Selective population of the $n = 3$ OVIII level during the expansion of a laser plasma in helium

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During the expansion of a laser plasma burst containing multiply charged oxygen ions into a helium atmosphere, there is a selective population of oxygen (OVIII) levels as a result of charge exchange of oxygen nuclei with helium ions.

Vinogradov and Sobel'man[1] have suggested that charge exchange might be used as a mechanism for arranging a population inversion in the levels of multiply charged ions with the goal of developing sources of electromagnetic radiation in the far ultraviolet. There are serious difficulties in using this method to excite levels under the particular conditions of laser-plasma experiments.[1,2] In the present letter we report what is apparently the first experimental realization of this charge-exchange mechanism for forming a population inversion in the levels of multiply charged ions.

The experimental apparatus consists of a neodymium-glass laser system, a vacuum chamber, and an x-ray spectrograph. The measurements are carried out with a spatial resolution along the axis of the plasma burst. The intensity of the laser system is such that there is a significant burning up of helium-like oxygen ions on the surface of the BeO target. The length of the pulse from the laser system is about 0.5 ns.

The experimental results are shown in Fig. 1 as curves of I_3/I_2, I_4/I_2, and $I_4/I_3 = f(l)$—the ratios of the observed emission intensities in the OVIII resonant lines $[I(ls-2p) \equiv I_2, I(ls-3p) \equiv I_3, I(ls-4p) \equiv I_4]$—versus the distance from the target (l) for plasma expansion into a vacuum and into helium. At distances $l \lesssim 1$ mm from the target the curves of I_3/I_2 and I_4/I_3 are nearly coincident for plasma expansion into a vacuum and into helium. At $l \gtrsim 1$ mm the curves become qualitatively different: Instead of the decrease in I_3/I_2 and the increase in I_4/I_3 in the case of expansion of plasma into a vacuum, we see an increase in I_3/I_2 and a decrease in I_4/I_3 for expansion into helium. On the other hand, the curves of $I_4/I_2 = f(l)$ are essentially the same for both types of plasma expansion over the entire range of l. These results indicate that at $l \gtrsim 1$ mm there is a preferential population of the OVIII level with principal quantum number $n = 3$. We attribute this result to a charge exchange of oxygen nuclei with helium ions, for the following reasons.

From the data of Ref. 3, we determine the population ratios of the OVIII resonant levels as functions of the electron density N_e (10^{20}–10^{18} cm^{-3}) for several fixed electron temperatures T_e (176, 88, and 44 eV). These N_e and T_e ranges include the electron temperatures and densities that occurred under these experimental conditions. Analysis shows that the changes in the plasma properties that accompany the expansion of the burst into the gaseous atmosphere do not explain the observed results either quantitatively or qualitatively.

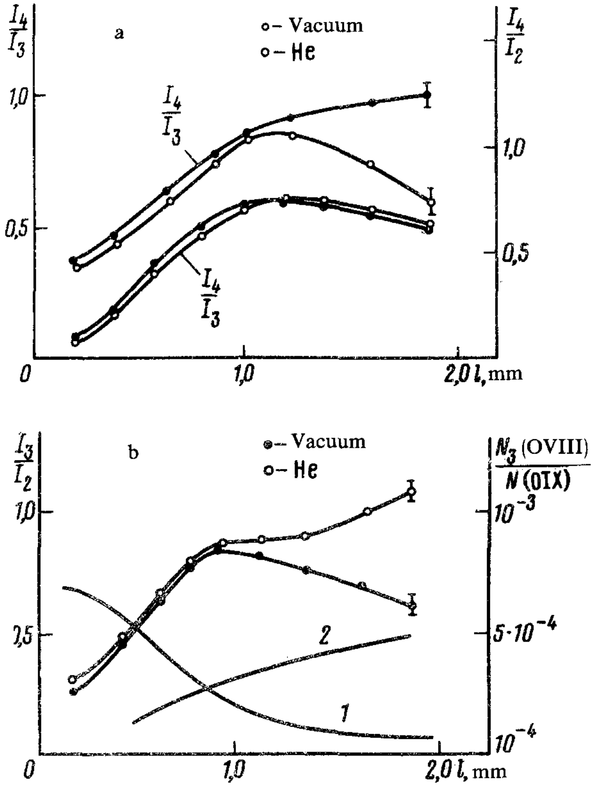

FIG. 1. a—Experimental ratios of the observed intensities of the OVIII resonant lines (I_3/I_2, I_4/I_2, I_4/I_3) versus the distance from the target during plasma expansion into a vacuum and into helium; b—calculated population of the OVIII $n = 3$ level during recombination pumping (curve 1) and during pumping due to charge exchange (2).

Theoretical calculations of the cross sections for the filling of the OVIII levels $n = 2,3,4$ during the charge exchange of oxygen nuclei with helium atoms and ions were carried out from the results of Ref. 4 (Fig. 2). According to Fig. 2, for a typical ion velocity $\sim 10^7$ cm/s (~ 0.05 a.u.), the charge exchange with helium atoms should give rise to a preferential filling of the $n = 4$ level, while charge exchange with helium ions should do the same for the $n = 3$ level. It should be concluded from these calculations and the data of Refs. 5 and 6 that selective excitation can result from charge exchange with helium ions. Furthermore, at the plasma properties corresponding to these experimental conditions the probability for electron-impact ionization of helium atoms is roughly ten times the charge-exchange probability, while for the helium ions the probabilities of these two processes become comparable in magnitude.

It is also pertinent to compare the calculated curves of the population of the OVIII $n = 3$ level versus the distance from the target. These results can be calculated in the model of impact-emission recombination[3] and under the assumption of selective

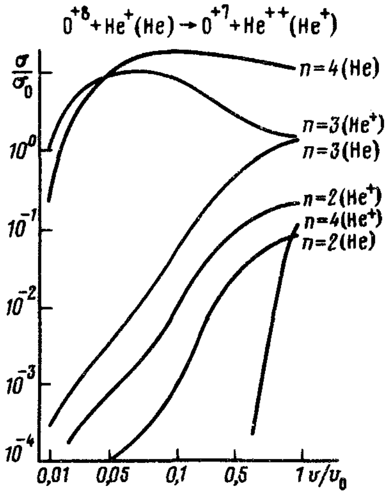

FIG. 2. Calculated effective cross sections for charge exchange of oxygen nuclei with helium atoms and ions, accompanied by capture to the $n = 2,3,4$ levels, versus the velocity of the ion (atomic units).

filling of the level due to charge exchange. For these calculations we used several model-based curves for the electron temperature and density, T_e, $N_e = f(l)$, found from the data of Ref. 7. The plasma ion composition was taken to be N(OVII):N(OVIII):N(OIX) = 0.5:1:1. The cross section for charge exchange of oxygen nuclei with helium ions was assumed to be $\sigma = 10^{-15}$ cm^2. The calculated level populations are shown in Fig. 1b, where they have been divided by the relative density of oxygen nuclei, N(OIX). We see from this figure that charge exchange can indeed become the governing factor for the filling of the OVIII $n = 3$ level if there is an effective mixing of the gas and plasma. Estimates show that far from the target ($l \simeq 1$–2 mm) the collision mean free path of a helium ion in the plasma exceeds the linear dimension of the plasma, while the length of the charge-exchange region becomes comparable to it.

The absolute population of the OVIII $n = 3$ level due to charge exchange is comparable to the population that results from the recombination pumping mechanism. However, the excitation by charge exchange is achieved at lower values of N_e, and this circumstance tends to weaken the restrictions imposed on the gain by the Stark effect and radiation capture.

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