Preface

Heavy-Fermion compounds comprise a great variety of strongly correlated systems such as two-dimensional (2D) quantum liquids (2D ^{3}He and electrons in metal oxide semiconductor field effect transistor (MOSFETs)), heavy fermion (HF) metals, high-temperature superconductors, quantum spin liquids confined in insulators, quasicrystals, and even the Universe itself. Numerous experimental facts unveiling the thermodynamic, transport, relaxation, etc., properties are collected on all these objects, and these facts represent all fields of the condensed matter physics. One might say that the physics of HF compounds represents a new edition of the condensed matter physics, for the observed behavior is quite unique while the edition is still under construction. Therefore, the problem of presenting a theory of HF compounds is both arduous and of great importance.

In this book, we construct the theory and illustrate it by numerous applications dealing with various physical phenomena and processes and explaining the corresponding experimental facts. To make the book understandable as much as possible, for the reader's convenience we, when considering a problem of the HF compounds, give the necessary elements of the theory within a particular place. Because of huge diversity in the considered topics, we hope that such a presentation allows the reader to learn the particular physical process without a laborious recursion to special chapters of the book.

One of the most fruitful concepts of modern solid state physics is a paradigm of quasiparticles. This concept permits to represent any solid as certain ground state and its elementary excitations in the form of quasiparticles. In the quasiparticle language, a complex system of strongly interacting electrons and ions is reduced to a gas of low-energy excitations, whose behavior could be described by various (primarily perturbative) well-established techniques. The quasiparticles paradigm permits to achieve a significant standardization of the description of different types of quantum solids and, by this virtue, similar formalism can be applied across a wide range of Condensed Matter systems.

Rapid development of condensed matter physics at the end of the twentieth century put many challenges to the conventional wisdom in this discipline, elaborated for previous 50 years. Such discoveries as high-T_c superconductivity, integer and fractional quantum Hall effects, as well as a multitude of quantum phase transitions still do not find their satisfactory and complete theoretical explanation. Moreover, many modern experimental findings in solids put such fundamental concepts of "classical" condensed matter physics, as quasiparticle, under scrutiny. As a result, there has been a growing body of theoretical and experimental studies showing that the conventional picture of quasiparticles is not always correct for systems with strongly interacting fermions. Examples of systems exhibiting significant deviations from the above quasiparticle picture are chemical compounds with heavy fermions (heavy-fermion compounds), whose experimental behavior is strongly different from that predicted by ordinary Fermi liquid theory. The body of these "strange" experimental facts is now commonly attributed to as non-Fermi liquid (NFL) behavior. As quasiparticle paradigm is inherent in other branches of condensed matter physics, the same NFL behavior is exhibited at low temperatures by two-dimensional electron gas and even ^{3}He, where its neutral atoms are fermions with spin 1/2. We believe that to meet the above challenges adequately, the new points of view on old ideas are necessary.

This monograph is written to explain how the standard quasiparticle paradigm can be modified to describe the striking NFL anomalies in the above classes of strongly correlated fermionic systems. The main emphasis is on physics of HF compounds and other systems with essentially NFL behavior. We show how revised quasiparticle concept can describe all the above systems in a unified manner. Here we present a comprehensive analysis of existing theoretical and experimental results for all listed systems with NFL behavior such as HF metals, high-temperature superconductors, quantum spin liquids, quasicrystals, and two-dimensional Fermi systems. The common feature of these systems is that their physical properties can hardly be understood within the framework of the Landau Fermi liquid theory and their behavior is so unusual that the traditional Landau quasiparticles paradigm fails to describe it. The important speciality of our monograph is that we compare a great deal of our theoretical observations with numerous experimental facts. As a result, the monograph contains more than 150 figures that facilitate understanding both the presented theory and the experimental facts collected on very different HF compounds.

In this book, we present a theoretical approach, which, based on modified and extended quasiparticles paradigm, permits to naturally describe the basic properties and the scaling behavior of the above substances. The essence of the approach is that due to the altering of Fermi surface topology, the substance undergoes so-called fermion condensation quantum phase transition, where Landau quasiparticles survive but completely change their properties. In contrast to the Landau statement that the quasiparticle effective mass is a constant, the effective mass of the above new quasiparticles strongly depends on temperature, magnetic field, pressure, and other external parameters. As a signal of such a fermion condensation quantum phase transition (FCQPT) serves unlimited increase in the effective mass of quasiparticles that determines the excitation spectrum and creates both flat bands and a fermion condensate; while FCQPT represents the unique quantum phase transition that occurs only at zero temperature.

Upon reading the book, it can be asserted, that strongly correlated Fermi systems with quite different microscopic nature exhibit the same NFL behavior, while the data collected on very different strongly correlated fermionic systems manifest a universal scaling behavior so that these substances are unexpectedly identical despite their diversity. For the reader's convenience, the analysis is carried out in the broad context of the explanation of salient and unusual experimental results. The numerous calculations of the thermodynamic, relaxation and transport properties, being in good agreement with experimental facts, offer the reader solid grounds to learn the FCQPT theory implications and applications. Finally, the reader will learn that FCQPT develops unexpectedly simple, yet complete and uniform description of the NFL behavior of many different classes of substances. As a result, these different classes are unified to create a new state of matter.

The book is organized as follows. The first chapter is of introductory character and gives the definition and classification of strongly correlated systems. The theoretical approaches to strongly correlated systems like Landau theory of Fermi-liquid (LFL) are introduced. It is shown that LFL theory is insufficient to describe NFL properties of HF compounds. For such description, the notion of FCQPT is introduced. To make the book self-contained, Chap. 2 gives a brief overview of Landau Fermi liquid theory, introducing famous Landau quasiparticles. Chapter 3 gives the explanation of our theory of fermion condensation. The theory relies on Landau approach to Fermi liquids description, outlined in Chap. 2. The essence of this theory is that under certain conditions, the Landau interaction (and Fermi surface topology, which is described in Chap. 4) alters so that at FCQPT point the quasiparticle effective mass starts to depend on temperature, magnetic field, and other external parameters. We show that this theory has deep implications on the properties of HF compounds and other strongly correlated electron systems. Chapters 5–8 show how the FCQPT concept works for specific HF compounds. Here we analyze and describe the thermodynamic, transport and relaxation properties of HF compounds. Extensive comparison with experimental data is performed. We show that many unexplained and puzzling experimental facts related to NFL behavior can be well explained within the above concept. We emphasize here that contrary to "ordinary" (like Kondo lattice) theoretical approaches ascribing the NFL properties of the HF compounds to the "death" of Landau quasiparticles, our FCQPT approach shows convincingly that quasiparticles survive, although their properties are strongly modified, for instance, their effective mass becomes temperature, magnetic field, and other external parameters dependent. We also demonstrate that the extended quasiparticles paradigm permits to naturally explain the scaling behavior of HF compounds.

In Chap. 9, it is demonstrated that the fermion condensation gives floor to the quasi-classical physics in HF compounds. This observation permits us to gain more insights into the puzzling NFL physics of HF compounds and explain challenging experimental facts. In Chaps. 10 and 11, we consider the paradoxical behavior of the residual resistivity of HF metals in magnetic fields and under pressure. Chapter 13 is devoted to asymmetric conductivity of strongly correlated compounds revealed by the methods of scanning tunneling microscopy and point-contact spectroscopy.

In Chap. 14, a violation of the Wiedemann–Franz law in HF metals is considered. In Chap. 15, we present the theoretical analysis of thermodynamics of HF compounds at high magnetic fields. Chapters 12 and 16 show non-typical applications of FCQPT approach. Namely, Chap. 12 shows that a new phenomenon called "merging," analogous to FCQPT, occurs in systems with finite number of fermions (so-called finite Fermi systems) like atomic nuclei and in two-dimensional electron systems in silicon. Chapter 16 deals with the baryon asymmetry in the early Universe, where FCQPT may also be realized. This shows that the phenomenon of Fermion condensation is ubiquitous in Nature. In Chaps. 17 and 18 we consider the quantum criticality of very different heavy-fermion compounds, such as quantum spin liquids, quasicrystals, high-T_c superconductors, HF metals, and 2D ^{3}He. Chapter 19 contains concluding remarks.

This monograph is written on the basis of the results of the present authors' theoretical investigations as well as on theoretical and experimental studies of other researchers. The book is intended for undergraduate and graduate students and researchers in condensed matter physics. Also, the material of the book has widely been presented in the form of lectures in Clark Atlanta University (USA), Hebrew University of Jerusalem (Israel), St. Petersburg University (Russia), Syktyvkar University (Russia), Opole University (Poland).

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