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Endless Quests: Theory, Experiments and Applications of Frontiers of Superconductivity

无尽的探索

——超导前沿理论、实验和应用

〔美〕范江弟　主编

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序　　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在2006年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会　主任
中国科学院院士，北京大学教授
王恩哥
2010年5月于燕园

Commemorating One Century of Advances Since Superconductivity's Discovery

Preface

While the international community celebrated the centennial anniversary of superconductivity, we were working hard to write this book in its memory. To date superconductivity has gone a long way to reach the point of applications, but it is still far from being widely used. Many of scientists and engineers in the world during the past century have contributed their entire life to superconductivity without regret! We are just a few of the players in the "relay race of superconductivity". We wish to promote the development of superconductivity in terms of the book we have just finished. This book consists of three parts: theory, experiment and application of superconductivity. The theory is basically out of the mainstream of theoretical studies in the community of superconductivity, indicating a new method for theoretical investigations that looks hopeful in unveiling the mystery of superconductivity. The second part consists of first hand experimental investigations and analyses of new superconductors discovered during the past years. The phenomenology derived from experimental work forms the foundation for verifying the validity of theoretical conjectures and provides new insights into advancing the science and technology of superconductivity. Lastly, the third part is one of the most successful applications of high-temperature superconductor (HTS) $YBa_2Cu_3O_{7t\delta}$ (YBCO) in mass transportation: high-temperature superconductive maglev train (HTSMT). China made the first HTSMT prototype under the leadership of Jia-Su Wang and Su-Yu Wang fourteen years after the discovery of the first HTS $La_{2-x}Ba_xCuO_{4t\delta}$ (LBCO). It is likely that it will become the safest, fastest, and most comfortable and environment-friendly means of mass transportation in the years to come.

Firstly, I would like to take this opportunity to express my heartfelt thanks to all the co-authors, Drs. T.-P. Chen, Shi-Xue Dou, Jia-Su Wang, Judy Wu and Nai-Chang Yeh, who made great contributions to the book with their first-hand investigation data. Also, my thanks go to Dr. Fu-Sheng Pan, President of Chongqing Academy of Science and Technology, China, who has provided me with the support and resources to complete the book. My work on writing the book was as well supported by Southern University and A&M College, USA, for my sabbatical leave, during which the book was started, and also for most of research results that were completed with Dr. Yuriy M. Malozovsky during the period when I served the institution from 1989–2012. My appreciation goes to Dr. D. Bagayoko, Chairman of the Department of Physics, Southern University and A&M College, USA, who has encouraged me to look for the physical picture of Cooper pairing due to Coulomb interaction during the difficult years when Dr. Malozovsky and I were trying to convey to the superconductivity community our new concept that superconductivity originates from repulsive Coulomb interaction between electrons. That is the work entitled "Sign Reversal of the Coulomb Interaction between Quasiparticles in Momentum Space."[*] Now, it is much easier for one to understand Cooper pairing without invoking electron-phonon interaction that in fact leads to metal-insulator transition. Moreover, my appreciation goes to Dr. Han Zhang, Peking University, and Dr. Ju Gao, University of Hong Kong, as well as Dr. Haiqing Lin, Chinese University of Hong Kong, who all have been my everlasting supporters in the series of New^{3}SC Conferences which I initiated and chaired. As a matter of fact, I have adopted the suggestion of Han Zhang for the title of this book. Lastly, I wish to show my special appreciation to Dr. Malozovsky, my colleague in Southern University and partner in research for our common interest in superconductivity mechanism and origin. Since he joined my research group in USA in 1992, he has cooperated with me together in research without discontinuity. Dr. Malozovsky is a hard-working scientist with genius and diligence. He remains his enthusiasm in superconductivity exploration till today.

Finally, it is my wish that the publication of this book will shed some light on unveiling the mystery of superconductivity.

J. D. Fan
Chongqing Academy of Science and Technology
Chongqing, China
May 2014

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[*] J. D. Fan and Y. M. Malozovsky, International Journal of Modern Physics B, 27, 15 (2013) 1362035.

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Part I

Theory of Superconductivity

Chapter 1 Diagrammatic Iteration Approach to Electron Correlation Effects and Its Application to Superconductivity

J. D. Fan[1] and Y. M. Malozovsky[2]

1.1 Introduction

One century has passed since Kamerlingh Onnes discovered the first superconductor in 1911. How much does one really understand superconductivity today? Yes, one did make a big step forward in explaining and describing superconductivity on the basis of BCS (Bardeen-Cooper-Schrieffer) theory [1]. In comparison to semiconductors and lasers, however, the development of superconductivity is rather slow. This fact itself implies that something in one's investigations of superconductivity must be inadequate, which prevents one from well understanding it. In the community of superconductivity it seems that one tries to establish a new mechanism theory for high-temperature superconductivity (HTS),while preserving the BCS theory for conventional superconductors. We believe that an acceptable and complete theory of superconductivity mechanism must be able to cover both low- and high-temperature superconductivity and possibly predict something new, while explaining a series of experimental phenomena consistently and uniquely. The attempt to parallely keep two mechanism theories for superconductivity is not desirable. In other words, conventional superconductivity should be a natural consequence of a general theory of superconductivity at some extreme physical and structural conditions. This is more or less like the relationship between relativity and classical mechanics, where in the condition of $V \ll c$, where V is speed of

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[1] Chongqing Academy of Science and Technology, Chongqing, China.

[2] Southern University and A&M College, Louisiana, USA.

motion and c is the speed of light, kinetic energy $K = (m - m_0)c^2$ with m and m_0 being the mass in motion and the rest mass, respectively, inn relativity tends to the classical formula $K = mV^2/2$, or that between Planck's theory and Rayleigh-Jeans law for the blackbody radiation law in quantum mechanics, where at low frequency ν Planck's formula is in agreement with the Rayleigh–Jeans law.

In this chapter, the main goal is to introduce a method termed diagrammatic iteration approach (DIA) to deal with many-particle systems and its application to superconductors. Before that we have summarized several points on the issues existing nowadays in the superconductivity community. Our attention is focused on the issues produced from the BCS theory and those followed from it.

1.2 A brief on the development of superconductivity theory

Before high-T_c superconductors (HTS) were discovered, one understood superconductivity based on the BCS theory in terms of the mean field approximation (MFA) applied to superconductivity leading to a great simplification of Hamiltonian–the BCS Hamiltonian with the concept of Cooper pairing. Since J. G. Bednorz and K. A. Mueller discovered the first cuprate superconductor with $T_c \sim 35$ K in 1986 [2], the BCS theory has appeared to be helpless in understanding and explaining the phenomena experimentally observed in cuprates despite of many efforts devoted to improving it with the basic assertion that attractive interaction is needed between two electrons, but none of them is really successful.

In 2001, a binary compound MgB_2 was discovered to be a superconductor at 39 K [3]. This success has promoted a great deal of new excitement in seeking new compounds with higher transition temperature and generated considerable interest in the mechanism of superconductivity. This excitement was enhanced in September of the same year by the increase in transition temperature T_c of fullerenes C_{60} to 117 K in terms of the field effect transistor setup [4]. The euphoria resulting from the discovery of the first cuprate high-T_c superconductor in 1986 has gradually faded in the past decade due to frustrations in reaching a consensus in understanding superconductivity [5]. The major issue still rests in consistently explaining a large number of anomalous properties observed in high-T_c cuprates and understanding both low- and high-temperature superconductivity in a unified framework. Following the discovery of MgB_2, a variety of experimental measurements has been performed all over the world attempting to identify its properties for better understanding of the mechanism of superconductivity. Among them are, for instance, the measurements of thermoelectronic power and resistivity of $Mg_{1-x}Al_xB_2$ by Chu's group [6], indicating a decrease of T_c with Al doping and no phonon drag contribution to the thermoelectric power of $Mg_{1-x}Al_xB_2$, and identification of the isotope effect by Bud'ko *et al.* [7, 8], giving the isotope effect exponent $\alpha = 0.32$ smaller than $\alpha_{BCS} = 0.5$. Measurements of the superconducting gap were carried out with a variety of techniques such as NMR, tunneling, high-resolution photoemission spectroscopy, scanning tunneling spectroscopy, IR reflectivity, specific heat, etc. [9–19] It showed the gap $\varDelta$ ranging from 2—8 meV; in particular, the measurements of the Raman spectroscopy [10] produce $2\varDelta_1/k_BT_c = 1.6$ and $2\varDelta_2/k_BT_c = 3.7$. Karapetrov [20], Lorenz [21] and co-workers found the negative change of T_c under high-pressure. Measurements of the penetration depth λ [22–26] and the electron-phonon coupling constant [24] were also performed, yielding $\lambda_{MgB_2} \sim 2 \gg \lambda_{BCS} \sim 0.4$. These measurements have confirmed that MgB_2 is a type-II superconductor with two gaps. Specific heat measurements [9, 27] support the s-wave symmetry of the gap [10], while existing tunneling data are not consistent with each other, which are in part attributed to junction interface flaws. From the clear isotope effect and s-wave symmetry of the superconducting gap, one claims MgB_2 as a BCS-like superconductor mediated by phonons. However, its structure similarity to a cuprate superconductor and rather high T_c casts a shadow on the claim.

Theoretically, based on the fundamental concept of Cooper pairing, Kortus *et al.* [28] calculated the electronic band structure of MgB_2 and reached at a consistent picture for the Fermi surface and suggested that pairing results from the strong electron-phonon interaction and the high-frequency phonon associated with the light boron element. Many of the experimenters also support this point based on the fact of the isotope effect and a BCS-like superconducting gap structure, while others [8] indicate that the gap in MgB_2 is too small to account for its high T_c. The existing data of electron-phonon coupling measurements are not strong enough to reach as high T_c as 39 K in contrast to the measurement of Walti *et al.* [27] that gave rise to a coupling constant as high as 2.0. Hirsch suggested a universal mechanism of superconductivity from his assertion that electron and hole are asymmetrical due to the Coulomb interaction. He emphasized [29] that (Cooper) "pairing of electron carriers cannot drive superconductivity" and "holes in nearly full bands yield the low normal state conductivity and high-temperature superconductivity," whereas Chu's group indicated the contrary of Hirsch's prediction of a positive pressure effect on T_c to the experimental measurements [21, 22].

The pnictides superconductivity discovered in 2008 [30–37] arouse new excitements in the superconductivity community. This new type of superconductors with rather high T_c has similar structures to cuprates but carries metal and pnictides elements in the structures. Much of the interest in pnictides is because the new compounds are very different from the cuprates and may help lead to a theory of non-BCS theory of superconductivity.

In 1987, P. W. Anderson proposed [38] an idea that a disordered antiferromagnet characterized by resonating singlet pairs of spins could be thought of as a superconducting state. This was then called the RVB model. Laughlin [39] and Kivelson [40] also suggested a related idea. Also, Chakravarty and Kivelson [41] proposed a mechanism of superconductivity in which attraction arises from repulsion between two like charges in a mesoscale structure. This interesting concept can trace back to twenty years ago [42–44] and is consistent with the over-screening idea we proposed in 1994 [45], and similar to, but different from the concept we worked out in 1994 [46] and 1997 [47]. They [41] also pointed out that "the strong electron-phonon interaction is always accompanied by self-trapping or bipolaron formation. The result is a large exponential Frank-Condon reduction of the energy scale for coherent motion of charge, inevitably leading to an insulating state." This point of view is in line with our conclusion for a given attractive interaction between two electrons due to phonons [48].

There are of course many experimental measurements that have not been cited here and many important but more or less conventional works in theory, such as the tight binding model with nearest neighbor approximation, Hubbard model, t-J model, spin bag model, spin-charge separation model, earlier van Hove singularity, nested Fermi liquid, and *ab*-initio calculations as well as the well-known phenomenological theory by Varma *et al.* [49], etc. Readers may consult Ruvalds' review [50]. We simply confine ourselves to the unconventional ideas and models which we have been interested in and working on.

Superconductivity, the one hundred-year long enigma, repeatedly arouses thoughts of science in its exploration. Despite countless forays into it, no consensus has been reached concerning the mechanism of superconductivity. We cannot help but ask whether we need to thoroughly examine the fundamental concepts and theory of superconductivity from the very beginning. After a hundred years since the discovery of superconductivity, it is time to unveil its mystery. However, we assert that on the basis of the conventional theory with whatever modification, if there is neither breakthrough in the fundamental concepts nor radical change in the physical and mathematical treatments, it will be impossible to reach a consensus.

It is helpful to look back on the history of physics. V. L. Ginzburg commented in 2000 [51], "... Actively working physicists usually take little interest in the past, and I myself am not an exception–I began studying the theory of superconductivity in 1943, but only in 1979 did I find time to look through the classical papers of Kamerlingh Onnes (1853-1926). And I found them fairly interesting. When a consensus cannot be reached after unprecedented efforts have been made, it becomes necessary and inevitable to review the history and examine the starting point, including those old concepts that have been widely accepted and believed to be true. It is likely that superconductivity is in such a situation. Take a look at the history of physics at the beginning of the twentieth century. One experienced the so-called 'ultraviolet catastrophe' in the blackbody radiation. Planck made a revolutionary change in the energy distribution by assuming that radiated energy $\varepsilon = nh\nu$, where n is integral number and ν is frequency of the radiation and h is the Planck constant, and correspondingly changed integration to summation, leading to a radiation law that is amazingly consistent with experimental data for all frequencies. Further, the Stefan-Boltzmann law can be deduced directly from Planck's radiation law. Of more importance is that the change in energy distribution from continuous to discrete brought about the birth of quantum mechanics.