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Low integer Landau level filling factors ν and indications for the fractional $\nu = 1/2$ in the 2D organic metal κ-(BEDT-TTF)$_2$I$_3$

E. Balthes[a,*], D. Schweitzer[a], P. Wyder[b]

[a] 3. Physikalisches Institut der Universität Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart, Germany
[b] Grenoble High Magnetic Field Laboratory, MPI-FKF and CNRS, BP 166, F-38042 Grenoble, France

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Abstract

In the two-dimensional (2D) organic metal κ-(BEDT-TTF)$_2$I$_3$ the low integer Landau level filling factors $\nu = 1$–4 are observed under specific experimental conditions. In high magnetic fields even the presence of the fractional $\nu = 1/2$ is strongly indicated in this multilayer material. These ν are detected by the chemical potential μ, i.e. a thermodynamic quantity, which could be probed under complex fermiological conditions.

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1. Introduction

In semiconducting two-dimensional electronic systems (2DESs), based on, e.g. Si-metal-oxide field effect transistors or realised as electron gases confined to the interface of GaAs/Al$_x$Ga$_{1-x}$As heterostructures, electron localisation is known to be possible at high magnetic fields, i.e. low Landau level filling factors ν and low temperatures. At integer ν these localisation effects may be introduced by Landau level broadening, thus generating the integer quantum Hall effect (IQHE) [1,2]. At fractional ν, however, localisation is based on electron correlation, thus leading to the fractional quantum Hall effect (FQHE) [3,4]. Up to now such electron localisation around low integer and fractional ν is widely investigated in single-layer 2DESs (e.g. Ref. [5] and references therein). In single-layer 2DESs electron correlation was found to generate stable ground states at fractional ν, in which electron localisation may occur around odd-denominator ν (e.g. $\nu = 1/7$, 1/5, 1/3, 2/3, etc.), whereas even-denominator ν are in general unstable states [4,6–10]. Both, the absence of the FQHE at $\nu = 1/2$ in experiments as well as ground state calculations, suggest that in a single-layer 2DES this special ν is forbidden [11]. This means that at $\nu = 1/2$ the correlated electronic system remains fermionic and, indeed, it was shown that a single-layer 2DES at $\nu = 1/2$ can be described by the so-called composite fermion approach (for a review see Ref. [12]). In contrast, in double- or multilayer 2DESs the ground state stabilities, i.e. the 'allowed' ν, may change drastically in the sense that $\nu = 1/2$ may even become a stable ground state, whereas odd-denominator ν may become unstable.

The stability criteria for $\nu = 1/2$, but also odd-denominator fractional ν as well as odd and even integer ν are found to be controlled by the interplay of intralayer electron–electron coupling and interlayer coupling [13,14], accompanied by interlayer electron tunnelling [15,16]. Up to now all these features were theoretically predicted and/or experimentally observed only on 2DESs based on semiconductors. In the present work, we took up the possibility

* Corresponding author. Fax: +49 711 685 5281.
E-mail address: e.balthes@physik.uni-stuttgart.de (E. Balthes).

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that such electron correlation and localisation effects (a) may be present also in metallic 2DESs and (b) that they may influence not only the quantum Hall effects, but also other transport phenomena at high magnetic fields as, e.g. magnetoquantum oscillations (QOs), i.e. the Shubnikov-de Haas (SdH) effect. Therefore, we performed SdH as well as de Haas-van Alphen (dHvA) experiments in the normal-conducting state of the organic superconductor κ-(BEDT-TTF)$_2$I$_3$—a substance which presumably provides the to date strongest 2DES within its class of materials.

The charge-transfer salt κ-(BEDT-TTF)$_2$I$_3$ based on the electron donor BEDT-TTF [Bis(ethylenedithio)tetrathia-fulvalene] is an organic metal with a superconducting transition at around 4 K [17,18]. κ-(BEDT-TTF)$_2$I$_3$ consists of 2D conducting BEDT-TTF sheets (which yield the (*b*,*c*)-planes), separated by I$_3$ layers. Tight-binding band structure calculations [17] yield a Fermi surface consisting of an elliptical ('A_2') and a circular ('A_3') hole orbit (Fig. 1(b)). This corresponds very well to the observed QO frequencies $F_2=570$ T and $F_3=3883$ T, respectively, [19]. As shown in Ref. [20], single crystals of this material represent a strongly 2D electronic system with a 'warping' (i.e. corrugation) of the cylindrical Fermi surface smaller than 0.035%. This corresponds to an electronic anisotropy given by the ratio of the transfer integrals *t* perpendicular and parallel to the conducting planes of $t_\perp/t_\parallel<1.5\times10^{-4}$. Despite, this strong two-dimensionality, the Lifshitz–Kosevich (LK) theory for

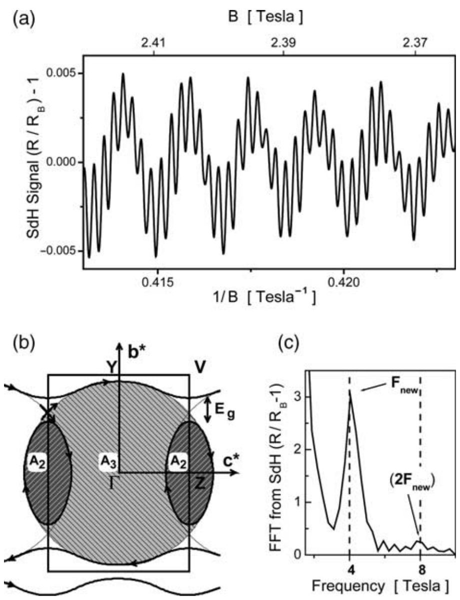

Fig. 1. (a) Low-field part of typical SdH oscillations (magnetoresistance) of κ-(BEDT-TTF)$_2$I$_3$ single crystals after division by the nonoscillatory background magnetoresistance (full curve see Ref. [31]); (b) Fermi surface according to Ref. [17]; (c) Low-frequency part of the Fourier transform of the signal from the field window below 10 T (discussion see later).

QOs in 3D systems [21,22] remains well applicable as long as the magnetic field is inclined from the orientation normal to the conducting (*b*,*c*)-planes, i.e. $\Theta\neq0°$ [23,24] (minor deviations from LK behaviour can be explained by the oscillation of the chemical potential μ with the QO frequency F_3 [25,26]). However, in the special field orientation $B\perp(b,c)$ (i.e. $\Theta=0°$) strong anomalous damping effects in the amplitudes of the SdH oscillations with the frequencies F_2 and F_3 are observed typically for $B>12$ T and $T<1$ K, so that under these specific experimental conditions the LK theory is not applicable any more [23,24,27]. It was found that these strong damping effects and especially their restriction to $\Theta=0°$ cannot be explained by 'conventional' features, such as spin splitting, magnetic interaction, magnetic breakdown [22], a warping or an instability of the Fermi surface, a geometrical resonance between different trajectories on the Fermi surface, quantum interference, eddy currents [23,28,29] and even not by considering results of the strong two-dimensionality such as μ oscillations with F_3 [25,26].

The restriction of the damping effects to $\Theta=0°$ (within $\delta\Theta<1°$ [24]) called for a reconsideration of this special experimental condition. Thereupon it was widely discussed in Refs. [23,28–30] (and is, therefore, not repeated here), why in a metallic multilayer 2DES $\Theta=0°$ is the exclusive field orientation, where two-dimensionality (and its results) may take effect. This has been taken as evidence of a further result of two-dimensionality at high fields, i.e. electron localisation, and thus the strong damping effects were attributed to a loss of mobile carriers contributing to QOs in transport. Due to the high carrier density in the present organic metal the possibility of electron correlations should not be disregarded. However, in this connection, electron correlation and localisation has been yet discussed mainly with 2DESs based on semiconductors at low ν, whereas the present 2DES is a metal and, moreover, $\nu_{F_j}\sim F_j/B$ is fairly high, at least for the known QO frequencies F_2 and F_3. In view of the limited resolution of tight-binding band structure calculations the possibility of further small closed orbits on the Fermi surface was followed by performing SdH experiments at $\Theta=0°$ and, indeed, a further QO frequency with $F_0=13$ T was found, thus revealing the presence of a small pocket on the Fermi surface of about 3.4×10^{-3} of the first Brillouin zone [28,30]. F_0 reaches $\nu_{F_0}=2$ at 19 T and it turned out that (a) F_0 imposes its own proximity to quantum limit onto the entire electronic system, even on the parts of high ν_{F_2} and ν_{F_3} and (b) F_0 controls the strong damping effects of the SdH amplitudes of F_2 and F_3 at 0° just by its own low integer $\nu_{F_0}=2$. These results (which in parts are recalled in more detail below, see discussion of Fig. 2), supported the supposition that the damping effects of QOs in the 2D organic metal κ-(BEDT-TTF)$_2$I$_3$, indeed, may be generated by electron localisation [30]. However, the preceding findings still left a number of open questions. The most recent results presented here, reveal that the behaviour of