# Population Inversions Inferred from Intensity Measurements in Stationary Recombing He Plasma

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Stationary population inversion between the low excited states of $\mathrm{He}^+$ has been observed in a helium plasma in contact with neutral helium. The ratio of population densities as deduced from Lyman line intensities is $n_2/g_2:n_3/g_3:n_4/g_4:n_5/g_5=1:0.6:1.1:1.2$, where $n_i/g_i$ is the population density with the principal quantum number $i$. The mechanism leading to the population inversion is discussed.

Generation of the population inversion through recombining plasma is considered one of the most promising ways of realizing vacuum-ultraviolet (VUV) or x-ray lasers.[1] The population inversion in this scheme has already been observed in the various plasma sources.[2] In this Letter, it will be reported that the populations of the levels $i=2$ and 3 of singly ionized helium are inverted relative to higher levels $i=4$ and 5 in a helium plasma in contact with neutral helium. To our knowledge, the present result is the first observation of a stationary population inversion between the levels which will lead to the induced emission of a line in VUV by this scheme.

The experiment was performed with use of a helium plasma flow in TPD-I[3] of Institute of Plasma Physics (IPP), Nagoya. TPD-I is a quiescent high-density plasma source normally operated with helium. It consists basically of two parts, namely, the discharge region with the cathode at the center of the cusped magnetic field and the plasma region with the axial magnetic field 1 m long. Normally the apparatus is operated at the gas pressure of $6\times10^{-4}$ Torr in the plasma region with a discharge current of 100 A, a discharge voltage of 130 V, and a magnetic-flux density of 5 kG. The diameter of the plasma column is about 1 cm, and the electron density is typically $10^{15}$ $\mathrm{cm}^{-3}$. When the extra neutral He gas is introduced directly into the plasma region through a leak valve, the downstream end of the plasma column begins to glow with remarkable brightness, and the bright region moves towards the anode when the gas pressure is increased. The location of the bright region is quite reproducibly dependent upon the amount of injected neutrals and the bright region can be fixed at any position. This phenomenon has already been investigated in detail by Otsuka, Ikee, and Ishii.[3] They found that the population densities in the highly excited levels ($n\geqslant4$) of $\mathrm{He}^+$ ions in the bright region are much higher than the values expected for the equilibrium state with the measured electron temperature $T_e$ and electron density $n_e$. The present experiment is an extension of their studies of the population anomaly of $\mathrm{He}^+$ to the lower excited states by measuring the relative and absolute intensities of He II Lyman series in x-ray ultraviolet (XUV).

The measurements have been made by using the rare-gas photoelectron counter (RPC), by which we can determine the true spectral distribution of incoming photons from the arbitrary polychromatic source in the XUV region. In this method we analyze the integral counts of photoelectrons emitted from the rare-gas target filling an Auger-type electron energy analyzer (Varian model No. 981-0223 with some modifications). Detailed descriptions of the RPC will be given elsewhere.[4]

The outline of the experimental procedure is as follows: Radiation from the TPD-I plasma was introduced directly into the analyzer through a collimator which consists of three diaphragms each with a circular aperture of 0.8 mm in diameter, and followed by an aluminum pipe. The target gas was photoionized at the center of the concentric spherical grids of the analyzer. Photoelectrons were analyzed in energy by the retarding potential, counted and accumulated in a multichannel scaler. The intensity of each member of the He II Lyman series was determined from the height of the corresponding step in the integrated photoelectron counts, together with the wavelength-dependent cross section of photoionization of the target gas, and the wavelength-independent overall analyzer efficiency.[4] In this experiment, the spectral intensity of the plasma was measured along the line of sight perpendicular to the axis of the plasma column through a fixed position.

Typical recordings of photoelectron spectra in an energy range from 30.8 to 55 eV are shown in Fig. 1. Neon was used as a target gas at a pressure of $1.2\times10^{-3}$ Torr. The energy resolution

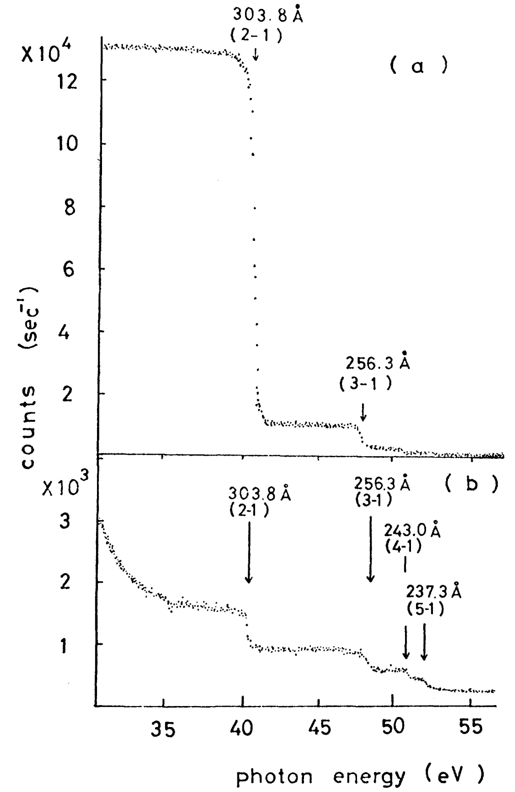

FIG. 1. Original record of photoelectron counts. (a) An example of the spectra under the normal operation. (b) The spectrum at the bright region of the plasma in contact with neutral helium.

was 0.4 eV. The spectrum (a) was obtained at the normal operation of the plasma and (b) for the plasma at the bright region when neutral He gas is in contact with the plasma. The neutral He pressure was $6\times10^{-4}$ Torr for (a) and $5\times10^{-2}$ Torr for (b). Two remarkable features are obseved in (b) compared with (a). Firstly, relative intensities of the members of the He II Lyman series in (b) are greatly changed from (a). Secondly, two continua are distinguished, one lying at the limit of the He II Lyman series and the other in a region of photon energy less than 40 eV. One of these continua corresponds to the radiative recombination of doubly ionized helium $\mathrm{He}^{++}$ into the ground state of singly ionized helium $\mathrm{He}^{+}$, and the other corresponding to the recombination of $\mathrm{He}^{+}$ into the ground state of neutral helium. The electron temperature $T_e$ of the recombining plasma was found to be $2^{+0.4}_{-0.2}$ eV from the energy dependence of the continuum radiation. With the knowledge of $T_e$, together with the absolute intensity of the continuum and the condition of charge neutrality, we found the electron density $n_e$, the

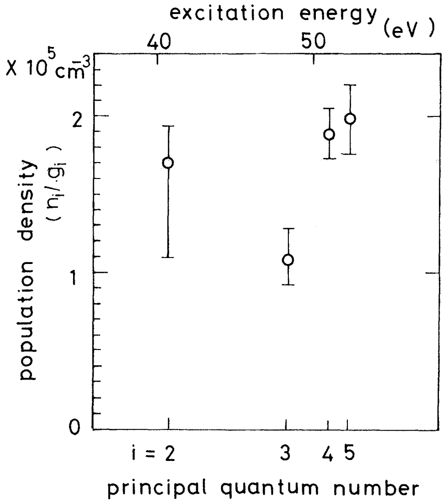

FIG. 2. Population densities as deduced from He II Lyman line intensities, corrected for self-absorption, are plotted as a function of the ionization energy of the respective level $i$. With respect to the effect of the neutral helium, the reduction of the He II Lyman series spectra, which is caused by the photoionization of the neutral helium atom existing between plasma and the detector, is taken into account. In addition to the relative errors shown on the figure, the absolute value of each point is uncertain by a factor of 2 arising from the method of assigning absolute value.

density of the ground state of singly ionized helium $n^{+}$, and the density of doubly ionized helium $n^{++}$ to be $5.8\times10^{14}$ $\mathrm{cm}^{-3}$, $5.4\times10^{14}$ $\mathrm{cm}^{-3}$, and $2\times10^{13}$ $\mathrm{cm}^{-3}$, respectively. These relative values can be determined to an accuracy of 20%, whereas the errors in the absolute values are estimated to be ± 50%. It should be pointed out that the density of doubly ionized helium is much higher than the value expected from the calculated rate of ionization in equilibrium. This suggests that the helium plasma in TPD-I in contact with neutral helium is not in equilibrium. We corrected the observed intensity for the resonance absorption assuming that the plasma is homogeneous within a diameter of 1 cm, and the ion temperature is 2 eV. The homogeneity of the plasma has been confirmed by measuring spatially resolved intensities of He II and He I spectra in visible region.[3] Relative populations were derived from the Lyman series spectrum and were put on an absolute basis using measurement of the population $n_4$ from the absolute intensity of line He II $(4\rightarrow3)$ 4686 Å. The population densities $n_i/g_i$ $(g_i=2i^2)$ for the low excited states of $\mathrm{He}^{+}$ are shown in Fig. 2. It is evident from Fig. 2 that the populations of the levels $n=2$ and 3 are inverted relative to higher levels $n=4$ and 5. It is important to note that the transitions $4\rightarrow 2$ and $5\rightarrow 2$ correspond to the emission lines in VUV region (1216 and 1085 Å, respectively).

A numerical calculation of the population $n_i$ in the level with the principal quantum number $i=2$–4 has been done to study the mechanism responsible for the population inversion. The relaxation time of the excited state is so short that one can assume $dn_i/dt=0$ for $i\geqslant 2$. The effect of the spacial divergence of ions can be neglected because of the small relaxation length ($\sim 10^{-3}$ cm) of the excited ions. Hence the population densities $n_i$ of the level $i$ of He$^+$ are given by the collisional-radiative model as follows,

$$n_i=\Big(\sum_{k>i} n_k A_{ki}\Lambda_{ki}+n_e\sum_{j<i} n_j C_{ji}+n_e\sum_{k>i} n_k F_{ki}+n_e n^{++}\Lambda_i\alpha_i+n_e^{\,2} n^{++}Q_i\Big)$$
$$\times\Big(\sum_{j<i} A_{ij}\Lambda_{ij}+n_e\sum_{k>i} C_{ik}+n_e\sum_{j<i} F_{ij}+n_e S_i\Big)^{-1}, \qquad (1)$$

where $A_{ki}$ is the probability of the spontaneous transition $k\rightarrow i$, $c_{ji}$ the rate coefficient of electron impact excitation $j\rightarrow i$, $F_{ki}$ the rate coefficient of electron impact deexcitation $k\rightarrow i$, $S_i$ the rate coefficient of impact ionization from the level $i$, $\alpha_i$ the coefficient of radiative recombination into the level $i$, $Q_i$ the coefficient of three-body recombination into the level $i$, $\Lambda_{ij}$ the optical escape factor of the $i$th level coupled with the level $j$, and $\Lambda_i$ the escape factor for the transition $i\rightarrow$ continuum. Estimates were made for the population densities $n_2$, $n_3$, and $n_4$ from the coupled rate equation (1) substitution of the measured values of $T_e$, $n_e$, $n^+$, $n^{++}$, and $n_5$. The contributions of $n_i$ for $i\geqslant 6$ to $n_2$, $n_3$, and $n_4$ turned out to be small due to small values of the relevant coefficients $A_{ki}$ and $F_{ki}$. The values of the cross sections and the rate coefficients are obtained by using the formula of Drawin,[5] and $\alpha_i$ by the formula of Kramers assuming that the $G$ factor is 1.

The number densities obtained are $n_2=2.5\times 10^6$ cm$^{-3}$, $n_3=4.3\times 10^6$ cm$^{-3}$, $n_4=9.0\times 10^6$ cm$^{-3}$, and agree qualitatively with the observed values. The calculated values also lead to the inverted population $n_2/g_2:n_3/g_3:n_4/g_4=1:0.7:0.9$. It is assumed that the plasma is optically thin for the recombination continua and the lines except for the Lyman series. It should be pointed out that especially for the He II Lyman $\alpha$ the equation of radiative transfer including scattering must be solved in order to explain the observed intensity and the escape factor. For the other member of Lyman series the assumption of constant source function is applicable to the transfer equation. Hence the values $\Lambda_{21}=0.3$, $\Lambda_{31}=0.3$, $\Lambda_{41}=0.7$ have been used in the calculation.[6]

The contribution of interatomic collisions to the population of excited levels has been neglected in the above calculation.[7] There will be possibilities that a few particular charge-transfer collisions, for example, He$^{++}$+He$^*$($2^3$S) − 1.2 eV → He$^+$+He$^{+*}$($3^2$S), may have an influence upon the population, while the other charge-transfer reactions between He$^{++}$ and He require in general so high additional energy transfer that it seems improbable that they play a major role in the population change in that plasma. However, it is hard for the moment to evaluate the error caused by neglecting these events altogether, because no cross section for the relevant charge-transfer processes is available.

The result of this analysis leads us to a qualitative understanding of what happens to the population of the singly ionized helium in a recombining plasma. The helium plasma of TPD-I under the normal operating condition is composed predominantly of He$^{++}$ ions, and has a high electron temperature, ~30 eV, and a high electron density, $\sim 1\times 10^{15}$ cm$^{-3}$. As soon as the neutral helium gas was introduced into the plasma, electrons were cooled down to 2 eV, and the density decreased to $5.8\times 10^{14}$ cm$^{-3}$ through recombinations, and the plasma became predominantly composed of He$^+$ ions under the condition of Fig. 1(b). When the electron temperature is quickly reduced through collisions with neutral helium atoms, the initial process is dominated by the three-body recombination, because the initial electron density is high. Electrons begin to fall into the orbit of He$^+$ with a high quantum number through mutual collisions. These ions in highly excited states are by no means stable because they are perturbed by frequent collision because of its large orbit radius and a high electron density of the plasma, and are ionized again or decay into the lower excited states. In the latter process, the collisional decay to the next lower level is dominant, and the electrons trapped in highly Rydberg states of ions shift to the lower states through such cascade transfers. When they come down to the states $n=2$ or 3, they are more quickly transferred to the lower level, because then the spontaneous radiative transitions overtake the other processes. However, especially for the level 2 reabsorption of the radiation reduces the rate of radiative decay. It is concluded therefore, that there is a general possibility of producing the population inversion giving rise to an amplification of emission in VUV simply by cooling a stationary plasma, TPD-I being a typical example.

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# Wave-Induced Transport in the Pure Electron Plasma

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The pure electron plasma is an excellent system in which to study transport across a strong magnetic field. We describe the basic experimental arrangement and report on measurements of transport due to an externally launched diocotron mode.

Plasmas which consist of a single charge species[1,2] are of interest in their own right and for the investigation of basic interactions common to all plasmas. We have found[3-5] that the pure electron plasma is an excellent system in which to investigate transport across a strong magnetic field. Here we describe the basic experimental arrangement and report on observations of electron spatial transport due to an externally launched diocotron[6,7] mode.

We have previously described[8] a simple apparatus which produces a steady-state electron-plasma column which is many Debye lengths in diameter, and proved experimentally that the residual ion density is very small compared to the electron density; i.e., the plasma is almost purely electrons. We now describe how the plasma may be trapped and used for investigation of transport. A schematic diagram of the apparatus is given in Fig. 1. The geometry is cylindrical. The entire system is immersed in a strong uniform axial magnetic field $\vec{B}_0$ and evacuated to a base pressure of $\sim 10^{-7}$ Torr. The system is pulsed repetitively in the following sequence: (i) Initially, conducting cylinder $A$ is grounded and $C$ is biased sufficiently negative to reflect all electrons coming from the negatively biased source. During this filling time ($\tau_f$) the plasma occupies cylinders $A$ and $B$. (2) Then the potential of cylinder $A$ is gated negative[9] to cut off the incoming electrons and trap those within cylinder $B$. The trapped-electron plasma is radially confined by