and Controlled Nuclear Fusion Research of the International Atomic Energy Agency at Novosibirsk, U.S.S.R., 1-7 August 1968 (to be published).

[3] C. E. Nielsen, A. M. Sessler, and K. R. Symon, in Proceedings of the Conference on High Energy Accelerators and Instrumentation, Geneva, 1959, edited by L. Kowarski (CERN Scientific Information Service, Geneva, Switzerland, 1959), p. 115

[4] A. Bers, Bull. Am. Phys. Soc. 10, 221 (1965).

[5] J. F. Clarke, G. G. Kelley, J. F. Lyon, and R. F. Stratton, in Proceedings of the Third Conference on Plasma Physics and Controlled Nuclear Fusion Research of the International Atomic Energy Agency at Novosibirsk, U.S.S.R., 1-7 August 1968 (to be published).

[6] A. E. Bazhanova, V. T. Karpuklin, A. N. Karkhov, and V. I. Pistunovich, Nucl. Fusion Suppl., Pt. 1, 227 (1962).

EXPERIMENTAL TEST OF H_β STARK-BROADENING THEORY AT HIGH ELECTRON DENSITIES*

J. C. Morris and R. U. Krey
Avco Corporation, Wilmington, Massachusetts

(Received 19 August 1968)

The profile of hydrogen beta has been measured for a temperature of 16 700°K and an electron number density of 2×10^{17} cm^{-3} using an arc-generated plasma. These data are compared with theory on area normalization and half-width bases and found to agree with theory within the accuracy quoted for theory.

A comparison of previous investigations of the line profile of hydrogen beta shows that there exist considerable differences for the agreement of theory and experiment between methods using dc-arc-[1] and discharge-tube-generated plasmas[2,3]. The arc work shows a 12% difference in the worst instance, whereas the pulse-discharge-tube experiments show agreement to within 2% with theory. Even though the authors feel that some might want to assign a bit larger uncertainty for the latter work,[2] the difference between the two results is too large to be ignored, casting doubt on the use of the dc arc as a precise tool for radiation studies or conversely, raising the question, "Is H_β as good as the latter work suggests?" It appears to the authors that the basic reason for the difference is the electron-number-density measurement in the arc experiment. A line intensity method was used for measuring N_e. However, this measurement for the plasma condition used was sensitive to errors in such parameters as temperature T, lowering of the ionization energy, partition-function cutoff ΔE, and intensity measurements I.

We and the authors of a companion paper, Shumaker and Popenoe,[4] have made measurements of H_β to provide an understanding of the problems outlined above and to provide experimental data for the line profile of H_β at high temperature and electron number densities. We have used essentially the same method as Wiese for determining N_e; however, we have operated our arcs at a plasma condition where the electron number density is not a sensitive function of the above parameters. Thus we can more precisely determine N_e from line and continuum intensity measurements. In looking for this plasma condition the authors noted that at temperatures where there is a relatively large percentage of the neutrals ionized, N_e is insensitive to both temperature and ΔE. For example, for a 1-atm plasma the electron density varies by less than 1% over a temperature range 16 100-17 200°K and by less than 5% from 15 400 to 18 900°K. Also at a temperature of 16 700°K an error of ±50% in the lowering of the ionization energy and partition-function cutoff using the Debye criteria gives an error of only ±1% in N_e.

To generate a stable plasma which was reproducible, we made use of a mechanically constricted arc generator. The general details of our device are described in the literature.[5] In our work we chose an arc-channel diameter of $\frac{3}{16}$ in. and operated our chamber at atmospheric pressure to help insure equilibrium and to obtain the high concentration of electrons. To reach the high temperature necessary for this experiment, we ran the arc to high currents from 200 to 300 A with $\frac{1}{2}$ cycle of the 60-Hz line current. An idling current of 20 A from a battery supply was used to sustain the arc between pulses.

To insure that H_β would be optically thin we ran an argon arc with a small concentration, 2.5%, of hydrogen added to it. As pointed out by Shumaker and Popenoe[4] the calculated N_e was not materially affected by this small addition of hydrogen. Furthermore, measurements of temperature using five argon-ion lines (4972, 4933, 4847, 4736, and 4806 Ar II) did not disclose any difference in temperature between the pure argon and the hydrogen-argon plasma for the arc currents reached in this experiment.

Two methods of viewing the arc column were possible, one perpendicular to the arc axis, the other along the axis. Our experiment used the latter, thus avoiding the Abel's correction for the radial temperature distribution. Shumaker and Popenoe used the side-on technique, thus providing data versus temperature in one arc run. For our measurements we avoided the possibility of systematic errors from the temperature gradients in the electrode region of the arc by limiting the flow of the hydrogen-argon mixture to the center sections of the arc and flushing the electrode chambers with pure argon.[5] Also, to reduce the influence of the radial temperature gradients we limited the field of view of the spectrometer, with apertures, to a small cone centered coaxially to the arc axis. With this method it was possible for the spectrometer to view an isothermal volume of plasma having a controlled percentage of hydrogen.

The spectrum from the arc was measured photoelectrically and compared with a National Bureau of Standards calibrated tungsten-ribbon lamp to correct for wavelength variations in the detecting system. To obtain as high a precision as possible the output of the photomultiplier tube, read on a peak-reading voltmeter, was simultaneously recorded on the three-channel strip chart recorder having gains of 1, 5, and 25. This method of recording allowed a repeated scale expansion of the line profile especially important at the outer wings of the line. Using the peak-reading voltmeter to obtain the spectral scans required us to make our measurements at the maximum N_e concentration and at a temperature where the line intensity of H_β had not reached its highest value.

The spectrum recorded was a mixture of radiation of the argon and hydrogen continuum and the lines of argon and hydrogen. To obtain the hydrogen-beta line profile it was necessary to subtract the unwanted radiation. To account for the continuum we tried a variety of techniques including subtraction of a calculation for the argon-plus-hydrogen continuum, the argon being obtained from an appropriate scaling of a pure argon run. None of the methods tried, however, was any more accurate than that obtained simply by laying two traces on top of one another, one trace for pure argon, the other for hydrogen plus argon. The pure argon trace was normalized electronically with the gain control of the amplifying system to the mixture intensity at 200 Å from the line center. The normalized argon provided the base line for the subtraction of the continuum.

The temperature for which the electron density reached a maximum was found from measurements of the absolute intensities of the ionic lines mentioned earlier. It was also possible to use the continuum on a relative basis to find this peak from the relationship $I_{\mathrm{cont}} \propto N_e^2/T^{1/2}$. This measurement was made for several wavelengths greater than 200 Å removed from the center of H_β in regions chosen to avoid interfering line radiation.

Four spectral scans for H_β were taken and averaged. The deviation of any individual run from the average was less than 3% for the highest scale readings. We have made two comparisons of our data with theory. For the first comparison we have converted our data to the parameters α and $S(\alpha)$ given by Griem and Kepple.[6] To reduce our wavelengths to α we used two values for the electron number density, 2.20×10^{17} and 1.80×10^{17} which is about ±10% of the value calculated through the composition equations. For each of these values of N_e we have area normalized the intensity measurements to the fraction of the line we measured. The net result shown in Fig. 1 is that our data appear as a series of bars inclined at an angle of 45 deg. The center of these bars represents 2.00×10^{17}.

The two values for N_e chosen above do not represent the error assigned to our N_e measurements but were selected for demonstrational purposes. The absolute accuracy of the N_e determination is believed to be within 4% of 2.00×10^{17} cm^{-3}. This includes a possible error of 30% in the transition probability for the ionic lines used in the temperature measurement, a 4% inaccuracy in the continuum intensities determining the peak electron concentration, a 100% error for the ΔE used in the composition calculations, and also a possible $\frac{1}{2}$% variation in pressure.

The greatest source of error believed to exist in this experiment lies in the intensity measurements. This error results basically from the somewhat uncertain contribution for the continuum below the line. At best, an educated guess would be to assign a value which would give a 5%

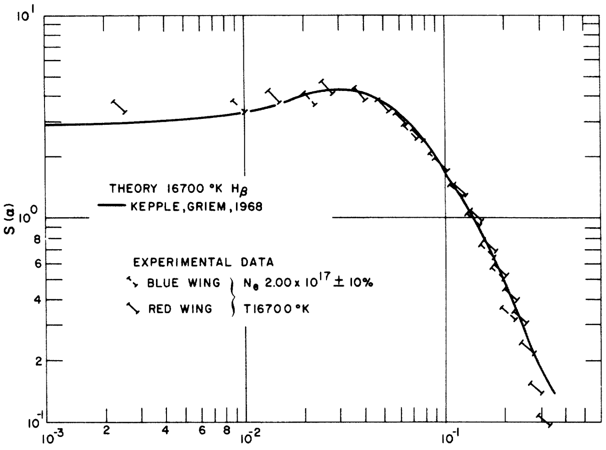

FIG. 1. A comparison of experimental measurements for a temperature of 16 700°K of the line profile of hydrogen beta with theory (Ref. 6). The data were reduced to $S(\alpha)$ and α, where α is the reduced wavelength in Angstroms per cgs field-strength units. For demonstrational purposes two values of electron density were used in converting wavelength to α: 2.20 $\times 10^{17}$ and 1.80 $\times 10^{17}$. The electron density for this experiment is within 4% of 2.00 $\times 10^{17}$.

accuracy for the intensity measurement at the center of the line. From the comparison shown in Fig. 1 we find that our experimental results are higher than theory at the line center. This, of course, is where our intensity measurements are most accurate. Kepple and Griem have noted that their results in this region are not as accurate as they are at the peak and the wings. This would lead us to believe that the disagreement in this region is not because of errors in the experiment. At this point we might say that our method of comparison with theory using the area normalization may be systematically biased because theory is too low in the center region of the line. On the other hand, this error is somewhat canceled because our data for the wings is systematically lower than theory. At the wings of the line the data are subject to considerable error from the assignment of the base of the line. This is also where recorder-reading errors are greatest. Since we have somewhat arbitrarily chosen the line contribution to the intensity at 200 Å from the line center to be zero, the data close to this wavelength is lower than theory.

Including these and the other considerations listed above, the comparison through area normalization shows that the H_β data from the constricted-arc technique supports the theoretical predictions. For example, in the regions of the profile where there is confidence in both the data and the theory, the deviation between the two is less than 5%. For the center of the line where theory is not reliable the data are higher by as much as 20%. Conversely, in the wings of the line where the data are strongly subject to errors in the selection of the base line we find a systematic trend lower than theory. It is obvious that we could have found a better fit for the wings by fudging a lower value for the underlying continuum, but there was no rigorous criterion justifying a lower value.

In addition to the above comparison we have also compared the electron density obtained from the half-width measurement with that obtained from the composition calculation. Here we find a difference of 5-8%, the half-width determination giving the lower value. We do not believe this error to be significant since we suspect a 5% uncertainty in the peak-intensity measurement of our data which in turn gives a 12% uncertainty in the N_e determination obtained from the half-width. It is interesting to note, however, that Shumaker and Popenoe also obtain a lower N_e value using their whole line profile with an iterative least-squares fitting routine.

In conclusion, it appears that the differences that do exist between the various measurements for the line profile of H_β, for those experiments where N_e is precisely known, appear to arise principally because of the form used for the comparison with theory and how it reflects the respective errors of experiment. It is also encouraging to note that experimental results agree with theory to within at least, and in most instances better than, the accuracy of theory for the wavelength region, temperature, and electron density range thus far investigated.

---

*Research is part of the research program on radiation from arc-heated plasma of the Aerospace Research Laboratories, Office of Aerospace Research of the U. S. Air Force, Contract No. AF33(615)-2976.

[1] W. L. Wiese, D. R. Paquette, and J. E. Solarski, Phys. Rev. 129, 1225 (1963).

[2] R. A. Hill and J. S. Gerardo, Phys. Rev. 162, 45 (1967).

[3] E. A. McLean and S. A. Ramsden, Phys. Rev. 140, A1122 (1965).

[4] J. B. Shumaker, Jr., and C. H. Popenoe, Phys. Rev. Letters 21, 1046 (1968).

[5] J. C. Morris and R. L. Garrison, J. Quant. Spectr. Radiative Transfer 6, 899 (1966).

[6] P. Kepple, University of Maryland Technical Report No. 831, 1968 (unpublished). We are indebted to H. R. Griem for a prepublication copy of some of the tables from this report.