Magnetotransport measurements of low dimensional conductors under pulsed ultra-high magnetic fields

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Abstract. Transport measurements of low-dimensional conducting crystals, graphite and NbSe3, have been carried out under destructive pulsed ultra-high magnetic fields up to 120T. RF reflection technique has been employed to pick up the signal from huge induction noise. Sample crystals have been fabricated into thin wire-shape to avoid self-heating due to induced eddy current. We report recent experimental results on two subjects; (1) enhancement of electron correlation in the magnetic quantum limit, and (2) characteristic energy spectra of Bloch electron systems under ultra-high magnetic fields.

1. Introduction
Although various electronic properties have been theoretically predicted in ultra-high magnetic field range beyond 100T, there have been few experimental trials to search for them because of the difficulty of ultra-high field experiments. We have developed the experimental techniques for transport measurements under pulsed ultra-high magnetic fields generated by destructive methods, and studied several research subjects on ultra-high magnetic field physics [1]. In this paper, we report the recent developments on two subjects among them.

One of these subjects is to observe the enhancement of electron correlation in the magnetic quantum limit, where only the lowest Landau level is occupied [2]. Such a situation means that the cyclotron radius (magnetic length) becomes smaller than the mean electron-electron distance. Electron correlation effect might modify the Landau level spectra in the magnetic quantum limit by the mass enhancement. To observe this effect experimentally, we have chosen semimetal graphite since it is easy to reach the magnetic quantum limit because of its low carrier density. Moreover, semimetals have two energy bands (electron’s and hole’s) and Fermi energy is fixed even if its energy band was modulated. Therefore, we can detect the mass enhancement as the shift of Shubnikov-de Haas (SdH) oscillation.

The other subject is to search for the electronic structure characteristic to Bloch electron systems under magnetic fields. In the low magnetic field range, the energy spectrum of an electron in the crystal is quantized into Landau levels in the same way as a free electron. Many electronic states with different center coordinates degenerate in each Landau level. As the magnetic field is increased, these states begin to couple with each other and form remarkable spectra: The degeneracy breaking causes the broadening of Landau levels (Harper broadening), and generates complicated fine gap structures in broadened Landau levels reflecting the interference between orbital periodicity and lattice periodicity. For example, an electron in the 2D square lattice potential shows energy spectrum with fractal fine structures (Hofstadter butterfly) [3]. Experimentally, it is almost hopeless to observe such spectra in...
most crystals since we cannot reach needed magnetic fields (4000T for the lattice constant of 1nm).
We have examined energy spectra of highly anisotropic Bloch electron systems, and found that quasi-
one-dimensional (Q1D) conductors could show Hofstadter-like spectra under much lower fields with
tilted orientations [4]. We have focused on a charge density wave (CDW) compound NbSe₃. This
system has only one lens-like Fermi surface at low temperature as a result of the Fermi surface
reconstruction due to two CDW transitions. It is expected that the high magnetic fields couple
different lens-like Fermi pockets in the periodic zone scheme, and cause the Harper broadening of
Landau levels and produce fine gap structures in them in the field range available for experiments.

In the followings, we mention our recent experimental results on magnetotransport of low
dimensional conductors, graphite and NbSe₃, under pulsed ultra-high magnetic fields.

2. Experimental details
To generate ultra-high magnetic fields, we have used the single-turn coil device installed at ISSP, Univ.
of Tokyo. In this device, magnetic field can be obtained as a single-shot short pulse. In our experiments,
typical coil diameter is 16φ and the peak strength is 120T and the pulse duration is 10μs. Large $dB/dt$
causes the superposition of huge induction noise to the signal in transport measurements. It also
induces large eddy current in the conducting crystal itself, and increases its temperature. Moreover,
large current discharge to the single-turn coil is accompanied by huge discharge noise. To perform
transport experiments, we have to overcome these problems.

To detect transport signal obscured in induced and discharge noises, we have developed radio
frequency (RF) reflection method [1, 5]. Figure 1 shows the schematic diagram of the RF reflection
measurement. RF bias from the signal source is applied to sample through electrodes. The amplitude
of reflected signal is modulated by the mismatch of sample impedance and characteristic impedance
(50 Ω). The reflected signal, from which most of noise are cut by filters, is recorded with a high-speed
oscilloscope, and only the modulated signal is extracted by numerical phase sensitive detection (PSD)
from it. The typical RF frequency used in this experiment was 77 MHz.

The heating of the sample crystal due to eddy current is the most serious problem in transport
measurements under pulsed ultra-high magnetic fields. Heating power and temperature rise are
proportional to the fourth power and the second power of the sample diameter, respectively. Therefore,
the effect of eddy current can be limited by decreasing sample size. We have fabricated the single
crystal graphite (Kish graphite) into thin wire structure with the width of 10μm by oxygen plasma
etching. Temperature rise of the fabricated graphite in pulsed magnetic fields is estimated to be lower
than 1 K by the calculation. In the case of NbSe₃, we do not need fabricate crystals since the width of

![Figure 1. Block diagram of the RF reflection method.](image-url)
crystals is thin enough (1\(\mu\)m or less).

3. Results and discussion

3.1. Graphite thin wire
We have carried out the RF reflection measurement of both non-fabricated bulk crystals and fabricated thin wires of graphite to check the reduction of heating by sample fabrication. Prior to ultra-high field experiments, we confirmed that the oxygen plasma process gives no damage to the transport properties of graphite by the lower field experiments using the 13T superconducting magnet and the 40T nondestructive pulse magnet.

Figure 2 shows the magnetoresistance traces of a bulk crystal and a fabricated thin wire of graphite measured in the pulsed ultra-high magnetic field up to 120T. The field was applied parallel to the crystallographic \(c\)-axis. Initial temperature before the field pulse was 4.2K. In contrast to the lower-field experiments, the measured signals of the bulk and the thin wire show different field dependence. In the fabricated thin wire, magnetoresistance shows broad minimum around 80 T, while in the bulk sample, it shows monotonous increase. This deviation can be attributed to dynamical temperature rise in the bulk sample.

One of the possible origins of the broad minimum in the thin wire is the SdH oscillation. The one-body theory based on the Slonczewski-Weiss-McClure model, which well reproduces the SdH positions in the low-field range, predicts a series of high-field SdH oscillations at 45T, 70T, 90T, and 130T [6, 7], so that it cannot explain the observed minimum around 80T. This deviation suggests the shift of the SdH oscillation due to the renormalization of electron correlation, and seems to support the many-body theory leading the enhancement of electron correlation in the magnetic quantum limit [2].

It has been known that graphite shows the field-induced reentrant phase transitions around 40-50T below 10K [8]. Absence of this phase transition in the thin wire trace suggests that the temperature is still higher than 10 K even in the thin wire. This shows that the heat transfer from electrodes cannot be negligible. We have to reduce the heating effect by fabricating not only sample but also electrodes.

3.2. NbSe\(_3\)
In the case of NbSe\(_3\), temperature increase due to eddy current can be neglected since the cross section of the ribbon-shaped crystal is very small in the configuration of this experiment. The magnetic field was applied parallel to the crystallographic \(c\)-axis. This field orientation is the easiest configuration to couple the lens-like Fermi pocket with that in the neighboring zone by tunneling. Figure 3 shows the magnetoresistance of NbSe\(_3\) measured by the RF reflection method. Magnetoresistance shows SdH...
oscillations below the local minimum at 40T above which only the lowest Landau level is occupied (the quantum limit). Although the magnetoresistance is expected to increase monotonously in the quantum limit above 40T, it shows anomalous decrease above 80T. This result confirms the similar behavior observed by the RF transmission measurement in our previous work [1].

The monotonous decrease of resistance in the quantum limit strongly suggests the Harper broadening of the lowest Landau level due to the coupling of lens-like Fermi pockets in the periodic zone scheme. The Harper broadening recovers electron dispersion along the 1D axis and increases the 1D axis conductivity. The further study on the Hall conductivity might confirm the above picture.

Figure 3. Magnetoresistance of NbSe$_3$.

4. Summary
We have developed the experimental techniques for the magnetotransport measurement under pulsed ultra-high magnetic fields. The RF reflection technique and the sample fabrication technique were employed to overcome the problems of huge noise and sample heating. We have observed a broad resistance minimum at 80T in the graphite thin wire, which might be a SdH oscillation shifted by electron correlation effect. We have also confirmed the monotonous resistance decrease in the quantum limit in NbSe$_3$, which can be explained by the Harper broadening of the lowest Landau level.

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