EHU | EHU Quantum Center

EHU Qc Seminar

Time frequency quantum information processing

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Abstract: Quantum information in photonic platforms can be encoded either on using discrete variables or continuous variables. Continuous-variable (CV) encoding traditionally relies field quadrature. An alternative and promising encoding exploits the time–frequency degrees of freedom of single photons. Single-photon time–frequency modes benefit from powerful spectral shaping tools that allow arbitrary single-photon operations. However, despite this versatility, generating measurement-free entanglement between independent single photons in the time–frequency domain remains a major challenge.

We theoretically propose a scalable, measurement-free approach to generating frequency entanglement between single photons using a quantum dot embedded in a single-mode nanophotonic waveguide. Starting from a generic four-level atomic-like system, we derive an effective quadratic two-photon Hamiltonian via an adiabatic elimination procedure in the Heisenberg picture, explicitly preserving the continuous frequency dependence of the light–matter interaction. Under realistic physical conditions — large one-photon detuning and appropriate interaction timescales — single-photon processes are suppressed while frequency-dependent two-photon transitions are resonantly enhanced. The resulting effective Hamiltonian features non-separable, frequency-dependent coupling terms, providing an ab initio microscopic justification for phenomenological quadratic models previously proposed in the literature. Using a Markovian scattering formalism, we show that an initially separable two-photon input state is reshaped into a frequency-entangled output state, a device we call FrEnGATE. For realistic system parameters, we find a maximum success probability of 15% with a Schmidt number of approximately 5, significantly outperforming conventional nonlinear optical sources such as spontaneous parametric down-conversion. Our results open a pathway toward deterministic, experimentally realizable frequency-entangling gates in integrated photonic platforms, as well as non-Gaussian operations in the quadrature domain. We further discuss applications of the FrEnGATE in quantum information processing, including its use for time and frequency delay estimation at the Heisenberg scaling limit.

Theoretical Physics Seminar Room
Thursday, June 4th , 2026
11:40 am

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