

Miron Ya. Amusia  
Konstantin G. Popov  
Vasily R. Shaginyan  
Vladimir A. Stephanovich

# Theory of Heavy-Fermion Compounds

Theory of Strongly Correlated  
Fermi-Systems

Miron Ya. Amusia · Konstantin G. Popov  
Vasily R. Shaginyan · Vladimir A. Stephanovich

# Theory of Heavy-Fermion Compounds

Theory of Strongly Correlated Fermi-Systems

Miron Ya. Amusia  
Racah Institute of Physics  
The Hebrew University  
Jerusalem  
Israel

and

A. F. Ioffe Physical-Technical Institute  
St. Petersburg  
Russian Federation

Konstantin G. Popov  
Ural Division Komi Science Center  
Russian Academy of Sciences  
Syktyvkar  
Russia

Vasily R. Shaginyan  
Petersburg Nuclear Physics Institute  
Gatchina  
Russia

and

CTSPS  
Clark Atlanta University  
Atlanta  
USA

Vladimir A. Stephanovich  
Institute of Physics  
Opole University  
Opole  
Poland

ISSN 0171-1873  
ISBN 978-3-319-10824-7  
DOI 10.1007/978-3-319-10825-4

ISSN 2197-4179 (electronic)  
ISBN 978-3-319-10825-4 (eBook)

Library of Congress Control Number: 2014950681

Springer Cham Heidelberg New York Dordrecht London

© Springer International Publishing Switzerland 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or

information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Introductory Remarks	1
1.1.1	General Consideration: Strong Versus Weak Correlations	1
1.1.2	Theoretical Approaches to Strongly Correlated Systems	3
1.1.3	Quantum Phase Transitions and NFL behavior of HF compounds	12
1.1.4	Limits and Goals of the Book	16
References		18
<b>2</b>	<b>Landau Fermi Liquid Theory and Beyond</b>	<b>21</b>
2.1	Quasiparticle Paradigm	21
2.2	Pomeranchuk Stability Conditions	23
2.3	Thermodynamic and Transport Properties	24
2.3.1	Equation for the Effective Mass and the Scaling Behavior	25
References		29
<b>3</b>	<b>Fermi Liquid with Fermion Condensate</b>	<b>31</b>
3.1	The Fermion-Condensation Quantum Phase Transition	31
3.1.1	The FCQPT Order Parameter	33
3.1.2	Quantum Protectorate Related to FCQPT	35
3.1.3	The Influence of FCQPT at Finite Temperatures	36
3.1.4	Phase Diagram of Fermi System with FCQPT	38
3.2	Two Scenarios of the Quantum Critical Point	40
References		49

<b>4</b>	<b>The Topological Phase Transitions Related to Fermion Condensate . . . . .</b>	51
4.1	Topological Phase Transitions Related to FCQPT . . . . .	51
References . . . . .		59
<b>5</b>	<b>Appearance of Fermion-Condensation Quantum Phase Transition in Fermi Systems . . . . .</b>	61
5.1	The Superconducting State with FC at $T = 0$ . . . . .	61
5.1.1	Green's Function of the Superconducting State with FC at $T = 0$ . . . . .	63
5.1.2	The Superconducting State at Finite Temperatures . . . . .	64
5.1.3	Bogolyubov Quasiparticles . . . . .	66
5.1.4	The Dependence of Superconducting Phase Transition Temperature $T_c$ on Doping . . . . .	68
5.1.5	The Gap and Heat Capacity Near $T_c$ . . . . .	69
5.2	The Dispersion Law and Lineshape of Single-Particle Excitations . . . . .	70
5.3	Electron Liquid with FC in Magnetic Fields . . . . .	73
5.3.1	Phase Diagram of Electron Liquid in Magnetic Field . . . . .	73
5.3.2	Magnetic Field Dependence of the Effective Mass in HF Metals and High- $T_c$ Superconductors . . . . .	78
5.4	Appearance of FCQPT in Fermi systems . . . . .	81
References . . . . .		84
<b>6</b>	<b>Highly Correlated Fermi Liquid in Heavy-Fermion Metals: The Scaling Behavior . . . . .</b>	87
6.1	Magnetic Field Dependence of the Quasiparticle Effective Mass . . . . .	87
6.2	Quasiparticles and the Temperature Dependence of the Effective Mass . . . . .	90
6.3	Scaling Behavior of the Effective Mass and Energy Scales . . . . .	93
6.3.1	Schematic Phase Diagram of a HF Metal . . . . .	95
6.3.2	Non-Fermi Liquid Behavior of $YbRh_2Si_2$ . . . . .	97
6.3.3	Heat Capacity and the Sommerfeld Coefficient . . . . .	98
6.4	General Properties of the Phase Diagrams of Heavy-Fermion Metals . . . . .	99
References . . . . .		109
<b>7</b>	<b>Highly Correlated Fermi Liquid in Heavy-Fermion Metals: Magnetic Properties . . . . .</b>	111
7.1	Magnetization . . . . .	111
7.2	Magnetoresistance . . . . .	113

7.2.1	Longitudinal Magnetoresistance . . . . .	113
7.2.2	Transverse Magnetoresistance in the HF Metal <i>CeCoIn<sub>5</sub></i> . . . . .	114
7.2.3	Electric Resistivity of HF Metals . . . . .	119
7.3	Magnetic Entropy . . . . .	120
7.4	Magnetic Susceptibility . . . . .	121
7.4.1	Magnetic Susceptibility and Magnetization Measured on <i>CeRu<sub>2</sub>Si<sub>2</sub></i> . . . . .	121
7.5	Magnetic-Field-Induced Reentrance of the LFL Behavior and Spin-Lattice Relaxation Rates . . . . .	123
7.6	The Relations Between Critical Magnetic Fields $B_{c0}$ and $B_{c2}$ in HF Compounds . . . . .	127
7.7	Scaling Behavior of the HF $\text{CePd}_{1-x}\text{Rh}_x$ Ferromagnet . . . . .	130
	References . . . . .	136
<b>8</b>	<b>Metals with a Strongly Correlated Electron Liquid</b> . . . . .	139
8.1	Entropy, Linear Expansion, and Grüneisen's Law . . . . .	139
8.1.1	Entropy, Linear Expansion, and Grüneisen's Law . . . . .	140
8.2	The $T - B$ Phase Diagram, the Hall Coefficient, and the Magnetic Susceptibility . . . . .	142
8.3	The Impact of FCQPT on Ordinary Continuous Phase Transitions in HF Metals . . . . .	146
8.3.1	The Comparison of $T - B$ Phase Diagrams for <i>YbRh<sub>2</sub>Si<sub>2</sub></i> and <i>CeCoIn<sub>5</sub></i> . . . . .	147
8.3.2	The Tricritical Point in the $B - T$ Phase Diagram of <i>YbRh<sub>2</sub>Si<sub>2</sub></i> . . . . .	150
8.3.3	Low Temperature Entropy of <i>YbRh<sub>2</sub>Si<sub>2</sub></i> . . . . .	152
	References . . . . .	153
<b>9</b>	<b>Quasi-classical Physics Within Quantum Criticality in HF Compounds</b> . . . . .	155
9.1	Second Wind of the Dulong-Petit Law at a Quantum Critical Point . . . . .	155
9.2	Transport Properties Related to the Quasi-classical Behavior . . . . .	162
9.3	Quasi-classical Physics and $T$ -Linear Resistivity . . . . .	168
	References . . . . .	176
<b>10</b>	<b>Magnetoresistance in the HF Metal at Zero Temperature</b> . . . . .	179
10.1	Introduction . . . . .	179
10.2	The HF Metal <i>CeCoIn<sub>5</sub></i> . . . . .	180
10.3	The HF Metal <i>YbRh<sub>2</sub>Si<sub>2</sub></i> . . . . .	187
10.4	Main Results . . . . .	196
	References . . . . .	197

<b>11 Zero Temperature Magnetoresistance of the HF Metal: Enigma of Sr<sub>3</sub>Ru<sub>2</sub>O<sub>7</sub></b> . . . . .	199
11.1 Introduction: Flat Bands and Enigma of Metamagnetic Quantum Critical Regime in Sr <sub>3</sub> Ru <sub>2</sub> O <sub>7</sub> . . . . .	199
11.2 Magnetoresistivity . . . . .	201
11.3 Fermion Condensation . . . . .	203
11.4 Phase Diagram . . . . .	204
11.5 Jumps . . . . .	205
11.6 Entropy . . . . .	209
11.7 Scaling Behavior . . . . .	210
11.8 Main Results . . . . .	212
References . . . . .	212
<b>12 Fermion Condensation in Finite Systems</b> . . . . .	215
12.1 Finite Systems . . . . .	215
12.2 Merging of Landau Levels in Two-Dimensional Electron System in Silicon . . . . .	226
References . . . . .	232
<b>13 Asymmetric Conductivity of Strongly Correlated Compounds</b> . . . . .	235
13.1 Normal State . . . . .	235
13.1.1 Suppression of the Asymmetrical Differential Resistance in YbCu <sub>5-x</sub> Al <sub>x</sub> in Magnetic Fields . . . . .	240
13.2 Superconducting State . . . . .	241
13.3 Relation to the Baryon Asymmetry in the Early Universe . . . . .	247
References . . . . .	249
<b>14 Violation of the Wiedemann-Franz Law in HF Metals</b> . . . . .	251
References . . . . .	259
<b>15 High Magnetic Fields Thermodynamics of Heavy Fermion Metals</b> . . . . .	261
15.1 Introduction . . . . .	261
15.2 Phase Diagram . . . . .	265
15.3 Results and Discussion . . . . .	266
15.3.1 Kinks . . . . .	269
15.4 Main Results . . . . .	271
References . . . . .	272
<b>16 Baryon Asymmetry Resulting from FCQPT in the Early Universe</b> . . . . .	273
16.1 Introduction . . . . .	273
16.2 Model . . . . .	274

16.3	The Asymmetry of the Universe . . . . .	279
	References . . . . .	282
<b>17</b>	<b>Quantum Criticality of Spin Liquids in Novel Insulators and Magnets . . . . .</b>	<b>285</b>
17.1	Thermodynamic Properties of Quantum Spin Liquid in Insulators . . . . .	286
17.1.1	Model . . . . .	286
17.1.2	Phase Diagram . . . . .	290
17.1.3	The Thermodynamic Properties . . . . .	290
17.2	Scaling in Dynamic Susceptibility of Herbertsmithite and HF Metals . . . . .	297
17.2.1	Theory of Dynamic Spin Susceptibility of Quantum Spin Liquid and Heavy-Fermion Metals . . . . .	298
17.2.2	Scaling Behavior of the Dynamic Susceptibility . . . . .	300
17.3	Spin-Lattice Relaxation Rate of Quantum Spin Liquid . . . . .	304
17.4	Heat Transport in Magnetic Fields by Quantum Spin Liquid in Insulators . . . . .	306
	References . . . . .	314
<b>18</b>	<b>Quantum Criticality of Heavy-Fermion Compounds . . . . .</b>	<b>317</b>
18.1	Quantum Criticality of High-Temperature Superconductors and HF Metals . . . . .	317
18.2	Quantum Criticality of Quasicrystals . . . . .	321
18.3	Quantum Criticality at Metamagnetic Phase Transitions . . . . .	329
18.3.1	Typical Properties of the Metamagnetic Phase Transition in $Sr_3Ru_2O_7$ . . . . .	329
18.3.2	Metamagnetic Phase Transition in HF Metals . . . . .	331
18.4	Universal Behavior of Two-Dimensional $^3He$ at Low Temperatures . . . . .	332
18.5	Scaling Behavior of HF Compounds and Kinks in the Thermodynamic Functions . . . . .	340
18.6	New State of Matter . . . . .	342
	References . . . . .	343
<b>19</b>	<b>Conclusions . . . . .</b>	<b>345</b>
	References . . . . .	348
<b>Index . . . . .</b>		<b>351</b>