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Time-domain Quantum Physics

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1. Extended Abstract

Fluctuations of the quantum vacuum are fundamental to a variety of physical phenomena such as spontaneous emission, the Lamb shift or Casimir forces. Also, relativistic quantum field theories emphasize their central relevance for elementary particle physics and cosmology. This contribution first introduces direct detection of the vacuum noise of the local electric field in free space [1]. Multi-terahertz electro-optic sampling and ultrabroadband Er:fiber laser technology together provide the extreme sensitivity needed for quantum-statistic readout. The amplitude ΔE_{vac} of vacuum fluctuations is given by the following expression [2],

$$\Delta E_{vac} = \sqrt{\frac{h}{\varepsilon\varepsilon_0 \Delta x \Delta y \Delta z \Delta t}} \qquad (1),$$

in accord with the uncertainty relation for electromagnetic waves derived by Werner Heisenberg in the 1920s [3]. Here, h is Planck's constant, ε_0 the permittivity of free space and ε the dielectric constant in the electro-optic crystal used for subcycle quantum detection. $\Delta x \Delta y$ stands for the transverse cross section of the sampled volume whereas $\Delta z \Delta t$ is the product of the spatial length and the temporal duration of the probe pulse. Distinction from detector shot noise is achieved by geometric modification of this space-time volume. Measuring with a bandwidth close to the center frequency of 70 THz maximizes the vacuum amplitude because the ground state energy approaches half a photon per optical cycle.

We then proceed to a first application of those new capabilities for detecting the quantum statistics of the electric field: subcycle analysis of multi-terahertz squeezed states [4]. So far, studying the quantum properties of light has been based on homodyning techniques and photon correlation measurements. These methods require a well-defined carrier frequency and photons contained in a quantum state need to be absorbed or amplified. They currently function in the visible to near-infrared and microwave spectral ranges. Generation of mid-infrared time-locked patterns of squeezed vacuum noise will be introduced. After propagation through free space, the quantum fluctuations of the electric field are investigated. With electro-optic sampling, we can directly compare the local noise amplitude to the level of bare vacuum fluctuations. This nonlinear approach is nondestructive since it operates off resonance without absorption or amplification of the field that is detected. Subcycle intervals with noise level significantly below the pure quantum vacuum are found. Enhanced fluctuations in adjacent time segments manifest generation of highly correlated quantum radiation as a consequence of the uncertainty principle.

As an outlook, we emphasize the intricate connection between this time-domain quantum electrodynamics and spatial manipulation of electronic phenomena on a sub-cycle and sub-wavelength scale [5,6]. Fascinating questions arise concerning the fundamentals of measurement processes of quantum fields. Also, the correlated photons and subcycle quantum resolution that are now at hand will be an ideal tool to study electronic correlations right in the frequency range where the collective resonances and electronic energy gaps typically occur in complex materials.

2. References

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