Magnetoresistance and Magnetization in Pulsed Magnetic Fields

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Abstract:
An inexpensive midrange field pulse magnet was used to analyze the magnetoresistance of bismuth from 0 to 22.9 Tesla at temperatures of 77 and 4.2 K, the magnetoresistance of the quasi one-dimensional organic $(TMTSF)_2AsF_6$ at 77, 4.2 and 2.1 K, to calibrate a double coil used to measure the magnetization of Mn_{12}-acetate in a rapidly changing field. The measurement confirmed magnetoresistance and quantum oscillations in bismuth and showed promising results in measuring $(TMTSF)_2AsF_6$ and Mn_{12}-acetate.

1. Introduction

Pulsed magnets can reach fields of 75 Tesla[1], however magnets like this require large amounts of energy, and incur significant costs. On the other hand, a pulsed magnet on the order of 20 to 30 Tesla, with a cryostat able to contain liquid helium under vacuum can be built for relatively low cost, and a wide range of valuable information can be gathered from this apparatus and readily available standard lab equipment. Magnets of this level are also much less expensive to build and operate than comparable resistive magnets and so may offer a good alternative to an expensive and lower field resistive magnet for high-field measurements.

The pulsed magnet was used to examine effects of magnetic fields on three substantially different materials. The first material, bismuth, is known to have magnetoresistance at liquid nitrogen temperatures[2], and has shown quantum oscillation[3] at temperatures in the 4.2 K range. Bismuth is a good material to use for calibration of equipment because it has been well studied.

The second material, $(TMTSF)_2AsF_6$ is a Bechgaard salt, a class of organic molecular metals that have shown superconductor or semiconductor properties[4], and the crystal lattice structure shows quasi-one dimensional electron paths. This means that resistance will change along different crystal axes and allowed path restricts electron flow in a magnetic field at low temperature. Around 2.2 K, the organic salt displays large magnetoresistance[4], but this effect should not be present at higher temperatures. $(TMTSF)_2AsF_6$ is also interesting as one of the less studied Bechgaard salts.

Mn_{12}-acetate is a high spin system, with a net spin of ten, from eight spin-up and four spin-down manganese atoms, and works as a molecular magnet[5]. At low temperatures, the magnetization will undergo a series of stair-step transitions as the field changes, rather than the standard smooth hysteresis plot exhibited by most ferromagnetic materials.

These materials provide interesting data using an inexpensive but effective measurement technique.

2. Short pulse 25 Tesla magnets

The magnet used to study the reactions of the materials talked about in this report is a short pulse magnet with a rise time of about eight milliseconds to its maximum field, which is about 25 Tesla.

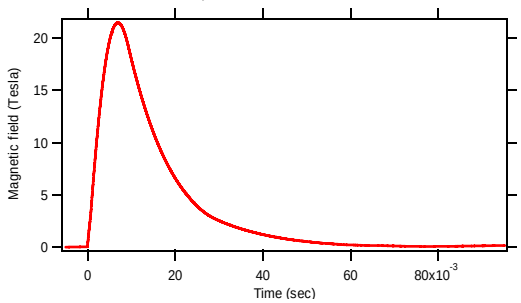


Figure 1: Typical calculated field measurement

A crowbar diode in the circuit supplying current to the magnet prevents current oscillations, and the resultant field curve can be approximated by a linear rise to about three quarters of full field, then tapers off to an exponential decay just past full field. The magnetic field for each shot can be measured using a centered pick up coil and calculating the magnetic field from induced voltage by the equations: $\varepsilon = -\frac{d\Phi}{dt}$ and $\Phi = \int B \cdot dA$, giving $B = -\int \frac{\varepsilon\, dt}{A}$, where A is the open loop area, $\pi r^2 * n$, where r, the radius was about 3.17 mm and the number of turns, n, was 10, ε is induced voltage in the coil as measured by the oscilloscope, Φ is magnetic flux and B is the final calculated magnetic field.

The magnet bore, which measured just over 8 mm in diameter, was centered on the tail of a vacuum-sealed cryostat, as pictured below. Samples were placed less than a millimeter away from the pick up coil and a solid state thermometer was centered immediately below the sample.

A magnetization measurement device was placed below the thermometer. In samples measuring magnetization, the magnet was centered over the lower magnetization coil at the calibrated level.

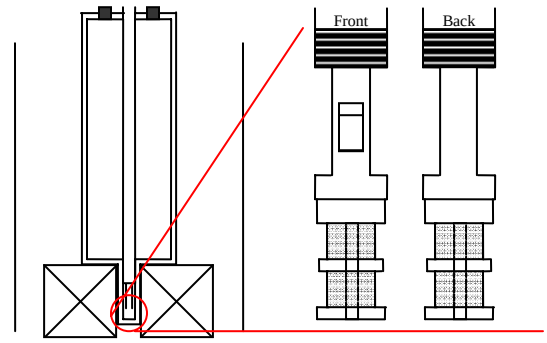


Figure 2: Magnet and cryostat (left), and probe tip (right). (not to scale)

3. Magnetoresistance

In certain materials electrical resistance is variable as a function of magnetic field at a given temperature. Bismuth provides a well-studied and interesting material as a calibration.

Bismuth samples were obtained from 99.999% pure bismuth using a new razor to cleave samples cooled in liquid nitrogen along the lattice. Gold wire leads were then attached by melting a small portion of the corner of the bismuth sample, onto which the wire

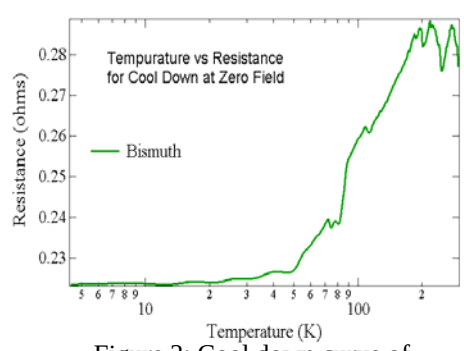


Figure 3: Cool down curve of resistance vs. temperature for Bi

was "soldered". The sample was then mounted with the large flat plane perpendicular to the direction of the magnetic field. Gold wires were then silver painted to larger twisted pair leads running to the top of the probe. This provided a solid connection to accept high current measurements.

Like most metals, the resistance of bismuth drops with temperature. Resistance data for the sample was obtained using a Stanford Research Systems lock-in amplifier, with a current of about 50 milliamps. Since the sample was in direct contact with liquid helium, the data in the 6 K to 50 K range is not as dense as desirable, but none the less shows a temperature to resistance curve typical of bismuth.

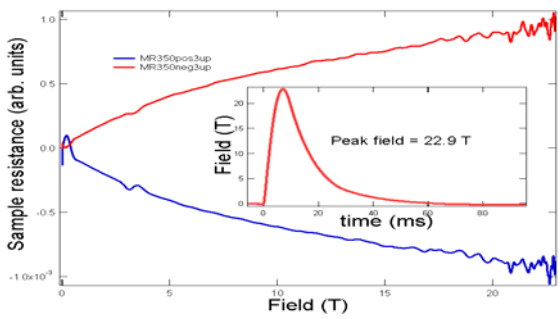


Figure 4: Magnetoresistance of Bi. Blue line indicates reverse current is symmetric. Field inset.

At liquid nitrogen temperatures, bismuth shows a typically high magnetoresistivity.

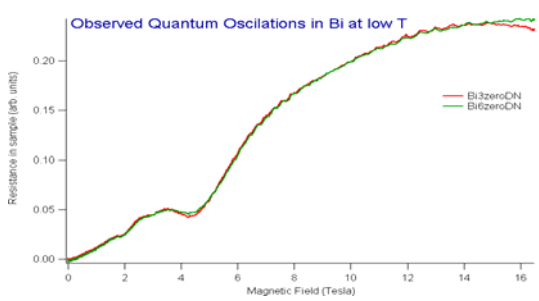


Figure 5: Magneto resistance of Bi at 4.2 K

At low temperatures, around 4.2 K, the magnetoresistance showed quantum oscillation as expected[3]. The oscillation also matched the typical frequency of bismuth quantum oscillation, as shown in figures 6 and 7. This demonstrates

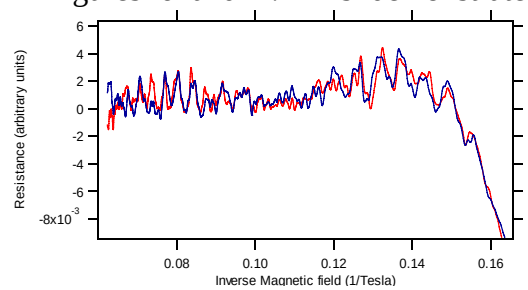
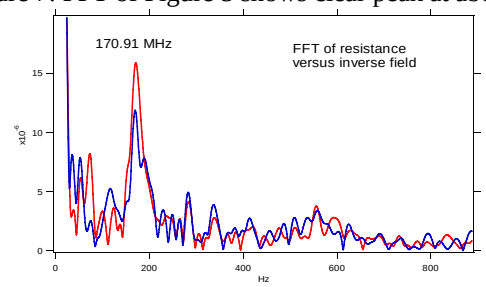


Figure 6: Resistance vs. inverse field to show period

Figure 7: FFT of Figure 5 shows clear peak at about 170 MHz



that the pulsed magnet is capable of taking accurate measurements at low temperature and relatively high field.

The $(TMTSF)_2AsF_6$ sample leads were silver pasted onto the sample across the wide plane and perpendicular to the long plane. The sample was mounted so that the plane that the wires touched on was perpendicular to magnetic field.

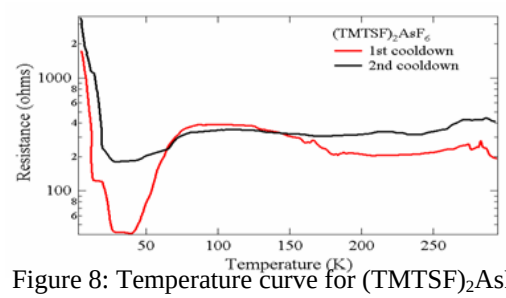


Figure 8: Temperature curve for $(TMTSF)_2AsF_6$ shows characteristic transition at 12 K

The resistance versus temperature of $(TMTSF)_2AsF_6$ exhibited the known conductor-to-insulator transition at about 12 K during cool down.

Measurement of magnetoresistance for $(TMTSF)_2AsF_6$ did not display as clearly as for bismuth, largely due to

Figure 10: Magneto resistance of $(TMTSF)_2AsF_6$ is not symmetric.

much lower current through the sample, necessitated by the higher resistance of the sample, and the less robust connections between the sample its contacts. In addition, there was some difficulty in obtaining a stable

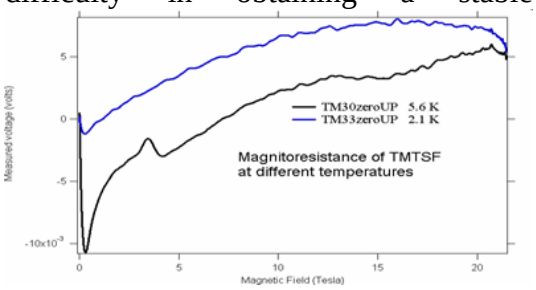
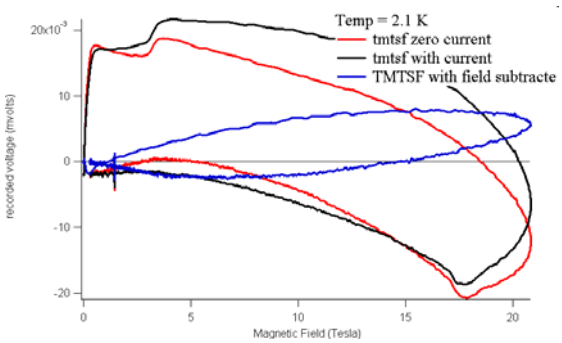


Figure 9: Magneto resistance of $(TMTSF)_2AsF_6$ at 5.6 K and 2.1 K

temperature in the base of the cryostat for this material. Despite these difficulties, the magnet provided some interesting results. Unfortunately, the expected resistance transition at about 4.5 K does not seem obviously present. In addition, the magnetoresistance is not symmetric on the upsweep and downsweep. Even with these problems,



the pulsed magnet was able to provide good data, and would probably be able to provide high quality data on this material with a minimum of further effort.

4. Magnetization

Magnetization is a measurement of the bulk magnetic moment of a sample. Measuring magnetization provides insight into the behavior and usefulness of compounds in a number of classes. Work on high spin system molecular magnets, especially on Mn_{12}-acetate, shows that changing magnetic fields create a "stair-step" effect in a magnetization versus magnetic field plot instead of the normal smooth transition to saturation. Previous work, however, has been done on SQIUD detectors that transition through magnetic fields over a matter of hours. Using a medium field pulse magnet, a method was developed to investigate magnetization versus magnetic field under a much higher rate of change for magnetic field.

In order to take measurements of magnetization at the high speeds of the pulsed magnet a balanced coil was created with an equal number of windings, one wound in reverse of the other one. Thus the induced current should be zero in the center of the two coils. Using this principle, the magnet was pulsed for a series of empty coil

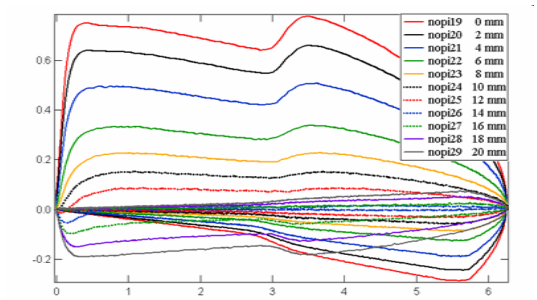


Figure 11: Calibration for centering balanced coils to measure magnetization.

measurements while moving the probe in increments of two millimeters from a point where the coils were notably above the center of field. It was then passed through the center of field, and then just slightly beyond, recording the points each time. A calibration plot was then made by integrating the field over time, in the same manner as the pick up coil

was used to calculate magnetic field, except with an unknown coil area. When the coil is centered, the calculated field runs through the center of the other field measurements, as shown in figure 11.

After calibrating the balanced coils, Mn_{12}-acetate was packed tightly into the lower coil and the probe was centered at the calibration point. Ideally the measurements would have indicated a series of transitions in the Mn_{12}-acetate, at temperatures less than 3.0 K as the field changed, however, due to dramatic temperature fluctuations and noise, it was difficult to see any of these fluctuations, or get reliable data.

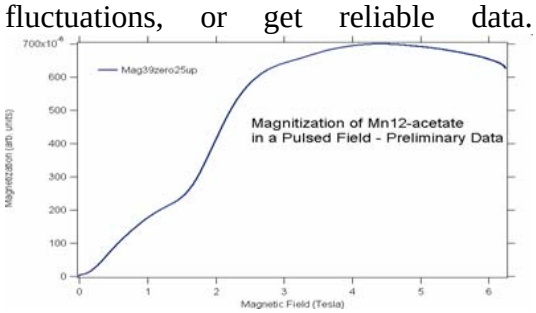


Figure 12: Magnetization of Mn_{12}-acetate shows possible stair stepping, but is inconclusive

However, the data obtained shows some stair-stepping, and this warrants further investigation, possibly with a set of coils with less separation between the ends, so that the field covers the coils more evenly.

5. Conclusion

A low cost pulse magnet is a useful tool for taking a quality measurement with low power costs and minimal set up. The disadvantages, however, are important to consider when using low cost equipment. Low cost pulse magnets can have large amounts of noise, need signal pre-amplification, and can have temperature variations that make data irregular. Also, like any pulse magnets, these low cost alternatives will eventually explode, and need to be replaced. However, the measurements that can be made on similar setups are adequate for taking good data, and are of a very low cost compared to the expense of owning and operating a similar level of resistive magnet.

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