Brief Introduction of Extreme Nonlinear Optics---

High Harmonic Generation and Attosecond Physics

Abstract: High harmonic generation is to produce higher frequency harmonics radiation emission after the interaction between atoms and intense laser field. In this article, semi-classical simple man model has been introduced. The characteristic feature of the emission spectrum make the generation of attosecond pulses train and single attosecond pulse possible. Detailed generation principles are also covered here.

Ⅰ. Introduction

Since the first observation of high harmonic generation (HHG) in 1987 [1,2], intense research on high harmonic generation has been conducted over the past decades. As an effective source of coherent radiation in the XUV (extreme ultraviolet) spectral region, HHG provides a unique method of observing ultrafast phenomena in atoms and molecules on the attosecond time scale. Briefly speaking, HHG is a process in which noble gas atoms are driven by an intense laser field of frequency ω and produce radiation of higher frequencies $q\omega$, where q is an odd integer.

Ⅱ. Theory of HHG

In 1993, P. B. Corkum proposed a semi-classical model of the physical processes of HHG [3]. According to this so called *simple man's theory*, high-harmonics are generated in the following 3 steps shown in Fig. 1.

1. Due to the distortion effect of atomic binding potential by the intense laser electric field, an electron can tunnel through the potential barrier and get ionized.
2. The ionized electron is accelerated by the driving laser filed thereby accumulating kinetic energy.
3. The electron comes back to the nucleus and recombines into ground state. Meanwhile, photons radiation with the ionization potential and the accumulated kinetic energy of the electron are emitted.

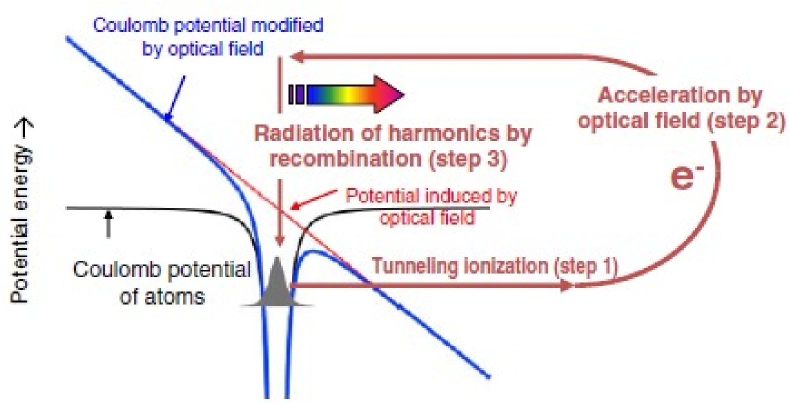

Fig. 1. Principles of HHG and three-step model [4].

This three-step process has a periodicity of T_L, where T_L is one cycle of the driving laser field. Thus, every half cycle of the laser field photon radiation is emitted , which results in a spectral frequency comb with peaks separated by twice the frequency of the driving laser field. Because the fundamental frequency can be considered as the first order $q = 1$, then the following harmonics will only appear when q is odd integers.

Newton's 2nd law predicts that the maximum accumulated kinetic energy is $3.17U_p$, where $U_p = \frac{E^2}{4\omega^2}$ is the so-called ponderomotive energy. In other words, the maximum energy of the radiated photon is $I_p + 3.17U_p$, where I_p is the ionization potential the source atom. This law also determines the position of cutoff in the high harmonic spectrum [5]. In general, the energy of the emitted radiation depends on the phase of the driving field. The maximum situation only happens when the phase satisfy certain condition, $\varphi_{\max} \approx 0.6\pi$. If the tunnel-ionization takes place before the driving field reaches its maximum at $\varphi = \pi/2$, the accelerated electron will never come back to the nucleus. Instead, if it happens at the peak, then the electron will come back with zero kinetic energy, which is not desirable [6].

The characteristic features of high harmonic spectrum are shown in Fig 2. At lower frequencies, intensity of emission decreases exponentially, followed by fairly uniform intensity, the plateau and then abruptly drops, the cutoff.

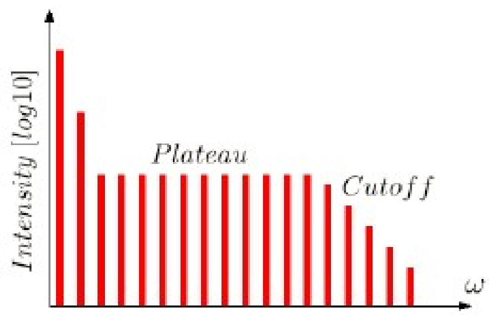

Fig 2. High harmonic spectrum [7]

Ⅲ Attosecond Pulse Synthesis

There are two focuses on the attosecond pulse synthesis for HHG. One is the formation of an attosecond pulses train (APT) from the broad plateau spectrum. The other one is the generation of single attosecond pulses utilizing HHG with few-cycle driving pulses.

1. Attosecond Pulse Train

Similar to a mode-locked laser, HHG can produce a train of pulses separated by a half the driving laser period ($T_L / 2$), each with a duration τ inversely proportional to the range of frequency $\Delta\omega$. The broad spectral structure of the harmonic plateau allows for the formation of a train of sub-femtosecond XUV pulses. The birth of the first attosecond scale pulses train was in 2001. Paul et.al. succeeded in measuring a train of 250 as pulses synthesized from 5 consecutive high harmonics of argon [8].

One important issue of APT is that harmonic fields of different orders have different dipole phases due to the fact that the electrons contributing to the same harmonic travel at different times. From the quantum mechanic point of view, these electrons undergo degenerate paths. The dominant contributions to the harmonic spectrum come only from the two shortest ones, labeled as "short" and “long” paths. To solve the potential problem mentioned before, one should only select only one of the degenerate electron paths so that the dipole phase of each harmonic is unique, in consequence, the harmonics in the plateau can be added coherently. In 1995, P. Salieres et. al. experimentally showed that this effect can be achieved by positioning the gas jet after the laser focus [9]. Another possibility is that utilizing a small aperture in the path to block the “long” path component, since the far field profile of long path is more divergent than that of short path [10].

2. Single Attosecond Pulses

By confining one of the pulses from the APT, single attosecond pulses can be achieved by driving HHG with few-cycle driving pulses [11]. They set the spectral filter around the cutoff frequency. And a single attosecond pulse will be produced since the fields of energy beyond the cutoff can be generated only during the one half-cycle in which the driving laser intensity is at its peak. Also, they figured out that the control of the carrier envelope phase (CEP) of few-cycle driving laser pulses, since HHG is sensitive to their CEP in this case (Fig. 3). Carrier envelope phase is the phase ϕ of a carrier wave with respect to its pulse envelope. When the amplitude of the field overlaps with the peak of a pulse envelope ($\phi = 0$ case), cutoff harmonics are emitted more than once and their spectrum is harmonic. When $\phi = \pi/2$, the emission of cutoff harmonics is temporally confined into one single burst (Fig. 4). So the manipulation of CEP is essential for attosecond pulse synthesis.

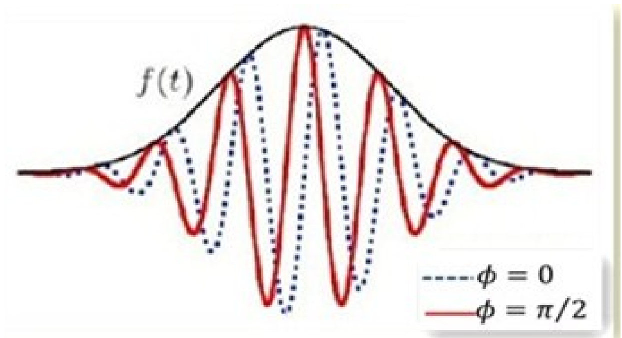

Fig 3. Few-cycle laser electric field [7]

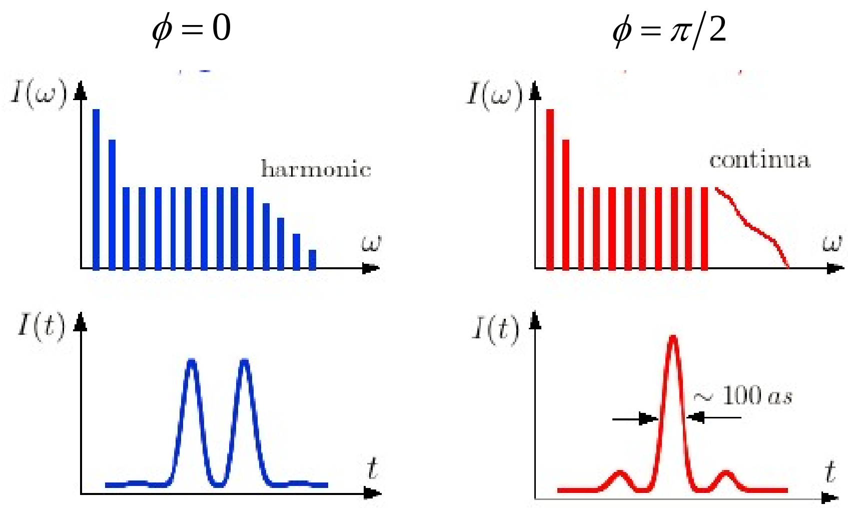

Fig 4. High harmonic generated with a few-cycle pulse [7]

Recently, the generation of pulses with a width of 80 attoseconds (as) has been reported [12].

Ⅳ. Conclusions

Over the past twenty years, as a high-output coherent light source in the XUV region and the sole source of attosecond pulses, HHG has attracted intense intention. So far, attosecond pulses train and single attosecond pulse are available to be obtained. With this great adventure, attosecond science has become the main stream of research focus in the whole world. Many ultrafast phenomenon inside the atoms and molecules are the new field of interest. Hopefully, in the near future, attoscience will get great progress and make the unknown world as smaller as possible.

References:

[1] A. McPherson et. al., Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gases, J. Opt. Soc. Am. B 4, 595-601 (1987)

[2] M. Ferray et. al., Multiple-harmonic conversion of 1064 nm radiation in rare gas, J. Phys. B: At. Mol. Opt. Phys. 21, L31-L36 (1988)

[3] P. B. Corkum, Plasma perspective on strong-field multiphoton ionization, Phys. Rev. Lett. 71, 1994-1997 (1993)

[4] K. Midorikawa, High-Order Harmonic Generation and Attosecond Science, Japanese J. App. Phys. 50 090001-0900012 (2011)

[5] J.L. Krause et. al., High-order harmonic generation from atoms and ions in the high intensity regime, Phys. Rev. Lett. 68, 3535-3538 (1992)

[6] A. Heinrich, Coherent control of high harmonic generation using attosecond pulse trains, Doctoral Dissertation

[7] M. Murakami, High harmonic generation by short laser pulses: time-frequency behavior and applications to attophysics, Doctoral Dissertation

[8] P. M. Paul et. al., Observation of a train of attosecond pulses from high harmonic generation, Science 292, 1689-1692 (2001)

[9] P. Antoine at. Al., Attosecond pulse trains using high-order harmonics, Phys. Rev. Lett. 77, 1234-1237 (1996)

[10] M. Bellini et. al., Temporal coherence of ultrashort high-order harmonic pulses, Phys. Rev. Lett. 81, 297-300 (1998)

[11] M. Drescher et. al., X-ray pulses approaching the attosecond frontier, Science 291, 1923-1927 (2001)

[12] E. Goulielmakis et. al., Single-Cycle Nonlinear Optics, Science 320, 1614-1617 (2008)