Observing Spin Polarons in Magnetic Semiconducting and Various Other Materials via μ^+SR

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Using μ^+SR to Observe a Spin Polaron

μSR (Muon Spin Research/Rotation/Relaxation/Resonance) is a technique that is similar to the standard nuclear magnetic resonance technique, except that μSR uses 100% spin polarized muons implanted in a material; which then, after a characteristic time, decay to a positron and two neutrinos. The positron is emitted preferentially in the direction to that of the spin [of the muon] at the time of decay. The positron count information is then collected in various counters that surround the sample and analyzed accordingly.

As a result of the specific properties of the muon (spin ½, γ=135.54 MHz/T, $m_\mu = m_p/9$), this technique can be used in a variety of ways. Relevant to the detection and observation of spin polarons and associated magnetic properties, the muon is a very sensitive local magnetic probe that can be used to probe the local magnetic fields and investigate local moments.

- Implantation of μ^+ frees e^- in host (along ionization track)
- 'Stopped' μ^+ acts as coulombic attractive center (relatively long-range potential)
- When e^- close enough, much stronger, short-range exchange interaction, ***J***, supersedes the coulombic attraction which further localizes e^- (known as known as the *auto-* or *self-*localization process) [1]
- Since a spin polaron (SP) is a collection of aligned spins that form a giant spin molecule; implanted μ^+ can be coupled to the giant spin molecule by the electron that is localized about the μ^+ and at the same time part of the giant spin molecule
- The electron transfers the spin information from the SP to the μ^+ which affects the depolarization of the μ which then decays and detected by the surrounding detectors
- Using an external magnetic field applied across the sample in a direction perpendicular to the initial muon spin direction (known as transverse field muon spin rotation, TF-μSR) the applied field will orient the giant spin molecule while the μ^+ precesses about the applied field, the spin coupling between the μ^+ and its e^- result in a different precession signal depending on the spin state of the μ^+ (c.f. the differing local field)
- Changing the externally applied TF, directly affects the hyperfine interaction of the μ^+ and e^-, which is measured and used as discussed in the comments below Fig. 2
- The rotation frequency of the muon can be extracted from the data via a Fourier transform. As in Fig. 1 or Fig. 3.

References

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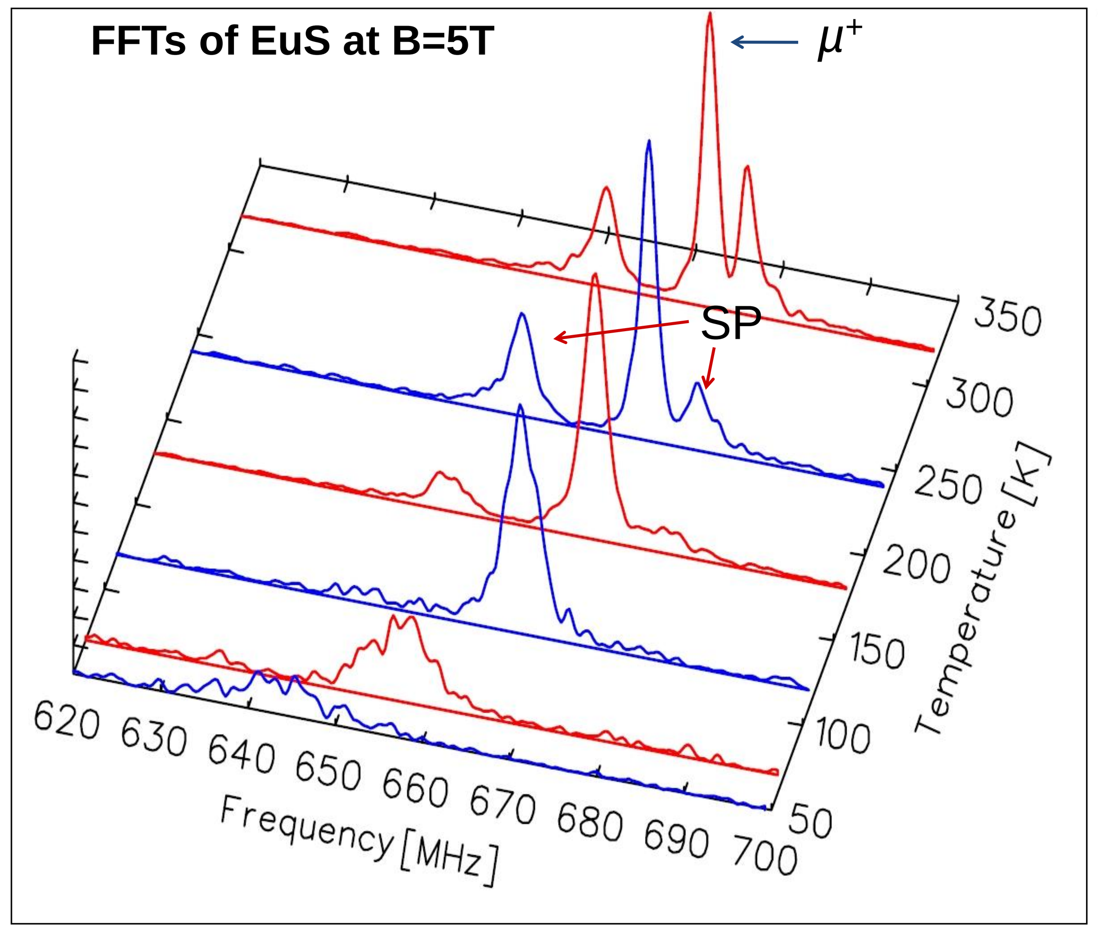
Introduction and Motivation

Since the development of the first integrated circuits, the continuing goal has been to make devices faster, smaller and more efficient. Current research in spin-based electronics is developing the ability to use the *spin* of the carrier in addition to the *charge* currently being used in conventional electronics. Current electronic devices are typically silicon or germanium based which, in either case, lack magnetic moments and therefore are not ideal for implementation in spin-based electronics. In addition to finding a magnetic semiconducting system that contains the desired properties to function appropriately in the aforementioned environment, one must understand the internal field structure of the material(s).

Recently, our group has observed, using muon spin research (μSR) methods (specifically, transverse field muon spin rotation), some interesting features associated with the internal magnetic field structure and coupling mechanisms within some semiconducting systems. Mainly, we have directly observed a spin polaron bound to an implanted muon. That is, by using μ^+ as a very sensitive magnetic probe, we have observed spin polarons within semiconductors with magnetic ions as a primary constituent.

The scope of this poster is to present a sample of the recent work as well as work that is currently underway that includes directly observing spin polarons in various materials, with an emphasis on the magnetic semiconducting systems.



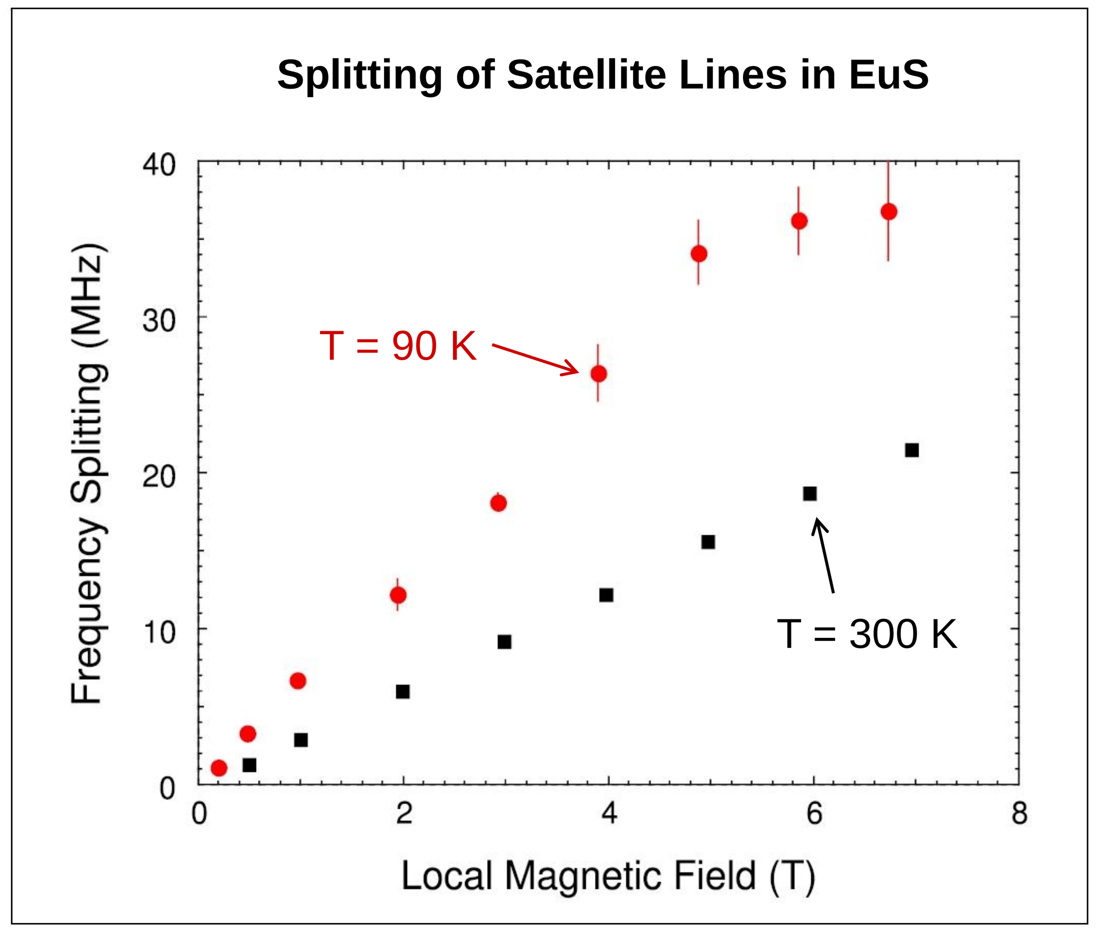


Fig. 1: Above is a series of FFTs at B=5T illustrating the temperature dependence of signals from TF-μ^+SR hyperfine spectroscopy on a single crystal sample of EuS [2]. The signal from the bare muon is marked as μ^+. The two lines, surrounding the μ^+ have been identified as lines as the signature of the polaron itself. There are two lines as a result of the spin-orbit coupling between the implanted μ^+ and the polaron mediated by the electron associated with the μ^+.

EuS is a paramagnetic semiconducting material with a band gap of E_g = 1.6 eV with long-range FM ordering below 17K [3]. EuS is of particular interest for its superb semiconducting properties as well as the magnetic features that could lead to advancements in applications related to magnetic memory [4].

Fig. 2: Above is a plot of the frequency splitting of the satellite lines in EuS as a function of applied (TF) magnetic field at two different temperatures. When the polaron spins are fully saturated, the splitting is at a maximum, at which point one can directly get compute the hyperfine constant and calculate the total spin of the SP itself. Using a mean field approximation, one can show that the splitting follows the function:

$$\Delta \nu = A\left(\frac{g\mu_B B}{3k_B T}\right)(S+1)$$

Where *A* is the hyperfine constant at saturation, *B* is the field and *S* is the composite spin of the SP. At T=90K, the saturation field is just above 5T with *A* = 37 ± 3 MHz and *S* = 36 ± 4. The SP is centered about the T-site which has 4 Eu nearest neighbors. [2]

Current and Future Work

To date, we have found several materials that show similar features that can be rather completely explained with a SP picture. Our group is continuing to investigate of several different types of materials in order to further understand the SP itself as well as other magnetic features that the SP may be a primary contributor and not yet adequately considered as such.

What is a Spin Polaron?

A *spin* polaron (SP) can be described as:

- '[T]he object made up of the carrier (e^- or h^+) plus the local modification of the spin configuration due to the presence of the carrier'[5].

The SP has also been referred to as a *magnetic* polaron and equivalently described as:

- '[a] cloud of magnetization composed of charge carriers and [the] neighboring magnetic ions'[2].

Contrary to a *lattice* polaron [6] (LP), which is comprised of a 'slow' charge carrier and the associated lattice deformation (carrier in its bound state comprise the LP); the SP is not a physical deformation and therefore requires an observational tool that is capable of probing the local magnetic environment.

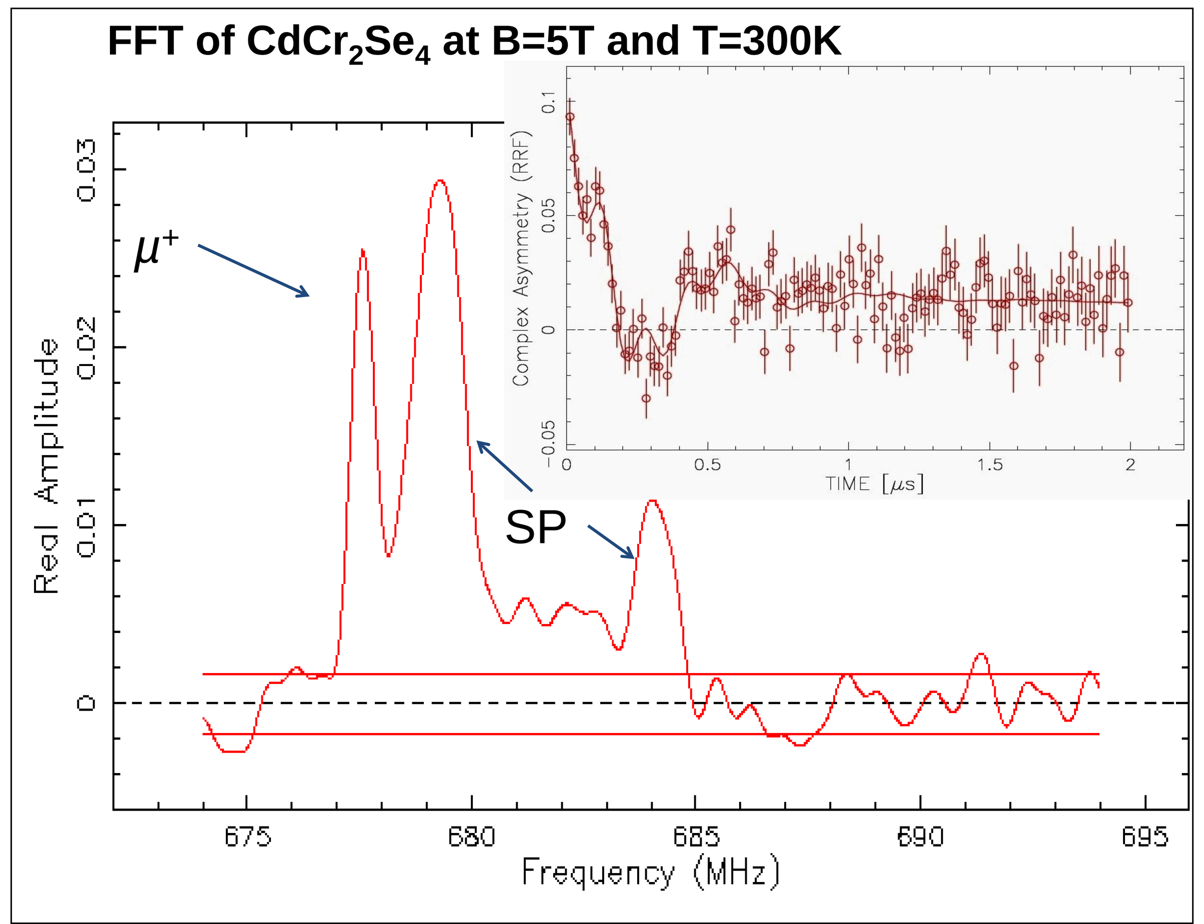


Fig. 3: Above is a single FFT from a TF-μ^+SR run taken at B=5T and T=300K on a sample of $CdCr_2Se_4$. The line marked as μ^+ is the signal from the bare muon. The two lines to the right of the μ+ line have been identified as lines as the signature of the polaron itself.

The inset graphic illustrates the precession signals in a rotating reference frame of 677.53 MHz (the exact frequency of the μ^+ in this particular applied field.

The SP lines in $CdCr_2Se_4$ are shifted to the right of the μ^+ line opposed to the EuS where there is a slight shift to the left. These shifts are a result of the mandated spin of the bound e^- to fill the vacancy in the outer shell. EuS has a half filled shell, so any additional e^- must be spin down opposed to the mostly empty outer shell of $CdCr_2Se_4$ accepting spin up.

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