Pis'ma v ZhETF, vol. 111, iss. 2, pp. 86 – 87

Metamorphoses of electron systems hosting a fermion condensate

V. A. Khodel[+*1)], J. W. Clark[*×], M. V. Zverev[+○]

[+]National Research Centre Kurchatov Institute, 123182 Moscow, Russia

[*]McDonnell Center for the Space Sciences & Department of Physics, Washington University, St. Louis, MO 63130, USA

[×]Centro de Investigação em Matema'tica e Aplicações, University of Madeira, 9020-105 Funchal, Madeira, Portugal

[○]Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia

Submitted 31 October 2019
Resubmitted 3 December 2019
Accepted 4 December 2019

DOI: 10.31857/S0370274X2002006X

We present a theory of interaction-induced flat bands, emergent in strongly correlated electron systems beyond a critical point, at which the topological stability of the Landau state breaks down, and apply this theory to analysis of phenomena that, seemingly, have little in common, including: (i) a specific metal-insulator transition with formation of the so-called quantum electron solid state in two-dimensional electron liquid, residing in MOSFETs and SiGe/Si/SiGe quantum wells, (ii) a second-order high-temperature superconducting phase transition in copper oxides, whose critical temperature T_c turns out to be proportional to the Fermi energy $T_F = p_F^2/2m_e$ and (iii) non-Fermi-liquid low-temperature chaotic-like behavior of many strongly correlated electron systems, documented in experimental studies of their resistivity $\rho(T)$ for two last decades. We propose that both these transitions are triggered by a *spontaneous* topological rearrangement of the conventional Landau state that consists in formation of a so-called *fermion condensate* (FC) [1–3], an interaction-induced flat portion $\epsilon(\mathbf{p}) = 0$ of the single-particle spectrum $\epsilon(\mathbf{p})$. The analogy with a boson condensate (BC) is evident from the respective densities of states $\rho_{\rm FC}(\varepsilon) = n_{\rm FC}\delta(\varepsilon)$ and $\rho_{\rm BC}(\varepsilon) = n_{\rm BC}\delta(\varepsilon)$, where $n_{\rm FC}$ and $n_{\rm BC}$ denote the fermion and boson condensate densities. A distinctive feature of electron systems, harboring such flat bands, is the presence of a finite *classical-like* entropy excess $S_0 = S(T = 0) \propto n_{\rm FC}$ obtained upon substituting a zero-temperature FC momentum distribution $0 < n_*(\mathbf{p}) < 1$ into the textbook Landau formula.

The original model of fermion condensation was introduced and analyzed in [1–3] more than 25 years ago. With further theoretical development, evidence for its essential role in coherent explanation of diverse non-Fermi-liquid behavior across a broad range of strongly correlated Fermi systems at low temperatures, has since been presented in numerous works, notably [1–10]. A significant advance toward a self-consistent theory of fermion condensation has been made in microscopic calculations based on a Hubbard model, performed in [11, 12] using well-established renormalization-group methods. In addition, the original FC formalism was recently updated [13] to properly account for interactions between the FC and normal quasiparticles that has made it possible to explain the topological nature of the metal-insulator transition in two-dimensional high-mobility electron systems of SiGe/Si/SiGe quantum wells [14–16].

The recent "second wind" of the original FC scenario has received specific impetus from the rapid progress in experimental (e.g., see [17–20]) and theoretical [21, 22] studies of doped monolayer graphene and, especially, twisted bilayer graphene, where flattening of the single-particle spectrum $\epsilon(\mathbf{p})$ can be *engineered*. In particular, in a recent experimental paper [23], the manifestation of interaction-induced flat bands in the electron system of monolayer graphene has been documented for the first time. It is also expected [24, 25] that the dispersionless FC spectrum with singular density of states is the trigger for possible granular room-temperature superconductivity in highly oriented pyrolitic graphite [26, 27] (and references therein).

In dealing with 2D strongly correlated low-density homogeneous electron liquid of MOSFETs we focus on a specific metal-insulator transition uncovered long ago in [28, 29], the nature of which remains unexplained yet. We demonstrate that proper accounting for interactions between normal quasiparticles and the FC, emergent at densities n, lower than the critical density n_t, at which the topological stability of the original Landau state breaks down, results in formation of a specific non-BCS gap $\Upsilon(\mathbf{p})$ in the single-particle spectrum, whose magnitude changes linearly with variation of the difference $n_t - n$. It is such a behavior of the activation energy that has been uncovered in measurements of the electrical resistivity of MOSFETs just in this density region [15] that reveals the topological nature

1)e-mail: vak@wuphys.wustl.edu

of this transition. Since none of Pomeranchuk stability conditions breaks down, homogeneity of systems under consideration *persists*, in agreement with the structure of the so-called quantum-electron-solid state uncovered in [14–16]. One might expect that these behaviors, revealed in MOSFETs, will be verified experimentally for SiGe/Si/SiGe quantum wells in near future.

Turning to high-T_c superconductors, the two-gap structure (Δ, Υ) of their single-particle spectra has been discussed. The gap Δ associated with Cooper pairing is distinguished by a non-BCS *linear* relation between the critical temperature T_c and Fermi energy T_F. Comparison of theoretical results with available ARPES data [30] demonstrates that our theory properly describes the angular structure of both the gaps $\Delta(\mathbf{p})$ and $\Upsilon(\mathbf{p})$. Moreover, it properly explains the interplay between the two gaps on different sides of the $T-x$ phase diagram of cuprates, including emergence of an optimal doping x_o at which the BCS critical temperature $T_c(x)$ reaches maximum.

A linear in temperature T behavior of the normal-state resistivity $\rho(T)$ of high-T_c superconductors, uncovered more than 20 years ago and still defying theoretical explanation, is attributed to scattering of light carriers by the FC. Because the properties of superconducting states of systems having a FC are unambiguously related to those of normal states, it is not surprising that such seemingly antagonistic characteristics as the critical temperature $T_c(x)$ and the coefficient $A_1(x)$ specifying the linear-in-T part of the normal-state resistivity $\rho(T)$, show similar behavior, as experiment demonstrates [31].

It is worth stressing that exhibitions of quantum chaos, discussed in our article, have the topological nature, associated with the respective spontaneous rearrangement of the Landau state. This is quite in contrast to a model [32] in which, despite something in common with the scenario of fermion condensation [33], the chaotic element is introduced *deliberately* in terms of the respective distribution of interaction matrix elements.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364020020010

1. V. A. Khodel and V. R. Shaginyan, JETP Lett. **51**, 553 (1990).
2. G. E. Volovik, JETP Lett. **53**, 222 (1991).
3. P. Nozières, J. Phys. I France **2**, 443 (1992).
4. G. E. Volovik, Springer Lecture Notes in Physics **718**, 31 (2007).
5. V. A. Khodel, V. R. Shaginyan, and V. V. Khodel, Phys. Rep. **249**(1), 86 (1994).
6. V. A. Khodel, J. W. Clark, and M. V. Zverev, Phys. Rev. B **78**, 075120 (2008).
7. V. R. Shaginyan, A. Z. Msezane, K. G. Popov, J. W. Clark, M. V. Zverev, and V. A. Khodel, Phys. Rev. B **86**, 085147 (2012).
8. G. E. Volovik, JETP Lett. **59**, 830 (1994).
9. M. Ya. Amusia, K. G. Popov, V. R. Shaginyan, and V. A. Stephanovich, *Theory of Heavy-fermion Compounds*, Springer, Berlin, Germany (2014).
10. G. E. Volovik, JETP Lett. **107**, 516 (2018).
11. V. Yu. Irkhin, A. A. Katanin, and M. I. Katsnelson, Phys. Rev. Lett. **89**, 076401 (2002).
12. D. Yudin, D. Hirschmeier, H. Hafermann, O. Eriksson, A. I. Lichtenstein, and M. I. Katsnelson, Phys. Rev. Lett. **112**, 070403 (2014).
13. V. A. Khodel, J. Low Temp. Phys. **191**, 14 (2018).
14. P. Brussarski, S. Li, S. V. Kravchenko, A. A. Shashkin, and M. P. Sarachik, Nat. Commun. **9**, 3803 (2018).
15. M. Yu. Mel'nikov, A. A. Shashkin, V. T. Dolgopolov, Amy Y. X. Zhu, S. V. Kravchenko, S.-H. Huang, and C. W. Liu, Phys. Rev. B **99**, 081106 (R) (2019).
16. A. A. Shashkin and S. V. Kravchenko, Appl. Sci. **9**, 1169 (2019).
17. Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Nature **556**, 80 (2018).
18. M. Yankovitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. F. Young, and C. R. Dean, Science **363**, 1059 (2019).
19. Y. Cao, D. Chowdhury, D. Rodan-Legrain, O. Rubies-Bigord, K. Watanabe, T. Taniguchi, T. Senthil, and P. Jarillo-Herrero, arXiv:1901.03710.
20. S. L. Tomarken, Y. Cao, A. Demir, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero, and R. C. Ashoori, Phys. Rev. Lett. **123**, 046601 (2019).
21. V. Y. Irkhin and Y. N. Skryabin, JETP Lett. **107**, 651 (2018).
22. T. J. Peltonen, R. Ojärvi, and T. T. Heikkilä, Phys. Rev. B **98**, 220504(R) (2018).
23. S. Link, S. Forti, A. Stöhr, K. Küuster, M. Rösner, D. Hirschmeier, C. Chen, J. Avila, M. C. Asensio, A. A. Zakharov, T. O. Wehling, A. I. Lichtenstein, M. I. Katsnelson, and U. Starke, Phys. Rev. B **100** 121407(R) (2019).
24. P. Esquinazi, JETP Lett. **100**, 336 (2014).
25. G. E. Volovik, JETP Lett. **107**, 516 (2018).
26. Y. Kopelevich, V. V. Lemanov, S. Moehlecke, and J. H. S. Torres, Phys. Solid State **41**, 2135 (1999).
27. T. Scheike, P. Esquinazi, A. Setzer, and W. Böhlmann, Carbon **59**, 140 (2013).
28. T. N. Zavaritskaya and E. I. Zavaritskaya, JETP Lett. **45**, 609 (1987).
29. S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **50**, 8039 (1994).
30. A. Kaminski, T. Kondo, T. Takeuchi, and G. Gu, Philos. Mag. **95**, 453 (2015).
31. R. A. Cooper, Y. Wang, B. Vignolle, O. J. Lipscombe, S. M. Hayden, Y. Tanabe, T. Adachi, Y. Koike, M. Nohara, H. Takagi, C. Proust, and N. E. Hussey, Science **323**, 603 (2009).
32. A. A. Patel and S. Sachdev, Phys. Rev. Lett. **123**, 066601 (2019).
33. G. E. Volovik, JETP Lett. **110**, 352 (2019).