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Quantum Vacuum Nonlinearities in Strong Electromagnetic Fields

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The physical vacuum of a relativistic quantum field theory amounts to a non-trivial quantum state. It encodes information about the full particle content of the underlying microscopic theory in the form of virtual processes. If the theory features charged particles, the latter give rise to nonlinear effective couplings between electromagnetic fields that vanish in the formal limit of a vanishing Planck constant, but persist for a nonzero physical value. These couplings inherently modify Maxwell's linear theory of classical electrodynamics. However, for the field strengths reached by macroscopic electromagnetic fields currently available in the laboratory the quantum vacuum nonlinearities induced by Standard Model particles are parametrically suppressed relatively to the linear contribution by inverse powers of the electron mass and thus very small. Therefore, this fundamental tenet has remained experimentally challenging and is yet to be tested in the laboratory.

In my talk I will focus on quantum vacuum nonlinearities in strong electromagnetic fields arising from quantum electrodynamics (QED). On the one hand, I will highlight fundamental aspects of the Heisenberg-Euler effective action that supersedes the classical Maxwell action in governing the physics of strong macroscopic electromagnetic fields in the vacuum. On the other hand, I will outline the dark-field approach devised to measure the leading (weak-field, low-frequency) quantum vacuum nonlinearity in a dedicated experiment at the European X-ray Free Electron Laser (EuXFEL) within the Helmholtz International Beamline for Extreme Fields (HIBEF) Collaboration.

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