Research Interests (2006-7)

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Overview: Condensed Matter Theory and Quantum Device Physics

As physics and engineering extend their reach to the control of single excitations of nature, we gain the ability to explore and even design the interaction of matter and energy in fundamentally new ways. One of the most interesting opportunities this presents is the controllable interaction between many quantum particles – such as electrons, photons, or plasmons – which is traditionally the realm of condensed matter physics. Another is the utilization of quantum phenomena like entanglement to invent new means of communication or computation, such as in a quantum computer or in less ambitious quantum information processing or pseudo-quantum (e.g. spin) devices.

Condensed matter, quantum many-body, and statistical physics are often integral to the design and interpretation of experiments in the nano- and meso-scale regimes. Over the last century powerful techniques have been developed in the solid state community to describe many particles in quantum systems, either atoms in a periodic matrix or in more fluid quantum systems, such as electron gases or superconductors. These must now be re-applied and often reinvented. My research has focused on the physics of new quantum devices, both ones I have designed and those imagined by others, to search for new physics, including decoherence effects, quantum phases, and computational potential. Practically, this has meant working closely with theorists, experimentalists, materials scientists, and engineers to design, build, investigate, and understand new physical systems.

Quantum phase transitions of light: Many-body quantum optics

Photons typically interact only weakly with each other. This makes them excellent information carriers but poor for computation, as fast 2-qubit gates (which generally means strong inter-particle interactions) are needed. But strong interactions between photons can be created artificially via a non-linear intermediary, namely, matter. The canonical example is photon blockade, where photons confined to a quantum optical cavity with an atom inside (cavity-QED) tend to repel each other and prevent further photons from entering the cavity. These cavity-atom-photon composite particles are often called polaritons or simply *dressed* atoms. My research extends this idea to many interacting cavity-polaritons and together with my collaborators we theoretically demonstrate that a quantum optical system comprised of a lattice of cavities, each containing a single two-level atom, can be viewed as being analogous to a Hubbard system, a standard model for the understanding of condensed matter quantum many-body behavior. Such a connection opens up the rich field of condensed matter physics to exploration by the quantum optics community and vice-versa. Because of the superb out-coupling potential of optical cavities, it is likely that new devices may be developed based on these approaches. A closely related system is the cold-atom optical lattice,

which has received saturating attention in the atomic, solid-state, and quantum information communities. Because our photon lattice has superior tenability and accessibility (each site is addressable) I believe this subfield of physics will rapidly grow to rival cold atom lattices. The photonic superlattice concept can be implemented in several architectures: microwave stripline cavities, Rb atoms in superconducting cavities, microcavities, and quantum dots in a PBG, as examples in addition to the NV/PBG array originally proposed in the first paper.
Focus areas: *Photonic band-gap materials; Nitrogen-Vacancy and other color-centers in Diamond; cavity-QED arrays; Polaritonic condensates; Photonic insulators (probing quantum critical phenomena; Quantum simulators.*

Silicon in the quantum limit: Nanoscale devices in silicon

Silicon and concrete are the two most studied materials on earth. Yet it is a mistake to assume that silicon is "known" because of all this attention. As the semiconductor industry pushes towards the 10 nm scale, quantum effects are playing a more important role in the construction of traditional transistors. On the other hand, quantum electronics may provide an avenue for alternative forms of computation, either in novel "classical" transistor circuits or through a quantum information paradigm. In either case, silicon at this length scale exhibits subtle properties that have typically been ignored in the semiconductor industry. Chief among these new unknowns are the physics of electron valleys in the silicon conduction band, the dephasing and relaxation times of electron spin and orbital states, and the spin-orbit coupling in these materials.
Focus areas: *Strained silicon-germanium heterostructures and 2D electron gases; Spin-relaxation and decoherence in quantum dots and wells; Spin-orbit coupling; Valley physics.*

Quantum information technology and materials physics

The pursuit of spin and quantum entanglement-based devices in solid-state systems has become a global endeavor. The approach of the quantum size limit in computer electronics, the many recent advances in nanofabrication, and the rediscovery that information is physical (and thus based on quantum physics) have started a worldwide race to understand and control quantum systems in a coherent and useful way. Semiconductors such as gallium-arsenide and silicon and carbon-based systems such as diamond, graphene, and carbon fullerenes have excellent properties for scalable quantum technology applications. In this conception, traditional solid-state physics can offer not only successful quantitative techniques but also new insights into quantum mesoscopic behavior. Consider a single electron trapped in a semiconductor quantum dot. It has only 2 spin states, up and down, yet its wave function sprawls over 100 nm and many thousands of atoms in its host crystal matrix. Here we have a curious combination of small Hilbert-space physics (the language of quantum optics) and traditional semiconductor and materials physics, at a scale with properties fundamentally different from the bulk but also much larger than atomic systems.

Focus areas: *Quantum computing; Quantum measurement and spin readout; Diamond and carbon-based devices (fullerenes and graphene); Quantum optics and communication.*

Nanotechnology and Society

Public and corporate concern over nanotechnology has lead governments around the world to invest directly in research on the societal implications of advanced technologies as an accompaniment to fundamental and applied funding. As evidence of this one only needs to look at the budget for the USA National Nanotechnology Initiative, which devotes roughly 10% of funding per year to societal impact studies (8% to environmental, 3% to societal/ethical). As a senior graduate student at the University of Wisconsin-Madison I taught an undergraduate seminar on the societal implications of nanotechnology, which I co-developed with professors in public policy, sociology, history of science, engineering physics, and materials science. With that foundation I have continued research in this area and have written several guest articles for books on nanotechnology and society and nanoethics. It is very unusual for a practicing physicist to also be a scholar in this field and this has lead to much cross-disciplinary collaboration and invitations to nanoethics advisory boards and nanotechnology task force groups.

Teaching: The more fantastic visions of nanotechnology naturally attract students. In my experience, *Nanotechnology and Society* is a very effective way to introduce younger students to the broad spectrum of science and engineering fields that are evolving rapidly. It also gives a context for introducing history of technology, science and technology studies, and ethics to the budding scientist, entrepreneur, or politician.

Outreach: With a portion of all NSF research grants now expected to go to outreach and education, research in nanotechnology and society provides a nice avenue for collaboration.

Industry: Input from scientists on both societal issues and fast-paced developments in technology are increasingly of value to businesses.

Atomic, Mesoscopic and Optical Physics Overview. Quantum gases and collective phenomena. Quantum Optoelectronics. Quantum Optical Materials and Systems. Many-body Quantum Dynamics. Biological and Soft Systems.Â Device Processing Cleanroom. Cryostat Systems. Surfaces, Microstructure and Fracture.Â The Theory of Condensed Matter Group (TCM) carries out world-leading research under three general headings: collective quantum phenomena, first principles quantum mechanical methods.