MISSION

Rice University’s Center for Quantum Materials seeks to sustain and grow fundamental research of quantum materials on campus, and develop an international network in this area, with Rice at its hub. The center will incubate new research collaborations and directions by organizing scientific workshops, supporting distinguished visitors to Rice, sponsoring postdoctoral scholars and student researchers and developing international and domestic partnerships.

AT A GLANCE

23 FACULTY MEMBERS
4 ACADEMIC DEPARTMENTS
2 WORKSHOPS
“Rice is well-positioned to lead in this area. First, the university has an intimacy that makes cross-disciplinary research the norm rather than the exception. Collaboration comes naturally here. We are small enough that almost everyone on campus can be on a first-name basis, and we have always used that to our advantage.”

“But in the area of quantum materials, we also have numbers. We woke up one day and said, ‘Wow. We’re big.’ That’s unusual for Rice, and it presents us with an opportunity to capitalize on our broad expertise in this field and on our unique collaborative culture.”
RCQM ADVISORY BOARD

RCQM has drawn on experts from across the country and around the world to serve on the advisory board.

Frank Steglich  
Max Planck Institute for Chemical Physics of Solids, Dresden

Hongjie Dai  
Stanford University

Laura Greene  
University of Illinois at Champaign-Urbana

Meigan Aronson  
Texas A&M University

Allan H. MacDonald  
University of Texas at Austin

Jason Ho  
Ohio State University

Elihu Abrahams  
UCLA (not pictured)
RCQM MEMBERSHIP

ATOMIC, MOLECULAR AND OPTICAL ENGINEERING

Kaden Hazard
Randy Hulet *
Tom Killian
Han Pu

CONDENSED MATTER

Pengcheng Dai *
Rui-Rui Du
Matt Foster
Emilia Morosan

Doug Natelson
Andriy Nevidomskyy
Qimiao Si * Director

ELECTRICAL AND COMPUTER ENGINEERING

Palash Bharadwaj
Kevin Kelly
Jun Kono *
Gururak Naik
Isabell Thomann

MATERIALS SCIENCE AND NANOENGINEERING

Pulickel Ajayan
Jun Lou
Emily Ringe
Boris Yakobson *

CHEMISTRY

Peter Rossky
Gus Scuseria
James Tour

*Executive Committee Members
VISITING SCHOLARS & INVITED SPEAKERS

FALL 2016

Elihu Abrahams / UCLA
Gabriel Aeppli / Paul Scherrer Institute, Switzerland
Meigan Aronson / Texas A&M
Immanuel Bloch / Max Planck, Garching
Hongjie Dai / Stanford University
Giulia Galli / University of Chicago
Jason Ho / Ohio State
David Hsieh / Caltech
Kenji Ishida / Kyoto University
Gabriel Kotliar / Rutgers University
Cornelius Krellner / Frankfurt University
Kathy Levin / University of Chicago
Allan MacDonald / UT Austin
Aditya Mohite / Los Alamos
Silke Paschen / TU Vienna
Heike Pfau / Stanford
Pramod Reddy / University of Michigan
Subir Sachdev / Harvard University
Andy Schofield / University of Birmingham
Zhi-Xun Shen / Stanford University
Boris Spivak / University of Washington
Frank Steglich / Max Planck, Dresden
Steffen Wirth / Max-Planck-Institute
Rong Yu / Rice University

SPRING 2017

James Analytis / University of California, Berkeley
Fakher Assaad / University of Wuerzburg, Würzburg
Collin Broholm / Johns Hopkins University
Jonathan Denlinger / Lawrence Berkeley National Lab
Maxim Dzsero / Kent State University
Zachary Fisk / University of California, Irvine
Pallab Goswami / University of Maryland
Pavan Hosur / University of Houston
Yuji Matsuda / Kyoto University
Andriy Nevidomskyy / Rice University
Johnpierre Paglione / University of Maryland
Catherine Pepin / CEA, France
Suchitra Sebastian / University of Cambridge
Lucia Steinke / Texas A&M University
Joe D. Thompson / Los Alamos National Laboratory
Mission Statement

Rice University’s Center for Quantum Materials seeks to sustain and grow fundamental research of quantum materials on campus, and develop an international network in this area, with Rice at its hub. The center will incubate new research collaborations and directions by organizing scientific workshops, supporting distinguished visitors to Rice, sponsoring postdoctoral scholars and student researchers and developing international and domestic partnerships.

Pictured at the center’s formal launch on December 15 are (from left) Ned Thomas, dean of the George R. Brown School of Engineering; Yousif Shamoo, Vice Provost for Research; Peter Rossky, dean of the Wiess School of Natural Sciences; Qimiao Si, director of the Center for Quantum Materials; Pulickel Ajayan, the Benjamin M. and Mary Greenwood Anderson Professor in Materials Science and NanoEngineering and of chemistry; and Tom Killian, department chair and professor of physics and astronomy.
WORKSHOP ON FRONTIERS
OF QUANTUM MATERIALS

November 4-5, 2016

Rationale and Scope
Quantum Materials is an emerging field of research that encompasses a broad range of studies in strongly correlated systems and applied materials physics. The breadth of the field calls for interactions among the different sub-communities. This workshop aims to bring together top experts from a variety of areas to highlight the recent achievements in each area, and to provide a forum for cross-talk among the subjects.

The workshop revolved around the following focus areas in the overarching field of Quantum Materials:

• Unconventional Superconductivity
• Quantum Criticality
• Ultracold Matter
• Low Dimensional Systems
• Energy Materials

Invited Speakers

Unconventional Superconductivity
Frank Steglich / Max Planck, Dresden
Zhi-Xun Shen / Stanford University
Gabriel Kotliar / Rutgers University

Quantum Criticality
Meigan Aronson / Texas A&M
Silke Paschen / TU Vienna
Subir Sachdev / Harvard University

Ultracold Matter
Jason Ho / Ohio State
Kathy Levin / University of Chicago
Immanuel Bloch / Max Planck, Garching

Energy Materials
Hongjie Dai / Stanford University
Aditya Mohite / Los Alamos
Pramod Reddy / University of Michigan

Low Dimensional Systems
Allan MacDonald / UT Austin
David Hsieh / Caltech
Rong Yu / Rice University

Broader Aspects
Gabriel Aeppli / Paul Scherrer Institute, Switzerland
Boris Spivak / University of Washington
Rong Yu / Renmin University
Giulia Galli / University of Chicago

Organizers
Elihu Abrahams / UCLA
Pulickel M. Ajayan / Rice University
Allan H. MacDonald / UT Austin
Qimiao Si / Rice University
Rationale and Scope
Topological states of matter are actively being explored in strongly correlated electron materials. Because strong correlations lead to a host of electronic ground states, this subject is inherently entwined with the physics of quantum phase transitions.

The workshop addressed open questions and explored new directions in the areas of topology and quantum phase transitions in Kondo insulators, heavy fermion metals, and related materials. It brought together experts in these different focus areas so that lively discussions can take place.

Invited Speakers
James Analytis / University of California, Berkeley
Fakher Assaad / University of Wuerzburg, Würzburg
Collin Broholm / Johns Hopkins University
Jonathan Denlinger / Lawrence Berkeley National Lab
Maxim Dzsero / Kent State University
Zachary Fisk / University of California, Irvine
Pallab Goswami / University of Maryland
Pavan Hosur / University of Houston
Yuji Matsuda / Kyoto University
Andriy Nevidomskyy / Rice University
Johnpierre Paglione / University of Maryland
Catherine Pepin / CEA, France
Suchitra Sebastian / University of Cambridge
Lucia Steinke / Texas A&M University
Joe D. Thompson / Los Alamos National Laboratory
In addition to seminars and workshops, RCQM hosted a series of fun, low-stress poster lunches as way to foster collaboration between research groups, refine presentation skills and highlight some of the center’s most recent results.
INTERNATIONAL INITIATIVES

RCQM continues to build strong international relationships with institutions around the world.
The Rice Center for Quantum Materials was proud to co-sponsor the capstone event for the 2017 TOMODACHI-STEM @ Rice University for Female Students Program.

The five-week research internship program for 10 female undergraduates from Japan, who are majoring in science and engineering (S&E), enabled students to gain real-world experience with S&E research, provided an introduction to U.S. higher education and provided opportunities for cultural engagement and collaboration with U.S. students. The program served as a catalyst for female Japanese students interested in Science & Engineering study and research and engagement with the U.S. through international research collaborations.

The 2017 program is modeled off of the 2016 TOMODACHI STEM @ Rice University Program. Out of the 10 participants in this program, six were female undergraduate students. The program’s impact can best be highlighted through the words of some of our 2016 TOMODACHI STEM participants.

The TOMODACHI Initiative is a public-private partnership, born out of support for Japan’s recovery from the Great East Japan Earthquake that invests in the next generation of Japanese and American leaders through educational and cultural exchanges as well as leadership programs. We seek to foster a “TOMODACHI generation” of young American and Japanese leaders who are committed to and engaged in strengthening U.S.-Japan relations, appreciate each other’s countries and cultures, and possess the global skills and mindsets needed to contribute to and thrive in a more cooperative, prosperous, and secure world.
Coherent light-matter interactions have entered a new regime where optical coherence is maintained over many seconds while thousands of atoms are prepared in precisely engineered quantum states. These capabilities have allowed us to achieve a new generation of atomic clocks with accuracy at the 18th digit. The progress of optical lattice clock to this level of accuracy has also benefited greatly from the understanding of atomic interactions. Meanwhile, the unprecedented precision of clock spectroscopy has enabled the exploration of many-body quantum systems including spin interactions under SU(N) symmetry. Our recent work on this combined front of quantum metrology and many-body physics includes the probe of spin-orbital physics in the optical lattice and the investigation of a Fermi degenerate gas of tens of thousands Sr-87 atoms configured as a band-insulator in a three-dimensional magic-wavelength optical lattice. We now demonstrate an atom-light coherent interaction time approaching 10 seconds, and show a clear path for improving the clock performance into the next decimal point.
Prof. Bühler-Paschen served as a Visiting Professor in the Center for Quantum Materials at Rice University from August 2016 to January 2017. While in Houston, she worked with many Rice University professors and students. She also co-organized two scientific workshops and one research symposium for the center. She plans to continue her collaboration with the Rice University Center for Quantum Materials as a Strategic International Partner when she returns to Vienna.

Silke Bühler-Paschen is an experimental condensed matter physicist, working in the fields of strongly correlated electron systems and thermoelectrics. She graduated in physics from Graz University of Technology in Austria, with an external diploma work at the Paul Scherrer Institute in Switzerland. After her PhD studies at EPFL in Lausanne and a postdoctoral stay at ETH Zurich she moved to Germany, where she joined the Max Planck Institute for Chemical Physics of Solids in Dresden, first as scientific collaborator and then as associate professor. After a visiting professorship at the Nagoya University in Japan she was appointed full professor at the Vienna University of Technology in Austria. She received a C3 professorship from the Excellence Program of the Max Planck Society for the Advancement of Outstanding Female Scientist in 2003 and an ERC Advanced Grant from the European Research Council in 2008. She is APS fellow and leader of various national and international research projects. Her team is active in materials synthesis and characterization, using a large pool of different physical property measurements under multiple extreme conditions—spanning, for instance, 7 orders of magnitude in temperature. Topics of current interest include quantum criticality, heavy fermion systems, Kondo insulators, new topological phases, and thermoelectrics.
The Rice Center for Quantum Materials welcomed former postdoc Rong Yu back to Rice for a semester to collaborate with Qimiao Si, Pengcheng Dai, Andriy Nevidomskyy and others in the center. While here he made a lively presence and contributed to a number of publications. He plans to continue his collaboration with the center as a Strategic International Partner.

**Rong Yu** obtained his B.S. degree from Peking University in 1998, M.S. degree from Tsinghua University in 2001, and Ph.D. degree from University of Southern California in 2007. He was a postdoctoral research associate at University of Tennessee, Knoxville (2007–2009) and at Rice University (2009–2013). Since 2013 he has been an associate professor at Department of Physics, Remin University of China. He has been working on theory of correlated electronic systems. Current main areas of his research includes phase transitions in heavy fermion systems, frustration and disorder effects in quantum magnets, superconductivity and correlation effects in iron-based superconductors.
Quantum Spin Hall States in Strained-layer InAs/GaInSb Quantum Wells

Quantum spin Hall effect (QSHE) is a fundamental and most spectacular phenomenon arising from topological protection. To date the leading material systems are made of semiconductor quantum wells (QWs), i.e., HgTe/CdTe QW and inverted InAs/GaSb QWs. Although quantized edge conductance plateaus have been observed in mesoscopic size devices (edge length ~ 1-4 μm) for both systems, it is realized that regular InAs/GaSb host strongly interacting edge states due to an unusually small Fermi velocity \(~(2 - 4) \times 10^4\) ms\(^{-1}\) associated with the edge modes. On the other hand, the archetypical quantum spin Hall insulator made of HgTe material appears to have suffered drawbacks of disorders, and consequently to the best of our knowledge it has not demonstrated clear time reversal symmetry (TRS) protection. Overall, in order to fully understand the topological nature of the QSHE, it is much desirable to develop a plain vanilla quantum spin Hall insulator (QSHI) with properties dominated by single-particle physics.

Our recent works on strained-layer InAs/GaInSb QWs is a major step in establishing clear QSHE in real materials. This advance can be attributed to the large gaps attainable in strained-layer QWs, and the remarkable control in bilayer system. Here we list several exciting features observed in the strained InAs/GaInSb QSHI:

1. The bulk hybridization gaps can be achieved to ~20 meV, enhancing by up to five folds as compared to the binary InAs/GaSb QSHI.
2. A large bulk gap leads to an increasing edge Fermi velocity, hence a decreasing interaction effect in the helical edge. Temperature and bias voltage dependence measurements of the edge conductance illustrate that the helical edge states of strained InAs/GaInSb is weakly interacting.
3. The edge conductance at zero and applied magnetic fields clearly manifests TRS-protected properties consistent with \(\mathbb{Z}_2\) topological insulator.
4. The maximum coherence length of helical edge states in strained InAs/GaInSb QWs achieve ~11 μm, significantly longer than those in previous studies.
5. The edge coherence length could be tuned by gates, demonstrating the edge conductance is correlated with the Fermi velocity \(v_F\), namely the interaction effects inside the helical edge states.

The potential impact of the present works would be that the strained-layer QWs have satisfied all essential requirements for the helical-edge/s-superconductor platform for building the scalable single-mode Majorana circuits, proving a competitive edge over any other approaches that so far proposed. Also our findings move one step closer to the device and circuit applications of QSHI based on semiconductor technology.
In the past year, my research focused on two fronts. The first one is to provide a unified theoretical mechanism for explaining the magnetic orders in the iron-based superconducting materials. Specifically, I focused on the iron-chalcogenides FeSe and FeTe, which, respectively, possess different nature. For FeSe, there is a “hidden” order, called the “quadrupolar order” which mimics a uniaxial molecule that selects an axis without selecting a direction along it and, therefore, cannot be easily probed by the experiments. For FeTe, it shows a particular magnetic order whose pattern is different from those observed other iron-based superconducting systems. Despite the variety of the orders in the iron-based superconducting families, I proposed a unified theoretical mechanism that can get access to different orders, which corresponds to different parameter regimes in the unified theoretical model.

The second topic that I have been focusing on more recently is the novel gapless state of matter with emergent relativistic fermions, named Weyl fermions adopted from the high energy field, in heavy-fermion systems. Such a state, called the Weyl semimetal, has been extensively studied in the weak- or non-interacting systems. The search for such an intriguing state has not been extended to the strongly correlated heavy-fermion systems yet. For providing a proof-of-concept example that such a phase do exist in a heavy-fermion system, I explicitly demonstrated such a phase in a well-defined lattice model in a heavy-fermion system, dubbed the Weyl-Kondo semimetal. Based on the well-defined model, we propose that the Weyl-Kondo semimetal can be identified by the thermodynamic properties, such as the specific heat. The utility of thermodynamical quantities as a key signature reflects an important distinction of the Weyl-Kondo semimetals from weakly correlated Weyl semimetals. Importantly, recently there has been an experimental evidence suggesting the realization of the Weyl-Kondo semimetal in the noncentrosymmetric heavy-fermion system Ce₃Bi₄Pd₃. Though several properties have not been experimentally explored yet, such as the negative magnetoresistance, it is expected that more Weyl-Kondo semimetals will be found or realized in the large families of heavy-fermion systems, which brings out the virtue of our first theoretical model proposal of such a phase.
POSTDOCTORAL FELLOWSHIP
IN QUANTUM MATERIALS

Vidya Kochat

Gallenene: Ultra-thin Gallium sheets from solid-liquid exfoliation

As an RCQM postdoctoral fellow in Quantum materials, I have been mainly working on growth of new 2D materials and exploring fundamental phenomena in 2D systems. One of my research directions is focused on 2D transition metal dichalcogenide (TMD) alloys. We have shown that addition of a dissimilar third element into a binary alloy system can induce phase separation in the alloy. Another direction was to study the light emission in an alloy system comprising of MoSe$_2$ and WSe$_2$ having characteristic contrasting light emission behavior as a function of temperature. These alloys are characterized by a non-monotonic photoluminescence (PL) intensity as a function of temperature in contrast to monotonic increase/decrease observed in the case of pristine WSe$_2$/MoSe$_2$ samples. We have also studied structural phase transition in TMDs having a stable 2H crystal structure by alloying them with Re which transforms them to a 1T’ phase. This structural transformation also correlates with an electronic phase transition from semiconducting to metallic phase. With our collaborators at SLAC, we have investigated light-driven phase transitions in MoSe$_2$ and MoTe$_2$ system. Optical manipulation of atomic motions and crystal structure is an extremely promising route for the synthesis and control of functional layered nanomaterials. However, this pathway is relatively unexplored due to the uncertainty about the strength of coupling between the electronic and atomic degrees of freedom in these materials. We demonstrated an ultrafast conversion of induced optical energy to lattice motion at near-unit efficiency in a model layered semiconductor, MoSe$_2$. While MoSe$_2$ system showed indications of electronic excitation induced phonon softening (lattice instabilities), MoTe$_2$ underwent transformation from 2H to 1T’ phase. This method of manipulating atomic motion along reaction coordinates towards desired structure phase is useful in optical phase change memories. Another initiative has been to explore growth of new 2D materials and study their properties and stability using DFT and QMD. As a result, we have successfully demonstrated the growth monolayer tellurene films (atomically thin Te films) using technique of physical vapor deposition from bulk Te. The structure was imaged and studied using HAADF-STEM from which various possible stable polymorphs of tellurene have been identified. Raman spectroscopy of these films as a function of temperature suggests possible bond softening at high temperatures >250K and a reversible crystalline phase at low temperatures.
POSTDOCTORAL FELLOWSHIP IN QUANTUM MATERIALS

Yu Song

Being a member of Rice and RCQM enables one to carry out focused research while being part of a close-knit community of scientists with varied ideas and a broad scope of interests. Such synergy not only fosters collaboration within RCQM, but more importantly brews a mindset that tends to actively seek new ideas and ways to tackle problems from multiple perspectives, often through collaboration with researchers across the world. Such an environment is well-suited for an experimental physicist focusing on neutron scattering as myself, because extensive collaboration and exchange of ideas have also been long traditions of the neutron scattering community.

Having a RCQM postdoctoral fellowship carries prestige, and with it opportunities to work with world class scientists on the forefront of quantum materials. It goes without saying the impact of the fellowship on one’s ability to carry out research is surely immense, but more important for me personally was the opportunities it presents to showcase and communicate research to a broad audience. Every year RCQM hosts/participates in multiple workshops, with sharply focused topics and renowned invited presenters, these events allows members of RCQM to meet and work with the best scientists in particular fields in close proximity, and also provides a unique platform to present the member’s own work in front of an expert audience with diverse specializations. I have had the fortune to present my own work on such occasions, and I really appreciate the effort from RCQM to organize these events that allow scientists, especially junior researchers such as myself, to learn and grow.

Of course, the endeavor of scientific research is a gradual progression, as is the development and growth of its practitioners. Nonetheless, the habit of striving for excellence in one’s own specialization while at the same time seeking collaborations on a broad scale are impacts from my stay at Rice and RCQM that should last long in my professional career.
COLLABORATIVE PROPOSALS

PIRE: U.S.-Asia Cooperative Research & Education on Quantum Materials

• Lead PI: Pengcheng Dai
• RCQM PIs: Pulickel Ajayan, Jun Kono, Qimiao Si, Emilia Morosan, Doug Natelson

Optical Probes and Electron Correlations in Far-From-Equilibrium Graphene

• Center PIs: Matt Foster, Jun Kono

InterDisciplinary Excellence Awards (IDEA) Fund: Correlated Electron Materials Driven Out of Equilibrium

• Center PIs: Qimiao Si, Jun Kono, Emilie Ringe
• International Collaborators:
  o Silke Bühler-Paschen (Professor, Institute of Solid State Physics, Vienna University of Technology); Gottfried Strasser (Professor, Institute of Solid State Electronics & Center for Micro- and Nanostructures, Vienna University of Technology)
  o Cornelius Krellner (Professor, Experimental Physics, Boethe University, Frankfurt),
  o Jean Leotin (Professor, Experimental Physics, University of Toulouse and Laboratoire National des Champs Magnétiques Intenses Toulouse, CNRS)
  o Oliver Portugall (Deputy Director, Laboratoire National des Champs Magnétiques Intenses Toulouse, CNRS)

LIFT Proposal: Transforming the Materials Paradigm from the Quantum to the Complex

• Center PIs: Qimiao Si, Pulickel Ajayan, Doug Natelson

Creative Ventures: 2018 RCQM Workshop Proposal, Topological superconductors: Topological order, materials, and disorder physics

• Center PIs: Matt Foster, Andriy Nevidomskyy
HIGH-IMPACT PUBLICATIONS 2016-17

COLLABORATIVE PUBLICATIONS

Dai-Morosan-Nevidomskyy-Si
• “A Mott insulator continuously connected to iron pnictide superconductors”, Nature Commun. 7, 13879 (2016)

Dai-Si
• "Spin excitations and the Fermi surface of superconducting FeS”, Npj Quantum Materials 2, 14 (2017)

Ringe-Tour-Yakobson

Dai-Nevidomskyy
• “NaFe0.56Cu0.44As: A Pnictide Insulating Phase Induced by On-Site Coulomb Interaction”, Phys. Rev. Lett. 117, 097001 (2016)

Ringe-Yakobson-Tour

Kono-Ajayan
• “Giant Terahertz-Wave Absorption by Monolayer Graphene in a Total Internal Reflection Geometry”, ACS Photonics 4, 121 (2017)
MEMBER-GROUP PUBLICATIONS

Pengcheng Dai Group
- “Robust upward dispersion of the neutron spin resonance in the heavy fermion superconductor Ce1-xYbxCoIn5”, Nature Communications 7, 12774 (2016)

Rui Riu Du Group

Kaden Hazzard Group
- “A solid more fluid than a fluid”, Nature 543, 47 (2017)

Randall Hulet Group

Jun Kono Group
HIGH-IMPACT PUBLICATIONS 2016-17

Gur Naik Group
• “Hot-Carrier-Mediated Photon Upconversion in Metal-Decorated Quantum Wells”, Nano Letters, 17, 4583 (2017)

Doug Natelson Group
• “Substantial local variation of Seebeck coefficient in gold nanowires”, Nanoscale 9, 9160 (2017)
• “Photothermoelectric effects and large photovoltages in plasmonic Au nanowires with nanogaps”, Phys. Chem. Lett. 8, 1739 (2017)

Peter Rossky Group
• “Relating Chromophoric and Structural Disorder in Conjugated Polymers”, Phys. Chem. Lett. 8, 1752 (2017)

Gus Scuseria Group
• “Predicting band gaps with hybrid density functionals”, Phys. Chem. Lett. 7, 4165 (2016)
Qimiao Si Group


Jim Tour Group

WE GRATEFULLY ACKNOWLEDGE THE FOLLOWING EXTERNAL FUNDING AGENCIES
FOR SUPPORTING RCQM ACTIVITIES

GORDON AND BETTY MOORE FOUNDATION

ICAM-I2CAM

NSF