Attosecond Physics: A New Adventure with Tony in the Ultrafast World

S. X. Hu (胡素兴)

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University of Rochester

In celebration of Prof. Anthony Starace's 70th Birthday
August 22, 2015

Outline

- **Attosecond physics: the forefront of ultrafast science**
- **My journey in the ultrafast world: probing/controlling ultrafast electron dynamics with attosecond pulses**
- **New adventure with Tony: attosecond control in AMO physics**
- **Summary**

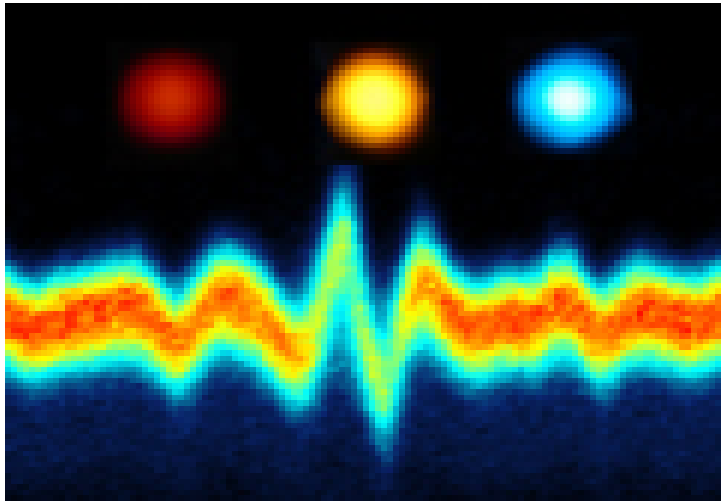
What is an attosecond?

1 attosecond = 10^{-18} second

1 attosecond to a second is like

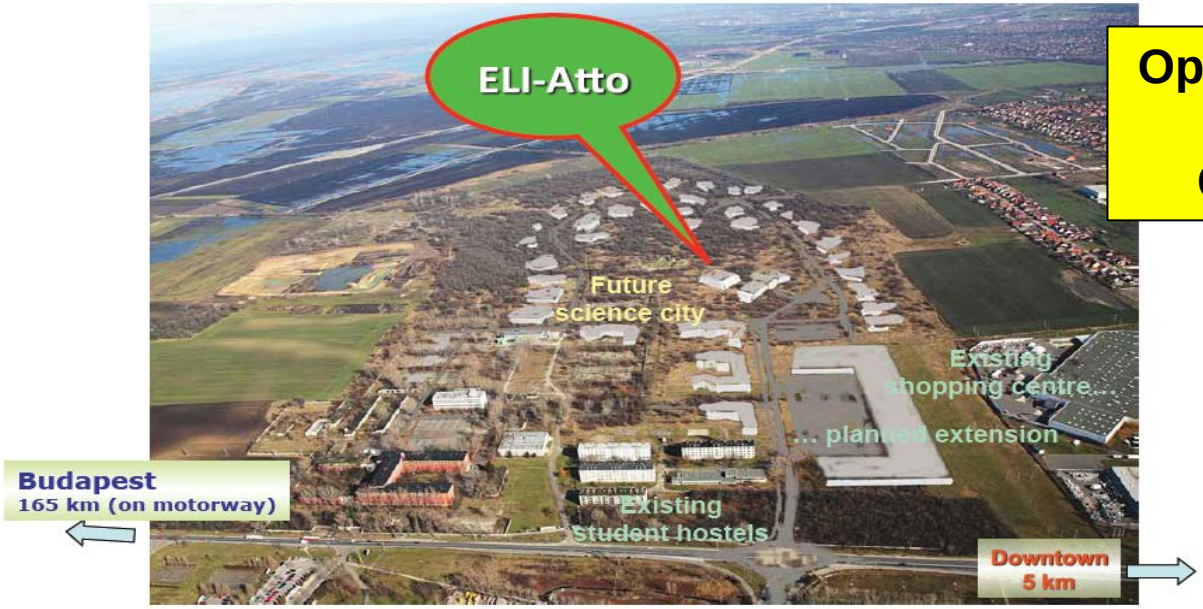
1 second to ~32 billion years!

Why do we need attosecond pulses?



To “take a picture” of the electron motion inside an atom or molecule, one needs attosecond pulses!

ELI-HU site and science park



Operational in 2018

Cost: ~300M €

MPC-AS
MAX-PLANCK CENTER FOR ATTOSECOND SCIENCE

Prof. F. Krausz, MPQ, Germany
Prof. J. Ullrich, MPI-NP, Germany
Prof. J.M. Rost, MPI-PCS, Germany
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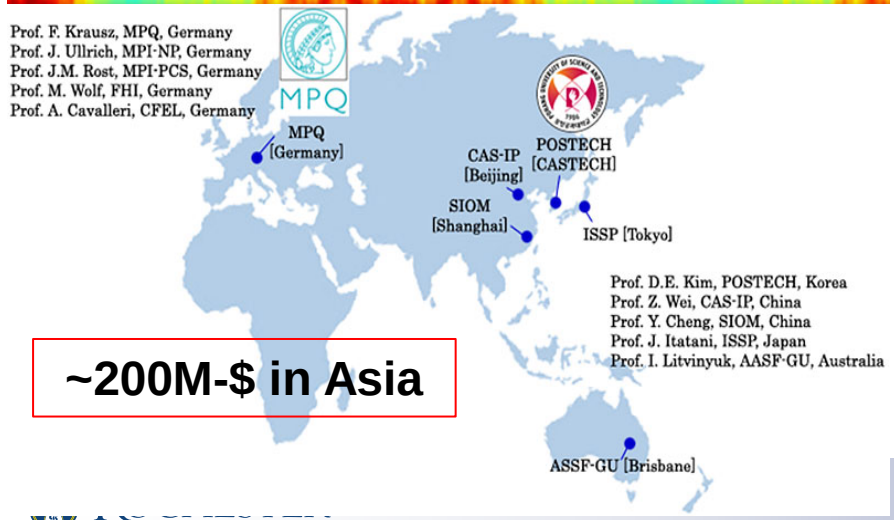

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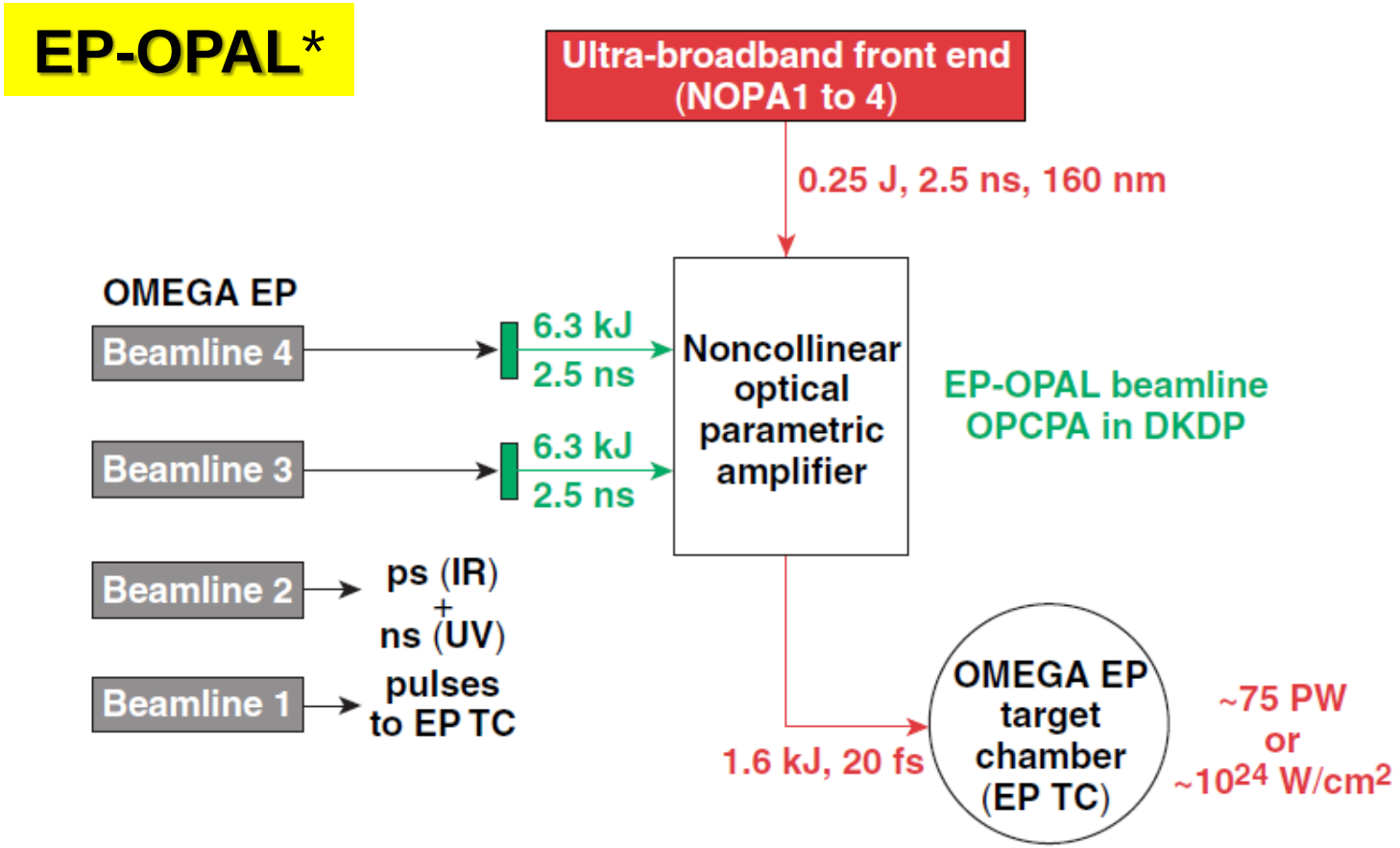
Prof. Z. Wei, CAS-IP, China
Prof. Y. Cheng, SIOM, China
Prof. J. Itatani, ISSP, Japan
Prof. I. Litvinyuk, AASF-GU, Australia

~200M-$ in Asia

< 50M-$

Attosecond science is one of the missions for the proposed super-powerful laser facility at LLE



* J. D. Zuegel *et al.*, CLEO (2014)
D. D.Meyerhoffer *et al.*, APS-DPP (2014)

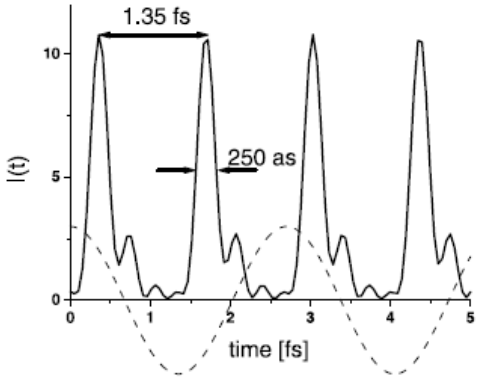
The "attosecond-era" has been begun since the two important papers published in 2001

SCIENCE VOL 292 1 JUNE 2001

Observation of a Train of Attosecond Pulses from High Harmonic Generation

P. M. Paul,[1] E. S. Toma,[2] P. Breger,[1] G. Mullot,[3] F. Augé,[3] Ph. Balcou,[3] H. G. Muller,[2]* P. Agostini[1]

In principle, the temporal beating of superposed high harmonics obtained by focusing a femtosecond laser pulse in a gas jet can produce a train of very short intensity spikes, depending on the relative phases of the harmonics. We present a method to measure such phases through two-photon, two-color photoionization. We found that the harmonics are locked in phase and form a train of 250-attosecond pulses in the time domain. Harmonic generation may be a promising source for attosecond time-resolved measurements.



NATURE | VOL 414 | 29 NOVEMBER 2001 | www.nature.com

Attosecond metrology

M. Hentschel*†, R. Kienberger*†, Ch. Spielmann*, G. A. Reider*, N. Milosevic*, T. Brabec*, P. Corkum‡, U. Heinzmann§, M. Drescher§ & F. Krausz*

* Institut für Photonik, Technische Universität Wien, Gusshausstr. 27, A-1040 Wien, Austria
‡ Steacie Institute of Molecular Sciences, NRC Canada, Ottawa, Canada K1A 0R6
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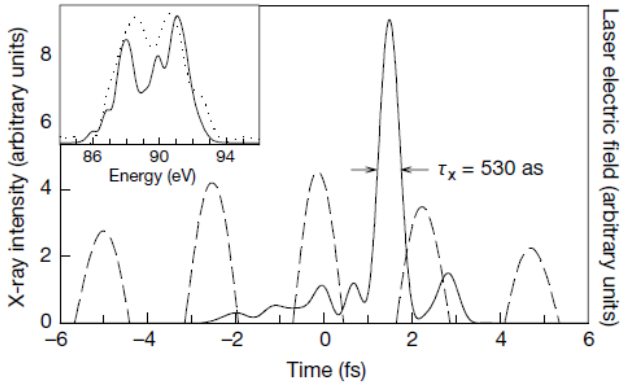
† These authors contributed equally to this work

The generation of ultrashort pulses is a key to exploring the dynamic behaviour of matter on ever-shorter timescales. Recent developments have pushed the duration of laser pulses close to its natural limit—the wave cycle, which lasts somewhat longer than one femtosecond ($1\ fs = 10^{-15}\ s$) in the visible spectral range. Time-resolved measurements with these pulses are able to trace dynamics of molecular structure, but fail to capture electronic processes occurring on an attosecond ($1\ as = 10^{-18}\ s$) timescale. Here we trace electronic dynamics with a time resolution of ≤ 150 as by using a subfemtosecond soft-X-ray pulse and a few-cycle visible light pulse. Our measurement indicates an attosecond response of the atomic system, a soft-X-ray pulse duration of 650 ± 150 as and an attosecond synchronism of the soft-X-ray pulse with the light field. The demonstrated experimental tools and techniques open the door to attosecond spectroscopy of bound electrons.



Some neat attosecond experiments in this "new-born" field

NATURE | VOL 419 | 24 OCTOBER 2002 | www.nature.com/nature

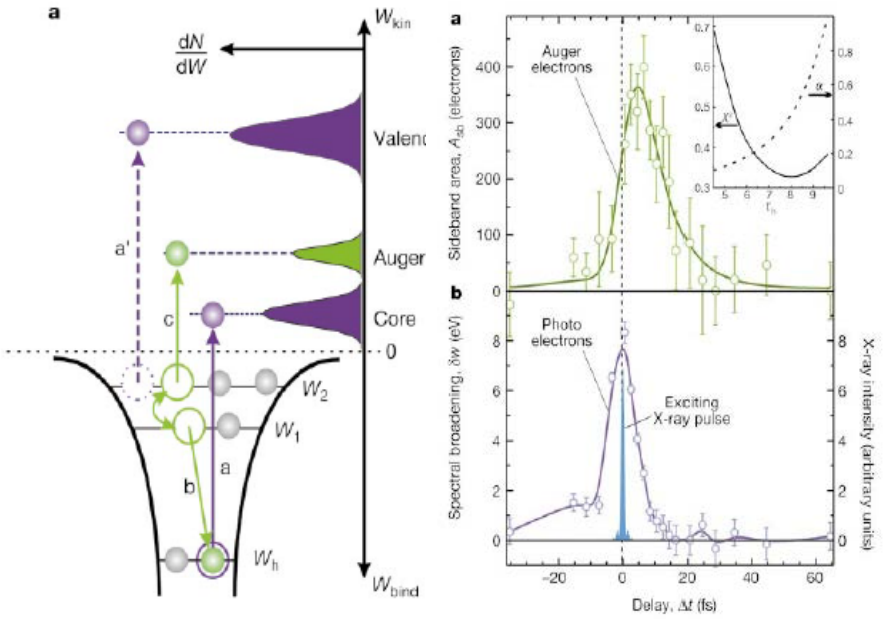
articles

Time-resolved atomic inner-shell spectroscopy

M. Drescher*†, M. Hentschel*, R. Kienberger*, M. Uiberacker*, V. Yakovlev*, A. Scrinzi*, Th. Westerwalbesloh†, U. Kleineberg†, U. Heinzmann† & F. Krausz*

* Institut für Photonik, Technische Universität Wien, Gusshausstrasse 27, A-1040 Wien, Austria
† Fakultät für Physik, Universität Bielefeld, Universitätstrasse 25, D-33615 Bielefeld, Germany

The characteristic time constants of the relaxation dynamics of core-excited atoms have hitherto been inferred from the linewidths of electronic transitions measured by continuous-wave extreme ultraviolet or X-ray spectroscopy. Here we demonstrate that a laser-based sampling system, consisting of a few-femtosecond visible light pulse and a synchronized sub-femtosecond soft X-ray pulse, allows us to trace these dynamics directly in the time domain with attosecond resolution. We have measured a lifetime of $7.9^{+1.6}_{-0.9}$ fs of M-shell vacancies of krypton in such a pump–probe experiment.

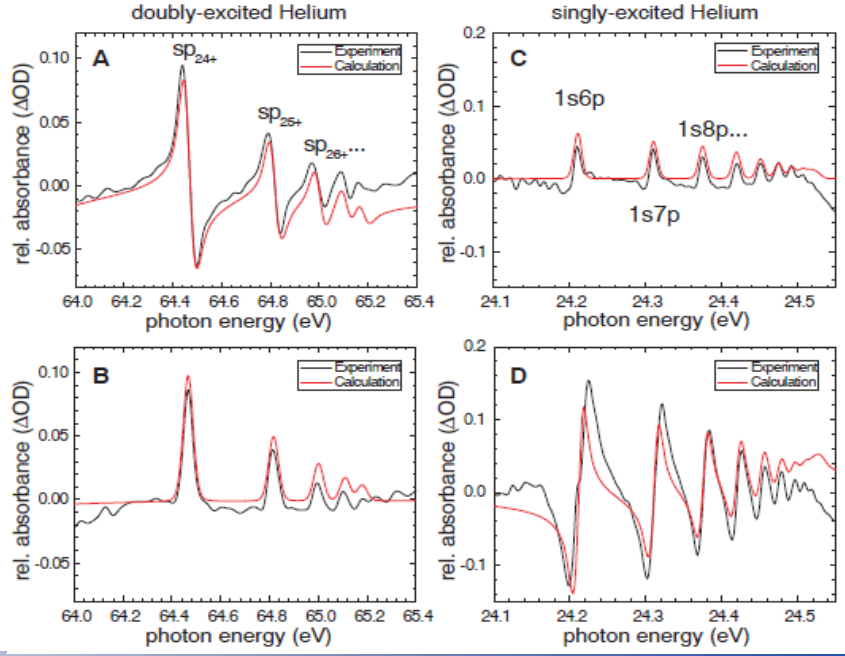


10 MAY 2013 VOL 340 SCIENCE www.sciencemag.org

Lorentz Meets Fano in Spectral Line Shapes: A Universal Phase and Its Laser Control

Christian Ott,[1] Andreas Kaldun,[1] Philipp Raith,[1] Kristina Meyer,[1] Martin Laux,[1] Jörg Evers,[1] Christoph H. Keitel,[1] Chris H. Greene,[3] Thomas Pfeifer[1,2]*

Symmetric Lorentzian and asymmetric Fano line shapes are fundamental spectroscopic signatures that quantify the structural and dynamical properties of nuclei, atoms, molecules, and solids. This study introduces a universal temporal-phase formalism, mapping the Fano

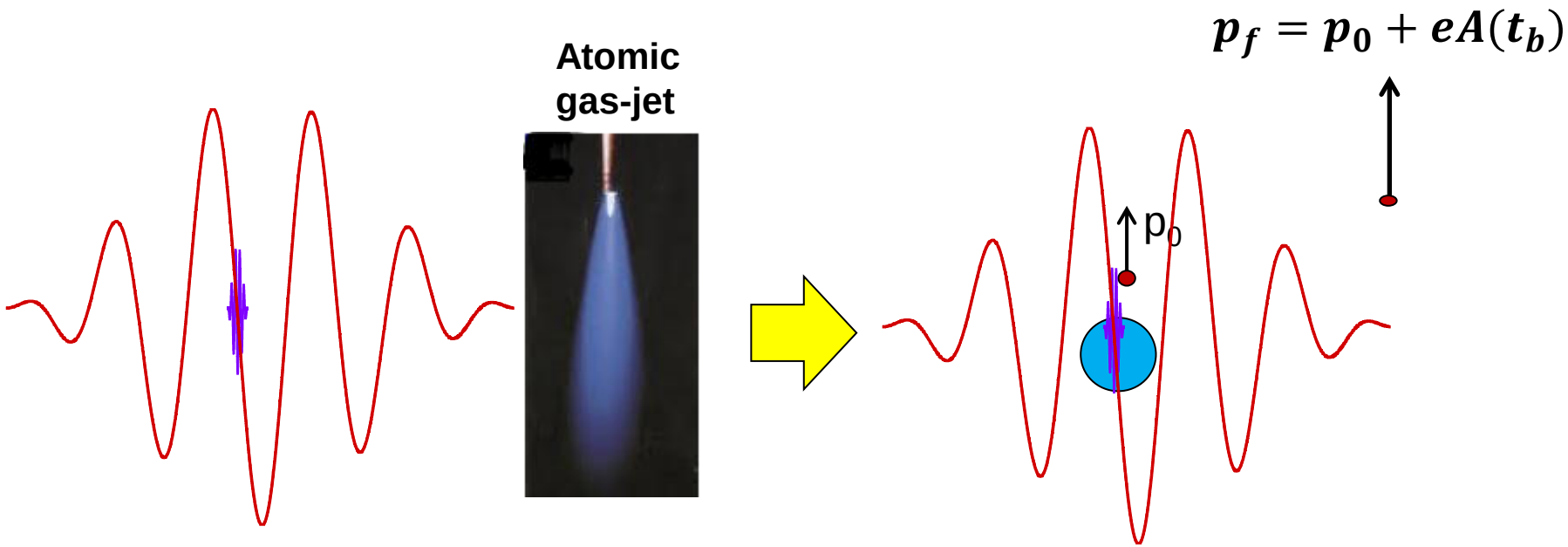


Outline

- Attosecond physics: the forefront of ultrafast science

- **My journey in the ultrafast world: probing/controlling ultrafast electron dynamics with attosecond pulses**

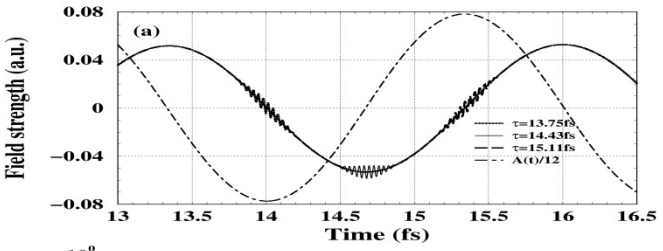
My “journey” of learning attosecond physics started in 2002 when I was a postdoc in Tony’s group

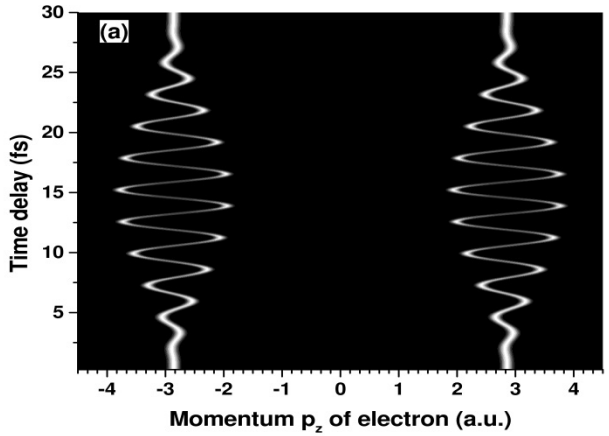


$$p_0 = \sqrt{2m(\hbar\omega_A - I_p)} \;\; ; \;\; \mathrm{E}(t) = -\partial A(t)/\partial t$$

By measuring the final electron momentum at different time delays, one can directly “map” out the oscillating field strength of an ultrashort IR-pulse!

The TDSE calculations showed that one can indeed "map-out" the dressing IR-field





VOLUME 89, NUMBER 28 PHYSICAL REVIEW LETTERS 31 DECEMBER 2002

Measuring the Electric Field of Few-Cycle Laser Pulses by Attosecond Cross Correlation

Andre D. Bandrauk,* Szczepan Chelkowski, and Nguyen Hong Shon†

Laboratoire de Chimie Theorique, Faculte des Sciences, Université de Sherbrooke, Quebec, J1K 2R1, Canada

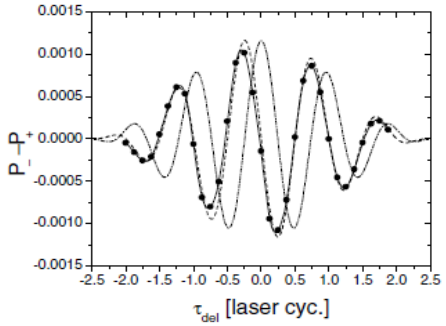
(Received 5 August 2002; published 31 December 2002)

A new technique for directly measuring the electric field of linearly polarized few-cycle laser pulses is proposed. Based on the solution of the time-dependent Schrödinger equation (TDSE) for an H atom in the combined field of infrared (IR) femtosecond (fs) and ultraviolet (UV) attosecond (as) laser pulses we show that, as a function of the time delay between two pulses, the *difference* (or equivalently, *asymmetry*) of photoelectron signals in opposite directions (along the polarization vector of laser pulses) reproduces very well the profile of the electric field (or vector potential) in the IR pulse. Such ionization asymmetry can be used for directly measuring the *carrier-envelope phase difference* (i.e., the relative phase of the carrier frequency with respect to the pulse envelope) of the IR fs laser pulse.

DOI: 10.1103/PhysRevLett.89.283903 PACS numbers: 42.65.Re, 32.80.Rm, 42.65.Ky

Recently, the first experimental results on the production and measurement of a single, soft x-ray, 650 as pulse, were reported [1–4] using high-order harmonic generation (HHG). Such as pulses can be focused to achieve the intensities that are comparable to the conventional Ti:sapphire lasers, i.e., $I_{as} \sim 10^{14}$ W/cm^2 [5,6]. This opens up new possibilities for studying and controlling electron dynamics in atoms and molecules on as time scales [7–10]. Few-cycle intense laser pulses in the 800-

pulses one ionizes an atomic (or molecular) gas. The UV photon energy $\hbar\omega_{as}$ is chosen to be close to the ionization potential W_p. It will be shown that under the action of combined IR fs and UV as pulses the ionization probability significantly increases (by $1 \sim 3$ orders as compared to the one produced by a single fs or as pulse). Plotting the *difference* of photoelectron numbers in opposite directions (along the polarization vector of the laser field) allows for measuring the *asymmetry* as a function of



"Great minds think alike"?

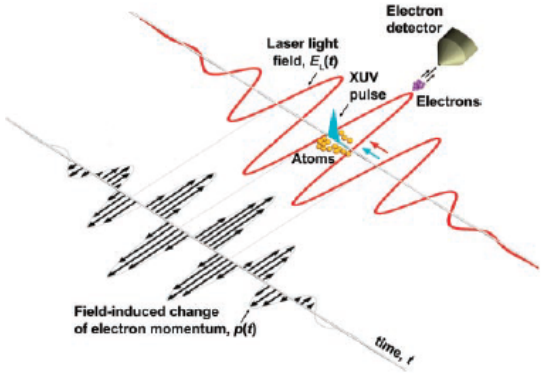
The exactly-same experiment was published in SCIENCE just two years later……

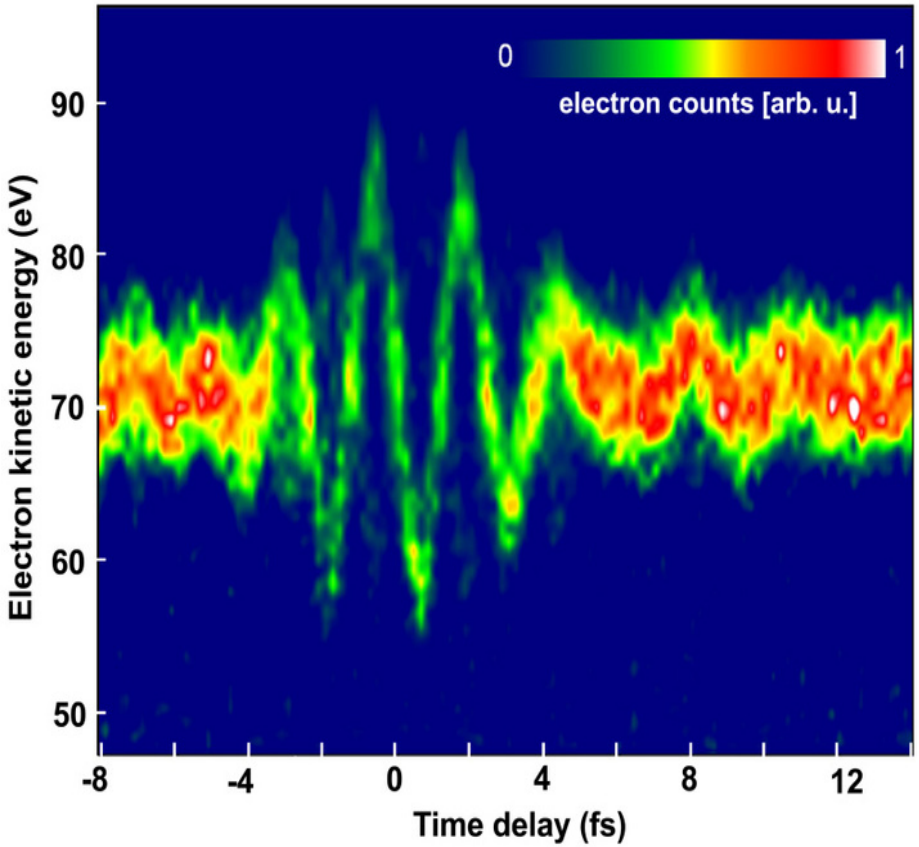
SCIENCE VOL 305 27 AUGUST 2004

Direct Measurement of Light Waves

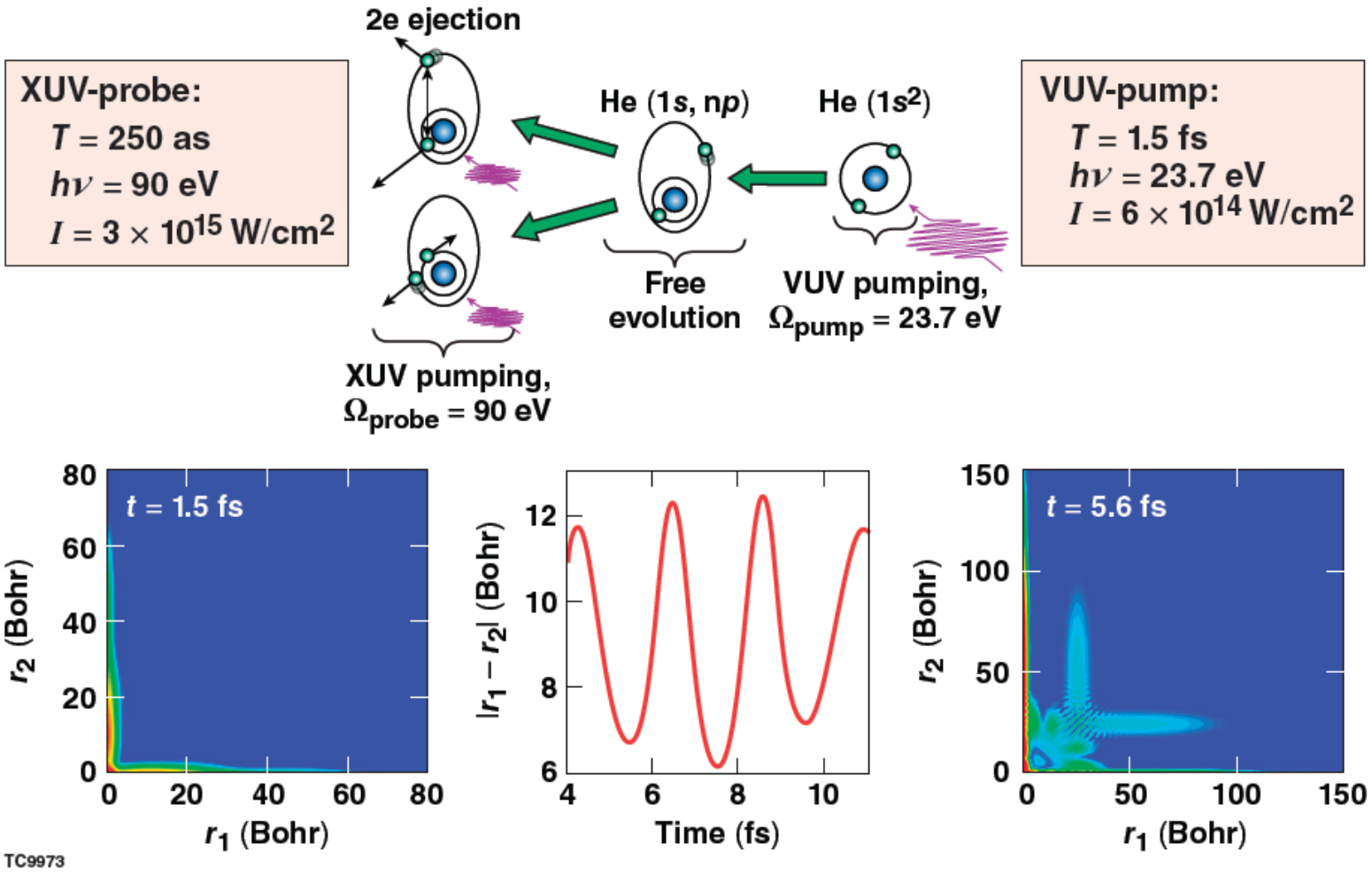
E. Goulielmakis,[1]* M. Uiberacker,[1]* R. Kienberger,[1] A. Baltuska,[1] V. Yakovlev,[1] A. Scrinzi,[1] Th. Westerwalbesloh,[2] U. Kleineberg,[2] U. Heinzmann,[2] M. Drescher,[2] F. Krausz[1,3]†

The electromagnetic field of visible light performs ~10^{15} oscillations per second. Although many instruments are sensitive to the amplitude and frequency (or wavelength) of these oscillations, they cannot access the light field itself. We directly observed how the field built up and disappeared in a short, few-cycle pulse of visible laser light by probing the variation of the field strength with a 250-attosecond electron burst. Our apparatus allows complete characterization of few-cycle waves of visible, ultraviolet, and/or infrared light, thereby providing the possibility for controlled and reproducible synthesis of ultrabroadband light waveforms.

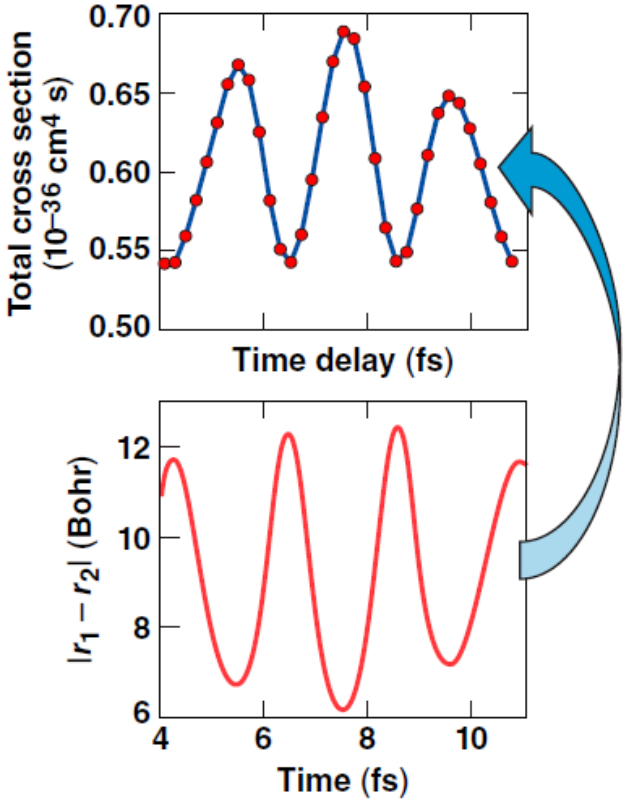


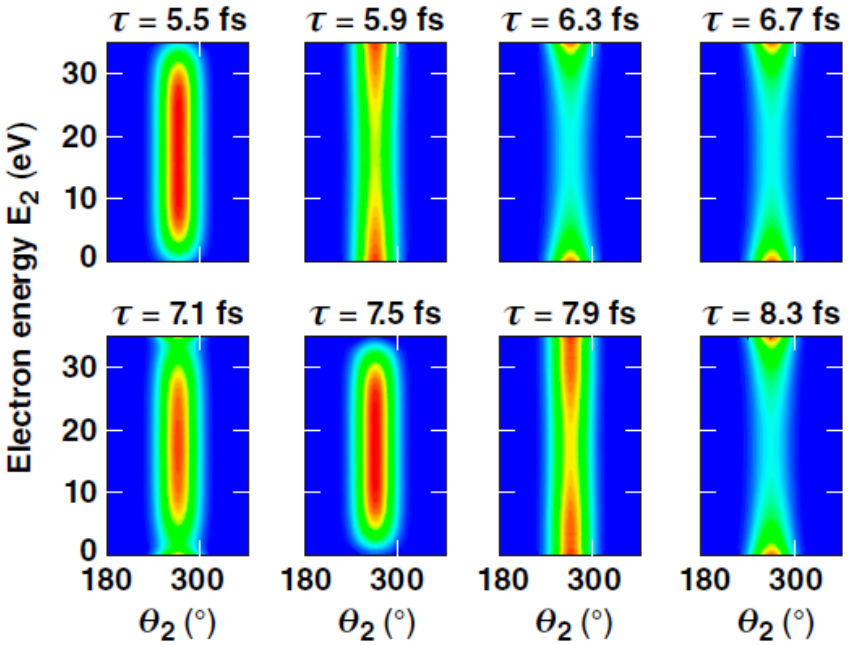


Attosecond pump-probe was proposed to explore the ultrafast electron motion in atoms in 2006



The ultrafast motion of electron wave-packet can be "mapped" out by time-delayed attosecond pulses





The two-electron energy sharing also indicates the dynamic evolution of the wave packet.

TC9974

*S. X. Hu and L. A. Collins, Phys. Rev. Lett. 96, 073004 (2006).

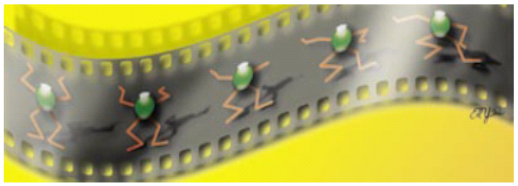
This work has been highlighted and widely cited shortly after its publication

Los Alamos NATIONAL LABORATORY EST. 1943

NewsLetter

Week of March 13, 2006 — Vol. 7, No. 6

Inside this issue ...



Attosecond pump-probe proposed to explore the dance of electrons

by Todd Hanson

Electrons in atoms move in a choreographed motion on a time scale of attoseconds (one quintillionth, or one billionth of a billionth of a second). To observe this ultrafast motion, physicists at Los Alamos have theoretically demonstrated an attosecond pump-probe technique that captures the steps in this intricate dance by ionizing the atom at selected times. The development of the proposed technique might someday allow scientists to actually see into a world of electron motion.

In research published recently in Physical Review Letters, Suxing Hu and Lab Fellow Lee Collins, both of Atomic and Optical Theory (T-4), describe their work in modeling the dynamics of an attosecond probe, one of the first steps in building such a device. Based on existing femtosecond (quadrillionths of a second) devices that use ultrashort laser pulses to capture the motion of atoms in molecules, an attosecond pump-probe would use extreme ultraviolet pulses to capture the motion of electrons in atoms.

According to Hu, the principal investigator for the project, "the generation of extremely short EUV pulses has shown great progress in the last few years. The attosecond pump-probe technique described in our paper could provide a substantial advance in the rapidly developing field of 'attosecond science' and could aid physicists, chemists and biologists in examining and manipulating ultrafast motions of electrons in atoms, molecules, clusters and even nanostructures."

Working much like a strobe light that helps capture stop-action photographs of a falling drop of water, a current generation of femtosecond probes use laser pulses to capture the fast motion of atoms during chemical reactions. Using attosecond pulses of extreme ultraviolet radiation, Hu and Collins believe it may be possible to capture the even faster motion of electrons within atoms and molecules.

UR LLE

REVIEWS OF MODERN PHYSICS, VOLUME 81, JANUARY–MARCH 2009

Attosecond physics

Ferenc Krausz

Department für Physik, Ludwig-Maximilians-Universitat, Am Coulombwall 1, D-85748 Garching, Germany and Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany

Misha Ivanov

Steacie Institute for Molecular Sciences, National Research Council of Canada, 100 Sussex Drive, Ottawa, Ontario, Canada K1A 0R6

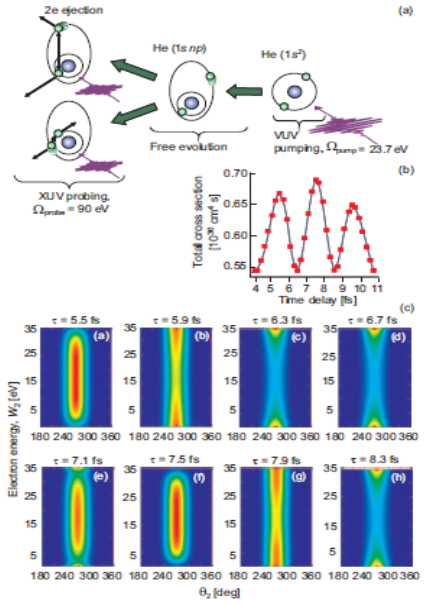


FIG. 51. (Color) Tracing intra-atomic electron motion and electron-electron interactions in helium (Hu and Collins, 2006). (a) Relevant interactions with the VUV pump (Ω_{pump} =23.7 eV, τ_{pump}=1.5 fs) and XUV probe pulse (Ω_{probe}=90 eV,

tion. Consequently, attos
copy (APS) uncovers the
in the bound electron wa
with spin-sensitive detecti
namics (Santra *et al.*, 200
time. Experimental imple
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In the above example, a
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ionizing IR field—it can a
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Attosecond atomic (mo
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electrons is therefore vary
Hu and Collins (2006) p
double ionization induc
XUV probe pulse signific

UNIVERSITY of ROCHESTER

The proposed pump-probe technique has been cited as a “drive-force” for producing intense attosecond pulses

nature photonics

REVIEW ARTICLES

PUBLISHED ONLINE: 18 SEPTEMBER 2011 | DOI: 10.1038/NPHOTON.2011.167

High-energy attosecond light sources

Giuseppe Sansone[1], Luca Poletto[2] and Mauro Nisoli[1]*

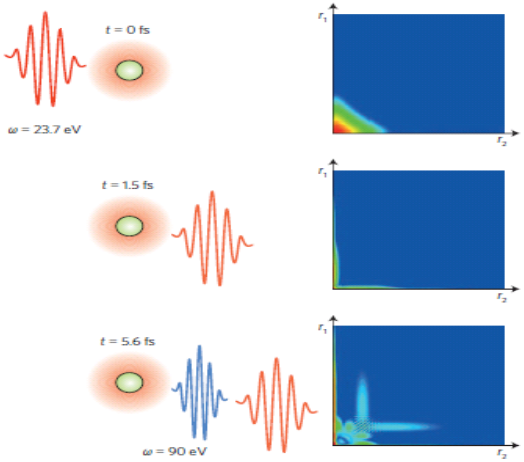


Figure 6 | Attosecond pump–probe experiment for investigating electron motion inside an atom. The first pump XUV pulse (central energy of 23.7 eV) excites the ground state to the superposition 1s + 1s*np*. The radial distributions in the (r_1, r_2) plane are shown before (t = 0 fs) and after (t = 1.5 fs) the pump pulse. The wave packet evolves in time on a timescale of a few femtoseconds, thus determining a 'breathing mode' of the radial density of the two electrons. This motion can be imaged by doubly ionizing the system using an intense attosecond pulse centred at 90 eV. After the probe pulse, the radial density distribution shows that the electrons are at large radial distances of r_1 and r_2, which corresponds to double ionization. Figure reproduced with permission from ref. 79, © 2006 APS.

Such an interferometric technique forms the basis of the recently developed attosecond nonlinear Fourier transform spectroscopy technique — a very powerful method for characterizing coupled electronic–nuclear dynamics in molecules. The first experiments to use this technique were performed in CO_2 (ref. 75) and D_2 (ref. 76). In general, the interferometric trace of the attosecond pulse train as a function of the delay between two pulse replicas, $I(\tau)$, can be written as:

$$I(\tau) = \sum_{p,q} I_{p,q}(\tau)$$

where the single terms $I_{p,q}$ can be expressed as:

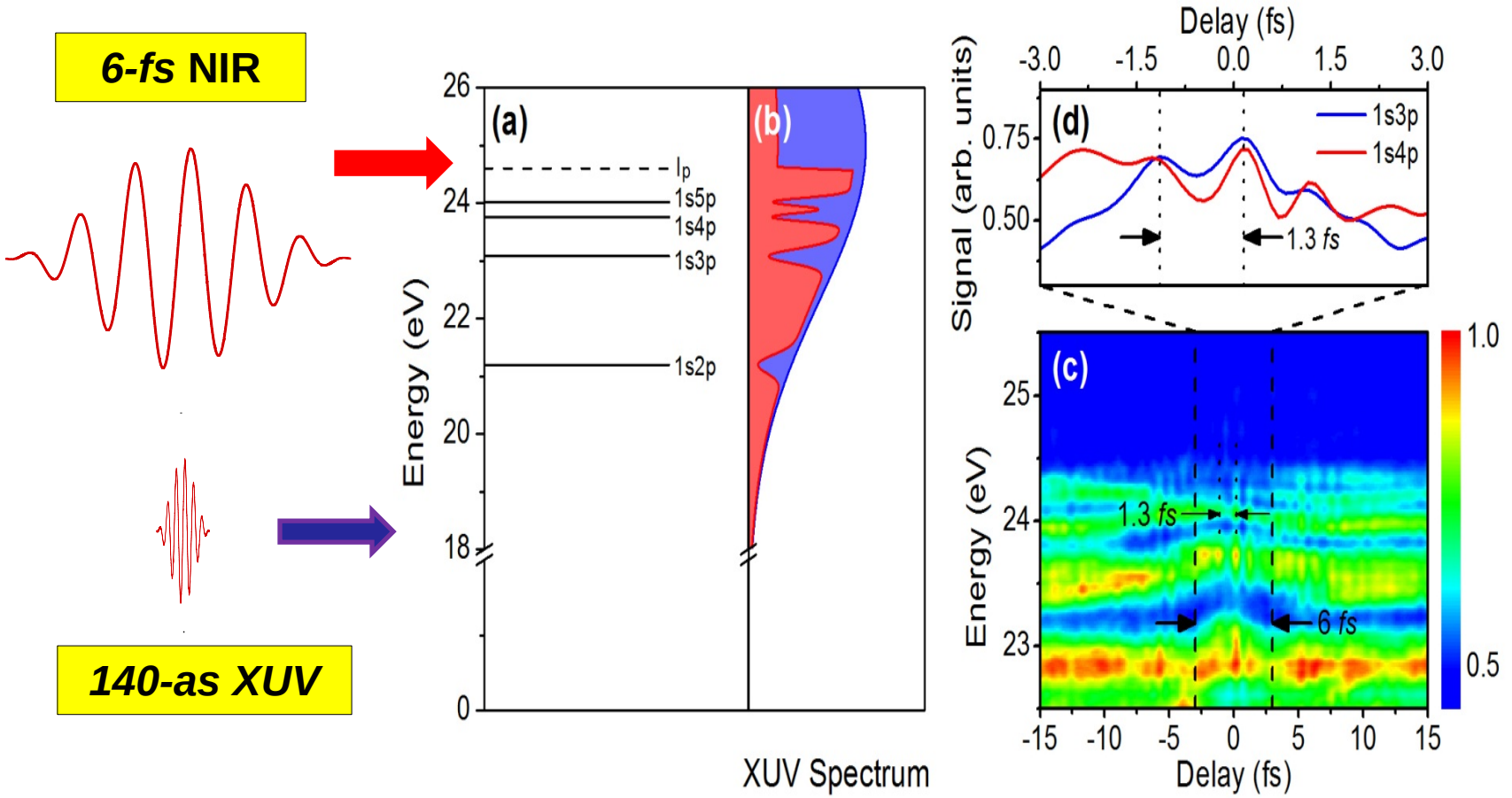
$$I_{p,q}(\tau) = \sigma_{p,q} \int \left| [E_{2p+1}(t-\tau) + E_{2p+1}(t)][E_{2q+1}(t-\tau) + E_{2q+1}(t)] \right|^2 \mathrm{d}t$$

$$= \sigma_{p,q} \int [F_b + F_{IC}(\tau) + F_p(\tau) + F_q(\tau) + F_{p-q}(\tau) + F_{p+q}(\tau)]\, \mathrm{d}t \quad (1)$$

The term $\sigma_{p,q}$ represents the cross-section for the absorption of one photon of the $2q + 1$ harmonic and one photon of the $2p + 1$ harmonic. The term F_b represents a constant background given by the two-photon signal associated with the two pulses separately, and does not depend on the relative delay τ. The term $F_{IC}(\tau)$ gives the intensity autocorrelation of the electric field; the terms $F_p(\tau)$, $F_q(\tau)$, $F_{p-q}(\tau)$ and $F_{p+q}(\tau)$ are functions oscillating at $2p + 1$, $2q + 1$, $2(p - q)$ and $2(p + q + 1)$ times the fundamental frequency ν_0, respectively. Fourier analysis of the measured signal allows the different Fourier components to be isolated and provides physical insight into the nonlinear photoabsorption process (that is, the order of the harmonic fields involved in the photoabsorption process).

Nonlinear Fourier transform spectroscopy has been used to retrieve information about the photodissociation of D_2 molecules by irradiating D_2 molecules with an attosecond pulse train containing harmonics from the first to the 19th order[76]. The D^+ signal, shown in Fig. 5a as a function of τ, exhibits periodic modulations with different periods in three kinetic energy regions, (i), (ii) and (iii), shown in Fig. 5a,b. Analysis of the oscillation frequencies indicates that the generation of D^+ ions proceeds through the absorp-

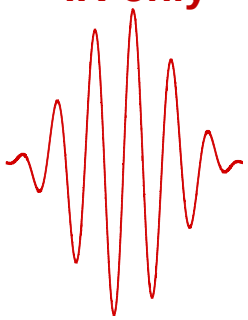
Instantaneous AC-Stark shift of excited states in He were probed with attosecond pulses (in collaboration with experimental group at UCF)*

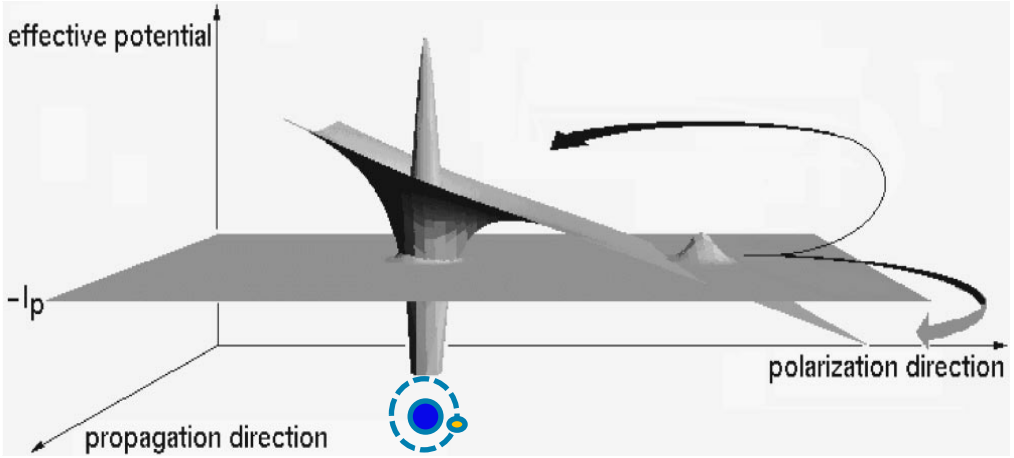


* M. Chini, B. Zhao, H. Wang, Y. Cheng, S. X. Hu, Z. Chang, Phys. Rev. Lett. 109, 073601 (2012).

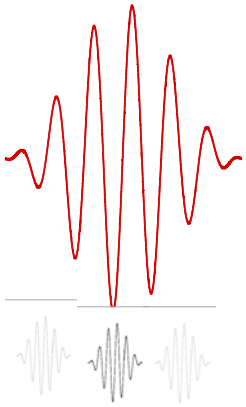
Can one control the electron correlation to boost photo-absorption in double-ionization (DI) of He?

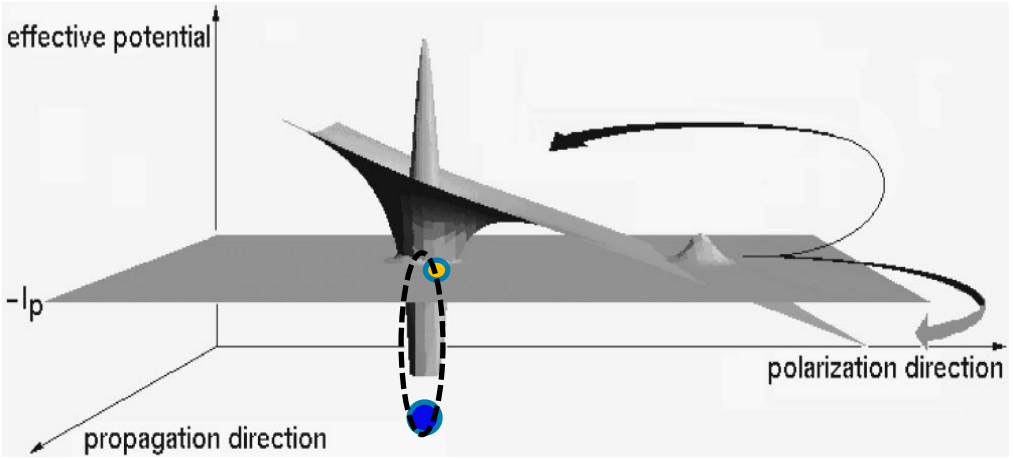
IR-only



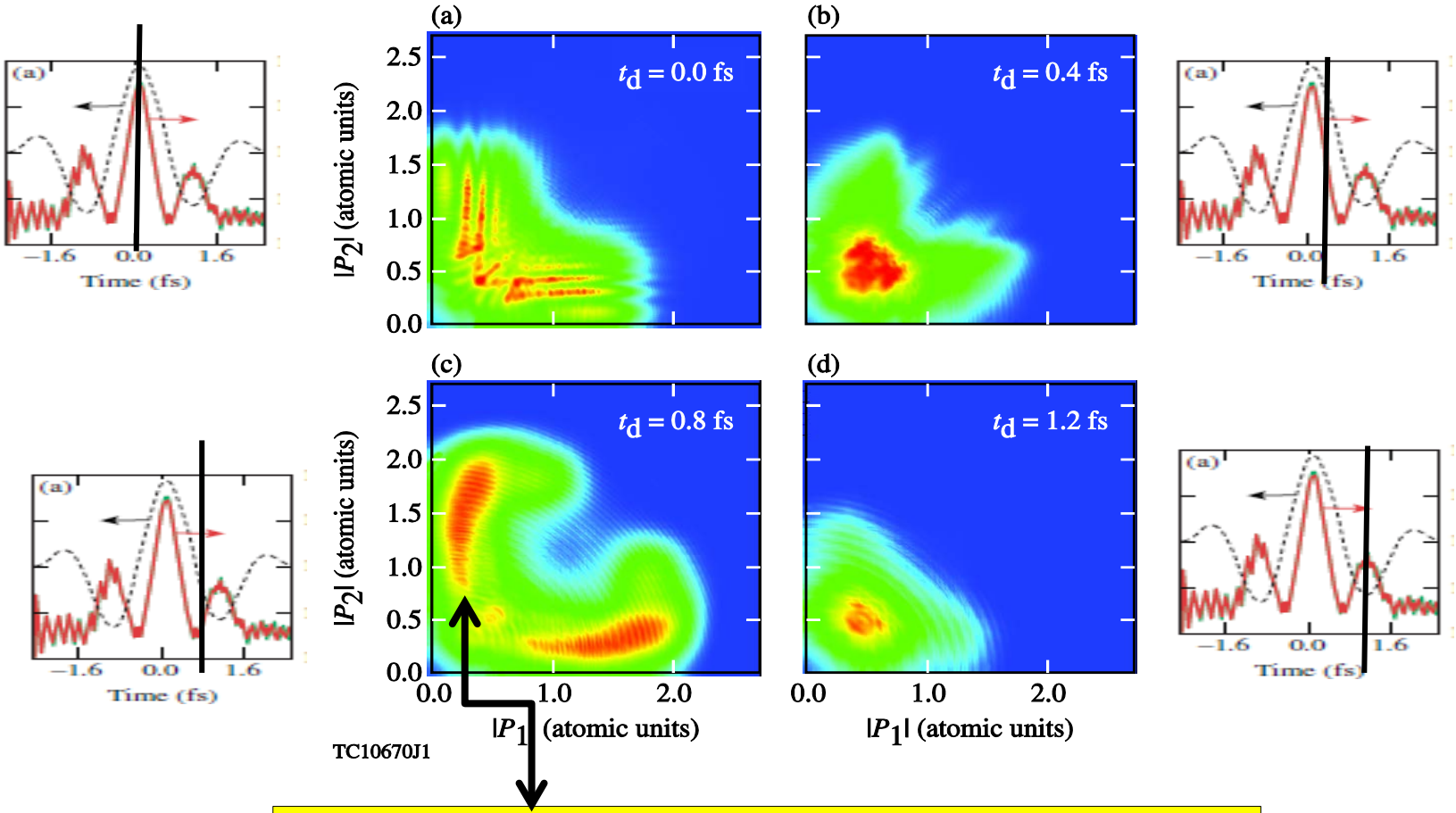


IR+Atto-EUV





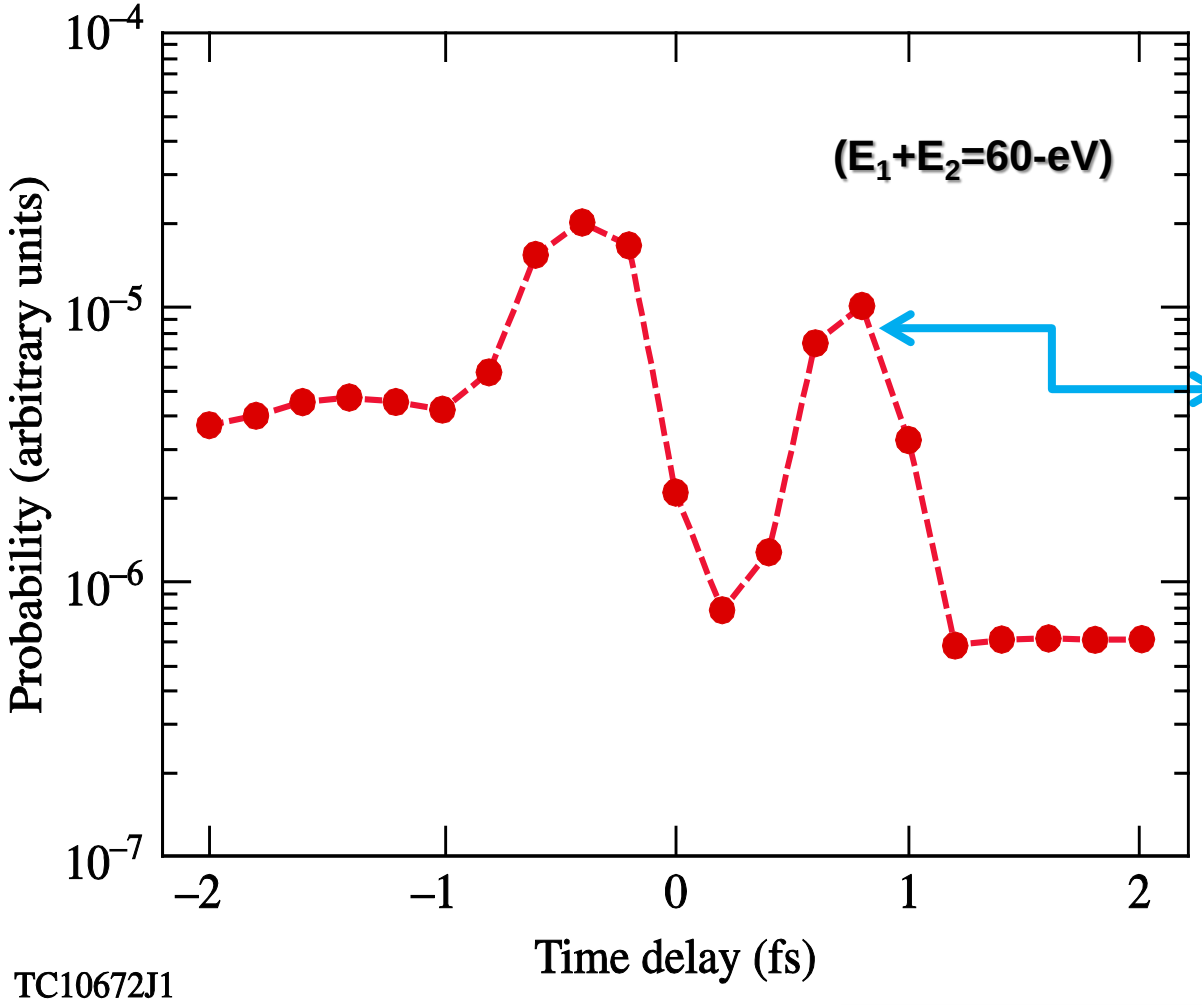
The momentum distribution of He-DI manifests the enhanced photo-absorption due to the strong *e*-*e* correlation



$E_1[E_2] = 3.2U_p + 12h\nu_{IR} \approx 36+18 = 54\text{-eV}$

$E_2[E_1] = h\nu_{EUV} - I_{p2} + 12h\nu_{IR} \approx 41-54.4+18 = 3.6\text{-eV}$

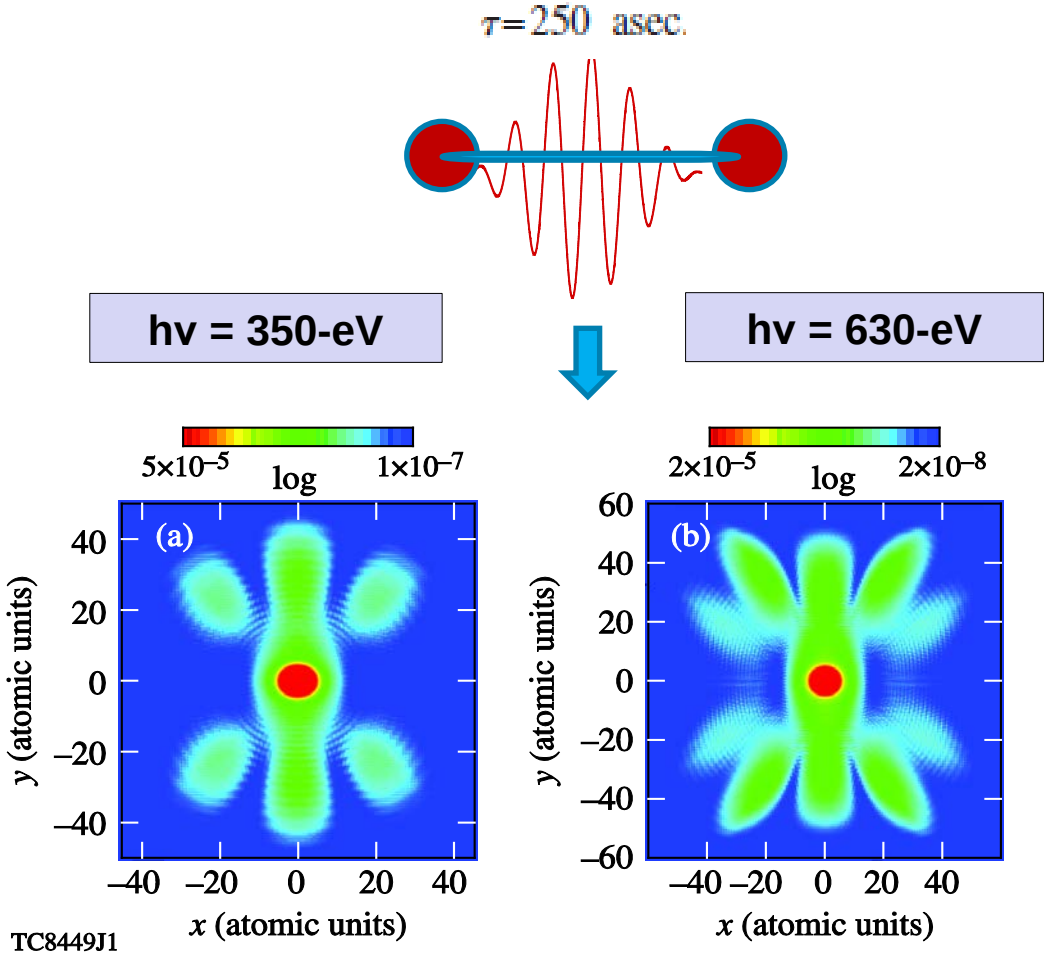
The probability of energetic electrons oscillates with the time delay by half-period of the IR field*



Due to excessive IR-photon absorption induced by the strong *e-e* correlation

* S. X. Hu, Phys. Rev. Lett. 111, 123003 (2013)

“Double-slit” interference patterns can be used to infer the inter-nucleus distance at the instant of the attosecond pulse striking*



❖ S. X. Hu, L. A. Collins & B. I. Schneider, Phys. Rev. A 80, 023426 (2009) (P).

Viewpoint

Illuminating molecules from within

Marc J. J. Vrakking
FOM Institute for Atomic and Molecular Physics (AMOLF), Science Park 113, Amsterdam, 1098 XG, The Netherlands

Published August 31, 2009

Calculations show that with new short pulse x-ray light sources, it should be possible to use photoelectr emission to make movies of changes in molecular structure.

Subject Areas: **Atomic and Molecular Physics, Optics**

A Viewpoint on:
Attosecond photoelectron microscopy of H_2^+
S. X. Hu, L. A. Collins and B. I. Schneider
Phys. Rev. A **80**, 023426 (2009) – Published August 31, 2009

Much of our knowledge about molecular structure and reactivity is based on interpreting how molecules interact with light. In particular, time-resolved pump-

have been observed previously at synchr the photoionization of CO molecules by La workers [2].

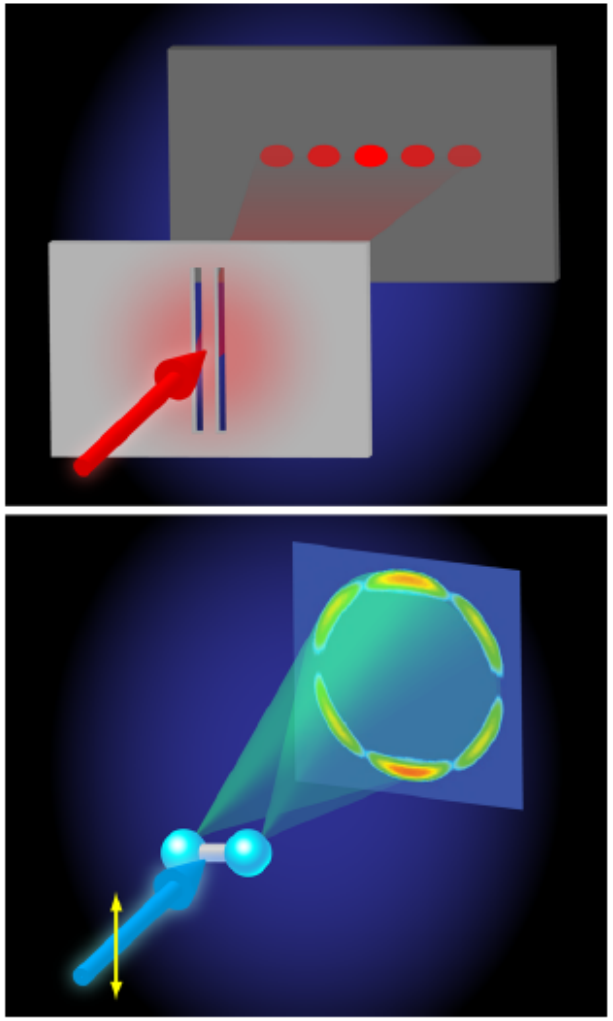


FIG. 1: (Top) In Young's double-slit experiment light falls onto two slits and is detected on a screen placed behind the slits. An interference pattern is observed, because one cannot determine whether the light passed through the right or left slit. (Bottom) In the experiment proposed by Hu, Collins, and Schneider, x-ray photons eject the single electron from H_2^+.

Outline

- Attosecond physics: the forefront of ultrafast science
- My journey in the ultrafast world: probing/controlling ultrafast electron dynamics with attosecond pulses
- **New adventure with Tony: attosecond control in AMO physics**

Electron correlation plays an important role in single ionization of He in the vicinity of autoionization resonance*

New Journal of Physics
The open-access journal for physics

Enhanced asymmetry in few-cycle attosecond pulse ionization of He in the vicinity of autoionizing resonances

J M Ngoko Djiokap[1], S X Hu[2], Wei-Chao Jiang[3], Liang-You Peng[3] and Anthony F Starace[1,4]

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Received 29 May 2012
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Online at http://www.njp.org/
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RAPID COMMUNICATIONS

PHYSICAL REVIEW A 88, 011401(R) (2013)

Asymmetries in production of $He^+(n = 2)$ with an intense few-cycle attosecond pulse

J. M. Ngoko Djiokap,[1] S. X. Hu,[2] Wei-Chao Jiang,[3] Liang-You Peng,[3] and Anthony F. Starace[1]
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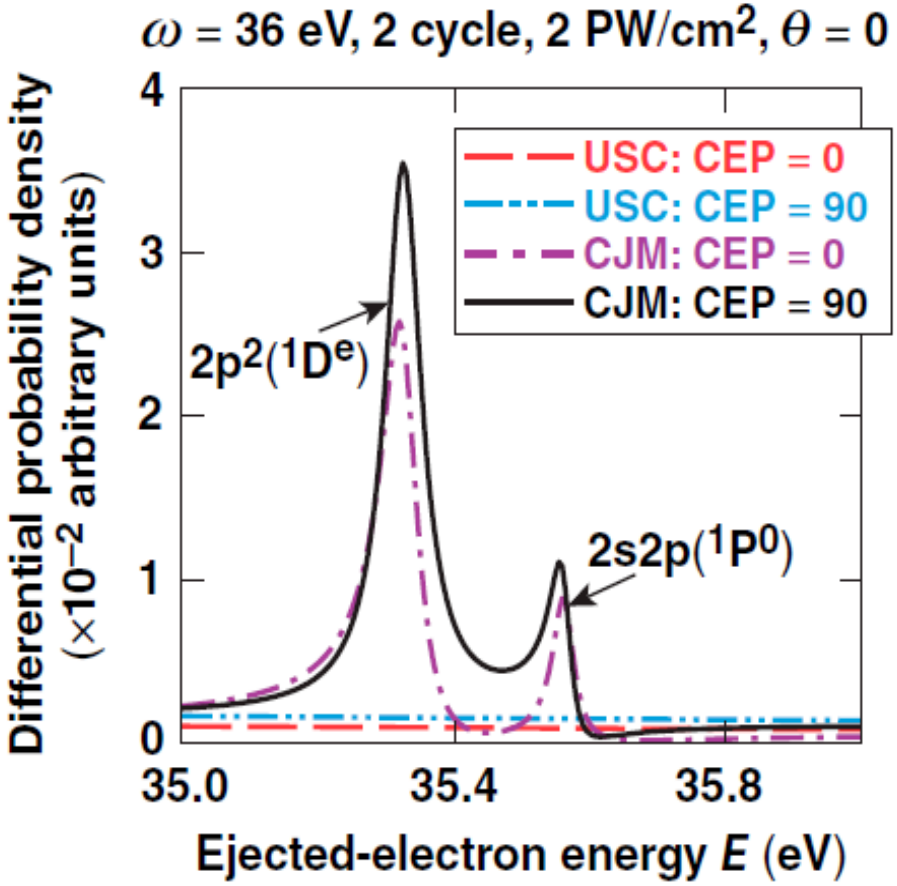
[2]*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*
[3]*State Key Laboratory for Mesoscopic Physics and Department of Physics, Peking University, Beijing 100871, China*
(Received 26 October 2012; published 8 July 2013)

By solving the two-electron time-dependent Schrödinger equation, we study carrier-envelope-phase (CEP) effects on ionization plus excitation of He to $He^+(n = 2)$ states by a few-cycle attosecond pulse with a carrier frequency of 51 eV. For most CEPs the asymmetries in the photoelectron angular distributions with excitation of $He^+(2s)$ or $He^+(2p)$ have opposite signs and are two orders of magnitude larger than for ionization without excitation. These results indicate that attosecond pulse CEP effects may be significantly amplified in correlated two-electron ionization processes.



Controlling double-ionization of He by an elliptically-polarized attosecond pulse has been demonstrated

PRL 113, 223002 (2014) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2014

Nonlinear Dichroism in Back-to-Back Double Ionization of He by an Intense Elliptically Polarized Few-Cycle Extreme Ultraviolet Pulse

J. M. Ngoko Djiokap,[1] N. L. Manakov,[2] A. V. Meremianin,[2] S. X. Hu,[3] L. B. Madsen,[4] and Anthony F. Starace[1]
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[3]*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*
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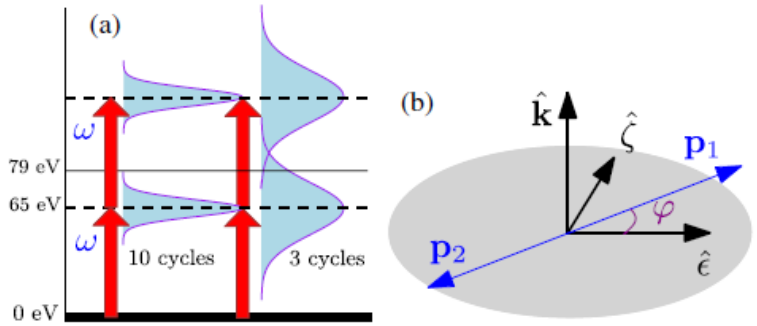
(Received 13 May 2014; revised manuscript received 2 October 2014; published 26 November 2014)

Control of double ionization of He by means of the polarization and carrier-envelope phase (CEP) of an intense, few-cycle extreme ultraviolet (XUV) pulse is demonstrated numerically by solving the six-dimensional two-electron, time-dependent Schrödinger equation for He interacting with an elliptically polarized XUV pulse. Guided by perturbation theory (PT), we predict the existence of a nonlinear dichroic effect ($\propto I^{3/2}$) that is sensitive to the CEP, ellipticity, peak intensity I, and temporal duration of the pulse. This dichroic effect (i.e., the difference of the two-electron angular distributions for opposite helicities of the ionizing XUV pulse) originates from interference of first- and second-order PT amplitudes, allowing one to probe and control S- and D-wave channels of the two-electron continuum. We show that the back-to-back in-plane geometry with unequal energy sharing is an ideal one for observing this dichroic effect that occurs only for an elliptically polarized, few-cycle attosecond pulse.

DOI: 10.1103/PhysRevLett.113.223002 PACS numbers: 32.80.Fb, 02.70.Dh, 02.70.Hm, 32.80.Rm



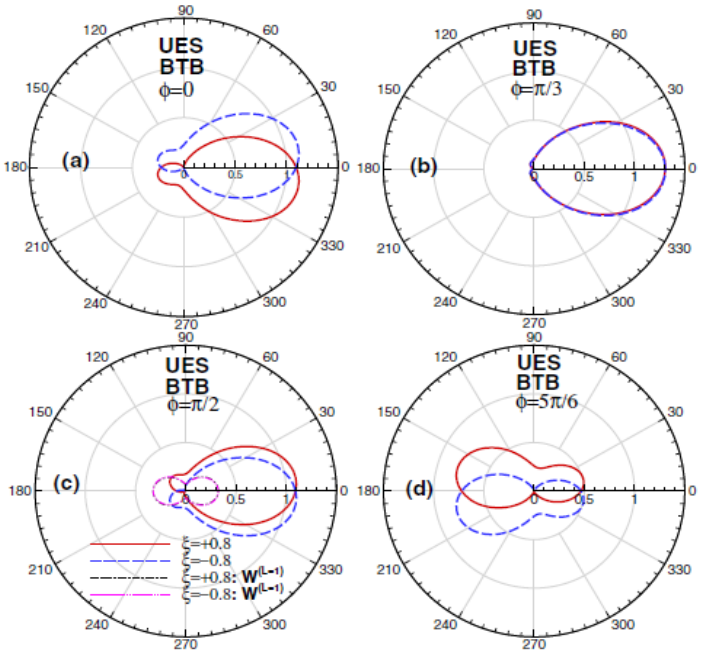


FIG. 2 (color online). The TDP $\mathcal{W}(\hat{\mathbf{p}}, \mathbf{e})$ [Eq. (6)] (in units of 10^{-5} a.u.) vs. φ [cf. Fig. 1(b)] for DPI of He by a three-cycle XUV pulse (with $\omega = 65$ eV, $I = 2$ PW/cm^2, $T = 190.9$ as, a $\cos^2$ envelope, and an ellipticity $\eta = \pm 0.5$ or $\xi = \pm 0.8$) for four CEPs: (a) $\phi = 0$, (b) $\phi = \pi/3$, (c) $\phi = \pi/2$, (d) $\phi = 5\pi/6$. All results are for the back-to-back geometry and unequal energy sharing (UES): $E_1 = 0.7$ eV and $E_2 = 3.3$ eV. In (c) we give for comparison $\mathcal{W}^{(L=1)}(\mathbf{p}, \mathbf{e})$; see text for discussion.

Matter-wave vortices can be produced in photoionization by delayed circularly-polarized attosecond pulses*

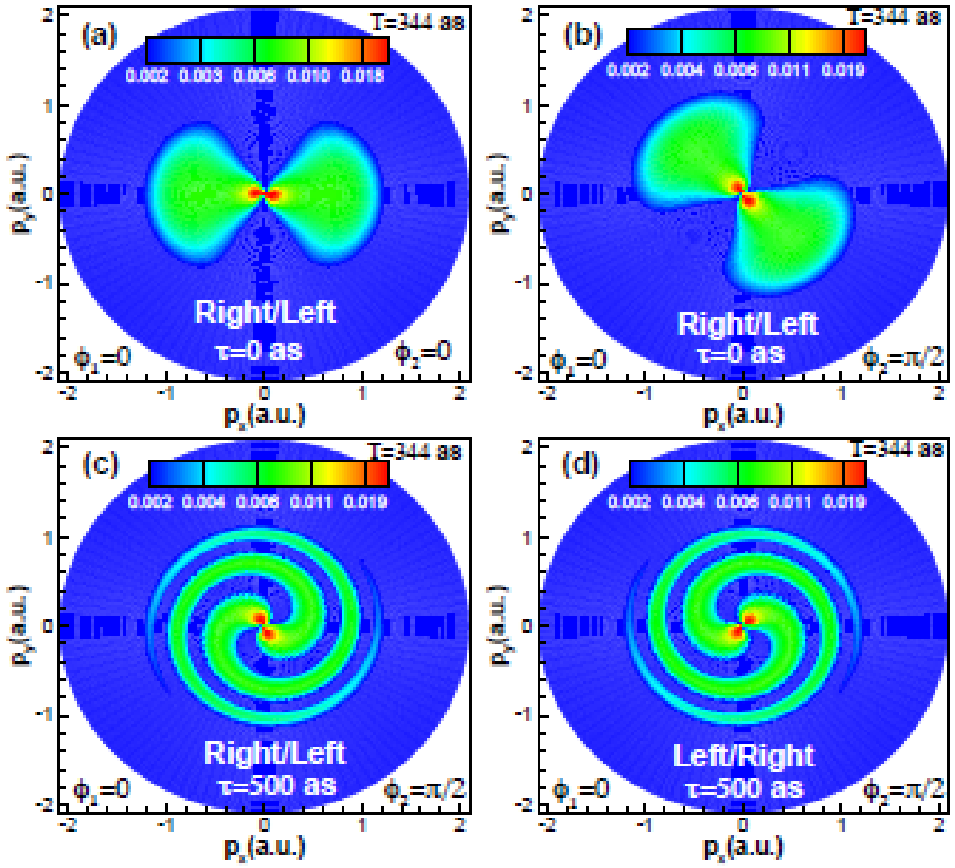


FIG. 2. (color online). Triply differential probability (TDP) $d^3W/d^3\mathbf{p}$ [see Eqs. (2), (4), and (5)] in the polarization plane for He ionization by (a,b,c) right/left and (d) left/right circularly-polarized attosecond pulses. Top row results: time delay $\tau = 0$; bottom row results: $\tau = 500$ as. In (a), $\phi_1 = \phi_2 = 0$; in (b,c,d), $\phi_1 = 0$, $\phi_2 = \pi/2$. In all panels $\omega = 36$ eV, $n_p = 3$ cycles, $I = 10^{14}$ W/cm^2, and the magnitudes in a.u. of the TDPs are indicated by the color scales.

* J.M. Ngoko Djiokap, S. X. Hu, L.B. Madsen, N.L. Manakov, A.V. Meremianin, A. F. Starace, Phys. Rev. Lett. 115, xxxxxx (2015).

Summary

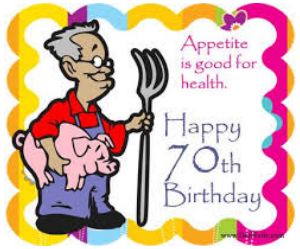
- **Attosecond physics has been an active field of study for the past decade.**
- **My “journey” in exploring the ultrafast world started with the inspiration from Tony!**
- **New adventure with Tony in attosecond AMO physics is bringing fun to us!!**

Best wishes from Suxing & Lishan's Family

2003

2014

Happy 70th Birthday to Tony!




Thank You

“The shortest pulse ever created” to date is ~67-attoseconds generated by gas-HHG using ~7-fs laser at UCF

September 15, 2012 / Vol. 37, No. 18 / OPTICS LETTERS 3891

Tailoring a 67 attosecond pulse through advantageous phase-mismatch

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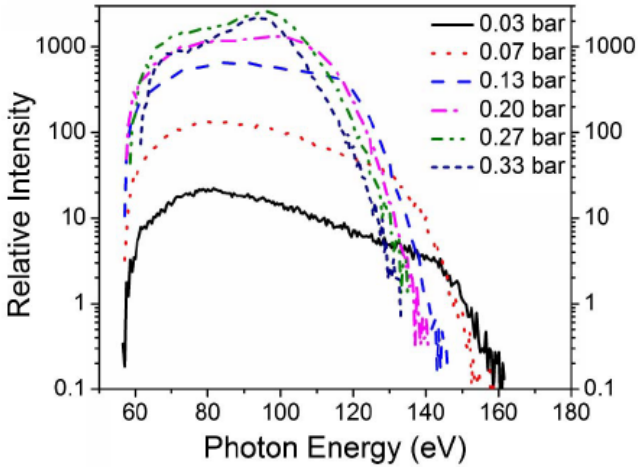
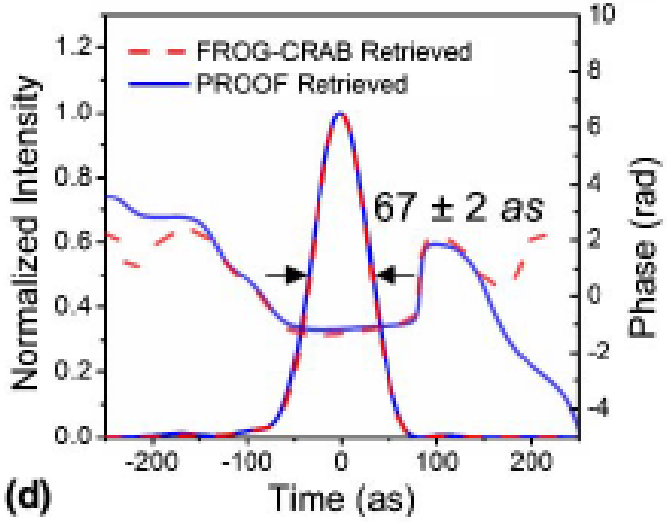
posted August 13, 2012 (Doc. ID 169268); published September 14, 2012

A single isolated attosecond pulse of 67 as was composed from an extreme UV supercontinuum covering 55–130 eV generated by the double optical gating technique. Phase mismatch was used to exclude the single-atom cutoff of the spectrum that possesses unfavorable attochirp, allowing the positive attochirp of the remaining spectrum to be compensated by the negative dispersion of a zirconium foil. Two algorithms, PROOF and FROG-CRAB, were employed to retrieve the pulse from the experimental spectrogram, yielding nearly identical results.





The classical double-slit picture becomes valid in APM only when $n\lambda_e < 0.65 \times R_0$ [independent slits: $R_0 \sin(\phi_n) = n\lambda_e$]

UR LLE

Comparison of the double-slit interference angles of the "classical" double-slit (DS) formula and our TDSE calculations as the photon energy ($\hbar\omega$) varies

$\hbar\omega$ (eV)	λ_e (Bohr)	Classical DS angles (ϕ_n)(°)	TDSE angles (ϕ_n)(°)
170	1.9587	$\phi_1 \approx 75.3°$	$\phi_1 \approx 52.0°$
210	1.7274	$\phi_1 \approx 58.5°$	$\phi_1 \approx 49.5°$
250	1.5258	$\phi_1 \approx 50.5°$	$\phi_1 \approx 46.5°$
300	1.4104	$\phi_1 \approx 44.1°$	$\phi_1 \approx 42.3°$
350	1.2955	$\phi_1 \approx 39.7°$	$\phi_1 \approx 39.9°$
430	1.1588	$\phi_1 \approx 34.9°$	$\phi_1 \approx 34.8°$
630	0.9462	$\phi_1 \approx 28.0°$	$\phi_1 \approx 28.4°$
		$\phi_1 \approx 69.1°$	$\phi_1 \approx 60.7°$

By measuring the diffraction angles, one can infer the transient structure of molecules.

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