**II. The μSR technique**

a. Experimental Setup

μSR experiments begin with the production of copious quantities of pi mesons. This occurs from the nuclear interaction of medium energy (500 - 800 MeV) protons with the nuclei in a production target, typically graphite. The pions decay with a lifetime of 27 ns into a muon and a neutrino:.

Most μ+SR experiments today utilize "surface' muons produced from pions at rest, that is those that stop in the outer skin of the production target. A ‘surface’ muon beam is 100% polarized, with the polarization anti-parallel to its momentum, which is 28 MeV/c. A 'decay' muon (µ±) beam results from the decay of pions in flight, and is used when higher momentum muons are needed, for example to penetrate a pressure cell. All µ- beams are decay beams.

Muons are collected in an evacuated magnetic channel (consisting of bending and focusing magnets) and implanted into the material of interest, where they thermalize and, at low enough temperatures, are self-trapped at an interstitial site in the lattice (µ+) or at an atomic site (µ-). In metals the muons undergo mainly elastic collisions with the electrons and do not lose their polarization during thermalization. In semiconductors and insulators, however, a fraction of the thermalized µ+ can loosely capture an electron to form a muonium-like structure (called Mu = µ+e-), where the muon-0electron 'radius' depends on the dielectric constant of the material. The interstitial trapping site for a µ+ in a metal is one of low electrostatic energy and often of high structural symmetry, such as an octahedral or tetrahedral site in a cubic lattice. Thermalized negative muons are captured into atomic orbits (cascading to the 1S state) with a capture cross section which is highly dependent on the capturing atom's nuclear charge. In this state µ-SR is analogous to NMR on a Z-1 nucleus.

The typical range for ‘surface’ muon beams is about 0.15 g/cm2 of material (0.03 mm for a density  = 5 g/cm3), while decay beams can penetrate orders of magnitude greater depths. Low energy muons (described below) are generated from thermal and epithermal µ+ accelerated to tens of keV and have a ranges 1-200 nm.

There are two primary types of accelerator sources for muons, those which produce a quasi-continuous beam (in time) and those which produce a pulsed muon beam. A continuous beam requires the rejection of all multiple muon stopping events which occur within a typical time window set by the muon lifetime, usually 10 - 15 μs. Furthermore, the time spectrum always contains a background from random positron events. The highest precession frequencies which can be measured in this setup are limited by the time resolution of the electronics and scintillation counters, typically a few ns. (In specially designed spectrometers, a factor of at least ten better is achieved, allowing GHz frequencies to be measured.)

In a pulsed-beam experiment, the muon beam is literally turned off between pulses and so there is no random background. This type of experimental arrangement is therefore best for measuring very small relaxation rates. The highest frequency one can measure with a pulsed beam is determined by the muon pulse width. At ISIS (Rutherford Appleton Lab) the synchrotron produces two proton pulses 70 ns wide separated by 340 ns; at MUSE (J-PARC) the comparable times are 140 ns and 600-700 ns, respectively. This necessitates chopping the muon beam itself, both to remove (or redirect) the second beam pulse and to narrow the final muon beam pulse itself. The current minimum muon pulse width after chopping is around 40 ns. This intrinsic muon pulse width in a pulsed-beam experiment limits the measurable frequencies to the MHz range and the applied or internal fields to less than about 500 Gauss.

In an attempt to create a near zero-background environment using a continuous beam proton source, a technique called Muons on Request (MORE) has been implemented for surface muons at PSI, and will soon be implemented at TRIUMF. When a stopped muon is recorded using MORE a signal is sent upstream to trigger a kicker magnet which deflects the incoming muon beam, effectively creating a pulsed-muon environment for that event. The beam is held off for 10-15 µs, during which a decay positron event can be recorded. The beam is then turned on again for the next stopped muon.

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b. The µSR methodology

The muon decays into a positron and two neutrinos with a lifetime in vacuum τμ of 2.2 μs: . Because this is a parity-violating weak decay the angular distribution of the decay positron with respect to the spin of the muon is asymmetric:

*dN(t)/dtdΩ = N0(1/τµ)exp(-t//τµ){1 +<a>G(t)cos(θe)}*.

Here *θ*e is the angle between the muon spin and the positron momentum vector, <*a***>** is the average asymmetry of the decay process, typically ≤ 1/3, and G(t) is the muon spin relaxation function.

In a material we are interested in monitoring the time-decay of the polarization G(t), which is due to the interaction of the muon’s spin with the local magnetic field. This is accomplished by detecting the time of emission of the positron relative to the implantation time of the muon, for a particular positron direction. This direction determines either a ‘longitudinal-field’ (LF) or ‘transverse-field’ (TF) geometry, depending on whether the applied field is directed along the axis of the initial muon spin direction or perpendicular to it. In a longitudinal- or zero-field geometry, the positrons are always detected along the initial direction of the muon spin.

In a real material the internal field **B** experienced by the muon arises from the nuclear and/or electronic dipole fields, as well as a transferred hyperfine interaction between the electronic and muon moments. The technique is often able to simultaneously measure both the magnitude |**B**0|, direction (in a single crystal) and spread Δ**B**rms of the static component of the internal field, as well as its fluctuating component δ**B**(t). By ‘static’ we mean that the time variation of **B**0 is much slower than the muon Larmor frequency, defined as ωμ = µ|**B**0|, where µ is the muon's gyromagnetic ratio given by 2 (13.55 x 103 Gauss-1 s-1). Local field correlation times between 10-4 and 10-11 s are frequently measureable. In favorable cases like the copper oxide superconductors it is often possible to measure the actual field distribution itself, rather than just Δ**B**rms, yielding the temperature dependence and magnitude of the magnetic field penetration depth and a quantity related to the superconducting coherence length.

c. μ+ Position in the Lattice

For some μSR experiments it is not necessary to have a precise knowledge of the muon position in order to achieve a meaningful result. This is true for measurements of the local field distribution in a type II superconductor, where the muon location is not essential because the flux lattice is incommensurate with the crystal lattice, and so the muon randomly samples the local field distribution surrounding the flux vortices. Also the vortex lattice constant is many atomic spacings. (It is necessary to know that the muon is stationary, however.) In other kinds of experiments, however, knowledge of the muon position is very important to interpret the data properly.

The most reliable method to determine the μ+ position is a measurement of the average muon precession frequency or frequencies in the presence of an ordered magnetic structure, followed by a comparison of the measured field(s) to the calculated dipole field(s) for the candidate muon site(s). This method works in principle because the dipole field is exactly calculable for a specific muon site in the presence of a known moment aligned in a known direction. The ordered magnetic structure can be produced by a magnetic phase transition or by an applied field inducing a ferromagnetic alignment of ionic spins. This method can sometimes yield ambiguous results, however, because either the magnetic phase is complicated or not well enough determined (with neutron scattering) or because of multiple muon stopping sites.