An electron walks into a quantum bar…

Quantum electron-light interaction may find use in microscopy applications

By **Fabrizio Carbone**

Since its conception more than a century ago, the duality between the wave and particle nature of light is perhaps the most well-known concept that connects classical and quantum physics. As such, one may expect it to play an indispensable role in explaining light phenomena. However, even the photoelectric effect, considered the first showcase for the quantum nature of light, can be described by treating light classically—as long as the energy distribution of the electrons in the material is quantized (*1*). On page XXX of this issue, Dahan *et al.* (*2*) describe an experiment in which the quantum properties of a quantum light source can be transferred through entanglement to electrons. This realization adds to the shortlist of situations where quantum light is strictly necessary to describe photon-matter interaction and offers intriguing possibilities for both fundamental studies and applications, such as in ultrafast transmission electron microscopy (TEM).

By monitoring the energy distribution of an electron beam interacting with either a coherent or a thermal light source, Dahan *et al.* devised an experiment in which the transition from classical to quantum statistics is observed. Their method demonstrates a way to control the quantum properties of the light-electron interactions through the quantum coherence of the photons, which may lead to new exploits in electron microscopy applications.

To explain the peculiarity of the experiment, one can borrow from a common analogy for explaining random walks—the drunken bar patron (see the figure).

In the first scenario, an electron goes to the pub and drinks classical beer, which represents coherent light. Because she does not get too drunk, some coherence is left in her and therefore her walk will not be completely chaotic, but rather a mixture of random alcoholic stumbles and conscious choices to go either way. Being a quantum object, the coherent electron will interfere with herself during her walk, enhancing the probability of finding her at specific distances from the pub; this can be called a "quantum walk."

In the second scenario, an electron orders quantum beer from the pub, which represents thermal light that undergoes a quantum interaction with the electron. Immediately, she becomes drunk and entangled with the drink, so her coherence is washed out. Her walk out of the pub is now completely random and the probability of finding her somewhere is a gradually widening normal distribution; this can be called a "random walk."

Most notably, when interacting with the classical beer in the "quantum walk" case, the electron wave function collapsed only once it was detected. By contrast, upon interacting with the quantum beer in the "random walk" case, the collapse of the electron wave function happened immediately as it entangled itself with it.

Dahan *et al*. observed the evolution between these two scenarios in their light-electron interaction experiment. By using a custom-made silicon-photonic nanostructure inside a TEM, the authors created a system in which individual free electrons can interact with light having statistics evolving from a thermal source all the way to a coherent one.

By requiring both the electron and the photon to be quantum to describe their observation, Dahan *et al.* present a purely quantum picture for the photon-induced nearfield electron microscopy (PINEM) (*3*) effect. For context, the PINEM effect has previously been modeled with electrons as quantum and light as classical, as in the alternative description of the photoelectric effect (*4*, *5*).

Provocatively, one can argue that in many situations in physics, the choice of whether to treat a system as quantum or classical has often been dictated by convenience rather than fundamental reasoning. These situations are generally thought of as "semiclassical." Although semiclassical theories may provide an adequate description for many experiments, they cannot always capture subtle quantum effects.

Dahan *et al.* have demonstrated such a case, namely the possibility of entangling light with an electron beam in a TEM, and obtaining de facto a quantum radiation source, in which the beam's particles are in a superposition of states that can be manipulated externally by light. The possibility of imprinting the quantum properties of photons into an electron beam may lead to new exploits for photonic quantum computers, which historically suffered from the fragility against decoherence of quantum light. Their observation that, after interacting with quantum light, an individual electron ceases to exist only to survive as a superposition of massive (electrons) and massless (photons) particles has intriguing consequences for interaction-free measurements, sometimes referred to as "ghost imaging" (*6*). This, and similar concepts, are currently explored to conceive the so-called quantum electron microscope, having among its main objectives the observation of radiation-sensitive biological specimens.

A full quantum mechanical treatment of PINEM has been developed only recently (*7*, *8*), and it is time to explore its consequences and opportunities. The findings of Dahan *et al.* open the door to reconstructing the quantum state of light in the proximity of nanostructures in TEMs with attosecond, millielectronvolt, and nanometer resolution. The ability to alter the wave function of electrons may help generate and control light beams for applications in sensing, biophysics, optoelectronics, accelerator physics, and even nuclear physics (*9*). Exploiting the quantum nature of light-electron interaction may be the next frontier in electron microscopy.

If the revolutionary operation of the transistor could have been summarized in its definition as a voltage-controlled current source, one may argue that we now have the ingredients for designing a light-controlled quantum radiation source.

REFERENCES AND NOTES

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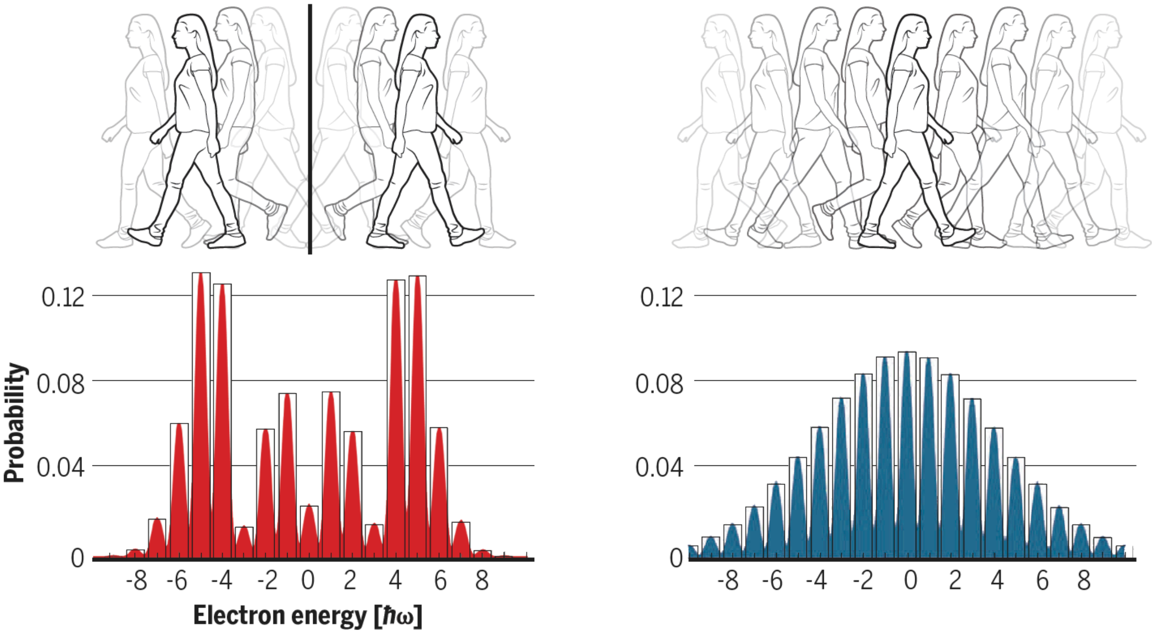
“Quantum walk” vs “random walk”

The electron interacting with “classical” beer and “quantum” beer and the subsequent probability distributions for the electron’s energy state, reflecting the degree of electron decoherence as a result of the type of electron-photon interaction.



If the electron drank **“classical”** beer, representing coherent light, the electron retains its coherence and shows an energy spectrum corresponding to quantum walk, with well-defined peaks away from the origin.

If the electron drank **“quantum”** beer, representing thermal light, the electron becomes entangled with the photon and shows an energy spectrum corresponding to random walk, with a single peak centered at the origin.

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