Quantum Optics Meets Attosecond Science: Novel Regimes of Coherent X-ray Generation with Strong Electron Correlation Dynamics and Attosecond Rabi Oscillations

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Ultrafast imaging and spectroscopies using coherent EUV – X-ray light based on the nonlinear process of high harmonic generation are already addressing grand challenges in complex molecular systems, plasmas, and advanced nanomaterials. The exquisite quantum control of the attosecond dynamics of the rescattering electrons in this extreme frequency upconversion makes it possible to sculpt the classical and quantum properties of the light with unprecedented tunability of the spectral, spatial, temporal shape, and spin and orbital angular momentum state. The superb coherence of this unique light allows for multi-dimensional imaging at the space-time extreme with 4D resolution of nanometers and femtoseconds, including access to an effective 5th dimension – the periodic table of elements – due to the X-ray absorption fingerprinting with elemental and chemical specificity.

In this talk, I will present two novel quantum regimes of coherent X-ray generation where the design of the light properties is dominated by the dynamics of the strongly correlated electrons in a simple He atomic system. Interestingly, the physics of these regimes extends beyond the well-established three-step high harmonic model.

In the first regime, using strong UV laser fields, the entangled electron dynamics yield a characteristic secondary plateau in the X-ray spectral region, extending well beyond the conventional cutoff. This is due to simultaneous double electron recombination where a single high-energy X-ray photon is emitted only in atomic systems with strongly correlated electrons. This low probability phenomenon paves a way to a sensitive attosecond spectroscopy as a probe of highly correlated interactions. Similar physics of high harmonics from solids might be able to characterize electron correlations in phase transition materials and nanosystems of relevance to quantum computing and superconductivity.

In the second extreme regime, using intense EUV driving fields tuned to a resonance frequency of He can result in very bright harmonic emission in the X-ray regime. Favorable quantum dynamics of the electron wavepackets, and phase and group velocity matching of the light fields enhance the X-ray yield. Furthermore, record-fast attosecond Rabi oscillations are predicted to suppress the depletion of the ground state, which otherwise terminates the emission of X-ray photons.

These new advances in quantum control over the coherent X-ray emission enable new insights into complex entangled electron dynamics and applications in nanoscience and quantum technology.