



Cross-polarized common-path temporal interferometry for high-sensitivity strong-field ionization measurements

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Abstract: Absolute density measurements of low-ionization-degree or low-density plasmas ionized by lasers are very important for understanding strong-field physics, atmospheric propagation of intense laser pulses, Lidar etc. A cross-polarized common-path temporal interferometer using balanced detection was developed for measuring plasma density with a sensitivity of ~ 0.6 mrad, equivalent to a plasma density-length product of $\sim 2.6 \times 10^{13} \text{ cm}^{-2}$ if using an 800 nm probe laser. By using this interferometer, we have investigated strong-field ionization yield versus intensity for various noble gases (Ar, Kr, and Xe) using 800 nm, 55 fs laser pulses with both linear (LP) and circular (CP) polarization. The experimental results were compared to the theoretical models of Ammosov-Delone-Krainov (ADK) and Perelomov-Popov-Terent'ev (PPT). We find that the measured phase change induced by plasma formation can be explained by the ADK theory in the adiabatic tunneling ionization regime, while PPT model can be applied to all different regimes. We have also measured the photoionization and fractional photodissociation of molecular (MO) hydrogen. By comparing our experimental results with PPT and MO-PPT models, we have determined the likely ionization pathways when using three different pump laser wavelengths of 800 nm, 400 nm, and 267 nm.

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1. Introduction

Strong-field ionization (SFI) [1] plays a central role in many physical phenomena in atomic and molecular physics such as above threshold ionization (ATI) [2], non-sequential ionization (NSI) [3], high-order harmonic generation (HHG) [4] and spin-dependent ionization [5–7]. Measuring the degree of strong-field ionization versus laser intensity is the critical measurement necessary for checking the validity of theoretical ionization models in different ionization regimes. Different ionization regimes are frequently bracketed using the Keldysh parameter $\gamma = \frac{\omega \sqrt{2mI_p}}{eE} = \sqrt{I_p/2U_p}$, where I_p is the ionization potential, E and ω are the laser-field strength and frequency, respectively, m and e are the electron mass and charge, respectively and $U_p = e^2 E^2 / 4m\omega^2$ is the ponderomotive potential seen by the electron in the laser field. In the adiabatic tunneling ionization (TI) regime ($\gamma \ll 1$), where the electron can tunnel through the depressed atomic potential barrier within half a laser cycle, the ADK model [8] is commonly used due to its simplicity. However, it is not applicable in the nonadiabatic TI regime ($\gamma \sim 1$) and multiphoton ionization (MPI) regime ($\gamma \gg 1$). Therefore, the so called PPT model [9], which is valid for all values of γ and wavelengths after correcting for the long-range Coulomb interaction [10] for linearly polarized laser (PPT-LP) case, is usually used. There have been numerous experimental studies intended to check these

ionization models using a LP laser [11–15]. However, this was not the case for a CP laser because appropriate theories were not developed at the time. The original PPT model [9] only considered electrons ionized from s orbitals, not applicable for most of atomic species. Barth and Smirnova [16] derived a modified PPT model for CP case (PPT-CP) that can be applied to electrons initially in the p orbital. One recent study [17] done in the adiabatic and non-adiabatic TI regime by using near-IR to mid-IR laser pulses found that the experimental results agreed quite well with this modified PPT-CP model with generalized Coulomb correction [10]. This experiment however employed ion yield measurements using a time-of-flight mass spectrometer, which didn't give information of in situ absolute ionization yields - in other words the plasma density. Therefore, it is of fundamental importance to verify all these ionization models using a single technique that measures absolute ionization yields.

Optical interferometry is a frequently used method to measure absolute electron densities of extremely short-lived laser-produced plasmas in the range of $10^{17} - 10^{21} \text{ cm}^{-3}$ [18–20]. However, at lower plasma densities, the commonly used interferometers, such as Michelson or Mach-Zehnder interferometers are prone to vibrations because of the two-optical-path geometry. Spectral interferometry (SI) [21–23] is another way of measuring the phase change induced by the plasma, including single-shot supercontinuum spectral interferometry (SSSI) [23,24], common-path two-color spectral-domain interferometry [25,26], etc. SI measures frequency interference or modulation from two common-path pulses separated in time. The sensitivity of SI is about tens of mrad, limited by spectrometer resolution. There are also other high-sensitivity methods that are not based on interferometry, such as avalanche ionization driven by a picosecond, mid-IR probe laser pulse [27] analogy to the avalanche effect in a photomultiplier tube, and ionization induced plasma grating method [28]. Suffice it to say that a robust and straightforward method is still lacking that will enable the measurement of absolute plasma density over a large range of plasma densities of interest in strong-field ionization experiments.

We have developed a cross-polarized common-path temporal interferometer to measure plasma density with high sensitivity. It is not prone to vibrations because of the common-path geometry of the reference and probe pulses and picosecond time delay between them. It has high sensitivity because of the balanced detection technique. Balanced detection [29] is a common technique for detecting small differences in optical power between two optical input signals while largely suppressing any common fluctuations of the inputs. A balanced photodiode, in the simplest form of balanced detection, consists of two photodiodes connected in the same circuit, such that their photocurrents cancel each other when they are equal. The difference in photocurrents is sent to a transimpedance amplifier, which produces an output voltage proportional to that difference. By using balanced detection without a boxcar integrator and lock-in amplifier, the phase sensitivity of our interferometer can already be as low as 0.6 mrad, equivalent to a plasma density-length product of $\sim 2.6 \times 10^{13} \text{ cm}^{-2}$ if using an 800 nm probe laser. Using this interferometer, we were able to measure photoionization yield over 5 orders of magnitude which allowed us to verify different ionization models in different regimes. In this paper we measured the absolute ionization yield of various noble gases (Ar, Kr, Xe) using 800 nm laser pulses with both linear (LP) and circular (CP) polarizations at different laser intensities and compared our experimental results with ADK [8] and PPT [9] ionization models. We also show one example of the usefulness of this method for revealing the dominant ionization pathway in the ionization of molecular gas by taking hydrogen gas as an example. We find that for the ultra-short 800 nm ionizing pulses (<60 fs) we used the so-called molecular PPT (MO-PPT) model (extended from PPT model to calculate ionization from diatomic molecules) fits the experimental data very well [30].

2. Cross-polarized common-path temporal interferometry

2.1. Principle of the interferometry

The schematic of our interferometer is shown in Fig. 1. A pump pulse is reflected by a dichroic mirror and focused (lenses not shown for brevity) into a static-filled gas tube to produce plasmas by photoionization. A second weaker LP (s-polarized or p-polarized) pulse is incident on the first birefringent crystal (2 mm thick calcite in our case) with its optical axis oriented at 45° with respect to the input beam polarization. Due to birefringence, this pulse splits into two orthogonally polarized pulses: the reference pulse (extraordinary ray) and the probe pulse (ordinary ray). The delay between two pulses is estimated to be ~ 1.6 ps (for 400 nm wavelength), which depends on the thickness of the birefringent crystal and the probe wavelength. The pulse timing is arranged so that the reference and probe pulse are before and after the pump pulse respectively. After the interaction, the pump beam is reflected by another dichroic mirror. The reference and probe beams pass through the dichroic mirror and the second birefringent crystal that has the same thickness but orthogonal optical axis as the first birefringent crystal. In this way, the extraordinary and ordinary rays are made to overlap in time again if there is no plasma, which is the so-called balanced position. (see details about balancing and calibration procedures in next subsection). Now in this balanced position, the reference and probe pulses are overlapped in time, however the polarizations of two pulses are still orthogonal. The amplitudes of the electric fields of the reference and probe pulses are:

$$E_{ref} = E_0(t) \sin(\omega t) \quad (1)$$

$$E_{probe} = E_0(t) \sin(\omega t + \phi_0 + \Delta\phi) \quad (2)$$

where $E_0(t)$ is the envelope of both pulses supposing both pulses have the same envelope, ϕ_0 is the offset phase shift manually adjusted to reach the balanced position, $\Delta\phi$ is the phase shift induced by the plasma. Since the polarizations of two pulses are orthogonal, each pulse is then decomposed by a Wollaston prism into x direction (p-polarization) and y direction (s-polarization). P-polarized (s-polarized) components of both pulses are directed to the upper (lower) detector of the balanced photodiode (Thorlabs PDB210A). The summed electric fields of both pulses on the upper and lower detectors are:

$$E_x = \frac{\sqrt{2}}{2}(E_{ref} + E_{probe}) \quad (3)$$

$$E_y = \frac{\sqrt{2}}{2}(E_{ref} - E_{probe}) \quad (4)$$

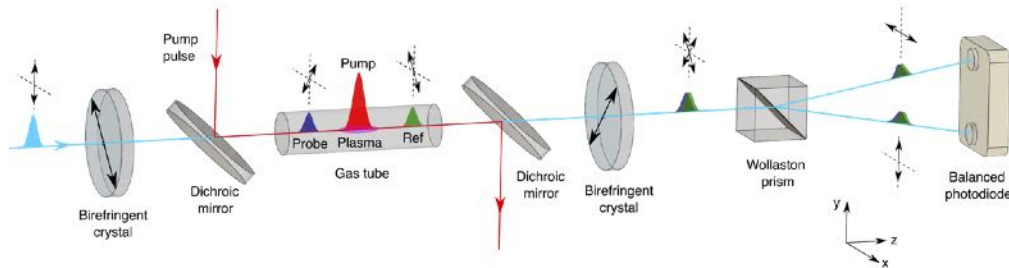


Fig. 1. Schematic of cross-polarized common-path temporal interferometer for plasma density measurements.

Thus, interference is observed in each photodiode. Since mutually orthogonal polarizations correspond to the given directions, interference signal of one photodiode is shifted with respect

to the signal from the other by π . This fact allows us to use the balanced photodiode to balance laser power instabilities using the difference of the two photodiode signals and amplify it to achieve high sensitivity. The amplified differential signal from the balanced photodiode can be expressed as:

$$U \propto \overline{E_x^2} - \overline{E_y^2} \propto \overline{E_{ref} \cdot E_{probe}} \propto \sin(\phi_0 + \Delta\phi - \pi/2) \quad (5)$$

where $\overline{E_x^2}, \overline{E_y^2}, \overline{E_{ref} \cdot E_{probe}}$ means the cycle-averaged values. If we finely adjust the phase between the reference and probe pulses (by finely adjusting the angle of one of the birefringent crystals) so that $\phi_0 = \pi/2$ (balanced position), then $U \propto \sin(\Delta\phi)$. If $\Delta\phi \ll 1$ (which condition is always satisfied in our measurements), then $U \propto \Delta\phi$. The exact phase shift value can be obtained by phase calibration before measurements, which is shown in the next subsection.

In our experiments, we measured the integrated phase shifts induced by the refractive index changes when the probe beam pass through the plasma region. The phase shift in 1D case can be expressed as:

$$\Delta\phi = \int_0^L \frac{2\pi}{\lambda_{probe}} \cdot \Delta\eta \, dz \quad (6)$$

where λ_{probe} is the probe wavelength, $\Delta\eta$ is the refractive index change induced by the plasma, L is the interaction length. If the refractive index changes are all contributed by the plasma, then the phase shift can be expressed as:

$$\Delta\phi = \int_0^L \frac{2\pi}{\lambda_{probe}} \cdot \frac{n_p}{2n_c} \, dz \quad (7)$$

where n_p is the plasma density and $n_c = \frac{m\omega_{probe}^2}{4\pi e^2}$ is the critical plasma density where the laser frequency becomes equal to the plasma frequency for the probe frequency ω_{probe} . The critical plasma density is around $n_c = 1.74 \times 10^{21} \text{ cm}^{-3}$ for an 800 nm probe pulse.

In the experiment the measured phase shift must be averaged transversely because the intensities of both the pump laser and the probe laser are not uniform transversely (focal volume averaging effect). To directly compare the experimental results with the theoretical results, we calculated the phase shifts for different theoretical models using carefully measured laser parameters, and compared them with the measured phase shifts, which is explained in the next section.

2.2. Balancing and calibration of the interferometry

Before plasma density measurements, the interferometer needs to be balanced and calibrated first. To have a better precision of balancing control, we inserted another pair of orthogonal birefringent crystals with thin thickness (0.2 mm thick calcite in our case, not shown in Fig. 1). This extra pair of birefringent crystals is not necessary but helpful to finely optimize the time overlapping in case there is a thickness manufacturing error between the two thick birefringent crystals. By rotating one of the thin birefringent crystals with a motorized rotation stage, precise balancing procedure and phase calibration can be done before the plasma density measurements.

In principle, the phase shift we measured corresponds to the change of time delay between the probe and the reference. This time delay can be changed by the density-length product of the plasma in an experiment or by rotating one of the birefringence crystals in the calibration processes. The phase calibration process was done without the pump pulse. We rotated the birefringence crystal in calibration processes to mimic the plasma in real experiments. Note that the calibration relations are different for different probe wavelengths. For the case shown here, the wavelength of the probe pulse is 800 nm. To do calibrations, we installed one of the birefringent crystals on a motorized rotation stage (Newport AG-PR100V6). We set the interferometer at a low-sensitivity mode first so that we can measure a large enough phase shift without saturation of the photodiodes. By rotating one of the birefringent crystals in a large range, the sinusoidal

oscillation of the phase shift due to interference was observed as shown in Fig. 2(a). Through calibration, we knew that 2π phase shift corresponded to ~ 1316.4 motor steps of the motorized rotation stage, which is 4.8 mrad per motor step. This calibration number doesn't change if the probe wavelength doesn't change. Now keeping the interferometer at around balanced position (dashed box in Fig. 2(a)), we switched the interferometer to high-sensitivity mode (the normal working mode) by increasing the intensity of the probe pulse into the photodiodes (by decreasing the neutral density filters before the photodiodes). In this mode, the sensitivity is much higher with the cost that the measurable largest phase shift is also much smaller. Since the working condition is at around balanced position, the signal amplitude from the balanced photodiode is linearly scaled with the phase shift $U \propto \Delta\phi$. Then we did another calibration to determine the linear scale between the signal amplitude and the phase shift as shown in Fig. 2(b). In the case shown here, the relation between the signal amplitude and phase shift was 15.75 mV/mrad. The signal amplitude error bar was about 10-20 mV, which correlated to the phase error bar of about 0.6-1.2 mrad. This phase sensitivity is equivalent to a plasma density-length product as low as $\sim 2.6 \times 10^{13} \text{ cm}^{-2}$, which could be further improved by over 2 orders of magnitude by adding a boxcar integrator and lock-in amplifier.

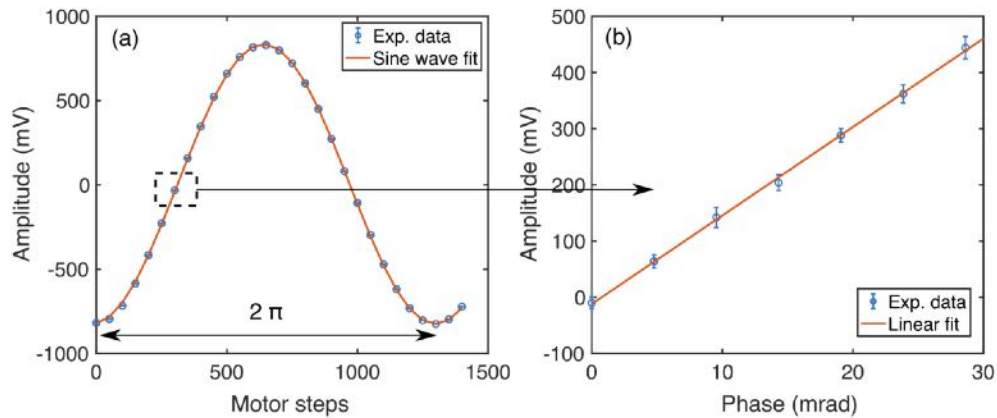


Fig. 2. Calibration of the interferometry. (a) The output signal of the balanced photodiode v.s. motor steps of the rotation stage at low-sensitivity mode. (b) The output signal of the balanced photodiode v.s. calibrated phase shift at high-sensitivity mode.

3. Plasma density measurements

The experiments were performed using a commercially available Ti:Sapphire laser system (Spectra-Physics Solstice ACE) operating at a kilohertz repetition rate with a central wavelength of 800 nm with energy stability of 0.5% (r.m.s). The laser beam was a Gaussian beam with a measured beam quality of $M^2 = 1.25$. The bandwidth of the laser can be adjusted between 10-60 nm. In our experiments, we set the bandwidth at 30 nm, so that the pulse duration of the 800 nm laser was 55 fs measured by Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER) using a commercial product of APE LX Spider.

Here, we show how we measured ionization fraction v.s. laser intensity using our interferometer. On one hand, the smallest measurable phase shift of our interferometer was $\Delta\phi \sim 0.6 \text{ mrad}$. On the other hand, the largest phase shift needed to be controlled $\Delta\phi \ll 1 \text{ rad}$ to keep the linearity of the signal. In all our measurements, we limited the largest phase shift to be less than 300 mrad. The gas pressure in the gas tube was adjusted to make sure that the measured phase shifts is in this range. To illustrate this process, we present an example of measuring phase shifts induced by photoionization of helium v.s. laser intensity as shown in Fig. 3(a). The pump beam

was an 800 nm, 55 fs laser pulse with focal spot size of 60.0 μm . The probe beam was a 400 nm, 130 fs laser pulse with focal spot size of 42.0 μm . At the highest pump laser intensity, we used a gas pressure of 3 Torr and at the lowest laser intensity, we used a gas pressure of 1500 Torr. Then we normalized the phase shifts at different gas pressures to one atmosphere. This is reasonable because the phase shifts are linearly scaled with the gas pressure at the same laser intensity as long as self-focusing of the ionizing laser is negligible. In all our measurements, we made sure that this condition was satisfied by monitoring the spot size of the pump beam so that the evolutions of the ionizing laser spot size at different gas pressures were always the same as in vacuum. At each experimental condition, we took 100 shots for statistics.

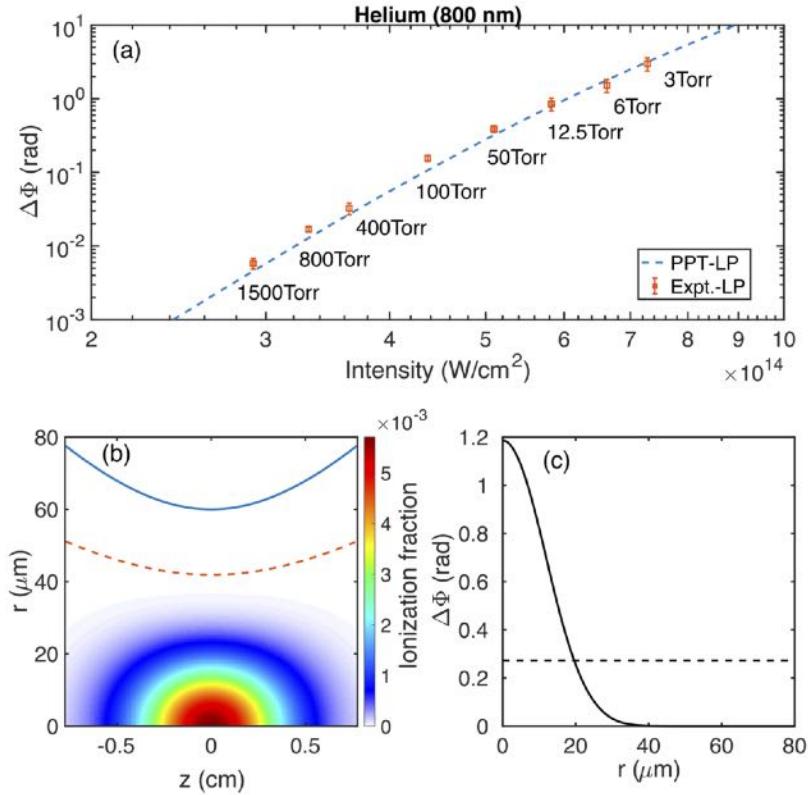


Fig. 3. An example of measuring ionization yield of helium pumped by a 55 fs 800 nm LP laser pulse. (a) Measured phase shift v.s. laser intensity. Different gas pressures are used at different laser intensities, but the phase shifts are all normalized to 1 atmosphere pressure. (b) The calculated r - z distribution of ionization fraction at intensity of $5 \times 10^{14} \text{ W/cm}^2$ using PPT-LP model. The blue solid line and the red dashed line show the spot size evolution of the pump and probe laser, respectively (Gaussian beam with $M^2 = 1.25$ assumed). (c) The calculated longitudinally integrated phase shift of probe beam v.s. radius respect to the axis. The dashed line shows the average phase shift, which is directly compared to the measured phase shift shown in (a).

To compare the experimental results with theoretical models, we had to consider focal volume averaging effect. By carefully measuring the spot size, pulse duration, laser energy and gas pressure at each experimental condition, we could accurately model the theoretical 3D distribution of the pump laser intensities based on these measured parameters and then calculate the theoretical 3D distribution of ionization fraction based on a specific ionization model such as ADK or PPT model. For example, in Fig. 3(b), we show the calculated r - z distribution of ionization fraction

of helium at peak pump intensity of $5 \times 10^{14} \text{ W/cm}^2$ using PPT-LP model. (The blue solid line and the red dashed line show the spot size evolution of the pump and probe laser, respectively.) And then considering the spatial distribution of both the pump and probe beams, the probe beam at different radius respect to the axis experienced different amount of phase shifts as shown in Fig. 3(c). Then we calculated the averaged phase shift at the same condition of the experiments as shown in the dashed line in Fig. 3(c), which was then directly compared to the measured phase shift shown in Fig. 3(a). From Fig. 3(a), one can see that the experimental results agreed well with PPT-LP model at all laser intensities we measured. This confirms that our measurement technique was working correctly.

3.1. Photoionization of argon, krypton, and xenon

Now we show our experimental results of the phase shifts due to photoionization of Ar, Kr, and Xe gases using an 800 nm laser with both linear and circular polarizations. We chose these three gases because the outermost electron is in the p orbital (with $m_l = 0, \pm 1$), therefore the PPT-LP or PPT-CP models could be tested by ionizing with LP or CP laser pulses respectively. The parameters of the pump and probe laser pulses are the same as the example shown above, which are also shown in the first line of Table 1. The comparison of our experimental results with ADK and PPT model is shown in Fig. 4. The vertical dashed lines in each panel mark the laser intensity where the Keldysh parameter $\gamma = 1.5$ (left) and $\gamma = 1.0$ (right), respectively. For the intensity range we used for all three gases, the ionization is in the adiabatic ($\gamma \ll 1$) or nonadiabatic ($\gamma \sim 1$) TI regime. As expected, our experimental results agree well with PPT model at all intensities except at close to saturation intensities where there is a small deviation for both LP and CP cases. These small deviations are attributed to small angular misalignment between the pump and probe beams. In calculating the phase change, we assume a perfect overlap between the two beams. At lower intensities, the ionization volume is rather small and located near the focal plane so that angular misalignment between the pump and probe beams does not affect the effective interaction length. This is why the experimental data agreed with the PPT theory curves. Also as we expected, ADK model agreed with both PPT model and our experimental results at high intensities in the adiabatic TI regime ($\gamma \ll 1$), but not at low intensities in the nonadiabatic TI regime ($\gamma \sim 1$). Note that for CP case, our experimental results agree well with the PPT-CP model, which is another proof of validity of this model in the both adiabatic and nonadiabatic TI regime.

Table 1. Pump and probe laser beam parameters

Pump	Pulse duration (fs)	Spot size (μm)	Probe	Pulse duration (fs)	Spot size (μm)
800 nm	55	60.0	400 nm	130	42.0
400 nm	130	27.5	800 nm	55	23.3
267 nm	160	25.0	800 nm	55	23.3

3.2. Photodissociation and photoionization of hydrogen molecules

When an intense laser pulse interacts with molecules instead of atoms, more than one pathway is possible that leads to the generation of free electrons. For example, a diatomic molecule can be dissociated first forming two neutral atoms followed by ionization. Another possibility is that ionization of the molecule can lead to a positively charged molecule plus an electron. Laser wavelength and pulse duration are two important factors that affect the molecular fragmentation dynamics of hydrogen. For hydrogen molecules, dissociation energy (4.5 eV) is much lower than ionization energy (15.4 eV) to form a positively charged hydrogen molecule, therefore for a given pulse-length we expect a shorter wavelength laser pulse to dissociate some of the hydrogen

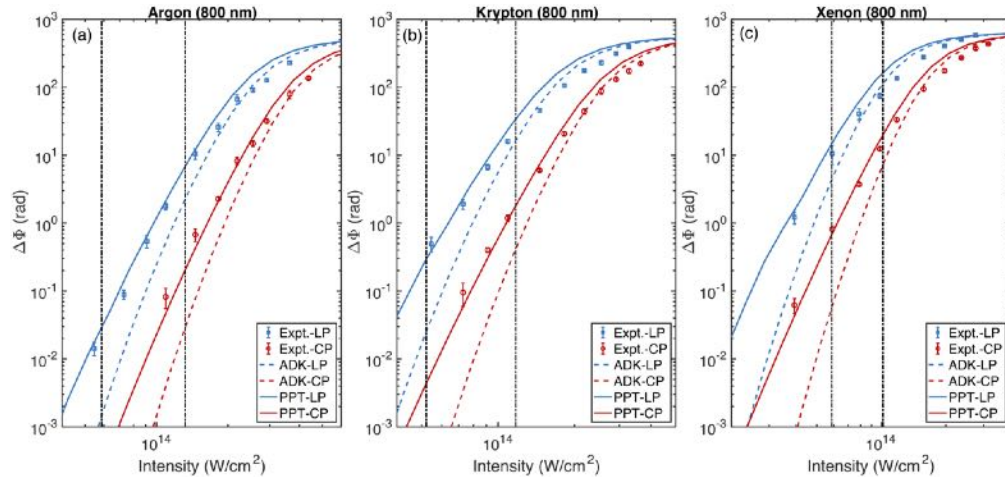


Fig. 4. Phase shifts of Ar, Kr, and Xe ionized by 800 nm, 55 fs laser pulses compared with ADK and PPT model for both LP and CP cases. The vertical dashed lines in each panel mark the laser intensity where the Keldysh parameter $\gamma = 1.5$ (left) and $\gamma = 1.0$ (right), respectively. As in Fig. 3 this data is taken using a range of gas pressures and subsequently normalized to 1 atmosphere. So a maximum phase change of 500 rad corresponds to 100% ionization of these noble gases (plasma density of $2.7 \times 10^{19} \text{ cm}^{-3}$).

molecules before ionizing them. However, dissociation is a slower process since requires the two (heavy) atoms to physically move apart and therefore is more efficient when longer-duration and/or shorter-wavelength laser pulses are used in the intermediate Keldish parameter regime. The two dominant pathways of molecular fragmentation dynamics of hydrogen [31–33] are shown in Fig. 5. In the upper pathway, a hydrogen molecule is first ionized to form a molecular hydrogen ion, then dissociated into a proton and a hydrogen atom, which is finally ionized to a proton; the other is that a hydrogen molecule is first dissociated into two hydrogen atoms, which are then ionized into two protons. In Fig. 5, green arrows represent dissociation; blue arrow represents ionization of molecular hydrogen; while red arrows represent ionization of atomic hydrogen.

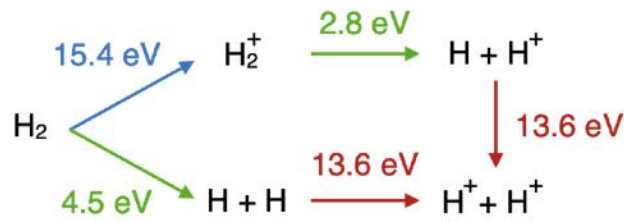


Fig. 5. Two dominant pathways of molecular fragmentation dynamics of hydrogen. Green arrows represent dissociation. Blue arrow represents ionization of molecular hydrogen, while red arrows represent ionization of atomic hydrogen. Not shown is another less likely pathway ($\text{H}_2^+ \rightarrow \text{H}_2^{2+}$, IP = 30.0 eV).

Now we show our experimental results of ionization of hydrogen molecules using 800 nm, 400 nm, and 267 nm LP laser pulses in Fig. 6. Note that when we use 800 nm pump laser, the wavelength of the probe beam is 400 nm; when we use 400 nm or 267 nm pump lasers, the wavelength of the probe beam is 800 nm instead. The detailed parameters of the pump and

probe laser beams are shown in Table 1. Since the plasma or electron density after ionization is measured by our method, we cannot measure the dissociation process and therefore cannot determine the accurate fragmentation of different pathways. However, regardless of different pathways, there are only two kinds of ionization: atomic ionization ($H \rightarrow H^+$, IP = 13.6 eV) and molecular ionization ($H_2 \rightarrow H_2^+$, IP = 15.4 eV), which have different slopes of yield v.s. intensity. By comparing our experimental results with two simple theoretical ionization models of either atomic ionization (PPT model [9]) or molecular ionization (MO-PPT model [30]), we can roughly estimate the ratio between these two ionization processes in different pump cases. For 800 nm pump case, the experimental results agree very well with the MO-PPT model, which suggests that in this case molecular ionization is clearly dominant and there is very little atomic ionization. However, when we switch pump wavelength from 800 nm to 400 nm and 267 nm, atomic ionization becomes more and more significant, especially for the 267 pump case. The slope of the experimental data curve now matches that of the multiphoton ionization of atomic hydrogen. By fitting the ratio between atomic and molecular ionization to match the measured phase change in experiments, we estimate that this ratio is 1:9 (1:1) when pumping with a 400 nm, 130 fs laser pulse (a 267 nm, 160 fs laser pulse). Unfortunately, we cannot conclude that these ratios are the same as the ratios between different pathways in Fig. 5 because ionization of atomic hydrogen can happen in both pathways (red arrows). We note that for 267 nm pump case with laser intensity at round 5×10^{13} W/cm² [Fig. 6(c)], the kink develops in both the PPT (atomic ionization) prediction and the experimental results, which is due to channel closing.

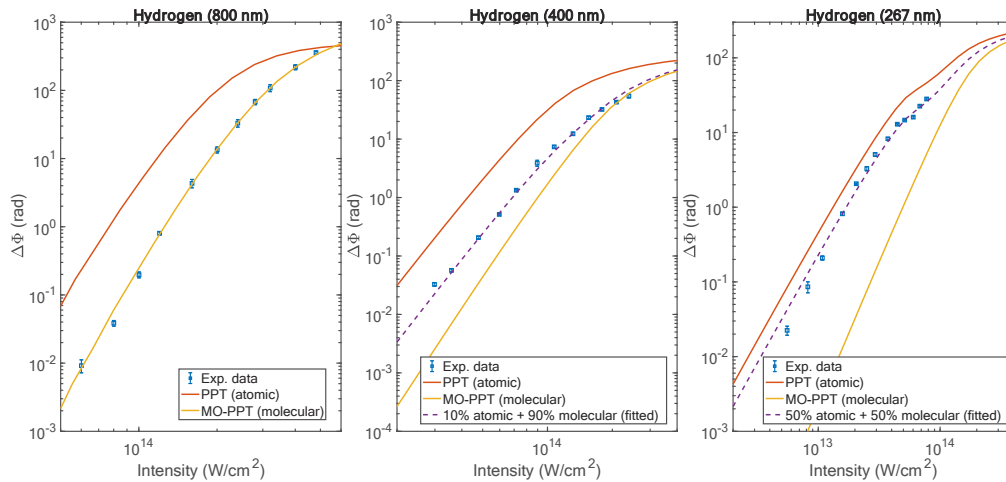


Fig. 6. Phase shifts of hydrogen molecules ionized by 800 nm, 400 nm, and 267 nm laser pulses compared with PPT and MO-PPT model.

When measuring molecular ionization using our interferometry, one important thing to note is that femtosecond laser-induced alignment and periodic recurrences induced by molecular rotation [34,35] can lead to periodic refractive index change for the probe pulse at different delay time, thus affect the ionization yield measurements. Specifically, in hydrogen case, the refractive index change induced by rotational echoes is almost negligible [34] compared with the refractive index change induced by plasmas. Therefore, our measurements were not affected in this case. However, for other linear molecules with a much greater moment of inertia, such as nitrogen, the refractive index variation induced by rotational echoes could be larger than the refractive index variation induced by plasma, then the delay between the pump and the probe needs to be properly chosen to avoid these periodic rotational revival peaks. If the pump pulse duration is at

picosecond to nanosecond level, the molecules will be aligned adiabatically and also induce large refractive index change of the probe, which is not the case in our experiments.

4. Conclusion

We have developed a cross-polarized common-path temporal interferometer for high-sensitivity plasma density measurements. Using this interferometer, we investigated strong-field ionization yield versus intensity for various noble gases (Ar, Kr, and Xe) using 800 nm laser for both LP and CP cases. The experimental results were compared to ADK and PPT models. We verified that ADK is only valid in the adiabatic TI regime, while PPT theory is applicable to a wider intensity range that covers both the MPI and TI regimes for both LP and CP cases. We have also measured the photodissociation and photoionization of hydrogen molecules. By comparing our experimental results with PPT and MO-PPT models, we have estimated the ratio of the atomic and molecular ionization of hydrogen when using different pump laser with wavelength of 800 nm, 400 nm, and 267 nm. Finally, by changing the delay time of the probe pulse this method can readily be adapted to measure the nonlinear refractive index of gases and molecular echoes [35,36]. Also, this technique could be used for measuring weak magnetic fields in the plasma by inverse Faraday effect [37–39].

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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