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Inverse Populations of Multicharged Ion Levels in a Z-Pinch Plasma as a Result of Interaction of Plasma Beams with Neutral or Low-Ionized Gas Targets

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Abstract

Systematic investigation of spectra of multiply ionized carbon, nitrogen, and oxygen from Z-pinch plasma interacting with a cold gas is presented. A possibility of the charge-exchange process between high- and low-charged (or neutral) ions being responsible for the observed inversion of level populations in H-, He- and Li-like ions is discussed.

1 Introduction

Charge exchange (CE) reaction was proposed as one of the most effective mechanisms for population inversion in the soft X-ray and VUV spectral region [1, 2, 3]. In this scheme, an inversion is created by a selective quasi-resonance population of excited ion levels due to interaction of a multi-charged-ion beam with cold gaseous or low-charged plasma targets. It was recently proposed [4] to use instabilities in axial discharges for the generation of strong jets of highly ionized plasma for a subsequent CE recombination at interaction with gas or plasma targets. Experimental results have been discussed for Z-pinches [5], capillary discharges [6], and plasma foci [7]. In this paper we present the results of a systematic experimental investigation of the population inversion in carbon, nitrogen and oxygen ions, observed in a Z-pinch plasma expanded into a cold gas.

2 Experimental setup and techniques

A simplified scheme of the experiment is presented in Fig.1. The Z-pinch mounting was described elsewhere [5]. Experiments were carried out with 12-20 kV voltages corresponding to peak currents of 500-800 kA. We used the stainless steel electrodes: the anode had a conic form; the cathode was made as a 2-mm thick disc with a 20-mm hole in a center connecting a discharge chamber and a "target region" - a volume above the cathode (Fig. 1). The anode-cathode distance was 12 mm. A working gas (CO_2 or N_2) was puffed through small holes in the anode using a high-pressure fast valve. The "target" volume above the cathode was filled with the working gas simultaneously with the discharge gap.

Plasma jets in axial directions appear as a result of plasma compression on the discharge axis. A beam composed of electrons and multi-charged ions was injected through the cathode hole into the "target" region and interacted with a gas or plasma above the cathode. The initial gas pressure in the "target" volume was measured by a probe technique and was found to vary from 10^{16} to 10^{17} cm^{-3} depending on the gas valve pressure (15-20 atm) and the time delay between a gas puff and a high voltage triggering (0.3-0.4 ms).

The VUV spectra of Z-pinch were recorded in side-on direction by using a 1-m grazing incidence spectrograph with a 600 l/mm grating and radiation incidence angle of 820. The entrance slit of 10 μm width was placed parallel to the Z-pinch axis at a 420 mm distance. An

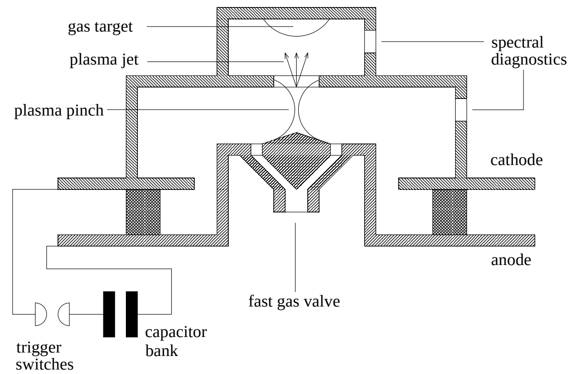

Figure 1: Simplified scheme of the experiment.

additional slit, placed between the entrance slit and the grating, provided spatial resolution along the Z-pinch axis z. As a result, we could observe the spectra between the electrodes and above the cathode ($z = 0-30$ mm) with a spectral resolution 0.2 Å and spatial resolution about 1 mm in the wavelength range of 30 - 300 Å. The spectra were photographed on a UV-4 photo film, usual exposures being 50-100 discharges.

For the time-resolved observation of the Z-pinch radiation, we used the four-channel camera-obscure with a microchannel plate (MCP) detector [8]. This camera permitted to obtain images of the discharge plasma in a soft X-ray and far UV radiation with a time frame of 10 ns.

The total number of ions in excited states in a cross section of plasma with a given axis coordinate was determined from the measured line intensities of $2-3$, $2-4$ and $2-5$ transitions in Li-, He- and H-like ions and is presented below as the reduced densities $\tilde{N} = I_{ij}/(g_i * A_{ij})$. Here I_{ij} is the relative line intensity, g_i is the statistical weight of the upper level, and A_{ij} is the corresponding radiative transition probability. The line intensities were measured over all fine structure contour for each transition by taking into account the photoemulsion response curve and the wavelength dependence of spectrograph efficiency. The latter has been measured earlier by the branching ratio technique using the resonance doublets of F-like ions from Al IV through As XXV, excited in a vacuum spark and in a laser-produced plasma [9]. The estimated error of the relative intensity measurements did not exceed 15-30%.

3 Results of observations

The time-framed pin-hole measurements of a discharge plasma with the MCP camera sensitive to VUV radiation show that the far-VUV emission lasts about 50 - 100 ns and coincides with the time of maximum plasma compression (see also [5]). The VUV spectra mainly consist of lines of Li-, He- and H-like ions. The discharge current partially penetrated into the region above the cathode. Nevertheless, the above-the-cathode plasma is not compressed as deeply as in between the electrodes and should therefore emit only lines of lower charged ions. Hence, we attributed the observed radiation of highly ionized atoms from this area to a result of interaction of plasma jets from instabilities in a main column with the low-charged ions. An intense continuum radiation was observed, especially strong in the near anode region ($z < 6$ mm).

The measured reduced densities $\tilde{N}$'s vs. z for Li-like N V and O VI ions are presented in Fig. 2a and Fig. 2b, correspondingly. A general increase of intensities of Li-like ion radiation is clearly seen for the "target" region with a maximum at $z \approx 20$ mm. The populations of $n = 4$ and $n = 5$ levels are significantly higher than those of $n = 3$ levels in practically all investigated region with an exception of the $3s$ level.

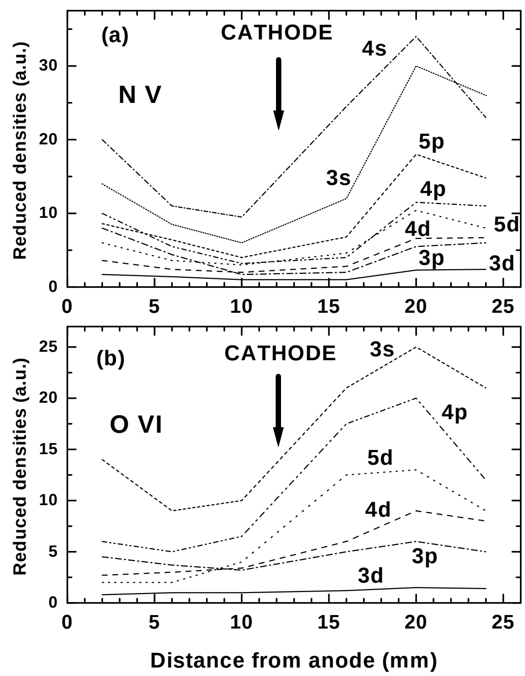

Figure 2: Reduced density $\tilde{N}$ of excited levels of Li-like ions of N V (a) and O VI (b). $\tilde{N}$'s of the ns levels are calculated from the $2p - ns$ transitions, np from $2s - np$, and nd from $2p - nd$.

To estimate the self-absorption effect on the measured values of reduced densities in a dense plasma, we have analyzed the fine structure component intensities of $2p - 3s$, $2s - 3p$ and $2p - 3d$ transitions in Li-like N V and O VI ions. In the region between the anode and cathode, the plasma is optically thick for these transitions in the discharge region. Nevertheless, above the cathode the fine structure components do not show any saturation and plasma may be considered as optically thin. One should mention that the $2s - 3p$ lines in N V (209.274 Å and 209.308 Å) are possibly blended by the $2s2p\ ^1P_1$ - $2s5s\ ^1S_0$ line in N IV (209.378 Å) that may cause some overestimation of the $3p$ level population in the "target" region ($z > 10$ mm).

The $\tilde{N}$ values for the triplet $1snd\ ^3D$ levels in He-like N VI derived from the $1s2p\ ^3P$ - $1snd\ ^3D$ transitions are given in Fig. 3. The singlet-singlet transitions gave a similar result, i.e., a strong population inversion for levels $n = 4$ and 5 towards the level $n = 3$. No optical thickness effects are expected for transitions where lower level is an excited one. Some data for He-like O VII ions are given in our previous work (Fig. 2 in [5]).

The results for the H-like C VI and N VII ions are presented in Fig. 4(a,b). The $\tilde{N}$ values were measured from the $n = 3, 4, 5 \rightarrow n = 2$ transitions. It is seen that the $n = 4$ and

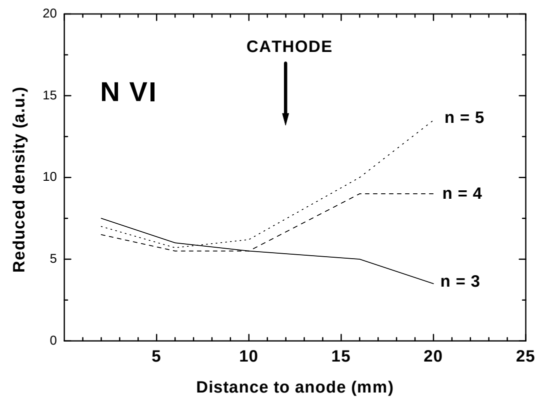

Figure 3: Reduced density $\tilde{N}$ of excited levels of He-like ion of N VI. $\tilde{N}$'s are calculated from the $1s2p\ ^3P$ - $1snd\ ^3D$ transitions.

$n = 5$ level populations show approximately the same behavior and are essentially higher than the $n = 3$ level population in the $z > 10$ mm region. The $2-3$ lines in C VI (182.097 Å and 182.230 Å) are blended by the line of the $2s2p\ ^1P_1$ - $2p3p\ ^1S_0$ transition between excited levels in O V (182.205 Å). The VUV radiation in the spectral region 100-300 Å can be absorbed by photoionization in a cold plasma or residual gas in the above-the-cathode region. In order to clarify this situation we measured the ratio of intensities of the $3 \rightarrow 1$ ($\lambda \approx 28,5$ Å) and $4 \rightarrow 1$ ($\lambda \approx 27$ Å) lines of C VI with a much smaller absorption by the residual gas. Our spectrograph was not relatively calibrated for this pair of lines, and so the measured ratio cannot be used straightforwardly for determination of the population density ratio. Nonetheless, it was found that both ratios (28.5Å/27Å and 182Å/135Å) have a similar behavior above the cathode, thus indicating that there was no essential photoabsorption also for the longer-wavelength pair of lines.

4 Discussion

We summarize briefly our observations:

1) The transitions $n = 4, 5 \rightarrow n = 2$ in Li-, He- and H-like ions of carbon, nitrogen, and oxygen show a general increase of intensities in the region above the cathode. It seems to be unlikely that these stages of ionization could be reached due to plasma compression and heating by the discharge current. We beleive that excitation of the observed transitions is due to a highly efficient process of recombination at interaction of plasma beams generated by neck instabilities in inter-electrode space with a low-temperature plasma or residual gas in the "target" volume above the cathode.

2) The sequential positions of maximums of radiation for different ions (for H-like close to the cathode, then for He-like, and finally at the most far distance for Li-like ions) could be interpreted as a subsequent recombination of ions in plasma jets - initially bare nuclei - by passing through the "target" plasma.

3) The relative populations of levels are essentially non-"equilibrium" ones, having an inverted character which can be seen from various transitions from levels with principal quantum numbers $n = 3, 4$ and 5.

When discussing a mechanism of recombination of ions in a plasma jet, one has evidently to take into account two options:

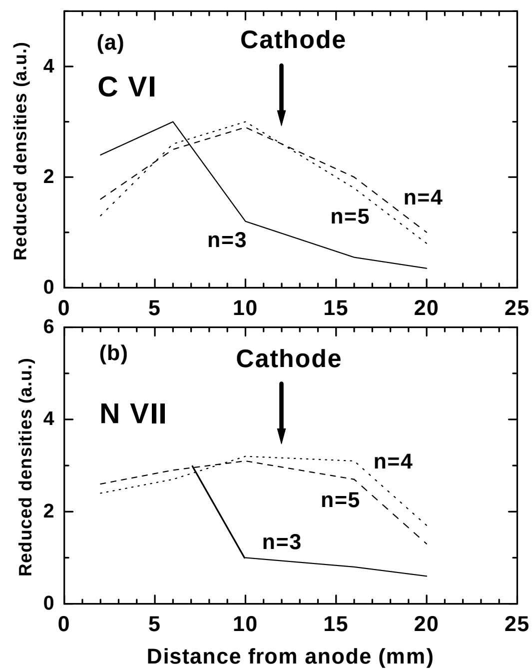

Figure 4: Reduced density $\tilde{N}$ of excited levels of H-like ions of C VI (a) and N VII (b). $\tilde{N}$'s are calculated from the $2-n$ transitions.

i) Charge-exchange recombination with preferable excitation of high levels; or/and

ii) Strong collisional-radiative recombination (CRR) due to a fast cooling of the expanding plasma jet in the "target" volume, which may, as it is well known, also lead to a non-equilibrium population of excited levels.

To check the possibility of CRR playing a significant role in population of excited levels, we have fulfilled numerical calculations for different plasma conditions. Two numerical codes have been used. The first one, the code NOMAD [10], provides a full time-dependent collisional-radiative modeling for oxygen ions. The atomic processes accounted for in our simulations are electron impact excitation, deexcitation and ionization; 3-body, radiative and dielectronic recombination; and spontaneous radiative decays. The opacity effects for the finite-size-plasma calculations were modeled with the escape factor formalism. The second code was a Monte-Carlo program TRACE [11], which could be used for accounting of the optical thickness effects in radially expanding or compressing plasmas with a strong Doppler motion shift.

A detailed comparison of experimental results and modeling will be published elsewhere. Here we will present main indications showing that CRR cannot result in the relative populations observed in Li-like ions N V and O VI. First of all, there seem to exist no plasma conditions when CRR would provide such an enhancement of the $4s$ level compared to the $3s$ level, which was detected for N V. In all calculations in the CRR regime the population of the $3s$ level was higher than the populations of all other levels. CRR modeling has also confirmed a well-known result, i.e., a possible considerable inversion between the $n = 4$ group of levels and the $3d$ level, with a strongest enhancement coefficient for the $3d - 4f$

transition. Nevertheless, our observations (e.g., $5p : 4p : 3p$ population inversion) could not find its explanation in a frame of CRR modeling. We believe that the present experimental results point out an important role of charge exchange reaction in the creation of population inversion.

We have made an attempt to estimate the absolute population inversions observed in our experiments. For this purpose we compared the line intensities in the spectra, obtained with the same source at the same conditions on the spectrograph used in this work, and on the E-580 spectrograph, which is analogous to the spectrograph absolutely calibrated in Ref. [12]. It was found that the absolute efficiency of the spectrograph used is $(1-3)\times 10^{-4}$ [density×cm^3/erg] in the wavelength region 70-300 Å. Assuming that the cross size of the radiating plasma is about 1 cm, the estimated absolute populations in the region of maximum intensity of the N V ions ($z \approx$ 18 - 20 mm) are: N/g($3s$) $= 8\times 10^{13}$ cm^{-3}, N/g(3p) $= 1.6\times 10^{13}$ cm^{-3}, N/g($3d$) $= 6\times 10^{12}$ cm^{-3}, N/g($4s$) $= 10^{14}$ cm^{-3}, N/g($4p$) $= 3\times 10^{13}$ cm^{-3}. This gives possible gains of the order of $0.5-5$ cm^{-1} for the $3-4$ transitions in the N V ion ($\lambda \sim 700$ Å). The estimated maximal gain for the $3-4$ transitions in the C VI ion ($\lambda \approx 520$ Å) is about 1 cm^{-1}.

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