**Effects of Rapidly Changing Applied Magnetic Fields on the Magnetic Ordering Characteristics of Metal-Organic Multiferroics,**

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**Introduction**

Much effort and many resources have been going into the development of exotic materials that offer the capability to develop novel electronics. Many such materials are of interest because of their intrinsic ability to couple the magnetic as well as the electric properties of materials and thus allow electronics that exploit spin degrees freedom. [1] This field of study is often referred to as spintronics. When one thinks of magnetism one immediately considers the ordering of spins, electron spins and nuclear spins, within a magnetic domain as well as the orientation of domains within a sample. It is not uncommon for materials to exhibit an ordering of electronic dipoles in a similar fashion to the ordering one would see in a magnetic material. These orderings are often independent of each other, where a material may have magnetic ordering, electric ordering or both. The latter case composes a class of materials called multiferroics, and these are the materials that have been the focus of my work during my 8 weeks at Los Alamos National Laboratory.

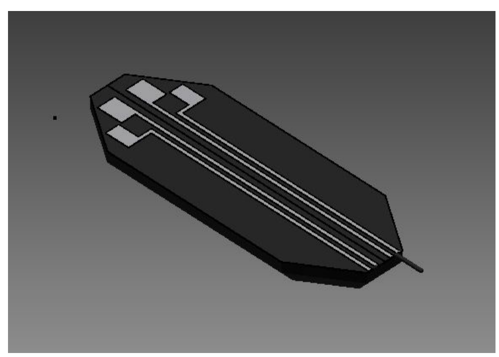
Despite the fact that electricity and magnetism are very much interrelated, many multiferroic materials exhibit an independence in the ordering that of magnetic and electric dipoles. This independence is undesirable if a material is to be used to couple magnetic and electric interactions, which is a requirement for spintronic applications. A new multiferroic material must then be created that has an intrinsic mechanism coupling these orderings. Metal-organic multiferroics such as $NiCl_2$-$4SC(NH_2)_2$ (DTN) exhibit this coupling behavior. [2] Much of my work this summer was focused on measurement of DTN's magnetic properties, specifically it's magnetostrictive properties in pulsed fields.

**Experimental Methods**

Because of the challenges associated with making precise measurements of the small affects of magnetostriction, a newly developed method was employed. [3] This method makes use of a commercially manufactured piezoresistive cantilever. The challenges associated with using this method include lack of documentation on the cantilevers as well as the fragile nature of the cantilevers. In order to gain an accurate calibration for the cantilevers, magnetostriction measurements of a DTN sample, were taken using a microcantilever as well as a traditional capacitive dilatometer. This was done in a quantum design 14 Tesla PPMS at a temperature of 2K. These two data sets were then cross compared to allow the microcantilevers to be used in absolute measurements.

In order to examine the ordering behavior of DTN in pulsed fields the cantilever configuration was then moved onto a pulsed field probe and further experiments were carried out in a pulsed field magnet. Previous data exists for the longitudinal magnetostriction of DTN at fields as high as ~14 Tesla. However transverse magnetostriction, with applied fields along the main axis, gave only been accurately measured at fields $<10$ Tesla. This was our motivation for studying the magnetostrictive behavior along the minor axis, with applied fields along the major axis.

The physical setup of the measurements making use of the piezoresistive cantilevers is as follows. The piezoresistive cantilever consists of a cantilever attached to a silicon base, conducting leads connect four soldering pads to the to either side of the cantilever, as well as to either side of a reference Cantilever that has been cut short so as not to interfere with the measurement.

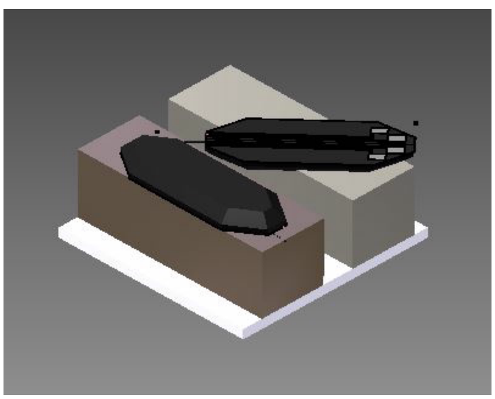


Rendering of piezoresistive microcantilever, shown without G-10 base.

The silicon base is attached to a roughly 1mm thick piece of G-10. The solder pads on the Silicon base are connected to larger solder pads on the G-10 base. In order to perform a measurement, a Wheatstone bridge setup is used to measure the difference in resistance between the cantilever and the reference lever.

For our purposes the G-10 base proved too large to fit the bore of the pulsed magnet, and had to be removed. This proved to be a nontrivial task due to the small size of the silicon base, the small size of the soldering pads on the base, and the fragile nature of the cantilever. Using .001 " platinum wire, and silver epoxy, new wires were successfully attached to the pads on the silicon chip, allowing direct electrical connections.

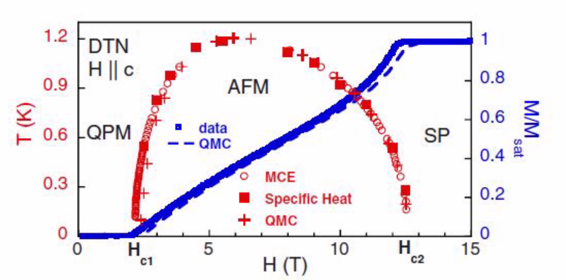
In order to prevent the cantilever from breaking due to thermal striction in the cooling process, the cantilever was placed on a $CdCl_2$-$4SC(NH_2)_2$ (CTN) sample that has a similar thermal expansion characteristic, but is invariant under an applied magnetic field. A silicon chip of comparable thickness was used to act as a spacer between the DTN sample, and the end of the cantilever.



Rendering of experimental setup.
The external field was applied along the length of the sample.

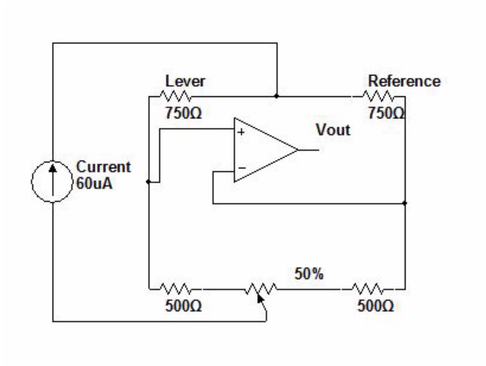
Then entire setup was then placed in a pulsed field probe, designed to take resistance measurements. Twisted pairs were used in the two current wires, and the two voltage wires to minimize the induced currents caused be the rapidly changing magnetic field present in a pulsed magnet. The motivation for taking these measurements in pulsed fields rather than in a DC field is to study the sweep-rate dependence of the magnetic properties and search for sweep-rate-induced topological defects in the magnetic structure. However in these early measurements, where we are testing the cantilever magneto-caloric effects will create unwanted sweep-rate dependence that we will eliminate in later experiments with more careful thermal design.

Measurements were taken at temperatures of 4K, 1.5K, and .6K based on previous data, it is known that at .6 K DTN under goes a transition from $S_z = 0$ state to antiferromagnetic state at ~2 Tesla and from antiferromagnetic to an aligned permanent magnet at ~12 Tesla, [4] it undergoes the reverse transition from antiferromagnetic, to ferromagnetic ordering. We wished to examine whether or not these changes in ordering will still occur at a higher sweep rate, or if heating caused by this rapid rate of change in the magnetic field will prevent the ordering to occur.




Previous data concerning the ordering of DTN. [4]

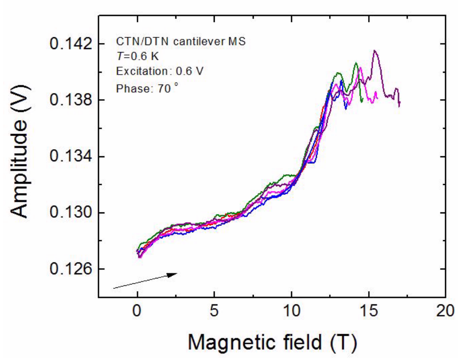
The electrical design of the experiment was based on a simple Wheatstone bridge configuration. Since the cantilever included it's own reference resister embedded on the chip, this was utilized along with a custom built box consisting of two 500 Ohm resistors and a 400 Ohm center tapped potentiometer that was used to balance the circuit. The circuit was supplied with a 60 uA current that was split approximately equally between the leg containing the cantilever and the leg containing the reference resistor. Any change in resistance can then be determined from a measurement of the potential difference between the ends of the piezoresistive cantilever not hooked up to the current source. This procedure allows a more accurate measurement than a traditional four wire resistance measurement. and is particularly simple to implement in our setup due to the provided reference resistor on the cantilever's silicon base.




Circuit Diagram outlining experimental wiring setup.

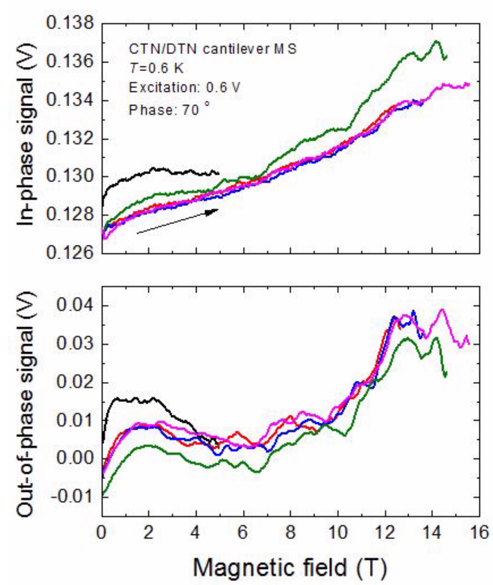
**Results**

Looking at the amplitude of the in phase and out of phase signal components we can see that there appears to be a change in ordering at the ~2T and ~12T. This seems to suggest that these transitions occur in applied fields having rapid sweep rates and that the magneto-caloric effects, while likely contributing noise to the measurements are not preventing transitions from occurring.




Amplitude of in-phase and out-of-phase signal.

If however we look at the in-phase and out-of-phase signals separately, it appears that the out-of-phase signal corresponds more closely to the expected result. This is likely due to use of an incorrect phase angle. In calibrating the system a background measurement was take at zero field and used to determine the phase shift. When the background measurement was taken the bridge was in the balanced configuration and it is likely that a capacitive component to the overall circuit impedance was dominant, causing an incorrect phase angle to be selected.

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[2] Zapf, V. S., Sengupta, P., Batista, C. D., Nasreen, F., Wolff-Fabris, F., and Paduan-Filho, A. *Phys. Rev. B* **83**, 140405 Apr (2011).

[3] Park, J. H., Graf, D., Murphy, T. P., Schmiedeshoff, G. M., and Tozer, S. *Review of Scientific Instruments* **80**(11), 116101–116101–3 (2009).

[4] Zapf, V. S., Correa, V. F., Sengupta, P., Batista, C. D., Tsukamoto, M., Kawashima, N., Egan, P., Pantea, C., Migliori, A., Betts, J. B., Jaime, M., and Paduan-Filho, A. *Phys. Rev. B* **77**, 020404 Jan (2008).