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BY

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OBSERVATION OF INVERTED POPULATION LEVELS IN THE FM-1 SPHERATOR

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Inversions in the populations of excited levels in hydrogen and HeII were observed in the FM-1 spherator. The inversion increases strongly as the ratio of the decay time of the electron temperature to the decay time of the electron density was decreased. Time dependent numerical calculations of the populations were in good agreement with the experimental measurements. More general calculations for high Z hydrogen-like ions are discussed.

The interest in obtaining high temperature plasmas stems historically from the fusion physics community and recently also from those interested in high power short wavelength lasers (VUV, and soft x-ray lasers). A high temperature plasma can be used to pump the excited levels of atoms and ions and to produce a strong inversion. A common feature of many of the early proposals to obtain an inversion in a high temperature plasma was to have the plasma expand quickly into a low density region (e.g., a vacuum). In this way, the plasma undergoes an adiabatic decompression resulting in a rapid decrease in the electron temperature.¹⁻³ The feasibility of this concept has been demonstrated.⁴ However,

the inversion was very much smaller than expected because it was impossible to achieve a sufficiently short electron temperature cooling time. The possibility of observing an inversion during the expansion of a plasma heated by irradiating a solid target by a high power laser has been widely discussed.⁵⁻⁷ Recently, Irons and Peacock⁸ have observed an inversion in hydrogen-like carbon ions in the wavelength range 25-50 Å when a high power laser beam was focussed on a polyethylene target.

Another promising approach to obtain a large inversion is to use a plasma in which the decay time of the electron density is long compared with the decay time of the electron temperature. Thus after initially heating and ionizing the plasma, the electron temperature decreases rapidly while the electron density changes only slightly. Hence, the electron density is enhanced above its equilibrium value and an inversion in the population levels of excited atoms and ions can be obtained. Such a condition can be achieved by surrounding the plasma by neutral gas.⁹ This concept, as was previously discussed,¹⁰ has been experimentally verified in the FM-1 spherator, a toroidal plasma confinement device, by measuring the population levels in hydrogen and in hydrogen-like HeII ions. To the best of our knowledge, this is the first experimental study of inversion of the population levels in a toroidal device. In the following, the experimental results will be presented and the theoretical model used in analyzing the data will be discussed. Finally, a brief generalization of these results for high Z hydrogen-like atoms will be presented.

During these experiments in the FM-1 spherator,¹¹ the plasma was created by preionizing the filling gas using electron cyclotron resonance heating (ECRH) to obtain typically $N_e \approx 5 \times 10^{11} \text{ cm}^{-3}$ and $T_e = 5\text{-}8 \text{ eV}$. The preionized plasma was ohmically heated by inducing a current in the poloidal direction for one cycle at 500 Hz. Ohmic heating increased the electron temperature to about $T_e \approx 40 \text{ eV}$ and the maximum electron density to $1 \times 10^{13} \text{ cm}^{-3}$ for an initial filling pressure of $3 \times 10^{-5} \text{ Torr}$. The density was measured by a 4 mm microwave interferometer. The electron temperature was measured from the relative intensity of the CIII 4647 Å to the CIII 2297 Å for $t = 0.1$ to 2.0 msec after the beginning of the ohmic heating. Between 1 and 2 msec, when non-thermal equilibrium has been established, the electron temperature was also determined from the relative intensities of the CIII 4647 Å line to the CII 4267 Å line using the electron density from the microwave measurement. The measurement of the electron temperature from the ratio of the carbon lines was based on the calculation of the level populations of allowed transitions¹² which also considered the effect of the forbidden transitions. Independent measurement of the local density and temperature was obtained by laser Thomson scattering measurements. Good agreement between the different techniques was obtained.

The electron temperature dropped rapidly after the first half cycle of ohmic heating. During this time, the density was increasing due to ionization of the influx of cold gas while later the density remained relatively constant. In general, 4 msec after the beginning of the ohmic heating, the electron

temperature decreased by a factor of 100-200 but the electron density decreased only by a factor of 2-4. Typically, the particle confinement time was 10-20 msec as determined both by limiter loss measurements^{11,13} and analysis of the hydrogen light emission while the energy confinement time was about ~ 0.2 msec.

The population of the excited levels was determined from absolute line intensity measurements using a Jarrell-Ash 1M Ebert monochromator. The resulting photomultiplier signal was digitized (50 μ sec sampling rate) and temporarily recorded on a Bio-mation Model 1015 Waveform Recorder and later stored on an IBM 1800 Process Controller. The spatial distribution of the line intensity and the effective dimensions of the radiating plasma were measured by a Jarrell-Ash 0.5M monochromator with a scanning mirror. It was found that for given optical transitions, the line emission originated in the same region of the plasma.

The excited population of the hydrogen levels with principal quantum numbers $n = 3$ to 9 were measured from the Balmer series and the population of HeII levels were measured for $n = 4$ to 11 for the transitions corresponding to the lower $n = 3$ and 4 levels. Typical populations of the hydrogen levels, N_n/g_n where g_n is the statistical weight of level n are presented in Fig. 1 for a filling pressure of 3×10^{-5} Torr for two different times, during the ohmic heating when $0.25 \leq t \leq 0.3$ msec and after the ohmic heating when $4.0 \leq t \leq 4.5$ msec. Similar curves for HeII obtained on three different runs are presented in Fig. 2 for $t = 0.45$ msec and $t = 4.2$ msec. Each point in Fig. 1 and 2 was

the average value of 5-10 shots depending on the fluctuations in the light intensity.

The maximum inversion occurred after the ohmic heating when $4.0 \leq t \leq 4.5$ msec (for $t > 5.0$ msec, the inversion was decreasing) while during the first half cycle of ohmic heating there was no inversion. The strongest inversion in hydrogen was for the $n = 5$ level in comparison with the lower levels and for HeII for the $n = 6$ and 7 levels. For $p = 2 \times 10^{-5}$ Torr, the strength of the inversion was less than for $p = 3 \times 10^{-5}$ Torr and for $p = 1 \times 10^{-5}$ and 5×10^{-6} Torr inversion was not observed for H and HeII. At higher pressures ($p = 4 \times 10^{-5}$ Torr), the inversion in hydrogen was found to occur even during the second half cycle of the ohmic heating for $t \geq 1.75$ msec. In general as the filling pressure was increased the ratio of the decay time of the electron temperature to the decay time of the electron density decreased and the inversion increased.

In Fig. 1 and 2, the experimental data is compared with the results of numerical calculation for the population levels. The theoretical results for temporal evolution of the population levels in hydrogen were obtained by solving a set of 25 coupled balance equations for an optically thin plasma including the influx of particles. Thus the equations were of the form

$$\frac{\partial N_n}{\partial t} = \left(\frac{\partial N_n}{\partial t} \right)_{\text{coll}} + \frac{N_0}{\tau_0} \delta_{1n} - \frac{N_n}{\tau_n} \quad (1)$$

where $(\partial N_n / \partial t)_{\text{coll}}$ accounts for the collisional and radiative transitions, N_0 corresponds to the initial filling gas pressure and δ_{1n} is the Kronecker delta, N_0 / τ_0 and N_n / τ_n are the flux of

particles into and out of the plasma respectively. Because the relaxation time constant for the excited levels is much shorter than for the ground level for our experiment, thus the following approximation was valid:

$$\frac{\partial N_1}{\partial t} \neq 0; \quad \frac{\partial N_n}{\partial t} = 0 \text{ for } n \geq 2 \quad (2)$$

This approximation considerably shortened the computation time. A similar set of differential equations was solved for HeII with the addition of two equations determining the state of ionization.

In the calculations for hydrogen, the transition rate coefficients of Johnson¹⁴ were used. Very similar results were obtained using the same spontaneous transition probabilities and Drawin rate coefficients as in Ref. 9.

Some discrepancies were observed between the calculations and the experiment during the first half cycle of ohmic heating for the $n = 4$ in hydrogen and for the $n = 5$ in helium using the independently measured electron temperature as described above. (For $p = 5 \times 10^{-6}$ Torr, good agreement was found for all levels.) For $t > 4.0$ msec the theoretical curves are our best fit to the experimental data using the electron temperature as an adjustable parameter. In this case, the absolute value of N_n/g_n as well as the slope of the curve N_n/g_n for the higher excited levels is very sensitive to the temperature. Although by increasing the electron temperature, the population of N_n/g_n decreases (see Fig. 3) in better agreement for the absolute value of the higher excited states, the slope decreases and the overall discrepancy is greater. Nonetheless, the agreement between theory and

experiment was satisfactory. A detailed theoretical analysis will be published elsewhere.

The results of this experiment can be understood qualitatively and generalized for plasmas of higher atomic number, Z , by considering a plasma with a reduced electron temperature $\theta_e = T_e/Z^2$, electron density $\eta_e = N_e/Z^7$ and neutral (ion) density $\eta_n = N_n/Z^{11}$. If for a given η_e and ground state neutral (ion) density η_1 , the temperature is decreased below some critical θ_e^* the excited levels are populated by radiative and collisional transitions from the upper levels which are populated mostly by three-body recombination. Because the radiative de-excitation rate for the lower levels is greater than that for the upper levels, there are levels m and n ($m < n$) for which $\eta_m/g_m < \eta_n/g_n$. For $\eta_e = 10^{13} \text{ cm}^{-3}$ and $\eta_1 = 10^{12} \text{ cm}^{-3}$, the critical temperature is $\theta_e^* \approx 1 \text{ eV}$ for $m = 2$ and $n = 4$ as shown in Fig. 3. For $\theta < \theta_e^*$ and $\eta_e \gg \eta_e(\text{Saha})$, where $\eta_e(\text{Saha})$ is determined by Saha equilibrium for a given η_1 , we observed a strong inversion in agreement with Fig. 3.

As a specific example of a high Z plasma consider a plasma with hydrogen-like ions such as C VI and O VIII. In this case, $T_e^* \approx 36 \text{ eV}$ and 64 eV respectively for C VI and O VIII and for $T_e < T_e^*$ an inversion can be expected to occur in the VUV and the soft x-ray region for plasmas with long particle confinement times and short temperature decay times.

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 Fig. 1. Population of hydrogen levels, $n = 3-9$, during ohmic heating ($t = .26$ and $.30$ msec) and after ohmic heating when the maximum inversion occurs ($4.0 \leq t \leq 4.5$ msec).

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 Fig. 2. Population of HeII levels $n = 4-11$.

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Fig. 3. Temperature dependence of the reduced population of two levels for a given reduced electron density, η_e , and ground state ion density η_1 .