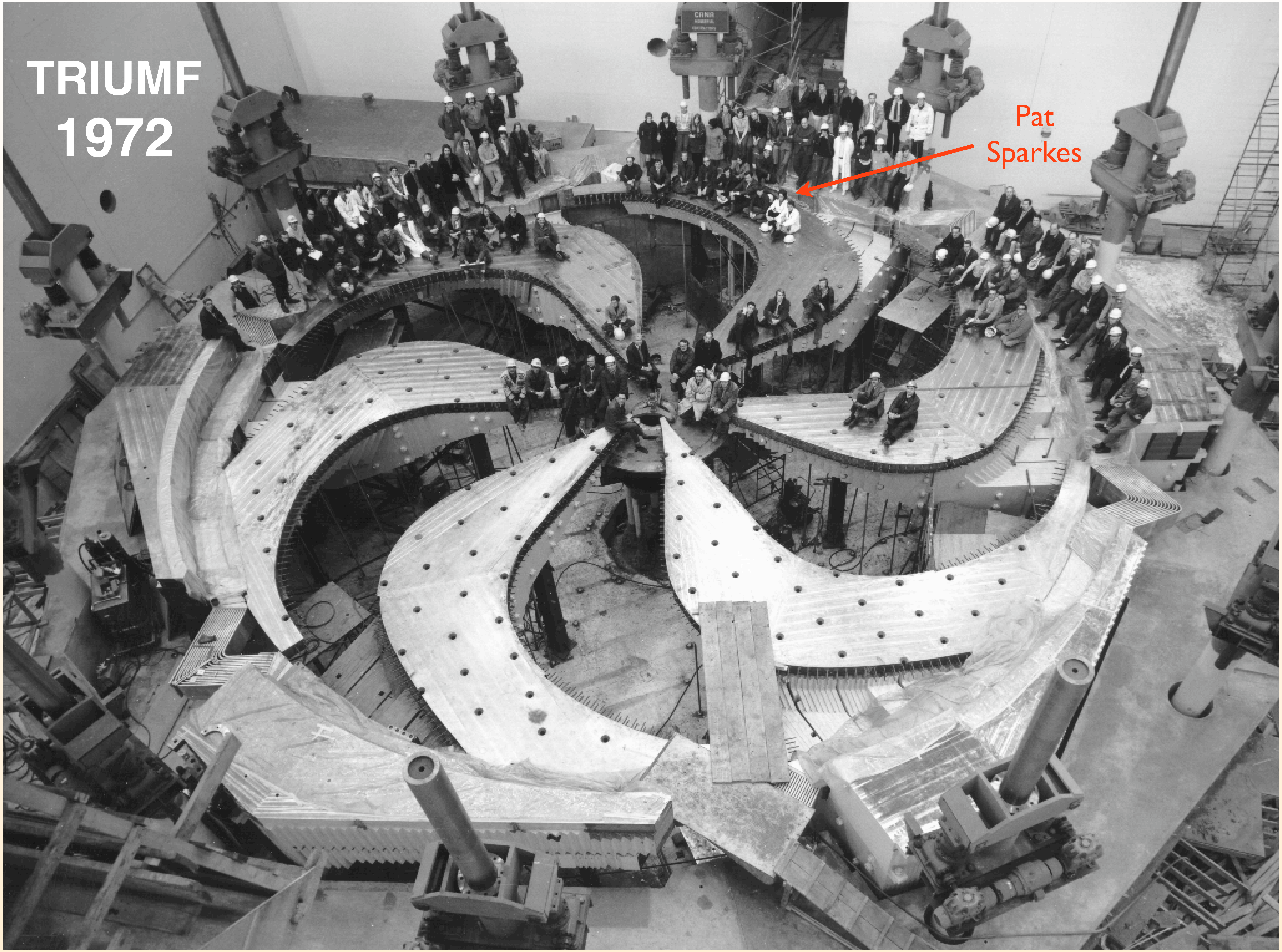
Where in the World is μSR?



TRIUMF

TRIUMF: World's Largest Cyclotron



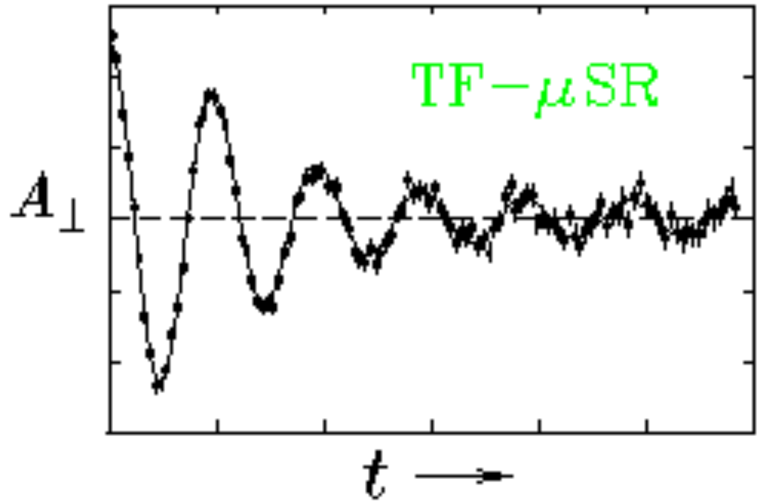

TRIUMF
1972
Pat
Sparkes

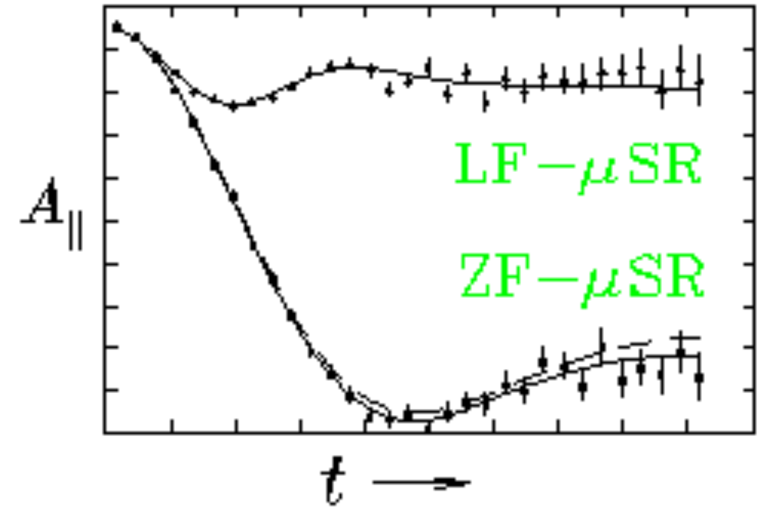
Back to **μSR** . . .

Brewer's List of μSR Acronyms

Transverse

Field





Longitudinal

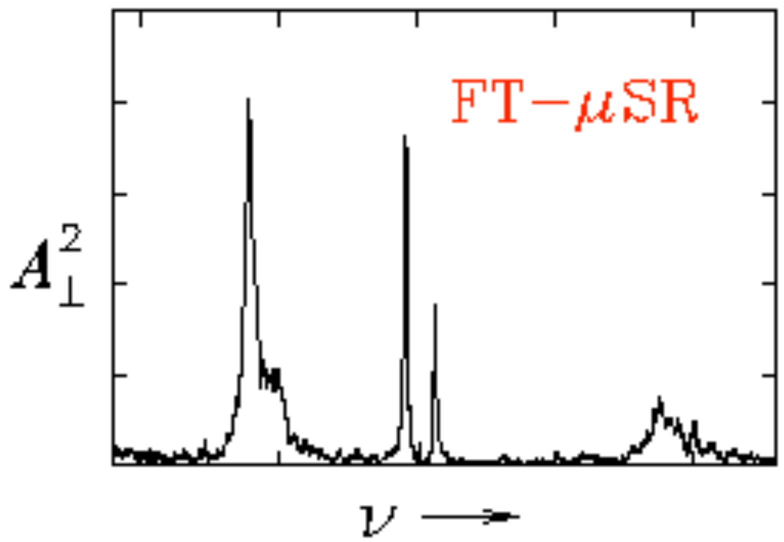
Field

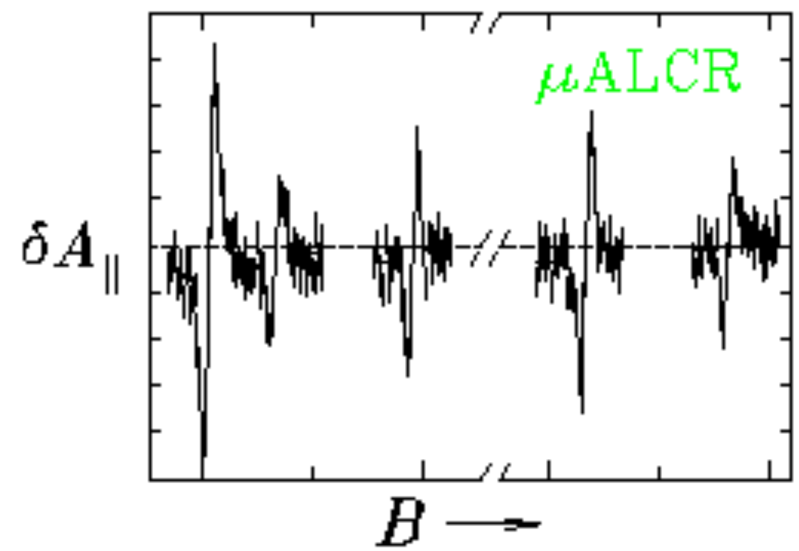
Zero Field

Fourier

Transform

μSR





Avoided

Level

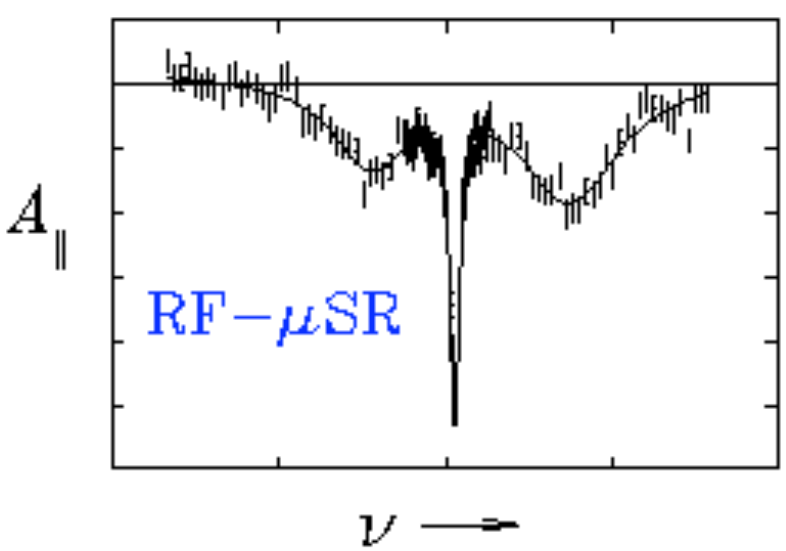
Crossing

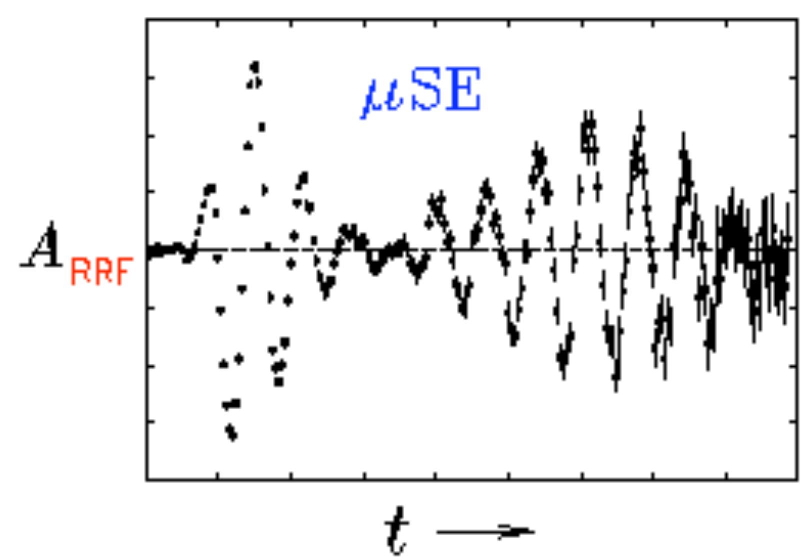
Resonance

Muon

Spin

Resonance





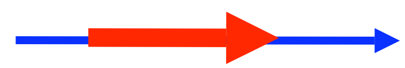
Muon

Spin

Echo

Motion of Muon Spins in Static Local Fields

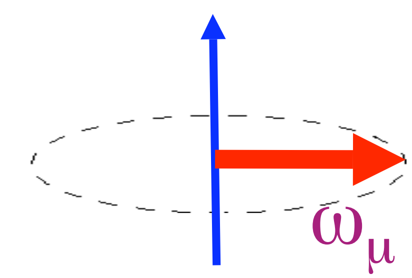
 = Expectation value of a muon's spin direction S_μ

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

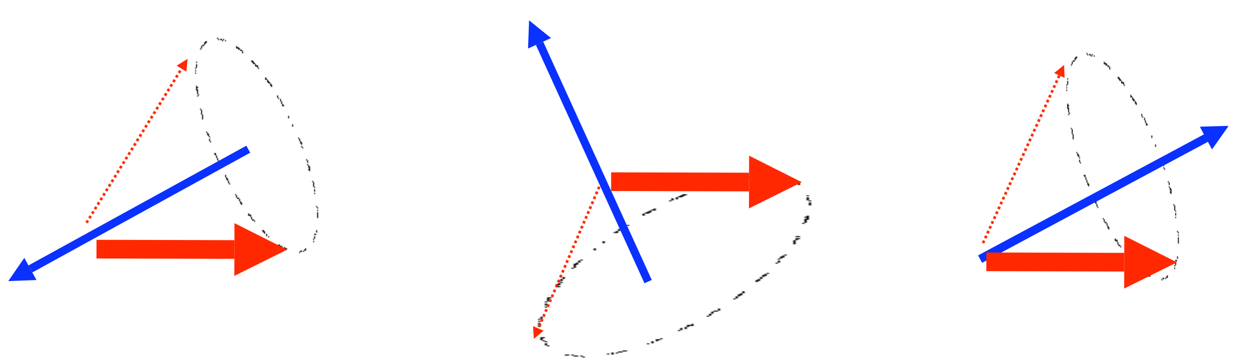
$\omega_\mu = 2\pi\, \gamma_\mu |\boldsymbol{B}|$

$\gamma_\mu = 135.5$ MHz/T

for $\boldsymbol{B} \perp \boldsymbol{S}_\mu$ Larmor precession:



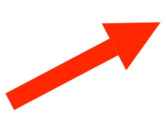
(b) All muons "see" same $|\boldsymbol{B}|$ but **random direction**:



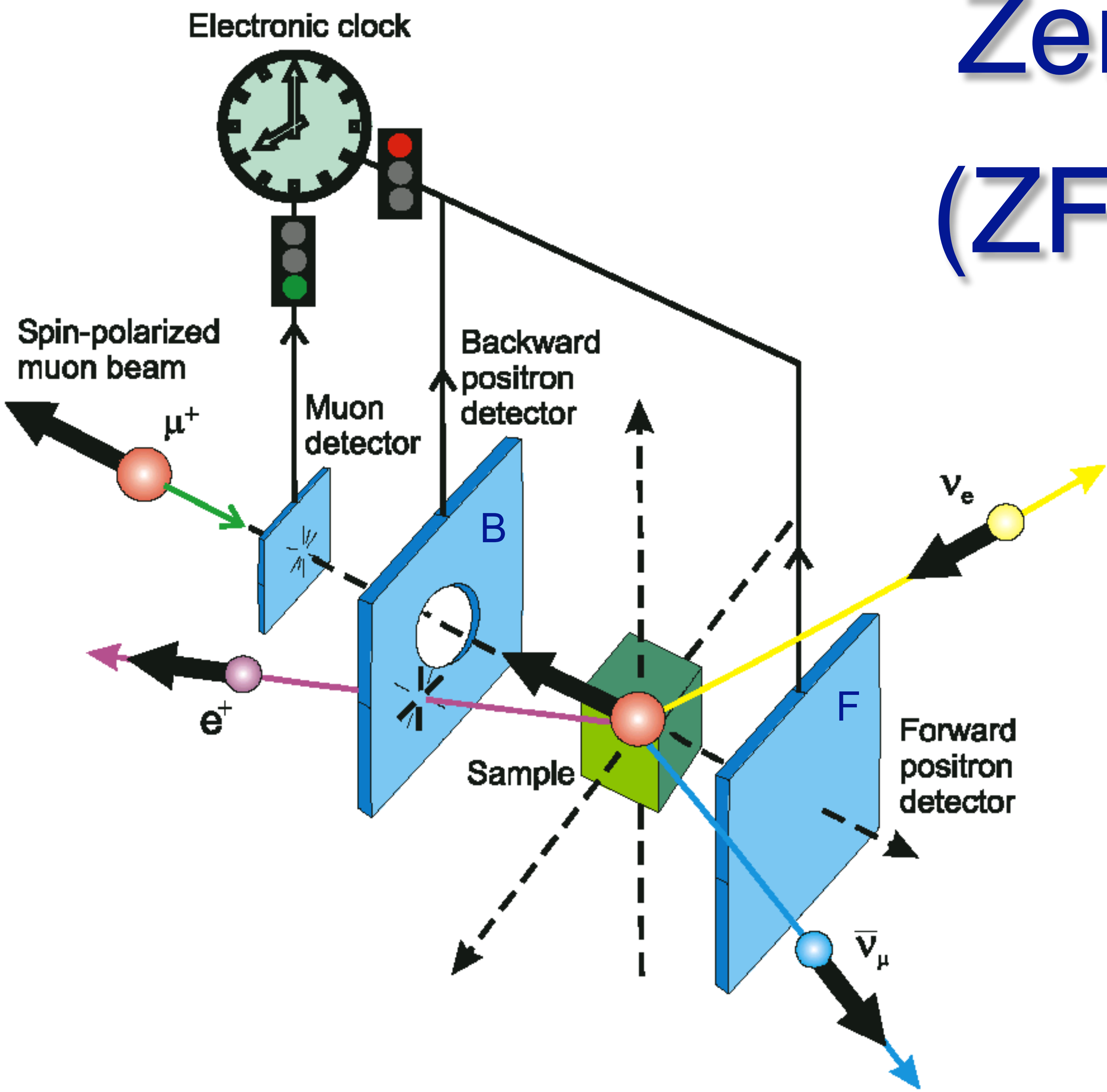
2/3 of $\boldsymbol{S}_\mu$ **precesses** at ω_μ

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

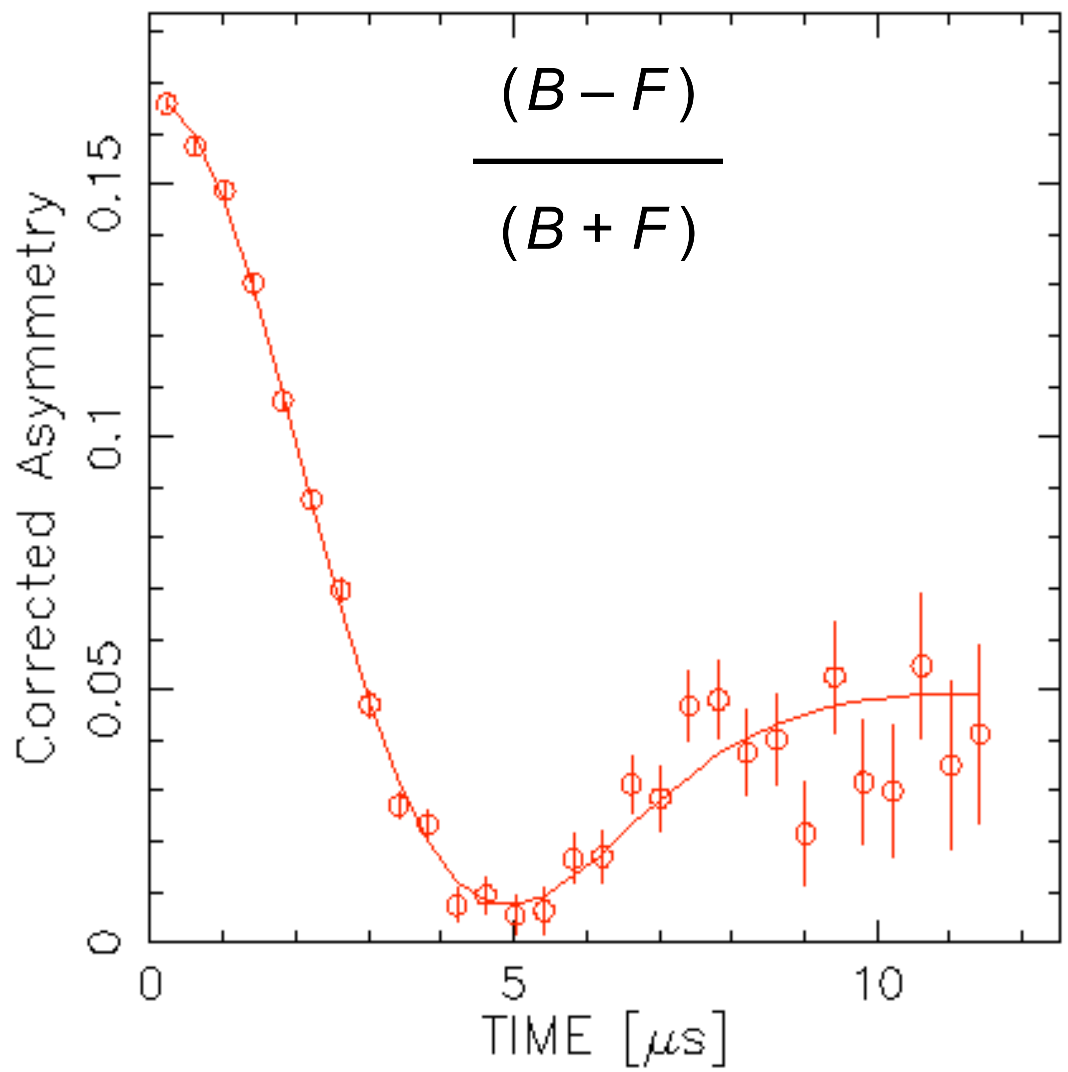
(c) Local field $\boldsymbol{B}$ **random** in **both** magnitude **and** direction:

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

Zero Field (ZF)-μ^+SR

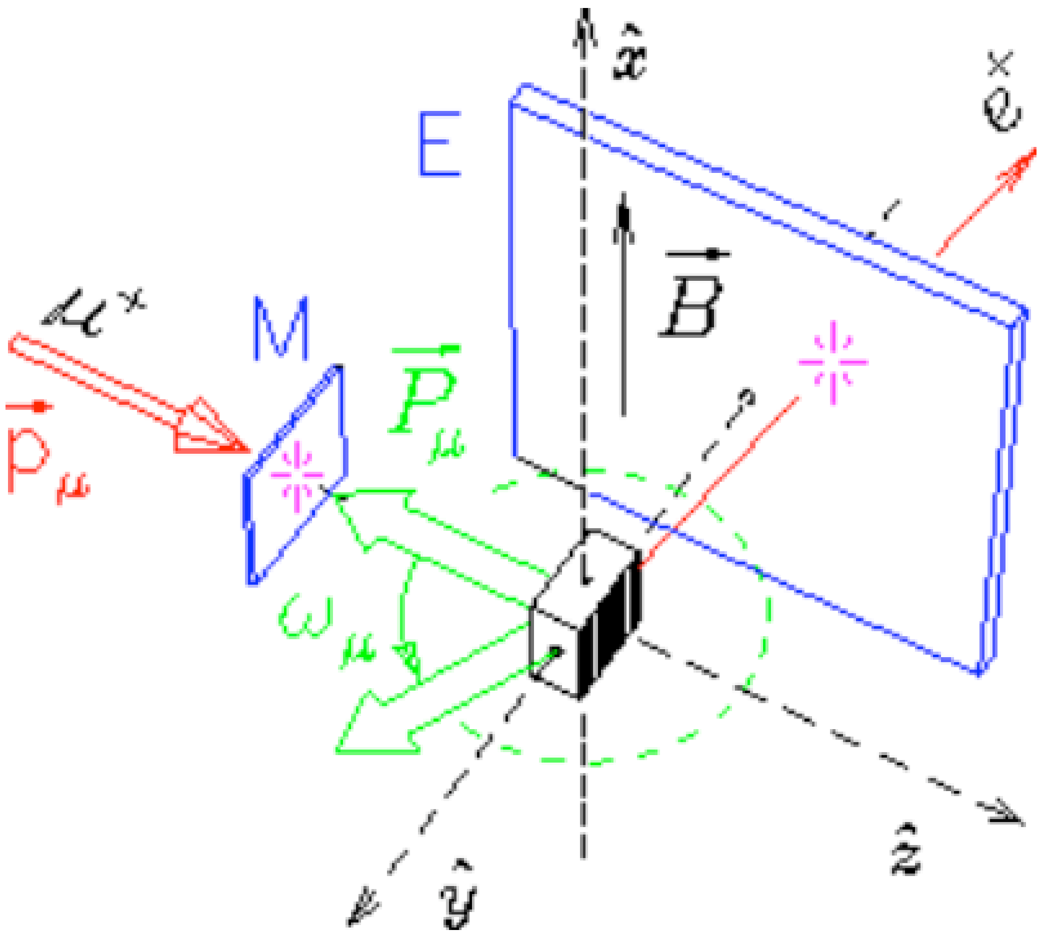


Typical asymmetry spectrum



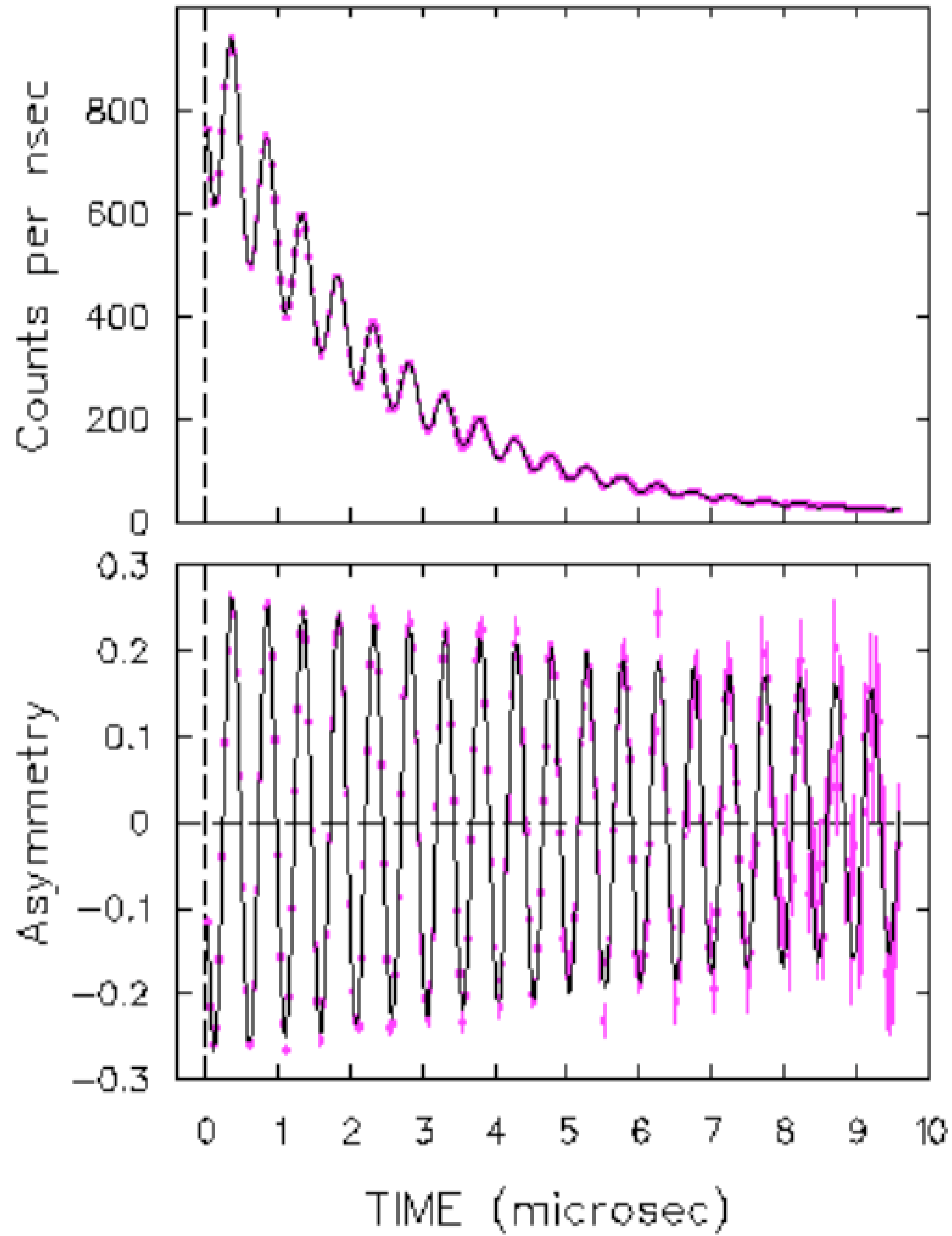
wTF-μ+SR:

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



$$A(t) = [N(t) - N_0 B]\, e^{+t/\tau_\mu} - 1$$

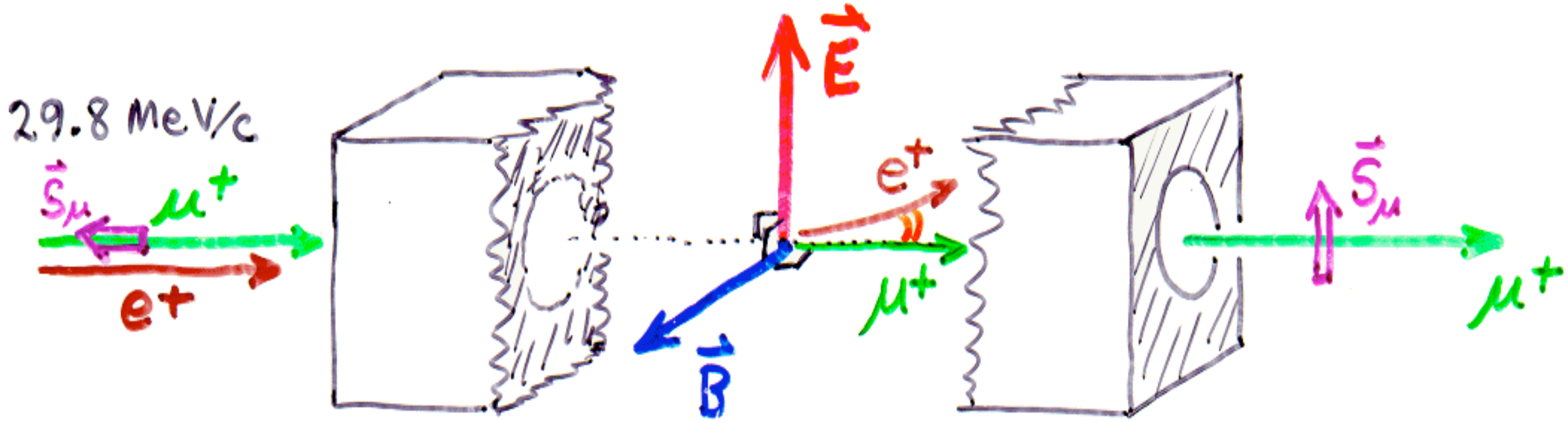
$$= A_0 G_{xx}(t) \cos(\omega_\mu t + \phi)$$

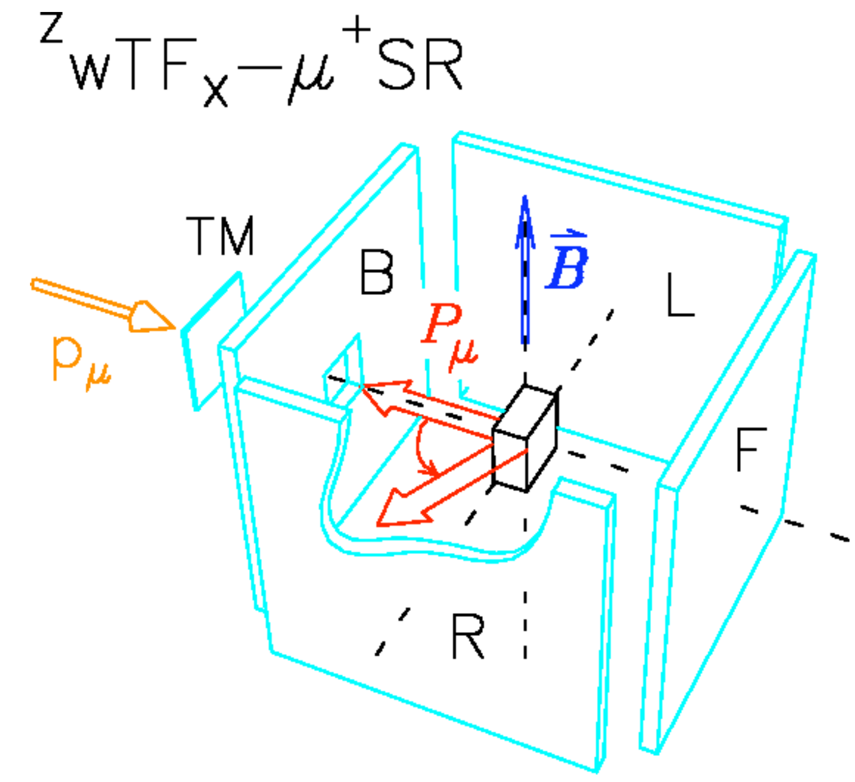


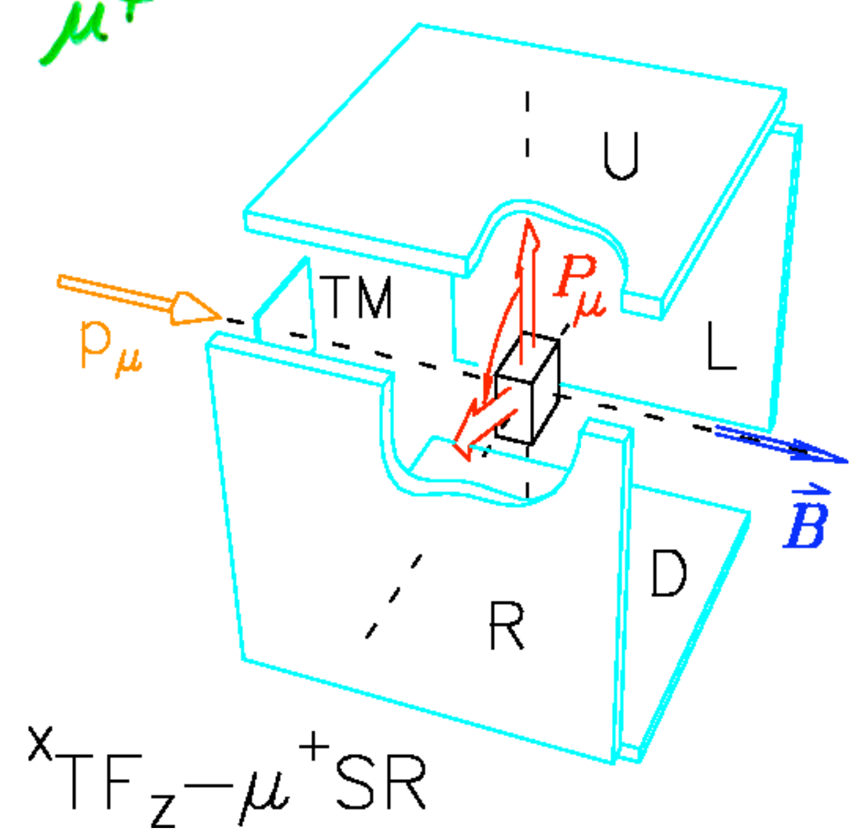
$E \times B$ velocity selector

("DC Separator" or Wien filter)

for **surface muons**:







- Removes beam positrons
- Allows TF-μ^+SR in high field (otherwise $\boldsymbol{B}$ deflects beam)

High Field μSR


Fields of up to 8 T are now available, requiring a "business end" of the spectrometer only 3 cm in diameter (so that 30-50 MeV decay positron orbits don't "curl up" and miss the detectors) and a time resolution of ~ 150 ps. Muonium precession frequencies of over 2 GHz have been studied.

"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).

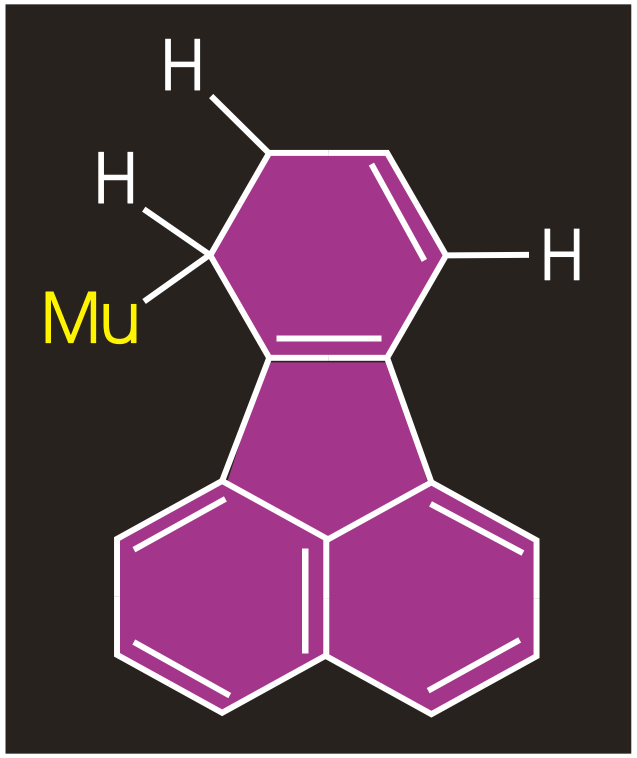
2000s: CMMS

The TRIUMF **C**entre for **M**olecular and **M**aterials **S**cience is an NSERC funded Facility at the TRIUMF National Laboratory, in Vancouver, Canada. It represents an expansion of the former TRIUMF *μSR* User Facility, with a mandate to facilitate research in chemistry and solid state physics using *μSR* and other accelerator-based techniques such as β-NMR.

Visit http://musr.ca for selected Research Highlights:

Chemistry Semiconductors Magnetism

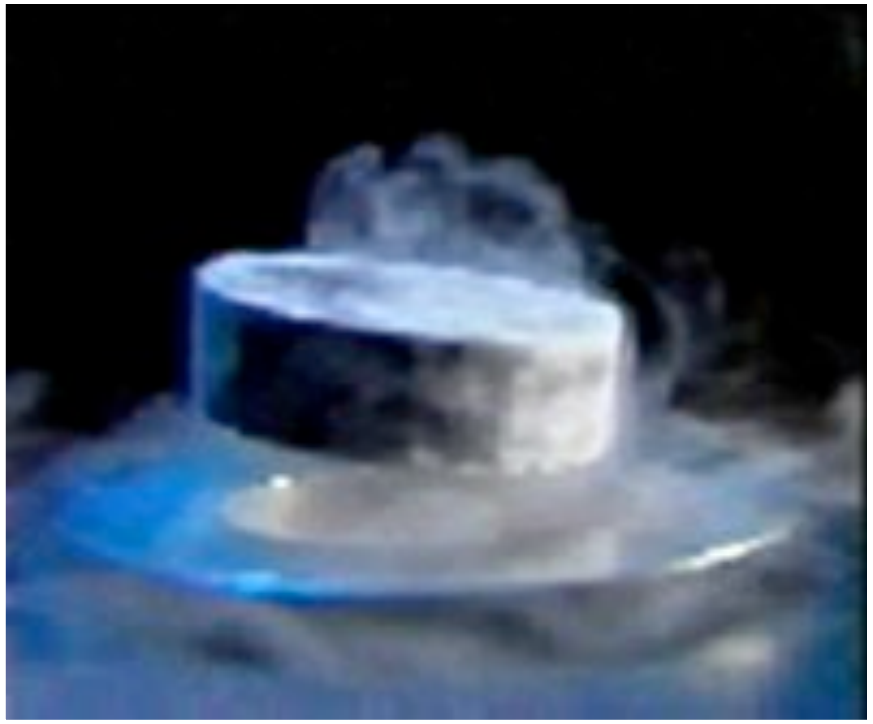
Superconductors Fundamental Physics



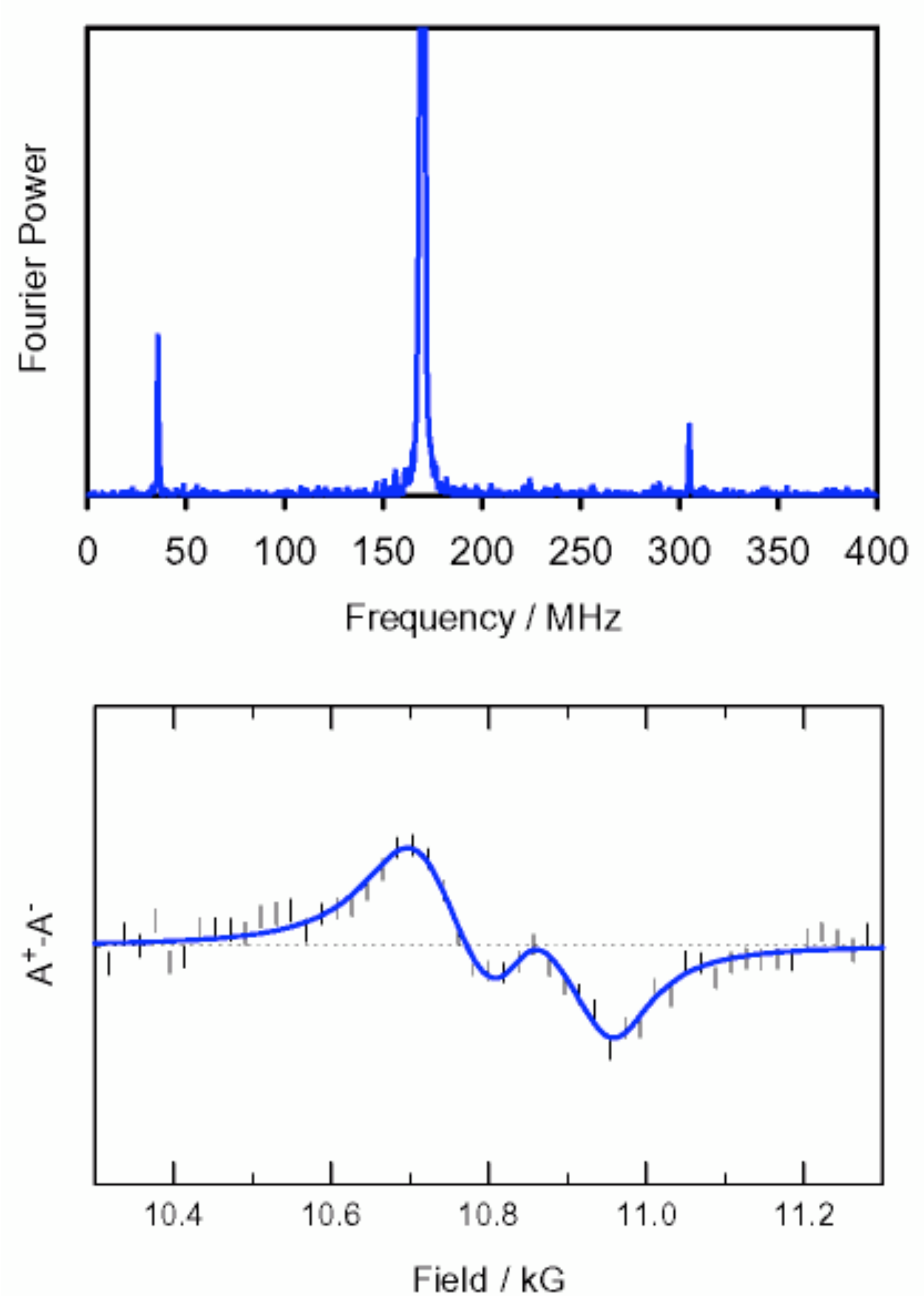
Recent Applications of *μSR*

- > Molecular Magnets & Clusters
- > Hydrogen in Semiconductors
- > **Magnetic Polarons**
- > Charged Particle Transport
- > Quantum Impurities
- > Metal-Insulator Transitions
- > Colossal Magnetoresistance
- > Spin Ice Systems
- > Thermoelectric Oxides
- > Photo-Induced Magnetism
- > Magnetic Vortices
- > Heavy Fermions
- > Frustrated Magnetic Systems
- > Quantum Diffusion
- > **Exotic Superconductors**

- > Molecular Structure & Conformational Motion of Organic Free Radicals
- > Hydrogen Atom Kinetics
- > "Green Chemistry" in Supercritical CO_2
- > Catalysis
- > Mass Effects in Chemical Processes
- > Ionic Processes at Interfaces
- > **Reactions in Supercritical Water**
- > Radiation Chemistry & Track Effects in Condensed Media
- > Reaction Studies of Importance to Atmospheric Chemistry
- > Reaction Kinetics as Probes of Potential Energy Surfaces
- > Electron Spin Exchange Phenomena in Gases & Condensed Media.



Muonium Chemistry

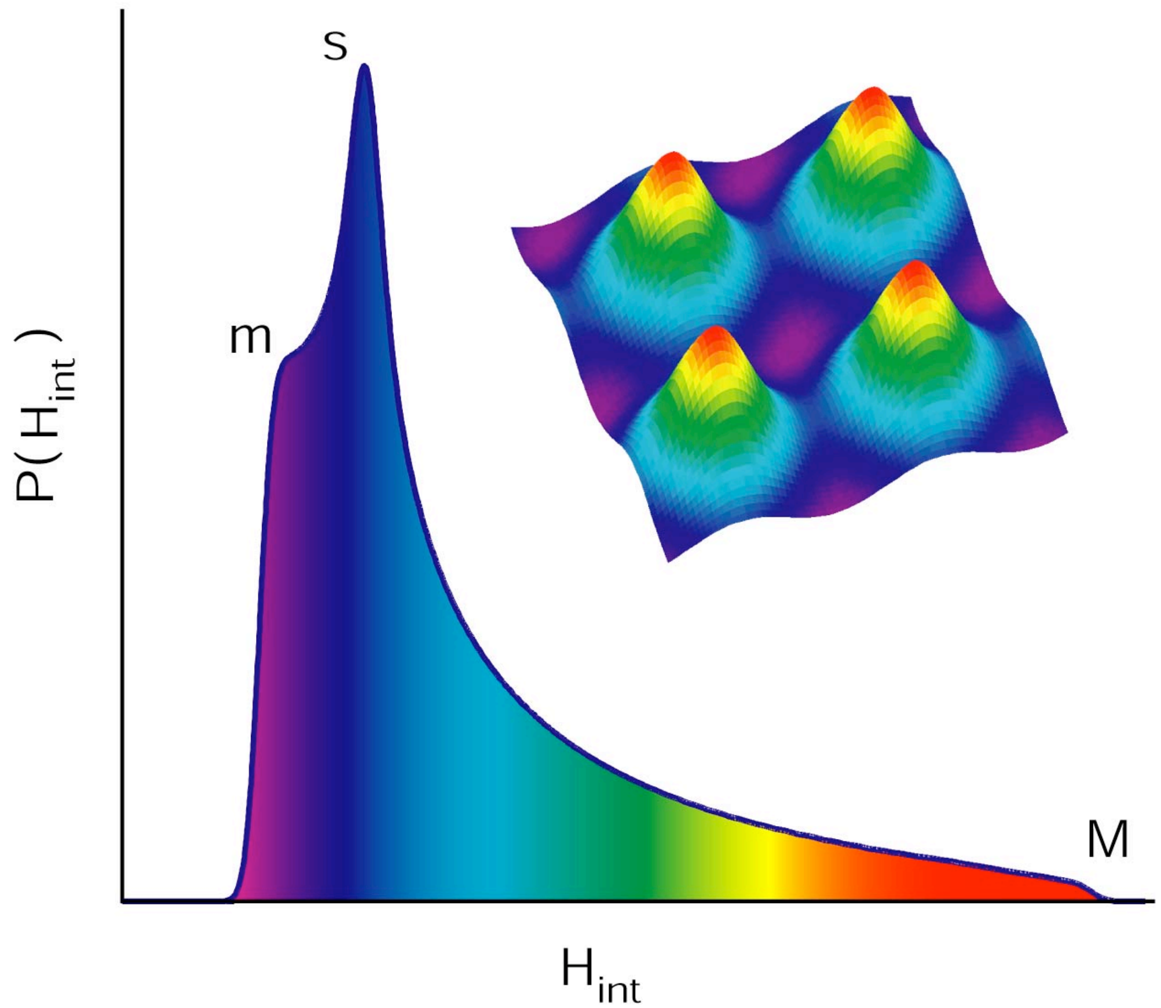


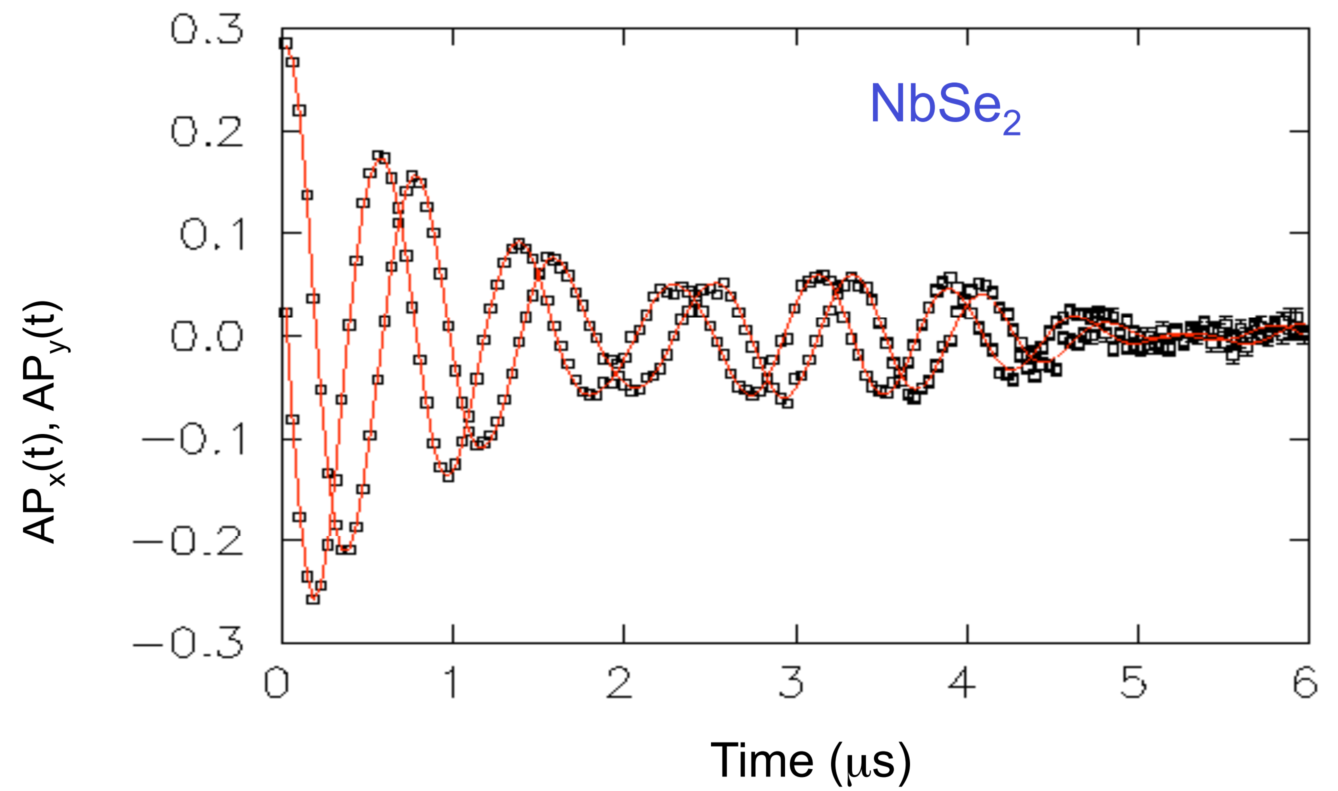
Organic Free Radicals in Superheated Water

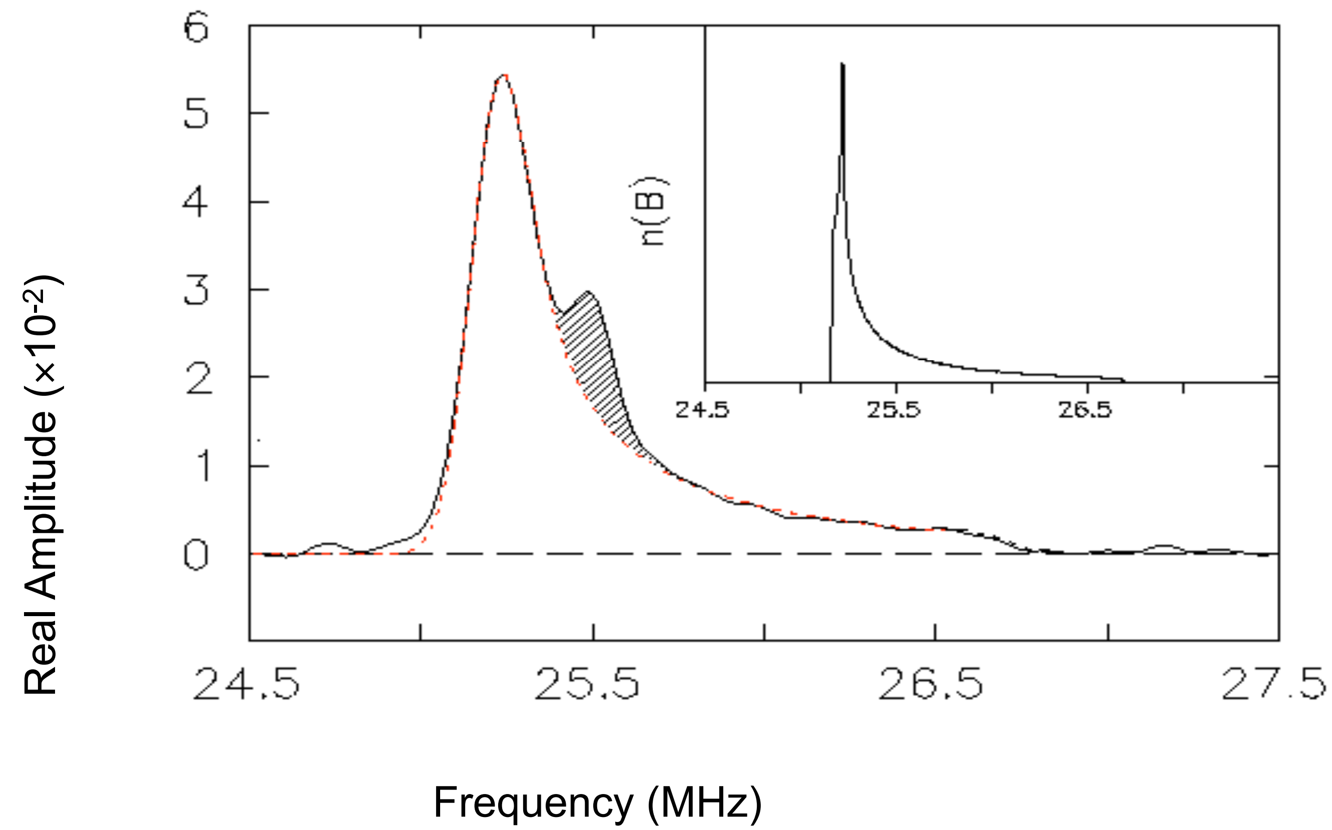
Paul W. Percival, Jean-Claude Brodovitch, Khashayar Ghandi, Brett M. McCollum, and Iain McKenzie

Apparatus has been developed to permit muon avoided level-crossing spectroscopy (μLCR) of organic free radicals in water at high temperatures and pressures. The combination of μLCR with transverse-field muon spin rotation (TF-μSR) provides the means to identify and characterize free radicals via their nuclear hyperfine constants. Muon spin spectroscopy is currently the only technique capable of studying transient free radicals under hydrothermal conditions in an unambiguous manner, free from interference from other reaction intermediates. We have utilized the technique to investigate hydrothermnal chemistry in two areas: dehydration of alcohols, and the enolization of acetone. Spectra have been recorded and hyperfine constants determined for the following free radicals in superheated water (typically 350°C at 250 bar): 2-propyl, 2-methyl-2-propyl (tert-butyl), and 2-hydroxy-2-propyl. The latter radical is the product of muonium addition to the enol form of acetone and is the subject of an earlier Research Highlight.   The figure shows spectra for the 2-propyl radical detected in an aqueous solution of 2-propanol at 350°C and 250 bar.

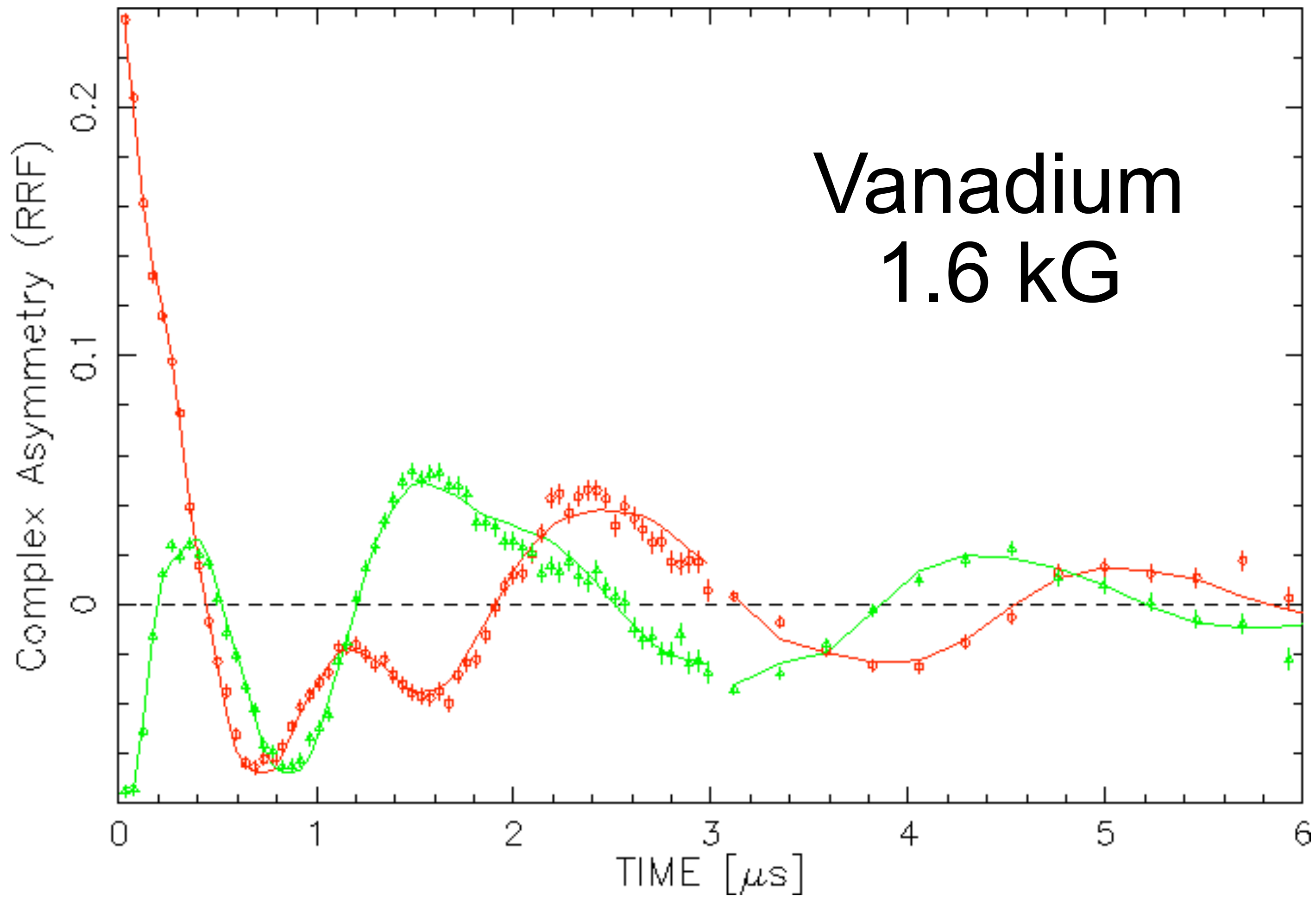
Magnetic Field Distribution of a Vortex Lattice

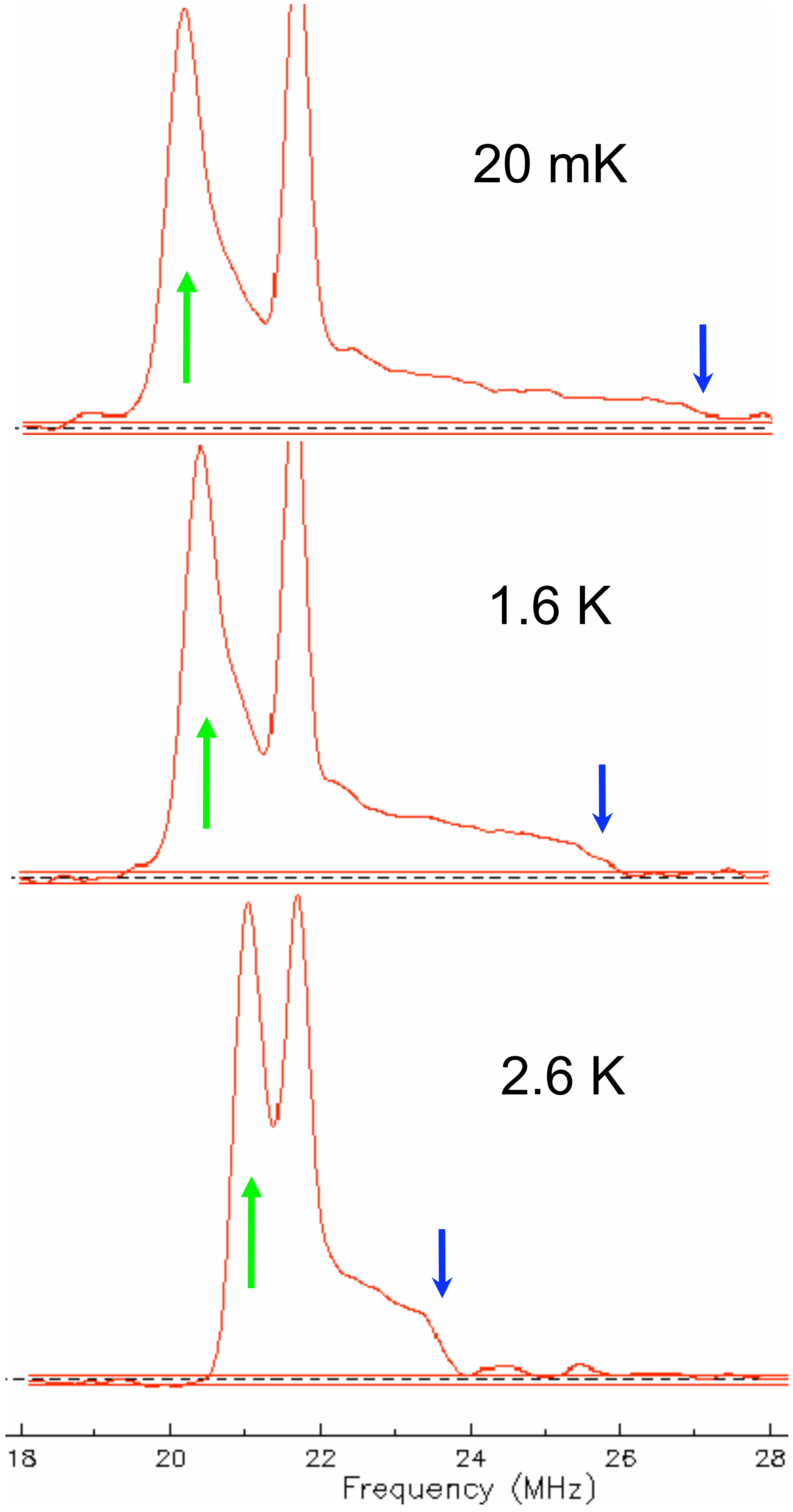






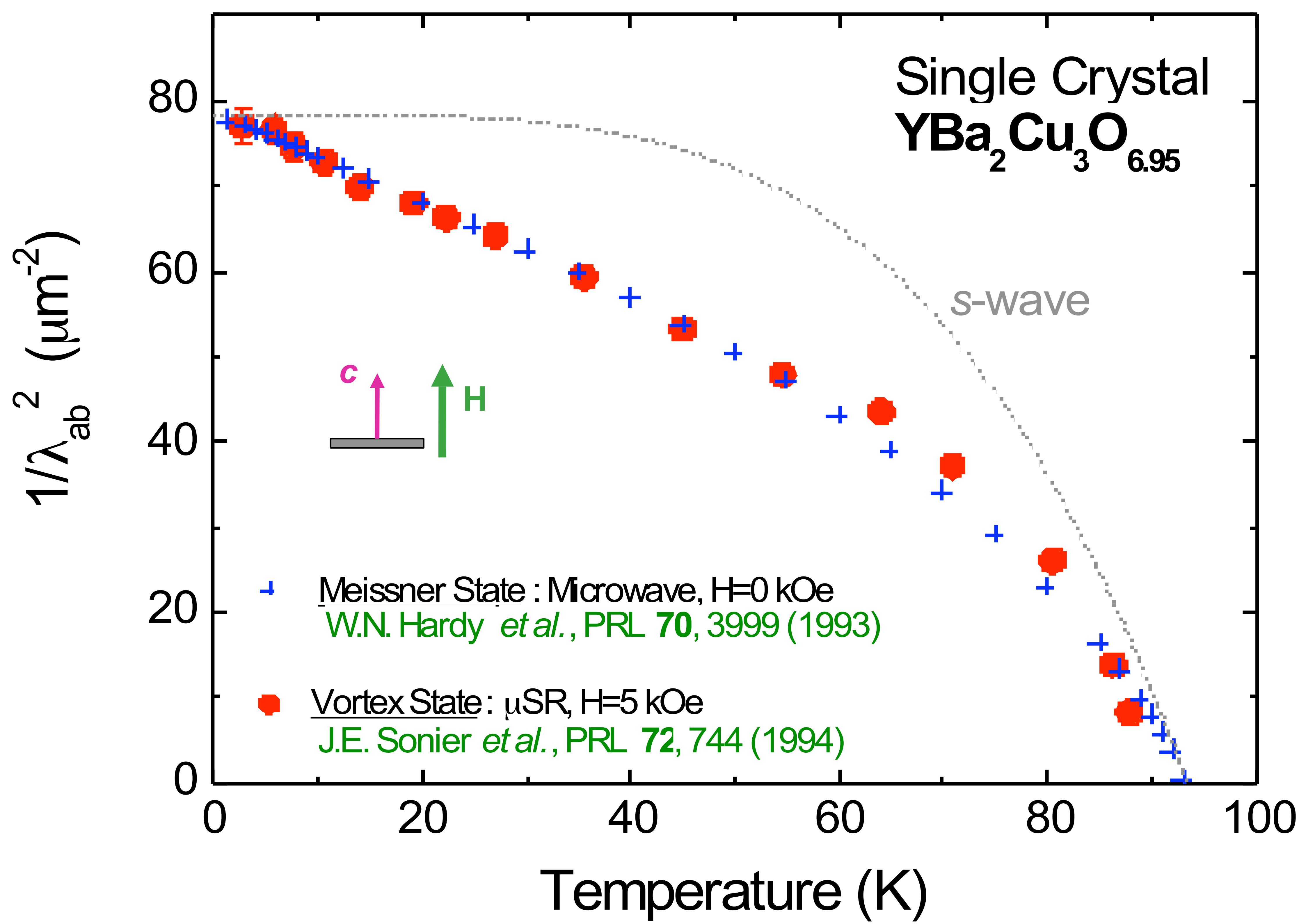
HTF-μ^+SR
FFT Lineshapes





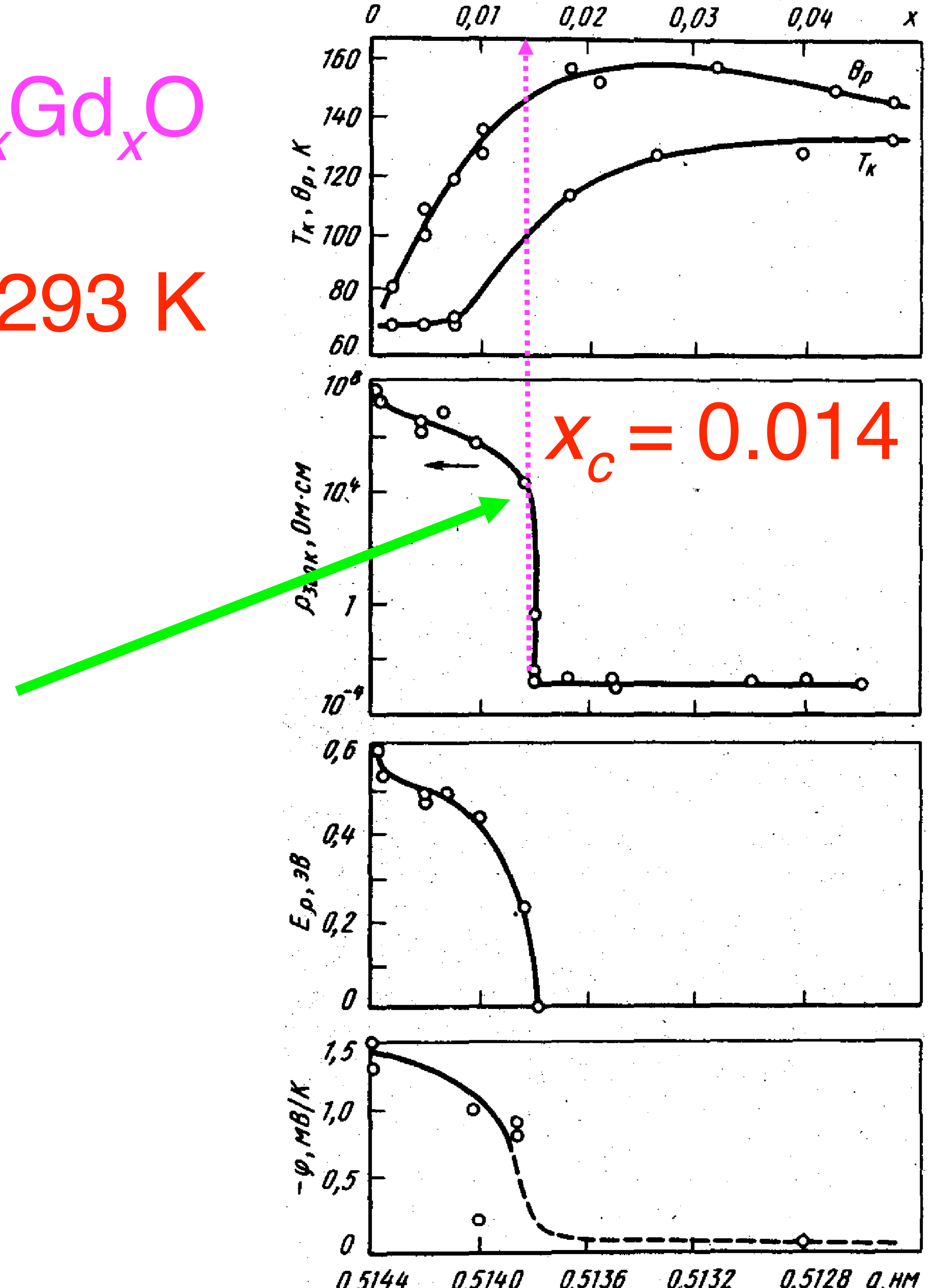
Fit in the **time** domain.

$1/\lambda_{ab}^2$ *in the Meissner & Vortex States*



$Eu_{1-x}Gd_xO$

$T = 293$ K



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A.S.Boruhovich
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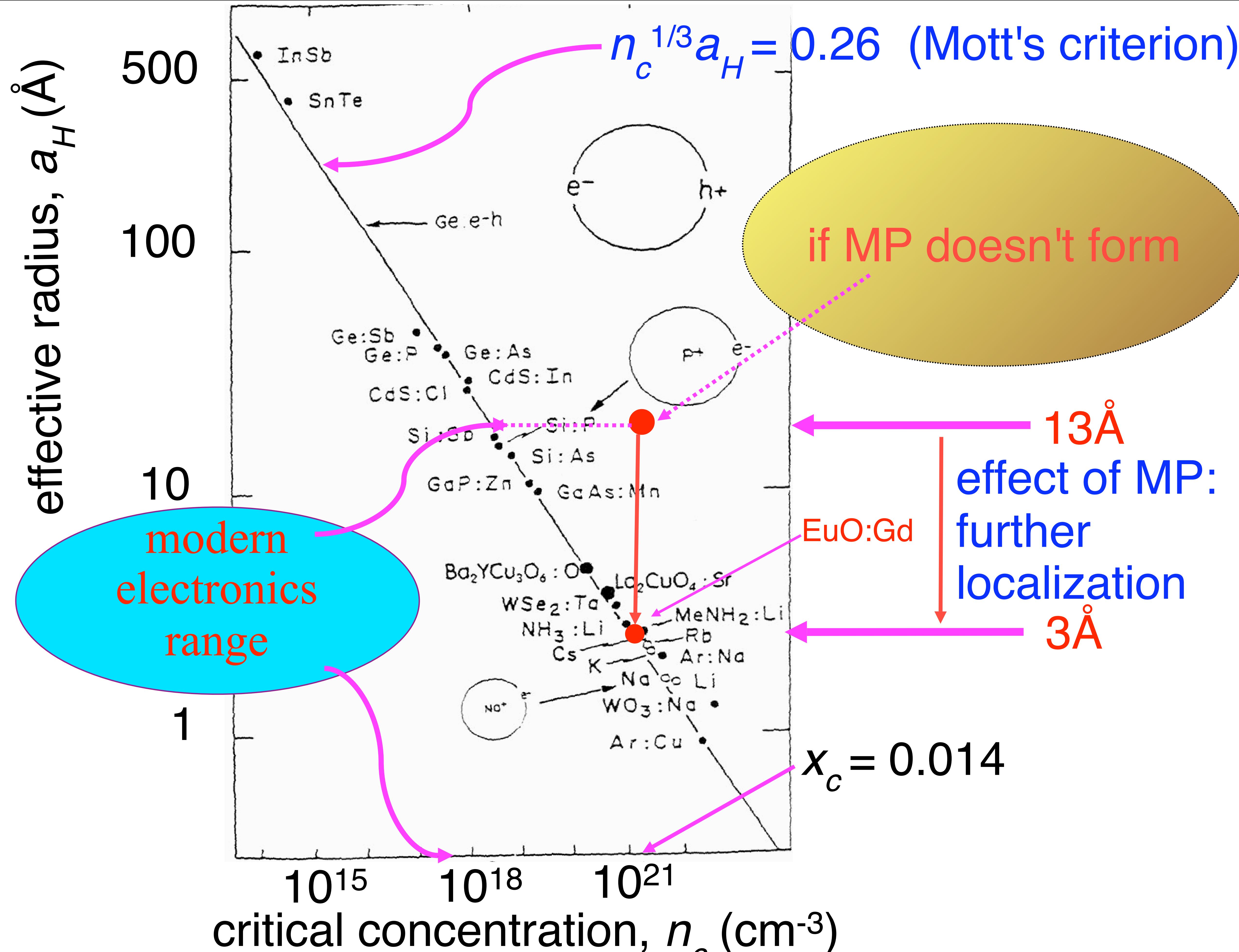
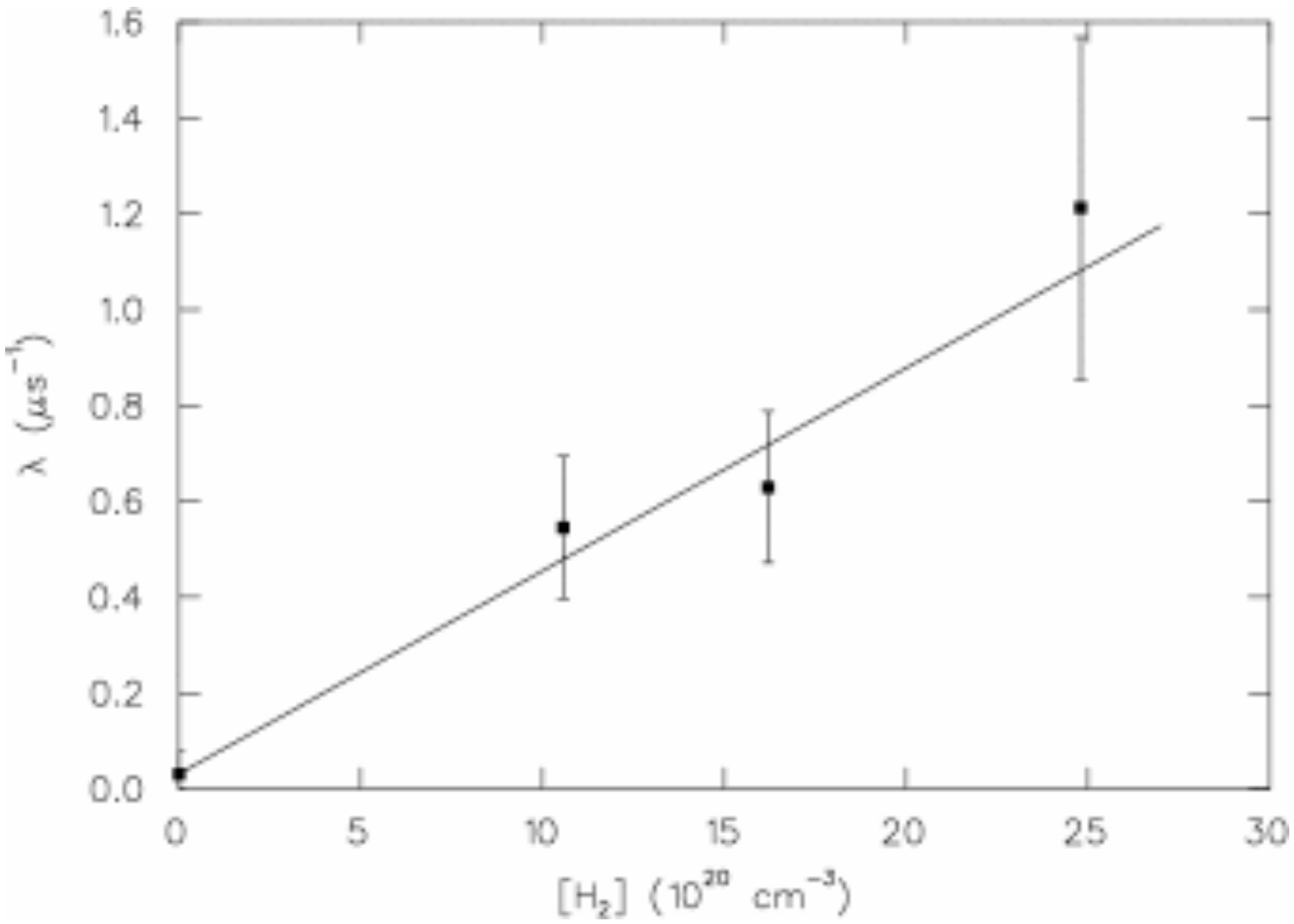


$n_c^{1/3} a_H = 0.26$ (Mott's criterion)
effective radius, a_H (Å)
500
100
10
1
InSb
SnTe
Ge e-h
e−
h+
Ge:Sb
Ge:P
Ge:As
CdS:In
CdS:Cl
Si:Sb
Si:P
Si:As
GaP:Zn
GaAs:Mn
p+
e−
if MP doesn't form
13Å
effect of MP: further localization
3Å
EuO:Gd
$Ba_2YCu_3O_6$:O
La_2CuO_4:Sr
WSe_2:Ta
$MeNH_2$:Li
NH_3:Li
Rb
Cs
Ar:Na
K
Na
Li
WO_3:Na
Ar:Cu
modern electronics range
$x_c = 0.014$
10^{15}
10^{18}
10^{21}
critical concentration, n_c (cm^{-3})

Reaction Rate of the Neutral Muonic Helium Atom ($^4He^{++}\mu^-e^-$) *with Hydrogen*

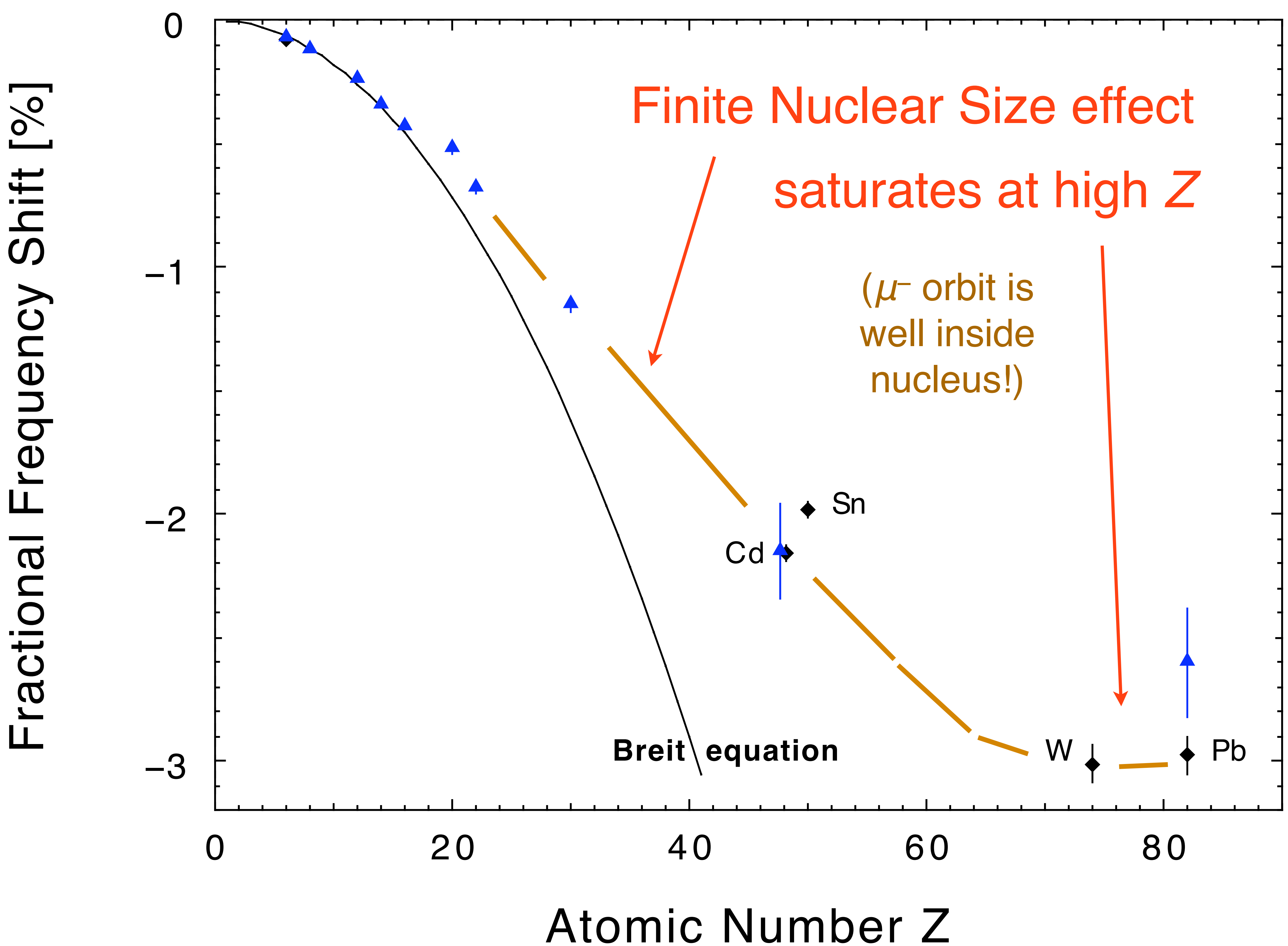
D.G. Fleming, D.J. Arseneau, O. Sukhorukov and J.H. Brewer

The chemical reaction rate of the neutral muonic helium atom $^4He^{++}\mu^-e^-$ (a *heavy* isotope of hydrogen with a mass 4.11 times that of protium) with H_2 gas has been measured for the first time at TRIUMF. Negative muons were stopped in high pressure helium gas with ammonia and hydrogen impurities added to provide (respectively) easily ionized electrons, to convert charged muonic helium to the neutral atomic species, and the chemical reaction partner of interest. Previous work at TRIUMF has concentrated upon the reactions of muonium (μ^+e^-) with hydrogen, providing crucial tests of rate chemistry theory through the largest isotopic range in history. This new measurement extends the isotopic range still further (from 0.11 to 4.11); yet all the species involved still qualify as legitimate isotopes of the simplest atom.



The reaction rate constant between H_2 and $^4He^{++}\mu^-e^-$ obtained at room temperature from these data is $k = (4.2 \pm 0.7) \times 10^{-16}$ cm^3/s, about 10^4 times faster than that estimated for Mu + H_2 at 300 K, ~ 5.3×10^{-20} cm^3/s. This huge difference is mainly due to the lower activation energy for the heavier atom, reflecting huge differences in zero point energy in the transition state. There should be little or no tunneling for the heavy muonic helium atom. Later experiments at different temperatures aim to measure the activation energy for this reaction.

Relativistic Shifts of Bound μ^- g-factor



History of μSR

- pre-1956: Fantasy
- 1956-7: Revolution!
  π-μ-e decay and μSR
- 1958-73: Science Fiction
  Michel Parameters
  QED tests with Muonium
  "Problems" → Applications
- 1970s: Meson Factories
  SIN/PSI, LAMPF, TRIUMF,
  KEK/BOOM, RAL/ISIS
- '80s & '90s: Routine Science
  μSR Methods developed
  "Themes" in *μSR*
- 2000s: TRIUMF **CMMS**:
  Chemistry & Semiconductors
  Magnetism & Superconductors
  Fundamental Physics
- FUTURE: Applied Science
  (No more magic? Don't count on it!)

Finis