2018 International Symposium on Light Driven Dynamics

LiDy 2018



Conference Program

Nov.6.-Nov.9, 2018 Shanghai, China The 2018 International Symposium on Light Driven Dynamics (LiDy), co-organized by East China Normal University and Goethe University Frankfurt, aims at bringing together the scientists in the research field of ultrafast dynamics of atoms, molecules and various materials driven by light, as well scientists from other fields interested in these topics to discuss the present status and future perspectives.

Chair:

Reinhard Dörner, Goethe University Frankfurt, Germany

Local chair:

Jian Wu, East China Normal University, China

Conference address:

Multimedia Hall, third floor, Yifu Building, East China Normal University (Zhongbei Campus) 华东师范大学(中山北路校区,上海市中山北路 3663 号)逸夫楼三楼多媒体报告厅

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Registration Fee: free

On-site Registration 18:00-20:00, Nov. 6, 2018 08:30-11:30, Nov. 7, 2018 Address: Yifu Building, East China Normal University (3663 Zhongshan North Road, Shanghai) 华东师范大学(中山北路校区,上海市中山北路 3663 号)逸夫楼

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Program:

Tuesday, November 6			
14:00-20:00	0-20:00 Registration		
Wednesday, November 7			
08:30-08:45	Opening remarks &Group photo		
Session 1	Chair	: Reinhard Dörner	
08:45–09:10	Thomas Baumert University of Kassel	Molecular chirality in the light of femtosecond multi-photon ionization	
09:10-09:35	Christiane Koch University of Kassel	Quantum control of photoelectron circular dichroism	
09:35–09:50	Kang Lin East China Normal University	Two-dimensional electron-ion rescattering driven by bicircular two-color laser pulses	
09:50-10:20		Coffee break	
Session 2	Chair: Jian Wu		
10:20–10:45	Olga Smirnova Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy	Controlling and probing ultrafast chiral dynamics in molecules	
10:45–11:10	Baptiste Fabre University of Bordeaux	Ultrafast dynamics in chiral molecules	
11:10-11:35	Kilian Fehre Goethe University Frankfurt	Strong field ionization of chiral molecules	

11:35-11:50	Alexander Hartung Goethe University Frankfurt	The photon momentum in strong-field ionization	
11:50-13:00	Lunch		
13:00-14:30	Lab tour		
Session 3	Chair: Olga Smirnova		
14:30–14:55	Ilya Averbukh The Weizmann Institute of Science	Selective orientation of chiral molecules by laser fields with twisted polarization	
14:55-15:20	Olivier Faucher Université de Bourgogne Franche-Comté	Optical detections of unidirectionally rotating molecules	
15:20-15:45	Henrik Stapelfeldt Aarhus University	Laser-induced rotation and alignment of molecules in helium nanodroplets	
15:45-16:45	Cof	fee break + Poster	
Session 4	Chiair: Ilya Averbukh		
16:45-17:10	Maksim Kunitski Goethe University Frankfurt	Rotating rotationless: nonadiabatic alignme of helium dimer and trimer	
17:10-17:35	Doerte Blume The University of Oklahoma	Statics and dynamics of small helium clusters	
17:35-18:00	Qi Wei East China Normal University	Pendular alignment and strong chemical binding of He ₂ molecules in intense laser fields	
18:00-20:00	Banquet		

Thursday, November 8			
Session 5	Chair: Lars Bojer Madsen		
08:30-08:55	Eva Lindroth Stockholm University	Many-electron effects on attosecond time delays	
08:55-09:20	Thomas Pfeifer Max-Planck-Institut für Kernphysik	Dynamics of excited states driven by strong laser fields	
09:20–09:45	Zenghu Chang University of Central Florida	From chirped pulse amplification to attosecond X-rays	
09:45-10:15	Coffee break		
Session 6	Chair: Thomas Baumert		
10:15–10:40	Matthias Wollenhaupt University of Oldenburg	Carrier-envelope phase control of free electron vortices	
10:40-11:05	Robert Moshammer Max-Planck-Institut für Kernphysik	Reaction microscope experiments with sho pulse lasers	
11:05-11:30	Yunquan Liu Peking University	Characterization of electron wavepackets from strong-field ionization	
11:30-11:45	Nicolas Eicke Leibniz Universität Hannover	Effective one-dimensional potentials from static current densities	
11:45-12:00	Meng Han Peking University	Spin-up electrons meet spin-down in a temporal double slit: a novel which-way information marker and its control	

12:00-13:00	Lunch		
Session 7	Chair: Eva Lindroth		
13:00-13:25	Lars Bojer Madsen Aarhus University	Signatures of a conical intersection in attosecond transient absorption spectroscopy	
13:25-13:50	Markus Kitzler-Zeiler Technische Universität Wien	Measurement and control of electron and nuclear dynamics in molecules	
13:50-14:15	Feng He Shanghai Jiao Tong University	Nondipole effects in photoionization of atoms and molecules	
14:15-14:45	Coffee break		
Session 8	Chair: Robert Moshammer		
14:45-15:10	Pengfei Lan Huazhong University of Science and Technology	Monitor the molecular vibration and unidirectional rotation with high-harmonic spectroscopy	
15:10–15:35	Sebastian Eckart Goethe University Frankfurt	Non-adiabatic tunnel ionization with tailored two-color laser fields	
15:35–16:00	Zhinan Zeng Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences	Ultrafast electron excitation with MIR las field	
16:00-16:25	Peifen Lu East China Normal University	Electron-nuclear energy correlation in dissociative ionization of molecules	
16:25-16:30	Closing remarks		
17:00-18:00	Dinner		

18:00-21:00	Free discussion	
Friday, November 9		
All day	Departure	

Molecular chirality in the light of femtosecond multi-photon ionization

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Molecular chirality is widely recognized for its relevance to the building blocks of life and its vital role for medicine and health. Chiral recognition in the gas phase using electromagnetic radiation is an emerging research field and promising for fundamental research as well as for applications due to the non-interacting nature of molecules in the gas phase.

Photoelectron angular distributions after one photon or multiphoton ionization turned out to be especially sensitive to that end and are usually measured by velocity map imaging (VMI) techniques. The corresponding circular dichroism is termed photoelectron circular dichroism (PECD) and reviewed in [1]. Based on electric dipole interaction, its magnitude of up to a few ten percent typically surpasses that of other chiroptical techniques and can be turned into a highly sensitive analytic tool with respect to investigation of enantiomeric excess. Resonance-enhanced multi-photon ionization (REMPI) gives access to electronic intermediates and, with

Resonance-enhanced multi-photon ionization (REMPI) gives access to electronic intermediates and, with the help of femtosecond laser excitation and ionization, PECD has been demonstrated on bicyclic ketones [2] with sub 1 percent sensitivity to enantiomeric excess [3]. As more angular momentum can be transferred in a multiphoton process in comparison to single photon ionization, higher order nodal structures were observed [4]. An exploration of the nuclear and electron dynamics of the intermediate resonance may stimulate the development of laser driven purification schemes.

In this talk I will present our experiments exploring the intermediate state dependence on PECD. References also to related work are compiled for example in our latest publication [5].

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Quantum control of photoelectron circular dichroism

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Photoelectron spectroscopy reveals important information on electron dynamics in atoms and molecules. A striking effect is photoelectron circular dichroism (PECD). It refers to the forward/backward asymmetry in the photoelectron angular distribution with respect to the light propagation axis. PECD has recently been demonstrated in femtosecond multi-photon photoionization experiments with randomly oriented chiral molecules [1,2]. We are able to explain the experimental observations, at least semi-quantitatively, by combining perturbation theory for the light-matter interaction with ab initio calculations for the bound spectrum and a single-center expansion of the photoelectron continuum [3].

In the non-perturbative regime, tailoring the pulsed electric field in its amplitude, phase or polarization allows for the control of ultrafast dynamics. Optimal control theory can be used to enhance desired features in the photoelectron spectra and angular distributions or in the photoion. I will discuss two examples of this type of control. First, XUV pulse shaping may result in directed electron emission [4] and improve hole coherence in the photoion. Second, pulse shaping can be used to create quantum pathway interference that significantly enhances PECD [5].



Fig. 1. PECD obtained with bichromatic control (a) and (b) and making use of interference in even-parity two-photon pathways (c), with the corresponding excitation schemes are shown in the bottom row (d-f).

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Two-dimensional electron-ion rescattering driven by bicircular two-color laser pulses

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Bound electrons in atoms and molecules can be released to continua when exposed to strong laser fields, in which scenarios freed electrons may be driven back to recombine with parent ions leading to the emission of attosecond bursts in extremely ultraviolet spectrum, or to kick out a second electron resulting in the non-sequential double ionization (NSDI). It is recently demonstrated that the NSDI of atoms via the electron rescattering can be controlled by bicircular two-color laser pulses [1-3]. Depending on the helicity and relative strength between the two colors, the motion of the liberated electron and thus the recollision process can be spatiotemporally manipulated.

Here, we experimentally investigate the strong-field ionization of atoms and molecules with comparable ionization thresholds, i.e. Ar/N_2 and Xe/O_2 , using bicircular two-color femtosecond laser pulses [4]. We find that the electron recollision probability is not only determined by the helicity and intensity ratio between the two colors, but also strongly depends on the species of the target, which can be traced back to the detailed electronic structure. For counter-rotating two-color fields, the electron recollision enhanced ionization is significant in N_2 and Ar, while this recollision process is hard to be observed in O_2 and Xe. Our results reveal the discrepancy in controlling the electron recollision dynamics between molecules and atoms using circularly polarized two-color laser fields, which is implicative for further important applications, e.g. directly generating circularly polarized high harmonics and attosecond pulses and steering two-dimensional electron motion in molecules.



Figure 1 : Experimentally measured yield ratios between counterrotating and corotating cases.

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Controlling and probing ultrafast chiral dynamics in molecules

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Distinguishing left- and right-handed molecular enantiomers is challenging, especially on ultrafast time scale. Traditionally one uses a chiral reagent, an object of known handedness, to determine the unknown handedness of a chiral molecule. In optics, one uses the spatial helix formed by circularly polarized light as a "chiral photonic reagent". However, in optical domain the pitch of this helix – the light wavelength – does not match the size of the molecule, leading to a very small chiral signal.

I will introduce a concept of efficient chiral measurements, which do not rely on using chiral reagents such as chiral light. They rely on inducing chiral dynamics with non-chiral light and probing it using a chiral experimental setup: a chiral observer is a powerful alternative to a chiral reagent [1].

However, the chiral observer cannot control the chiral response. To efficiently control chiral optical response in molecules, one needs a chiral reagent of appropriate size. I will introduce a new concept of locally chiral electric fields, which serve as such photonic reagent. I will show how this chiral photonic reagent can be tuned to "react" with the desired enantiomer of a chiral molecule and not with its mirror twin, achieving the ultimate limit in efficiency of chiral discrimination [2]. The simplicity of generating such "locally chiral light" in a laboratory opens a broad field of shaping and controlling chiral matter with light.

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Ultrafast dynamics in chiral molecules

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Each molecule can be recognized by its chemical composition and its structural conformation that dictates how it will interact with other molecules. Life has found an extra parameter to stock durably information: chirality. This asymmetry property appears at the molecular level when two molecules have the same chemical composition and structure but cannot be superimposed to each other by a mirror transposition. The two mirror images are called enantiomers. Enantiomers are able to regulate different biological mechanisms through their handedness. This chiral recognition is the key element in how we perceive odor and taste and is as well as of major importance in many mechanism for drug action. Chirality is as such, one of the most subtle example of broken symmetry with a huge impact in chemistry, pharmacology and biochemistry and even the origin of life.

In the photoionization of randomly-oriented pure enantiomers by circular polarization light, an asymmetry of the emitted photoelectron is observed along the photon propagation axis. This forward/backward asymmetry can reach several percentage and reverses with the handedness of the enantiomer or the helicity of the light polarization.[1] By comparing different ionization mechanisms, all using femtosecond pulses, we found that PECD exists in all regimes (single photon, multiphoton, tunneling).[2]

On the basis of these experiments, we have performed the first (to our knowledge) experimental investigation on time-dependent chiral dynamics. The molecular dynamics investigated are vibronic coupling from Rydberg states in Fenchone and Camphor ($C_{10}H_{16}O$). These two molecules are isomers of each other.[3]

The time-resolved approach opens new horizons and questions on what are the most important dynamical aspects of the scattering of an electron in chiral potential that is as well evolving.

Finally, in order to measure the time delay between the backward and forward electron wavepackets ejected from a chiral molecule using circularly polarized photons, we have set up a self-referenced attosecond photoelectron spectroscopy We measured a delay between electrons ejected forward and backward, which depends on the ejection angle and reaches 24 attoseconds. [5]

Acknowledgments:

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Strong field ionization of chiral molecules

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Most building blocks of living nature are chiral (their mirror image cannot be superimposed with the initial object). The development of efficient analysis techniques is thus of central importance in chemistry and pharmacy. Chiral signals such as the PECD (Photoelectron Circular Dichroism), which shows up in an asymmetric electron flux direction in forward/backward direction, are promising candidates. In addition, these chiral signals have been shown to be sensitive probes for the structure and dynamics of larger molecules [1,2]. Whereas previous experiments focused on single- or multiphoton ionization processes [3,4], we investigate the process of strong field ionization, as this regime is particularly interesting, especially as a future analysis tool. Multi-coincidence measurements with the COLTRIMS [5] (CoLd Target Recoil Ion Momentum Spectroscopy) technology give us not only insights into exciting new effects but also an intuitive understanding of the underlying mechanisms.

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The photon momentum in strong-field ionization

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If a photon is absorbed by an atom leading to the ionization of the atom, momentum conservation dictates that the momentum of the photon is passed on to the system of ion and emitted electron. In the widely used dipole approximation the momentum of the photon is neglected. However, for a precise and complete description of the ionization the effect of the photon momentum has to be accounted for. In the long studied simple case of one-photon ionization, the sharing of the momentum between ion and electron is still under investigation, for a theoretical suggestion see [1]. For the case of multi-photon ionization the current status of research is even more unsettled. Over the span of the last few years quite a few theoretical works have treated the effect of photon momentum in strong-field physics, see e.g. [1] and [2]. The common view is, that the ion acquires the momentum of 70% of the photons, which are absorbed to overcome the ionization potential, and the electron acquires the momentum of the remaining 30% of the "under the barrier"-photons and additionally all the momentum of the photons leading to the end kinetic energy of the electron. To our knowledge, only two experimental works have studied the effect of the photon momentum for the case of strong-field ionization in detail [3], [4]. Both works used a VMI for detection and showed basic non-dipole effects.

In our presented work, we use a new methodical approach to experimentally investigate the role of photon momentum in strong-field ionization. A new COLTRIMS reaction microscope was designed and built. To obtain a credible zero of the momentum distribution with the new chamber it is possible to shoot in the laser from two diametrically opposed sides and compare both directions. In the difference of both distributions (Direction 1 & 2) all instrumental disruptive effects cancel out. The ellipticity and intensity of both laser arms as well as their temporal overlap are independently and fully automized. Contrary to the typical assigned strong magnetic fields in a COLTRIMS here a magnetic shielding is used to cancel out any magnetic field and thereby avoiding unwanted spectrometer non-linearities. The size of the gas jet can be changed automatically to create a small reaction region needed for the precise measurement of momenta. In Fig. 1 one of our results is shown. The theoretical prediction of [1] and [2] that the electron acquires the momentum of the photons absorbed after ionization is confirmed, whereas contrary to theory our data show no offset of the electron momenta by 30% of the ionization potential I_P. Therefore, our work should stimulate further investigation of this quantitative small, but still fundamental feature in strong-field physics.



Fig. 1. Average momentum in laser direction. Laser comes in from the bottom. Red line shows exp. results, confirming quadratic dependency (Theory A), but not a shift dependent on I_P (Theory B).

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Selective orientation of chiral molecules by laser fields with twisted polarization

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We suggest [1, 2] a pure optical approach for enantioselective orientation of chiral molecules by means of laser fields with twisted polarization. Several field implementations are considered, including a pair of delayed cross-polarized laser pulses, an optical centrifuge, and polarization shaped pulses. We show that such an excitation leads to out-of-phase time-dependent dipole signals for different enantiomers, and we also predict a substantial permanent molecular orientation persisting long after the laser fields are over. The underlying classical orientation mechanism is discussed, and its operation is demonstrated for a range of chiral molecules of various complexity: hydrogen thioperoxide (HSOH), propylene oxide (CH₃CHCH₂O) and ethyl oxirane (CH₃CH₂CHCH₂O). The presented results demonstrate generality, versatility and robustness of this optical method for manipulating molecular enantiomers in the gas phase.



Fig. 1. An ensemble of propylene oxide molecules is excited by a pair of delayed non-resonant crosspolarized femtosecond pulses. The excitation is applied at t = 0. One of the enantiomers is shown in panel (a). Panels (b) and (c) show the average projection of the dipole moment on the propagation direction as a function of time at (b) zero temperature and (c) 50 K. Shortly after the application of the pulses, $\langle \mu \rangle(t)$ signal is observed, implying a partial orientation. The two colors correspond to the two enantiomers of the molecule.

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Optical detections of unidirectionally rotating molecules

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The present work reports on the polarization analysis of shortpulse ultraviolet radiation produced by thirdharmonic generation in a gas of coherently spinning molecules [1,2]. A pulse of twisted linear polarization imprints a unidirectional rotational motion to the molecules leading to an orientation of their rotational angular momenta [3]. A second pulse, time-delayed with respect to the first one, circularly polarized in the plane of rotation of the molecules, acts as a driving field for third-harmonic generation. The angular momentum and energy conservation applied to this process foresees the generation of two Doppler-shifted circularly polarized harmonics of opposite handedness. Our analysis reveals that spinning molecules enable the generation of a well-polarized third-harmonic radiation exhibiting a high degree of ellipticity. As illustrated in Fig. 1, tracking the orientation of the latter allows a time-capture of the molecular axis direction from which the average angular velocity of the rotating molecules is inferred. This method provides a user-friendly polarization-based tachometer for optical detection of spinning nonlinear rotors.



Fig. 1. Time-lapse images of the angular distribution of the molecular axis depicted in the polarization plane of the THG field. The simulations are performed at different times during the first revival of O₂ molecule. The calculated polarizations of the THG field are represented by the ellipsoidal curves. Between the beginning and the end of the revival, the polarization of the THG rotates clockwise by 90 °.

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Laser induced rotation and alignment of molecules in helium nanodroplets

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I will show how laser pulses can align molecules embedded in helium nanodroplets and how the ability to place molecules in advantageous spatial orientations allows structural determination of molecular complexes. The talk will cover the following topics:

1) Alignment with pulses much shorter than the molecular rotational periods. Here the focus is on understanding how the coherence of rotational wave packets is influenced by the dissipative environment of the helium droplets [1,2].

2) Quasi-adiabatic alignment induced by pulses that are turned-on on the time scale of molecular rotations. It will be shown how the 0.4 K temperature of the droplets, shared with the molecules, enables unprecedented high degrees of alignment at the peak of the alignment [3]. In addition, we show that when the pulse is rapidly turned-off the strong alignment persists for 10-15 ps thanks to an impeding effect of the helium environment on the molecular rotation. This creates molecules that are strongly aligned, either 1D or 3D, under conditions that are essentially laser-free [4]. The method works particularly well for large, complex molecules.

3) We show how dimers of molecules in He droplets can also be sharply aligned and how this makes it possible to image their structure through fs-laser-induced Coulomb explosion. Results for both small linear molecules such as carbonylsulfide [5,6] and larger molecules such as tetracene are presented. Perspectives for time-resolved imaging of exciplex formation and bimolecular reactions are discussed.

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Rotating rotationless: nonadiabatic alignment of helium dimer and trimer

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Quantum mechanically rotational and vibrational dynamics in molecules is time evolution of corresponding wave packets. Such dynamics can be periodic, as well-known rotational and vibrational revivals with wave packets consisting of many coherently prepared bound states. How the rotational and vibrational dynamics would look like in a molecular system with a single bound state? One of such extreme quantum system is helium dimer, where the two-body potential supports only one state.

We applied a nonadiabatic "kick" to the helium dimer and trimer by a femtosecond laser pulse (pump) and watched evolution of the system by Coulomb explosion imaging, which was initiated by the second much more intense delayed probe pulse. The observed time-dependent alignment of the helium dimer, as well as time evolution of the rovibronic wave packet, is going to be discussed in the talk. Preliminary results on helium trimer will be presented.

Statics and dynamics of small helium clusters

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With a binding energy of 1.3mK or 1.1*10⁻⁷eV, the helium dimer is one of the most weakly-bound naturally occurring homo-nuclear diatomic molecules. It is, to a good approximation, described by a universal one-parameter theory, which states that the fall-off of the wave function is governed by the s-wave scattering length. Closely related to this is the fact that a large portion of the helium dimer wave function is located outside the classical turning point. Correspondingly, the helium dimer, as well as the trimer and tetramer, have long served as model systems with which to theoretically test few-body universality. Few-body universality is a powerful concept that explains, e.g., the binding of systems as diverse as di-mesons like the charmonium resonance near 3870MeV, which has a binding energy of about 0.5MeV, and Feshbach molecules, whose typical binding energy is less than 10⁻¹⁰eV. Recent ingenious experiments, which send a helium beam through a matter wave grating and subsequently image the system via Coulomb explosion with single atom detection, have provided the first experimental images of the helium dimer density and of structures of the ground state helium trimer and the excited helium Efimov trimer, thereby opening the door for the experimental study of universal few-body systems with single-atom detection.

After discussing selected static properties of small helium clusters, the tunability of the helium-helium interaction through an external electric field is investigated theoretically. For a static external field, electric-field induced resonances and associated electric-field induced bound states are calculated for the ⁴He-⁴He, ³He-⁴He, and ³He-³He systems. Qualitative but not quantitative agreement is found with the literature for the ³He-⁴He system [1]. The fingerprints of the predicted electric-field induced resonances on the ro-vibrational wave packet dynamics, initiated by an intense and relatively long laser pulse, is explored. While the realization of such a laser pulse is beyond current state-of-the-art technology, the theory predictions provide useful insights.

Considering shorter and more realistic pump laser pulses, the dissociative wave packet dynamics of the ⁴He-⁴He dimer is investigated. Excellent agreement between theory and experiment is found for this pump-probe set-up. The alignment, a quantity that has been studied extensively for more strongly-bound rigid-rotor-like molecules that possess a much larger static dipole polarizability than the helium dimer, is analyzed and interpreted in terms of a double-slit like interference pattern. The coupling between the rotational and vibrational degrees of freedom, which is prominent for weakly-bound systems, is highlighted. Last, the wave packet dynamics is discussed from the perspective of few-body universality.

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Pendular alignment and strong chemical binding in He₂ molecules induced by intense laser fields

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Intense pulsed laser fields have provided means to both induce spatial alignment of molecules and enhance strength of chemical bonds. The duration of the laser field typically ranges from hundreds of picoseconds to a few femtoseconds. Accordingly, the induced "laser-dressed" properties can be adiabatic, existing only during the pulse, or nonadiabatic, persisting into the subsequent field-free domain. We exemplify these aspects by treating the helium dimer, in its ground $(X^1\Sigma_g^+)$ and first excited $(A^1\Sigma_u^+)$ electronic states. The ground-state dimer when field-free is barely bound, so very responsive to electric fields. We examine two laser realms, designated (I) "intrusive" and (II) "impelling." (I) employs intense nonresonant laser fields, not strong enough to dislodge electrons, yet interact with the dimer polarizability to induce binding and pendular states in which the dimer axis librates about the electric field direction. (II) employs superintense high-frequency fields that impel the electrons to undergo quiver oscillations, which interact with the intrinsic Coulomb forces to form an effective binding potential. The dimer bond then becomes much stronger. For (I), we map laser-induced pendular alignment within the X state, which is absent for the field-free dimer. For (II), we evaluate vibronic transitions from the X to A states, governed by the amplitude of the quiver oscillations.

Many-electron effects on attosecond time delays

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The dynamics, during for example a photoionization process, is encoded in the amplitude and *phase* of the released electron wave packet. A key quantity is the spectral derivative of this phase, the *group delay*. It reflects the delay or advance of the electron when it travels through the atomic potential to eventually emerge in the continuum: attosecond interferometric techniques have made such phase information obtainable. In the contribution I will discuss attosecond delays in laser-assisted photoionization with an emphasis on the theoretical treatment and the role of many-body effects, [1, 2, 3, 4]. With the recent possibility to combine high temporal and spectral resolution [5], attosecond experiments start to be sensitive to a range of many-body effects such as resonances and shake-up processes, highlighting the importance of electron correlation.

In time-delay measurements attosecond XUV pulses are used to photoionize target atoms at well-defined times, followed by a probing process in real time by a phase- locked, infrared laser field. In this way, the laser field serves as a "clock" to monitor the ionization event. It is well established, see e.g. Ref. [6], that the observable delays do not correspond directly to the delay associated with single-photon ioniza- tion. Instead, a significant part of the observed delay originates from a measurement induced process, which obscures the single-photon ionization dynamics. This effect has mostly been studied when the electron leaves a Coulomb field. Here the new situation when the there is no long range potential, as in a negative ion, will be discussed, as well as the effects of resonances and shake-up channels. Another interesting aspect that will be



Fig. 1. The difference between the two-photon atomic delay and the one-photon Wigner delay for the outermost shell of Ne, Ar, F⁻, and Cl⁻. The gray line is the analytica expression for the continuum-continuum delay discussed in Ref.[6].

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Dynamics of excited states driven by strong laser fields

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Strong-field physics has traditionally evolved by observing, understanding and controlling ionization processes. Ionization of atoms, molecules, clusters, and condensed-phase samples occurs by the interaction with (optical) laser pulses of high intensity, achieving ponderomotive potentials on the order or in excess of the photon energy of the laser pulses used. Early on in experiments, excited states, e.g. the so-called Freeman resonances [1] in above-threshold ionization spectra, were identified to play a significant role in strong field processes.

Here, we discuss recent experimental efforts focusing explicitly on the dynamics of excited states in strong laser fields. The dynamics of bound states can be isolated from ionization dynamics by observing transmission spectra of light, exhibiting characteristic state-specific (Fraunhofer) absorption features imprinted in the spectrum after passage through a dense gas. These spectral features vary in strength and line shape when the atoms or molecules interact with short-pulsed laser light of variable intensity and at different delays with respect to an exciting pulse. From these observed changes, information about the dynamical evolution of these excited states can be extracted [2-6].

Another manifestation of strong-field interactions, few-cycle-pulse driven Rabi oscillations, occurs in the strong coupling of excited states, and we observe this effect for autoionizing states driven with optical lasers. In recent experiments, we employed intense XUV fields from free-electron lasers (FELs) to observe the onset of Rabi cycling between the ground and a doubly excited state near 60 eV transition energy. The measured modification of the natural Fano absorption line shape in the intense XUV-pulse interaction provides evidence for a macroscopic population of doubly-excited Helium atoms in a 100 mbar gas cell.

Very recently, the full reconstruction of the strong-field-driven temporal dipole response from a single absorption spectrum has been achieved (see Figure). Without the need for scanning time delays between two pulses, it is now possible to observe strong-field dynamics. Here, we study the competition between Rabi cycling and strong field ionization as the intensity of the driving laser is increased. We pinned down the critical threshold intensity for the onset of complex dynamics in a few-body system[7].



Figure Illustration (not to scale) of the correspondence between various ionization spectra (top row), e.g. photoelectron or - absorption spectrum and their time-domain response functions (bottom row). While Photoionization produces a broad spectral feature and an instantaneous response, autoionization produces sharp Fano line shapes. In this talk, it will be shown what the spectrum of a strong- field ionizing system looks like and how its temporal response can be fully retrieved from experimental data.

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From chirped pulse amplification to attosecond X-rays

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Chirped Pulse Amplification (CPA) was demonstrated in 1985 by Donna Strickland and Gerard Mourou, for which a portion of the 2018 Noble Prize in Physics has been awarded to them. CPA is a revolutionary technique to achieve both ultrashort laser pulse duration and unprecedented light intensity. The applications of CPA lasers to atomics physics study has opened a new research area: attosecond (1018 s) science. Several generations of attosecond driving lasers have been developed to meet the unique requirements of generating high flux, large photon energy and shortest X-ray pulses. Recently, 50-as soft X-ray pulses at the carbon K-edge (280 eV) have been produced in our laboratory using the latest generation CPA lasers centered at 1.7 micron, which may open the door for observing electron dynamics in atoms, molecules and condensed matter via core to valence level transitions. The next generation CPA lasers at the mid- and far- infrared are being developed to explore attosecond science in the keV photon energy range.

Carrier-envelope phase control of free electron vortices

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Three-dimensional free electron wave packets of arbitrary rotational symmetry are created by multiphoton ionization of atoms using polarization-tailored laser fields. Their properties are manipulated with the help of optical phase modulation including the CEP and relative phases. In the experiment, we combine advanced supercontinuum pulse shaping with high-resolution photoelectron tomography [see Figure 1(a)]. We employ a 4f polarization pulse shaper to sculpture bichromatic fields from a CEP-stable over-octave spanning white light supercontinuum by spectral amplitude and phase modulation [1,2].



Fig. 1. (a) Setup: combination of shaper-based generation of bichromatic pulses [1] and photoelectron tomography using a velocity map imaging spectrometer. Inset: measured polarization profile of CRCP and COCP pulses. (b)-(e) Results: ionization of potassium atoms with a single-color sequence of CRCP femtosecond laser pulses creates free electron vortices with c6 rotational symmetry at the ionization threshold (b) and c8 rotational symmetry by ATI (c). Bichromatic ionization of sodium atoms with CRCP pulses creates electron wave packet with c7 rotational symmetry (d). The electron wave packet from ionization with COCP pulses exhibit no rotational symmetry (e).

The experimental results [see Fig. 1(b)-(e)] show that multiphoton ionization of potassium atoms with a single-color sequence of counterrotating circularly polarized (CRCP) femtosecond laser pulses produces vortex-shaped photoelectron momentum distributions [3,4] with c6 or c8 rotational symmetry [Fig. 1(b) and (c)]. In contrast, bichromatic CEP-stable polarization-tailored counter- and corotating (COCP) femtosecond laser pulses generate c7 rotationally symmetric [Fig. 1(d)] and asymmetric [Fig. 1(e)] momentum distributions. Our results reveal that in the multiphoton regime the symmetry of the free electron wave packets is not fully determined by the field symmetry, but completely described by the quantum interference of states with different angular momenta.

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Reaction microscope experiments with short-pulse lasers

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Recent results on the fragmentation of atoms and (small) molecules in intense IR laser fields will be presented. Emphasis is given to the time-resolved dynamics in ultrashort and strong fields by means of kinematically complete measurements using many-particle spectrometers (COLTRIMS or Reaction-Microscopes [1]). They are ideally suited to unravel the correlated multi-particle dynamics in ultrafast processes occurring in atoms and molecules if combined with modern short-pulse IR and/or high harmonic radiation sources based on high-power table-top lasers. For example, pump-probe experiments allow the observation of moving electronic wave-packets in bound sates of atoms [2], and in case of molecules vibrational and electronic excitations [3] as well as the transfer of energy within a molecule can be imaged with unprecedented resolution and in real time.

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Characterization of electron wavepackets from strong-field ionization

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In the presentation, I will talk about our recent works on the characterization of electron wavepackets from strong-field ionization of atoms. In theory, we have develop a subcycle nonadiabatic strong-field tunneling theory and have derived the position of tunnel exit, the transverse and longitudinal momentum distributions at the tunnel exit, and the ionization rate in an instantaneous laser field. These tunneling coordinates are shown to nonadiabatically couple with each other in an instantaneous laser field when the electron tunnels through the Coulomb barrier. We have further incorporated the nonadiabatic tunneling theory with the quantum-trajectory Monte Carlo approach to investigate the nonadiabatic effect on the photoelectron angular distributions. The simulated photoelectron angular distributions with the nonadiabatic corrections have been validated by comparison with the *ab initio* results through numerically solving the time-dependent Schrödinger equation [1,2]. Eperimentally, we have perfermed the elliticity-dependent measurement on electron momentum distributions and have verified the nonadiabatic effect [3].

Beside characterization of momentum distributions of electron wavepackets, we have also tried to understand the sub-barrier phase of electron wavepackets by strong-field ionization using the orthorgal polarized fields [4]. In order to measure the phase structure, we recently used the two-color co-rotating circularly polarized fields to probe the phase and amplitude of electron wavepackets [5]. Along the line, the position of tunneling exit, momentum distributions and the initial phase structure of electron wavepackets have been studied.

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Effective one-dimensional potentials from static current densities

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To reproduce dynamic properties in strong-field ionization of atoms by low-dimensional calculations Majorosi et al. suggested an effective one-dimensional potential based on the condition that the ground-state density of the 1D system reproduces the projection of the 3D density onto the polarization axis of the laser field [1]. For hydrogen this leads to a somewhat counter-intuitive potential with an asymptotic behavior corresponding to the effective nuclear charge Z = 1/2.

We generalize this result to 1D and 2D atoms and arbitrary values of the ionization potential. Comparing weak-field static ionization rates [2] of the ground state in the 3D potential with the lower-dimensional models confirms the density-based effective nuclear charge in the sense that both models give the same scaling of the ionization rate with field strength. However, the (field-independent)prefactor is different, resulting in the 1D model always underestimating the total rate.

To find a potential with the correct ionization rate we apply a static electric field to the 3D system and calculate the density as well as the current density from the ionizing state. Projecting both quantities onto the laser-polarization axis gives an effective 1D density and effective 1D current density from which one can construct an ionizing 1D wave function as well as an effective potential.

We show that this effective potential is not the same as the ground-state density based potential plus the laser potential. In the weak-field limit the major difference is a step in the tunneling barrier that allows the wave function to ionize easier and reproduce the correct prefactor in the ionization rate. For large field strengths we find, in addition to the step, that not only the effective nuclear charge is different from Z = 1, but also that the effective field strength is not equal to the one applied to the 3D system.



Fig. 1. Effective 1D potentials from 3D ground-state density (blue) and 3D current density (orange).

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Spin-up electrons meet spin-down in a temporal double slit: a novel whichway information marker and its control

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Spin, as a unique degree of freedom, has attracted much attention to control electron dynamics in many branches of physics. Apart from the conventional way that exerting magnetic fields to control electron spin, recently the coupling between spin and orbit has been exploited in strong-field physics [1-4]. Benefiting from the nonadiabatic interaction between intense light and atoms or molecules, it is possible to use circularly polarized pulses to control the orbital state of the ionized atoms. With the help of spin-orbit coupling, strong-field community has entered a new stage of generating spin-polarized electrons and controlling the spin dynamics.

We demonstrate a temporal double-slit experiment, in which spin-up and spin-down electrons pass through the two slits respectively, and the spin polarization of each pathway serves as a which-way information marker. Using the orthogonal two-color (OTC) laser pulses to ionize krypton atoms, we prepare the spin-up photoelectrons in a half laser cycle and the spin-down photoelectrons in the next half cycle (i.e., a temporal double slits). By measuring the contrast of two-slit interference fringes, we obtain the electron spin polarization through the temporal slit and reveal the universal spin effect on photoelectron interference spectroscopies. We show that the spin polarization and its effect on the interference can be controlled by tuning the light intensity ratio of two-color pulses. This study may pave the way to control the spatiotemporal spin dynamics using ultrafast tailored laser pulses in strong-field physics.



Fig. 1. The ionization process of the krypton ${}^{2}P_{1/2}$ state with the OTC field at the phase delay of 0.5 π . When the synthesized electric field is clockwise rotating (blue arrow) in one half cycle, the spin-down electrons are mostly produced, and when the field vector (red arrow) is anticlockwise rotating in the next half cycle, the spin-up electrons are mostly produced. (b), The calculated momentum distributions when the electron solely passes through one of the two slits. (c), The calculated time-resolved spin polarization in one laser cycle. (d), The square of Clebsch-Gordan coefficients for different m_i states of the ${}^{2}P_{1/2}$ and ${}^{2}P_{3/2}$ states.

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Signatures of a conical intersection in attosecond transient absorption spectroscopy

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In this talk, I will discuss how attosecond metrology can be used to elucidate ultrafast coupled electron and nuclear motion. Specifically, I will characterize attosecond transient absorption spectroscopy (ATAS) in molecules in the vicinity of a conical intersection, and in this way combine one of the challenging concepts from theoretical chemistry with attosecond science. Some of the main finding have recently been published in Ref. [1]. Historically, nonadiabatic electron-nuclear couplings have been the subject of numerous investigations in physics and chemistry. It is now understood that points of degeneracy between adiabatic Born-Oppenheimer potential energy surfaces (i) are abundant in polyatomic molecules and (ii) the dynamics close to such conical intersections is important for a range of photophysical and photochemical processes [2]. There has recently been a series of works addressing the signatures of conical intersections in time-resolved settings (see Refs. [3-4] and references therein). ATAS [5] seems particularly well suited to reveal such dynamics, and has previously been successfully applied to investigate atoms, molecules and solids. To be able to capture general aspects of the problem and to cover a large parameter space for the characterization of the conical intersection, a simple model for a conical intersection is considered – the linear vibronic coupling model, which has been successfully used for more than 40 years [6], and which shares essential features with real molecules. I will describe how this model can be extended to the case of ATAS by introducing the appropriate extra states and couplings [Fig. 1]. Using this generic model, it is possible to categorize the dynamics into three distinctly different regimes: Weak, intermediate and strong with respect to the coupling between the electronic and nuclear degrees of freedom and to identify the typical signatures of the conical intersection and the vibronic couplings in the ATAS spectra. This theory work may guide future experiments. It emphasizes the general aspects of the problem and leaves consideration of particular molecules for future studies.



Fig. 1. Illustration of diabatic electronic states and the couplings between them. In the figure, XUV and NIR denote attosecond and femtosecond pulses, while VC denotes a vibronic coupling between two of the involved states

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Measurement and control of electron and nuclear dynamics in molecules

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When an intense laser pulse impinges on a molecule, the laser electric field couples to the molecular electronic system and can drive various ultrafast electronic processes that may reach into the attosecond time domain. The laser-field-induced distortions of the molecular electronic system might leave the molecule in an (ionic) electronically and/or vibrationally excited state (and superpositions of them), which in turn may give rise to nuclear dynamics that typically takes place on considerably longer time-scales ranging from about ten femtoseconds to picoseconds. While a number of methods for the measurement of attosecond electronic dynamics have been developed, e.g., intra-cycle interferometry with electron wavepackets [1], it is difficult to capture simultaneously both the fast electronic and the slower nuclear motion.

In this talk I will introduce, using the H_2 molecule as an example, a method that closes this gap. This method, termed attosecond molecular clock, exploits the concept of angular streaking with elliptically polarized laser fields for which the absolute values of the momenta of the electrons and their emission angles, associated with the hour respectively the minute hand of the clock, encode the release times of the electrons [2]. To obtain absolute timing, the clock needs to be calibrated by the carrier-envelope phase (CEP) of the laser pulses [2]. To apply the clock to molecules, an additional hand for encoding the nuclear motion that may take place during double ionization needs to be added. We show that the kinetic energy release (KER) can serve as this hand of the clock. Using the resulting molecular attoclock we experimentally trace the sub-cycle dynamics of two-electron emission from H_2 that underlies the fragmentation dynamics into two protons.

Elliptically polarized laser fields are, however, not the only type of field that have varying components in two dimensions. Orthogonally polarized two-color (OTC) laser fields offer a still larger flexibility in shaping the field-evolution on sub-cycle time-scales [3]. As a second point of my talk I will show how OTC fields can be used to control the properties of Rydberg wavepackets created during the laser interaction [4]. This experimental result, when applied to molecules and molecular clusters, may open up fascinating prospects for controlling the outcome of bond-breaking and possibly also bond-making reactions. The capability of OTC pulses to steer electron wavepackets in two dimensions can also be exploited in sub-cycle electron wavepacket interferometry where they can be applied to control the appearance of interference structures. This will be the third topic discussed in my talk, in which I will describe the observation of sub-cycle interferences originating from nonadjacent quarter cycles. These interferences may be used for tracing attosecond phenomena that lead to spatiotemporal variations of charge density such as hole-wave packets created by ionization. This might be of particular interest for studying attosecond charge density oscillations in molecules.

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Nondipole effects in photoionization of atoms and molecules

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Nondipole effects in photoionization of atoms and molecules have been studied. In the single ionization of atoms, we built the strong field theory beyond the dipole approximation, and used this theory to investigate momentum partition laws for multiphoton and tunneling ionization and explicitly shows that the complex interplay of a laser field and Coulomb action may reverse the expected photoelectron momentum along the laser propagation direction. In the double ionization, the magnetic field modifies the rescattering electron trajectories, and thus significantly changes the rescattering cross section, as well as the double ionization rate. In molecules, such as H2+,N2,and O2, the photoelectron momentum shifts along the laser propagation, and characterize the photon momentum sharing in atoms and molecules, presenting the double-slit interference structure.

Figure 1 presents the correlated electron-electron momentum distribution (a), which can be disentangled into the first (b), second (c) and third(d) rescattering events according to the time interval between tunneling and rescattering. Though the magnetic field does not change the correlated electron-electron momentum distribution severely, it does change the double ionization probability significantly.



Fig. 1. (a) The correalted electron-electron momentum distribution. (b), (c) and (d) : the correlated electron-electron momentum distribution induced by the first rescattering, second rescattering, and the third rescattering, respectively.

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Monitor the molecular vibration and unidirectional rotation with highharmonic spectroscopy

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It is a dream of ultrafast sciences to visualize the molecular structure and dynamics with both good spatial resolution and time resolution. It will provide an intuitionistic picture to understand how nucleus evolves in chemical reactions like to see a movie. In the past decades, lots of efforts have been paid to develop the imaging methods with ultrashort X-ray pulses and electron pulses. Even through a good spatial resolution can be achieved, the temporal resolution is limited to several tens or even hundreds femtoseconds at present. In recent years, an alternative method has also been developed based on the high harmonic spectroscopy. In this talk, we will reports our recent developments about the probing of molecular structure and dynamics with high harmonic spectroscopy.

We investigate the HHG of H2 and D2 molecules. HHG spectra of H2 and D2 show a frequency shift compared with that of Ar atom. The simulation with Born-Oppenheimer approximation model fails to explain the frequency shift. The frequency shift is ascribed to the nonadiabatic effect induced by the molecular vibration motion in the laser field. Beside the laser-driven molecular vibration, we also control and probe the molecular rational dynamics with HHS. By using two time-delayed, polarization-skewed pump pulses, the molecular ensemble is impulsively kicked to rotate unidirectionally, which is subsequently irradiated by another delayed probe pulse for HHG. By scanning the polarization directions and time delays of the probe pulse, the time dependence of the angular distributions of the generated harmonics for N2 and CO2 are measured. We call this method angular HHS. Different from the previous techniques, the angular HHS method can also reveal additionally the electronic structure and multiple orbitals of the sampled molecule. Moreover, we discuss how to reconstruct the molecular rotation dynamics from the measured HHG spectrum.



Fig. 1 (a) The schech of the experiment. Pulses P₁ and P₂ are used to create the unidirectional rotation of N2 molecules. Probe P3 is used to produce HHG. (b)-(e) show the angular distribution of the HHG yield at differnt delays.

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Non-adiabatic tunnel ionization with tailored two-color laser fields

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Strong field single ionization of noble gas atoms using circularly polarized light can be considered to be a simple scenario compared scenarios involving molecular targets, linear polarization or tailored laser fields. But even in the simple case, we observe non-adiabatic features in the three-dimensional electron momentum distribution [1]. Fig. 1(a) shows such a three-dimensional electron momentum distribution that has been measured using cold-target recoil-ion momentum spectroscopy (COLTRIMS) [2] upon ionization of argon atoms by a single-color circularly polarized field at 780 nm. The momentum radius of the experimentally observed donut-like distribution increases for increasing momentum in the light propagation direction (see Fig. 1(b) and 1(c)). We show that the increase in radial momentum is due to the non-adiabatic offset of the initial electron momentum distribution [3] in the plane of polarization. Further, we demonstrate how to experimentally control the degree of non-adiabaticity using counter- and co-rotating two-color fields (390 and 780 nm). Based on the two-color scheme we introduce a simple method for the direct access to the non-adiabatic offset and prove that classical Coulomb interaction after leaving the quantum mechanical tunnel cannot explain the experimental observations. Finally, a mechanistic picture [4] is used that links the measured non-adiabatic offset to the magnetic quantum number of virtually populated intermediate states.



Fig. 1 (a) shows the three-dimensional electron momentum distribution upon strong field ionization of argon by a single-color circularly polarized field at 780 nm. (b) shows the same data as (a) but integrates out the angle in the plane of polarization using the radial momentum $p_r = p_y^2 + p_z^2$. (c) shows the same data as (b) after each column has been normalized separately. An increase in p_r for $|p_r| > 0$ a.u. is observed.

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Ultrafast electron excitation with MIR laser field

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As one of the most important physical processes of strong-field laser-matter interaction, laser-driven electron-ion recollision is the fundamental process. As we known, the well-known three-step model of HHG predicts that the cutoff law obeys Ecutoff = I_p + 3.17U_p (Ip is the ionization potential; Up∞I λ^2 is the ponderomotive energy), implying that the maximum kinetic energy of returning electron can be greatly extended by increasing the driving wavelength. With the long wavelength mid-infrared laser pulse, it is easy for the pondermotive energy of the returning electron to be very large to excite the deep inner shell electron, which may be used to investigate the ultrafast inner shell electron dynamics.



Fig. 1. The fluorescence spectra from the excited Ne (green line) and Kr (red line) atoms. The signal from the Ne is mainly from the K-shell transition with a weak continuum that stretches up to ≈1600 eV. In the Kr spectrum there is a sharp line, belonging to the L-shell transition, on top of a pronounced continuum.

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Electron-nuclear correlation in strong-field dissociative ionization of molecules

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Photon energy deposition between the electron and nuclei is the primary step of the interaction of a strong laser field with molecules, which plays an important role in the photon-induced chemical and physical molecular dynamics. Here, we experimentally investigate the energy deposition in strong-field dissociative ionization of molecules by electron-ion coincidence measurement using Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS). The results indicates that the electron and nuclei in the molecule share the absorbed multiphoton energy in a correlative manner [1,2]. The molecule as a whole absorb the photon energy in the ionization process. Moreover, the electron-nuclear energy sharing assisted by the rescattering leads to the observation of the long-sought-after experimental signatures of high-order above-threshold dissociation [3], which results from the intercycle interference of the periodically emitted electron-nuclear wave packet in the oscillating strong laser fields.



Figure 1. Observation of electron-nuclear correlation of molecules in strong laser fields by the joint energy spectrum (JES).

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Posters:

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12	High harmonic generation of the heteronuclear hydrogen molecular ion in strong infrared laser fields Yu-Ning Yang, <i>Shanghai Jiao Tong University, China</i>
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16	Timing ultrafast attosecond photoelectron emission time delay by strong laser fields and attosecond pulses Xiaochun Gong, <i>East China Normal University, China</i>

Dissociative frustrated double ionization of molecules driven by ultrashort laser pulses

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By recapturing the liberated electron into the Rydberg states, highly excited neutral atoms are generally produced in strong-field ionization of atoms and molecules. For molecules in strong laser fields, a liberated electron can be recaptured by the ejected ionic fragments. Taking the double ionization of hydrogen molecules (H_2 or D_2) as an example, one of the tunneling electrons may be recaptured by one of the outgoing ionic cores, leading to the dissociative frustrated double ionization (FDI). Although the dissociative FDI channels were generally observed for various molecules, the most fundamental issues on when and where such process occurs stand yet experimentally unobserved. For the symmetric breaking of a doubly ionized diatomic homonuclear molecule, the recapture probability of the tunneled electron to two nuclei should be identical in general. However, the steering of the recapture of the electron to a desired ionic core, not realized yet, will open the possibility to selectively excite the nuclear fragment into high-lying Rydberg states.

Here, we experimentally investigate the dissociative FDI of hydrogen molecules in strong laser fields by measuring the ejected neutral and ionic fragments as well as the freed electron in coincidence in a reaction microscope. We real-time visualize the dissociative FDI of hydrogen molecules by performing a pump-probe measurement with two linearly polarized few-cycle (7 fs) laser pulses ^[1]. Three internuclear distances of the stretching molecular ion are recognized to enhance the dissociative FDI at different instants. By further utilizing a linearly and an elliptically polarized few-cycle laser pulses in a pump-probe scheme, the electron recapture dynamics of the dissociative FDI of D₂ is tracked by monitoring the polarization-dependent momentum distributions of the detected freed electron as a function of the time delay ^[2]. Although the electron released from both ionization steps can be recaptured, we found that the electron released in the second ionization step is preferred to be recaptured by the ionic core in producing the dissociative FDI channel of molecules in strong laser fields. By finely adjusting the phase of a two-color laser pulse, the recapture of the tunneling ionized electron to one of the outgoing ionic cores can be steered ^[1]. Our results not only strengthen the understanding of the mechanism of the dissociative FDI of molecules, but also open the possibility to selectively excite the neutral fragments ejected from a breaking molecule by using waveform-controlled ultrafast laser pulses.



Fig. 1: (a) Schematic diagram of the experimental setup. (b) Measured PIPICO spectrum of the (H⁺, H⁺) and (H⁺, H^{*}) channels. (c) Schematic illustration of the stepwise dynamics of the dissociative FDI of hrdrogen molecules.

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Channel resolved multiorbital double ionization of molecular Cl₂ in an intense femtosecond laser field

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With the development of the ultrafast laser technique, the molecular dynamic process in the intense femtosecond laser field has attracted extensive attention. [1-4] In recent work, we measure the sequential double ionization and the subsequent Coulomb explosion of molecular Cl2 in an intense femtosecond laser field by using the DC-sliced ion imaging technique. The measurement results indicate that not only the highest occupied molecule orbital (HOMO) but also the next two lower-lying molecular orbitals are involved in three distinguished reaction pathways. For pathways (1, 1)2 and (1, 1)3, in which the two electrons are removed from HOMO and HOMO-2 in reverse sequence, the ionic excited states $3\Pi g$ and $1\Pi g$ are populated, respectively. The kinetic energy release differences observed in these two channels is ascribed to the nuclear motion during the ionization process. For pathway (1, 1)1, the isotropic angular distribution of fragment ions is attributed to the combination of the electron density distribution of HOMO-1, vibrational electronic wave packet evolution, and field excitation. Our results propose a feasible method to manipulate the electronic dynamics which take place in the attosecond time domain via accurately tuned laser parameters of a femtosecond laser field.



Fig. 1. (Top left) The sliced images of the Cl⁺ ions at the intensity of 1×10^{15} W/cm², (Top right) the corresponding kinetic energy distribution, (Down left) the relate channel ion's angular distribution, and the molecular orbitals, (Down right) and the corresponding vertical ionization energy and calculated PESs of ground and several excited states [1]

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The nonsequential double ionization of Argon in orthogonal two-color laser fields

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The laser parameter dependence of nonsequential double ionization (NSDI) of atomic Ar with orthogonally polarized two-color laser fields is investigated by utilizing 2D classical ensemble method. We study the relationship between the double ionization yield and travel time, and the RII and RESI channels have been determined according to the delay time between electron recollision and final double ionization. By tracing the trajectories of the two electrons, it's indicated that the electron correlation spectra as well as the competition between the two channels are sensitive to the laser field parameters.



Fig. 1. (Color online) Yield of Ar²⁺ as a function of the ratio of the electric field strength at intensities of 0.2PW/cm², 0.4 PW/cm², 0.6 PW/cm², 0.8 PW/cm². Ib represents the electric field strength of 400nm laser field, and Ir represents the electric field strength of 800nm laser field.



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Spin and angular momentum in strong-field ionization

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As a fundamental property of the electron the spin plays an important role in the buildup of atoms, matter and its macroscopic properties, e.g. magnetism. Hence studying effects regarding the spin is highly interesting. In the field of strong-field physics however the role of the spin remains largely unexplored so far. A few pioneering theoretical works have investigated electron spin dynamics in strong laser fields [1-4]. As is described in [1] the tunnel ionization probability for circular light is dependent on the magnetic quantum number m₁. In combination with spin-orbit-interaction (energy splitting of different j-states) this leads to spin polarization of electrons created by strong-field ionization of noble gas atoms. This prediction was confirmed in a first experimental study by Hartung et al. [5].



Fig. 1. Time-of-flight(TOF)-Mott spectrometer. The electron energy is extracted from TOF spectra as shown in the inset. An electrostatic lens is employed to enhance the accepted solid angle to compensate for the low detection efficiency of the Mott detector. From [6].

Here we present experimental data recently published in PRL [6], being able to resolve the initial total angular momentum *j*. Xenon was ionized with an 395 nm, 40fs, circularly polarized laser at $6 \cdot 10^{13}$ W/cm ? A Mott detector was used for the measurement of the electron spin, while simultaneously recording the electron time-of-flight, i.e. energy information (Fig. 1). The *j*-dependent degree of spin polarization as well as the energy dependence of the effect shown in Fig. 2 are in good qualitative agreement with theory.



Fig. 2. a) Measured *j*-resolved spin polarization of photoelectrons emitted from Xenon dependent on their kinetic energy. Green circles corresponding to the ${}^{2}P_{3/2}$ state of the core; blue marks corresponding to ${}^{2}P_{1/2}$. b) Electron energy spectrum on one of the Mott polarimeter's MCP detectors. The two ²P states separated by 1.3 eV can clearly be identified. From [6].

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All-optical field-free three-dimensional orientation of asymmetric-top

molecules

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Alignment and orientation of molecules by intense, ultrashort laser fields are crucial for a variety of applications in physics and chemistry. These include control of high harmonics generation, molecular orbitals tomography, control of molecular photoionization and dissociation processes, production of molecular movies with the help of X-ray free-electron laser sources and ultrafast electron diffraction of relativistic electrons. While the dynamics of laser-induced molecular alignment has been extensively studied and demonstrated, molecular orientation is a much more challenging task, especially for asymmetric-top molecules. Over the years, several optical approaches have been used to break the symmetry and define preferred directions in space so that molecules can be oriented. Early on, intense nonresonant laser fields were combined with weak electrostatic fields for symmetry breaking [1], and this was followed by introduction of single-cycle THz pulses alone [2] or in combination with optical pulses. Of special interest for us is an all-optical approach that uses nonresonant two-color laser field (collinear fundamental wave and its second harmonic) where the orientation is achieved via the nonlinear interaction with the molecular hyperpolarizability

Here, we report the first experimental demonstration of all-optical field-free orientation of asymmetric-top molecules (SO₂) using phase-locked Orthogonal Two-Color (OTC) laser fields [3]. In our experiments, the fundamental field aligns the major molecular axis (the one with the highest polarizability) along the polarization direction. The second harmonic field is temporally overlapping with the fundamental field. The two fields together couple to the molecule via the offdiagonal components of the molecular hyperpolarizability tensor. This interaction orients the minor molecular axis (the one with the second highest polarizability) after the OTC pulse is over and results in the field-free 3D molecular orientation. The same principle applies to other nonlinear molecules similar to SO₂, but with different arrangements of the polarization axes. Such orientational methodologies provide a new toolbox for 3D-molecular-imaging by means of X-ray free electron laser beams with extremely high spatio-temporal resolution, and by ultra-fast electron diffractrion techniques.



Fig. 1. Coincidentally measured momentum distributions of S⁺ and O⁺.

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Probing time delays and coherent imaging of multiphoton resonant

ionization

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Recently, attosecond time delays in photoemission from atoms ^[1], molecules and solids have been experimentally studied with the help of advanced techniques. So far, most of previous works focus on the time delay of one- or few-photon process. Only a few works extend the time delay measurement to multiphoton ionization regime. As known, resonant excitation or ionization is a general process in multiphoton ionization. Revealing the temporal dynamics of the multiphoton resonant states is particularly important.

Experimentally, we measure the laser intensity-dependent photoelectron momentum and energy spectra and identify the emerged resonant (4s, 3d and 4f) states of multiphoton ionization of Ne at 400 nm. We employ parallelly polarized two-color fields involving a strong ionizing 400nm field and a weak 800nm field to probe the relative time delay of resonant states. By analyzing phase-resolved three-dimensional photoelectron momentum distributions, we find the time delay of resonant states has an anisotropic angle-dependence, which is remarkably different with the RABBITT measurement for the few-photon process. Using an intuitive model, we show that the angle-dependent time delay carries the information of sub-cycle evolution of quantum states and reflects the temporal coherent properties of multiphoton resonant states when absorption and emission of photons. We find that the relative time delays among the resonant ionization via 4s, 3d and 4f states along the polarization depend on the number of photons absorbed and the Coulomb potential. This work would advance the study on photoemission time delay anisotropy for multiphoton resonant ionization and would motivate coherent imaging of atomic wave function via multiphoton ionization.



Fig. 1. The intensity-resolved photoelectron momentum distribution along the polarization direction (a) and energy distribution (b). The color scale is normalized to the maximum yield at each laser intensity. The arrows in (a) and (b) represent ionization via resonant states. The dashed lines in (b) denote the n-photon ATI peaks and the vertical line indicates the intensity where the three resonant states coexist. (c) The scheme of the involved atomic states and their corresponding multiphoton resonant excitation paths. (d). A schematic illustration of our model. Here 4f resonant ionization channel is taken for example. The inset describes the electron yield oscillation versus the relative phase and the temporal evolution of quantum states in the PTC field. **Fig. 2.** (a), (b) The extracted angle-resolved photoelectron yield oscillations for resonant ionization via 4f and 3d states. (c) The measured angle-resolved photoemission time delays relative to polarization axis for 4f and 3d resonant ionization. (d) The constructed phase-resolved angular distribution via 4f resonant state using the model.

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Probing molecular spinning dynamics with high-harmonic spectroscopy

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An angular high-harmonic spectroscopy (HHS) method is proposed to probe the spinning dynamics of molecular rotational wave packet (RWP) in real time. With a double-pulse excitation scheme, unidirectional rotations (UDR) of the sample molecules are created in experiment. By measuring the time-dependent angular distributions (ADs) of high harmonic generation (HHG), the spatiotemporal evolution of molecular RWP is intuitively visualized. The harmonic ADs also reveal the electronic structure of the sample molecules. Moreover, due to the correlation of HHG and molecular UDR, HHG from the spinning molecules shows obvious nonadiabatic frequency shift at the rotation revivals. The spinning dynamics of molecular RWP can also be revealed from the angle-dependent frequency shift of HHG.

Determination of the ionization time using attosecond photoelectron

Interferometry

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Laser-induced electron tunneling ionization from atoms and molecules plays as the trigger fora broad class of interesting strong-field phenomena in attosecond community. Understanding the extremely fast dynamics of electron tunneling is vital to achieving the ultimate accuracy in attosecond metrology. We propose a novel attosecond photoelectron interferometer, which is based on the interference of the direct and near-forward rescattering electron wavepackets, to determine the time information characterizing the tunneling process. Adding a weak perturbation in orthogonal to the strong fundamental field, the phases of the direct and the near-forward rescattering electron wavepackets are modified, leading to the shift of the interferogram in the photoelectron momentum distributions. By analyzing the response of the interferogram to the perturbation, the real part of the ionization time, which denotes the instant when electron exits the potential barrier, and the associated rescattering time are precisely retrieved. Moreover, the imaginary part of the ionization time, which has been interpreted as the time of the electron motion under the potential barrier, is unambiguously determined.

Multiphoton-induced dissociation of tetrafluoromethane in a 400 nm laser

field

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We present experimental data on the angular distributions of photoelectrons in the molecular frame of CF₄. Its symmetric structure and three energetically low-lying dissociative ionized states make tetrafluoromethane an ideal target to extend previous work for the single-photon case [1] to the multiphoton regime.



Fig. 1. The kinetic energy release (KER) of the breakup $CF3^+$ and F vs. the electron energy. Using a 400 nm linearly polarized laser field at 1.1 $\cdot 10^{14}$ W/cm², we ionize the two states X^2T_1 and A^2T_2 . This can also be seen in the ATI-Peaks of both states.

To identify the two states populated in our experiment (X^2T_1 and A^2T_2), the electron energies in Fig. 1 were compared to the binding energy diagram in [2]. As can be seen in Fig. 2, the energetic higher state A^2T_2 is the dominant ionization channel for dissociation parallel to the light polarization axis, while X^2T_1 gets more incisive for perpendicular orientation.

In Fig. 3 the molecular frame photoelectron angular distributions (MFPADs) of the state A^2T_2 are shown. With higher ATI-Peaks i.e. electron energy more nodes in the angular distribution become visible. Between 3.6 eV and 6.6 eV the predominant photoelectron emission direction flips from the side of the charged CF_3^+ fragment to the side of the neutral fluorine atom. Those results are in agreement with the data in [1].



Fig. 1. I) Electron momentum distribution in the molecular frame. The x-axis is defined as the light polarization axis. a) no condition on molecular orientation, b) parallel (+15 °) molecular orientation, c) molecule tilted by 45 °(±7.5°), d) perpendicular (±7.5°) molecular orientation relative to the light polarization. II) MFPADs of CF₃⁺-F for parallel (+15 °) molecular orientation relative to the light polarization for the state A²T₂ and the ATI-Peaks at 3.6 eV, 6.6 eV and 9.6 eV. The angular distribution strongly changes with electron energy. The error bars account for the statistical error.

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Proton migration in hydrocarbons induced by highly charged ion impact

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Proton migration of hydrocarbon molecules plays a vital role in the chemical reactions concerning, e.g., combustion and interstellar media, which can significantly change the molecules' properties and thus result in bond rearrangement and/or isomerization processes. Different from the most of previous studies using the light to generate and steer the proton migration channels, the present study reports the dynamics of corresponding channels in three typical hydrocarbon molecules, i.e. CH_4 , C_2H_2 and C_2H_4 , observed on the 150 kV highly charged ion collision platform at Fudan University in Shanghai [1]. As shown in Fig. 1, kinetic energy releases (KERs) are determined for all two-body breakup channels of CH_4 , C_2H_2 and C_2H_4 dications produced by 3 keV/u Ar⁸⁺ ion impact.

Compared to previous photon-induced proton migration studies [2, 3], in the present work the trihydrogen ion (H_3^+) formation channel is observed with much lower abundance in CH_4 , and so does the isomerization channel $(C^++CH_2^+)$ in C_2H_2 . As for C_2H_4 not containing the methyl group, both of the above two kinds of breakup channels are intriguingly present, namely the $H_3^++C_2H^+$ and $CH^++CH_3^+$ channels. In particular, for the channel $H_3^++C_2H^+$, we have explored the multi-dimensional potential energy surface of the $C_2H_4^{2+}$ dication by density functional theory calculations to find the responsible transition states, in order to figure out the H_3^+ ion formation mechanism. Furthermore, to "control" the proton migration processes of e.g. $C^++CH_2^+$ employing the highly charged ion beam of different parameters (projectile species, charge state and velocity), as using the light [4, 5], corresponding collision experiments combined with time-dependent density functional theory calculations [6, 7] are being planned.



Fig. 1. KERs of two-body breakup channels of CH4, C2H2 and C2H4 dications produced by 3 keV/u Ar8+ ion impact

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Tunneling exits of H₂⁺ in strong laser fields

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Tunneling exits of H_2^+ at large inter-nuclear distance in strong laser fields have been studied. We simulated the tunneling process of H_2^+ under Bohr-Oppenheimer approximation by numerically solving 2D time-dependent Schrödinger Equation. The inter-nuclear distance is fixed at R=12, and a carefully chosen half-cycle laser is introduced to kill rescattering process while minimizing the interference between over-barrier ionization and tunneling ionization to simplify the analysis. The ionized wave packet is then transferred to a classical ensemble by calculating the local momentum, and the classical trajectories of the ensemble is obtained. Some criteria are imposed to filter out those OBI processes and non-physics signal caused by numerical error , and revealed the non-trivial tunneling exit structure which seems like a crescent. Such a result is closely related to the saddle-shaped potential structure of H_2^+ molecule.

Figure 4 shows the crescent shaped tunneling exits in a logarithmic scale color bar in configuration space. The two white dots are the positions of the two Hydrogen nuclei.



Fig.1. (color online) the tunneling exit distribution in the logarithmic scale. The two stars in the figure represent the position of the two nuclei. Overbarrier part and downstream ionization part occupy only 0.02% of ionized final state, which are not shown on this figure.

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High harmonic generation of the heteronuclear hydrogen molecular ion in

strong infrared laser fields

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The high harmonic generation of heteronuclear hydrogen molecular ions in few-cycle infrared strong laser fields is studied by numerically simulating the time-dependent Schrödinger equation. By reversing the carrier envelope phase of the few-cycle laser pulse, the electron dynamics is reversed as well. However, due to the different nuclear masses, two nuclei move with different repulsive speeds, which makes the rescattering processes not identical when the carrier envelope phase shifts by π . The different rescattering processes lead to distinct harmonic spectra in the cutoff region. The mass- dependent harmonic spectrum offers a view angle to diagnose the isotope dynamics in molecules with unprecedent high time and spatial resolutions.

Figure 1 plots the laser pulses and the sketch of the electron trajectories. For $\varphi = \pi/2$, the electron tunnels out and propagates along the positive z axis. When the electric field changes the direction, the electron first rescatters the proton instead of the tritium. In another case, the electron rescatters with the tritium. In the time interval between ionization and rescattering, the two nuclei have the displacement δR and δR_{\circ} . The different harmonic spectra are observed, as shown in Fig. 2 (a).



Fig1. The electric field of the laser and the sketch of the rescattering for two opposite phases. The red dashed curves sketch the electron trajectories between tunneling and rescattering. δR_1 and δR_2 are the displacements of the proton and the tritium. $\delta R_1 > \delta R_2$



FIG. 2. (a) The HHG for the laser interacting with HT+ with the laser wavelength 800 nm, intensity $I_0 = 2 \times 10^{14} \text{W/cm}^2$ and the pulse duration $\tau = 1$ optical period. (b) The HHG in the single ionization of HT in the laser field with the intensity 6×10^{13} W/cm², and other parameters are same as those in (a). The black solid and red dash-dotted curves represent the spectra when CEPs are $\pi/2$ and $-\pi/2$, respectively. The vertical axes in both panels are in the logarithmic scale.

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High energy direct photoelectron spectroscopy in strong field ionization

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We report a specific wing structure in the momentum distribution around 2 Up.

Recently, in the tunneling regime of strong field ionization an unexpected Coulomb field effect has been identified by numerical solution of time-dependent Schrödinger equation [1] in photoelectron spectra in the upper energy range of the direct electrons. We investigate the mechanism of the Coulomb effect employing a classical theory with Monte Carlo simulations of trajectories, and a quantum theory based on the generalized eikonal approximation for the continuum electron. The effect is shown to have a classical nature and is due to momentum space bunching of photoelectrons released not far from the peak of the laser field [2]. Moreover, our analysis reveals specific features of the angular distribution of high energy direct electrons which can be employed for molecular imaging. For the H2+ molecule as an example we show the signatures of the molecule orientation and the molecular structure in the investigated angular distribution.



Fig. 1. The electron initial phase space $(p_{\perp i}, \varphi)$ with color coded probabilities, which finally contributes to the photoelectron energy interval (1.9Up, 2.1Up) (first row): (left column) Ip = 0:42I_a, (middle column) Ip = 0.79I_a, (right column) Ip = 1.35I_a. Asymptotic momentum distribution (second row) for the corresponding Ip values. The phase space of the trajectories A, B, and C type are indicated in the panel (b). The parameters are E0 = 0.0315 a.u., $\omega = 0.0456$ a.u. and Z = 1.

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Method for direct observation of Bloch oscillations in semiconductors

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We propose a scheme for real-time observations of Bloch oscillations in semiconductors using time-resolved band gap emission spectroscopy. By solving the time-dependent Schrödinger equation^{1,2}, we find one remarkable band gap emission besides the normal high harmonics generated in the interaction of a mid-infrared laser pulse and a semiconductor. It is shown that the band gap emission yield is directly connected to the population in the conduction band (CB). By adopting a pump-probe scheme, the time-dependent population in the CB, that is the dynamical Bloch oscillation, can be probed by measuring the band gap emission signal versus pump-probe delay. We also present a model based on accelerated Bloch states to explain the time-resolved measurement of dynamical Bloch oscillation.



Fig. 1. The time-dependent population imaging picture (a) and the band gap emission signal versus the time delay. The dynamical Bloch oscillation is well traced by the pump-probe scheme.

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Pure even and odd harmonics produced in modelled hydrogen molecular ions in single-color strong laser fields

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The even and odd high-order harmonic generation in a modelled hydrogen molecular ion in strong laser fields is studied by numerically simulating the time-dependent Schrodinger equation. By applying a linearly polarized laser pulse whose polarization axis is perpendicular to the molecular axis, the pure odd harmonics polarized along the laser polarization direction are produced. Meanwhile, the pure even harmonics polarized along the molecular axis may be produced simultaneously either by adding an extra weak static electric field along the molecular axis, or by artificially setting asymmetric charges for the two nuclei. The Bohmian trajectories reveal that during the tunnelling ionization and the rescattering process, the counter-intuitive asymmetric expansion of the electronic wave packet along the molecular axis contributes the pure even harmonics. This interesting phenomena shows the wave character of the ionized electron and is vitally important to classical/quantum Monte Carlo simulations in the ultrafast field. Finally the relationship between the symmetry of molecular orbital and the parity of high-order harmonics is explored.

 H_2^+ is aligned along the x-axis, as shown in Fig. 1 (a). The polarization axis of the linearly polarized laser field is perpendicular to the molecular axis, and the weak static field points to the positive x axis. Figure 1 (b) presents the harmonic spectra polarized along the y and x axes. Not surprisingly only odd harmonics are generated along the y axis. However, pure even harmonics are observed along the x direction though they are much weaker.

For a molecule with difference nuclear charges and the H_2^+ ion, the Bohmian trajectories are shown in Fig. 2 (b). For H_2^+ , the left ten trajectories are just the mirror of the right ten trajectories. Therefore, the expected displacement for the tunneling electron along the molecular axis is $\langle x \rangle = 0$. No harmonic radiation polarized along the *x* axis can be generated. However, for the modelled hydrogen molecular ion with asymmetric nuclear charges, the twenty Bohmian trajectories are not symmetric with respect to the axis of x = 0. The electron is driven by the laser field along the *y* axis, meanwhile, almost all trajectories deflect to the left side compared to the case of H_2^+ though the Q_2 charge is larger. So this counter-intuitive asymmetric expansion of the electronic wave packet contributes the pure even harmonics.



Fig. 1. (a) The ground state probability distribution of H_2^+ ion. The internuclear distance is fixed at D = 2 a.u..(b) The calculated HHG polarized along the *x* (red solid curve) and *y* (black solid curve) direction. The laser intensity is $I=5*10^{14}$ W/cm². The magnitude of static electric field is $E_x=0.01E_y$. For comparison, the HHG polarized along the *x* axis has been multiplied by 100.

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Fig. 2. (a) Bohmian trajectories for (a) H_2^+ and (b) the modelled hydrogen molecular ion with two nuclear charges $Q_1=1$ and $Q_2=1.2$. The starting points for the twenty trajectories from left to right are $x = [-0.25 \ 0.25]$ a.u., y = 3.2 a.u..The curves show the electron trajectories in the time interval 88 a.u.. The two black dots represent two nuclei. The laser intensity is $8*10^{14}$ W/cm² (CW laser:1T, $\sin(\omega t + \pi)$).

Timing ultrafast attosecond photoelectron emission time delay by strong laser fields and attosecond pulses

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Abstract: A Freeman Resonance time delay of 140 ± 40 attoseconds between photoelectrons emitted via the 4f and 5p Rydberg states of argon is observed in strong laser fields. Recently, an attosecond coincidence interferometer assisted with high harmonic pulse trains was constructed to directly measure the ultrafast photoelectron emission time delay in molecular frame.

A novel attosecond time delay is experimentally observed for photoelectrons emitted via various excited states driven by strong laser fields [1]. A photoelectron can be freed from an atom as it is irradiated by a light. The photoemission is not an instantaneous process as verified for the long-term debated field-induced tunneling process. Interestingly, the potential of the excited Rydberg states may be Stark lifted to be resonant with the energy of multiple photons of the driving laser field. The resonant population of the intermediate Rydberg states leads to significant enhancement of photoelectron emissions, i.e., the Freeman resonance ionization as it is firstly observed about 30 years ago[2].



Fig. 1. Freeman Resonance delay measured in strong laser fields.

Experimentally, a phase-controlled orthogonal two-color (OTC) femtosecond laser pulse is employed to probe the time delay of photoelectron emission in the strong-field ionization of Argon atoms. The OTC field spatiotemporally steers the emission dynamics of the photoelectrons and meanwhile allows us to unambiguously distinguish the main and sideband peaks of the above-threshold ionization spectrum. The phase-of-phase (PP) ϕ_{PP} retrieved from laser phase dependent PADs reveals ultrashort time delays in photoelectron emissions. We observe a Freeman resonance delay of 140 ± 40 attoseconds between the photoelectrons emitted via the 4f and 5p Rydberg states schematically illustrated in Fig. 1(a)] of argon when they are ac-Stark shifted to be resonant with the energy of multiple photons of the driving fields. Meanwhile, the relative phase shift between the main and sideband peaks, retrieved from the ϕ_{PP} of the photoelectron spectrum as a function of the laser phase, gradually decreases with increasing electron energy, and becomes

zero for the fast electron which is mainly produced by the rescattering process.

As compared to the well-known photon transition time delay [3-5] and the recently predicted absorption time delay in two-photon ionization of Helium [6], here we experimentally observed a Freeman resonance time delay in multiphoton ionization of Argon atoms by using a phase-controlled two-color femtosecond laser pulse. Our findings promise new insights into the understanding of sub-cycle photoelectron emission dynamics, and will hopefully spur more interests and works on the accurate control of ultrafast electron dynamics in light matter interactions.

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上海伯东代理品牌包含: 德国 Pfeiffer 全系列真空产品、美国 KRI 离子源、美国 Brooks Polycold 制冷机, 美国 HVA 真空阀门,美国 inTEST(Temptronic)高速温度循环测试机,美国 Ambrell 感应加热设备,日本离子蚀刻机, 真空镀膜系统及配套真空零配件等。

上海伯东作为国际知名真空品牌指定授权代理商,全权负责在中国地区的销售和维修服务,100% 使用原厂进口零部件以及国外受训维修工程师;拥有完全的拆解,维修,校正能力并提供24 小时在线服务。







聚焦和扫描

纳米精度、动态吞吐量



普爱纳米位移技术(上海)有限公司

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飞秒激光器/飞秒光参量放大器

CARBIDE系列紧凑型Yb:KGW飞秒激光器

- ▶ 最大单脉冲能量: >400uJ
- ➢ 最大平均功率: >40W
- ▶ 重复频率: 60-1000kHz
- ▶ 脉冲宽度: <290fs-10ps
- ▶ 输出光斑: TEM₀₀, M²<1.2
- ▶ 体积小巧、全自动控制

PHAROS系列Yb:KGW飞秒激光器

- ▶ 中心波长: 1028±5nm
- ▶ 最大单脉冲能量: >2.0mJ
- ▶ 最大平均功率: >20W
- ▶ 重复频率: 1-1000kHz
- ▶ 脉冲宽度: <190fs 20ps</p>
- ▶ 脉冲宽度和重复频率一键可变

ORPHEUS系列: 波长可调谐飞秒放大器

- ▶ 型号: ORPHEUS、ORPHEUS-HP、ORPHEUS-ONE
- ▶ 重复频率: 1kHz-1MHz
- ▶ 脉冲宽度: <120fs 250fs</p>
- ▶ 波长调谐范围: 210-16000nm
- ▶ 电脑控制,全自动波长切换





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