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Experimental study of conversion from atomic high-order harmonics to x-ray emissions*

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There are two physical phenomena in a strong laser intensity. One is the high-order harmonic emission; the other is x-ray emission from optical-field ionized plasmas. The experiment of conversion from high-order harmonics to x-ray emissions was given with a 105fs Ti:sapphire laser by adjusting laser intensities. The ingredient in plasma was investigated by the numerical simulations. Our experimental results suggested that the free electrons have detrimental effects on harmonic generation but are favourable for x-ray emission from optical-field ionized plasmas. If we want to obtain more intense harmonic signals as a coherent light source in the soft x-ray region, we must avoid the production of free electrons in plasmas. At the same time, if we want to observe x-rays for the development of high-repetition-rate table-top soft x-ray lasers, we should strip all atoms in the plasmas to a necessary ionized stage by the optical-field-ionization in the field of a high-intensity laser pulse.

Keywords: high-order harmonic, x-ray emission, experimental conversion
PACC: 4265K, 9260L, 5250J

1. Introduction

Recent advances in the short-pulse laser technology have stimulated research on the production of coherent radiation in the extreme ultraviolet by high-order harmonic generations of an intense laser field.[1−5] The high-order harmonics are promising as a coherent light source in the soft x-ray regime. At the same time, multiple-charged ions are generated directly by the optical field but not by collisional ionization at light intensities above $10^{14}\mathrm{W/cm^2}$. Optical field ionization (OFI) can be described quasi-statically with Ammosov–Delone–Krainov (ADK) or barrier-suppression ionization (BSI) models.[6−8] Scheme based on the OFI of atoms in an intense laser field provided by commercial TW femtosecond laser facilities is one of the most promising ways of developing table-top x-ray lasers for practical applications.[9−13] In experiments, the free electrons generated during the process of laser-atom interactions have a great influence on the process of high-order harmonic generations and x-ray emissions from OFI plasmas. In this paper, we report the experimental study and theoretical consideration of the conversion from high-order harmonic generations to x-ray emissions from OFI plasmas. This aspect is of importance to x-ray lasers.

2. Theoretical consideration

At laser intensities above $10^{14}\mathrm{W/cm^2}$, OFI becomes a key mechanism for plasma production and heating. With ultrashort pulse laser systems, a plasma in strong nonequilibrium state can be created by OFI of a gaseous medium in an intense laser field. In this paper, we use the tunnelling ionization theory of ADK[6] to describe laser-atom interactions in strong fields because the experiments in Ref.[7] confirm that the ADK rates are in better agreement with the data than the Keldysh rates. The ADK ionization rate for a linearly polarized light is given by

$$W_{\mathrm{lin}} = 4.182\frac{Z^2}{n^{*4.5}}\left(10.873\frac{Z^3E_b}{n^{*4}E_0}\right)^{2n^*-1.5} \times \exp\left[-\frac{2}{3}\left(\frac{E_{\mathrm{i}}}{E_{\mathrm{h}}}\right)^{3/2}\frac{E_b}{E_0}\right]\omega_0, \quad (1)$$

where ω_0 $(4.1\times10^{16}\mathrm{s^{-1}})$ is the atomic unit of fre-

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quency, Z denotes the charge number of the created ions, E_b (5.1×10^9V/cm) is the atomic field strength, n^* is the effective quantum number which can be obtained by equating the ionization potential E_i of the critical electron orbit with $(Z^2/n^{*2})E_\mathrm{h}$,

$$n^* = Z/(E_\mathrm{i}/E_\mathrm{h})^{1/2}, \tag{2}$$

where E_h (13.6eV) is the ionization potential of hydrogen.

Assuming a stepwise ionization process, the electron number N_j of the charge state j at time t can be expressed by

$$\begin{cases} \dot{N}_0(t) = -W_1(E(t))N_0(t), \\ \cdots\cdots \\ \dot{N}_j(t) = W_j(E(t))N_{j-1}(t) - W_{j+1}(E(t))N_j(t), \\ \cdots\cdots \\ \dot{N}_{Z_\mathrm{max}}(t) = W_{Z_\mathrm{max}}(E(t))N_{Z_\mathrm{max}-1}(t), \\ \sum\limits_{j=0}^{Z_\mathrm{max}} N_j(t) = 1, \end{cases} \tag{3}$$

where $W_j(t)$ is the ionization rate for the production of charge state j. Figures 1–3 show that the typical evolutions of the charge-state population in nitrogen for the 105fs linearly polarized laser pulses with peak intensities of 0.8×10^{14}W/cm^2, 1×10^{14}W/cm^2, and 7.5×10^{14}W/cm^2 respectively. One can see from Fig.1 that there are only N atoms in the plasma before arriving at the laser peak. This implies that at this peak intensity one can only observe the high-order harmonic emission. With increasing laser intensity, one can see from Fig.2 that a little of C-like N ions is produced, but at this peak intensity there are more N atoms in the plasma. So we have probably obtained x-ray emissions from the C-like N ions. When the laser intensity is increased up to 7.5×10^{14}W/cm^2 (Fig.3), one can see that the N atoms are completely stripped into C-like and B-like N ions before arriving at the laser peak. This implies that at this peak intensity high-order harmonic generations cannot be observed while x-ray emissions from the C-like and B-like N ions can be obtained.

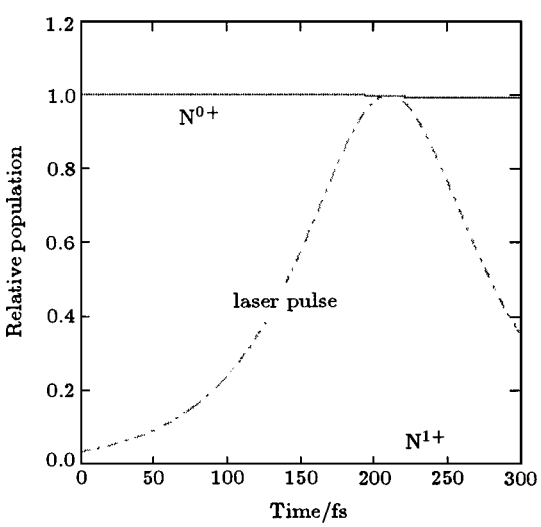


Fig.1. Evolution of the relative populations of the charge states in nitrogen for a 105fs linearly polarized laser pulse with a peak intensity of 0.8×10^{14}W/cm^2.

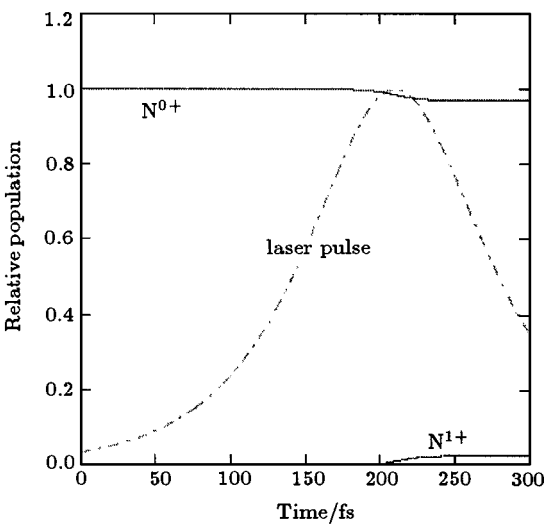


Fig.2. Evolution of the relative populations of the charge states in nitrogen for a 105fs linearly polarized laser pulse with a peak intensity of 1.0×10^{14}W/cm^2.

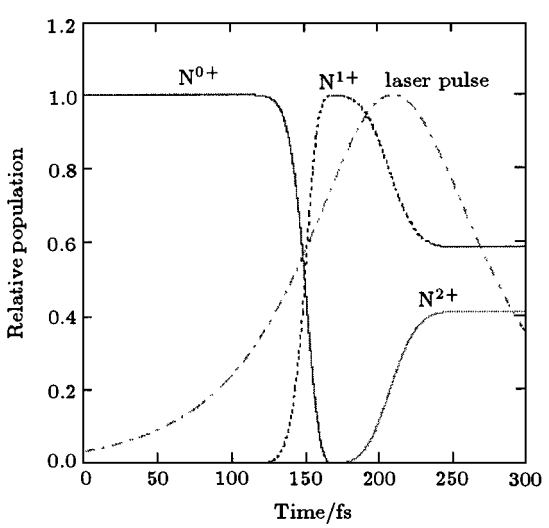


Fig.3. Evolution of the relative populations of the charge states in nitrogen for a 105fs linearly polarized laser pulse with a peak intensity of 7.5×10^{14}W/cm^2.

3. Experimental set-up

The experimental set-up is shown in Fig.4. The femtosecond laser system used in the experiment is a commercial (America Spectra Physics Co), high-repetition rate (10Hz), Ti:sapphire chirped pulse amplification system with a maximum energy output of 60mJ. A 105fs 795nm linearly polarized laser pulse is passed through a 50.8mm diameter, 5mm thick MgF_2 window into an evacuated chamber, which is focused by a 320mm focal length lens into a pumped nitrogen gas cell. In the target cell two replaceable pinholes of diameter $< 500\mu$m, whose separation can be varied by means of transition stages, provide the entrance orifice for the pump laser and the exit orifice for the pump and XUV lasers. These pinholes are drilled in brass stocks by the femtosecond laser pulse.

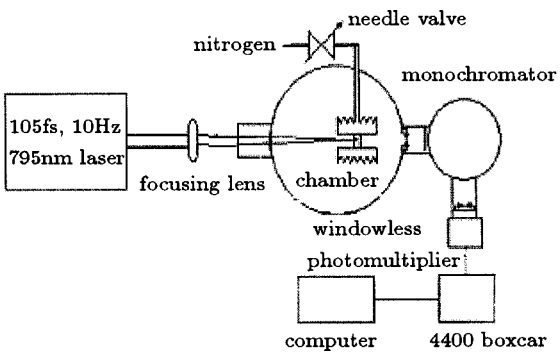


Fig.4. Experimental set-up of high-order harmonics and x-ray generations in N_2.

The XUV radiation escaping from the target cell enters a 0.5mm vacuum Seya Namioka scanning monochromator (Acton Research Corp. model VSN-515), whose entrance slit is located 460mm from the centre of the target cell to protect the grating entrance, slits are 100μm wide and 10mm high, and the grating has a groove density of 1200 lines/mm. The spectrometer has an accuracy of 0.01nm and a resolution of 0.05nm in the vicinity of 121.6nm with a scanning speed 10nm/min. The signal is detected by a windowless photomultiplier mounted on the monochromator. Electronic signals from the windowless photomultiplier are transferred to the average signal interfaced with an oscillograph and a boxcar integrator with a 20ns time gate. All the measured voltage data have been normalized to be directly compared with a signal corresponding to a bias of 1600V. The spectra shown in this paper have not been corrected for the spectral response of the detection system.

4. Results and discussion

The high-order harmonic spectra and x-ray emission observed in nitrogen at different laser intensity are shown in Figs.5–8. The corresponding intensities are 0.8×10^{14}W/cm^2 in Fig.5, 1×10^{14}W/cm^2 in Fig.6, 1×10^{14}W/cm^2 in Fig.7 and 7.5×10^{14}W/cm^2 in Fig.8. The saturation intensity of nitrogen is about 1.5×10^{14}W/cm^2 for the laser with wavelength of 795nm and pulse duration of 105fs deduced from barrier suppression ionization. Thus the laser intensity applied is high enough to ionize neutral nitrogen to N^+ and N^{2+}, and the effect of free electrons on the high-order harmonic generations and x-ray emission can be well studied in this intensity regime. With relatively low laser intensity (Fig.5), the second spectra of high-order harmonic and the spectral line of N^+: $2p^2$-3d is not evident, and the first high-order harmonic signals can be obtained. When the laser intensity is increased up to 1×10^{14}W/cm^2 (Fig.6), the weak line of N^+: $2p^2$-3d and the second spectra of the high-order harmonics appear while the intensity of the first harmonic signals are the most intense among these three cases. With the laser intensity of 1.5×10^{14}W/cm^2 (Fig.7), the spectral line of N^+: $2p^2$-3s becomes intense and the intensity of the first harmonic signals becomes weakened. With the laser intensity of 7.5×10^{14}W/cm^2 (Fig.8), the spectral line of N^+: $2p^2$-3d becomes very intense and the spectral lines of N^{2+} appear. However, the high-order harmonic emissions are completely dispersed. Thus, we have revealed evidently that the free electrons generated in the interactions between the atoms and intense laser field have a deep influence on the converting process of high-order harmonic generations and x-ray emission based on the OFI. The experimental results shown in Figs.5–8 agree well with the theoretical interpretation.

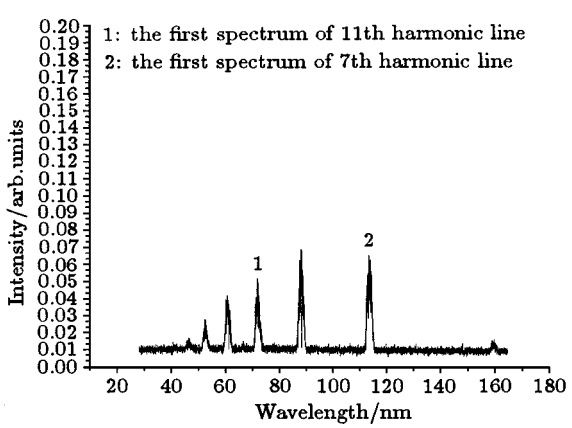


Fig.5. High-order harmonic spectra and x-ray emission in N_2. The laser intensity is about 0.8×10^{14} W/cm^2, the pressure is 1.03kPa.

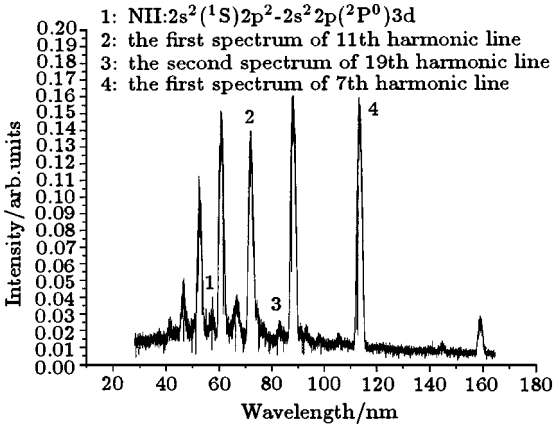


Fig.6. High-order harmonic spectra and x-ray emission in N_2. The laser intensity is about 1×10^{14} W/cm^2, the pressure is 1.03kPa.

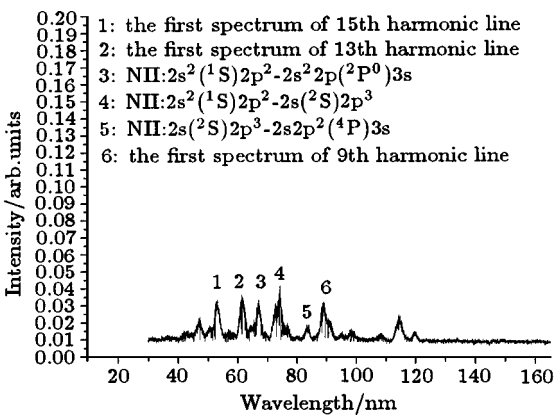


Fig.7. High-order harmonic spectra and x-ray emission in N_2. The laser intensity is about 1.5×10^{14} W/cm^2, the pressure is 1.03kPa.

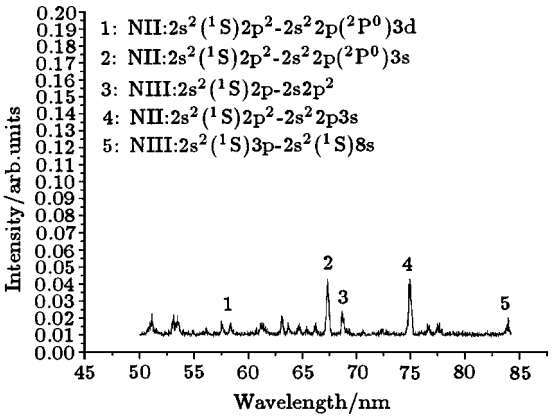


Fig.8. High-order harmonic spectra and x-ray emission in N_2. The laser intensity is about 7.5×10^{14} W/cm^2, the pressure is 1.03kPa.

5. Conclusion

In conclusion, our experimental results presented in this paper provide a clear experimental demonstration of conversion from high-order harmonic generations to x-rays emissions from the OFI plasmas due to the influence of ionization by directly observing the spectral line of N^+:$2p^2$-3d. The results also show that the free electrons have detrimental effects on harmonic generations but are favourable for x-ray emissions from the OFI plasmas. If we want to have more intense harmonic signals as a coherent light source in the soft x-ray region, we must avoid the production of free electrons in plasmas. However, if we want to observe x-rays for the development of high-repetition-rate table-top soft x-ray lasers, we should strip all the atoms in plasmas to a necessary ionized stage by OFI in the field of the high-intensity laser pulses.

References

[1] Sarukura N *et al* 1991 *Phys. Rev.* A **43** 1669
[2] Huillier A L and Balcou P 1993 *Phys. Rev. Lett.* **70** 774
[3] Lewenstein M *et al* 1994 *Phys. Rev.* A **49** 2117
[4] Nagata Y *et al* 1996 *Opt. Lett.* **21** 15
[5] Xu Z Z *et al* 1998 *Opt. Commun.* **158** 89
[6] Ammosov M V *et al* 1986 *Sov. Phys.–JETP* **64** 1191
[7] Augst S *et al* 1989 *Phys. Rev. Lett.* **63** 2212
[8] Penetrante B M and Bardsley J N 1989 *Phys. Rev.* A **43** 3100
[9] Wang Q, Chen J X, Xia Y Q and Chen D Y 2002 *Acta Phys. Sin.* **51** 1035 (in Chinese)
[10] Sebban S *et al* 2001 *Phys. Rev. Lett.* **86** 3004
[11] Lu P X *et al* 1999 *Opt. Commun.* **170** 71
[12] Nagata Y *et al* 2001 *J. Physique* **11** 2205
[13] Balcou Ph *et al* 2001 *J. Physique* **11** 2175