Broadening of the He II Line $\lambda = 4686$ Å in a Plasma

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The profile of the He II $\lambda = 4686$ Å line has been measured in a plasma with an electron density of $5.5 \cdot 10^{17}$ cm^{-3} and a temperature of $6 \cdot 10^4$ °K. The measured halfwidth is consistent with that predicted by the Griem and Shen theory. On the far wings the intensity approaches the value expected when ions and electrons are treated by the static theory, although the electrons are far outside the static broadening regime.

The broadening of the He II line $\lambda = 4686$ Å by the electric fields of electrons and ions in a plasma was first discussed by UNSÖLD [1] and WULFF [2] using the Holtsmark theory. BERG [3] measured the half-width $\Delta\lambda_h$ of this line emitted from a plasma of known electron density N_e and electron temperature T, and found $\Delta\lambda_h$ in good agreement with the calculation of GRIEM and SHEN [4]. Recently the whole profile has been determined by EBERHAGEN and WUNDERLICH [5]. They obtained much lower intensities on the far line wings than theoretially predicted. Their profile could be explained if the contribution of the electrons to the intensity of the wings were negligible.

Since the last result is unexpected, the profile measurements have been repeated with the aim of improving the accuracy by avoiding the main difficulties in [5]: the correction for insufficient resolution of the spectrometer and the modification of the theoretical profiles to include doubly ionized atoms. We have achieved an improvement by choosing appropriate plasma conditions, i. e. high densities (to give broad profiles) and low temperatures (to reduce double ionization).

The plasma was produced in the following way: a quartz tube of 3.6 cm inner diameter was filled with helium at a pressure of 0.4 Torr. It was surrounded by a single turn coil of 30 cm length and 4.2 cm diameter. By discharging a 0.5 μF, 25 kV condenser into this coil, the gas was preheated. Then, by switching the main condenser bank of 1 kJoule energy, 25 kV charging voltage to the same coil, magnetic compression produced a plasma of 0.1 μs life time with $N_e = 5.5 \cdot 10^{17}$ cm^{-3}, $T = 6.0 \cdot 10^4$ °K and a ratio of double to singly ionized atoms $N_i^{++}/N_i^{+} = 15\%$.

The absolute intensity I_λ of the continuum at 5200 Å and of the profiles of the He II lines $\lambda = 4686$ Å and $\lambda = 3203$ Å has been measured photoelectrically with a spectrometer having 1 Å resolution. The intensity calibration was performed with a carbon arc.

Side-on and end-on observations of the $\lambda = 3203$ Å line gave equal half-widths within $\pm 5\%$. This observation justifies the assumption of an optically homogeneous plasma layer. Owing to self-absorption the 4686 Å line appears much broader end-on than side-on. By comparison of both profiles, an optical depth $\tau = 2.6$ has been found in the line centre. Thus the temperature could be derived from I_λ at 4686 Å by using the equation of radiative transfer for a homogeneous layer and Planck's law.

$$I_\lambda = B_\lambda (1 - e^{-\tau}) ;$$
$$B_\lambda = 2\, h\, c^2 / \lambda^5 \cdot (\exp\{h\, c / \lambda\, k\, T\} - 1)^{-1} .$$

The electron density was determined from the continuum intensity at $\lambda = 5200$ Å, the ratio N_i^{++}/N_i^{+} from the intensity of the 3203 Å line, the temperature, and the electron density using the Saha equation. Since for $N_e = 5 \cdot 10^{17}$ cm^{-3} thermal equilibrium for quantum states with $n \gtrsim 2$ can be expected [6] the Saha equation can be applied.

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The full half-widths $\Delta\lambda_h$ of the 3203 Å and 4686 Å lines are related to the electron density approximately by

$$N_e = C\,\Delta\lambda_h^{3/2}.$$

Several theoretical and experimental C-values are summarized in Table 1. The agreement between them is surprisingly good, especially for the 3203 Å line which is not very sensitive to temperature variations.

Author	λ=3203 Å	λ=4686 Å
BERG [3]	$2.2\cdot10^{15}$	$13.9\cdot10^{15}$ cm^{-3} A$^{-3/2}$
EBERHAGEN and WUNDERLICH [5]	$2.3\cdot10^{15}$	$11\ \cdot10^{15}$ cm^{-3} A$^{-3/2}$
Present Paper	$2.3\cdot10^{15}$	$11.5\cdot10^{15}$ cm^{-3} A$^{-3/2}$
GRIEM and SHEN [4, 6] interpolated for $T=6\cdot10^4$ °K, $N_e=5\cdot10^{17}$ cm^{-3}	$2.2\cdot10^{15}$	$12\ \cdot10^{15}$ cm^{-3} A$^{-3/2}$

Table 1. C-values for the relation $N_e = C\,\Delta\lambda^{3/2}$.

The intensity of the far wings is compared with that derived from different theories and experiments by using the normalized profile:

$$S(a) = I_\lambda F_0/I_0 \quad \text{with} \quad a = \Delta\lambda/F_0,$$
$$F_0 = 2.61\, e N_e^{2/3}, \qquad I_0 = \int I_\lambda\, d\lambda.$$

The correction of F_0 for doubly ionized atoms has been negected. Applying this correction the theoretical $S(a)$ curves for ion broadening would increase by about 10%, the curves including ion and electron broadening by about 5% on the far wings. The results are given in Fig. 1. Side-on and end-on observations agree at a typical a-value of $5\cdot10^{-2}$ Å/cgs unit within $\pm 6\%$. The total error is estimated to be less than $\pm 20\%$. The experimental curve is compared with calculations of GRIEM and SHEN [4, 6]. They use the static theory for the perturbing ions and a collision theory for the electrons in accordance with the prediction [7] that the static broadening theory is not applicable till $\Delta\lambda_W \approx 1300$ Å, which is far outside the wavelength range considered. From the cases they have treated those of $N_e = 10^{17}$ cm^{-3}, $T = 80\,000$ °K, giving too low half-width, and $N_e = 10^{18}$ cm^{-3}, $T = 80\,000$ °K, giving too high half-width, are plotted. The wing intensities given by GRIEM [6] at $a = 5\cdot10^{-2}$ Å/cgs unit are a factor 2.35 or 3.25 higher than calculated from the ion broadening alone, whereas the experiment indicates a factor of about 2. The over-estimate of the intensity of the wings in the collision broadening theory may be caused by the fact that the long range Coulomb forces impose a faster decrease than $\Delta\lambda^{-2}$ in the line profile. Also dynamical corrections to the Holtsmark theory recently discussed by GRIEM [8] produce a steeper decay on the wings.

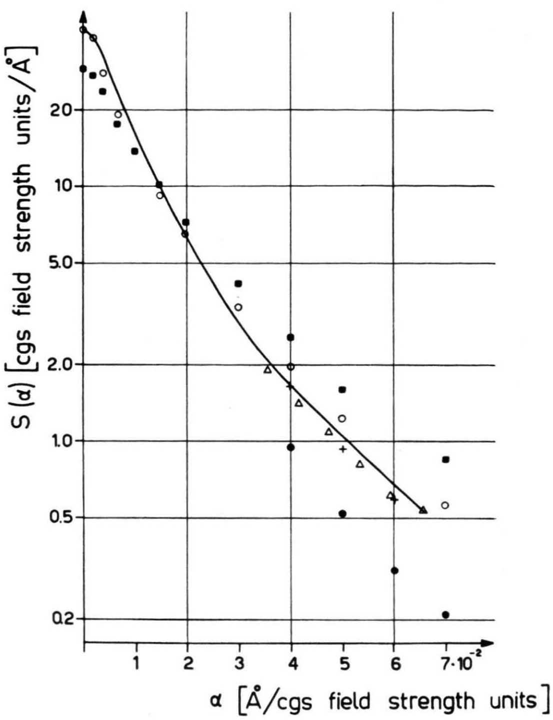

Fig. 1. $S(a)$ curves for F_0=840 cgs field strength units.
——— experimental values observed side-on;
△△△ experimental values observed end-on;
○○○ GRIEM and SHEN for $N_e = 10^{17}$ cm^{-3}, T=80 000 °K;
■■■ GRIEM and SHEN for $N_e = 10^{18}$ cm^{-3}, T=80 000 °K;
+++ asymptotic formula for perturbing electrons and ions;
●●● static broadening by ions only.

The wings of the Balmer lines of hydrogen can be described over a wide range of a by the asymptotic formula

$$S(a) = \text{const}\; a^{-5/2}$$

considering electrons and ions as static perturbers [9, 10]. Fig. 1 shows that this formula gives a good approximation to our experimental results for large a. When the broadening by ions only is taken

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into account and the field distribution function of MOZER and BARANGER [11] is used, the intensities obtained are too low.

In summary, the results indicates that the electrons give about the same contribution to the wing broadening as the ions even for values $\Delta\lambda_{W}/\Delta\lambda > 25$ where collision theory should be used for the electrons. Our results are not in good agreement with those obtained by EBERHAGEN and WUNDERLICH [5]. The discrepancy would be partly removed if their corrections for doubly ionized atoms were omitted.

On the other hand the profile measured by WULFF [2] agrees with our result when $N_e = 3.2 \cdot 10^{16}$ cm^{-3} instead of $N_e = 3.9 \cdot 10^{16}$ cm^{-3} is assumed. This correction is very favourable since it gives a much better fit to Wulff's other electron density determinations.

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