



**QUANTUM MATERIALS PERSPECTIVES AND OPPORTUNITIES:
The Rice Center for Quantum Materials Launch**

December 15-16, 2014

Rice University

Organized By:

The Rice Center for Quantum Materials, Professor Qimiao Si, Director

Topics:

- *Unconventional Superconductivity*
- *Quantum Criticality*
- *Ultracold Matter*
- *Materials out of Equilibrium*
- *Materials at Low Dimensions*
- *Functional Materials for Energy*

Honored Guests, Faculty and Students,

Welcome to Perspectives and Opportunities – The Rice Center for Quantum Materials Launch. This launch belongs not only to Rice, but – because of participants like you – to the growing worldwide community in Quantum Materials. We have high expectations for this event, particularly in learning about the state of the science, stating our expectations for its future and identifying pathways to reach that future.

You will see in the enclosed program that we have a stellar list of presenters and panelists. This is, of course, by design: the mission of the RCQM is to build and sustain fundamental research in Quantum Materials, not by focusing on Rice University's strengths in the area, but by providing a hub for the growing international network in its topics. Please take advantage of the unscheduled parts of the agenda to deepen old relationships and build new ones, establish collaborative contacts and visit Rice groups and laboratories.

We are grateful to many Rice offices and departments for supporting the Center in its startup, including:

- The departments of Physics and Astronomy, Materials Science and NanoEngineering, Chemistry, Electrical and Computer Engineering
- The Office of the Provost
- The Office of the Vice Provost for Research
- The Schools of Engineering and Natural Science
- The Smalley Institute for Nanoscale Science and Technology.

Thank you and best regards,

Profs. Emilia Morosan and Isabell Thomann
RCQM Launch Event Organizers

Prof. Qimiao Si
Director, RCQM

RICE CENTER FOR QUANTUM MATERIALS FACULTY MEMBERS

Pulickel Ajayan
Pengcheng Dai
Rui-Rui Du
Matthew Foster
Kaden Hazzard
Randall Hulet
Thomas Killian
Junichiro Kono
Kevin Kelly
Jun Lou
Daniel Mittleman
Emilia Morosan
Douglas Natelson
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Han Pu
Peter Rossky
Gustavo Scuseria
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Jason Ho (Ohio State University)
Allan H. MacDonald (University of Texas at Austin)
Frank Steglich (Max Planck Institute for Chemical
Physics of Solids, Dresden)

SCOPE

In quantum materials, strong interactions between particles and quantum entanglement lead to the emergence of exotic phenomena such as high temperature superconductivity. Materials with such effects are either in the bulk form or with reduced dimensionality. Research in this area seeks to develop materials with unusual electronic, magnetic and optical properties, characterize such properties with spectroscopy techniques, understand the properties using many-body theory, and explore the materials functionality in energy and information technology. At the present time, RCQM involves nearly 20 faculty from both Natural Sciences and Engineering Schools.

PRESENTATION GUIDANCE

Oral sessions

All oral sessions will be held in Dell Butcher Hall Room 180.
Each talk is 20 minutes long and includes 10 minutes of discussion time.

Poster sessions

The poster sessions will be held in the Brockman Hall for Physics Room 101.
The maximum poster board size is 48 x 48.

WIRELESS INTERNET ACCESS

Wireless access is available through the wireless network 'Rice Guest.' Simply select this network, agree to the terms and conditions, and you should have full access, including electronic journals supported by the Rice library.

Program Schedule ~ Monday December 15, 2014

11:00-11:45 Check In and Coffee Reception, *Brockman Hall for Physics Foyer*

Opening Luncheon *Brockman Hall for Physics Room 101*

11:45-12:45 Welcome Remarks by Prof. Qimiao Si, Director, Rice Center for Quantum Materials, George L. McLendon, Howard R. Hughes Provost and Professor of Chemistry, Yousif Shamoo, Vice Provost for Research and Professor of Biosciences

Session 1: *Dell Butcher 180, Chair: Tom Killian*

Energy Materials /Ultracold Matter I

1:00-01:30 Pulickel Ajayan, "Developing 2D Materials Science"

1:30-02:00 Jason Ho, "Quantum gases in curved space"

2:00-02:30 Kaden Hazzard, "Ultracold molecules: quantum magnetism far-from-equilibrium"

2:30 Group Photo

2:35-03:00 Coffee Break (Poster Presenters please report to Brockman 101 for set up instructions)

Session 2: *Dell Butcher 180, Chair: Matthew Foster*

Quantum Criticality

3:00-3:30 Frank Steglich, "Kondo screening, Kondo coherence and onset of quantum criticality in lanthanide - based heavy fermions"

3:30-4:00 Qimiao Si, "Quantum Criticality, Emergent Phases and Strongly Correlated Electrons"

4:00-4:30 Meigan Aronson, "Quantum Criticality and Incipient Order in Layered $\text{YFe}_2\text{Al}_{10}$ "

Poster Preview: *Dell Butcher 180, Chair: Doug Natelson*

4:30-4:45 Blitz Poster Presentation (1 minute per poster)

4:45-6:00 **Poster Session & Reception, Brockman 101**
Food, wine and beer will be served

6:30 Organized Dinner for Speakers & RCQM Faculty

08:00-08:30 Coffee and Light Breakfast, *Dell Butcher 180*

Session 3: *Dell Butcher 180*, Chair: Gus Scuseria

Energy Materials/Ultracold Matter II

08:30-9:00 Hongjie Dai, "Innovating advanced electrocatalysts for renewable energy"

09:00-9:30 Isabell Thomann, "Light Management in Extremely Thin Photoelectrode Architectures for Solar-Fuel Generation"

09:30-10:00 Randy Hulet, "Antiferromagnetism in the Hubbard Model with Ultracold Atoms"

10:00-10:30 Coffee Break (Poster Presenters please report to Brockman 101 for set up instructions)

Session 4: *Dell Butcher 180*, Chair: Han Pu

Unconventional Superconductivity

10:30-11:30 Laura Greene, "Detection of electronic nematicity in Fe pnictides and chalcogenides"

11:30-11:30 Emilia Morosan, "Exotic superconductivity at the itinerant-to-local moment crossover"

11:30-12:00 Andriy Nevidomskyy, "Topological Surface States in the Heavy Fermion Superconductor UPt3"

Poster Preview: *Dell Butcher 180*, Chair: Doug Natelson

12:00-12:15 Blitz Poster Presentation (1 minute per poster)

12:15-2:00 **Lunch & Poster Session**, *Brockman 101*

Session 5: *Dell Butcher 180*, Chair: Kevin Kelly

Materials in Low Dimensions

2:00-2:30 Allan MacDonald, "Bilayer Exciton Condensates"

2:30-3:00 Boris Yakobson, "2D materials canvas: carbon, h-BN, metal-disulfides, and topological defects therein"

3:00-3:30 Junichiro Kono, "Cooperative Recombination of Electron-Hole Pairs in Two Dimensions"

3:30-4:00 Coffee Break

4:00-5:15 *Dell Butcher 180*, Moderator: Prof. Qimiao Si

Panel Discussion - "Quantum Materials - Perspectives and Opportunities"

Prof. Elihu Abrahams, UCLA

Dr. Charles Day, Physics Today

Prof. Laura Greene, UIUC, APS Vice President Elect

Prof. Neal F. Lane, Rice, former Director of the NSF & the White House Office of Science and Technology

Dr. Peter Reynolds, Senior Research Scientist, Army Research Office

Mr. Stephen B. Squires, Quantum Materials Corp Founder and President

Dr. Marc Ulrich, Physics Division Chief & Condensed Matter Physics, Army Research Office

5:30-6:30 **Reception**

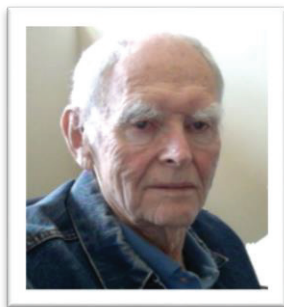
Smalley Institute, Space Science 301A – Smalley-Curl Room

Food, wine and beer will be served from 5:30-6:30

7:00 Organized Dinner & RCQM Advisory Board Meeting

“QUANTUM MATERIALS - PERSPECTIVES AND OPPORTUNITIES” Panel Discussion

Prof. Elihu Abrahams, UCLA



Elihu Abrahams was born in New York State, USA. He obtained his Ph. D. degree (1952) from the University of California, Berkeley. He was a research associate (1953-55) and a research assistant professor (1955-56) at the University of Illinois at Urbana-Champaign. He was assistant professor (1956-59), associate professor (1959-1966), full professor (1966-1998), and professor emeritus (1999-2010) at Rutgers University. Since 2010 he has been adjunct professor at the University of California, Los Angeles. He has worked on various aspects of condensed matter theory, including superconductivity, phase transitions, and strongly-correlated electron systems, and disorder.

Dr. Charles Day, Physics Today



Charles Day is Physics Today's online editor. From 2003 to 2010 he ran the magazine's Search & Discovery department. In that capacity he covered several major discoveries in condensed-matter physics, including iron-based superconductors, topological insulators and the various spin Hall effects. His background is in astrophysics. After earning a PhD in astronomy from Cambridge University, he did a postdoc at Japan's Institute of Space and Astronautical Science. He went on to work at NASA's Goddard Space Flight Center, where he helped to run two x-ray satellite observatories.

Prof. Laura Greene, UIUC, APS Vice President Elect



Laura H. Greene is a Swanlund Chair and a Center for Advanced Study Professor of Physics at the University of Illinois at Urbana-Champaign. Her research is in experimental condensed matter physics, investigating strongly correlated electron systems, and focusing primarily on revealing the mechanisms of unconventional superconductivity by planar-tunneling and point-contact electron spectroscopies. Her research also involves developing methods for predictive design of new families of superconductors. She is recognized for her work on superconductor/semiconductor proximity effects, elucidating the physical properties of the pure and doped high-temperature superconductors, the discovery of broken time-reversal symmetry in high-temperature superconductors, and spectroscopic studies of the electronic structure in heavy-fermion metals. Greene's service includes: vice president elect for APS, AAAS Board of Directors, I2CAM Board of Governors Chair and editor in chief of Reports on Progress in Physics. Greene is a member of the NAS, fellow of AAAS, IOP and APS. She was a Guggenheim Fellow, and received the E. O. Lawrence and Maria Goeppert-Mayer Awards.

Prof. Neal F. Lane, Rice University, former Director of the NSF & the White House Office of Science and Technology



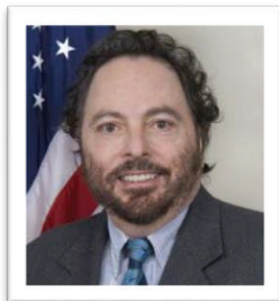
Neal F. Lane, Ph.D., is the senior fellow in science and technology policy at the Baker Institute. He is also the Malcolm Gillis University Professor at Rice University and professor in the Department of Physics and Astronomy.

Previously, Lane served in the federal government as assistant to the president for science and technology and director of the White House Office of Science and Technology Policy (OSTP) from August 1998 to January 2001, and as director of the National Science Foundation (NSF) and member (ex officio) of the National Science Board from October 1993 to August 1998. Before his post with NSF, Lane was provost and professor of physics at Rice, a position he had held since 1986.

He first came to the university in 1966, when he joined the Department of Physics as an assistant professor. In 1972, he became professor of physics and space physics and astronomy. He left Rice from mid-1984 to 1986 to serve as chancellor of the University of Colorado at Colorado Springs. Additionally, from 1979 to 1980, while on leave from Rice, he worked at the NSF as director of the Division of Physics.

Lane has received the National Academy of Sciences Public Welfare Medal, the American Institute of Physics K.T. Compton Medal, the Association of Rice Alumni Gold Medal and the Distinguished Friend of Science Award from the Southeastern Universities Research Association. In 2013, the National Science Board presented Lane with the Vannevar Bush Award, which recognizes exceptional, lifelong leaders who have made substantial contributions to the nation through public service activities in science, technology and policy. He is a fellow of AAAS and other honorary and professional associations. Lane received his Ph.D., M.S. and B.S. in physics from the University of Oklahoma.

Dr. Peter Reynolds, Senior Research Scientist, Army Research Office



Peter Reynolds received his undergraduate education at U.C. Berkeley, completing an A.B. in Physics as well as the Honors Program in Physics with great distinction in 1971. While at Berkeley he was also a Regents Scholar, elected to Phi Beta Kappa, and awarded the Physics Department Citation. From Berkeley he went to MIT where he studied statistical physics. He was an NSF Fellow and an IBM pre-doctoral Fellow during this time. In 1978 he received his Ph.D. for research in critical phenomena in disordered systems. Relating Monte Carlo and real space renormalization group methods, this work has been widely used by others, and now appears in numerous textbooks as an example of real-space renormalization.

After an appointment as assistant research professor at Boston University, he returned to Berkeley in 1980 to take a staff scientist position at the Lawrence Berkeley Laboratory (now LBNL). His more recent research interests have been on quantum simulations using ideas from statistical mechanics. That body of work has also been widely cited and applied. Since 1988, he has been a Program Manager in atomic and molecular physics, chemical physics, and computational physics, for 15 years at the Office of Naval Research, and then at the Army Research Office (ARO). His program led to the current excitement in cold-atom physics including Bose-Einstein condensation, atom optics, atom lasers, quantum degeneracy, optical lattices, and quantum emulation. He funded the work that led to the first qubit. He was also the Navy's science and technology advisor to the DoD program for high performance computing. Since coming to ARO he has been Associate Director of Physical Sciences, Physics Division Chief, and now Senior Research Scientist and Chief Scientist for the Physical Sciences. He is a Fellow of the APS, and is listed in Who's Who in America.

Mr. Stephen B. Squires, Quantum Materials Corp Founder and President



Mr. Squires is the founder, Chief Executive Officer and Board Chair for both Quantum Materials Corp., and its subsidiary, Solterra Renewable Technologies, Inc. He has over 30 years experience in advanced materials, nanotechnology and other emerging technologies. Prior to forming his present company, Squires consulted on these fields with emphasis on applications engineering, strategic planning, commercialization and marketing. From 1983 to 2001, Squires was founder and CEO of Aviation Composite Technologies Inc. (ACT), which he grew to have over 200 employees and \$20 million in revenue. ACT was merged with USDR Aerospace in 2001. In the late 1970s at McDonnell Douglas, he developed and adapted advanced materials for combat aircraft applications.

Dr. Marc Ulrich, Physics Division Chief and Condensed Matter Physics, Army Research Office (ARO)



Dr. Marc Ulrich graduated with a degree in Physics from Auburn University in 2001 after which he was a National Research Council Postdoctoral Fellow for a couple of years with Dr. Jack Rowe. Dr. Ulrich has been the ARO program manager for Condensed Matter Physics since 2003 and the ARO Physics Division Chief since about 2008. In the ARO Condensed Matter Physics program Dr. Ulrich currently emphasizes strong correlations in electronic systems - most notably complex oxide heterostructures and topological electronic phases - and is considering research in areas such as quantum criticality and non-equilibrium phenomena. Concurrently, Dr. Ulrich is an adjunct professor in the Physics Department at North Carolina State University where he conducts research on the physics and chemistry of interfaces between graphene and functional oxides.

Session 1: Energy Materials/Ultracold Matter I

Developing 2D Materials Science

Pulickel Ajayan
Rice University



Pulickel Ajayan is the Benjamin M. and Mary Greenwood Anderson Professor in Engineering, Materials Science and Nanotechnology at Rice University. His research interests include the application of nanomaterials for energy generation and storage, the synthesis and characterization of nano-based composites and nano-enabled bio-mimetic systems and the study of nanoelectronics, nanosensors and active nanosystems. Ajayan is a pioneer in the field of carbon nanotechnology, having been actively involved in the earliest studies of carbon nanotubes during his time at NEC Corp. in Japan. He has published more than 325 journal papers. His numerous awards include the Senior Humboldt Prize, the Materials Research Society's MRS Medal, Top 50 recognition in Scientific American, the Burton Award from the Microscopic Society of America and the Hadfield Medal for the outstanding student metallurgist in India. Ajayan is a fellow of American Association for the Advancement of Science and an honorary member of both the Mexican Academy of Sciences and the Materials Research Society of India. He has served as a distinguished visiting professor at the Institute of Physics, Chinese Academy of Sciences in Hefei; a distinguished guest professor in materials sciences at Tsinghua University; and a visiting professor at ISIS, University of Louis Pasteur in France. Ajayan has been part of two Guinness World Records, one for the creation of the smallest brush and the other for creating the darkest material. After three years of post-doctoral experience at NEC Corp. in Japan, Ajayan spent two years as a research scientist at the Laboratoire de Physique des Solides, Orsay in France and nearly a year and a half as an Alexander von Humboldt Fellow at the Max-Planck-Institut für Metallforschung, Stuttgart in Germany.

Quantum Gases in Curved Space

Jason Ho
The Ohio State University

I would like to suggest a new direction in cold atom research — to study quantum gases in traps that form a two dimensional curved surface. For closed curved surfaces, the number of vortices in a superfluid confined to it is given by the Gauss-Bonnet theorem and is specified by the genus of the surface. For large spin quantum gases, one can also produce scalar and non-abelian gauge on these curved surfaces with no heating through Berry's phase effects, which in turn leads to unusual vortex structures.



Tin-Lun (Jason) Ho, professor of physics, has taught at Ohio State since 1983 and has a Ph.D. from Cornell University. A world leader in theoretical research on Bose-Einstein Condensation, the condensation of many identical atoms into the same macroscopic quantum state, Ho was elected Fellow of the John Simon Guggenheim Memorial Foundation in 1999 and the American Physical Society in 2000. Revolutionary applications of Ho's BEC research could include tinier electronic circuits, extremely accurate clocks and distance-measuring devices, and use in super-fast quantum computers. Colleagues have praised Ho as "a great teacher and an outstanding mentor" and "a world-class theoretical physicist."

Ultracold Molecules: Quantum Magnetism Far-From-Equilibrium

Kaden Hazzard

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Ultracold molecules are a new arena in which to explore strongly correlated quantum phenomena. They possess many of the same exciting possibilities as ultracold atoms but also extend the ultracold toolbox in new directions. Like cold atoms, they have precisely known properties and widely tunable interactions, geometries, and lattice structures. They add to these features their strong, long-range dipolar interactions and a rich internal structure of rotational and vibrational excitations.

I will discuss how experiments on ultracold molecules in optical lattices have harnessed these new degrees of freedom to realize models of quantum magnetism. I will describe experiments that drive the spins far from equilibrium and present the new theoretical techniques that we developed to describe the resulting strongly-correlated dynamics. Finally, although present experiments motionally freeze the molecules to suppress chemical reactions, I will discuss how using either quantum Zeno physics or nonreactive molecules can realize models with coupled spin and motional degrees of freedom.



Prof. Kaden Hazzard is a theoretical physicist who works at the interface of atomic, molecular, and optical (AMO) physics with condensed matter and many-body physics. Often collaborating closely with experimentalists, his work focuses on devising novel ways to use the unique, precise control and microscopic knowledge of AMO systems to engineer quantum matter, and the dual question of understanding the many-body physics that arises in these systems. He received his Bachelor's degree in physics and mathematics from The Ohio State University, then received his Master's degree and PhD in physics at Cornell University. He was a NIST NRC

postdoctoral fellow at JILA, University of Colorado Boulder before starting as an Assistant Professor at Rice University in 2014. He has developed new theoretical methods and studied diverse many-body phenomena, and he has worked closely with several AMO experimental groups to help pioneer new strongly interacting quantum systems: ultracold molecules, ion crystals in Penning traps, and microtraps with single-atom imaging and control.

Session 2: Quantum Criticality

Kondo screening, Kondo coherence and onset of quantum criticality in lanthanide - based heavy fermions

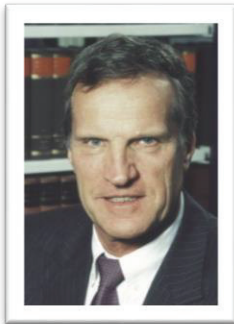
Frank Steglich

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We report results of transport, calorimetric and scanning - tunneling spectroscopic (STS) measurements on Ce - and Yb - based heavy - fermion systems of 122 type. These results point to the following conclusions: (i) For La - substituted CeNi_2Ge_2 (ref. 1) as well as Lu - substituted and pure YbRh_2Si_2 (ref. 2), the effective (on - site) Kondo scale T_K , referring to the crystal - field ground state of the localized $4f$ shell, is found to be nearly identical with the temperature T_{coh} , at which spatial coherence starts to develop upon further cooling (ref. 3). (ii) Magneto - transport, i.e., anomalous Hall - effect and Nernst - effect, results on CeCu_2Si_2 reveal that the on - site Kondo scattering is dominating until the renormalized band structure is almost completely built up at a temperature T_L , well below T_{coh} (ref. 4). This is consistent with very recent results of low - temperature STS experiments on stoichiometric YbRh_2Si_2 which, in addition, indicate that in this compound quantum - critical phenomena become visible at temperatures below $T \approx T_L$ (ref.5). Work done in cooperation with S. Ernst, S. Kirchner, A. Pikul, Q. Si, U. Köhler (now U. Stockert), P. Sun and S. Wirth.

References:

1. A. Pikul et al., Phys. Rev. Lett. **108**, 066405 (2012).
2. U. Köhler et al., Phys. Rev. B **77**, 104412 (2008).
3. S. Ernst et al., Nature **474**, 362 (2011).
4. P. Sun and F. Steglich, Phys. Rev. Lett. **110**, 216408 (2013).
5. S. Wirth et al., to be published.



Frank Steglich received a Dr. rer. nat. from the University of Göttingen (Germany) in 1969. 1978-1998, he was Professor of Physics at the Technical University of Darmstadt (Germany). In 1996, he became Founding Director of the Max Planck Institute for Chemical Physics of Solids, Dresden (Germany). After his retirement in 2012, he became Qiyushi Distinguished Visiting Professor and Director of the Center for Correlated Matter at Zhejiang University, Hangzhou (China) and Distinguished Visiting Professor at the Institute of Physics, Chinese Academy of Sciences, Beijing (China). From 2001 to 2007 he served as Vice President of the German Research Foundation (DFG).

Quantum Criticality, Emergent Phases and Strongly Correlated Electrons

Qimiao Si

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Strongly correlated electron systems display a variety of orders, and the associated quantum criticality gives rise to both non-Fermi liquid (also called “strange-metal”) behavior and unconventional superconductivity. Among the important questions is whether the quantum criticality conforms to the Landau framework of order-parameter fluctuations, or goes beyond it.

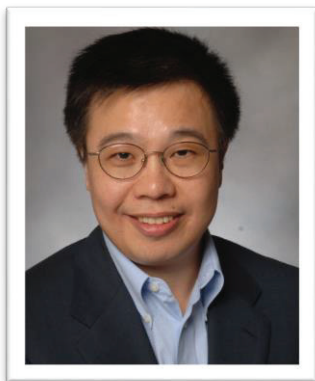
I will discuss this general issue in the prototype setting of antiferromagnetic heavy fermion metals. A conceptual framework has been provided through the beyond-Landau notion of Kondo destruction [1]. The corresponding quantum critical point has elucidated the unusual dynamical scaling, and predicted a jump of Fermi surface that was verified by subsequent experiments. The notion has led to novel phases as characterized by a global phase diagram [2], which has motivated much recent experiments, and a theoretical understanding for heavy-fermion superconductivity [3]. I will close by discussing some directions for future studies, including the role of spin-orbit coupling [4] and an emerging overarching theme for correlated superconductivity.

[1] Q. Si, S. Rabello, K. Ingersent and J. L. Smith, *Nature* **413**, 804 (2001).

[2] J. H. Pixley, R. Yu and Q. Si, *Phys. Rev. Lett.* **113**, 176402 (2014).

[3] J. H. Pixley et al. arXiv:1308.0839; J. H. Pixley, A. Cai and Q. Si, arXiv:1409.1090.

[4] X-Y Feng, J. Dai, C-H Chung and Q. Si, *Phys. Rev. Lett.* **111**, 016402 (2013).



Prof. Qimiao Si works in theoretical condensed matter physics, with an emphasis on strongly correlated electron systems. One area of Prof. Si's current interest is quantum criticality. He and his collaborators have advanced a new type of quantum critical point that has considerably shaped the development of the heavy-fermion field. Another focus of Prof. Si's current research concerns iron-based superconductivity. His work has elucidated the bad-metal behavior in the normal state, and its relationship with magnetism and superconductivity. Prof. Si obtained his B.S. degree in Physics from University of Science and Technology of China in 1986, and his Ph.D. degree in Physics from the University of Chicago in 1991. He did his postdoctoral works at Rutgers University and University

of Illinois at Urbana-Champaign. In 1994 he joined the faculty of Rice University, where he is the Harry C. and Olga K. Wiess Professor of Physics. Prof. Si was named a Sloan Research Fellow in 1996, and received a Cottrell Scholar Award from the Research Corporation for Science Advancement in 1998. He was elected a Fellow of the British Institute of Physics in 2004, the American Physical Society in 2005, and the American Association for the Advancement of Science in 2008. He received a Humboldt Prize from the Alexander von Humboldt Foundation in 2012.

Quantum Criticality and Incipient Order in Layered YFe₂Al₁₀

Meigan Aronson

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Quantum Critical Points (QCPs) where ordered phases are suppressed to $T=0$ are a central feature of virtually all systems with strong electronic correlations. Nonetheless, there is relatively little experimental evidence for quantum critical fluctuations among the $T=0$ states of the system. A summary of our experimental results on metallic YFe₂Al₁₀ is presented here, where the layered crystal structure is based on nearly square nets of Fe atoms. The magnetic properties are definitively two-dimensional, and the magnetic susceptibility displays a strong $T \rightarrow 0$ divergence, but only for small fields lying in the Fe-planes. No order is found for temperatures larger than 0.02 K. Our detailed work on the low temperature transport, magnetic, and thermodynamic properties has shown that diverging quantum critical fluctuations lead here to the breakdown of the standard Fermi liquid description of metals. High precision scaling of the magnetization and specific heat in YFe₂Al₁₀ reveals an underlying free energy that is quantum critical in zero field, without the need for fine-tuning by pressure or doping as required in other quantum critical systems.

Augmented by a specific expression for the scaling function, whose argument is $T/B^{.59}$, we have reproduced the observed field and temperature dependencies of the quantum critical magnetization and specific heat using a single set of critical exponents ($d=z$, $\nu=1.4$, $\nu z=0.59$). The general success of this heuristic analysis, based on the hypothesis of hyperscaling, suggests that YFe₂Al₁₀ is a system that is below its upper critical dimension, where quantum criticality is likely protected by its two-dimensional character. Hyperscaling generally implies universality, where the form of the free energy does not depend on the details of the system, implying that critical points can be classified into universality classes based on the values of the critical exponents themselves. We propose that YFe₂Al₁₀ is the first confirmed member of such a universality class.



Dr. Meigan Aronson's research centers on discovering and studying strongly correlated electron materials that are on the verge of electronic instabilities and order. She received her M.S. and Ph.D. from the University of Illinois at Urbana-Champaign, followed by a postdoc at Los Alamos National Laboratory. She was a member of the Physics faculty at University of Michigan from 1990-2006, and since 2007 has been jointly appointed in the Department of Physics and Astronomy at Stony Brook University and in the Condensed Matter Physics and Materials Science Department at Brookhaven National Laboratory.

Session 3: Energy Materials/Ultracold Matter II

Innovating advanced electrocatalysts for renewable energy

Hongjie Dai
Stanford University



Hongjie Dai is the J.G. Jackson & C.J. Wood Professor of Chemistry at Stanford University. He is a leading figure in the study of carbon nanotubes.

Dai received a B.S. in Physics from Tsinghua University, Beijing, in 1989, and M.S. in applied sciences from Columbia University in 1991, and a Ph.D. in Applied Physics from Harvard University in 1994 under the direction of Prof. Charles Lieber. After postdoctoral work with Richard E. Smalley at Rice University, he joined the Stanford faculty as an assistant professor in 1997.

Among his awards are the American Chemical Society's ACS Award in pure chemistry, 2002, the Julius Springer Prize for Applied Physics, 2004, and the American Physical Society's James C. McGroddy Prize for New Materials, 2006. He was elected to the American Academy of Arts and Sciences in 2009 and to the American Association for the Advancement of Science in 2011.

Light Management in Extremely Thin Photoelectrode Architectures for Solar-Fuel Generation

Isabell Thomann

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Concepts from metamaterials, plasmonics and nanophotonics are expected to aid the design of future solar energy conversion devices. Here, I will describe how we use these concepts to create advanced photoelectrode architectures for solar-to-chemical-fuel conversion reactions, including water splitting and CO₂ reduction. We focus on light management in extremely thin absorber structures to achieve broadband, omnidirectional solar absorption while carefully choosing materials systems that allow for efficient charge separation and catalytic activity. Such thin-film absorber photoelectrodes hold promise for achieving enhanced charge carrier extraction, increased photovoltages and the possibility to exploit hot carriers for purposes of driving chemical reactions.

I will discuss our analytical models and three-dimensional electromagnetic simulations that we employ to engineer light absorption in two-dimensional materials and plasmonic metal nanostructures, and describe our progress towards the experimental realization and characterization of such structures. Complementing these materials and device design efforts, we are developing an experimental characterization toolbox, including photoelectrochemical and ultrafast spectroscopic techniques.



Dr. Isabell Thomann is an expert in nanophotonics, plasmonics, photoelectrochemistry, and ultrafast spectroscopy. She has experience with the creation and characterization of attosecond laser pulses and demonstrated that surface plasmons can be engineered for strong light concentration close to an electrode-liquid interface for more efficient H₂O splitting. She received her Master's degree in physics at ETH Zuerich, and her PhD in physics at JILA, University of Colorado at Boulder. She then moved to Stanford University, where she was a postdoctoral fellow, and worked with chemical engineers, materials scientists, electrical engineers, chemists and applied physicists,

investigating novel photoelectrode structures based on metallic (plasmonic) and dielectric nanostructures to enhance photoelectrochemical processes for energy applications. She is the recipient of an NSF CAREER Award (2014). She is also the chairwoman of the IEEE Photonics Society – Houston Chapter, and was the PI and event coordinator of the recent Army Research Office sponsored “Workshop on surface plasmons, metamaterials, and catalysis” at Rice University, October 21-23, 2013.

Antiferromagnetism in the Hubbard Model with Ultracold Atoms

Randall G Hulet

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Ultracold atoms on optical lattices form a versatile platform for studying many-body physics, with the potential of addressing some of the most important issues in strongly correlated matter. Progress, however, has been stymied by an inability to create sufficiently low temperatures in an optical lattice. In this talk, I will present our experimental results on the characterization of the three-dimensional Hubbard model near half-filling, realized using two spin-states of fermionic atomic lithium (${}^6\text{Li}$). We have developed a compensated optical lattice that has enabled, for the first time, the achievement of temperatures that are below the tunneling energy in the lattice, t . We image the density distribution to extract the central density of the gas, and to determine its local compressibility. For intermediate to strong interactions, we observe the emergence of a density plateau and a reduction of the compressibility, indicative of the formation of a Mott insulator. Comparisons to state-of-the-art numerical simulations of the Hubbard model over a wide range of interactions set an upper limit for the temperature.

The Hubbard model is known to exhibit antiferromagnetism at temperatures below the Néel temperature T_N . We have detected antiferromagnetic correlations in this system by spin-sensitive Bragg scattering of light. We deduce the temperature of the atoms in the lattice by comparing the light scattering to quantum Monte Carlo and numerical linked-cluster expansion calculations to find that $T/t = 0.51 \pm 0.06$, corresponding to $1.4 T_N$. Further refinement of the compensated lattice technique may produce even lower temperatures which, along with light scattering thermometry, have important implications for achieving other novel quantum states of matter.



Randall G. Hulet earned a BS degree at Stanford University and a Ph.D. in Physics at MIT. He was a National Research Council Fellow at the National Institute of Standards and Technology, where he worked on laser cooling of trapped atomic ions. He joined the faculty of Rice University in 1987 and he currently holds the Fayez Sarofim Chair in Natural Sciences. He has received many awards, including the I.I. Rabi Prize of the American Physical Society, the National Science Foundation Presidential Young Investigators Award, a NASA Medal for Exceptional Scientific Achievement, and the Willis E. Lamb Medal

for Laser Science and Quantum Optics. He is a Fellow of the American Physical Society and the American Association for the Advancement of Science, and he is a member of the American Academy of Arts and Sciences. Hulet is known for many important contributions to atomic physics. He played a leading role in the development of laser cooling and laser trapping of atoms. Among his achievements are the first realization of Bose-Einstein condensation in an atomic gas with attractive interactions, the creation of a degenerate Bose-Fermi mixture, and the observation of antiferromagnetic order in the Fermi-Hubbard model using ultracold atoms.

Session 4: Unconventional Superconductivity

Detection of electronic nematicity in Fe pnictides and chalcogenides

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Electronic nematicity occurs when the electronic fluid exhibits a lower symmetry than the underlying lattice; exhibiting non-Fermi liquid-like (NFL) behavior. It can be detected a variety of ways and we have found that point contact spectroscopy (PCS) is surprising sensitive to the resulting density of states (DoS) arising from a NFL. In the Fe pnictides and chalcogenides the electronic nematicity is seen as an excess conductance around zero bias appearing at the onset of the fluctuating nematic phase above the structural phase transition (T_{SPT}) and surviving into the electronic nematic state, below T_{SPT} . This can be explained by an increased density of states at the Fermi level arising from orbital fluctuations above T_{SPT} and as an over-damped collective mode below T_{SPT} . We will also show how PCS detects hybridization in heavy fermions, such as URu_2Si_2 and YbAl_3 , and in the later, our measurements suggest a new way to define the coherence temperature. We present a new quantum mechanical theory that shows how PCS can be used as a filter for correlated electron states; thereby aiding in our search for new superconductors.

Collaborators: H.Z. Arham, C.R. Hunt, J. Misuraca, W.K. Park, W.-C. Lee, P. Phillips, J. Gillett, S.D. Das, S.E. Sebastian, Z.J. Xu, J. S. Wen, Z. W. Lin, Q. Li, G. Gu, A. Thaler, S. Ran, S.L. Bud'ko, P.C. Canfield, D.Y. Chung, and M.G. Kanatzidis

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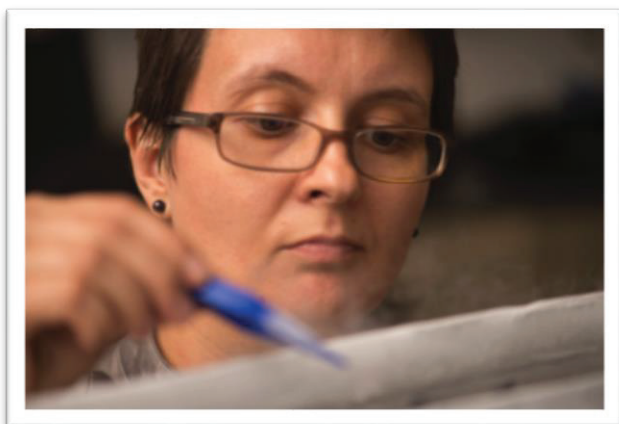
Laura H. Greene is a Swanlund Chair and a Center for Advanced Study Professor of Physics at the University of Illinois at Urbana-Champaign. Her research is in experimental condensed matter physicist, investigating strongly correlated electron systems focusing primarily on revealing the mechanisms of unconventional superconductivity by planar-tunneling and point-contact electron spectroscopies. Her research also involves developing methods for predictive design of new families of superconductors. She is recognized for her work on superconductor/semiconductor proximity effects, elucidating the physical properties of the pure and doped high-temperature superconductors, the discovery of broken time-reversal symmetry in high-temperature superconductors, and spectroscopic studies of the electronic structure in heavy-fermion metals. Greene's service includes: Veep-elect for APS, AAAS Board of Directors. I2CAM Board of Governors, Chair, and editor in chief of Reports on Progress in Physics. Greene is a member of the NAS, Fellow of the Am. Acad. of Arts & Sciences, IOP, AAAS, and APS; was Guggenheim Fellow, received the E.O. Lawrence and Maria Goeppert-Mayer Awards.

Exotic superconductivity at the itinerant-to-local moment crossover

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The conventional wisdom that magnetism and superconductivity are immiscible has been losing ground for more than 25 years, in favor of the concept of magnetism-mediated superconductivity. Not only are magnetic interactions required for electron pairing in the famous Cu oxides and the Fe pnictides, but they seem to be *the* key ingredient for high temperature superconductivity. In this talk, I will follow one of the emerging empirical strategies for design and discovery of novel superconductors: at the crossover between itinerant and local moment magnetism, such exotic, high T_c states have been unveiled. I will illustrate with examples some properties of itinerant magnets, and discuss the interplay of crystallographic and physical properties of a few compounds as design tools for novel, practical superconductors.



Emilia Morosan is an Associate Professor of Physics and Astronomy, Chemistry and Materials Science and Nanoengineering at Rice University. After receiving a BS in Physics in Romania in 1999, she moved to US for graduate work. Prof. Morosan got her PhD in Physics in 2005 from Iowa State University, and subsequently moved to Princeton University as a postdoctoral research associate in Chemistry. Since joining Rice in 2007, she received several early career awards, including the Presidential Early

Career Award for Scientist and Engineers (PECASE) and the NSF CAREER. Prof. Morosan was recently selected as a Gordon and Betty Moore Foundation fellow in Materials Synthesis.

Topological Surface States in the Heavy Fermion Superconductor UPt_3

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The concept of topological states of matter has captured the imagination of physicists in the last decade, with possible applications for quantum computing. Traditionally, such topological phases are predicted to occur in fully gapped insulating or superconducting materials and are characterized by topologically protected gapless excitations on the surface. Here, I will demonstrate a generalization of this concept to metallic materials with gapless bulk excitations, focusing in particular on the B-phase of the heavy fermion superconductor UPt_3 . Recent phase sensitive measurements provide strong evidence for the triplet, chiral pairing symmetry, which endow the Cooper pairs with orbital angular momentum $L_z = \pm 2$ along the c -axis. Such pairing supports both line and point nodes of the superconducting gap, and both types of nodal quasiparticles possess nontrivial topology in the momentum space. In particular, the point nodes located at the intersections of the closed Fermi surfaces with the c -axis act as the double monopoles and the anti-monopoles of the Berry curvature. Consequently, we predict that the B phase should support an anomalous thermal Hall effect, various magneto-electric effects such as the polar Kerr effect, in addition to the topologically protected Fermi arcs on the $(1,0,0)$ and $(0,1,0)$ surfaces. The line node at the Fermi surface equator acts as a vortex loop in the momentum space and gives rise to the zero energy, dispersionless Andreev bound states on the $(0,0,1)$ surface. At the transition from the B-phase to the A-phase, the time reversal symmetry is restored, and only the nodal ring survives inside the A-phase.



Dr. Andriy Nevidomskyy is an expert in theoretical condensed matter physics, working in the field of strong electron correlations in quantum materials. The collective behaviour of electrons in such materials often results in the emergence of new exotic quantum phases, such as the unconventional superconductivity. Nevidomskyy is working on the heavy fermion materials and a new class of iron-based superconductors, and is particularly interested in the novel quantum phases emerging in frustrated magnets. Originally from Ukraine, he received his PhD in physics from Cambridge University in the UK, before moving to Université de Sherbrooke in Canada as a postdoctoral fellow to work on high-temperature cuprate superconductors. Prior to joining Rice in 2010, he was a postdoctoral researcher in the Center for Materials Theory at Rutgers University, conducting research into heavy fermion materials. He is the recipient of the NSF CAREER Award and the Cottrell Scholar Award from Research Corporation for Science Advancement.

Session 5: Materials in Low Dimensions

Bilayer Exciton Condensates

Allan H. MacDonald
The University of Texas at Austin

Spatially indirect equilibrium bilayer exciton condensates exhibit a variety of anomalous electrical transport properties that are fundamentally interesting and potentially valuable for low-power electronics. I will explain some of the principle transport anomalies which have so far been observed only at temperatures below 1 Kelvin and only in the strong magnetic field quantum Hall regime. I will then discuss prospects for achieving this type of condensate at greatly enhanced temperatures using two-dimensional semiconductors like transition-metal dichalcogenides.



Allan H. MacDonald received the B.Sc. degree from St. Francis Xavier University, Antigonish, Nova Scotia, Canada in 1973 and the M.Sc. and Ph.D. degrees in physics from the University of Toronto in 1974 and 1978 respectively. He was a member of the research staff of the National Research Council of Canada from 1978 to 1987 and has taught at Indiana University (1987-2000) and the University of Texas at Austin (2000-present) where he now holds the Sid W. Richardson Chair in Physics. He has contributed to research on the quantum Hall effect, electronic structure theory, magnetism, and superconductivity among a variety of other topics.

Dr. MacDonald is a fellow of the American Physical Society, a member of the American Academy of Arts and Sciences and the National Academy of Sciences, and a recipient of the Herzberg Medal and the Buckley Prize.

2D materials canvas: carbon, h-BN, metal-disulfides, and topological defects therein

Boris I. Yakobson

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It is of great interest and importance for materials design to uncover, through theory and computational modeling, the following relationships: {basic atomic interactions → structure/morphology → functionality (including electronic)}. I will discuss recent examples from low-dimensional materials, where we seem to achieve satisfactory degree of understanding. These include 1D carbon nanotubes [1] and carbyne [2], but I will mostly focus on 2D graphene [3-5], transition metal disulfides [6-8], phosphorene [9].

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Boris I. Yakobson is an expert in theory and computational modeling of nanostructures and materials, of their synthesis, mechanics, defects and relaxation, transport and electronics. Presently, Karl F. Hasselmann Chair in Engineering, professor of Materials Science and Nano-Engineering, and professor of Chemistry, Rice University, Houston, Texas. Born in Moscow, Russia, received PhD 1982 in Physics and Applied Mathematics, from Russian Academy of Sciences. 1983-1989, Head of Theoretical Chemistry laboratory at the Institute of Solid Materials of the Russian Academy. 1990-1999, on the faculty of the Department of Physics, North Carolina State University. His research, sponsored over the years by the National Science Foundation, Department of Energy, NASA, Department of Defense, Army Research Office, Air Force Research Laboratory and AFOSR, Office of Naval Research, as well as private industry and

foundations, resulted in over 270 publications and seven patents. Received Department of Energy Hydrogen Program Award, Nano 50 Innovator Award from Nanotech Briefs (Boston), Royal Society (London) Professorship Award, Department of Energy R & D Award, NASA Faculty Award. Yakobson has mentored a number of PhD students and postdoctoral associates, serves on the editorial boards of several journals and on steering committees.

Cooperative Recombination of Electron-Hole Pairs in Two Dimensions

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Quantum particles sometimes cooperate to develop an ordered state, where macroscopic coherence appears *spontaneously*. Here, we demonstrate that such spontaneous appearance of coherence occurs in an optically excited semiconductor quantum well in a high magnetic field [1-3]. When we create a dense electron-hole (e-h) plasma with an intense laser pulse, after a certain delay, an ultrashort burst of coherent radiation emerges. We interpret this striking phenomenon as a manifestation of superfluorescence (SF), in which a macroscopic polarization spontaneously builds up from an *initially incoherent ensemble of excited quantum oscillators* and then decays abruptly, *producing giant pulses of coherent radiation*. SF has been observed in atomic gases, but the present work represents the first observation of SF in a semiconductor, where not only real-photon exchange but also virtual-photon exchange (Coulomb interactions) is responsible for the formation of macroscopic coherence. We found that Coulomb interactions dramatically enhance and modify the collective superradiant decay of the e-h plasma. Unlike typical spontaneous emission from semiconductors, which occurs at the band edge, the observed SF occurs at the quasi-Fermi energy of the highly degenerate carrier distribution, up to 150 meV above the band edge. As the carriers are consumed by ultrafast radiative recombination, the quasi-Fermi energy goes down, and we observe a continuously red-shifting streak of SF at zero magnetic field and a series of sequential SF bursts from higher to lower Landau levels in a magnetic field. This Coulomb enhancement allows the magnitude of the giant dipole to exceed even the maximum possible value for ordinary SF (i.e., the total sum of in-phase oscillations of individual dipoles), making e-h SF even more “super” than atomic SF.

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2. J.-H. Kim *et al.*, *Physical Review B* **87**, 045304 (2013)
3. J.-H. Kim *et al.*, *Scientific Reports* **3**, 3283 (2013)



Professor Junichiro Kono received his B.S. and M.S. degrees in applied physics from the University of Tokyo in 1990 and 1992, respectively, and completed his Ph.D. in physics from the State University of New York at Buffalo in 1995. He was a postdoctoral research associate in condensed matter physics at the University of California, Santa Barbara, in 1995-1997 and the William W. Hansen Experimental Physics Laboratory Fellow in the Department of Physics at Stanford University in 1997-2000. He joined the Department of Electrical and Computer Engineering of Rice University in 2000 as an Assistant Professor and was promoted to Associate Professor in 2005 and to Professor in 2009. He is currently a Professor in the Departments of Electrical & Computer Engineering, Physics & Astronomy, and Materials Science & NanoEngineering at Rice

University. Professor Kono was a recipient of the National Science Foundation CAREER Award in 2002 and has been a Fellow of the American Physical Society since 2009 and a Fellow of the Optical Society (OSA) since 2014. Professor Kono is also the founder of the nationally recognized international program for science and engineering undergraduate students, [NanoJapan](#), funded by the U.S. National Science Foundation, receiving the Heiskell Award for Innovation from the Institute of International Education in 2008.

RCQM Posters

Poster #	Poster Title	First Name	Last Name
1	<i>Investigations of Tunable Long Range Interactions in Ultracold Strontium</i>	Jim	Aman
2	<i>One-dimensional atomic chains: rich physics in simple structures</i>	Vasilii I	Artyukhov
3	<i>Extraordinary Absorption of Sunlight in Nanostructured Monolayer Molybdenum Disulfide</i>	Shah Mohammad	Bahauddin
4	<i>Ising-nematic order and spin excitations in the bilinear-biquadratic model for the iron pnictides</i>	Patricia	Bilbao Ergueta
5	<i>Enhanced Pairing Correlations near a Quantum Critical Point in Two</i>	Ang	Cai
6	<i>Strontium BEC Apparatus</i>	Francisco	Camargo
7	<i>Enhanced ferromagnetism induced by structural phase transitions in Co₂As_{1-x}P_x</i>	Chih-Wei	Chen
8	<i>Nano-scale characterization of magnetic and electronic properties in novel materials</i>	Jesse	Choe
9	<i>Conductivity and thermoelectric power in graphene</i>	Hongyi	Xie
10	<i>Ultracold Nonreactive Molecules in an optical lattice</i>	Andris	Docaj
11	<i>Femtosecond Structural Dynamics of Photocatalytic Hydrogen and Oxygen Evolution</i>	Chloe	Doiron
12	<i>2D Majorana fluids: Instabilities, universal statistics, and quantized transport at the surface of a topological superconductor</i>	Matthew	Foster
13	<i>Quantum phases and their transitions in a pyrochlore Kondo lattice</i>	Sarah	Grefe
14	<i>Distribution functions and probes of far-from-equilibrium topological matter</i>	Yunxiang	Liao
15	<i>Collisions of matter-wave solitons</i>	Henry De	Luo
16	<i>Orbital-selective Correlation Effects in Alkali Metal Iron Pnictides</i>	Weicheng	Lv
17	<i>Global Phase Diagram of an Ising-Anisotropic Kondo Lattice Model</i>	Emilian	Nica
18	<i>Superconductivity in R₃T₄Ge₁₃ (R = Y, Lu and T = Rh, Co, Os) single crystals</i>	Binod	Rai
19	<i>Superfluidity in One- and Three-Dimensional Spin-Imbalanced Fermi Gases</i>	Melissa	Revelle
20	<i>Hot-electron Induced Photoelectrochemical solar-to-fuel energy conversion</i>	Hossein	Robotjazi
21	<i>Novel Itinerant Antiferromagnet TiAu</i>	Eteri	Svanidze
22	<i>Lie Algebraic Similarity Transformed Hamiltonians</i>	Jacob	Wahlen-Strothman
23	<i>Magnetic vortex crystals in frustrated 3D Mott insulators</i>	Zhentaο	Wang
24	<i>Quantum Critical Phenomena in Disordered Topological Superconductors</i>	Yang-Zhi	Chou
25	<i>Strongly interacting fermions in 1D</i>	Li	Yang
26	<i>Time-reversal symmetry breaking, quantum criticality and anomalous Hall effect in heavy fermion metals</i>	Wenxin	Ding

Poster # 1

Investigations of Tunable Long Range Interactions in Ultracold Strontium

J. A. Aman, B. J. DeSalvo, and T. C. Killian

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We describe our progress towards experimental realization of an ultracold atomic gas with tunable, long-range interactions. Long-range interactions are predicted to give rise to novel phenomena, such as phase transitions to strongly correlated classical crystals, roton-maxon excitations, exotic spin and magnetic states, three-dimensional solitons, and super-solids. We create long range interactions in thermal gases and Bose-Einstein condensates of atomic strontium by optically dressing the ground electronic atomic state with a small admixture of a highly excited Rydberg state. This induces strong van der Waals interactions which we detect using Bragg spectroscopy, wherein we probe the dispersion relation of long-wavelength excitations of the condensate. A major obstacle that must be overcome is a large-atom loss rate observed at high sample density and significant Rydberg dressing.

Poster # 2

One-dimensional atomic chains: rich physics in simple structures

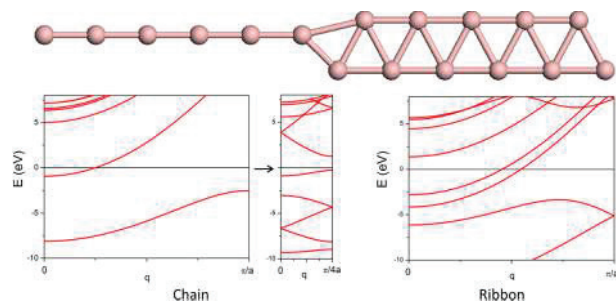
Vasilii I. Artyukhov, Mingjie Liu, Boris I. Yakobson

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Carbyne—1D polymorph of carbon—has been hypothesized since 1960's, however reproducible techniques of fabricating long carbon chains and measuring their properties have arrived only in the last decade. More recently, 1D chains of other compositions have been fabricated, such as Csl and BN. The rich and unusual properties of such 1D materials, which can show extreme mechanical performance [1] as well as strongly strain-sensitive electronic properties [2], motivates the search for other possible compositions with interesting behaviors. We use first-principles calculations to uncover the rich structural and mechanical properties of 1D boron [3]. While the ground state structure of linear boron is a two-atoms-wide ribbon with metallic properties, tension can reversibly unravel it into a single-atom string structure which is an insulator with an unusual antiferromagnetic ground state. We analyze the mechanical and electronic properties of these two 'phases' and study the thermodynamics and kinetics of transition between them using first-principles calculations and semiempirical (DFTB) molecular dynamics. The interesting properties of 1D boron nanostructures make them an attractive system for experimental investigations.

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- [3] V. I. Artyukhov, M. Liu, and B. I. Yakobson, in preparation



Poster # 3

Extraordinary Absorption of Sunlight in Nanostructured Monolayer Molybdenum Disulfide

Shah Mohammad Bahauddin,¹ Hossein Robotjazi,¹ Chloe Doiron,¹ Elisabeth Bianco,² and Isabell Thomann^{1, 2, 3}

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Abstract: The promise of nanophotonic photoconversion devices lies in the ability to engineer nanostructures that are thinner than the diffusion length of the photogenerated carriers and yet exhibit sufficiently strong light-matter interactions to completely absorb incoming light in the spectral range of interest. Monolayer MoS₂ is an attractive candidate for such an approach, since it exhibits semiconducting properties with a direct bandgap and a high absorption coefficient in the visible spectrum. Yet, monolayer MoS₂ does not achieve full absorption of sunlight. Here we will show that the absorption characteristics of monolayer MoS₂ can be enhanced by employing sub-wavelength nanostructuring on the active material itself. We will show three-dimensional full-field electromagnetic simulation data in which we analyze the influence of geometric parameters such as disk diameter, inter-disk spacing and spacer layer thickness on absorption. On the experimental side, we will show preliminary results on large area MoS₂ growth and patterning, and if time permits optical absorption and photocurrent measurements. This demonstration concludes that two-dimensional nanostructured MoS₂ is indeed a promising candidate for efficient photoconversion devices e.g. for direct solar- to-fuel conversion and photovoltaics.

Ising-nematic order and spin excitations in the bilinear-biquadratic model for the iron pnictides

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Motivated by the recent inelastic neutron scattering (INS) measurements in the iron pnictides which show a strong anisotropy of spin excitations in directions perpendicular and parallel to the ordering wave-vector even above the magnetic transition temperature T_N [1], we study the frustrated Heisenberg model with a biquadratic spin-spin exchange interaction. Using the Dyson-Maleev (DM) representation, which proves appropriate for all temperature regimes, we find that the spin-spin dynamical structure factors are in excellent agreement with experiment, exhibiting breaking of the C_4 symmetry even into the paramagnetic region $T_N < T < T_\sigma$ which we refer to as the Ising-nematic phase. In addition to the Heisenberg spin interaction, we include the biquadratic coupling $-K(\mathbf{S}_i \cdot \mathbf{S}_j)^2$ and study its effect on the dynamical temperature range $T_\sigma - T_N$ of the Ising-nematic phase. We find that this range reduces dramatically when even small values of the interlayer exchange J_c and biquadratic coupling K are included.

To supplement our analysis, we benchmark the results obtained using the DM method against those from different non-linear spin-wave theories, including the recently developed generalized spin-wave theory (GSWT) [2], and find good qualitative agreement among the different theoretical approaches as well as experiment for both the spin-wave dispersions and the dynamical structure factors. For more details see [3].

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Enhanced Pairing Correlations near a Quantum Critical Point in Two Impurity Anderson Model with a Pseudogap

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Significant progress has been made on the understanding of quantum critical heavy fermion metals [1]. In addition to the spin density wave quantum critical point (QCP), a Kondo destruction QCP beyond the Landau framework has been discovered. It describes a type of second order quantum phase transition where the destruction of Kondo effect and the magnetic order coincide. At this interacting fix point, spin correlation function are found to demonstrate energy over temperature scaling, which agrees with the result found in neutron scattering experiment.

Recently there has been an increasing interest in the implications of Kondo destruction critical point on the formation of unconventional superconductivity. Motivated by a cluster-Extended Dynamical Mean Field (EDMFT) approach [2], we address this question in simplified models for Kondo destruction QCP, as arising in the two impurity pseudogap Anderson model, using the continuous time quantum Monte-Carlo method. Here two magnetic impurities are allowed to interact, with either an Ising or Heisenberg interaction. They also hybridize with a conduction electron band, whose density of states vanish in the vicinity of the Fermi energy in a power-law fashion. Both the pseudogap and the inter-impurity interaction alone can serve as the tool to access a Kondo destruction critical point in a simplified setting. Here we will study their combined effect.

For either type of inter-impurity interaction we have found a QCP distinct from either the case of a single impurity pseudogap Anderson model or a conventional two impurity model without the pseudogap. We observe critical local moment fluctuations with a power-law divergence in the staggered spin susceptibility, and show that the single-particle spectral function obey energy over temperature scaling. We find that the singlet pairing susceptibility is significantly enhanced near the QCP. Implications for unconventional superconductivity in quantum critical heavy fermion systems will be discussed.

Work supported by NSF and Welch Foundation

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Poster # 6

Strontium Bose-Einstein Condensate for study of Rydberg Interactions

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We present the design and construction of a new apparatus for creating and studying long-range interactions in ultracold degenerate gasses of strontium by incorporating Rydberg states in a condensate. Sr features three bosonic isotopes (^{84}Sr , ^{86}Sr , ^{88}Sr) and access to both singlet and triplet Rydberg states by UV excitation from the $1P_1$ and $3P_1$ states used for cooling. Direct excitation and state dressing will be used to tune the strength of the dipole-dipole (C_3/R_3) and van der Waals (C_6/R_6) interactions. In particular, the narrow $1S_0$ - $3P_1$ transition offers reduced scattering off the intermediate state for two-photon Rydberg dressing. Sr features an optically active core electron which can be used in addition to electric field plates and a microchannel plate for manipulating and detecting Rydberg atoms. These features make Sr a promising candidate for observing the transition from two-body to many-body interactions.

Poster # 7

Enhanced ferromagnetism induced by structural phase transitions in $\text{Co}_2\text{As}_{1-x}\text{P}_x$

Chih-Wei Chen, Jiakui K. Wang, and Emilia Morosan

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P doping in Co_2As induces two structural transitions, resulting in an enhanced ferromagnetic state at intermediate P compositions. In $\text{Co}_2\text{As}_{1-x}\text{P}_x$, doping induces a room temperature α -to- β structural distortion around $x = 0.04$, similar to that taking place around 725 K in the parent $x = 0$ compound. The resulting β -phase displays an enhanced ferromagnetic ground state. Close to $x = 0.85$, a hexagonal-to-orthorhombic phase transition occurs, concomitant with the quenching of the magnetic order. The enhancement of the ferromagnetism in the hexagonal β -phase ($0.04 \leq x \leq 0.85$) is due to the Fermi surface reconstruction, which is demonstrated by the electronic specific heat coefficient and further supported by the band structure calculations.

Nano-scale imaging of magnetic and electronic properties in novel materials

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The synthesis and characterization of new materials is a hotbed for new and exciting electronic and magnetic properties. In addition to the interesting physics of these systems, many of these materials are alluring because of their potential applications: increasing hard drive capacity, non-volatile memory, spintronics, and quantum computing to name a few. We present two examples of novel materials, GeBi_2Te_4 , a topological insulator, and Fe_xTaS_2 , an unusual ferromagnet. GeBi_2Te_4 shows topological surface conduction due to strong magnetic coupling which we investigate with dI/dV scanning tunneling spectroscopy to compliment ARPES and DFT calculations of the band structure. The Fourier transform of the spectroscopic images provide rapid analysis of the Fermi surface compared to more traditional methods like ARPES. In Fe_xTaS_2 , we demonstrate a dramatic change in magnetoresistance with slight changes in amount of doped iron as an impetus for performing spin polarized scanning tunneling microscopy measurements to further investigate this unexpected result. Here we present an analysis of the coupling of electronic and magnetic properties in the sub-micron domain of these materials.

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Conductivity and thermoelectric power in graphene: Interplay of disorder, Coulomb interaction, and optical phonons

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We study the electric and thermoelectric transport of Dirac fermions in graphene using the Boltzmann-equation approach. We consider the effects of quenched disorder, Coulomb interactions, and optical-phonon scattering and analyze the electric conductivity and the thermoelectric power (TEP) as functions of temperature T and chemical potential μ by unbiased numerical solutions to the Boltzmann equation. In the absence of optical phonons, for very clean graphene we observe the crossover from the interaction-limited hydrodynamic regime $\mu \ll T$ to the disorder-limited Fermi liquid regime $\mu \gg T$. In the hydrodynamic regime, the TEP significantly deviates from Mott's law and follows the result anticipated by the relativistic hydrodynamic theory. Moreover, we analyze the doping and screening effects upon the quantum minimal conductance which indicates the dissipation induced by inelastic electron-hole scattering. On the other hand, we find that optical phonons start to contribute at relatively low temperatures, about one order of magnitude less than the phonon excitation energy. Especially, the TEP shows a non-monotonic temperature dependence and a peak appears at about $T \approx 200 \sim 300$ K for a large variety of doping.

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Ultracold Nonreactive Molecules in an optical lattice

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Ultracold nonreactive (NR) molecules open up new possibilities for studying strongly interacting quantum matter: Like other ultracold systems, they are clean and flexible, but unlike atoms they possess strong, long range interactions and a large number of internal degrees of freedom[1,2]. Although ultracold NR molecules are free from the two-body losses that occur in other ultracold molecules, they interact in extremely complex ways -- not captured by a delta function contact interaction -- due to the enormous number of rotational and vibrational states[3]. We calculate the bound state energies of two NR molecules confined to a single site of an optical lattice, as a first step to deriving the effective lattice model that can describe these many-body systems. Because the short-range collisional properties are presently experimentally unknown, we model them using random matrix theory. However, our formalism is capable of handling arbitrary short-range collisional physics.

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Femtosecond Structural Dynamics of Photocatalytic Hydrogen and Oxygen Evolution

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Efficient photocatalytic splitting of water into oxygen and hydrogen gas is a highly attractive way of converting sunlight into chemical fuels for use in a “Hydrogen Economy”. Yet, our understanding what makes a material a good catalyst or photocatalyst for a given reaction is immature. To improve photo-catalytic devices the materials and catalytic reactions occurring at their surfaces need to be understood, requiring a system that is able to map out the charge carrier and structural dynamics of the chemical reactants with high chemical specificity and high temporal resolution. Femtosecond Stimulated Raman Spectroscopy (FSRS) has been shown to be a powerful technique for structural dynamics on femtosecond timescales with high vibrational resolution ($<10\text{ cm}^{-1}$) and temporal resolution ($<50\text{ fs}$). Here we will show our FSRS system capable of producing actinic pumps and Raman probes with pulse durations less than 15 fs in a wavelength range from 400 to 1000 nm. The femtosecond Raman probe supports enough bandwidth to simultaneously probe Raman shifts from 300 to 3500 cm^{-1} . Our system operates at 1 MHz pulse repetition rate allowing us to efficiently characterize dynamics from femtosecond to second time scales.

2D Majorana fluids: Instabilities, universal statistics, and quantized transport at the surface of a topological superconductor

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Superconductivity is a remarkable phenomenon that occurs in many-electron systems, due to quantum mechanics. Topological superconductors are even more peculiar: these are predicted to host exotic particles called Majorana fermions at the material surface [1,2]. In three dimensions, Majorana fermions can occur in multiple “colors,” and the number of colors is known as the winding number. The Majorana fermions are the loose ends of a bulk quantum knot, and the winding number encodes the topology of this knot. Another system where quantum knots appear is the 2D quantum Hall effect, where measuring the Hall conductance reveals the winding number. In this work [3], we argue that the surface spin and thermal conductivities of 3D topological superconductors are universal and topologically-quantized at low temperature. Surface spin and heat transport measurements can provide a “smoking gun” for a surface Majorana fluid.

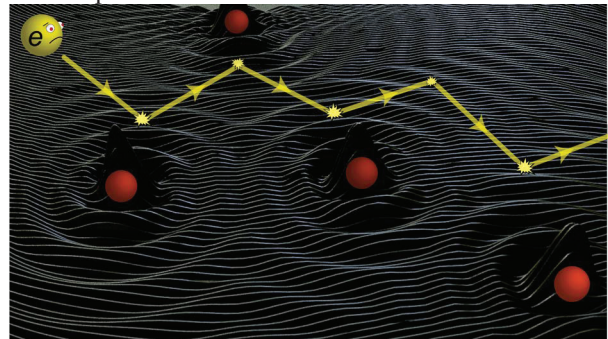
Impurities and other forms of static disorder are unavoidable at a solid surface. In the absence of interactions, it was already known that the spin and thermal conductivities that describe the flow of surface Majorana fermions are independent of disorder, and proportional to the winding number [4,5]. These particles also mutually interact via screened Coulomb interactions. Typically, interactions give rise to quantum corrections to the conductivity. We argue that all corrections vanish for the surface Majorana fluid, since the anomalous form of time-reversal symmetry prevents ripples in the Majorana “density.” We confirm this in two expansions: perturbative in the interactions, and in the limit of large winding numbers. At the same time, we show that the interactions can destabilize surface states, leading to insulating behavior [5,6]. The mechanism is the “Russian doll” nesting of rarified multifractal wavefunctions [5,7,8].

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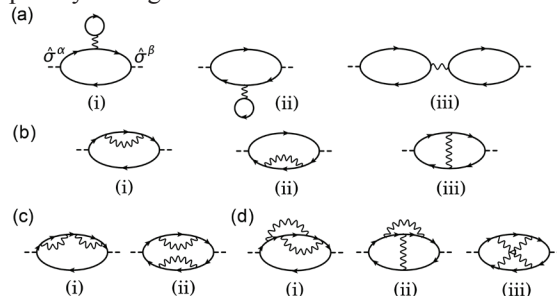
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Fig 1: In an ordinary 2D system, carriers scatter off of both impurities and off of the Friedel oscillations (density ripples) induced in the background density. At sufficiently low temperatures, the propagation is phase coherent. Scattering off of impurities results in weak localization or antilocalization corrections to the conductance, while scattering off of density ripples gives Altshuler-Aronov corrections. Both can induce Anderson localization. At the surface of a topological superconductor, weak localization corrections to the heat or spin conductance vanish to all orders.



Ripples by Leonardo Nuevo Arenas

Fig 2: Interaction corrections to the spin conductance can be formally organized as a Feynman series in the interactions, using the exact non-interacting Green’s functions (in a fixed realization of disorder). We argue that all such corrections vanish, and demonstrate this explicitly through the second order.



Quantum phases and their transitions in a pyrochlore Kondo lattice

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The pyrochlore heavy fermion $\text{Pr}_2\text{Ir}_2\text{O}_7$ is a frustrated Kondo lattice system that has a large zero field anomalous Hall Effect [1,2,3] and may have a chiral spin liquid ground state of the local moments. Recently, thermodynamic measurements reveal a divergent Grüneisen ratio [4], which indicates a nearby quantum critical point. In this work, we study the effect of Kondo coupling on various spin liquid states of the Heisenberg model on pyrochlore lattices, including states exhibiting time-reversal-symmetry-breaking. Using a slave fermion representation for the f-moments which are coupled to conduction electrons, we study the large-N limit and show that chiral spin liquid solutions of the f-moment are candidate states with favorable ground state energies. We discuss the implications of our results for the anomalous Hall response across the quantum phase transition, and for the experiments in $\text{Pr}_2\text{Ir}_2\text{O}_7$.

This work has been supported by ARO, the Welch Foundation and IRISE (NSF EHR-0966303).

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Distribution functions and probes of far-from-equilibrium topological matter

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We investigate radio-frequency (RF) spectroscopy and superconductor-normal metal tunneling as probes of out-of-equilibrium topological systems. As an example, we study a 2D p+ip superfluid following an instantaneous quench of the coupling strength [1, 2]. The long-time asymptotic order parameter of this system can be constant or time-periodic. In both cases, the post-quench Cooper pairs each occupy a linear combination of two states, with coefficients determined by the distribution function. In strong quenches where the order parameter is periodic, the bases are two Floquet states with opposite quasi-energy. We derive expressions for the RF and tunneling spectra for these post-quench states, examining both average values and harmonics. While the distribution function strongly affects the RF signal, it disappears from the tunneling spectrum. We show that the bulk RF signal obtained by occupying the lower Floquet band is dramatically different from that of the post-quench states. This is intimately related to the difference between the topology of the state, which cannot change under closed evolution, versus the topology of the non-equilibrium excitation spectrum.

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Collisions of matter-wave solitons

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A soliton is a localized wave packet that maintains its shape while propagating at a constant velocity, a result of a nonlinear interaction that cancels the wave packet dispersion. Solitons emerge in systems that are governed by a nonlinear integrable equation, such as the one-dimensional (1D) nonlinear Schrödinger equation (NLSE), which describes motion in a wide range of wave contexts, including guided matter waves [1,2]. A remarkable consequence of the integrability is that when two solitons collide, they emerge from the collision unaltered in shape, amplitude or velocity, but with a different trajectory reflecting a discontinuous jump.

In this work we create a pair of matter-wave solitons from a Bose-Einstein condensate (BEC) of ⁷Li atoms in a quasi-1D harmonic trap and observe their collisions. With phase-contrast imaging [3], we can take multiple images within a single realization of the experiment, and the result is compared to numerical simulation of the 1D Gross-Pitaevskii equation (GPE).

We show that the collision is a complex event that differs markedly depending on the relative phase of the solitons. When the solitons are in-phase, a peak forms in the center, giving the appearance of an attractive interaction between the solitons, whereas when the solitons are out-of-phase, a node forms in the center, and the apparent interaction is repulsive.

The quasi-1D nature and the presence of the harmonic confinement put our system on the edge of integrability. As we increase the strength of the nonlinear interaction, we observe fusion or annihilation of the solitons in the case of in-phase collisions (Fig. 1). This is a result of the density-dependent inelastic collision between the atoms, in which our system becomes effectively 3D. However, for the same interaction strength, the out-of-phase solitons prove to be extremely robust against collapse, as they survive more than 20 collisions.

We also observe that the oscillation frequency of the soliton pair is slightly higher than the radial trap frequency, a result of the discontinuous jump following each collision. As a comparison we also prepare two BECs with repulsive nonlinear interaction, and we find that the frequency of the oscillation negatively deviates from the trap frequency. We conclude that the discontinuous jump is caused by the density-dependent mean-field interaction between the atoms and is independent of the relative phase of the solitons. The

result agrees reasonably well with numerical simulation of the 1D GPE and our analytical approximation.

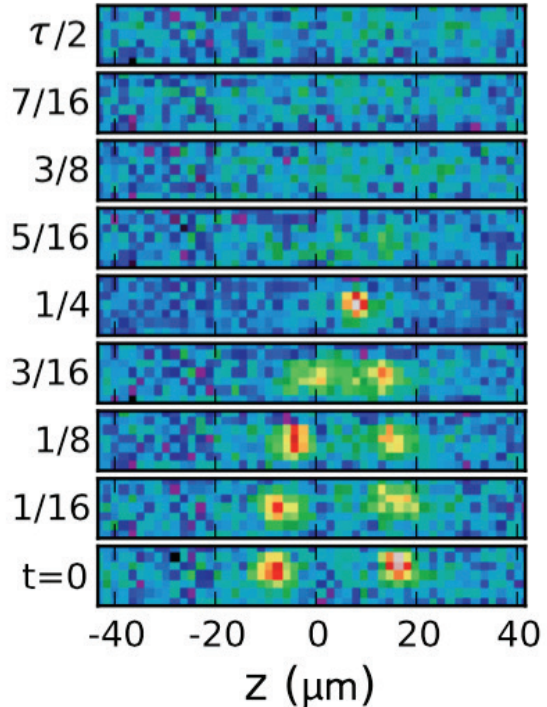


Figure 1. A collision between two solitons results in collapse. During the collision, the density exceeds a critical value and becomes unstable against collapse. No remaining atoms are observed.

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Orbital-selective Correlation Effects in Alkali Metal Iron Pnictides

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Abstract

There is growing evidence for the substantial electronic correlations in the iron based superconductors. In particular, recent experiments have revealed strong orbital-selective correlation effects in the series of alkali metal iron pnictides $A\text{Fe}_2\text{As}_2$ ($A = \text{K}, \text{Rb}, \text{Cs}$). Among the important questions is how these systems, with a 3d-electron filling $n = 5.5$ per site, differs from the parent iron pnictides, which has $n = 6$. Here, we address these issues in a five-orbital Hubbard model with filling $n = 5.5$, using the $U(1)$ slave-spin method. As the lattice parameters increase from K to Rb, then to Cs, we are able to identify the systematics in the orbital-selective Mott behavior as the correlation effects are enhanced due to the reduced bandwidth. We discuss the implications of our results for the quasiparticle mass as well as for the spin spectral weight.

Global Phase Diagram of an Ising-Anisotropic Kondo Lattice Model

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Heavy fermions are compounds containing rare earth or actinide elements with a partially filled 4f or 5f shell [1]. They can be modeled by a lattice of localized moments coupled to a band of conduction electrons (Kondo lattice)[1]. Below the single-impurity Kondo temperature, the conduction electrons in these materials exhibit a tendency to screen the local moments by forming static local Kondo singlets. As one goes below a coherence temperature, the system can become a (heavy) Fermi liquid. In this case, the ground state corresponds to an entanglement between the conduction electrons and the local moments, and the resulting single-particle excitations are in one-to-one correspondence with those of an electron gas with the exception of a strongly increased effective mass which is a direct consequence of the hybridization with the local moments. Heavy fermion materials exhibit a rich variety of phase transitions. Of particular interest are quantum phase transitions associated with the breakdown of the Fermi liquid picture and the concomitant emergence of a magnetic order of the local moments. A theoretical example of this is the Kondo destruction scenario in the context of local criticality in which the static Kondo screening disappears exactly at the critical point [2]. To capture this effect and others, a zero temperature global phase diagram for heavy fermion materials has been proposed [1,3]. It incorporates the competition between the Kondo effect and the local-moment quantum fluctuations. The Ising-anisotropic Kondo lattice in a transverse magnetic field captures this competition. We present some new results for this model within the Extended Dynamical Mean-Field Theory (EDMFT) and their implications for the global phase diagram.

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Superconductivity in single crystals of $\text{Lu}_3\text{T}_4\text{Ge}_{13-x}$ ($\text{T} = \text{Co}, \text{Rh}, \text{Os}$) and $\text{Y}_3\text{Os}_4\text{Ge}_{13-x}$

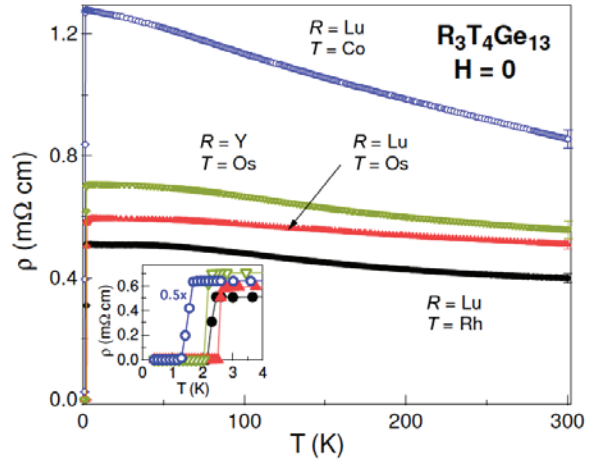
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In general, superconductivity is observed upon cooling from the metallic state of the respective compounds, as is the case for all $\text{R}_3\text{T}_4\text{Sn}_{13}$ stannides^{1,2,3}, where R is a rare earth, and T is a transition metal. By contrast, a normal state semi-metal or semiconductor is rarely reported to precede a superconducting state in these 3-4-13 germanides family.

Single crystals of $\text{Lu}_3\text{T}_4\text{Ge}_{13-x}$ ($\text{T} = \text{Co}, \text{Rh}, \text{Os}$) and $\text{Y}_3\text{Os}_4\text{Ge}_{13-x}$ have been grown using the self-flux method and found to adopt the $\text{Yb}_3\text{Rh}_4\text{Sn}_{13-x}$ structure type. Magnetization and specific heat measurements confirm that all four compounds are bulk superconductors, with reduced superconducting gaps determined from specific heat suggesting multiband superconductivity. An unusual increase of the electrical resistivity and a decrease of the charge carrier density is observed in the normal state in all four reported compounds. However, band structure calculations reveal a metallic ground state for all four compounds, consistent with the emergence of superconductivity at low temperatures. We empirically show that large atomic displacement parameter ratios in $\text{R}_3\text{T}_4\text{Ge}_{13-x}$ compounds are correlated with the semiconductor-like behavior, resolving the contradiction between the experiment and the calculations.



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Superfluidity in One- and Three-Dimensional Spin-Imbalanced Fermi Gases

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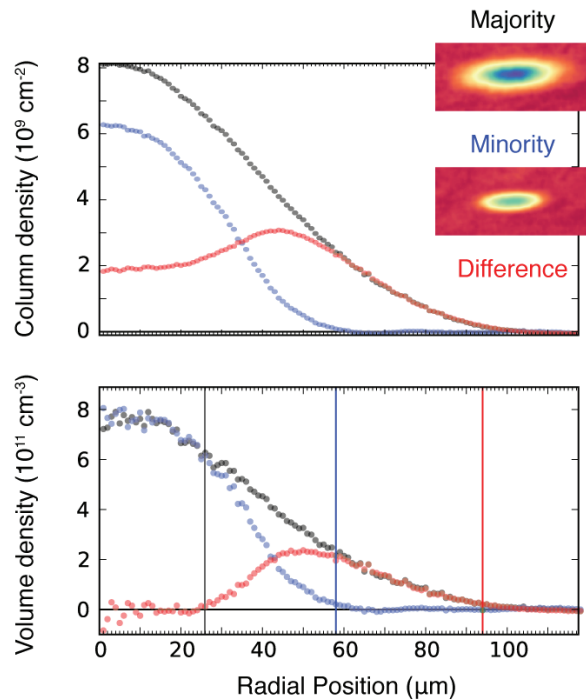
We experimentally study the phases of an ultracold two-spin component gas of atomic fermions. The phase separation between the superfluid and normal phases in trapped Fermi gases in the Bose-Einstein Condensate (BEC)-Bardeen-Cooper-Schreiffer (BCS) crossover between tightly-bound molecules and weakly-bound Cooper pairs reveals the interplay between superfluid pairing, interactions, and dimensionality.

We prepare gases with around 5×10^5 ⁶Li atomic fermions in the lowest two hyperfine sublevels (spin-up and spin-down), trapped in an optical potential formed by infrared laser beams. After cooling the gas to ~ 100 nK, we measure density profiles of both spins using near-resonant probe light. Gases in 3D are confined by focused laser beams that form harmonic trapping potentials. To confine the atoms to motion in 1D, we load the atoms into a 2D optical lattice composed of standing waves of light formed by interfering two pairs of counter-propagating laser beams. We tune the interactions between the spin species by changing a bias magnetic field near a Feshbach resonance.

In 3D, the core of the gas has an equal number of atoms in the two spin components; this phase is a balanced superfluid. The core is surrounded by thin a partially polarized shell, with an excess of spin-up particles; this shell is surrounded by the outer shell, composed entirely of spin-up particles. We varied the overall spin-polarization in the cloud and measured the resulting sizes of the three phases. Above a critical polarization called the Chandrasekhar-Clogston limit (CCL), the balanced superfluid core is suppressed, and the core of the gas is partially polarized. We measured the CCL as the interaction strength in the gas was varied across the BEC-BCS crossover.

For a 1D gas in an optical lattice, the phase separation matches exactly-solved 1D models, where the central phase is partially polarized [1]. This partially polarized phase is predicted to support both superconducting and magnetic order, as predicted by Fulde and Ferrel, Larkin and Ovchinnikov (FFLO). Starting from such a 1D gas, we increase the inter-tube tunneling rate by decreasing the lattice depth. By varying to investigate

the dimensional crossover between 1D and 3D Fermi gases. In this crossover regime, the FFLO order parameter is predicted to be correlated between tubes [2], and its modulation length constant over larger regions of the trap [3]. These features are predicted to enhance the observable signatures of FFLO correlations; we report progress towards such measurements.



Density profiles for a single run of the experiment averaged along trap equipotentials. The inset shows the camera images. The volume density is computed from the column density via an inverse Abel transform. Vertical lines indicate phase boundaries—the black line marks the superfluid core edge, the blue line marks the polarized shell edge, and red marks the majority edge.

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Hot-electron Induced Photoelectrochemical Reduction of Carbon Dioxide

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Abstract

Relentless increase of CO₂ emission into the atmosphere is becoming a major concern in the 21st century by virtue of the fact that CO₂ has substantial contribution in global warming and climate change [1, 2]. Unfortunately, despite years of research, efficient CO₂ reduction is an unresolved problem in part due to lack of efficient photocatalysts and the complex chemistry underlying CO₂ reduction [3]. Hence, development of novel photocatalysts that could convert CO₂ to value-added hydrocarbons and alcohols with high efficiency as well as selectivity of products is still a significant challenge. In addition, there is an urgent need for advanced experimental in-situ techniques that can provide detailed information on the role of the catalytic surface and other physical and chemical phenomena occurring during this process.

Here we aim to develop a novel efficient plasmonic photocatalyst based on hot-electron generation in plasmonic nanodot arrays for multi-electron reduction of CO₂. Large-scale gold plasmonic arrays can be patterned on the substrate of interest using anodized aluminium oxide as an evaporation mask. The pore size can be tuned down to sub-20 nm with periodicity of sub-50 nm to fabricate a dense array of gold nanodots. We used Finite Difference Time Domain (FDTD) simulations to optimize the photocatalyst structure and achieve maximum light absorption within the gold nanodots.

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Novel Itinerant Antiferromagnet TiAu

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The origin of magnetism in metals has been traditionally discussed in two diametrically opposite limits: itinerant and local moments. Surprisingly, there are very few known examples of materials that are close to the itinerant limit, and their properties are not universally understood. In the case of the two such examples discovered several decades ago, the itinerant ferromagnets $ZrZn_2$ and Sc_3In , the understanding of their magnetic ground states draws on the existence of $3d$ -electrons subject to strong spin fluctuations. Similarly, in Cr, an elemental itinerant antiferromagnet (IAFM) with a spin density wave ground state, its $3d$ -electron character has been deemed crucial to it being magnetic. Here we report the discovery of the first IAFM metal with no magnetic constituents, TiAu. Antiferromagnetic order occurs below a Neel temperature $T_N \sim 36$ K, about an order of magnitude smaller than in Cr, rendering the spin fluctuations in TiAu more important at low temperatures. This new IAFM challenges the currently limited understanding of weak itinerant antiferromagnetism, while providing long sought-after insights into the effects of spin fluctuations in itinerant electron systems.

Lie Algebraic Similarity Transformed Hamiltonians

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We present a class of Lie algebraic similarity transformations generated by exponentials of two-body, hermitian operators whose Hausdorff series can be summed exactly without truncation. The correlators are defined over the entire basis and include the Gutzwiller factor $n_{i\uparrow}n_{i\downarrow}$, and two-site products of density ($n_{i\uparrow} + n_{i\downarrow}$) and spin ($n_{i\uparrow} - n_{i\downarrow}$) defined as a general diagonal operator. The resulting non-hermitian many-body Hamiltonian can be solved in a biorthogonal mean-field approach with polynomial computational cost. Jastrow factors such as these are commonly used in quantum Monte-Carlo [1] and other applications. We demonstrate an alternative approach by transforming the Hamiltonian and solving a projected system of equations with no stochastic error. The proposed similarity transformation generates locally weighted orbital transformations of the reference determinant. Although the energy of the model is unbound, projective equations in the spirit of coupled cluster theory [2] lead to well-defined solutions, and properties can be calculated with response equations. Accurate results are produced for 1D and 2D systems in both the strong and weak correlation regimes. The theory is compatible with additional transformations and many extensions and generalizations.

References:

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Magnetic vortex crystals in frustrated 3D Mott insulators

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Topological spin textures, such as skyrmions, are of great interest to the field of spintronics and usually arise due to the interplay of Dzyaloshinskii-Moriya and exchange couplings. By contrast, using the BCC and FCC lattices as examples, here we demonstrate that frustrated spin exchange interactions alone can produce topological vortex crystals near the magnetic field-induced saturation transition of 3D bulk Mott insulators. Because of the magnetic frustration, the magnon spectrum of the high field fully polarized state has multiple degenerate minima at different Q-vectors. This quantum paramagnet becomes gapless and goes through a Bose-Einstein condensation at the saturation field (quantum critical point). In this limit, we apply the dilute bosonic gas approximation to study the rich topological structures produced due to multi-Q condensation. We find that the vortex crystal phases span sizable regions in the phase diagrams of frustrated 3D Mott insulators with isotropic Heisenberg interactions, and are further stabilized by exchange anisotropies. Vortex strings emerge in the direction of the magnetic field and, depending on the distributions of the condensed modes, can form different exotic patterns.

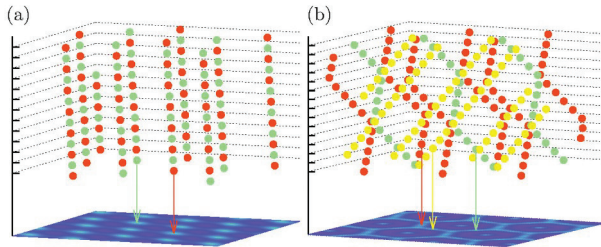


Fig. 1: String patterns formed by vortex cores, where different colors denote different helicities.

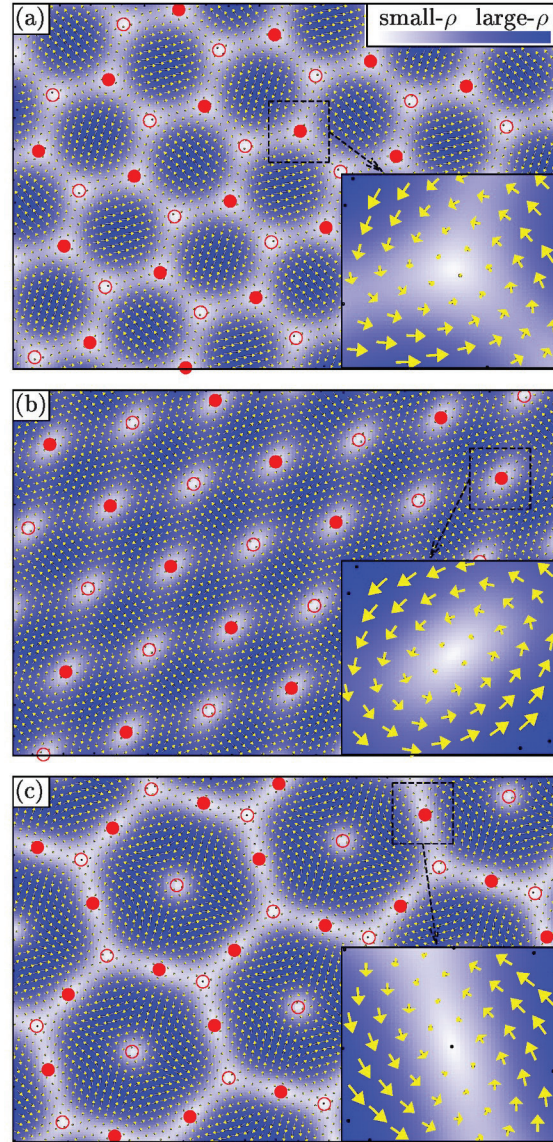


Fig. 2: Magnetic vortex crystals in each layer perpendicular to the magnetic field. Patterns depend on how the different modes are condensed at these Q-vectors. Full(empty) symbols denote vortex(anti-vortex).

Poster # 24

Quantum Critical Phenomena in Disordered Topological Superconductors

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We numerically investigate critically delocalized wavefunctions in models of 2D Dirac fermions, subject to vector potential disorder. These describe the surface states of 3D topological superconductors, and can also be realized through long-range correlated bond randomness in artificial materials like molecular graphene. A “frozen” regime can occur for strong disorder in these systems, wherein a single wavefunction presents a few localized peaks separated by macroscopic distances. Despite this rarefied spatial structure, we find robust correlations between eigenstates at different energies, at both weak and strong disorder. The associated level statistics are always approximately Wigner-Dyson. The system shows generalized Chalker (quantum critical) scaling, even when individual states are quasilocalized in space. We confirm analytical predictions for the density of states and multifractal spectra. For a single Dirac valley, we establish that finite energy states show universal multifractal spectra consistent with the integer quantum Hall plateau transition. A single Dirac fermion at finite energy can therefore behave as a “Quantum Hall critical metal.” For the case of two valleys and non-abelian disorder, we verify predictions of conformal field theory. Our results for the non-abelian case imply that both delocalization and conformal invariance are topologically-protected for multivalley topological superconductor surface states.

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Poster # 25

Strongly interacting fermions in 1D

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Under second order degenerate perturbation theory, we show that the physics of N fermions with arbitrary spin in one dimension in Tonks-Girardeau (TG) and super-Tonks-Girardeau (sTG) regions can be described by super-exchange interaction. An effective spin chain Hamiltonian (non-translational-symmetric Sutherland model) can be obtained from this procedure. For spin-1/2 particles, this model is the non-translational-symmetric Heisenberg model, where a transition between Heisenberg anti-ferromagnetic (AFM) and ferromagnetic (FM) states is expected to occur when the interaction strength is tuned from TG to sTG limit. We show that the FM and AFM states can be distinguished in two different methods: the first is based on their distinct response to a spin-dependent magnetic gradient, and the second is based on their distinct momentum distribution. We examine the validity of the spin-chain model by comparison with results obtained from unbiased techniques such as exact diagonalization and TEBD.

Time-reversal symmetry breaking, quantum criticality and anomalous Hall effect in heavy fermion metals

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Recently, the interplay of geometric frustration and Kondo coupling has attracted much attention. The pyrochlore iridate $\text{Pr}_2\text{Ir}_2\text{O}_7$ is a frustrated Kondo system that has a large zero field anomalous Hall Effect and shows proximity to a quantum critical point. Motivated by these findings as well as the prospect of realizing electronic states at heavy fermion interfaces, we study the effect of Kondo coupling on a spin liquid ground state of the J_1 - J_2 model on (two-dimensional) square lattices. We use a slave fermion representation for the f -moments which are coupled to conduction electrons, and study the Kondo lattice model in the large- N limit. We show that a chiral spin liquid state with time-reversal-symmetry-breaking induces unusual topology in the electronic states. We calculate the anomalous Hall response for the chiral states of both the Kondo destroyed phase and Kondo screened phase, showing that it jumps across the quantum critical point due to a change of the Berry curvature. Finally we discuss the implications of our results for the pyrochlore iridate, and propose for systematic studies of both the field and temperature dependence of the anomalous Hall effect.

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