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Spectral Caracteristics of Balmer Series Lines in Dense Hydrogen Plasma Produced by a Linear z-Pinch Discharge

by

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Abstract

The excited level population of hydrogen in dense plasma has been calculated by the collisional-radiative model. We took the ion density and the ground-state atom density as parameters, instead of assuming an ionization balance. We have found that, in the ionizing phase, the population density follows the distribution proportional to $p^{-4.1}$ (p is the principal quantum number of the exited level.) In the recombining phase it is proportional to $p^{2.3}$. The Balmer series spectrum corresesoponding to these phases has been calculated, where the Stark line broadening and the continuum emissions were taken into account. It was found that these spectra differ substantially from each other.

By using an optical multichannel analyzer, the Balmer series spectrum has been observed from a z-pinch plasma. The spectrum taken at the time of the maximum compression is consistent with the recombining plasma.

On the basis of the above finding, we discuss the problem of the "transparency window": a substantial reduction of the emission intensity near the series limit, which has been observed in dense plasmas. We conclude that our spectrum of the ionizing phase plasma could account for the apparent transparency window so far reported.

§ 1. Introduction

In laboratory plasma physics, the emission characteristics of neutral hydrogen plays an important role, because neutral hydrogen serves as a good example for a test of a theory of radiation properties of various atoms and ions in plasma. For this reason, a large number of experimental and theoretical studies has been done. One of the interesting phenomena, and still in dispute, is its spectral characteristic in dense plasmas. Under this plasma condition, atoms and ions are

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not isolated any more, but are subject to a strong influence from surrounding plasma particles; for a hydrogen atom the interaction potential between the electron and the proton suffers screening effects by the surrounding electrons and ions. By using the Debye-Hückel potential, Weisheit and Shore1) and other authors2,3) have calculated the dnsity dependent oscillator strengths and photo-ionization cross sections from the ground state. In the first of the above references and in a series of papers by Russian workers4-6) the existence of a "transparency window" has been claimed: a drastic decrease in the oscillator strengths in the vicinity of the series limit as compared with those in the pure Coulomb potential case. Recently, Höhne and Zimmermann7) have reexamined this problem by using the Debye-Hückel potential and the cut-off Coulomb potental. They found no appreciable decrease in the oscillator strength. They claim that the "transparency window" found by Weisheit and Shore is the result of a mere numerical artifact in the process of averaging the oscillator strengths over a finite energy width. Actually, the experimental obsevation of the Balmer series lines from a dense hydrogen arc plasma by Radtke and Günters8) did not reproduce the "transparency window". Recently, however, Garilov et al.9) have reported a considerable reduction in the intensity of the continuum emission in the region of the series limit for a dense optically transparent hydrogen plasma. This was produced by a pulsed discharge in a closed quartz capillary with a small cross section. In the mercury plasma, Kurilenkov and Minaev10) have observed the disappearance of the spectral lines near the photorecombination threshold. Therefore, the question whether the "transparency window" exists or not is still unsettled.

In discussing characteristics of the emission line intensities from a plasma, it is an essential requirement to abandon the assumption of the ionization balance. Rather, we must distinguish the phases to which this particular plasma belongs. These are the ionizing phase or the "I-phase" and the recombining phase or the "R-phase". The emission intensity distribution over series lines, for example, is completely different for plasmas in these two phases. If we confuse these two classes of plasmas it well lead to an erroneous conclusion.

The main objective of this paper is to investigate the spectral characteristics of a dense plasma by using a refined treatment of the excited atom population, i.e., the collisional-radiative model, and taking into account the departure of the plasma from the ionization balance.

In the following, we define the ionizing plasma and the recombining plasma, and we calculate the population density distribution among the excited levels in these plasmas. We then calculate the Balmer series spectrum by incorporation the Stark line broadening and continuum emissions. We compare the observed spectrum with the calculation and discuss the spectral characteristics in terms of the ionizing and recombining plasmas. Finally, we give a possible explanation to the observed apparent "transparency window" on the basis of our findings.

§ 2. Calculation by C–R model

We consider hydrogen atoms in a plasma with electron density N_e and electron temperature T_e. The temporal variation of the population density $N(p)$ of level p (p denoted the principal quantum number) is described by the rate equation

$$\begin{aligned}\frac{dN(p)}{dt}=&\sum_{q=1}^{p-1}C(q,p)N(q)N_e-[\{\sum_{q=1}^{p-1}F(p,q)+\sum_{p+1}^{\infty}C(p,q)\\&+S(p)\}N_e+\sum_{q=1}^{p-1}A(p,q)]N(p)\\&+\sum_{p+1}^{\infty}\{F(q,p)N_e+A(q,p)\}N(q)+\{\alpha(p)N_e+\beta(p)\}N_iN_e,\end{aligned}\tag{1}$$

where N_i is the ion density which is assumed equal to N_e, $C(p,q)$ and $F(p,q)$ are the rate coefficient for the collisional excitation from level p to q by electron collisions and its inverse deexcitation rate coefficient, respectively, $S(p)$ and $\alpha(p)$ are the ionization rate coefficient and the three-body recombination rate coefficient for level p, respectively, $A(p,q)$ is the Einstein coefficient for the spontaneous emission from level p to q, and $\beta(p)$ is the radiative recombination rate coefficient for level p.

In the collisional-radiative (C–R) model, a set of the coupled differential Equation (1) is solved on the following assumption:

[1] For a sufficiently higher lying level p than r that is chosen from a physical consideration, the level population is in LTE (local thermodynamic equilibrium), viz.

$$N(p)=N_E(p)\equiv Z(p)N_iN_e \qquad (p>r),\tag{2}$$

with the Saha-Boltzmann coefficient

$$Z(p)=\frac{g(p)}{2\omega_i}\left(\frac{h^2}{2mkT_e}\right)^{3/2}\exp(\chi(p)/kT_e)\tag{3}$$

Here, $g(p)$ and ω_i are the statistical weight of level p and the partition function of the ion, respectively.

[2] The magnitude of the time-derivative of Eq. (1) is small, except for the

ground state, so that we entirely neglect the time derivative for the excited state, viz,

$$\left.\begin{array}{ll}\dot{N}(p)=0 & (2\leqq p\leqq r)\\ \dot{N}(1)\neq 0 & \end{array}\right\} \tag{4}$$

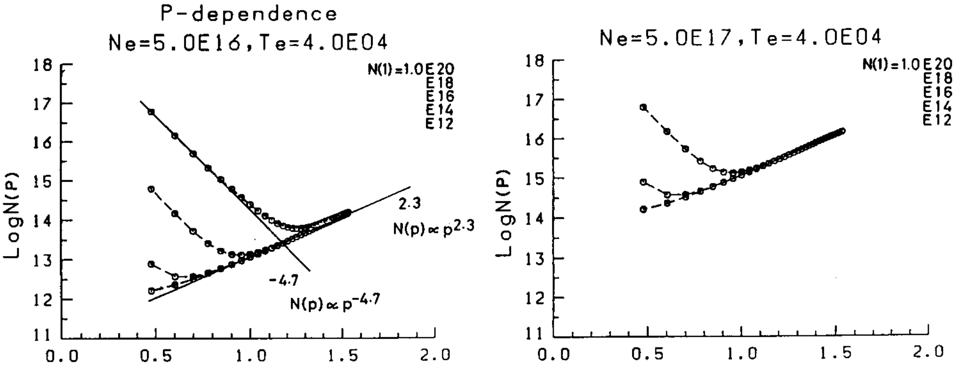
Under assumption [2], the population density of the excited level is given as a superposition of the two terms which include $N(1)$ as a parameter along with N_e and T_e

$$N(p)=Z(p)r_0(p)N_iN_e+\frac{Z(p)}{Z(1)}r_1(p)N(1) \tag{5}$$

where r_0 (p) and r_1 (p) are called the population coefficients. These are determined by the collisional and radiative processes in the plasma and are functions of T_e and N_e. Therefore, if the plasma parameters $N_e=N_i$, T_e and $N(1)$ are given, the population of the excited levels is given according to Eq. (5).

It has been shown that, if the plasma is in the ionization balance, both terms in Eq. (5) are important, sometimes equally impotant. In many practical situations, however, only the first term is dominant and the second term can be entirely neglected. We call this class of plasma the "R-phase" plasma, and the plasma in which only the second term is important is called the "I-phase" plasma.11-14)

By employing the rate constants for the collisional and radiative processes given in ref. 15, we have calculated the population coefficients and thus the population density distribution over the excited levels under various plasma conditions. Figure 1 (a) and (b) shows examples of the p dependencies of N



(a) (b)

Fig. 1. Calculated population density N (p) distribution over the excited levels with the principal quantum number p, where the ground-state atom density N (1) is included as a parameter. (a) $N_e = 5\times10^{16}\,\mathrm{cm}^{-3}$, $T_e = 4\times10^4$ K, and (b) $N_e = 5\times10^{17}$, m^{-3}, $T_e = 4\times10^4$ K.

(p) at $T_e = 4 \times 10^4$ K for $N_e = 5 \times 10^{16}$ and 5×10^{17} cm^{-3}, respectively. in case (a) with$N(1) = 1 \times 10^{20}$ cm^{-3}, for example, it is found that for the lower lying levels ($p < 10$) the second term of Eq. (5) is dominant, and the population density distribution has an asymptote $N(p) \propto p^{-4.1}$. This feature may be regarded as a characteristic of the "I-phase" plasma. For the higher lying levels, on the other hand, the first term is dominant, and the population density follows $N(p) \propto p^{2.3}$. This corresponds to the "R-phase" plasma. These distributions are consistent with the $p^{-4.0}$ and LTE distributions for the "I-phase" and "R-phase" plasmas, respectively, which are obtained in an approximate procedure.[11-14]

§ 3. Spectral distribution over the Balmer series lines and continuum

The total emission line intensity is given by

$$I(p) = \frac{h\nu(p)}{4\pi} A(p, 2) N(p) \tag{6}$$

where h is Planck's constant and $\nu(p)$ is the frequency of the line. In calculating the emission spectrum, we included the Stark Broadening. The line profile was taken from calculations by Griem[16] and Vidal *et al*[17]. for the lower members with $p \leqq 5$. For the higher members, the line profile was assumed to be the same as the H_γ line, and the width is assumed to be proportinal to $(p/5)^4$. These assumptions may be claimed too rough. However, in our case, since these higher members are broad enough and merge into the quasi continuum as will be seen later, it is expected that the above rough approximation will cause some substantial difficulties in the overall spectrum.

The recombination continuum is given by

$$I_R(\nu) = N_i N_e g_{f-b} \frac{K}{(kT_e)^{3/2}} \exp\left(-\frac{h\nu}{kT_e} + \frac{E_H}{p^2 kT_e}\right) \frac{1}{p^3} \tag{7}$$

and the Bremsstrahlung (the free-free continuum) is given by

$$I_B(\nu) = N_i N_e g_{f-f} \frac{K}{2E_H} (kT_e)^{-1/2} \exp\left(-\frac{h\nu}{kT_e}\right), \tag{8}$$

where E_H is one Rydberg (13.6 eV), g_{f-b} and f_{f-f} are, respectively, the free-bound and free-free Gaunt factors, and K is a constant.

Figue 2 (e) and (b) shows examples of the Balmer series spectra corresponding to the population distributions in Fig. 1 (a). The difference is the population density in the ground state, and this figure is intended to demonstrate the difference in the spectral characteristics of the two different phases of the plasma. Figure 2 (a) corresponds to the "R-phase". With an increase in p, the broadening of the Balmer lines increases and the merging lines smoothly lead to

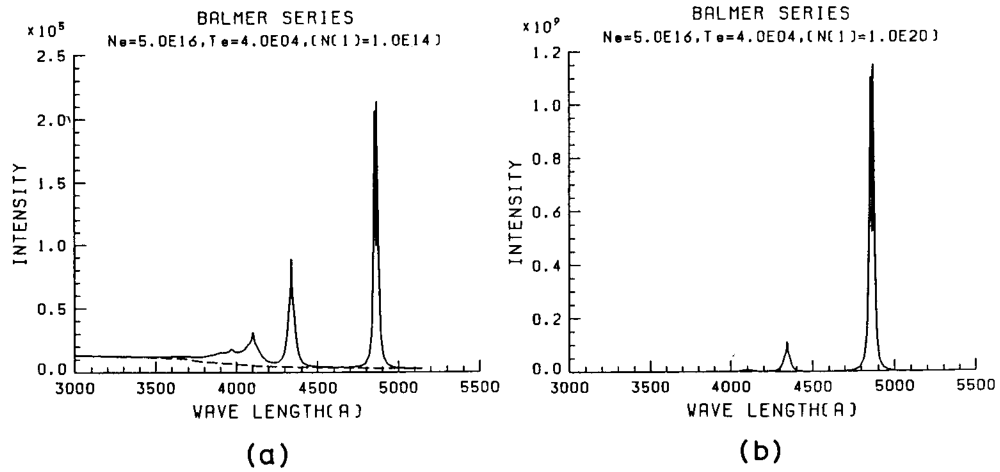


Fig. 2. Calculated spectrum of the Balmer series lines and continuum. (a) $N_e = 5 \times 10^{16}$ cm^{-3}, $T_e = 4 \times 10^4$ K and $n\,(1) = 1 \times 10^{14}\,\mathrm{cm}^{-3}$, corresponding to the "R-phase" plasma. (b) $N_e = 5 \times 10^{16}\,\mathrm{cm}^{-3}$, $T_e = 4 \times 10^4$ K and $n\,(1) = 1 \times 10^{20}\,\mathrm{cm}^{-3}$, corresponding to the "I-phase" plasma.

the quasi continuum, and further to the true continuum. The dotted curve shows the contribution from the recombination continuum and the Bremsstrahlung. In Fig. 2 (b), which corresponds to the "I-phase" plasma, with an increase in p, the series lines simply decrease and finally disappear. These different p-dependencies are typical features of the spectrum observed for these two classes of plasma.

§ 4. Experiment

Figure 3 shows the cross sectional view of the z-pinch descharge tube, and Fig. 4 shows the schematic diagram of the apparatus used in the present experiment. Emission radiation from the plasma was observed through the

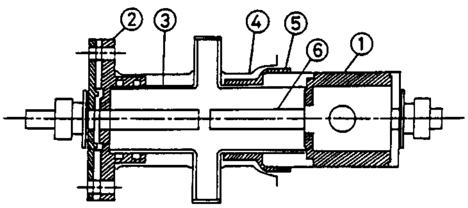


Fig. 3. Cross sectional view of the z-pinch discharge tube. 1. anode (Cu), 2. cathode (Cu), 3. quartz tube, 4. return conductor (Cu mesh sheet), 5. insulator and 6. quartz tube with a viewing window.

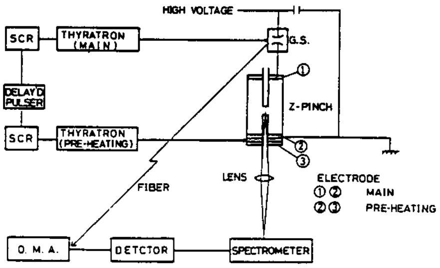


Fig. 4. Schematic diagram of the appratus.

viewing port and the lens, both made of fused quartz, by a spectrometer with the focal length of 100 cm equipped with a grating of 150 grooves/mm. The linear reciprocal dispersion was 6.4 nm/mm. The entrance slit width was 25 μ. An optical multichannel analyzer (OMA, PAR-1215) was used for the detection of the spectrum. The number of the channels was 700, and each channel had the width of 25 μ and the height of 2.0 mm. Therefore, this detector covered the wavelength range of 110 nm. The photo-sensitive material was of multi-alkali, and the photoelectrons were amplified by 2-tage multichannel plates. Phosphorescence induced by the output electrons was transmitted through a bundle of optical fibers, and the light was detected by a diode array.

The filling pressure of molecular hydrogen was 1.17 torr. The capacitor bank

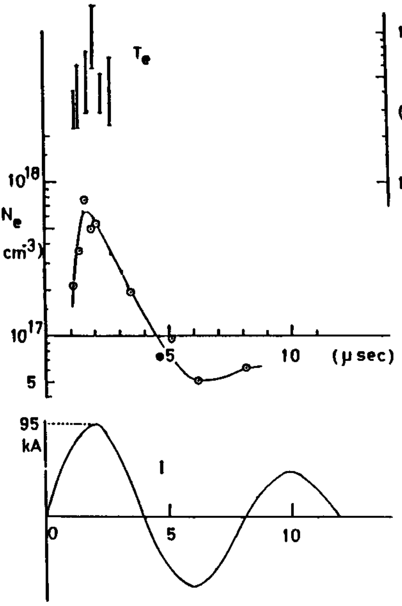
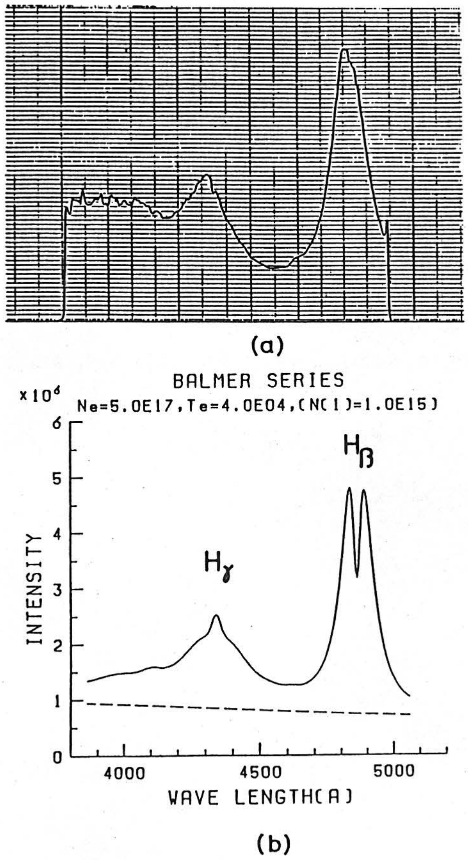


Fig. 5. Temporal variations of T_e, N_e and the discharge current.

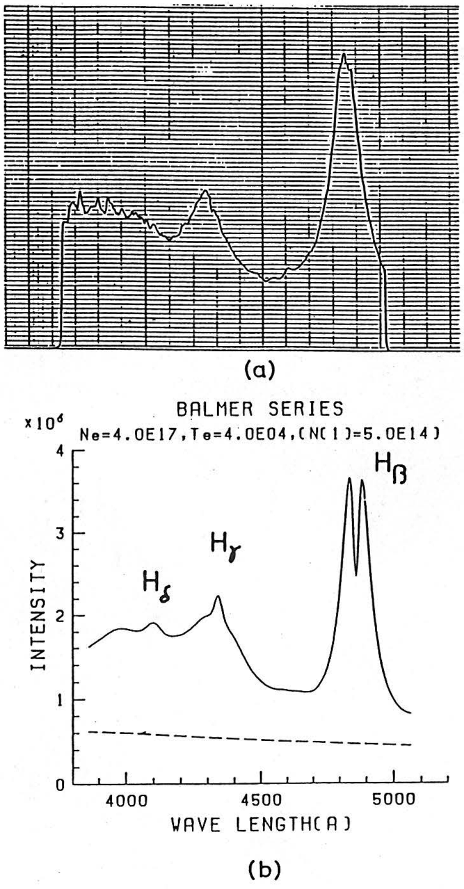
of ten 1 μF condensors was charged to 15 kV, and a discharge was run through the z-pinch tube. The current reached the maximum of 95 kA and decayed in the under-damping mode with a period of 8 μs, as seen in Fig. 5. In order to improve the reproducibility of the break down of the main discharge, a pre-heating discharge was applied just before the main discharge. A pinched plasma was produced on the axis of the tube. For the purpose of adjusting the optical thickness of the plasma, the length of the plasma was adjusted by moving the two viewing windows attached to glass tubes, which were inserted into the tube at both ends of the main discharge tube. In the present experiment the length



(a)

(b)

Fig. 6. Emission spectra of the Balmer series lines and continuum. (a) experimental result; (b) calculated result for $N_e = 5 \times 10^{17}\,\mathrm{cm}^{-3}$, $T_e = 4 \times 10^4$ K and $n(1) = 1 \times 10^{15}\,\mathrm{cm}^{-3}$.



(a)

(b)

Fig. 7. Emission spectra of the Balmer series lines and continuum. (a) experimental result; (b) calculated result for $N_e = 4 \times 10^{17}\,\mathrm{cm}^{-3}$, $T_e = 4 \times 10^4$ k and $n(1) = 5 \times 10^{14}\,\mathrm{cm}^{-3}$.

was chosen to be 10 mm. The whole detection system was placed in a shield room for the purpose of isolating the system from the electrical noise stemming from the discharges. The OMA was triggered by a light emission from the gap switch; it was transmitted by an optical fiber into the shield room. The OMA was operated in a pulsed mode with the gate of 0.2 μs. The spectral sensitivity of the whole system was calibrated against a tungsten ribbon lamp which had been calibrated on the basis of the NBS radiation standards.

Fugure 5 shows an example of the temporal variations of the discharge current together with the experimentally determined N_e and T_e. The plasma temperature was determined from the intensity ratio of the free-free continua at 310 nm and at 360 nm, and N_e was determined from the Stark broadening of the H_α line.

We recorded the Balmer spectrum at various temporal points. Figures 6 and 7 give examples of the spectra; Fig. 6 (b) is taken at 1.42 μs in the time scale of Fig. 5, and Fig. 7 (b) is taken at 1.82 μs. Both spectra are the results of an average over 5 shots.

§ 5. Comparison of experiment with theory

In Figs. 6 and 7, we show the calculated Balmer spectra for the plasma parameters obtained in the experiment. The ground-state atom density was determined from the best fit of the calculated spectrum to the experiment. It is found that in both cases, the ratio $N_i/N(1)$ is larger than the value under the assumption of the ionization balance, or the plasma is regarded as in the "R-phase". The overall characteristic of the spectrum is in reasonable agreement, except for some features; the first is the line profile of the H_β and H_γ lines in the core regions. For example, the central dip of the former line predicted from theory is not reproduded by experiment. This is probably due to a plasma inhomogeneity along the line of sight. The second is the continuation from the line profile to the quasi continuum; the theoretical contunuum intensity is lower than the experiment. It is a well konwn fact that the line spectrum toward the series limit continues smoothly to the true contunuum if the line intensities are averaged over a finite width of energy. In our case, the continuum intensity is lower than the averaged line spectrum. Therefore, it is concluded that the present disagreement is due to a failure in our calculation. In particular, our negect of the higher members of the Balmer lines than $p=10$ may be responsible for this.

§ 6. Discussion

In our experiment, the spectrum we observed belongs to the "R-phase" plasma. Under our experimental condition this "R-phase" plasma is very close to the one in local thermodynamic equilibrium (LTE), which is usually assumed for this kind of plasmas. We could not observe a spectrum corresponding to the "I-phse" plasma; the plasma before the maximum compression would have shown this feature. Due to electrical noise and a low intensity of the emission radiation, we could not record this kind of spectrum with a good quality.

A comparison of Fig. 6 (a) and (b), which are for the same electron density, suggests that, if we observe the spectral distribution of series lines from a plasma in the "I-phase", and if we analyze this spectrum under the conventional assumption of LTE, or effectively the "R-phase", we would be led to the conclusion that the higher members of the series lines are much weaker than those expected. We would then conclude that the "transparency window" exists. Therefore, the present study strongly suggests that there is a possibility that the "transparency window", so far reported, is interpreted from the "I-phase" spectrum. In an experiment concerning the "transparency window", extreme care should be taken of the ionization imbalance of the plasma, or we should be careful whether our plasma is in the "R-phase" or in the "I-phase".

In the present study, we adopted the Stark profile calculated in refs. 16 and 17. Recently, theoreticians have made substantial progress in understanding the line profile by taking into account the dynamic effect of the ion motion. In the lower electron density regions, this theory showed a good agreement with the experiment[22]. However, for the higher densities treated here and in ref. 9, agreement is still rather poor. We hope our experiment will make a substantial contribution in this respect.

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