Observation of an ion effect in the profile of the 4471-Å line of He I

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We have measured the profile of the 4471-Å line of He I at electron densities $n_e = 3\times10^{15}$, 10^{16}, and 3×10^{16} cm^{-3} in plasmas of different chemical composition. We have observed a smearing of the central dip of the line varying with the inverse square root of the reduced mass of the radiator-perturber system. A comparison with a calculation using ion dynamics at $n_e = 3\times10^{15}$ cm^{-3} shows a better agreement for the dip intensity than with the usual quasistatic ion calculations.

Comparison over the last ten years of the experimental profiles of the 4471.5-Å line and its forbidden 4470-Å component with the theories of Griem[1] and Barnard *et al.*[2] (BCS I), while showing a fair agreement for the allowed line, exhibits systematic discrepancies, especially for the intensity of the dip between the two lines. In 1970, Burgess[3] imputed these discrepancies to the failure of the usual quasistatic-ion approximation when applied to the line center of the forbidden line, at low electron densities ($n_e \leq 5\times10^{15}$ cm^{-3}); he suggested taking the ion motion into account in the calculations. Subsequently, Lee[4] and Barnard *et al.*[5] (BCS II) calculated an important ion-motion effect at low electron densities in agreement with the experiments,[6,7] while Segre and Voslamber[8] and Brissaud *et al.*[9] predicted a negligible influence of this effect.

A quite similar controversy existed for the line H_β. An important experimental improvement was completed by Kelleher and Wiese[10] (KW), who observed a smearing of the central structure of H_β depending on the inverse square root of the reduced mass of the radiator-perturber system, $(\mu)^{-1/2}$. These authors attributed this effect, observable at high electron densities ($n_e \sim 10^{17}$ cm^{-3}), to the influence of the ion motion. In contradiction, Griem[12] interpreted the KW experiment in terms of a collective interaction of plasma particles with the radiator. Such collective effects were reported by Ramette and Drawin[13] and Ramette[18] in a plasma in strong recombination stage. But recently, Seidel[11] calculated an ion-motion effect at high electron densities (in contradiction with the predictions by Burgess) of about the same importance as the one observed by KW but with only a passable agreement. Thus, owing to a lack of good theory-experiment agreement no final conclusion concerning the actual influence of the dynamical ion effect can be made.

For the 4471-Å line of He I, no ion effect has yet been demonstrated; thus, it is the purpose of this paper to put forth experimental evidence of an ion effect of a similar appearance to the one observed in H_β. For this study, the lines of He I were emitted in a plasma arc which was created in the form of a conventional plasma jet with the addition of a transfer anode (anode *B* in Fig. 1). Thus, an electrical arc between anode *B* and the cathode could be superimposed to the usual one. This modification improved the spatial stability and decreased the axial and radial gradients of electron density. Furthermore, the additional energy delivered to the plasma increased the intensity of the helium lines by a factor of 10–20.

Three different plasmas were studied, each one characterized by a different reduced mass μ of the radiator-perturbing ion couple, specifically $\mu = 0.8$ for the He-H plasma, $\mu = 2$ for the He-He plasma, and $\mu = 3.34$ for the He-Ne plasma. The flow rates of hydrogen and neon were calculated to provide more than 99% of ions in the plasma. In the case of a He-H mixture, the He I lines were weakly excited but this disturbance was easily overcome by our data-recording equipment (see below). An electron-density range from 2×10^{15} to

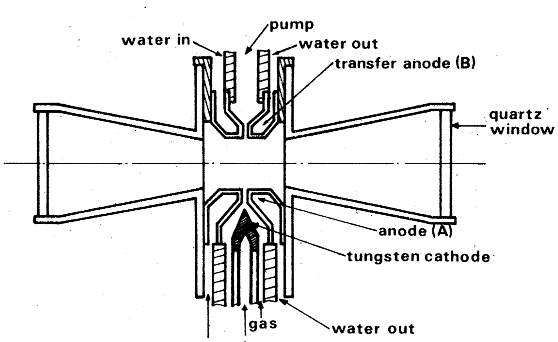

FIG. 1. Schematic diagram of the plasma source.

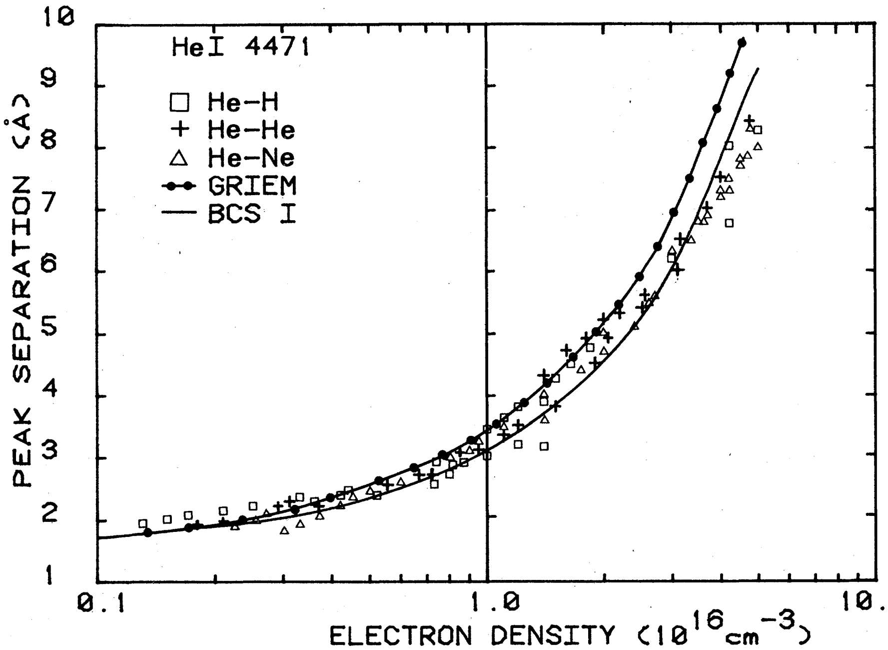

FIG. 2. Peak-separation measurements compared with theoretical data.

5×10^{16} cm^{-3} was obtained by variations of the dc electrical power together with the use of different pressures from 150 to 760 Torr.

The optical setup consisted of a 1.7-m Hilger and Watts monochromator with a 1200 lines/mm grating, having a reciprocal dispersion of 4.4 Å/mm in the first order. The data were either digitally recorded with an optical multichannel analyzer[14] (OMA), or recorded on photographic plates. Most of the data were collected with the OMA permitting numerous summations, especially for the low-intensity signals, over short periods. Up to 4000 summations were achieved in about 2 min for the 4471-Å line in He-H plasma leading to very reliable results. The apparatus width at $1/e$ was found to be the width of three channels, i.e., 0.33 Å in the first order and 0.12 Å in the second order for the 4471-Å line. The photographic techniques were used for the very unstable He-H plasma at atmospheric pressure ($n_e \gtrsim 3 \times 10^{16}$ cm^{-3}) with time exposures of about 1 sec.

The cylindrical symmetry of the jet required side-on observations and the use of the Abel inversion process. Therefore, the arc was mounted on

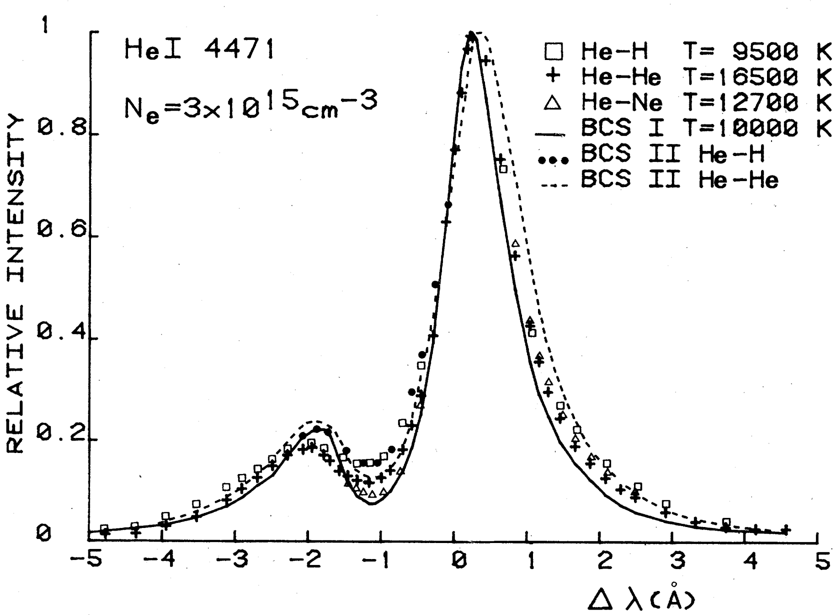

FIG. 3. Experimental and theoretical profiles of the 4471-Å line of He I at an electron density of $N_e = 3 \times 10^{15}$ cm^{-3}. The electron temperature is indicated for each plasma.

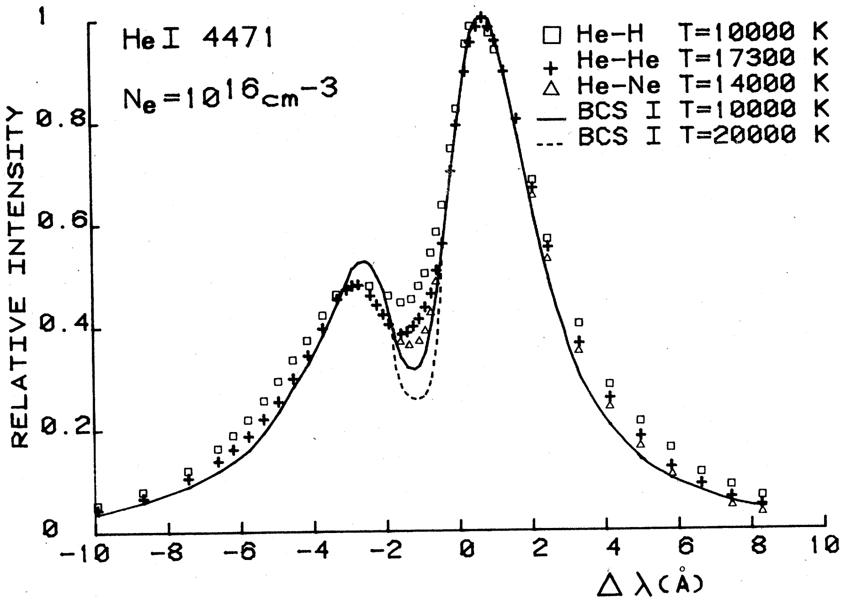

FIG. 4. Experimental and theoretical profiles of the 4471-Å line of He I at an electron density of $N_e = 10^{16}$ cm^{-3}. The electron temperature is indicated for each plasma.

a bench allowing very precise alignment of the image across the entrance slit. The electron density was first estimated from the measurements of the half widths of the isolated lines of He I by using the theory by Griem[15] and some previous studies[16] in this laboratory. The errors were estimated to be about ±15%. The peak separation of the two components of the 4471-Å line was then plotted as a function of electron density (Fig. 2). No important discrepancies were observed in this curve between the different experiments and the theories, mainly by BCS I from $n_e = 3 \times 10^{15}$ to 3×10^{16} cm^{-3}. Therefore, the averaged experimental curve of the peak separation was used as a common reference for the electron-density determination for further comparison. The determination of the electron temperature was performed by measuring the absolute intensities of several lines and by using the collisional-radiative transfer model of Drawin and Emard[17] to take nonlocal-thermodynamic-equilibrium effects in consideration. The errors were estimated to be ±10%. No reliable measurements of ion temperature were made; they could only be estimated from the Doppler widths of the 3889- and 5016-Å lines of He I, to be about 3000–6000 K lower than the electron

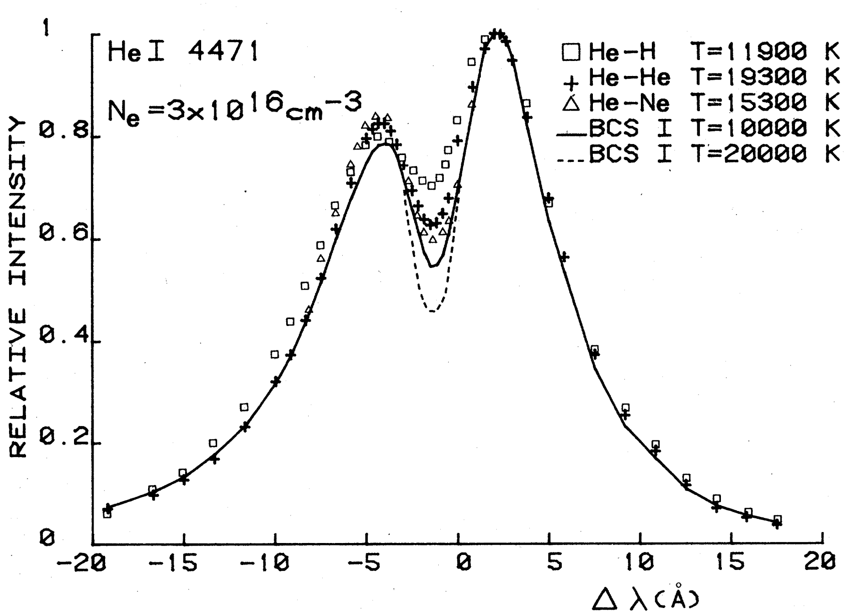

FIG. 5. Experimental and theoretical profiles of the 4471-Å line of He I at an electron density of $N_e = 3 \times 10^{16}$ cm^{-3}. The electron temperature is indicated for each plasma.

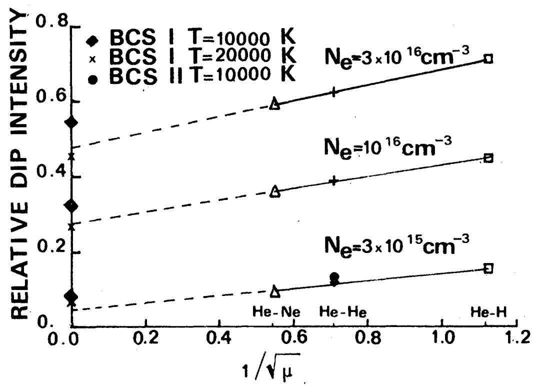

FIG. 6. Relative dip intensity vs the inverse square root of the reduced mass at different electron densities. The extrapolations of the experimental data at infinite reduced mass are indicated by the dashed lines.

temperature for the He-He and He-Ne plasmas. For the He-H plasma, owing to the weak deviation from local thermodynamic equilibrium, they were assumed not to differ from the electron temperatures.

The normalized (in amplitude) profiles of the 4471-Å line at $n_e = 3\times10^{15}$, 10^{16}, and 3×10^{16} cm^{-3} are presented in Figs. 3–5 for the different plasmas together with theoretical data by BCS I and BCS II, which give the best fits with the experiments. The experimental profiles are averaged over two to four experiments, the divergence between each individual profile being less than ±5%. The determination of the underlying continuum was made over a spectral range of 21 Å at $n_e = 3\times10^{15}$ cm^{-3} and 55 Å at the other electron densities. It has been checked that no impurity or molecular lines (from H_2) could perturb the line profile as well as the lines 4475.6 and 4466.8 Å of Ne I. Thus the total error in the 4471-Å line profile can be estimated to be ±5% in the line core up to ±20% as we go further in the line wings.

The most remarkable feature that appears in Figs. 3–5 comes from the smearing of the dip in the line center especially for the He-H plasma. The linear variation of the dip intensity as a function of $(\mu)^{-1/2}$ plotted in Fig. 6 illustrates the strong correlation which exists between these two quantities. Furthermore the extrapolation of the data (dashed lines in Fig. 6) at infinite reduced mass exhibits a noteworthy agreement with the static results by BCS I. The use of the actual parameter of the ion motion, $(T_i/\mu)^{1/2}$, with the ion temperature T_i, would probably not change the curves in Fig. 6 because the ion temperatures were estimated not to differ by much for the three different plasmas. The dip intensity is found to be in best agreement with the calculations by BCS II, including ion dynamics at $n_e = 3\times10^{15}$ cm^{-3} than with the previous theories. We can also point out that the forbidden linewidths for the He-H plasma are slightly wider than for the others, leading to the conclusion that an extra broadening arises for low reduced masses. Nevertheless, as discussed above for H_β, an interpretation in terms of an ion-motion effect cannot be made definitely, furthermore, for the time being, no theory predicts such effects at high electron densities. In another connection the comparison with the theory shows a quite good agreement for the allowed line profile, mainly at $n_e = 3\times10^{16}$ cm^{-3} within the uncertainty in the electron-density determination. For the forbidden line we note that the theoretical widths are narrower than the experimental ones, while the discrepancies in peak intensities change with the electron density.

Finally, we may state that an ion effect exists, even at high electron densities, for the 4471-Å line of He I which depends on the reduced mass of the radiator-perturbing ion system. This effect can be physically interpreted only by processes involving the reduced mass, and among them, the ion-motion effect seems the more likely. Besides, the interpretation by a coupling with the ion or electron plasma waves does not hold because the spectral position of the resulting satellites would be either in the forbidden peak (ion waves) or in the line wings (electron waves).

ACKNOWLEDGMENT

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[1]H. R. Griem, Astrophys. J. 154, 1111 (1968).
[2]A. J. Barnard, J. Cooper, and L. T. Shamey, Astron. Astrophys. 1, 28 (1969).
[3]D. D. Burgess, J. Phys. B 3, L67 (1970).
[4]R. W. Lee, J. Phys. B 5, L23 (1972).
[5]A. J. Barnard, J. Cooper, and E. W. Smith, J. Quant. Spectrosc. Radiat. Transfer 14, 1025 (1974).
[6]D. D. Burgess and C. J. Cairns, J. Phys. B 4, 1364 (1971).
[7]A. J. Barnard and D. C. Stevenson, J. Quant. Spectrosc. Radiat. Transfer 15, 123 (1975).
[8]E. R. A. Segre and D. Voslamber, Phys. Lett. A 46, 397 (1974).
[9]A. Brissaud, C. Golbach, J. Leorat, A. Mazure, and G. Nollez, J. Phys. B 9, 1129 (1976); 9, 1147 (1976).

[10]D. E. Kelleher and W. L. Wiese, Phys. Rev. Lett. 91, 1431 (1973); see also Phys. Rev. A 11, 1854 (1975).
[11]J. Seidel, Z. Naturforsch. A 32, 1207 (1977).
[12]H. R. Griem, in *Advances in Atomic and Molecular Physics*, edited by D. R. Bates and B. Bederson (Academic, New York, 1975), Vol. II.
[13]J. Ramette and H. W. Drawin, Z. Naturforsch. A 31, 401 (1976).
[14]Princeton Applied Research model No. 1205 I-ISIT.
[15]H. R. Griem, *Spectral Line Broadening by Plasmas*, (Academic, New York, 1974).
[16]C. S. Diatta, C. Fleurier, J. Chapelle, and S. Sahal, Phys. Lett. A 49, 450 (1974).
[17]H. W. Drawin and F. Emard, EURATOM CEA Report No. EUR-CEA-FC-534, 1970 (unpublished).
[18]J. Ramette, EURATOM CEA Report No. EUR-CEA-FC-904, 1977 (unpublished).