Statement by Collin Broholm to the Committee on Science, Space, and Technology Subcommittee on Energy of the US House of Representatives

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Seventy years ago when amplification of an electrical signal by a transistor was first demonstrated, no one could have imagined that the average person in 2016 would employ billions of transistors in their energy and information intensive lives. What will be the next materials based technological revolution and how can we ensure the United States once again leads the way?

Since its 1947 discovery of the transistor, Bell Laboratories (now part of Nokia), has shrunk and is no longer active in fundamental materials research. Other companies that used to support long-term basic research now focus on short-term development work. While the opportunities for ground breaking progress from new advanced materials have never been greater, the research required for transformational progress has a broad and fundamental character that no single company can sustain for the required period of time.

The specific example I would like to focus on is quantum materials. If we can master the quantum realm these materials have the potential for transformative technological impacts. Quantum mechanics has key effects in all materials but wave interference, coherence, and tunneling, which are integral to quantum uncertainty usually fade from view beyond the atomic scale. A stark counter example is offered by elemental helium that fails to solidify upon cooling. Instead an astounding superfluid state occurs where atoms form a coherent matter wave that flows without friction. The ghostly wave function that describes the atomic scale has become apparent at our length scale. We now find it may be possible to realize the counterintuitive properties of quantum mechanics in "quantum materials" and in the following I would like to provide a couple of examples.

Superconductivity is a low temperature property of many materials including aluminum wherein electrons form a macroscopic wave much as the atoms in superfluid helium. Because electrons carry charge, an electrical current can flow through a superconductor with zero resistance and no energy loss. Superconducting materials are already the basis for Magnetic Resonance Imaging and high voltage DC power transmission. However, presently available superconductors require cryogenic cooling. Fortunately we know of no fundamental reason that superconductivity like ferromagnetism should not be possible at much higher temperatures. A practical superconductor would have enormous technological consequences including the ability to generate, store, and transport electrical energy with no resistive losses. The impacts on the entire transportation sector would also be far reaching. There is much progress in the development and scientific understanding of materials where superconductivity is enhanced as magnetism collapses and reason to expect that a breakthrough is possible.

In **Topological materials** the geometry of the wave function that describes electrons gives rise to anomalous electrical transport that is insensitive to atomic scale disorder. In topological insulators for example all surfaces of a sample are electrically conducting even though the core is insulating and topological protection ensures high electron mobility. This is an appealing effect considering that surface transport must typically be engineered into electrical devices and is associated with significant resistive energy losses. In suitable topological insulators high mobility spin polarized surface conduction can appear spontaneously.

Finally we turn to **magnetism and information**. Digital archiving of events from those of individual families to those that define our times is based on magnetic information storage. While hard disk storage densities now exceed 1 TB per square inch, each such bit involves of order a million atoms. By using collective quasi-particles such as skyrmions within a quantum material to store information, it may be possible to dramatically reduce this number and get close to the information storage density of DNA. A new form of information processing called "quantum computing" has the potential to transform computing and more broadly decision making. One of the approaches now being pursued is to utilize collective particles within a quantum material to carry and process information. While this may be a reach today, it seems as feasible now as an integrated circuit with 10 billion transistors must have seemed in 1947.

Given the potential technological impacts, quantum materials are now receiving huge worldwide attention. Research centers for quantum materials are proliferating and I would argue that within the DOE as well, quantum materials should be an area of high priority. In the Basic Research Needs Report on quantum materials for energy relevant technology (see background material), we describe four priority research directions that would accelerate scientific progress in quantum materials and their deployment to improve energy efficiency and extend the information technology revolution.

I would like to add that as in much of modern development of advanced materials, world-class tools to probe quantum materials are absolutely essential. Here I am referring to the neutron sources at ORNL and the synchrotron and free electron laser based light sources. While these are excellent facilities that are having strong scientific impacts, all are in urgent need of upgrades to sustain international leadership.

As we continue to bend materials to satisfy our needs it is inevitable that we should reach the atomic scale. To lead the world in the development of the quantum materials a concerted investment in the underlying fundamental science is needed along with strong support for the operation and upgrades of the DOE operated national facilities for materials research that offer a rich atomic scale view of advanced materials.