Charge-state distribution in a photoionized laser-produced plasma

Feilu Wang\textsuperscript{1,4}, Shinsuke Fujioka\textsuperscript{1}, Hiroaki Nishimura\textsuperscript{1}, Daiji Kato\textsuperscript{2}, Yutong Li\textsuperscript{3}, Gang Zhao\textsuperscript{4}, Jie Zhang\textsuperscript{3,5} and Hideaki Takabe\textsuperscript{1}

\textsuperscript{1} Institute of Laser Engineering, Osaka University, Osaka 565-0871, Japan
\textsuperscript{2} National Institute for Fusion Science, Gifu 509-5292, Japan
\textsuperscript{3} Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
\textsuperscript{4} National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
\textsuperscript{5} Shanghai Jiao Tong University, Shanghai 200030, China

E-mail: flwang@ile.osaka-u.ac.jp

Abstract. We present the first x-ray spectroscopic measurements of the ionization balance relevant to astrophysics with intense laser. Independent measurement of the radiation flux indicates values of the ionization parameter $\xi \sim 10$ erg cm$^{-1}$ s$^{-1}$ and Planckian radiation source of 80 eV to photoionize the nitrogen gas. The observed emission spectra of nitrogen of relatively low density ($n_i = 1.4 \times 10^{19}$ cm$^{-3}$) shows a good agreement with the synthetic spectra by a time-dependent DCA (Detailed Configuration Accounting) atomic model. In this model, it solves the rate equations for level population distributions by considering collisional and radiative atomic processes based on screened hydrogenic model. The $jj$ configuration atomic states and transition probabilities are calculated with HULLAC to synthesize spectrum. With this model, we can obtain a reasonable range of the electron temperatures of $20 - 30$ eV. Comparisons of charge-state distribution with a non-LTE atomic model FLYCHK show reasonable agreement.

1. Introduction

In the universe, photoionization and photoexcitation often prevail over collisional processes in the vicinity of strong radiation source such as a hot star [1] and an accretion disk [2]. Thanks to Chandra and XMM-Newton satellites, detailed spectra could be obtained and provide us quantitative features of these nonlocal thermodynamic equilibrium (non-LTE) plasmas. The extraction of information of plasmas such as density, temperature, and element abundance from astronomical spectra correctly relies on the theoretical collisional-radiative model. In general, the charge-state distribution of non-LTE plasmas is governed by a balance between collisional and radiative processes such as ionization, recombination, excitation, and radiative decay. It requires a complete set of detailed atomic energy levels and the transitions of all the atomic processes affecting the level population distribution. However, in most cases, this is too numerous to treat, which has led to a number of approximate theoretical models. These models differ in treatment of the atomic rates and complexity of energy levels included. From various non-LTE models, predictions for the average charge have been shown both agreement in some cases [3] and disagreement by more than ten ionization stages in others [4]. This emphasized the need for experimental data of photoionized plasmas.
In the present work, laser facility was used to photoionize gas sample to investigate photoionization process relevant to astrophysics for the first time. The nitrogen was filled in an x-ray generation cavity confining an intense radiation field with radiation temperature $T_r = 80$ eV so that relatively low density ($n_i = 1.4 \times 10^{19}$ cm$^{-3}$) photoionized plasma formation has been achieved. Temporal evolution of emission spectra was recorded with a spectrometer in the spectral range of 9 – 20 nm. Nitrogen is found to be photoionized beyond He-like state (open K-shell). A model, including a quick rate equation solver and detailed atomic data, was used to analyze the experimental spectra to estimate the range of electron temperatures ($T_e$) to be 20 – 30 eV and provided the charge-state distribution. Comparisons of the distribution with x-ray photoionization model $flychk$ [5] show reasonable agreement.

2. Experiment

Photoionization experiment of nitrogen was performed on the Gekko-XII laser facility [6]. The x-ray generation gold cavity consists of two x-ray conversion cavities at both ends and one x-ray confining cavity [7]. X-ray radiation from the conversion cavities propagated diffusively toward the confining cavity for ionizing the sample. The confining cavity has two observation windows of 200 $\times$ 200 $\mu$m$^2$ and 300 $\times$ 300 $\mu$m$^2$, and they were covered with polyimide films of 0.1 $\mu$m.

Six beams of the Gekko-XII laser (0.53 $\mu$m in wavelength and 0.5 ns in pulse-duration) were focused through two inlet holes of 520 $\mu$m diameter onto the inner surface of the x-ray generation cavity. The radiation temperature in the confining cavity was measured with a transmission grating spectrometer coupled with a cooled backillumination x-ray CCD camera. The spectrum of the thermal radiation through an observation window in the confining cavity were fitted with the Planck function to derive $T_r = 80$ eV.

The confining cavity was filled with nitrogen gas of $2.7 \times 10^4$ Pa. For the photoionization experiment, the low electron density is required so that photoionization dominates over collisional ionization. Simulation with radiation-hydrodynamic code ILESTA-1D [8] predicts an averaged density of the heated nitrogen of $1.4 \times 10^{19}$ g cm$^{-3}$ at 2.1 ns after the peak of the heating x-ray pulse. At the peak of the radiation pulse, ionization parameter [9] $\xi$ reaches the peak value near 10 erg cm s$^{-1}$.

Emission spectra were observed with a grazing incidence flat field spectrometer coupled with an x-ray streak camera. The grating pitch was 1200 l mm$^{-1}$, and spectral range was 9 – 20 nm with a spectral resolution of 3 nm.

3. Theoretical Modeling

In order to interpret the experimental emission spectra, we have composed a photoionization model [10]. In order to make the model simple, we made following assumptions:

1. The plasma is uniform and optically thin so that its self-emission passes through the plasma without absorption by plasma.
2. Maxwellian distribution is applied for free electrons.
3. Doubly excited states are neglected, and recombination and photoionization occur between each state of charge state $Z$ and the ground state of ions $Z + 1$.
4. Relativistic effects are not taken into account since relatively low-Z elements are used.

We assess population distribution with a screened hydrogenic model (SHM)[11] and analytical approximation of cross sections. However, these atomic data are not accurate enough to synthesize emission spectra in many cases. To improve on this, $n$-based level populations are statistically redistributed among the $jj$ configuration populations by using detailed atomic data from HULLAC [12].
4. Analysis
The observed emission spectra are mainly composed of emissions from photionized plasma and the gold plasma close to the observation windows. Some emission from the outer surface of the gold cavity was also superimposed on the spectra due to the heating with unconverted fundamental 1.06 \( \mu \)m light shining on the cavity. An empirical fit was applied to remove the continuum emission component from observed spectra. The line identification shows some oxygen lines, such as \( \lambda = 184 (O \ VI \ 3s - 2p) \) are also been observed since oxygen is involved in the polyimide films used in the x-ray confining cavity, and on the cavity surface as contamination.

We picked up three lines at 134 \( \AA \) (\( L_{134} \)), 174 \( \AA \) (\( L_{174} \)), and 187 \( \AA \) (\( L_{187} \)) as benchmarks. For experimental data, the intensity of \( L_{134} \) is comparable to and slightly larger than \( L_{174} \), and the intensity of \( L_{187} \) is much weaker than \( L_{134} \) and \( L_{174} \). With the given radiation temperature 80 eV and the electron temperature as a free parameter, it is concluded that we can obtain a good agreement with experimental spectra when we assumed the electron temperatures were 20\( - 30 \) eV, which were reasonable temperatures in the present experiment (Fig. 1). Figure 2 shows that the average ionization remains constant for densities lower than approximately \( 10^{19} \) cm\(^{-3} \) above which point 3-body recombination becomes important. In order to investigate the role of photoionization, the theoretical spectra of nitrogen without radiation field show that the experimental features could be reproduced for \( T_e = 100 \) eV [10]. However, under the present experimental condition, the electron temperature 100 eV is unrealistically high since experimental radiation temperature is only 80 eV. And we note that observed spectra can be reproduced when we assume LTE with \( T_r = T_e = 60 \) eV [10]. Under the present experimental condition, \( T_r \) was set to be 80 eV. Therefore, the plasma is deemed as in non-LTE.

![Figure 1](image1.png)

**Figure 1.** Theoretical spectra of nitrogen with \( T_r = 80 \) eV and \( T_e \) from 10\( - 40 \) eV. Also shown for comparison is emission spectrum of \( t = 2.1 \) ns.

Figure 3 shows the distributions of the nitrogen charge states of various \( T_r \) and \( T_e \) as well as the FLYCHK calculations. Four calculations with present model are shown: The first calculation (P-a) used the electron temperature of 20 eV, the radiation temperature of 80 eV and an ion density of \( 1.4 \times 10^{19} \) cm\(^{-3} \). The second calculation (P-b) is based on LTE with same radiation and electron temperatures of 60 eV. The third (P-c) excludes the radiation field. For comparison, two calculations with FLYCHK are also shown: the first (F-a) used radiation temperature of 80 eV and electron temperature of 20 eV and the second (F-b) decreases the radiation temperature to 70 eV.

The most abundant ions based on non-LTE (P-a) and LTE (P-b) are N VI and N VII respectively. The charge-state distribution shows more ions are ionized in LTE than that in non-LTE. As mentioned, both of the cases could reproduce the observed experimental spectrum. It reveals more ions locate in excited states, such as \( n = 3 \), even though less highly-ionized ions in non-LTE since radiative excitation dominates. Compared the distributions of cases P-a and P-c, an inclusion of radiation field causes N VI ions to be ionized further to VII. It reveals that radiation field is considered of such importance that has to be taken into account in these experiment. The non-LTE atomic model FLYCHK with radiation temperature of 80 eV and
Figure 2. Average ionization of N with varying number density \( n_e \) (in cm\(^{-3}\)).

Figure 3. Comparison of the ionization distribution with detailed modeling using the code FLYCHK

electron temperature of 20 eV (F-a) gives the similar distribution with P-b, while with radiation temperature 70 eV and electron temperature 20 eV similar to P-a.

5. Summary
We have carried out the first experiment with intense laser to study the photoionized plasma relevant to astrophysics with large-scale laser system Gekko XII and presented the spectra that has allowed us to test detailed calculations of atomic spectra for photoionized plasma. Simulations with and without the radiation field also directly confirmed that photoionization was the dominant ionization process for these plasmas. We find the charge-state distribution is sensitive to the treatment of radiative processes in various models. More detailed discussion about differences between the codes is beyond the scope of this work, but we hope will be addressed in the future.

Acknowledgments
The authors thank R. M. More and D. Salzmann for helpful discussions, and Gekko-XII laser facility team for their technical assistance. This paper used the photoionization code FLYCHK, written by H. K. Chung, R. Yuri, and R. W. Lee, which can be used at NIST (http://nlte.nist.gov/FLY/). This work was performed under the auspices of Joint Research Project of Japan-China (No.10510490). Wang is supported by the JPSP Postdoctoral Fellowship For Foreign Researchers. This work was also supported by the National Natural Science Foundation of China under grant No. 10403007.

References
[1] Osterbrock D E 1989 Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Sausalito: University Science Books)
[2] Ballantyne D R, Ross R R and Fabian A C 2002 Mon. Not. R. Astron. Soc. 336 867
[3] Foord M E et al 2004 Phys. Rev. Lett. 93 055002
[4] Lee R W, Nash J K and Ralchenko Y 1997 J. Quant. Spectrosc. Radiat. Transfer 58 737
[5] Chung H K, Chen M H, Morgan W L, Ralchenko Y and Lee R W 2005 High Energy Density Physics 1 3
[6] Yamanaka C, Kato Y, Izawa Y, Yoshida K, Yamanaka T, Sasaki T, Nakatsuka M, Mochizuki T, Kuroda J and Nakai S 1981 IEEE J. Quantum Electronics 17 1639
[7] Fujioka S et al 2005 Phys. Rev. Lett. 95 235004
[8] Takabe H et al 1988 Phys. Fluids 31 2884
[9] Tarter C B, Tucker W H and Salpeter E E 1969 Astrophys. J. 156 943
[10] Wang F L, Fujioka S, Nishimura H, Kato D, Li Y T, Zhao G, Zhang J and Takabe H, 2007, Astrophys. J., submitted
[11] More R M 1982 J. Quant. Spectrosc. Radiat. Transfer 27 345
[12] Bar-Shalom A, Klapisch M, and Oreg J 2001 J. Quant. Spectrosc. Radiat. Transfer 71 169 and refs. in it