Carrier-envelope phase effects on the strong-field photoemission of electrons from sharp metallic tips

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Outline

- Strong-field phenomena around metallic nanostructures:
  - Emission
  - Acceleration in the near field
- Strong-field regime
- Methods: experimental and numerical
- Experimental observation of CEP-effect on acceleration
- New control mechanisms for electron motion
Strong-field phenomena

Observation of strong-field effects with metal nanostructures:

- High harmonic generation
- Attosecond pulses and x-ray radiation
- **Electron emission from metal nanostructures**

MPI (Multi-Photon Ionisation)

ATI (Above-Threshold Ionisation)

Strong-field Photoemission

Strong-field phenomena

Characterization: Keldysh parameter

Transition ATI $\Rightarrow$ Strong-field photoemission

$$\gamma = \frac{\omega \sqrt{2m_e \Phi}}{e \cdot f \cdot E_0}$$

$\gamma < 1$

L.V. Keldysh, Soviet Physics Jetp-Ussr 20, 1307 (1965)
Atomic system vs. nanostructures

**Emission:** Similar to atomic systems

- New phenomena discovered:
  - High harmonic generation
  - Attosecond generation

**Difference:** Electron motion in the near field

- New phenomena in strong near field:
  - Suppression of quiver motion
  - \( \Rightarrow \) Sub-cycle electrons

- CEP control required
Atomic system vs. nanostructures

Characterization: Spatial adiabaticity parameter

\[ \delta = \frac{l_F}{l_q} \quad \text{and} \quad l_q = \frac{e \cdot f \cdot E_0}{m_e \omega^2} \]

Sharp metal structures \( \Rightarrow \) short near-field decay length

\[ \delta < 1 \]

Acceleration \( \propto \) gradient of potential

Four regimes of photoemission
Four regimes of photoemission
Four regimes of photoemission

\[ \delta > 1, \quad \gamma < 1 \]

\[ \delta < 1, \quad \gamma < 1 \]

\[ \delta > 1, \quad \gamma > 1 \]

\[ \delta < 1, \quad \gamma > 1 \]
Regime: $\gamma < 1$, $\delta < 1$

Emergence of a pronounced plateau $\Rightarrow$ Signature of strong-field acceleration

Gold tip

30-fs-pulses at 1.4 $\mu$m

Counts (e⁻/pulse/eV) vs. Kinetic energy (eV)

- $0.08$ nJ
- $0.1$ nJ
- $0.14$ nJ
- $0.2$ nJ
- $0.4$ nJ
- $0.6$ nJ

Gold tip

$E_{loc} \leq 25$ V/nm, $f = 9$ at $0.6$ nJ

$E_{loc} \leq 9.3$ V/nm, $f = 9$ at $0.08$ nJ

Acceleration
Regime: $\gamma<1, \delta<1$

- Strong-field-induced tunneling
- Acceleration within one half cycle
  $\Rightarrow$ Sub-cycle electrons form a plateau

New sub-cycle regime
  $\Rightarrow$ unique to nanostructures

- Recollisions are suppressed
- Electrons follow field lines
  $\Rightarrow$ Fundamentally different electron dynamics

First experiments in sub-cycle regime performed only recently:
Angle-resolved energy spectra

Emission cone narrowing of the fastest electrons from $\geq 30^\circ$ down to $12^\circ$

Control of electron motion

Steering effect of the fastest electrons
⇒ a new control handle via the spatial field distribution

Control via the temporal field distribution, too?
⇒ study the influence of carrier-envelope phase
Experimental setup

- Ti:Sapphire regenerative amplifier
- NOPA 30 fs 1000-1500 nm
- Cassegrain objective
- Gold taper
- Faraday cage
- PES
Experimental setup

- Center wavelength: $1.65 \, \mu m$
- Pulse duration: $14 \, fs$

Source:
Experimental setup

Experimental setup

Experimental setup

- Passive CEP stability: <50 mrad over 20 min
- CEP control: 8.8\(\pi\) linear shift

Nanotips for electron emission

Field enhancement: $f = 9$

Decay length: $L_f = 1.7$ nm

Localized electron emission

Numerical model

Spatio-temporal electric field distribution

\[
\vec{E}(\vec{r}, t) = E_0(\vec{r}) \exp(-2\sqrt{\ln 2}t^2 / \tau^2) \cos(\omega t)
\]

Fowler-Nordheim tunneling describes emission probability

\[
J(t) \propto \Theta(E(t)) |E(t)|^2 \exp\left(\frac{-4\sqrt{2m\Phi}^{3/2}}{3\hbar e|E(t)|}\right)
\]


G. Herink \textit{et al.}, Nature \textbf{483}, 190 (2012)
Numerical model

**Classical equation of motion** for the released electron, in temporally and spatially varying electric field

\[ m \ddot{r} = -e \vec{E}(\vec{r}, t) \]

Rescattering with the tip: 100% elastic collisions

Electron motion per emission site and time \( \Rightarrow \) (angle-resolved) kinetic energy spectra
Numerical model

Classical equation of motion for the released electron, in temporally and spatially varying electric field

\[ m \ddot{\vec{r}} = -e \vec{E}(\vec{r}, t) \]

Consider charged particle effects

⇒ Requires fully three-dimensional trajectory calculations

B. Piglosiewicz et al., Nature Photon. 9, 37 (2014)
B. Piglosiewicz et al., Quantum Matter (2014)
CEP dependence: expectation

B. Piglosiewicz et al., Nature Photon. 9, 37 (2014)
CEP dependence: measurement

B. Piglosiewicz et al., Nature Photon. 9, 37 (2014)
First observation of CEP effect from metallic nanostructures in strong-field regime

New control mechanism on sub-femtosecond electron motion

B. Piglosiewicz et al., Nature Photon. 9, 37 (2014)
New electron source

1. Controlled emission
   ⇒ few-nm area

2. Spatial motion control
   ⇒ order of nanometers

3. Temporal control
   ⇒ sub-femtosecond

⇒ A new class of electron source
⇒ Towards attosecond control and electron streaking
Summary

Strong-field emission and acceleration of electrons: unique to nanostructures

Control of electron motion

• Steering along field lines:
  Control via nanostructure shape

• Velocity change through the laser field phase:
  Control via temporal field

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