Exotic Cases of Few- and Multi-Photon Physics in Atoms: From Extremely Low Intensity, State-Selective Pathways, to Applications in Quantum Machine Learning

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The interaction of light with atoms is a testing ground for our understanding of fundamental quantum physics. At low light intensities, precision spectroscopy of atoms and ions allows for verification of quantum electrodynamics and tests of the standard model. Exciting opportunities emerge since highly charged ions (HCIs) can now be sympathetically laser cooled in beryllium-crystal matrices and, due to the inertness of the rigid electronic structure of HCIs, can be used for building ultrastable clocks based on quantum-logic spectroscopy.

Moving to higher intensities, nonlinear interactions of atoms with two or multiple photons challenge our understanding of time-dependent quantum dynamics, as the coupling of excited or even continuum states to light substantially increases complexity and thus the demand on theory, but at the same time creates new opportunities.

To experimentally shed light on these processes, we measure angular distributions of photoelectrons produced in the interaction of two or more photons with atoms. We developed a range of novel methodologies, including high-repetition-rate (100 MHz) enhancement cavities for the generation of high-order harmonics, but also with an intra-cavity velocity-map imaging spectrometer, allowing to measure above-threshold-ionization by multi-photon absorption down to unprecedentedly low intensity. Also, a new ghost-imaging related spectroscopy technique was implemented at the free-electron-laser (FEL) FLASH at DESY, Hamburg. Recording the statistically produced extreme-ultraviolet (XUV) spectrum for every shot of the FEL, it was possible to enhance the spectral resolution in the two-photon double-excitation process of helium atoms and to measure the angular distribution of photoelectron emission by recoil-ion imaging with a reaction microscope. In separate, two-color experiments, by tuning the FEL photon energy in combination with an optical near-infrared (NIR) laser, we were able to address specific intermediate states in a few-photon ionization pathway and measure the corresponding free-electron distributions.

With all this control over atomic systems by light, and besides our aim to test fundamental physics understanding and theory, one could ask for potential future application. One such application is quantum machine learning on atomic time and length scales, and the talk will discuss one such potential route and preliminary computational results.