Pis'ma v ZhETF, vol. 118, iss. 2, pp. 102 – 103

A method to reveal and investigate almost 2D Fermi surfaces in layered conductors: Universal resistivity in a parallel magnetic field

A. G. Lebed[1)]

Department of Physics, University of Arizona, 1118 E. 4-th Street, Tucson, AZ 85721, USA

Landau Institute for Theoretical Physics, 117334 Moscow, Russia

Submitted 30 May 2023
Resubmitted 11 June 2023
Accepted 12 June 2023

DOI: 10.31857/S1234567823140069, EDN: gzfseg

One of the most important questions in area of the quasi-two-dimensional (Q2D) conductors and superconductors is the existence or not of the Fermi surfaces (FS's) in their non-superconducting phases. This question is still very controversial, where some experiments show the existence of the so-called pseudogap non-Fermi-liquid (n-FL) phase (for reviews, see [1, 2]), whereas some others demonstrate the FL quantum oscillations of resistivity [3].

In [4, 5], we suggested a new original method to investigate the FS's in the Q2D conductors in parallel magnetic fields. In the framework of the Boltzmann kinetic equation in the so-called τ-approximation [6, 7], it was shown that in a clean limit perpendicular resistivity did not depend on impurities concentration and was a linear function of the parallel magnetic field,

$$\rho_{zz} \sim C_1 |H|, \tag{1}$$

in a broad region of the fields. This theoretical result was confirmed later in some publications (see, for example, [8]) and was experimentally observed [4, 8, 9]. The important point is that coefficient C_1 depends on some characteristics of a 2D cross-section of the Q2D electron FS, which can be measured in in-plane rotated magnetic fields. Nevertheless, the suggested method has not received still a broad application mainly due to the fact that a validity of the Boltzmann kinetic equation in metallic phases of organic and high-T_c superconductors, in particular in the τ-approximation, is not generally justified.

The goal of our paper is a two-fold. First, we show that Eq. (1) has to be valid for perpendicular resistivity of a clean Q2D conductors also in a quantum case. We demonstrate that it survives even in the quantum picture, where electrons in a strong parallel magnetic field tunnel from one conducting layer to another. This indicates that the universal resistivity is a very general phenomenon. The second our goal is to suggest possible observations of the above discussed phenomenon as the good test of the existence of the 2D FS's, which is a central question for the majority of organic, high-T_c, and some other layered superconductors in a metallic phase.

Below, we consider a layered superconductor in the so-called tight-binding model [6] with the following Q2D electron spectrum, which is an anisotropic one within the conducting plane:

$$\epsilon(\mathbf{p}) = \epsilon(p_x, p_y) - 2t_\perp \cos(p_z c^*), \quad t_\perp \ll \epsilon_F, \tag{2}$$

[Here, $\epsilon(p_x, p_y) = \epsilon_F$, $t_\perp$ is the integral of the overlapping of electron wave functions in a perpendicular to the conducting planes direction; ϵ_F is the Fermi energy; $\hbar \equiv 1$.] As to the parallel magnetic field, it is assumed to be inclined by angle β with respect to $\mathbf{x}$ axis, whereas alternative current (a.c.) electric field with small frequency is applied perpendicular to the conducting layer,

$$\mathbf{H} = (\cos\beta, \sin\beta, 0)H, \;\; \mathbf{A} = (-\sin\beta, \cos\beta, 0)Hz, \tag{3}$$

$$\mathbf{E}(t) = [0, 0, \exp(i\omega t - \nu t)]E_0, \quad \nu \to +0 \tag{4}$$

(see Fig. 1).

Let us rewrite Hamiltonian (2) in the absence of the fields in the following form:

$$\hat{H} = \epsilon\left(-i\frac{\partial}{\partial x}, -i\frac{\partial}{\partial y}\right) + \frac{1}{2m}\left(-i\frac{\partial}{\partial z}\right)^2 - \sum_{n=-\infty}^{\infty} U(z - c^* n), \tag{5}$$

which can be used before the tight binding procedure, performed in Eq. (2) for electron motion along $\mathbf{z}$ axis; m is free electron mass, $U(z - c^* n)$ is potential energy from atomic plane, located at the position $z_n = c^* n$ along $\mathbf{z}$ axis. Let us introduce the magnetic field (3) into the

[1)]e-mail: lebed@arizona.edu

Hamiltonian (5) by using the so-called Peierls substitution method [6, 7]:

$$-i\frac{\partial}{\partial x} \to -i\frac{\partial}{\partial x} - \frac{e}{c}A_x, \quad -i\frac{\partial}{\partial y} \to -i\frac{\partial}{\partial y} - \frac{e}{c}A_y. \quad (6)$$

As a result, we obtain:

$$\hat{H} = \epsilon\left(-i\frac{\partial}{\partial x} + \frac{eHz\sin\beta}{c}, -i\frac{\partial}{\partial y} - \frac{eHz\cos\beta}{c}\right) + \frac{1}{2m}\left(-i\frac{\partial}{\partial z}\right)^2 - \sum_{n=-\infty}^{\infty} U(z - c^* n). \quad (7)$$

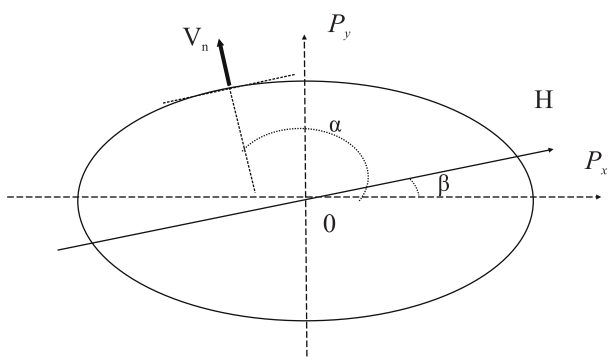

Fig. 1. 2D cross-section of the electron Q2D FS (2) is shown, where the magnetic field (3) is applied at the polar angle β counted from $\mathbf{x}$ axis. The position of electron on the 2D cross-section is characterized by the polar angle α

Quantum Hamiltonian (7) is considered by us in [10], where it is shown that the quantum Kubo formula allows us to write the low frequency conductivity in the form

$$\sigma_{zz}(\omega \to 0) = \frac{2e^2 t_\perp^2 c^*}{\pi} \oint \frac{dl}{|\mathbf{v}_n(l)|}\delta[\omega_c(\alpha, \beta)], \quad (8)$$

where

$$\omega_c(\alpha, \beta) = \left(\frac{e}{c}\right)|\mathbf{v_n}(\alpha)|Hc^* \sin(\alpha - \beta), \quad (9)$$

with $\mathbf{v_n}(\alpha)$ being velocity component perpendicular to the 2D FS (see Fig. 1). In the case, where $R(\beta) \neq 0$, it is possible to show that Eq. (8) gives the following result:

$$\sigma_{zz}(\beta) = \frac{2et_\perp^2 cR(\beta)}{\pi v_n^2(\beta)|H|} \sim \frac{R(\beta)}{v_n^2(\beta)}\left(\frac{1}{|H|}\right), \quad (10)$$

where $R(\beta)$ – radius of a curvature of the $2D$ cross-section of the Q2D FS (2).

Note that in the Letter we have used the Landau FL theory [6] and quantum mechanical description for electron motion in a Q2D conductor as well as quantum mechanical description of conductivity – the Kubo formula. So, if the FL theory is valid in some Q2D conductor, experimentalists can conduct experiments in parallel magnetic fields and can discover unusual linear magnetoresistance (1) and (10). Then, they can rotate the field and extract angular dependence of the important 2D FS parameter $\frac{v_n^2(\beta)}{R(\beta)}$ (see Fig. 1) which allows to make some conclusions about the shape of the 2D FS.

On the hand, Eq. (10) can be used for testing of a validity of the Landau FL description and of the existence of the Q2D(2D) FS in a given layered conductor. To get metallic phase in high-T_c superconductors, we typically need pulsed ultrahigh magnetic fields (see, for example, [11]), whereas in organic superconductors [9], UTe_2 [12–14], NbS_2, and $NnSe_2$ [15] steady high parallel magnetic fields can be experimentally applied.

The author is thankful to N. N. Bagmet (Lebed) for useful discussions.

This is an excerpt of the article “A method to reveal and investigate almost 2D Fermi surfaces in layered conductors: Universal resistivity in a parallel magnetic field”. Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364023601707

1. P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. **78**, 17 (2006).
2. S. I. Vedeneev, Phys.-Uspekhi **64**, 890 (2021).
3. N. Barišić, S. Badoux, M. Chan, C. Dorow, W. Tabiś, B. Vignolle, G. Yu, J. B’eard, Xudong Zhao, C. Proust, and M. Greven, Nature Phys. **9**, 761 (2013).
4. A. G. Lebed and N. N. Bagmet, Phys. Rev. B **55**, R8654 (1997).
5. A. G. Lebed and N. N. Bagmet, Synth. Met. **85**, 1493 (1997).
6. A. A. Abrikosov, *Fundamentals of Theory of Metals*, Elsevier Science, Amsterdam (1988).
7. I. M. Lifshits, M. Ya. Azbel and M. I. Kaganov, *Electron Theory of Metals*, Consultants Bureau, N.Y. (1973).
8. A. J. Schofield and J. R. Cooper, Phys. Rev. B **62**, 10779 (2000).
9. *The Physics of Organic Superconductors and Conductors*, ed. by A. G. Lebed, Springer-Verlag, Berlin (2008).
10. A. G. Lebed, Phys. Rev. Lett. **95**, 247003 (2005).
11. A. S. Dzurak, B. E. Kane, R.G. Clark et al. (Collaboration), Phys. Rev. B **57**, R14084 (1998).
12. S. Ran, C. Eckberg, Q. P. Ding, Y. Furukawa, T. Metz, S. R. Saha, I.-L. Liu, V. Zic, H. Kim, J. Paglione, and N. P. Butch, Science **365**, 684 (2019).
13. A. G. Lebed, Mod. Phys. Lett. B **34**, 2030007 (2020).
14. V. P. Mineev, JETP Lett. **111**, 715 (2020).
15. Ch.-w. Cho, Ch.Y. Ng, Ch. H. Wong, M. Abdel-Hafiez, A. N. Vasiliev, D. A. Chareev, A. G. Lebed, and R. Lortz, New J. Phys. **24**, 083001 (2022).