Muon spin rotation facility development in U.S.: a call for a SSSC Study

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Muon spin rotation, relaxation, resonance (μSR)

- A well-established technique.
  - Conceptually (but not technically) similar to NMR.
- Has made important contributions:
  - ü Superconductivity
  - ü Magnetism
  - Semiconductors
  - Chemistry
  - Biophysics

Need

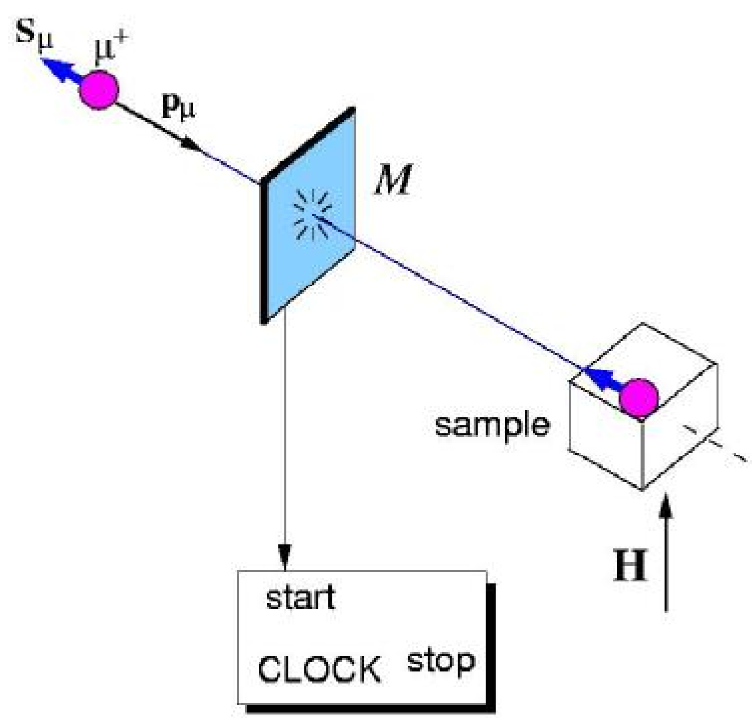
- μSR is an important area of medium-sized science, *with no U.S. facilities*.
  - There is a need for a critical review of μSR science and future developments.
  - Would lay groundwork for competitive U.S. position.
- *We urge the SSSC to undertake such a study*.

The μSR technique

Muons are produced at a “meson factory” by pion decay:

$$\pi^+ \rightarrow m^+ + \nu_m \, .$$

A spin-polarized muon is stopped in the sam-ple. A clock is started.



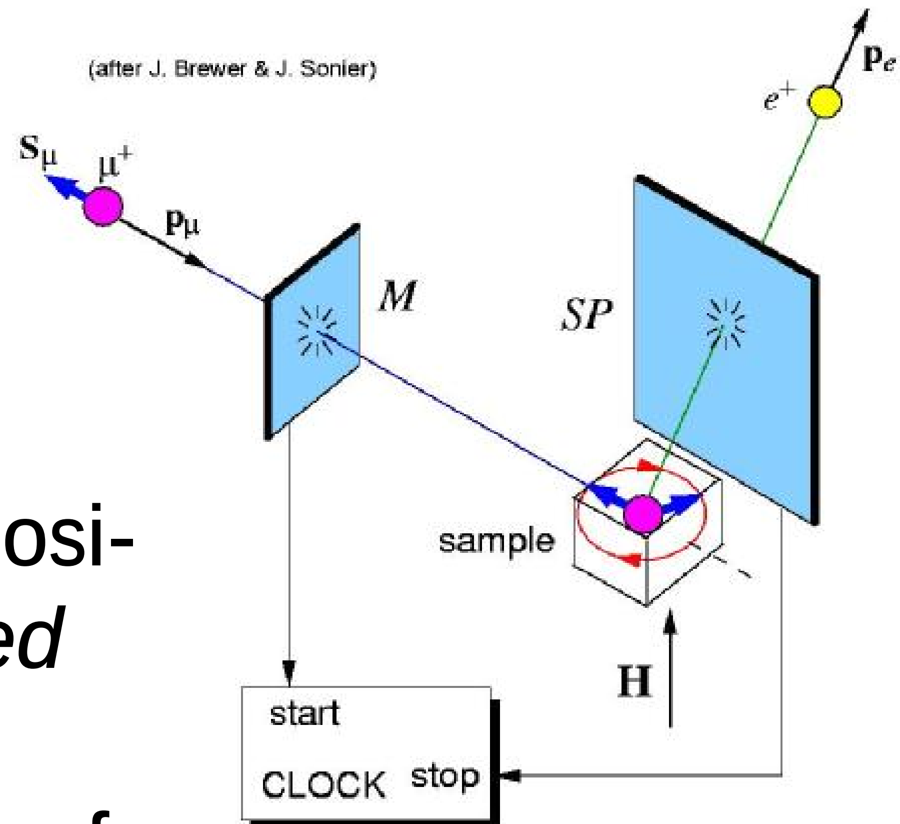
The muon precesses in an applied field **H**.

Muon *b* decay:

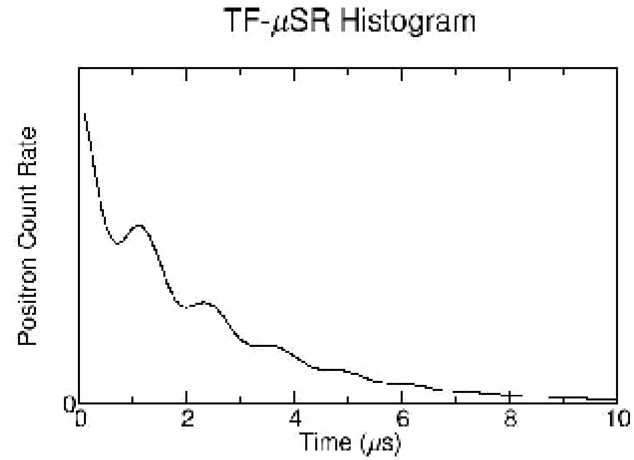
$$m^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{m}.$$

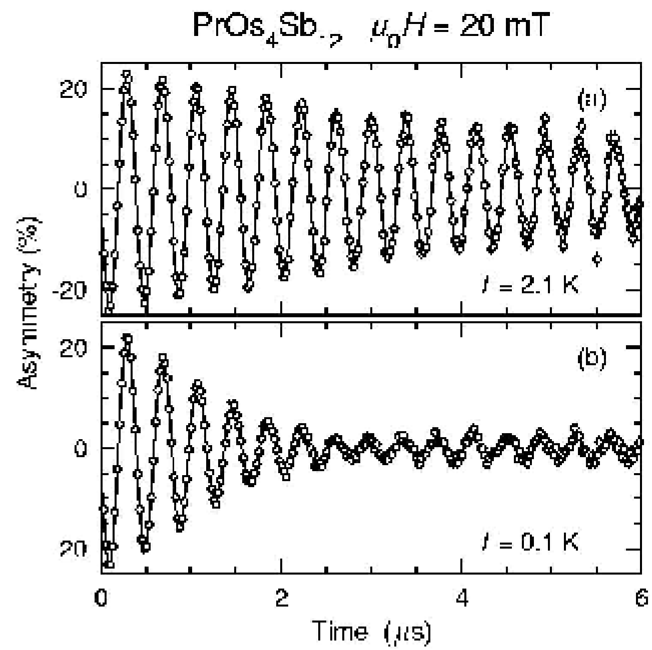
Muon lifetime ~2.2 μs. Positron direction is *correlated with muon spin*.

Decay time and *direction* of positron are recorded.



- Obtain a *time histogram* of positron count rate;
  - Typically 10^6–10^8 events recorded. 10 min–10hr.
- *Asymmetry plot* : time evolution of muon spin polarization.
  - Analogous to NMR free induction signal.

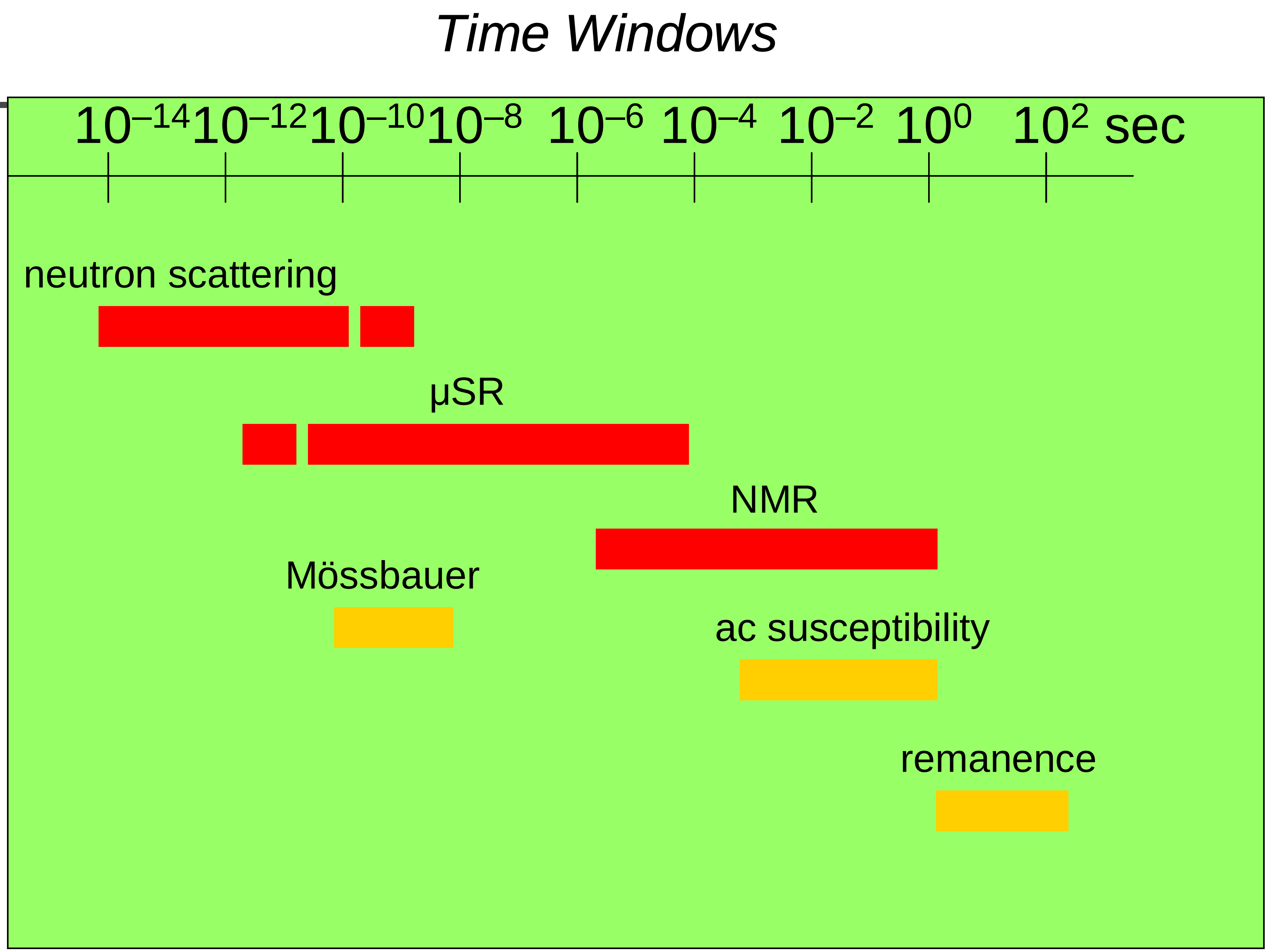




Advantages of µSR

- *Can be used on any system*.
  - No problems with neutron-absorbing or NMR-unfavorable nuclei.
- *A local probe*—no need to search reciprocal space (but need scattering to obtain structure).
- *Extremely high sensitivity*—can easily detect magnetic moments $\sim 10^{-3} \mu_B$.
- *Needs no applied field*, unlike NMR.
- *Simple spin*-1/2 *probe*.

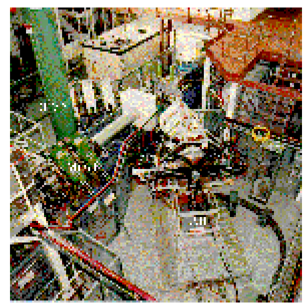
Complementary time scales



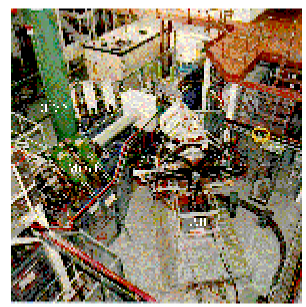
Existing μSR Facilities

- TRIUMF, Vancouver, Canada
- ISIS, Rutherford Appleton Lab., UK
- Paul Scherrer Institute (PSI), Switzerland
- J-PARC, JAEA, Japan (under construction)

- About 400 μSR users worldwide.

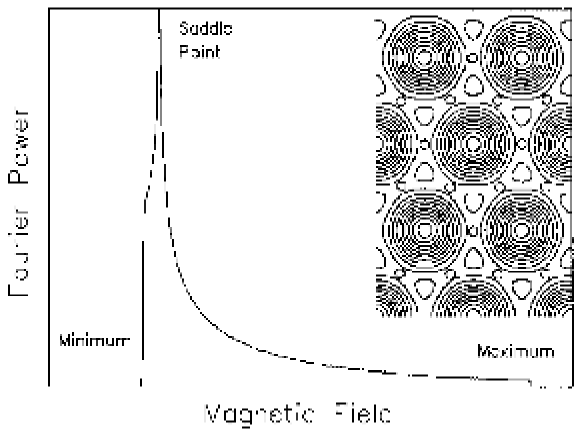


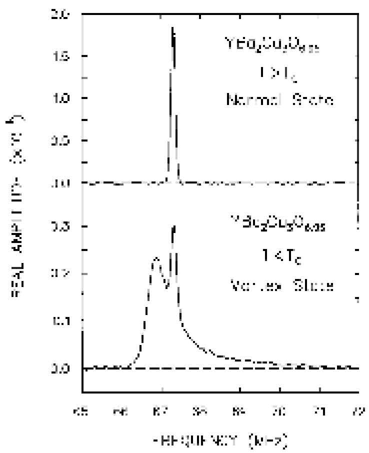
- TRIUMF and PSI are *con-tinuous* muon sources;
- ISIS and J-PARC are *pulsed* sources.
- Each has specific advan-tages and disadvantages (like reactor vs. spallation neutron sources).

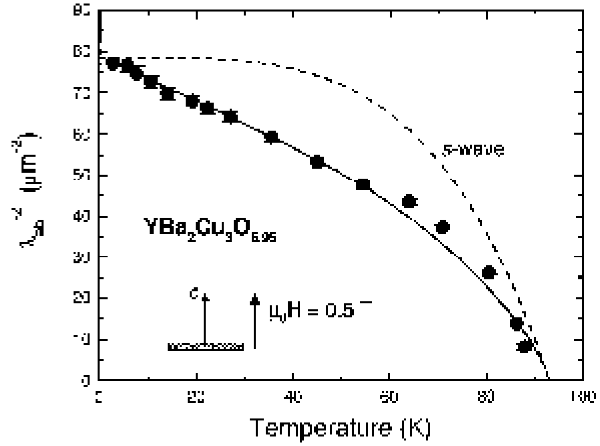


Applications

Superconductivity: vortex-state magnetic field distribution



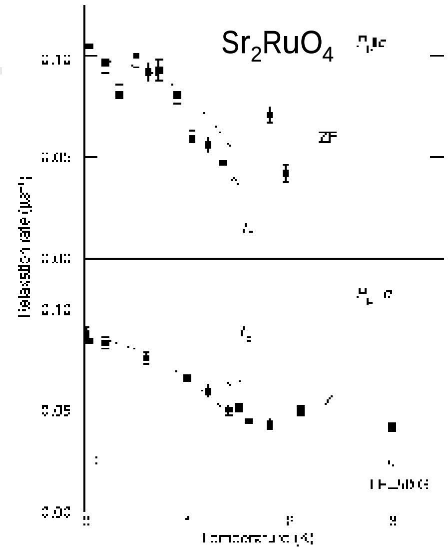


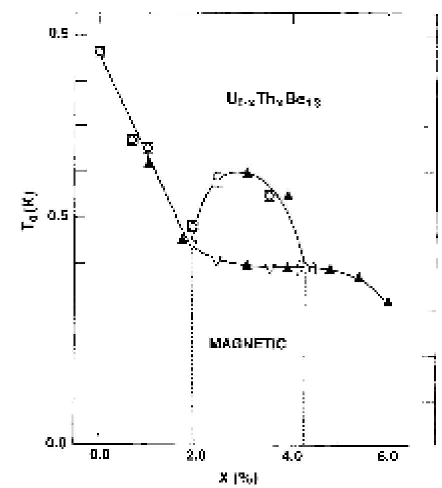


- Detailed information on *supercurrent distribution in vortex lattice*.
- Gives *penetration depth* and *coherence length*.
- Temperature dependence ⇒ *strong evidence* for d-wave superconductivity in YBCO.

Time-reversal symmetry violation in superconducting state

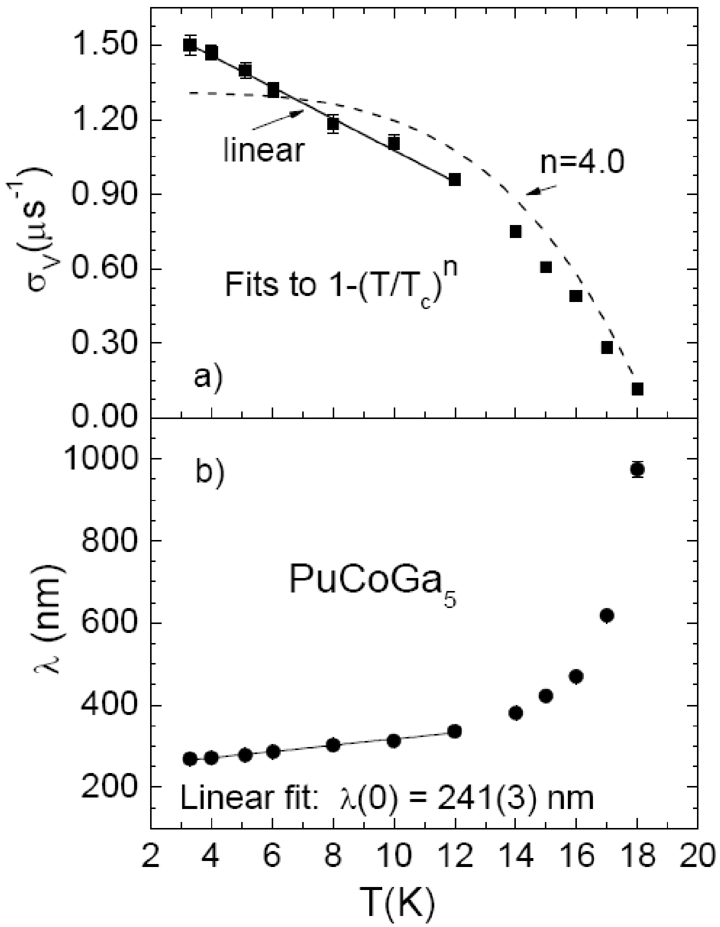
- *Uncommon form* of unconventional superconductivity.
- μSR evidence: onset of *spontaneous magnetic field* below T_c .
  - Increase of relaxation rate ⇒ magnitude of spontaneous field.
- *Unique capability* of μSR.
  - TRS-violating fields *very weak*; not easily seen by other techniques.





Actinide superconductivity

- PuCoGa$_5$: T_c = 18 K!
  - Intermediate between heavy-fermion and high-Tc superconductivity?
- Temperature dependence of penetration depth:
  - *clear evidence* for broken point-group symmetry (lines of energy gap nodes).



Magnetism–highlights

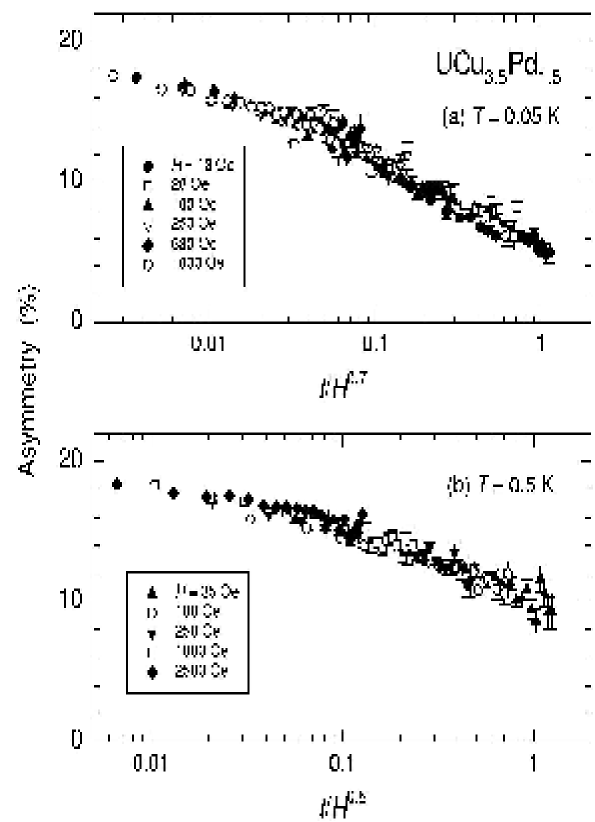
- A probe of *static and dynamic internal fields*.
  - Yields temperature dependence and magnitude of *static magnetic moment* (ordered or disordered).
- Examples:
  - *Weak-moment magnetism* in heavy-fermion metals.
  - *Disorder* and *inhomogeneous magnetism* in spin glasses, CMR materials and non-Fermi liquids.
    - Disordered spin freezing;
    - Interplay of lattice, charge, and spin degrees of freedom.

Example: Singular spin dynamics in f-electron non-Fermi liquids

- *Dynamic* (spin-lattice) muon relaxation. Probes $\chi''(\omega)$.
  - Muon depolarization function exhibits *time-field scaling:*

    $$P(t,H) = P(T/H^x).$$

  - $\Rightarrow \chi''(\omega)$ *divergent at extremely low frequencies*. Novel spin dynamics.
  - Interplay between *disorder* and *quantum criticality*.

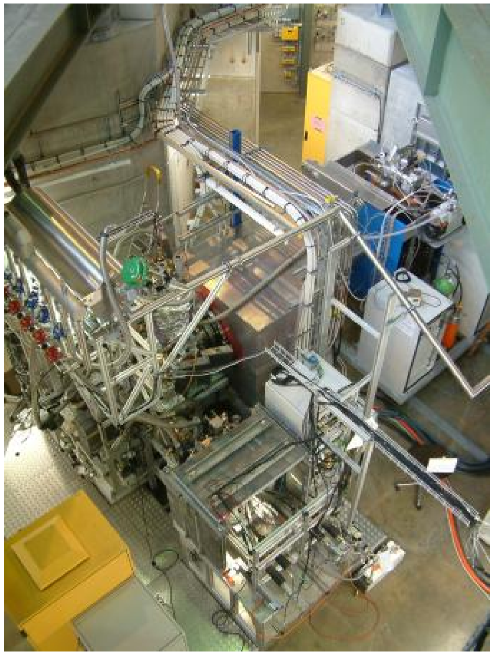


Other areas

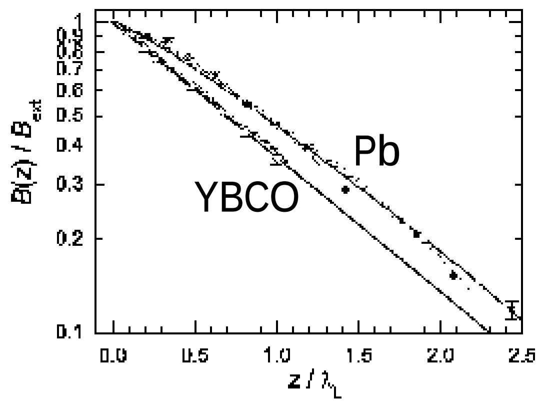
- Magnetism in *reduced dimensions*; *geometrical frustration*;
- Magnetism and superconductivity in *organic conductors*, *magnetic polymers*, other novel materials;
- *Muonium* atom (m^{+}–e^{-}) as a light hydrogen isotope in *semiconductors* & insulators;
- *Muonic* and *muoniated radical chemistry* in liquids and gases;
- . . .

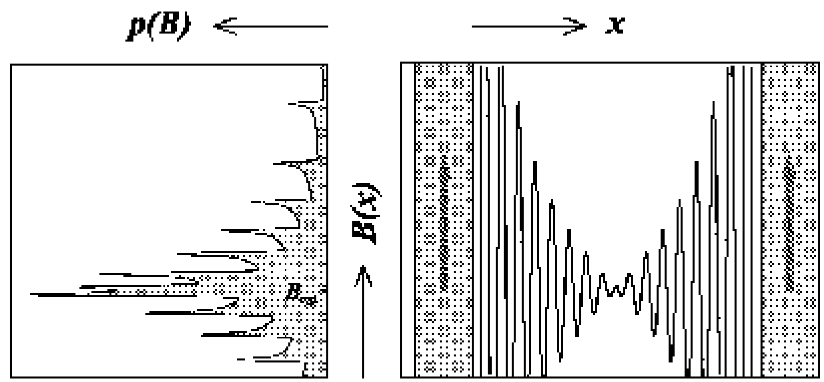
Slow muons— a new development

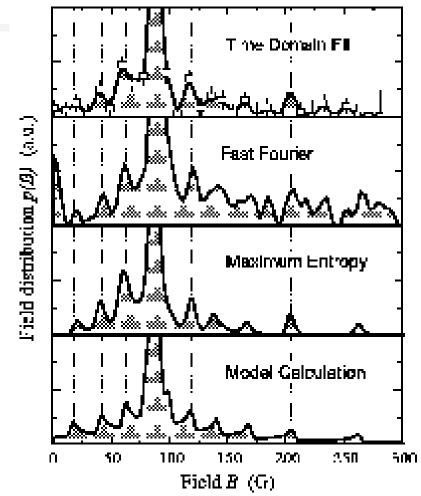
- *Very low energy muons* (eV–keV) for study of films, surfaces, & interfaces.
  - *Tunable implantation depths* over range <1 nm–1000 nm.
  - Available at PSI; under develop-ment at ISIS/RIKEN and J-PARC.
  - PSI facility was *immediately over-subscribed* when it came on line!



First applications of slow muons







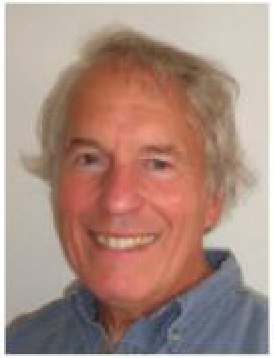
- Direct measurement of *Meissner-state field penetration*:
  - *Non-local corrections* to London relation.
- *Field distribution* in Fe-Ag-Fe trilayers:
  - *RKKY-like oscillations* in nonmagnetic Ag layer.

ISMS

- International society for μSR spectroscopy (ISMS):
  - founded four years ago to promote technique and facility development.
  - First president (elected by membership) was Bob Heffner (Los Alamos, JAEA).

Recent μSR prizewinners

- Don Fleming—2004 ACS Seaborg Prize for Nuclear Chemistry
  - For studies of muonium and muoniated free radical chemistry.



- Tomo Uemura—2005 ISMS Yamazaki Prize for μSR Science
  - For studies of magnetism and superconductivity using μSR.

No μSR facilities in U.S.

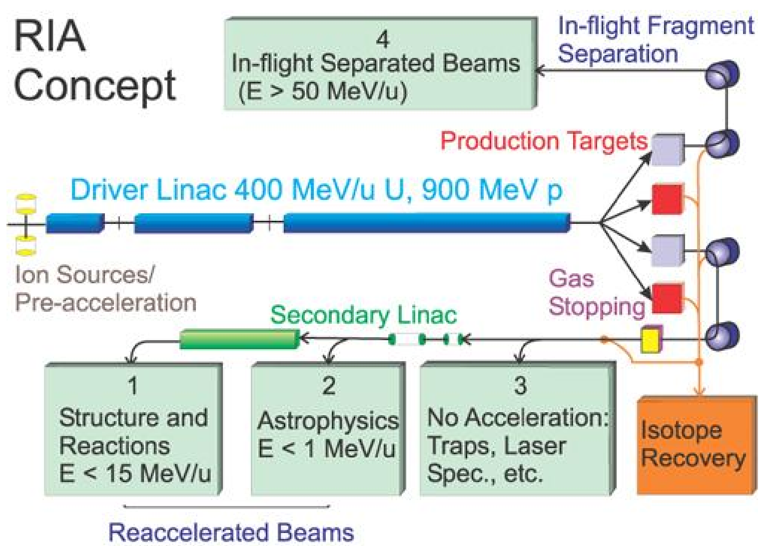
- Lack of suitable U.S. muon sources $\Rightarrow$ small (but productive) U.S. user community.
- A U.S. μSR facility will ensure future growth:
  - Large body of specialists in related fields (neutron scattering, NMR);
  - In host countries most growth from users with other primary specialties.
- *μSR is certain to produce important new physics*.

Current situation; cost

- Design study in progress at LANSCE/LANL:
  - High-acceptance channel, laser ionization technique for low energy muon production.
  - Depends on refurbishing the LANSCE accelerator at Los Alamos.
- Relatively modest cost:
  - Beam line + general-purpose µSR instrument: comparable to cost of a modern neutron scattering spectrometer.

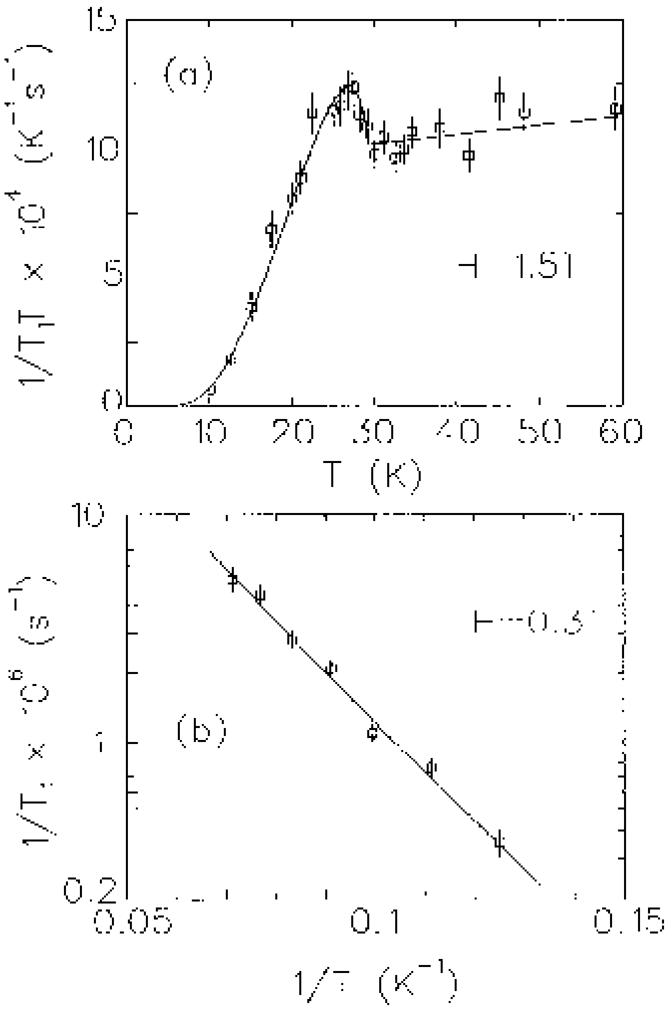
Call for SSSC study

- We propose a study committee of experts in μSR and related areas.
  - Review of the science.
  - Study of resources:
    - Existing proton accelerators (LANL, BNL)?
    - Proposed Rare Isotope Accelerator?
    - Completely new accelerator (FFAG)?
  - Recommendations for new facilities.

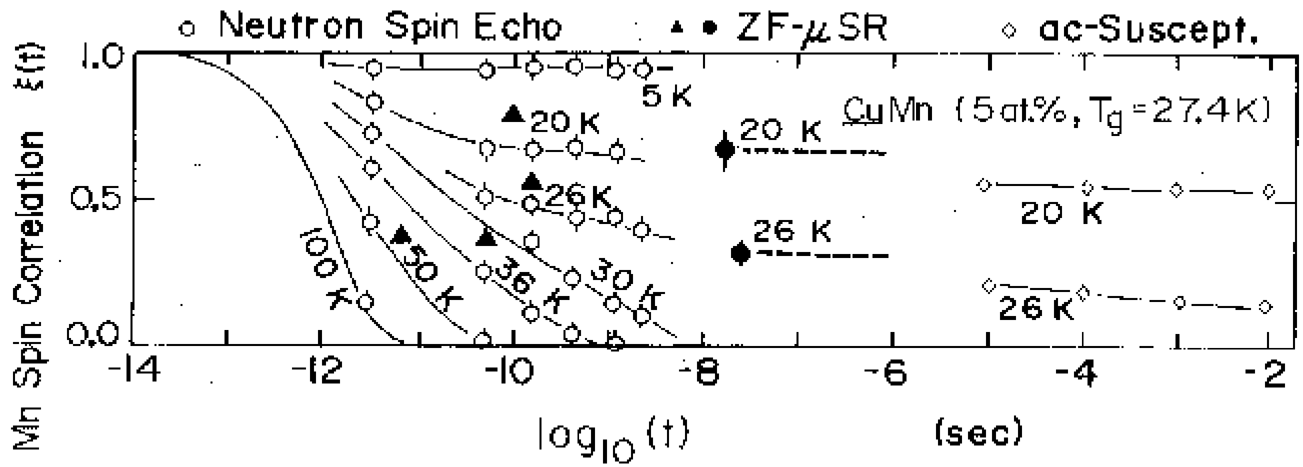


BCS superconductivity in Rb_3C_{60}

- Relaxation rate $1/T_1$ of muon in endohedral muonium.
- "Hebel-Slichter peak" just below Tc.
- *Conventional* supercon-ductivity!



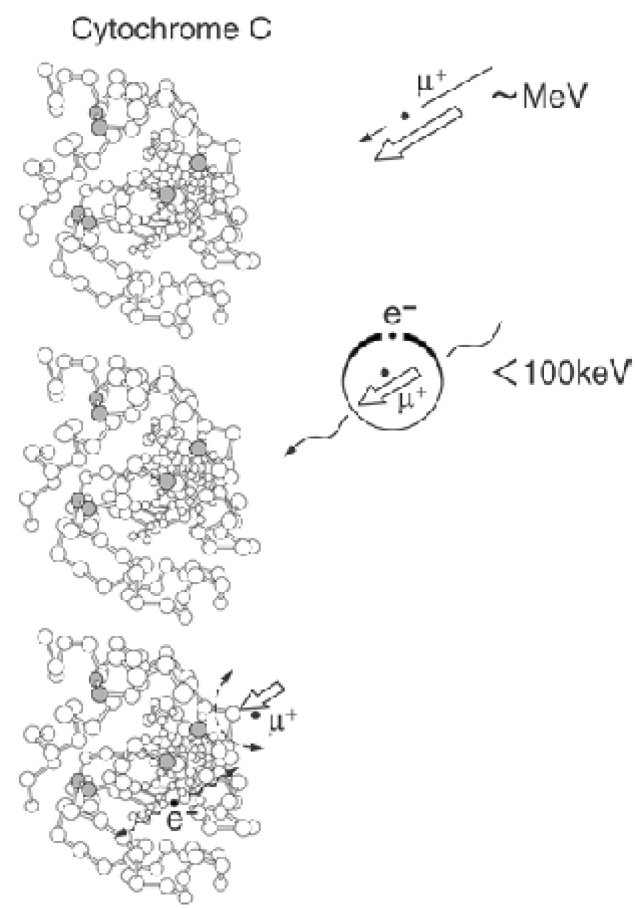
Spin glasses



- Development of long-time tails in spin correlations below (and above) spin-glass transition temperature.

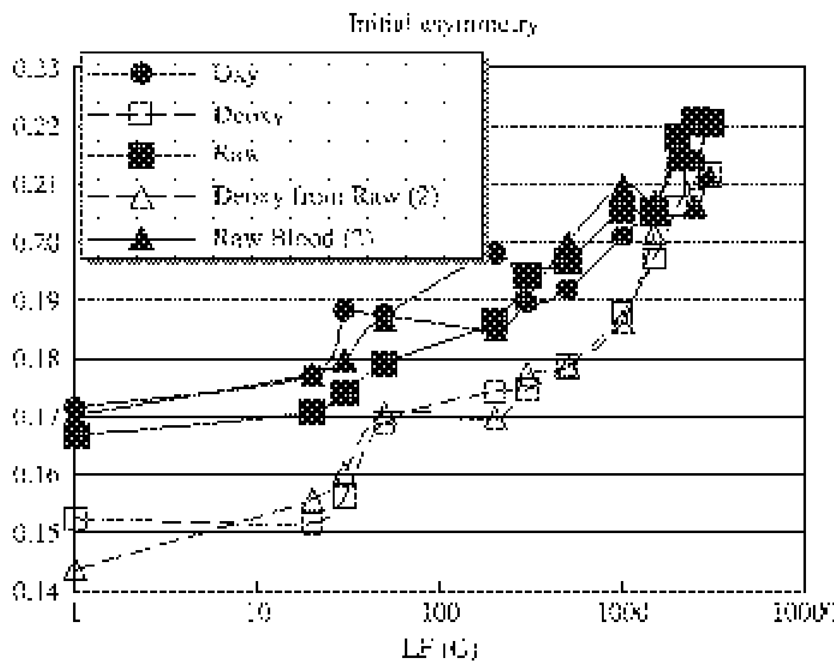
Electron transfer in macromolecules

- Muon-injected electronic state
- Conducting polymers:
  - Polyacetylene
- Biological macromolecules:
  - Cytochrome c
  - DNA



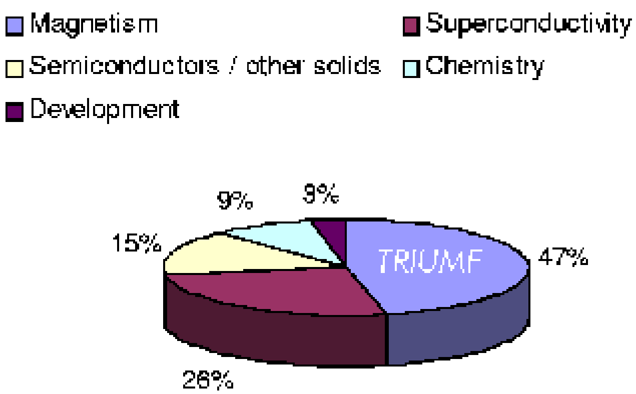
Medicine

- μSR in human blood.
- Field dependence of asymmetry different for oxygenated and deoxy-genated blood.
- Potential as a diagnostic tool.



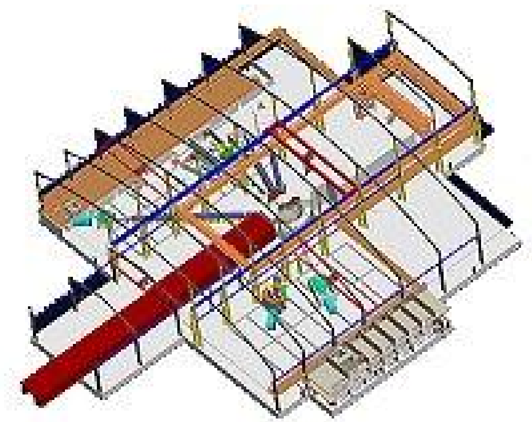
Facility usage

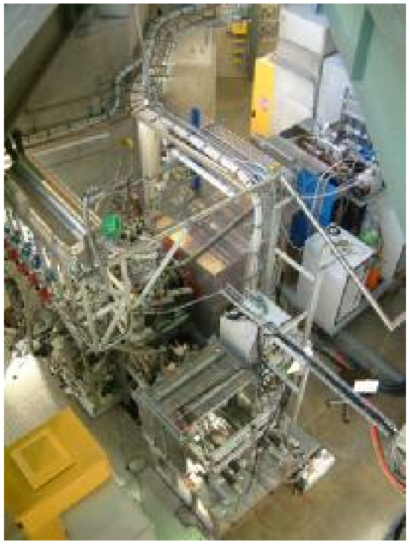
- Most current μSR research is in magnetism.
- Then superconductivity, then semiconductors, chemistry, ...
- TRIUMF data; similar usage at other facilities.



New facilities

- New μSR facilities being built at TRIUMF, ISIS, PSI, J-PARC .





J-PARC, Tokai

- Integrated with spallation neutron & synchrotron radiation facilities.
- Will be brightest source of short-pulse muons in the world.