TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Muons (and Isotopes) for Material Science

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KEK – TRIUMF Scientific Symposium

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μSR and βNMR: Scientific Problems for Local Probes

Isotopes have broad applications in condensed matter and materials science as a low-density, very-high-signal-to-noise in situ detectors of local environments and dynamics.

μSR and βNMR offer as much as *10-orders-of-magnitude improvement* in signal over conventional NMR through the combination of high polarization and beta-decay anisotropy.

Magnetism

- Local fields and magnetic ordering
- Dynamics: electronic, nuclear spins
- Heterostructures and near-surface

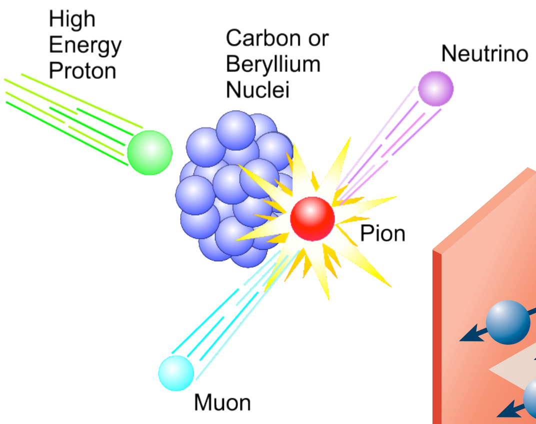
Superconductivity

- Co-existence of SC and magnetism
- Measure magnetic penetration depth λ and coherence length ξ

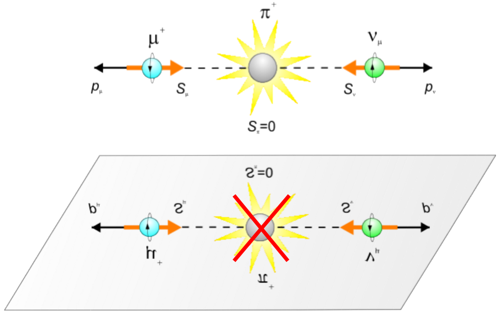
Chemistry and Soft Matter

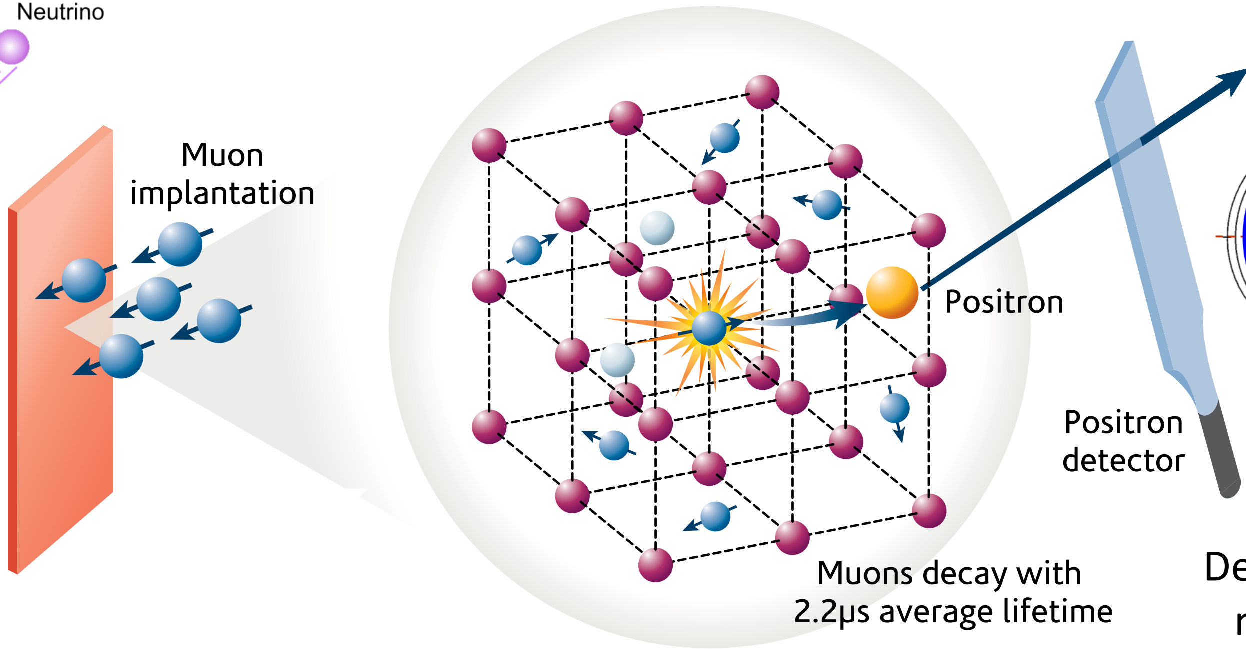
- Study “unobservable” H atom rxns
- Discover new radical species
- Probe ionic diffusion
- Depth dependent polymer dynamics

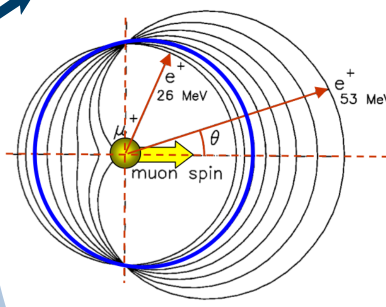
The Basics of μSR



Positive muons are produced with *100%* spin polarization







Decay e^+ used to monitor time dependence of muon spin polarization

Mu^+ is sensitive to magnitude and fluctuation rate of magnetic field inside materials

Static field distribution
Sensitivity: $10^{-3} – 10^{-4}$ μ_B

Fluctuation rates
$10^5 – 10^9$ Hz

CMMS Facility Staff

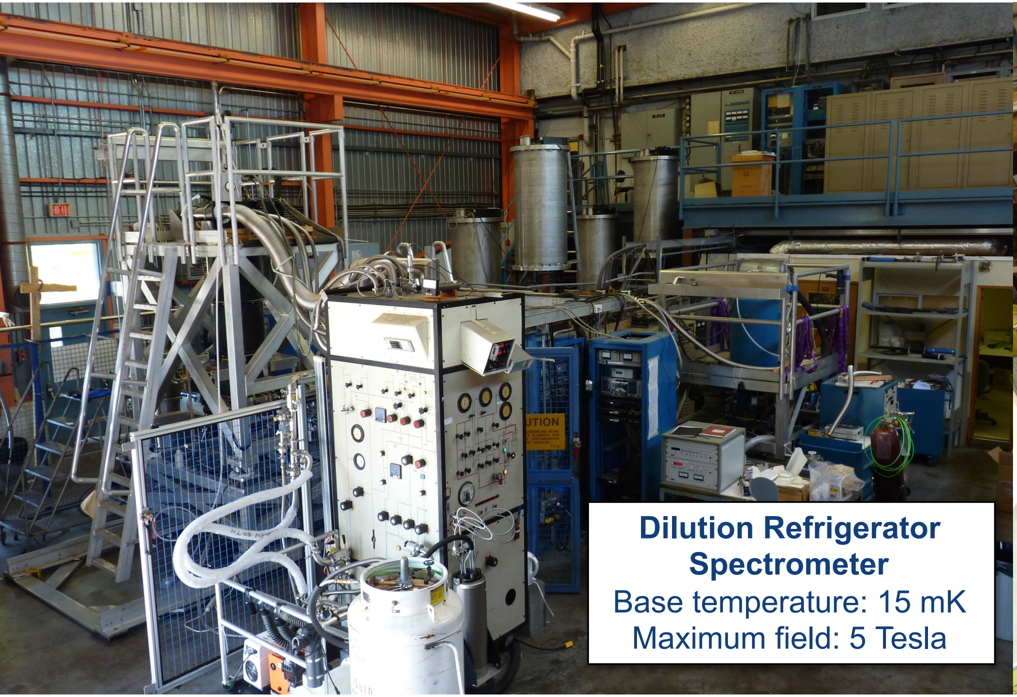
1. Bassam Hitti: Operations Manager
   i. Experimental Setup, Operations and User support
   ii. L-He Coordination
   iii. MRO Coordination
   iv. Device electromagnetic simulation (i.e. Opera)
   v. Semiconductor Solid State Physics
2. Gerald Morris: Deputy Manager
   i. M20 project management
   ii. βNMR Management & beam line coordinator
   iii. Experimental Setup and User support
   iv. CMMS Experimental Safety reviews
   v. Subsurface layer CM Physics
3. Donald Arseneau: IT /DAQ & Programming Management
   i. Experimental Setup and User Support
   ii. Facility IT, DAQ and programming
   iii. Spectrometer design
   iv. Common Account Assessment Management
   v. Physical Chemistry and Fundamental Kinetics
4. TBA: New (2018) SBQMI funded (5 Yrs.) BAE
5. Iain McKenzie: Outreach & User Support
   i. Outreach Planning and Implementation
   ii. Liaison with User Community
   iii. EEC Secretary
   iv. Experimental Setup and User Support
   v. Physical Chemistry of Soft Materials Structure and Dynamics of Free Radicals
6. Syd Kreitzman: Manager
   i. Liaison with TRIUMF Management
   ii. M9 beamline project management (to date)
   iii. Spectrometer design coordinator
   iv. Experimental Setup and User Support
   v. MuSR Techniques ,Tools & Toys
   vi. Spin relaxation theory

Facility Technicians:

1. Rahim Abasalti: High Vacuum Specialist
2. Mike McLay: Design Technologist
3. Deepak Vyas: Millwright & Work Area Safety Coordination
4. Collin Dick: Liquefier Technician (cryogenics group)

Muon Beam Lines at TRIUMF

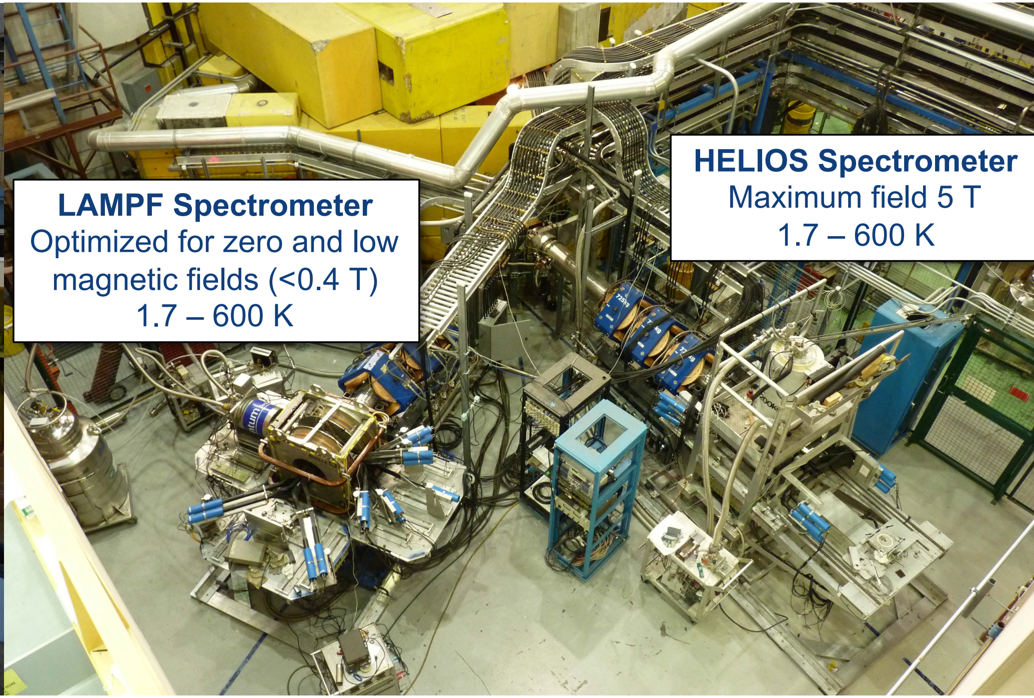
M15



Dilution Refrigerator Spectrometer
Base temperature: 15 mK
Maximum field: 5 Tesla

M20D

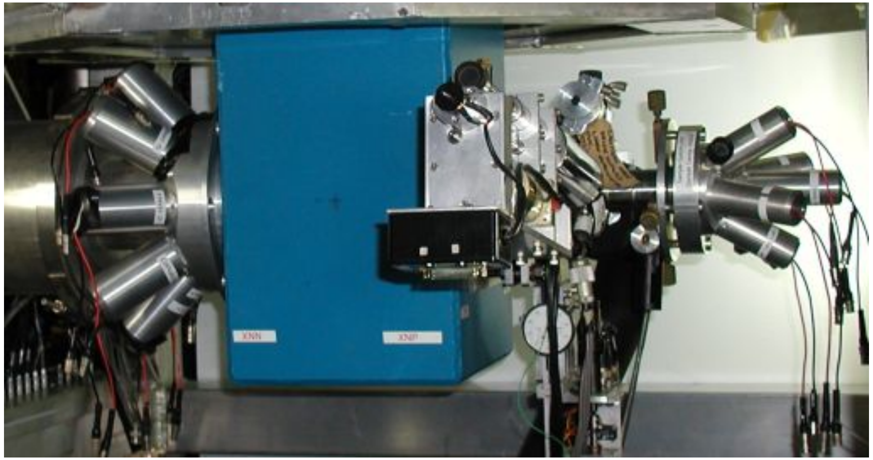
M20C

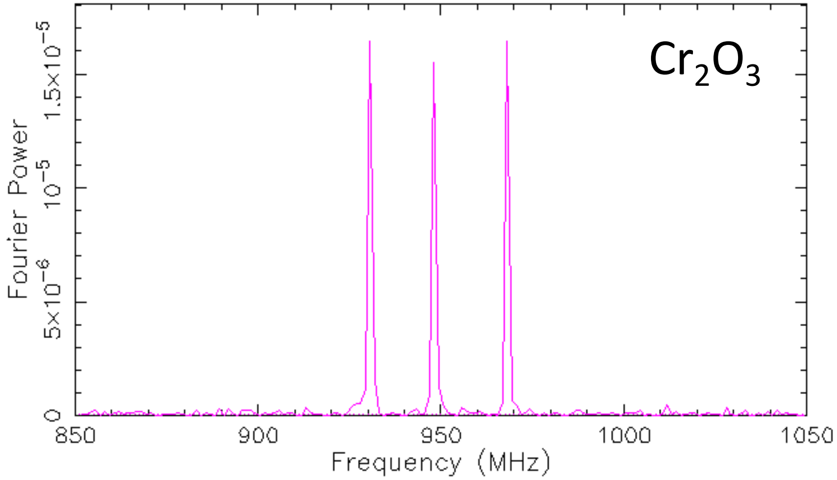


LAMPF Spectrometer
Optimized for zero and low magnetic fields (<0.4 T)
1.7 – 600 K

HELIOS Spectrometer
Maximum field 5 T
1.7 – 600 K

- 7 T replacement for HiTime with improved field homogeneity (10 ppm over 1 cm diameter disk ±3 mm in z) and alignment (within 0.25° of physical bore).
- \$300k awarded for magnet and ^{3}He cryostat from NSERC RTI - J. Sonier (SFU) + G. M. Luke (McMaster) + contributions from facility users





High homogeneity + unique detector design ➜ amazing high frequency / field spectra

Japanese Involvement in Materials Science at TRIUMF

- Toshi Yamazaki
- Tomo Uemura
- Ryu Hayano
- Jun Imazato
- Nobu Nishida
- Ken Nagamine (not pictured)

In 1988 the KEK MSL Group (Yamazaki, Nagamine et al) were responsible for the procurement and installation of M9B

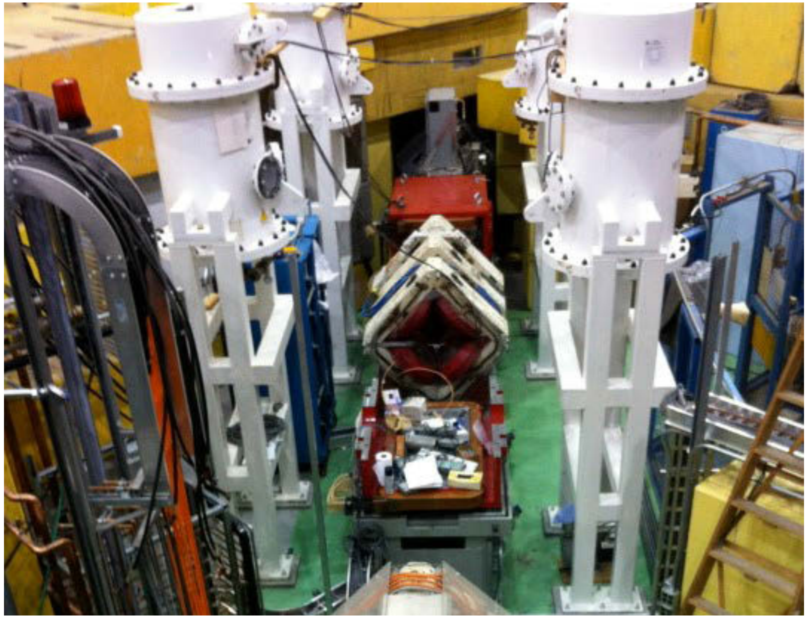
Japanese Involvement in Materials Science at TRIUMF

Toshiki Kaifu, the Japanese Prime Minister, visits TRIUMF and is greeted by Stan Hagen (left, Minister of Advanced Education), Bill Vander Zalm (B.C. Premier), and Erich Vogt (Director of TRIUMF).

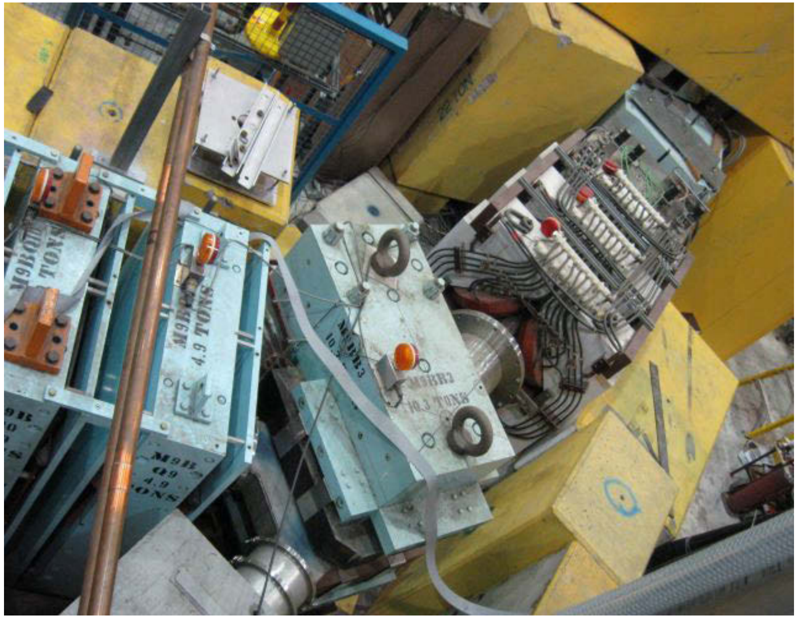
As they overlooked M9B Erich Vogt explained to the Prime Minister why having an operational muon decay channel is so important to a Laboratory that does Muon Science.

M9A and M9B

M9A: Surface μ^+



M9B:High momentum SR $\mu^\pm$



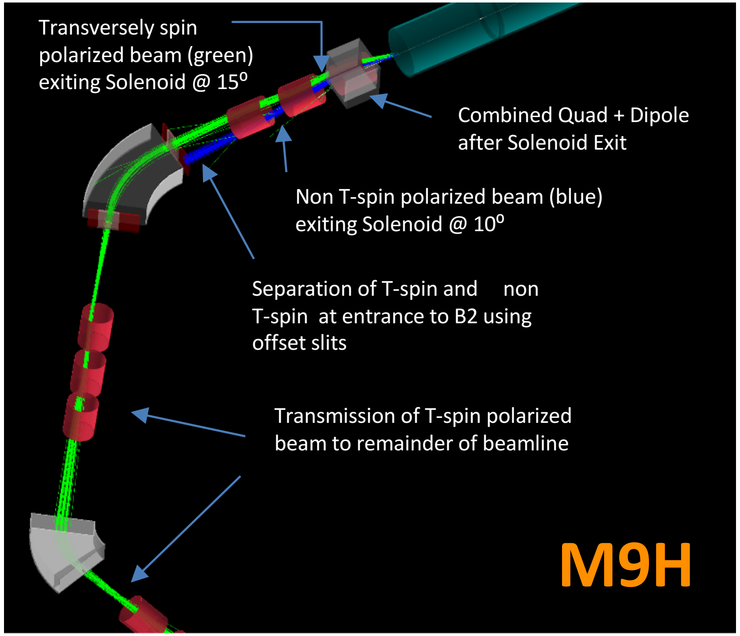
Not operational since 2012 due to M9-T2 vacuum leak

Expanding Muon Beam Lines at TRIUMF

Multi-Institutional CFI Proposal *Approved Nov. 2017*

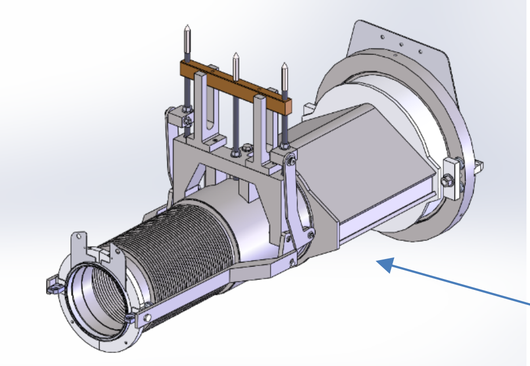
- Replace M9B with M9H
  - Upgraded beam line including new persistent coil solenoid
  - New spectrometer for high pressure, high field studies in a DR
- M9-T2 repair + M9A completion + 3T spectrometer

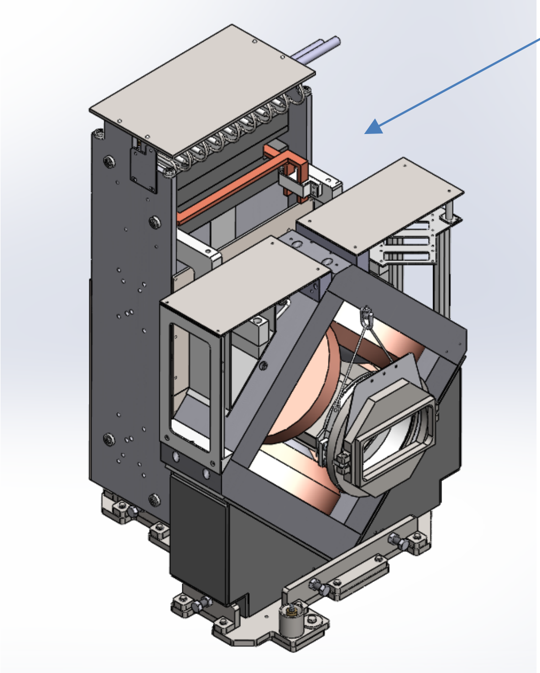
CFI	4,290,724
Total Prov. Funding	4,290,724
Vendor Discounts	951,699
TRIUMF Contribution	1,193,662
Total Project	**10,726,809**



- One of a kind beams on M9H; i.e. spin-rotated decay muons and high flux μ^-.
- Unique physical parameter space (high pressures + ultra-low temperature + high magnetic fields on M9H)
- M9A to focus on highly efficient sample characterization for the increasingly important broad non-expert (in μSR) user community.

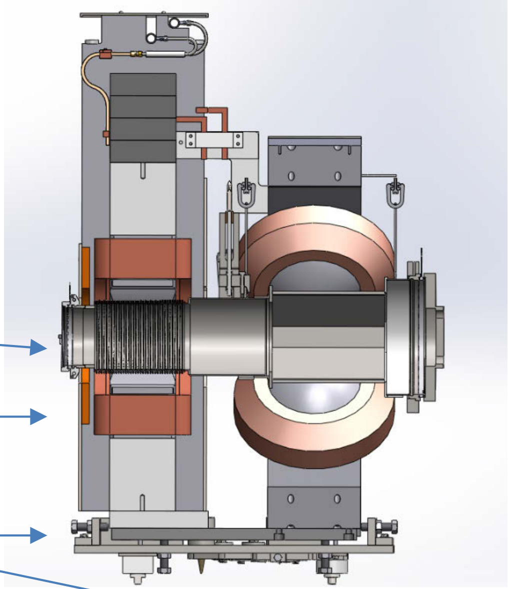
Developing the M9-T2 Front End Fix

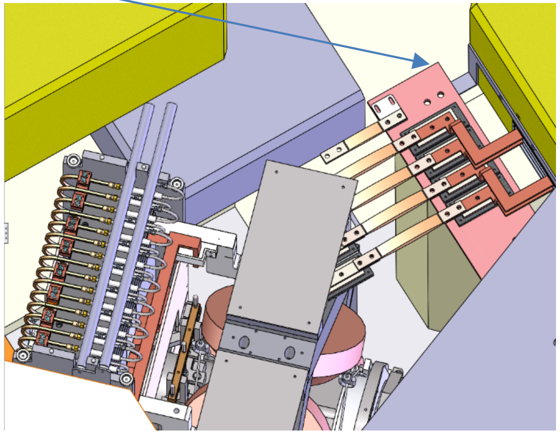




The required elements to repair the M9-T2 front end are being developed & new engineer is here!

- Retractable beam pipe
- New Q1
- Field Adjustable Q1Q2 base
- Removable service stand

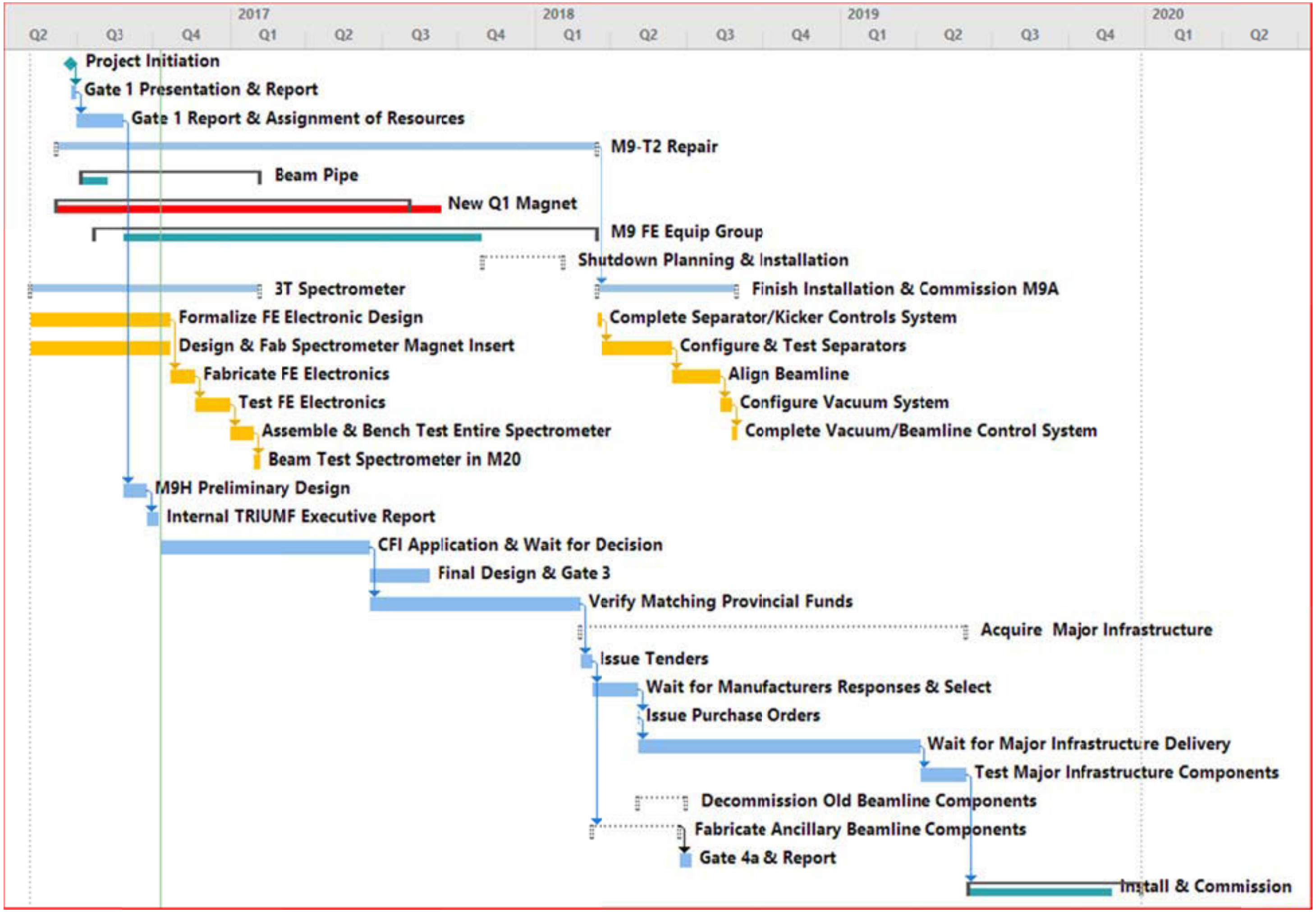




Foremost in mind are:

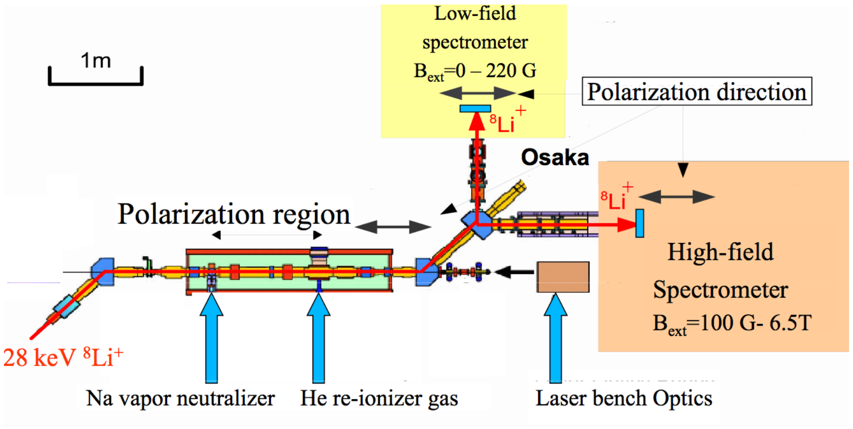
1) safety (reduced dose) for installation and maintenance.
2) Utility and practicability for remote handling
3) Capability to withstand high neutron doses >5E22 n/m^2 over 15 years.

Expanding Muon Beam Lines at TRIUMF

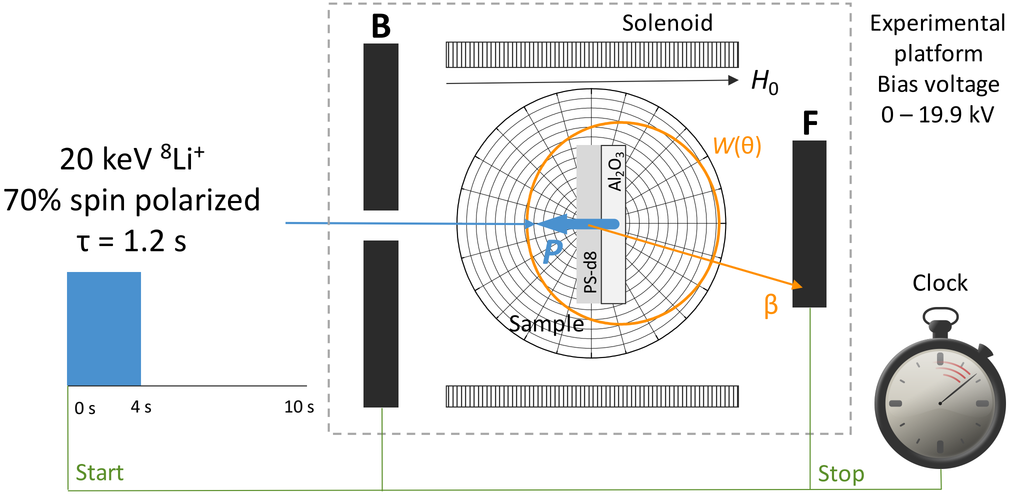


The Basics of βNMR

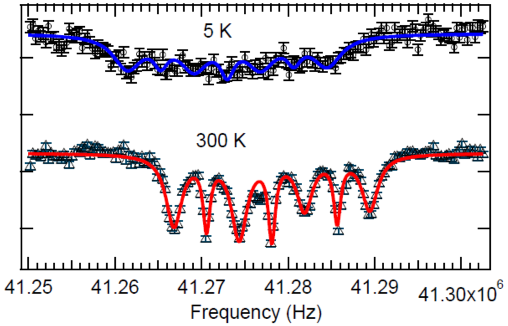
High spin polarization from optical pumping



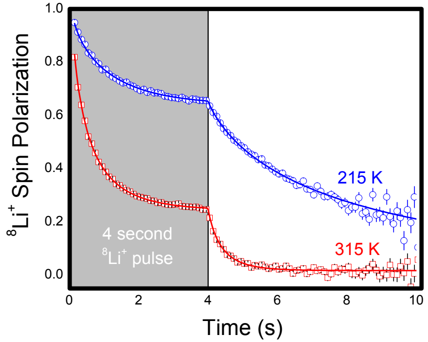
Magnetic resonance with depth resolution



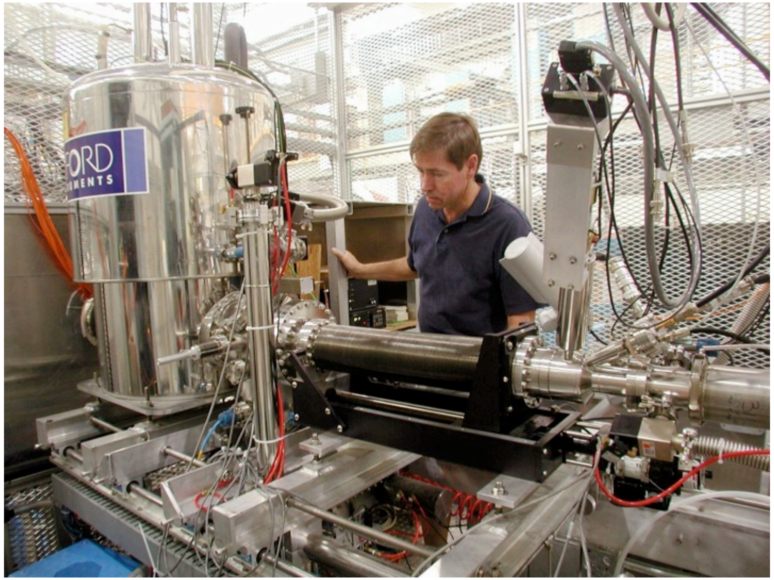
Resonance techniques used to study interaction of $^8Li^+$ with local environment



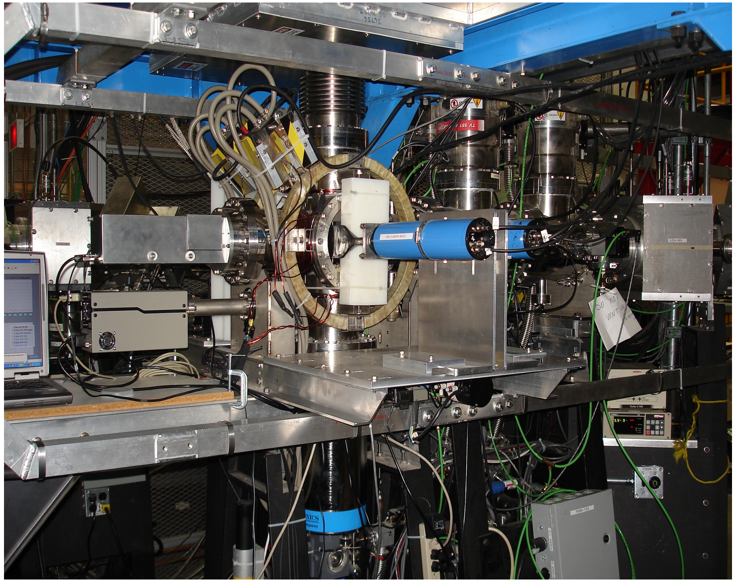
Relaxation methods used to study dynamics of $^8Li^+$ and the local magnetic field



βNMR Spectrometers



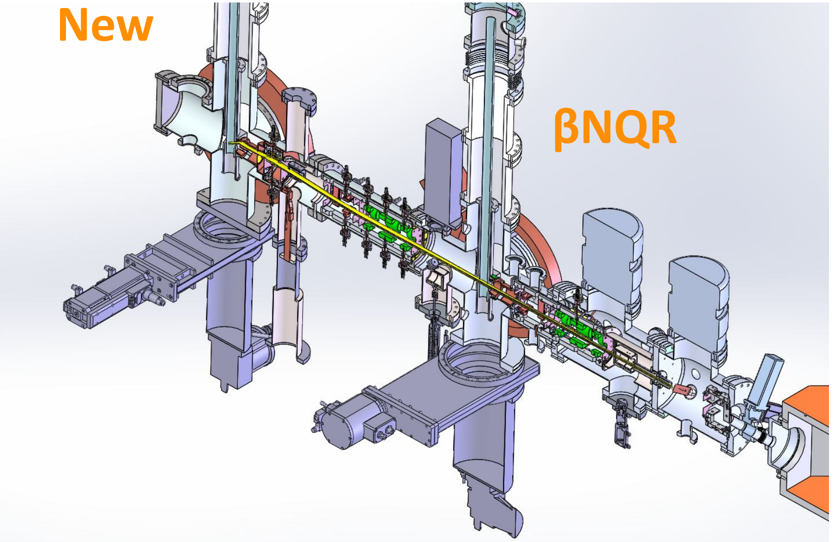
βNMR: High Field (9 T) Spectrometer

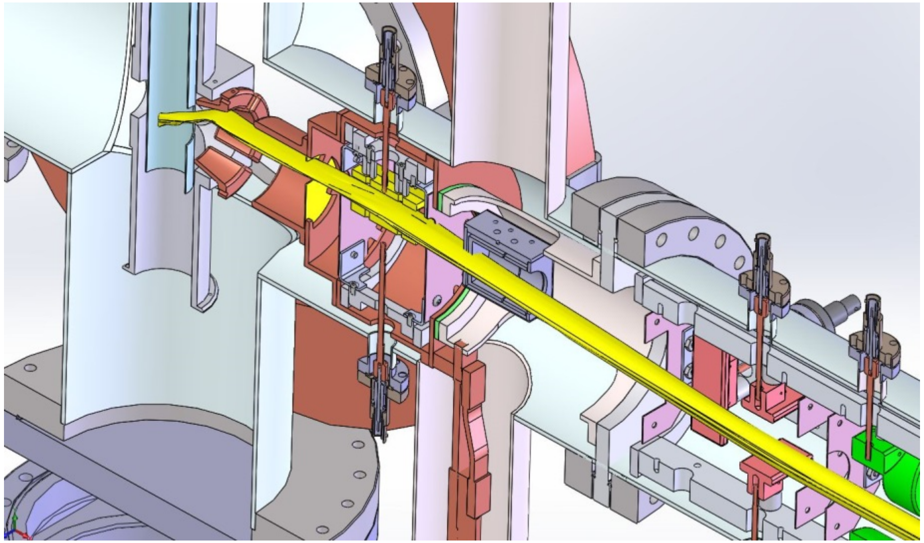


βNQR: Low (20 mT) and Zero Field Spectrometer

- $^{8}Li^{+}$ implanted at energies between 0.1 and 28 keV.
- Near-surface probe up to hundreds of nm.
- Temperature range 5 – 320 K.

New Low Temperature Mid-Field βNMR Spectrometer



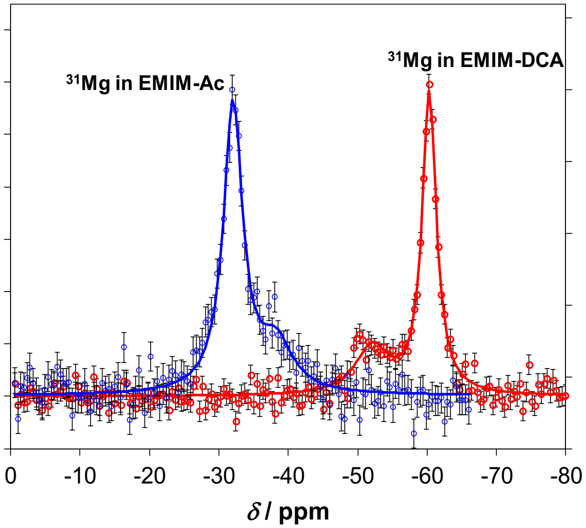


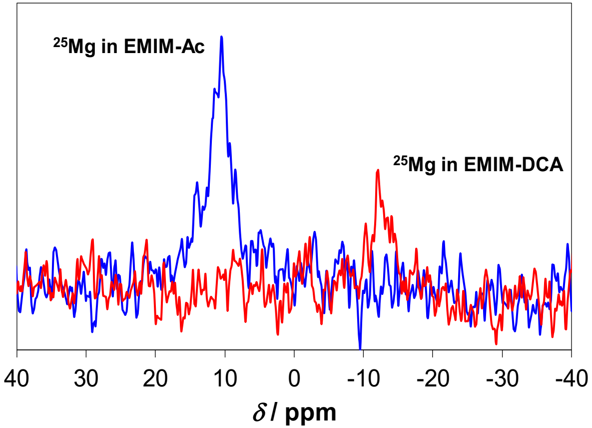
Extremely flexible new βNMR spectrometer

- 0 – 0.22 T (magnetic field between βNMR and βNQR)
- 300 mK – 300 K (lower temperatures than βNMR and βNQR using ^{3}He cryostat)

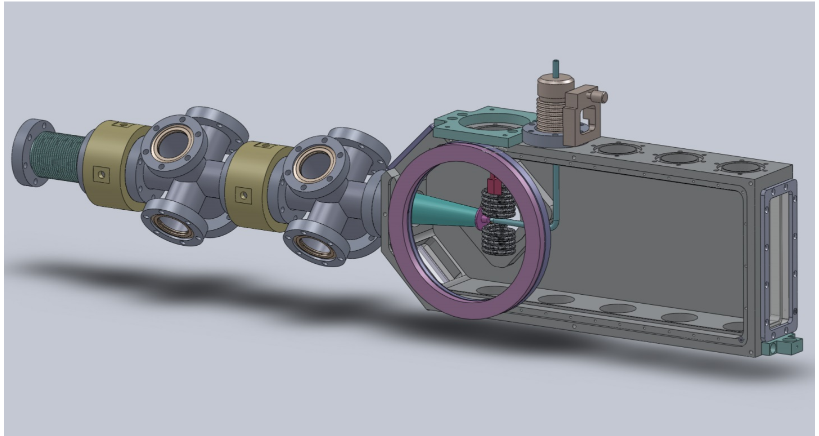
Measure field penetration profiles in Nb cavity materials relevant to advanced superconducting RF accelerator research

Ongoing Developments: ^{31}Mg βNMR





- ^{31}Mg (I = 1/2) will be used to study the local chemical environment of magnesium in biologically important contexts, e.g. where Mg is part of an enzyme.
- Superior to conventional NMR with ^{25}Mg.
- Experiments performed on ionic liquids.
- New spectrometer for liquid samples under construction.



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Japanese Experiments at CMMS in 2017

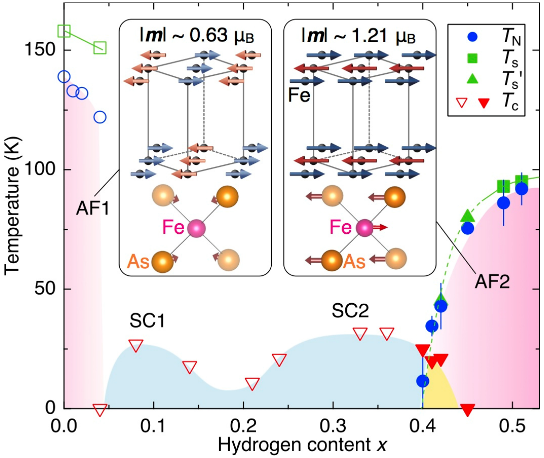
Exp.	Title	Investigators
M1459	Mechanism of hydrogen-induced vacancy formation in PdAg alloy studied by Muon Knight shift measurements	M. Mihara
M1497	µSR investigation of stable open-shell singlet molecules	S. Ito
M1647		no
M1672		hita
M1678		ızaki
M1711		
M1712		no
M1734	Transition between localized- and itinerant-electron states in the solid-solution system of $CaCu_3Ti_{4-x}Ru_xO_{12}$	J. Sugiyama
M1738	µSR study for magnetic polarization on apical oxygen in Ruddlesden Popper series	W. Higemoto

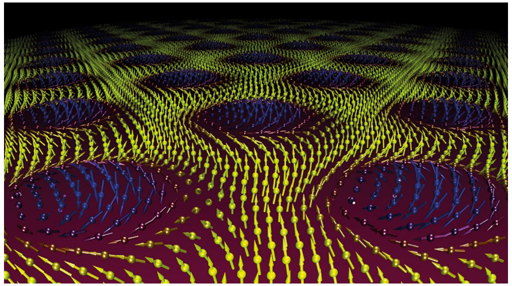
Japanese-led experiments received 20% of delivered beam in 2017

Recent Scientific Highlights

Magnetism

- Magnetic materials underpin much of modern technology
- Advances in such technology require new materials and greater understanding of existing ones.

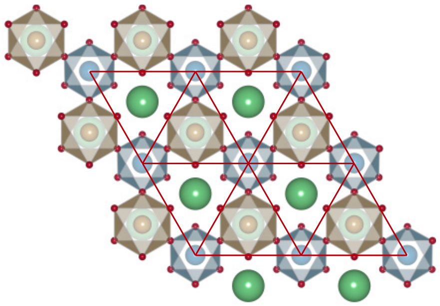


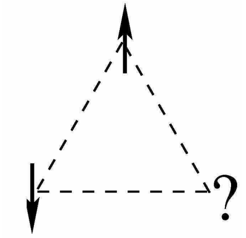


- Magnetic moments order into a pattern controlled by the symmetry of the material and the interactions between the atoms.
- Magnetic moments within materials also fluctuate and this gives a further window on how they are interacting.
- Determine magnetic phase diagrams and characterize novel magnetic states.

Exotic Magnetic Systems: Frustration

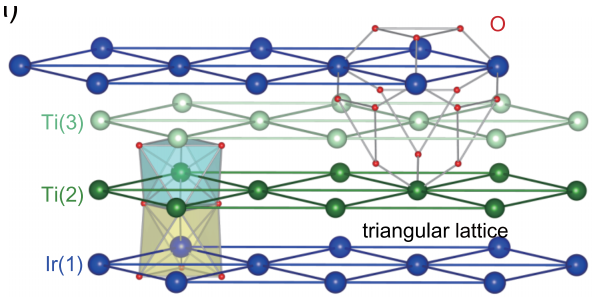
$Ba_3LuRu_2O_9$

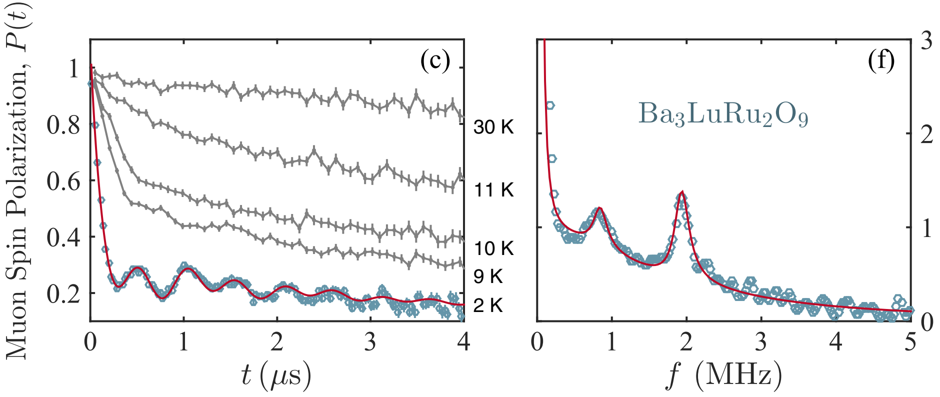


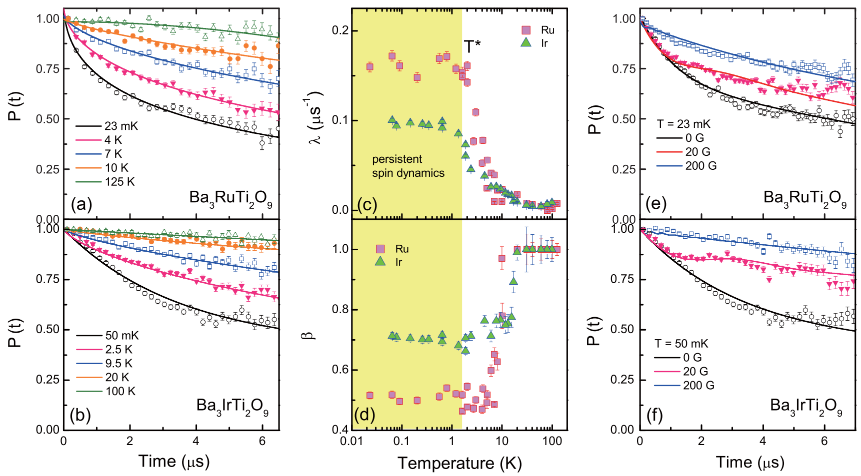


Frustration on triangular lattice

$Ba_3IrTi_2O_9$





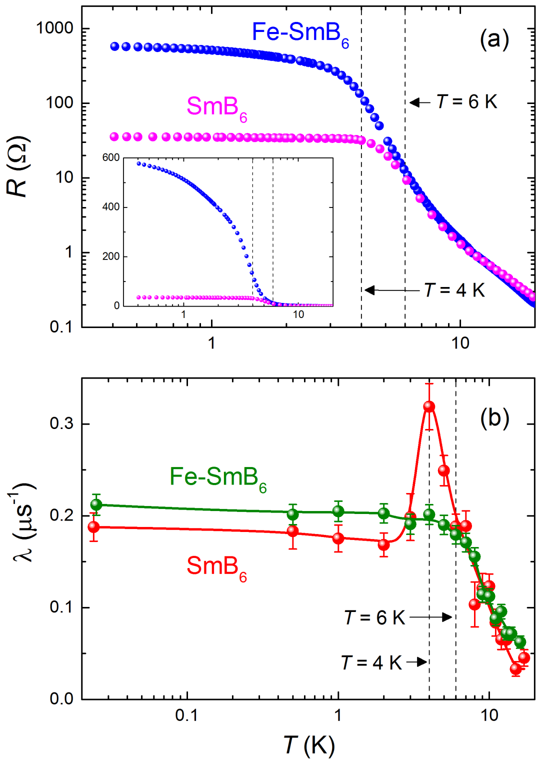


J. Quilliam et al. *Phys. Rev. B* **2017**, *95,* 184424

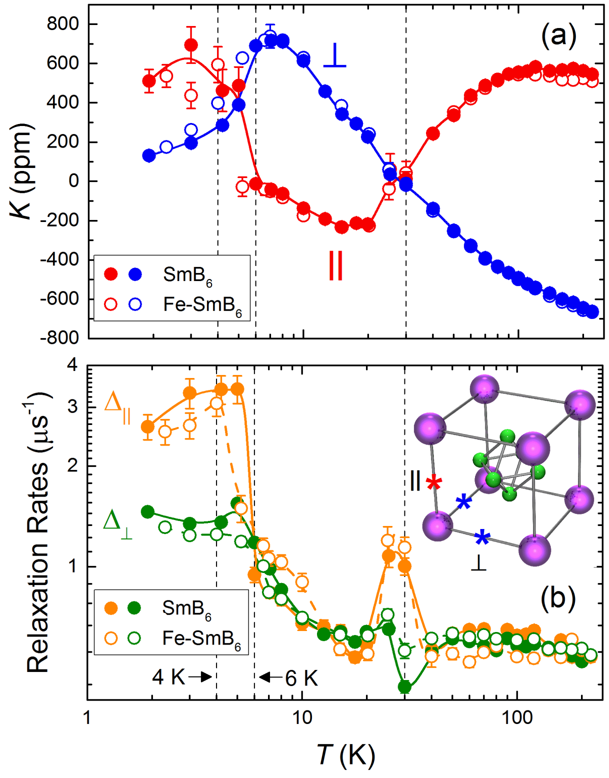
W.-J. Lee et al. *Phys. Rev. B* **2017**, *96,* 014432

SmB_6 – Topological Kondo Insulator

ZF-μSR: Quantum spin fluctuations below 4 K
- Predicted low-energy spin exciton branch

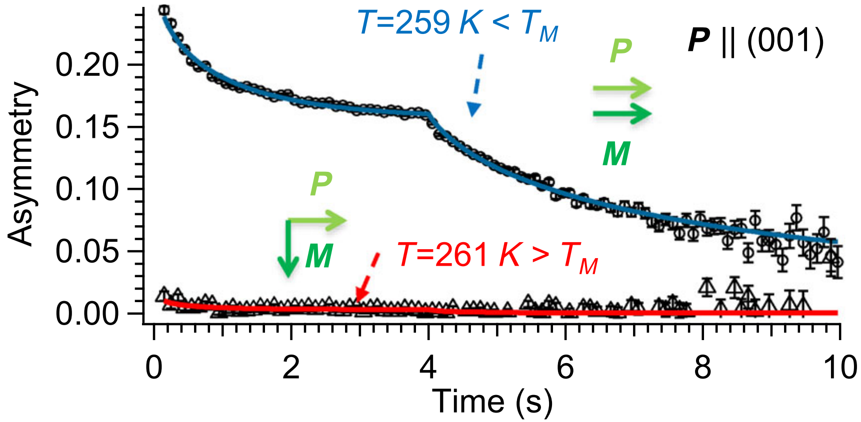


High TF-μSR: Partially Kondo-compensated Sm-4*f* sub-lattice



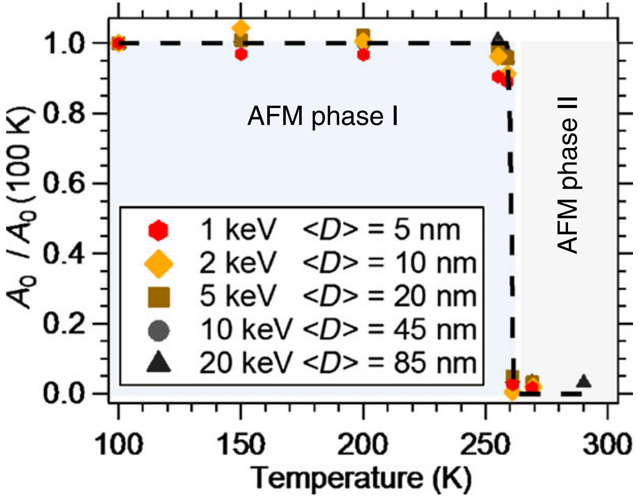
K. Akintola et al. *Phys. Rev. B* **2017**, *95,* 245107

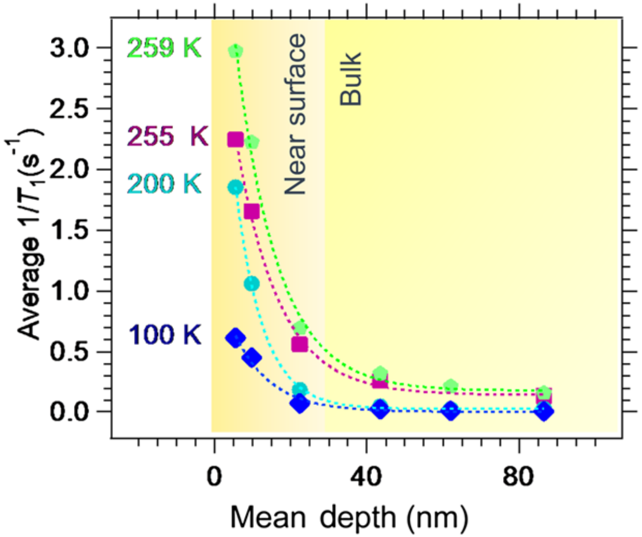
Depth-Dependent Magnetic Properties



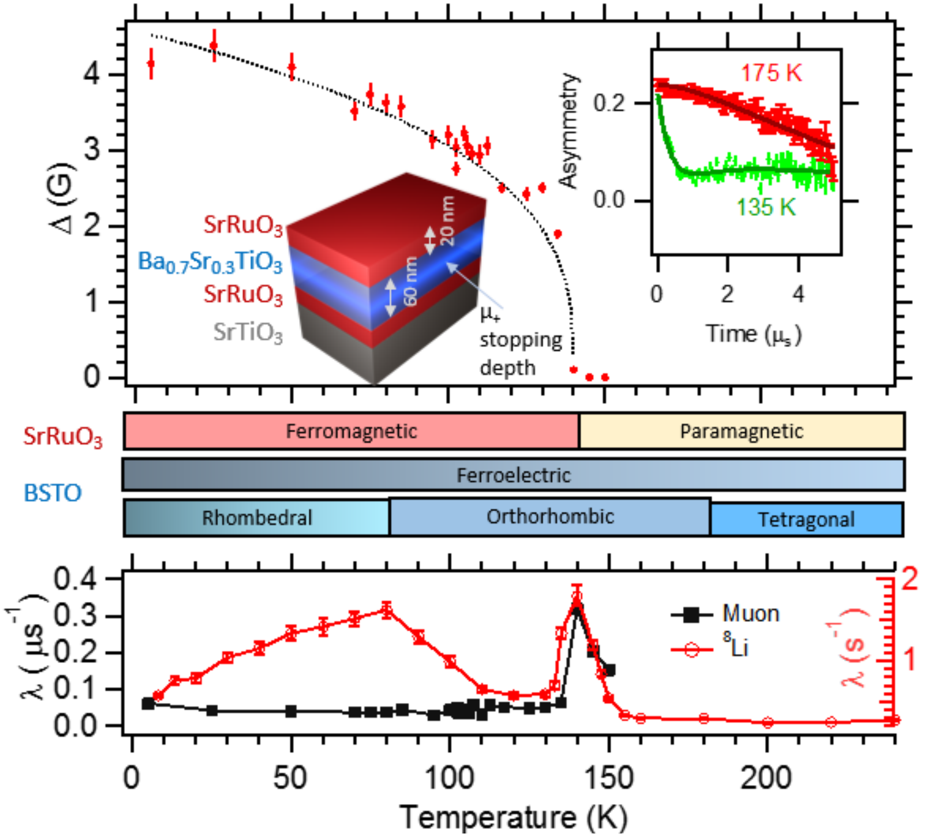
- Depth dependence of the Morin spin reorientation in α-Fe_2O_3
- Surface-localized dynamics decay with characteristic length of 11 nm, indicating presence of soft surface magnons.

Cortie *et al*. *PRL* **2016**, ***116,*** 106103





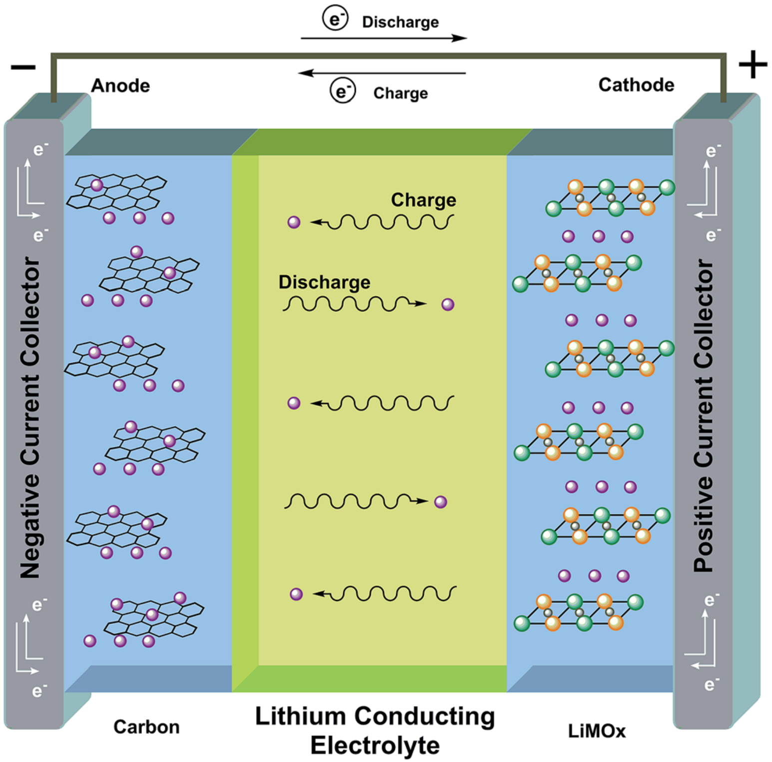
Sensitivity to both magnetic and electric phenomena



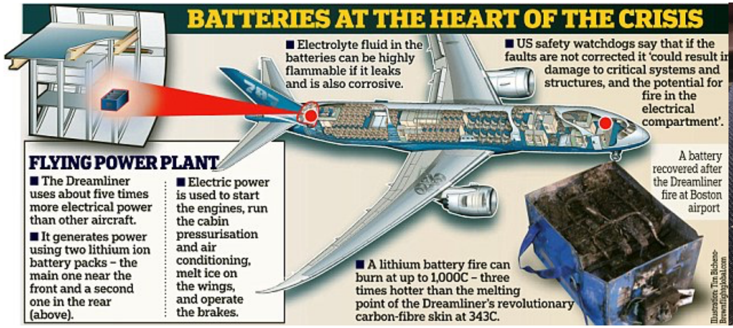
- The muon which is a $I = 1/2$ particle and detects only the magnetic dynamics.
- $^{8}Li^{+}$ has $I = 2$ and thus a finite electric quadrupole moment q = 31.4 mb.
- For instance, in the case of multiferroic structures containing a ferroelectric $Ba_{0.7}Sr_{0.3}TiO_3$ and ferromagnet $SrRuO_3$, this dual-sensitivity allows us to detect both the ferromagnetic and ferroelectric dynamics.

D. L. Cortie *et al. in preparation* 2017

Lithium Ion Batteries



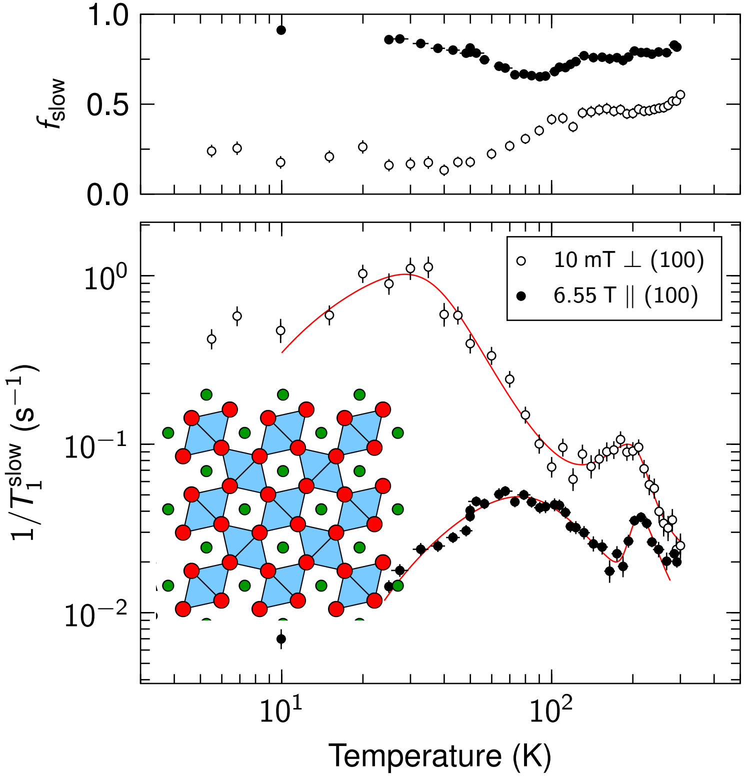
Present rechargeable batteries use electrolytes with organic solvents. Solid state batteries (SSB) are highly desirable for *safety considerations* but also for *performance and lifetime*.



The <u>key issue</u> in future materials developments for SSB is to understand the ion diffusion processes in the solid state at an <u>atomic level</u>, opening the door for tailored materials and improved device performance.

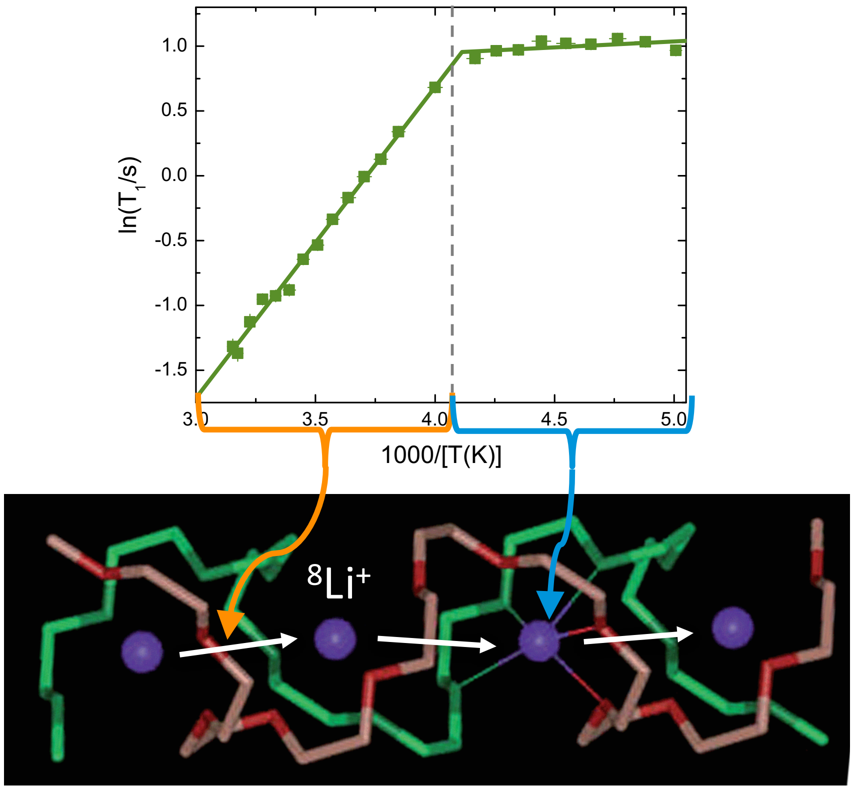
βNMR Studies of Li^+ Diffusion in Battery Materials

Rutile TiO_2



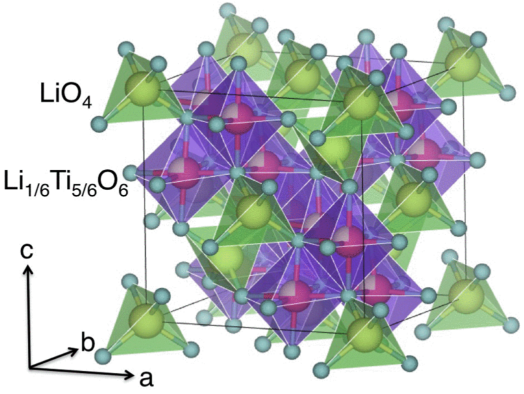
R. M. L. McFadden et al. *Chem. Mater.* **2017**, *accepted*

Polymer electrolyte Poly(ethylene oxide)



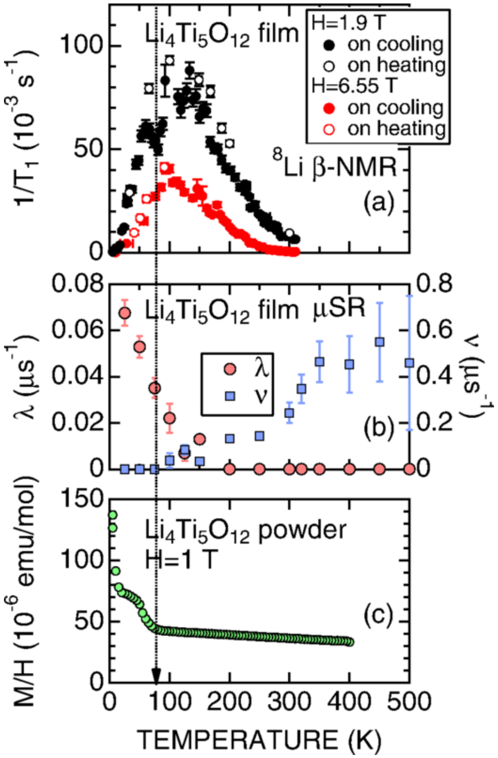
I. McKenzie et al. *J. Chem. Phys.* **2017**, *146*, 244903

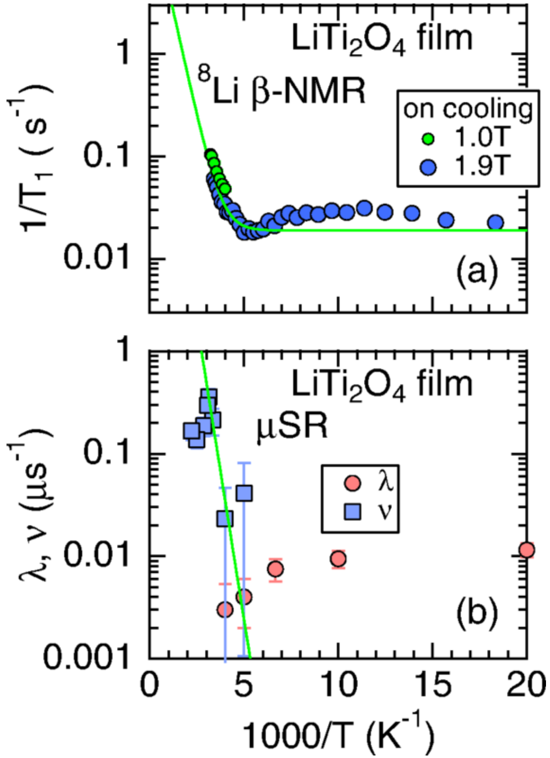
Diffusion of Li^+ in $Li_4Ti_5O_{12}$ and $LiTi_2O_4$ films



- Li^+ starts to diffuse in $Li_4Ti_5O_{12}$ above 100 K with an activation energy of 0.11(1) eV.
- Li^+ diffusion occurs in $LiTi_2O_4$ above 200 K with an activation energy of 0.16(2) eV.

J. Sugiyama et al. *Phys. Rev. B* **2017**, *96,* 094402

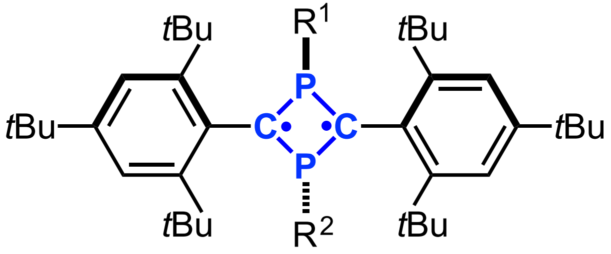




TOYOTA CENTRAL R&D LABS., INC.

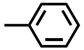
Chemistry: μSR of Stable Singlet Biradical

BR

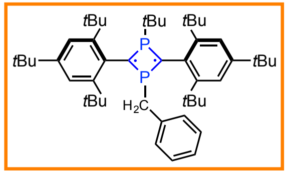


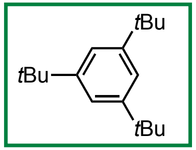
air-stable

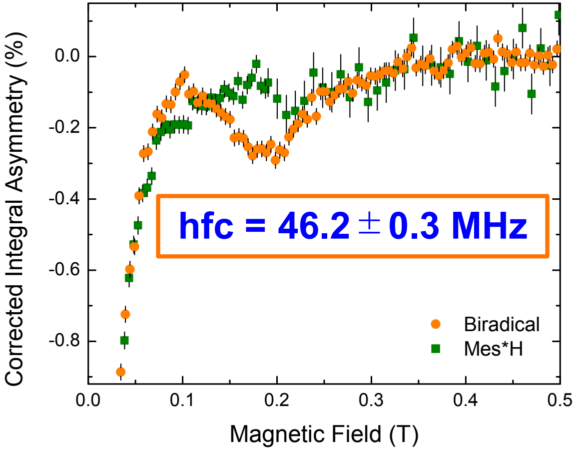
R^1 = *t*Bu
R^2 = CH_2Ph

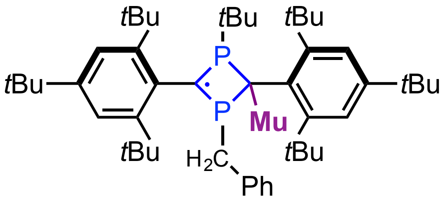
Ph = 

*t*Bu = $C(CH_3)_3$



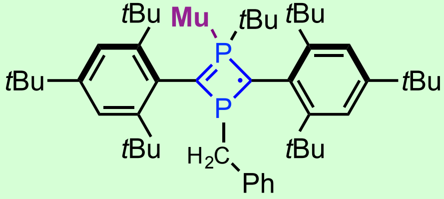






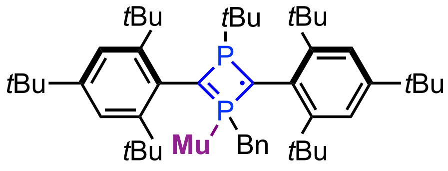
E_{rel} = 0.0 kcal mol^{-1}

hfc = 6.7 MHz



E_{rel} = 15.3 kcal mol^{-1}

hfc = 51.5 MHz



E_{rel} = 20.0 kcal mol^{-1}

hfc = 394.4 MHz

UBP86-D/TZ2P

Aryl-attack structures are completely excluded.

Mu predominantly adds on the skeletal phosphorus.

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TRIUMF

Canada’s national laboratory for
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Thank You!
Merci
どうもありがとうございます

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