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 . . .

Before 1956: *Fantasy*

- 1930s: **Mistaken Identity**

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

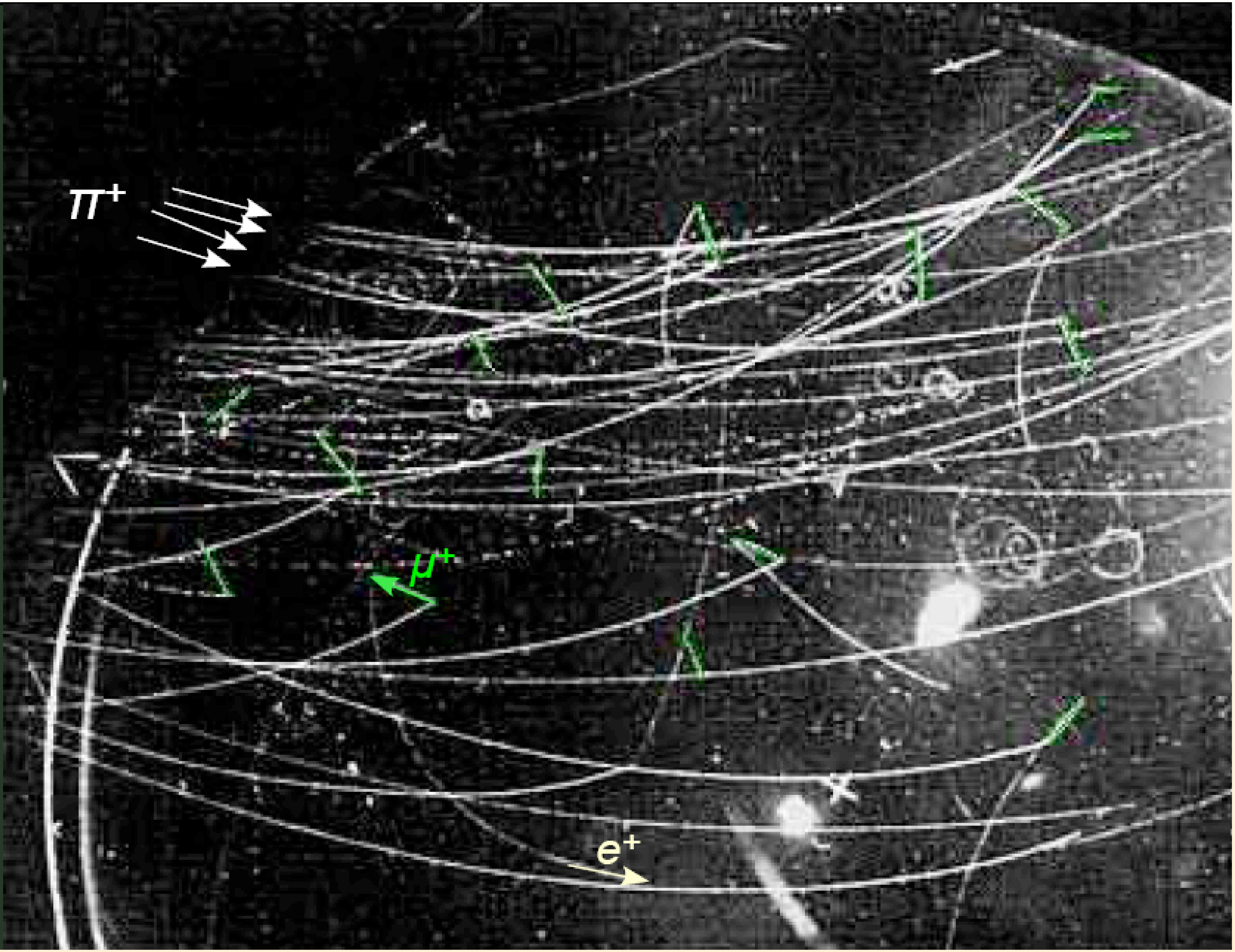
- 1940s: "**Who Ordered That?**"

  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****!*

What do you see?



Before 1956: *Fantasy*

- 1930s: **Mistaken Identity**

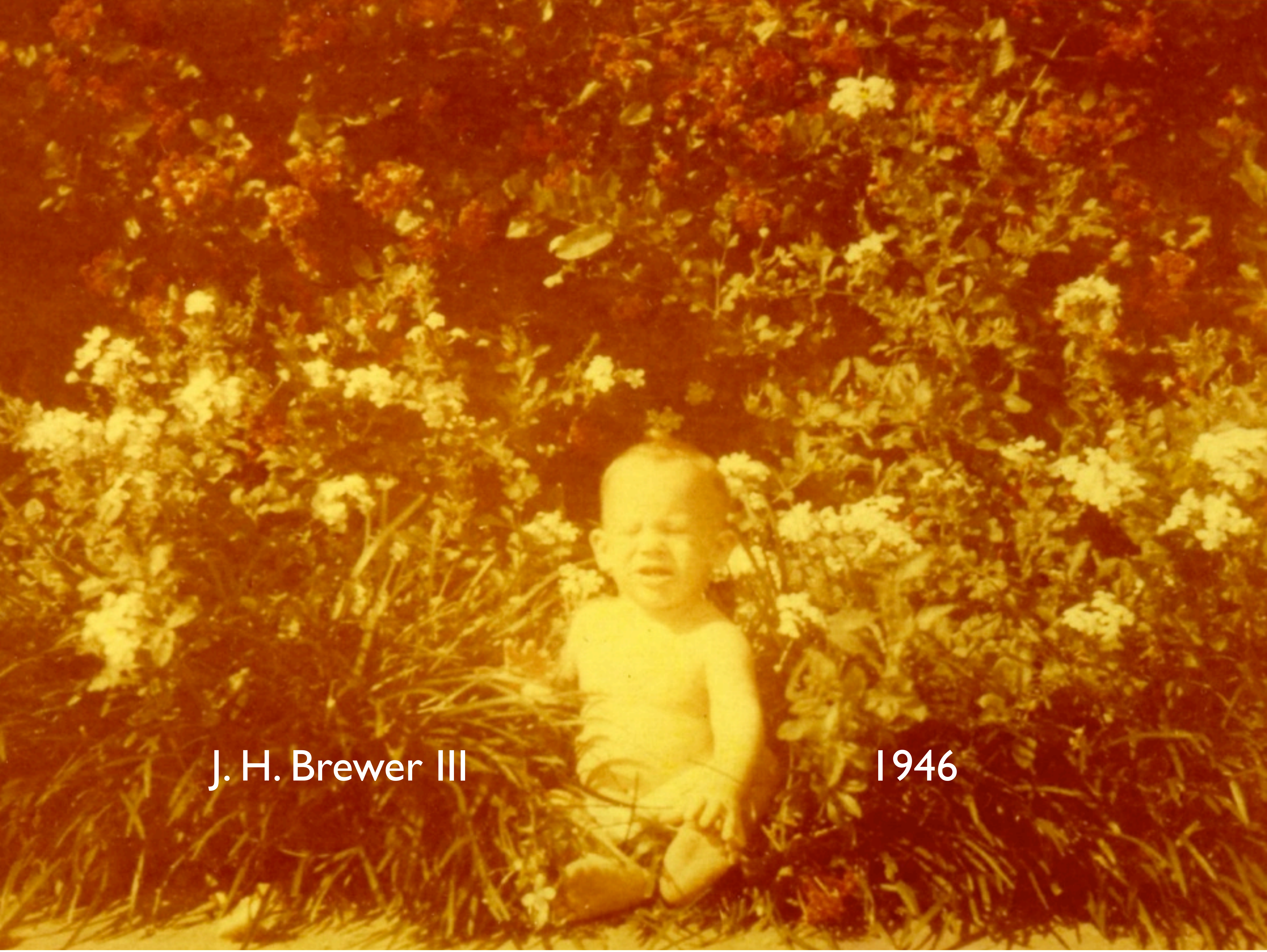
  Yukawa's "nuclear glue" mesons ≠ cosmic rays
  1937 Rabi: Nuclear Magnetic Resonance

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

  1940 Phys. Rev. Analytical Subject Index: "mesotron"
  1944 Rasetti: 1^{st} 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!***

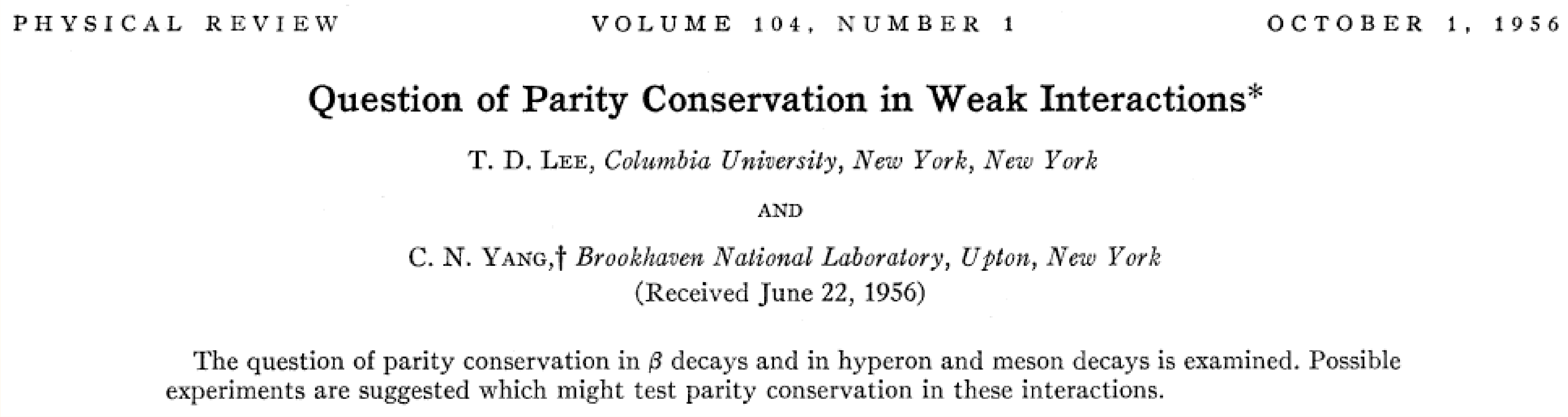

J. H. Brewer III 1946

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*

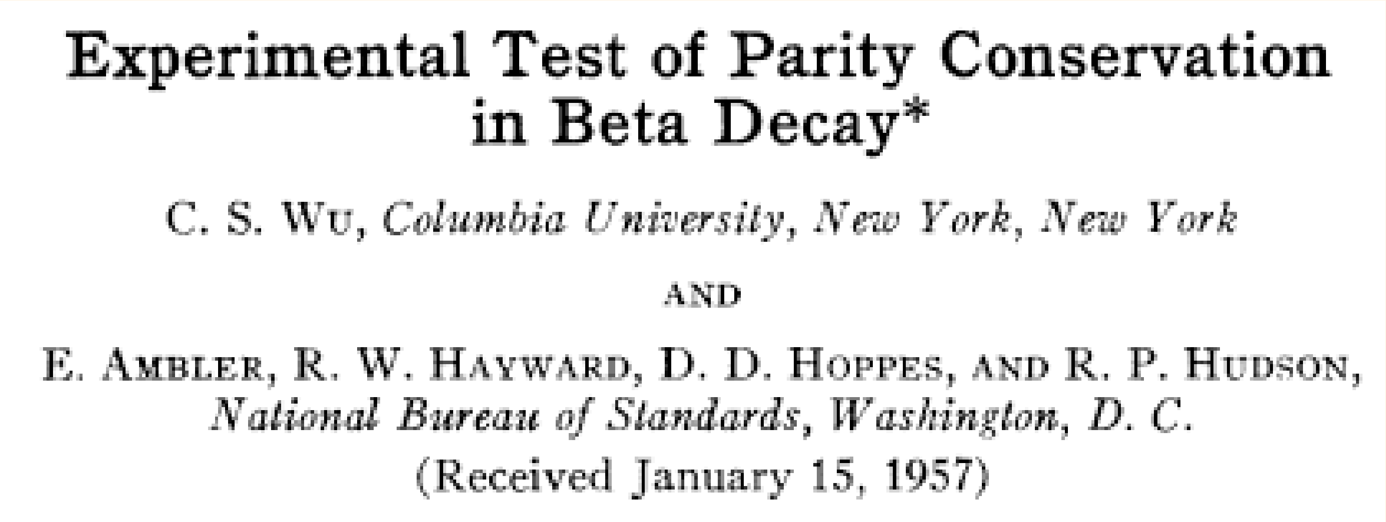
AND

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.

↓



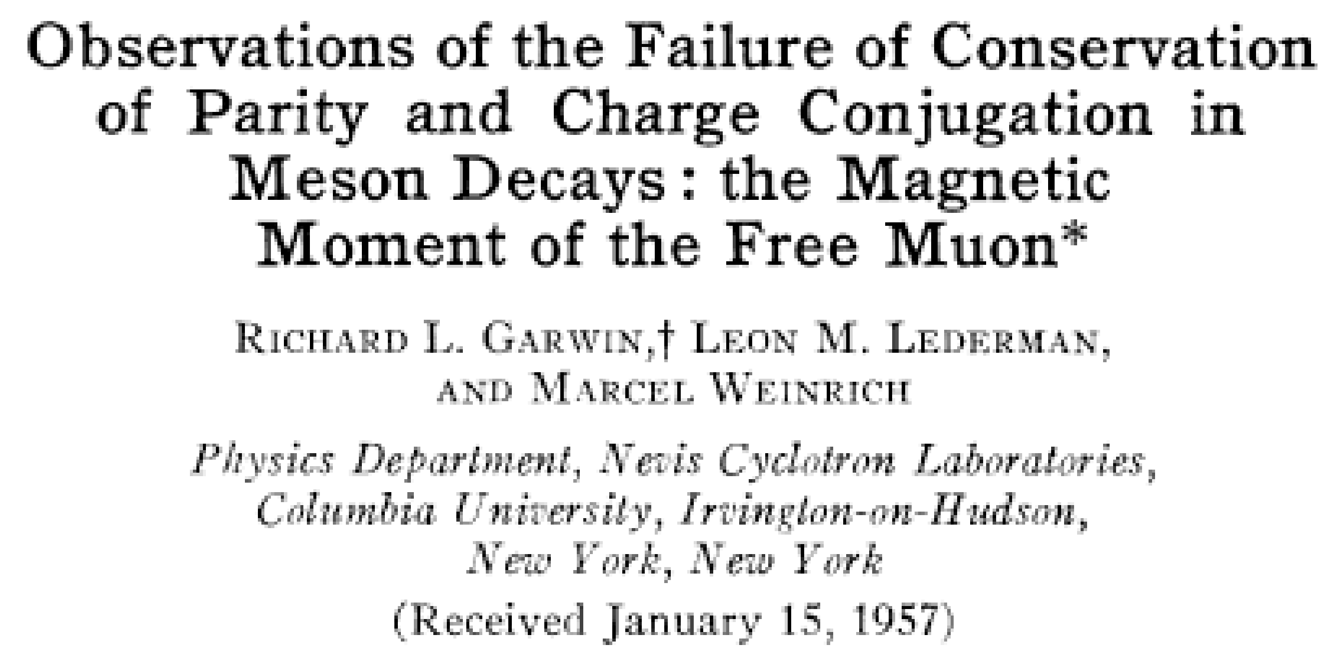
Experimental Test of Parity Conservation in Beta Decay*

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)

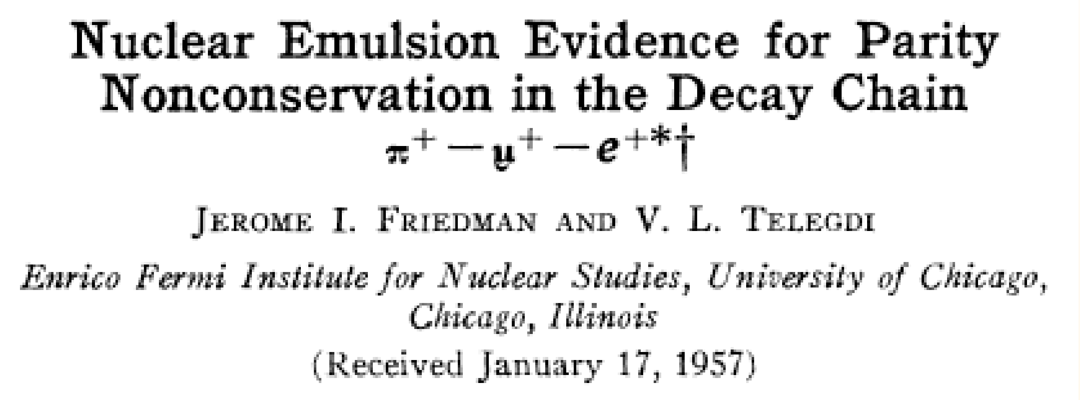


Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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)

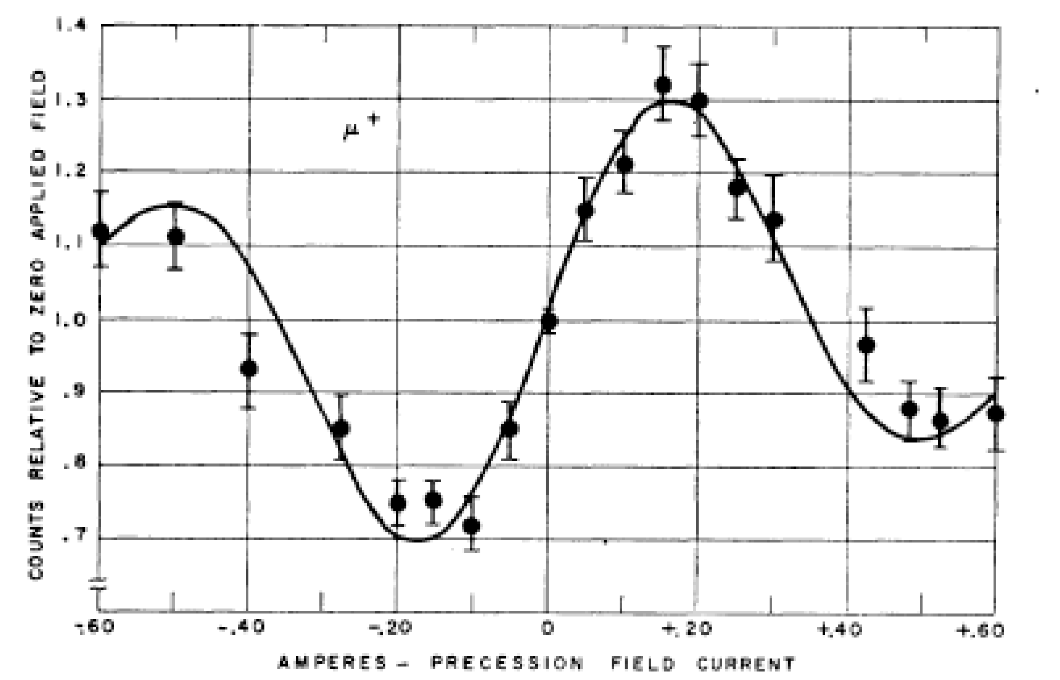
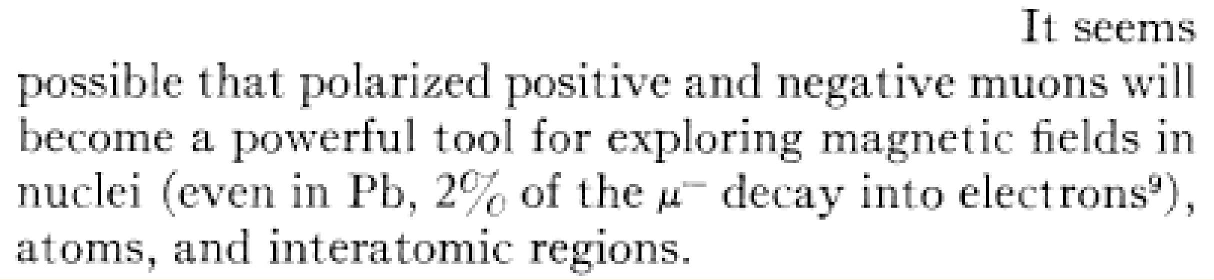


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.



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.

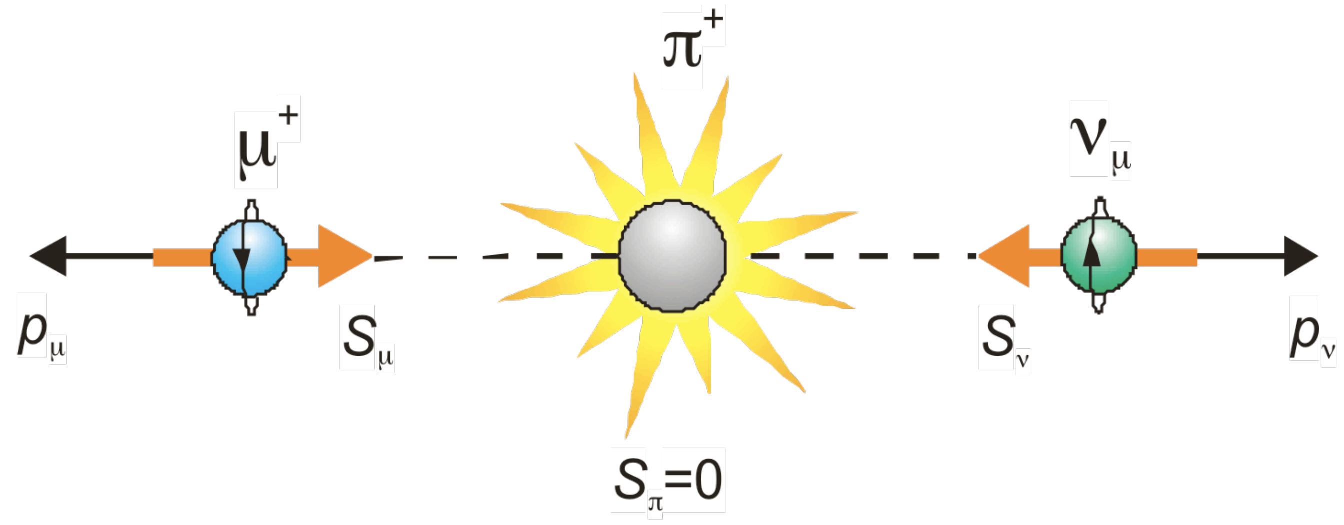
Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ .

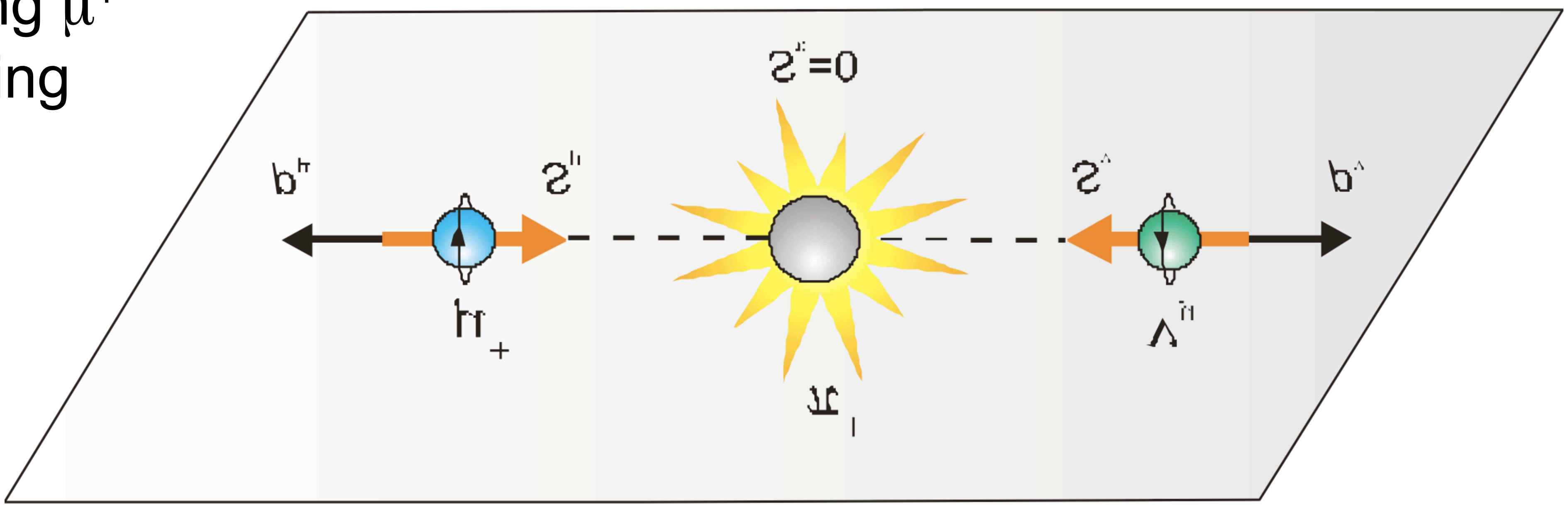
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite spin.

Weak Interaction:

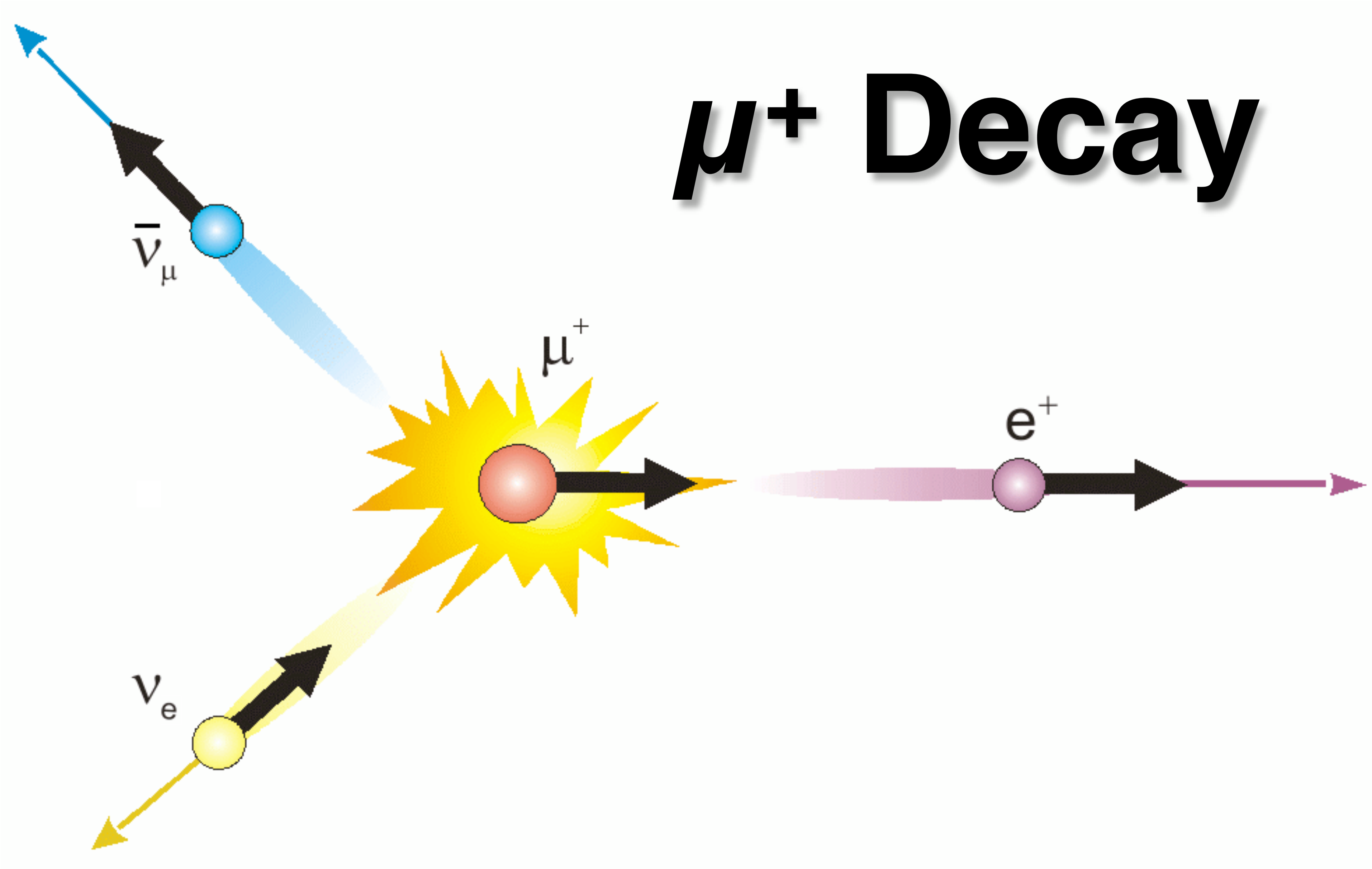
Only “left-handed” ν_μ are created.

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





μ^+ Decay

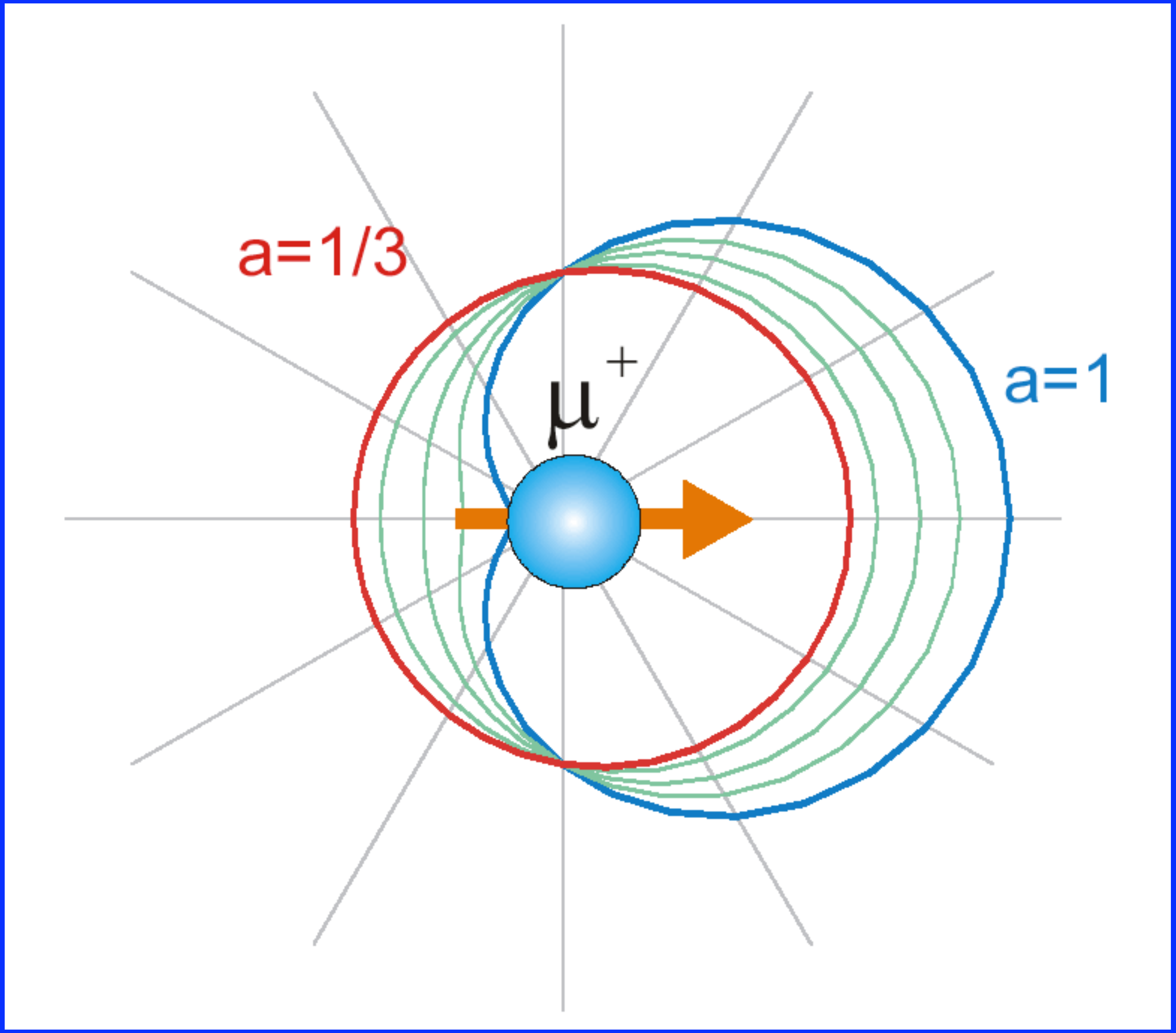


Neutrinos have negative helicity, antineutrinos positive.

An ultrarelativistic positron behaves like an antineutrino.

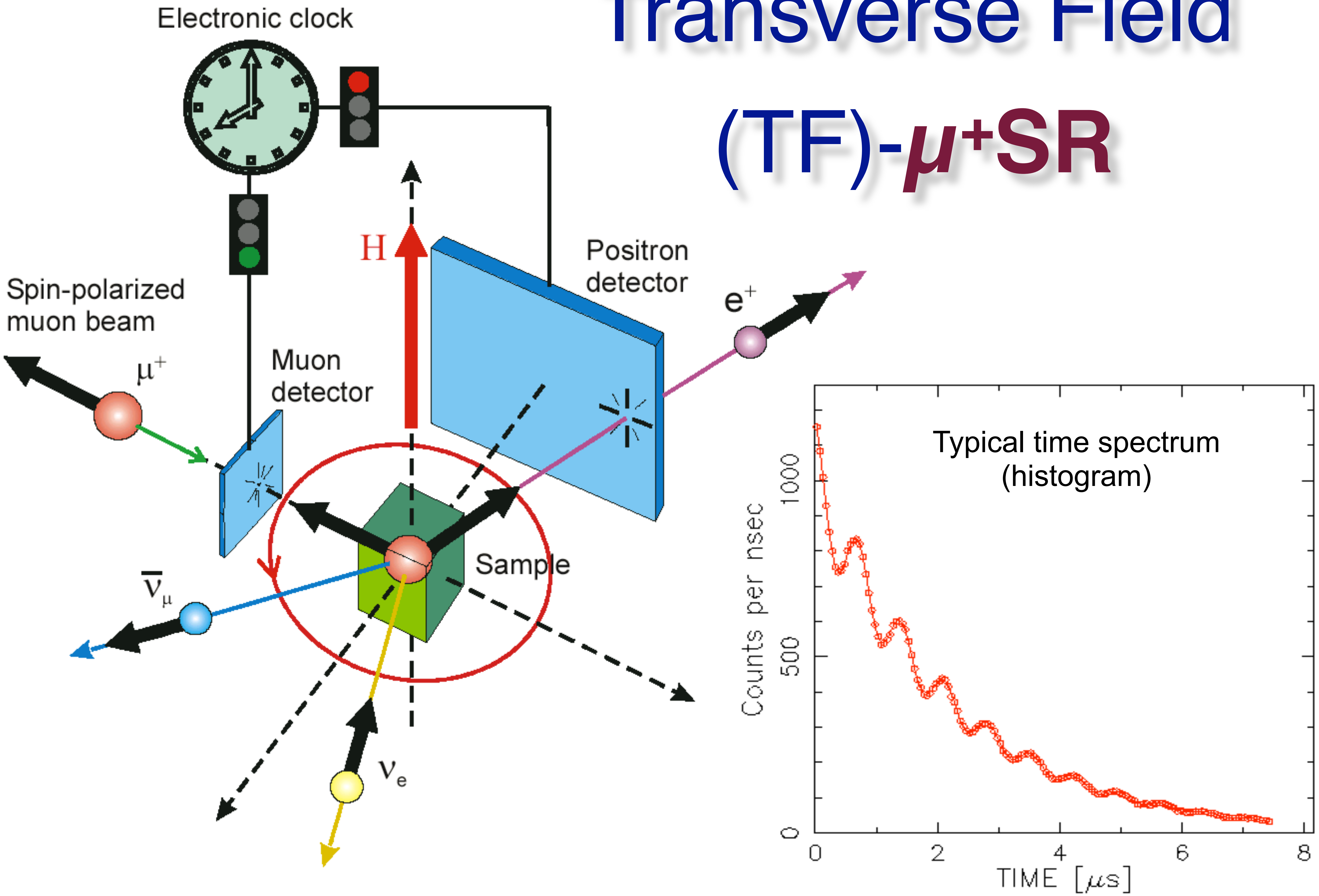
Thus the positron <u>tends</u> to be emitted along the μ^+ spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

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



Typical time spectrum (histogram)

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

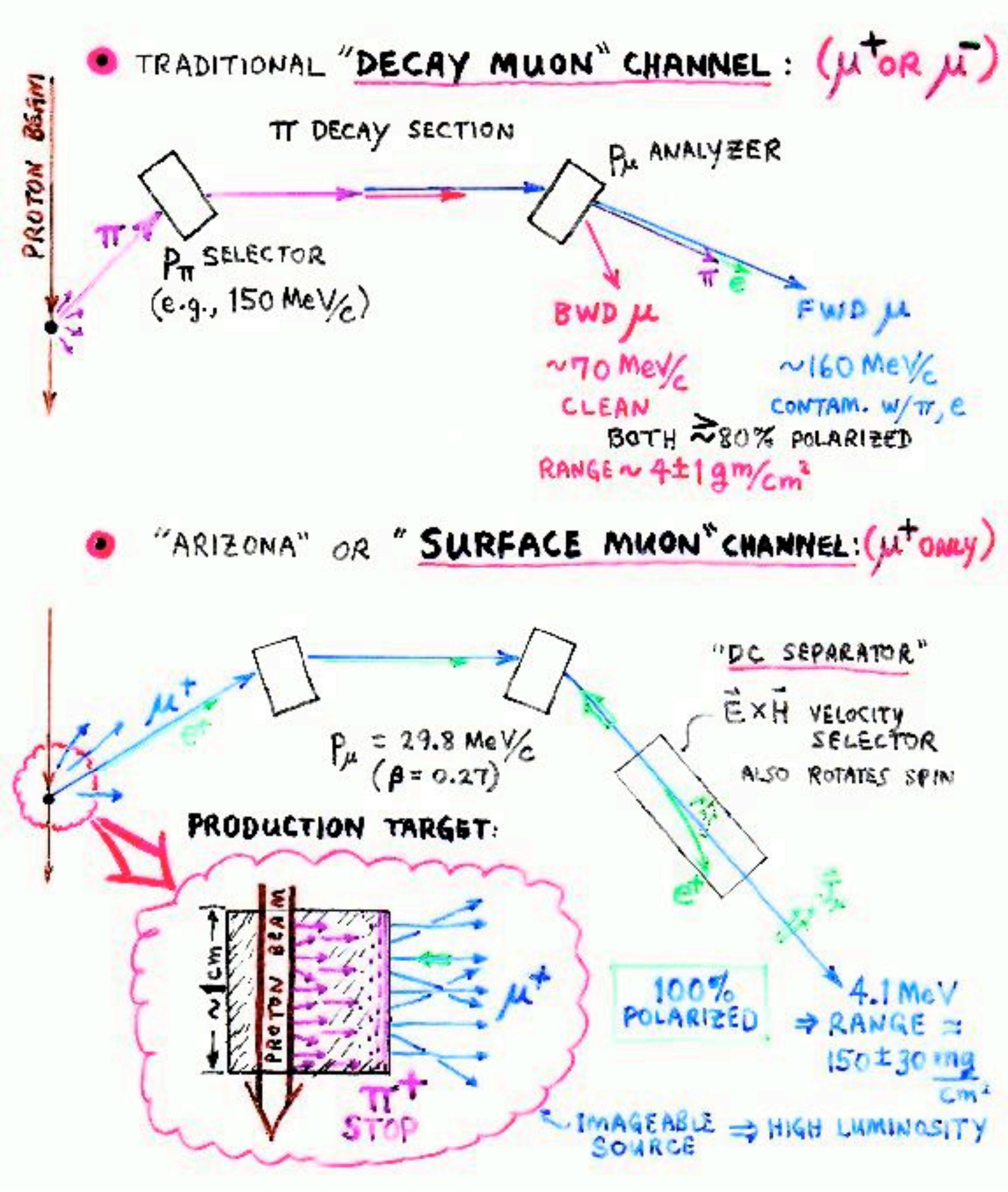
- 1967: **Brewer goes to Berkeley** – *to study Radicals*
  Rationale: a *science fiction author* needs credibility; what better credential than a Ph.D. in Physics? (But *μSR* was too much fun!)

- 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**
  Japan: **KEK/BOOM** (→ **J-PARC**)

Beamlines for Polarized Muons



1958-1973: *Science Fiction*

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

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

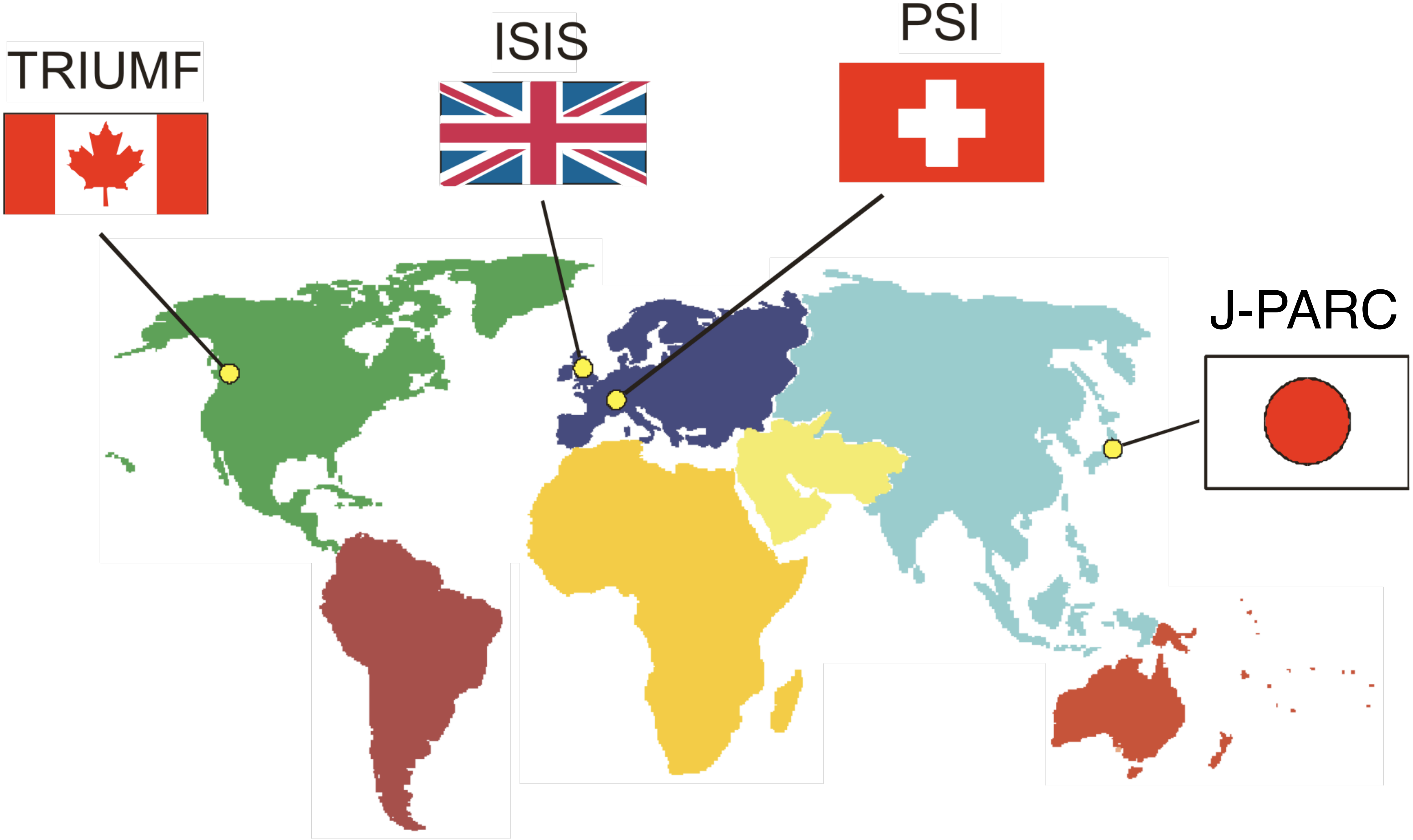
- 1967: Brewer goes to Berkeley – *to study Radicals*
  Rationale: a *science fiction author* needs credibility; what better credential than a Ph.D. in Physics? (But *μSR* was too much fun!)

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

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

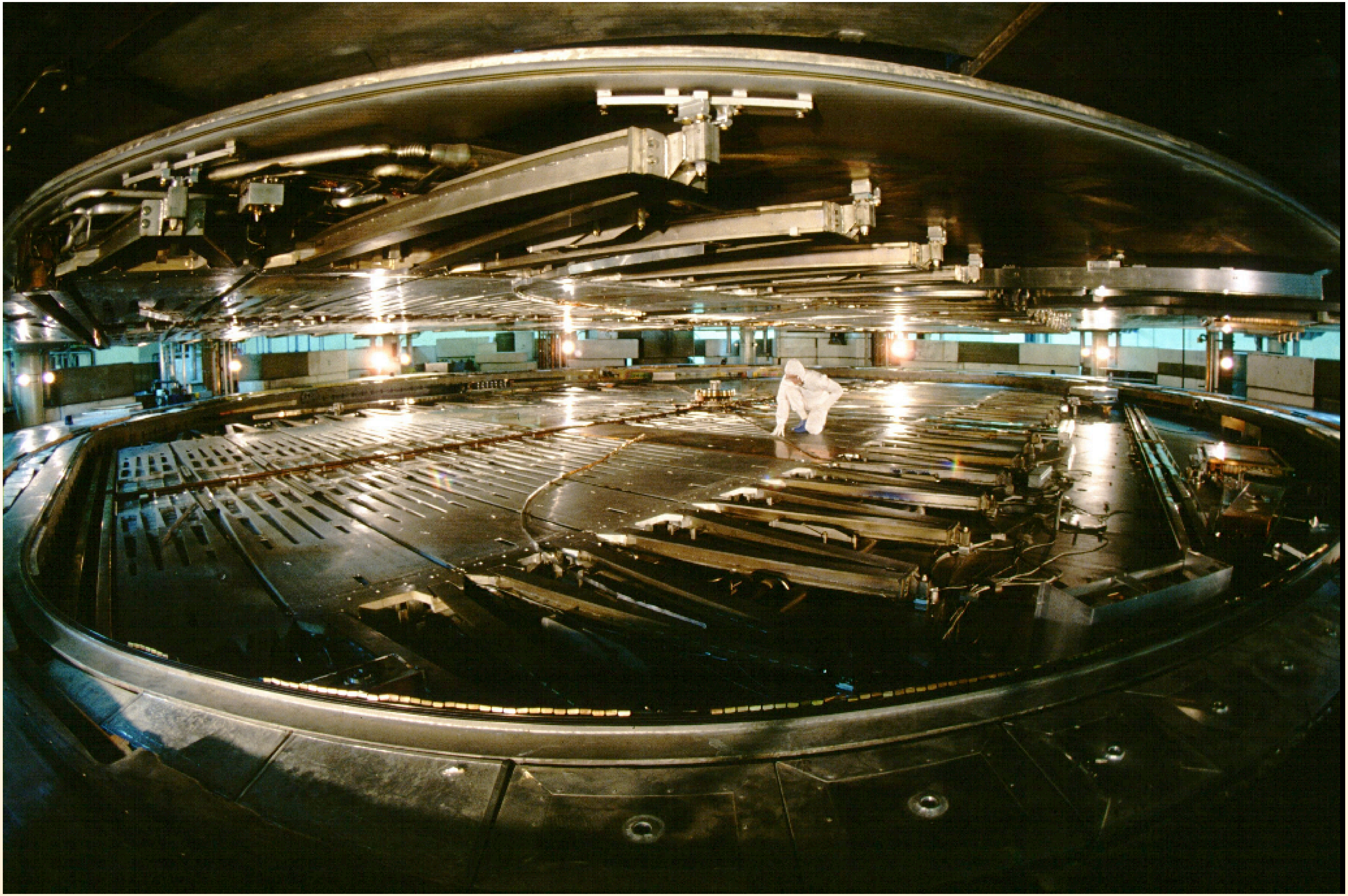
  USA: **LAMPF** (now defunct)
  Canada: ***TRIUMF***
  Japan: **KEK/BOOM** (→ **J-PARC**)
  Switzerland: **SIN** (now **PSI**)
  UK: **RAL/ISIS**

Where in the World is μSR?

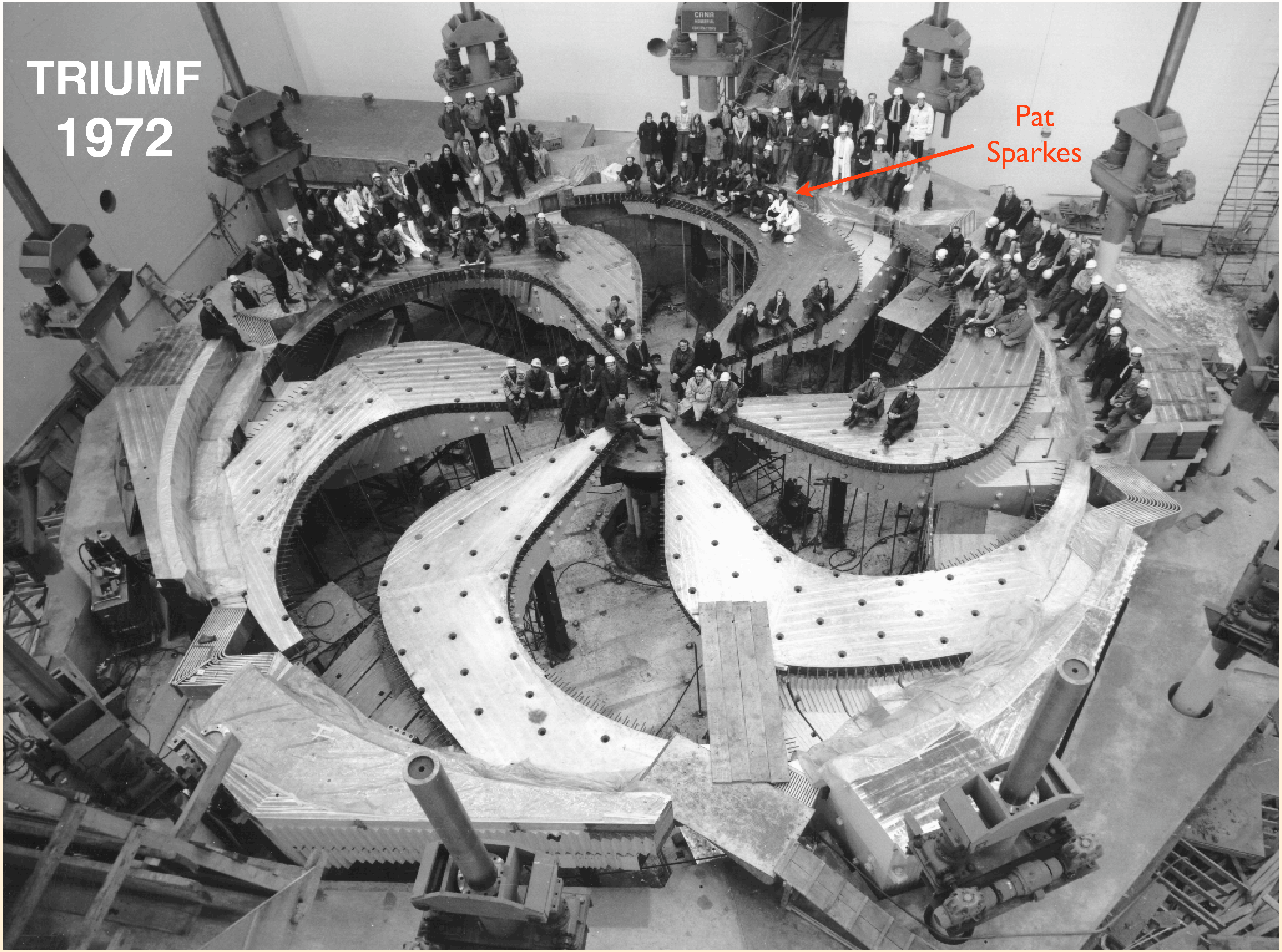


TRIUMF

TRIUMF: World’s Largest Cyclotron



TRIUMF 1972



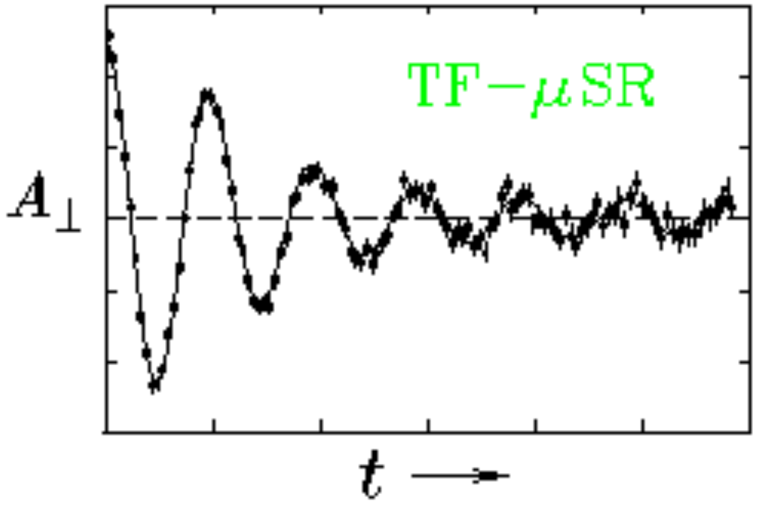
Pat Sparkes

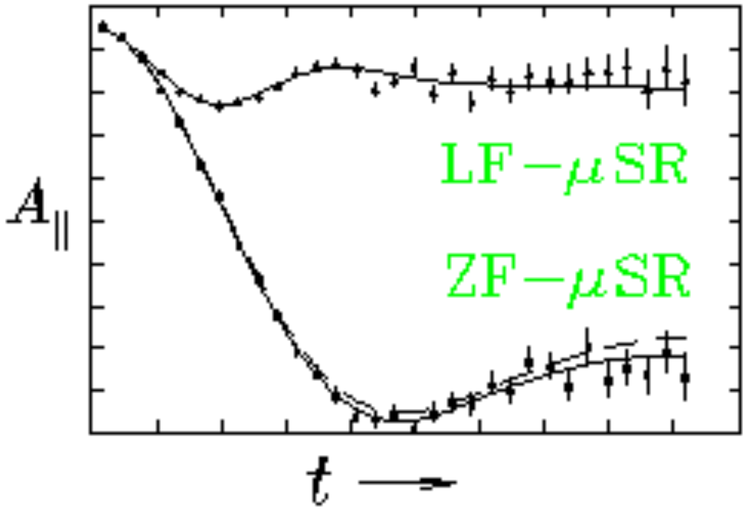
Back to **μSR** . . .

Brewer's List of µSR Acronyms

Transverse

Field





Longitudinal

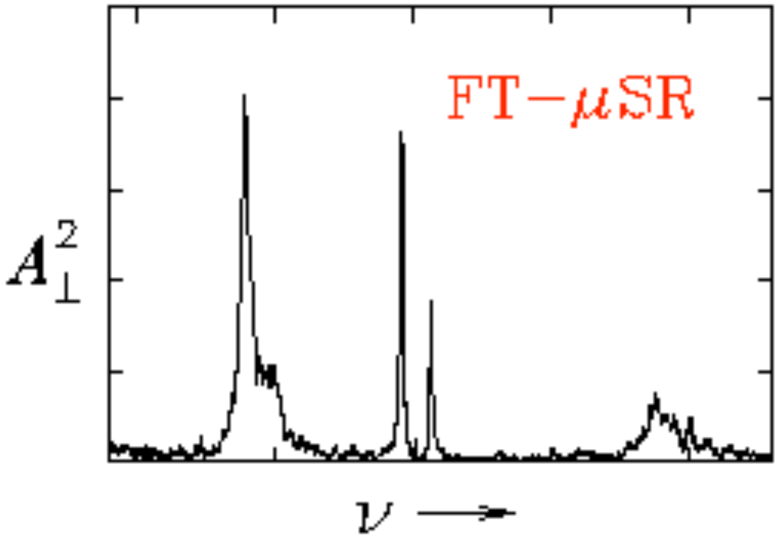
Field

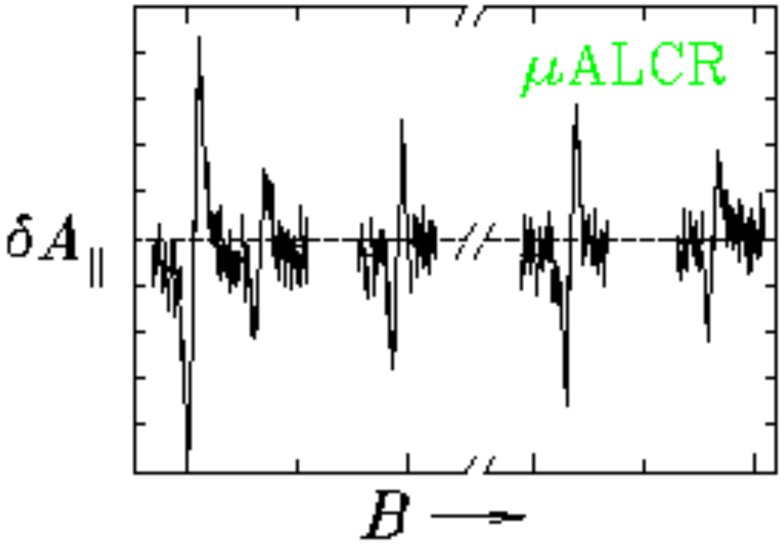
Zero Field

Fourier

Transform

µSR





Avoided

Level

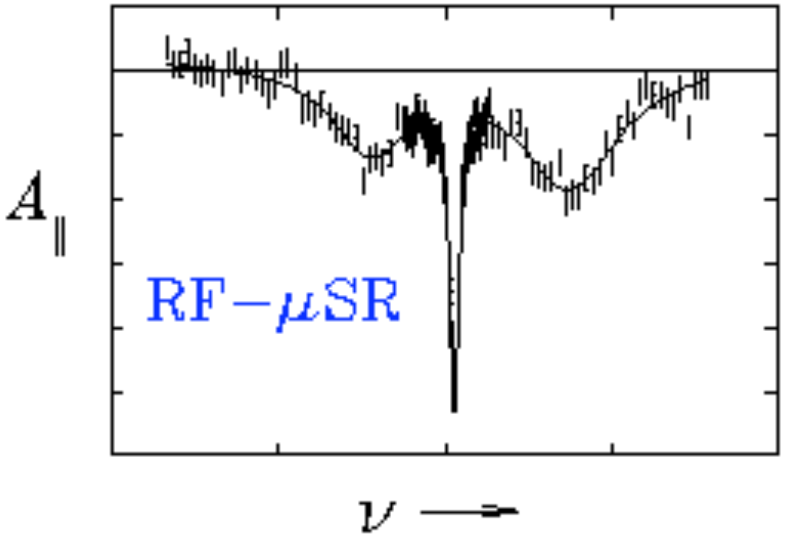
Crossing

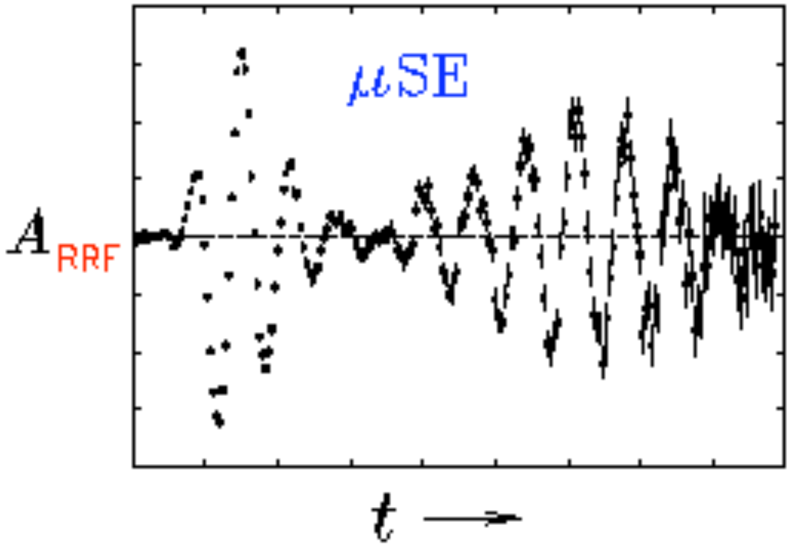
Resonance

Muon

Spin

Resonance





Muon

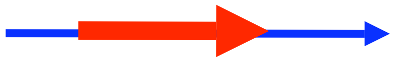
Spin

Echo

Motion of Muon Spins in Static Local Fields

→ $\mathbf{S}_\mu$ = Expectation value of a muon's spin direction

(a) All muons "see" same field $\mathbf{B}$:

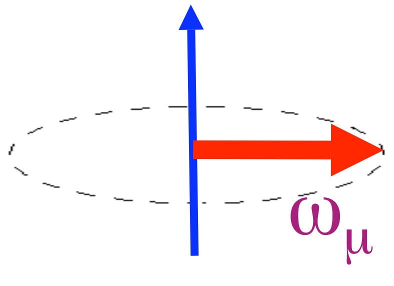


for $\mathbf{B} \parallel \mathbf{S}_\mu$ nothing happens

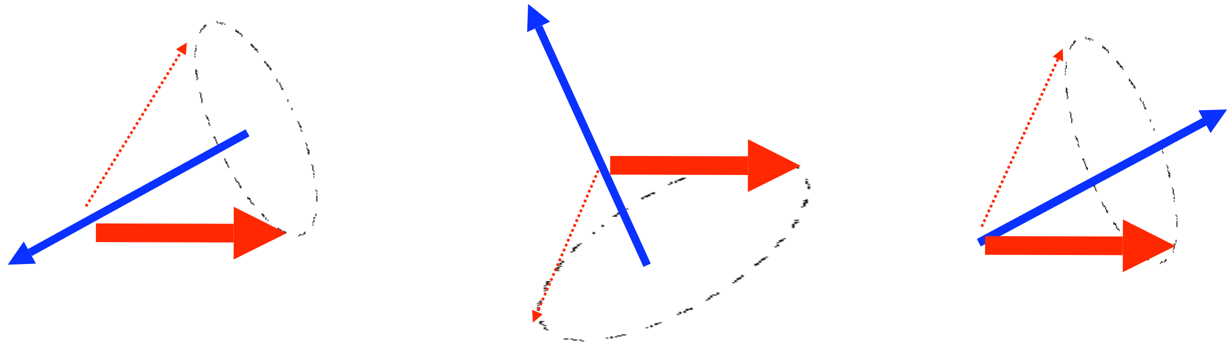
$\omega_\mu = 2\pi\,\gamma_\mu\,|\mathbf{B}|$

$\gamma_\mu = 135.5$ MHz/T

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



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



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

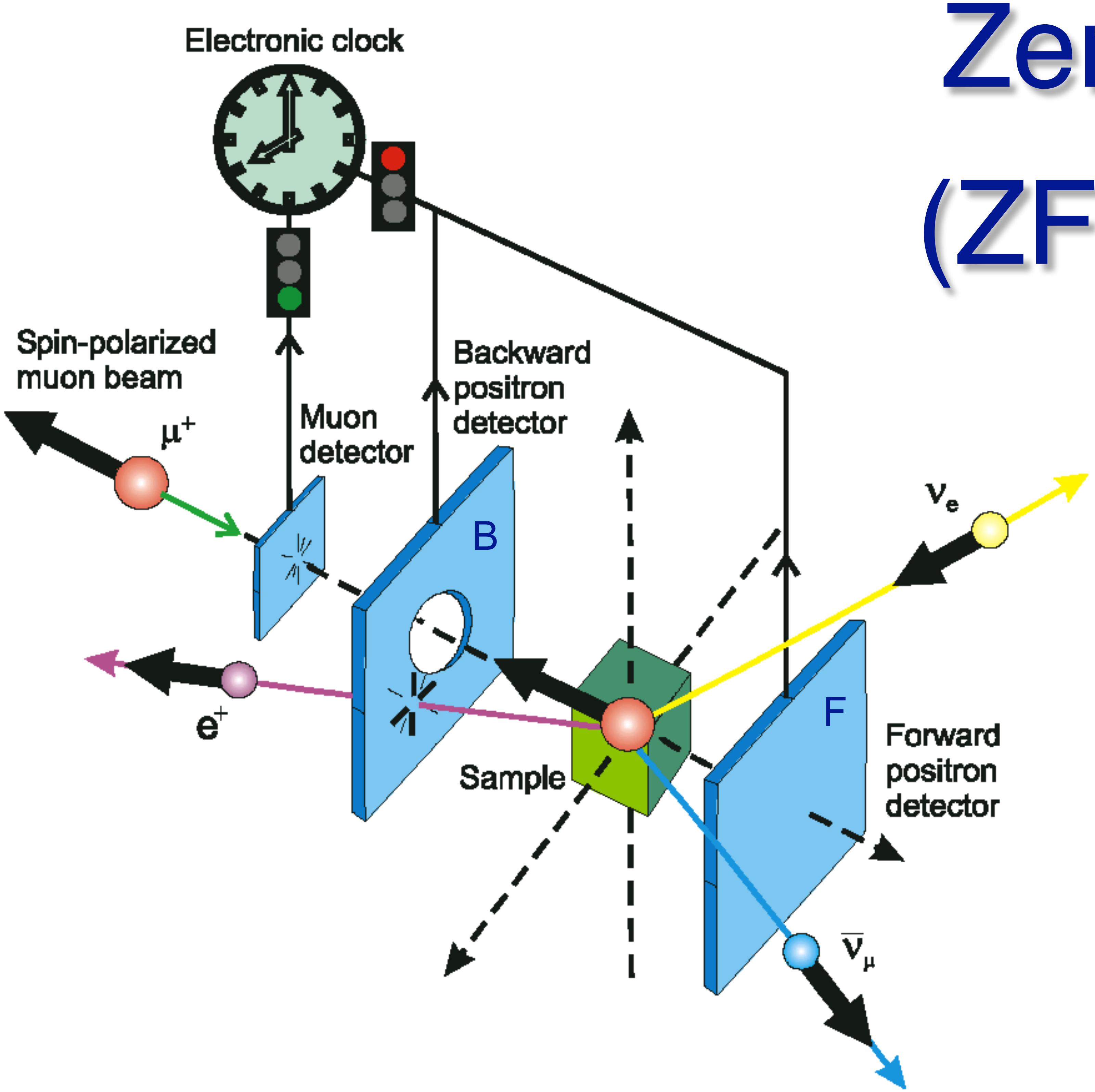
1/3 of $\mathbf{S}_\mu$ **stays constant**

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

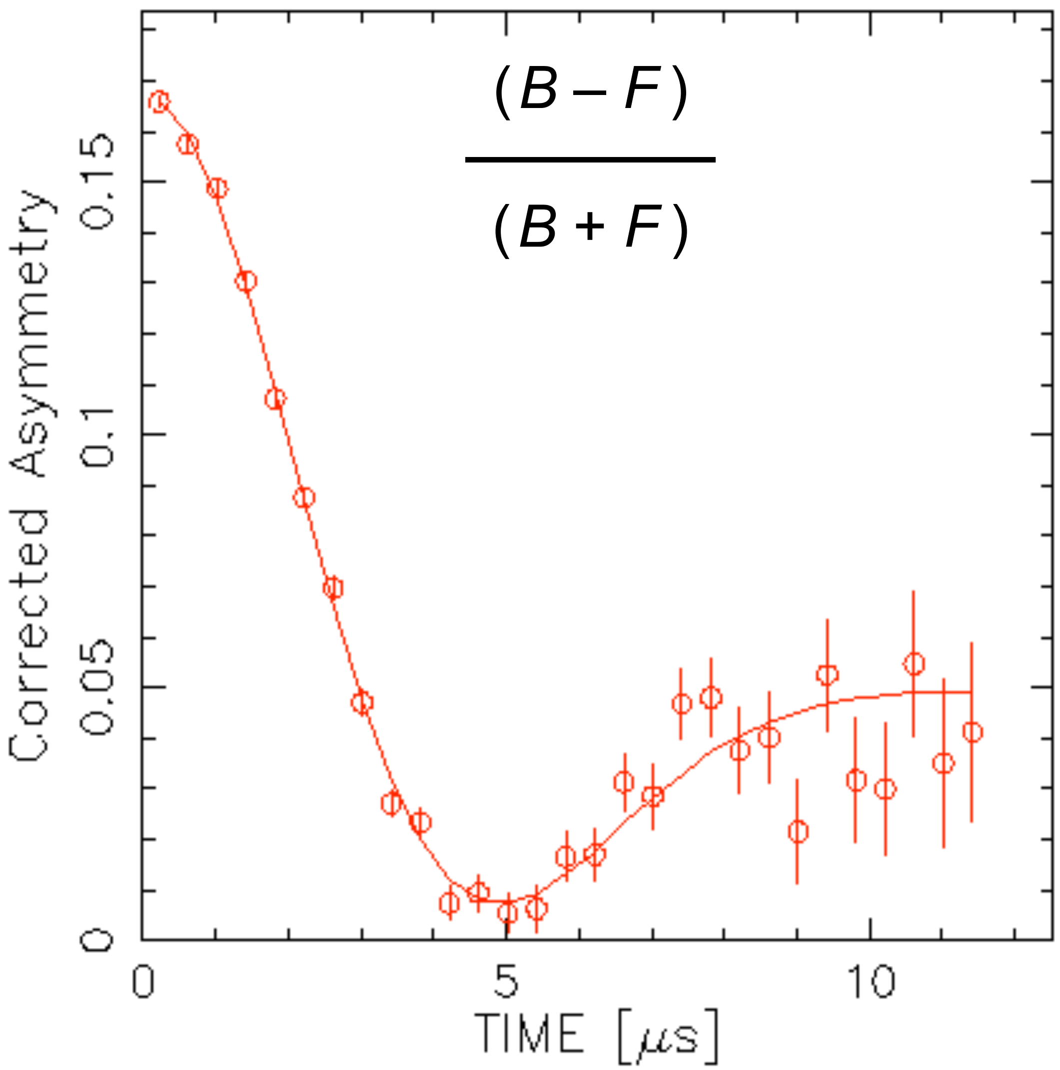
All ↗ do not return to the same orientation at the same time

(dephasing) $\Rightarrow$ $\mathbf{S}_\mu$ "**relaxes**" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

Zero Field (ZF)-μ^+SR

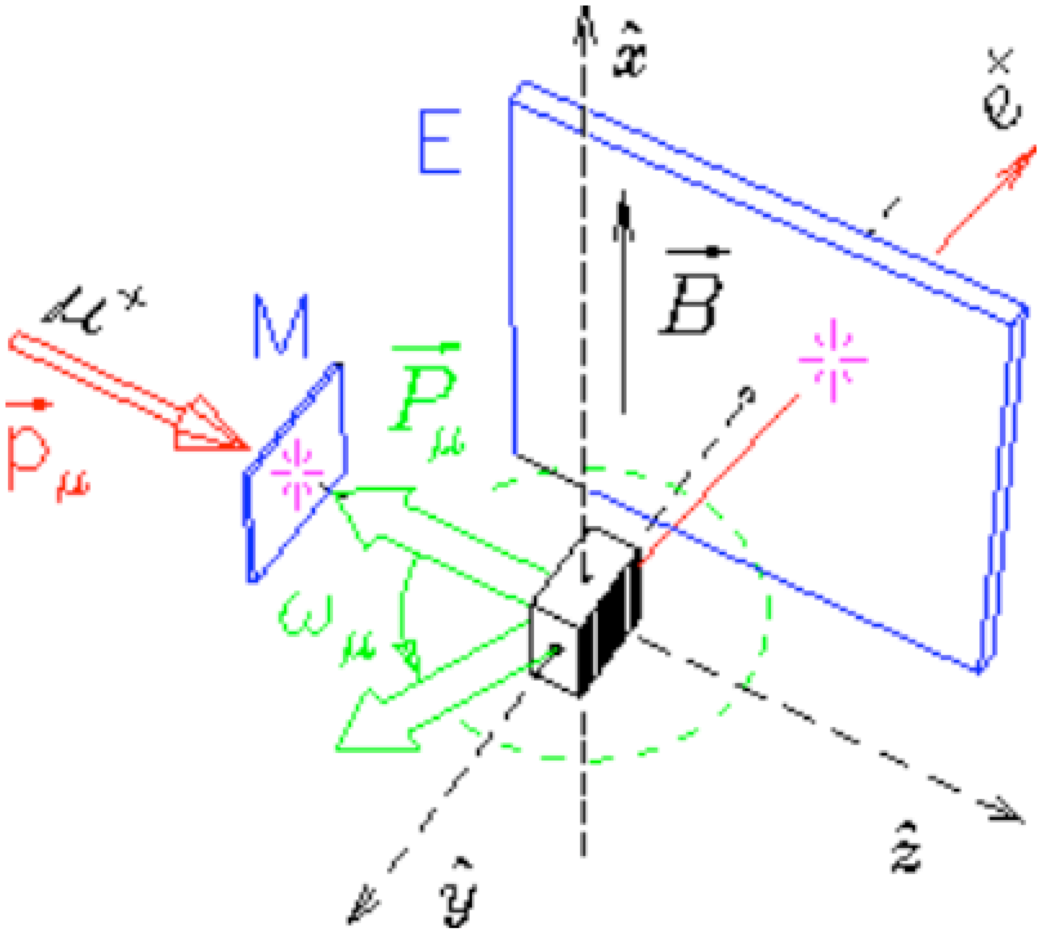


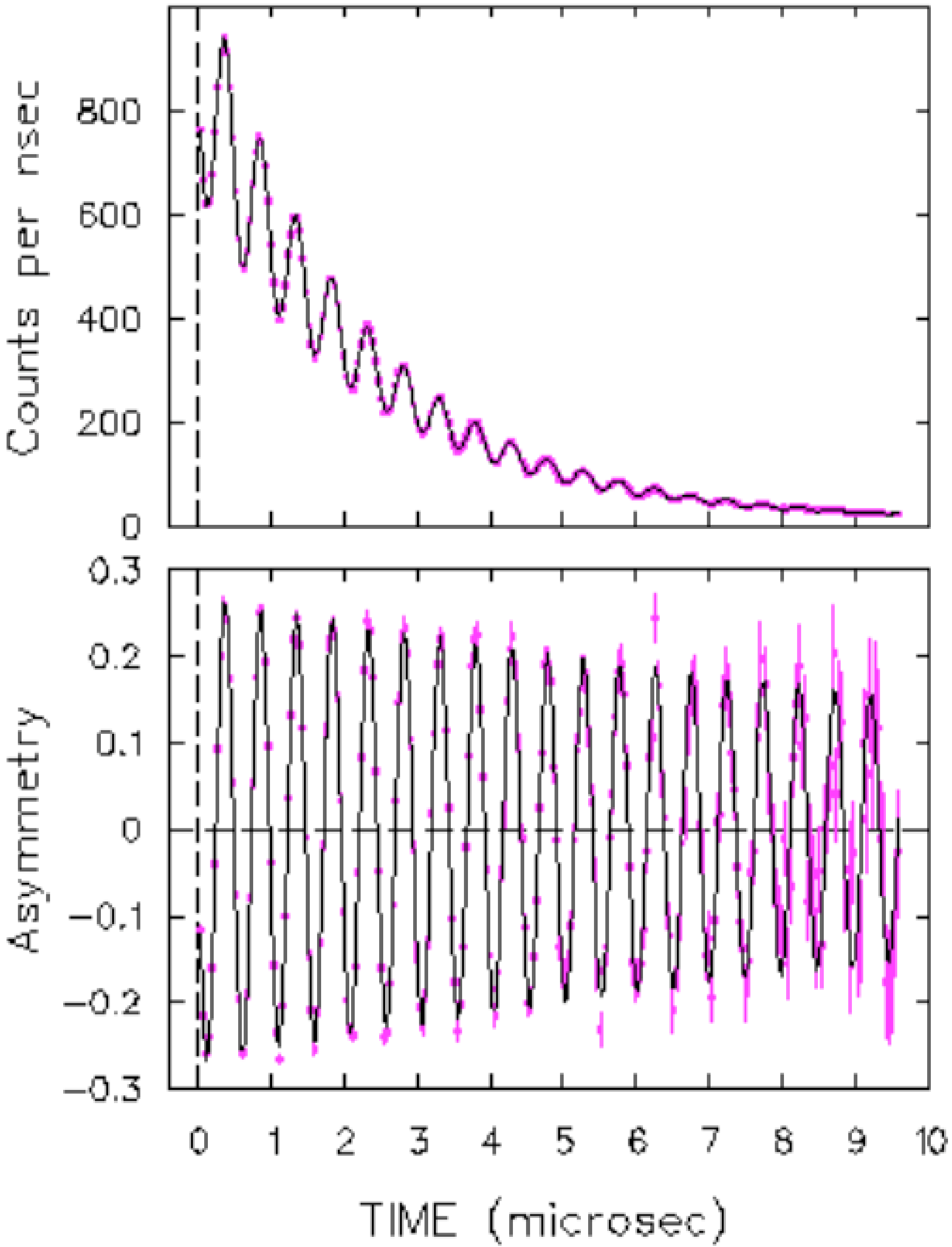
Typical asymmetry spectrum



wTF-μ^+SR:

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



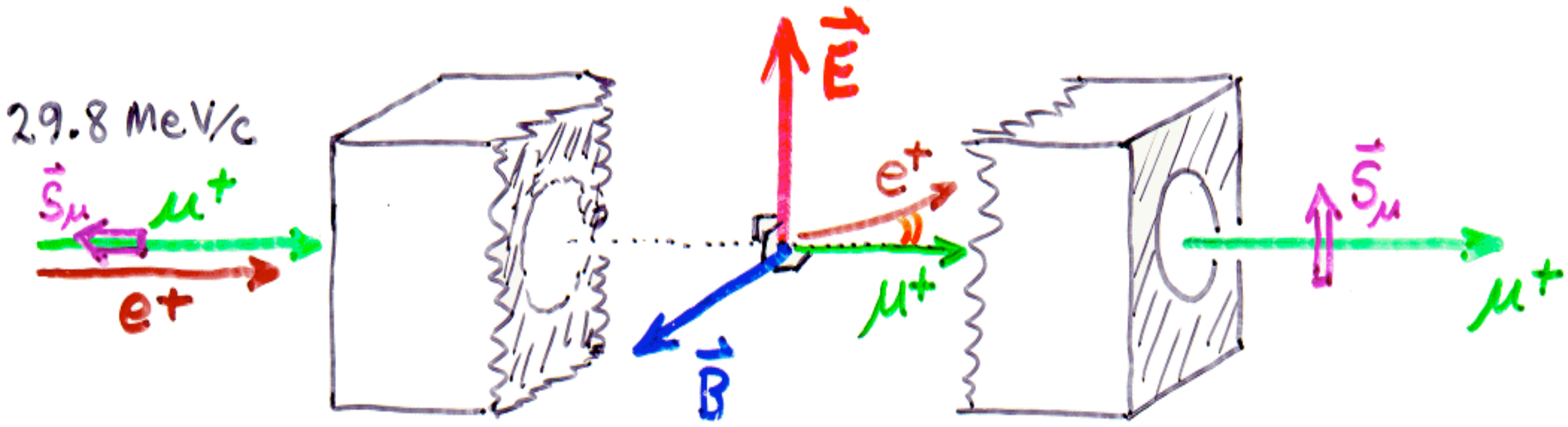


$$\begin{aligned} A(t) &= \left[N(t) - N_0 B \right] e^{+t/\tau_\mu} - 1 \\ &= A_0 G_{xx}(t) \cos(\omega_\mu t + \phi) \end{aligned}$$

E×***B*** velocity selector

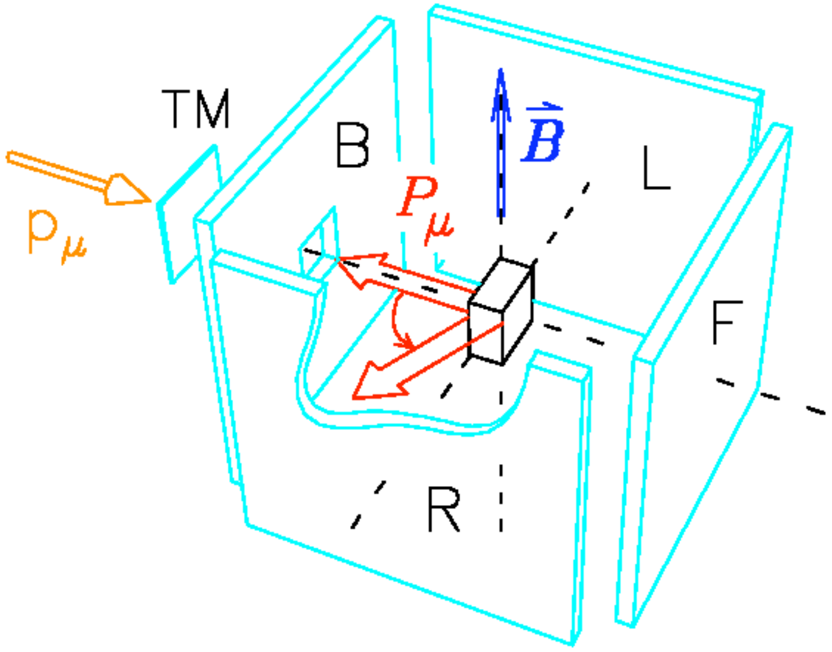
("DC Separator" or Wien filter)

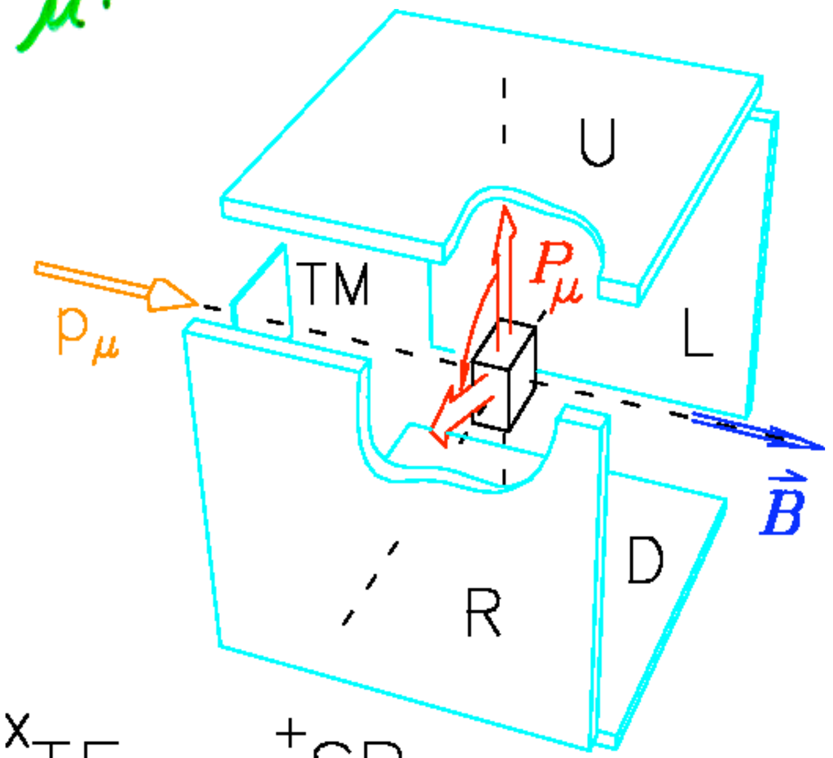
for **surface muons**:



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

$^{z}\mathrm{wTF}_{x}-\mu^{+}\mathrm{SR}$





$^{x}\mathrm{TF}_{z}-\mu^{+}\mathrm{SR}$

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).

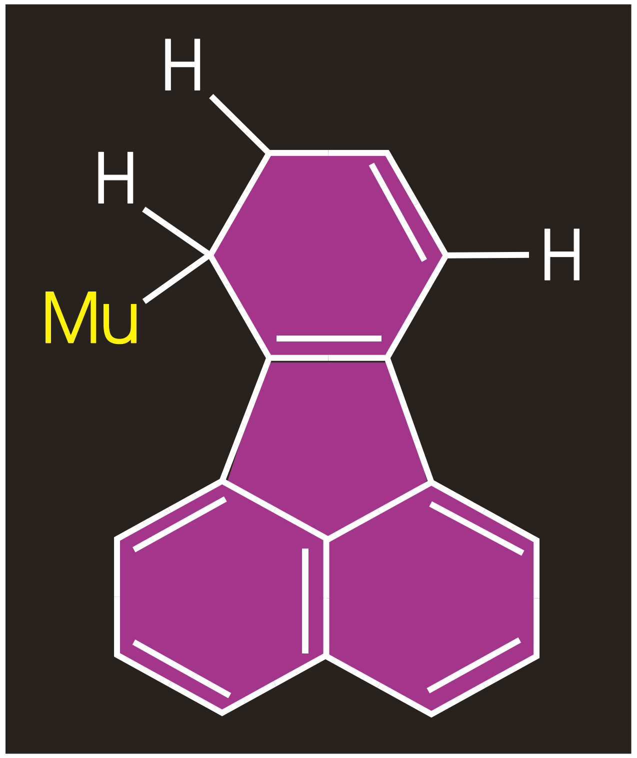
2000s: CMMS

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:

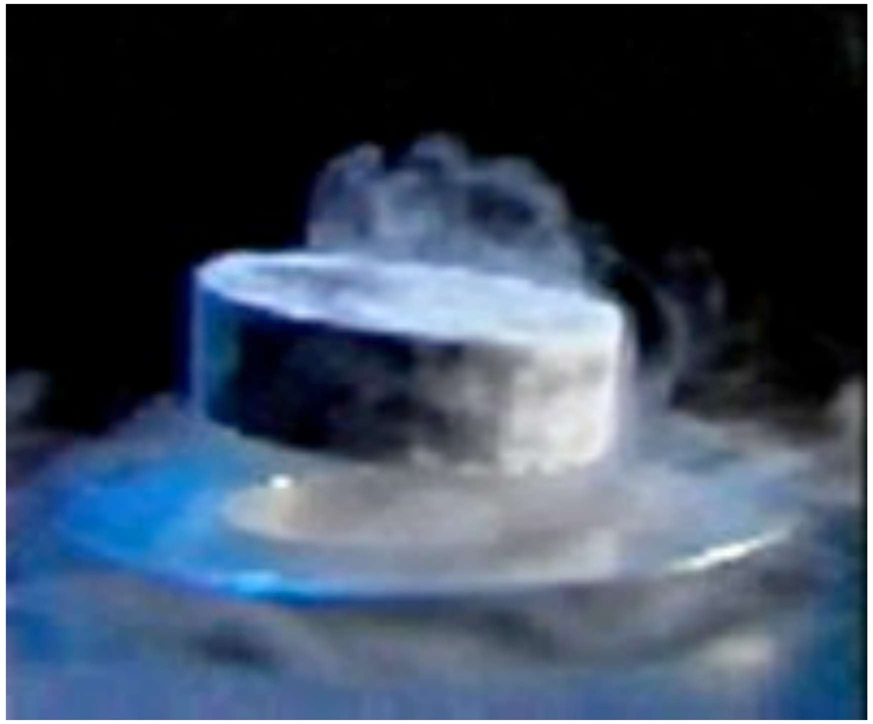
Chemistry Semiconductors Magnetism

Superconductors Fundamental Physics



Recent Applications of *μSR*

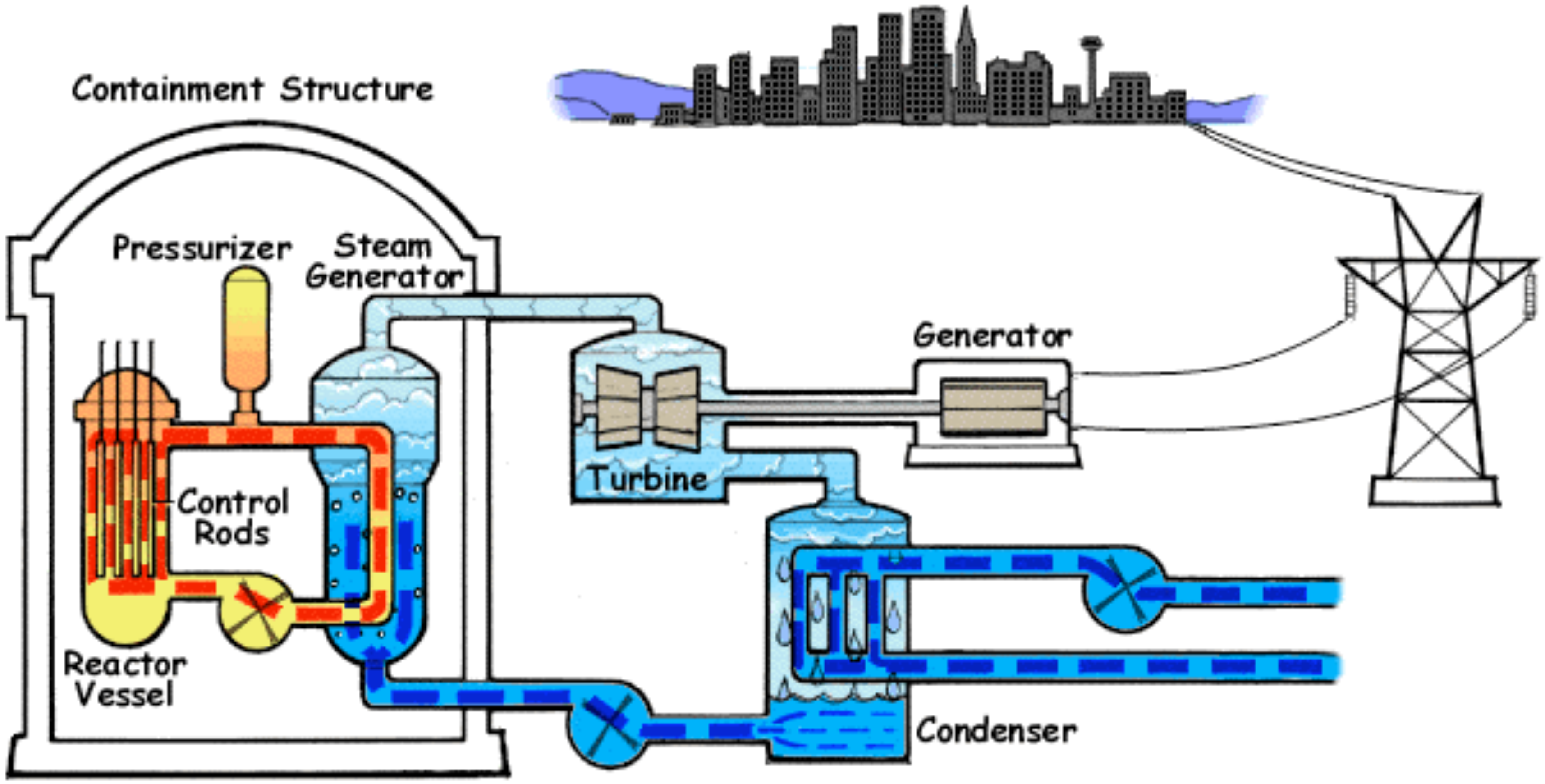
- > Molecular Magnets & Clusters
- > Hydrogen in Semiconductors
- > **Magnetic Polarons**
- > Charged Particle Transport
- > Quantum Impurities
- > Metal-Insulator Transitions
- > Colossal Magnetoresistance
- > Spin Ice Systems
- > Thermoelectric Oxides
- > Photo-Induced Magnetism
- > Magnetic Vortices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

Pressurized Water Nuclear Reactors

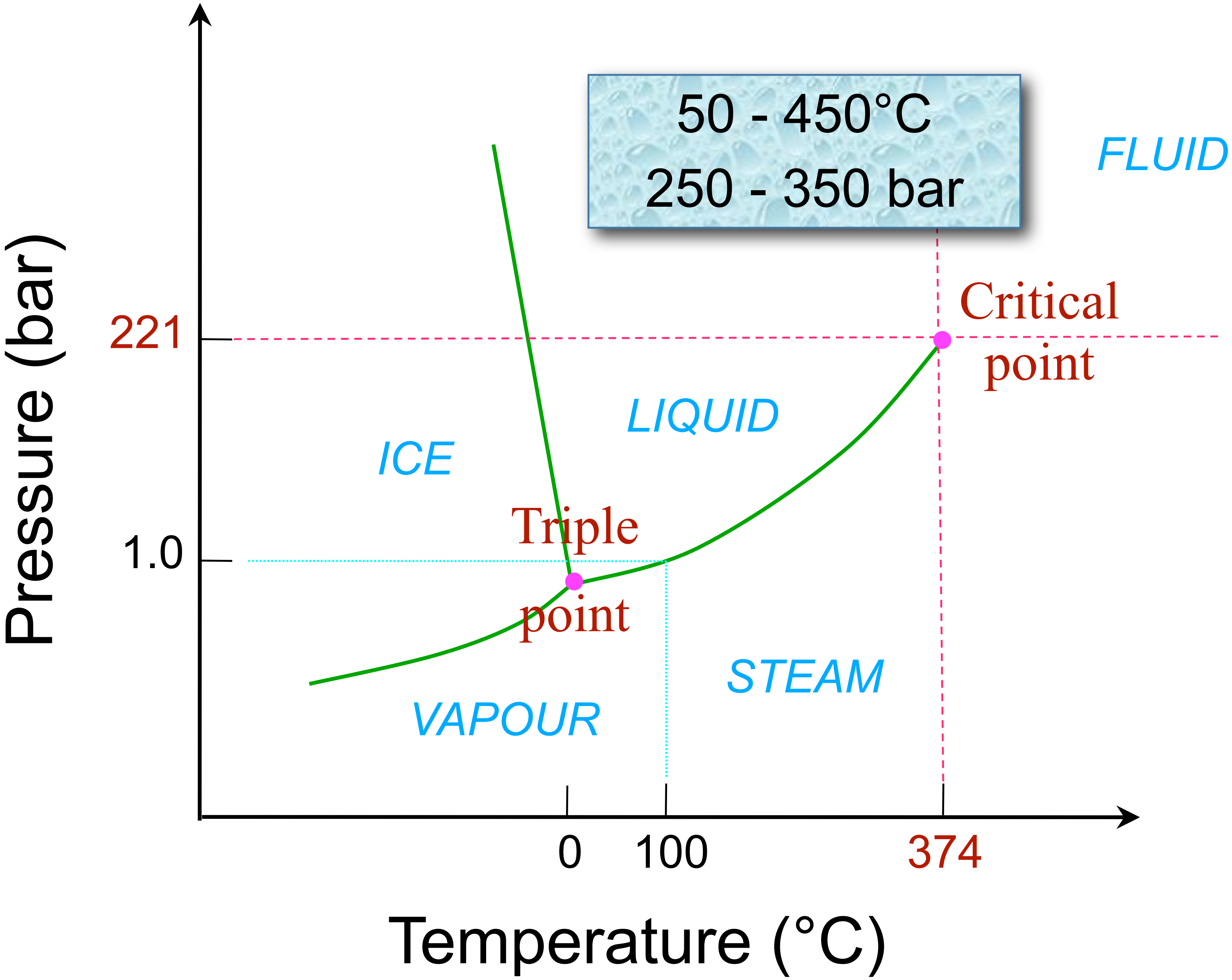
Corrosion in steam power generation systems is serious.



Typical water temperature in primary loop = 325°C

"Next generation" PWR designs use supercritical water at $T > 500^\circ$C.

The Phase Diagram of Water



Supercritical Water Oxidation

There are drastic changes in the physical properties of water close to and above the critical point ($T_c = 374°C$, $P_c = 221$ bar).

This leads to unusual chemistry:

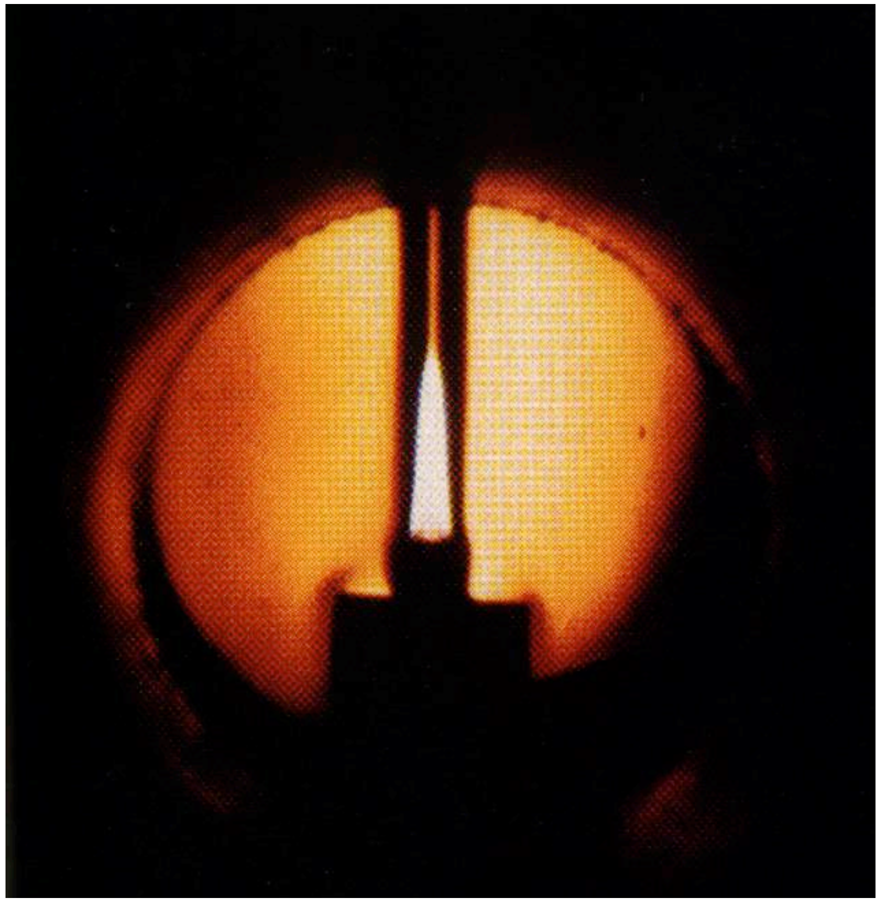
- organic compounds are miscible in SCW
- combustion of organic materials is possible

A Flame in Water!

30% methane in water

2000 bar, 450°C

W. Schilling and E.U. Franck, Ber. Bunsenges. Phys. Chem. 92 (1988) 631.



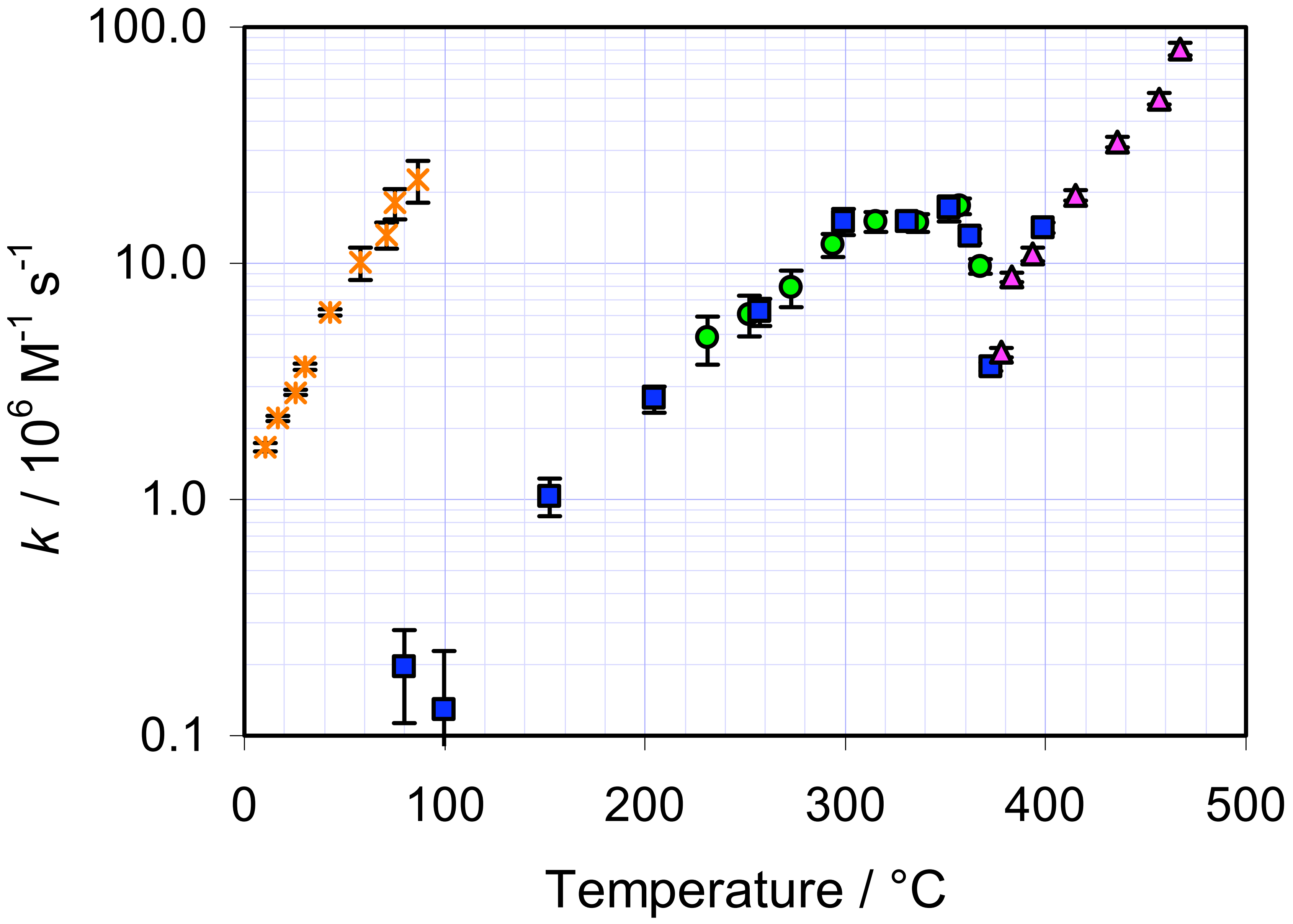
H abstraction from methanol by H (Mu)

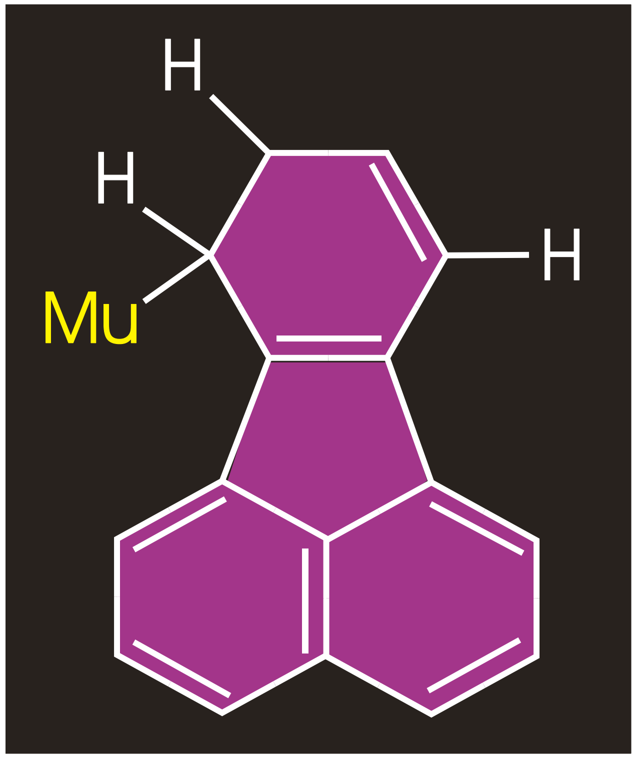
$H + CH_3OH$

Mezyk & Bartels, 1994

$Mu + CH_3OH$

Percival *et al.*, 2007

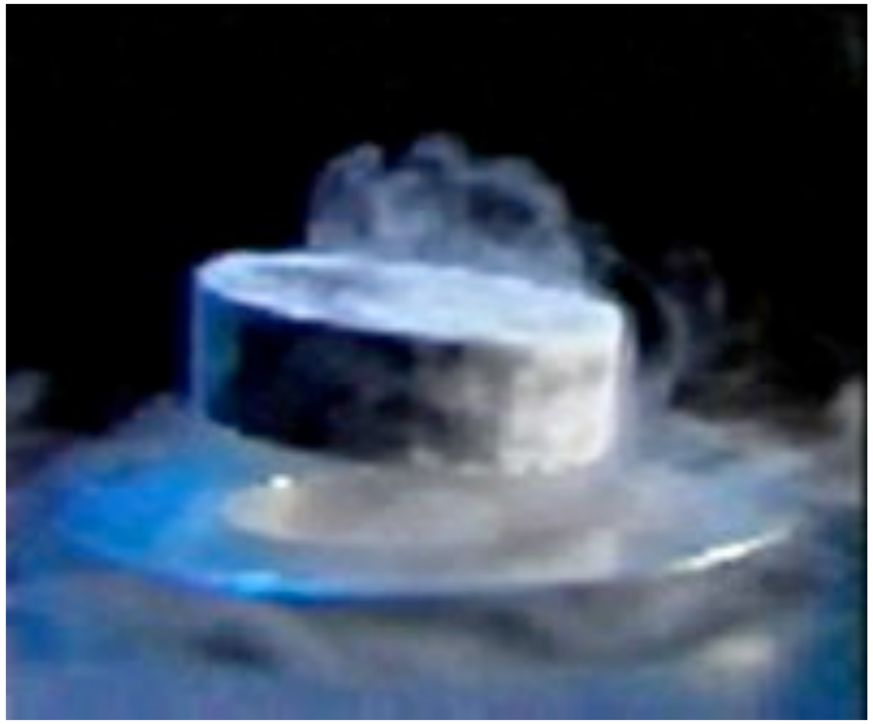




Recent Applications of *μSR*

- > 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.

- > 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**



Unsolicited Advice

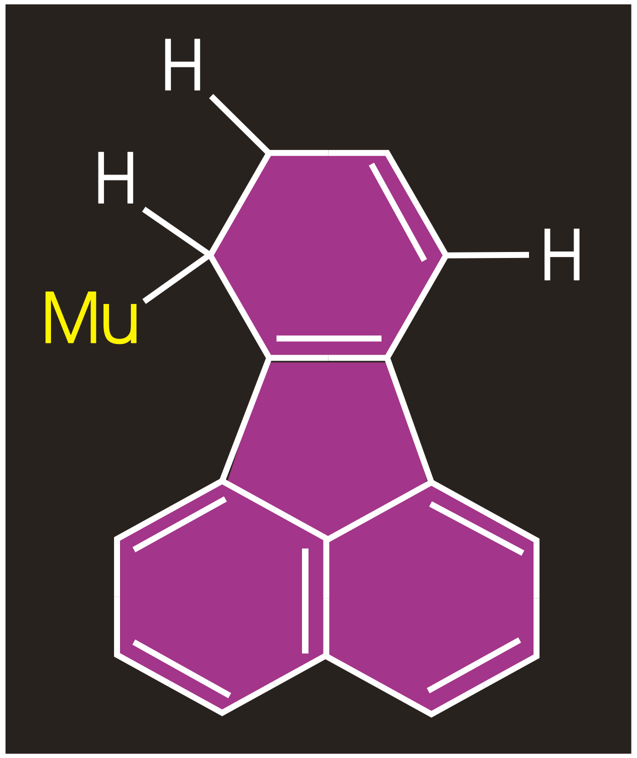
- Find out what you can't stand ***not*** to do. That's what a University education is **for**.
- Have *fun* doing it **well**!
- Take *risks* on **intuition**. Security is an illusion, and not much fun anyway. Read *"Blink"*.
- Compete in **athletics**. Be a good sport in mind and body.
- Learn to ***write***. It is the **most essential skill** of a *scientist*. Take some creative writing courses. I'm not kidding!
- *Don't follow the pack.* Pick a research topic that no one else thinks is important (but make sure they're all wrong). Do the definitive work in the field and get out just before it becomes fashionable, or else you'll have to put up with a lot of bad behaviour from otherwise nice people.

Finis

Appendices

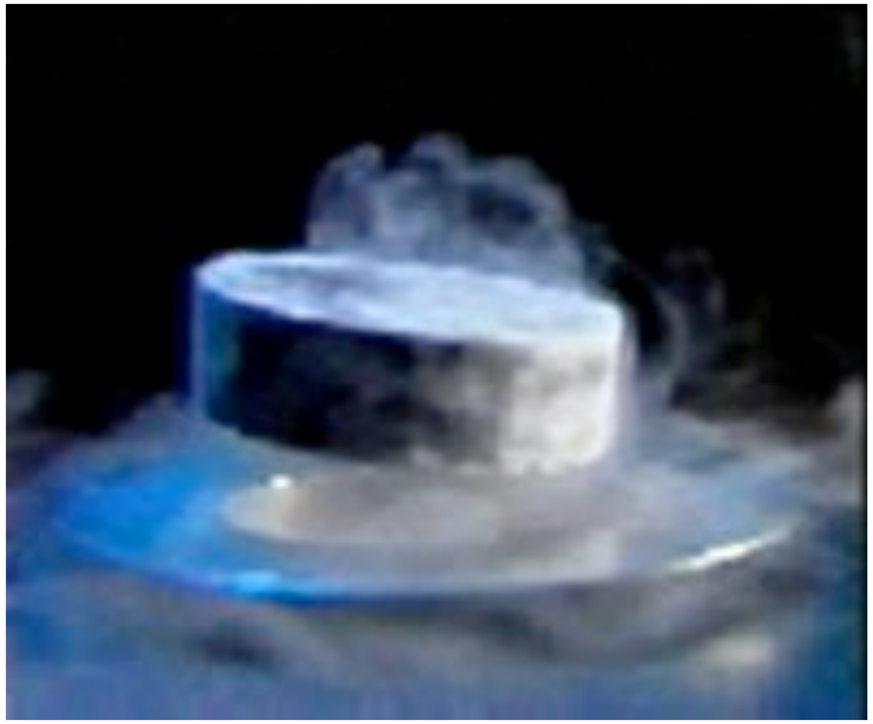
↓

Recent Applications of *μSR*

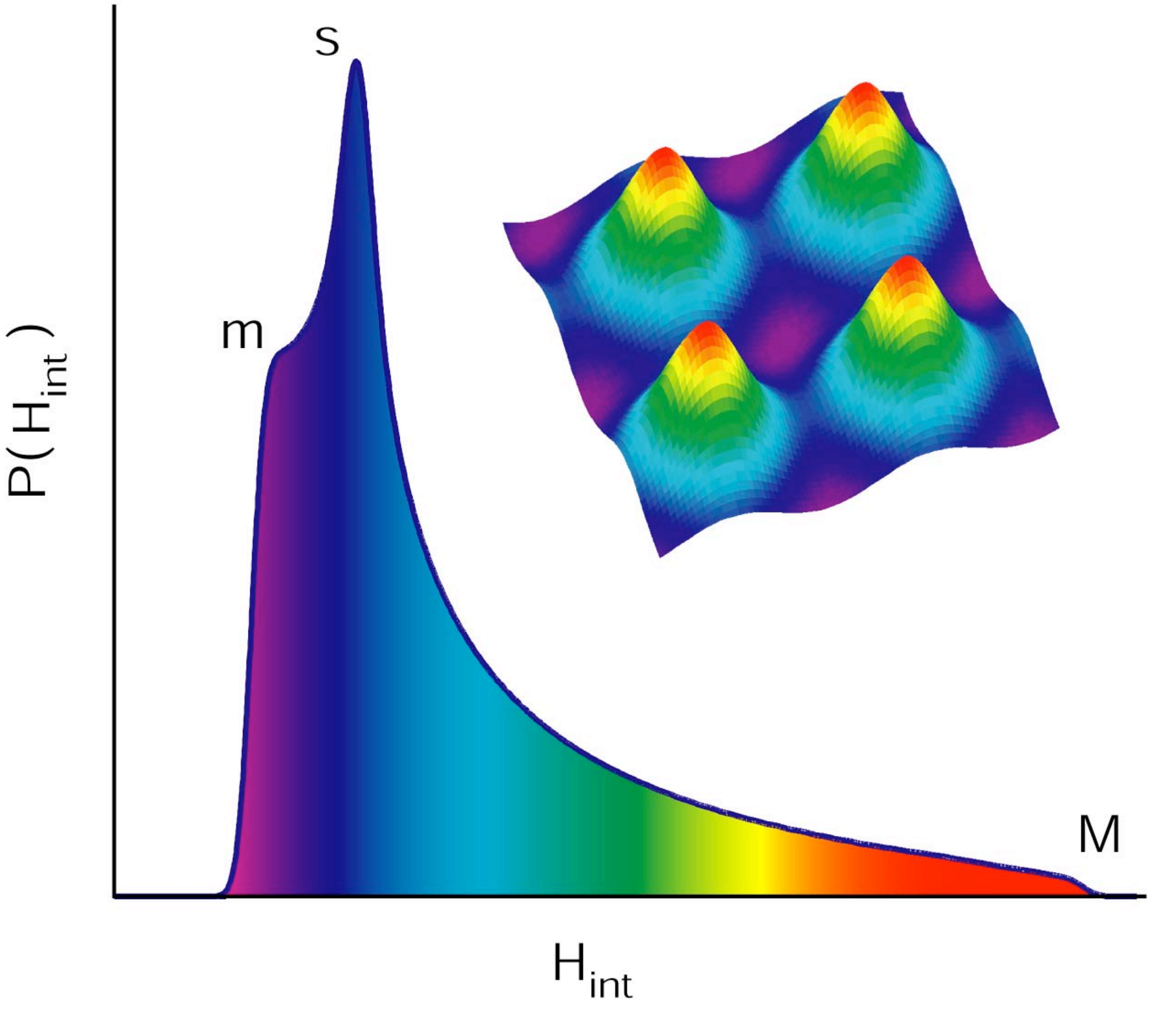


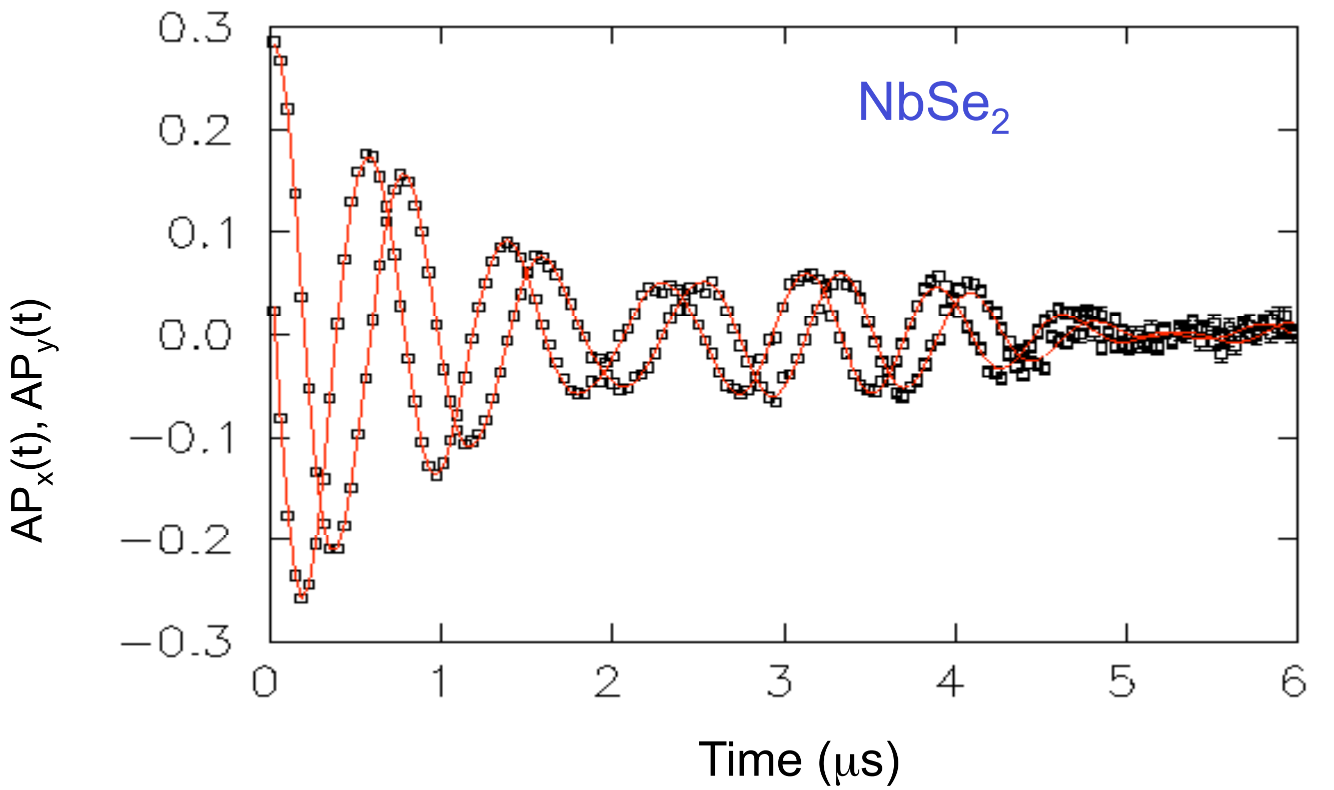
- Molecular Structure & Conformational Motion of Organic Free Radicals
- Hydrogen Atom Kinetics
- “Green Chemistry” in Supercritical CO_2
- Catalysis
- Mass Effects in Chemical Processes
- Ionic Processes at Interfaces
- **Reactions in Supercritical Water**
- Radiation Chemistry & Track Effects in Condensed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

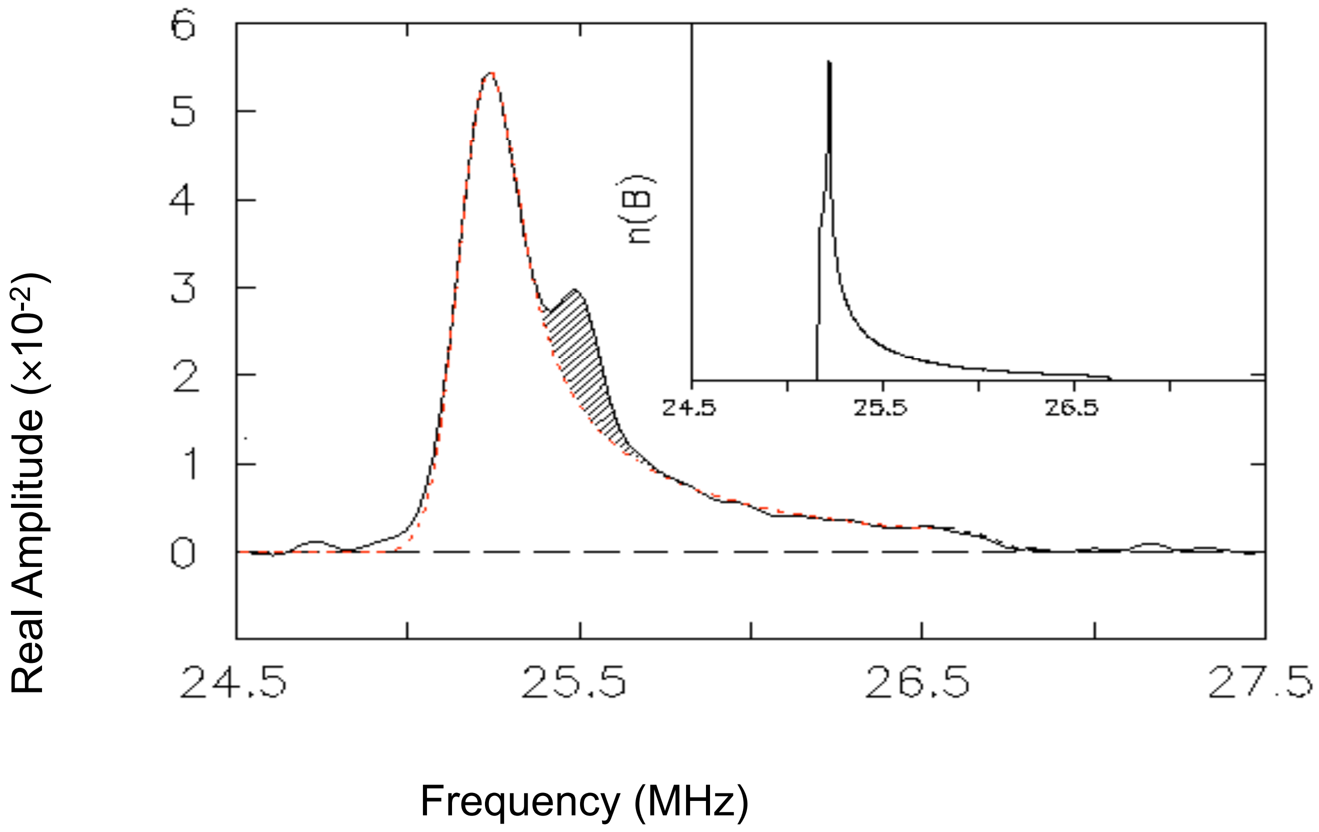
- Molecular Magnets & Clusters
- Hydrogen in Semiconductors
- **Magnetic Polarons**
- Charged Particle Transport
- Quantum Impurities
- Metal-Insulator Transitions
- Colossal Magnetoresistance
- Spin Ice Systems
- Thermoelectric Oxides
- Photo-Induced Magnetism
- Magnetic Vortices
- Heavy Fermions
-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



Magnetic Field Distribution of a Vortex Lattice

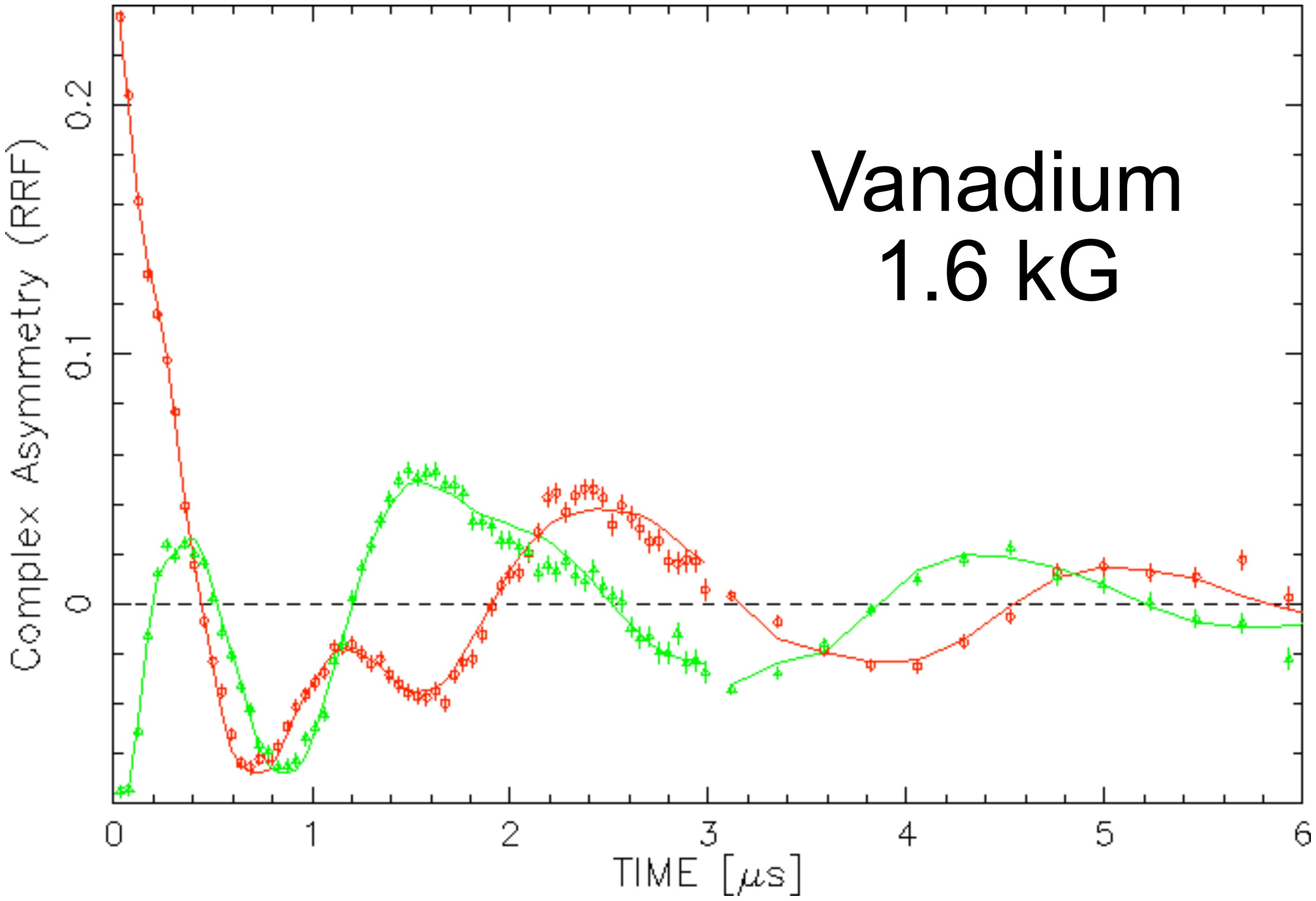




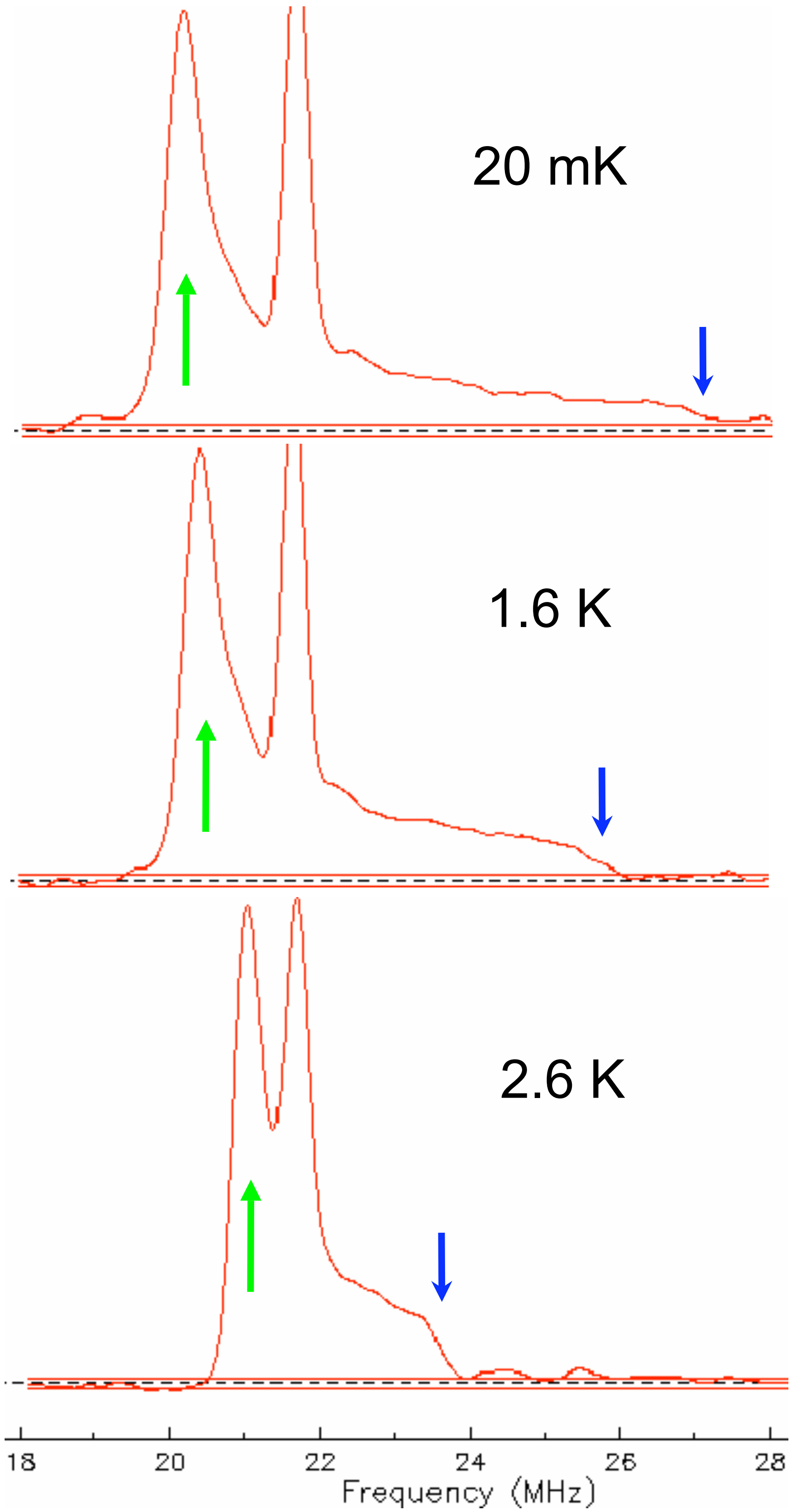


HTF-μ^+SR

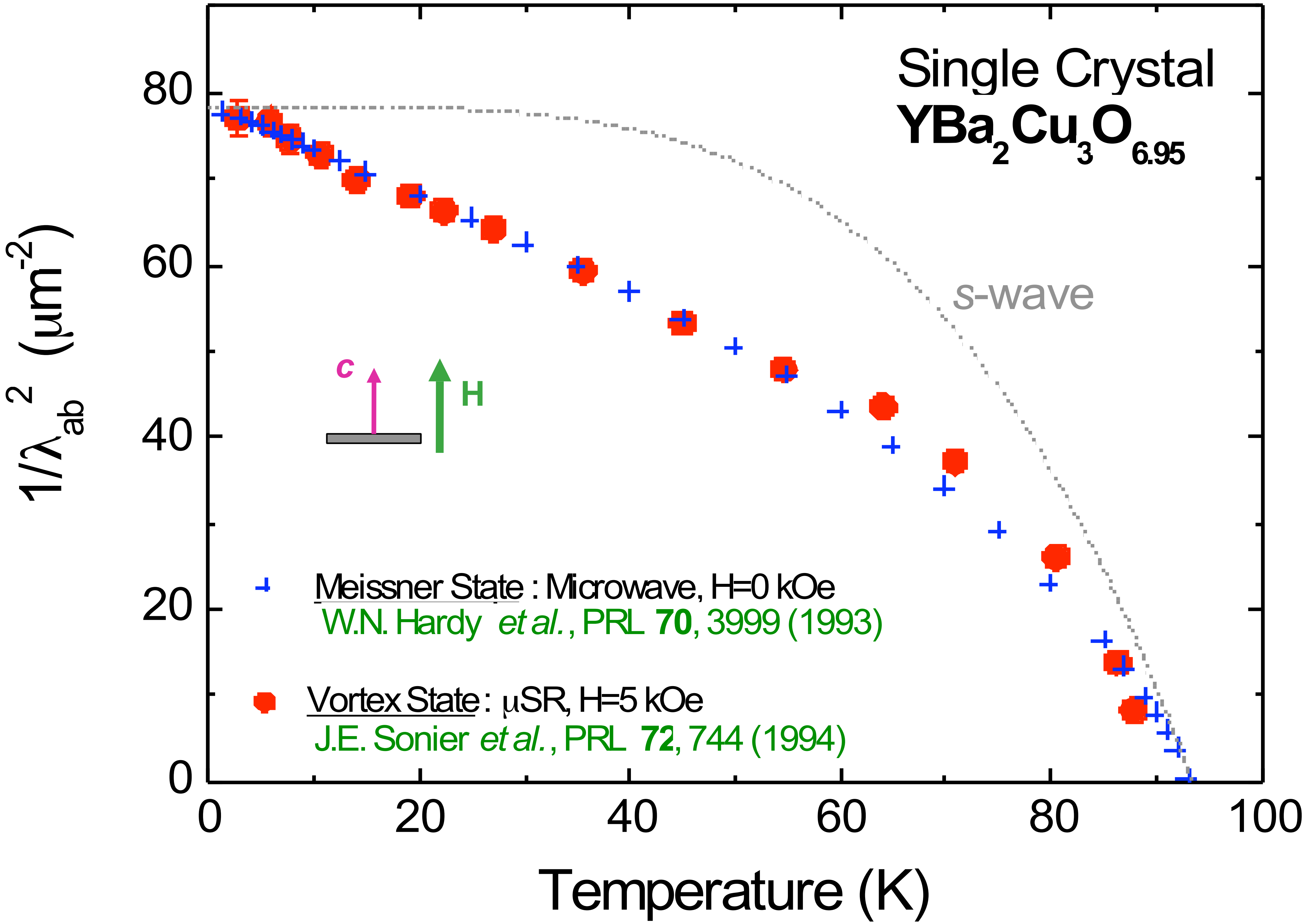
FFT Lineshapes



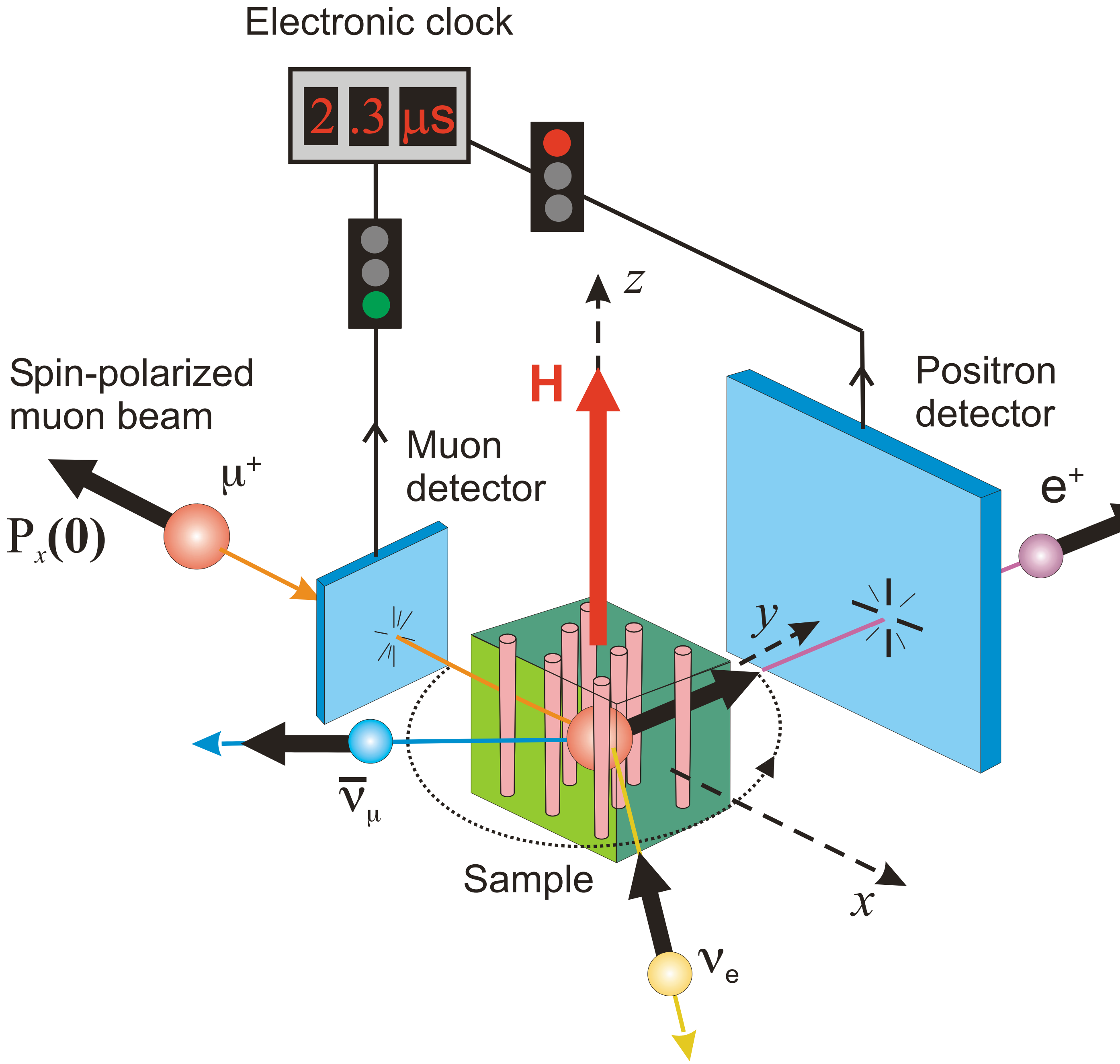
Fit in the time domain.

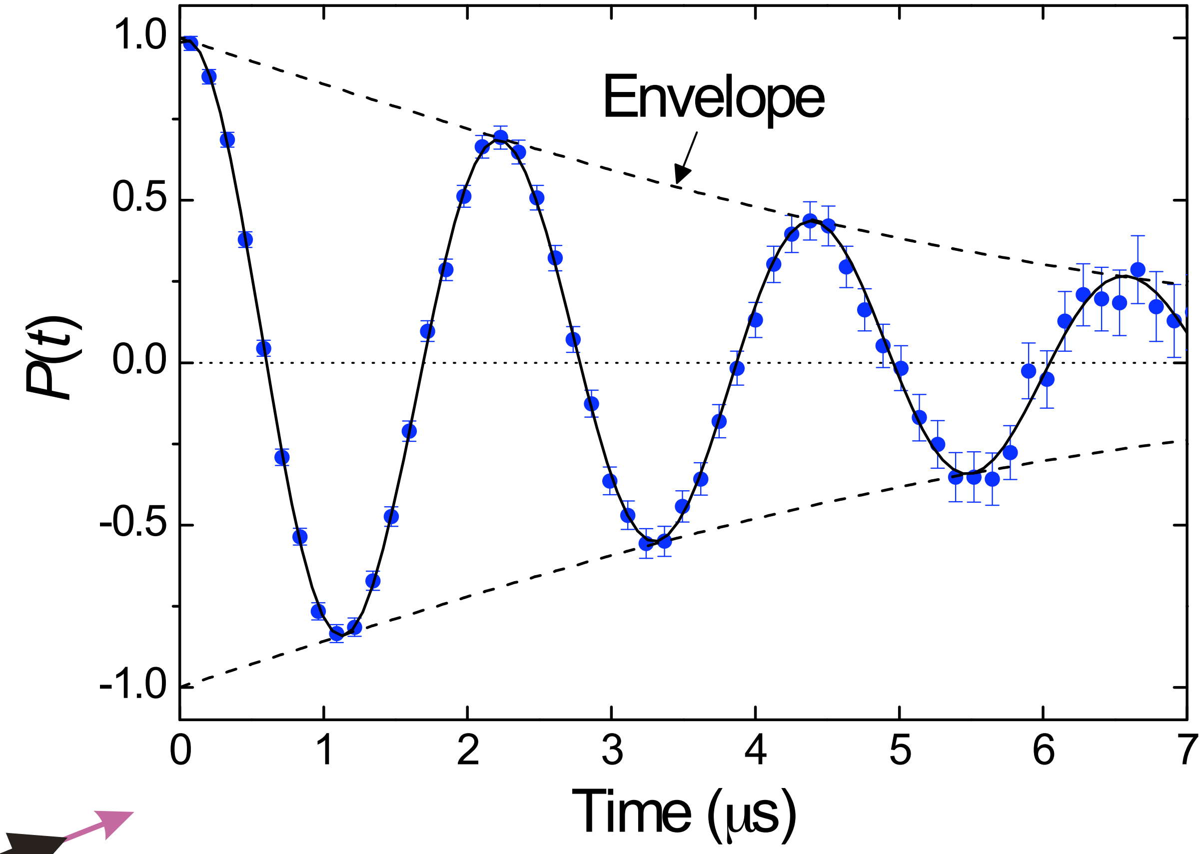


$1/\lambda_{ab}^2$ *in the Meissner & Vortex States*



Transverse Field μSR





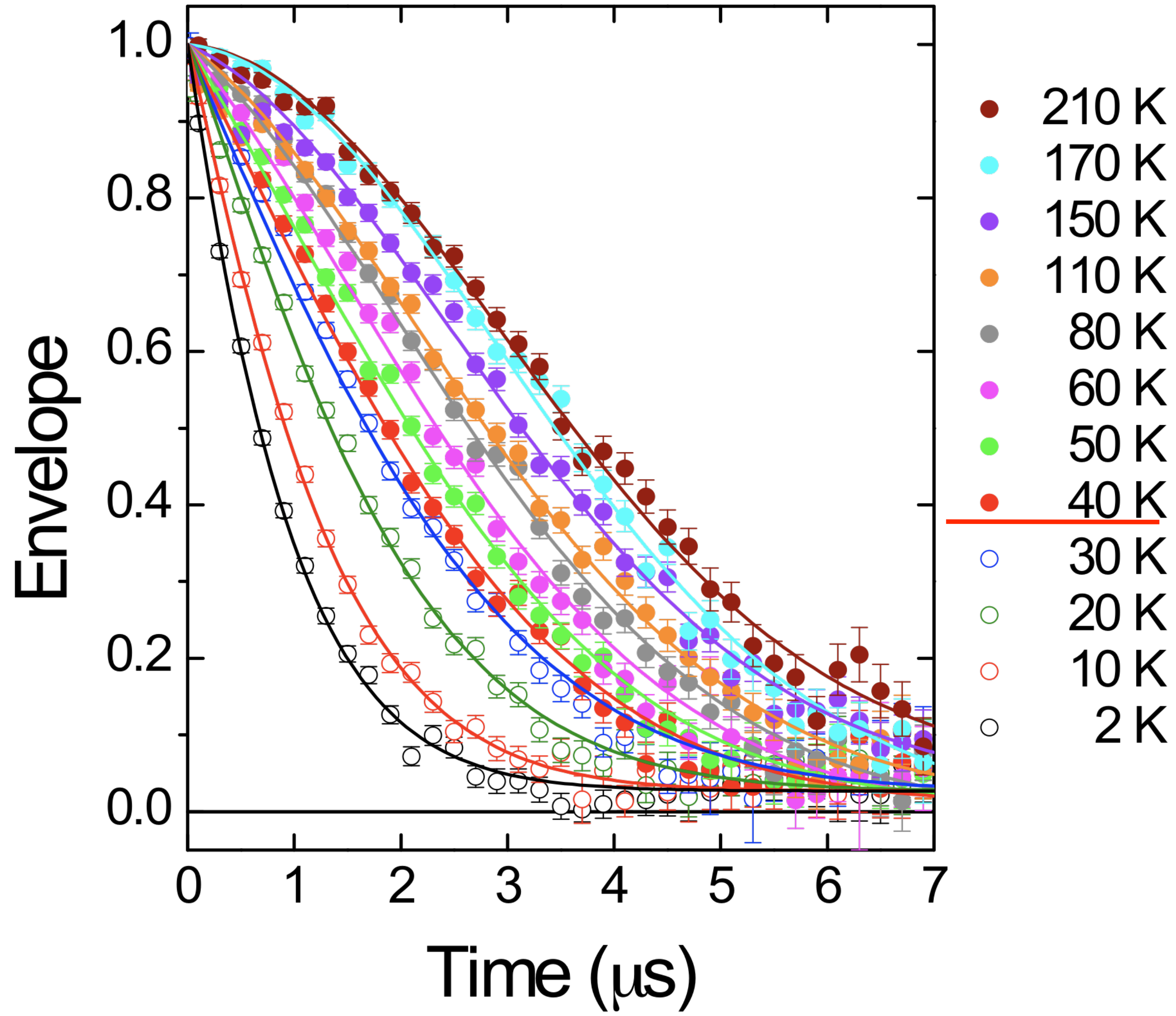
The time evolution of the muon spin polarization is described by:

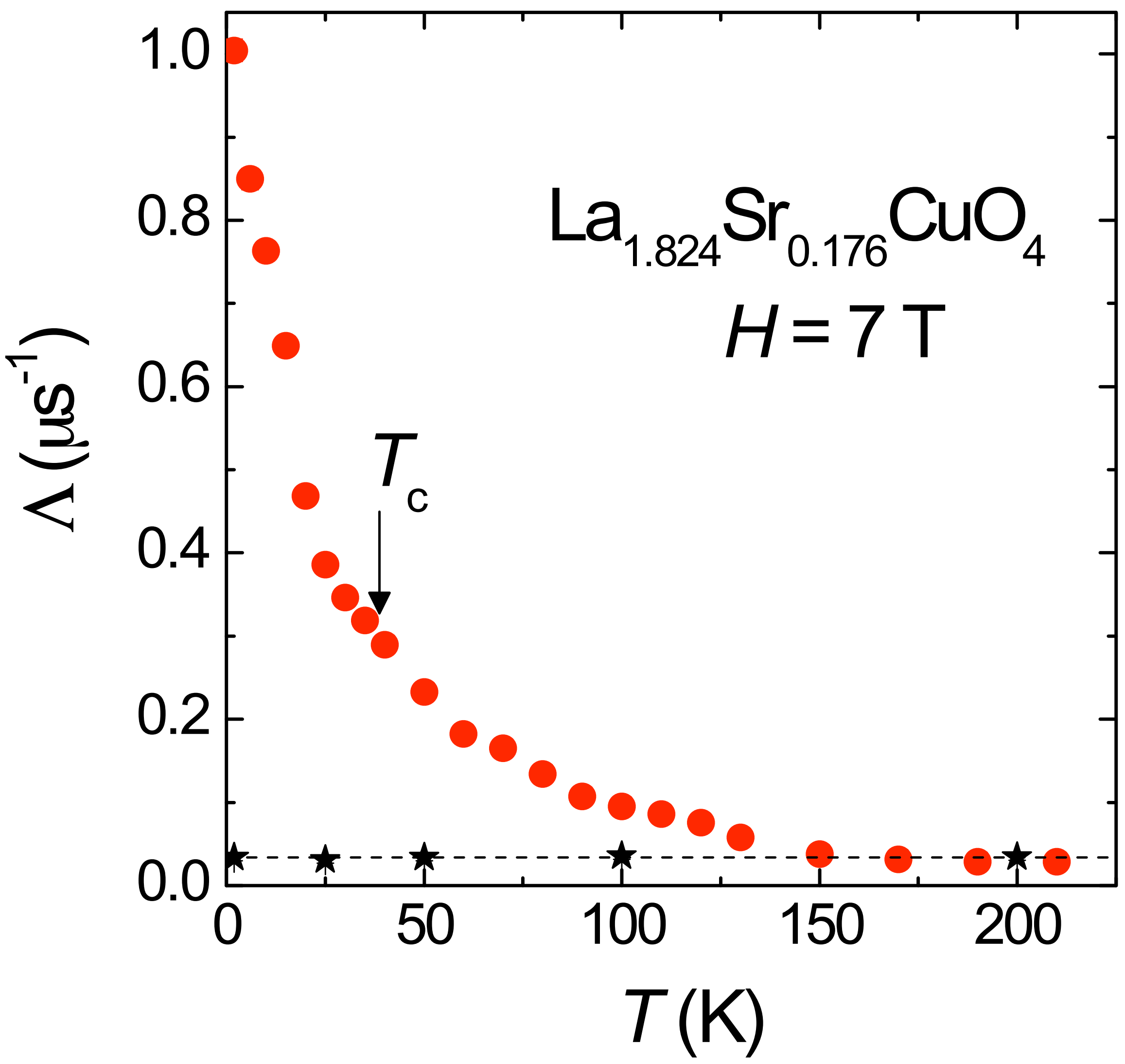
$$P(t) = G(t) \cos(\gamma_\mu B_\mu + \varphi)$$

where $G(t)$ is a relaxation function describing the ***envelope*** of the TF-μSR signal.

With high-field capability and dual spin rotators, TRIUMF is the premiere facility in the world for TF-μSR!

Relaxation of TF-μSR Signal in $La_{1.824}Sr_{0.176}CuO_4$ (T_c = 37.1 K) at H = 7T





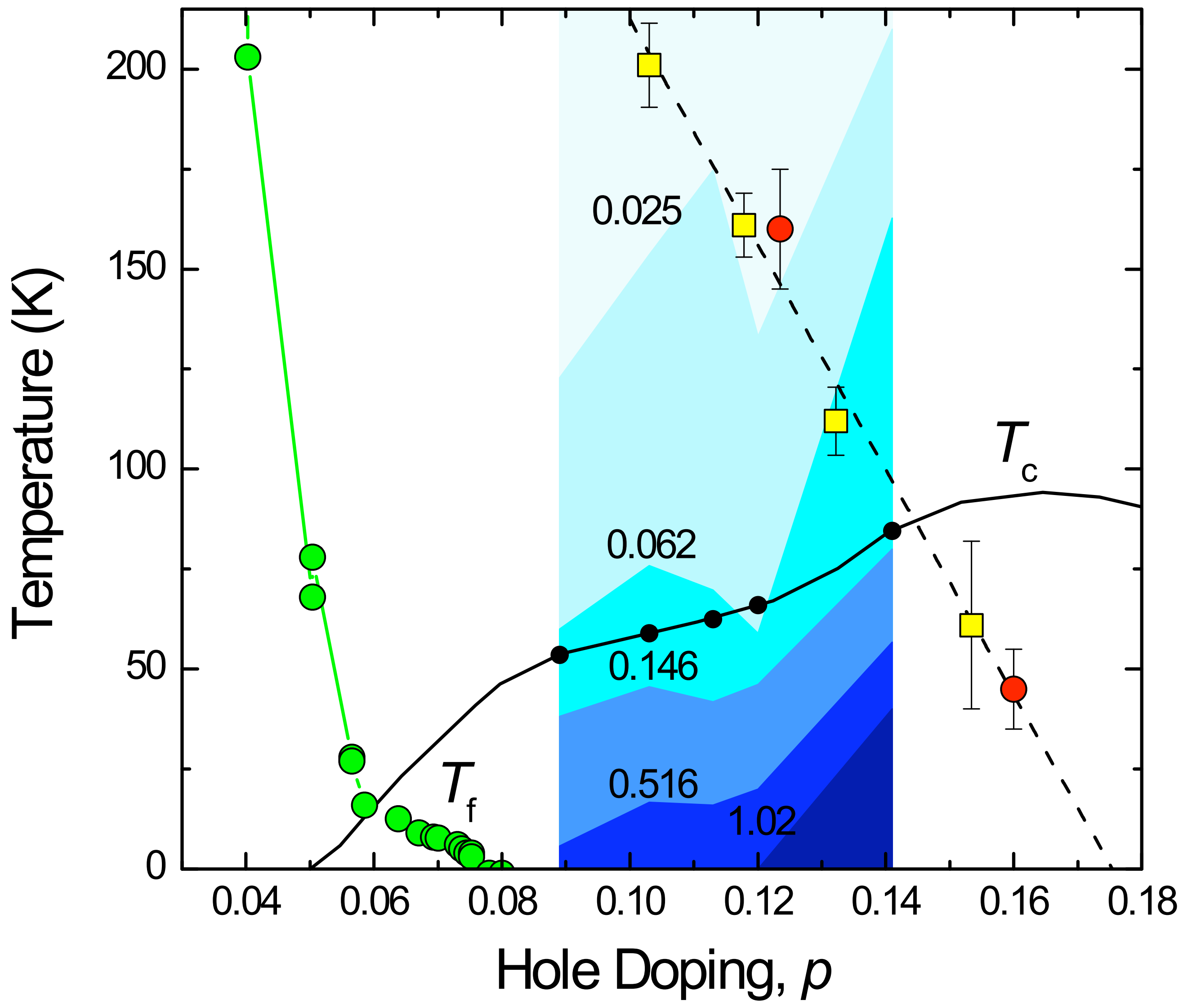
$$G(t) = \underbrace{\exp(-\Lambda t)}_{\text{spatial field inhomogeneity}}\overbrace{\exp(-\Delta^2 t^2)}^{\text{nuclear dipoles}}$$

♥ $\Lambda \neq 0$ at $T < T_c$ due to field inhomogeneity created by a vortex lattice.

♥ $\Lambda \neq 0$ at $T > T_c$. **Why?**

Inhomogeneous Magnetic Response of $YBa_2Cu_3O_{6+x}$ Above T_c

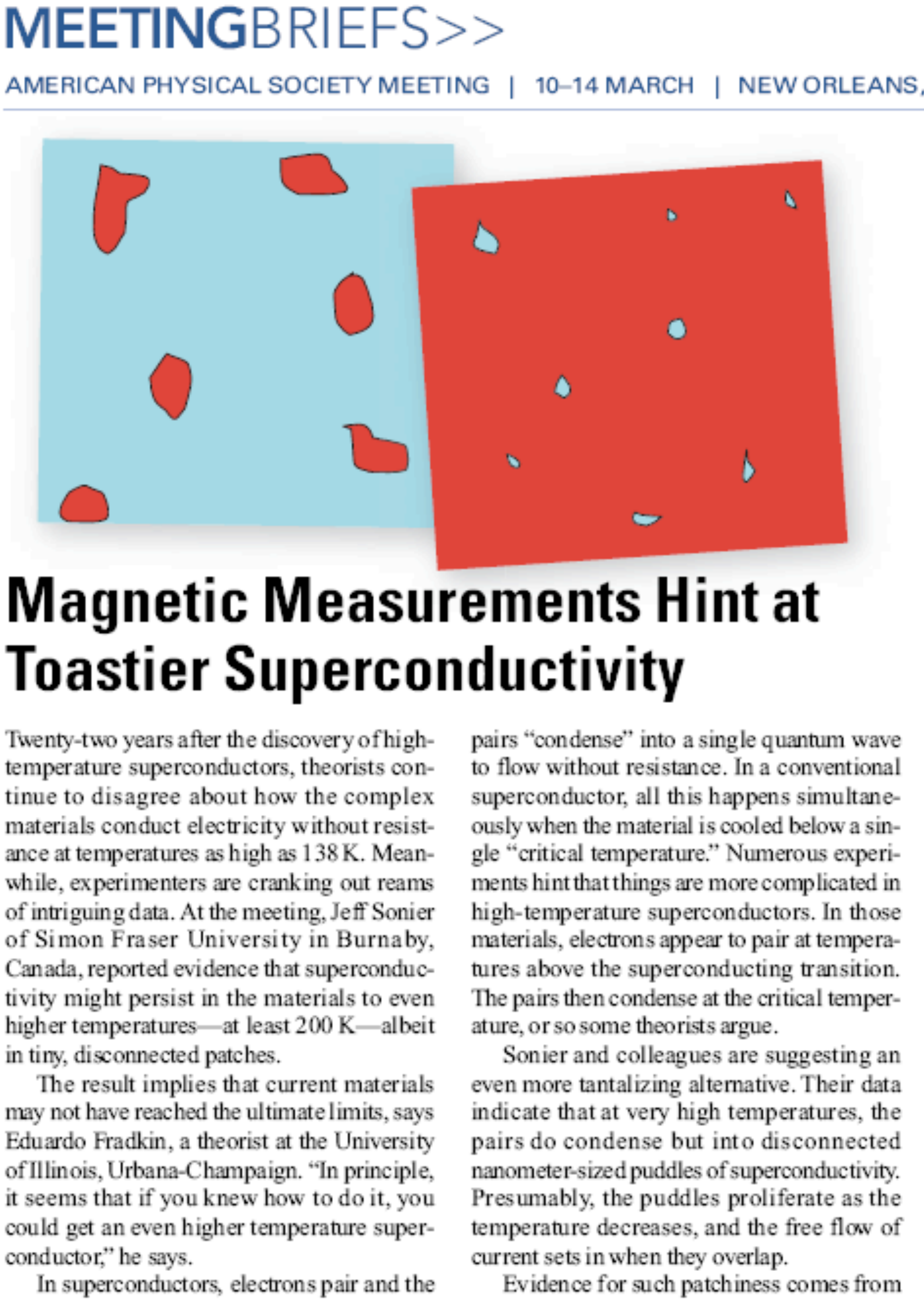
Physical Review Letters **101**, 117001 (2008)



- 🟢 Kiefl *et al.* Physical Review Letters **63**, 2136 (1989)
- 🔴 Sonier *et al.* Science **292**, 1692 (2001)

Magnetic phases previously discovered by μSR at TRIUMF

Science **320**, 42-43 (2008)



MEETINGBRIEFS>>

AMERICAN PHYSICAL SOCIETY MEETING | 10–14 MARCH | NEW ORLEANS

Magnetic Measurements Hint at Toastier Superconductivity

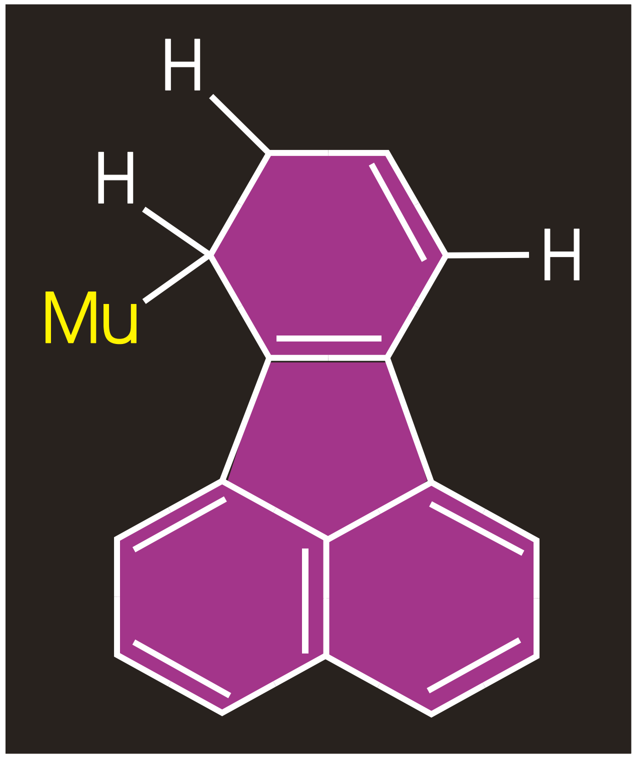
Twenty-two years after the discovery of high-temperature superconductors, theorists continue to disagree about how the complex materials conduct electricity without resistance at temperatures as high as 138 K. Meanwhile, experimenters are cranking out reams of intriguing data. At the meeting, Jeff Sonier of Simon Fraser University in Burnaby, Canada, reported evidence that superconductivity might persist in the materials to even higher temperatures—at least 200 K—albeit in tiny, disconnected patches.

The result implies that current materials may not have reached the ultimate limits, says Eduardo Fradkin, a theorist at the University of Illinois, Urbana-Champaign. "In principle, it seems that if you knew how to do it, you could get an even higher temperature superconductor," he says.

In superconductors, electrons pair and the pairs "condense" into a single quantum wave to flow without resistance. In a conventional superconductor, all this happens simultaneously when the material is cooled below a single "critical temperature." Numerous experiments hint that things are more complicated in high-temperature superconductors. In those materials, electrons appear to pair at temperatures above the superconducting transition. The pairs then condense at the critical temperature, or so some theorists argue.

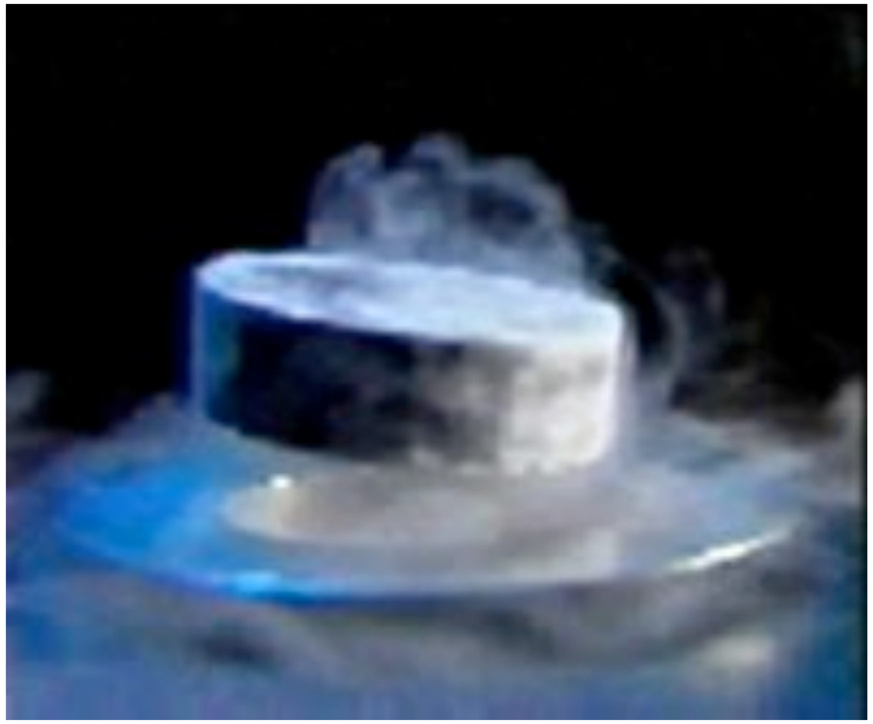
Sonier and colleagues are suggesting an even more tantalizing alternative. Their data indicate that at very high temperatures, the pairs do condense but into disconnected nanometer-sized puddles of superconductivity. Presumably, the puddles proliferate as the temperature decreases, and the free flow of current sets in when they overlap.

Evidence for such patchiness comes from



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**

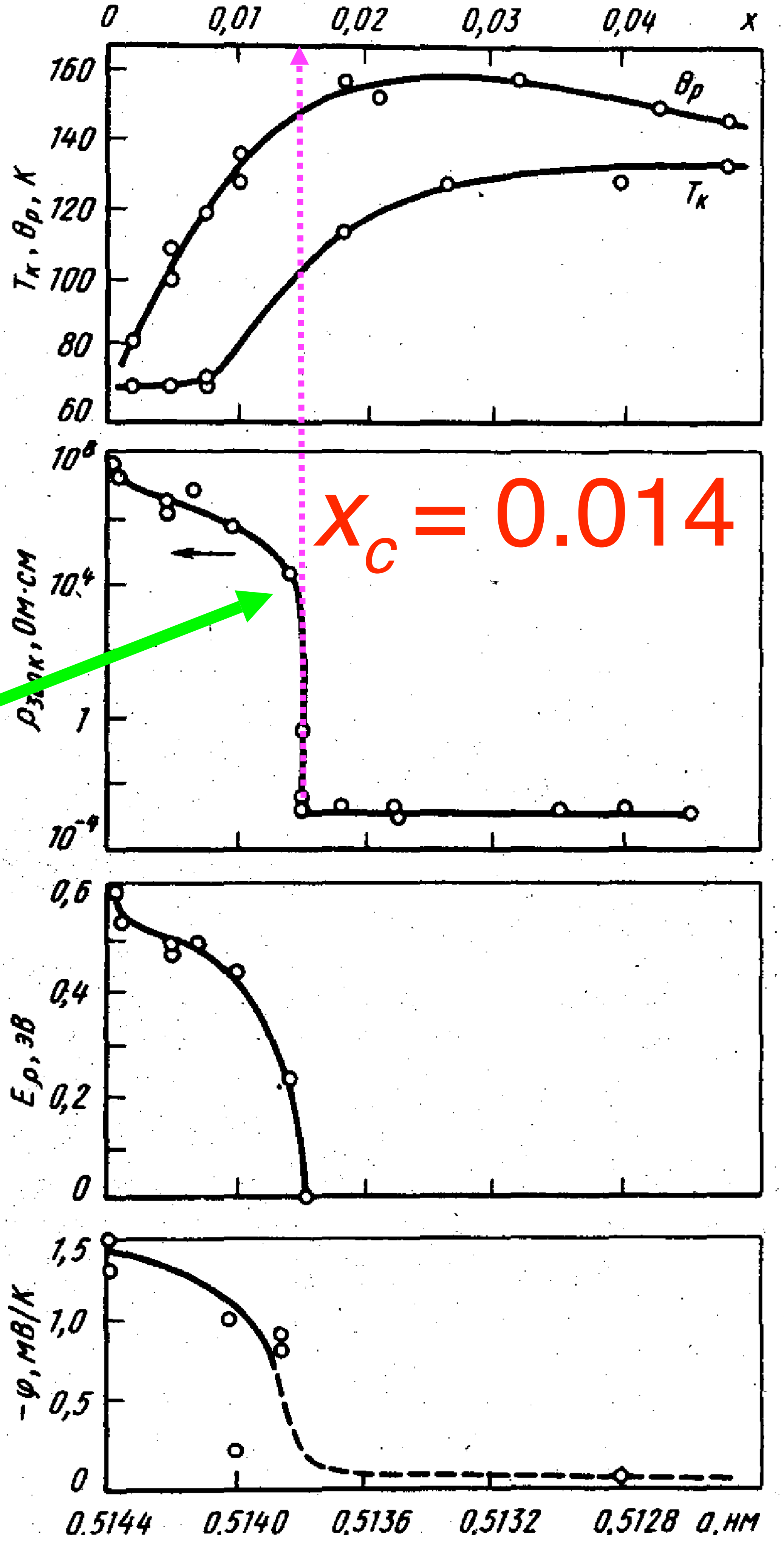


- > Molecular Structure & Conformational Motion of Organic Free Radicals
- > Hydrogen Atom Kinetics
- > "Green Chemistry" in Supercritical CO_2
- > Catalysis
- > Mass Effects in Chemical Processes
- > Ionic Processes at Interfaces
- > **Reactions in Supercritical Water**
- > Radiation Chemistry & Track 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.

$Eu_{1-x}Gd_xO$

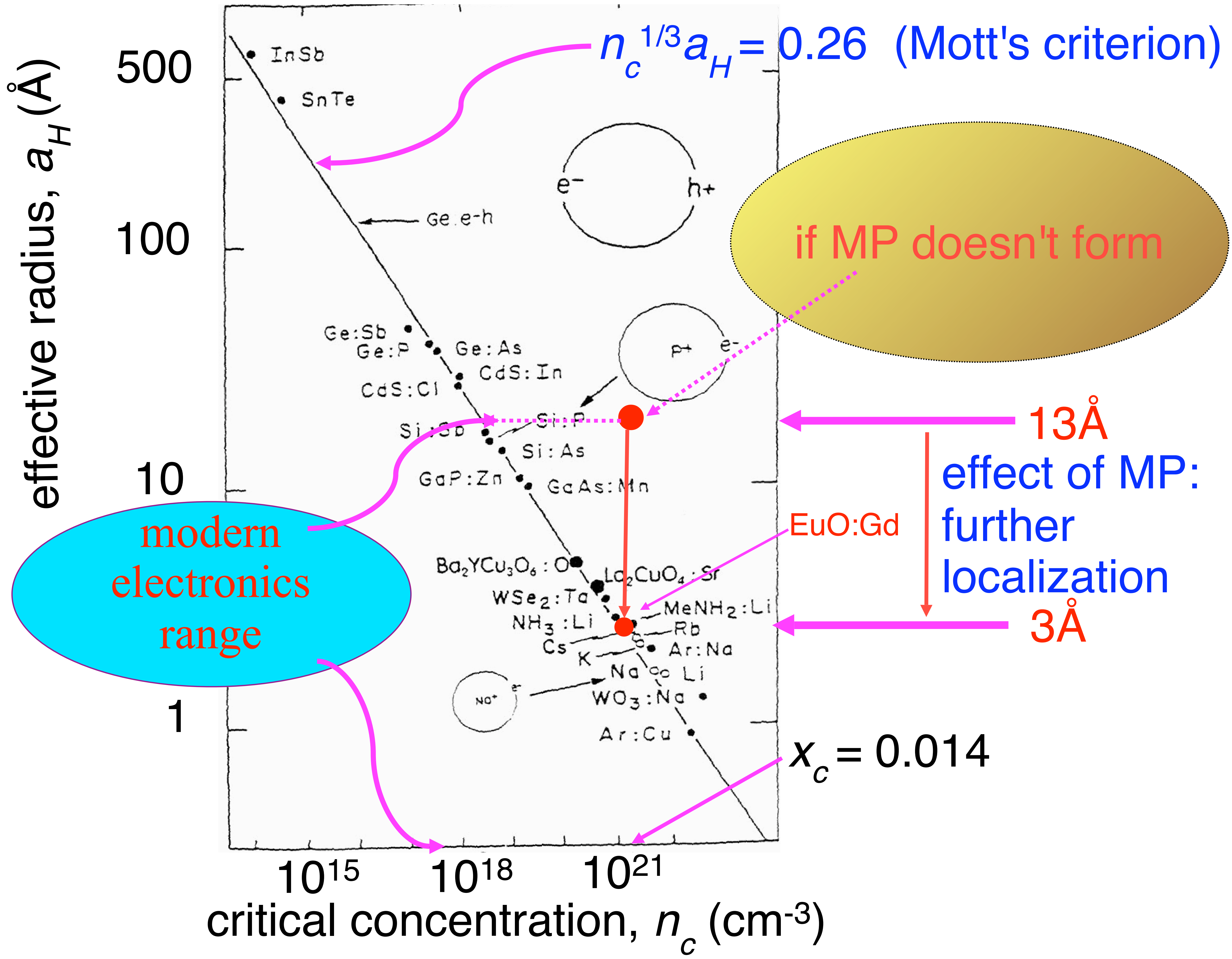
$T = 293$ K

!!!



$x_c = 0.014$

V.G.Bamburov
A.S.Boruhovich
A.A.Samohvalov



$n_c^{1/3} a_H = 0.26$ (Mott's criterion)

if MP doesn't form

13Å

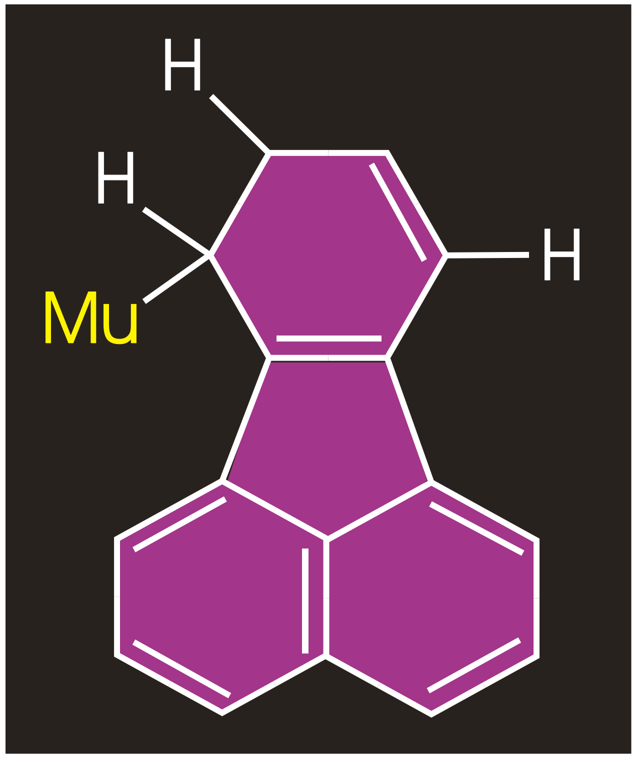
effect of MP: further localization

3Å

EuO:Gd

modern electronics range

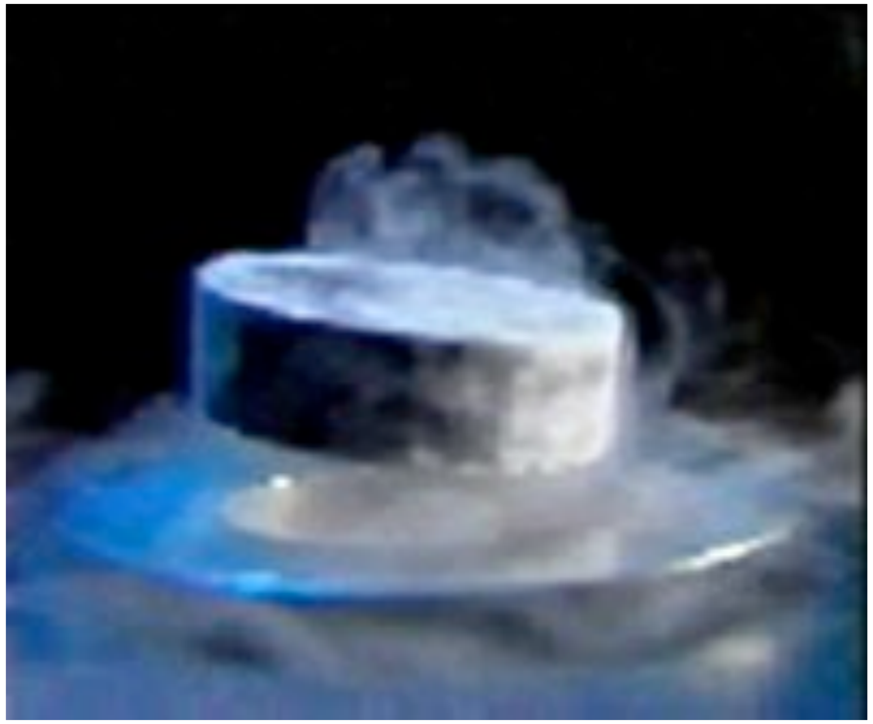
$x_c = 0.014$



Recent Applications of *μSR*

- > 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.

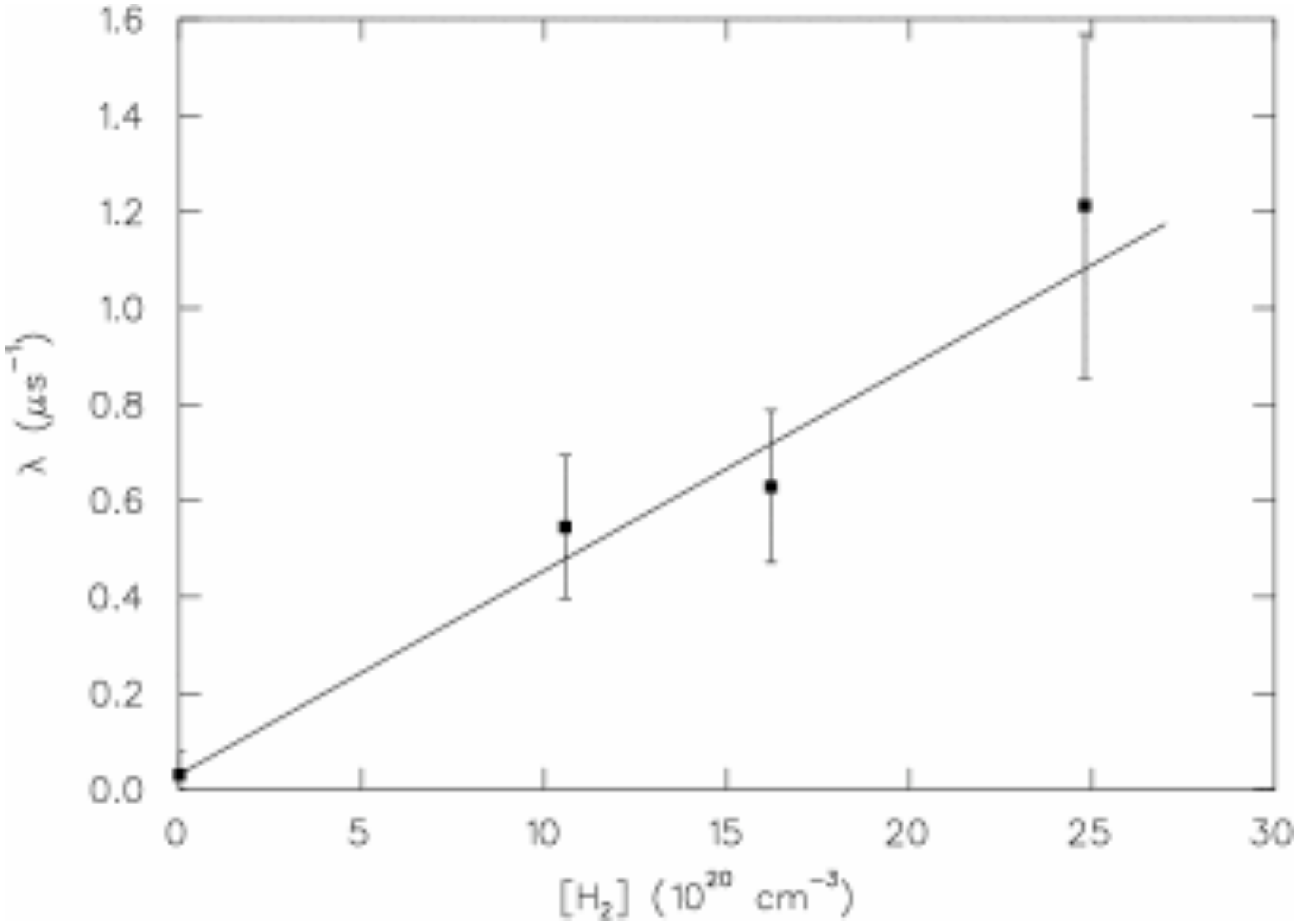
- > Molecular Magnets & Clusters
- > Hydrogen in Semiconductors
- > **Magnetic Polarons**
- > Charged Particle Transport
- > Quantum Impurities
- > Metal-Insulator Transitions
- > Colossal Magnetoresistance
- > Spin Ice Systems
- > Thermoelectric Oxides
- > Photo-Induced Magnetism
- > Magnetic Vortices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



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

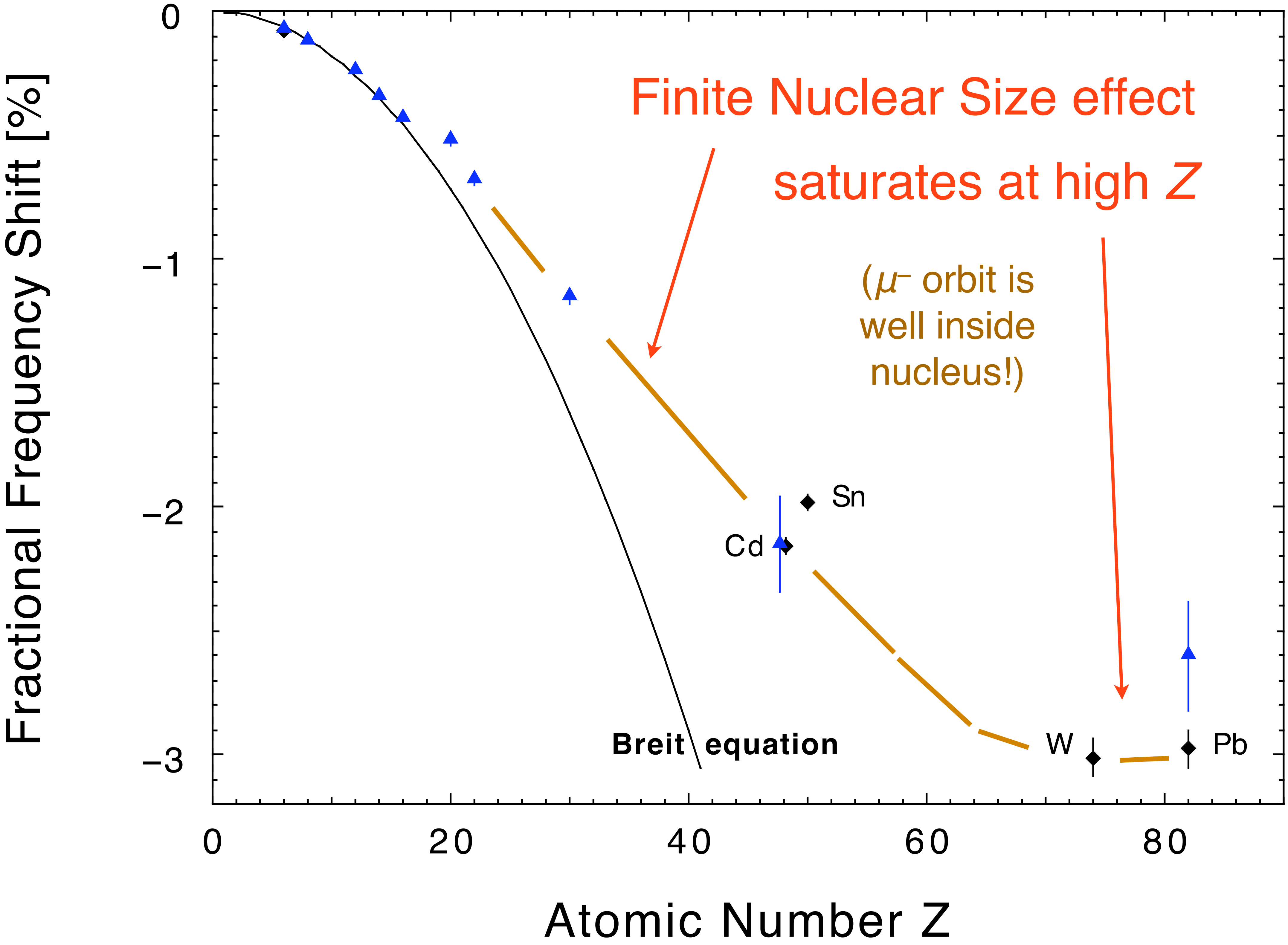
D.G. Fleming, D.J. Arseneau, O. Sukhorukov and J.H. Brewer

The chemical reaction rate of the neutral muonic helium atom $^{4}\mathrm{He}^{++}\mu^{-}e^{-}$ (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 ($\mu^{+}e^{-}$) 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 $^{4}\mathrm{He}^{++}\mu^{-}e^{-}$ 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



Finite Nuclear Size effect saturates at high *Z*

(μ^- orbit is well inside nucleus!)

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!)

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**

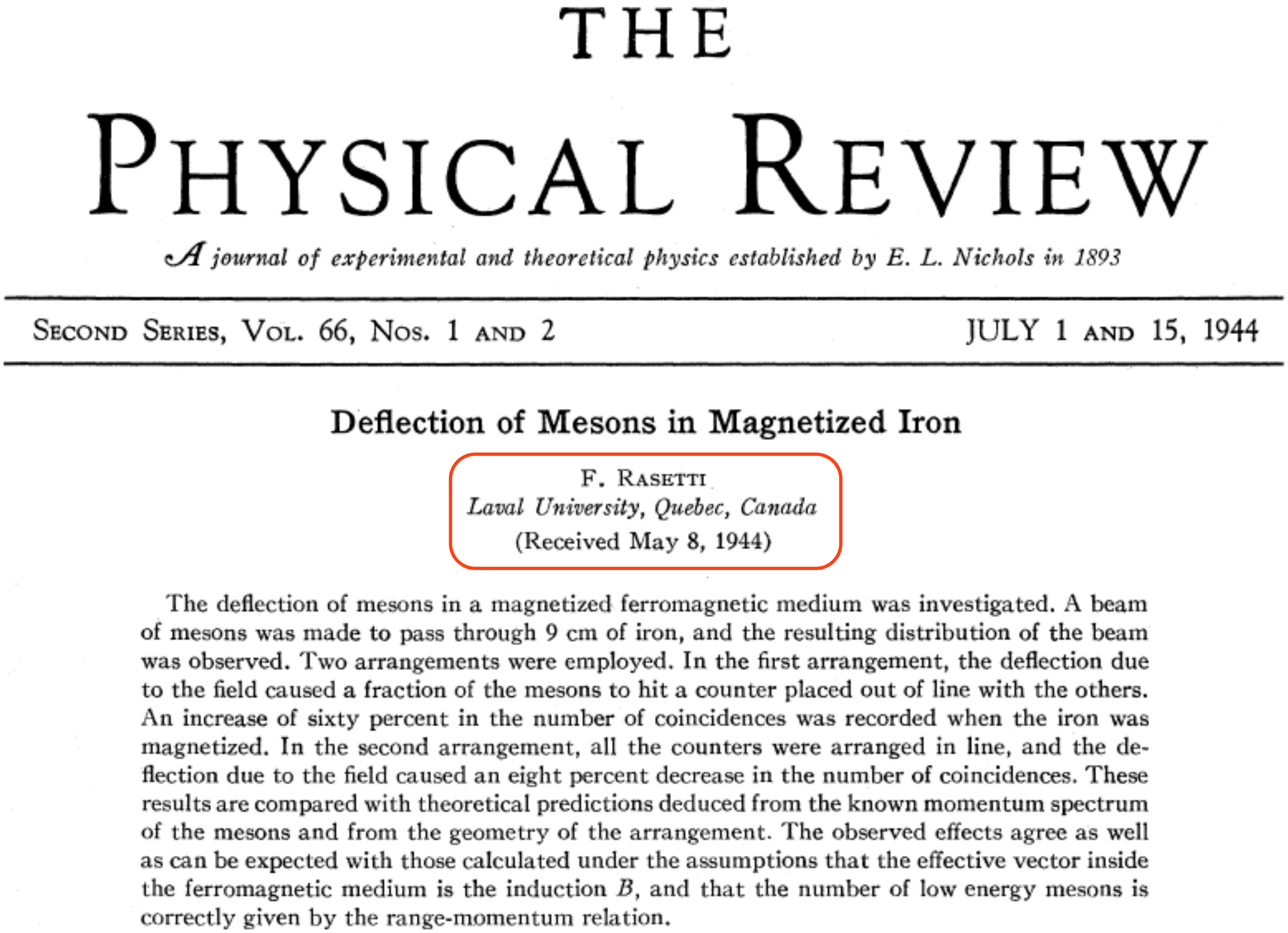
  Yukawa's "nuclear glue" mesons ≠ cosmic rays
  1937 Rabi: Nuclear Magnetic Resonance

- 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.