THE STUDY OF THE MAGNETIC BREAKDOWN EFFECT AS A FUNCTION OF ANGLE IN THE ORGANIC CONDUCTOR K- (BEDT-TTF)$_2$Cu(NCS)$_2$ IN HIGH MAGNETIC FIELDS

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The magnetic breakdown effect can be seen by the growth of new frequencies in the quantum oscillations in clean metals as a function of magnetic field. We have studied the variation of the amplitudes in the quantum oscillations in the resistance (the Shubnikov-de Haas effect) as a function of angle in the quasi-two dimensional-organic conductor κ-(BEDT-TTF)$_2$Cu(NCS) $_2$. The measurements were made by means of a radio frequency (rf) tank circuit (~50 MHz) at very high magnetic fields(50T-60T) and low temperature(500 mK). The geometry of the rf excitation we used excited in-plane currents, and therefore we measured the in-plane resistivity. In contrast to conventional transport measurements that measure the inter-plane resistivity, the in-plane resistivity is dominated by the magnetic breakdown frequencies. As a result we measured much higher breakdown frequency amplitudes than conventional transport experiments. As is expected, the angular dependence of the Shubnikov-de Haas frequencies have a 1/cosθ behavior. This is due to the change of the cross sectional area of the tubular Fermi surface as the angle with respect to the magnetic field is changed. The amplitude of the oscillations changes due to the spin splitting factor which takes into account the ratio between the spin splitting and the energy spacing of the Landau levels which also has 1/cosθ behavior. We show that our data agree with the semi-classical theory (Lifshitz-Kosevich formula).

1 Introduction

Many efforts have been made to understand and explain the mechanism of magnetic breakdown phenomena. Semi-classical and quantum models have been developed, but there is still not complete agreement with the experimental data. One of the most studied materials where magnetic breakdown frequencies have been observed is the quasi-two dimensional organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. The Fermi surface (FS) of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ consists of a quasi-one-dimensional (1D) and a quasi-two-dimensional (2D) FS sections. It has been shown that the fundamental frequency F_α seen in Shubnikov de Haas or de Haas van Alphen oscillations, is associated with the 2D FS while the magnetic breakdown frequency F_β is related to the tunneling across the gap between the 2D and 1D FS. The tunneling between the two FS occurs when the magnetic energy is greater than the gap, in this case about 35 T. As the magnetic field increases more combinations ($F_{\beta-\alpha}$, $F_{\beta+\alpha}$, $F_{\beta-2\alpha}$ etc.) of original frequencies are observed. When the sample is rotated in the magnetic field the amplitude of the frequencies changes due to the geometry of the Fermi surface and the effects of electron spin.

We have studied the magnetic breakdown effect by measuring the quantum oscillations in the resistance in the organic conductor κ- (BEDT-TTF $)_2$ Cu(NCS$)_2$ using a contact-less measurement method, called the TDO method.[1] In the TDO method the sample is placed in the coil of a rf tank circuit oscillating at 50 MHz. We then applied magnetic fields to the sample and measured the frequency shift of the oscillations. The sample could be rotated about the axis perpendicular to the magnetic field. We made all measurements at low temperature, below 500 mk. In contrast to conventional transport measurements that measure the inter-plane component of the resistivity, the TDO method measures the in-plane resistivity. Using the TDO method we found that the magnetic breakdown frequencies are much more dominant than in conventional transport measurements. Our goal was to measure ratio of the amplitudes of quantum oscillations as a function of angle.

2 Experimental Details

The sample was placed in the one of two1 mm dia. counter –wound coils of the self-resonant tank circuit.[1] The angle was changed by fixing the set of balanced coils on a platform, which had the flexibility of rotating approximately (+ 30^0,-30^0) with respect to the magnetic field. The frequencies and the amplitudes of the circuit oscillations were measured after the signal from the TDO circuit was routed through a series of amplifiers and mixer.[1] The measurements were done in 50 T pulse magnet at the NHMFL with 38 ms rise-time and decay over 500 ms and at temperature below 500 mK.

3 Results and Discussion

3.1 Contact-less measurement method versus 4-lead conventional measurement method.

Oscillations in the resistance using both a conventional four lead transport technique and a contact-less TDO measurement technique are shown in Fig 1. The measurements are taken close to zero angle meaning the conducting planes are perpendicular to the field. It can be clearly seen that at the same temperature and at high magnetic field, the amplitude of breakdown SdH oscillations as compared to α-oscillations are much stronger using the TDO technique. It is not well understood why this is true.

3.2 Magnetic breakdown frequencies as a function of angle

In order to investigate the magnetic breakdown effect we carried out angle dependent measurements. The SdH frequencies were calculated by a fast Fourier transform (FFT). It has already been determined that the angular dependence of the

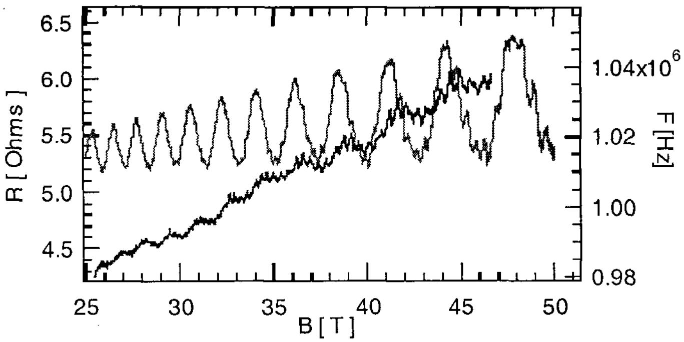


Figure 1: The large oscillations were measured using the 4-lead measurement method and the predominant frequency is the α-frequency. The small oscillations were taken using the TDO method besides the α-frequency in the magnetic breakdown oscillations were clearly seen.

α -frequency (F_α) obeys a ($1/\cos\theta$)–law.[3] We used this result to measure the orientation of our sample. The magnetic breakdown frequencies as a function of angle are shown in Fig. 2 (a-c). Previous work done by Meyer *et al.*,[4] shows that the breakdown frequency F_β follows the ($1/\cos\theta$)–law. Our data suggest the same behavior (Fig. 2(a)). In addition to the angular dependency of the F_β we present the angular dependency of the breakdown frequencies $F_{\beta-\alpha}$ and $F_{\beta+\alpha}$. The ($1/\cos\theta$)–law is also suggested for these frequencies(Fig 2 (b-c)).

3.3 Amplitude of magnetic breakdown frequencies versus angle

To study the evolution of the amplitudes of the breakdown frequencies as a function of angle we measured the amplitude of the oscillations using a FFT. The amplitudes of each of the frequencies were normalized by the amplitude of the α frequency to allow us to compare results with different samples and runs. In Fig. 3, we present the ratio of the $(\beta-\alpha)/\alpha-$, $\beta/\alpha-$ and $(\beta+\alpha)/\alpha$ - amplitudes versus angle. At high angles, the amplitude of the ($\beta-\alpha$)–orbit is larger than the amplitude of ($\beta+\alpha$) –orbit, but smaller than the amplitude of the the β–orbit. As the sample is rotated towards the perpendicular direction on the magnetic field, the amplitude of the ($\beta-\alpha$–orbit increases while the amplitude of the β-orbit decreases considerably. At zero angle, the dominant amplitude is the ($\beta-\alpha$) –orbit. The amplitude of the ($\beta+\alpha$) –orbit does not vary dramatically and it has a minimum around 17°.

3.4 Comparasion of the experimental data to the semi-classical theory

The changes in the quantum oscillations of the resistance when the magnetic field is tilted can be explained as a consequence of the spin splitting of the Landau levels. In the calculated amplitudes for different orbits, this effect is included by the well-

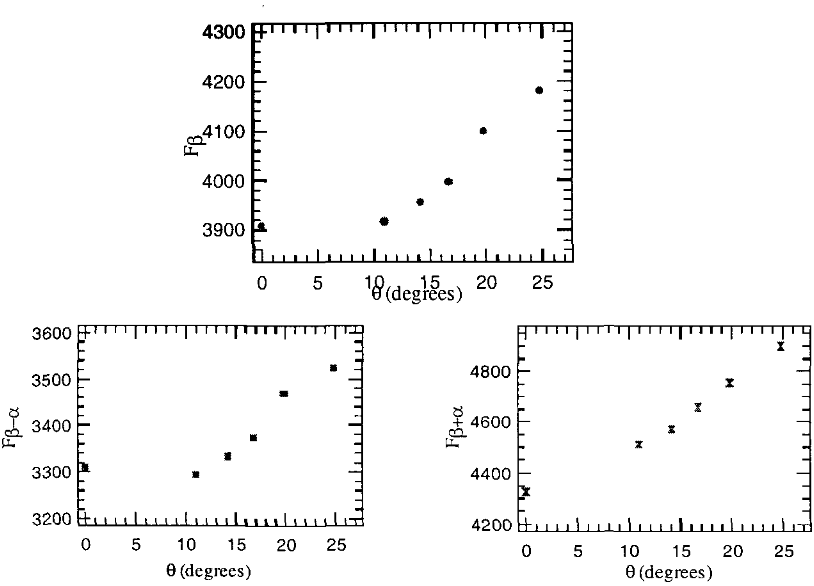
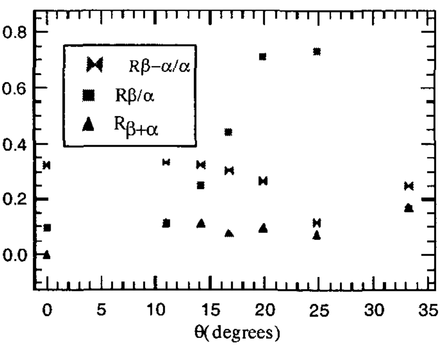


Figure 2(a-c): Magnetic breakdown frequencies versus angle



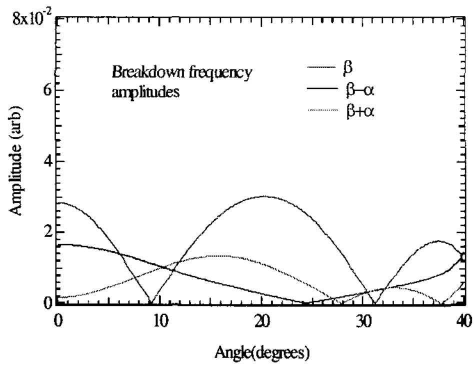


Figure 3: Ratio of the amplitudes versus angle.
Figure4: The calculated Ratio of the amplitudes versus angle.

known spin splitting factor of the Lifshitz-Kosevich (LK) formula.[3]

$$A(\theta) \sim R_D\, R_T\, R_S \qquad (1)$$

where Rs is the spin splitting factor and R_D, R_T are other damping factors.[3] The equation below shows the spin splitting term:

$$R_s = \cos(1/2p\pi\, g\, m/m_e) \text{ and } m/m_e \sim 1/\cos\theta. \quad (2)$$

R_D, R_T also depend on m/m_e ,but they are not periodic. The amplitudes of the magnetic breakdown frequencies calculated using the LK formula are presented in Fig. 4. The values of the parameters used for simulation are given in Table 1.

m_α =3.22	m_β =7..25	$m_{\beta-\alpha}$ =3.6	$m_{\beta+\alpha}$ =8.49
g_α =1.62	g_β = 1.77	$g_{\beta-\alpha}$ =1.77	$g_{\beta+\alpha}$ =1.77

These values are in good agreement with the experimental values found by Meyer *et al.*,[4] Harrison *et al.*,[5] shown in Table 2.

Meyer et al.	m_α =3.22	m_β = 7.13	$m_{\beta-\alpha}$ =n/a	$m_{\beta+\alpha}$ =10.4
Harrison et al.	m_α =3.59	m_β = 7.29	$m_{\beta-\alpha}$ =3.69	$m_{\beta+\alpha}$ =8.42

Given the above values for the effective mass of each orbit we found good agreement between experiment and semi-classical theory prediction.

4 Conclusion

We have studied the quantum oscillations in the in-plane resistance in the organic conductor κ-(BEDT- TTF)$_2$Cu(NCS)$_2$ in a tilted magnetic field. We showed that using the contact-less measurement method the magnetic breakdown frequencies are much more dominant. We found 1/cosθ behavior for the magnetic breakdown frequencies versus angle. We studied the changes of the amplitudes of the magnetic breakdown frequencies as a function of magnetic field and we found good agreement between the experiment and the predicted semi-classical behavior.

Support came from the NSF and the experiments were done at the NHMFL in Los Alamos.

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