Attosecond Tunneling Interferometry

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Abstract: By applying a weak perturbation to HHG we modulate the tunneling barrier in subcycle timescale. This gives rise to nontrivial temporal interference between consecutive attosecond bursts. The extracted interference patterns reveal nonadiabatic tunneling dynamics within the ~ 160 as ionization window.

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1. Introduction

When tunneling is induced by a strong laser field [1], its basic properties are subjected to the rapid modification of the electromagnetic field, having a natural time scale in the attosecond regime. Within a small fraction of the optical cycle both the width and the height of the tunneling barrier increase substantially leading to an exponential fall of the tunneling probability and a significant shift of the exit point. Pioneering experiments have measured the tunneling ionization yield [2], the time delay associated with tunneling [3] and the exact moment at which the electron exits the barrier [4]. In this work we provide a unique and extremely accurate insight into the basic mechanism behind field induced tunneling. By applying sub-cycle modulations to the barrier we are able to follow how the instantaneous tunneling probability changes within a temporal window of 160 as. Most importantly, we identify a clear signature of the memory accumulated by the electron during the tunneling process, leaving its fingerprint on both the amplitude as well as phase of the electronic wavefunction.

2. Interferometry

In our work we induce a temporal analogue of Young's two slit interferometer via a high harmonic generation (HHG) measurement. In HHG, each laser half-cycle gives rise to a tunnel-ionization event followed by emission of an XUV atto-pulse. Atto-pulses originating from consecutive half-cycles interfere in the spectral domain and define a temporal interferometer, in which the two tunnel ionization events take the role of "temporal slits". Resolving two neighboring (odd and even) harmonics is equivalent to the detection of a single fringe in the interference pattern.

By adding a weak second harmonic (SHG) field, polarized parallel to the strong fundamental field [5, 6] we induce a small difference between the tunneling barriers in consecutive half-cycles as well as between the two trajectories in the continuum. The total complex phase difference between the two paths, σ, modifies the interference pattern in the spectral domain leading to the generation of both odd and even harmonics. By analyzing the intensity oscillations in each harmonic order (N) as we vary the two color delay, ϕ, we extract both $Re(\sigma(N,\phi))$, associated with the semi-classical propagation, and $Im(\sigma(N,\phi))$, dictated by the tunneling process (see Fig. 1(A,B)).

3. Results

The strong field light matter interaction can be described according to the stationary phase approximation (SPA) in the language of quantum trajectories. In this picture, each harmonic is dominated by the stationary values of the ionization time t_0, instant of return t_1 and canonical momentum p. By comparing to the analytic expression for σ evaluated at the stationary points with the measured $\sigma(N,\phi)$ we are able to extract $Im(t_0)$ and $Re(p)$ for each harmonic order.

The imaginary part of the ionization time, $Im(t_0)$, introduces imaginary components to the action and determines the decay of the wavefunction under the barrier. Figure 1(C) describes the reconstruction of $Im(t_0)$ compared with the stationary solution, showing a negative (positive) slope with the harmonic order (ionization time). This reflects the reduction of the instantaneous value of the field as time progresses within the optical cycle, leading to an increase if the barrier height and width.

Our measurement captures the modification of the tunneling probability within the optical cycle. The imaginary part of the action defines the particle's probability to propagate in any specific path. Figure 1(D) presents the evolution of

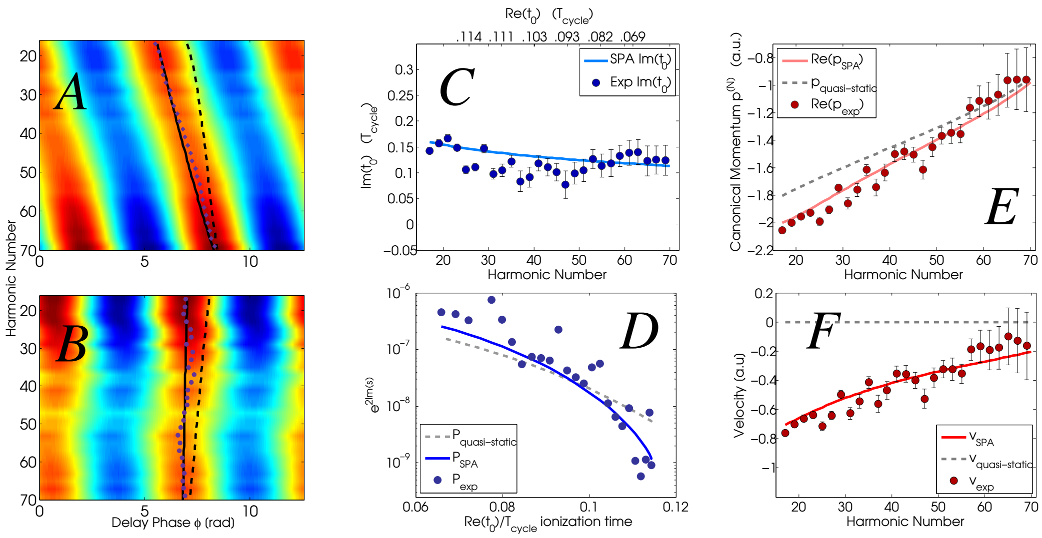

Fig. 1: (A) Real and (B) imaginary parts of $\sigma(N,\phi)$ as a function of phase delay and harmonic number. The black solid (dashed) line represents maximal value of $\sigma(N,\phi)$ according to SPA (quasi-static approximation). Reconstruction of (C) $Im(t_0)$ and (E) $Re(p)$. The reconstructed stationary parameters are used to calculate (D) the instantaneous ionization probability and (F) the initial velocity of the electron in the continuum (red dots) compared to quasi-static ($v=0$) velocities (dashed) and SPA prediction (solid).

the instantaneous tunneling probability during the ionization window, based on the reconstruction of $Im(t_0)$. Indeed, our experiment maps the rapid fall of the tunneling probability within a temporal window of 160 as.

The reconstruction of $Re(p)$, Fig.1(E), shows clear deviation from the quasi-static model [1] and an excellent agreement with the SPA values. What is the origin of this deviation? A fundamental assumption of the quasi-static picture is that the electron begins its journey in the continuum with zero velocity. The quantum analysis suggests that the electron exits the tunneling barrier with an initial velocity leading to a total shift in the canonical momentum. Using the relation between the vector potential $A(t)$ and the measured canonical momentum $Re(v(Re(t_0)) = Re(p) - eA(Re(t_0))$ we are able to follow the electron's initial velocity, Fig. 1(F). The dashed gray line marks the static limit where the solid red line describes the initial velocity predicted by SPA, in agreement with our experimental results. Indeed, our ability to probe the electronic wavefunction along its propagation direction enables us to directly reveal the non-adaiabatic nature of the tunneling mechanism.

4. Conclusions

In this work we demonstrate the ability to resolve how the properties of the tunneling wavefunction evolve in time, and expose its non-adiabatic nature. Our study extends the temporal accuracy provided by attosecond measurements observing how the basic properties of field induced tunneling evolve during a fraction of the optical cycle. Extension of our approach, providing unprecedented temporal accuracy, to multichannel ionization will shed new light on yet unexplored ultrafast electron dynamics, challenging the basic models that have so far described strong field light-matter interactions.

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