Common Problems in Condensed Matter and High Energy Physics

Round Table Discussion

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BES-HEP Connections

Round Table Discussion on
'Common Problems in Condensed Matter and High Energy Physics'

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Executive Summary

On February 2, 2015 the Offices of High Energy Physics (HEP) and Basic Energy Sciences (BES) convened a Round Table discussion among a group of physicists on 'Common Problems in Condensed Matter and High Energy Physics'. This was motivated by the realization that both fields deal with quantum many body problems, share many of the same challenges, use quantum field theoretical approaches and have productively interacted in the past. The meeting brought together physicists with intersecting interests to explore recent developments and identify possible areas of collaboration.

Two Associate Directors in the Office of Science, James Siegrist for HEP and Harriet Kung for BES approved the Roundtable. Eduardo Fradkin, University of Illinois and Juan Maldacena, Institute for Advanced Study co-chaired the meeting and 12 additional attendees with expertise in these areas participated in the discussions. Each attendee agreed to provide a short talk and to contribute to a report summarizing the discussion.

The Round Table met for a full day and was also attended by HEP and BES management. This report highlights the discussions and contributions from the Round Table. Rather than make specific recommendations, the report outlines areas where further work could have dramatic impact on science in both fields and describes those areas in the form of 12 Grand Challenge Questions. The Grand Challenge Questions address recent results with importance for analytical theory, computational science and experiment.

Several topics were identified as offering great opportunity for discovery and advancement in both condensed matter physics and particle physics research. These included topological phases of matter, the use of entanglement as a tool to study nontrivial quantum systems in condensed matter and gravity, the gauge-gravity duality, non-Fermi liquids, the interplay of transport and anomalies, and strongly interacting disordered systems. Many of the condensed matter problems are realizable in laboratory experiments, where new methods beyond the usual quasi-particle approximation are needed to explain the observed exotic and anomalous results. Tools and techniques such as lattice gauge theories, numerical simulations of many-body systems, and tensor networks are seen as valuable to both communities and will likely benefit from collaborative development.

This report also recognizes that these fields have productively interacted in the past by exchanging or co-developing theoretical and computational methods, and notes some of the current activities that are already providing a bridge between the two communities and the science to which these are dedicated.

Introduction

Condensed matter theory (CMT) and high energy physics (HEP) naturally have common interests. Both deal with systems with a large number of spatially organized degrees of freedom. In each case it is highly non-trivial to go between the laws of physics at short distances and emergent behavior at long distances. The techniques of quantum field theory are useful in both areas.

This interaction was historically important, from Nambu's applications of the theory of superconductivity to elementary particles that culminated on the Higgs mechanism to the analysis of second order phase transitions that led to the renormalization group.

These interactions are still going on today and there are several areas which are of common interest to both fields, with several researchers actively working in the interphase between the two fields or crossing over back and forth. There are particular developments that make these interactions stronger today. One is the study of topological phases of matter. These theories have potential applications to quantum computing, but they are also very interesting on their own as new phases which are missed by the traditional Landau classification. Topological effects in field theory are important both in high energy physics and mathematics. Another factor is the interest in using entanglement as a tool to study quantum systems. This is relevant to the characterization of topological phases as well as the study of quantum gravity and the structure of spacetime. It has been also useful for formulating sharper versions of the black hole information paradox. The gauge/gravity duality has provided examples of strongly coupled systems which can be easily analyzed using the gravity description. This has been a useful testing ground for theoretical ideas about strongly coupled systems in general. In addition, having a solvable example made it possible to discover some phenomena which are actually valid for general systems, such as the anomaly induced terms in hydrodynamics. In addition there are many tools and techniques which are of common interest, such as lattice gauge theories and the numerical simulation of many body systems. Numerical methods have also made it possible to carry out the conformal bootstrap program in some three dimensional examples, such as the three dimensional Ising model. The development of entanglement based renormalization approaches led to tensor networks which are useful both as numerical and theoretical tools.

There have already been research activities that try to bridge these different communities, including high-energy and condensed matter physics, and quantum information science, and encourage interdisciplinary research on quantum entanglement in many-body physics.

Examples of recent activities which are jointly organized by CMT and HEP theorists:

- The "Entanglement in Strongly-Correlated Quantum Matter" workshop, at the KITP in Santa Barbara, April-July 2015.
- The summer school on topological insulators at IAS/Princeton University, July 20-31, 2015.
- The DOE supported "Field theoretic computer simulations for condensed matter and high energy theory" workshop, at Boston University, May 8-10, 2014.

- The Aspen Center for Physics 2015 Winter Conference "Progress and Application of Modern Quantum Field Theory", February 16-21, 2015.
- The Aspen Center for Physics Summer program "Understanding Strongly Coupled Systems in High Energy and Condensed Matter Physics", May 24 -June 14, 2015.
- Simons Foundation Symposium "Quantum Entanglement", March 15-21, 2015.

Grand Challenge Questions

To focus our discussion, we formulate here a set of Grand Challenge Questions providing particularly enticing opportunities, though of course our list is far from complete. One thing these questions have in common is that people with a deep understanding of more than one area will be especially well positioned to lead future developments.

1) How do we characterize and study highly entangled systems?

Entanglement has emerged as an important notion for characterizing complex quantum systems, ranging from topological phases in condensed matter to quantum gravity and black holes.

Some of the most exciting developments in condensed matter theoretical physics in recent years have centered on entanglement. It has become clear that to understand many of the most interesting strongly correlated systems one must understand their entanglement. Measures of entanglement, such as the von Neumann entropy, provide key insights: for example, entanglement entropy can be used to distinguish topological phases, such as quantum spin liquids and quantum Hall states, which cannot be distinguished by ordinary order parameters. It has also given new insights into the nature of quantum phase transitions by unveiling the existence of new scaling laws associated with non-local correlations encoded in the entanglement. In the process it has become a powerful tool to study these strongly coupled systems. On a different front, entanglement has also been useful in discussing many-body localization and other inherently complex quantum systems. In continuum quantum field theory the study of the entanglement properties of the vacuum has led to new results such as the F-theorem in 2+1 dimensions, which provides a quantity, the entanglement entropy of a circle, that decreases under the renormalization group flow. In the study of quantum gravity, the entanglement entropy is computed by a simple area formula which generalizes the black hole entropy formula. This suggests a close connection between entanglement and the geometry of spacetime. Entanglement also plays a prominent role in the study of renormalization at the level of the wavefunction and has led to the development of tensor networks, a set of numerical methods designed to efficiently compute and manipulate wavefunctions of many-body systems. A new community of physicists has formed with interests in both quantum lattice systems and in quantum information.

In general, the problem is to characterize the level of quantum complexity of the system. Entanglement has proven to be theoretically useful. However, we lack effective ways to measure it experimentally. So a question of common interest is to devise observables that are particularly useful at characterizing this quantum complexity, including the entanglement entropy, the entanglement spectrum, etc. The answer to this question will be helpful in understanding which phases can arise from local Hamiltonians and which states can be simulated efficiently by a quantum (or classical) computer. It might even be important for understanding the geometry of spacetime itself.

The behavior of entanglement during dynamical processes is also a problem of fundamental importance that has attracted the attention of both condensed matter and high-energy physicists. In 1+1 dimensions, the growth of entanglement entropy after a quench was found to be linear before saturation. In higher dimensions, the problem has been investigated using holographic techniques, but further study is necessary to ascertain the universality of these results.

2) How do we form a tensor network description for quantum field theories in more than 1+1 dimensions? Can we include chiral theories?

A tensor network can be viewed as a compressed representation of the wavefunction, with a tradeoff between accuracy and the amount of storage needed, controlled by a single parameter which is the range of values of the indices of the tensors. The type of network is carefully chosen to exploit the pattern of entanglement of the target state.

The prototypical tensor network is the density matrix renormalization group (DMRG), where each renormalization step truncates the system based on entanglement rather than energy. It is now understood as the optimal low entanglement approximation for gapped 1+1 dimensional quantum lattice systems. It is so efficient that it has almost completely supplanted quantum Monte Carlo, which was the previously used technique. Quantum Monte Carlo (QMC) is extensively used in lattice gauge theory and it is useful for many problems, but it suffers from a "sign problem", where the probability being sampled becomes negative. The sign problem occurs in doped fermion systems, such as the high temperature superconductors, and in frustrated magnetic systems; these two sets of systems are some of the most important in condensed matter. In high-energy theory it arises in finite density chromo-dynamics. For higher dimensional systems DMRG is much less efficient – a "dimensionality problem" replaces the sign problem. For 2+1 dimensional systems, including models of hightemperature superconductors, DMRG is still very useful, competing successfully with approximate QMC methods. In 3+1 dimensional systems we have no efficient method for systems with a sign problem.

In the last decade tensor networks adapted for higher dimensions and/or scale invariant theories have been developed. The two most important of these are projected entangled pair states (PEPS) and the multi-scale entanglement renormalization ansatz (MERA). These have shown promise in 2+1 dimensions, such as the t-J model of the high temperature superconducting cuprates. For tensor network methods to be useful for higher dimensional field theories, we need to understand better how to formulate them in a way that facilitates the algorithms.

Several questions remain: How do we put the theory on the lattice, respecting gauge invariance, with small lattice-spacing errors and with the minimum number of degrees of freedom? What is the most efficient tensor network algorithm? Are there restrictions on what types of theories can be efficiently represented on a tensor network, e.g. are chiral theories efficiently representable? How does one efficiently represent systems with a Fermi surface in higher dimensions? Can one construct an efficient enough tensor network algorithm in 3+1 dimensions?

Tensor networks are not only a numerical method. They can also be used as a theoretical tool to explore various system properties. For example, it is possible to construct networks that can be used to construct a unitary operator that produces the target state from a set of decoupled qubits. This could be useful for producing the state in a quantum simulator. Furthermore, studying the scaling of the number of needed qubits in terms of system size one can classify the corresponding systems. This connects the subject to quantum information theory.

A connection with high-energy theory is the realization that the geometry of the tensor network has several parallels to the actual geometry that is dual to gauge theories with a holographic dual. This parallel is being extended actively and it is likely that it will lead to new ways to think both about the renormalization group as well as about the emergence of the geometry of spacetime. For example, tensor networks make manifest the ER=EPR relationship in quantum gravity, which connects spacetime wormholes to entanglement.

3) What are the topological phases of matter?

Since the discovery of the fractional quantum Hall (FQH) effect, topological phases of matter have been studied intensively by condensed matter physicists. This is an arena that has nurtured intense interactions between condensed matter and high energy theorists. Experimental work on these states is at the cutting edge of technology. The theoretical work combines ideas from condensed matter, quantum field theory, string theory and mathematics. The FQH states have a finite energy gap in the bulk (hence are incompressible) and have a topologically-protected fractional Hall conductivity (in units of e^2/h), providing the most accurate determination of the fine structure constant α. The low energy regime is described by a topological field theory, the Chern-Simons gauge theory. This theory was originally studied in high energy physics in connection to the parity anomaly in odd-spacetime dimensions and later as the quantum field theory of knots in 2+1 dimensions. The finite energy excitations are vortices that carry a fractional charge and exhibit fractional statistics. They are described by representations of the braid group coming from Chern-Simons theory.

Of particular interest are the so-called non-Abelian FQH states whose vortices are described by non-Abelian representations of the braid group. These vortices are being investigated as a possible physical platform for topological qubits for quantum computation. On the other hand, FQH fluids on a sample with a boundary exhibit chiral edge states whose properties are described by chiral conformal field theories, which originally were developed for string theory. The edge states play a key role in experiments since they are accessible to tunneling and noise experiments. An area of intense research is the study of quantities such as the Hall viscosity which embodies the universal coupling between the FQH fluid and the background geometry of the surface on which the two dimensional electron gas (2DEG) resides. These edge modes are also related to the entanglement properties of the ground state.

The recent discovery of topological materials, topological insulators and topological superconductors, has revolutionized the field of topological phases of matter by providing a large class of new topological systems, in one, two and three space dimensions. While most of the systems found to date are weakly interacting, strongly coupled systems are beginning to be investigated. The development of this broader field of research will depend crucially on the interaction between condensed matter and high energy theorists. The case of 3D topological insulators and superconductors, with their protected Weyl fermionic surface states, is a particularly fertile setting for this interaction, both for novel analytical approaches and for powerful numerical simulations.

The connection between some topological phases and chiral anomalies in field theory has been realized early on, but recently the subject has been revitalized by the discovery of a new class of anomalies which are not due to chiral fermions, but rather to topological terms in the action for the gauge fields. A new kind of global gravitational anomalies has also been identified. A complete classification of ’t Hooft anomalies, for both internal and geometric symmetries, seems within reach, at least for field theories. It appears to be closely connected to the problem of classifying short-range entangled (SRE) topological phases of matter. However, the precise connection is not clear. Partly this is due to a lack of a sufficiently precise definition of an SRE topological phase, and partly to a lack of understanding about what sort of phases of matter can be described by Euclidean field theory at long distances.

The problem of classifying topological phases with long-range entanglement in arbitrary spatial dimension is probably too difficult at present. But in low spatial dimensions it is amenable to algebraic treatment. Recently the focus has shifted to symmetry-enhanced topological phases. Novel examples of such phases in four spacetime dimensions are given by non-Abelian gauge theories. It has been noted recently that the Wilson-’t Hooft classification of such phases can be restated in terms of higher-form symmetries, i.e. symmetries which arise not from groups, but from more complicated algebraic objects (d-groups). It would be very interesting to find realizations of such phases in condensed matter systems, such as quantum materials.

4) Can we create a laboratory system with dynamical gauge fields, supersymmetric theories, the standard model, or emergent dynamical gravity?

In the study of quantum field theory the lattice is usually introduced to perform a numerical computation. A more exciting possibility is to be able to design a physical lattice, sometimes called a Hamiltonian lattice, such that the theory of interest emerges at long distances. This would provide a full quantum simulation of the theory. Theoretically one would like to understand how to construct lattice systems giving massless fermions, abelian and non-abelian gauge fields, chiral interactions, supersymmetry, etc. There are condensed matter systems that display some of these elements individually, but getting them all together is a big challenge. Finding systems with emergent gravity is also interesting. Here the most promising route would be to find a system with a gravity dual. Typically this would require a large N system, where N is the number of fields. However, it should be possible to find cases where a relatively small N, which can be experimentally realized, could be large enough to display some of the features we expect in gravity.

Although supersymmetry is believed to be hard to find in condensed matter systems, there are hints that this may not be so. It has been known for some time that the states of the spectrum of the edge states of certain fractional quantum Hall states (e.g. the non-Abelian FQH state at filling fraction 5/2) are supersymmetric. There is also strong theoretical evidence that spacetime supersymmetry emerges in the low energy regime of boundary states of 3D topological superfluids. These two examples show that this problem deserves close attention. Likewise, it is also generally believed that, mainly due to the pervasive presence of lattice effects, it is hard to construct condensed matter analogs of gravity. Recent work on the general theory of the Hall viscosity, both in quantum Hall fluids and in topological insulators, has revealed that these topological fluids sense the geometry of the underlying substrate. More interesting are also recent findings that long distance nematic fluctuations in these systems act on the fermionic degrees of freedom in the same way as a fluctuating geometry.

5) What theories can be put on the lattice and which ones cannot? the Standard Model? If you allow extra dimensions, are the gauge fields of the Standard Model emergent from some more fundamental theory?

The lattice is a very powerful tool for addressing non-perturbative features of quantum field theory. For quantum chromodynamics (QCD) it has provided solid evidence for confinement as well as computations for matrix elements used in flavor physics and searches for deviations from the Standard Model.

Putting chiral gauge theories on the lattice remains challenging. One popular approach involves domain wall fermions, where chiral fermions arise for topological reasons on a domain wall in an otherwise gapped system. Condensed matter physicists have been studying topological insulators where massless fermions similarly arise on interphases between different materials. The study of these symmetry protected topological (SPT) states has led to a deeper understanding of gauge and gravitational anomalies. These developments could lead to constructions of (non-anomalous) chiral gauge theories on the lattice. These would be useful both for the Standard Model and for theories beyond the standard model. For example, one could numerically simulate baryogenesis in a variety of theories or one could study theories where the Higgs and some of the Standard Model fermions are emergent.

Fermions with chiral interactions are also important in supersymmetric theories. Numerically simulating these would be useful for testing conjectures in theoretical physics, such as weak/strong coupling dualities or the gauge/gravity duality. Recent proposals to simulate maximally supersymmetric theories led to interesting lattice models based on topological theories.

In condensed matter physics one often knows the lattice and wishes to derive a continuum model for long wavelengths and low energies. In high energy physics one starts from a quantum field theory which is then discretized on a lattice. In both cases lattice simulations are a powerful tool for discovery.

6) What is the fixed point theory of non-Fermi liquids?

A number of candidate fixed point theories of non-Fermi liquids have been found in the past few years, involving different analytic tools: patch constructions, 1/N expansions, novel methods of dimensional continuation, and holographic mappings to charged horizons. With the examples available, it becomes possible to address bigger and more general questions. Do the fixed-point theories have to satisfy constraints, such as inequalities on critical exponents? What is the entanglement structure of such fixed points: do they all violate the area law of entanglement entropy logarithmically? Do they have any emergent symmetries? How do they respond to external magnetic fields, and do they have any experimental signatures in quantum oscillations? What is the matrix large-N limit of such non-Fermi liquids, and does it have a stringy formulation? Are such fixed points generically unstable to superconductivity, and is there any route to computing the critical temperature? The list of questions is large and fascinating, and it is clear that even partial progress will have a tremendous impact on experimental and theoretical studies of quantum materials.

The importance of the problem of quantum critical metals in condensed matter physics is hard to overstate. Novel phases emerging from the interaction of a Fermi surface with a critical scalar or emergent gauge boson are thought to be central in the physics of heavy fermions, high Tc cuprates, spin liquids, and so forth. This problem also arises in the study of high density QCD, where the gauge bosons are the ordinary gluons. This problem has been attacked using large N_F (fermion flavors) techniques, but infrared divergences have prevented the approach to the low energy fixed point. It is also possible to consider large N_B (boson) techniques, or to promote the bosons to large N_B matrices. This problem is ripe for attack from both new theoretical and new numerical perspectives.

7) Can we understand the dynamics of matter without quasiparticles? Can we classify/understand finite density, compressible phases of matter, and their possible instabilities to symmetry breaking phases?

Many of the new “quantum materials”, including the copper-based high temperature superconductors, display metallic regimes often referred to as “strange metals”. These are metals which do not display any experimental signatures of the quasiparticle excitations that are the foundation of the theory of conventional metals. A complete understanding of such strange metals is of fundamental importance for both practical and conceptual reasons. It will only be possible to design quantum materials for which we can predict the critical temperature of superconductivity after we have an understanding of the strange metal state which appears after the loss of superconductivity with increasing temperature. Conceptually, strange metals constitute the most experimentally accessible examples of quantum matter with long-range quantum entanglement: hence any progress on the theory of strange metals will reverberate across many fields of physics via their common interest in quantum entanglement. New ideas are needed for a theory of such gapless states of matter with long-range quantum entanglement, and many proposals have emerged in recent years at the interface between condensed matter and particle theorists. Strongly coupled conformal field theories (in greater than 2 spacetime dimensions) are the simplest realizations of states without quasiparticle excitations, and these examples have lent much insight to the more general problem of strange metals. Gauge theories at finite density and temperature are the prototype theories of strange metals and are clearly challenging problems in both fields.

The list of well-understood phases of matter which are compressible at zero temperature is very short: solids, superfluids, and Fermi liquids. Fermi liquids are found in all common metals, and are the only state in this list that do not break a symmetry. However the ubiquity of strange-metal states which are clearly not Fermi liquids in many correlated electron compounds makes the problem of classification of compressible quantum phases quite urgent. Some of the most interesting recent proposals involve fermions at non-zero density coupled to emergent and deconfined gauge fields. Such a field theoretic formulation also exposes the connection between this condensed matter-motivated question and the problem of the plasma in high density and high temperature quark matter. In condensed matter, essentially all non-Fermi liquid compressible phases found so far have instabilities to symmetry breaking of some variety at low temperatures: superconductivity, spin and charge density waves, or some form of “intertwined” order. The quantum phase transitions associated with these instabilities involve both conventional symmetry breaking and the onset of confinement. A great deal remains to be understood on the nature of such transitions, and progress will surely require contributions from condensed matter and particle theorists.

8) What are the possible emergent symmetries of non-trivial fixed points? Can we use them to solve these problems? What is the fixed point theory of non-Fermi liquids?

Many interesting condensed matter systems are strongly coupled: their observables cannot be computed as a series expansion in a small parameter. Bootstrap techniques provide a way of calculating in such systems when the theory has an emergent conformal symmetry (CFT). The bootstrap philosophy is to constrain the structure of observables using symmetries and consistency conditions, with the hope that sufficiently powerful constraints might actually determine those observables, either exactly or approximately. This type of reasoning applies even in the absence of quasiparticles. In the 80’s, bootstrap techniques were spectacularly successful in elucidating two dimensional conformal theories. More recently, the bootstrap has lead to a successful numerical approach for theories in higher dimensions, for example the three dimensional critical Ising model. This is despite the fact that, contrary to the two dimensional case, the conformal group is finite dimensional in three or more dimensions. This recent progress was initially driven by a desire to explain the electroweak naturalness problem.

These considerations raise several questions:

- When does conformal symmetry emerge from a microscopic theory (so that current bootstrap techniques can be applied)?
- What other symmetry groups can emerge at long distances?
- Can bootstrap techniques be applied for more general quantum critical points, such as non-Fermi liquids?

9) What is the interplay between anomalies and transport?

Anomalies play extremely important roles in quantum field theories, acting as a bridge between short and long distances. Recently, considerable attention has been given to the role of anomalies in the collective dynamics of systems at finite temperature and density. It started with the discovery that the equations of hydrodynamics of a normal fluid are modified due to the effects of quantum anomalies. This was made almost accidentally by using the methods of gauge/gravity duality. Subsequently, these modified equations were derived without using holography, relying only on symmetries and the second law of thermodynamics, so that they now apply to any theory with anomalies.

The new terms in the hydrodynamic equations lead to two novel effects: the chiral magnetic effect, i.e., the appearance of an equilibrium current in a magnetic field; and the chiral vortical effect, i.e., the appearance of current when the fluid undergoes rotation. Recent experiments with Dirac and Weyl semimetals raise hope that these effects can be observed in a controlled experimental setting. In fact, a large negative magnetoresistence of a Dirac semimetal has been reported, which has been predicted to arise from quantum anomalies. There have been attempts to use the anomalous effects to explain pulsar kicks.

10) Are there fundamental quantum mechanical bounds on transport, dissipation, or other quantities?

There are few handles to analyze strongly interacting systems which are not describable in terms of quasiparticles. However, due to conservation laws it is always possible to define heat and charge currents, for example the electrical conductivity and viscosity. While it may be difficult to compute these quantities from first principles, a recent attractive idea is that such transport quantities may be subject to fundamental universal bounds, originating purely from the structure of quantum mechanics.

There is both theoretical and experimental evidence for such bounds. Theoretically, there is evidence from the gauge/gravity duality which relates certain strongly interacting field theories at finite temperature to black holes. First a bound on the viscosity to entropy ratio was suggested. More recently an argument for a bound on the quantum version of Lyapunov exponents was given. Experimentally, many strongly interacting “bad metals” have conductivities that behave in a very similar way, with a linear in temperature resistivity and an underlying universal timescale determined by $1/k_BT$. A possible explanation for this behavior is that they are saturating a conductivity bound.

Collaboration between fields seems crucial both for suggesting and for proving or disproving these bounds, since it is useful to have a large suite of systems to get inspired to make proposals and also to test these proposals.

11) How do we describe strongly interacting disordered systems?

The interplay of quenched disorder and quantum fluctuations presents fascinating challenges to theory. Because disorder is present at all length scales, disordered quantum critical points and phases are possible. These are described by scale invariant theories in which momentum is not conserved. Such a system is very difficult to describe using the conventional quantum field theoretic techniques. This is because, for a start, if the long wavelength description is to be translation invariant but not conserve momentum, it must be intrinsically dissipative. A tractable model of a disordered quantum critical system would likely offer insight into the mystery of bad metals that are able to conduct despite having extremely large resistivities.

It has recently been discovered that a holographic description of disordered fixed points is possible. Here the near horizon (low energy) geometry is described by an event horizon that is very rugged on all length scales, but whose thermodynamic properties are controlled by a disorder-averaged scale-invariant metric. These will likely provide uniquely tractable models of strongly interacting disordered quantum critical systems. A key problem in these inherently complex systems is that of "many-body localization".

Disorder can drive quantum phase transitions (QPT) from conducting to insulating phases. In most cases the nature of the phases and the universality class and the exponents describing the transition are still open questions. Also of interest are the dynamical response functions (conductivity, susceptibility) in the quantum critical regime in the absence of well-defined quasi-particles. One of the paradigmatic Hamiltonians is the Bose Hubbard model with site or hopping disorder. At integer fillings this model maps onto a Josephson junction array (JJA) with disorder in the charging or Josephson coupling term. While it is well known that the clean d-dimensional quantum JJA maps onto the D=d+1 dimensional anisotropic classical Wilson-Fisher renormalization group fixed point, the situation in the presence of disorder is still open. Does the dynamical exponent z equal 1 or is there breaking of Lorentz invariance in the presence of disorder? In the quantum to classical mapping the random disorder becomes correlated along the time dimension, hence its effect can be quite non-trivial and lead to novel phases that are not simple generalizations of classical phases. Is the insulating phase a Mott glass that is incompressible or a compressible Bose glass?

There has been some success of comparing quantum Monte Carlo and anti-de Sitter-conformal field theory (AdS-CFT) methods for the dynamical conductivity at the QPT for the clean problem. It will be important to continue this dialog in the presence of disorder. While there are some QMC results in the presence of disorder, similar results using gravity methods are yet to be developed. The situation is more complicated away from half filling because of a sign problem. There are several puzzles seen in the experiments on disordered superconductors in a magnetic field. There is evidence for pairs in the insulator and a positive magnetoresistance that can become as large as 10^{12} Ohms. The field of disorder-driven phase transitions is ripe for bringing together and consolidating a variety of theoretical methods from self-consistent mean-field to strong disorder RG methods, to quantum Monte Carlo and AdS-CFT to address different portions of the phase diagram.

12) Can we develop numerical algorithms to deal with finite density systems, frustrated models, etc.?

It is important to develop numerical methods that can deal with problems that have a "sign problem", for which the standard method, quantum Monte Carlo, fails. Nowadays, "solving the sign problem" is often interpreted as finding any broadly applicable, systematically improvable, and efficient quantum simulation method which can treat, say, doped fermion systems in 2+1 or 3+1 dimensions.

Attempts have been made to solve the QMC-specific sign problem since the 1980's. Two types of successful treatments have emerged: sign-free treatments for specific models, and useful approximate approaches. We now understand that one cannot go well beyond these types of solutions: a general solution to the sign problem would solve NP-hard problems, which is extremely unlikely. The useful approximate approaches generally take an approximate solution to the problem, typically a variational wavefunction, and use it to constrain the minus signs.

However, as these methods have been developed, we have also learned that some of the most interesting condensed matter systems, such as the doped fermion Hubbard model in 2+1 D, seem to have very complicated phase diagrams with many competing phases. To resolve this competition, it appears that relative energies must be resolved to about 10^{-4}, a very tough standard when essentially all the energy is "correlation energy". The competition is also very sensitive to biases, say from constraining wavefunctions. So an efficient method to treat a system like the Hubbard model would be real progress.

As discussed above, tensor networks offer one approach for dealing with the sign problem, but they have yet to be extended to 3+1 dimensions. In the context of lattice QCD one method involves using a complexified Langevin equation. The problem with this approach has historically been that this solution is not unique and there has been no way to guarantee convergence to the correct solution. Recently there has been substantial progress on this problem within the lattice QCD community using a so-called gauge cooling algorithm. In addition an independent approach has been investigated based on the Picard-Lefschetz theory, which involves a clever choice of integration contour where the phase of the integrand is constant. This is a rapidly developing field which potentially may offer new ways of simulating a variety of systems which suffer from sign problems.

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Email to Participants

Dear Colleagues:

Thank you very much for agreeing to participate in a roundtable discussion on 'Common Problems in Condensed Matter and High Energy Physics' to be held at DOE Germantown on Monday, February 2, 2015, chaired by Eduardo Fradkin and Juan Maldacena.

The goal of the Roundtable is to bring together physicists with intersecting interests in High Energy Physics (HEP) and Condensed Matter especially recent developments in quantum field theory and strongly interacting systems to identify opportunities for possible areas of collaboration.

HEP and Basic Energy Sciences (BES) have been discussing Connections between the two Programs that can accelerate science by drawing on unique expertise in their communities and avoiding duplication in developing tools for discovery science valuable to both communities. Identified broad areas include research into quantum field theory and condensed matter and atomic systems (such as strongly interacting systems) that substantiate particle physics models.

The Associate Directors in the Office of Science, James Siegrist for HEP and Harriet Kung for BES have approved this meeting and have asked us to work with the group on planning.

We expect the Round Table Discussions to result in a short report (10-15 pages) describing the findings. These might include novel techniques in condensed matter and high energy physics with an emphasis on areas where the two fields may fruitfully interact. The report should identify major unsolved problems and opportunities to advance science – in particular areas of theory and computation.

This is also to confirm that DOE will be offering you travel support provided you are not a Federal employee and our DOE Contractor ORISE/ORAU will contact you for travel and logistics details.

We will be sending more information including tentative agenda and other details soon. Meantime, please let us know if you are a US Citizen as we have to process additional forms for non US Citizens.

Sincerely

Lali Chatterjee and Jim Davenport

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