AC Susceptometry for Characterizing Magnetic Spin Structures

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AC Susceptometry for Detecting Magnetic Phase Transitions

Thesis directed by Professor Minhyea Lee

Magnetic phase transitions between non-trivial ordered states are investigated through AC Susceptibility measurements. An AC Susceptometer was built for the purpose of detecting variations in a material's magnetic structure in response to adjustments of external conditions. The AC Susceptometer is sensitive to subtle changes in magnetic ordering, indicated by distinct features in measured AC Susceptibility data when a phase transition occurs. The coil design and characterization is discussed in detail. The dependence of AC Susceptibility on temperature and applied DC field conditions are explored in samples of $Cr_{1/3}NbS_2$, 10% Iron-doped MnSi ($Mn_{0.9}Fe_{0.1}Si$), and $CeRu_2Ga_2B$ (CRGB). Distinct and well-defined phase boundaries are reported, highlighting the advantages of this AC Susceptometry technique.

Keywords: Magnetism, AC Susceptibility, Spin Structures, Phase Transitions

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1 Introduction

1.1 Motivation

The phenomenon of magnetism in materials has always been a topic of great interest to researchers in condensed matter physics. Even though magnets have been used for navigational purposes by civilizations throughout history, magnetic ordering is at its root a quantum mechanical phenomenon. Because of this, the source of magnetic ordering was not well-understood until the 20th century, when advances in measurement techniques finally allowed scientists to probe the inner workings of compounds on the atomic level. As a result, continued studies of magnetic ordering have led to the discovery of very complex magnetic structures as well as applications in novel spintronic and magnetic-based memory storage devices. Therefore, further developments in measurement techniques for the study of magnetism in materials are important for continued progress in this field.

The purpose of this paper is (1) to describe the process for building and calibrating an AC Susceptometer; (2) to report measurements of the phase transitions of a variety of magnetic materials; (3) and finally to discuss the pros and cons of AC Susceptometry for the purpose of detecting subtle changes in a materials' magnetization and determining a sample's critical temperature at which a magnetic phase change occurs. Chapter 1 provides an overview of relevant concepts as well as a discussion of AC Susceptibility and other common measurement techniques. Chapter 2 describes the AC Susceptometer design, measurement set up, and calibration procedures. Chapter 3 presents the application of the AC Susceptometer through measurements on samples of 10% Iron- doped MnSi ($Mn_{0.9}Fe_{0.1}Si$), $Cr_{1/3}NbS_2$, and $CeRu_2Ga_2B$ (CRGB). Finally, the paper concludes with an assessment of AC Susceptometry and its use for studying magnetic phases, followed by a brief summary of potential future applications for this measurement device.

1.2 Spin structures and magnetic ordering

Magnetism in materials is a phenomenon that arises from the ordering of magnetic moments within the material, such that their vector sum is nonzero. The intrinsic spin of unpaired valence electrons in atoms result in localized magnetic dipole moments at the locations of atoms within the crystal. Magnetization is defined as the vector some of all individual magnetic moments per unit volume, and is nonzero if the magnetic moments/electron spins orient themselves in such a way that an emergent magnetic field is produced. An external magnetic field can influence these moments to align either parallel or antiparallel with the field; however, if exchange interactions with neighboring moments are non-negligible with respect to the thermal energy (k_BT) , then more complex spin structures can form. The resultant spin textures are dependent on conditions such as the temperature, pressure, and applied field; and therefore, a material can have multiple different magnetic phases depending on which interactions govern the spin alignment in those conditions.

There are several types of magnetic ordering that can occur in solids, with some being trivial and others very complex. In the case of paramagnetism, thermal fluctuations dominate the energy scales, and thus no specific alignment of spins is energetically favorable and the ordering is random. Paramagnetic solids therefore will have no net magnetization unless an external field is applied that forces the magnetic moments to align parallel to the field. In diamagnetic materials the magnetic moments of atoms arise from the orbital angular momentum of electrons, rather than the intrinsic spin of unpaired valence electrons. The resultant behavior is similar to that of paramagnets, except that the moments align antiparallel to the applied field. In the case of ferromagnetic solids, spontaneous magnetization occurs even without an applied magnetic field, as exchange interactions cause long range order to occur in the ground state. In the simplest case, ferromagnets have magnetic moments all aligned in one direction; however, it is also possible for spontaneous magnetization to occur in which the electron spins order in nontrivial arrangements, as is the case for several of the compounds being investigated in this study. Figure 1(a) depicts a Skyrmion domain, a type of magnetic structure found in B20 ferromagnetic compounds such as MnSi. Figure 1(b) shows the evolution of a spin structure that is initially in the form of a helix, but transitions to a soliton lattice and eventually becomes field-polarized in the presence of a sufficiently strong applied field. This spin evolution is observed in the compound $Cr_{1/3}NbS_2$, when the external field is applied perpendicular to axis of the helix (i.e. the field is oriented along the *ab*-plane of the sample) [1]. The spontaneous magnetization in ferromagnetic compounds occurs below a "Curie" temperature, T_C . Above T_C , they are in a paramagnetic state because the exchange energy between spins is overcome by the thermal energy, and therefore the material lacks an energetically favorable arrangement of spins.



Figure 1: Models of nontrivial spin structures: (a) A Skyrmion Domain [2], (b) Helical to Field-polarized spin evolution [3]

1.3 AC Susceptibility and Other Measurement Techniques

There are several methods by which one can probe the inner workings of a magnetic material. Magnetic force microscopy, shown in Figure 2(a), involves the use of a vibrating cantilever to scan over a sample surface. The tip of the cantilever has a magnetic coating, and the cantilever vibrates at some resonance frequency. As the cantilever passes over a magnetic domain, the magnetic interaction with the cantilever tip results in a phase shift of the resonance frequency. Analysis of these phase shifts as the cantilever scans over the surface is then used to form an image of the magnetic structure on the sample surface.

Electrical transport properties of a material, namely hall and magnetoresistivity, can also provide much insight into the properties of magnetic spin textures. Magnetic domains interact with conduction electrons, affecting their mean free path through the sample. By driving a current through a sample while measuring the voltage parallel and perpendicular to the applied current, the resistivity tensor of the material can be extracted. Figure 2(b) depicts a resistivity measurement setup, in which the applied field is oriented at an angle θ with respect to the z-axis. This method requires placement of electrical contacts directly onto the sample, which can potentially be problematic depending on sample size and fragility.

Additional techniques commonly used for the characterization of magnetic materials include Lorentz Transmission Electron Microscopy (Lorentz TEM), figure 2(d), and Smallangle Neutron Scattering (SANS), shown in figure 2(c). For Lorentz TEM, a thin sample is bombarded with electrons. The magnetic domains in the sample exert Lorentz forces that deflect the incoming electrons. In the absence of any magnetic structures, the electrons would tunnel through to the sample rather than being deflected. Thus, an image of the magnetic domains can be formed by interpreting the deflection of electrons. Small angle neutron scattering involves shooting neutrons at a sample surface, and the scattering of the neutrons can then be used to interpret the magnetic structure on the sample surface. Since neutrons are spin-1/2 particles with neutral charge, there is no coulomb interaction between the electrons/ions in the sample. The scattering of the neutrons is therefore purely caused by the interactions between their intrinsic spins and magnetic moments within the sample, enabling the formation of an image of the sample's magnetic structure.



Figure 2: Diagrams depicting the different types of measurement techniques for characterizing a magnetic material. (a) Magnetic Force Microscopy [4] (b) Hall effect and magnetoresistivity (MR) measurement setup for H oriented at an angle θ with respect to the z-axis [5] (c) Small Angle Neutron Scattering [6] (d) Lorentz Transmission Electron Microscopy [7]

Magnetic materials are often also characterized through magnetization measurements. A Superconducting Quantum Interference Device (SQUID) is a highly sensitive magnetometer that utilizes superconducting coils and Josephson junctions to measure a sample's magnetization. The shortcoming of this method is that a material's magnetization often appears linearly dependent on the applied field, as the dynamic response indicating a magnetic transition may perturb the system on scales too small to be easily detected in magnetization measurements. Figure 3 highlights the advantages of AC Susceptibility as a complementary detection method for samples undergoing magnetic phase transitions, evidenced by the high resolution by which transitions can be observed when comparing the data in figure 3(a) to that of figure 3(b).



Figure 3: Magnetization (top) and AC Susceptibility(bottom) vs Applied Field for pure MnSi [8]

In "linear" media, such as paramagnets and diamagnets, the magnetization M is a linear function of the applied field H, such that

$$M(H) = \chi H,\tag{1}$$

whose slope, $\chi \equiv \frac{M}{H}$, is the magnetic susceptibility. In ferromagnets this linearity is broken by dynamic effects to the magnetization under applied field. In order to extract these dynamic effects, consider the magnetization of a material in the presence of a static magnetic field, H_0 , as well as being perturbed by a small AC field, $\delta H_{ac} \ll H_0$. The magnetization can be Taylor expanded in powers of the applied field H, and is given by [9]:

$$M(H_0 + \delta H_{ac}) = M(H_0) + \left(\frac{\partial M}{\partial H}\right) \bigg|_{H_0} \delta H_{ac} + \left(\frac{\partial^2 M}{\partial H^2}\right) \bigg|_{H_0} (\delta H_{ac})^2 + \dots$$
(2)

The zeroth order term, $M(H_0)$ is the DC magnetization due to the static field H_0 . From the first-order term we can define the differential susceptibility, χ_{ac} , such that [9]

$$\chi_{ac} \equiv \frac{dM}{dH},\tag{3}$$

where χ_{ac} is called the "AC susceptibility". The higher order terms in the expansion of $M(H_0 + \delta H_{ac})$ represent additional nonlinear effects to the magnetization with applied field, and are smaller than the first order term [9]. The principle behind AC susceptometry is to drive a sample with a small oscillating field, δH_{ac} , while measuring the voltage induced across a set of balanced search coils in which the sample is placed. A static external field, $H_0 >> \delta H_{ac}$, is applied in order to induce magnetic ordering in the sample; however, the spontaneous magnetization in ferromagnets, with $H_0 = 0$, can also be observed by cooling/warming the sample past its Curie temperature with no external field applied. The design for such an "AC Susceptometer" is described in the next section.

2 Experimental Design of the AC Susceptometer

2.1 Function

The AC Susceptometer consists of two sets of circular coils; a primary coil which creates the oscillating field, and a secondary coil set in which voltages are induced and measured. The secondary coil set consists of two in-series coils that are wound in opposite directions and this sits within the primary coil. When an AC driving current is applied to the primary to create an oscillating flux through the secondary coils, an equal and opposite voltage is induced in each of the two coils, thus cancelling and resulting in 0 volts measured across the entire secondary circuit. Now a magnetic sample is placed inside one of the secondary coils. The AC field created by the primary induces a magnetic response in the sample, resulting in unequal flux through each of the secondary coils, and therefore, unequal voltages induced. Consequently, a measurement of the voltage across the entire secondary circuit is now non-zero and directly attributable to the magnetic susceptibility of the sample. Figure 4 depicts the internal set-up of the AC Susceptometer: the secondary coils (green) are inscribed within the primary coil (red), while the sample sits inside the upper (or lower) part of the secondary coils. A mount(not shown) can be used in order to keep the sample centered within the coils, provided that its length spans both secondary coils in order to avoid the measurement from being affected by any magnetic signature arising from the mount itself.



Figure 4: Diagram depicting the function of the AC Susceptometer with a sample in place. An AC current is driven through the primary coil, while voltage is measured across the secondary coil set.

2.2 Coil Design

The coils of the susceptometer were wound with 44 gauge (AWG) copper wire. Before winding the coils, shells were 3D printed out of a VeroWhitePlus PolyJet plastic. The dimensions of the coils are shown in figure 5. The primary coil consists of 3150 turns and the upper and lower portions of the secondary coil consist of 760 turns each. A sapphire mount was also cut to a width slightly less than the inner diameter of the secondary coil. The sample is glued to the mount and then inserted into the secondary coil, keeping the sample centered in the coils in order to ensure a uniform magnetic field across the sample volume. The length of the mount is about 2 mm longer than the susceptometer itself, as this helps the mount (and sample) cool/warm more quickly, allowing for better thermal

control of the sample. Sapphire is used for this purpose due to its high thermal conductivity, which ensures that the sample temperature is in agreement with measured temperature. This temperature agreement is important for determining $T_{\rm C}$ accurately when sweeping the temperature.



Figure 5: Dimensions of Primary Coil, Secondary Coil, and Sapphire Mount

2.3 Instruments and Experimental Setup

Figure 6 shows a diagram of the experimental setup. A Keithley 6221 AC Current source is used to drive the current through the primary coil. Voltages across the primary and secondary coils are measured with two separate SR830 Lock-in Amplifiers. The Lock-in amplifier is referenced to the frequency of the driving current, which allows for the reference frequency to be isolated from the measured input. This isolated signal ignores any noise present in the experiment with frequencies above or below the reference frequency. The the primary coil voltage is not strictly necessary for the AC Susceptibility measurements; however, one can easily calculate the impedance by dividing the voltage by driving current, and this serves as a good preliminary check to ensure that the coil is hooked up properly and no connections have broken. The susceptometer is attached to a probe and lowered into the cryostat which contains the liquid helium used for cooling the sample. For these

measurements, a Quantum Design Magnetic Properties Measurement System (MPMS) was used as the cryostat because the temperature and applied field can be controlled and regulated precisely.



Figure 6: Experimental setup for AC Susceptibility measurements.



Figure 7: Susceptometer attached to a measurement probe

2.4 Primary Coil Characterization

2.4.1 Field Produced

The magnitude of the AC field produced by the primary coil as a function of driving current can be calculated using the equation for a finite length solenoid:

$$|H_{ac}(x,I_0)| = \frac{1}{2} n_p I_0 \left(\frac{x + \frac{L_p}{2}}{\sqrt{(x + \frac{L_p}{2})^2 + R_p^2}} - \frac{x - \frac{L_p}{2}}{\sqrt{(x - \frac{L_p}{2})^2 + R_p^2}} \right).$$
(4)

$$\begin{split} H_{ac} &: magnetic \ field \ in \ \frac{A}{m} \\ I_0 &: magnitude \ of \ driving \ current, \ in \ Amps \\ n_p &: turn \ density \ of \ primary \ coil, \ in \ \frac{\#turns}{m} \\ x &: sample \ location, \ in \ m \ (x = 0 \ is \ the \ middle \ of \ the \ coil, \ along \ center \ axis) \\ R_p &: the \ radius \ of \ the \ primary \ coil, \ in \ m. \end{split}$$

This gives the magnetic field in units of $\frac{A}{m}$. One can convert this to Oersted using

$$[1 \ Oe] = \left(\frac{4\pi}{1000}\right) \left[\frac{A}{m}\right] \tag{5}$$

Figure 8 shows a plot of the applied field produced by the primary coil, at the sample location. The field (y-axis) is in units of Oe, and the current amplitudes (x-axis) are given in units of milliAmps. For many of the measurements taken using the susceptometer, 1 mA and 4 mA were favored amplitudes.



Figure 8: H_{ac} as a function of current amplitude through the primary coil. The units of H_{ac} are in Oersted

2.4.2 Resistance vs Temperature

The resistances of the wires in the primary and secondary coils change with temperature. By measuring the voltage across the primary coil for a temperature sweep, the resistance of the primary coil is given by dividing this voltage by the driving current. This temperature dependence of the resistance of the wire is plotted in figure 9, for temperature sweeps at different frequencies of driving current. The resistance of the wire is frequency independent, as expected, and shows a decrease by a factor of about 20 between 300 K (room temperature) and 2 K. The secondary coil consists of the same 44 AWG wire as the primary, so the resistance of the secondary coil is just rescaled by the ratio of the length of wire used.



Figure 9: Resistance vs Temperature of the Primary(a) and Secondary(b) Coils

2.4.3 Phase vs Temperature

As the resistance of the wire changes with temperature, so does the impedance of the primary coil. The coil's self inductance introduces a complex impedance that shifts the phase of the measured signal. The self inductance and phase can be calculated using

$$L = \mu_0 \frac{N^2 A}{l_p} \tag{6}$$

$$\Phi_L = \tan^{-1}\left(\frac{\omega L}{R}\right),\tag{7}$$

where ω is the frequency, L is the self inductance, R is the resistance, A is the cross sectional area of the coil, l_p is the length of the primary coil, N is the number of turns, and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the vacuum permeability. For this primary coil, the self inductance is about 0.022 H. Due to the temperature dependence of the wire resistance, the phase is also temperature dependent. When the coil temperature decreases, the phase increases. Figure 10 shows the measured phase of the primary coil as the temperature is decreased from 300K to 2K at different driving frequencies. The solid lines represent the measured phase and the dashed lines were generated by calculating the phase using equation (7).



Figure 10: Phase vs Temperature of the Primary Coil wire. Dashed lines represent calculated phase based on equation (7).

2.5 Secondary Coil Characterization

2.5.1 Background Signal and Turn Imbalance

In order to understand and characterize the secondary coil, the susceptometer's dependence on frequency and current amplitude must be observed while there is no sample in place. Keeping the frequency fixed, one can increase the driving amplitude in steps while measuring the output voltage through the secondary coil. The linear dependence of the voltage on driving amplitude can be understood as being the result of a turn imbalance between the upper and lower portions of the secondary coil. The effect of a difference in number of turns, $\Delta N = N_{upper} - N_{lower}$, can be modeled as a single coil with ΔN turns, whose induced voltage is

$$V = -\Delta N \frac{d}{dt} \left[B(t)A \right],\tag{8}$$

using Faraday's law. Since the oscillating field, B(t), depends linearly on the driving current through the primary coil, the induced voltage should also be linearly dependent on the current. Figure 11 shows data from a current amplitude sweep for the empty susceptometer. One can fit this data with a line to determine the slope, and then use equation (8) to determine the turn imbalance ΔN . For this susceptometer, the turn imbalance was found to be about 23 turns.



Figure 11: Voltage signal for increasing driving current amplitudes with no sample in the Susceptometer and a driving frequency of 20 Hz. The linear dependence of the signal on current amplitude is due to the turn imbalance in the secondary coil

Next, the current amplitude is held fixed while the frequency is increased. Figure 12 shows plots of such a frequency sweep for a logarithmic range of frequencies between 10 Hz and 10⁴ Hz. The plot on the bottom shows $\frac{V_y}{frequency}$ vs frequency, and can be used to determine the range of the linear frequency regime (the interval in which the graph is flat). At frequencies above 100 Hz, the $\frac{V_y}{frequency}$ data begins to change, indicating that the voltage is no longer linearly dependent on the frequency. For a previous susceptometer version that consisted of only 120 turns in the upper and lower parts of the secondary coil, the upper limit for the linear frequency regime was about 1 kHz. The turn imbalance for that version was found to be only around 6 turns. Since the number of turns was much larger for the susceptometer discussed here, there exists also a higher degree of imperfections in the winding of the coils. As a result, coils with high turn imbalance have their linearly dependent frequency regime restricted to lower frequencies than coils that are more uniformly wound and balanced. These frequency sweeps serve to show that even though the peaks in data due to magnetic phase transitions in a material may be sharper and easier to observe at high driving frequencies, spurious effects are also prevalent such that one can not confidently interpret features in the data as actual changes in magnetic ordering.



Figure 12: Voltage signal for increasing frequencies with no sample in the Susceptometer. Current amplitude is 0.5 mA. The left is V_y and the plot on the right is V_x , while $\frac{V_y}{frequency}$ is shown in the bottom. The x-axis scale is logarithmic and the y-axis is linear.

2.5.2 Real and Imaginary Voltage

As shown previously, the voltage data that is measured across the secondary coil using an SR830 lock-in Amplifier is given in two components: V_x and V_y . The Lock-in Amplifier is designed to measure AC voltage signals at a specific reference frequency, allowing the measurement of signals that are otherwise much smaller than the magnitude of the background noise. The Lock-in Amplifier outputs the DC rms voltage in terms of an in-phase (real) and out-of-phase (imaginary) component. When measuring the voltage across the primary coil, most of the signal is in the real component (V_x) , while the imaginary component (V_y) arises from the phase shift caused by the self-inductance of the coil. In the case of the secondary coil however, the signal of interest lies in the imaginary component. The voltage induced in the secondary coil is the time derivative of the flux through the secondary coil. Since the oscillating magnetic field is created by the current through the primary coil, and the Lock-in Amplifier measuring the secondary coil voltage references the phase and frequency of this current, the induced voltage through the secondary coil will be 90 degrees out of phase from the reference signal. Therefore, the measured voltage will primarily be in the imaginary (y-component), while V_x just corresponds to the resistance of the coil. At high frequencies however, an undesired phase shift results in some of the signal showing up in the x-component as well. If V_x changes significantly throughout a measurement, then it becomes difficult to extract the component of the measured voltage that actually corresponds to the susceptibility of the sample. It is therefore important to operate in a frequency regime for which V_x is constant throughout the measurement.

2.5.3 Extracting AC Susceptibility and a Note on Units

So far, it has been discussed that the V_y measurement relates to the magnetic susceptibility. However, there is still an extra step involved for extracting the actual AC susceptibility of the sample from the measured voltage. First, the background signal due to the turn imbalance in the secondary search coils must be subtracted from the measured voltage. This background signal depends on the driving frequency and current amplitude through the primary coil, and can be found using frequency and current amplitude sweeps for the empty susceptometer, such as those shown in figures 11 and 12. For a specific frequency and current amplitude, the background signal can be determined and subtracted. The resultant voltage can now be used to determine the AC susceptibility of the sample. Next, a calibration constant, α can be calculated with the assumption that the sample dimensions are much smaller than the radius of the secondary search coils, such that the sample can be approximated as a magnetic dipole [10]. Thus α is given by,

$$\alpha = \frac{10^8}{8\pi^2 n_s} \frac{\sqrt{l^2 + d^2}}{l},\tag{9}$$

where l is the length of one of the secondary search coils (in cm), d is the diameter of the search coil (in cm), and n_s is the turn density of the search coils (in # turns/cm). For this susceptometer, $\alpha = 1230$ cm. Faraday's law states that the voltage induced, V, in a coil is equal to the (negative) time derivative of the magnetic flux through the coil area. Therefore, V is proportional to the time-rate-of-change of the sample's magnetization $\left(\frac{dM}{dt}\right)$, coil geometry, and sample volume:

$$V = -\left(\frac{1}{\alpha}\right) V_s \frac{dM}{dt}.$$
(10)

Taking the time derivative of M(H) in equation (2) gives

$$\frac{dM}{dt} = \left(\frac{\partial M}{\partial H}\right)\frac{\delta H}{\delta t} + 2\left(\frac{\partial^2 M}{\partial H^2}\right)\delta H\frac{\delta H}{\delta t} + \dots$$
(11)

For an applied ac field, $H_{ac}(t) = h_0 sin(\omega t), \frac{dM}{dt}$ becomes

$$\frac{dM}{dt} = \frac{\partial M}{\partial H_{ac}} \frac{dH_{ac}}{dt} + \dots$$
(12)

$$=\chi_{ac}\frac{dH_{ac}}{dt}+\dots$$
(13)

$$= -h_0 \omega \chi_{ac} \cos(\omega t) + \dots \tag{14}$$

The SR830 lock-in amplifier outputs a DC rms voltage, which will need to be multiplied by $\sqrt{2}$ in order to get the full amplitude of the DC voltage signal. Neglecting the higher order terms in (14), this voltage can now be related to the ac susceptibility by [10],

$$V = \left(\frac{1}{\alpha}\right) V_s f h_0 \chi_{ac} \tag{15}$$

$$\chi_{ac} = \frac{V\alpha}{V_s f h_0} \tag{16}$$

where χ_{ac} is the AC susceptibility in Gauss/Oersted, V_s is the sample volume in cm^3 , f is the frequency of applied field in Hz, and h_0 is the magnitude of the applied field (calculated using (5)).

The AC Susceptibility calculated here is the volume susceptibility of the sample, and is given in the cgs units Gauss/Oersted. In SI units, this volume susceptibility is dimensionless. One can convert to SI units simply by multiplying the cgs AC susceptibility by a factor of 4π . Sometimes it is more meaningful, however, to express magnetic quantities in terms of the atoms in the compound that cause the magnetic ordering to arise in the first place. For example, in the case of $Cr_{1/3}NbS_2$, one could convert the volumetric AC Susceptibility to molar susceptibility such that it has units of emu/(Oe \cdot mol Cr). In this case, the sample mass would need to be known as well as it's volume. Then the volume susceptibility can be converted to molar susceptibility using

$$\chi_{molCr} = \left(\frac{M_{Cr}V_{sample}}{m_{sample}}\right)\chi_v,\tag{17}$$

where M_{Cr} is the molar mass of Chromium (grams/mol), V_{sample} and m_{sample} are the sample volume and mass, and χ_v is the volume ac susceptibility from (16)

3 AC Susceptibility of Magnetic Materials

3.1 Mn_{0.9}Fe_{0.1}Si

3.1.1 Spin Structures and Motivation

Manganese Silicide (MnSi) is a B20 transition metal compound belonging to the cubically symmetric space group, P2₁3 [11]. Materials with this lattice structure have been found to exhibit long-range helimagnetic order at zero field and below a critical temperature, due to competing DM and ferromagnetic exchange interactions. With the application of a small applied field, a transition from helical to a conical phase occurs. Further increase of this field results in the field polarized state. However, for a specific range of temperatures and applied fields known as the A-phase, an additional nontrivial spin texture can be found in the form of vortex-like magnetic domains [8]. The recent discovery of these magnetic vortices, or "skyrmion" domains, has revived interest in the spin properties of B20 transition metal compounds [8]. The precise tunability of domain shapes in materials hosting a variety of complex magnetic phases is a quality much sought after in the search for suitable candidates for improving the efficiency of spintronic and magnetic-based data storage devices [12]. Since the transition temperatures and fields for the various magnetic phases of pure MnSi are well established, this study used AC susceptometry to observe the magnetic phase transitions for a sample that was subjected to a 10% Fe substitution; $Mn_{0.9}Fe_{0.1}Si$. Previously, resistivity measurements have been performed on this sample and a phase diagram was constructed based on these measurements, as shown in figure 13. The ρ_{yx} and $\rho/\rho(H = 0)$ data figure 13(a) shows peaks near 0.25 T (2500 Oe) that indicate the transition into the A-phase, wherein Skyrmion domain formation occurs. Figure 13(b) depicts the phase diagram constructed using the resistivity measurements.



Figure 13: Resistivity data and phase diagram of $Mn_{0.9}Fe_{0.1}Si$ near the A-phase [5]. (a) Applied field dependence of the topological hall effect (THE) resistivity, ρ_{yx} , and fractional magnetoresistivity (fMR) resistivity, $\frac{\rho}{\rho(H=0)}$

(b) H-T Phase Diagram of $Mn_{0.9}Fe_{0.1}Si$, constructed using topological Hall resistivity measurements

3.1.2 AC Susceptibility Data and Phase Diagram

The first set of measurements performed on the sample were temperature sweeps, in which the applied magnetic field was held constant while the temperature was slowly increased from 2 K to 15 K. The temperature was increased from 2 - 10 K at a rate of 0.3 K/min, and 10 - 15 K at 3 K/min. The critical temperature for transitions between paramagnetic and magnetic ordering was found to be 7.1 Kelvin, as can be seen from the 0 Oe temperature sweep in figure 14. Temperature sweeps were performed at fixed field values between 0 Oe and 3500 Oe. The data is offset such that the evolution of the transition temperatures can be observed as the applied field is increased for each sweep. Also plotted

in figure 14 (right) is the numerical derivative of each temperature sweep, which is useful for determining the exact temperature at which a transition in magnetic structure occurs. This was especially helpful in determining the zero-field T_c at which the sample undergoes a transition between paramagnetic and helical ordering.



Figure 14: (a) χ_{ac} vs Temperature of Mn_{0.9}Fe_{0.1}Si with applied dc fields between 0 and 3500 Oe. (b) Numerical derivative, $d\chi_{ac}/dT$ vs Temperature. The curves were given a 0.0021 $G/Oe T^{-1}$ offset for clarity.

Figure 15 shows AC Susceptibility vs applied field data for which the temperature was held constant and the applied field was increased from 0 Oe to 7000 Oe. The first feature, which can be observed for all sweeps at temperatures at or below 7.1 K, indicates the transition from helical to conical ordering. This transition appears to occur at progressively lower fields as the temperature for each sweep is decreased. For sweeps in the temperature range between 5.25 and 6.75 K, depicted in figure 16, there appears to be a transition into and out of a phase right in the region where Skyrmion ordering is expected to occur. suggesting that the AC Susceptometer was in fact able to detect the transition into the A-phase. At about 3000 Oe, the susceptibility returns to its previous value before the transition from conical to the A-phase, which indicates that the sample actually returns to a conical structure after the field is sufficiently strong to break the Skyrmion domain formation. However, for temperatures approaching 7.1 K (the boundary between ordered and paramagnetic states), the transition at 3000 Oe is less defined and it seems as though the Skyrmion domains are dissolving into the ferromagnetic state as H is increased. This observation is supported by the phase diagram in figure 13(b), and was noted as well in reference [5].



Figure 15: (a) AC Susceptibility vs Applied field of $Mn_{0.9}Fe_{0.1}Si$ at temperatures between 2K and 8K. The curves were given a 0.002 G/Oe offset for clarity. (b) $d\chi_{ac}/dH$ vs H. Curves were given a 0.00001 G/Oe^2 offset for clarity.



Figure 16: (a) AC Susceptibility vs Applied field of $Mn_{0.9}Fe_{0.1}Si$ at temperatures near the A-phase. The curves were given a 0.002 G/Oe offset for clarity. (b) $d\chi_{ac}/dH$ vs H. Curves were given a 0.00001 G/Oe^2 offset for clarity.

Using the χ vs H sweeps, a phase diagram was constructed and is shown in figure 17 (a). In contrast to the phase diagram in figure 17 (b), which used resistivity measurements instead of AC susceptibility, the helical-conical and conical-field polarized boundaries are distinct and clear. The region where the A-phase was expected does indeed show a distinctly different state from the surrounding conical regime. Resistivity measurements showed a diffusion of the A-phase into the field polarized state for temperatures closer to T_C (region 3 in 13(b)) [5]. This difference in behavior in subregions within the A-phase can be observed from AC Susceptibility as well. It is clear that the AC Susceptometry technique can be used to clearly map out the regions of interest for a material able to form several different magnetic spin structures. Sample preparation for AC susceptibility analysis is virtually effortless compared to that of resistivity measurements, suggesting that AC Susceptometry is an advantageous technique for preliminary analysis of a material whose phase boundaries are yet to be determined.



Figure 17: (a) Phase Diagram for $Mn_{0.9}Fe_{0.1}Si$ using χ vs H data. (b) Phase diagram from topological Hall resistivity data [5], on the same field and temperature scales as (a) for better comparison.

$3.2 \quad Cr_{1/3}NbS_2$

3.2.1 Spin Structures and Motivation

The crystal structure of the chiral helimagnet, $Cr_{1/3}NbS_2$, belongs to the noncentrosymmetric space group, P6₃22. Materials with this structure have been found to exhibit he-

limagnetic ordering in the ground state, incommensurate with their underlying crystal structure, when no external field is present [1]. In helically ordered materials, the magnetic moments in the material form a helix in which all moments point orthogonally away from the axis of the helix. This type of ordering is caused by the competing symmetric exchange interactions and Dzyaloshinsky-Moriya (DM) interactions. The symmetric exchange interactions favor a parallel orientation with neighboring spins while the antisymmetric DM interactions favor perpendicular alignment. The result is a helical spin texture, which (in the case of $Cr_{1/3}NbS_2$) involves ferromagnetic arrangement in the *ab*-plane and the helix oriented along the *c*-axis [1].

When an external magnetic field is turned on and oriented along the *ab*-plane of the sample, a chiral soliton spin lattice forms in which more of the spins in each helix align ferromagnetically in parallel with the external field direction while still maintaining the periodicity of the helix. Once the field is sufficiently strong, the helical ordering breaks down altogether and a simple field-polarized state results [1]. Through the use of AC Susceptibility measurements, the temperature and applied field dependence of these magnetic phases is determined and will be discussed in this chapter.

Figure 18 shows the results of a previous study on $Cr_{1/3}NbS_2$ from reference [1]. The H-T phase diagram, figure 18 (b), was constructed using MvsH and MvsT sweeps. The MvsT sweeps determined the contour lines, and MvsH (figure 18 (a)) sweeps were used to plot the points along the boundaries of the HM, SL, FM, and PM states. The '?' represents the region of transitions between paramagnetic (PM) and helimagnetic (HM) states where the boundary is not clearly defined. It can be shown that AC Susceptibility measurements can map out these phase boundaries with a heightened level of clarity, along with the possible detection of an intermediate transition within the soliton lattice (SL) phase that was not found in reference [1].



Figure 18: Published MvsH data (a) and H-T Phase Diagram (b) of $Cr_{1/3}NbS_2$ from [1]

3.2.2 AC Susceptibility Data and Phase Diagram

In order to better determine the boundaries for the HM and PM transitions, denoted by the '?' in figure 18 (b), the AC susceptibility is measured as a function of temperature at fixed fields between 0 and 1000 Oe and is plotted in figure 19. For the temperature sweeps below 300 Oe, a single trough in the susceptibility data is observed, indicating that only the transition between HM and PM states occurs in this regime. However, for fields between 300 and 800 Oe, the temperature sweeps show two separate features that suggest that two transitions occur for this field range. These two features correspond to a HM \rightarrow SL transition, followed by a SL \rightarrow PM transition as the temperature is steadily increased. Above 900 Oe, just one feature is observed in the χ_{ac} vsT sweeps, as the sample merely transitions from the SL to PM phases. In contrast to the published phase diagram of figure 18 (b), the use of χ_{ac} vsT sweeps results in well defined phase boundaries at all fixed fields. The zero-field temperature sweep can be used to determine a T_C of 121.5 K with a much higher precision than the MvsT sweeps of reference [1].



Figure 19: AC Susceptibility vs Temperature of $Cr_{1/3}NbS_2$ with applied dc fields between 0 and 1000 Oe. Curves were offset by 0.006 G/Oe for clarity, where the unaltered curve is the 0 Oe sweep at 0.423 G/Oe



Figure 20: (a)AC Susceptibility vs Temperature of $Cr_{1/3}NbS_2$ with applied dc fields between 200 and 800 Oe. Curves were offset by 0.006 G/Oe for clarity. (b) $\frac{d\chi}{dT}$ vs T data for 700 Oe sweep

Next, the field dependence of the AC susceptibility of $Cr_{1/3}NbS_2$ is explored for a range of fixed temperatures between 5 K and 130 K. Since the transition temperature between ordered and paramagnetic states is 121.5 K, previous studies of this material have only focused on temperatures above 100 K. In figure 21, several χ_{ac} vsH sweeps are shown for fixed temperatures of 5K, 25K, 75K, and 100K. The HM \rightarrow SL transition, which was expected to occur at 900 Oe in the temperature range above 100 K, is indeed visible as an abrupt increase in susceptibility, as shown in figure 21. The saturation of the AC susceptibility at about 1300 Oe indicates that the sample has entered the ferromagnetic (FM) state. A notable feature regarding the comparison of field sweeps at 20- 25K temperature steps is the difference is susceptibility, $\Delta \chi$, between FM and HM states. As the fixed temperature of the χ_{ac} vsH sweeps is increased, this $\Delta \chi$ between the HM and FM states progressively decreases. In the limit where the temperature is above 121.5 K, such that the sample is in the paramagnetic state, the susceptibility changes minimally with applied field, as shown in the topmost (122 K) field sweep of figure 22.

Another notable feature of the χ_{ac} vsH sweeps below 120 K is a subtle step occurring in between the HM \rightarrow SL (900 Oe) and SL \rightarrow FM (1300 Oe) transitions. The existence of this feature at about 1050 Oe is not observed in the MvsH data of figure 18 (a) from [1]. The AC Susceptometry technique was therefore able to detect an additional transition when increasing the applied field within the SL phase. A feature such as this seems to suggest that the evolution of the soliton lattice phase with increasing field is not simply a steady increase of the number of spins aligning ferromagnetically in the direction of applied field; instead there appears to be a field threshold at which a large number of spins instantaneously snap into ferromagnetic alignment. However, the periodicity of the chiral soliton lattice remains until the field is sufficiently strong to force the sample into fully ferromagnetic state, at which the periodicity of the soliton lattice is broken.



Figure 21: (a)AC Susceptibility vs Applied Field for temperatures of $Cr_{1/3}NbS_2$ below 100 K. Curves were given a 0.01 G/Oe offset. (b) $\frac{d\chi_{ac}}{dH}$ vs H. Curves were given a 0.00005 G/Oe^2 offset for clarity.



Figure 22: (a)AC Susceptibility vs Applied Field for temperatures of $Cr_{1/3}NbS_2$ near T_C . Curves were given a 0.01 G/Oe offset. (b) $\frac{d\chi_{ac}}{dH}$ vs H. Curves were given a 0.00005 G/Oe^2 offset for clarity.

The AC Susceptibility data for $Cr_{1/3}NbS_2$ can now be used to construct H-T phase diagrams as before. The color plots in 23 are created using the numerical derivative of χ_{ac} vs H data. Black lines are drawn according to features from χ_{ac} vs H data and indicate phase transitions from the HM to SL state, followed by the intermediate transition within the SL state, and finally the transition from SL to field polarized state. In 23 (b), the phase diagram for the shorter 100 K - 130 K temperature range is shown. Red dots are plotted according to the extrema in χ_{ac} vs T data. The AC Susceptibility measurements were successful in forming a better map of the $Cr_{1/3}NbS_2$ phase transitions than that of figure 18 (b), especially in regions where the magnetization measurements from [1] failed to clearly define a phase boundary.

3.2.3 Phase Diagram and Discussion



Figure 23: Annotated phase diagrams of $Cr_{1/3}NbS_2$ created using $\frac{d\chi_{ac}}{dH}$ vs H data. Black lines were drawn according to the phase transitions indicated in χ_{ac} vs H data. (a) Phase Diagram for the full 5 K to 130 K temperature range. (b) Phase Diagram for temperatures from 100 K to 130 K. Red dots correspond to spikes from χ_{ac} vs T data.

3.3 CeRu₂Ga₂B (CRGB)

3.3.1 Spin Structures and Motivation

Unlike the previous compounds discussed, in which the competing symmetric exchange and DM interactions dictate the magnetic domain formation, the magnetic phases in uniaxial ferromagnets such as in Cerium-based intermetallic compounds, are caused by the balancing of Ruderman-Kittel-Kasuya-Yosida (RKKY) and Kondo interactions [12]. The Kondo effect describes the coupling of localized spins with conduction electrons, resulting in the spin polarized conduction electrons effectively "screening" the localized spins. The spin polarized electrons can also couple with other neighboring spins, resulting in induced magnetic ordering. RKKY interactions are these indirect exchange interactions in which the conduction band electrons serve to mediate the interactions between localized magnetic moments [13]. This form of interaction is therefore "indirect" as it doesn't involve a direct coupling between neighboring moments, but rather use the conduction electrons as mediators for the interaction. The Kondo screening and RKKY interactions favor different ground states [14] and the competition of these effects can result in multiple magnetic phase transitions in a metal.

In the case of Ce-based intermetallic compounds, such as CeRu₂Ga₂B (CRGB), a phase consisting of magnetic "bubble" domains has been found after field cooling a sample through TC. At increasing applied fields these bubble-shaped domains become elongated, resulting in a "stripe" phase before the field is sufficiently strong for a spin polarized ferromagnetic state to arise in the sample [12]. Figure 24(b) shows the H-T phase diagram of CRGB constructed from MFM (Magnetic Force Microscopy) and Magnetization data, from [12]. However, AC Susceptibility measurements to aid in characterizing the evolution of the magnetic phases in CRGB have been absent until now.

Magnetization and phase diagram



Figure 24: CRGB Magnetization data (a) and H-T Phase Diagram (b) of CRGB [12]

3.3.2 AC Susceptibility data and Phase Diagram

Figure 25 shows χ_{ac} vs T and $d\chi_{ac}/dT$ vs T plots for CRGB. T_C is found to be 15 K, in agreement with the published phase diagram in figure 24(b). At fields above 700 Oe, the troughs in the χ_{ac} data appear to smooth out and become shallower as the applied field in increased towards saturation. This evolution in the shape of the susceptibility feature could relate to the progressive elongation of the striped magnetic domains as the applied field is increased.



Figure 25: (a):CRGB χ_{ac} vs Temperature with applied dc fields between 0 and 2000 Oe. Curves were offset by 0.025 G/Oe for clarity, where the unaltered curve is the 0 Oe sweep at at around 0.1816 G/Oe.

(b): $\frac{d\chi_{ac}}{dT}$ vs Temperature for 0, 400, 600, and 800 Oe. Curves were offset by 0.025 G/OeT^{-1} for clarity, with the unaltered 0 Oe curve centered at 0 G/OeT^{-1} .

Figure 26 depicts χ_{ac} vs H and $d\chi_{ac}/dH$ vs H sweeps for temperatures between 2 and 15 K. While the susceptibility is the same at saturation for all temperatures, the zero-field susceptibility is substantially reduced at temperatures approaching the transition to the paramagnetic state. Even though the χ_{ac} vs H data does not directly suggest a transition between the states of bubble and stripe domains, the numerical derivative ($d\chi_{ac}/dH$ vs H) does have a peak that occurs right in the intermediate field regime (600-800 Oe) between bubble and striped phases. In this case, it is clear that the evolution from bubble to striped/elongated bubble domains is indicated by an inflection point in χ_{ac} vs H data.



Figure 26: (a):CRGB χ_{ac} vs H for temperatures between 2 and 15K (b): $\frac{d\chi_{ac}}{dH}$ vs H for temperatures between 2 and 15K

Using the χ_{ac} vs H and χ_{ac} vs T data above, a phase diagram can once again be constructed. Figure 27 (a) shows a phase diagram created by plotting features from χ_{ac} vs H, $\frac{d\chi_{ac}}{dH}$ vs H, and χ_{ac} vs T data onto a blank H-T plot. The red stars correspond to the saturation of the χ_{ac} vs H, when the sample enters the field polarized state. Peaks in $\frac{d\chi_{ac}}{dH}$ vs H are plotted as green stars. The local extrema in χ_{ac} vs T curves are plotted as black and grey dots, where the black dots correspond to the first spike and grey dots correspond to the second spike that appears for the temperature sweep at 500 Oe. Figure 27 (b) shows the same points plotted on top of the published phase diagram from [12]. The regions corresponding to the bubble and striped phases agree well with the published phase diagram. The AC Susceptibility data is able to clearly indicate the phase boundaries for this CRGB sample.



Figure 27: (a) CRGB phase diagram constructed using AC Suceptibility data. Red stars correspond to the saturation of χ_{ac} from χ_{ac} vs H sweeps. The green stars mark the peaks in $\frac{d\chi_{ac}}{dH}$, and black and grey dots correspond to the extrema in χ_{ac} vs T data. (b) The markers from (a) plotted on top of the published CRGB phase diagram from [12] for better comparison

4 Conclusion

The use of an AC Susceptometer had several notable advantages for studying magnetic materials. To begin with, this technique is non-invasive, meaning that the sample does not need to be tampered with in order to conduct these measurements. If the sample is very small and delicate, AC Susceptibility measurements are preferable over electrical transport measurements, in which electrical contacts must be placed directly on the sample. Another advantage is that the AC Susceptometer is very simple in design, and parameters can be varied depending on the size of the sample being measured. Under the assumption that a cryostat, lock-in amplifier, and AC current source are already house-hold pieces of equipment in any condensed matter lab, the additional cost to build an AC Susceptometer such as the one described here is a mere \$30; the cost of the wire and the 3D printed shell. However, the AC Susceptometer has been shown to be a powerful tool in determining the phase boundaries of a magnetic material. While the AC susceptibility of a material does not give a lot of information on the specific nature of a material's magnetic state (other methods are needed for that), this technique is a great way to perform the preliminary analysis on a material whose temperature and applied field regions of interest are not yet know.

There are a few difficulties in using an AC Susceptometer for measurements of magnetic

phase transitions. First of all, when winding the coils by hand it is impossible to construct two exactly identical coils for the upper and lower secondary coil set. This imperfect balancing of the coils results in a background voltage that will show up in the measurements. While it is possible to correct for this background voltage and subtract it from the measurement, there is still the risk that a poorly enough wound coil will have a background signal so large that the lock-in amplifier overloads at the sensitivity required to resolve meaningful features from the AC Susceptibility of the sample. If one wants to increase the number of turns in the primary and secondary coils in order to increase the magnitude of the AC field and the sensitivity of the search coils, this increase in turns amplifies the self inductance and stray capacitance in the coils, leading to more spurious effects appearing in the data. However, as long as enough care is taken in the winding process and appropriate frequencies within the linear regime are used, as discussed in Section 2.5.1, the AC Susceptibility can still be calculated accurately from the measured voltage after appropriate calibration steps are taken.

Overall, the AC Susceptometer was found to be extremely powerful of a tool for detecting subtle changes in a sample's magnetization. AC Susceptometers, such as the ones described in this paper, can be used to determine the critical temperatures at which the underlying properties of a sample changes. Currently many physicists are interested in high- T_C superconductors, and determining the temperature at which a metal transitions into a superconducting state can be done using an AC Susceptometer technique, just like the one described here. The future measurements that will be performed using the AC Susceptometer described here aim to further characterize and understand skyrmion domains in Iron-doped MnSi samples. An interesting parameter to vary is the samples' orientation in the applied field. By measuring AC Susceptibility while rotating the sample in the applied field, one can determine the magnetic anisotropy of the skyrmion domains. This highlights the versatility of the AC Susceptometer, as it was designed to be used in both commercially available magnetic measurement systems as well as cryostats that allow for angle rotation. The AC Susceptometer described in this paper was designed with the end goal of performing such angle dependence measurements, and the high sensitivity of this AC Susceptometer shows that it will be well suited for the task.

References

- N. J. Ghimire, M. A. McGuire, D. S. Parker, B. Sipos, S. Tang, J.-Q. Yan, B. C. Sales, and D. Mandrus, "Magnetic phase transition in single crystals of the chiral helimagnet cr_{1/3}nbs₂," *Phys. Rev. B*, vol. 87, p. 104403, Mar 2013. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevB.87.104403
- R. Duine, "Skyrmions singled out," Nature Nanotechnology, vol. 8, no. 11, pp. 800–802, 2013. [Online]. Available: https://browzine.com/articles/48438266
- [3] K. Tokushuku, J. Kishine, and M. Ogata, "Tunable spin dynamics in chiral soliton lattice," *Journal of the Physical Society of Japan*, vol. 86, 05 2017.
- [4] L. Abelmann, "Magnetic force microscopy," in *Encyclopedia of Spectroscopy and Spectrometry (Third Edition)*, third edition ed., J. C. Lindon, G. E. Tranter, and D. W. Koppenaal, Eds. Oxford: Academic Press, 2017, pp. 675 684. [Online]. Available: http://www.sciencedirect.com/science/article/pii/B9780128032244000297
- [5] P. E. Siegfried, A. C. Bornstein, A. C. Treglia, T. Wolf, and M. Lee, "Multiple magnetic states within the *a* phase determined by field-orientation dependence of mn_{0.9}fe_{0.1}Si," *Phys. Rev. B*, vol. 96, p. 220410, Dec 2017. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevB.96.220410
- [6] S. Mühlbauer, D. Honecker, E. A. Périgo, F. Bergner, S. Disch, A. Heinemann, S. Erokhin, D. Berkov, C. Leighton, M. R. Eskildsen, and A. Michels, "Magnetic small-angle neutron scattering," *Rev. Mod. Phys.*, vol. 91, p. 015004, Mar 2019. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.91.015004
- [7] N. Rubiano da Silva, M. Möller, A. Feist, H. Ulrichs, C. Ropers, and S. Schäfer, "Nanoscale mapping of ultrafast magnetization dynamics with femtosecond lorentz microscopy," *Phys. Rev. X*, vol. 8, p. 031052, Aug 2018. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevX.8.031052
- [8] A. Bauer and C. Pfleiderer, "Magnetic phase diagram of mnsi inferred from magnetization and ac susceptibility," *Phys. Rev. B*, vol. 85, p. 214418, Jun 2012.
 [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevB.85.214418
- [9] M. Balanda, "Ac susceptibility studies of phase transitions and magnetic relaxation: Conventional, molecular and low-dimensional magnets," Acta Physica Polonica A, vol. 124, no. 6, pp. 964 – 976, 12 2013.
- [10] M. Nikolo, "Superconductivity: A guide to alternating current susceptibility measurements and alternating current susceptometer design," *American Journal of Physics*, vol. 63, no. 1, pp. 57–65, 1995. [Online]. Available: https://doi.org/10.1119/1.17770

- [11] B. J. Chapman, M. G. Grossnickle, T. Wolf, and M. Lee, "Large enhancement of emergent magnetic fields in mnsi with impurities and pressure," *Phys. Rev. B*, vol. 88, p. 214406, Dec 2013. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevB.88.214406
- [12] D. W. et al., "Domain engineering of the metastable domains in the 4f-uniaxialferromagnet ceru2ga2b," *Scientific Reports*, vol. 7, no. 46296, 2017.
- [13] H. P. et al., "Interplay between the kondo effect and the ruderman-kittel-kasuya-yosida interaction," *Nature Communications*, vol. 5, p. 5417, Nov 2014.
- [14] S. R. Yu, Clare C.; White, "The interplay of the kondo effect and rkky interactions in the one-dimensional kondo insulator," *Physica B: Physics of Condensed Matter*, vol. 199, pp. 454–456, 04 1994.