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High Temperature Superconductivity: The Mystery We Are Ever After

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INTERNATIONAL WORKSHOP ON ADVANCED MATERIAL FOR NEW AND RENEWABLE ENERGY;
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ABSTRACT

Mukunda P. Das
Department of Theoretical Physics Institute of Advanced Studies The Australian National University Canberra,
ACT 0200, Australia

Superconductivity was an unanticipated property of matter. Perhaps no history of a scientific subject is as impressive as the history of superconductivity. Over the past nine decades the history remains exciting, where some of our best minds were and are engaged on understanding how this remarkable property is manifested in some materials under certain conditions. In 1986 Alex Müller and Georg Bednorz from IBM, Zurich reported Ba-doped lanthanum cuprate is a superconductor with an onset temperature of 35 K. Since then an unprecedented race continues. High T_c superconductors are difficult to understand because they involve a number of electronic and structural phase transitions between anti-ferromagnetic insulators, highly correlated metals, superconductors and normal metals. The general consensus is that the parent materials are Mott insulators, where strong electronic Coulomb repulsion suppresses charge fluctuations on the Cu sites. Upon doping the holes/electrons become mobile and exhibit various mysterious phases. At present the key issue remains to be resolved—how do we understand a variety of anomalies in the normal state, particularly in the underdoped part of the density-temperature (n - T) phase diagram? What do these anomalies indicate towards the microscopic mechanism of superconducting pairing? ©2009 American Institute of Physics

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BCS theory, electronic structure, Hubbard model, Fermi liquid, phase diagrams

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CONTENTS

Preface	vii
---------------	-----

PLENARY SESSION

PEM Fuel Cells for Transport Applications: State of the Art and Challenges	3
F. A. de Bruijn	
Redox-Active Nitroxide Radical Polymers: From Green Catalysts to Energy Storage Devices	13
W. Waskitoaji, T. Suga, and H. Nishide	
High Temperature Superconductivity: The Mystery We Are Ever After	19
M. P. Das	
Characterization of Solar Cells Using Nano Titanium Oxide and Nanocomposite Materials	25
N. N. Dinh, N. M. Quyen, L. H. Chi, T. T. C. Thuy, and T. Q. Trung	
Energy Conversion: Nano Solar Cell	32
M. Yahaya, C. C. Yap, and M. M. Salleh	
Development of Lithium-Ion Battery as Energy Storage for Mobile Power Sources Applications	38
M. A. Sulaiman and H. Hasan	
The Fractional Quantum Hall Effect: The Cases of 5/2 and 12/5	48
K. N. Shrivastava	
Study of Lead-free Ferroelectric Films for New Solar Cells	55
D. Fasquelle, M. Mascot, J. C. Carru, M. Hikam, Y. Iriani, and B. Soegijono	
A View of Compatible Heat-resistant Alloy and Coating Systems at High Temperatures	63
T. Narita	

PARALLEL SESSION

Material Development and Characterization

Quantum Size Level Structure of Colloidal CdTe Quantum Dot Nanocrystal: A Multi-band Approach . . .	77
M. A. U. Absor, M. D. Umar, and K. Abrahama	
Mechanical Properties of Clay Thin Plate as Pre-Evaluation for Solid Oxide Fuel Cell Manufacture . . .	87
Sulistyo, S. Mahzan, and S. Ariffin	
Mechanical Properties of Nature Graphite Compacts Electroplated by Copper	93
C.-C. Wen, H. Tsou, C.-H. Pai, and W.-S. Kuo	
Development of Clay Thin Plate as First Preparation for Solid Oxide Fuel Cell Manufacture—Preliminary Study	101
S. Mahzan, S. Ariffin, and, Sulistyo	
The Effect of Time Delumination and Solvent Concentration in Synthesis of Zeolite Catalyst and Catalytic Test for Diethyl Ether Production Process	106
D. Widayat, A. Roesyadi, and M. Rachimoellah	
Low Cost Highly Absorbing CuInS₂ Layer for Solar Cell Applications	113
M. H. Sayed, M. Boshta, and F. A. Mahmoud	
Materials for Hydrogen Production with Integrated CO₂ Capture	119
R. W. van den Brink and F. A. de Bruijn	
Study of Monolayer Films for Organic Solar Cells	127
S. Vidawati, U. Rothe, B. Soegijono, and M. Hikam	
Commensurate Effects in the Square Superconductor with a Regular Holes Array	132
Harsojo, K. Abrahama, and P. Nurwantoro	
Thermal Dissipation Efficiency in a Microprocessor Using Carbon Nanotubes Based Composite	138
B. H. Thang, C. V. Quang, V. T. Nghia, P. N. Hong, N. V. Chuc, N. T. T. Tam, L. D. Quang, P. H. Khoi, and P. N. Minh	

Influence of Optical Filter Effect on the Incident Photon to Current Efficiency of Heterojunction Organic Photovoltaic Devices	144
K. Triyana, P. Nurwantoro, and T. Tsutsui	
Characteristics of High Efficiency InGaP/InGaAs Double Junction Solar Cells Grown on GaAs Substrates	149
H. P. T. Nguyen, K. H. Kim, H. Lim, and J. J. Lee	
Study of Barium Strontium Titanate Thin Film Doped by Indium	155
M. Hikam, B. Soegijono, Y. Iriani, I. Mudzakir, and D. Fasquelle	
Influence of Ultrasonic Waves on the Formation of High Pores Silicon Carbide	161
M. C. F. Toana, B. Soegijono, and M. Hikam	

Energy, Process, and Applications

Microcontroller-based Control Design for Fuel Cell System	169
I. Firmansyah, B. Prihandoko, and E. Suwandi	
Production and Purification of Bioethanol from Molasses and Cassava	174
R. Maryana and S. K. Wahono	
Partial Replacement of Nonrenewable Fossil Fuel Energy by the Use of Waste Materials as Alternative Fuels	179
V. I. Judarta, A. Manaf, and G. Purwadi	
Biogas Purification Process to Increase Gen-Set Efficiency	185
S. K. Wahono, R. Maryana, and M. Kismurtono	
Epoxidised Natural Rubber Based Composite Polymer Electrolyte Systems for Use in Electrochemical Device Applications	190
R. Idris, A. Tasnim, M. R. Hakim, D. Hj. Mohd, Z. Ghazali, and K. M. Mahbor	
Production of Biodiesel from Jatropha Curcas Using Nano Materials	197
M. B. Khan, A. Bahadur, and W. Anjum	
Development of Electrolysis System Powered by Solar-cell Array to Supply Hydrogen Gas for Fuel-cell Energy Resource Systems	206
P. S. Priambodo, F. Yusivar, A. Subiantoro, and R. Gunawan	
New Material Development for Surface Layer and Surface Technology in Tribology Science to Improve Energy Efficiency	214
R. Ismail, M. Tauviquirrahman, Jamair, and D. J. Schipper	

Theoretical Studies

How Do Gas, Temperature and Oxygen Pressure Change the Conductivity of Metal Oxide Semiconductor (MOS) Thin Film?—A Theoretical Study with Point Defect Theory	225
M. D. Umar	
Extracting Physical Observables Using Macroscopic Ensemble in the Spex-Mixer/Mill Simulation	235
Muhandis, F. Nurdiana, A. S. Wismogroho, N. T. Rochman, and L. T. Handoko	
Pfaffian States: Quantum Computation	241
K. N. Shrivastava	
Theoretical Determination of the Optimum Thickness of Perylene Layer in Bilayer Phthalocyanine/Perylene Photovoltaic Device	247
H. Pratiwi, T. Siahaan, M. Satriawan, P. Nurwantoro, and K. Triyana	
DFT Calculation of Vibrational Frequencies in Clusters of Fe and As Atoms	256
N. A. Rosli, H. A. Kassim, C. G. Jesudason, and K. N. Shrivastava	
The Electronic Structure Band Structure of KFe_2As_2	261
N. A. Zabidi, H. A. Kassim, and K. N. Shrivastava	
Miso Model Identification of Proton Exchange Membrane Fuel Cell (PEM-FC) Using Least-Square Method	265
F. Yusivar, A. Subiantoro, D. Aryani, R. Gunawan, and P. S. Priambodo	
pFaffian, Gaffnian, and Haffnian States: Quantum Computations	275
M. M. A. Ali, H. A. Kassim, and K. N. Shrivastava	
Computerized Simulation of Magnetoresistive Random Access Memory Material	279
L. L. Ling, C. Jesudason, and K. N. Shrivastava	

DFT Computation of the Electronic Band Structure of FeSe	283
T. Y. Lin, H. A. Kassim, and K. N. Shrivastava	
List of Participants	289
Author Index	295

PREFACE

International Workshop on Advanced Material for New and Renewable Energy (AMNRE) is organized by Research Center for Physics, Indonesian Institute of Sciences, Indonesia in Putri Duyung Cottage, Ancol, Jakarta on 9- 11 June, 2009. This workshop is also realization of the commitment of Sub Committee of Material Science and Technology (SCMST) and Sub Committee of Non Conventional Energy Research (SCNCER) of ASEAN Committee of Science and Technology (ASEAN COST) in contributing to the enhancement of the international scientific cooperation among the ASEAN countries .

International Workshop on Advanced Material for New and Renewable Energy (AMNRE) provides an international forum for the sharing of the knowledge, information, experience and research result as well as the review of progress and discussion on the state of the art and future trend in the research and development of advanced material for new and renewable energy among the ASEAN member countries and others in the world

(Australia, Algeria, France, Japan, India, Pakistan, China, Egypt, Chinese Taiwan etc). The papers will published in the proceeding and the selected papers will be published on ASEAN Journal on Science and Technology for Development and American Institute of Physics (AIP) Proceeding.

We would like to express our deep gratitude to United Nation of Education, Scientific and Cultural Organizations (UNESCO), World Association of Industrial and Technological Research Organization (WAITRO) and other sponsors for the financial supports.

We would also like to express our heartiest to thank to all speakers and participants for the active participation in International Workshop on Advanced Material for New and Renewable Energy and to all the paper reviewers, member of steering committee, member of the organizing committee and Indonesia Institute of Science staff for their support to the success of this workshop.

We cordially wish all participants the ebullient scientific discussion and enjoyable meeting at the Workshop and a pleasant stay in beautiful Ancol, Jakarta. We do hope that all foreign participants will have good impression on Indonesia hospitality.

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Table of Contents

AIP Conference Proceedings Volume 1169

[View Volume Detail](#)

INTERNATIONAL WORKSHOP ON ADVANCED MATERIAL FOR NEW AND RENEWABLE ENERGY

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FRONT MATTER (PDF)

☐ PEM Fuel Cells for Transport Applications: State of the Art and Challenges

Frank A. de Bruijn

pp. 3-12

Abstract Full Text [PDF (1972 kB)] Order

☐ Redox-Active Nitroxide Radical Polymers: From Green Catalysts to Energy Storage Devices

Wihalmoko Waskiloaji, Takeo Suga, and Hiroyuki Nishide

pp. 13-18

Abstract Full Text [PDF (1423 kB)] Order

☒ High Temperature Superconductivity: The Mystery We Are Ever After

Mukunda P. Das

pp. 19-24

Abstract Full Text [PDF (803 kB)] Order

☐ Characterization of Solar Cells using Nano Titanium Oxide and Nanocomposite Materials

Nguyen Nang Dinh, Nguyen Minh Quyen, Le Ha Chi, Tran Thi Chung Thuy, and Tran Quang Trung

pp. 25-31

Abstract Full Text [PDF (1303 kB)] Order

☐ Energy Conversion: Nano Solar Cell

Muhammad Yahaya, Chi Chin Yap, and Muhamad Mat Salleh

pp. 32-37

Abstract Full Text [PDF (1626 kB)] Order

☐ Development of Lithium-ion Battery as Energy Storage for Mobile Power Sources Applications

Mohd Ali Sulaiman and Hasimah Hasan

pp. 38-47

Abstract Full Text [PDF (4293 kB)] Order

☐ The fractional quantum Hall effect: The cases of 5/2 and 12/5

Keshav N. Shrivastava

pp. 48-54

Abstract Full Text [PDF (385 kB)] Order

☐ Study of Lead Free Ferroelectric Films for New Solar Cells

D. Fasquelle, M. Mascot, J. C. Carru, M. Hikam, Y. Iriani, and B. Soegijono

pp. 55-62

Abstract Full Text [PDF (1790 kB)] Order

☐ A View of Compatible Heat-Resistant Alloy and Coating Systems at High-Temperatures

Toshio Narita

pp. 63-73

Abstract Full Text [PDF (3422 kB)] Order

☐ Quantum Size level Structure of Colloidal CdTe Quantum Dot Nanocrystal : A Multi-band Approach

Moh. Adhik Ulii Absor, Moh. Darwis Umar, and Kamsul Abrahama

pp. 77-86

Abstract Full Text [PDF (696 kB)] Order

☐ Mechanical Properties of Clay Thin Plate as Pre-Evaluation for Solid Oxide Fuel Cell Manufacture

Sulistyo, Shahrudin Mahzan, and Saparudin Ariffin

pp. 87-92

Abstract Full Text [PDF (1846 kB)] Order

☐ Mechanical Properties of Nature Graphite Compacts Electroplated by Copper

Chan-Chao Wen, Hung Tsou, Chia-Hung Pai, and Wen-Shyong Kuo

pp. 93-100

Abstract Full Text [PDF (2541 kB)] Order

☐ Development of Clay Thin Plate as First Preparation for Solid Oxide Fuel Cell Manufacture—Preliminary Study

Shahrudin Mahzan, Saparudin Ariffin, and Sulistyo

pp. 101-105

Abstract Full Text [PDF (1241 kB)] Order

☐ The Effect of Time dealumination and Solvent Concentration in Synthesis of Zeolite Catalyst and Catalytic Test for DiEthyl Ether Production Process

Widayat, A. Roesyadi, and M. Rachimoellah
pp. 106-112
Abstract Full Text [PDF (1001 kB)] Order

Low Cost Highly Absorbing CuInS_2 Layer for Solar Cell Applications 1-Atomization gas type effect
M. H. Sayed, M. Boshla, and Fawzy A. Mahmoud
pp. 113-118
Abstract Full Text [PDF (1292 kB)] Order

Materials for Hydrogen Production with Integrated CO_2 Capture
Ruud W. van den Brink and Frank A. de Bruijn
pp. 119-126
Abstract Full Text [PDF (1032 kB)] Order

Study of Monolayer Films for Organic Solar Cells
Sri Widawati, Ulrich Rothe, Bambang Soegijono, and M. Hikam
pp. 127-131
Abstract Full Text [PDF (873 kB)] Order

Commensurate effects in the square superconductor with a regular holes array
Harsojo, Kamsul Abraha, and Pekik Nurwantoro
pp. 132-137
Abstract Full Text [PDF (1785 kB)] Order

Thermal Dissipation Efficiency in a Micro-Processor Using Carbon Nanotubes Based Composite
Bui Hung Thang, Cao Van Quang, Van Trong Nghia, Phan Ngoc Hong, Nguyen Van Chuc, Ngo Thi Thanh Tam, Le Dinh Quang, Dao Duc Khang, Phan Hong Khoi, and Phan Ngoc Minh
pp. 138-143
Abstract Full Text [PDF (1833 kB)] Order

INFLUENCE OF OPTICAL FILTER EFFECT ON THE INCIDENT PHOTON TO CURRENT EFFICIENCY OF HETEROJUNCTION ORGANIC PHOTOVOLTAIC DEVICES
Kuwal Triyana, Pekik Nurwantoro, and Tetsuo Tsutsui
pp. 144-148
Abstract Full Text [PDF (1547 kB)] Order

Characteristics of high efficiency InGaP/InGaAs double junction solar cells grown on GaAs substrates
H. P. T. Nguyen, K. H. Kim, H. Lim, and J. J. Lee
pp. 149-154
Abstract Full Text [PDF (2270 kB)] Order

Study of Barium Strontium Titanate Thin Film Doped by Indium
M. Hikam, B. Soegijono, Y. Iriani, I. Mudzakir, and D. Fasquelle
pp. 155-160
Abstract Full Text [PDF (1653 kB)] Order

Influence Of Ultrasonic Waves On The Formation Of High Pores Silicon Carbide
Musfirah C. F. Toana, B. Soegijono, and M. Hikam
pp. 161-166
Abstract Full Text [PDF (1555 kB)] Order

Microcontroller-based Control Design for Fuel Cell System
I. Firmansyah, B. Prihandoko, and E. Suwandi
pp. 169-173
Abstract Full Text [PDF (826 kB)] Order

Production and Purification of Bioethanol from Molasses and Cassava
Roni Maryana and Satriyo Krido Wahono
pp. 174-178
Abstract Full Text [PDF (1006 kB)] Order

Partial replacement of non renewable fossil fuels energy by the use of waste materials as alternative fuels
V. Indrawati, A. Manaf, and G. Purwadi
pp. 179-184
Abstract Full Text [PDF (645 kB)] Order

Biogas Purification Process to Increase Gen-Set Efficiency
Satriyo Krido Wahono, Roni Maryana, and M. Kismurtono
pp. 185-189
Abstract Full Text [PDF (1821 kB)] Order

Epoxidised Natural Rubber Based Composite Polymer Electrolyte Systems For Use In Electrochemical Device Applications
Razali Idris, Anis Tasnim, Mas Rosemal Hakim, Dahlan Hj. Mohd, Zulkafli Ghazali, and Kamisah Mohamad Mahbor
pp. 190-196
Abstract Full Text [PDF (1100 kB)] Order

Production of Biodiesel from *Jatropha Curcas* using Nano Materials
M. Bilal Khan, Ali Bahadar, and Waqas Anjum
pp. 197-205
Abstract Full Text [PDF (1185 kB)] Order

Development of Electrolysis System Powered by Solar-Cell Array to Supply Hydrogen Gas for Fuel-Cell Energy Resource Systems
Purnomo Sidi Priambodo, Feri Yusivar, Aries Subiantoro, and Ridwan Gunawan
pp. 206-213
Abstract Full Text [PDF (2400 kB)] Order

New Material Development for Surface Layer and Surface Technology in Tribology Science to Improve Energy Efficiency
R. Ismail, M. Tauviquirrahman, Jamani, and D. J. Schipper
pp. 214-221
Abstract Full Text [PDF (2298 kB)] Order

How Do Gas, Temperature and Oxygen Pressure Change the Conductivity of Metal Oxide Semiconductor (MOS) Thin Film? : A Theoretical Study with Point Defect Theory
Muhamad Darwis Umar
pp. 225-234
Abstract Full Text [PDF (692 kB)] Order

Extracting physical observables using macroscopic ensemble in the spex-mixer/milli simulation
Muhandis, F. Nurdiana, A. S. Wismogroho, N. T. Rochman, and L. T. Handoko
pp. 235-240
Abstract Full Text [PDF (375 kB)] Order

Pfaffian States: Quantum Computation
Keshav N. Shrivastava
pp. 241-246

[Abstract](#) [Full Text](#) [[PDF \(272 kB\)](#)] [Order](#)

└ **Theoretical Determination of The Optimum Thickness of Perylene Layer in Bilayer Phthalocyanine/Perylene Photovoltaic Device**
Herlina Pratiwi, Timothy Siahaan, Mirza Satrawan, Pekik Nurwantoro, and Kuwal Triyana
pp. 247-255
[Abstract](#) [Full Text](#) [[PDF \(1349 kB\)](#)] [Order](#)

└ **DFT CALCULATION OF VIBRATIONAL FREQUENCIES IN CLUSTERS OF Fe AND As ATOMS**
Nazrul Ahmad Rosli, Hasan Abu Kassim, Christopher G. Jesudason, and Keshav N. Shrivastava
pp. 256-260
[Abstract](#) [Full Text](#) [[PDF \(961 kB\)](#)] [Order](#)

└ **The Electronic Structure Band Structure of KFe_2As_2**
Noriza Ahmad Zabidi, Hasan Abu Kassim, and Keshav N. Shrivastava
pp. 261-264
[Abstract](#) [Full Text](#) [[PDF \(577 kB\)](#)] [Order](#)

└ **Miso Model Identification of Proton Exchange Membrane Fuel Cell (PEM-FC) using Least-Square Method**
F. Yusivar, A. Subiantoro, D. Aryani, R. Gunawan, and P. S. Priambodo
pp. 265-274
[Abstract](#) [Full Text](#) [[PDF \(770 kB\)](#)] [Order](#)

└ **pFaffian, Gaffnian and Haffnian states : Quantum Computations**
Maher M. A. Ali, Hasan A. Kassim, and Keshav N. Shrivastava
pp. 275-278
[Abstract](#) [Full Text](#) [[PDF \(889 kB\)](#)] [Order](#)

└ **Computerized Simulation of Magnetoresistance Random Access Memory Material**
Lee Li Ling, Christopher Jesudason, and Keshav N. Shrivastava
pp. 279-282
[Abstract](#) [Full Text](#) [[PDF \(748 kB\)](#)] [Order](#)

└ **DFT Computation of the Electronic Band Structure of FeSe**
Teh Yee Lin, Hasan Abu Kassim, and Keshav N. Shrivastava
pp. 283-288
[Abstract](#) [Full Text](#) [[PDF \(926 kB\)](#)] [Order](#)

[BACK MATTER \(PDF\)](#)

[\[Previous / Proceedings | All Proceedings | Top of Page \]](#) [\[Search This Proceedings \]](#)

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High Temperature Superconductivity: The Mystery We Are Ever After

Mukunda P. Das

*Department of Theoretical Physics
Institute of Advanced Studies
The Australian National University
Canberra, ACT 0200, Australia
Email: mukunda.das@anu.edu.au*

Abstract: Superconductivity was an unanticipated property of matter. Perhaps no history of a scientific subject is as impressive as the history of superconductivity. Over the past nine decades the history remains exciting, where some of our best minds were and are engaged on understanding how this remarkable property is manifested in some materials under certain conditions. In 1986 Alex Müller and Georg Bednorz from IBM, Zurich reported Ba-doped lanthanum cuprate is a superconductor with an onset temperature of 35K. Since then an unprecedented race continues.

High T_c superconductors are difficult to understand because they involve a number of electronic and structural phase transitions between anti-ferromagnetic insulators, highly correlated metals, superconductors and normal metals. The general consensus is that the parent materials are Mott insulators, where strong electronic Coulomb repulsion suppresses charge fluctuations on the Cu sites. Upon doping the holes/ electrons become mobile and exhibit various mysterious phases. At present the key issue remains to be resolved - how do we understand a variety of anomalies in the normal state, particularly in the underdoped part of the density-temperature (n - T) phase diagram? What do these anomalies indicate towards the microscopic mechanism of superconducting pairing?

Keywords: BCS Theory, High T_c Superconductivity, Doped Cuprates, Mott Insulator, Anomalous Normal State, Phase Diagram, Charge/Spin Density Wave

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INTRODUCTION

Shortly after Landau's Fermi liquid theory was published, five decades ago, in 1957, Bardeen, Cooper and Schieffer (BCS) presented their famous paper, what is known as the BCS theory of superconductivity. The BCS theory explains the superconductivity in low temperature superconductors that remained as a mystery for about fifty years. The Fermi liquid theory has a lot of predictions regarding the normal state of the superconducting materials at elevated temperatures. At a low temperature the Fermi liquid becomes unstable due to phonon-mediated attractive electron-electron interaction. This instability arises out of pairing of electrons followed by superconducting condensation at a certain critical temperature T_c . It has been essential that the BCS superconductors require the Fermi liquid description for their normal states above T_c . Until 1986 almost all low T_c superconductors could be described within the framework of the Fermi liquid and BCS theories.

In 1986 Ba-doped La cuprate superconductor was discovered with a T_c above 30K. Following that within a few years over two dozens of superconductors were found, with the highest $T_c \sim 165$ K, that of Thallium-doped Mercuric Cuprate (comprised of Tl, Hg, Ca, Ba, Cu and O) under high pressure. During the past two decades both the theory and experimental work on high T_c materials have been carried out with unprecedented enthusiasm. On the experimental front it is gratifying to note that it is possible to produce well-characterised high T_c samples without any doubt for unidentified superconducting anomalies. With ingenious techniques of material making, a rich variety of measured properties are available. Surprisingly several of the properties are found to be anomalous in comparison to the low T_c materials, posing a great challenge for understanding for the theorists- what really makes these oxides to superconduct?. In this paper we shall focus on some of the crucial points regarding the anomalies in the observed properties of high T_c materials.

a hole, which travels to the CuO_2 layer and gets accommodated by the Cu ion due to its property of mixed valency. Similar situation happens for electron doping when tetravalent Ce replaces trivalent Nd in Nd_2CuO_4 .

The electronic structure and the nature of magnetism in the pure or weakly doped regimes in the phase diagram is reasonably understood with the famous and popular Hubbard model [1-4], where the electron correlations (U) are highly dominant over the hopping (t) of the holes/electrons. In this limit $U/t \gg 1$, the Hubbard Hamiltonian is transformed to the Heisenberg Hamiltonian or t - J Hamiltonian (t for hopping and J for exchange). This helps to understand the excitations in the low energy sector. In 1987 Anderson [5] made an important suggestion that the Hubbard model is a suitable candidate for understanding the high T_c superconductivity. Based on the observation that a Mott insulator when doped, becomes a superconductor by losing long range antiferromagnetic correlations. A new state 'resonating valence bond state' (RVB), a quantum liquid of spin singlet pairs with only short range magnetic order is created that at the mean field level produces superconductivity. This exotic picture has passed through many ups and downs and still remains blurred for understanding the high T_c phenomenon. Besides this point of view there are several other competing proposals, namely fluctuations dominated antiferromagnetic Fermi liquid theory [5], marginal Fermi liquid theory [6], bipolaron condensation mechanism [7], Fermion-Boson mechanism [8], Gauge models [9] etc. Because of space reasons we shall not be able to discuss these proposals. An interested reader may consult the relevant refs as given above.

Coming back to the phase diagram of Fig.1, most part of the overdoped normal phase behaves like a Fermi liquid. Therefore, it is tempting to use a BCS-type of pairing theory for the superconductors in this regime. The only question remains what mediates the pairing of the charge carriers. However, interesting nontrivial physics has emerged in the NonFermi liquid phases (both marginal Fermi liquid and pseudogap phases) mostly in the underdoped part. In the next Sec. we discuss in what way the normal state properties of these materials are anomalous in relation to the Fermi liquid predictions and what can be done about that.

ANOMALOUS NORMAL STATE

Landau's Fermi liquid theory is universally accepted as an important realisation in condensed matter physics. It is based on the following idea- unlike in free Fermi gas, the particles are weakly interacting. Interaction is switched on adiabatically, so that there is one to one correspondence between noninteracting and interacting particles. In the low energy sector the interacting particles are known as quasi-particles, which are dressed by picking up the effect of many-particle interaction through a self-energy. Apart from quasi-particles, there are collective modes. The Fermi liquid theory has certain definite predictions, which are clearly verified for a large number of metallic systems [10].

Table I Comparison of some properties in the Fermi liquid and Pseudogap regimes

Properties	Fermi liquid regime	Pseudogap regime
DOS $N(0)$	T-independent	$dN(0)/dT < 0 \implies$ pseudogap
Compressibility $\kappa = dn/d\mu$	T-independent $\kappa = N(0)/(1+F_0^s)$	finite and T-independent.
Susceptibility χ_s	T-independent (Pauli) $\chi_s = N(0)/(1+F_0^a)$	$\chi_s \sim N(0)$ $d\chi_s/dT < 0$
NMR relaxation $1/T_1T$	T-independent (Korringa) $1/T_1T \sim [N(0)]^2$	$1/T_1T \sim \chi_s(T)$ Strong T-dep $\implies$ spin gap
$n(k)$	Fermi surface at low T	Rounded $n(k)$ at low T
Excitations	$Q=1, S=1/2$	$Q=1, S=1/2$ & $Q=2, S=0$ collective excitation
Low T Resistivity	$R \sim T^2$	$\sim T$
Wiedemann-Franz law	$\kappa/\sigma = LT$	Violated

systematically as a function of doping, the stability of the system against the lattice deformation created by the density waves. We give here an example. The result of our calculations provides the following details. For onsite Coulomb interaction parameter $U = 6$ eV, the electron-phonon coupling $\lambda = 1$, the groundstate energy per cell is antiferromagnetic for low doping. CDW state is lower in energy than the paramagnetic state for lower doping. However, the CDW state takes over both for antiferromagnetic and paramagnetic state for relatively higher doping. This model calculation indicates that a CDW state can be sustained in the underdoped regime. From this result we infer that CDW order parameter may compete with the superconducting order parameter. The CDW order parameter arises due to the nontrivial effect of electron-phonon interaction. For details see Ref [23].

SUMMARY

In this brief review we presented an outline of the history of low and high temperature superconductors. The key to the understanding of high T_c phenomenon starts with the temperature-doping phase diagram. The phase diagram has two distinct parts, overdoped and underdoped regimes. The crucial properties, which have helped to understand the conventional low T_c superconductors via the Fermi liquid theory, are now at odd with the unusual normal states of the underdoped phase. The experimental controversy regarding the nature of the pseudogap has created two theoretical camps whether PG is a mate or an enemy for the superconducting order. One need to wait for more sophisticated experimentation and serious computational results on the nature and origin of PG. Our modest view is to carefully consider the role of electron correlations in presence of spatial disorder. Particularly in the PG regime any simplified analytic theory will not succeed because of the complexity of distribution of charge carriers, which are very sparse. Too many states for too little occupants, where fluctuations heavily dominate. A good statistical theory is nonexistent. As mentioned before, there are smoking gun experiments by STM and ARPES, which seem to provide valuable information [24-25]*.

There are other issues regarding the extreme type II phase of the $HTcS$, in view of their small coherence lengths and large penetration depths. The magnetic field and temperature (H-T) phase diagram is far more complex than that of the conventional superconductors. Since an important application depends on the high critical currents, study of the H-T phase diagram is of pivotal interest [26-28].

Summarising, in the past two decades study of $HTcS$ has brought to our attention a host of novel physics. We do understand now much better the novel phenomena associated with magnetism, role of disorder, metal-insulator transition etc. All these features have their lively presence in the underdoped regime.

New experimental and modern computational techniques have advanced to a great deal. Since the microscopic BCS theory is out of action in the underdoped part of the phase diagram, a new theory is the demand of the day. Interestingly there are number of suggestions, yet none has been at par with the standard model of condensed matter (example, BCS theory). In view of constrained scope of this review I apologise to many of our colleagues, whose work did not get cited here. The choice that I have made has been to focus on certain key issues, therefore in a subject like $HTcS$ it is very likely to be subjective. However, despite these weaker points, I am contented to say that there are many interesting and burning issues left to be brought to light by future investigations.

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