Experimental evidence and theoretical analysis of photo-ionized plasma under intense x-ray radiation produced by laser

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INTRODUCTION

In the Universe, radiation plays an important role to characterize the plasmas and in general these plasmas are not in local thermodynamic equilibrium. Intense laser made it possible to study such plasmas in laboratory by converting laser energy to x-ray radiation with irradiating inside a gold cavity. In the present work, intense laser facility was used to photoionize a gas sample to investigate photoionization process relevant to astrophysics for the first time. Nitrogen is found to be photoionized beyond He-like state (open K-shell).

EXPERIMENTAL CONDITION AND RESULTS

Photo-ionized nitrogen plasma experiment was performed on the Gekko-XII laser facility. Figure 1(a) shows the experimental setup. An x-ray generation cavity, called dog-bone, consists of one x-ray confining cavity and two x-ray conversion cavities at the both ends. The cavity is made of pure gold. Geometry of the dog-bone cavity is a body of axial rotation. Diameter and length of the confining cavity were 800 µm and 1020 µm, respectively. Conversion cavity had a laser inlet hole of 520 µm in diameter. Total length of the dog-bone cavity was 2564 µm. The confining cavity had two observation windows of 200 ± 200 µm\textsuperscript{2} and 300 ± 300 µm\textsuperscript{2}, and they were covered with parylene films of 0.1 ± 0.02 µm in thickness. Both observation windows were made on a line-of-sight of the spectrometers, the spectrometers see the sample plasmas in the cavity through the 200 × 200 µm\textsuperscript{2} window so that no emission from the cavity wall is detected.

Six beams of the Gekko-XII laser (250 J/beam in energy, 0.53 µm in wavelength, Gaussian pulse shape, and 0.5 ns of full width at half maximum in pulse duration) were focused through the two inlet holes onto the inner surface of the x-ray conversion cavity. Focal spot pattern was a flat top circle, and its size was 240 µm in diameter, thus laser intensity was about 1 × 10\textsuperscript{15} W/cm\textsuperscript{2} on the inner wall of the cavity.

The radiation temperature in the confining cavity was measured with a free-standing transmission grating spectrometer coupled with a cooled back-illumination-type x-ray CCD camera. Emission spectra were observed with a grazing incidence flat-field spectrometer coupled with an x-ray streak camera. The grazing incidence spectrometer consists of an entrance slit of 100 µm in width and a varied line spacing groove concave grating that focuses all diffracted rays onto the flat plane. The grating [1], which is shipped from Hitachi Co. Ltd., is covered with gold, and its groove has a braze-type shape of 3.2 deg. in the braze angle, and the groove pitch is 1200 lines/mm. Observable spectral range was 90 - 200 Å with spectral resolution of 0.3 Å.

The confining cavity was filled with nitrogen gas of 2.7 × 10\textsuperscript{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 predicts an averaged temperature and density of the heated nitrogen of 30 eV and 1.4 × 10\textsuperscript{19} g/cm\textsuperscript{3} at 2.1 ns after the peak of the heating x-ray pulse. At the peak of the radiation pulse, the ionization parameter ξ reaches the peak value near 10 erg cm s\textsuperscript{-1}. We note that 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 µm light shining on the cavity.

SPECTRA ANALYSIS

In order to interpret the experimental emission spectra, we have composed a photoionization model. Prior to the achievement of a steady state, interactions between particles and radiation field change the population, which could be described by a set of rate equations mathematically. To solve such equations for each level of each ion of an atom, in principle, requires a complete set of detailed atomic energy levels and rates of all the atomic processes affecting the level population distribution. In order to avoid computational complexity, a model, with a reduced set of energy levels and rates, was composed instead. In order to make the model simple, we made following assumptions: (1) The plasma is uniform and optically thin so that its self-emission

Figure 1 (a) Experimental setup of photoionized nitrogen plasma. (b) X-ray emission spectra of the thermal radiation measured through an observation window in the confining cavity measured at peak power.
passes through the plasma without absorption by plasma. (2) Maxwellian distribution is applied for free electrons. (3) Doubly excited states are neglected. The ionization energy of each ion for a given ionization state and excited state is calculated by a screened hydrogenic model [2, 3].

In order to compare the emission spectra of nitrogen with the model, we have to eliminate continuum emission arising from gold plasma. An empirical fit was applied to remove the continuum component from observed spectra. For experimental spectra, the error of wavelength is within 0.3 Å. Some strong lines could be identified (Fig. 2). To find the plausible range of electron temperatures, theoretical emission spectra with radiation temperature of 80 eV and electron temperature $T_e$ from 10 to 40 eV are shown from bottom to top in Fig. 3. In the case of $T_e = 10 \text{ eV}$, lines of N VI (1s3d-1s2p, $\lambda = 174$ Å) and N V (2s64d-2s2d, $\lambda = 187$ Å) are distinct. With increasing $T_e$ from 10 to 40 eV, lines of NV and N VI get weaker, while L-shell emission lines of NVII ($n = 4 \rightarrow n = 2, \lambda = 99$ Å and $n = 3 \rightarrow n = 2, \lambda = 134$ Å) get stronger. We picked up three lines at 134 Å ($L_{134}$), 174 Å ($L_{174}$) and 187 Å ($L_{187}$) as benchmarks. For the experimental data, (a) the intensity of $L_{134}$ is comparable to and slightly larger than $L_{174}$, and (b) the intensity of $L_{187}$ is much weaker than $L_{134}$ and $L_{174}$. For the theoretical results in the range of $T_e = 20-30 \text{ eV}$, the intensities of these three lines are consistent with the above features. If $T_e$ gets lower, such as 10 eV, $L_{187}$ is so strong that its intensity is comparable to $L_{134}$, which does not agree with (b). If higher, such as 40 eV, $L_{174}$ is too weak to be comparable with $L_{134}$, which cannot explain (a). Therefore, $T_e = 20-30 \text{ eV}$ are the reasonable range of electron temperature in this experiment.


Figure 2. Emission spectra of (a) $t = 0 \text{ ns}$, (b) $t = 1.1 \text{ ns}$ and (c) $t = 2.1 \text{ ns}$ from top to bottom.

**SUMMARY**

We have carried out the first experiment with intense laser to study the photoionized plasma relevant to astrophysics with a large-scale laser system. Planckian radiation source was generated by irradiating lasers at the inside of gold cavity and ionized the high pressure nitrogen gas. The radiation temperature was identified as 80 eV experimentally with the x-ray spectrometer. With the given radiation temperature 80 eV and the electron temperature as a free parameter, the typical lines ($L_{134}$, $L_{174}$, & $L_{187}$) were compared with the experimental spectra. 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.

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