Attosecond laser systems and applications

Adrian N. Pfeiffer

Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

8th Annual Laser Safety Officer Workshop

September 11, 2012
Characteristic length and time scales

Atomic unit of time: 24 as

Electron orbit time around the nucleus in the first Bohr orbit: 150 as

Outline

Motivation for research on the attosecond timescale

Attosecond pulse generation
  – Femtosecond pulse generation
  – High harmonic generation
  – Isolating attosecond pulses

A few experiments
  – Inner-shell spectroscopy
  – Attoclock measurements
  – Valence electron motion

Conclusion
Femtosecond pulse generation

- Laser: Ti:Sapphire: 30 fs, 1 mJ, 800 nm, 1 kHz

- 2-stage filament compressor in Argon:
  - Self guiding in a noble gas - spectral broadening
  - Chirped mirrors for pulse compression and pre-compensation

Carrier Envelope Phase

\[ E_y = E_{0y}(t) \sin(\omega t + \phi_{CEO}) \]

Strong field ionization

Atomic potential in a strong laser field (length gauge)

Standard model for strong field ionization:
Semi-classical model

1st step:
Tunneling
Quantum picture

2nd step:
Newtonian motion
Classical picture

A. N. Pfeiffer et al., Nat. Phys. 8, 76 (2012)
Electron recollision

Possible consequences of recollision (i-iv)

(i) energetic electron emission by elastic backscattering of the electron

(ii) energetic photon emission upon the electron recombining into its ground state

(iii) detachment of another electron: non-sequential double ionization (NSDI)

(iv) excitation of bound electrons upon inelastic collision

High Harmonic Generation

Phase matching

Isolating attosecond pulses I: Amplitude Gating

Isolating attosecond pulses II: Double Optical Gating

Florida team sets new ultrashort pulse record

04 Sep 2012

*Laser pulse lasting just 67 attoseconds improves on previous best of 80 attoseconds set by German team in 2008.*

A new tool to watch quantum effects such as the movement of electrons in chemical reactions is closer to being realized, after a Florida research team set a new record for the world’s shortest laser pulse.

Measured at just 67 attoseconds, the mark set by Zenghu Chang and colleagues at the University of Central Florida improves on the previous best of 80 attoseconds, and gets closer to what is regarded as the crucial figure required to "see" electron dynamics and chemical reactions in action.

Chang told *optics.org* that, based on research published in 2005, it is believed that when an electron is suddenly removed, the universal response of molecular and atomic systems lasts for approximately 50 attoseconds. "67 attoseconds is a step closer to meeting the requirement of observing the 50 attoseconds universal response," he pointed out.

Chang and colleagues have been able to improve on the previous record, which was set by a group at the Max-Planck Institute for Quantum Optics in Garching that included the ultrashort-pulse pioneer Ferenc Krausz, thanks in part to the use of a new optical technique.
Outline

Motivation for research on the attosecond timescale

Attosecond pulse generation

– Femtosecond pulse generation

– High harmonic generation

– Isolating attosecond pulses

Applications

– Inner-shell spectroscopy

– Attoclock measurements

– Valence electron motion

Conclusion
Linear electron streaking

Atomic inner-shell spectroscopy

Time domain measurement of the M-shell vacancy lifetime in krypton: 7.9 fs

Angular electron streaking: Attoclock

Infrared electric field rotates around 360° within one optical cycle

Magnitude of electron momentum (envelope of the electric field)

Emission angle of electrons (rotating electric field vector)

Hour hand of the “Attoclock”

Minute hand of the “Attoclock”

Attoclock setup

COLTRIMS
(Cold Target Recoil Ion Momentum Spectroscopy)

A. N. Pfeiffer et al., Nat. Phys. 8, 76 (2012)
Attoclock measurements

Tunneling delay time
(He, single ionization)

Ionization times
(Ar, double ionization)

P. Eckle et al., Science 322, 1525 (2008)

Electro-Photography
Electro-Photography: Fast Systems

Frame rate: 60 /s

Frame rate: 1500 /s

Etienne Jules Marey, 1894

Attosecond transient absorption

Absorption of Kr$^{2+}$ and Kr$^{3+}$

Transient absorption

Population dynamics of the density matrix

Reconstruction of valence-shell electron wave-packet motion

Conclusion

**Attosecond pulse generation**

*Double optical gating*

![Diagram](image1)


**Attosecond experiments**

*Inner shell spectroscopy*

![Diagram](image2)


*Attoclock measurements*

![Diagram](image3)


*Valence electron motion*

![Diagram](image4)

E. Goulielmakis *et al.*, *Nature* **466**, 739 (2010)