External Evaluation of the Emergent Phenomena in Quantum Systems Initiative Phase 2

Executive Summary

Prepared for

The Gordon and Betty Moore Foundation

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The Emergent Phenomena in Quantum Systems (EPiQS) Initiative, launched by the Gordon and Betty Moore Foundation in 2013, represents a significant investment in the capacity for synthesis, analysis, and experimentation in quantum materials. This initiative supports three critical aspects of research – quantum theory, materials synthesis, and experimental investigation – which together form the foundation for breakthroughs in understanding quantum materials.

Overview of the EPiQS Initiative

Phase 1 of the EPiQS Initiative, running from 2013 to mid-2018, comprised an investment of $90 million in grants supporting investigators, new instrumentation, and community-building activities focused on quantum materials. Following an evaluation of Phase 1, the foundation's Board of Trustees approved a Phase 2 investment of $95 million in August 2018, extending through 2024, with grants similar to those awarded in Phase 1. Due to disruptions caused by the COVID-19 pandemic, Phase 2 grants were extended through the end of 2025.

EPiQS funds are distributed across four strategies:

1. People (university-based theory centers and grants to individual experimental investigators).
2. Materials synthesis (grants to individual materials synthesis investigators and early-career Moore Fellows in Materials Synthesis).
3. Flexible funding (grants for equipment development and for exploring emerging topics).
4. Community building.

These four strategies were maintained across Phases 1 and 2. Phase 2 conducted new competitions across the strategies, and awardees funded under Phase 1 were allowed to compete for funding under Phase 2. All six theory centers funded in Phase 1 were supported in Phase 2, and two additional theory centers were established (at Caltech and Princeton University). Across the other research grant types, 25 of the 45 researchers funded in Phase 1 also received Phase 2 research awards.

Phase 2 grants and awardees have similarities with Phase 1 grants, such as the integration of materials synthesis, experimental work, and theoretical research, promoting a comprehensive approach to scientific discovery. The primary distinctions between Phase 1 and Phase 2 grants include an expanded framework for theory work and increased support for collaborative and community-building efforts.

Evaluation Questions, Process and Methods

The evaluation of the EPiQS Initiative constitutes a summative evaluation of Phase 2, focused on the impacts generated by these investments. The design of the evaluation is also meant to inform the transition to a hypothetical Phase 3. The evaluation activities pursued by the RTI team included analyzing the theory of change produced by the EPiQS Initiative's team, developing an extension on the existing theory of change with associated evaluation questions, designing indicators to constitute evidence of the answers to each question, and leveraging data from administrative records and third-party databases.

The evaluation framework developed for EPiQS Phase 2 defined the ultimate objective for this phase: “By 2024, knowledge of emergent electronic properties in quantum materials has been significantly advanced and new advances have been broadly adopted.” Goals set for Phase 2 focused on how EPiQS-funded research would contribute to knowledge about quantum phenomena in materials and posited that there would be evidence that the ideas and discoveries of EPiQS investigators would be adopted by others in the quantum materials field.

The evaluation framework for Phase 2 incorporated four components representing different components of potential impact – knowledge (including the objective for Phase 2 stated above), talent, infrastructure, and investment. The evaluation focused on questions relevant to each of the four components:

- **Evaluation question 1:** To what extent has the EPiQS Initiative enabled the discovery or development of new theories, new emergent phenomena, new experimental techniques, and new materials that significantly advance understanding of the nature and behavior of quantum materials?
- **Evaluation question 2:** In what ways, if any, has EPiQS contributed to the growth and development of new talent in the quantum materials research community?
- **Evaluation question 3:** To what extent has EPiQS enabled the development and use of new research infrastructures useful to quantum materials research?
- **Evaluation question 4:** To what extent has EPiQS leveraged other support for quantum materials research and incentivized or induced other organizations to make similar investments?

To assemble evidence relevant to each evaluation question, the evaluation framework formulated indicators from available data, including qualitative data. The indicators were designed to use data collected in the most efficient and feasible manner, synthesized across multiple data sources for cross-validation. The Phase 1 evaluation focused on the outcomes of the launch and initial program management of the EPiQS Initiative. This evaluation focuses more on the impact of the initiative based on Phase 2 activities.

However, the impact of Phase 2 of the initiative cannot be isolated from the impacts of Phase 1 since knowledge and investments have cumulative effects, so the evaluation findings reflect impacts of the entire initiative to date.

Evaluation Data Sources and Analytical Methods

The evaluation of the initiative utilized various data sources and analytical methods to assess its impact. The primary data sources included:

- **Expert panel:** Provided informed opinions on the importance and impact of the EPiQS Initiative based on grantee reports, publication records, and their expert opinions.
- **Bibliometric analysis:** Provided citation data from articles published in peer-reviewed literature to understand the influence and visibility of EPiQS-funded research.
- **Funding landscape analysis:** Examined trends in agency-level budgets for programs related to quantum materials.
- **Survey of EPiQS postdoctoral researchers:** Gathered insights into the experiences, challenges, and successes of postdoctoral researchers supported by EPiQS.
- **Grantee report analysis:** Reviewed progress reports submitted by EPiQS grantees to extract data on funding received from other sponsors, research personnel supported by EPiQS funding, and equipment expenditures.
- **Key informant interviews:** Conducted interviews with federal research program managers and research leaders from universities housing EPiQS grantees to provide detailed information on investments in quantum materials R&D.

These data sources were used to formulate indicators measuring separate aspects of the four domains. Collectively, the indicator analysis provides the evidence used to answer the evaluation questions. The indicators were synthesized across multiple data sources to allow cross-validation of findings and provide a comprehensive assessment of the impact of the EPiQS Initiative.

Outcomes for EPiQS Phase 2 by Indicator

Using the evaluation framework, the data gathered for this project generated indicators suggesting four types of impacts attributable to EPiQS Phase 2 – knowledge, talent, infrastructure, and investment.

- **Knowledge:** The EPiQS Initiative has significantly advanced the understanding of emergent phenomena in quantum materials. The scientific expert panel concluded that Phase 2 generated transformational discoveries, including new materials, novel phenomena, and findings that reshaped modes of thinking about quantum materials. Bibliometric analysis supports this, showing that EPiQS-funded articles are recognized by peers as notable contributions to the literature and largely accepted by top-tier journals.
- **Talent:** EPiQS has contributed to the growth and development of new talent in the quantum materials research community. Postdoctoral researchers supported by EPiQS have gained valuable experiences and skills, making them competitive candidates in the academic job market. Most of those individuals continue to engage in quantum materials research in subsequent positions. EPiQS funding has also helped investigators attract additional research grants, further expanding the pool of researchers.
- **Infrastructure:** EPiQS funding has enabled the development and acquisition of new laboratory instrumentation and equipment, crucial for advanced quantum materials research. Grantees have used EPiQS funds to purchase expensive equipment and develop novel instruments. Due to the constraints associated with federal grants, these investment and activities could not be undertaken but for the flexible structure of EPiQS awards.
- **Investment:** EPiQS has incentivized other organizations to invest in quantum materials research. Federal program managers and university research leaders confirm that EPiQS has bolstered internal arguments to increase agency investments in the field. EPiQS investigators have also used their research results to attract additional funding from federal sponsors. In part due to EPiQS, leading research universities are using institutional funds to fund additional faculty positions and facilities focused on quantum materials.

These outcomes demonstrate the significant impact of the EPiQS Initiative on advancing knowledge, developing talent, enhancing infrastructure, and attracting investment in quantum materials research.

Evaluation Findings by Evaluation Question

The report provides a detailed assessment of the impact and outcomes of the EPiQS Initiative during Phase 2 following the identified evaluation questions:

Evalution Question 1: Discovery and Development of Quantum Materials

The EPiQS Initiative has enabled significant advancements in the understanding of quantum materials. The scientific expert panel concluded that Phase 2 generated “truly transformational discoveries,” highlighting specific examples of groundbreaking work that challenged conventional thinking about quantum materials and providing platforms for entirely new streams of research. Contributions of EPiQS researchers in materials synthesis were pivotal in these discoveries. The panel also notes that this pioneering work has been followed up and extended by many other scientists, both within and outside the EPiQS community. Bibliometric analysis supports this, showing that EPiQS-funded articles are recognized by peer researchers as noteworthy advances and selected for publication in top-tier journals. Finally, EPiQS funding has reshaped the quantum materials community as the collaborative networks involving EPiQS investigators have become more distinct but also more connected.

Evaluation Question 2: Growth and Development of New Talent

EPiQS has contributed to the growth and development of new talent in the quantum materials research community. Postdoctoral researchers supported by EPiQS have gained valuable experiences and skills, making them competitive candidates in the academic job market. Their experiences working with EPiQS grantees also motivates them to pursue research careers in quantum materials. EPiQS funding has also helped investigators attract additional research grants, further expanding the pool of researchers. EPiQS has supported a vibrant and engaged cohort of early-career researchers dedicated to advancing the field of quantum materials. The Moore Fellows in Materials Synthesis awards have also helped encourage universities to create new positions for synthesis-focused faculty. The stability and flexibility of EPiQS funding have provided postdocs with job security and creative freedom, which are crucial for advancing high-level research.

Evaluation Question 3: Development and Use of Research Infrastructure

EPiQS funding has enabled the development and acquisition of new laboratory instrumentation and equipment, crucial for advanced quantum materials research. EPiQS provided grantees with the flexibility to obtain essential equipment without requiring lengthy proposals or a long waiting period before funding. For higher-cost items, EPiQS grants often supplemented federal funding, enabling researchers to leverage their resources to obtain sophisticated instruments. This unique approach effectively addressed the resource limitations of federal grants, fostering significant advancements in quantum materials research infrastructure that might otherwise have been unattainable. As a result, EPiQS has enabled the acquisition and development of

equipment and instruments that are fundamental to the ongoing progress in quantum materials research and would not have been obtained through other funding.

Evaluation Question 4: Incentivizing Investments in Quantum Materials Research

EPiQS has incentivized other organizations to invest in quantum materials research. The analysis indicates that EPiQS has played a unique role in supporting fundamental research to improve our understanding of emergent phenomena in quantum materials. Federal program managers and university research leaders confirm that the success of EPiQS in achieving breakthroughs and discoveries has bolstered internal arguments to increase agency investments in the field. EPiQS funding has demonstrated a "multiplier effect," where EPiQS Investigators produce discoveries that attract follow-on investments by federal sponsors.

Conclusions and Options for the Future

The evaluation supports the argument that the EPiQS Initiative has made a significant and distinctive contribution to advances in the critical field of quantum materials. This investment in fundamental academic work not only benefits the research community but also provides a foundation for future technology development. Research of this type provides ideas and insights that are needed to enable innovation in future decades.

The expert panel and research leaders interviewed in the evaluation offered ideas on new directions for future support from EPiQS. Two themes emerged from these discussions.

- First, EPiQS could be more intentional in funding interdisciplinary exchanges and collaborations to encourage “knowledge spillovers” that would benefit other fields and also feed new ideas into quantum materials research.
- Second, EPiQS could explore opportunities to accelerate the transfer of knowledge from academic basic research to more applied research.

By its nature, quantum technology will advance only with concurrent discoveries and insights provided by fundamental research in quantum materials. This is not to suggest that EPiQS should itself support more applied work but instead encourage efforts to tighten the feedback loop between basic academic science and downstream work.

With the EPiQS Initiative, the foundation has created a distinctive mechanism for supporting transformative research in quantum materials that cannot be replicated in federal agencies or corporate research. The work supported by EPiQS aids those other research sponsors in finding new and promising research to support. However, the foremost requirement for successful fundamental research is a reliable and sustained source of support over multiple years, providing the stability and security that enables

high-risk transformative research. Given current funding uncertainties, the rationale for supporting EPiQS is even more clear than at the launch of the initiative.