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Low-Dimensional Organic Conductors under High Magnetic Fields

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Abstract. — Novel electronic properties of low-dimensional organic conductors, under high magnetic fields are briefly reviewed and some topical problems are discussed. Magnetic field effects to electron spins and electron orbital motions are discussed in the quasi one-dimensional conductors (R1R2DCNQI)2Cu and (TMTSF)2X and in the quasi two-dimensional conductor (BEDT-TTF)2XHg(SCN)4. Electronic properties in the anomalous state of (BEDT-TTF)2KHg(SCN)4 are discussed in the light of the angle dependent magnetoresistance oscillations. Properties of field-induced spin-density waves are studied in relation to the superlattice potential made by the anion ordering in (TMTSF)2ClO4. Possible origins of the rapid oscillations in magnetoresistance of (TMTSF)2X are examined. Introduction is made to theoretical ideas of field-induced superconductivity and experimental trial to find it.

1. Introduction

Low-dimensionality is one of the most characteristic properties of organic conductors. It is due to the shape of constituent molecules far from spherical symmetry. TMTSF (tetramethyltertaselefulvalene) and BEDT-TTF (bis(ethylenedithio)-tetrathiafulvalene) molecules, which are most popular ones to make organic conductors and superconductors, usually form columnar or sheet-like structures in crystal because of their planar shape. In those conductors one obtains quasi one- or two-dimensional conduction electron systems.

Magnetic fields play several roles in electronic properties of low-dimensional organic conductors: First, it gives the Zeeman energy to the system leading to possible phase changes due to reduction of the free energy of spins parallel to the magnetic field. Second, magnetic fields modify the orbital motion of electrons by exerting the Lorentz force. Electrons lose the freedom of translational motion perpendicular to the magnetic fields. This provides a clue to investigate electronic structures and their dynamics and, moreover, to control the electronic state. Under high magnetic fields other kinds of electronic state are formed such as the Landau quantized state.

This article reviews the magnetic field effects to spins and orbital motion in low-dimensional organic conductors followed by discussion on novel electronic states in them under high magnetic fields.

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2. Basic Properties of Low-Dimensional Electronic Systems under High Magnetic Fields

2.1. Magnetic Field Effects to Electron Spins - A Field-Induced Metal-Insulator Transition. — The quasi one-dimensional conductor, (DMeDCNQI)$_2$Cu has columns of DCNQI molecules interconnected by Cu [1,2]. It is metallic in the high-temperature or low-pressure regime and is insulating in the opposite one [3] as shown in Figure 1. So-called chemical pressure effects have been found in deuterated samples: When hydrogen atoms of a DMeDCNQI molecule are replaced with deuterium, the sample shows properties similar to those of pristine samples under pressures. This is ascribed to the C-D bonding shorter than the C-H one leading to reduction of intermolecular distance. Therefore, replacement of a suitable number of hydrogen atoms with deuterium makes it possible to have samples at ambient pressure showing properties of pristine samples near the critical pressure below which the system remains metallic down to the lowest temperature range.

XPS and infrared studies have verified that Cu has the mixed valence Cu$^{4/3+}$ in the metallic state [4,5]. Therefore, d-electrons of Cu are expected to take part in the electronic states near the Fermi level. Band calculations have shown this intuitive expectation to be valid [6]. It is formed by one-dimensional $\pi$-like bands originating in DCNQI molecular orbitals and three-dimensional $d$-like ones from Cu. Electrical, magnetic and structural studies have shown that the insulating state has paramagnetic spins of Cu$^{2+}$ and a three-fold superstructure parallel to the one-dimensional c-axis [7,8].

The essential mechanism of the metal-insulator transition is ascribed to the Peierls instability in the $\pi$-like band and the Mott transition in the $d$-like one [9]. The Peierls instability is accompanied by the three-fold superstructure [10,11]. This superstructure makes the Mott transition easy to undergo because the Brillouin zone is reduced to 1/3 leading to the half-filled state of the $d$-like band.

One of novel properties of this material is the metal-insulator-metal re-entrant transition observed in the narrow pressure range shown in Figure 1. Electrical resistance measurements under high magnetic fields and heat capacity ones of partially deuterated samples were made in order to clarify its origin [12,13]. The magnetoresistance is found to be quite normal unlike that observed in the heavy electron system. The electronic heat capacity was measured to be about 10 – 20mJ/mol/K$^2$ at low temperatures. This is also normal as organic conductors suggesting that the re-entered metallic state has basically the same properties as ordinary metallic states far from the re-entrant regime.

Under high magnetic fields of the order of 10 T, however, we found a field-induced transition from the metallic state to the insulating one as shown in Figure 2. This transition occurs when the system is close to the insulating phase. It has a hysteresis for the field cycling. By
analyzing experimental results we propose the following picture: The magnetic field reduces the free energy of the insulating state because of a negative contribution of the Zeeman energy. Therefore the metallic state is made unstable by high magnetic fields when the metallic system is close enough to the insulating regime. The above idea is consistent with theoretical studies from both phenomenological and microscopic view points [14, 15].

The de Haas-van Alphen effect has been observed in the metallic phase of (DMeDCNQI)$_2$Cu as shown in Figure 3 [16] suggesting the presence of both one- and three-dimensional Fermi surfaces which are consistent with the band calculations [6]. However, no Shubnikov-de Haas oscillations have been found in magnetoresistance. It is presumably too small compared to the background resistance.
Fig. 3. — De Haas-van Alphen oscillations of (DMeDCNQI)$_2$Cu. The insets show the FT spectra. (a) Magnetic fields parallel to the one-dimensional c-axis. (b) Magnetic fields in the ab-plane making the angle $\omega$ from [110] direction. (Reproduced from Ref. [16] with kind permission from American Physical Society).

2.2. Magnetic Field Effects to Orbital Motion - Angle-Dependent Magnetoresistance Oscillations. — Examples of magnetic field effects to the orbital motion of electrons are found in quasi one-dimensional conductors (TMTSF)$_2$X ($X = \text{ClO}_4, \text{PF}_6$ etc.) and quasi two-dimensional ones (BEDT-TTF)$_2$X ($X = \text{I}_3, \text{IBr}_2, \text{KHg(SCN)}_4$ etc.). When one rotates the direction of magnetic fields, the electrical resistance oscillates as a function of the angle between the field direction and a lattice vector but not of the field strength. This phenomenon called angle-dependent magnetoresistance oscillations was found for the first time in $\beta$-(BEDT-TTF)$_2$IBr$_2$ by Kartsovnik et al. and in $\theta$-(BEDT-TTF)$_2$I$_3$ by Kajita et al. independently [17, 18].

In the quasi two-dimensional (BEDT-TTF)$_2$X the resistance perpendicular to the two-dimensional plane shows a series of resistance maximum as a function of the angle $\theta$ between the magnetic field direction and the normal to the two-dimensional plane as shown in Figure 4. The oscillations were found to be a function of $\tan \theta$. 
Fig. 4. — Angle-dependent magnetoresistance oscillations observed in \((\text{BEDT-TTF})_2\text{IBr}_2\). The angle \(\theta\) is measured from the normal to the two-dimensional plane. (Reproduced from Ref. [17], with kind permission from The American Institute of Physics).

Fig. 5. — Real space trajectories of an electron at the Fermi level under magnetic fields applied at general angles (left) and magic angles (right).

A theoretical idea to explain this phenomenon was given by Yamaji [19]. When the field direction is general, the electron trajectory in real space is spiral-like leading to a finite resistance perpendicular to the two-dimensional plane. At magic angles given by the relation, \(\tan \theta = (k_F/c^*)(n + 1/4)\) where \(k_F\), \(c^*\) and \(n\) are the Fermi wave number, the reciprocal lattice vector and an arbitrary integer, respectively, the real space trajectory becomes a closed loop as shown in Figure 5. This makes the perpendicular resistance infinite. Quantum mechanical calculations of electronic energy spectra have shown that the band width at the Fermi level vanishes at the magic angles [20]. We consider this corresponds to the above naive picture of closed orbit in real space.
Fig. 6. — Angle-dependent magnetoresistance oscillations of (TMTSF)$_2$ClO$_4$ for the field rotation in the $b'c'^*$-plane. The angle $\theta$ denotes that between the magnetic field and the $c^*$-axis. Note that second-derivative traces are shown. The hatched peaks correspond to the onset of field-induced spin-density waves. The angles that satisfy $\tan \theta = 1.1p/q$ are shown. Right inset: Plot of the tangent of peak position vs the fraction $p/q$. Left inset: Semi-classical electron trajectory on the Fermi surface. (Reproduced from Ref. [22], with kind permission from The American Physical Society).

This phenomenon and the interpretation were found to be universal ones common to quasi two-dimensional conductors such as GaAs/GaAlAs. This phenomenon gives a clue to find the size and the shape of the cross-section of the warped cylindrical Fermi surface cut by a plane normal to the cylinder axis if the cross-sectional shape is not far from a circle and the degree of warping is not too much.

Similar phenomena have been found also in quasi one-dimensional conductors. When magnetic fields are rotated in the plane perpendicular to the one-dimensional $a$-axis of (TMTSF)$_2$ ClO$_4$, the transverse resistance shows a series of local minimum as a function of the angle between the magnetic field and a crystalline axis perpendicular to the one-dimensional axis as shown in Figure 6 [21,22].

This type of angle dependent magnetoresistance oscillations has been ascribed to a commensurability effect between the electron trajectory in momentum space and the reciprocal lattice. The left inset of Figure 5 depicts the trajectory on the Fermi surface. When the field direction is general, the trajectory reduced to the first Brillouin zone covers all over the Fermi surface. Transverse components of the Fermi velocity of electrons are averaged out leading to the net electron motion parallel to the one-dimensional axis.

When the field direction satisfies the relation $\tan \theta = pb'/qc'$, the trajectory gives only a finite number of lines on the Fermi surface in the first Brillouin zone. Here $p$ and $q$ are arbitrary integers and $b'$ and $c'$ are projections of the lattice vectors $b$ and $c$ onto the plane perpendicular
to the one-dimensional $a$-axis, respectively. As the cancellation of the transverse components becomes imperfect, the trajectory of electrons in real space has the component perpendicular to the one-dimensional axis causing the local minima in the transverse resistance. A fully quantum mechanical calculation has given a result consistent with experimental results and this interpretation [23].

Different interpretations have been proposed for this phenomenon: One of them assumes presence of “hot spot” area on the Fermi surface where electrons suffer strong scattering due to some origins [24]. When magnetic fields are applied at the magic angles, some amount of electrons do not go through the hot spot leading to the resistance minima. It is difficult to find at the present stage which interpretation is more adequate. Other ideas are also proposed stressing the role of electron-electron interactions or non-Fermi liquid behavior [25–29].

Other types of angle dependent magnetoresistance oscillations have been found for magnetic fields rotated in the plane containing the one-dimensional $a$-axis and one of two other axes. When the field is rotated from the $a$-axis toward the $c$ in the $ac$-plane, the resistance shows many local maxima near the $a$-axis followed by a large peak as shown in Figure 7 [30]. The data pattern is nicknamed as “Batman-type.” The angular position of the “Batman ears” gives an excellent measure of $t_b/k_F$ where $t_b$ is the transfer integral parallel to the $b$-axis and $k_F$ the Fermi wave number.

When the rotation is made from the $a$-axis to the $b$ in the $ab$-plane, the resistance shows a minimum at a field direction nearly parallel to the one-dimensional $a$-axis. This phenomenon was first found in (DMET)$_2$I$_3$, as shown in Figure 8 [31], which is considered to have an electronic structure similar to (TMTSF)$_2$X, and was verified to occur also in (TMTSF)$_2$ClO$_4$ [32]. This magic angle has been interpreted as the angle above which no closed orbit is formed on the Fermi surface [32].

Fig. 7. — Angle-dependent magnetoresistance oscillations observed in (TMTSF)$_2$ClO$_4$ at 0.5 K for the field rotation in the $ac$-plane. The angle $\theta$ is measured from the $a$-axis. The 2 T and 1 T traces exhibit superconductivity at smaller angles. (Reproduced from Ref. [30], with kind permission from The American Physical Society).
Fig. 8. — Angle-dependent magnetoresistance oscillations observed in \((\text{DMET})_2\text{I}_3\) for the field rotation in the \(ab\)-plane where the \(a\)- and the \(b\)-axes are the secondary conducting and the most conducting axes, respectively. The angle \(\phi\) is measured from the \(b\)-axis. (Reproduced from Ref. [31], with kind permission from Physical Society of Japan).

Fig. 9. — Schematic phase diagram of \((\text{BEDT-TTF})_2\text{XHg(SCN)}_4\).

The above three types of magnetoresistance oscillations can be reproduced by an elementary calculation of the conductivity tensor on the basis of the Boltzman equation approximation.


3.1. An Anomalous Electronic State of the Quasi Two-Dimensional Conductor \((\text{BEDT-TTF})_2\text{XHg(SCN)}_4\). — The quasi two-dimensional conductor \((\text{BEDT-TTF})_2\text{XHg(SCN)}_4\) has conducting layers of \text{BEDT-TTF} molecules sandwiched by amon layers of \text{XHg(SCN)}_4 [33]. When \(X\) is \text{NH}_4, it shows simple metallic properties at all temperatures and undergoes a superconducting transition at about 1.5 K [34, 35]. The angle dependent magnetoresistance oscillations, analyzed by Yamaji's model above, suggest the presence of a quasi two-dimensional Fermi surface [36].
Fig. 10. — Angle dependent magnetoresistance oscillations of (BEDT-TTF)$_2$KHg(SCN)$_4$ at ambient pressure. The angles $\theta$ and $\phi$ denote the polar angle measured from the normal of the two-dimensional plane and the azimuth one from the $a$-axis, respectively. (Reproduced from Ref. [39], with kind permission from Physical Society of Japan).

When X is K, however, the compound has an anomalous state in the low-temperature (\(< 8\) K)-low-pressure (\(< 5\) kbar)-low-magnetic-field (22 T) regime as shown in Figure 9 [37]. The magnetoresistance has a broad peak around 10 T accompanied by a kink-like structure at about 22 T while the NH$_4$ compounds has no broad peak nor the kink in magnetoresistance [38]. In addition the angle dependent magnetoresistance oscillations show a feature quite different from NH$_4$ compound and Yamaji's model.

To investigate possible origins of the anomalous state the angle dependent magnetoresistance oscillations were measured under high magnetic fields and high pressures. Figure 10 shows an example of the angle dependent magnetoresistance oscillations obtained by rotating a sample around two axes perpendicular to each other and to the magnetic field [39]. One finds a series of resistance minimum. This suggests the presence of a quasi one-dimensional Fermi surface rather than quasi two-dimensional one. However, the geometry of thus expected quasi one-dimensional Fermi surface is different from that of the band calculation [40].

Kartsovnik et al. ascribed the origin of the observed quasi one-dimensional Fermi surface to a possible nesting of the original one due to the Peierls instability as shown in Figure 11 [41].
Blundel et al. showed that the reconstructed quasi one-dimensional Fermi surface explains qualitatively the observed results [42].

This idea seems to be consistent with the possible anti-ferromagnetism suggested by the anisotropy of magnetic susceptibility measured by Sasaki et al. [43] Magnitude of magnetic moment is measured by µSR to be of the order of 10⁻²\(\mu_B\) [44]. The Fermi surface nesting is considered to cause SDW rather than CDW. Under high pressures above about 5 kbar (0.5 GPa) the angle dependent magnetoresistance shows the presence of both the quasi one- and two-dimensional Fermi surfaces in consistent with the band calculation [33].

In the intermediate pressure range of the anomalous state the angle dependent magnetoresistance shows predominantly the presence of the quasi one-dimensional Fermi surface made by the nesting. However, as shown in Figure 12, another series of resistance minima was found [39]. We verified that its angular position is really angle dependent rather than field-strength dependent although its magnitude increases with increasing the field strength. Figure 12 suggests that the possible origins for this resistance minimum have some circular symmetry in the two-dimensional plane. However, the Fermi surface predicted by the band calculation cannot explain the presence of such circular symmetry. Therefore, the origin of this anomaly is remaining puzzling. Some unknown mechanisms are expected to work in the intermediate pressure range.

It has been proposed that more complicated phases are present in the anomalous state [45, 46]. Actually magnetic susceptibility measurements have shown a hysteretic nature suggesting presence of several first-order-like changes in the anomalous state. Moreover recent studies suggest that the phase separation curve in the temperature-magnetic-field plane shown in Figure 9 is related to transport properties and another curve should be drawn to specify magnetic properties. One can expect possible presence of more novel electronic states in relation to the anomalous state.

3.2. Field-Induced Spin-Density Waves in the Superlattice Potential of (TM

TSF)₂ ClO₄. — (TMTSF)₂ PF₆ undergoes the Peierls transition at 12 K accompanied by the onset of SDW [47–50]. The wave vector of SDW was measured by \(^1\)H NMR as (0.5, 0.24, 0.0). Under high pressures above about 6 kbar (0.6 GPa) it becomes superconducting below
about 1 K. However, (TMTSF)$_2$ClO$_4$ remains metallic at ambient pressure and undergoes the superconducting transition at about 1 K. This difference between two materials is ascribed to the higher one-dimensionality of the former material than the latter. Therefore one may say that the Peierls instability is suppressed in (TMTSF)$_2$ClO$_4$ by the two- or three-dimensional coupling of TMTSF molecular stacks.

It was found that application of high magnetic fields in the superconducting state restored SDW that is called the field-induced spin-density waves (FISDW) [51, 52]. This suggests that the magnetic field lowers the effective system dimensionality. With further increasing magnetic fields a series of SDW subphases and a quantized Hall effect were found as shown in Figures 13 and 14 [53–57]. Each subphase of FISDW is discriminated from neighboring one by some anomalies of electrical resistance, heat capacity etc.

This phenomenon has been interpreted in terms of the so-called standard model [58–60]. It takes account of the interplay between the Peierls instability and the Landau quantization of two-dimensional electrons and holes in small pockets made by an imperfect nesting of the Fermi surface: Magnetic fields give the quasi one-dimensional electronic system a periodic potential specified by the magnetic length $G = beB/h$ in addition to the lattice periodicity,
Fig. 13. — Temperature-pressure-magnetic-field phase diagram of \((\text{TMTSF})_2\text{X}\). \((\text{TMTSF})_2\text{ClO}_4\) has the origin of pressure axis at pressures higher than 6 kbar of this figure because it is superconducting below about 1 K at ambient pressure. (Reproduced from Ref. [54], with kind permission from The American Physical Society).

where \(b\) is the lattice parameter for the secondly conducting axis, \(B\) the magnetic flux density and \(h\) the Planck constant. The system possibly undergoes the Peierls instability with the nesting vector of \(Q_n = Q_0 + nG\) where \(Q_0\) is the nesting vector in the low-field limit and \(n\) is an arbitrary integer. When the nesting occurs with the \(n\)-th nesting vector \(Q_n\), there remain electron pockets and hole ones because of the imperfect nesting causing \(n\) Landau levels below the Fermi level in those pockets. It is considered that this interplay of the Peierls instability and the Landau quantization dominates the nesting vector of SDW so as to keep the Fermi level just at the middle of two Landau levels across the Fermi level leading to the quantized Hall effects.

The quantized Hall effect is realized when the number of two-dimensional electrons increases proportionately to the field strength within some field range, jumps back to the original one, and this process occurs repeatedly. In ordinary quantized Hall effect this requirement is satisfied by the Anderson localization of two-dimensional electrons. In the present case, however, the key mechanism for this is ascribed to a successive change of the SDW wave vector. In other words the wave vector changes with magnetic fields so as to keep the number of remaining two-dimensional electrons proportional to the field strength within some field range. This is equivalent to the situation of the Fermi level kept at the middle of two Landau levels. When the magnetic field reaches a critical value the index \(n\) of the SDW wave vector changes by one and the Fermi level jumps to the middle of neighboring Landau levels.
Fig. 14. — The quantized Hall effect observed in (TMTSF)$_2$PF$_6$. (Reproduced from Ref. [53], with kind permission from The American Physical Society).

The standard model described above seems to explain satisfactorily the observed phenomena. However, some problems are still remaining to be solved; nature of electronic state in the high field limit [61,62], mechanisms of sign change of the quantized Hall resistance [63–65] etc. For example, with increasing magnetic-field strength (TMTSF)$_2$PF$_6$ under pressure shows the successive phase transition of FISDW which is well explained in terms of the standard model. In (TMTSF)$_2$ClO$_4$, however, the subphase in the high field limit specified by the Landau number of 0 appears to be missing.

Osada et al. explained this in terms of the superlattice potential given by an orientational ordering of ClO$_4$ at about 24 K [66]. This structural change makes the original unit cell doubled along the b-axis that is perpendicular to the one-dimensional axis. Therefore the first Brillouin zone is reduced to a half of the original causing the presence of two pairs of Fermi surface near $k_F$ and $-k_F$, respectively. This suppresses the divergence of the polarization function (generalized susceptibility) at $2k_F$ responsible for the Peierls instability as shown in Figure 15 leading to the lowering of the Peierls transition temperature of subphases specified by even Landau numbers.

However, it has been pointed out that another phase might be present in the higher field regime. There remains a controversy in identifying the electronic state in the high field regime.

3.3. RAPID OSCILLATIONS IN MAGNETORESISTANCE OF (TMTSF)$_2$X. — Some TMTSF salts such as (TMTSF)$_2$PF$_6$ [64,67], (TMTSF)$_2$AsF$_6$, [68] (TMTSF)$_2$ClO$_4$ [62,69–71], (TMTSF)$_2$ReO$_4$ [65,72], and (TMTSF)$_2$NO$_3$ [73] show oscillations in magnetoresistance as a function of the inverse of field strength as shown in Figure 16. This is sometimes called rapid oscillations. If one ascribes the oscillation frequency, ranging 200-330 T in these materials, to the Shubnikov-de Haas effects, the area of the closed Fermi surface responsible for the oscillations is estimated as about 2.5–4% of that of the first Brillouin zone. Why do the rapid
Magnetic-field dependence of the polarization function (generalized susceptibility) \( \chi_0 \) of (TMTSF)_2ClO_4 under the superlattice potential made by the orientational ordering of ClO_4. The label \( N \) denote the Landau number. The solid curve denote the largest value that is realized in real system. (Reproduced from Ref. [66], with kind permission from The American Physical Society).

Oscillations occur in these quasi one-dimensional conductors having no closed Fermi surface but a warped-planar open one?

Magnetoresistance and thermodynamic measurements have revealed that several kinds of mechanism are responsible for the rapid oscillations depending on the type of underlying electronic state. All of the above materials show the rapid oscillations in the SDW state. Its amplitude decreases with lowering temperature. At least in (TMTSF)_2ClO_4 the oscillations are ascribed to a thermodynamic origin because they are found also in the magnetization [69,74], the heat capacity [75] and the sound velocity [76].

Up to now only (TMTSF)_2ClO_4 shows the rapid oscillations in the normal metallic state above the superconducting critical temperature or in that above the critical field of superconductivity. The oscillation amplitude in this case increases with decreasing temperature [77,78] and the magnetization does not oscillate suggesting a non-thermodynamic origin of this [79].

It has been proposed that the rapid oscillations in the SDW state of (TMTSF)_2PF_6 are ascribed to oscillations in the band gap [80]: When the SDW is incommensurate with the lattice, many narrow gaps appear in the Landau bands formed in the band gap of the original band. The width of these min-gaps can oscillate as a function of the inverse of the field strength leading to the oscillations in conductivity caused by carriers activated thermally across the min-gaps. This mechanism explains well the thermodynamic nature and the decrease in the oscillation amplitude with decreasing temperature because a thermal activation process is involved.

Similar mechanisms are expected to work also in the SDW state of (TMTSF)_2NO_3 and (TMTSF)_2ClO_4. However, the orientational ordering of the anion, NO_3 or ClO_4, can play some roles in the rapid oscillations. The orderings of NO_3 and ClO_4 give the electron system periodic potentials described by the wave vector (1/2, 0, 0) and (0, 1/2, 0), respectively, in the unit of the reciprocal lattice vector [81,82]. When the other potential (1/2, 1/2, 0) due to SDW is superposed, the reconstructed Fermi surface is composed of a few pockets. It is possible to explain the observed rapid oscillations in terms of closed orbits made by magnetic breakdown from a pocket to the neighboring one [83].
Another mechanism has been proposed to explain the rapid oscillations in (TMTSF)$_2$ClO$_4$ in terms of the anion ordering potential and the suppression of the Peierls instability for FISDW with even Landau indices [66]. Some features of the rapid oscillations are well explained by this mechanism.

The rapid oscillations in the normal metallic state of (TMTSF)$_2$ClO$_4$ have been ascribed to the anion ordering potential of (0, 1/2, 0) [74]. As depicted in Figure 17 this anion potential reconstructs the Fermi surface resulting in two Fermi surfaces near $+k_F$ and $-k_F$, respectively.
Fig. 17. — The Stark interference effect expected for two Fermi surfaces made by the superlattice potential in (TMTSF)2ClO4.

Under magnetic fields applied perpendicular to the $ab$-plane an electronic wave-function component on one of the two surfaces interferes with another component on the other surface. This is called the Stark interference effect [84]. This phenomenon makes the conductivity parallel to the $b$-axis oscillate as a function of the inverse of field strength in agreement with experimental results [85]. This mechanism has nothing to do with thermodynamic quantities and, actually, magnetization measurements give no rapid oscillations.

Thus some aspects of the rapid oscillations are explained in terms of a few types of mechanism as described above. At the present stage, however, it is not certain whether or not these mechanisms are enough to cause the rapid oscillations.

3.4. FIELD-INDUCED SUPERCONDUCTIVITY. — As shown in Figure 18 it is proposed theoretically that magnetic fields enhance the critical temperature of superconductivity of low-dimensional conductors [86]. The following is one of basic ideas for this "field-induced superconductivity". In quasi one-dimensional conductors such as (TMTSF)2ClO4, conduction electrons move predominantly in the plane spanned by the most conducting and the secondarily conducting axes. However, the motion along the least conducting axis is usually neglected. When magnetic fields are applied parallel to the secondarily conducting $b$-axis of (TMTSF)2ClO4, field effects are negligibly small because the motion of electrons is almost confined in the $ab$ plane. Therefore it is expected that the magnetic fields do not necessarily suppress the superconductivity. Several theoretical ideas are proposed predicting qualitatively the enhancement of the superconducting critical temperature [86–91].

Experimental trials have been made to find this superconductivity enhancement. Some sign of superconductivity under high magnetic fields are obtained although no definite evidence has been obtained for the presence of field-induced superconductivity [92]. Besides technical difficulties in measurements one may have to take account of another mechanism which suppresses the superconductivity such as the Pauli limit. When high magnetic fields are applied to the Cooper pair, the singlet spin state is made unstable leading to the suppression of superconductivity. More experimental and theoretical investigations are necessary to give a decisive answer to these theoretical predictions.
4. Summary

Magnetic field effects to electron spins and electron orbital motions are discussed in the quasi one-dimensional conductors (R1R2DCNQI)2Cu and (TMTSF)2X and in the quasi two-dimensional conductor (BEDT-TTF)2XHg(SCN)4.

Magnetic fields induce a metal to insulator transition in (R1R2DCNQI)2Cu whose Cu atoms have the mixed valence state Cu4+/3+. This is explained in terms of the Zeeman energy of Cu2+ spins present in the insulating state.

The orbital motion of electrons in low-dimensional conductors is affected by magnetic fields giving rise to the angle-dependent magnetoresistance oscillations. This phenomenon is basically explained in terms of a semi-classical kinetics of electrons under magnetic fields. In quasi two-dimensional conductors such as (BEDT-TTF)2I3 the resistance shows oscillations as a function of the angle between the magnetic field direction and the normal to the two-dimensional plane. The resistance shows a series of maxima at magic angles. This phenomenon is explained by Yamaji’s model and provides a clue to estimate the diameter of a semi-cylindrical Fermi surface.

In quasi one-dimensional conductors like (TMTSF)2ClO4 the angle-dependent magnetoresistance oscillations cause three types of phenomena depending on the plane of field rotation. Two of them show resistance minima at magic angles and the other resistance peak. These phenomena are explained in terms of geometrical conditions between electrons’ trajectory and the warped-planar Fermi surface in the first Brillouin zone although exact origins must be further examined.

Electronic properties in an anomalous state of the quasi two-dimensional conductor (BEDT-TTF)2KHg(SCN)4 are discussed in the light of the angle dependent magnetoresistance oscillations. It is found that the Fermi surface is reconstructed by the onset of SDW causing a one-dimensional Fermi surface whose geometry is different from those in the normal metallic state or in (BEDT-TTF)2NH4Hg(SCN)4 having no anomalous state. However, some phenomena observed in the anomalous state suggest presence of more complicated electronic states.

Properties of field-induced spin-density waves are studied in relation to the superlattice potential made by the anion ordering in (TMTSF)2ClO4. Most of phenomena are well interpreted in terms of the so-called standard model. However, more investigations are necessary to reveal
puzzling properties such as the electronic properties in the high field limit.

Possible origins of the so-called rapid oscillations in magnetoresistance of (TMTSF)$_2$X are examined. It is found that not single but several types of mechanism are responsible for this phenomenon because, at least, the rapid oscillations in SDW state has a thermodynamic origin but that in the normal metallic state has not. Especially the superlattice potential made by the orientational ordering of anions is considered to play important roles in causing the rapid oscillations.

It is proposed that magnetic fields enhance the superconductivity of quasi one-dimensional conductors. However, no experimental evidences has been obtained.

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