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Radio frequency measurements of the superconducting transition in κ-$(ET)_2Cu(NCS)_2$ using a tunnel diode oscillator in pulsed magnetic fields

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Abstract

We have measured the penetration depth in the superconductor κ-$(ET)_2Cu(NCS)_2$ as a function of magnetic field at constant temperature. We consistently find a sharp transition as the experiment is repeated with the sample at different orientations with respect to the magnetic field. When the magnetic field is near parallel to the conducting planes we see an inflection in the data that may indicate a change of state. We have also shown that the tunnel diode oscillator can be used effectively in ms pulsed magnetic fields.

Keywords: Organic conductors, superconducting phase transitions.

1. Introduction

In a recent paper[1], we showed that we could make contactless measurements of penetration depth or resistance by placing a sample in the coil of a tank circuit powered by a tunnel diode oscillator (TDO). We further demonstrated that we could use this circuit in a pulsed magnetic field to do experiments in the highest magnetic fields attainable. To avoid problems caused by the large dB/dt inherent in a pulsed field, our first experiments were done in the long pulsed field at NHMFL Los Alamos where the pulse length is 2.4 seconds. We now have modified the TDO method so it can be used in shorter pulsed fields. In this article we present preliminary results of the superconducting transition in the organic compound κ-$(ET)_2Cu(NCS)_2$ with the field parallel to the conducting layers, measured in a pulsed magnetic field with a 150 ms pulse length. These measurements are more consistent than resistance measurements and we believe give a better measure of the critical magnetic field, H_{c2}. There is also the possibility that these rf measurements could be sensitive to the existence of a Fulde Ferrel Larkin Olchinikov (FFLO) state[2].

2. Experimental

The method of using a TDO to study superconducting transitions is not new. Our innovation is to use the TDO in pulsed magnetic fields to reach magnetic fields over 30 tesla. Using this system we can reach fields of 50 T in our own laboratory and 60+ tesla at the NHMFL in Los Alamos. In the conventional TDO system a sample is placed inside the small inductor of the tank circuit. The inductor can be an irregular coil wound around, or close to the sample to maximize the filling factor of the coil. In a pulsed magnetic field this coil will pick up a voltage due to the dB/dt of the magnet that will destabilize the TDO electronics. Our innovation, described in our recently submitted paper, is to use two counter-wound coils to cancel out the induced voltage from the pulse magnet. For the long pulse magnet at Los Alamos, where the largest dB/dt is 385 T/s, winding two coils that look the same size by eye is sufficient. To successfully run the system in a short pulse magnet such as the one in our laboratory at Clark University, where the max dB/dt is 2500 T/s, a more precise method of balancing the coils was necessary. Our eventual goal is to use lithographed flat coils to get near perfect compensation, but for this experiment we found that we could manually balance a set of coils by running an ac current through our magnet at room temperature and measuring the pickup from the coils with a lock-in amplifier tuned to the same frequency. By adjusting the windings on the coils by hand we could reduce the effective area of the set of coils to less than 0.05 mm^2.

The samples for this experiment were approximately 0.75 mm^2 and 0.1 mm thick. The sample was placed in one of two 1 mm dia. counter-wound coils. The set of balanced coils was fixed to a rotating platform. A separate coil on the platform was used to measure the angle of the platform with respect to the applied magnetic field. The angle measurements were made by exciting the magnet with an ac current and measuring the voltage on the rotating pickup coil with a lock-in amplifier. The resolution of our rotator corresponded to an angle of 0.25°. The rotating coil could measure to an accuracy of 0.3°.

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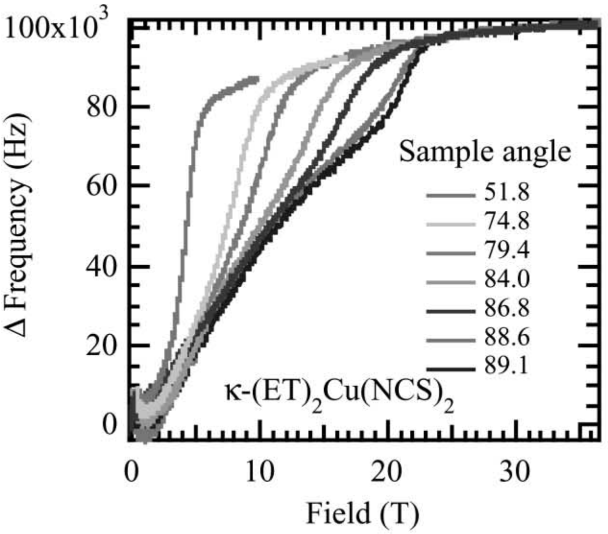

Fig. 1. The superconducting transition measured for different angles at 1.6 K. The angles correspond to the traces from left to right.

Therefore, our absolute and relative accuracy were almost the same.

3. Data and discussion

The superconducting state causes all electromagnetic fields to be expelled due to the Meissner effect. In this state, the sample, inside the inductor, reduces the effective volume of the inductor and causes the frequency of the TDO to rise. Upon application of the magnetic field, magnetic flux is reintroduced into the sample and the Meissner state is destroyed causing the frequency to drop. We created a measurement system for fast recording of this frequency drop that is described in detail in our recent paper[1]. Although, in the first approximation, the TDO signal comes from the change in penetration depth of the sample and the resulting change of the effective volume of the inductor, in the case of a type II superconductor the situation is somewhat more complicated as vorticies populate the sample when the field is above H_{c1} and are set into oscillation around their pinning centers by the rf field. A number of previous works [3,4] have treated this problem and calculated the effective penetration depth as a function of field. Our data is consistent with these calculations.

There were three new aspects to this experiment that were not incorporated into our last TDO experiment. They were, the carefully balanced coils, a low field magnitude at the TDO electronics because they were placed far from the center of the magnetic field, and new tunnel diodes with nonmagnetic cases. The background frequency shift with no sample mounted was less than 20 kHz up to 40 T. In contrast, in our older dc or pulsed systems the background was over 70 kHz for the same field range. The change in frequency due to the superconducting transition in the samples studied ranged from 70 to 120 kHz. The noise level of the raw data was 200-300 Hz. Therefore, most of the raw signal we measured was a result of the superconducting transition, although subtraction of the background removes some spurious signals at low fields.

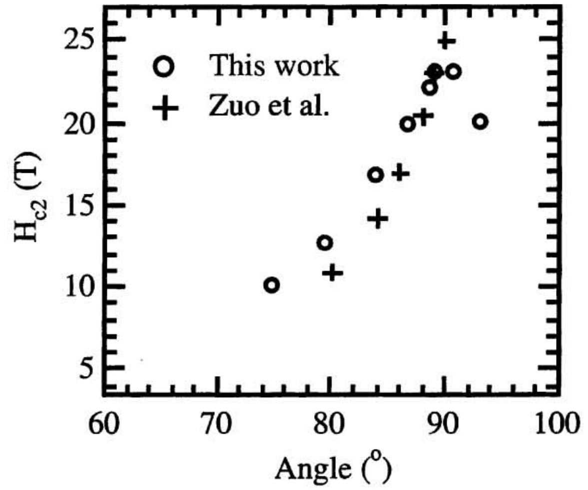

Fig. 2. The critical field as a function of angle plotted with the results of Zuo et al[5].

An example of a superconducting transition with the applied field at various angles from the perpendicular (0° is field perpendicular to the layers 90° denotes the field parallel to the layers.) is shown in Fig. 1. The transition is sharp, and an unambiguous plateau exists when the sample has become normal. In our experience this transition will become even sharper upon subtraction of the background, although the flat signal in the normal state region suggests that the background is small. A large background is characterized by a rapidly changing signal even in the normal region. This is not to be expected because the signal in the normal region is dominated by effective diamagnetism caused by eddy currents, and this signal is much smaller that the penetration depth signal[1].

As the sample is rotated towards 90°, the shape of the penetration depth curve develops an inflection near 15 T that becomes more pronounced as the angle approaches 90°. We have attempted to explain this change in slope as a vortex depinning transition, but it does not fit easily into any current theory. Other groups have claimed that this inflection is due to the creation of a FFLO state[2].

In Fig. 2 we compare the angular dependence of H_{c2} with similar data found by resistance measurements[5]. Or data is similar to the previous published data, but there are systematic differences that we will investigate in further experiments.

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