Free-Electron Quantum Optics

Research of cavity quantum electrodynamics (CQED) has enabled new capabilities in quantum optics, quantum computation, and various quantum technologies. So far, all the work in this field has included light interacting with *bound-electron systems* such as atoms, quantum dots, and quantum circuits. In contrast, *free-electron systems* enable fundamentally different physical phenomena, as their energy distribution is continuous and not discrete, and allow for tunable transitions and selection rules.

We have developed a platform for studying free-electron CQED at the nanoscale and demonstrated it by observing coherent electron interaction with a photonic cavity for the first time. Our platform includes femtosecond lasers in an ultrafast transmission electron microscope, which created what is, in many respects, the most powerful nearfield optical microscope in the world today. We resolve photonic bandstructures as a function of energy, momentum, and polarization, simultaneously with capturing the spatial distribution of the photonic modes at deep-subwavelength resolution.

These capabilities open new paths toward using free electrons as carriers of quantum information. As examples, we show how to create free-electron qubits and implement quantum gates with femtosecond lasers. We further show how to measure quantum decoherence in space and time using the free-electron quantum interactions. Such interactions also enable new avenues for tunable X-ray sources, as we demonstrate with theory and experiments.

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