Materials Science and Quantum Materials a TRIUMF

Rob Kiefl, TRIUMF, Department of Physics and Astronomy and
Stuart Blossom Quantum Matter Institute UBC

Yamazaki Prize presentation Sapporo June 25 2017

μSR2017
Sapporo, Japan June 25-30, 2017

3rd such award for work at done at TRIUMF. Uemura and Brewer previous winners

"for development and use of μSR and also β NMR in the area of condensed matter physics"

International Society for Muon Science (ISMS)

"The search for discoveries in experimental physics is not only an effort to find and interpret interesting experimental facts, but is also a creative intellectual effort to invent new experimental techniques that extend the frontiers of experimental feasibility"

Ted Bowen, The Surface Muon Beam, in PHYSICS TODAY , JULY 1985

Plan

1. Introduction to muon and μSR

2. The early days

3. High Tc Superconductivity

4. Beta NMR

5 Future

Muon Science

1. Muon is a fundamental particle and muonium ($\mu^+ e^-$) is the simplest atom

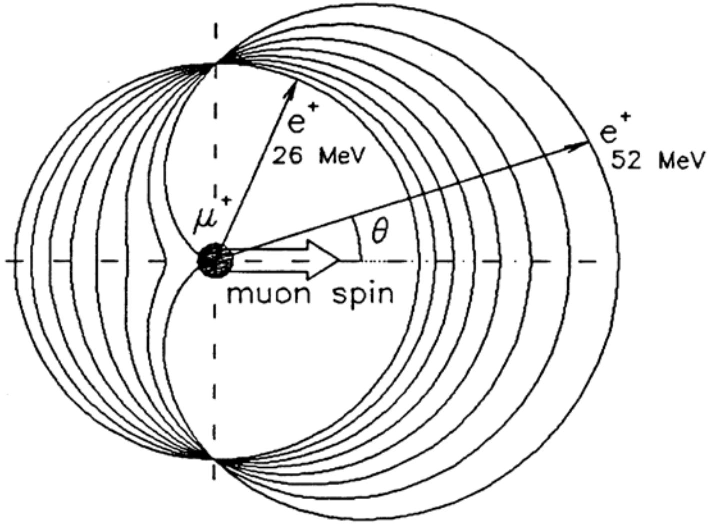
2. Electronic structure of muonium (and its charged states) in a solid nearly identical to that of hydrogen. Most of what we know about isolated hydrogen in semiconductors comes indirectly from μSR.

3. Chemistry, bonding and reaction dynamics are similar to the hydrogen atom except QM aspects are enhanced due to lighter mass. Don Fleming winner of ACS Seaborg Award in Nuclear Chemistry 2004 for his work on Mu reactions in gas phase.

4. The muon is sensitive magnetic probe of electronic and magnetic properties of quantum materials, (collective behavior of all the electrons and ions in a material, e.g. superconductivity).

μSR

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Spin = 1/2

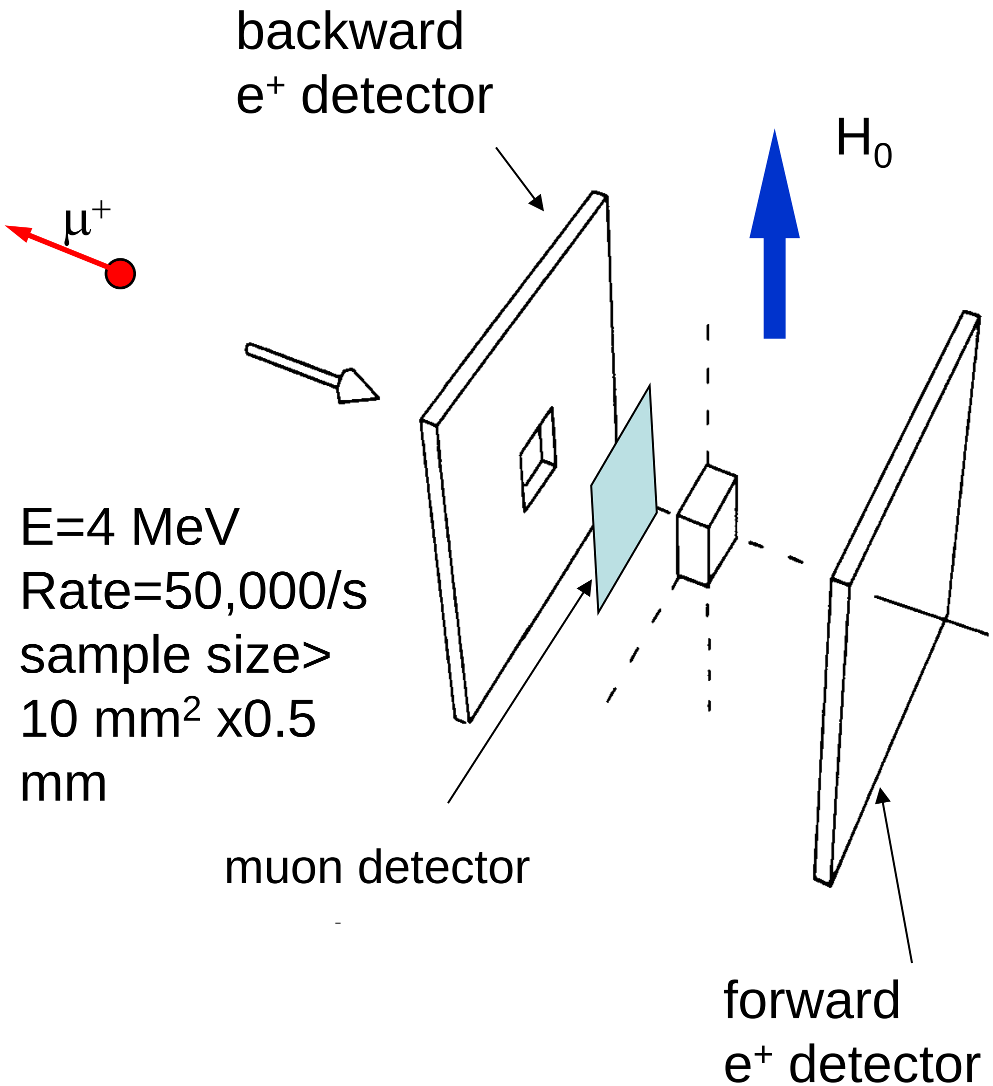
γ = 135.55MHz/T

<A>= 0.33

Polarization = 95%

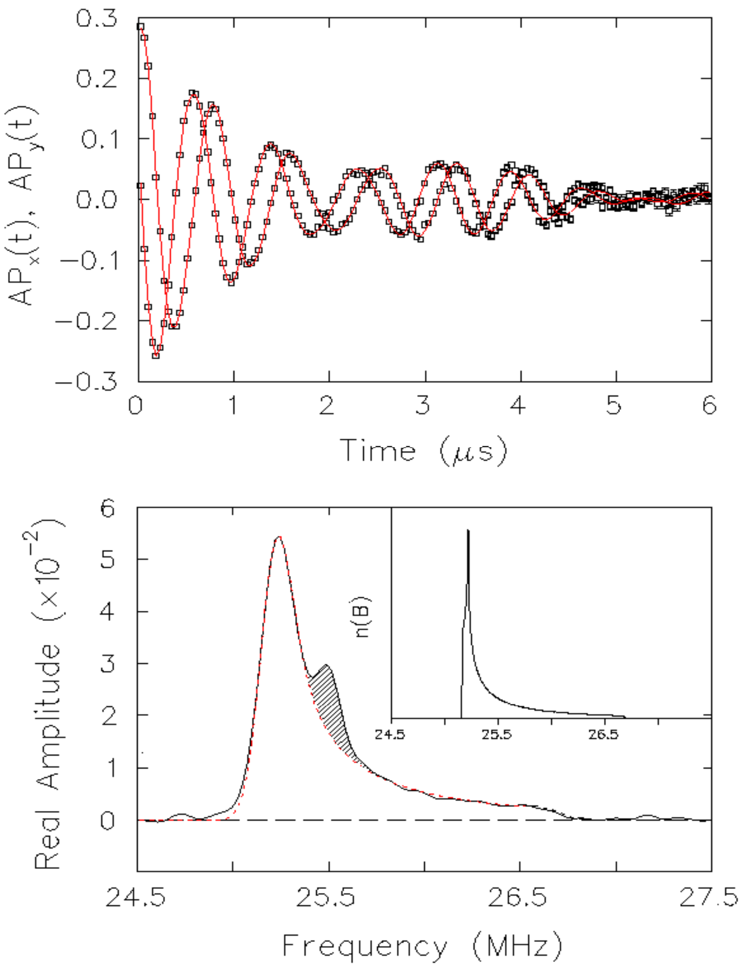
Lifetime = 2.19714(7) μs

Schematic of a conventional μSR Experiment



E=4 MeV
Rate=50,000/s
sample size>
10 mm^2 x0.5
mm

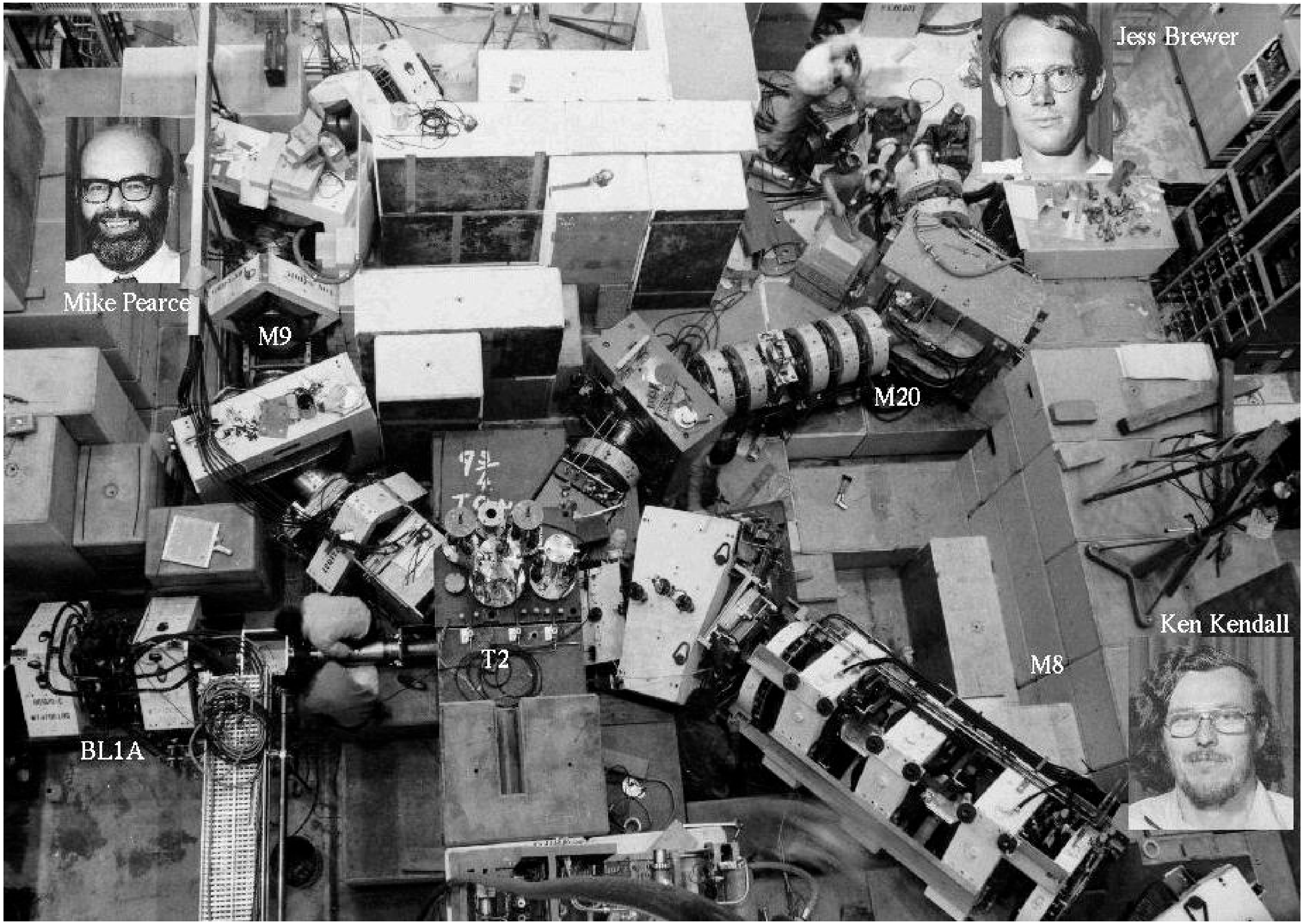
NbSe$_2$ T=0.33T$_c$, H=1.9 kOe



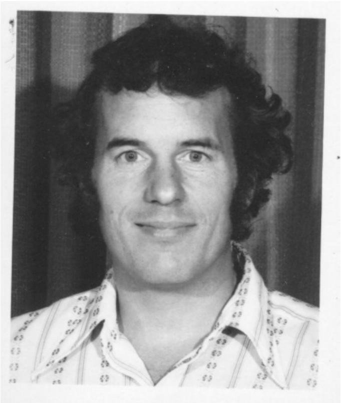
Advent of the Meson Factory and the surface muon beamline

Beginnings of μSR at TRIUMF ~1972

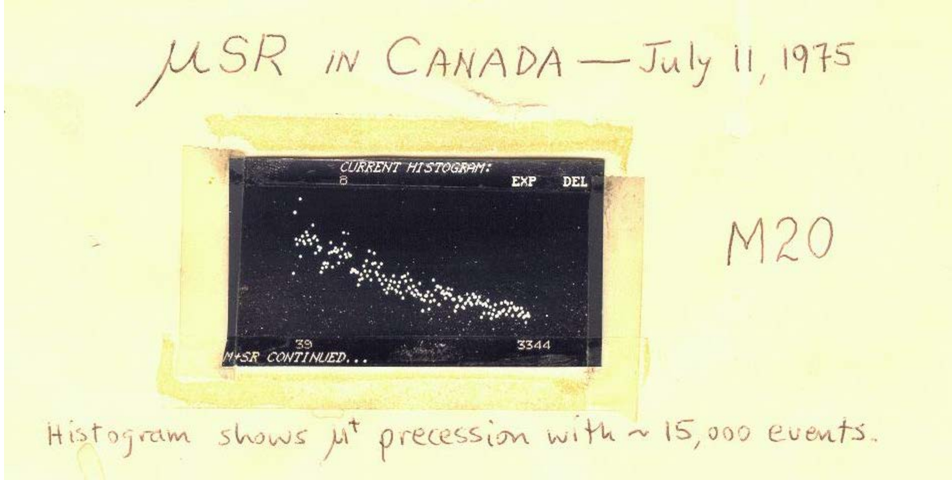
M20 surface muon beam for materials science

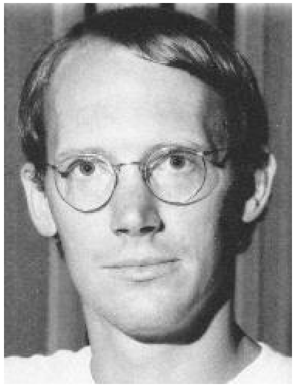


T. Yamazaki



D. Fleming





J. Brewer

K. Nagamine

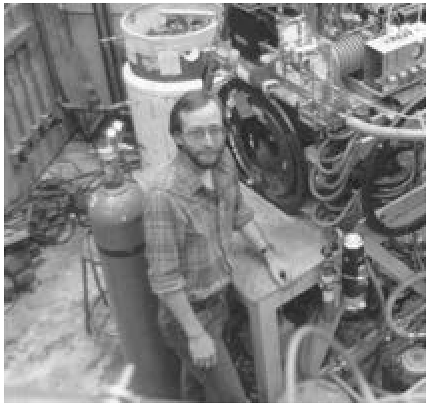
Some early graduate students

Dave Garner

Ryu Hayano

Tomo Uemura. Rob Kiefl, Carl Clawson

Glen Marshall, Randy Mikula



Dale Harshman

Yamazaki group and the University of Tokyo

PHYSICAL REVIEW B VOLUME 20, NUMBER 3 1 AUGUST 1979

1. Zero Field μSR

739 citations

Zero- and low-field spin relaxation studied by positive muons

R. S. Hayano, Y. J. Uemura, J. Imazato, N. Nishida, T. Yamazaki, and R. Kubo
Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo, Japan
and TRIUMF, Vancouver, Canada
(Received 27 February 1979)

Zero- and low-field spin-relaxation functions have been studied for the first time by using positive muons, and results are compared with the stochastic theory of low-field relaxation formulated by Kubo and Toyabe. The dipolar broadening of the zero-field relaxation has been studied in detail. In ZrH_2, the zero-field relaxation function of μ^+ has been found to decay $(5)^{1/2}$ times faster than the high-field relaxation function, which is explained in terms of the contribution of the nonsecular part of the dipolar interaction. Advantages of the zero-field method over the conventional muon-spin rotation method in practical applications, especially for studies of the μ^+ diffusion/trapping, are discussed.

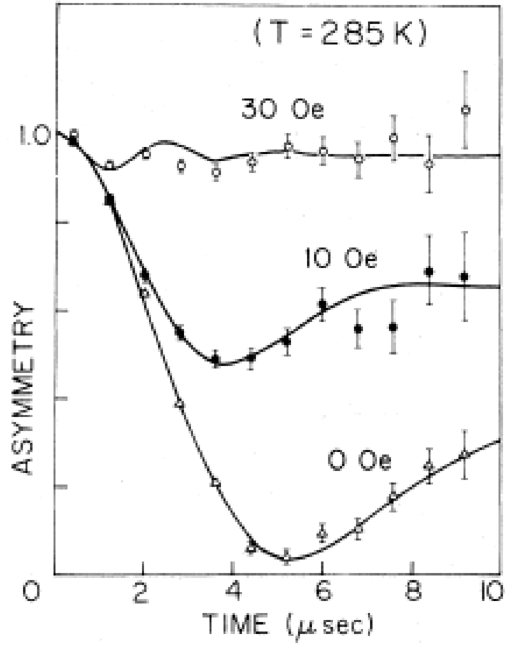
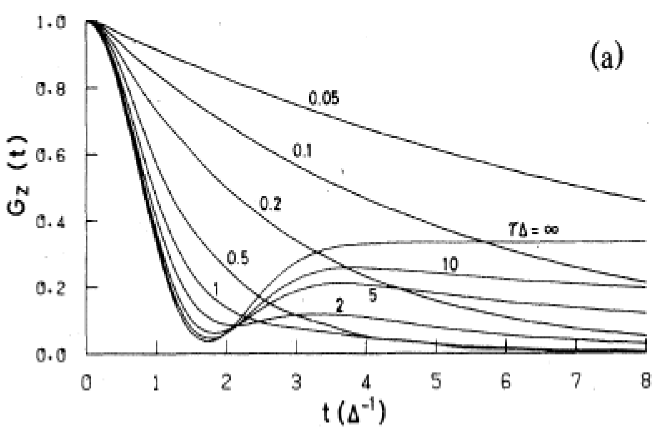


FIG. 2. Observed μ^+ longitudinal relaxation functions in MnSi at room temperature with 0, 10, and 30 Oe external fields. The solid curves are the best fits to Eq. (10).



Luke, Kadono Storchak,Brewer

Quantum Diffusion

PHYSICAL REVIEW B VOLUME 43, NUMBER 4 1 FEBRUARY 1991

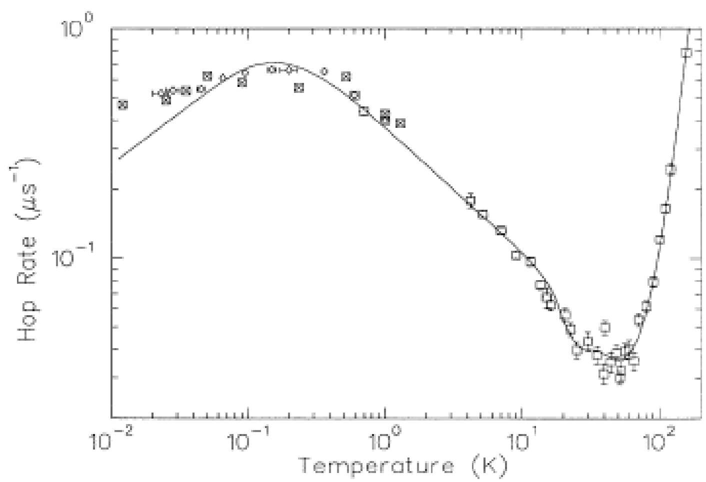
Muon diffusion and spin dynamics in copper

G. M. Luke,* J. H. Brewer, S. R. Kreitzman, and D. R. Noakes†
Department of Physics, University of British Columbia, Vancouver, Canada V6T 2A3

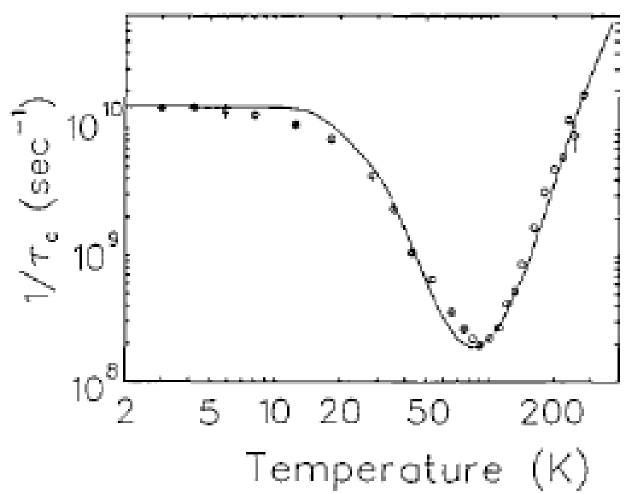
M. Celio‡ and R. Kadono§
TRIUMF, 4004 Wesbrook Mall, Vancouver, Canada V6T 2A3

E. J. Ansaldo
Department of Physics, University of Saskatchewan, Saskatoon, Canada S7N 0W0

Quantum diffusion of muons in Cu



Quantum Diffusion of Mu in GaAs



Muon as a test of time reversal symmetry breaking in superconductors

VOLUME 71, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1993

Muon Spin Relaxation in UPt_3

Luke and Uemura

G. M. Luke, A. Keren, L. P. Le, W. D. Wu, and Y. J. Uemura
Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027

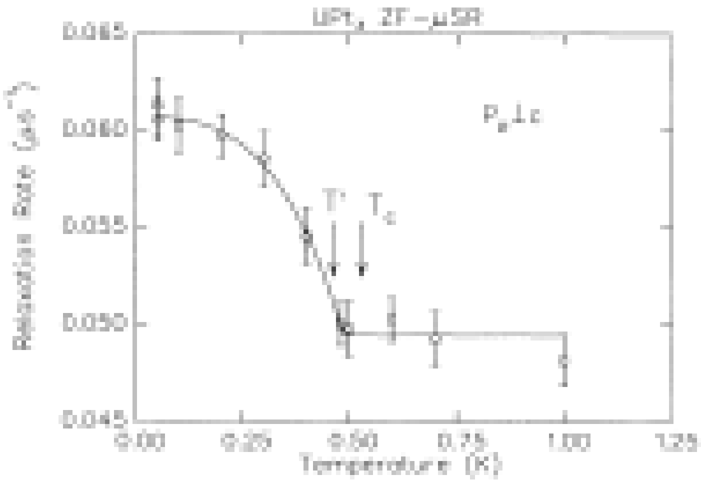
D. A. Bonn
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada V6T 2A3

L. Taillefer
Department of Physics, McGill University, Montreal, Canada H3A 2T8

J. D. Garrett
Department of Physics and Institute for Materials Research, McMaster University, Hamilton, Ontario, Canada L8S 4M1

(Received 27 May 1993)

We report muon spin rotation-relaxation measurements of the heavy fermion superconductor UPt_3. The broadening of the transverse field muon precession signal sets in approximately 60 mK below T_c, a temperature which corresponds to the lower superconducting transition. In zero applied magnetic field, we observe an increase in the internal magnetic field within the superconducting state which can be explained if the "lower superconducting phase" in the *H-T* phase diagram of UPt_3 is characterized by broken time-reversal symmetry.



Spin Dynamics in Geometrically frustrated magnets

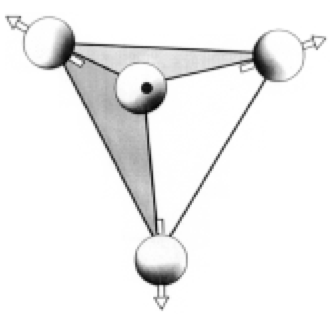
483 citations

VOLUME 82, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1999

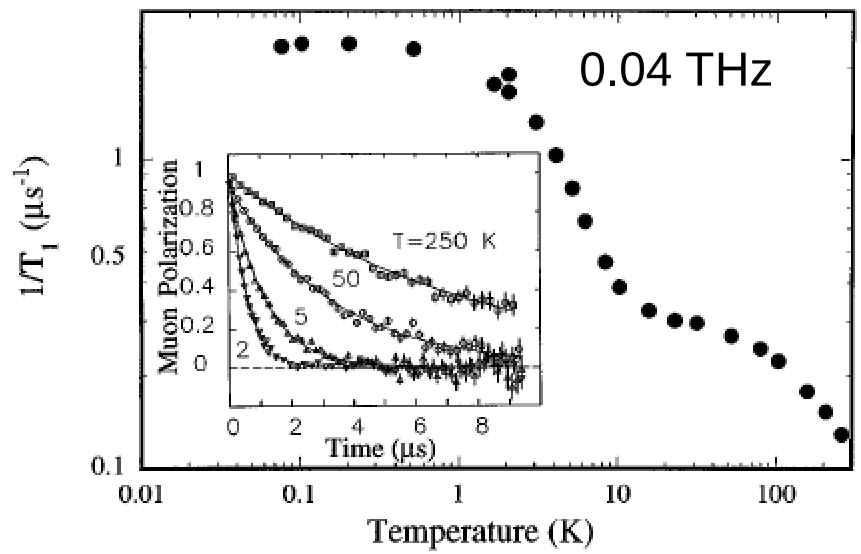
Sarah Dunsiger

Cooperative Paramagnetism in the Geometrically Frustrated Pyrochlore Antiferromagnet $Tb_2Ti_2O_7$

J. S. Gardner,[1] S. R. Dunsiger,[2] B. D. Gaulin,[1] M. J. P. Gingras,[3] J. E. Greedan,[4] R. F. Kiefl,[2] M. D. Lumsden,[1] W. A. MacFarlane,[2] N. P. Raju,[4] J. E. Sonier,[2] I. Swainson,[5] and Z. Tun[5]



local spin correlation from neutrons



2. Muon Level Crossing Resonance

VOLUME 56, NUMBER 2 PHYSICAL REVIEW LETTERS 13 JANUARY 1986

Longitudinal-Field μ^+ Spin Relaxation via Quadrupolar Level-Crossing Resonance in Cu at 20 K

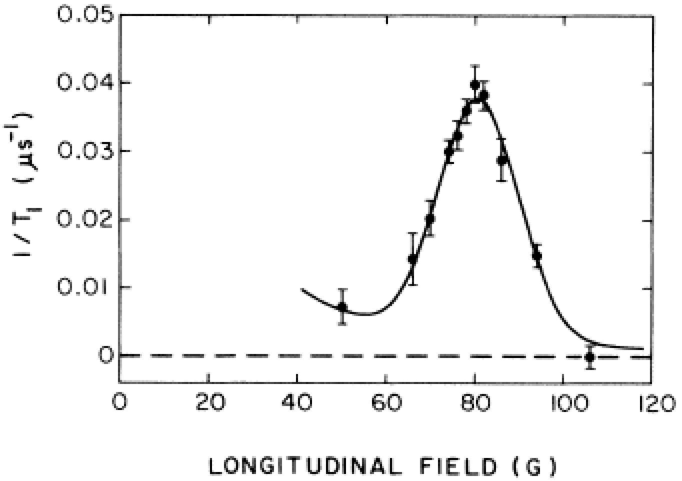
Kreitzman and Brewer

S. R. Kreitzman, J. H. Brewer, D. R. Harshman, R. Keitel, and D. Ll. Williams
TRIUMF and Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A3, Canada

K. M. Crowe
Department of Physics, University of California, Berkeley, California 94720

and

E. J. Ansaldo
Department of Physics, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0, Canada



Structure of Muonium Substituted Free Radicals

RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 34, NUMBER 1 JULY 1986

Resolved nuclear hyperfine structure of a muonated free radical using level-crossing spectroscopy

Paul Percival

R. F. Kiefl, S. Kreitzman, M. Celio, and R. Keitel
TRIUMF, University of British Columbia, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

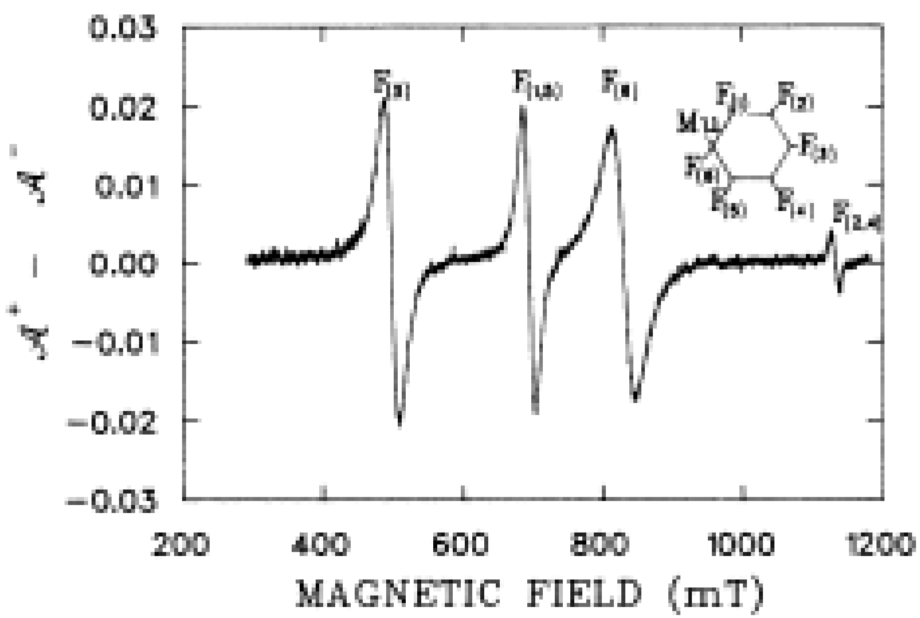
G. M. Luke, J. H. Brewer, and D. R. Noakes
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada V6T 1W5

P. W. Percival
Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

T. Matsuzaki and K. Nishiyama
Meson Science Laboratory, University of Tokyo, Tokyo 113, Japan

(Received 10 February 1986)

SLC Magnet
U of Tokyo



Muonium in Semiconductors

Tom Estle and Moreno Celio

VOLUME 60, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1988

[29]Si Hyperfine Structure of Anomalous Muonium in Silicon: Proof of the Bond-Centered Model

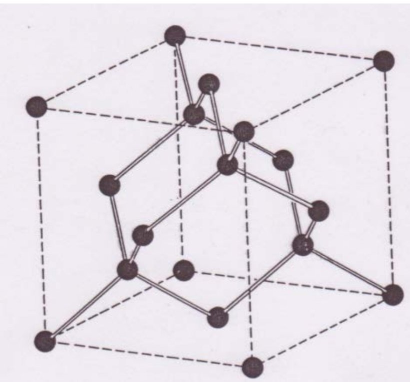
R. F. Kiefl[(a)] and M. Celio
TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

T. L. Estle
Rice University, Houston, Texas 77251

S. R. Kreitzman, G. M. Luke, and T. M. Riseman
ersity of British Columbia, Vancouver, British Columbia, Canada V

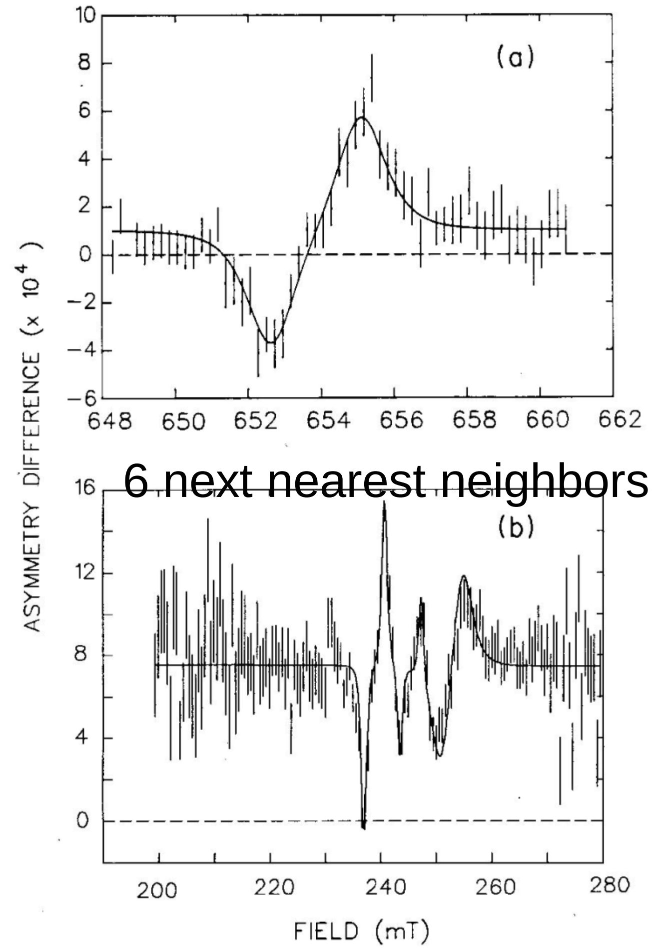
and

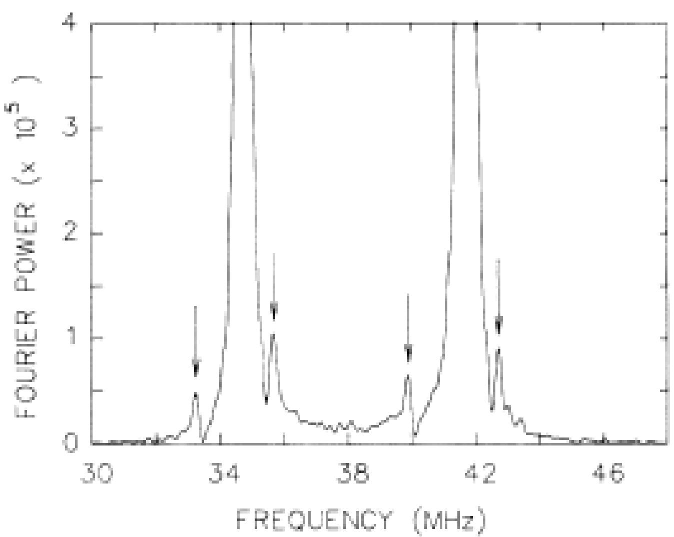
E. J. Ansaldo
niversity of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N



2 nearest neighbors

6 next nearest neighbors





3. Production of low energy muons and the low energy muon beamline at PSI

VOLUME 56, NUMBER 26 PHYSICAL REVIEW LETTERS 30 JUNE 1986

Observation of Low-Energy μ^+ Emission from Solid Surfaces

Dale Harshman

D. R. Harshman[a] and J. B. Warren
Department of Physics, The University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada

J. L. Beveridge, K. R. Kendall, R. F. Kiefl, and C. J. Oram
TRIUMF, Vancouver, British Columbia V6T 2A3, Canada

E. Morenzoni LE μSR

A. P. Mills, Jr., and W. S. Crane
AT&T Bell Laboratories, Murray Hill, New Jer.

and

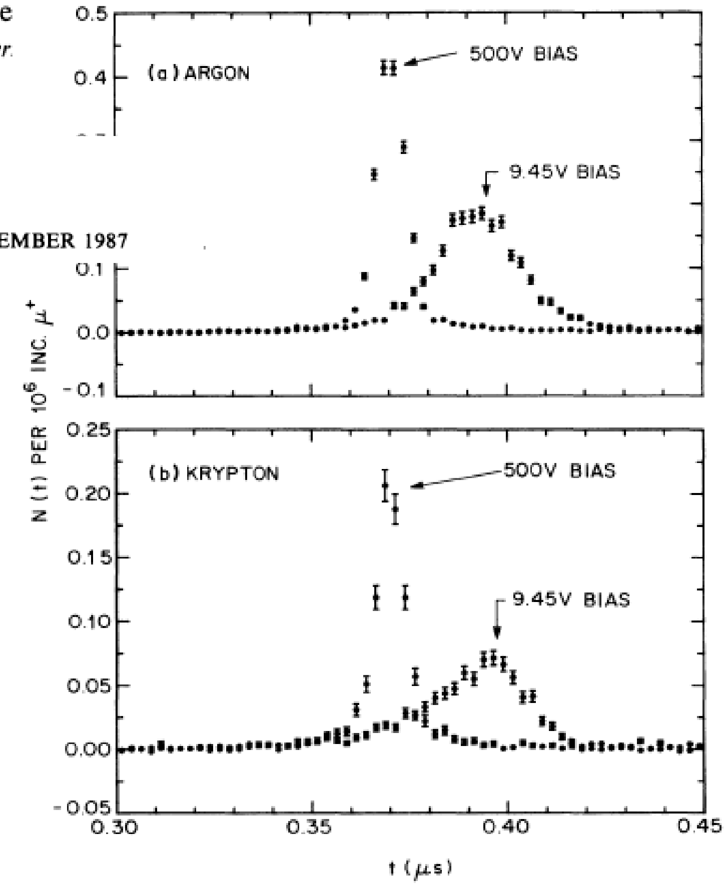
ID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 36, NUMBER 16 1 DECEMBER 1987

D. R. Harshman and A. P. Mills, Jr.
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

J. L. Beveridge, K. R. Kendall, G. D. Morris, M. Senba, and J. B. Warren
TRIUMF, University of British Columbia, Vancouver, British Columbia, V6T 2A3, Canada

A. S. Rupaal and J. H. Turner

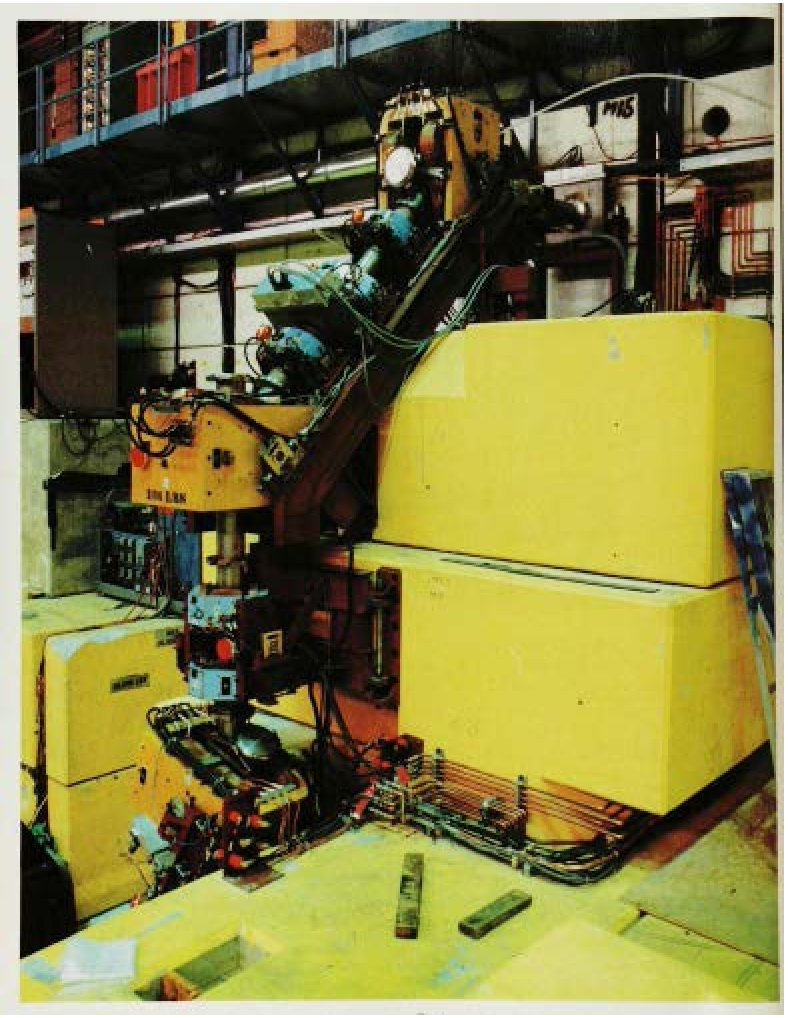


4. Spin Rotator

High Transverse Field μSR

M15; A dedicated surface muon beamline with a spin rotator 1984 then M20 as well.

Dave Garner



5. Background suppression methods

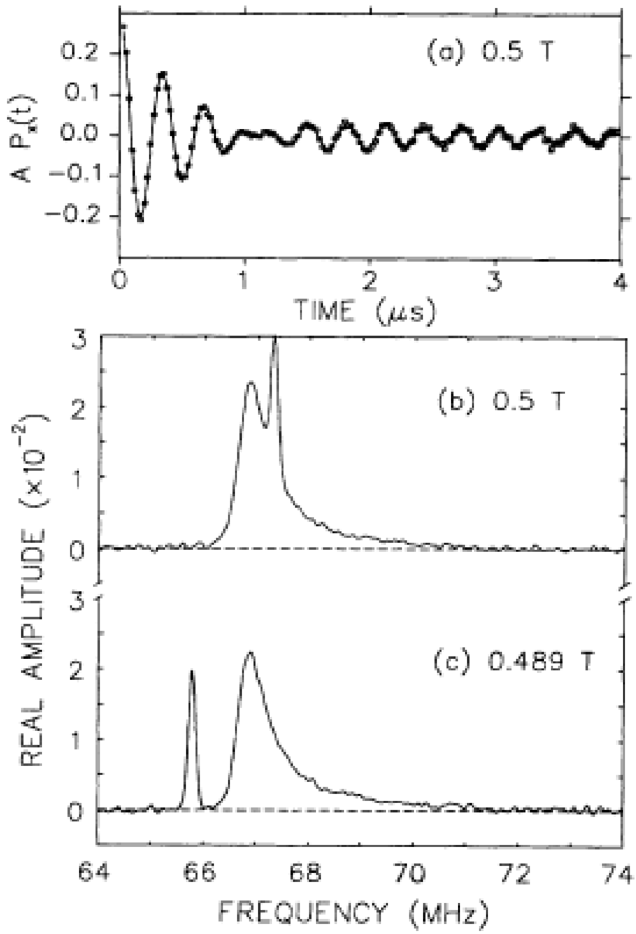
VOLUME 72, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1994

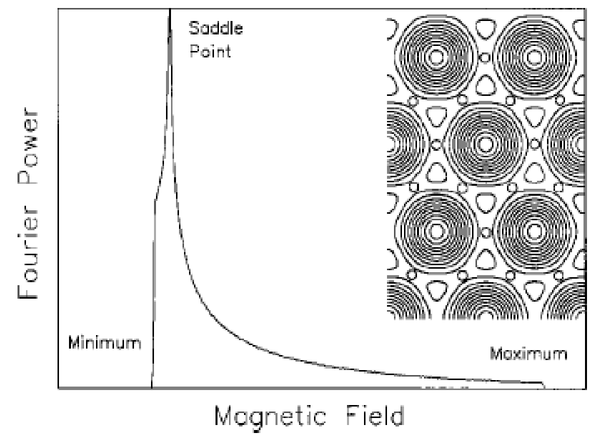
Jeff Sonier

New Muon-Spin-Rotation Measurement of the Temperature Dependence of the Magnetic Penetration Depth in $YBa_2Cu_3O_{6.95}$

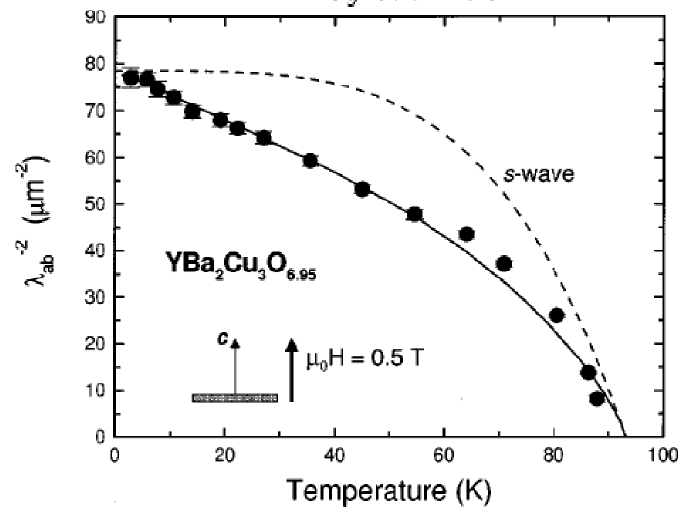
J. E. Sonier, R. F. Kiefl, J. H. Brewer, D. A. Bonn, J. F. Carolan, K. H. Chow, P. Dosanjh, W. N. Hardy, Ruixing Liang, W. A. MacFarlane, P. Mendels,* G. D. Morris, T. M. Riseman,* and J. W. Schneider

Vortex lattice





UBC XL's



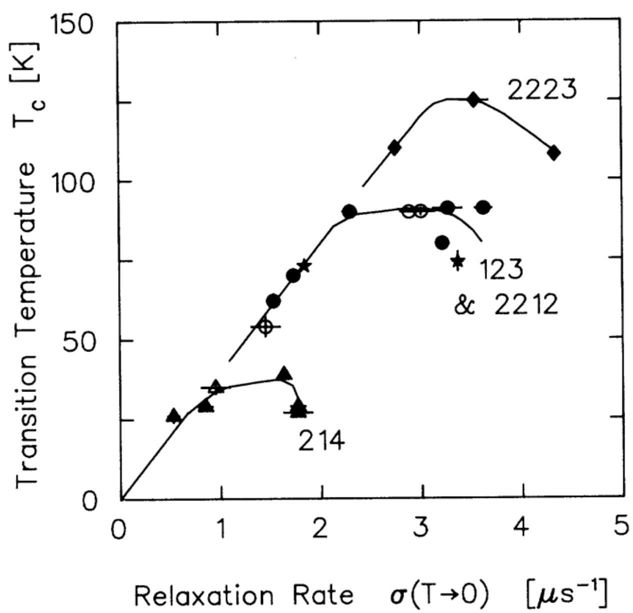
d-wave SC

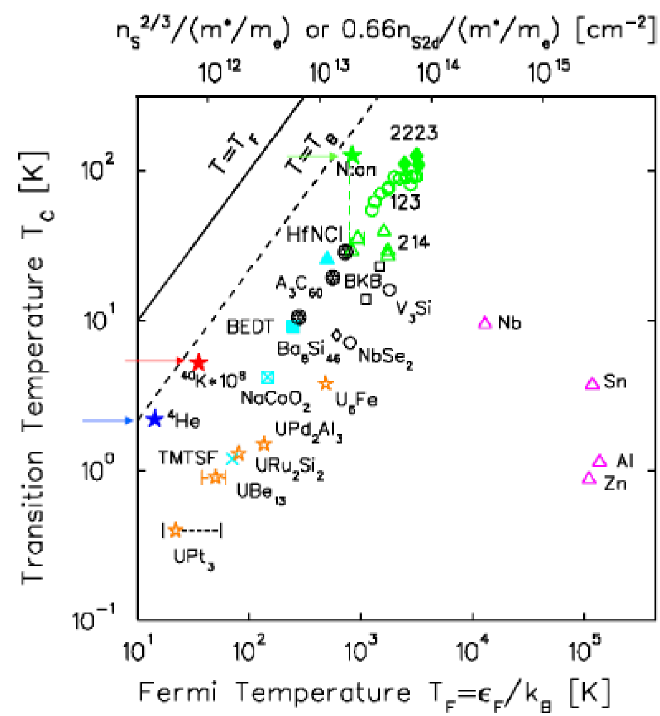
Uemura Plot 1250 citations **Tomo Uemura**

VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

Universal Correlations between T_c and n_s/m^* (Carrier Density over Effective Mass) in High-T_c Cuprate Superconductors

Y. J. Uemura,[1] G. M. Luke,[1] B. J. Sternlieb,[1] J. H. Brewer,[2] J. F. Carolan,[2] W. N. Hardy,[2] R. Kadono,[2] J. R. Kempton,[2] R. F. Kiefl,[2] S. R. Kreitzman,[2] P. Mulhern,[2] T. M. Riseman,[2] D. Ll. Williams,[2] B. X. Yang,[2] S. Uchida,[3] H. Takagi,[3] J. Gopalakrishnan,[4] A. W. Sleight,[4] M. A. Subramanian,[4] C. L. Chien,[5] M. Z. Cieplak,[5] Gang Xiao,[5] V. Y. Lee,[6] B. W. Statt,[7] C. E. Stronach,[8] W. J. Kossler,[9] and X. H. Yu[9]





6. Really High Transverse Field μSR

VOLUME 83, NUMBER 20 PHYSICAL REVIEW LETTERS 15 NOVEMBER 1999

Field Induced Reduction of the Low-Temperature Superfluid Density in $YBa_2Cu_3O_{6.95}$

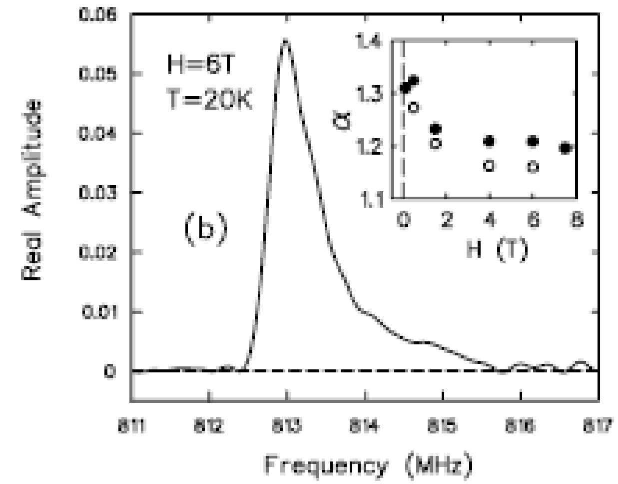
J. E. Sonier,[1,2] J. H. Brewer,[2,3] R. F. Kiefl,[2,3] G. D. Morris,[2] R. I. Miller,[2,3] D. A. Bonn,[3]
J. Chakhalian,[2,3] R. H. Heffner,[1,2] W. N. Hardy,[3] and R. Liang[3]

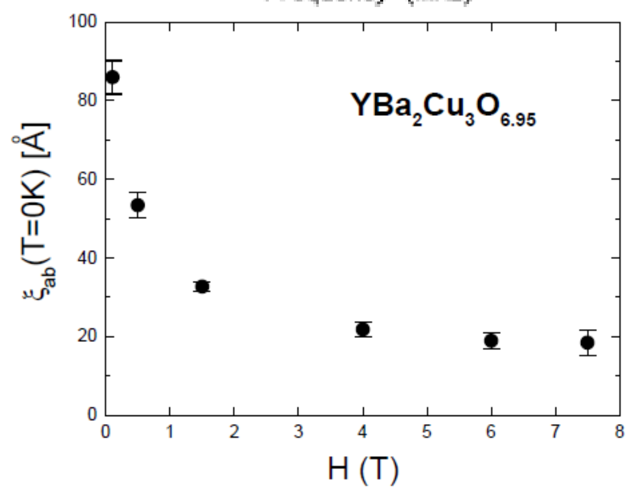
Syd Kreitzman

Belle the HTR/HTF 7T spect.

Muon & Active Coll-imator Detector Array | Compact 7T Magnet | 1.6K Cryostat | Positron & Muon-Veto Detectors

TRIUMF Centre for Molecular and Materials Science CMMS

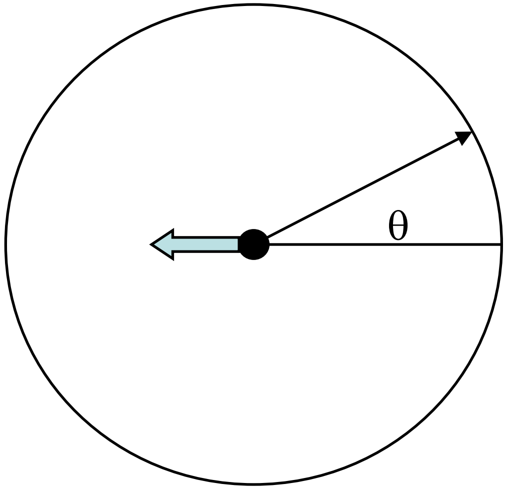




7. β-NMR

Alan Astbury

$^{8}Li \longrightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$



Spin=2, Q=33 mb

γ =6.30 MHz/T

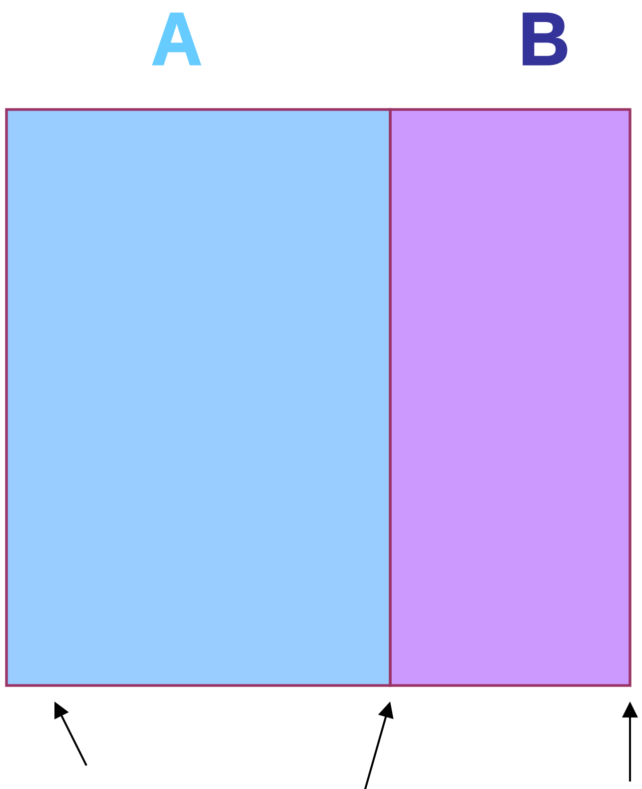
<A>=-0.30

Polarization= 70%

Lifetime= 1.2s

Energy 0.5-30 keV

Exploring the collective behaviour of electrons near an interface or in a thin film.



NMR
Neutrons
μSR

LEμSR
Resonant
Xray scatt.
βNMR

ARPES
STM

-superconductor/vacuum YBCO

-metal/vacuum Pd

insulator/vacuum Bi2Se3

antiferromagnet/vacumm Fe2O3

-ferromagnet /metal, GMR Fe/Ag

-semiconductor/ferromagnet,

-insulator/insulator SrTiO3 /LaAlO3,

-superconductor/metal, Ag/Nb.

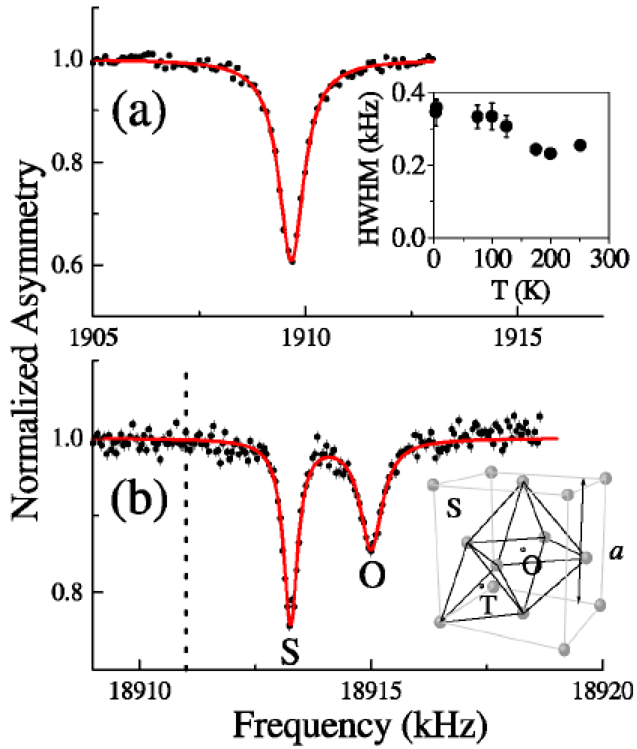
Gerald Morris, Andrew McFarlane,Zaher Salman and Phil Levy

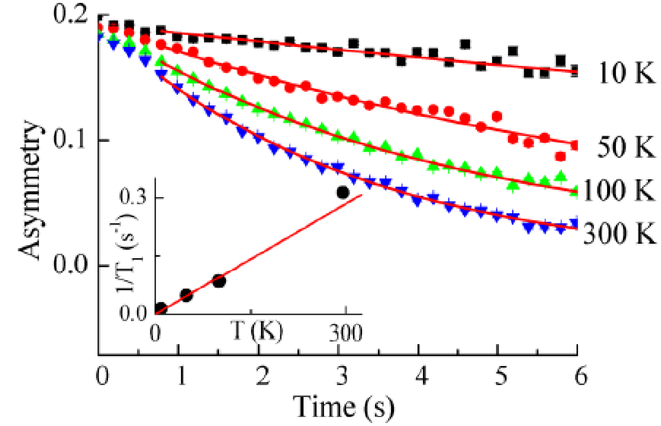
VOLUME 93, NUMBER 15 PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2004

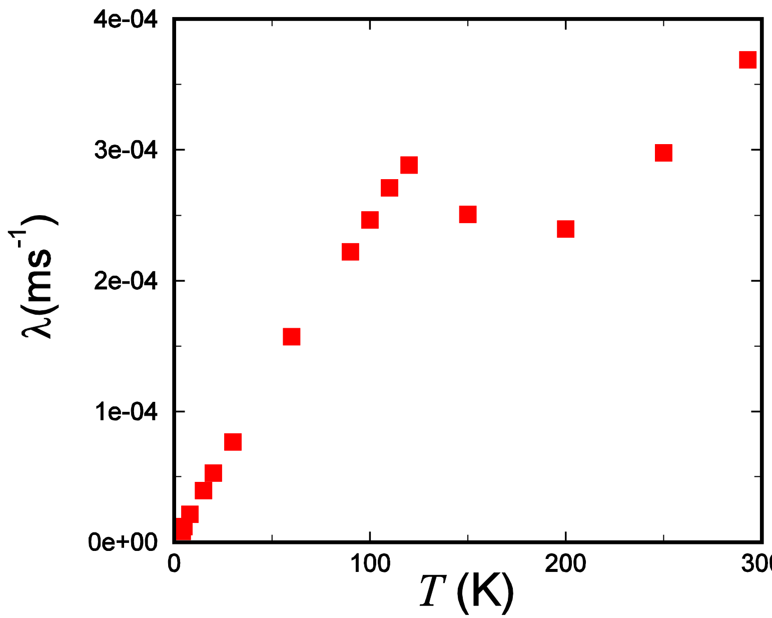
Depth-Controlled β-NMR of ^{8}Li in a Thin Silver Film

G. D. Morris,[1] W. A. MacFarlane,[2,3] K. H. Chow,[4] Z. Salman,[3] D. J. Arseneau,[3] S. Daviel,[3] A. Hatakeyama,[3]
S. R. Kreitzman,[3] C. D. P. Levy,[3] R. Poutissou,[3] R. H. Hei

Kreitzman
Daviel
Poutissou
Arseneau
Pearson
Salman
Chow





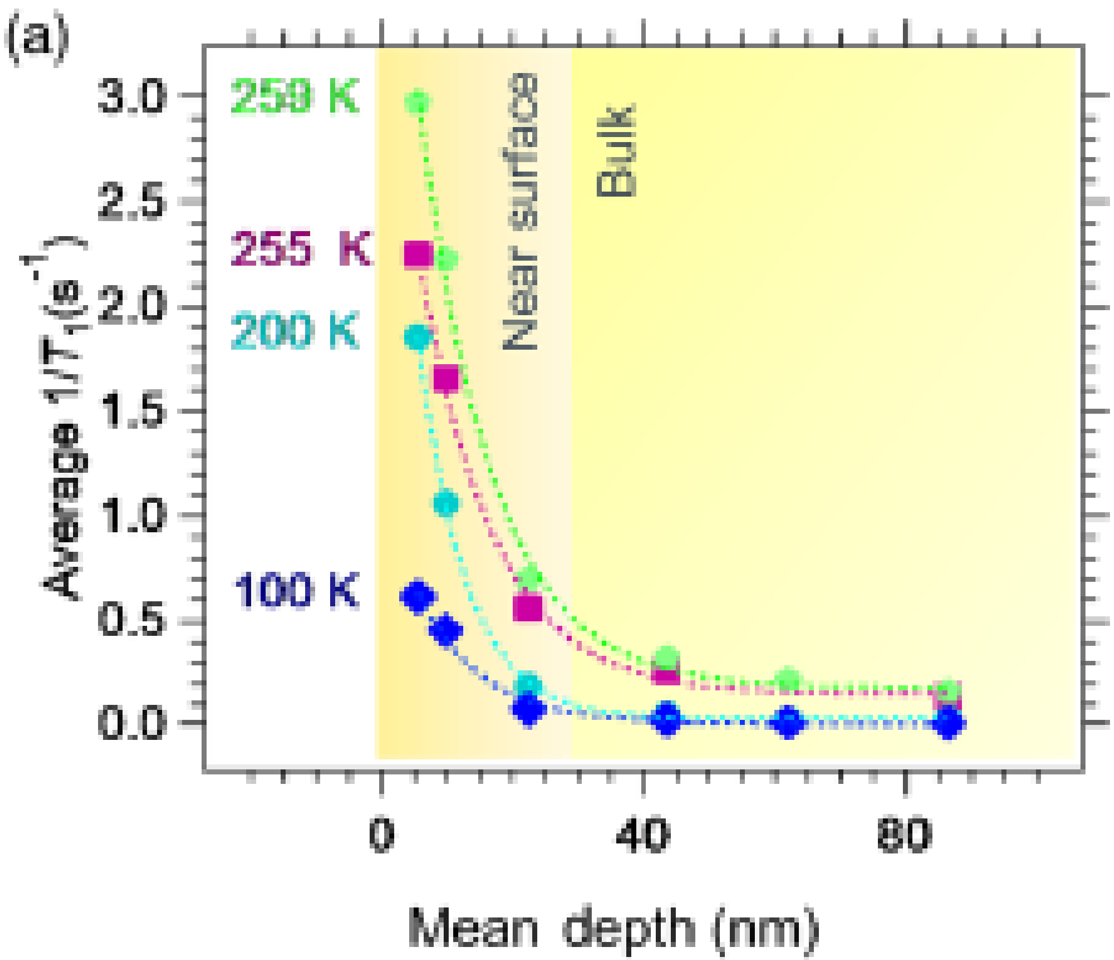


$$\frac{1}{T_1 T K^2} = \frac{4\pi k_B}{\hbar}\left(\frac{^8\gamma}{\gamma_e}\right)^2 = 8.32 \times 10^4\ \mathrm{K}^{-1}\mathrm{s}^{-1},$$

David Cortie

β-NMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface

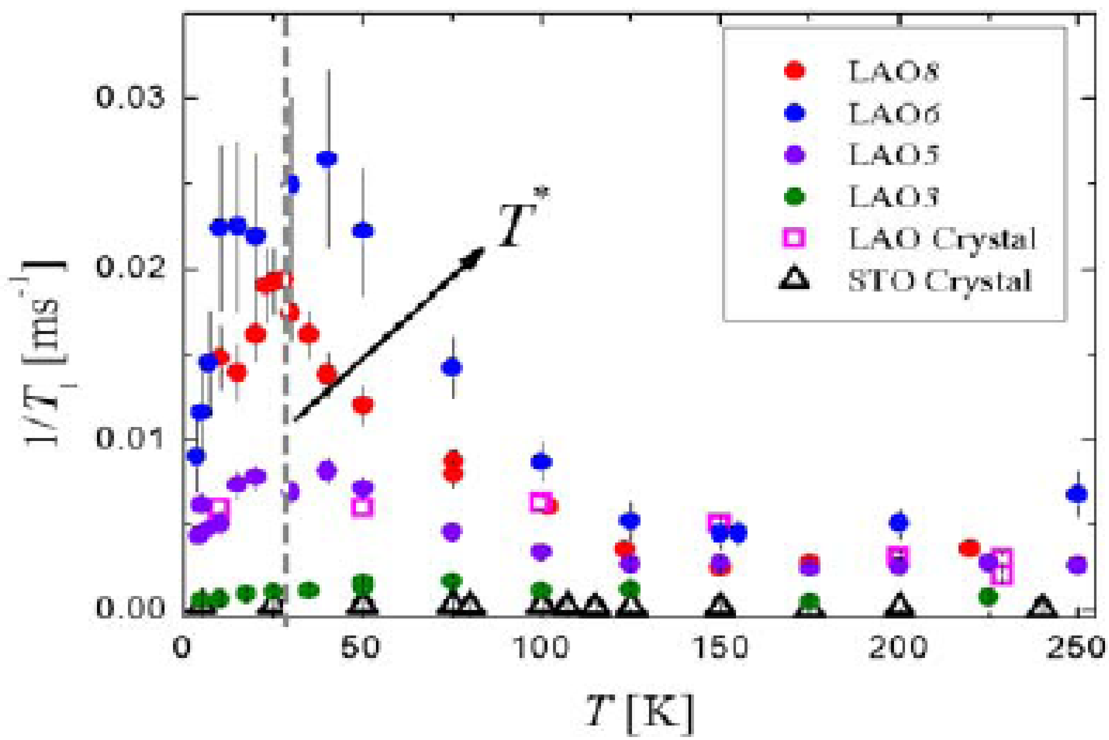
D. L. Cortie,[1,2,3,4] T. Buck,[5] M. H. Dehn,[6] V. L. Karner,[5] R. F. Kiefl,[2,1,4] C. D. P. Levy,[4] R. M. L. McFadden,[3] G. D. Morris,[4] I. McKenzie,[4] M. R. Pearson,[4] X. L. Wang,[7] and W. A. MacFarlane[3,1]

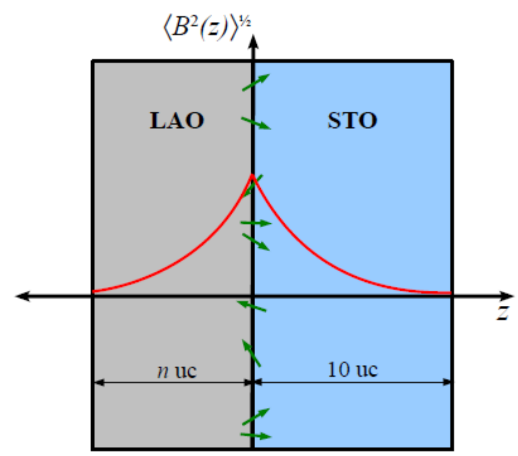


Zaher Salman

Nature of Weak Magnetism in $SrTiO_3/LaAlO_3$ Multilayers

Z. Salman,[1,*] O. Ofer,[2] M. Radovic,[3,4] H. Hao,[5] M. Ben Shalom,[6] K. H. Chow,[7] Y. Dagan,[6] M. D. Hossain,[5] C. D. P. Levy,[2] W. A. MacFarlane,[8] G. M. Morris,[2] L. Patthey,[3] M. R. Pearson,[2] H. Saadaoui,[1] T. Schmitt,[3] D. Wang,[5] and R. F. Kiefl[5,2]





Iain McKenzie

Soft Matter

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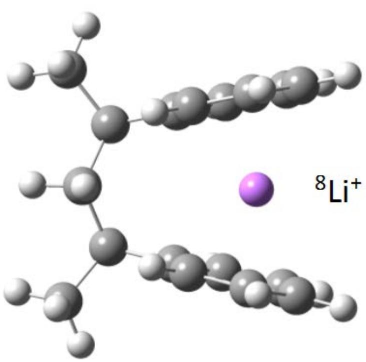
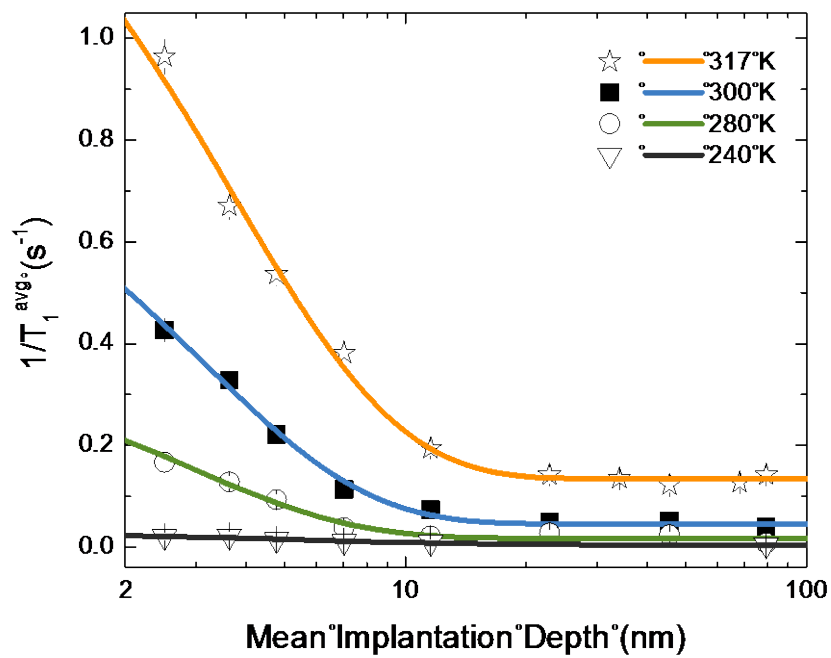
Enhanced high-frequency molecular dynamics in the near-surface region of polystyrene thin films observed with β-NMR

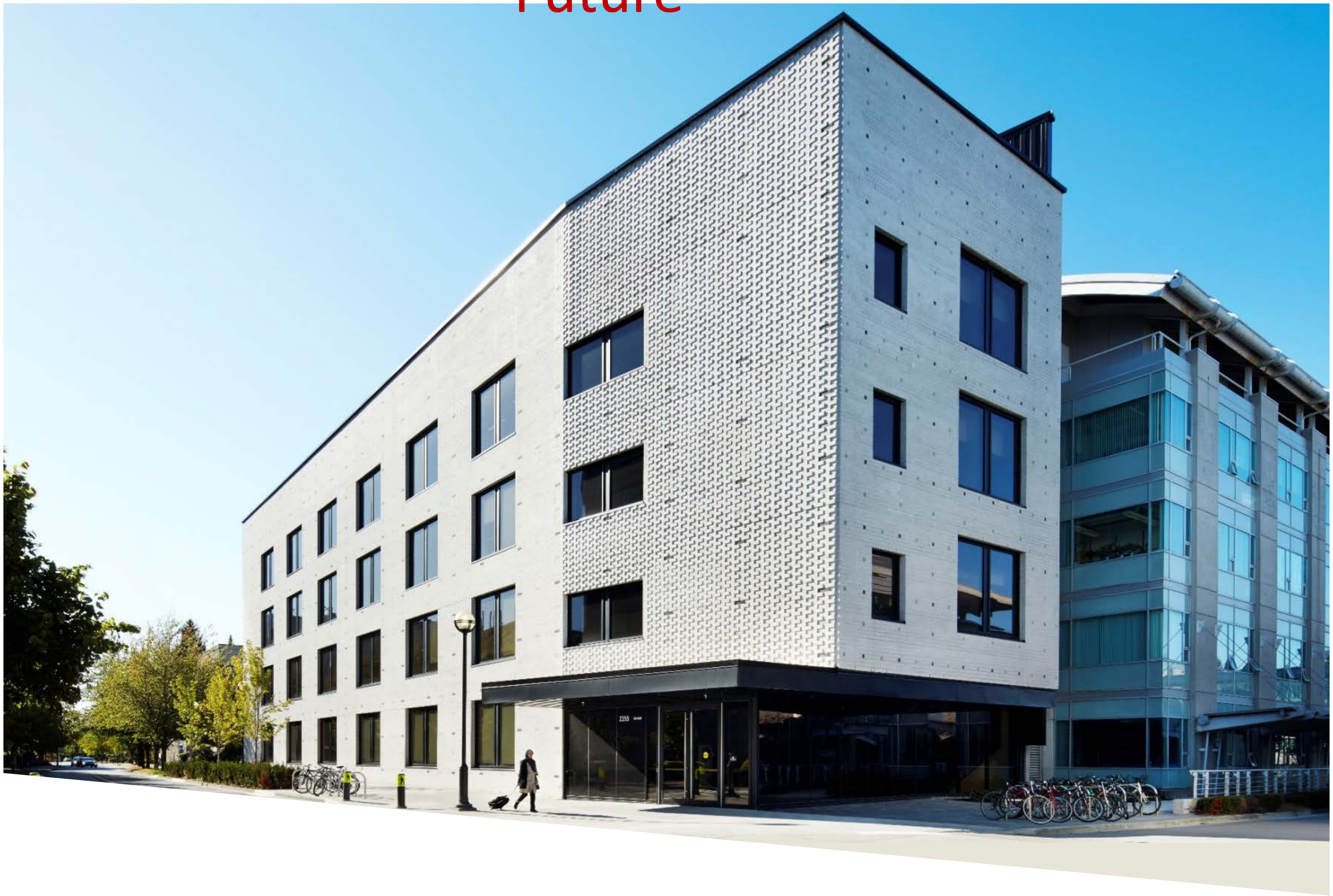
Iain McKenzie,*[ab] Chad R. Daley,[c] Robert F. Kiefl,[ade] C. D. Philip Levy,[a] W. Andrew MacFarlane,[f] Gerald D. Morris,[a] Matthew R. Pearson,[a] Dong Wang[d] and James A. Forrest[c]





- Spin relaxation of implanted $^8Li^+$ sensitive to torsional motion of phenyl rings.
- Faster relaxation → faster dynamics

Future



Director: Andrea Damascelli

Stewart Blusson
Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA

UBC

SBQMI FACULTY AND ASSOCIATE MEMBERS

- **μSR & β-NMR** (@TRIUMF)
  Kiefl - MacFarlane
- **Scanning Probe Microscopy**
  Burke - Bonn
- **Optical, Electron, and x-ray spectroscopy**
  (TEM / Tr-ARPES & Spin-ARPES / REIXS @CLS)
  Damascelli - Dierker - Jones - Sawatzky - Ye
- **Quantum devices and nanophotonics**
  Folk - Chrostowski - Young - Nojeh
- **New Materials** (Crystals, films, molecular)
  Aronson - Bonn - Berlinguette - Hallas - MacLachlan - Zou
- **Theory** (DFT, QI, computational, many-body)
  Affleck - Berciu - Franz - Raussendorf - Rottler - Sawatzky

MP-UBC-UTokyo Centre for Quantum Materials

MAX PLANCK - $2.5M
UNIVERSITY OF TOKYO - $2.5m

東京大学
THE UNIVERSITY OF TOKYO

MAX-PLANCK-GESELLSCHAFT

OBJECTIVE: To promote and further the cooperation between researchers and research groups of both parties by:

UBC

- Student mobility agreement with University of Stuttgart
- Joint MP-UBC-Stuttgart PhD program in Quantum Materials

Universität Stuttgart

The CMMS group July 2018

Conclusion

- Positive muons are a unique and sensitive probe of internal magnetic fields which can help us understand magnetic and electronic properties of new quantum materials.

- The electronic, magnetic, structural properties(dynamics) of an interface/surface are distinct from the bulk properties. They will play crucial role in development of future devices which continue to shrink in size. Beta-NMR at TRIUMF is unique and is one of the few methods which can probe these properties.

- TRIUMF and the CMMS have an important role to play in the SBQMI at UBC.