国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

中外物理学精品书系

高瞻系列 · 4

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铜氧化物高温超导电性实验与理论研究

韩汝珊 主编

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图书在版编目(CIP)数据

铜氧化物高温超导电性实验与理论研究 ：英文版 = Advances in Theoretical and Experimental Research of High Temperature Cuprate Superconductivity/韩汝珊主编. —北京 ：北京大学出版社，2014.7
(中外物理学精品书系. 高瞻系列)
ISBN 978-7-301-24242-1

Ⅰ. 铜… Ⅱ. ①韩… Ⅲ. ①铜－氧化物－高温超导性－研究－英文 Ⅳ. O511
中国版本图书馆 CIP 数据核字(2014)第 096163 号

书　　　名：**Advances in Theoretical and Experimental Research of High Temperature Cuprate Superconductivity(铜氧化物高温超导电性实验与理论研究)**
著作责任者：韩汝珊　主编
责 任 编 辑：王剑飞
标 准 书 号：ISBN 978-7-301-24242-1/O·0972
出 版 发 行：北京大学出版社
地　　　址：北京市海淀区成府路 205 号　100871
网　　　址：http://www.pup.cn
新 浪 微 博：@北京大学出版社
电 子 信 箱：zpup@pup.pku.edu.cn
电　　　话：邮购部 62752015　发行部 62750672　编辑部 62765014
出版部 62754962
印　刷　者：北京中科印刷有限公司
经　销　者：新华书店
730 毫米×980 毫米　16 开本　33.5 印张　641 千字
2014 年 7 月第 1 版　2014 年 7 月第 1 次印刷
定　　　价：190.00 元

“中外物理学精品书系”
编委会

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

内 容 简 介

本书汇集了超导实验方面和理论方面的第一线专家的综述介绍。这些作者立足于他本人熟悉的工作，从全局的视角，回顾了高温超导二十多年来实验研究取得共识的主要结果和分歧的要点以及有影响的理论模型可解决和无力解决的方面，并力争明确进一步努力的方向。这本文集的出版会对我国高温超导电性机制的研究起到推动作用。

本书适合超导及相关专业领域的研究生、教师及研究人员使用和参考，对凝聚态物理相关人员也是值得一读的参考书。

Preface

"The Assessment Seminar on High-Temperature Superconducting Mechanism Research" has been jointly held by China Center of Advanced Science and Technology (CCAST); Institute of Physics, Chinese Academy of Sciences(CAS); National Lab for Superconductivity, Institute of Physics, CAS; School of Physics, Peking University; Center of Advanced Study Tsinghua University on March 1-5 2008. The experts of experimental and theoretical aspects on the first front have been invited to give reviews and attempt to conclude the main consensuses, differences, solvable and unsolvable aspects by some influential theoretical models in the last twenty years in superconductivity from a global perspective to clear the striving direction and inspire a new enthusiasm and motivation of high-temperature superconductivity (HTSC) research. It requires the reporters to introduce the raw experimental data and the problems objectively, to point out the trend of the theoretical study impartially and discuss the real situation and provided recommendations more deeply.

The conference is a great success, and basically achieves its purpose. The scientists have made careful preparations, and are concise and insightful. Participants' enthusiastic participation and serious discussion make the conference very fruitful.

At the time of the arrangement, having a meeting and preparing for the corpus, i.e. 2008, a new class of superconductors–FeNi-based oxygen-chalcogenide layered superconductors have occupied the center of the superconducting field, and Chinese scientists have made outstanding contributions. After about a year of exploration, the scientists have basically sorted out the general picture and could summarize that only the Fe-based small family has superconductivity in the hundreds of materials with ZrCuSiAs class structure. From the point of experiment, they are on the borderline between BCS, superconductors and cuprate oxide superconductors, close to the BCS superconductors with the traces of cuprate oxide superconductors.

Its characteristics are following: the strong e-p interaction with distorted s-wave symmetry; while above the T_C, the appearance of e-e interaction turning out–the resistivity $\rho\alpha T^2$; the parent compound is bad metal, neither nearly free electron nor insulator; not $\boldsymbol{k}$-space pairing and not completely real space pairing, and its H_{C2} is between the BCS and cuprate oxide superconductors, about 50-60 Tesla, (the low T_C samples showed a higher H_{C2}); the angle-resolved photoemission spectroscopy (ARPES) data is in good agreement with the band structures calculation, indicating that they are weakly correlated multi-band system; the penetration depth is approximately 190 nm; direct exchange in intra-layer and ionization interaction in interlayer in this layered compounds; the superconducting area and magnetic area are close neighbors, but it is unclear whether they co-exist so further study is needed; including the additional data for the magnetic ordering with the doping evolution, it is one of the controversial issues whether the pseudogap exists or not. In short, the preparation of good single crystals is still present major challenge, which will provide conclusive results for some experimental properties. It will help to accurately conclude the similarity and sample differences, and promote the study of the superconducting mechanism.

I think it is certain that the mechanism of superconductivity in cuprate is a more urgent task. Finding out they are the extreme cases, can promote the thinking of this new family situation between the BCS and cuprate oxide superconductors. As an important control system of the high-T_C cuprate oxide superconductor, Fe-based superconductors will also promote the study of the mechanism of cuprate oxide superconducting system. Fe-based superconductors are the direct exchange interaction, while cuprate is super-exchange interaction. So we should put the exchange interaction on the extremely important position and take it as the starting point to build the framework of the theory of high-temperature superconducting cuprate mechanism. At this point, it seems that most of superconducting researchers have reached a consensus. Outwardly, the difference lies in the model, and in fact there are very fundamental differences. In my personal view, the following points should be emphasized.

1. The super-exchange concept was proposed by H. A. Kramers seventy years ago. The difference is that the transition metal wave function does not directly over-

lap. Owing to the presence of the oxygen ion O^{2-}, making the transition metal ions such as Cu ions, the electron wave functions have overlap. However, the lack of oxygen ions O^{2-} will affect the strength of super-exchange. The phase diagram shows the hole injection on the oxygen sites makes the antiferromagnetic ordering gradually disappear and transit to a conventional Fermi liquid, during the emergence of high-temperature superconductivity in cuprate oxide superconductors. The oxygen ions O^{2-} should be serious discussed. The simplified models, ignoring the oxygen ions, may be successful in other antiferromagnetic materials, but can be said to be unsuccessful in high-temperature superconducting mechanism. It should take the three-band model or two-component model as the starting point. Unfortunately, the Zhang-Rice has led the problem in a wrong direction, back to single-band model from the three band model. This is the theoretical reason why some people still insist on a single-band model.

2. Using pure two-dimensional (2D) model on layered compounds is successful in many systems. But the research of high-temperature superconductivity mechanism in the high-temperature superconducting couprate oxide is not very successful. Quasi-2D (actual three-dimentional (3D)) model should be used, which will greatly expand the imagination and processing space.

3. The RVB picture may be the correct picture, especially for the bad metal system. In the three-band or called two-component model, it should be short-range pairing of oxygen holes (or electrons). It is still hotly debated whether the glue exists or not.

4. In recent years, there is a debate on the pseudogap state, i.e. below the T^*, the density of states near Fermi surface decreases, and Fermi surface decreases a lot, up to T_C, the superconducting gap appears, and Fermi surface disappears—strictly speaking only leaves some points (nodes). There are two opposing views about the pseudogap state, one is pre-pairing, also known as single energy gap; the other is two-gap of ordering competition. In fact, please do not ignore the correlated order of Cu^{2+} which also takes responsibility for the decrease of density of state near Fermi energy. At zero-doping, the system is an insulator, completely eating the density of state near Fermi energy. This process is gradual and the localization of Cu^{2+} co-exists with the superconducting state.

The book named "Advances in Theoretical and Experimental Research of High Temperature Cuprate Superconductivity", is a collection of reports on the seminar of high-T_C superconductors 20 years research. Such as the name of the seminar "The Assessment Seminar on High-Temperature Superconducting Mechanism Research", the meeting is a clearing inventory. After two decades of research, the mystery of the known high-temperature superconductivity, although do not reach a consensus on the mechanism, but for the existed problems from the perspective of global, it is a clean-up to guide future work. There are some people, who do the same work internationally, such as J. S. Brooks and J. R. Schrieffer editing "Handbooks of High Temperature Superconductivity" (Springer, 2007). I hope this collection will play a role in promoting high-temperature superconductivity mechanism research. Thank you all for the contribution to the publication of this book.

Ru-Shan Han

During the Beijing Olympic Games in 2008

Contents

The Electronic State Phase Diagram of Copper Oxide High-Temperature Superconductors

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High-temperature superconductors are discovered by J. G. Bendnorz and K. A. Müller in 1986. Before the discovery of high-temperature superconductivity in copper oxide perovskites, the transition temperature has increased from 4 K to 22~23 K since Kammerlingh Onnes firstly observed superconductivity in mercury in 1911. But since the Ba-La-Cu-O system at 40 K discovered by Bednorz and Müller, the transition temperature increased to 163 K in the Hg-Ba-Ca-Cu-O system under pressure in a very short time, several times higher than before. Recently, the ironbased superconductor with T_C higher than 50 K has become the superconductors of the highest transition temperature except cuprates. The superconducting transition temperature and the discovery time are shown as Fig. 1.

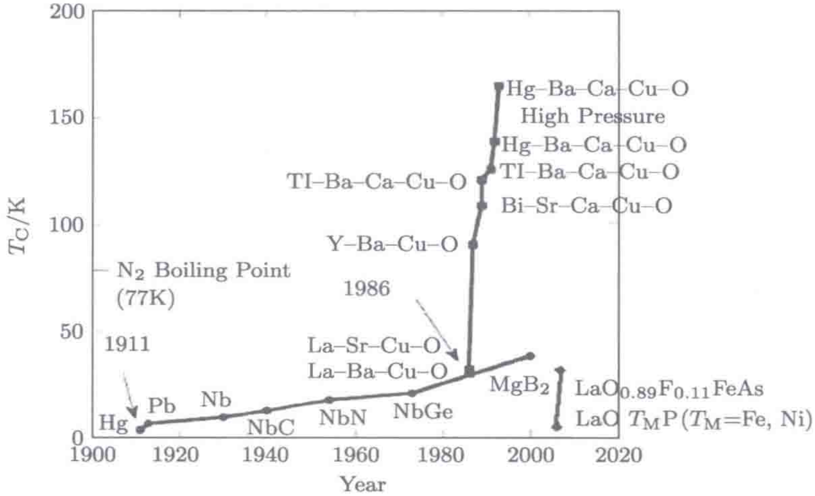

Fig. 1 The superconducting transition temperature T_C and the discovery time.

As the superconductors' transition temperature T_C is very high, higher than liquid nitrogen temperature, which makes they have a wide range of applications, and in turn promotes the high-temperature superconductors' application research. In addition, the high-temperature superconductor is a strongly correlated electron system, and its physical properties are very complex and rich, so it is very important to study the mechanism of the superconductivity. In condensed matter physics, no other systems like high-temperature superconductors, get so much concern of physicists, and so many different experimental methods to study.

Crystal structures of the cuprates: the high-temperature superconductors adopt a perovskite structure, which mainly include the weakly coupled copper-oxide layers and other charge-providers components, see Fig. 2. According to the type of carrier, the cuprates can be divided into hole-and electron-type superconductors, and in the hole-type superconductors based on the number of CuO_2 layers, they can be divided into single, two, three, and infinite-layer superconductors. The cuprates' main characters are dominated by the CuO_2 planes. The copper-oxide planes are checkerboard lattices with squares of O^{2-}ions and a Cu^{2+} ion at the centre of each square (see Fig. 3), its structure as follows: the Cu^{2+} ion has a $3d^9$ configuration,

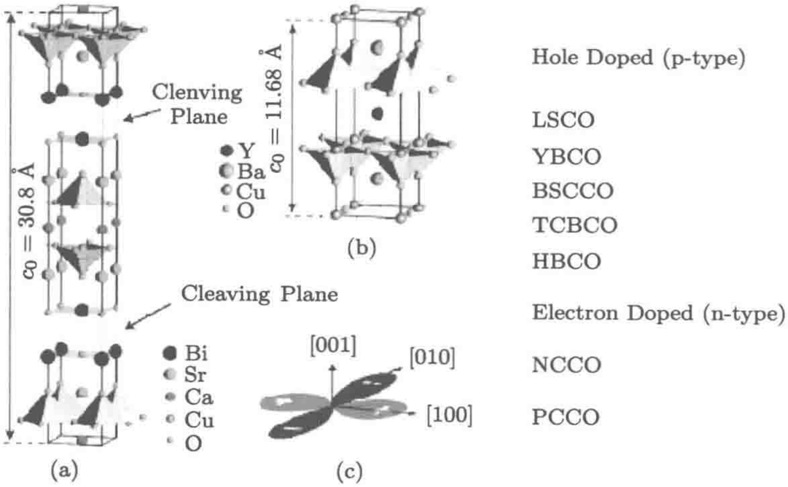

Fig. 2 (a) $Bi_2SrCaCu_2O_8$ and (b) $YBa_2Cu_3O_7$ crystal structure and the type of high-temperature superconductors.

and the antiferromagnetic spin correlation between copper ions is the super-exchange interaction by the medium of the oxygen 2p electrons.

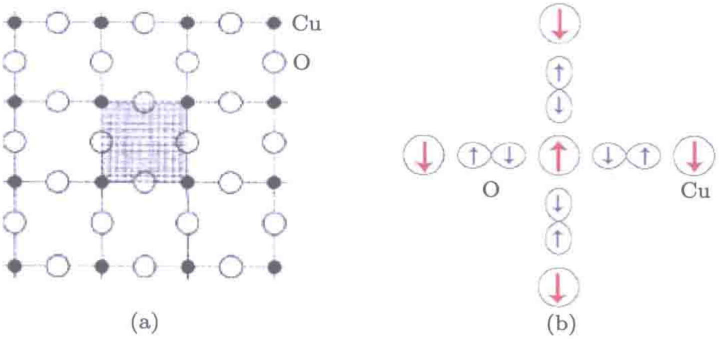

Fig. 3 The structure of CuO_2, spin correlation between copper ions is the super-exchange interaction by the medium of the oxygen 2p electron.

Electron-and hole-doped electronic state phase diagram: with the change of doping concentration, the properties of high-temperature superconductors have changed a lot. Fig. 4 shows the phase diagram of high-temperature superconductors. The left is the electron-doped region, while the right is the hole-doped region. The undoped "parent" and the low carrier doping compounds are Mott insulators with three-dimentional (3D) long-range anti-ferromagnetic ordering. However, as

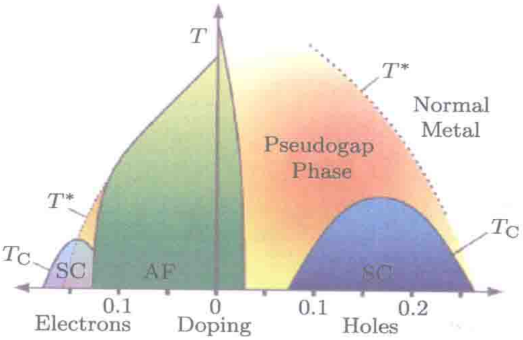

Fig. 4 The electronic state phase diagram of the high-T_C superconductor (AF: antiferromagnetic region; SC: superconducting region).

the doping increases it slowly becomes conductive, then a relatively large region of doping turns up, called pseudogap region, which means there is a gap found in the normal state. With the carrier concentration increasing, it becomes a superconductor, and then as the carrier concentration continues to increase, it will basically become a Fermi liquid, normal metallic state. In cuprate superconductors, the T_C as a function of doping concentration of the different systems basically can be represented by the universal parabola, the empirical formula. This paper is basically to discuss the electronic state phase diagram of hole-type superconductors.

Actually, the more comprehensive electronic state phase diagram of hole-type cuprate superconductors is shown in Fig. 5. The phase diagram shows it is basically a non-Fermi liquid state in a large region, but as the doping concentration increasing it becomes a Fermi liquid behavior. Why does its properties have such a big change, as a function of doping concentration? And why does the system finally become the Fermi liquid state of normal metal from a strongly correlated 3D anti-ferromagnetic ordering system? How to explain these phenomena in the phase diagram of cuprate superconductors is very important.

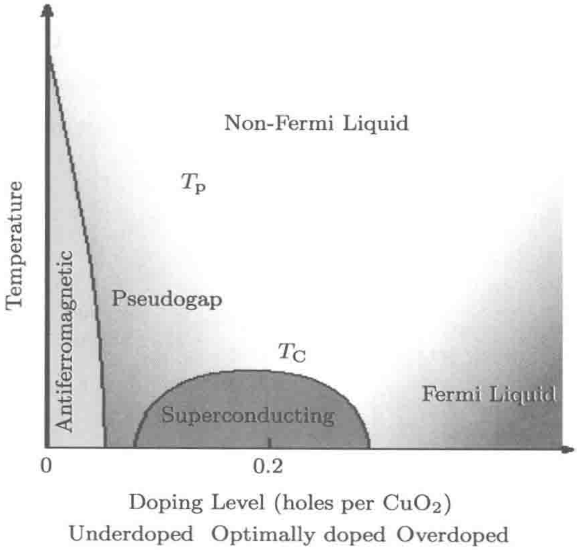

Fig. 5 The electronic state phase diagram of the hole-type high-T_C superconductors.

The following is the discussion about the basic physical properties of the various