

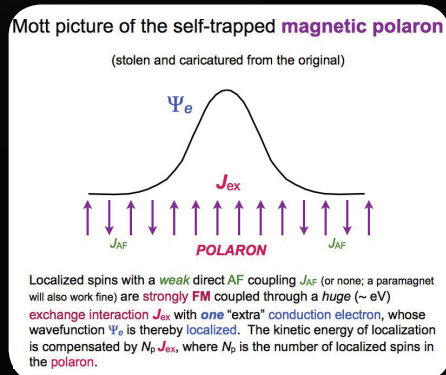
# Muon measurements

Dr Jess Brewer discusses his work at TRIUMF, Canada's national laboratory for accelerator-based research, where he and his team use 'μSR' spectroscopy to probe the exotic properties of materials

To begin, how would you sum up Muon Spin Rotation/Relaxation/Resonance (μSR)?

Like nuclear magnetic resonance (NMR) and electron spin resonance (ESR), μSR is basically a type of magnetic resonance, analogous to free induction decay in NMR. The positive muon, which is nominally the antimuon because we think of the negative muon as the 'particle' (by analogy to its lighter cousin the electron), has its spin aligned 100 per cent antiparallel to its momentum. This is due to parity violation in the weak decay of its precursor, the positive pion. Furthermore, the muon also decays asymmetrically, emitting a high energy (up to 52 MeV) positron along its spin direction about twice as probably as in the opposite direction. The easily detected positron can penetrate the walls of a cryostat or other apparatus containing the sample. Compared with the faint magnetic free induction decay signal in NMR, this gives μSR a sensitivity advantage over NMR of a factor of around  $10^{12}$ . Another advantage is our ability to perform μSR experiments in zero applied magnetic field and/or without any RF irradiation. The main disadvantage of μSR is the short lifetime

FIGURE 1. EXPLANATION OF THE MP QUASIPARTICLE



of the muon (2.2 microseconds), which limits its spectroscopic resolution to around 1 part per million; but it also gives access to faster phenomena (on a time scale of nanoseconds) so we are not complaining.

Could you describe what led to your current research and what continues to interest you in μSR?

In 1969, after two years of graduate work at Berkeley, I was given a precious opportunity: my supervisor left to become Head of the Physics Department at Northwestern, so I had to go looking for a new one. With a little experience under my belt I was both wiser and more employable; so I got to pick between several enticing choices. Ken Crowe explained how one might utilise the then-exotic parity-violating decays of pions and muons as a probe of matter, and after that there was no turning back. It actually worked! And for the ensuing four decades I have been 'listening' to muons telling me what they 'see' in various magnetic environments, from the interior of a heavy nucleus to reactive molecules in a gas to the vortex lattice of a high temperature superconductor. What I love most about muons is that they can go anywhere, providing unparalleled insights into their environments.

What are the main objectives of your present research and your overall mission and vision?

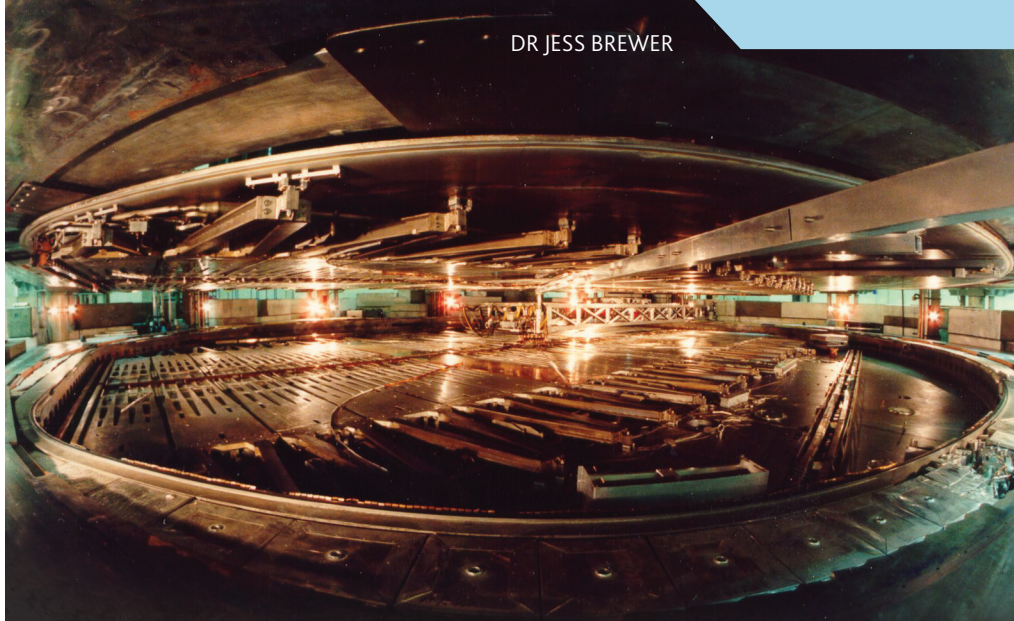
I still get thrilled stopping muons in new materials to see what they can tell me, and I rarely turn down a chance to 'look' at something new with μSR; but insofar as I have any responsible, pragmatic streak at all, I am especially interested in the role muons can play in the formation and detection of magnetic polarons, also known as spin polarons – tiny droplets of ferromagnetically



aligned spins in an otherwise nonmagnetic (or weakly magnetic) crystal. These fascinating quasiparticles were predicted by de Gennes half a century ago and are thought to explain a variety of exotic and useful magnetic properties of certain types of solids, but they have only been directly observed by μSR.

How important to your research is collaboration?

I collaborate with everyone on everything; that is the whole point of science! One of the greatest difficulties for μSR practitioners is finding 'arm's-length' referees for papers and promotions, given that everyone works everywhere with everyone in this community of around 1,000 people. Perhaps this is because μSR is so much fun! Together this community has published many thousands of papers, a few hundred of which have my name on them. These span many areas of science, from subatomic physics through chemistry and condensed matter physics to molecular biology and evolution, so I would be hard pressed to



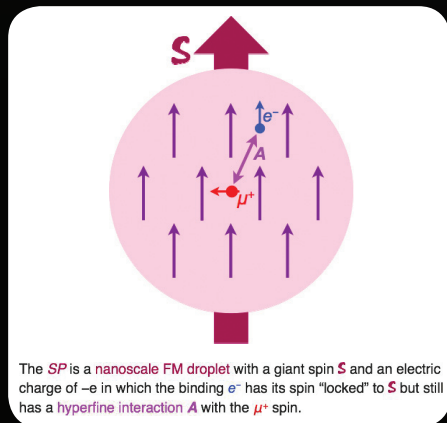
# Spinning around

summarise succinctly; but the majority of my recent publications involve high temperature superconductors and/or magnetism.

**Where do you think  $\mu$ SR research is heading in the next decade?**

Some trends are clear, but no one can really know. While a core of 'old guard' practitioners continue to press for newer, better facilities, more exotic and powerful techniques, and novel new applications of  $\mu$ SR, the field is now in an expansion phase where the well-established facilities and techniques are becoming more readily accessible to people who just want to use  $\mu$ SR to find out some specific thing about their sample and then go home to think about its implications. This is the stage at which society 'cashes in on its investment' by harnessing it to practical questions. I am always nervous that this might lead to bad science – science without imagination or innovation – but I recognise its necessity and I trust the younger leaders in this field to guard against that hazard.

**FIGURE 2. INTERACTING SPINS IN THE SP**



The *SP* is a nanoscale FM droplet with a giant spin *S* and an electric charge of  $-e$  in which the binding  $e^-$  has its spin "locked" to *S* but still has a hyperfine interaction *A* with the  $\mu^+$  spin.

Using  $\mu$ SR, a versatile technique for probing materials, an international team based in Canada has been revealing the secrets of superconductors, creating new quasiparticles, and carrying out many other investigations

**PROBING THE PROPERTIES** of matter on the nanoscale requires innovative new technologies such as Muon Spin Rotation/Relaxation/Resonance (so named in order to create the acronym ' $\mu$ SR' in deliberate analogy with Nuclear Magnetic Resonance, or NMR). A team at TRIUMF has developed  $\mu$ SR into a powerful tool for investigating materials under a wider variety of conditions than other, more conventional approaches allow.

In the type of  $\mu$ SR used at TRIUMF, a positive muon enters the sample having first passed through a thin scintillator, which starts an electronic 'stopwatch' that is stopped by a fast positron (an average of just over two microseconds later) when the muon decays. The time interval so measured is digitised and the corresponding bin in a time histogram is incremented. This happens thousands of times per second until the histogram contains millions of such counts. The resulting time distribution has a time resolution of less than a billionth of a second. Thanks to parity violation in the weak interaction, the muons arrive 100% spin polarised and decay asymmetrically, emitting the positron preferentially along their spin direction at the time of the decay. Thus the time spectra of a  $\mu$ SR experiment reveal the time evolution of the muon spin and, through it, the muon's local magnetic environment.

One of the major advantages of  $\mu$ SR is the level of sensitivity that it offers. In fact,

its intrinsic sensitivity is higher than NMR by a factor of around  $10^{12}$ . Because it is a trillion times more sensitive,  $\mu$ SR 'works' in a large variety of places that NMR does not, or where it has a signal which is hard to find. Furthermore,  $\mu$ SR does not require application of a radio frequency field or an external magnetic field, so it can be used to study metallic or superconducting materials just as easily as insulators and semiconductors.

The  $\mu$ SR techniques developed at TRIUMF have generated vast amounts of data since the mid-1970s, all of which are on public display at: <http://musr.ca/mud/runSel.html>. Most recent experiments have been on superconductors and exotic magnetic materials, but also include many studies of semiconductors as well as the chemical reactions of the hydrogen-like atom muonium (Mu), formed when a positive muon captures an electron. This atom has one ninth the mass of a protium atom but otherwise obeys the same chemistry. Experiments on muonium have provided a deeper understanding of basic quantum chemistry, as well as revealing molecules incorporating muonium that have been impossible to detect in the conventional hydrogen atom versions. They also offer insights into chemistry in extreme environments, such as supercritical water, which have been crucial to the design of some fourth generation nuclear reactors.

## INTELLIGENCE

### MUON SPIN ROTATION/RELAXATION/ RESONANCE IN SOLIDS

#### OBJECTIVES

To harness the magic of the weak interaction to new methods for investigating properties of 'ordinary' matter, thus helping to fulfil the promise of subatomic physics to become directly 'useful' someday. Over the years, the  $\mu$ SR community at TRIUMF has developed many of the most powerful techniques used worldwide to make  $\mu$ SR an indispensable general-purpose probe of matter in molecular and materials science.

#### KEY COLLABORATORS

Users from around the world, in particular (for Brewer's personal collaborations):

**Vyacheslav Storchak**, Kurchatov Institute, Moscow

**Jun Sugiyama**, Toyota Central Research & Development Laboratory, Japan

All Brewer's esteemed colleagues at the CMMS

#### PARTNERS

- The International Society for  $\mu$ SR Spectroscopy (ISMS) and  $\mu$ SR facilities at PSI (Switzerland), RAL/ISIS (UK) and J-PARC (Japan)
- The TRIUMF accelerator laboratory in Vancouver, Canada, a joint venture by a consortium of universities, supported by the Government of Canada (via a contribution through the National Research Council) and by the Government of British Columbia (via building infrastructure)
- The TRIUMF Centre for Molecular & Materials Science (CMMS)

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Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grant ' $\mu$ SR in Solids'; NSERC Major Resources Support Grant 'CMMS' (with PW Percival et al.)

#### CONTACT

**Dr Jess H Brewer**  
Professor Emeritus

Department of Physics & Astronomy  
University of British Columbia  
Vancouver, British Columbia  
Canada, V6T 1Z1

T +1 604 222 1047 ext 6471  
E [jess@phas.ubc.ca](mailto:jess@phas.ubc.ca)

**JESS BREWER** completed a PhD in Physics at Berkeley in June 1972. He joined the Department of Physics and Astronomy at the University of British Columbia in 1977 and has been a Professor since 1986. In 2011 he retired and was granted Emeritus status at UBC. He is still active in research, primarily at the CMMS facility of TRIUMF in Vancouver, Canada. He is also a Visiting Professor at the University of Huddersfield.

## MAGNETIC INVESTIGATIONS

The use of  $\mu$ SR to probe high temperature superconductors has been celebrated in the last few decades, and more broadly exotic forms of magnetism have been widely studied by the technique. These include highly frustrated magnetism and highly correlated electron systems where other investigative techniques have had problems uncovering the issues. Professor Jess H Brewer, a longtime developer and advocate for the team in Canada, has been at the forefront of work

One of the major advantages of  $\mu$ SR is the level of sensitivity that it offers. In fact, its intrinsic sensitivity is higher than NMR by a factor of around  $10^{12}$

being done with muons, but is also asking questions about the way the technique has previously been applied: "Many of the experiments on magnetism are predicated on the assumption that the muon does nothing to disturb its environment, which I now view as highly optimistic given the work that has been done on magnetic polarons and muonium formation in solids".

#### ELEMENTARY EXPERIMENTS

By mapping the initial spin relaxation of muons in silver and aluminum, the TRIUMF  $\mu$ SR group has been able to assist the TWIST experiment on fundamental muon decay parameters. The research involved mapping pion to muon to electron decays with a level of precision that has never before been achieved. The  $\mu$ SR measurements were important because the initial microsecond of the muon's lifetime was previously unmapped, and therefore could have posed some difficulties. Brewer is pleased with the results: "We used conventional  $\mu$ SR to make the most precise measurements ever of an extremely slow muon spin relaxation (about one inverse millisecond) and were able to offer some reassurance that the shape of the relaxation was as expected". Thus  $\mu$ SR was able to contribute to elementary particle physics, returning the favour originally provided by the discovery of parity violation, and further illustrating the breadth of applicability of  $\mu$ SR.

#### DIVING INTO NUCLEI

In another subatomic adventure, Brewer stopped negative muons in various elements and observed the relativistic shifts of their precession frequencies in a 2 tesla magnetic field. This effect was calculated by Breit for pointlike nuclei in 1928, so it is no surprise; what is interesting is how it deviates from Breit's predictions as the muon is captured in orbits around heavier nuclei: for very heavy nuclei

(eg. tungsten or lead) the muon's orbit is so tight that it is almost entirely contained within the nucleus itself, leading to a relativistic shift that is independent of the atomic number – the muon is orbiting in solid nuclear matter. Comparing this effect with the weak nuclear capture rate of the  $\mu$  may help determine the distribution of protons in the nucleus.

#### MAKING MORE MUONS

Progress has been made despite the fact that  $\mu$ SR relies entirely on expensive facilities which tend to be controlled by other scientists. The only practical way to create numerous pions, which decay into muons, is in proton accelerators, which tend to be operated by particle physicists who may have conflicting priorities. In the past Brewer has sometimes been frustrated by this tension: "The scientists who built the 'meson factories' sometimes regarded  $\mu$ SR as 'parasitic', and tolerated our presence primarily because  $\mu$ SR contributed anomalously high publication rates and high profile scientific results to the host laboratory". Nevertheless, and possibly due in part to such Darwinian pressures,  $\mu$ SR has thrived in the four countries where it exists: Canada, Switzerland, Japan and the UK. Furthermore, in Europe scientists are exploring the possibility of building a 'muon source', an accelerator laboratory dedicated to producing muons for  $\mu$ SR, which would empower individuals and investigative teams to continue pushing the boundaries of experimental science by working with  $\mu$ SR to uncover exciting physical and chemical properties of materials. The hope is that this will allow an improvement of several orders of magnitude over what is currently possible for the various  $\mu$ SR teams, opening up a new age of discovery within Europe, and, hopefully, worldwide.

#### CREATING QUASIPARTICLES

The work of  $\mu$ SR is only just beginning, and it is hoped that new developments will continue for this fruitful technique. One potential future application is the continued discovery of new materials by  $\mu$ SR. In fact, one major success of  $\mu$ SR has been the observation of the elusive magnetic polaron (MP), a quasiparticle that is thought to drive exotic magnetic properties including metal to insulator transitions in magnetic semiconductors. Not only does the muon help probe the size and spin of the MP, in some cases it also helps create it, through its Coulomb attraction for the electron that mediates the strong ferromagnetic coupling of nearby spins. The effects of MP could lead to magnetoresistance effects many times greater than those used in today's important technological applications. Brewer is excited about other possibilities for such materials: "It is also possible that magnetic polarons could be used to enable low power 'spintronics' devices or integrated circuits that do not require the extreme cleanliness of today's silicon fabrication facilities". Even if these possibilities never materialise, the investigative power of  $\mu$ SR means that it will continue to be at the forefront of materials exploration, providing details which are unavailable from other techniques.

