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Origins of Very-Low and Zero-Energy Electron Structures in Strong-Field Ionization with Intense Mid-IR Pulses

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Synopsis Intense long wavelength ($\lambda \geq 2\,\mu$m) laser pulses enable experiments in the tunneling ionization regime ($\gamma \ll 1$) and reveal surprising low electron energy features, which can not be described with the strong-field approximation (SFA). These features, universal for all target species, include the low-energy structure (LES), the very-low-energy structure (VLES) and the zero-energy structure (ZES). Using full 3D electron-ion coincidence detection in combination with our ultrafast 160 kHz mid-IR source, we reveal the entire 3D momentum spectrum well below 1 eV. Quantum and classical simulations allow for an interpretation of the LES, VLES and of the newly identified ZES.

In strong-field ionization for $\gamma \ll 1$, the post-tunneling behavior of the electron wave packet is expected to be dominated by the laser electric field rather than the Coulomb field of the parent ion. With the recent availability of intense mid-IR pulses ($\lambda \geq 2\,\mu m$) this simplification of tunneling-ionization has changed. Several unexpected low-electron-energy features such as the low-energy structure (LES) [1], the very-low energy structure (VLES) [2] and the zero-energy structure (ZES) [3] were found that could not be described within the strong-field approximation (SFA). To date classical calculations can explain the LES in terms of multiple recollisions of the tunnel-ionized electron at the Coulomb field of the residual ion. Yet the VLESs have not been quantitatively characterized and the origin of the ZES remained speculative.

Here we present a joint experimental and theoretical study of the 3D momentum space of photoelectrons which allows for a quantitative interpretation of all three structures [4]. Using a reaction microscope (ReMi) in combination with our ultrafast 160 kHz mid-IR source, we accurately resolve multiple orders of LES, the VLES and the ZES in momentum space. By comparing the experimental data with classical trajectory Monte Carlo (CTMC) and quantum simulations, we find agreement for all structures. Further analysis permits an identification of the VLES in terms of high-order two-dimensional Coulomb focusing. Moreover the ZES is conclusively attributed to electrons being recaptured into high-lying Rydberg states via frustrated tunnel ionization (FTI) [5] followed by subsequent field ionization by the static electric field of the ReMi.

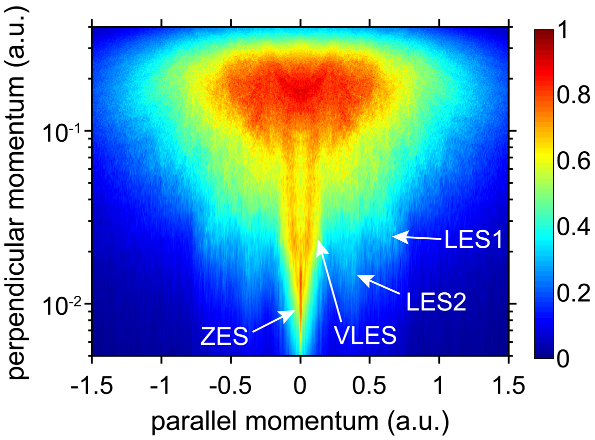

Figure 1. Experimental electron momentum distribution for argon interacting with 6-cycle mid-IR pulses with a peak intensity of $I_0 = 0.9 \times 10^{14}\,\mathrm{W/cm^2}$.

References

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