Dynamical medium depletion in high-order above-threshold ionization with few-cycle laser pulses

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The influence of dynamical medium depletion in high-order above-threshold ionization (ATI) in left/right asymmetry of photoelectron energy spectra is analyzed. Based on a classical analysis of high-order ATI electrons produced by few-cycle laser pulses, calculated asymmetry maps of electron spectra reproduce very well the experimental results reported in Lindner *et al.* [Phys. Rev. Lett. **92**, 113001 (2004)], utilized for determining the Guoy phase shift of few-cycle laser pulses. The anomalous behavior of the high-energy part of the ATI electron spectra is, then, fully understood in terms of earlier medium depletion occurring in the leading edge of the laser pulse. In order to correctly reproduce the experimental findings a physical temporal envelope of the laser pulse, which only vanishes at the infinity, plays a crucial role.

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The availability of few-cycle laser pulses over the past few years has made possible the generation of single attosecond pulses [1] thanks to the production of coherent soft x rays through the interaction of such few-cycle laser pulses with noble gases targets [2,3]. Beyond the above applications, few-cycle laser pulses have attracted even greater attention for their huge potential usefulness in many other fields ranging from coherent control of molecular dynamics to particle acceleration. All these processes depend on the time variation of the laser field and thus, on the phase of carrier frequency with respect to the envelope, i.e., the carrier-envelope phase (CEP). Therefore, measuring and precisely stabilizing the CEP has become a crucial step in view of many possible applications. Techniques have been developed for controlling and stabilizing the phase of femtosecond oscillators (see for example [4]) and very recently, the phase of the amplified laser systems [5]. Once stabilized, the CEP of amplified pulses has been determined by exploiting the sensitivity of nonlinear photoionization of gases to the CEP of the few-cycle ionizing laser pulse [6,7]. In a recent experimental demonstration Lindner *et al.* [8] reported on the measurement of the Gouy phase [9] influence on focused few-cycle, linearly polarized laser pulses. The authors measured the CEP shift of laser pulses (5-fs, 20-μJ, phase stabilized titanium-sapphire) by investigating the left/right asymmetry of the number of detected above-threshold ionization (ATI) electrons produced by the nonlinear photoionization of xenon. A strong, well-defined asymmetry is present at high electron energies, 25–60 eV [Figs. 3(a) and 3(f) in Ref. [8]] in the outer part of the focal range whereas, near focus, it shifts towards the lower electron energy range, 20–25 eV [Figs. 3(b)–3(e) in Ref. [8]]. Such a behavior was unexpected and, in the authors' words, "its nature is not completely understood." However, the asymmetry at low energy was still found to depend on CEP, and was exploited to retrieve the CEP variation along the focal region. In this Brief Report we address the issue of the asymmetry map modification observed in the ATI spectra produced from the focal region [8]. We demonstrate here the role of the medium depletion as the basic mechanism underlying the partial smearing out of the spectra for high intensities. Relying on a fully classical model proposed by Paulus *et al.* [10] and recently developed by Milošević *et al.* [11] to account for few-cycle laser pulses, we reconstruct the electron dynamics after ionization, extending it to an ionizing medium in order to calculate the ATI spectra. In particular, we concentrate only on *rescattered* electrons which constitute the high-energy region of the ATI spectra. In fact, the so-called *direct* electrons, namely those that, once ionized, leave the ion and do not interact with the binding potential again, can reach a maximal energy of twice the laser field ponderomotive energy, U_P [12], whereas the rescattered electrons can even reach up to $10U_P$ [11]. More interestingly, only rescattered high-energy electrons exhibit the characteristic left/right asymmetry in the ATI spectra that is extremely sensitive to the CEP of the ionizing field. According to the above model, amongst all the trajectories followed by the freed electron in the continuum only those which fulfill two special conditions strongly contribute to the high-energy part of the ATI spectra. These conditions are: (i) the electron must rescatter with the parental ion close to a zero of the electric field, and (ii) the subsequent electric field must be still sufficiently strong to transfer high energy to the rescattered electron. The first condition limits the production of free electrons to only discrete, sub-fs bursts, whereas the second condition selects only the bursts occurring within the leading edge of the laser pulse. The number of electrons, thus, produced by the kth trajectory with energy between E and $E+dE$, is given by

$$dN_k = \nu_k(E)dE = N_0(t)w_{ADK}(t)dt, \tag{1}$$

with t being the ionization time, w_{ADK} the ionization rate as given by the Ammonosov-Delone-Krainov (ADK) model [13], $N_0(t)$ the number of atoms still neutral at the time t, and $\nu_k(E)$ the number of electrons per energy unit. Therefore,

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from Eq. (1), the overall number of left/right electrons per energy unit reads

$$\nu^i(E) = \sum_k \frac{w_{ADK}(t)}{|dE_k^i/dt|} \exp\left[- \int_0^t w_{ADK}(t')dt' \right], \qquad (2)$$

with $E_k^i(t)$ (i=left or right) being the energy gained by an electron released in the continuum at time t during the kth trajectory, calculated as in [11]. When more than one trajectory needs to be taken into account in the investigated electron energy range, we assumed an equal weight for all trajectories.

Our calculation shows that in order to achieve a good agreement with the measured asymmetry maps reported for Xe in [8], it is necessary to choose a "physical" profile for the temporal envelope of the laser electric field, such as, e.g., the sech^2 or the Gaussian (as in our case), which only vanishes at the infinity. In fact, using a $\sin^2$-type envelope which identically vanishes after its first two zeros, as done in [11], does not lead to a close agreement with the experimental results, although convenient because most of the steps can be analytically carried out. This is due to appreciable depletion of neutrals during the first few oscillations of the electric field, occurring when the gas target, such as Xe, is easily ionized. Thus, in this case, a 5-fs full width at half maximum (FWHM) titanium-sapphire laser pulse cannot be properly described by a four-cycle function, as it does not take into account the first field oscillations which produce significant ionization [see the inset in Fig. 1(a)].

We show in Fig. 1 the calculated left/right asymmetry maps as a function of the electron energy and the CEP of the ionizing laser pulse, for a peak intensity of (a) 1.1×10^{14} and (b) 4.4×10^{14} W cm^{-2}. In the experiment by Lindner *et al.* [8] these intensities are reached approximately at 1.75 and 0.25 mm before focus, respectively [Figs. 3(a) and 3(c) therein reported]. The evidenced areas in Figs. 1(a) and 1(b), surrounded by dotted lines, correspond to the most extended regions of the highest asymmetry. The excellent agreement between simulations and the experimental results reported in [8] is also confirmed for other values of the peak intensities in the range $1.1–4.4\times10^{14}$ W cm^{-2}, which is reached between 1.75 and 0.25 mm before focus. For high intensities the computed spectra demonstrate that the smearing out of the asymmetry around 40–50 eV is due to a fast depletion of the xenon medium as a consequence of the laser-induced tunnel ionization. Indeed, at the highest intensities reached around the focus the gas target is rapidly ionized in the first few cycles of the laser electric field and significant contributions to the ATI spectra are basically lost at later cycles. Thus, near focus, contributions to the ATI spectra are temporally confined to a few optical half cycles in the leading edge of the laser pulse. This leads to the emission of low-energy electrons (20–25 eV) during the leading edge of the pulse and, in turn, to the dependence of their spectra on CEP measured at the focus. Consequently, the use of pulses of lower intensities and/or gas targets of higher ionization potential should improve the accuracy of the measurement, facilitating the application of a stereo ATI method to control the CEP of few-cycle lasers. In fact, simulations performed for Ar and Ne, namely gases that are harder to ionize, demonstrate that for peak intensities up to 5×10^{14} W cm^{-2}, the highest left/right asymmetry contrast is always reached in the high-energy part of the ATI spectrum. Also, the smearing out of the asymmetry at high energies does not occur.

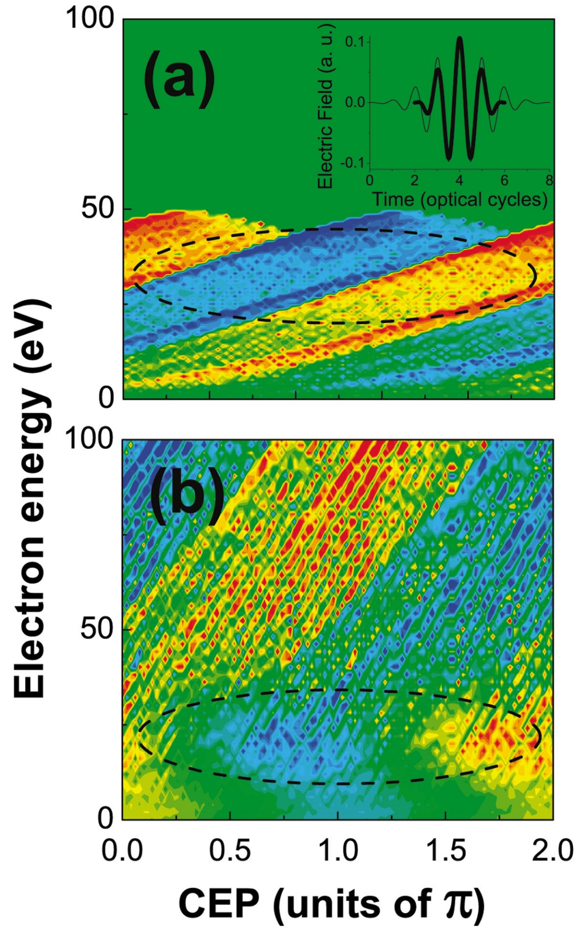

FIG. 1. (Color) Left/right asymmetry maps (logarithmic scale) as a function of the electron energy and the CEP of the ionizing laser pulse for a peak intensity of (a) 1.1×10^{14} and (b) 4.4×10^{14} W cm^{-2}. These maps have to be compared with Figs. 3(a) and 3(c) of Ref. [8]. The color scale used in the figure is the same for (a) and (b) and goes from 0.1 (deep blue) to 10 (full red) for (a) and from 0.2 to 5 for (b). Green corresponds to an asymmetry of 1. The inset in (a) shows the temporal profile of the electric field for a 5-fs (FWHM) laser pulse having a Gaussian envelope (solid line) and a $\sin^2$-type envelope truncated after its first two zeros (thick solid line).

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