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Universal T/B scaling behavior of heavy fermion compounds (Mini-review)

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Topological approach is a powerful method to gain information about a wide class of physical systems. Knowledge of the topological properties allows us to improve a general knowledge about physical systems without solving specific equations, which describe concrete systems and are often very complicated. As usually, the microscopic approach to a heavy fermion (HF) metal (for example, computer simulations) gives only particular information about specific solids, but not about universal features, inherent in the wide class of HF compounds. HF compounds can be viewed as the new state of matter, since their behavior near the topological fermion condensation quantum phase transition (FCQPT) acquire important similarities, making them universal. The idea of this phase transition, forming experimentally discovered flat bands, started long ago, in 1990 [1–3]. At first, this idea seemed to be a curious mathematical exercise, and now it is proved to be rapidly expanding field with uncountable applications [1, 2, 4–7].

The scaling behavior of HF compounds is a challenging problem of condensed matter physics [6, 8, 9]. It is generally assumed that scaling with respect to T/B (temperature-magnetic field ratio) is related to a quantum critical point (QCP) that represents the endpoint of a phase transition being tuned to $T = 0$ by such control parameters as magnetic field, pressure, and composition of the heavy-fermion compounds. As soon as the tuned endpoint of the phase transition reaches $T = 0$, it becomes a quantum phase transition (QPT). At QCP involved quantum fluctuations like valence, magnetism, etc. can take place and influence on the properties of system in question [9, 8]. Fluctuations can also occur at second-order phase transitions, but in all cases the temperature range of these fluctuations is very narrow; in contrast, T/B scaling can span a few orders of magnitude in T/B [6]. An attendant problem to be addressed by theory stems from the experimental finding that scaling behavior can take place without both QCP realization and effective mass M^* divergence [8]. The divergence of effective mass M^* at $T \to 0$ is of crucial importance for understanding technological applications of quantum materials. For example, the divergence leads to the high heat capacity C of quantum material, while under the application of magnetic field both M^* and C diminishes. As a result, one can exploit this property, for example, constructing low temperature refrigerators. To solve these problems, one needs to have a reliable theoretical framework for analysis of experimental facts related to the scaling behavior. A universal T/B scaling behavior is generated by quasiparticles belonging to flat bands, formed by topological FCQPT. In narrow electronic bands in which the Coulomb interaction energy becomes comparable to the bandwidth, interactions drive the topological FCQPT; as a result, at $T = 0$ flat bands are emerged. Such flat bands in twisted graphene have been experimentally observed, see e.g. [3].

In our mini-review, we show that the fermion condensation (FC) theory, which entails the topological FCQPT, provides the appropriate framework for describing and analyzing the universal scaling behavior of HF compounds. We show that T/B scaling behavior can be observed in a wide range of T/B values, pro-

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vided the given HF compound is located near a topological FCQPT. We consider the HF metal $YbCo_2Ge_4$, and show that its scaling behavior is violated at low temperatures. The results of the FC theory are in good agreement with experimental observations collected on different strongly correlated Fermi systems like HF metals, quasicrystals and quantum magnets, holding quantum spin liquids.

One of the main experimental manifestations of the topological FCQPT phenomenon is the scaling behavior of the physical properties of HF compounds located near such a phase transition. As an example, Fig. 1

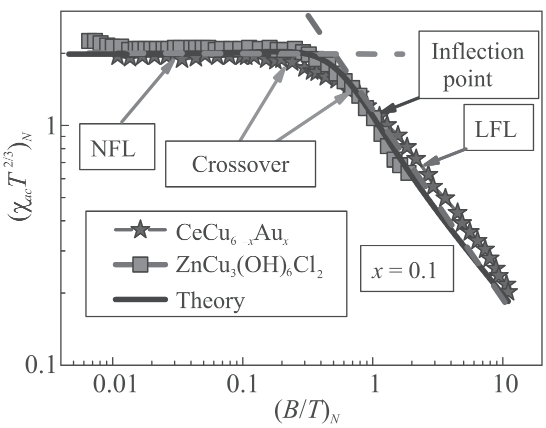

Fig. 1. (Color online) Universal B/T scaling of strongly correlated Fermi systems. Scaling of the HF metal $CeCu_{6-x}Au_x$ is extracted from data [10], and that of $ZnCu_3(OH)_6Cl_2$ from data in [11]. At $B/T \ll 1$ the systems demonstrate the non-Fermi liquid behavior with $\chi \propto M^*$. At $B/T \gg 1$ the systems exhibit the Landau Fermi liquid behavior. The non-Fermi liquid, crossover and the Landau Fermi liquid behavior are indicated by the arrows

displays the universal T/B scaling behavior of very different HF compounds like the HF metal $CeCu_{6-x}Au_x$ and the quantum spin liquid of the frustrated insulator herbertsmithite $ZnCu_3(OH)_6Cl_2$ [10, 11]. The existence of such universal behavior, exhibited by various and very distinctive strongly correlated Fermi systems, supports the conclusion that HF compounds represent a new state of matter formed by FCQPT [7].

We also consider the statement that the scaling behavior can be observed without the presence of both QCP and divergent effective mass M^* [8]. The T/B scaling behaviors experimentally observed in measurements of the magnetization dM/dT on the HF metals $YbCo_2Ge_4$ [8]. We show that the HF metal $YbCo_2Ge_4$ is located before the topological FCQPT and, therefore, exhibiting the Landau Fermi liquid behavior at sufficiently low temperatures. For the same reason, the effective mass does not diverge at the lowest temperatures. Based both on the theoretical consideration and the experimental facts, we demonstrate that there is no scaling without both the topological FCQPT and the divergence of the effective mass. Thus, HF compounds exhibit the T/B scaling down to the lowest temperatures, provided these systems are located at the topological FCQPT. We suggest that measurements of the thermodynamic properties at very low temperatures and magnetic fields on $YbCo_2Ge_4$ can clarify the physics of scaling behavior accompanied by the divergence of the effective mass. We outline that the divergence of effective mass M^* at $T \to 0$ is of crucial importance for projecting possible technological applications of quantum materials like HF compounds. We also demonstrate that the fermion condensation theory gives a good description of the scaling behavior of various HF compounds. As a result, the theory can be used as well to evaluate the technological perspectives of quantum materials.

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