Experiment 4: Observing Quantum Oscillations and the Implications

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ABSTRACT

In this experiment we sought to observe the change in magnetoresistance of Tantalum arsenide due to change in temperature and applied magnetic fields. The purpose of this is to observe the quantum oscillation of the conduction electrons and gather data related to the topology of the observed semi-metal. When oscillating the resistivty you can observe the Fermi energy, angular frequency, and effective mass of the material that undergoes the process, giving us valuable information of the properties of this material. In our particular experiment, when varying the field we are able to find the frequency and amplitude by preforming a Fourier transform on the decaying oscillation; this also allowed us to find the mass of the system. In our experiment we observed peaks of frequency at around 7 Tesla occurring around the point of .16 1/Tesla of applied field, as well as the decay of resistivity amplitude with temperature, and lastly an effective mass of about $4.4 * 10^{-4} AtomicMassUnits$.

I. BACKGROUND INFORMATION

In this experiment we sought to observe oscillations of the resistance of Tantalum Arsenide (TaA) by applying a varying magnetic field. This can be classified as quantum oscillations since we are observing the conduction electrons orbit of the fermi surface of the metal. TaA is a weyl semi-metal, where its topology cannot be generalized, thus to find its structure we have to go through empirical methods. A semi metal is that where multiple bands cross the Fermi surface, this can cause the bands to be partially filled beyond the natural order expected of a normal metal. For our weyl semi metal, we can take the density of carriers as filled electrons in conduction band and the unoccupied states in valence band, where the unoccupied states are labelled as holes. We can model the dispersion relation in equation 1

$$\frac{1}{M} = \frac{1}{h^2}\frac{d^2E}{dk^2} \qquad [1]$$

Though the equation fails because the applied magnetic field re-quantizes the states since the wave vector k is inapplicable, but we can still observe the mass by looking at the average of circular orbits, which we can relate to the angular frequency, as long as the scattering in the system is sufficiently low.

$$E_n = h\omega(n+\gamma) \qquad [2]$$

$$\omega_c = \frac{eBc}{m} \qquad [3]$$

In our particular experiment, we are measuring resistance at various temperatures and fields, the applied field and temperature changes the occupied area of the holes and electrons, leading to different frequencies, we can observe this area of reciprocal space with equation 4

$$\delta\frac{1}{B} = \frac{2\pi e}{hcA} \qquad [4]$$

In our case, we apply the magnetic field in 2D, this simplifies the decay we expect to see in our resistance, corresponding to the Lifshitz-Kosevitch formula, in equation 5.

$$S \sim e^{\frac{-2\pi^2 k_b T}{h\omega_c}} \qquad [5]$$

In our particular experiment to properly measure everything we used a device to be an all purpose measurement and application device called the Physical Properties Measurement System (PPMS), sold by Quantum Design. To properly work the device, you make a connection of the material, in our case TaA, to an electronic puck on a particular channel of the puck. The puck can then read resulting voltages and current as well as apply them to the material at hand. For our experiment we had to manually load the material onto the puck. This had several steps, first we had to place wire two at each end of a face of the material, this was for the applied current and voltage, as well as making sure both sides had a positive and negative polarity for proper flow. After making the connections for the current and voltage we then had to connect the wires other ends to the proper place of the puck, that the PPMS is programmed to read and send voltages to. The final thing we do with the puck is get a long pole and then place the puck in a connection at the bottom of the PPMS device, where it is then cooled, and measured by the PPMS. Afterwards we are then tasked with programming the PPMS to vary the magnetic field strength which is exclusively in the z direction, as well as the temperature of the device. We also receives measurement for the Resistance though the relation is simply from ohms law given as $R = \frac{V}{I}$. The effective mass can be determined by measuring over a range of temperatures and varying the magnetic field from -9 to 9 Tesla at those various temperatures, we can relate the oscillation with the frequency of oscillation. This method of analysis is good for mapping the Fermi surface structures. We then then look at the data we collected.

II. TABLES AND GRAPHS

For this experiment the main target was to view the resistivity of magnetization, the way we can gather this is by measuring the frequency of the resistance change, we then also apply a Fourier transform to view the oscillation peak points. In this section we simply present the data that we collected in graphs, of the oscillation compared to the inverse magnetic field, where we can then extract the frequency and amplitude of oscillation. The effective mass in this experiment can be calculated by looking at the amplitudes of oscillation and then comparing them at different effective masses, all this can be found in the following figures.

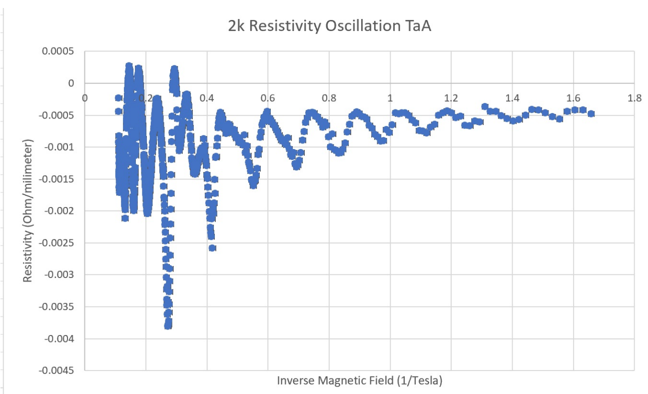

Figure 1: This table shows the resistivity oscillation of Tantalum Arsenide at 2 Kelvin.

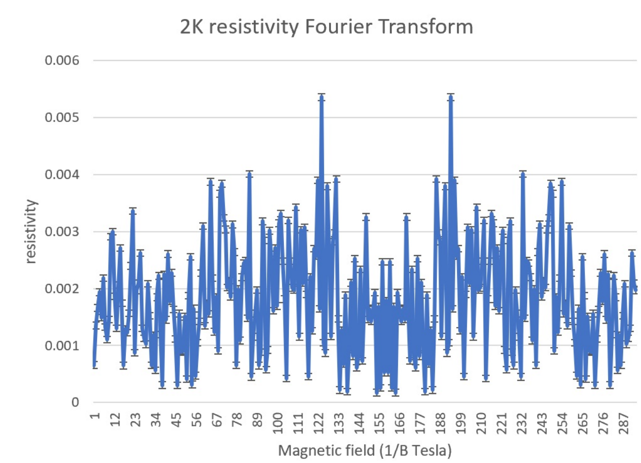

Figure 2: This Graph shows the fourier transform of the resistivity graph at 2K.

The next segment of data will be the data at various temperatures but still the oscillation of resistivity and its fourier transform.

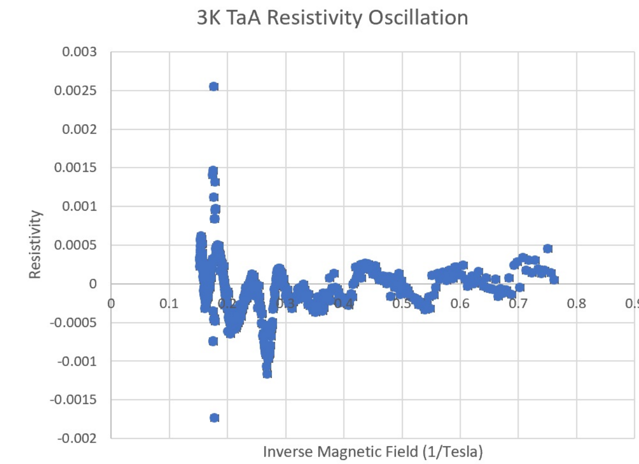

Figure 3: This table shows the resistivity oscillation of Tantalum Arsenide at 3 Kelvin.

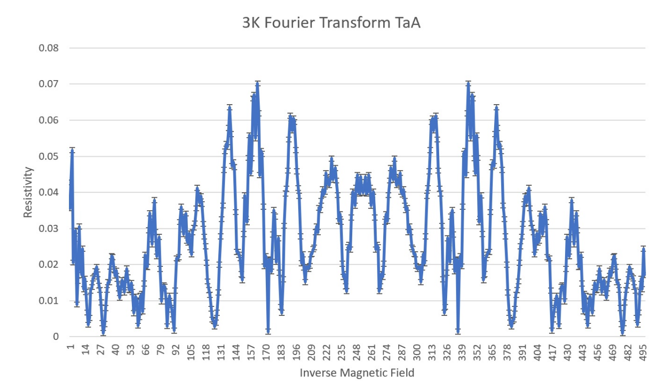

Figure 4: This Graph shows the fourier transform of the resistivity graph at 3K.

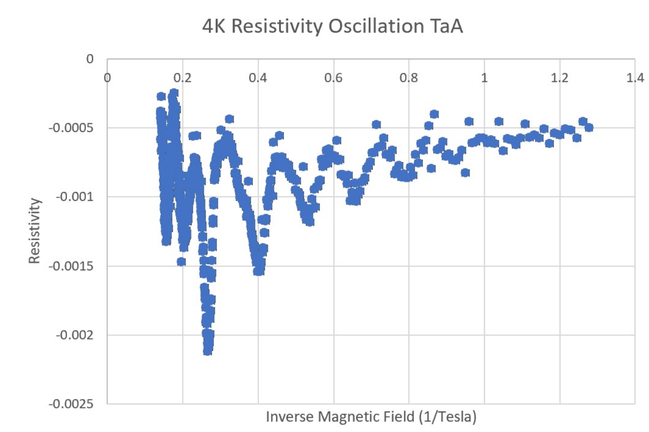

Figure 5: This table shows the resistivity oscillation of Tantalum Arsenide at 4 Kelvin.

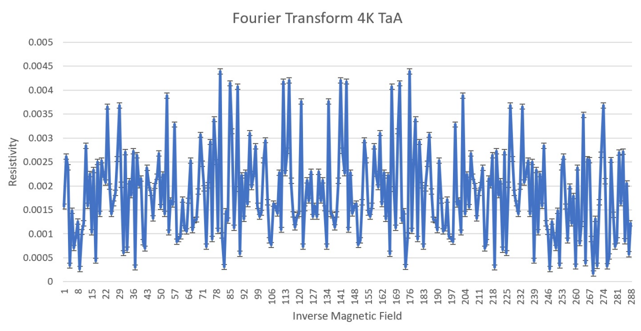

Figure 6: This Graph shows the fourier transform of the resistivity graph at 4K.

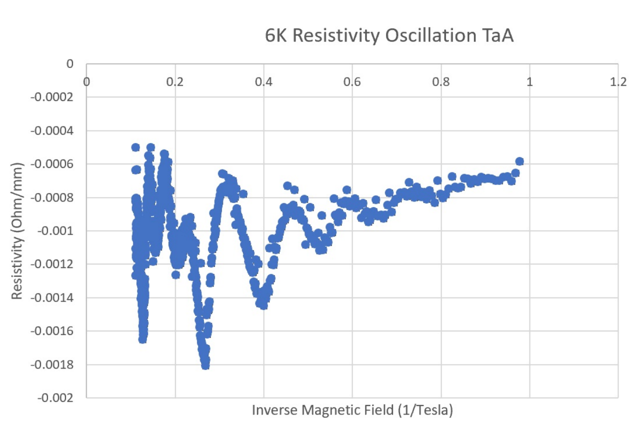

Figure 7: This table shows the resistivity oscillation of Tantalum Arsenide at 6 Kelvin.

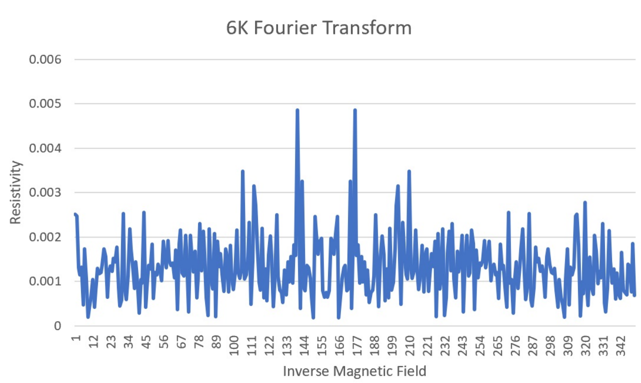

Figure 8: This Graph shows the fourier transform of the resistivity graph at 6K.

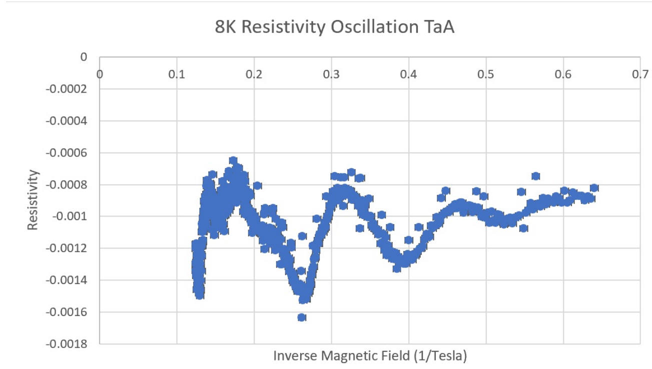

Figure 9: This table shows the resistivity oscillation of Tantalum Arsenide at 8 Kelvin.

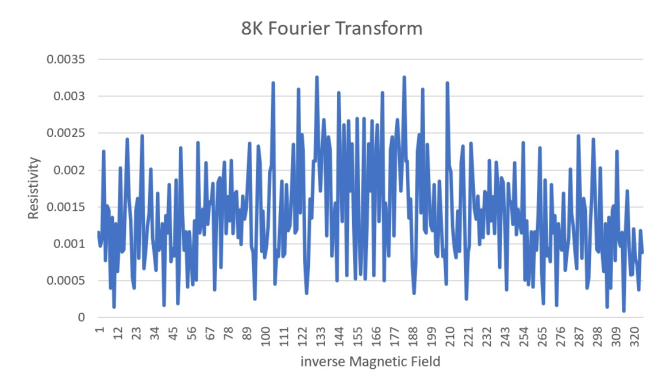

Figure 10:This Graph shows the fourier transform of the resistivity graph at 8K.

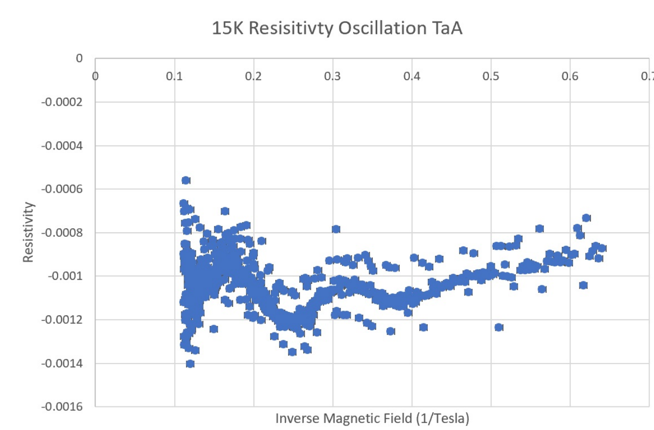

Figure 11: This table shows the resistivity oscillation of Tantalum Arsenide at 15 Kelvin.

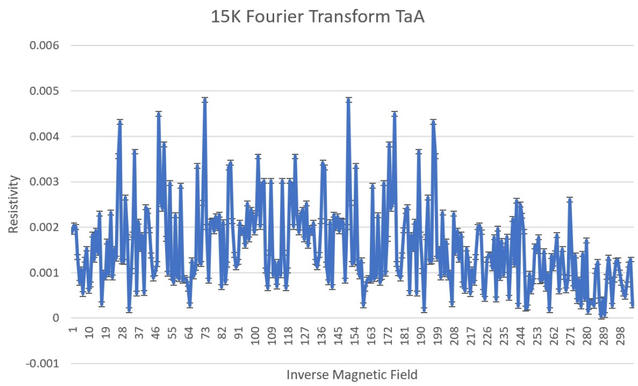

Figure 12:This Graph shows the fourier transform of the resistivity graph at 15K.

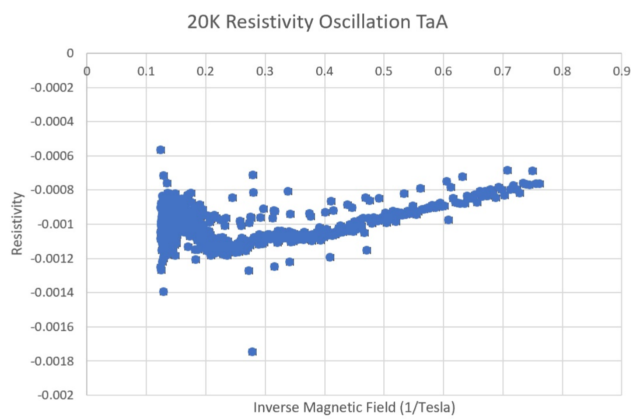

Figure 13: This table shows the resistivity oscillation of Tantalum Arsenide at 20 Kelvin.

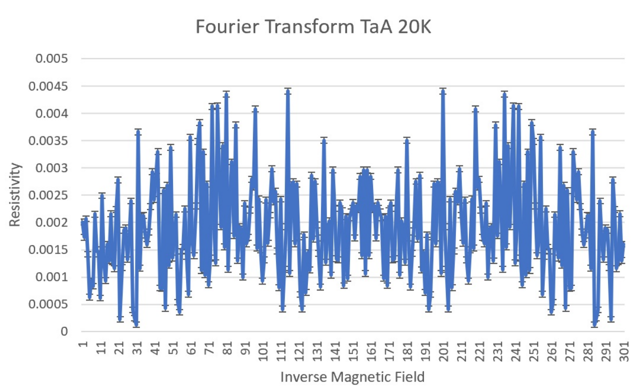

Figure 14: This Graph shows the fourier transform of the resistivity graph at 20K.

The last segment of data that is then analyzed is the amplitude vs temperature measurement that will allow us to calculate the effective mass of the system.

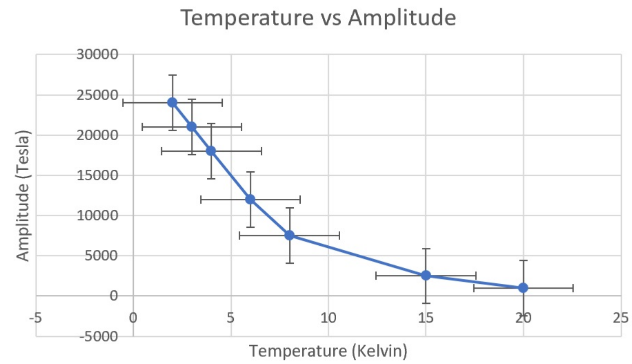

Figure 15: This figure shows the temperatures vs Amplitude for TaA.

III. ANALYSIS

There were many calculations that had to be made, some observed others calculated. The first calculation made was the change of resistance to resistivity given by equation 6.

$$p = R\frac{tw}{l} \qquad [6]$$

This equation is important for the calculations we made. The rest of the data analysis afterwards had us symmetrize the data, such that the negative and positive magnetism for the resistance will not have a hall voltage applied to it. This can be seen in equation 7. After symmetrizing we then removed the linear relationship found in the data, that varied but its removal allowed for the data to have clear oscillations we could observe as seen in the data above.

$$R = (R[B] + R[-B])/2 \qquad [7]$$

After applying all of this we have a clear view of our data and its oscillation. From here we then apply a Fourier transform to view the data more closely see the frequency and to capture the points where peaks occur in the frequency, indicating its amplitude and then allowing us to further analyze the effective mass of what we are observing by allowing us to compare to the Lifshitz-Kosevich formula, shown earlier and calculate an effective mass of $4.4*10^{-4} AtomicMassUnits$, which can be found by relating the graph of Temperature vs Amplitude and observing the correlation to the Lifshitz-Kosevich formula. A note about the Amplitude through the fourier Transform. We expected to see the highest peak at 7 Tesla typically which we do, and the temperture increase makes the data more fuzzy and indeterminate which again we do, but we see peaks around the 2.3 Tesla point for many materials as well. Since we have indicated the 7 Tesla as more accurate we considered these points when accounting for the amplitude of oscillation. The frequency was found by choosing a good oscillation and seeing the change in inverse magnetic field.

The Area occupied of the Brillouin Zone inferred from the frequency, varied with temperature, though in the high temperatures for 20 kelvin was incredibly weak around 2000 Tesla Ohm and the area for the low temperature of 2 Kelvin was high around 20 thousand Tesla Ohm. This corresponds to what we would expect experimentally and allows us to calculate the effective mass by relating equation 5 to the areas calculated, and the graph of figure 15.

IV. CONCLUSION

In this lab we sought to observe the topology of weyl semi-metal due to magnetic field applied to Tantalum Arsenide. To cause this oscillation we simply applied a magnetic field to a sample of TaA that we made lead connections to and put on a puck. The temperature and field we were able to control using the Physical Properties Measurement system, allowing us also to read the resulting resistance.The way we were able to observe the mass and frequency of the system was by observing the resistivity oscillation associated with the change in temperature and field that the PPMS supplies; The material absorbs what is given to it and it causes change in frequency and Amplitude. Specifically We observed that the lower the temperature, the material had a higher amplitude and frequencies. The equipment we are using are within physical ranges after testing, though they do produce significant error which is understandable since we are translating several measurements over to reach our results. In our particular experiment we had some issues, we were not able to properly place connections on the material and puck so we had assistance, also the data we collected had much noise that had to be subtracted out but did not always work, and overall error with received values, though all can be mitigated with carefulness and repeated measurements in the overall experiment. The final results match the theoretical expectations of what Tantalum Arsenide, we went through a large temperature range but our results were effected by sources of error from equipment or systematically, a particular problem caught later was hair was on the material and connections. Though despite all this the calculated effective mass, amplitudes, and frequencies were within ranges we want.