Free-Electron Quantum Optics and Quantum Recoil

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Until recently, quantum optics was mainly limited to the interaction of photons with each other in nonlinear media, and the interaction of photons with bound electrons in atoms and atom-like structures, such as vacancies in solids and quantum dots. As a result of such interaction, light-matter states are generated, in which matter has a discrete spectrum and most often remains stationary, while photons transfer quantum information. In the last few years, quantum optics has moved away from this concept with the emergence of the new field of free-electron quantum optics. Free electrons, straight-forwardly generated in an electron microscope, represent a new unusual object for quantum optics: matter with a continuous spectrum, easily controlled by electromagnetic fields, flying at near-light speeds and capable of efficient interaction with photons.

The field of free-electron quantum optics was so far limited to high electron energies (100 keV), experimentally realized with transmission electron microscopes. In this energy realm, the photon recoil effect (the change in momentum of an electron after the emission of a photon) was deemed unimportant and was hence so far neglected. In our work, we introduce the recoil effect to the electron-photon coupling, and show various avenues to generate new electron and/or photon quantum states based on this. Furthermore, our work pushes the boundaries of free-electron quantum optics to the promising energy range of scanning electron microscopes (1-30 keV) and below, providing new opportunities and accessibility to experiments.

We develop a model that provides an exact solution for the problems of free-electron quantum optics with recoiled electrons. We find and describe a new effect—recoil-induced shaping of free electrons—the phenomenon of changing the electron-photon state under the influence of recoil and show the possibility of generating both known and fundamentally new types of states with its help: photon and electron-photon Bell, Greenberger-Horne-Zeilinger (GHZ) and NOON states, coherent state, squeezed vacuum, twin beams, as well as shaped coherent and shaped squeezed vacuum states. These new states can expand the capabilities of quantum optics, attosecond physics and electron microscopy.