Fermiology and metamagnetism in the tri-layered ruthenate $Sr_4Ru_3O_{10}$

Claudia Niculas
NHMFL, Tallahassee, FL
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Introduction

The triple-layered crystal $Sr_4Ru_3O_{10}$ is one of the layered ruthenates of general formula $(Ca, Sr)_{n+1}Ru_nO_{3n+1}$ within what is called the Ruddlesden-Popper (RP) series. It is known from previous measurements that $Sr_{n+1}Ru_nO_{3n+1}$ compounds generally exhibit metallic, insulating, and magnetic behavior. In particular, it has been found that $Sr_4Ru_3O_{10}$ becomes ferromagnetic (i.e. exhibits spontaneous magnetization) at a Curie temperature of 105 K and displays an additional magnetic transition, possibly antiferromagnetism, at 50 K, mainly along the c axis. Previous studies (G. Cao et al., Phys. Rev. B, **68**, 174409 (2003)) have also found evidence of critical fluctuations driven by a metamagnetic transition in one direction and ferromagnetic behavior in the other direction, as well as Shubnikov de Haas oscillations, as shown in Figure 1.

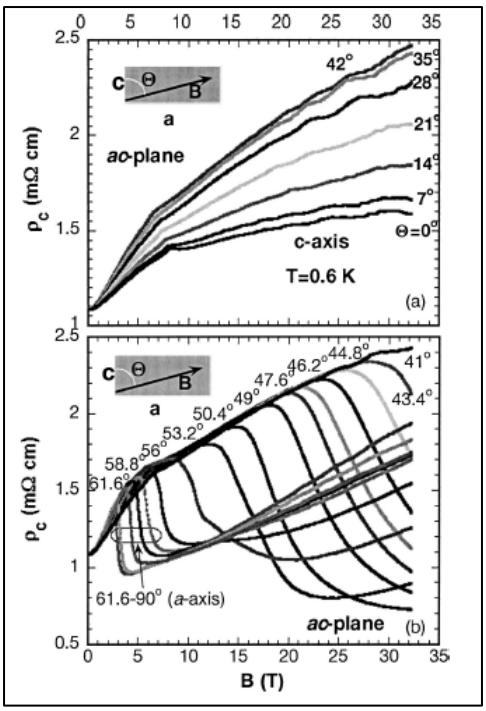

Figure 1. Plot of resistivity ρ (mΩ cm) as a function of magnetic field B (T) at T=0.6 K

In this experiment, a high quality $Sr_4Ru_3O_{10}$ sample was measured using the hybrid magnet at the National High Magnetic Field Laboratory in Tallahassee, FL. Its main purpose was to investigate the material's Fermi surface and its possible implications. As defined by N.W Ashcroft and N.D. Mermin, the Fermi surface is a constant energy surface in k-space, where the energy in question is known as the Fermi energy, i.e. the smallest possible increase in ground state energy when exactly one particle is added to the system. In other words, as particles in a non-interacting fermion system follow the Pauli exclusion principle, they fill up the lowest unoccupied quantum states one at a time until the desired number of particles has been reached, at which point the system has reached its Fermi energy. Obtaining information about the Fermi surface of a metal normally requires high quality crystals measured at low temperatures and high magnetic fields.

The Experiment

As mentioned above, the primary equipment used to measure the $Sr_4Ru_3O_{10}$ sample was the hybrid magnet at NHMFL, which is the most powerful continuous magnet in the world to date, as it can create magnetic fields up to 45.17 T. The hybrid is composed of a resistive insert (~36 T) and a superconductive outsert magnet (~21 T). Figures 2a) and b) show a sketch and a picture of the hybrid, respectively.

a) b)

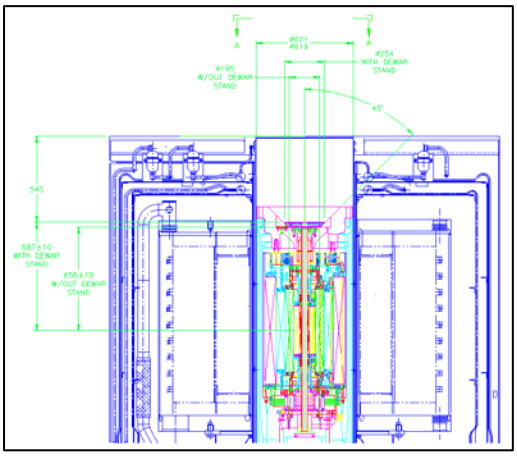

Figure 2. a) Sketch of the NHMFL Hybrid; b) Picture of the NHMFL Hybrid.

The 0.5-1 mm sample was glued to the sample holder, which was placed inside a probe. The probe was inserted into the cryostat, which was then lowered into the hybrid, i.e. after the sample was cooled down to about 77 K using liquid Nitrogen. Once inside the hybrid, the sample was cooled down further to about 1.5 K using pumped liquid He_4 and to about 0.5 K using pumped liquid He_3. During the experiment, it was necessary to rotate the probe periodically in order to measure the sample at different angles and thus obtain a more complete picture of its Fermi surface, which is most likely non-uniform. What we actually measured was our sample's resistance as a function of magnetic field strength.

Data analysis

Figure 3 shows a plot of the resistance as a function of magnetic field at a temperature of 0.5 K. The black curve displays the resulting Shubnikov de Haas oscillations, which, in order to be analyzed further, needed to be separated from the background resistivity. Thus a fourth-order polynomial (red curve) was fitted to our original curve, and the two subtracted using a graphing program. The resulting subtraction for this particular plot, i.e. the pure oscillatory component, is shown in Figure 4. Furthermore, by performing a Fast Fourier Transform (FFT) analysis we obtained several peaks corresponding to a series of frequencies of 114, 172, 626, and possibly 820 T, respectively, as shown in Figure 5. Frequencies are significant because they are related to the extremal cross-sectional areas (A) of the Fermi surface in a plane normal to the magnetic field via the Onsager equation:

$$\Delta F = (2\pi e) / (\hbar c A)$$

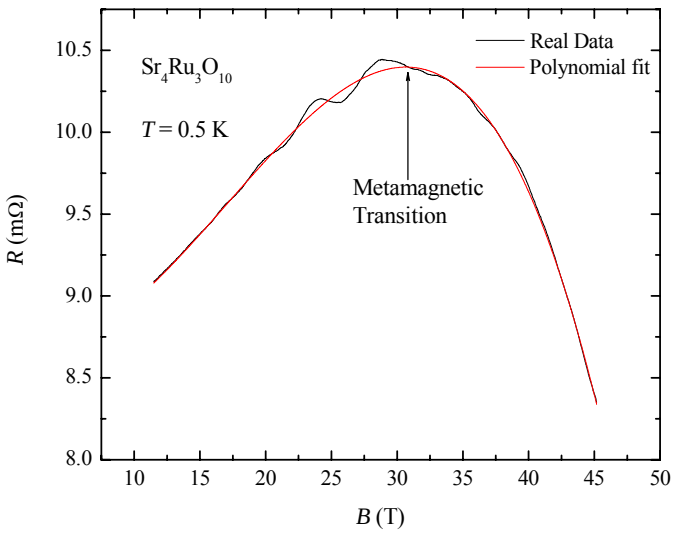

Figure 3. Plot of the inter-plane resistance R versus B *at* T = 0.5 K for an angle $\theta = 17^0$ between B and the inter-plane axis. The metamagnetic transition is indicated by the arrow. The red line is a polynomial fit.

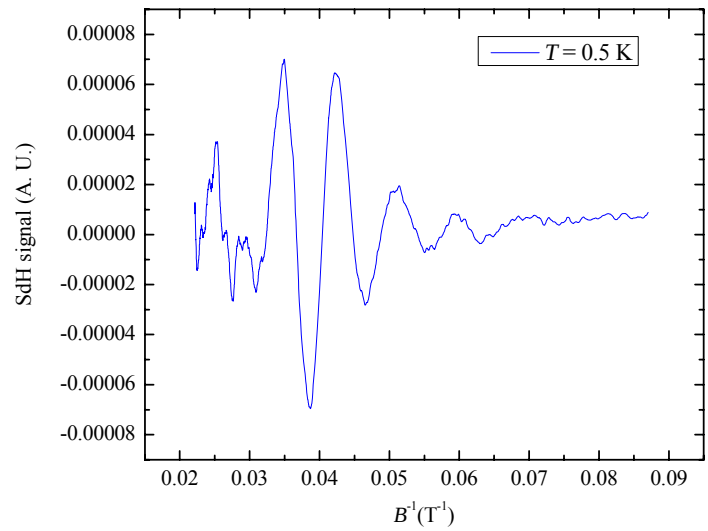

Figure 4. The oscillatory component of the inter-plane resistivity, i.e., the Shubnikov de Haas effect in $Sr_4Ru_3O_{10}$.

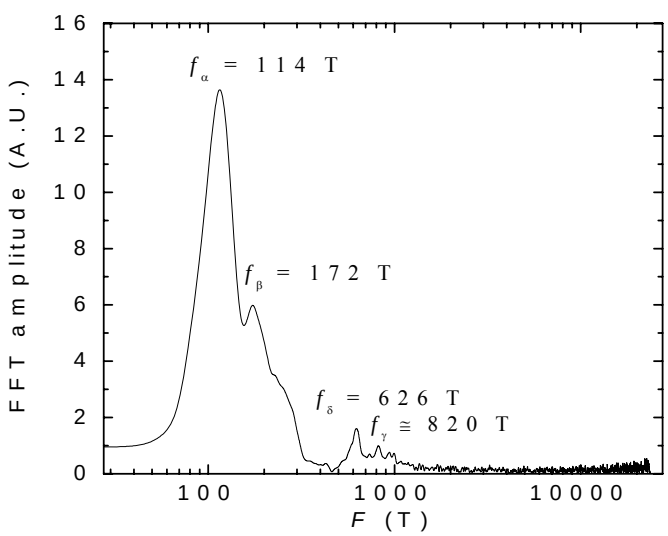

Figure 5. FFT analysis and resulting frequencies.

Finally, Figure 6 is a plot of amplitude (of the peaks extracted using FFT) divided by temperature as a function of temperature, which was fitted using an equation of the form y=x/sinh(x) (red curve). The Lifshitz-Kosevich relation, x=14.96μT/B, then enabled us to solve for the effective masses (μ_n) for each of the observed orbit, which are indicated in Figure 6 along with their corresponding frequencies.

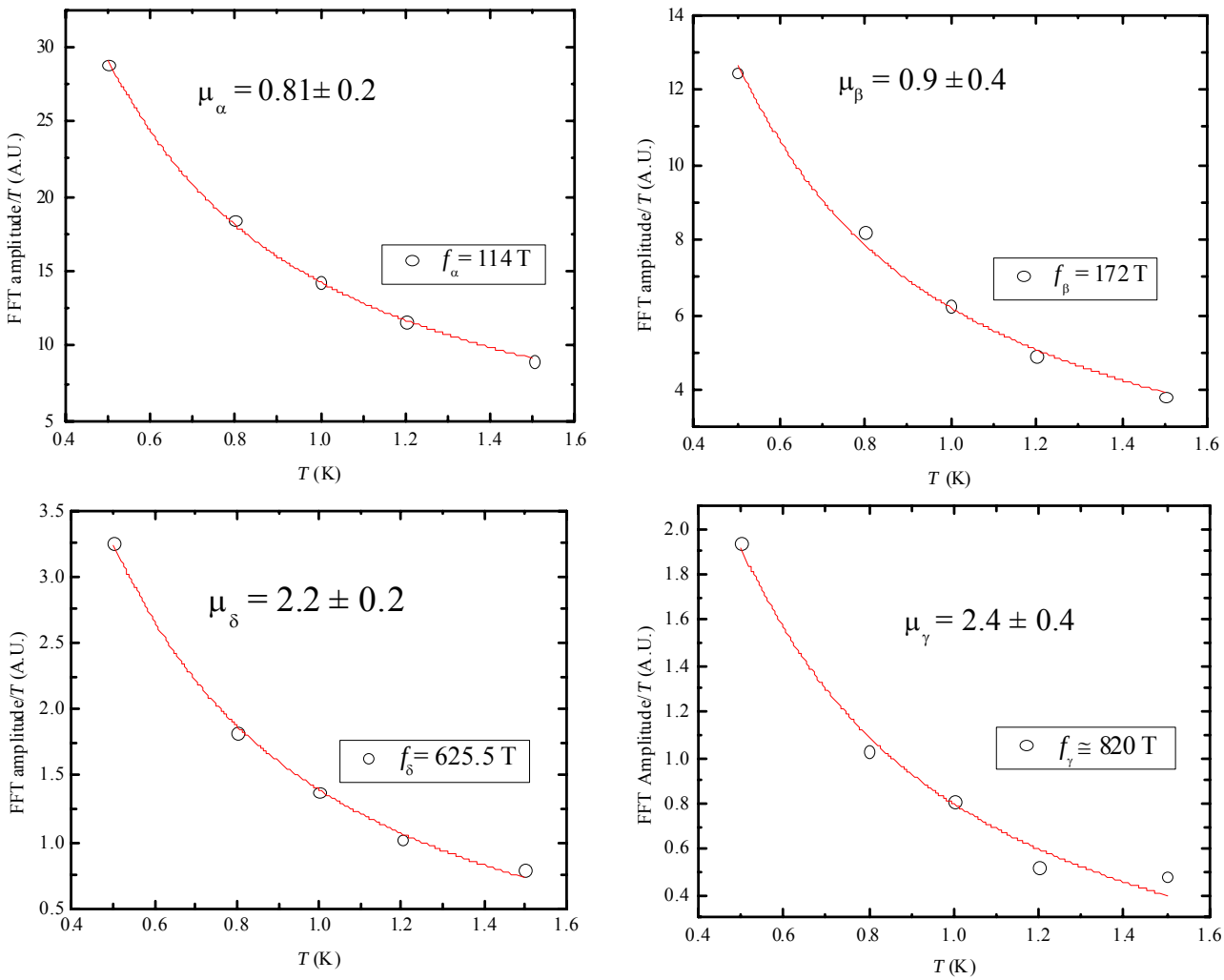

Figure 6. Effective masses for the corresponding frequencies found in the FFT spectrum.

Conclusions and discussion

Further measurements, preferably at lower temperatures, are required in order to map the entire Fermi surface of $Sr_4Ru_3O_{10}$, thus expanding our present knowledge of the material's properties, such as electrical conductivity, heat transport, possibility of new electronic phases at low temperatures, existence of superconductivity, etc. The FS portion we have seen and analyzed thus far confirms the high purity of our sample (Shubnikov de Haas effect) and suggests the possibility of exotic behavior and a promising future for $Sr_4Ru_3O_{10}$. In particular, our observations point toward a dramatic reconstruction of the Fermi surface at the metamagnetic transition and a possibility of quantum critical behavior. Further exploration of the material's properties around its metamagnetic transition as well as further study of its quantum phase transitions are required in order to learn more about the behavior and potential applications of $Sr_4Ru_3O_{10}$.

References

G. Cao, L. Balicas, "Competing ground states in triple-layered $Sr_4Ru_3O_{10}$: Verging on itinerant ferromagnetism with critical fluctuations", Physical Review B 68, 174409 (2003).

N. Ashcroft, N. Mermin, "Solid State Physics", Thomson Learning, Inc., 1976.

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