Observation of the Stimulated Quantum Cherenkov Effect

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Abstract: We present the first observation of the quantum nature of the Cherenkov effect, by phase-matching light & electron waves. Interacting coherently along hundreds of microns, each electron simultaneously absorbs and emits hundreds of photon quanta.

The Cherenkov effect (also called Vavilov-Cherenkov effect) has attracted vast interest since its discovery in 1934 [1] and the Nobel Prize of 1958, yet to this day, all experiments on the subject have been perfectly accounted for by classical electrodynamics. Similarly, all demonstrations of analogous effects in a wide range of fields—such as water waves, acoustics, and even phononics [2]—are also explained entirely classically. Likewise, all experiments using the stimulated Cherenkov effect for electron acceleration [3] and for other electron–laser interactions are described classically [4]. Theoretical work predicts new Cherenkov phenomena coming from quantum electrodynamics that provide new concepts and designs of highly controllable light sources, more efficient accelerators and detectors [4,5]. Here we demonstrate the quantum nature of the stimulated Cherenkov effect and observe how the quantum wavefunction of each electron evolves into a coherent plateau, analogous to a frequency comb in ultrashort laser pulses, containing hundreds of quantized energy peaks. By precisely matching the group velocity of the relativistic electron wavefunction and the phase velocity of light, we achieve the Cherenkov phase matching condition so that each point in the electron’s wavefunction experiences a constant electric field (see Fig. 1).

Figure 1. Quantum vs. classical phase-matching in the Cherenkov effect. (a) Illustration of the phase-matching effect for both the classical and quantum interpretations. The electron interacts with an evanescent field. Classical: a point electron (small particle) velocity matches the light phase velocity. Quantum: a delocalized electron wavefunction interacts simultaneously with multiple cycles of the light field. (b)–(c) Comparison of theoretical classical (black) and quantum (orange) energy spectra. (d) Example of measured (blue) and theoretical (orange) electron energy spectra. These results show the strong quantum interaction of the electron wavefunction by quantized energy gain/loss of up to 60 photon (ℏω ≈ 1.7 eV).

The experimental setup (Fig. 2a) that we used to demonstrate the coherent resonant interaction is an ultrafast transmission electron microscope (UTEM) [6], where a laser pulse is splits to a pump and a probe. The probe generates electrons from the UTEM’s cathode, while the pump is focused on a BK7 prism wall to interact with the electrons at the Cherenkov angle (see Fig. 2b). We tune the electron velocity to match laser-pump angle by changing the accelerating voltage to 207.2 keV. The key to the effects is achieving a grazing-angle interaction with the sample surface, where the electrons remain at a distance of a few hundred nanometers from the surface for hundreds of
microns. The achievement of such a grazing angle condition is, to the best of our knowledge, realized here for the first time in any transmission electron microscope. This condition maximizes the strength of the electron–laser interaction. The interaction can be explained by a single dimensionless constant $g$ [6,7], which in our case can be simplified to:

$$g(x_0) \equiv \frac{q_e}{\hbar \omega} \int_{-\infty}^{\infty} E_0(x_0, y_0, z) e^{-\frac{\lambda}{v_0} z} dz \equiv \frac{q_e}{\hbar \omega} \int_0^L E_{0,x} e^{ik_x x + ik_z z} dz,$$

with $x_0$ being the electron distance from a prism wall of length $L$, $q_e$ the electron charge, $\omega$ the laser frequency, $v_e$ the electron velocity, $E_{0,x}$ the evanescent electric field amplitude of the $x$ component, $k_x$ and $k_z$ the wave vector components. $k_x$ is imaginary due to the evanescent wave decay, while $k_z$ is real and represents the phase velocity in the direction of the electron propagation. When $k_z$ equals to $\omega/v_e$, each point in the electron’s wavefunction sees a constant field and $g$ grows linearly with the interaction length $\rightarrow$ resulting in coherent constructive interference.

Figure 2. Experimental setup and extreme electron–photon energy exchange. (a) Illustration of the ultrafast transmission electron microscope (UTEM) setup. The electron pulse (generated by a UV pulse) grazes the surface of a prism and interacts with an evanescent field (generated by another laser pulse that undergoes total internal reflection at the same surface). We measure the electrons’ energy with an electron energy spectrometer. (b) Zoom-in on the interaction area. Inset: an image of the prism positioned on the edge of a hole through which the electrons pass. (c) Acquired electron energy spectra showing the different acceleration profile for different laser pulse durations (pink 280 fs, blue 600 fs, green 1300 fs), while the electron’s pulse duration is 300 fs. The black line represents the predicted classical profile for a 600 fs laser pulse duration.

The phase-matched interaction in the UTEM opens the door for utilizing quantum electrodynamics for new applications in electron microscopy and in free-electron pump-probe spectroscopy [8]. The free-electron combs we created has been previously observed only in pulsed photoexcitation of bound electrons. Free electrons have markedly different physical phenomena and applications as compared to bound electrons and can induce new relativistic effects, such as the Cherenkov effect that we observed in this work. The energy comb spectra of free electrons are expected to generate new kinds of radiation composed of high harmonic orders, with intriguing prospects in attosecond science.

References
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