Isolated attosecond electron wave packet diffraction*

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Wave-particle duality is one of the most fundamental and mysterious natures of matters. Here, we present an interesting scheme of isolated electron wave packet diffraction with a few-cycle laser pulse and an extreme ultraviolet (XUV) pulse. The diffraction fringes are clearly present in the laser dressed XUV photoelectron spectra, strongly resembling the Airy diffraction pattern of optical waves. This phenomenon suggests a great potential of attosecond diffractometry. According to this scheme we also propose a simple method to determine the XUV pulse duration from the photoelectron spectra with a rather high resolution.

Keywords: electron wave packet diffraction, extreme ultraviolet pulse, attosecond diffractometry

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1. Introduction

With the development of laser technology, intense laser pulse duration falls continually and has approached a few optical cycles in recent years. Control of the waveform of few-cycle pulses then opens a new way for studying and steering ultrafast electronic processes, which has made a breakthrough of attosecond pulse generation.[1−5] Attosecond pulses along with the few-cycle pulses constitute a robust tool for ultrafast measurement.[6,7] It resembles the traditional pump-prob technique, but the attosecond resolution enables one to probe and control the electronic dynamics in atoms and molecules in real time, thereby opening a new area of attosecond science. This approach has been used to observe the electron relaxation in atoms,[8] measure the waveform of laser fields,[9,10] attosecond pulse duration,[11,12] steer the electron motions,[13,14] and high harmonic generation.[15−20]

In this work, we present an interesting scheme for the single-slit diffraction of an attosecond electron wave packet, so as to explicitly reveal the wave-particle duality of electrons. However, we demonstrate the diffraction in the time-energy domain rather than the space domain in contrast to the traditional optical diffraction. Our scheme also relies on the few-cycle pulses along with attosecond pulses, but yet we focus on the diffraction of an electron wave packet. Figure 1 illustrates our scheme. The dashed and solid lines in

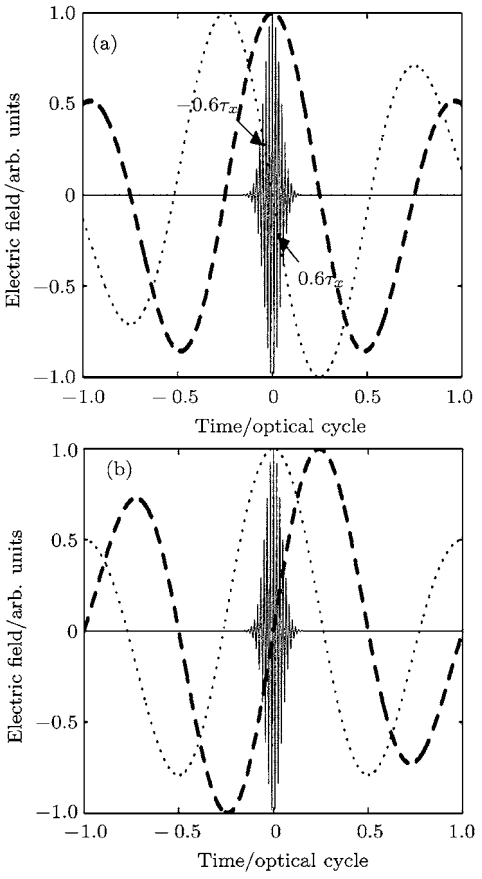


Fig. 1. Electric fields (dashed lines) and vector potentials (dotted lines) of the cos-like (a) and sin-like (b) few-cycle pulses, the solid lines show the attosecod XUV pulse. The fields are normalized for easy comparison.

Fig. 1(a) shows the electric fields of the cos-like few-

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cycle pulse and attosecond XUV pulse, respectively. When the atom is subjected to these fields, the XUV pulse first frees an electron wave packet via single photon ionization, the electron wave packet subsequently propagates freely in the laser field.[21] Compared with the single-slit diffraction of optical waves, the XUV pulse, which triggers the electron wave packet, acts as the slit. Subsequently, the electron wave packet propagates in the laser field, resembling the optical wave, and it will accumulate a phase difference along different quantum paths. Finally, like optical diffraction, diffraction fringes are expected to be observed from the photoelectron emission. The slit width can be adjusted by changing the XUV pulse duration, which conversely can be read out from the diffraction pattern. Also, changing the waveform of laser field will adjust the propagation of electron wave packet and further control the diffraction.

2. Results and discussion

The simulation is carried out by solving the time-dependent Schrödinger equation (TDSE), as in Ref. [3], and the photoelectron spectral is implemented using the wave function splitting technique.[22] In the simulation, we choose a 4-fs laser pulse with a wavelength of 800 nm and an intensity of 5×10^{13} W/cm^2. The electric field reads $E(t) = E_0\cos^2(t\pi/4/T_0)\cos(\omega_0 t+\varphi_0)$, where $-2T_0 \le t \le 2T_0$, E_0, ω_0, T_0, and φ_0 are the laser amplitude, frequency, optical cycle and carrier-envelope phase (CEP), respectively. CEP $\varphi_0 = 0$ corresponds to the cos-like pulse in Fig. 1(a) and $\pi/2$ to the sin-like pulse in Fig. 1(b). The isolated XUV pulse, which is produced by filtering the cutoff high harmonics,[1] is transform limited. The electric field reads $E_x(t) = E_{x0}\exp(-t^2/\tau_x^2)\cos(\omega_x t)$ where τ_x is the XUV pulse duration. The XUV pulse intensity is 2×10^{13} W/cm^2, photon energy is 93 eV. We take helium as the target gas. Owing to the high ionization potential (24.5 eV), the laser field induces an inappreciable photoionization at the intensity in our simulation and the photoionization is triggered dominantly by the XUV pulse. This approach highly improves the visibility of the laser dressed XUV photoionization signal, which carries the information about electron wave packet diffraction.

Figure 2 shows the photoelectron spectra (solid lines) in the cos-like pulse. One can see that the spectra each exhibit a central maximum, but no other fringes at all. By broadening the slit width, i.e., XUV pulse duration, the bandwidth of the central maximum will increase. This behaviour is counterintuitive, since the energy spacing ΔE and the temporal distance Δt are expected to satisfy the relation $\Delta E\Delta t \sim 2\pi$.[23,24] This counterintuitive behaviour is a unique property of the isolated electron wave packet much shorter than the half-cycle of laser field (< 600 as). We also carry out the simulation with the semiclassical model the strong field approximation (SFA). Following Ref. [25], the electron spectrum (in atomic units) is

$$b(\boldsymbol{p}) = \mathrm{i}\int_{-\infty}^{\infty}\boldsymbol{E}_x(t')\,\mathrm{d}[\boldsymbol{p}-\boldsymbol{A}(t')] \times\exp\left[-\mathrm{i}\int_{t'}^{\infty}[\boldsymbol{p}-\boldsymbol{A}(t'')]^2/2\,\mathrm{d}t''+\mathrm{i}I_\mathrm{p}t'\right]\mathrm{d}t', \quad (1)$$

where I_p is the ionization energy, $\boldsymbol{A}(t)$ is the vector potential and the dipole momentum $\mathrm{d}(\boldsymbol{p}) \propto \boldsymbol{p}/(\boldsymbol{p}^2+2I_\mathrm{p})^3$. The electron spectra are shown as the dotted lines in Fig. 2, which are agree quite well with the quantum results from TDSE. This consistence also suggests to us to interpret the above results with the semiclassical model.[21] Following Ref. [21], the electron wave packet is freed with an initial energy of $W_0 = \boldsymbol{p}_0^2/2 = \omega_x - I_\mathrm{p}$ by absorbing one XUV photon and then propagates freely in the laser field. We can easily obtain the electron motion and energy $\boldsymbol{p}(t) = \boldsymbol{A}(t)+\boldsymbol{p}_0-\boldsymbol{A}(t_\mathrm{i})$, $E_k(t_\mathrm{i}) = W_0+2U_\mathrm{p}\sin^2(\omega_0 t_\mathrm{i}+\varphi_0)+\sqrt{8U_\mathrm{p}W_0}\sin(\omega_0 t_\mathrm{i}+\varphi_0)$, where t_i is the ionization time and U_p is the ponderomotive energy. In the cos-like field shown in Fig. 1(a), the electron wave packet is freed at the peak of the electric field, which corresponds to a zero cross of the vector potential. Then the laser field induces an inappreciable momentum shift and inappreciable phase shift of the electron wave packet, thus the diffraction fringe is not apparent in the cos-like pulse. In this case, the electron wave packet is particle-like. The photoelectron bandwidth can be determined by the energy separation between the ascending and descending parts of electron wave packet. As indicated in Fig. 1(a), the XUV pulse decreases to its half maximum around $\pm0.6\tau_x$, then we obtain $\Delta E = E_k(0.6\tau_x) - E_k(-0.6\tau_x) = 2\sqrt{8U_\mathrm{p}W_0}\sin(0.6\omega_0\tau_x)$. For attosecond XUV pulses, $\tau_x \ll T_0$,

$$\Delta E = 2\sqrt{8U_\mathrm{p}W_0}\sin(0.6\omega_0\tau_x) \cong 1.2\sqrt{8U_\mathrm{p}W_0}\omega_0\tau_x. \quad (2)$$

This equation clearly shows that the bandwidth of photoelectron spectrum increases almost linearly with the increase of XUV pulse duration.

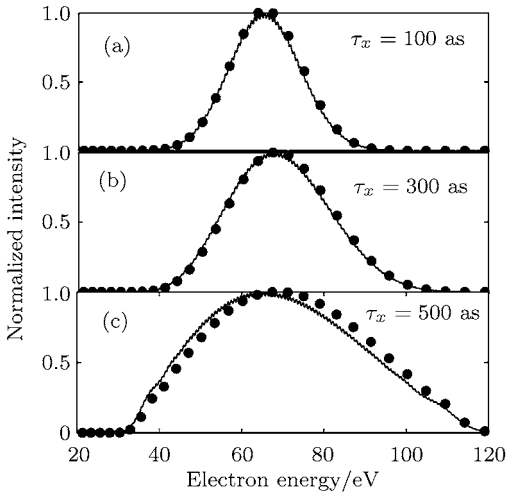


Fig. 2. In the cos-like pulse, photoelectron spectra in the positive direction of laser field with different XUV pulse durations. Solid and dotted lines correspond to the results from TDSE and SFA, respectively. The spectra are normalized for easy comparison.

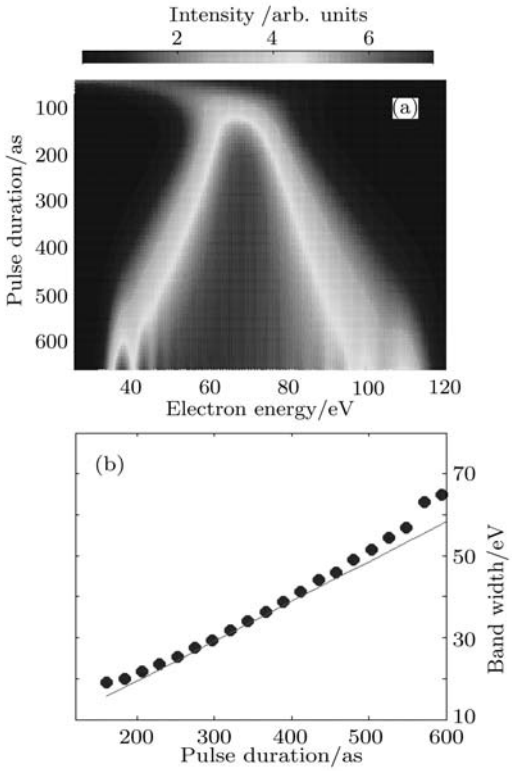


Fig. 3. In the cos-like pulse, (a) a series of photoelectron spectra for XUV pulses ranging from 100 as to 650 as and (b) the dependence of the bandwidth of photoelectron spectra on XUV pulse duration. The colourbar in panel (a) shows the photoelectron intensity in the linear scale.

In Fig. 3(a), we present the overall photoelectron spectra for the XUV pulses ranging from 100 as to 650 as. The photoelectron spectrum bandwidth (dots) is shown in Fig. 3(b) as a function of XVU pulse duration. For comparison, we also show the bandwidth predicted by Eq. (2) (solid line). One can see that the bandwidth of photoelectron spectra increases linearly with the XUV pulse duration from 100 as to 500 as, which is also predicted quite well by Eq. (2). However, beyond 500 as, the deviation slightly increases. The extraordinary agreement between the results from Eq. (2) and the quantum results from TDSE confirms the validity of the above discussion on the semiclassical model, which actually recovers the electron behaviour on the stationary quantum paths. On the other hand, it is worth while noting the simplicity and the usefulness of Eq. (2). Although the quantum and semiclassical theories of laser dressed XUV photoionization have been established,[11,12] a direct quantitative relationship between the photoelectron spectrum bandwidth and XUV pulse duration has not been achieved yet. Equation (2) predicts the photoelectron bandwidth in a rather simple and accurate way, which is very useful for many applications.

In the following, we discuss the electron wave packet diffractions in the sin-like pulse. In contrast to the cos-like pulse, the electron wave packet is freed at the peak of the vector potential in the sin-like pulse [see Fig. 1(b)], which leads to a significant momentum and phase shift and the diffraction fringes thus are clearly present (see Fig. 4). As shown in Fig. 4(a), a notable maximum is exhibited, and accompanied by a minor side peak. By increasing the XUV pulse duration, the notable maximum becomes a little narrower, the side peak becomes larger and two new side peaks are also present. These fringes strongly resemble the diffraction patterns of optical waves. The notable maximum is comparable to the Airy spot, and the side peaks correspond to the –1st, –2nd, etc. maxima. Note that we also observe the 1st, 2nd, etc. maxima in the negative direction, which is symmetric with respect to the photoelectron spectrum in the positive direction and so not shown. In Fig. 4(c), we show the overall photoelectron spectra for XUV pulse ranging from 100 as to 500 as in a logarithmic scale, which more clearly exhibit the diffraction fringes. Also, we can see that the fringe number increases with the increase of XUV pulse duration.

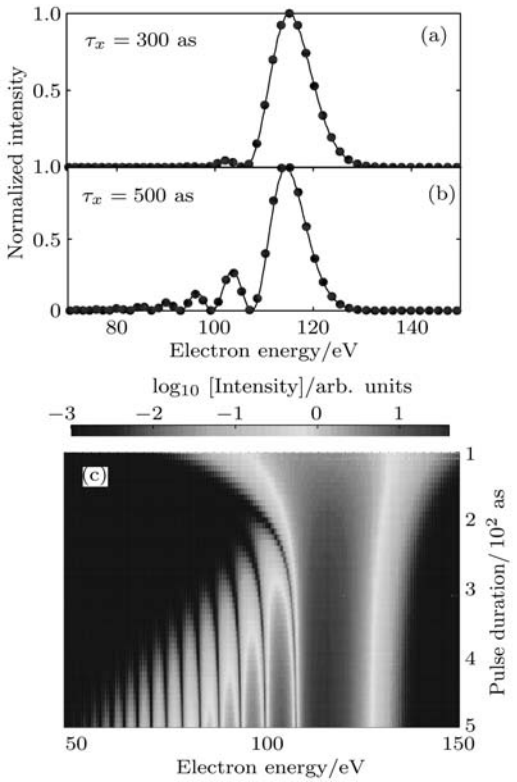


Fig. 4. In the sin-like pulse, the photoelectron spectra in the positive direction of laser field with different XUV pulse durations. Solid and dotted lines correspond to the results from TDSE and SFA, respectively. (c) A series of photoelectron spectra for XUV pulses ranging from 100 as to 500 as. The colour bar (c) shows the photoelectron intensity in the log10 scale.

The diffraction of electron wave packets makes it possible of attosecond diffractometry. For an application, we present a new and simple way to measure the slit width, i.e., XUV pulse duration, which is a crucial issue in attosecond science. In a similar way to optical diffractometry, the pulse duration can be simply determined by counting the fringe number in the sin-like pulse as shown in Fig. 4. This method requires only one laser-dressed photoelectron spectrum rather than many photoelectron spectra,[1,12] and is thus more efficient and simple. The drawback is that the higher order fringes decline rapidly and are only visible in the logarithmic scale. We then put insight to the electron wave packet diffraction in the cos-like pulse. As shown in Fig. 3, the XUV pulse duration can be directly read out from the bandwidth of photoelectron spectra, which is also quite simple. Here, we stress that equation (2) allows one to directly determine the XUV pulse duration in a rather simple and accurate way. Although equation (2) is accurate only for the attosecond pulse shorter than 500 as shown in Fig. 3, a wider range is possible using a laser field of longer wavelength. Our simulation shows that the validity of Eq. (2) is broadened up to about 1 fs in the 1600-nm laser field. Moreover, the temporal resolution, which is related to the energy resolution, is very high for our method. For instance, the resolution of an electron spectrometer, i.e., the ability to distinguish the electron energy shift, is less than 1 eV in Ref. [13]. Such a 1-eV resolution of the photoelectron bandwidth guarantees a temporal resolution of about 10 as. However, the fluctuation of laser intensity and CEP will degrade the resolution. Currently, a Ti:sapphire laser pulse with an intensity stability of 5% and a CEP stability of 50 mrad is realizable. In this case, a temporal resolution of about 50 as still can be achieved in our method. Also, as indicted by Eq. (2), a higher temporal resolution will be achieved by increasing the ponderomotive and XUV photon energies. This can be easily implemented by increasing the laser intensity. However, an intense laser field will lead to significant background electrons, which is profitless to obtain a clear laser dressed XUV photoelectron signal. Therefore, a better way is to reduce the wavelength of the laser field, which is more efficient for improving the resolution.

3. Conclusion

We present an interesting scheme for the single-slit diffraction of electron wave packets in the time-energy domain. In the cos-like pulse, the laser field induces a less momentum and phase shift of electron wave packet. Then the photoelectron spectra only exhibit a central maximum but no diffraction fringes, and the bandwidth of photoelectron spectra increases linearly with the increase of XUV pulse duration. Based on the semiclassical model, we also derive a simple but useful formula, which predicts the photoelectron bandwidth in a rather simple and precise way. While in the sin-like pulse, a larger momentum and phase shift are induced, then the photoelectron spectra clearly exhibit diffraction fringes, strongly resembling the Airy diffraction pattern of optical waves, and the fringe number increases as the increase of XUV pulse duration. These results explicitly demonstrate the wave-particle duality of electron wave packets and also open the door to attosecond diffractometry. For an application, we propose a new method to measure the attosecond pulse duration, which is shown to be more simple and accurate. In addition, we note that

diffractometry is a robust way for ultrafast measurements, which is promising to find other applications beyond the XUV pulse measurement.

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