2019 Summer Student Project Description

OBJECTIVES: All electronic, magnetic and structural properties are altered near a boundary between two materials (or a surface) due to the broken translational symmetry. Consequently a thin film or the near surface region of a crystal has properties that in general are different than in the bulk. Furthermore it may be possible to control such properties with an external electric or magnetic field. Giant magneto-resistance in magnetic multilayers an example which has had a dramatic impact on magnetic storage. A central theme of modern condensed matter physics is to understand the collective state of electrons in systems which have strong effective interactions. Our short term objective is to explore and eventually control the electronic/magnetic properties near the interfaces and surfaces of so called *quantum materials*. Ultimately we aim help create a more unified picture of how electrons and magnetic ions organize themselves into coherent states of matter at low temperatures, how these properties change near interfaces and within heterostructures and how they can controlled with external fields. The potential impact comes from the expectation that future devices will increasingly utilize the properties of interfaces and quantum materials.

METHODS: Few experimental methods are suitable for of probing local magnetic and electronic properties in a depth resolved manner. We have developed one of them at TRIUMF called low energy beta-detected nuclear magnetic resonance (βNMR) [1]. A closely related method, low energy muon spin rotation/relaxation (μSR), has been developed at the Paul Scherrer Institute (PSI) [2]. The two methods have similar principles but provide complementary information. The magnetic moment of the muon (or radioactive nucleus) acts as a probe of the local magnetic/electronic environment. All forms of nuclear magnetic resonance involve generation of a non-equilibrium spin polarization followed by observation of the time dependent polarization. μSR and β-NMR are distinct in that a large non-equilibrium spin polarization is generated in the beam before they are introduced into the sample. In addition, the polarization is detected through the anisotropic decay properties of the muon or nucleus. Consequently a signal requires only about 10^7 spins, which is about 10^{10} fewer than is required from conventional NMR. Conventional μSR and βNMR were invented in 1957 along with the discovery of parity violation in weak interactions [3]. However, the particular variants, which will be used are still being developed. The key points are that unlike conventional NMR, the signals in βNMR and μSR are independent of sample size and can be monitored as a function of the mean depth on a nm length scale. The observed signals are averaged over the stopping distribution but the mean depth is controlled very precisely on a nm length scale. Consequently both methods are ideally suited to studies of thin films and how they respond to external electric fields.

The student will be to participate in one or more of the following projects at a level which depends on his/her interests and abilities. This could involve design of new instruments, sample characterization, spectrometer operation and data analysis.

PROJECTS:

1. Controlling Properties in thin $SrTiO_3$ (STO) Films Thin oxide films have a wide range of useful properties that can be controlled through a variety of methods,-strain induced from the substrate, doping, oxygen vacancies, and electric fields. Thin films of STO are particularly interesting since STO is on the verge of becoming a ferroelectric. Bulk STO is a quantum para electric with a dielectric constant which saturates below 10K at a very large value of 20000 or more [4]. Application of an electric field causes a significant reduction (factor of 2) in the dielectric constant whereas Raman spectra show that some soft mode phonon frequencies increase significantly with electric field [5]. Preliminary results from TRI-

UMF have shown the spin relaxation rate of ^{8}Li in bulk STO increases dramatically in an electric field, demonstrating that βNMR is sensitive to the dielectric properties through the quadrupole moment of ^{8}Li. We will be investigating the electric and magnetic properties of MBE grown STO films as function of substrate strain and applied electric field.The films will be grown and characterized at the SBQMI in collaboration with Bruce Davidson. We expect the properties such films will depend sensitively on substrate strain. We also expect the oxygen stoichiometry and vacancies will introduce a dilute concentration of Ti^{3+} magnetic moments which can be monitored using both low energy μSR and βNMR.

2. Search for Time Reversal Symmetry Breaking (TRSB) is Exotic Superconductors. An important test of theories on exotic superconductors is whether or not they break time reversal symmetry as evidenced by small static or slowly fluctuating internal magnetic fields. Slow magnetic fluctuations reported in the pseudo-gap phase of underdoped$YBa_2Cu_3O_x$ using μSR [6]. However the observed relaxation is small and at the limit of what can be seen with μSR. We are proposing to look at these same crystals with βNMR which is more sensitive to slow spin relaxation due to the much longer lifetime of a spin polarized radioactive nucleus compared to the muon.

3. Help design and build a βNMR Microscope. Recently, large increases (more than a factor of 10) in the ^{8}Li yield from ISAC targets at TRIUMF have been achieved. One can use the added intensity to create a ^{8}Li "microscope" where the beam spot has an area at 10 times smaller (~ 1 mm^2). The first step is to install an adjustable iris upstream of the spectrometer and modify the focusing elements to limit aberrations in the beam. The second step is to build a Paul trap to store cool and pulse the polarized beam [7]. Designing and building a first version of the microscope would be done in collaboration with TRIUMF scientists. Such an instrument would have an enormous impact on how βNMR can be used to study devices which often can only be made in the sub mm size.

4. **Tracer diffusion in of ^{8}Li.** We have now demonstrated it is possible to make precise measurements of ^{8}Li diffusion in TiO_2 using the decay alpha particles [8]. The next step is apply this to important battery electrode materials such as $Li_4Ti_5O_{12}$. In addition it should be possible to extend the temperature range of the cryo-oven up to 600K and improve the alpha detection method by incorporating Si detectors which have a much higher energy resolution than the current ZnS scintillator. This would extend the range of diffusion constants that can be measured. It should also be possible to measure Li diffusion in thin films and the trapping rate at interfaces.

References

[1]R.F. Kiefl et al Physica B **326** (2003) 189-195]; G.D. Morris, W.A. MacFarlane, K.H. Chow, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, Z. Salman, et al, Depth Controlled Beta-Detected NMR of Low Energy ^{8}Li In a Silver Film, Phys. Rev. Letts. **73,** 157601 (2004).

[2] T. J. Jackson *et al.*, Phys. Rev. Lett. **84**, 4958(2000);A. Suter *et al.*, Phys. Rev. Lett. **92**, 087001(2004).

[3] R.L. Garwin, L.M. Lederman, M. Weinrich, Phys. Rev. **105,** 1415 (1957).

[4] M. Itoh, R. Wang, Y. Inaguma,T. Yamaguchi,Y-J. Shan, and T. Nakamura, Phys. Rev. Letts, **82**, 3450 (1999).

[5] J.M. Worlock and P.A. Fluery, Phys. Rev. Letts. **19**, 1176 (1966).

[6] Zhang et al., Sci. Adv. **4**: eaao5235 (2018).

[7] A. Kellerbauer, T. Kim, R.B. Moore, P. Varfalvy, Nuclear Instruments and Methods in Physics Research A **469** , 276, (2001); F. Herfurtha et al, Nuclear Instruments and Methods in Physics Research A **469** , 254 (2001).

[8] A. Chatzichristos, R. M. L. McFadden, M. H. Dehn, S. R. Dunsiger, D. Fujimoto, V. L. Karner, C. D. P. Levy, I. McKenzie, G. D. Morris, M. R. Pearson, M.Stachura, J. Sugiyama, J. O. Ticknor, W. A. MacFarlane and R. F. Kiefl, et al in preparation for Applied Physics Letters (2018), for preprint see http://arxiv.org/abs/1810.12537 .