APPLIED PARTICLE PHYSICS

http://musr.org/intro/ppt/OhioColloq06.pdf

by

Jess H. Brewer

What would have been pure Fantasy (*i.e.* forbidden by the Known Laws of Physics) when I started school was Science Fiction (*i.e.* possible but obviously impractical) by the time I finished school, is now Routine Science, and is rapidly becoming Applied Science, thanks to the advent of Meson Factories in the 1970s. I refer of course to the maximally Parity-violating weak interactions of leptons, which give us supremely sensitive magnetic probes of "ordinary" matter in the guise of μSR and β-NMR. I will outline the history of this progression and list a few of its current manifestations at TRIUMF.

Visit our Website at http://musr.org (It's all there!)

OUTLINE

- pre-1956 **FANTASY**
  - 1956-7 Revolution!
  - π-μ-e decay and μSR
- 1958-1973 **SCIENCE FICTION**
  - Michel Parameters
  - QED tests with Muonium
  - "Problems" $\rightarrow$ Applications
- 1970s **MESON FACTORIES**
  - SIN/PSI, LAMPF, TRIUMF
  - KEK/BOOM, RAL/ISIS
- '80s & '90s **ROUTINE SCIENCE**
  - μSR Methods developed
  - "Themes" in μSR
- 2000s **APPLIED SCIENCE**
  - TRIUMF CMMS
  - Chemistry & Semiconductors
  - Magnetism & Superconductors
  - β-NMR at ISAC
  - Fundamental Physics
- **CONCLUSIONS**

Acknowledgements: Those who came before; the hundreds of people who make up the World μSR Community; and especially Jeff Sonier & Andrew MacFarlane, whose slides I stole.

Before 1956: FANTASY

1930s **MISTAKEN IDENTITY**

Yukawa's "nuclear glue" mesons $\neq$ Cosmic rays

1937 Rabi: Nuclear Magnetic Resonance

1940s "**WHO ORDERED THAT?**"

1940 *Phys. Rev.* Analytical Subject Index: "mesotron"

1944 Rasetti: $1^{\rm st}$ 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)

$\longrightarrow$ *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

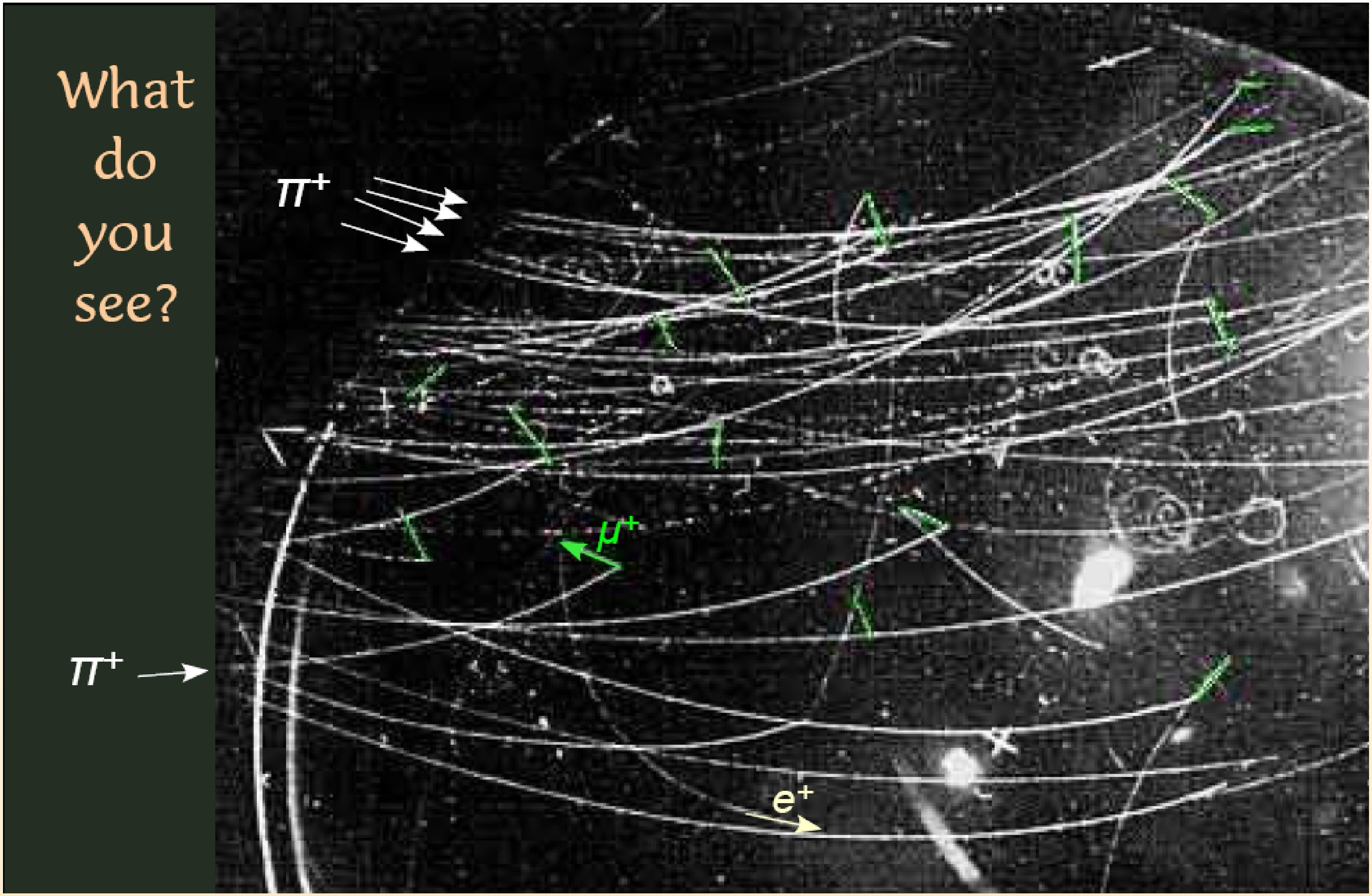
Deflection of Mesons in Magnetized Iron

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.


What do you see?
π^+
π^+
μ^+
e^+

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)

↓

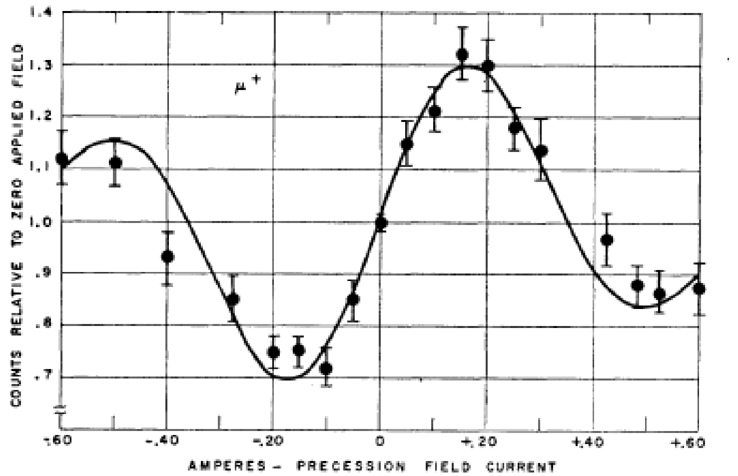


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

→

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.

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

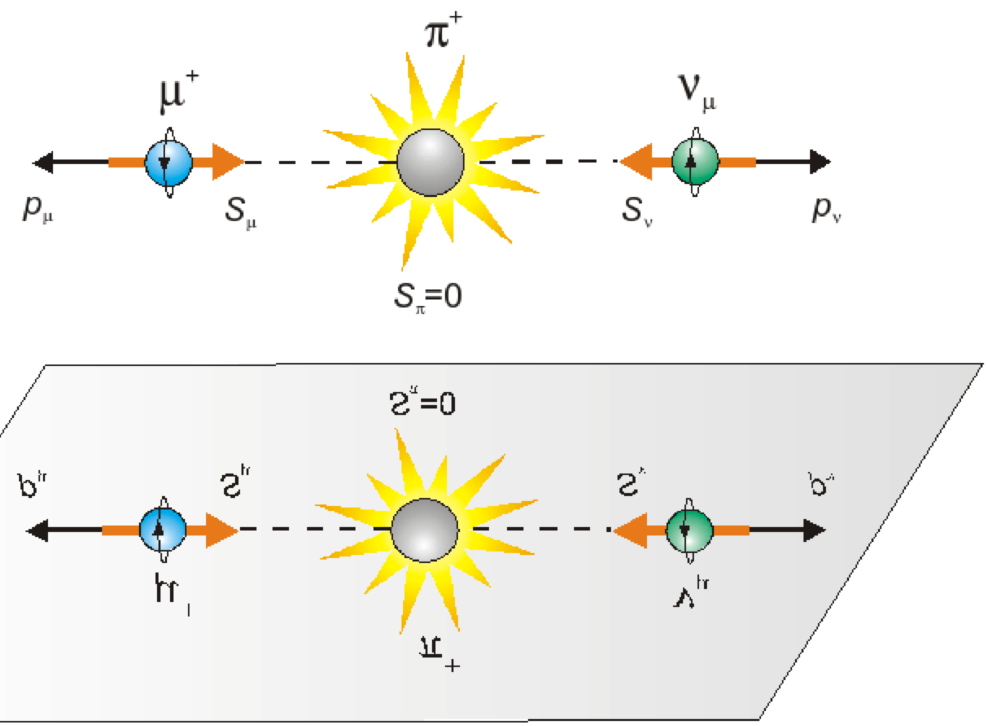
A pion **stops** in the “skin” of the primary production target.
It has zero linear momentum and zero angular momentum.

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

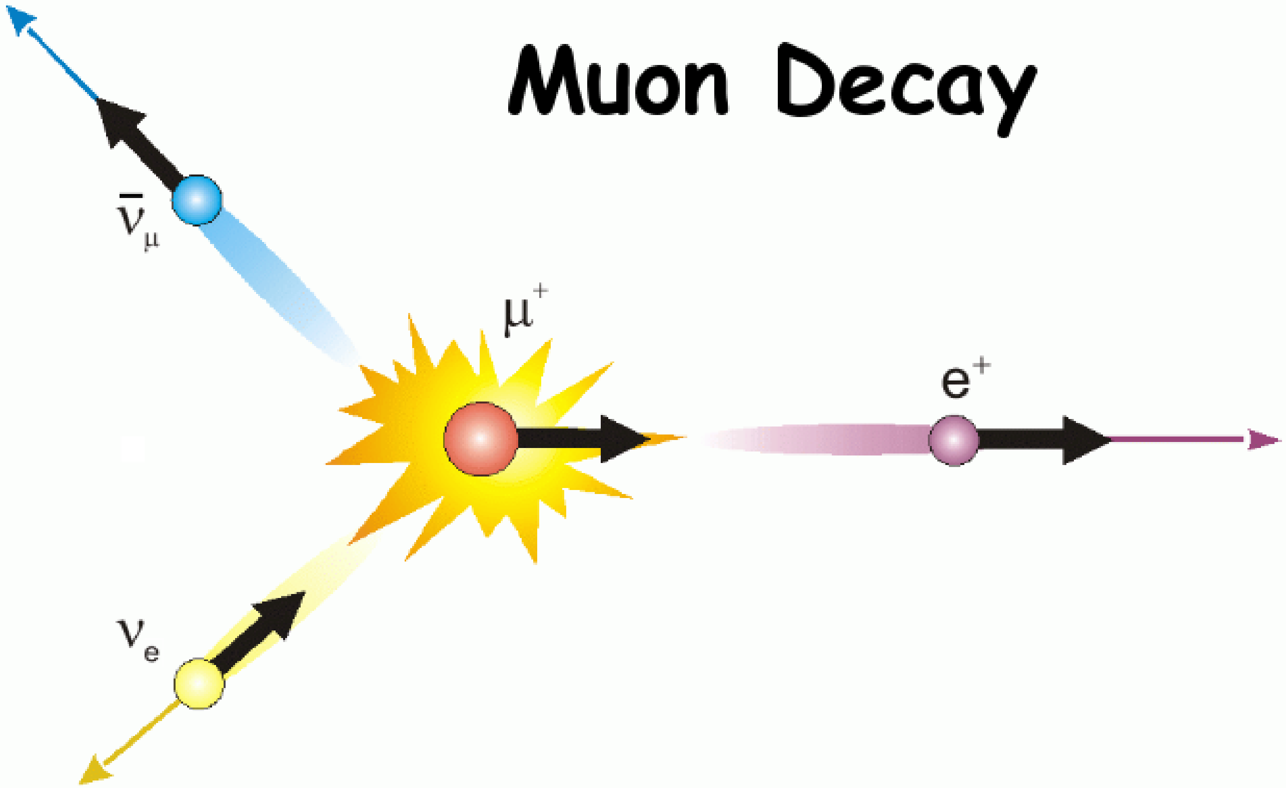
Conservation of Angular Momentum: μ^+ and ν_μ have equal and opposite spin.

Weak Interaction:
Only “left-handed” ν_μ are created.

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

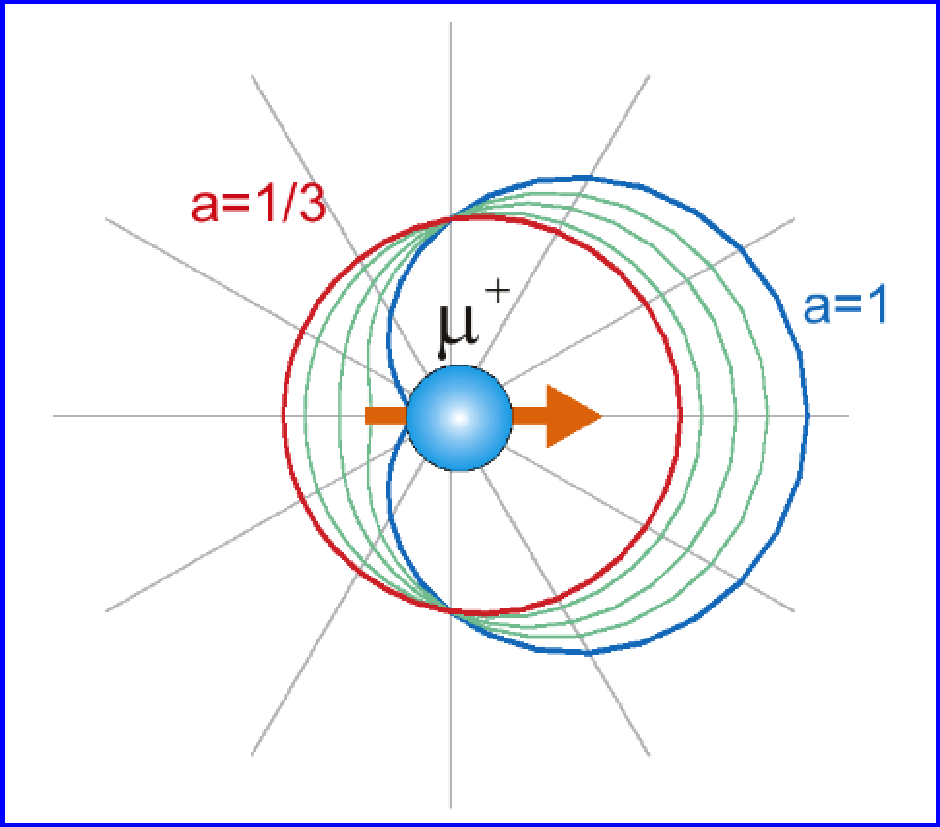


Muon Decay



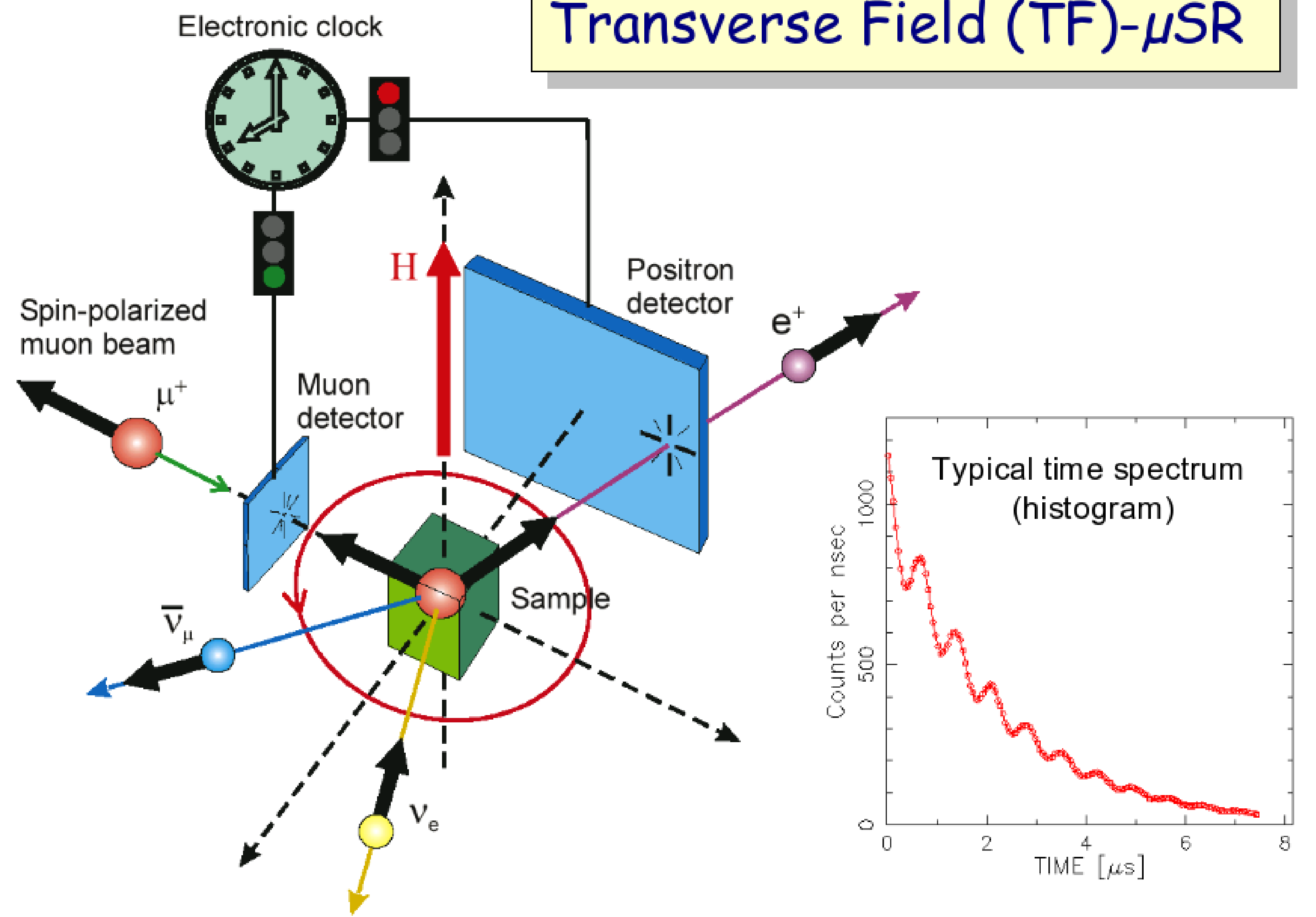
Neutrinos have negative helicity, antineutrinos positive.
An ultrarelativistic positron behaves like an antineutrino.
Thus the positron <u>tends</u> to be emitted along the μ^+ spin
when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

μ^+-Decay Asymmetry



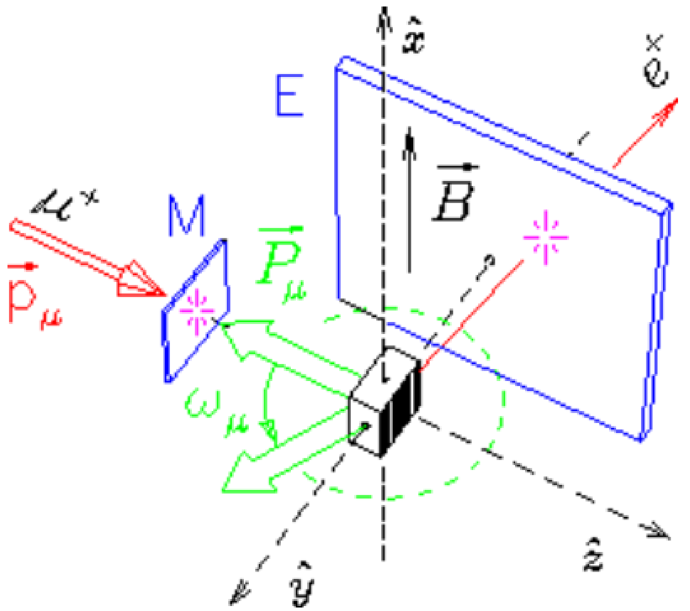
Angular distribution of positrons from μ^+ decay. The asymmetry is $a = 1/3$ when all positron energies are detected with equal probability.

Transverse Field (TF)-μSR



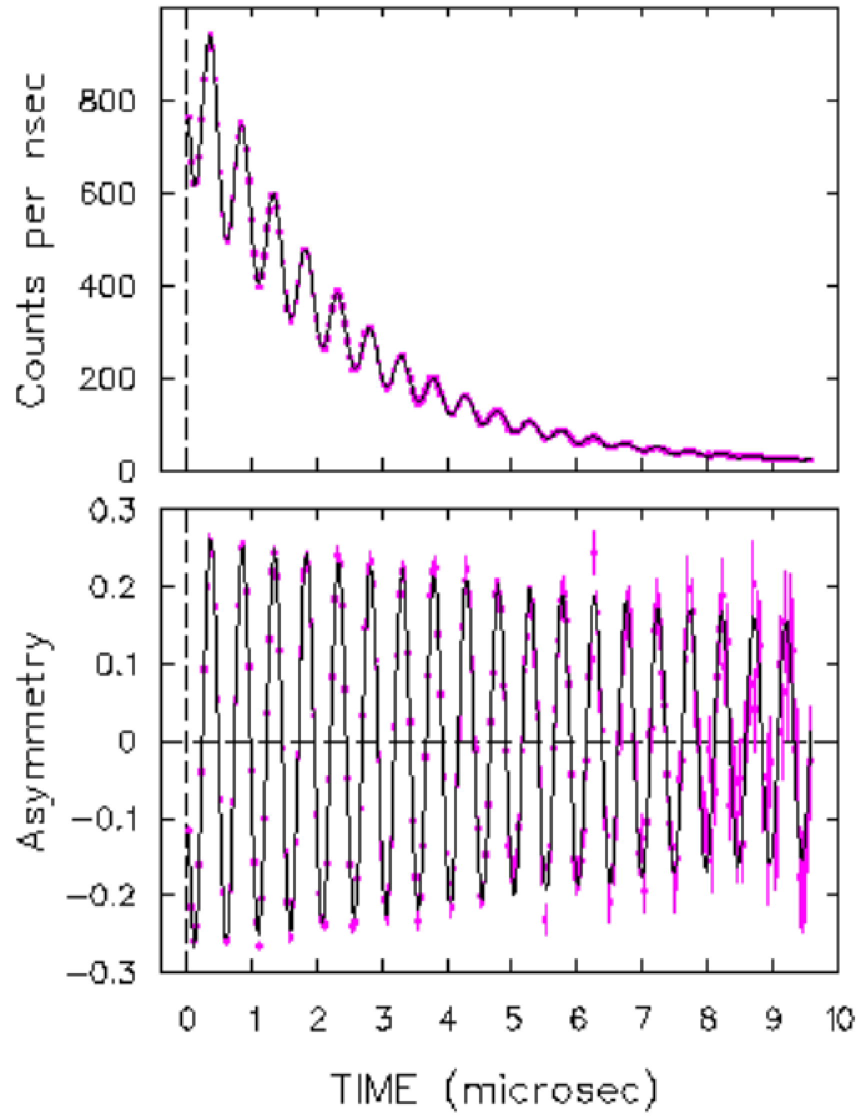
wTF-μ^+SR:

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



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

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



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, $g_\mu - 2$

Arizona/surface muon beam for $\mu^+ e^- \to \mu^- e^+$

All lead to *refined* μ*SR techniques*.

Applications: Muonium Chemistry, Semiconductors, Magnetism

1970s **MESON FACTORIES** — *Intensity Enables!*

USA: **LAMPF** (now defunct)

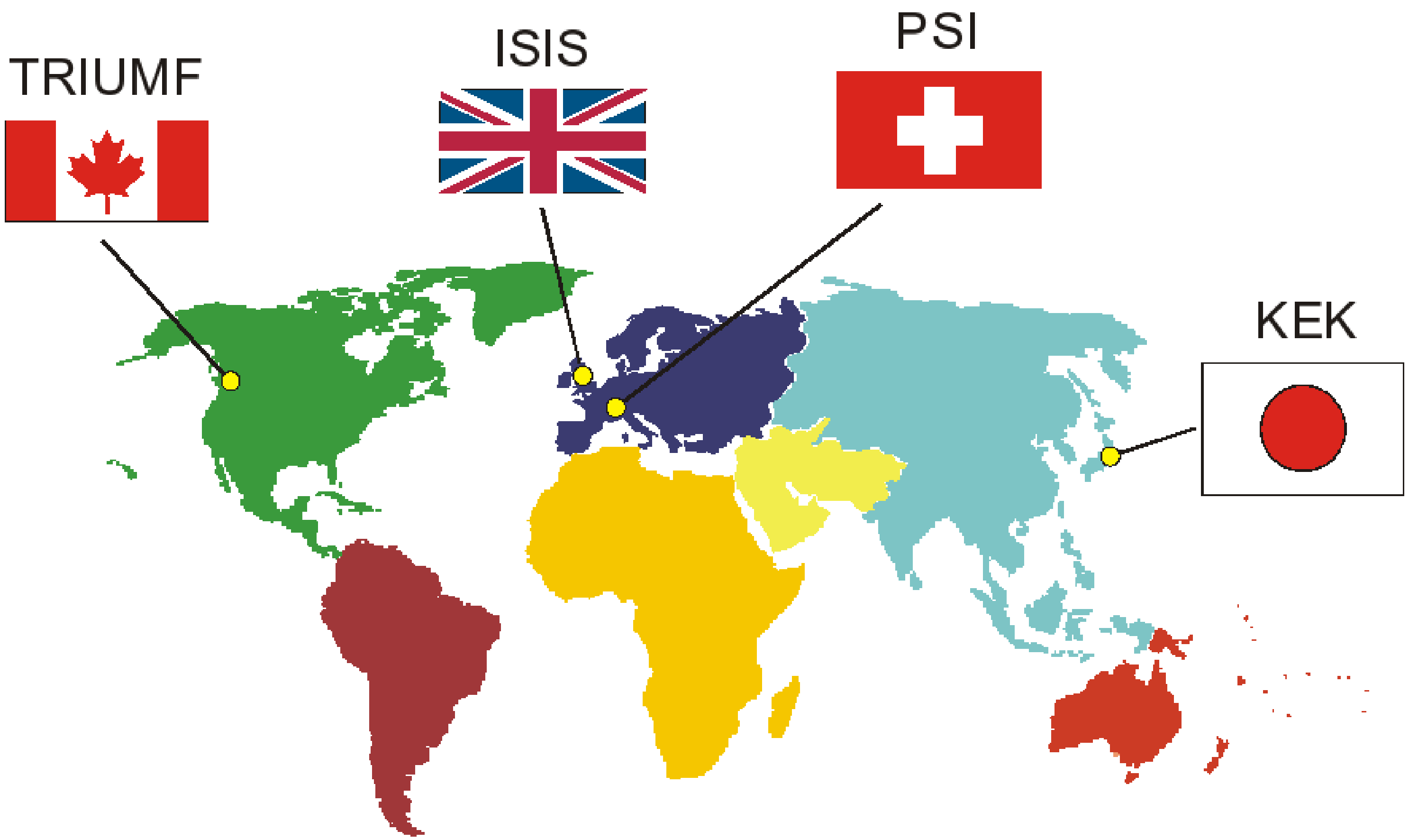
Switzerland: **SIN** (now **PSI**)

Canada: **TRIUMF**

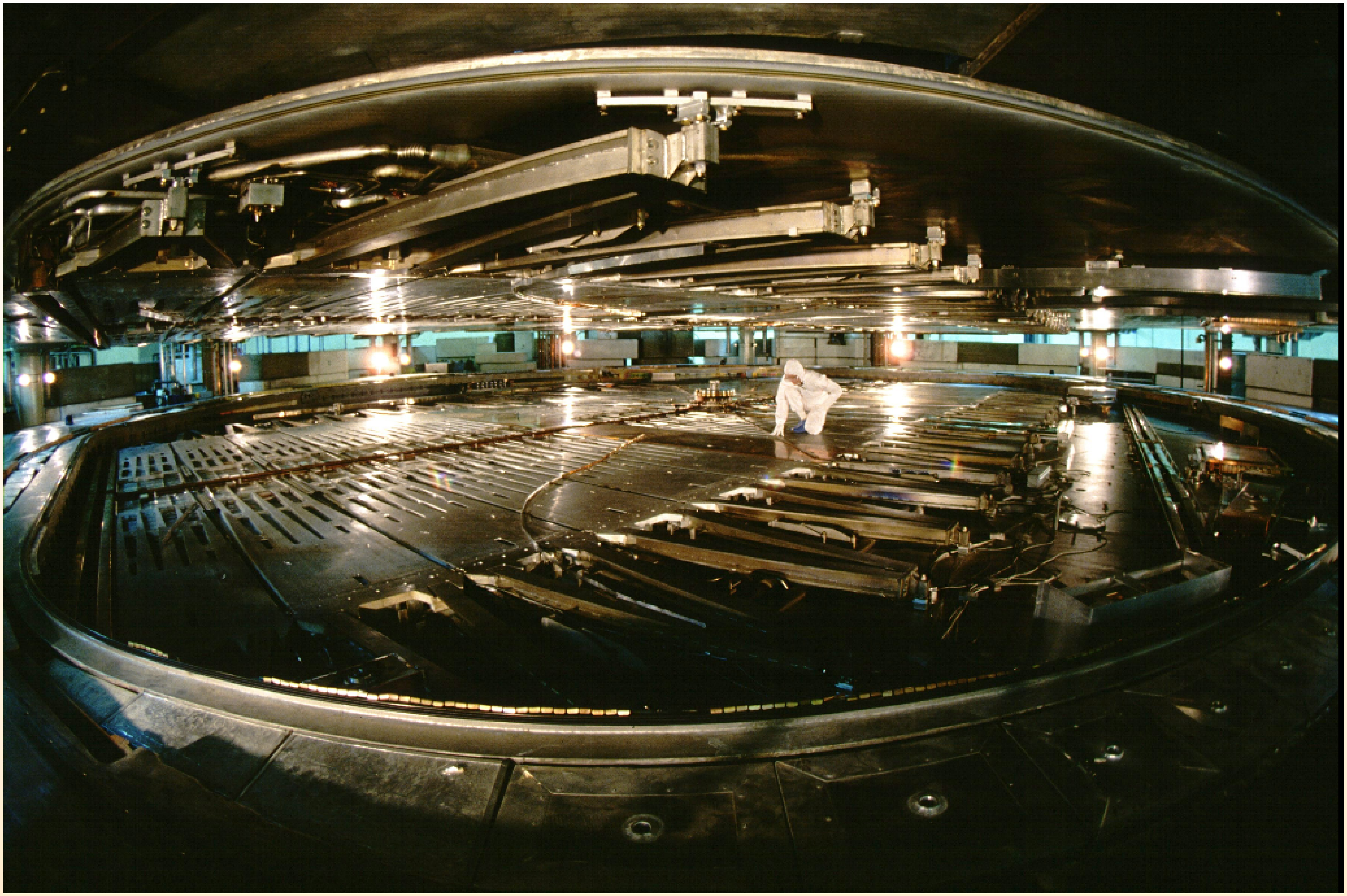
UK: **RAL/ISIS**

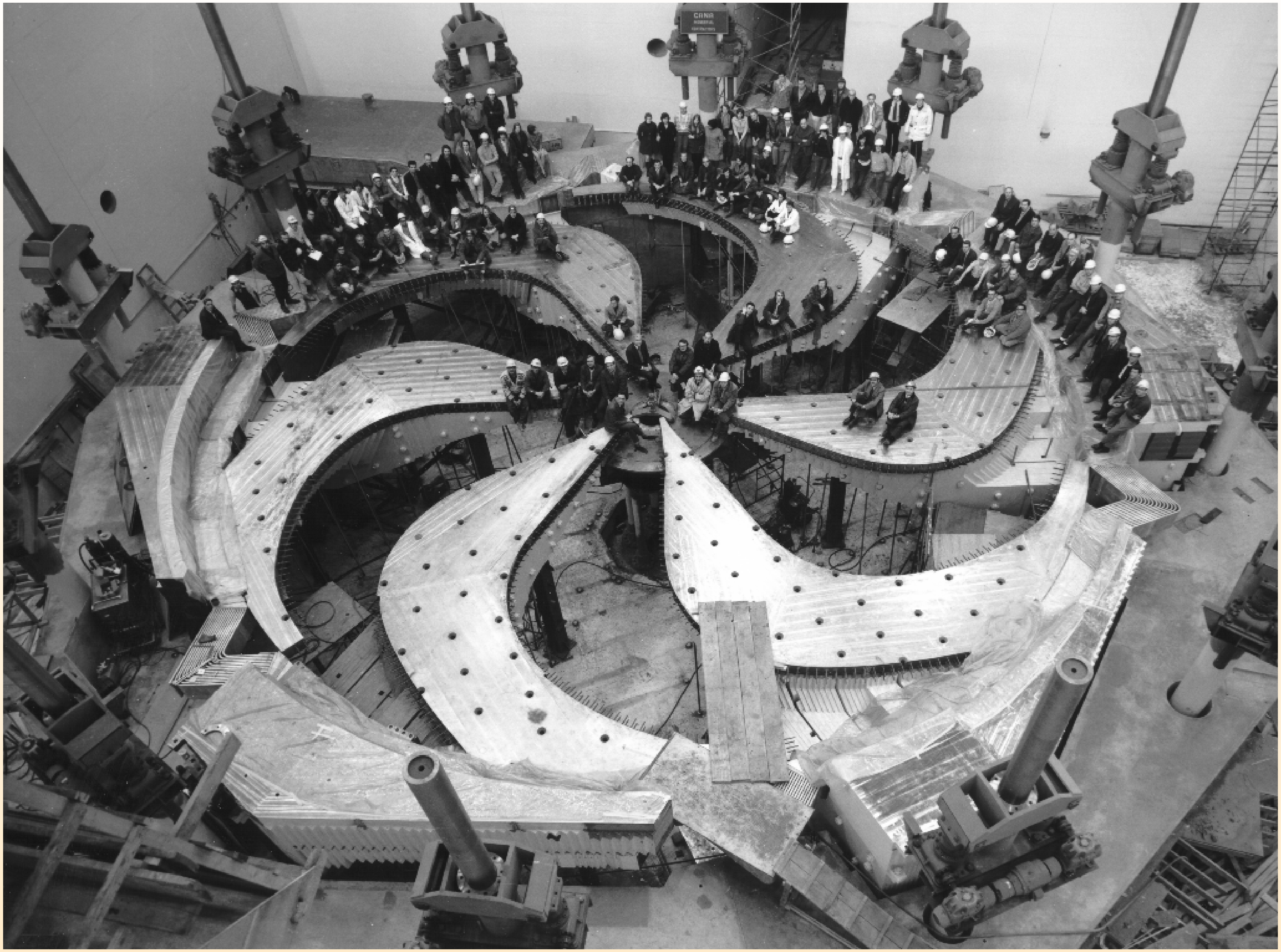
Japan: **KEK/BOOM** ($\to$ **J-PARC**)

Where in the World is μSR?

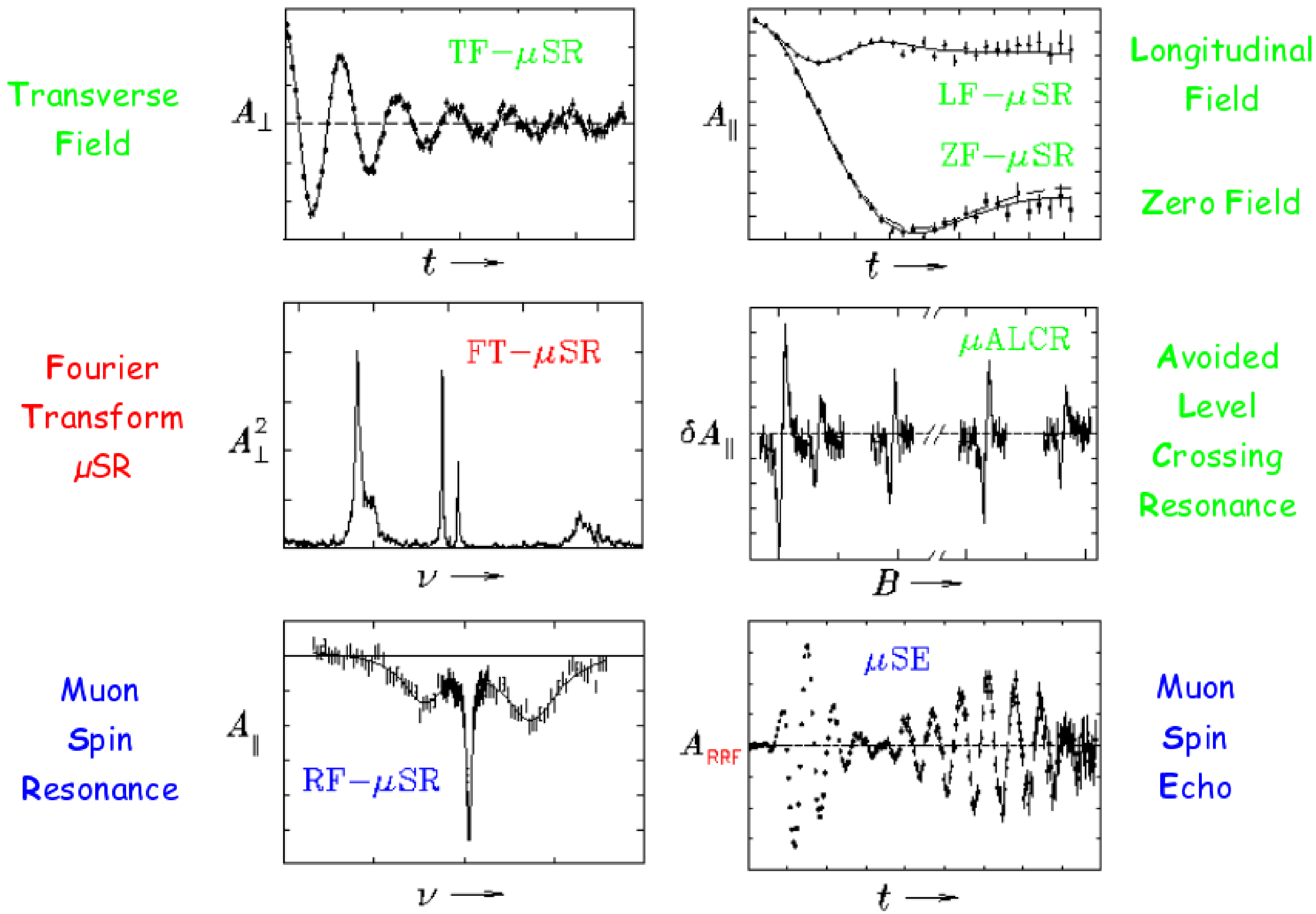


TRIUMF





Brewer's List of μSR Acronyms



Motion of Muon Spins in Static Local Fields:

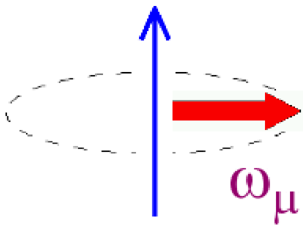
(red arrow) S_μ = Expectation value of one muon's spin direction

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

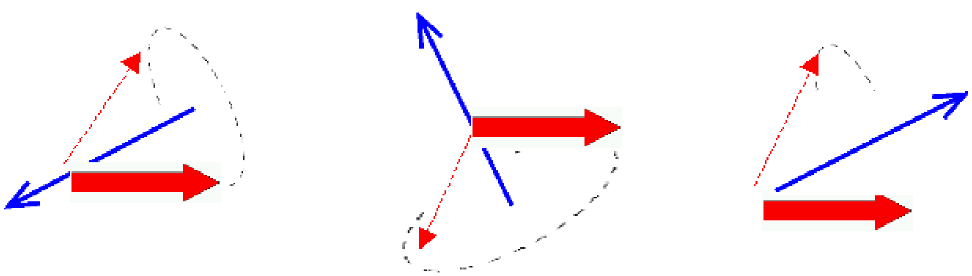
$\omega_\mu = 2\pi \, \gamma_\mu \, |\boldsymbol{B}|$

$\gamma_\mu = 135.5$ MHz/T

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



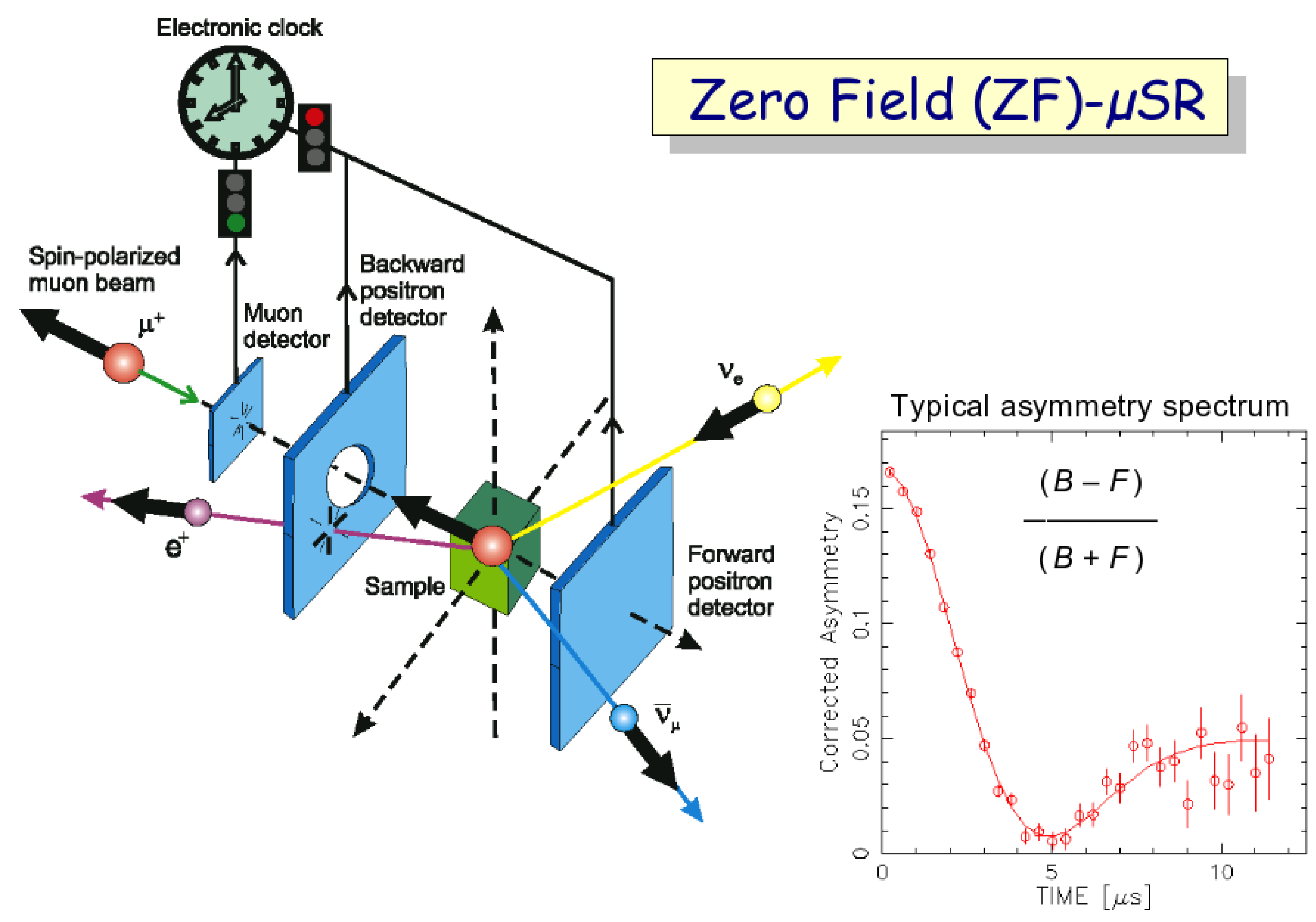
(b) All muons "see" same $|\boldsymbol{B}|$ but *random direction*:



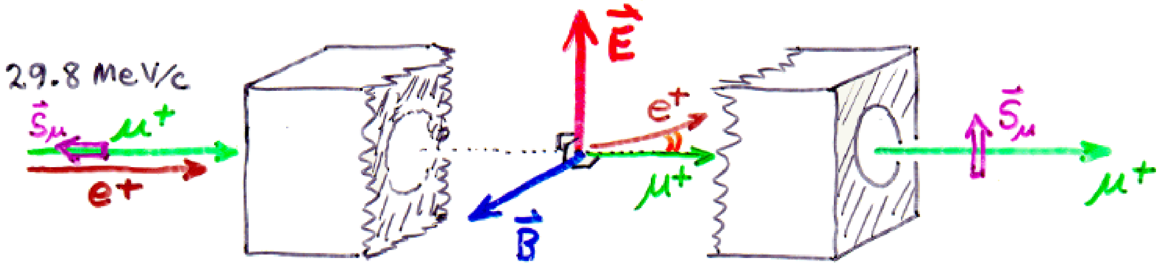
2/3 of $\boldsymbol{S}_\mu$ precesses at ω_μ

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

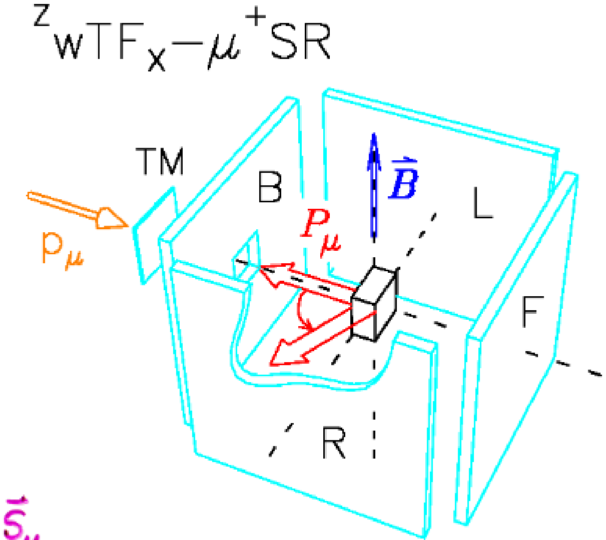
Zero Field (ZF)-μSR

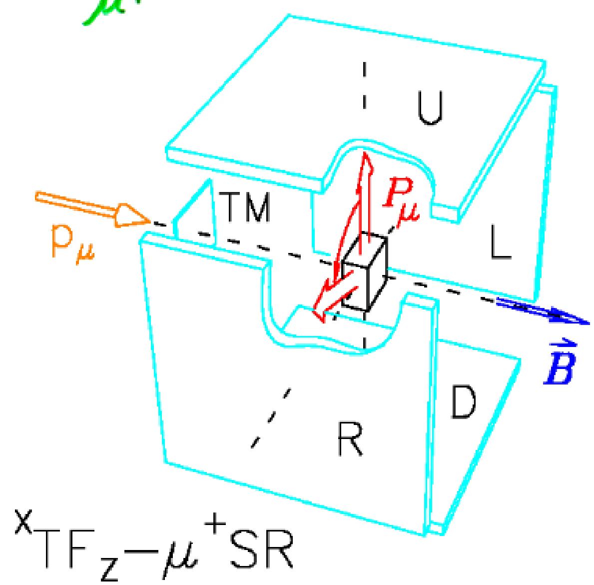


$E \times B$ velocity selector
("DC Separator" or Wien filter) for surface muons:



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





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 $\longrightarrow$ **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: TRIUMF Centre for Molecular & Materials Science

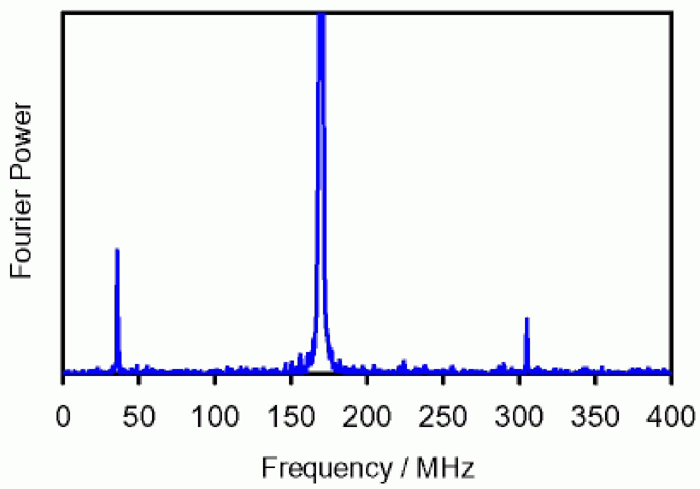
The TRIUMF **C**entre for **M**olecular and **M**aterials **S**cience is an NSERC funded Facility at the TRIUMF National Laboratory, in Vancouver, Canada. It represents an expansion of the former TRIUMF μSR User Facility, with a mandate to facilitate research using **μSR** and other accelerator-based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

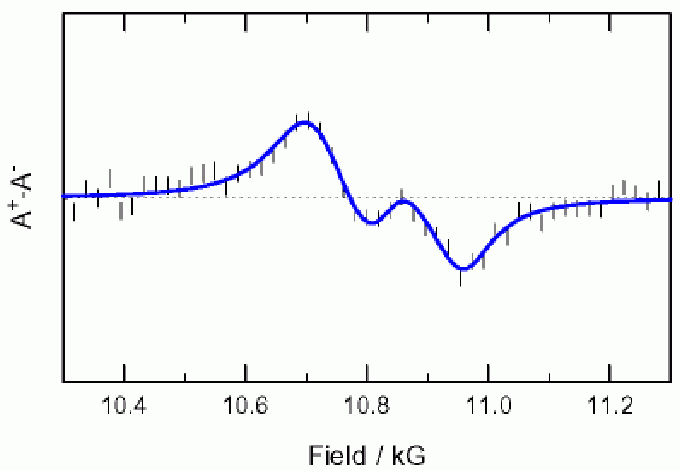
Chemistry Semiconductors Magnetism Superconductors

β-NMR Fundamental Physics

Muonium Chemistry

See TRIUMF Experiment # **1012**





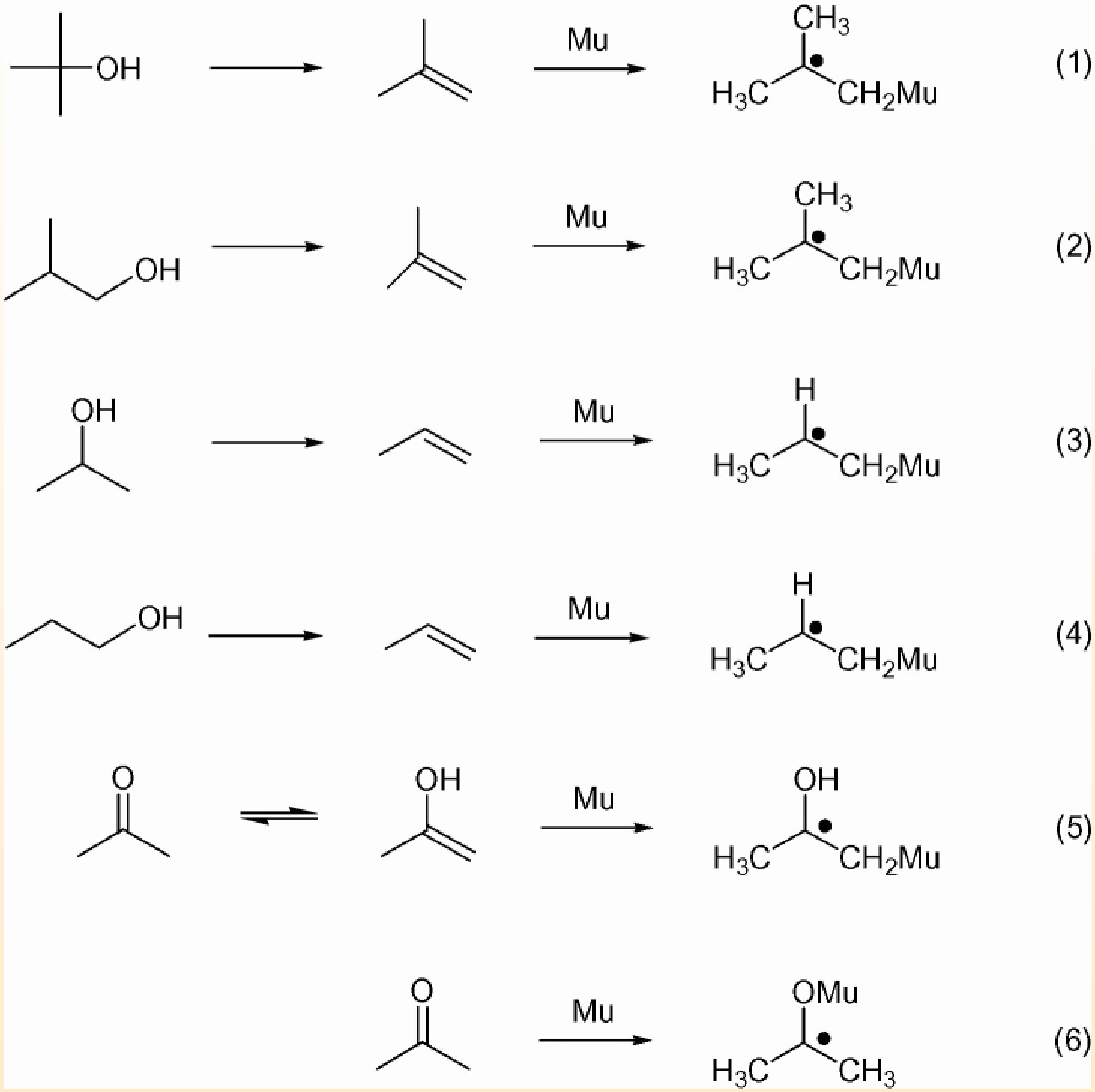
TRIUMF μSR Research Highlight # **13** :

Organic Free Radicals in Superheated Water

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

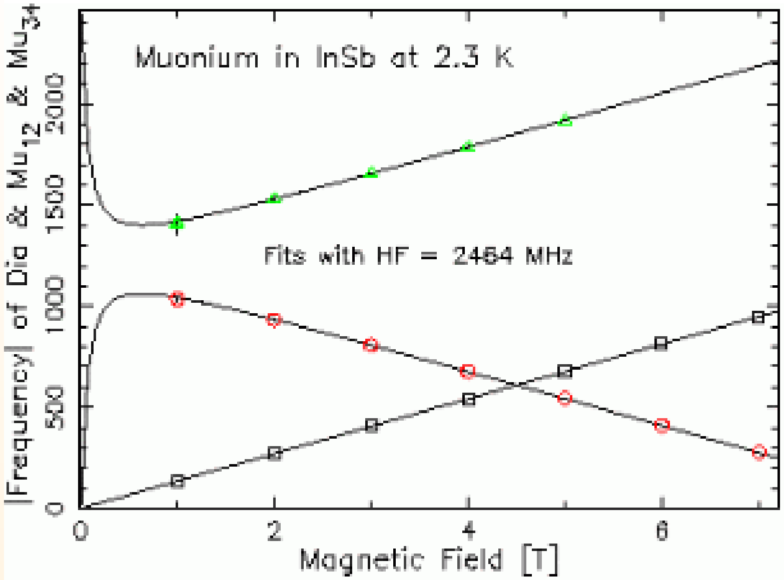
Apparatus has been developed to permit muon avoided level-crossing spectroscopy (μLCR) of organic free radicals in water at high temperatures and pressures. The combination of μLCR with transverse-field muon spin rotation (TF-μSR) provides the means to identify and characterize free radicals via their 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,#5.

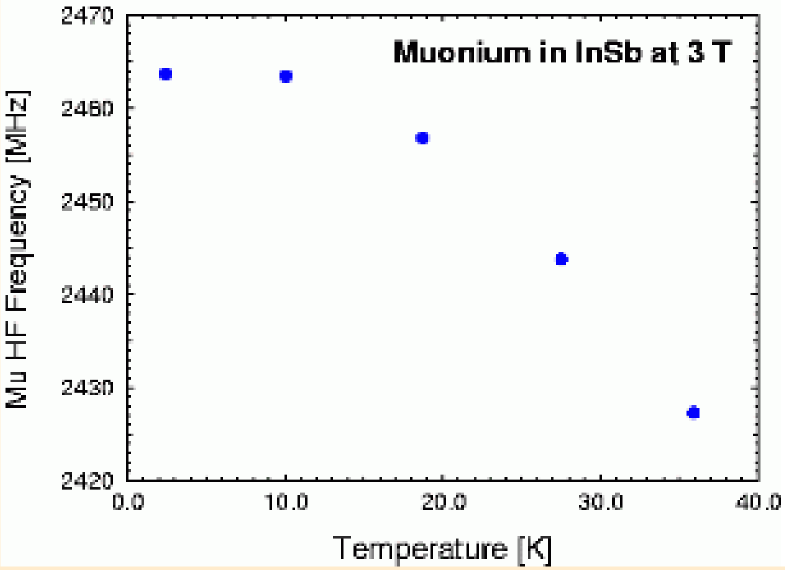
The figure shows spectra for the 2-propyl radical detected in an aqueous solution of 2-propanol at 350°C and 250 bar.


OH
Mu
CH3
H3C
CH2Mu
(1)
OH
Mu
CH3
H3C
CH2Mu
(2)
OH
Mu
H
H3C
CH2Mu
(3)
OH
Mu
H
H3C
CH2Mu
(4)
O
OH
Mu
OH
H3C
CH2Mu
(5)
O
Mu
OMu
H3C
CH3
(6)

Semiconductors

See TRIUMF Experiment # **938**





TRIUMF *μSR* Research Highlight # **3** :

Muonium in InSb

V.G. Storchak, D.G. Eshchenko, J.H. Brewer et al.

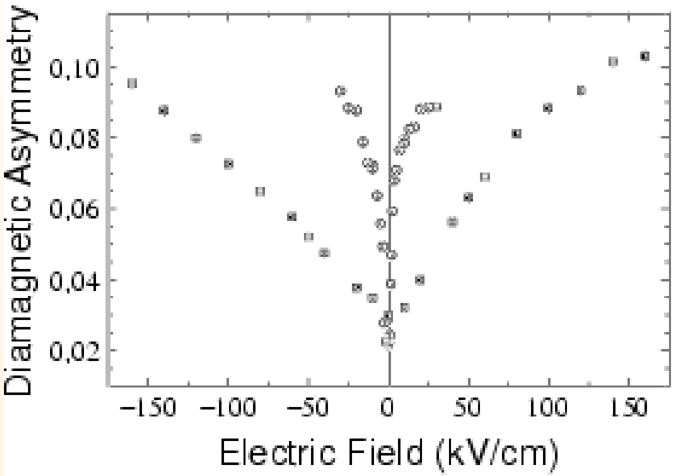
The exquisite time resolution and high magnetic field capabilities of TRIUMF's *HiTime μSR* spectrometer have facilitated the first direct observation of a muonium ($Mu = \mu^+ e^-$) bound state in indium antimonide.

The small-amplitude Mu signal was characteristic of "deep" tetrahedral muonium (Mu_T); there was no sign of the bond-centred Mu_{BC} state that has been so ubiquitous in other semiconductors, nor was there any hint of the metastable "shallow" (weakly bound) Mu_{WB} state expected (given the high mobility and low effective mass of electrons in InSb).

However, there is a substantial "missing fraction". Either Mu_{BC} or the shallow Mu_{WB} state may show up in subsequent experiments at dilution refrigerator temperatures.

See TRIUMF Experiment # **775**

TRIUMF *μSR* Research Highlight # **4** :



Weakly Bound Muonium State in GaP

V.G. Storchak, D.G. Eshchenko, R.L. Lichti and J.H. Brewer

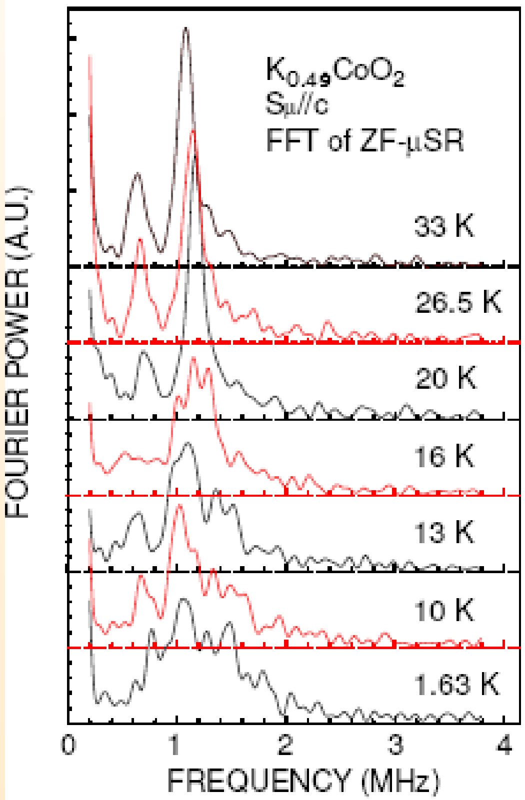
Muonium formation *via* electron transport to a positive muon implanted into semi-insulating GaP has been studied using muon spin rotation/relaxation with alternating electric fields up to 160 kV/cm. Formation of the muonium ground state is prohibited by a characteristic electric field of about 50 kV/cm in GaP compared to 5 kV/cm in GaAs, implying that formation of the Mu ground state may proceed through a weakly-bound intermediate state with a binding energy of about 23 meV in GaP or 7 meV in GaAs. These results are discussed and justified within the effective mass model.

See *μSR* Literature Entry # **2437**

Magnetism

See TRIUMF Experiment # **917**

TRIUMF *μSR* Research Highlight # **16** :



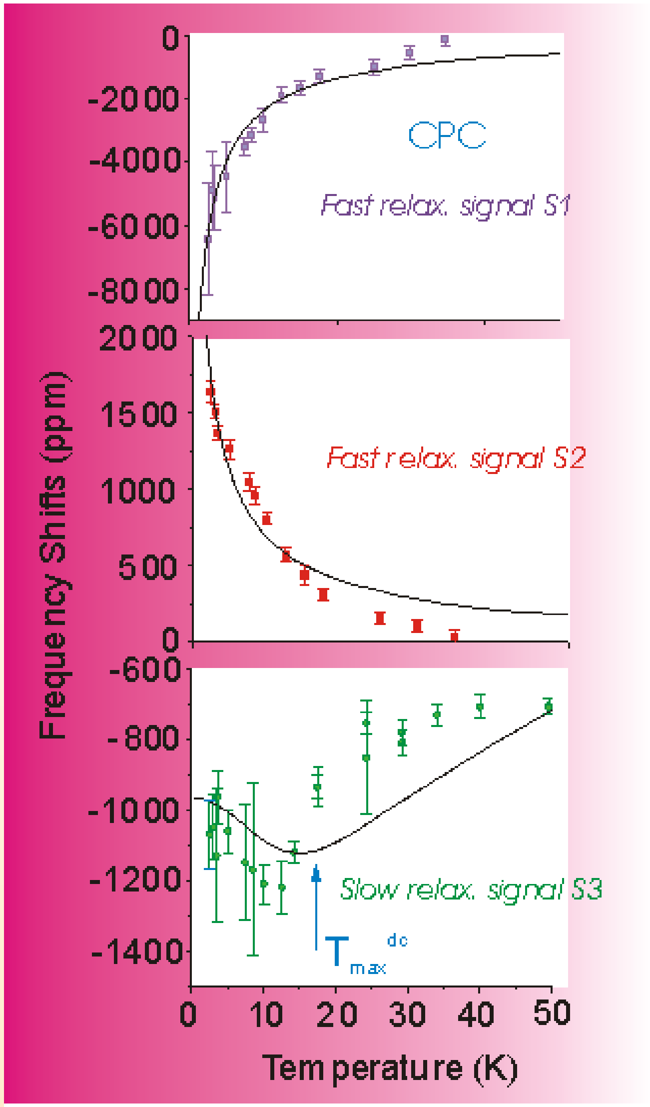
Static magnetic order in metallic $K_{0.49}CoO_2$

J. Sugiyama, H. Nozaki, Y. Ikedo, K. Mukai, J.H. Brewer, E.J. Ansaldo, G.D. Morris, D. Andreica, A. Amato, T. Fujii and A. Asamitsu

The sodium cobaltite (Na_xCoO_2 or NCO) system poses a new paradigm of low-dimensional, strongly correlated systems because connections between enhanced thermopower, frustrated magnetic ordering in triangular lattices and unconventional superconductivity can be studied as a function of doping in the complex NCO phase diagram. In particular, magnetic and superconducting order parameters are based on the cobalt oxide planes, as for the cuprates, with interlayers playing a crucial role for doping and couplings. However, mobility and aggregation of the sodium ions confuses experimental results on magnetic ordering, especially in the metallic region. Hoping to alleviate these problems by doping with heavier potassium atoms, we have used positive muon spin rotation/relaxation (μSR) spectroscopy to survey the magnetic properties of potassium cobaltite (K_xCoO_2 or KCO) as a function of x. We found that at x = 0.49 (where the analogous NCO sample is a charge-ordered, magnetic insulator at low temperature) KCO undergoes successive magnetic transitions from a high-temperature paramagnetic state to a magnetically ordered state below 60 K and then to a second ordered state below 16 K, even though it is metallic down to 4 K. This suggests that magnetic order is more strongly affected by the Co valence than by the interlayer distance/interaction and/or the charge-ordering. system

See TRIUMF Experiment # **844**

TRIUMF *μSR* Research Highlight # **9** :



Local Magnetic Susceptibility of μ^+ in the Quasi 1D S=1/2 Antiferromagnet dichlorobis (pyridine) copper (II)

J. A. Chakhalian, R. F. Kiefl, R. Miller, J. Brewer, S. R. Dunsiger, G. Morris, W. A. MacFarlane, J.E. Sonier, S. Eggert, I. Affleck, A. Keren & M. Verdaguer

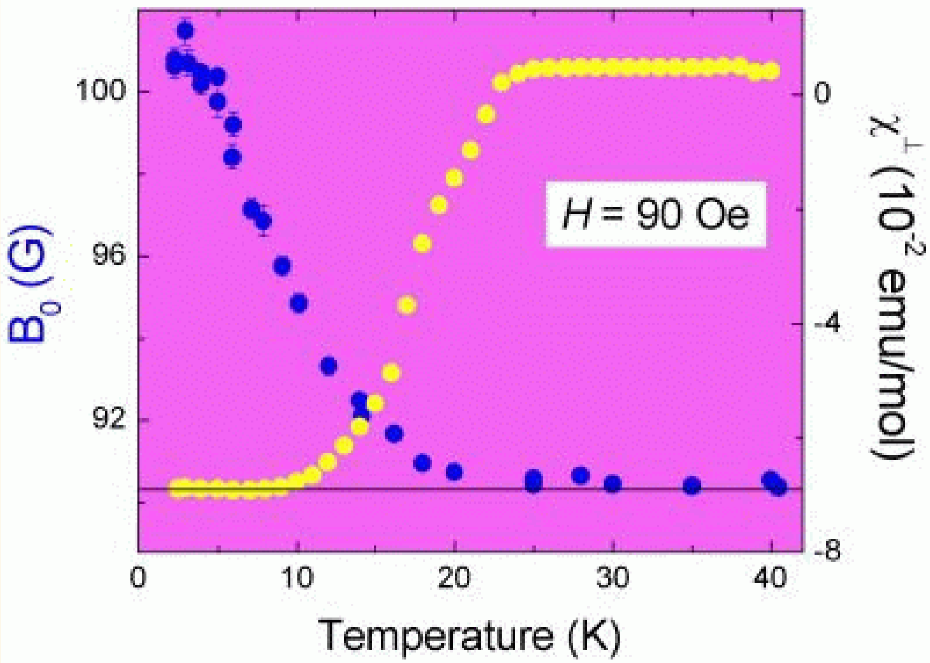
The local magnetic susceptibility around the positive muon in the quasi 1D S=1/2 antiferromagnetic chain compound dichlorobis (pyridine) copper (II) (CPC) has been investigated using the μSR technique. Signals from three distinct sites are identified and shown to have the local magnetic susceptibilities which are different from each other and for two locations are also significantly different from the bulk susceptibility. The theoretical fits capture the effect of muon perturbation rather well. These results confirm the predicted high sensitivity of one dimensional spin 1/2 chain compounds to impurity effect.

Physical Review Letters ***91***, *027202 (2003)*

See *μSR* Literature Entry # **2561**

Superconductors

See TRIUMF Experiment # **847**



TRIUMF *μSR* Research Highlight # **8** :

Superconductivity and Field-Induced Magnetism in $Pr_{2-x}Ce_xCuO_4$ Single Crystals

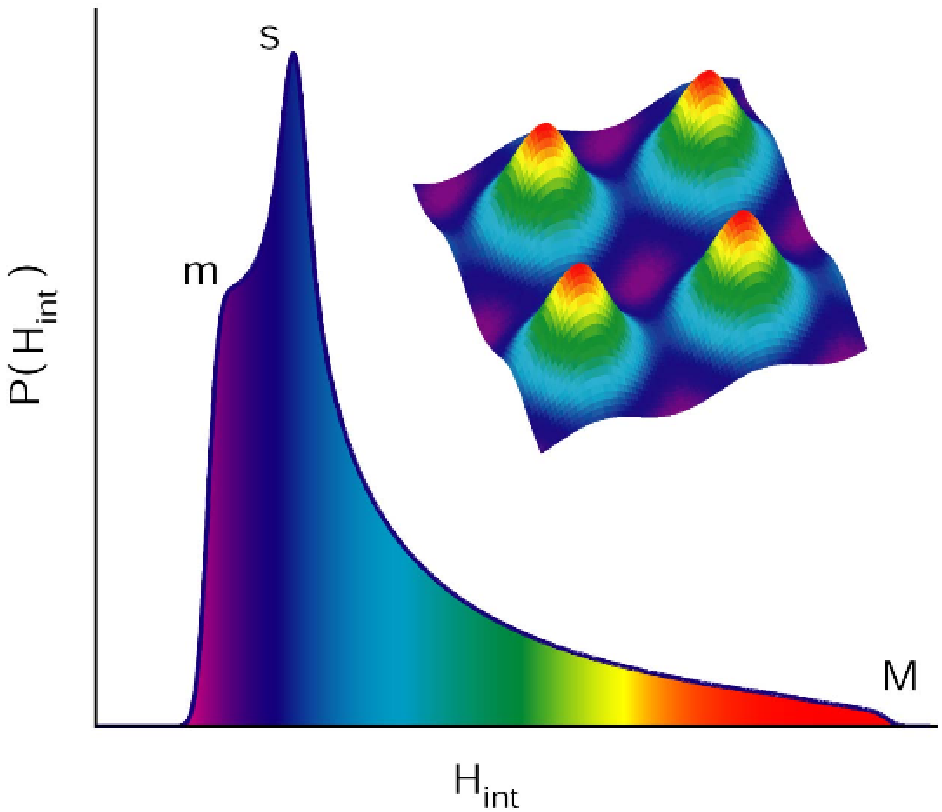
J.E. Sonier, K.F. Poon, G.M. Luke, P. Kyriakou, R.I. Miller, R. Liang, C.R. Wiebe, P. Fournier and R.L. Greene

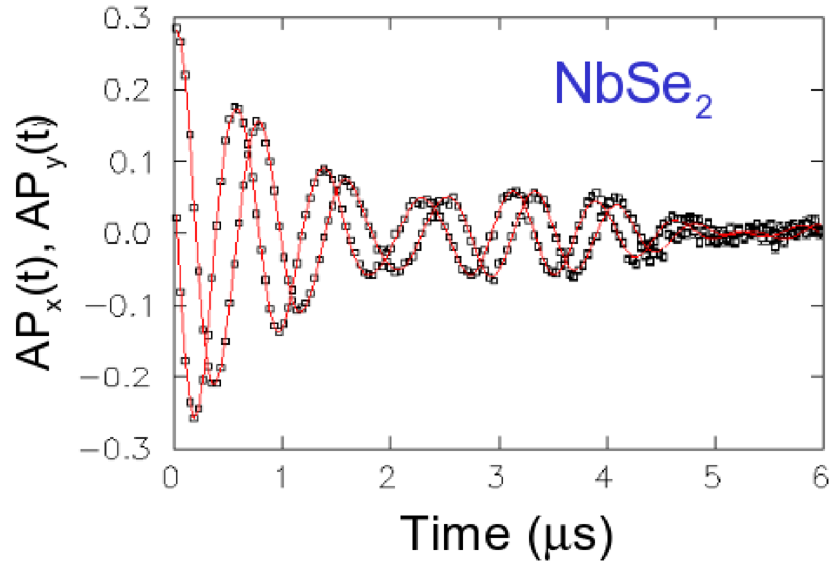
We have carried out μSR measurements on single crystals of the electron-doped high-T_c superconductor $Pr_{2-x}Ce_xCuO_4$. In zero external magnetic field, superconductivity is found to coexist with dilute Cu spins that are static on the μSR time scale. In an applied field, we observe a μ^+-Knight shift that is primarily due to the magnetic moment induced on the Pr ions. Below the superconducting transition temperature T_c, an additional source of local magnetic field appears throughout the volume of the sample. This finding is shown to be consistent with field-induced antiferromagnetic (AF) ordering of the Cu spins.

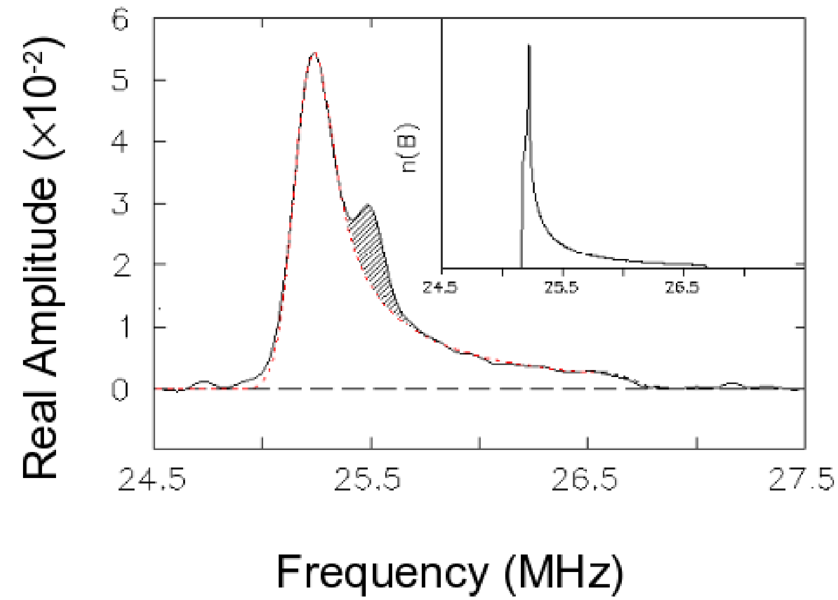
Physical Review Letters ***91***, *147002 (2003).*

See *μSR* Literature Entry # **3057**

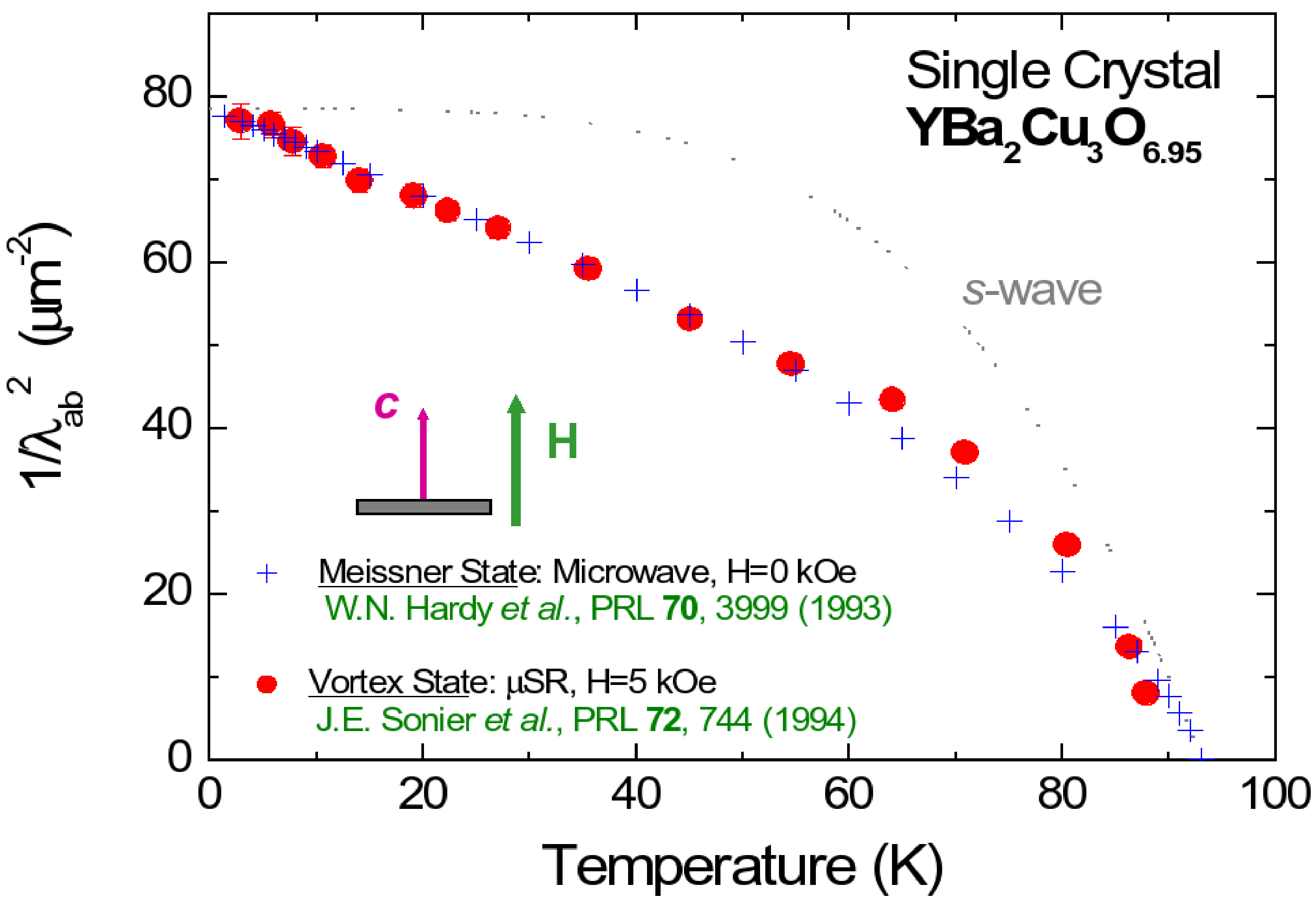
Magnetic Field Distribution of a Vortex Lattice







λ_{ab} in the Meissner & Vortex States



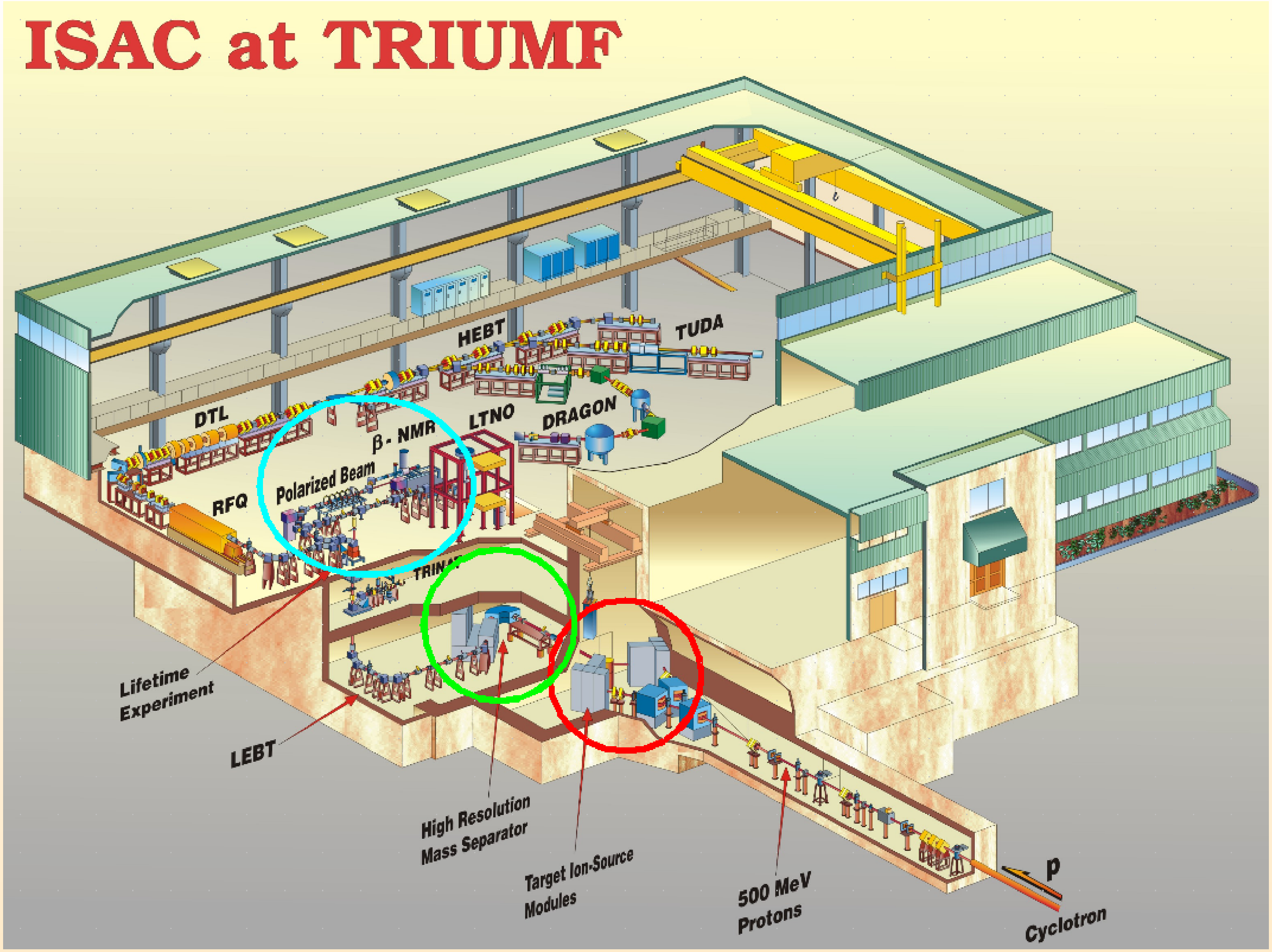
2000s: β-NMR at ISAC

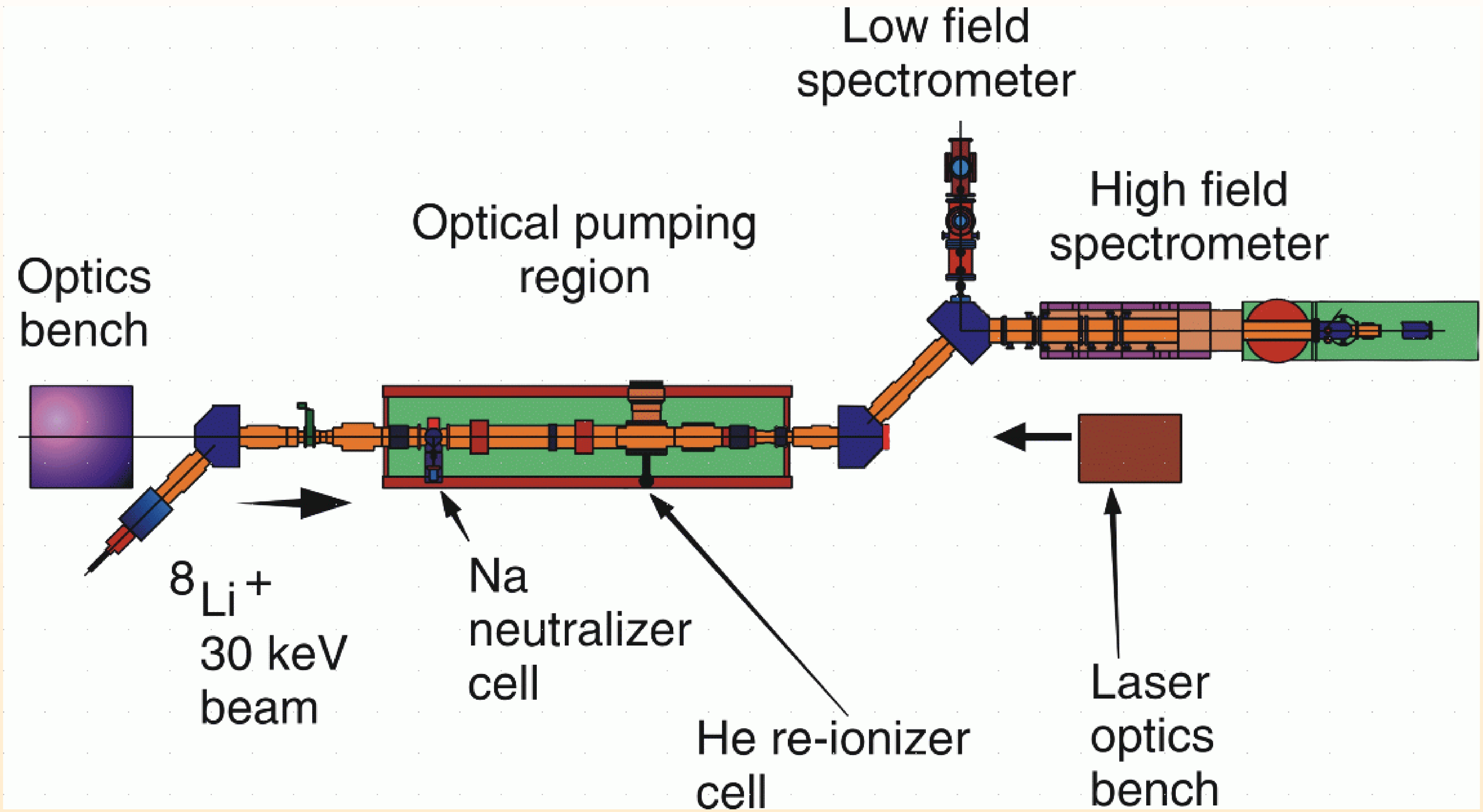
ISAC Layout Spectrometers

UHV Target ^{8}Li Beam Spot

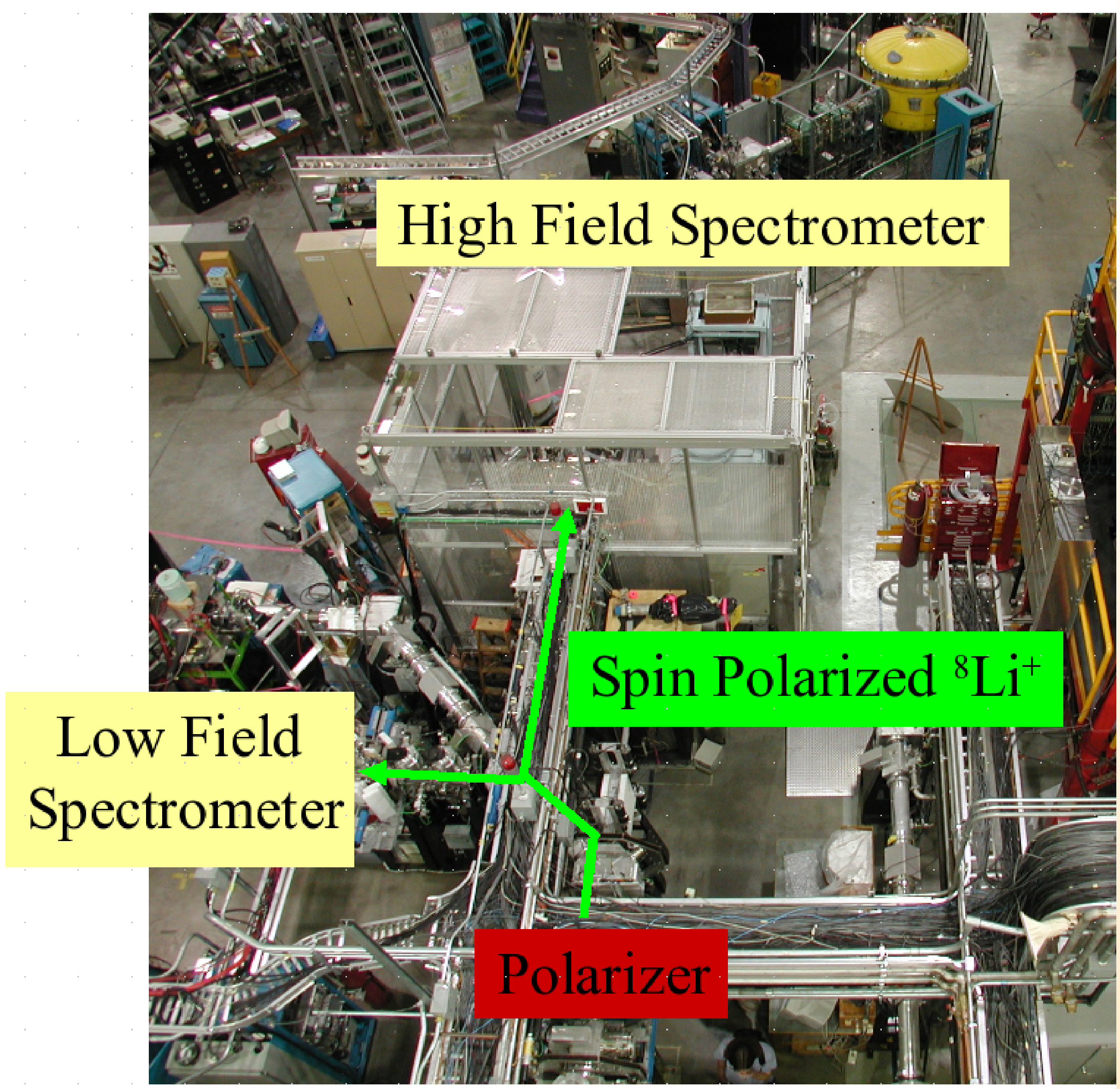
Advantages Depth Profile

Vortex Layer Sites in Ag on MgO


ISAC at TRIUMF
HEBT
TUDA
DTL
β - NMR
LTNO
DRAGON
Polarized Beam
RFQ
Lifetime
Experiment
LEBT
High Resolution
Mass Separator
Target Ion-Source
Modules
500 MeV
Protons
p
Cyclotron

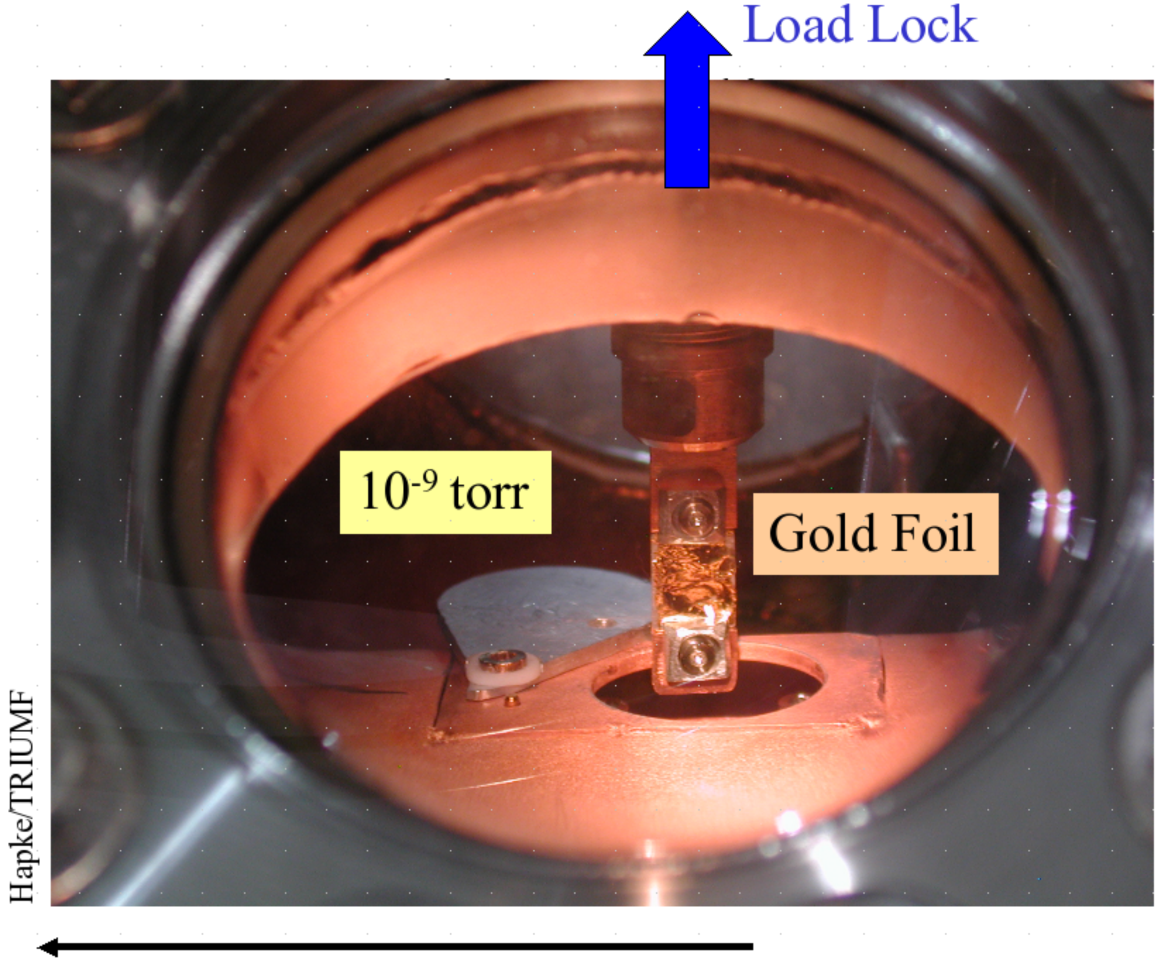

Low field
spectrometer
High field
spectrometer
Optical pumping
region
Optics
bench
8Li+
30 keV
beam
Na
neutralizer
cell
He re-ionizer
cell
Laser
optics
bench

β-NMR



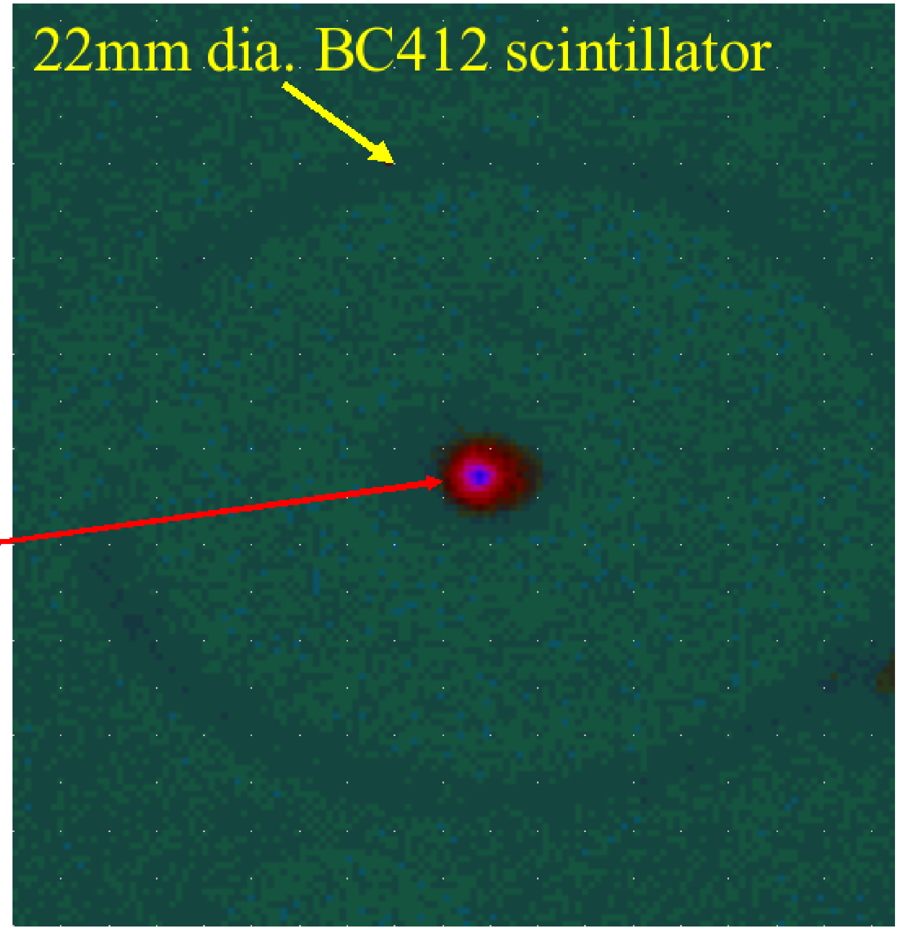
High Field Spectrometer
Spin Polarized $^{8}Li^{+}$
Low Field Spectrometer
Polarizer

Loading a sample into the high-field βNMR spectrometer



Cryostat drives into solenoid bore (9 Tesla)

Beamspot at 123 eV

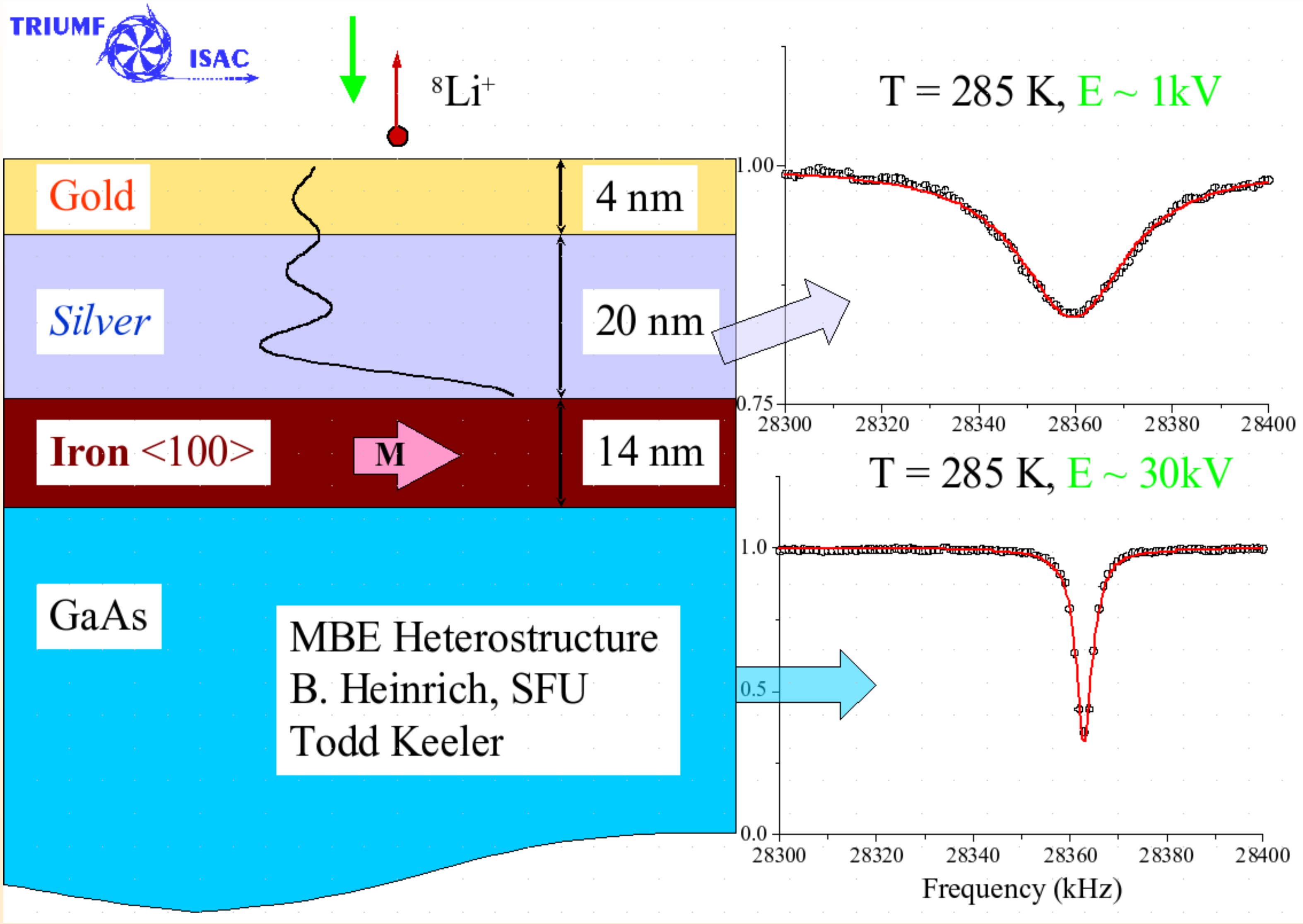


10^7 $^8Li^+$ /s
in 3mm dia.

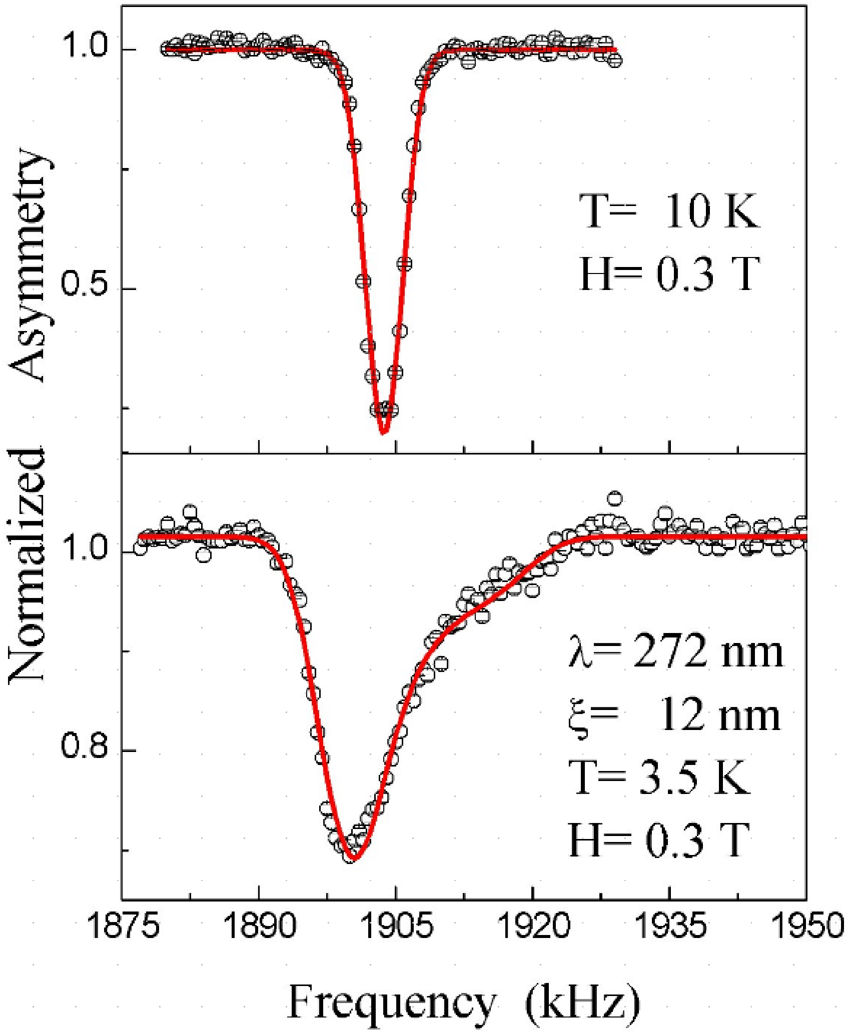
Comparison of NMR with Nuclear Detected Methods

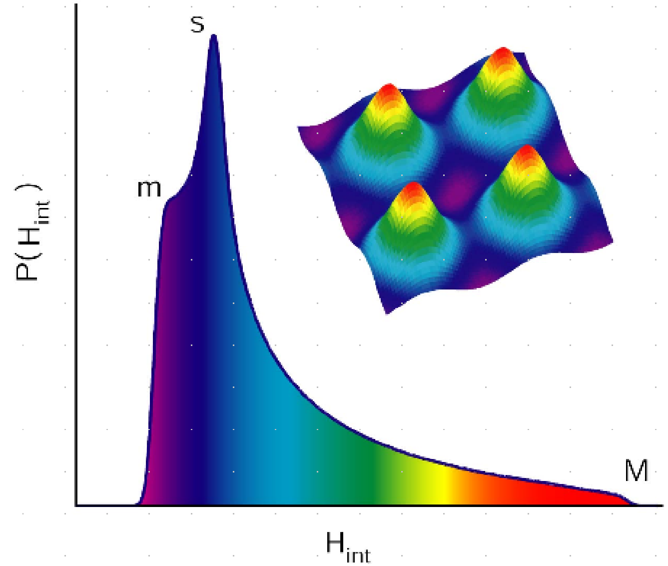
	NMR	μSR	β-NMR
Polarization	<0.01	>0.8	
detection method	electronic pickup	anisotropic β decay	
Sensitivity	10^{17} spins	10^{7} spins	
T_1 range (s)	$10^{-5} - 10^{2}$	$10^{-8} - 10^{-4}$	$10^{-3} - 10^{3}$
range	N/A	0.5 mm	10 Å –3000 Å*
Applied field	high	any	small-high

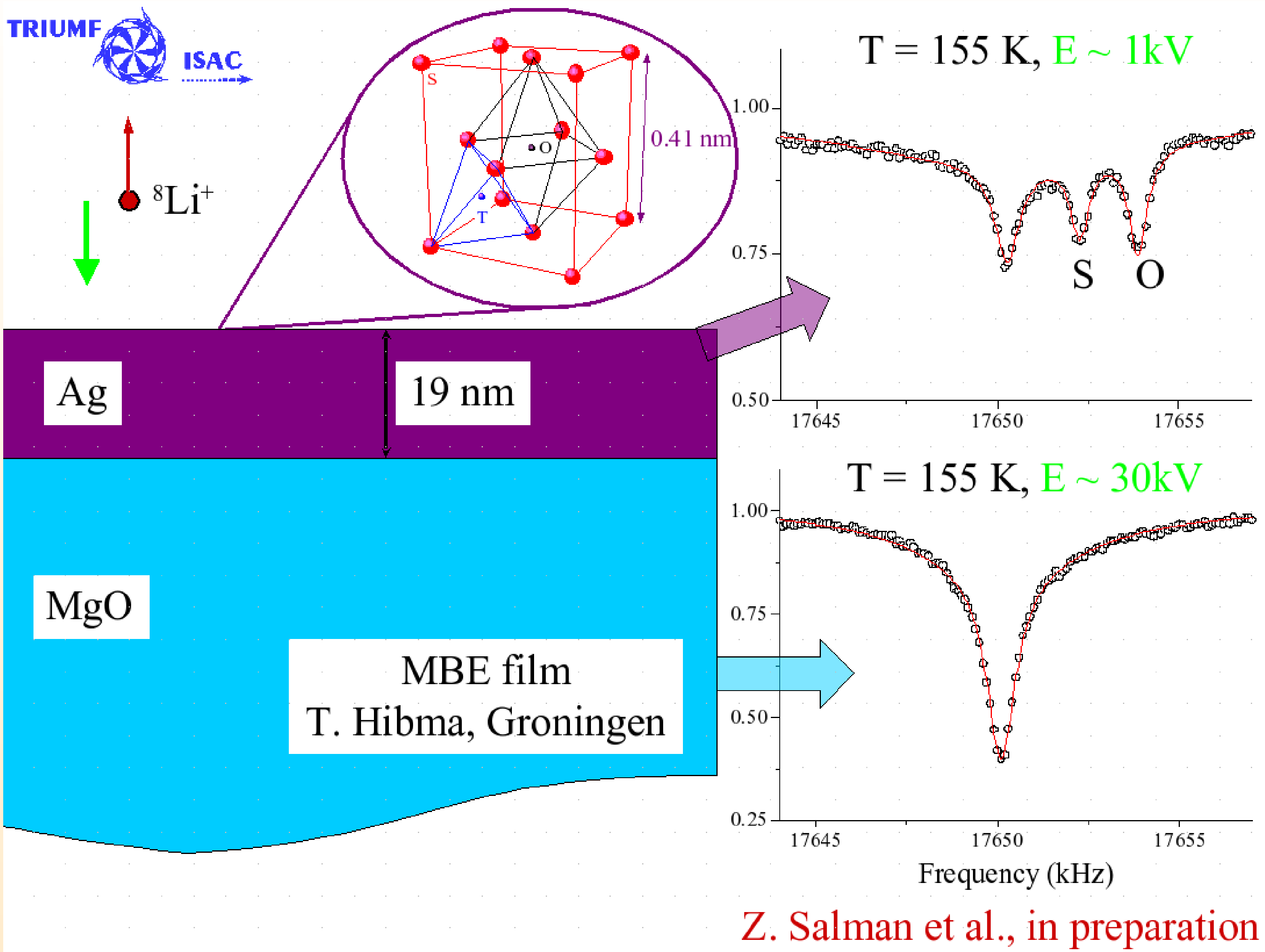
* Depth Sensitivity!


TRIUMF
ISAC
$^8Li^+$
Gold
4 nm
Silver
20 nm
Iron <100>
M
14 nm
GaAs
MBE Heterostructure
B. Heinrich, SFU
Todd Keeler
T = 285 K, E ~ 1kV
T = 285 K, E ~ 30kV
1.00
0.75
28300
28320
28340
28360
28380
28400
1.0
0.5
0.0
Frequency (kHz)

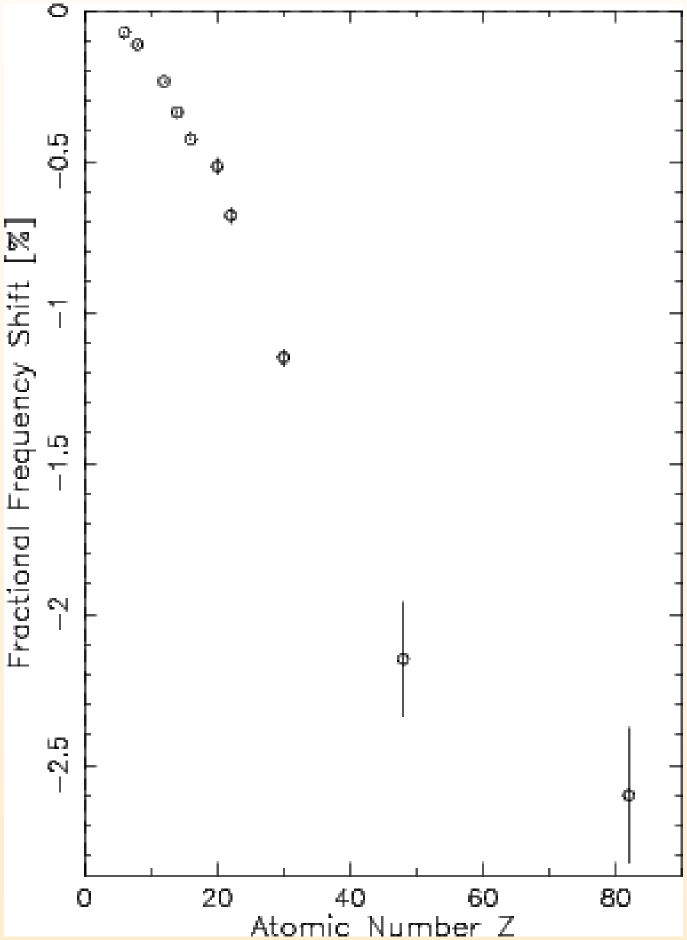
Field Distribution in Vortex state of $NbSe_2$ with ^8Li β-NMR






TRIUMF
ISAC
^{8}Li$^+$
S
T
O
0.41 nm
Ag
19 nm
MgO
MBE film
T. Hibma, Groningen
T = 155 K, E ~ 1kV
1.00
0.75
0.50
S
O
17645
17650
17655
T = 155 K, E ~ 30kV
1.00
0.75
0.50
0.25
17645
17650
17655
Frequency (kHz)
Z. Salman et al., in preparation

Fundamental Physics



System	Frequency [MHz]
μ^+ in graphite	271.69888(72)
μ^+ in Al	271.58520(38)
μ^-C (graphite)	271.3684(16)
μ^-O (H_2O)	271.258(10)
μ^-Mg (metal)	270.9259(27)
μ^-Si	270.6502(69)
μ^-S (powder)	270.406(8)
μ^-Ca (metal)	270.164(69)
μ^-Ti (metal)	269.719(66)
μ^-Zn (metal)	268.440(72)
μ^-Cd (metal)	$265.73^{+0.46}_{-0.57}$
μ^-Pb (metal)	$264.50^{+0.59}_{-0.62}$

TRIUMF μSR Research Highlight # **11** :

Relativistic Shifts in Muonic Atoms

Jess H. Brewer *et al.*

Thanks to the discovery of a substantial transverse spin polarization in the negative muon beam from M9B, we were able to perform μ^- spin precession measurements in fields as high as 2T, more than twice the previous standard. In the first application of this new capability, the relativistic shifts of negative muon g-factors in very high Coulomb fields (*i.e.* bound to nuclei of intermediate and high atomic number Z) were measured to unprecedented precision.

The uncertainties shown are purely statistical. An additional systematic uncertainty of about 0.006 MHz due to variable positioning in the Helios magnet should be added in quadrature. For reference, the Knight shift of the μ^+ in Al is $+80(4)$ ppm [Schenck, 1986].

These results promise a new testing ground for quantum electrodynamics under extreme conditions.

See μSR Literature Entry # **3096**

See TRIUMF Experiment # **932**

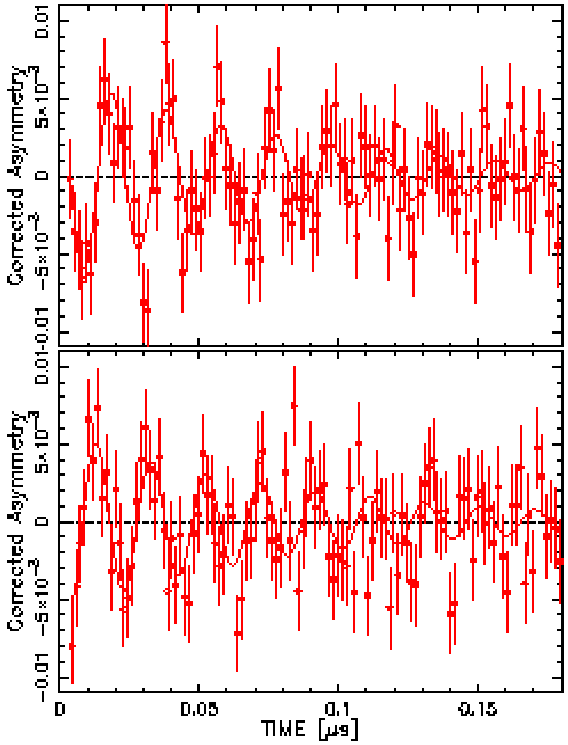


FIG. 1: Precession signal of the F^+ hyperfine state in muonic ^{23}Na, showing the rapid decay into the F^- state.

TRIUMF *μSR* Research Highlight # **12** :

μ^-*SR* Measurement of Hyperfine States of Muonic Sodium

Jess H. Brewer et al.

Both hyperfine states of muonic ^{23}Na and the rate *R* of conversion between the higher F^+ state and the lower F^- state have been observed directly in a high field negative muon spin precession experiment using a backward muon beam with substantial transverse spin polarization. The result, $R = 13.7 \pm 2.2\ \mu s^{-1}$, is consistent with Winston's prediction in 1963 based on Auger emission of core electrons. The decay of the F^+ state is evident in its precession signal, shown in the Figure at left. The signal from the F^- state, shown in the alternate Figure (click on the Figure at left) is one of the smallest ever measured.

See *μSR* Literature Entry # **3092**

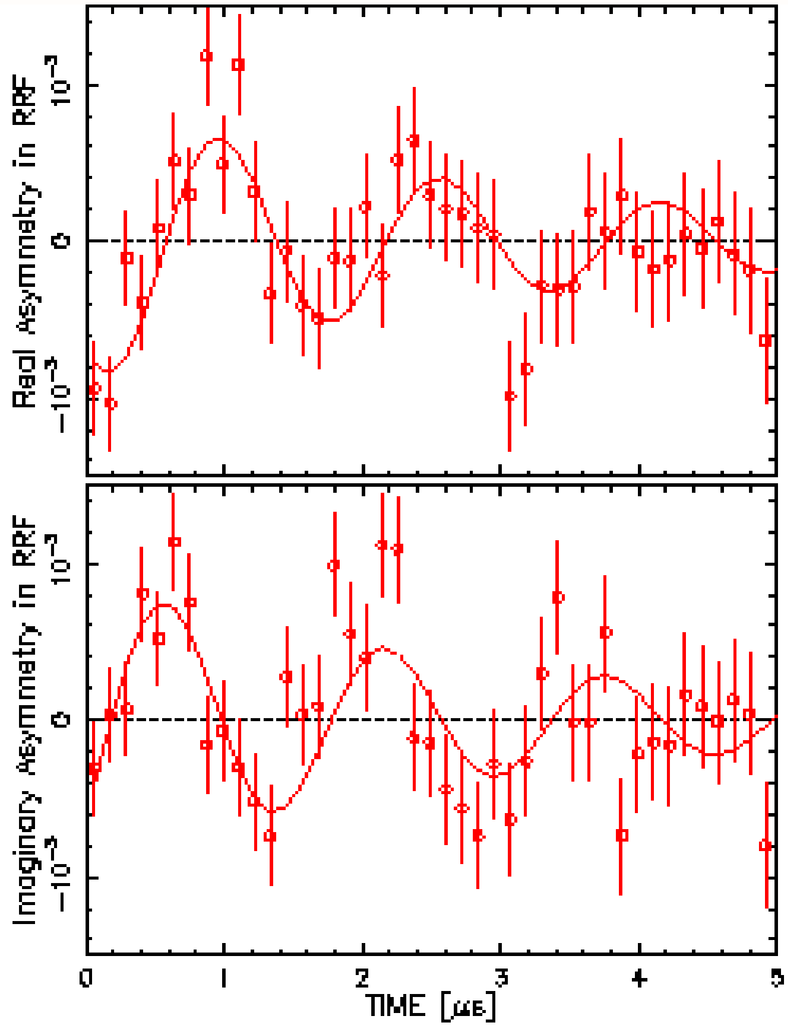
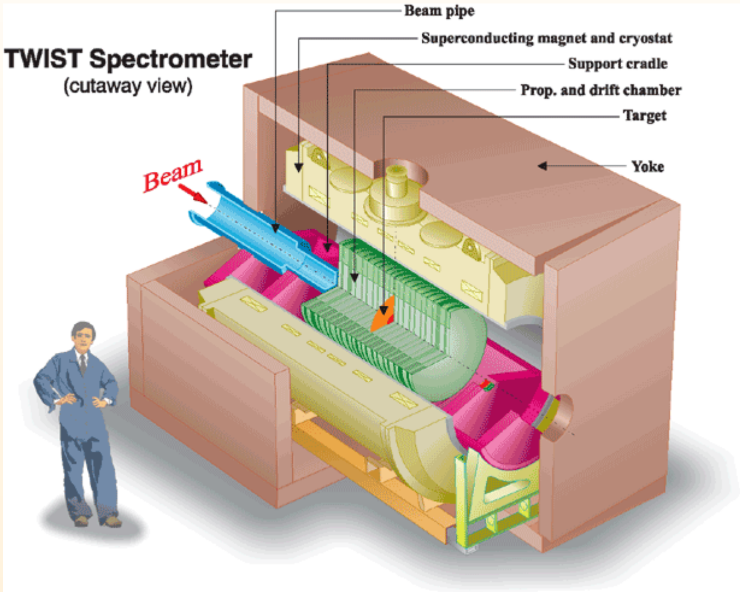
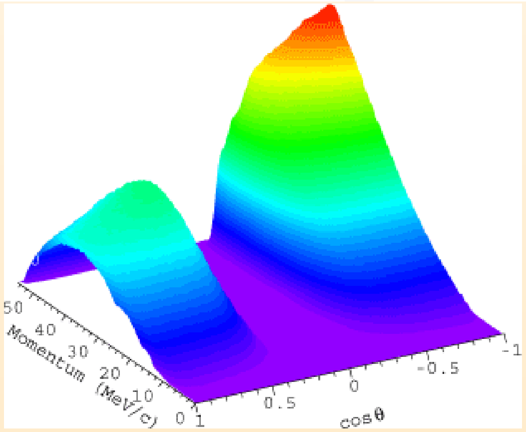


FIG. 2: Precession signal of the F^- hyperfine state in muonic ^{23}Na, viewed in the rotating reference frame at Ω_{RRF} = −95.3 MHz.

We also do the TWIST!





2005: TWIST's new measurement of $\rho = 0.75080 \pm 0.00032$(stat.) ± 0.00097(syst.) ± 0.00023 (last uncertainty due to the current PDG error in η) sets an upper limit on the mixing angle of a possible heavier right-handed partner to the W boson, $|\zeta| < 0.030$ at 90% c.l. Combining ρ with the new measurement of $\delta = 0.74964 \pm 0.00066$(stat.) ± 0.00112(syst.), and the PDG value of $P_\mu \xi \delta / \rho$, an indirect limit is set on $P_\mu \xi$: $0.9960 < P_\mu \xi \leq \xi < 1.0040$ with 90% c.l. The lower limit $0.9960 < P_\mu \xi$ slightly improves the limit on the mass of the possible right-handed boson, $W_R \geq 420$ GeV/c^2. Finally, an upper limit is found for the muon right-handed coupling probability, $Q_R^\mu < 0.00184$ at 90% c.l.

Muon decay, combined with complementary measurements from experiments at higher energies and in nuclear beta decay, help our understanding of the asymmetry in the weak interaction's handedness and whether symmetry may be restored at higher energy scales. In the future phases of the experiment, TWIST aims to produce a direct measurement of $P_\mu \xi$ with a precision of few parts in 10^4 and to increase its sensitivity to ρ and δ by approximately another factor of five.

Conclusions

The world is too much with us; late and soon,
Getting and spending, we lay waste our powers:
Little we see in Nature that is ours;
We have given our hearts away, a sordid boon!
This Sea that bares her bosom to the moon;
The winds that will be howling at all hours,
And are up-gathered now like sleeping flowers;
For this, for everything, we are out of tune;
It moves us not. — Great God! I'd rather be
A Pagan suckled in a creed outworn;
So might I, standing on this pleasant lea,
Have glimpses that would make me less forlorn;
Have sight of Proteus rising from the sea;
Or hear old Triton blow his wreathèd horn.

— *William Wordsworth, 1807*