Expert Panel Report Assessing the Emergent Phenomena in Quantum Systems Initiative

February 20, 2018

Executive summary

The panel met on January 18-19, 2018, to evaluate the scientific achievements of the EPiQS Initiative, which is approaching the end of its initial funding period (2013-2019), and to assess prospects for future progress in the research field of quantum materials. Driven by a plethora of new ideas, methods, and materials, research on quantum materials has recently gone through a period of worldwide expansion, with substantial investments in China (at the Chinese Academy of Sciences and several leading universities), Germany (especially at the Max Planck Institutes), and Japan (with a large new institute at RIKEN). Following the demise of fundamental research at industrial laboratories such as Bell Labs and IBM, the US had fallen behind in quantum materials research, particularly in the synthesis of new materials. In a remarkably short period of time, EPiQS has begun to reverse this trend and has already made a unique and highly visible impact on the field.

EPiQS investigators have driven many major developments at the frontier of the field. In particular, they showed that the topological properties of electron wavefunctions can generate metallic states with highly unusual optical and transport properties at the surface of some insulators. They also discovered novel electronic ordering phenomena in metal-oxide multilayers with atomically sharp interfaces, and in genuinely two-dimensional crystals synthesized by separating single atomic layers from complex materials. And they used coherent light fields to obtain an unprecedented degree of control over correlated many-electron systems in quantum materials. The panel strongly endorses the strategy of carefully selecting top experimental and synthesis investigators based on their past record of accomplishment and the strength and originality of their proposals, and of providing generous, unrestricted funding to pursue their most creative ideas. At the same time, the Theory Centers have created an intellectually vibrant environment and have energized the field through novel concepts and ideas, often in synergy with parallel developments in high-energy and gravitational physics.

Based on the resounding success of the program, the panel strongly recommends continuation of the EPiQS initiative. Many new research opportunities will arise from a highly diverse set of new materials that can now be created from precisely stacked atomic monolayers, and from devices that are structured at length scales comparable to those characterizing electronic wavefunctions in quantum materials. Novel experimental methods developed within the EPiQS program, such as unique quantum-optical techniques and spectroscopies with unmatched spatial and time resolution, will yield fresh insights into strongly interacting electron systems. Emerging ideas that will motivate and guide materials synthesis and experimentation include converging concepts of topology and many-electron physics, as well as new perspectives on quantum entanglement in solids. The panel also sees a multitude of innovative concepts for applications of quantum materials in spin-based electronics, photovoltaics, quantum sensors, etc. As the quantum materials community in general – and the EPiQS initiative specifically – has been very successful at nurturing new talent, there is no shortage of bright young scientists who will drive these ideas forward.

1. Scientific achievements

Topological effects in solids. In the last decade, the concept of topological materials has revolutionized solid-state research by bringing concepts from high energy physics to condensed matter. EPiQS investigators have been at the forefront of this revolution. This research trend has been in part ignited by the prediction and subsequent measurement of three-dimensional (3D) topological insulators and the metallic state of electrons with Dirac dispersion that appears on their surface. Efforts to elucidate the physics of their peculiar surface states are continuing (**Seongshik Oh**). New approaches to materials discovery, based on theoretical insights and the database of known materials led to the discoveries of a number of new topological insulators and semimetals, including the "Weyl semimetals" with Weyl quasiparticle modes in the bulk in 2015 (**Zahid Hasan**). Shortly thereafter, the unique surface metal which Weyl semiconductors exhibit, the so-called Fermi arc surface states, were observed in crystals that were microstructured using the focused ion beam (FIB) technique (**James Analytis**). Other exotic properties of Weyl semimetals resulting from its chiral anomaly (e.g. anomalous negative magnetoresistance) have also been extensively investigated (**N.P. Ong**, **Bob Cava**). The interaction between light and matter was found to exhibit interesting topological effects. New photogalvanic and non-linear optical effects were discovered in Weyl semimetals (**Joel Moore**, **Joe Orenstein**). Additional classes of topological materials protected by space-group symmetries were also discovered, such as topological crystalline insulators in anti-perovskites (**Liang Fu**), and higher-order topological materials supporting corner states were proposed (**Taylor Hughes**). The discovery of topological quantum materials also motivated the search for topological superconductors. In particular, reports of Majorana zero modes in atomic-width iron chains placed on a conventional superconductor, lead, have excited the field (**Ali Yazdani**).

Metal-oxide films and electronics. In early 2000s, experiments on an artificial quantum material composed of two metal-oxide electrical insulators revealed an interfacial metallic state which even becomes superconducting at low temperatures (**Harold Hwang**). This discovery led to the realization that novel properties can arise at interfaces of oxide quantum materials. This field has grown into a huge worldwide activity in which US scientists funded by the EPiQS program are playing a leadership role. EPiQS has provided essential funding for the synthesis of these new classes of materials using atom-by-atom deposition techniques such as molecular beam epitaxy, as well as theoretical efforts to understand the basic physics involved in these observations and the development of characterization methods to study the atomic and electronic structure and properties of “buried” interfaces. Within the EPiQS program, new ferroelectric materials with unique properties and great potential for applications in electronic devices have been discovered (**R. Ramesh**), and free-standing metal-oxide layers generated by a novel methodology are opening up new perspectives for research on two-dimensional solids (**Harold Hwang**). EPiQS also provides funding for new instrumentation that combines modern growth facilities with state-of-the-art electronic structure probes such as photoelectron spectroscopy, scanning tunneling microscopy, and electron energy-loss spectroscopy. The program involves world-leading experts in the various aspects of this research in several laboratories (Cornell, Illinois). These instruments are mostly still under development. To realize prospects for electronic properties by design, strong interaction between theory, materials synthesis, and characterization expertise is required.

2D materials. The possibility to produce atomically thin crystals of many different materials by exfoliating bulk crystals of layered van der Waals compounds is one of the major developments of the last five years in the field of quantum materials. These atomically thin crystals –or “2D materials”– are of outstanding electronic quality and possess unique properties that are drastically different from those of the bulk compounds from which they originate. At the start of the EPiQS initiative, research focused on a handful of 2D materials, such as graphene, MoS_2, and hBN; only a few breakthrough experiments had been reported that had started to show the possibility to manipulate atomically thin layers. Some of the EPiQS grantees are among the pioneers who had contributed to establish the state of the field. For instance, the discovery of graphene/hBN heterostructures and of the techniques to assemble this system are due to **Philip Kim**, and the identification of MoS_2 monolayers as direct band gap semiconductors is a discovery of **Tony Heinz**.

Over the last few years progress has accelerated further. Major breakthroughs are drastic improvements in the quality of the fabricated devices that have enabled the observation of new physical phenomena, the realization of new types of van der Waals heterostructures obtained by stacking different 2D materials, and the exploration of atomically thin crystals of new compounds. More specifically, new techniques have been found to assemble graphene devices encapsulated in hBN with enormous increase in mobility values and unprecedented electronic quality: a new generation of hBN-encapsulated devices has enabled the observation of new even-denominator fractional quantum Hall states (Andrea Young[1], Cory Dean) and of transport in the electron hydrodynamical regime (**Philip Kim**, **Subir Sachdev**, **Leonid Levitov**). Heterostructures of different semiconducting transition metal dichalcogenides have started to be understood (**Tony Heinz**): they offer the possibility to realize new types of excitons, which may be conducive to room-temperature excitonic condensation under appropriate conditions (Leonid Butov). The ability to protect air-sensitive 2D materials by encapsulation is enabling the investigation of an immense new variety of 2D materials, such as monolayers of superconducting $NbSe_2$ (Kin Fai Mak), of WTe_2 which was discovered to be a 2D topological insulator with a relatively large 10 meV band gap (David Cobden, Xiaodong Xu, **Liang Fu**), and of magnetic 2D crystals such as CrI_3 (Xiaodong Xu, **Pablo Jarillo-Herrero**). It should be emphasized how many of these breakthroughs, which are opening several new research directions, have been established by a new generation of very young scientists whose portfolio of achievements is already more than impressive at a very early career stage (Kin Fai Mak, Andrea Young, Cory Dean). In parallel to this already published work, new (but yet-unpublished) exploratory research by EPiQS grantees is ongoing, which has very high-potential for the future. The work by **Philip Kim** on atomically thin layers exfoliated from cuprate superconductors is a representative example.

Spin liquids and complex magnets. Quantum many-body entangled states of electron spins are expected in magnetic materials with spin frustration. Examples are materials having two-dimensional (2D) triangular, kagome, and honeycomb lattices, and the 3D pyrochlore lattice. Instead of forming spin-liquid states, most of these frustrated magnets exhibit long-range magnetic order, or a spin solid state, at low temperatures. In search of quantum spin-liquid and spin-ice states, pyrochlore titanates and iridates have attracted much interest. As a smoking gun effect, the thermal Hall effect characterizing a quantum spin-ice state has been revealed in a pyrochlore titanate (**N.P. Ong**). Another prominent class of systems is honeycomb-lattice compounds such as A_2IrO_3 (A = Li and Na) and α-$RuCl_3$, for which the Kitaev model is expected to be applicable. A Kitaev quantum spin-liquid state would host Majorana zero modes. α-$RuCl_3$ is particularly promising to realize such a state. Neutron scattering from single crystals of exceptionally high quality revealed a magnetic excitation continuum suggesting a chiral spin-liquid state with fractionalized quasiparticles in high magnetic fields (**David Mandrus**). Further experiments with time-domain THz spectroscopy set an upper limit on the spectral weight of such a continuum (**Joe Orenstein**, **David Mandrus**). These results are promoting worldwide efforts to demonstrate Majorana particles in quantum magnets. Concerning other magnetic materials with novel properties, it was shown that

[1] We use regular font for names of researchers outside of the EPiQS program and bold font for EPiQS researchers.

half-Heusler antiferromagnets exhibit a large anomalous Hall effect ascribable to the Berry phase (**Joseph Checkelsky**).

High-temperature superconductivity. EPiQS has also given new impetus to an enduring grand challenge in quantum materials research – the origin of high temperature superconductivity in layered cuprates, where a quantum-disordered state emerges as charge carriers disrupt long-range antiferromagnetic order. Funding for research in this field has been difficult to obtain from government-funded programs, which are often driven by short-term trends. New results made possible by EPiQS funding include scanning tunneling spectroscopy evidence of the “pair density wave”, an unusual spatially modulated superconducting state (**Seamus Davis**), manifestations of quantum criticality in transport experiments (**Louis Taillefer**), as well as magnetization data that indicate the persistence of superconducting correlations to unexpectedly high magnetic fields in underdoped cuprates (**N.P. Ong**).

Driven quantum materials. The field of non-equilibrium emergent phenomena is of great current interest. The possibility of steering matter coherently and achieving functional properties not possible at equilibrium is a very attractive target. Progress in this area has been highly dependent on the development of new instrumentation, explaining a sudden explosion of activity in the past decade. For example, the development of x-ray free electron lasers like the Stanford LCLS has made studies of ultrafast phenomena in quantum materials quantitative, as one is no longer bound to extrapolating highly complex dynamics from indirect measurement of the dielectric constant at visible frequencies. Nowadays, it is possible to measure the crystallographic arrangements of a solid along a dynamical pathway, or the rearrangement of spin and electronic orders with resonant soft x-ray scattering at femtosecond resolution. Many other techniques are becoming important, including XUV radiation through high-order laser harmonics and new types of nonlinear THz techniques. Note that the costs involved in non-equilibrium condensed matter research have sometimes limited progress, except for very few well-funded individuals. In many cases, user facilities have carried the banner of innovation, whilst many creative scientists at US Universities have struggled to keep up.

Nuh Gedik’s program is a good example of non-equilibrium science in quantum materials. In the case of Gedik’s award, EPIQS resources have been employed to optimize a wide variety of instruments, ranging from dynamical microscopy to electron diffraction and time resolved photo-emission. A highlight of this program has been the measurement of Weyl fermion chirality by detecting photo-currents, which is an important advance in this area. **Joe Orenstein** has used EPIQS funding to explore the nonlinear optical manifestation of Berry curvature in Weyl semimetals. Especially, he has discovered that in the case of TaAs the second harmonic is very large, which may enable various applications in quantum optics. Current work is aimed at extending these measurements to THz frequencies. The two examples above are of strong scientists who are not necessarily only focusing on instrumentation as much as on their application to important problems in non-equilibrium quantum materials research.

In a newer instrument grant, **Alessandra Lanzara** has been supported to develop new types of angle-resolved photoemission spectroscopy (ARPES) techniques. The equipment grant to ARPES specialist **Andrea Damascelli** and ultrafast-optics specialist **David Jones** (UBC) is also expected to produce advances in time-resolves ARPES. Funding collaborations like this may help in alleviating the need for experts in both technology and science. **Margaret Murnane**, a pioneer in laser techniques, has developed interesting sources in the XUV. She discusses various applications of these sources, from ultrafast measurements of electron thermalization at short timescales to measurements of materials at nanometer length scales by coherent diffraction.

New theoretical concepts. The results from the theory component of the program were highly impressive, and clearly dominating the research landscape internationally. In addition to discoveries made by EPiQS theorists mentioned elsewhere in this section, the Theory Center postdocs have been engaged in a variety of cutting edge activities. An emerging theory focus was many-body localization. When considering the effect of interactions on quantum systems localized by disorder, it became clear that a finite strength of interaction is necessary to delocalize the system, contrary to expectations. Several investigators of the EPiQS program contributed heavily to the understanding of this new class of quantum dynamical phase transition. New transport information on the delocalized ergodic phase of disordered interacting systems was obtained using state-of-the-art computing (UIUC); and several universal properties of the ergodicity loss transition in the many-body localized phase were elucidated (Berkeley, UCSB).

The Theory Centers were key players in the development of holographic methods to approach strongly correlated metals. In a highly impressive paper, the Sachdev-Ye-Kitaev model of strongly interacting Majorana particles was used to explain the universal properties of strange metals (**Leon Balents**, **Subir Sachdev**). Moreover, holography – the conjectured correspondence between gravity theory and correlated quantum systems at one dimension less – was used to explain universal dissipation rates in bad metals (**Sean Hartnoll**, Stanford) and entanglement dynamics (**Shinsei Ryu**, **Eduardo Fradkin**, **Eugene Demler**). New dualities between fermions and bosons were also explored, following the discovery of new topological correlated quantum-Hall states (**Cenke Xu**, UCSB; **Todadri Senthil,** MIT).

New measurement techniques. New instruments and methods can open new windows on quantum correlations in solids and often drive major experimental advances in this field of research. The EPiQS program has funded the development of a range of innovative instruments including scanning tunneling spectroscopy at mK temperatures and high magnetic fields (**Seamus Davis**, **Ali Yazdani**), a capability that has already provided fresh insights into the physics of heavy-fermion formation as well as quasi-particle interference in transition-metal oxides and promises further important advances such as imaging of quantum-Hall states. Microwave impedance imaging (**Z.X. Shen**), scanning near-field optical microscopy (**Dimitri Basov**), and highly sensitive scanning magnetometry with NV centers in diamond (**Amir Yacoby**) have revealed domains of electronically ordered states in quantum materials as well as novel behavior at domain walls and interfaces. A new high-resolution electron energy-loss spectroscopy instrument (**Peter Abbamonte**) has been developed and has already generated interesting data on high-temperature superconductors and exciton condensation in dichalcogenides.

Patterning of quantum materials into nanoscale device architectures is an additional powerful research strategy. Within EPiQS, **Jason Petta**'s group has used this approach very successfully for circuit quantum electrodynamics experiments on SiGe heterostructures and single-electron devices. The field of non-equilibrium phenomena is also enjoying a breathtaking improvement of experimental techniques, driven not only by this community, but also by chemists and atomic physicists. In this class of instruments we mention novel neutron scattering instrumentation designed to drive and probe quantum phase transitions with GHz electromagnetic fields (**Collin Broholm**), and new XUV and soft x-ray sources that can be applied to both coherent imaging and extreme timescale dynamics (**Margaret Murnane**). Finally, EPiQS is supporting a new generation of time resolved ARPES techniques, developed by awards to **Alessandra Lanzara** (UC Berkeley) and to **Andrea Damascelli** and **David Jones** (UBC). These instruments probing non-equilibrium phenomena are still under development.

Cold atoms. The EPiQS program has funded one cold-atom experimentalist, **Marcus Greiner,** joint with theorist **Eugene Demler** and Moore Theory Postdocs at Harvard. Their work was highly successful. In a ground-breaking experiment they measured the (Renyi) entanglement entropy in a chain of interacting atoms hopping on a lattice. Building on their success, they managed to show that the thermodynamic entropy produced in a quenched lattice atomic chain is attributable to the quantum entanglement entropy. In addition, they stabilized an antiferromagnetic state, which had previously been out of reach of cold atom experimentalists. The grant allowed Demler and Greiner to develop new quantum control principles enabling these and potentially many other experiments.

Collaborations. EPIQS has catalyzed numerous scientifically fruitful collaborations, both within the EPiQS community and with outside investigators. The most extensive collaborations were centered on high-quality materials prepared by EPiQS Synthesis Investigators and shared with EPiQS Experimental Investigators and other experimental groups worldwide. These materials include $RuCl_3$ (**David Mandrus**), dichalcogenides (**Mandrus**), topological materials (**Bob Cava, Seongshik Oh**), iron pnictides and chalcogenides (**Paul Canfield, Ian Fisher, Johnpierre Paglione**), SmB_6 (**Paglione**), heavy-fermion materials (**Emilia Morosan**), and metal-oxide thin films (**Jak Chakhalian**). The GaAs MBE program at Princeton University operated by **Loren Pfeiffer** and **Mansour Shayegan** is a special case, because the facility has been systematically optimized for many years and has yielded (and is continuing to yield) heterostructures with record-setting mobility. These samples have been the basis for many highly influential experiments, both inside and outside the EPiQS program. Funding to sustain this unique resource for quantum materials research would have been very difficult to obtain without EPiQS.

In addition to the Pfeiffer/Shayegan project, EPiQS has also funded another highly successful collaborative project at Cornell University, where **Darrell Schlom** and **Kyle Shen** have built an instrument that combines their complementary expertise in oxide molecular beam epitaxy and angle-resolved photoemission spectroscopy. An EPiQS grant to them, together with **Seamus Davis**, allows them to build a new instrument that also includes a scanning tunneling microscope. The in-situ characterization capability of this instrument will enable experiments on a variety of epitaxially stabilized metal-oxide compounds that are unstable in bulk form. Likewise, the Equipment Development Grant to **Vidya Madhavan** and her colleagues at UIUC combines MBE, ARPES, scanning tunneling microscopy, and momentum-resolved electron energy-loss spectroscopy to develop a novel integrated probe system for multiple excitations in quantum materials. The Damascelli/Jones project at UBC described above as well as the Rapid-Response Grant to **R. Ramesh** and **Lane Martin** in Berkeley also combine complementary expertise of two investigators for the development of a novel instrument. Whereas local scientific collaborations can also be seeded by government programs such as MRSEC, successful collaborations that combine complementary expertise across different locations are much rarer. Within EPiQS, particularly visible collaborations include joint work of theorists **Leon Balents** (UCSB), **Steve Kivelson** (Stanford) and **Eduardo Fradkin** (Illinois) with experimental groups nationwide. EPiQS also seeded a collaboration between **Aharon Kapitulnik** (Stanford) and **Amir Yacoby** (Harvard) on highly sensitive transport measurements in quantum materials, which has now attracted additional support from government agencies.

2. Funding strategy

The committee is extremely impressed by the lucidity of the Moore Foundation's strategy and by the very clear vision the Foundation has formed of the field of quantum materials. The deep knowledge of quantum materials research and the community of researchers the Moore Foundation staff have acquired are unique among funding organizations worldwide. This knowledge is kept at the cutting edge in part through the EPiQS Investigator Symposia, which provide invaluable opportunities for scientific exchange both among scientists and between scientists and Foundation staff.

The Foundation's approach of identifying scientists at the top their research field based on a research proposal and their 8-10 year record, and giving them ample freedom to pursue their most creative ideas is essentially sound. The committee agrees that the record of accomplishment in this time frame is the most potent predictor of success in an EPiQS funding period. The resounding success described under part 1 above confirms this view. The generous, flexible, long-term funding provided by EPiQS for established researchers selected in this way fills a glaring gap in the US system. Such funding allows researchers to address serious technical challenges without quick publications, and to pursue research on enduring grand challenges that have fallen out of fashion with government funding agencies. Many flexible ad-personam grants (Packard Foundation, PECASE, DOE Early Career) are available for young investigators. However, the panel recognizes (both from personal experience and from conversations with US colleagues) that such funding dries out quickly for senior researchers, sometimes resulting in dramatic loss of productivity of some of the most creative scientists.

The Foundation has also provided support to small groups of investigators who are using their complementary expertise to build or upgrade a complex instrument (Schlom/Shen/Davis, Pfeiffer/Shayegan, Damascelli/Jones). This approach works well in these special cases. The committee discourages a more general multi-investigator funding strategy analogous to other programs (MRSEC, MURI, EFRC etc.), because it often results in "forced" collaboration and detracts from the unique and highly successful single-investigator strategy which has been the mainstay of EPiQS. As the amount of funding Moore investigators receive from other sources varies strongly, the Foundation might want to consider awards of different sizes and/or separate competitions according to career stage in order to maximize the scientific return of their investment.

By virtue of its high selectivity, the EPiQS program has quickly built up a sterling reputation, and has significantly raised the stature of quantum materials research at academic institutions, particularly in the US. Anecdotal evidence indicates that EPiQS funding has already been influential in tenure and hiring decisions in physics departments. These developments could in principle be quantitatively assessed by screening advertisements of faculty positions in condensed matter physics and materials synthesis, as well as documentation reported by the American Physical Society. Tracking the career paths of EPiQS-funded postdocs may be another relevant source of information. However, due to the short duration of the program, firm statistical evidence of the impact of EPiQS may turn out to be elusive at this stage.

Several investigators have successfully used their EPiQS support to leverage proposals to government agencies. In the longer term, the high profile of the EPiQS program may persuade these agencies to increase their support for quantum materials research as a whole. Close communication with these agencies is required to emphasize that EPiQS supports exceptionally high risk / high gain projects complementary to standard funding programs. The committee also commends the Foundation for supporting publications (such as the recent special edition of Nature Physics and Nature Materials) that explain the frontiers research on quantum materials to a wider audience of scientists, and encourages an expansion of the public outreach to lay audiences.

In the following, we address specific science aspects of the EPiQS funding strategy.

Materials synthesis. Well characterized, high quality materials are the fundamental basis for all of solid-state research. Yet funding for the systematic exploration of potential model compounds and the systematic optimization of the quality of extant quantum materials has been hard to obtain in US system, ever since the demise of fundamental research at large industrial labs such as Bell Laboratories and IBM. Reviving the US materials synthesis effort (after many years of fruitless lobbying funding agencies) and greatly increasing its international visibility will be widely seen as crucial accomplishments of EPiQS. The Moore Fellows in Material Synthesis program has been particularly effective, because it provides direct incentives for physics or chemistry departments to hire outstanding young faculty members who can then attract bright young students to materials synthesis. To ensure a lasting impact on the field, however, the support of materials synthesis has to be maintained in the longer term. Since different quantum materials often require different synthesis and crystal growth methods, it is important to support a group of experts with a variety of expertise. The committee therefore strongly recommends that the Synthesis Investigator and Materials Synthesis Fellows programs be maintained, with the same focus on high-quality materials and innovative synthesis methods.

New measurement techniques. Experimental advances in research on quantum materials rely to a large extent on the development of innovative instrumentation.

Designing, building, and testing a new instrument that pushes the state of the art often takes several years. Since the instrument does not yield scientific publications while it is under development, it is difficult to obtain funding for truly innovative instrumentation within mainstream funding schemes. By providing generous funding to outstanding experimentalists for the development of novel methods without asking for immediate payoff in terms of publications, EPiQS has laid the foundation for many new insights, some of which are already visible (section 1). Most of the impact of this investment will however only become apparent after several years, and would be greatly enhanced if EPiQS funding for the scientific exploitation of the most promising instruments were sustained in another program period.

Theory. The EPiQS program has made a remarkable impact on the quantum many-body theory landscape in the US and worldwide. In a short period of time, EPiQS has managed to greatly energize the field. It hastened a broad range of discoveries by creating centers of activity which were able to attract the very best postdocs, and created a highly collaborative and intellectually vibrant environment which also enabled them to promote their own research.

The unusual center-based funding structure requires a discussion of the merits and drawbacks of the approach. It is clear that the approach of funding group postdocs in high profile places is effective and produces a higher impact than individual grants. This is evident in the ability to attract top-notch postdocs, and in the significant number of direct collaborations between postdocs without PI participation. The environment in the Theory Centers is clearly conducive both for producing cutting edge research and for the education of the next generation of leaders in the field. The flexibility that the Center affords both the postdocs and the PIs is allowing theorists to concentrate on the most exciting problems, and to respond quickly to new ideas. A drawback of the funding structure is that it leaves out outstanding investigators in less central locations. Furthermore, by allowing a relatively small number of institutions to hire a larger set of the best postdocs on the market, invariably groups not funded by EPiQS might have decreased access to the pool of excellent postdocs. There is also a sense in the committee that more could be done to encourage collaboration and information exchange between theorists and experimentalists, which will help inspire new science, and also fulfill the material-centric spirit of the program.

In light of these arguments, we believe that the Theory Centers are an excellent funding instrument and should be maintained. To mitigate the drawbacks, we suggest opening up the funding competition for outstanding individual theory investigators, and using up to a quarter of the funding to support individual researchers. This will be instrumental for involving key quantum-materials theorists in the community. In addition, we recommend continuing and even increasing the number of workshops that bring theorists and experimentalists in the program together. Also, the program could support meetings focused on new experimental discoveries with a relatively small number of participants. Such meetings could entice the theorists in the program to engage directly with the wide range of experimental discoveries emerging in the program. Likewise, the Postdoc Symposium appears to have been a great success in fostering broad collaboration in the program and should be continued.

Computational ab-initio methods that aim at a realistic description of specific quantum materials can be highly valuable for the interpretation of experimental data (for instance in optical, x-ray and electron spectroscopy and resonant x-ray scattering), and can generate and/or validate ideas for the design of new materials. Enhanced interaction with experts in this area of theoretical research could thus enhance the impact and success of the experimental and materials synthesis effort in the EPiQS program. Since the Simons Foundation has recently initiated a large-scale funding program on computational many-body physics, a direct engagement of the Moore Foundation is not advisable. However, joint meetings of Moore and Simons investigators and/or add-on funding for collaboration could be an effective means of generating new science.

3. Evolution of the field and future opportunities

The committee has identified a number of areas in which we expect greatly accelerated progress in the next few years. Most of these areas involve closely coupled synthesis, experiment, and theory developments. The scientific growth areas discussed in the following are by no means exclusive. The great diversity of ideas, methods, and materials being pursued implies that new developments are often ignited by unforeseeable discoveries, so that it is very difficult to predict the “next big thing”.

Topology and correlated electrons. The fields of correlated matter and topological phases will increasingly converge. This will result in new classes of topological superconductors, magnetic materials with topological magnon excitations, and new classes of non-Abelian excitations in correlated magnets and quantum Hall states, possibly even in three dimensional materials. These developments are likely to occur with increased material control in van der Waals-cuprate heterostructures, Kitaev magnetic materials such as $RuCl_3$, 4d- and 5d-electron systems where the strengths of electronic Coulomb correlations and spin-orbit coupling are comparable, and high quality heterostructures. The direct observation of topological order in correlated metals and the development of direct probes of quantum entanglement will be grand challenges in this domain of research.

Nanostructured quantum materials. Building on the rapid development of layer-by-layer deposition methods for complex materials in the past decade, we expect a steadily growing impact of nanostructured quantum materials both in fundamental and in application-oriented research. Artificial superlattices, quantum dots, field-effect devices, and micromachined crystals will open up new perspectives for the systematic investigation and control of electron systems in tailored geometries. New insights are also expected from in-situ imaging and spectroscopy of device structures. High-resolution electron microscopy is capable of accurately mapping out atomic positions at buried interfaces, and resonant x-ray reflectometry can expose their basic electronic structure in a non-destructive fashion, thus providing unique insights into structure-property relationships at the atomic scale. Coherent x-rays at 3^{rd}- and 4^{th}-generation synchrotron facilities will allow in-situ imaging of the magnetization and charge densities of nanoscopic magnetic devices in operando, and low-temperature scanning probes will make it possible to image edge channels in spintronic or quantum-Hall devices with atomic resolution.

Spintronics. The field of spintronics has developed enormously over the last decade. The use of the spin-Hall effect to inject and/or detect spin currents has become a standard tool and is now enabling spin transport to be investigated in insulators (magnonics). Controlling magnons at all levels will be an area in which new developments are expected. Goals include the realization of devices to amplify spin currents ("magnonic transistors"), of patterned meta-materials to control magnon propagation, or of new ways to tune the magnon density (possibly to achieve condensation). Other perspectives include the study of magnons in new (anti)ferromagnetic compounds or the use of quantum materials to achieve drastically enhanced spin Hall signals and spin-to-charge conversion efficiencies.

2D materials. Thanks to the substantial momentum gathered during the last couple of years, different research directions in the field of 2D materials are likely to lead to new discoveries already in the near future. The continuously increasing quality of graphene devices will certainly lead to discoveries of new transport phenomena and regimes. Fractional quantum-Hall states supporting non-Abelian excitations is one example, the investigation of the hydrodynamic flow of both electron and electron/hole plasmas is another one (with the latter possibly related to quantum criticality). Investigating the physics of 2D van der Waals heterostructures will be another main theme. Very little is understood about the microscopic processes that "mediate the interaction" between the different layers: what are the microscopic processes that determine the interfacial electronic properties starting from the properties of the constituent 2D materials? Answering this question will create an enormous potential to create new 2D electronic systems with properties created by design. The ability to investigate air-sensitive 2D materials is possibly one of the most important recent results. It allows the investigation of a huge variety of unexplored 2D materials in which the discovery of new phenomena is likely: magnetic 2D materials or even just atomically thin metals are illustrative examples. Electrostatic control by means of ionic liquid gating –which has been shown to allow accumulation of carrier densities close to one electron per atom– will provide a powerful experimental knob. An important aspect that certainly calls for more research is the development of new experimental techniques enabling the measurement of a much broader variety of physical properties of atomically thin 2D materials than what is possible now (for instance specific heat, magnetization, etc.)

Quantum materials in non-equilibrium. Non-equilibrium materials research is expected to evolve strongly in the future. Firstly, the study of cooperative phenomena in quantum materials away from equilibrium is thought to be conducive to new discoveries, with many new phenomena already being observed. Photo-induced superconductivity, steady state magnetic control in ruthenates through electrical currents, measurements of coherent Higgs-mode dynamics in superconductors, or the control of topological order with light fields are only a few examples of the new scientific frontiers. Secondly, as devices become faster and their size is reduced, non-equilibrium phenomena become progressively more important. Fast memories, optoelectronic and optomagnetic applications, and generally control of function at fast speed are expected. Consequently, non-equilibrium quantum materials research is to be considered a strategic area of development for technology as well as science. Thirdly, new opportunities for the discovery and characterization of new phenomena will emerge because of the rapid developments in laser technology, extending from new nonlinear THz techniques to ultrafast X-ray Free Electron Lasers and ultrafast electron sources. These advances are especially rapid because of the large community driving the field, including chemists, atomic physicists, and plasma physicists.

Quantum optics in quantum materials. We expect that new types of optical control and strong light-matter interactions will become possible, opening up new research directions. Techniques that have been traditionally in the realm of quantum optics, such as cooling or parametric amplification of different fluctuations, could be applied to control the emergent properties of matter. For example, one can use THz light fields to cool phase fluctuations in high temperature superconductors or change the spectrum of fluctuations of lattices near phase transitions, hence accelerating or decelerating them. Also, stronger light-matter coupling and new types of control may become possible if one embeds quantum materials in cavities, hence reshaping the electromagnetic continuum and with it the spectrum of optically active fluctuations. Finally, one can use photon exchange to mediate electronic order, as for example stimulating electron pairing with virtual photon excitations as opposed to phonons in a BCS state. In this area, the study of exciton and polariton condensates is expected to stimulate new science and applications.

Superconductivity. New experimental and theoretical methods will open up new approaches to the grand challenge of high-temperature superconductivity. Magnetic fields in excess of 100 T will become available and will steadily approach the intrinsic upper critical field of cuprate high-temperature superconductors, so that normal-state quantum transport properties can be probed. Resonant inelastic and elastic x-ray scatterings with high energy and momentum resolution are now at a stage that the momentum dependence of elementary excitations like magnons and phonons can be studied in atomically thin films and heterostructures, as well as microcrystals and device structures. Following recent developments, transmission electron spectro-microscopy is now capable of studying the low-energy elementary excitations with high energy and momentum resolution. This is a very promising method to study the dielectric matrix and the screening of short range electron-electron interactions in correlated electron systems including the superconducting cuprates. At the same time, molecular-beam epitaxy and exfoliation techniques will allow the synthesis of device structures where the charge carrier density can be adjusted continuously, and the interplay between superconductivity and competing electronic orders can be studied systematically on the atomic scale. Finally, controlled pumping of individual phonons or electronic modes will yield new insights into the mechanisms driving superconductivity and will allow the preparation of novel non-equilibrium states.

Theory. New numerical methods based on new insights into the structure of many-body wave functions and their dynamics are expected to emerge. While ab-initio methods like density functional theory (DFT) will continue to be instrumental in obtaining basic knowledge regarding the electronic structure and properties of systems in which electron correlation effects are less important, such as the topological insulators and conventional semiconductors and metals, new developments such as the combination of DFT and dynamic mean field theory are reaching a level capable of describing strongly correlated electron systems, including phase transitions and ground state correlation functions. Developing these methods to the level that large clusters can replace the presently mostly used single-impurity approaches is essential to properly describe the momentum dependent self-energy in correlated electron systems. In addition, the combination of DFT and exact diagonalization calculations in small clusters is essential for the interpretation of new high-resolution resonant x-ray scattering methods which provide unique information about the ground state and elementary excitations in solids. These theoretical methods are reaching a stage of development where they can make reliable predictions regarding potential properties of correlated-electron systems at interfaces and in heterostructures and superlattices. These new classes of materials are expected to play an important role in a wide range of electronic devices of the future. The theoretical methods are getting to the stage of providing the information needed for the future of materials by design. This trend will be strengthened by access to stronger computing, as well as by the increased introduction of machine learning techniques for materials discovery and Hamiltonian engineering for desired quantum effects.

Theoretical developments not directly or immediately related to experiment are harder to predict. Increasingly we find connections between effects in quantum materials and concepts in cosmology and quantum gravity. The dynamics of matter falling into black holes, for instance, is related through holography to the dynamics of quenched correlated matter. Innovative field theory based approaches to correlated matter are inspired by attempts at quantum gravity descriptions. The concept of quantum entanglement entropy is emerging as crucial both in understanding physics at an event horizon, and in strongly entangled quantum phases.

Applications. Quantum materials offer a large variety of perspectives for device applications. The combination of quantum materials with different electronic ground states in heterostructures and multilayers allows the design and bottom-up synthesis of magnetic semiconductors and thermoelectrics that are qualitatively different from today's materials. Topological phenomena in solids enable novel schemes for infrared detection and photovoltaics. Transition metal oxides with both high electronic and high ionic conductivity offer promise as ion sensors, and may ultimately develop into a novel platform for reconfigurable electronic circuits. Both quantum condensates and topological effects support dissipationless charge conduction, which are being utilized in a new generation of "superconducting spintronic" devices and may point out new routes to quantum computation. We also expect increasingly fruitful cooperation between the quantum materials and the quantum sensing and metrology communities. Electronic phase transitions can greatly increase the sensitivity of quantum sensors, and conversely, quantum sensors (such as magnetometers based on NV centers in diamond) can serve as powerful tools for solid state physics. In the long term, this synergy can engender novel applications such as a brain-machine interface based on the detection of neuromagnetic fields.

Cold atoms. The field of cold atomic gases and liquids, and atomic physics in general, lies at the fringe of the field of quantum materials. It can provide valuable insights into the many-body dynamics in quenched electronic systems, as well as produce new tools and concepts for many-body quantum control. In the future, we expect increasingly complex many-body phases and states to emerge in a variety of platforms such as optical lattices, Rydberg atoms, and ion traps. Nonetheless, because of the very different hardware platforms, the potential for fruitful collaboration between cold-atom and solid-state experimentalists is limited, and both communities do not tend to mingle. This divergence makes it difficult to recommend a full engagement of the EPiQS initiative in this field. Nonetheless, exceptional proposals should still be considered, particularly if the cold-atom investigator is clearly amenable to intellectual exchange with the quantum materials community.

In summary, research on quantum materials will continue to evolve rapidly on a diverse set of frontiers. Based on the internationally leading role EPiQS grantees have played in this field, the panel is firmly convinced that a new funding period of EPiQS would generate many important advances both in fundamental and in applications-oriented research. A continuation of this extremely successful program is therefore strongly recommended.

Name Index and Acronym Glossary

EPiQS researchers mentioned in the text and grant portfolio they are part of

Abbamonte, Peter (U. Illinois, Urbana-Champaign) – EPiQS Experimental Investigator
Analytis, James (UC Berkely) – EPiQS Moore Fellow in Materials Synthesis
Balents, Leon (UC Santa Barbara) – EPiQS Theory Center
Broholm, Collin (Johns Hopkins U.) – EPiQS Experimental Investigator
Cava, Robert (Princeton) – EPiQS Materials Synthesis Investigator
Chakhalian, Jak (Rutgers U.) – EPiQS Experimental Investigator
Checkelsky, Joseph (MIT) – EPiQS Moore Fellow in Materials Synthesis
Damascelli, Andrea (U. of British Columbia) – EPiQS Equipment Development grant
Davis, J.C. Seamus (Cornell) – EPiQS Experimental Investigator
Demler, Eugene (Harvard) – EPiQS Theory Center
Fisher, Ian (Stanford) – EPiQS Materials Synthesis Investigator
Fradkin, Eduardo (U. of Illinois, Urbana-Champaign) – EPiQS Theory Center
Fu, Liang (MIT) – EPiQS Theory Center
Gedik, Nuh (MIT) – EPiQS Experimental Investigator
Greiner, Markus (Harvard) – EPiQS Rapid Response grant
Hasan, Zahid (Princeton) – EPiQS Experimental Investigator
Heinz, Tony (Stanford) – EPiQS Experimental Investigator
Hughes, Taylor (U. of Illinois, Urbana-Champaign) – EPiQS Theory Center
Hwang, Harold (Stanford) – EPiQS Materials Synthesis Investigator
Jarillo-Herrero, Pablo (MIT) – EPiQS Experimental Investigator
Jones, David (U. British Columbia) – EPiQS Equipment Dev. grant (with A. Damascelli)
Kapitulnik, Aharon (Stanford) – EPiQS Experimental Investigator
Kim, Philip (Harvard) – EPiQS Experimental Investigator
Kivelson, Steven (Stanford) – EPiQS Theory Center
Lanzara, Alessandra (UC Berkeley) – EPiQS Rapid Response grant
Levitov, Leonid (MIT) – EPiQS Theory Center
Madhavan, Vidya (UIUC) – EPiQS Equipment Development grant
(with P. Abbamonte, T.-C. Chiang, and J. Eckstein)
Mandrus, David (U. of Tennessee) – EPiQS Materials Synthesis Investigator
Martin, Lane (UC Berkeley) – EPiQS Rapid Response grant (with R. Ramesh)
Moore, Joel (UC Berkeley) – EPiQS Theory Center
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Non-EPiQS researchers mentioned in the text

Butov, Leonid (University of California at San Diego)
Cobden, David (University of Washington)
Dean, Cory (Columbia University)
Hartnoll, Sean (Stanford)
Kitaev, Alexei (California Institute of Technology)
Mak, Kin-Fai (Cornell University)
Xu, Xiaodong (University of Washington)
Young, Andrea (University of California at Santa Barbara)

Acronyms and physics units

2D, 3D – two-dimensional, three-dimensional
ARPES – angle-resolved photoemission spectroscopy
BCS – Bardeen-Cooper-Schrieffer (referring to their theory of superconductivity)
DoD – the U.S. Department of Defense
DOE – the U.S. Department of Energy
EFRC – Energy Frontier Research Centers, funded by the DOE
GHz – gigahertz, 10^9 hertz
hBN – hexagonal boron nitride
LCLS – the Linac Coherent Light Source at the SLAC National Accelerator Laboratory
MBE – molecular beam epitaxy (method for synthesis of thin films of materials)
mK – millikelvin, one thousandth of a degree kelvin

MIT – Massachusetts Institute of Technology
MRSEC – materials research science and engineering center (funded by the NSF)
MURI – Multidisciplinary University Research Initiatives, sponsored by DoD
NSF – the U.S. National Science Foundation
NV – nitrogen-vacancy
PECASE – Presidential Early Career Awards for Scientists and Engineers (NSF)
PI – principal investigator
T – tesla, unit of magnetic flux density
THz – terahertz, 10^{12} hertz
UBC – University of British Columbia, Vancouver
UC – University of California
UCB – University of California at Berkeley
UCSB – University of California at Santa Barbara
UIUC – University of Illinois at Urbana-Champaign
UPenn – University of Pennsylvania
UT – University of Texas
XUV – extreme ultraviolet radiation, spanning wavelengths 10-124 nanometers