Eur. Phys. J. D **37**, 305–311 (2006)
DOI: 10.1140/epjd/e2005-00273-7

THE EUROPEAN PHYSICAL JOURNAL D

Negligible carrier envelope phase dependence of total single and double ionization yields of xenon

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Received 28 June 2005 / Received in final form 19 August 2005
Published online 11 October 2005 –

Abstract. We investigate the carrier-envelope phase dependence of the total ionization yield for single and double ionization of xenon. We compare our results to theoretical calculations and to the phase dependent asymmetry in photoelectron emission. We observe that the phase dependence of the photoion yields, regardless if single or double ionization, is at least 2−3 orders of magnitude below the photoelectron emission signal. We conclude that total photoionization yields are only very weakly dependent on the carrier envelope phase, and that they are not a useful means for measurement of the phase. It seems possible that the broad bandwidth of few-cycle pulses facilitates multiphoton ionization, which leads to a randomization of strong field ionization phase dependencies. Besides, we observe that the spatial asymmetry in photoelectron emission appears to be useful as an indicator for the laser pulse duration in the few cycle regime.

PACS. 32.80.Fb Photoionization of atoms and ions – 34.80.Kw Electron-ion scattering; excitation and ionization – 42.65.Re Ultrafast processes; optical pulse generation and pulse compression

1 Introduction

Today, ultrashort laser light pulses can be engineered so short that only a couple of optical cycles fits under the pulse envelope. Such a pulse is commonly called a few-cycle pulse. Few-cycle pulses have attracted a lot of attention in physics recently, because of their ability to control electric fields with attosecond precision. One great expectation for such precisely designed fields is the coherent measurement and control of electronic motion with attosecond resolution. In few-cycle pulses the temporal evolution of a sine-wave electric field with frequency ω

$$E(t) = E_0(t)\cos(\omega t + \phi) \tag{1}$$

under the pulse envelope $E_0(t)$ depends strongly on the so-called carrier envelope phase (CE-phase) ϕ. This dependence is of fundamental importance, because it governs the quasi-classical trajectories of the particles subjected to such fields. Typically, such particles are electrons which have been liberated by tunnel ionization during the ultra-short moments when electric field values have been close to their extremum (≈200 as). In a general sense control over the CE-phase is equivalent to precision trajectory steering, which opens up the opportunity for various new types of coherent control. Thus, the CE-phase has become one of the most critical parameters in few-cycle light-matter interaction. Given its importance a lot of effort has been made to gain precise control over the phase. Suitable phase stable oscillators have been available for some time [1–3]. However, the intensity delivered by such oscillators is typically not high enough to perform strong-field studies. Only until recently have amplified phase stable pulses become reality [4]. A couple of experiments have since been reported on CE-phase effects dealing with high order harmonic radiation (HHG) [4], above-threshold ionization (ATI) [5,6] and non-sequential double ionization (NSDI) [7]. CE-phase stabilization was also a key for direct measurement of the electric field in the laser focus using the attosecond streak camera principle [8]. On the other hand, in many experiments phase stabilization would not be a prerequisite to observe interesting phase effects [9, 10]. For such types of experiments the CE-phase can be measured online using a free running laser. Phase dependent physical effects can then be extracted using statistical data treatment.

In (1) the CE-phase describes the temporal position of the maximum of the electric field with respect to the maximum of its envelope. For a typical envelope (Gaussian) the maximum field strength that will be reached during the pulse at a given intensity then depends on the CE-phase. Regarding strong field ionization the tunneling probability is strongly non-linearly dependent on the instantaneous electric field E because of the the Gamow-factor $\exp(-2(2|U_I|)^{3/2}/3|E(t)|)$, with U_I the ionization potential. This suggests that the total yield for strong field

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ionization should depend on the CE-phase if the laser pulse is short enough. The open question is, what duration is short enough in this context, and can it be reached experimentally. The aim of the present study is therefore to investigate CE-phase effects in atomic field ionization when operating with extremely short pulses. If these phase effects turn out to be significant, they would have to be taken into account in the evaluation of other quantitative studies dealing with CE-phase control, like for example ATI experiments. Moreover, phase dependent total ion yield could also be used as another indicator to measure the CE-phase itself. Here, we study such effects in detail based on a simulation and in addition we compare such results to experimental data on single as well as double ionization yield of xenon. Other studies have already been performed which have investigated the effect of few-cycle pulses in non-sequential double ionization (NSDI) [7,11, 12]. However, such studies have focussed exclusively on the electron and ion momentum distributions and not on the total yield of the produced doubly charged ions. Here, we will demonstrate that the total ionization yield for most pulse durations is apparently so weakly dependent on the CE-phase that such side-effects can be neglected under almost all circumstances. Our experimental and theoretical result also excludes that total ionization could be a promising candidate for CE-phase diagnostics. Besides, we present here a precision study of the left-right asymmetry in ATI electron emission as a function of the pulse duration. It has been suggested that electron asymmetry should be in the order of 20% for a pulse duration of 5 fs [13]. We can confirm such a value roughly experimentally and suggest that stereo-ATI [5] (or similar techniques) could additionally be used for in-situ diagnostics of the pulse duration for the few-cycle regime.

2 Theoretical aspects

First, we would like to note that in contrast to the commonly held opinion a femtosecond laser electric field is in general not correctly described by a sine wave enclosed by a Gaussian envelope

$$E_G(t) = \exp\left(-\frac{(t-t_0)^2}{2\Delta t^2}\right)\cos(\omega(t-t_0)+\phi). \quad (2)$$

If the number of optical cycles within the envelope is large, then (2) may be a valid approximation. However, in the few-cycle limit the approximation becomes easily inaccurate because the bandwidth for such pulses rises exponentially and therefore parts of the frequency spectrum rapidly approach zero frequency. Numerically this leads to a DC component in the electric pulse which is unphysical, because it does not propagate. A given pulse can be tested immediately for its DC component if $\int E_G(t)dt$ is calculated. If the integral deviates significantly from 0, the pulse contains DC components. Here we consider as a DC component all frequencies which have periods close to or longer than the time integration window in (5). Such DC components are generally strongly dependent on the CE-phase.

A much better model for a few-cycle pulses is obtained if the pulse is calculated by a Fourier-sum. In addition this is an approach which is much closer to physical reality because real laser cavities naturally emit a series of n frequency modes $\omega_n = 2\pi nc/L$, where L denotes the cavity length. For a typical femtosecond oscillator, n will be about 10^7. For pulse synthesis like the one performed here it is enough to restrict oneself to about 10^5 frequencies. This means that frequency spacing will be approximately 100 times larger than in a real cavity. Conceptional this would be equal to the use of a very short cavity ($L \approx 1$ mm). Like in nature, the frequency spacing itself should be kept constant in the simulation, only the number of frequencies and their respective intensities A_n should be varied. The electric field can then be calculated from the Fourier-sum

$$E_F(t) = \sum_{n=-N}^{N} A_n \cos\left((n+N_0)\omega t + \phi\right). \quad (3)$$

Here, N_0 is the center frequency. Again, if the bandwidth in the Fourier-sum exceeds the central frequency, the Fourier-coefficients for very small frequencies will become easily larger than zero. This would once more lead to DC components and it is obvious that the bandwidth of the pulse must be carefully limited, especially on the low frequency side. In addition, in the simulation the integration time window must be kept large enough to avoid steep edges at t_{min} and t_{max}, which would cause additional high frequencies to appear. In our simulation we have used a time window of ± 100 fs or longer, which appears sufficient for bandwidths exceeding 0.5 THz. Moreover, Gaussian frequency distributions have been avoided because their wings are never reaching zero. Instead, we have applied a Hanning-window function, which is defined by $w_n = 0.5(1-\cos(2\pi n/(2N+1)))$. Such a Hanning window guarantees very short laser pulses for relatively large bandwidths, without any significant DC components from the wings. For electric fields synthesized in this manner with CE-phases $\phi = 0$ and $\phi = \pi/2$ we have calculated the instantaneous photoionization rate $W_L(t)$ based on the Landau-formula and then integrated in time to obtain the total ionization probability $P_I = 1 - \Gamma$ after the laser pulse

$$W_L = 4\frac{(2|U_I|)^{5/2}}{|E|}\exp\left(-2\frac{(2|U_I|)^{3/2}}{3|E|}\right) \quad (4)$$

$$\Gamma = \exp\left(-\int_{t_{min}}^{t_{max}} W_L(t)dt\right). \quad (5)$$

The result of our simulation is shown in Figure 1. It can be seen that for pulse durations significantly larger than 5 fs at an ionization of 20% or higher there is no significant difference between a cosine ($\phi = 0$) and sine ($\phi = \pi/2$) pulse observable. For shorter pulses the CE-phase dependence remains weak. Differences between sine and cosine pulses become only significant, if the laser intensity is kept

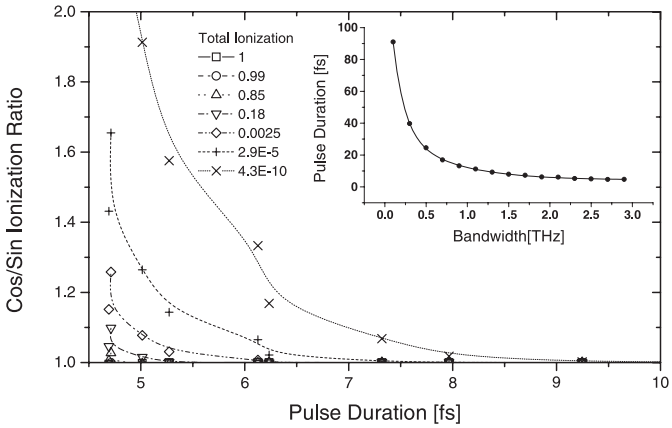

Fig. 1. Calculated ratio of the total ionization yield for cosine and sine pulses in dependence of the pulse duration and the average ionization probability. The insert shows the pulse duration as a function of bandwidth when a Hanning filter type frequency distribution is used.

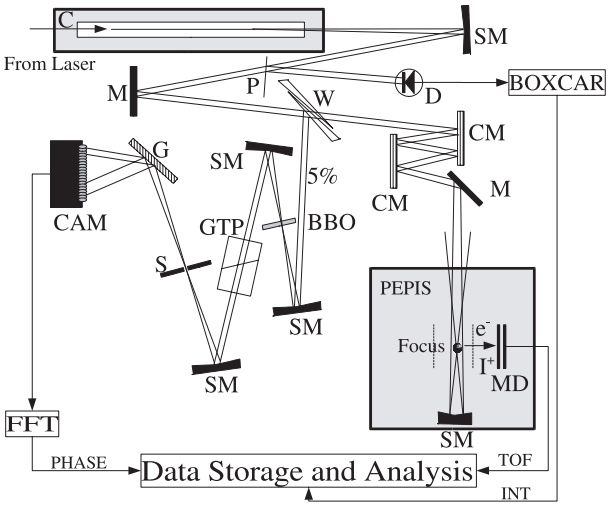

Fig. 2. Experimental set-up: C-Hollow Fibre, D-Diode, P-Pellicle, W-Wedges, M-Mirror, CM-Chirped Mirror, SM-Spherical Mirror, GTP-Glan-Thompsom Polarizer, G-Grating, BBO-Doubling Crystal (Type II), S-Slit, CAM-Line Camera, MD-Microchannelplate Detector. During the experiment for each laser shot the phase, the intensity and the ion signal are recorded.

well below saturation (the total ionization must be below 10%). For an ionization probability of 10^{-10}, which however makes no sense experimentally, the difference between sine and cosine pulses could be up to 100%. It is interesting to note that any exploitable dependence of the total ion yield on the CE-phase seems to demand a bandwidth which comes close to or exceeds the central laser frequency of 2.48 THz (Ti:sapphire). This points towards a fundamental limit: only if the bandwidth clearly exceeds one octave we can expect significant experimental CE-phase dependencies. This represents a fundamental experimental constraint, because such large bandwidths are extremely hard to handle. With the present technology chirped multilayer mirrors are currently limited to less than one octave. Moreover, broad bandwidth pulses are usually produced via self-phase modulation in hollow-fibers or bulk, and the resulting spectra are generally not as nicely shaped as we have assumed in the simulation. In reality, in almost all cases where broadband few-cycle pulses have been reported, the pulse contrast is relatively poor and the field exhibits quite significant ringing of 5−10% on a much longer time scale. Poor pulse contrast can easily suppress the small CE-phase effects that we are looking for and which we expect from the present simulation. This simple calculation already demonstrates that CE-phase effects for the total ionization yield should be at least 2−3 orders of magnitude less significant than effects in spatial electron emission that have been reported in [5].

3 Experimental set-up

The experimental setup has been described in some detail previously [10]. A home-built 10 pass amplifier system [14] with a repetition rate of 1 kHz is used to generate pulses with energies of 1.3 mJ. These pulses are compressed to a duration of approximately 25 fs before being sent into a 1 m long hollow fibre of diameter 180 μm, filled with 1.5 bar neon. The resulting spectral broadening caused by self-phase modulation [15] allows for pulses after the fibre that can be compressed to approximately 10 fs.

For our experiments an 18% split of the beam is taken after the fibre and its polarization is cleaned using three consecutive pellicles at Brewster's angle. Approximately 30 μJ/pulse at 10 fs are available for the experiment, as illustrated in Figure 2. Such pulses are sent into a second hollow fibre of 166 μm diameter and 70 mm length. The second hollow fibre (C) is operated with 2.5 bar of krypton. This way the spectrum is broadened to over two octaves. Large broadening is a prerequisite to support compression into the few-cycle regime as well as for efficient $f-2f$ interferometry. A thin pellicle (P) is also placed in the beam after the fibre so that the intensity of the pulses can be monitored throughout the experiment by taking the reflection from its front surface and directing it onto a photodiode (D). The signal from this diode is sampled for each shot using a Stanford Research Systems boxcar. Thus, the intensity of each pulse after the fibre is recorded online during the experiment. This makes it possible to filter the data by an appropriate intensity window. For pulse compression after the fibre a pair of broadband multilayer mirrors (CM) is used. In order to balance the negative dispersion introduced by the mirrors a variable amount (between 0 and 2.0 mm) of fused silica glass is placed in the beam.

A 5% reflection from the first surface of a pair of wedges (W) is sent to an $f-2f$ interferometer. This part of the beam is first focused into a 100 μm BBO type II crystal. The resulting copropagating f and $2f$ beams have orthogonal polarizations so that by passing them through a Glan-Thompson polarizer (GTP) it is possible to adjust the ratio of the intensities of both beams. A polarizer projects the orthogonal beams onto each other and

the resulting interference is measured with a spectrometer (MS125 ORIEL). This interferometer is similar to the one described in [16]. The resolution of the spectrometer can be about 1 nm, using a 600 l/mm grating (400 nm Blaze) and a 1024 pixel laser clocked linescan CCD camera (Basler L102). For the present experiment only every second pixel is read in order to reduce the time taken for the camera to be read to within 65 μs by the frame grabber (National Intruments, PCI-1422). The interference spectra are recorded for each laser shot and they are evaluated via FFT online within 500 μs using LabView 6i FFT routines. The resulting power spectra exhibit a distinguished peak at which the phase can be evaluated. This phase, Φ, should not be confused with the absolute CE-phase, ϕ, since Φ is the pulse to pulse change of the phase and not its absolute value. However, Φ is related to the absolute CE-phase by $\phi = \Phi + \Phi_0$, where Φ_0 is an offset constant.

After compression the main part of the beam is sent into a small photo-electron photo-ion spectrometer which allows for detection of electrons produced via ATI and ions produced via strong field ionization. The spectrometer is basically a miniaturized time-of-flight detector (TOF) with a drift tube of 25 mm in length. The TOF can be used to detect both, electrons and ions. To detect electrons a +1.8 kV bias voltage is applied to a chevron type dual-MCP detector with capacitive output coupling. No extraction voltage is applied in the case of electrons since this would destroy any spatial emission effects which are a signature of the CE-phase [5]. In order to detect the ions an extraction voltage is applied as it is the total yield of the ions and not the spatial dependence which is of interest. In this case about −1.8 kV extraction voltage is used. This serves the purpose of extracting ions but also of deflecting electrons from the detector. Using such an arrangement to measure both ion and electrons has the advantage that in order to switch between electron and ion detection it is only necessary to adjust the extraction voltage, which can be done very quickly. Therefore the conditions between both sets of data are ensured to be as close as possible.

4 Results

In order to obtain the shortest pulses possible the same method as described in [10] was used. Using the photoelectron part of the PEPIS the electron yield was first measured. The amount of glass after the fibre was carefully adjusted in order to compensate the group delay dispersion of the pulse. Since the electron yield is very sensitive to the pulse duration it is possible to determine the optimum pulse duration by finding the maximum of the electron yield by fine-tuning of the tin wedges. The electron/ion yield is then measured for each laser shot together with the relative phase Φ and the laser intensity, the data is recorded shot-by-shot. After the measurement the data evaluation leads to a histogram of the respective electron or ion signal versus the relative phase.

By applying an extraction voltage of approximately −1.8 kV the total yield of ionized atoms in the focus can

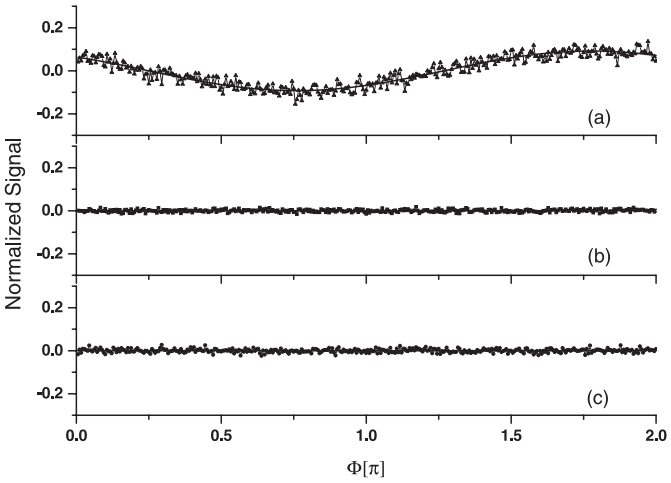

Fig. 3. Histograms of the normalized signals versus the relative phase using 5.81 fs pulses. Histogram (a) shows the asymmetric photoelectron current emitted towards one side versus the phase. The signal is normalized on the basis of uncorrelated events as described in [10]. The modulation of the histogram is approximately 10%. Histogram (b) shows the normalized total photoion yield from singly ionized atoms versus the phase. Histogram (c) shows the normalized total photoion yield from doubly ionized atoms versus the phase. No phase effect is visible in either (b) or (c).

be measured. By adjusting the delay of the boxcar window it is possible to measure either singly or doubly ionized signals. We present here only data for Xe, but in a series of experiments we have additionally studied other rare gases like Ne, and also small molecules like H_2, all showing identical results. Regarding such data, Xe has shown the strongest contrast in phase dependent electron emission, which facilitates the detection of the CE-phase, and significantly reduces data acquisition time. A scan of 2 million laser shots of Xe^+ and Xe^{2+} signals was taken in order to obtain a good statistic in the measurement. In principle even longer measurements would be possible. However, it was found that the laser operated in a stable manner for approximately 40−45 minutes, thus making 2 million laser shots roughly the largest number of shots that should be measured under the same operating conditions. Regarding the Xe^{2+} measurement it is well known that contributions from NSDI can only be significant for intensities at which single ionization remains unsaturated, which sets an upper limit to the focal intensity of 8×10^{13} W/cm^2 (see e.g. [17]). In order to ensure that the intensity would meet such conditions, the focus of the beam in the spectrometer was moved away from the detection zone. This has the additional advantage that the phase of the laser pulses is not distorted by the Gouy phase shift of π, which occurs directly at the focal center [6]. Evaluation of the data leads to histograms for single and double ionization signals versus phase which are shown in Figures 3b and 3c. It is clear from Figures 3b and 3c that there is no statistically discernable phase effect present in the yield of singly or doubly ionized atoms for these pulse durations. It should be noted that this is in contrast to the strong

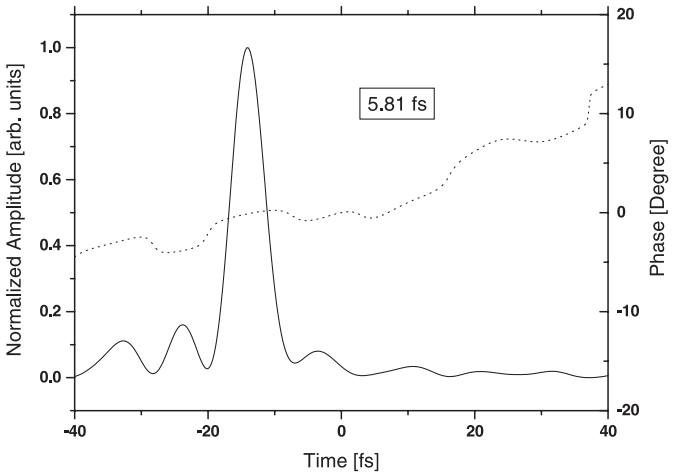

Fig. 4. SPIDER measurement using multilayer chirped mirrors. The retrieved pulse duration is 5.81 fs.

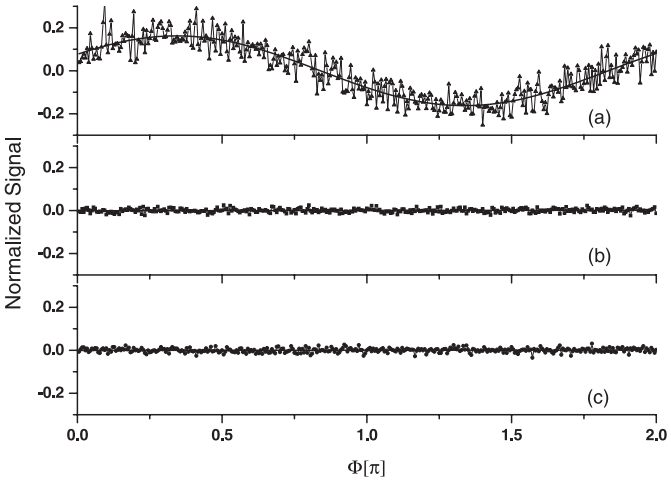

Fig. 5. Histograms of the normalized signals versus the relative phase using 5.09 fs pulses. Histogram (a) shows the photoelectron current emitted to the right versus the phase. The modulation of the histogram is approximately 20%. Histogram (b) shows the normalized total photoion yield from singly ionized atoms versus the phase. Histogram (c) shows the normalized total photoion yield from doubly ionized atoms versus the phase. No phase is effect is visible in either (b) or (c).

modulation present in the case of the electron yield case presented in Figure 3a. This electron yield has been measured immediately before and after the ion yield curves. From the data we conclude that any phase dependence in total ion yield is at least two orders of magnitude smaller than spatial ejection of electrons. It should also be noted that such a strong modulation in the spatial electron ejection can only be reached if the ionization in the focus is not saturated or distorted by the Gouy phase shift. In order to compare these cases to the previous theoretical discussion an accurate determination of the pulse duration was performed. In [10] a broadband autocorrelator was used to determine the pulse duration. Although autocorrelation gives a reasonable idea of the pulse duration, in this ultrashort regime we have also used the SPIDER [18] technique to characterize the spectral phase and the pulse duration in detail. The retrieved pulse and phase are shown in Figure 4. The pulse duration retrieved from the SPIDER measurement is 5.81 fs, which corresponds also well to autocorrelation measurements. The modulation in the photoelectron histogram for this pulse duration is approximately 10% as seen in Figure 3a.

The same experiment was repeated with an improved set of compression mirrors [19]. Again the photoelectrons were measured for each value of the phase and the resulting histogram was calculated. The data are shown in Figure 5a. As can be seen, using the improved compression mirrors results in a significantly stronger modulation of the electron signal, which is a clear indicator for better pulse compression. The pulse duration was once more carefully determined using SPIDER, yielding a pulse duration of 5.09 fs. The SPIDER results are presented in Figure 6. As can be seen from Figure 5a there is a 20% modulation in the photoelectron histogram. According to the theoretical work performed in [13] an asymmetry of ±20% in the photoelectron signal is indicative of a 5 fs pulse. The measurement shown here strongly supports this prediction. With this 5.09 fs pulse another test for CE-phase dependence of total ion yield of Xe^+ and Xe^{2+} was performed. As can be seen in Figures 5b and 5c there is no

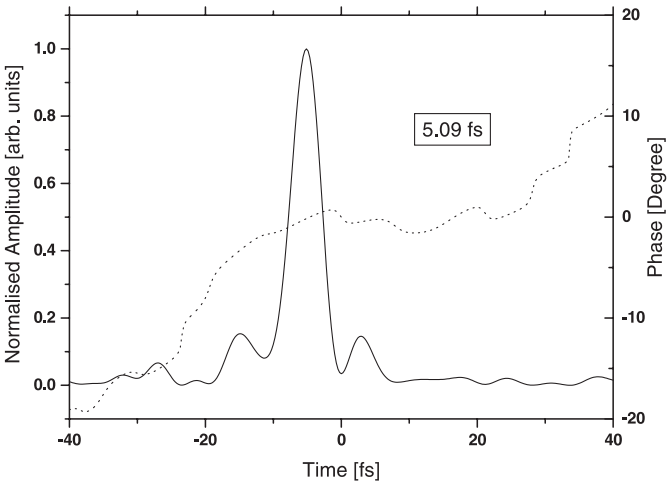

Fig. 6. SPIDER measurement using improved multilayer chirped mirrors. The retrieved pulse duration is 5.09 fs.

significant phase effect observable in direct as well as in double ionization. In sum we can conclude that no statistically relevant dependence of ionization on the CE-phase can be found for pulse durations down to roughly 5 fs. With the present technique it would be possible to detect an effect of 0.5% without being smothered by the noise. Comparing the 20% modulation in the photoelectron histogram Figure 5a to the double ionization histogram Figure 5c we can claim that if there is a phase effect present in the case of double ionization then it would be approximately 400 times less prominent than in the case of the photoelectron signal and beyond the means to be detected without significantly higher effort in instrumentation and techniques.

5 Conclusion

We conclude from simulations and from experimental data that the total Xe ion yield, whether produced via direct single ionization or via double ionization, is insensitive to the CE-phase at pulse durations $\geq$5 fs. This is surprising when taking the exponential dependence of the Gamow-factor into account. It remains an open question if there would be a phase dependence detectable if pulses can be made significantly shorter or if totally different target molecules are selected. In the case of $Xe \rightarrow Xe^{+}$ the Keldysh-parameter γ is smaller than unity for intensities above 10^{14} W/cm^2, which indicates that we have been operating experimentally with intensities in a mixed regime between strong field (SFI) and multiphoton (MPI) ionization. In this respect, it should be noted that for long laser pulses the Xe photoelectron spectra have shown Freeman resonances which are characteristic for multiphoton processes [20]. Nevertheless, we would expect that in a suitably chosen intensity window multiphoton effects should play a limited role. This is supported by our observation that for Ne, with γ down to 0.5, the photoion current is also independent on the phase. For the case of multiphoton ionization of Xe, additional quantum mechanical simulations have been performed by Scrinzi, which show that the CE-phase can also significantly influence the total MPI yield. However, compared to SFI the phase dependence in MPI appears to be strongly dependent on the intensity and often deviates from a sine [21]. It is therefore possible that in the MPI-regime small laser intensity fluctuations randomize the phase dependence. Regarding now double ionization it is well-known, that the rescattering mechanism for NSDI is similar to that for HHG and ATI [22]. The electron is first ionized by a laser pulse and then returns to the parent ion within a laser period. The maximum energy of the returning electron is $3.17U_p$, where $U_p = E_{max}^2/4\omega^2$ is the pondermotive energy. Because of its dependence on the electric field strength the recollision energy should be, in principle, sensitive to the phase of a few-cycle laser pulse. In order for the returning electron to ionize the parent ion a second time, its return energy has to exceed the ionization energy of the parent. In the case of xenon this would require $3.17U_p \geq 21.21$ eV, the binding energy of Xe^{+1}, corresponding to an intensity of $\sim 3.5 \times 10^{14}$ W/cm^2. At this intensity one could expect that NSDI is enhanced for specific phases in a rescattering model. In addition, at this intensity $\gamma \approx 0.54$, well in the SFI-regime. It is also interesting to note that for comparable pulse durations the ion momenta of nonsequential doubly ionized atoms did clearly exhibit prominent phase effects [7]. Compared to this the total double ionization yield seems to be independent on the phase which can have two explanations. First, competing effects between tunnelling of the first electron and the maximum energy upon rescattering could be made responsible. In [7] the strongest effects for NSDI have been visible at a CE-phase of $\phi \approx 60°$. In contrast, for the first step in NSDI, the single ionization event, we would expect strongest signals for a pure cosine pulse. That double ionization remains resistive to the phase could be interpreted such that the influence of the CE-phase on the pondermotive energy is of the same order of magnitude or weaker than for the initial ionization process. Secondly, concerning double ionization of Xe experimental results in [17] indicate that the mechanism of double ionization is not always rescattering, as it is for other noble gases with higher ionization potential. Resonance effects, only comprehensible via multiphoton absorption, appear to be active for double ionization at low intensities. Such effects can be made responsible for an enhanced Xe^{2+} ion yield, which has been reported to be wavelength dependent below 5×10^{13} W/cm^2. In this respect it should be mentioned that already in [23] the inability of the rescattering model to predict the low intensity behavior of NSDI was noted. This MPI interpretation can, however, barely justify why it has been impossible to detect a CE-phase dependence in Ne, where the NSDI mechanism should, in principle, be maintained. An exception would be, that in the few-cycle limit essentially all investigated systems have been ionized via some sort of MPI or mixed MPI/SFI mechanism. In this respect it should be emphasized that the experimental bandwidth has been very broad and in its wings exceeding two octaves (from 400 nm up to 1400 nm). Such a broad bandwidth is necessary for the measurement of the phase and cannot be avoided in the present set-up. It is possible that when using such bandwidth many paths for MPI are intrinsically opened, so that a simple Keldysh-model can not be applied, and that the influence of the CE-phase on the total ion yield becomes much more complicated than we have initially assumed. This is a general problem as few-cycle pulses always have a broad bandwidth, so that it is probably difficult to find a way to get around this problem. Here we suggest that further research is required within a more elaborated theoretical model to explain, why the total ionization yield remains so remarkably resistive to the CE-phase. We believe that our result points towards a fundamental failure of quasi-static ionization models when approaching the few-cycle limit in the visible, so that a phase dependent ionization yield can perhaps only be observed if significantly longer central wavelengths are applied.

With respect to technical applications, because of the vanishing phase dependence observed from our Keldysh-model, as well as experimentally, it is hard to believe that straightforward ion spectrometry will ever become a good candidate for phase diagnostics or phase sensitive measurements in the visible. Consequently, without additional photoelectron detection the phase can probably not be determined in-situ in ion spectroscopy experiments. Such in-situ diagnostics of the CE-phase is desired for various upcoming experiments in attosecond science and technology. Restricting in-situ phase diagnostics to photoelectron spectroscopy limits the possible target density in the focus significantly, because otherwise space-charge and plasma effects will affect the result. On the other hand, regarding spatial photoelectron emission, it appears possible to obtain a measure for the pulse duration for extremely short pulse durations. The asymmetry of the emitted electrons is indeed a promising indicator for the laser pulse duration,

in correspondence to [13]. It is certainly possible to calibrate a set-up accurately enough so that a given maximum electron spatial asymmetry will correspond to a specific laser pulse duration, provided that the intensity in the focus is known and can be carefully controlled. Such a detector would be advantageous for in-situ diagnostics of ultra-short pulses, when the pulse duration becomes increasingly difficult to be measured via autocorrelation or SPIDER due to inherent bandwidth limitations of optical components or due to experimental accessibility restrictions (vacuum chambers). In future we expect that measuring the emitted photoelectrons represents a useful means to determine the duration of ultrashort pulses in the sub-10 fs regime.

This work was funded by the Austrian Research Funds, grant number P14447 and F016. This work has benefited from helpful discussions with G.G. Paulus and A. Scrinzi.

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