On the Influence of Ion Collisions on the Population Distribution of Atoms in a Theta Pinch Discharge +)

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Abstract: Line intensities of the Balmer series as emitted in the early phase of a theta pinch discharge show unexpected deviations from thermal equilibrium conditions. Because of the high ion temperature ($\frac{T_i}{T_e} \approx 10$) ion collisions can compete with electron collisions in populating levels with quantum numbers $n \gtrsim 3$.

1. Introduction. Line intensity measurements on a plasma frequently provide datas from which important plasma parameters can be deduced such as electron density and electron temperature. Usually lines are chosen starting from levels which are supposed to be thermally populated. Criteria for estimating whether local thermal equilibrium (LTE) exists have been reported by several authors /1,2/. Measurements on hydrogen or deuterium plasmas produced by fast theta pinch discharges /3/ however have shown considerable deviations from thermal equilibrium population distributions, although all criteria for LTE were fullfilled. Spatial and time resolved absolute intensity measurements of the first three members of the Balmer series of hydrogen have been carried out in the early phase of a fast theta pinch discharge. All necessary plasma parameters were additionally measured. Several possibilities which may be responsible for the departure from a thermal equilibrium population distribution have been discussed leaving the influence of ion collisions on higher lying levels as the most likely cause.

2. Experimental Results. The plasma investigated has been produced by a theta pinch discharge of 52 kG maximum field and 2.75 µsec quarter period. The discharge coil measured 100 cm in length and 10 cm in diameter. The filling pressures used ranged from 10 to 80 mtorr. Two axial current pulses of 1 µsec duration each served for preionization providing an about 40 percent ionized plasma at the time when the main discharge is fired. The electron temperature of the plasma was measured by Thomson scattering of laser light, the ion temperature was calculated from the neutron emission rate and from diamagnetic measurements. The electron density was gained from free-free continuum radiation measurements from Thomson scattering and from Mach-Zehnder interferometry. The radiation emitted in the visible from the plasma has been investigated by scanning the plasma radially with an absolutely calibrated monochromator. The emission coefficient of the observed lines was then obtained as a function of radius by Abel's inversion. Thus the emission coefficients for H_α, H_β, and H_γ, were determined in discharges of 11,17,40 and 72 mtorr filling pressure.

The lines peak rather independent of filling pressure at 0.3 to 0.4 µsec after the ignition of the main discharge. Afterwords they fall off rapidly in intensity and are essentially vanished after 1 µsec. They are approximately homogeneously emitted over the whole discharge volume with slightly increasing intensity towards the wall of the vessel. The relative radial distribution does not alter during the whole time this radiation is observed. The intensity ratios of $H_\alpha : H_\beta : H_\gamma$ for all filling pressures are typically 100:10:1 with deviations not larger than 30 % for either of the ratios. Using the Boltzmann factor this would yield an electron temperature of 0.4 to 0.6 eV. Quite different temperatures result if the absolute value of the emission coefficient and the electron density (at a distinct radius and time) is taken and the temperature calculated via the Saha equation again assuming LTE. Temperatures determined this way are usually by a factor of 10 to 100 higher than those evaluated from line ratios. Hereby H_α yields a lower temperature than H_β, and H_β a lower temperature than H_γ. The by Thomson scattering reliably measured electron temperature is at 0.5 µsec 100 eV for 11 mtorr, 70 eV for 17 mtorr, 45 eV for 40 mtorr and 20 eV for 72 mtorr filling pressure. All these findings indicate that the relative population density decreases much more rapidly towards increasing quantum numbers than as given by the Boltzmann factor. The absolute population density however exceeds at least for n=3 (H_α) the density as given by the Saha-equation.

3. Discussion of the results. Estimates considering relaxation effects for the population of the levels $n > 2$, transport of radiation by resonance charge exchange or lack of LTE by inhomogeneities do not reveal that any of these processes is responsible for the observed anomaly. The strongest deviation from thermodynamic equilibrium is the difference in electron and ion temperature. The ratio of ion to electron temperature as determined from the neutron yield, diamagnetic measurements and from laser scattering is $8 \leq \frac{T_i}{T_e} \leq 12$ during the first microsecond and depends only weakly on the filling density since both electron and ion temperatures decrease at higher filling densities. Drawin /4/ has mentioned that under such circumstances higher lying levels might be influenced by ion collisions.

Therefore the stationary rate equations, as described by Mahn /5/ for a limited number of levels with collisional rate coefficients for ions included have been solved numerically for a set of the parameters n_e, T_e and T_i. To calculate the ionic rate coefficients the same cross sections as functions of the relative velocity of the colliding particles have been taken for the ions as for the electrons. The results show two effects.

1) Overpopulation of low lying levels $n \lesssim 3$ for electron densities $n_e < 3.10^{14} cm^{-3}$ and high electron temperatures ($T_e > \chi_H = 13.6$ eV).

2) Depopulation of high lying levels $n \gtrsim 3$ by proton collisions if $\frac{T_i}{T_e} \gg 1$.

Altough these solutions are well in the direction of the experimental observations they do not quantitatively meet the measured population densities. The observed anomaly still exceeds the calculated one. Possible causes for this discrepancy may bee: the crossections used for the ions in the calculations, the non Maxwellian velocity distribution of the ions in the plasma and relaxation effects for levels $n \lesssim 3$. The last possibility will be checked by solving the time dependent rate equations.

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