Imprinting the quantum statistics of photons on free electrons

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Abstract: We observe for the first time the breakdown of the wave nature of light in free-electron–light interactions. Our experiment demonstrates a new way of measuring quantum states of light using high-precision electron energy spectroscopy. © 2020 The Author(s)

The fundamental interaction between the free electron and the photon stands at the base of both classical and quantum physics. In classical physics, this interaction has enabled numerous applications of free-electron radiation sources and the field of laser-driven electron accelerators [1]. In quantum physics, this phenomenon has recently facilitated electron wavepacket shaping in time & space [2] and inspired the idea of electron-photon entanglement [3, 4] that could have new applications in quantum optics [5–7]. Yet, in all free-electron experiments to date, the light was still regarded as a classical wave phenomenon, disregarding its quantum nature. Theoretical works on quantum free-electron–light interactions have revealed the role of the quantum photon statistics, as first predicted as the quantum optical regime of photon-induced nearfield electron microscopy (Q-PINEM) [3,5,6]. However, these effects have never been observed experimentally.

Here we observe for the first time the consequences of quantum photon statistics in free-electron–light interactions. Such interactions spawn a new area of quantum optics and enable using free electrons to extract the quantum statistics of light (Fig. 1). We demonstrate this capability by measuring the continuous transition from coherent light to thermal light in a fiber amplifier, unveiling a surprising manifestation of the correspondence principle: transition from free-electron quantum walk to classical random walk (Fig. 1a,b) on the energy ladder. The electron walker measures the second-order correlation $g^{(2)}$ of the light (Fig. 1d) as well as its higher-orders $g^{(n)}$ in a non-destructive manner. Unlike conventional quantum-optical detectors, the electron evolves into a joint entangled state with the light. This unique detection scheme reveals the transition from weak measurement by coherent light to full collapse by thermal light, despite the light having full spatial and temporal coherence in both cases. We achieve this free-electron–quantum–light interaction using the inverse design of silicon-photonic nanostructures recently used for miniaturizing particle accelerators [1] (Fig. 2).

Figure 1 Experimental reconstruction of photon statistics from electron energy spectra: transition from classical to quantum walk. (a) Electron energy spectra for coherent and thermal states for varying CW power. The behavior is similar to the continuous transition between classical and quantum walk. Theory gives an excellent agreement with experimental results. The white circle marks corresponding points of the same driver power: having the same energy width in both figures for the same driver power, i.e., electron interactions with thermal states are as efficient as interactions with coherent states. This correspondence has important consequences: showing that thermal light interaction with the free electron causes no decoherence in time/space but causes entanglement with the electron in the energy domain. (b) Selected cases of measured electron energy spectra following the interaction with different states of light. The dashed black curve is the OPINEM theory; the colored solid curve is the experiment. (c) Reconstructed photon statistics corresponding to (b). (d) Second-order correlation $g^{(2)}(0)$ extracted from the experiment.
Figure 2 Free-electron–quantum-light interaction in a custom-made silicon-photonic nanostructure, inspired by dielectric laser accelerators. (a) Specially-made nanostructure used in a transmission electron microscope to facilitate extremely efficient interaction of free electrons with continuous wave (CW) light, which we use to observe the effect of photon statistics in electron–light interaction. The electron energy spectrum is measured with an energy resolution better than the single-photon energy, using electron energy loss spectroscopy (EELS). (b) A range of different photon statistics (Poissonian to super-Poissonian and up to thermal) created using an amplifier. (c) Simulation of the longitudinal electric field in the silicon-photonic nanostructure, optimized with photonic inverse design methods for extremely efficient free-electron–quantum-light interaction. (d) Scanning electron microscope images of the nanostructure: based on a dielectric laser accelerator structure consisting of an accelerating channel and Bragg mirror.

In all experiments to date, the quantum state of a free electron illuminated by light has been accurately captured by the classical electromagnetic potentials in the time-dependent Schrödinger equation (or a direct relativistic generalization). The underlying reason for the success of this description is the lack of entanglement, which enables the separability of the joint electron-photon state. For example, a paraxial free electron in a well-defined energy state \( |E_0\rangle_{el} \) (having energy uncertainty smaller than single photon energy) that propagates through an intense classical light wave, i.e., coherent state of light \(|\alpha\rangle_{ph}\), evolves into \( |\psi\rangle_{el} = \sum_{k=-\infty}^{\infty} e^{ik\omega} J_{|k|} (2|g|) |E_0 - k\hbar\omega\rangle_{el} \), where \( g = \frac{e}{\hbar c} \int dz E_z(z) e^{-i\omega z/v} \) is the coupling strength, \( \omega \) the frequency of the light field, \( v \) the electron velocity, and \( J_{|k|}(x) \) is the Bessel function of order \( k \). This theory describes the PINEM effect [8]. The post-interaction electron-photon state remains separable \( |\Psi\rangle_{el-ph} \approx |\psi\rangle_{el} \otimes |\alpha\rangle_{ph} \).

In contrast, states of light exist for which the joint electron-photon state becomes entangled, resulting in dynamics that cannot be captured by a time-dependent Schrodinger theory. To find the exact entangled state, one must employ Q-PINEM [3,5,6]. The photon statistics can dramatically change the measured electron energy spectrum [6] due to its entanglement with the state of light after the interaction. In our experiment, the free electron interacts with light emanating from a ytterbium-doped fiber amplifier. The amplifier allows us to explore the continuous transition from a coherent state with Poissonian statistics through super-Poissonian statistics and up to a thermal state with Bose-Einstein statistics. In the limiting case of Poissonian statistics, the electron-light state remains separable. In the other limiting case of thermal statistics, the electron-light state becomes strongly entangled. Both limiting cases, and all cases in between, can be accurately captured by the Q-PINEM theory [3,5,6], as shown in Fig. 1.

The efficient interaction we achieved (Fig. 2) enables continuous-wave [9] laser shaping of electron quantum wavepackets, which could bring attosecond time resolution into the mainstream of electron microscopy through on-chip devices that can be integrated into the column of state-of-the-art microscopes. This constitutes an important step in the way toward the vision of a combined attosecond-temporal and sub-A-spatial resolution microscopy. Our work enables the concept of free-electron-based quantum-optical detection for ultrafast non-destructive quantum tomography of light [6]. Such capabilities enable exploring a hitherto inaccessible area of quantum optics: quantum light pulses with ultrafast modulation of their quantum state – also constituting a novel platform for continuous-variable quantum information.

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