EXPERIMENTAL DETERMINATION OF THE CROSS SECTION FOR NEUTRAL BREMSSTRAHLUNG II. HIGH TEMPERATURE AIR SPECIES - O, N, AND N_2*

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RESEARCH REPORT 312

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*This research was supported by the Advanced Research Projects Agency of the Department of Defense and Space and Missile Systems Organization, Air Force Systems Command and was monitored by Space and Missile Systems Organization, Air Force Systems Command under Contract F04701-68-C-0036.

AVCO EVERETT RESEARCH LABORATORY
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SAMSO-TR-68-375 RESEARCH REPORT 312

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†To be published in J. Quant. Spectrosc. Radiat. Transfer

FOREWORD

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"This research was supported by the Advanced Research Projects Agency of the Department of Defense and Space and Missile Systems Organization, Air Force Systems Command and was monitored by Space and Missile Systems Organization, Air Force Systems Command under Contract F04701-68-C-0036." The secondary report number as assigned by AERL is Avco Everett Research Laboratory Research Report 312, and the authors are Raymond L. Taylor and George Caledonia. The Air Force program monitor for this contract is Major Walter D. McComb, Jr., SMYSE.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions; it is published only for the exchange and stimulation of ideas.

Major Walter D. McComb, Jr.
SMYSE

ABSTRACT

The low energy cross sections for neutral Bremsstrahlung for the major species of high temperature Air-O, N, and N_2 have been measured. The experiments were performed behind reflected shocks by measuring the absolute, infrared intensity of appropriate shock heated gas mixtures. The radiation was detected with a rapid scanning infrared spectrometer covering a total spectral range of 2.0 - 5.4 μ. The data were analyzed by assuming that the observed continuum was due to free-free scattering of electrons from the neutral species in the gas studied. The neutral Bremsstrahlung cross section was determined for (1) atomic oxygen in O_2-Ne mixtures, (2) atomic nitrogen in N_2-Ne mixtures, and (3) for molecular nitrogen from data on pure N_2. Further checks on the experimental values were obtained by comparing the measured cross sections against intensity data from air and N_2-Ar and N_2-Ne mixtures. The data were analyzed for the "effective nuclear charge squared" and radiation absorption cross section of the active species. The data are compared with previous experimental measurements and with theoretical calculations.

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I. INTRODUCTION

As has been indicated by a number of theoretical estimates and confirmed experimentally, the radiative scattering of electrons from neutral species is an important source of continuum free-free radiation for high temperature ionized gases. For example, in air at 8000°K and 1 atm density it has been estimated [1-4] that the neutral Bremsstrahlung contributes about 10% of the total spectrally integrated emission. Unfortunately, there have been few experimental measurements of the cross sections for neutral Bremsstrahlung, and the theoretical calculation of these cross sections presents a formidable problem in inelastic scattering of low energy electrons from many-electron, neutral atoms and/or molecules.

Wentink et al[5] were the first to attempt to directly measure the neutral Bremsstrahlung component of air in the spectral region of 1 - 4.8μ using a shock tube to heat the air to 8000°K. They interpreted the observed continuum intensity to be due to free-free scattering from atomic oxygen and nitrogen. Later, using a very similar experimental technique, Taylor[6] measured the continuum infrared radiation from high temperature air and nitrogen. By varying the gas temperatures over the range of 6000-9000°K, Taylor attempted to separate the Bremsstrahlung into its various components arising from the free-free scattering from the important neutral species of high temperature air - O, N, and N_2. This approach was not too successful. Although some estimates for the free-free cross sections for N and N_2 were obtained, the value for O was essentially undetermined.

Electric arcs have been used extensively to study the continuum radiation from high temperature gases.[7-10] Boldt[7] has studied radiative continua in the visible spectral region from both N_2 and O_2 at temperatures between 10,500 - 13,000°K. Under these conditions the continuum intensity is primarily due to Kramers' radiation (coulomb scattering) and to free-bound radiation (formation of O^- and possibly N^-), and it is not possible to separate the neutral free-free contribution. More recently, Morris and co-workers[10] have been using an arc to study the continuum radiation from high temperature air and its components. These measurements have extended into the near IR to 3.7 μ, and some estimates of neutral Bremsstrahlung cross sections for N have been made.

In a companion paper[11] the authors reported on the determination of the neutral Bremsstrahlung cross sections for the noble gases Ne, Ar, and Xe. Having determined these cross sections, it is possible to use a noble gas, particularly Ne which has the smallest neutral free-free cross section, as a carrier gas to determine the neutral Bremsstrahlung for other species. For example, by making measurements on high temperature O_2-Ne and N_2-Ne mixtures, it should be possible to determine the neutral Bremsstrahlung cross sections for O, N, and possible N_2. These latter cross sections can then be used to synthesize the experimental intensities for air and N_2 as a further check. This is the work that is described in this paper.

II. EXPERIMENTAL

The experimental arrangement was identical to that employed in the experiments on the noble gases.[11] The gases were heated with reflected shocks produced in a metal shock tube, the test section of which was

3.5-cm-square. The gas conditions were calculated assuming thermodynamic equilibrium, from the measured incident shock velocity extrapolated to the end wall. The radiation intensity was measured absolutely with a rapid scanning spectrometer[12] which can scan about 1.0 μ with a spectral resolution of about 0.07 μ. The data obtained cover a total spectral range of about 2.0 - 5.4 μ.

The noble gases used in these mixtures, Ne and Ar, were of the same purity as reported previously.[11] The N_2 used was Matheson prepurified grade which the manufacturer claims to contain only 2 ppm of O_2 as the largest impurity. The O_2 was Matheson extra dry grade stated to be 99.6% O_2 with no specification of the impurity content. The air used in these experiments was synthetic and was prepared by mixing O_2 and N_2 in the ratio of 1:4. In preparing the various gas mixtures, standard procedures for handling high purity gas were followed; the component gases were also passed through appropriate cold traps before entering the mixing tank. However, mixtures made without using the traps showed no change in the data. The mixtures were prepared to a final total pressure of about 2-5 atmospheres and were allowed to stand at least overnight and generally for several days before using to insure complete mixing.

III. DATA

Gas conditions were needed that would emphasize the neutral Bremsstrahlung contribution of O, N, and if possible, N_2. The equilibrium concentrations of neutral species and electrons that are obtainable behind reflected shocks at various temperatures are shown in Fig. 1 for 10% C_2 - 90% Ne, 20% N_2 - 80% Ne, N_2 and air.[13] It is apparent that by choosing

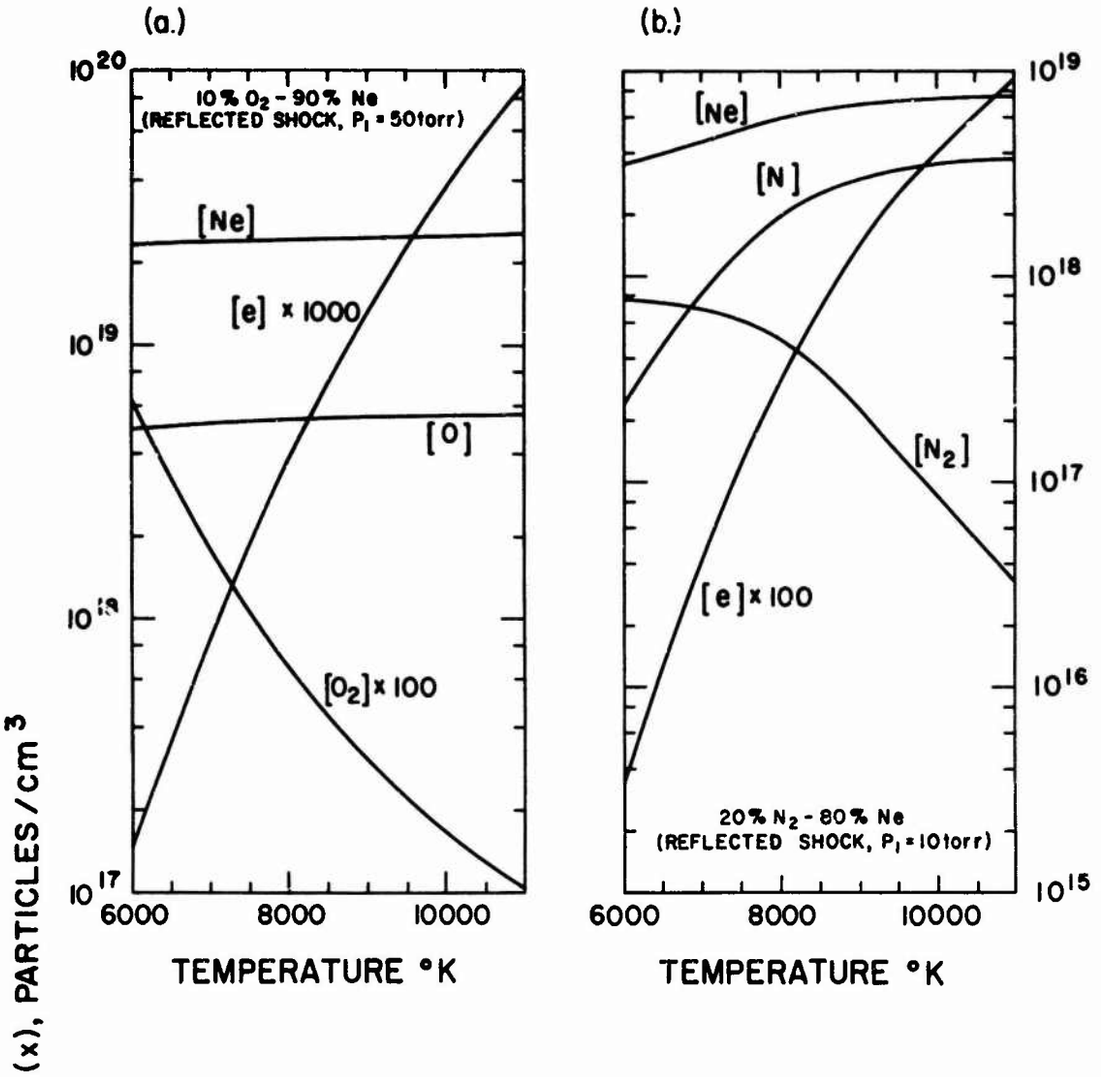
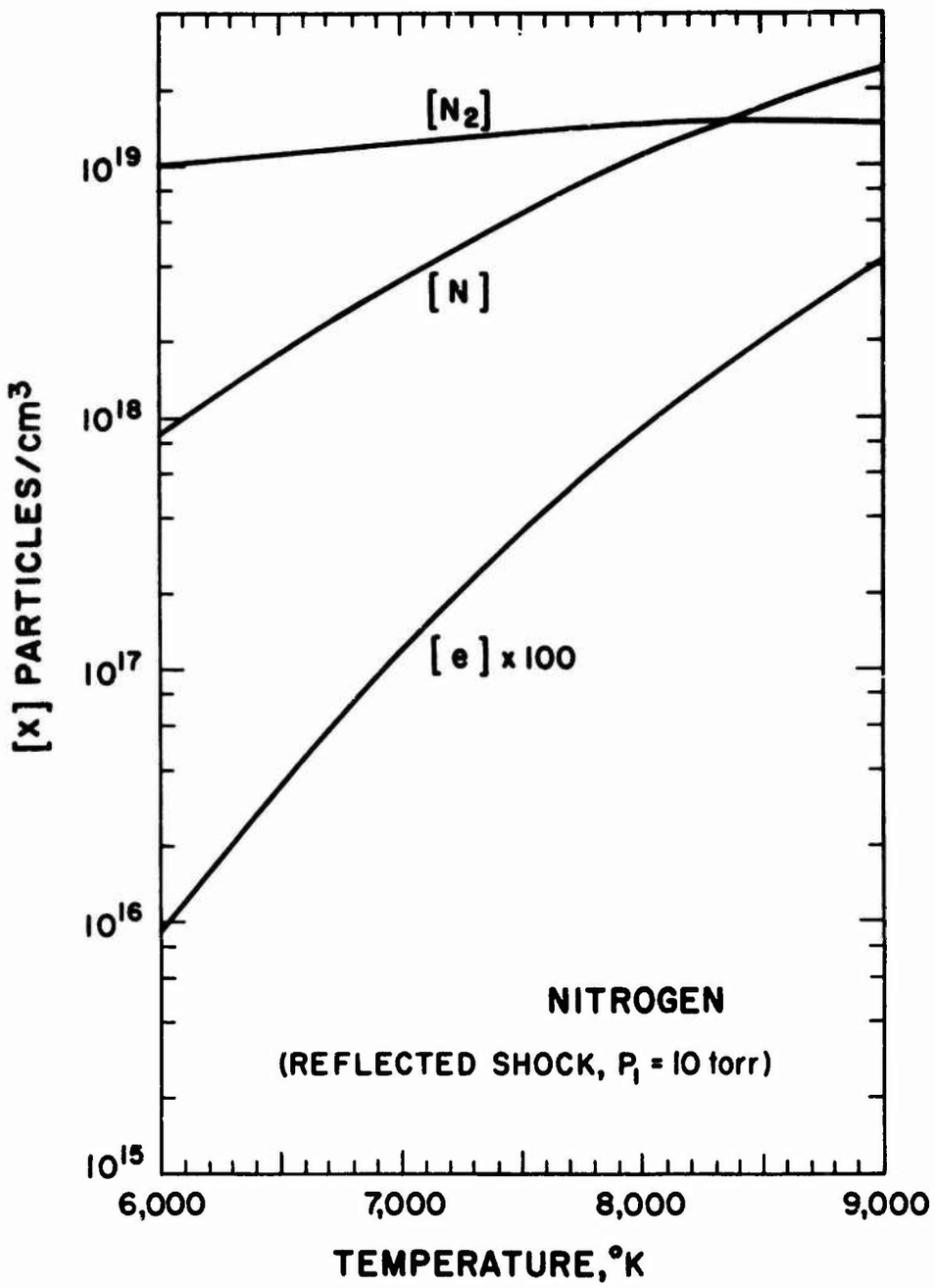


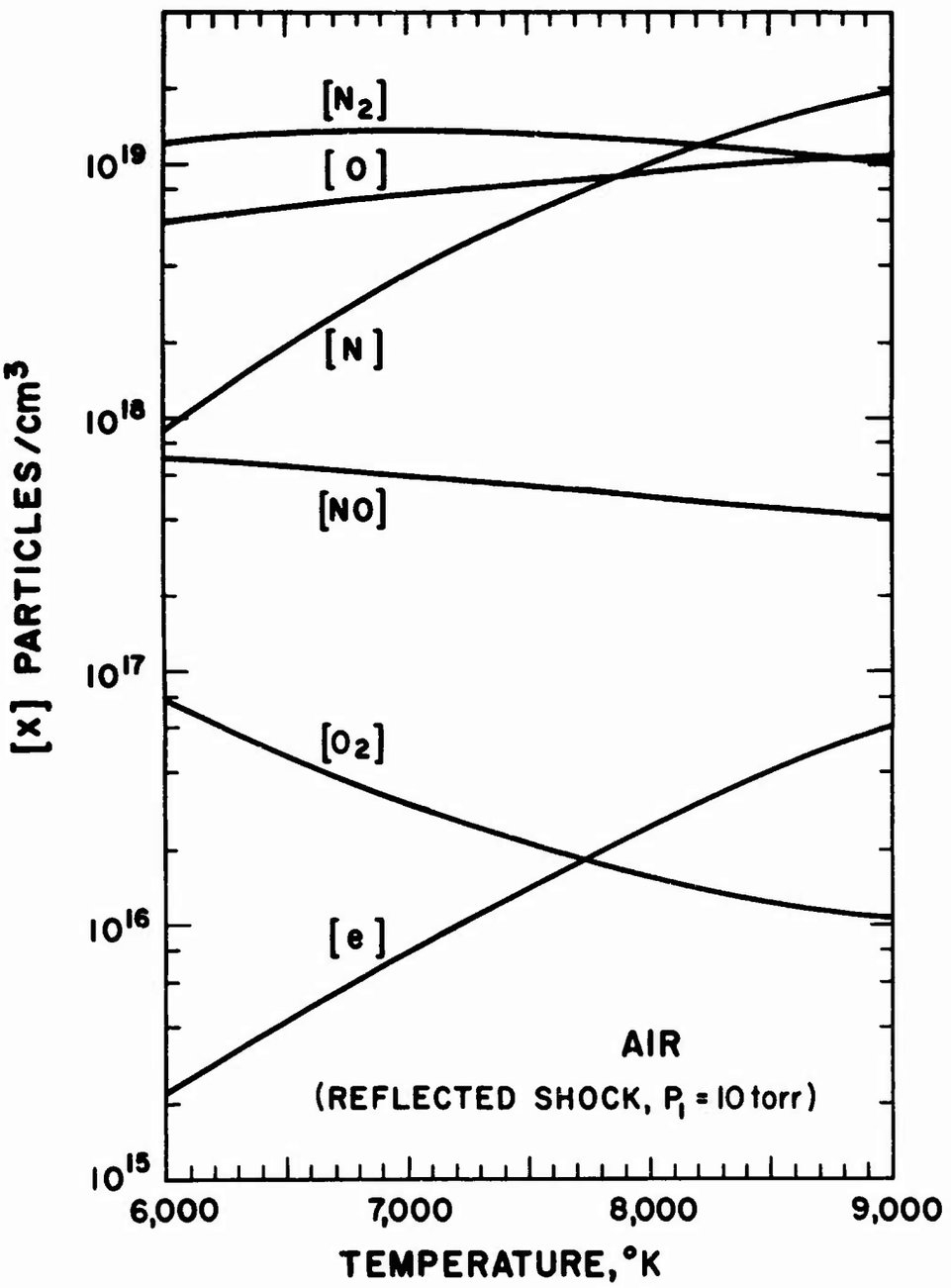
Fig. 1 Experimental conditions for various gas mixtures. Shown are various species concentrations [ ] in particles/cm^3 at the equilibrium temperature behind a reflected shock for (a) 10% O_2-90% Ne at an initial pressure p_1 = 50 torr, (b) 20% N_2-80% Ne at p_1 = 10 torr, (c) N_2 at p_1 = 10 torr, and (d) air at p_1 = 10 torr. Only the concentrations of the major neutral species and electrons have been shown.

(c.)


[N2]
[N]
[e] x 100
NITROGEN
(REFLECTED SHOCK, P1 = 10 torr)
[X] PARTICLES/cm3
10^19
10^18
10^17
10^16
10^15
6,000
7,000
8,000
9,000
TEMPERATURE, °K

9865

(d.)


[N2]
[O]
[N]
[NO]
[O2]
[e]
AIR
(REFLECTED SHOCK, P1 = 10 torr)
[x] PARTICLES/cm3
10^19
10^18
10^17
10^16
10^15
6,000
7,000
8,000
9,000
TEMPERATURE, °K

9843

an appropriate temperature, it is possible to emphasize one or more of the various neutral species. For example, in the 10% O_2 - 90% Ne mixture at about 9000°K the O_2 is completely dissociated, and the only significant neutral species are O and Ne. If the Bremsstrahlung cross section for O is significantly greater than that of Ne, it should be possible to determine the value for O from radiation measurements on such a mixture. However, in air at 8000°K, O, N, and N_2 all have about equal concentration, and the difficulty of separating the various Bremsstrahlung components is readily apparent.

The various gas mixtures and conditions studied in this experiment are listed in Table I. Listed are the gas compositions, initial pressure in the shock tube p_1, incident shock velocity u_s, equilibrium temperature behind the reflected shock T, density of the shocked gas relative to standard density ρ/ρ_o, and fractional electron concentration (e). Also shown in the last column is the major neutral specie (or species) for which that mixture was investigated in order to determine a cross section.

The oscillograms for the various gas mixtures are all relatively similar, although the experimental test times for N_2 and air are smaller than those for the noble gas mixtures. A sample oscillogram for a shock run into a 10% O_2 - 90% Ne mixture is shown in Fig. 2 where p_1 = 50 torr and T = 10, 100°K. The top oscillogram, Fig. 2a, displays the signal from the scanning spectrometer and the monitor PM at a sweep speed of 20 μsec/div. After an initial transient of about 10 μsec for chemical relaxation, the monitor signal displays a relatively constant signal which corresponds to the equilibrium gas and good test time. The signal begins

TABLE I

Gas Composition	p_1 torr	u_s^* mm/μsec	T^* °K	ρ/ρ_o atm.	(e)	Species
10% O_2 - 90% Ne	50	3.30	9700	1.1	9×10^{-4}	O
20% O_2 - 80% Ne	30	3.64	9800	0.97	1.5×10^{-3}	O
20% N_2 - 80% Ne	10	4.22	9175	0.35	1.7×10^{-3}	N
N_2	10	4.67	8350	0.88	5.4×10^{-4}	N_2
Air (20% O_2 - 80% N_2)	10	4.60	7900	0.91	7.1×10^{-4}	O, N, N_2
20% N_2 - 80% Ne	50	3.89	8800	1.4	5.1×10^{-4}	N, N_2
50% N_2 - 50% Ar	10	4.11	9050	0.67	1.5×10^{-3}	N, N_2

*Nominal values

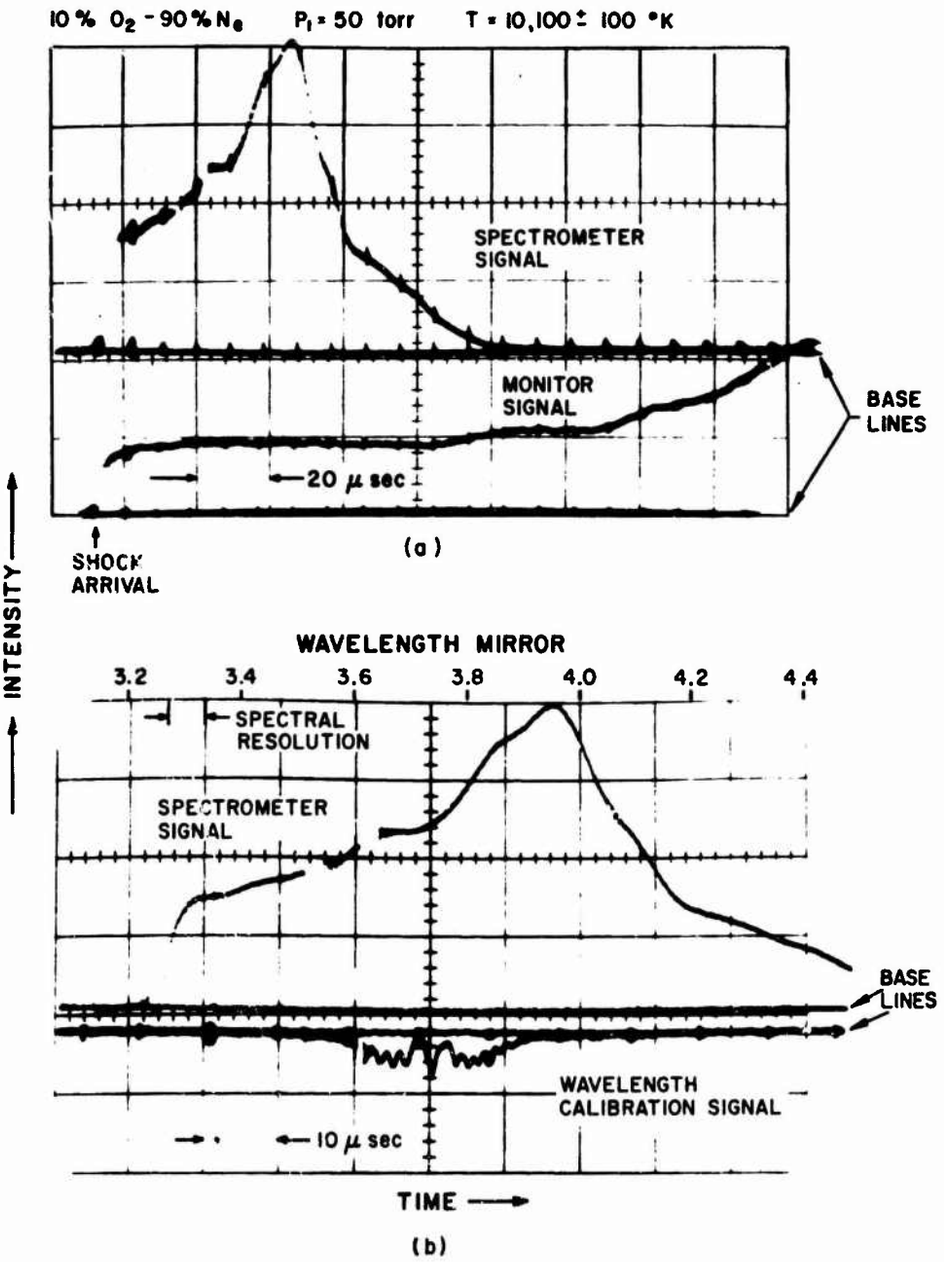


Fig. 2 Oscillograms illustrating data obtained from a shock into p_1 = 50 torr of a 10% O_2-90% Ne mixture. Final equilibrium temperature was 10,100°K. Scope (a) shows the signals from the scanning infrared spectrometer and monitor PM at a sweep speed of 20 μ-sec/div. Scope (b) shows signals from the scanning spectrometer and the wavelength calibration at a sweep speed of 10 μ-sec/div.

to increase at about 100 μsec after shock arrival indicating the appearance of the contact surface or other aerodynamic disturbances.

The bottom oscillogram, Fig. 2b, displays the spectrometer signal and wavelength calibration signal at a sweep speed of 10 μsec/div. The wavelength scale across the top of the oscillogram has been constructed from the calibration signal and indicates that in this run useful data were obtained from about 3.3 - 4.4 μ. The appearance of significant line radiation is apparent in the vicinity of 3.9 μ. The breaks in the spectrometer signal in the vicinity of 3.5 - 3.6 μ are due to electrical pick-up from the scanning spectrometer. These regions are omitted in the analysis of such a run. The close similarity between the data of Fig. 2 for a 10% O_2 - 90% Ne Mixture and the data on pure Ne in ref. 11 is apparent and indicates that the addition of O_2 and subsequent chemical effects have not degraded the experimental technique, i.e. all the chemistry and ionization is over in a time short compared to the experimental test time.

IV. DATA ANALYSIS

The analysis of the data is identical to that described previously.[11] In this experiment each set of intensity data from a mixture contains a Bremsstrahlung component from at least two neutral species. Therefore, in order to determine the unknown cross section it is necessary to subtract the contributions from known species, e.g. Ne or Ar. This subtraction has been accomplished as a function of wavelength by using the curve fits to the Z^2 data for Ne and Ar given in ref. 11. This procedure is straightforward. The data have been analyzed for the effective nuclear charge squared Z_i^2, of the neutral scattering species and the radiative absorption cross sections Qa_i.

V. RESULTS

A. Atomic Oxygen

To determine the Bremsstrahlung cross section for atomic oxygen, Ne-O_2 mixtures were employed. As can be seen from Fig. 1a, at about 9000°K the O_2 is completely dissociated into atoms and the fractional electron concentration is about 10^{-3}, optimal conditions for measuring the neutral Bremsstrahlung. Figure 3 shows a plot of the absolute spectral intensity versus wavelength for a 10% Ne - 90% O_2 mixture at an average temperature of 9700°K. Such a plot is constructed from a number (18) of overlapping scans, and the data have been normalized to the given conditions. The normalization procedure is described in ref. 11. The dashed regions indicate areas of considerable line radiation.

The heavy dot-dash curve on Fig. 3 is a calculation of the blackbody radiation for the given experimental conditions divided by a factor of ten. The experimental continuum intensity is clearly a small percentage of the blackbody limit for the experimental path length of 3.5 cm, as it is for all the conditions discussed in this paper. The Kramers' contribution to the observed intensity is about 10%. After subtracting the Kramers' radiation and the neutral Bremsstrahlung component of Ne from the data of Fig. 3, an average $Z_O^2 = 1.7 \times 10^{-2}$ is obtained.

The other curves on Fig. 3 indicate the contribution of the O (dashed line) and Ne (dotted line) Bremsstrahlung to the total intensity (solid line); the solid line in this and all subsequent figures includes Kramers' radiation. Since for the 10% O_2 - 90% Ne mixture the O Bremsstrahlung is less than that due to Ne, some additional experiments

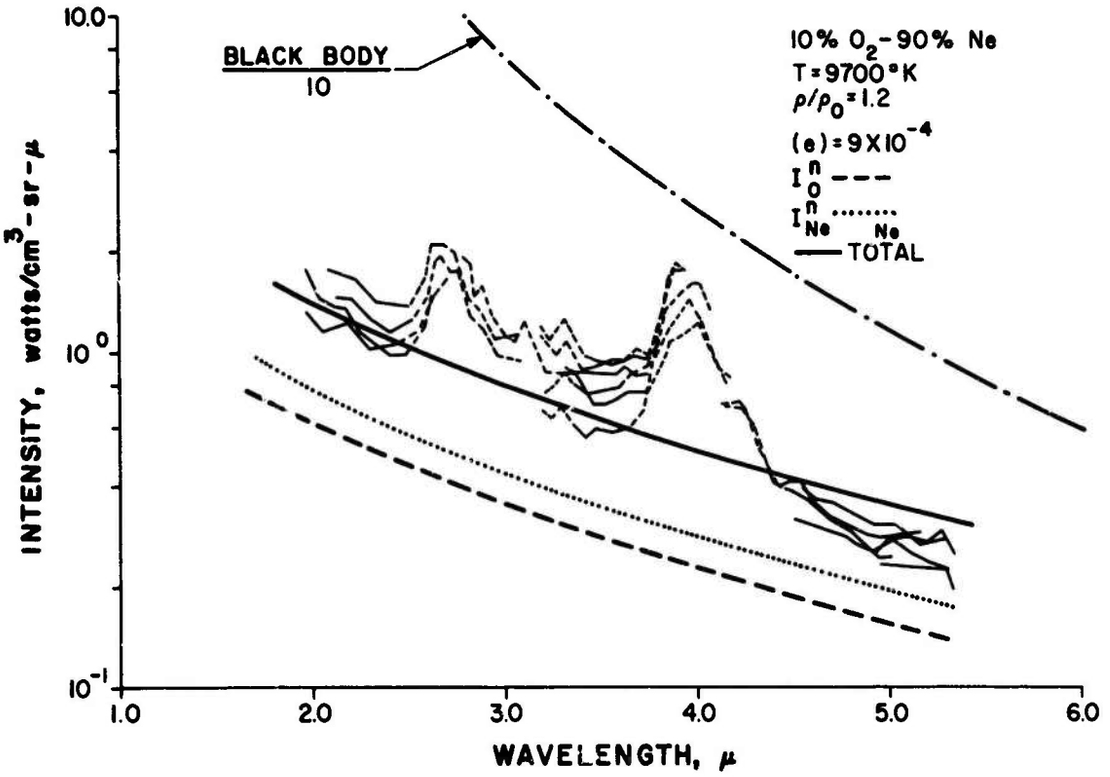


Fig. 3 Composite absolute spectral intensity of a 10% O_2-90% Ne mixture shock heated to 9700°K. The dashed portions of the data indicate regions of line radiation. The heavy dot-dash line is a calculation of the blackbody intensity for T = 9700°K divided by a factor of 10. The other lines are calculations of the neutral Bremsstrahlung component for O (dashed) and Ne (dotted) and the total including Kramers (solid).

were also run in a 20% O_2 - 80% Ne mixture. In the latter, the O free-free component is expected to be about 1.8 times larger than the Ne Bremsstrahlung since about 55% of the experimental intensity is due to O neutral scattering. A limited number of runs were made in the richer mixture at an average temperature of 9800°K. Upon analysis, these data give an average value of $Z_O^2 = 1.8 \times 10^{-2}$ which agrees well within the experimental scatter to the value obtained in the 10% mixture.

The data for Z_O^2 as a function of λ are shown in Fig. 4 for both the 10% mixture (circles) and 20% mixture (squares). The curve through the data is a two parameter function of the form

$$Z^2(\lambda) = a\,\lambda^b \qquad (1)$$

which has been fit through the combined data to indicate the general wavelength trend. For Z_O^2, $a = 4.2 \times 10^{-2}$ and $b = -0.70$ where λ is in microns. These values are listed in Table II together with values of the radiative absorption cross section Qa, which have been derived from the experimental data as outlined in ref. 11.

B. Atomic Nitrogen

To determine the Bremsstrahlung cross section for N, a 20% N_2 - 80% Ne mixture was used. At a temperature of 9175°K the concentration of N is about 10 times that of N_2, hence under these conditions the contribution to the radiation from N_2 can be neglected to a first approximation. Figure 5 shows the intensity versus λ data for this N_2-Ne mixture at a normalized temperature of 9175°K and $(e) = 1.7 \times 10^{-3}$. The Kramers contribution to the data of Fig. 5 amounts to about 10%.

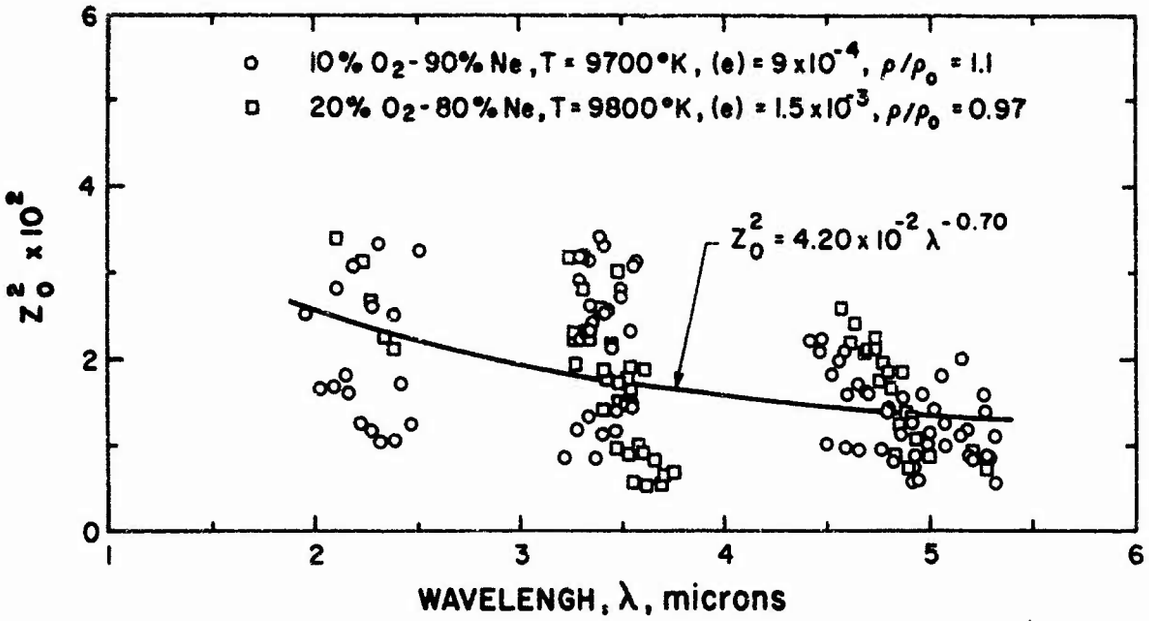


Fig. 4 Experimental values of Z_O^2 obtained from the 10% O_2-90% Ne mixture (circles) and the 20% O_2-80% Ne mixture (squares). The solid curve is a two parameter function which has been fit to the data to indicate a general wavelength trend.

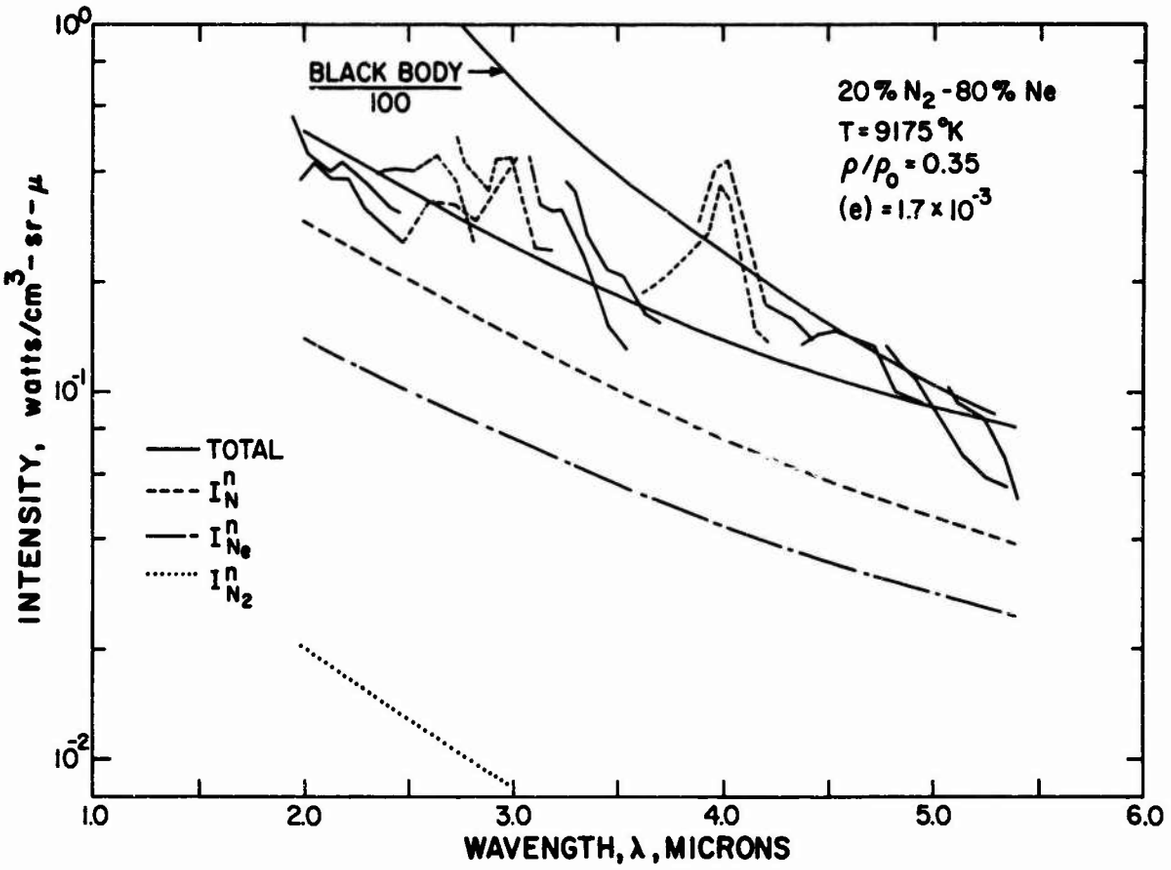


Fig. 5 Composite absolute spectral intensity for a mixture of 20% N_2-80% Ne at T = 9175°K. The dashed areas of data indicate regions of line radiation. The lines represent calculations of the neutral Bremsstrahlung intensity for N_2 (dot), N (dash), Ne (dot-dash), and total including Kramers (solid).

TABLE II

Species	T °K	(e) x 10^3	Z^2(average) x 10^2	a x 10^2	b	Qa x 10^{37} cm^5 (Experimental) λ = 2.0	3.5	5.0	Qa x 10^{37} cm^5 (Theoretical) λ = 2.0	3.5	5.0
O	9700	0.9	1.7 ± 0.7	4.2	-0.70	0.29	1.0	2.6	0.024	0.12	0.36
N	9175	1.7	2.1 ± 0.6	4.1	-0.54	0.32	1.3	3.0	0.069	0.31	0.91
N_2	8350	0.54	2.1 ± 0.5	5.3	-0.75	0.38	1.3	3.0	0.14	0.70	2.0

The average value of Z_N^2 obtained from the data of Fig. 5 is $Z_N^2 = 2.1 \times 10^{-2}$. This value and the following data on Z_N^2 include a correction for the effect of molecular nitrogen. This correction, which is small, was applied by an iterative procedure, after obtaining a value for $Z_{N_2}^2$ as described in the next section.

A plot of Z_N^2 versus λ is shown in Fig. 6. In contrast to the result for O, there is slightly less wavelength dependence to Z_N^2 than Z_O^2. The result of fitting the two parameter curves, equation (1), to the data of Fig. 6 leads to $a = 4.1 \times 10^{-2}$ and $b = -0.54$. Values of Qa, for N obtained from this data are also listed in Table II. The various curves on Fig. 5 show the Bremsstrahlung contributions for N (dashed), Ne (dot-dash), and N_2 (dotted) to the total intensity (solid). These curves have been calculated using the final λ dependent expressions for Z_N^2, Z_{Ne}^2, and $Z_{N_2}^2$, i.e. curve fits of the type shown on Fig. 6 for Z_N^2. It can be seen for this 20% N_2 - 80% Ne mixture, that the neutral free-free contribution from N is considerably larger than that for Ne or N_2.

C. Molecular Nitrogen

The most straightforward approach to measuring the Bremsstrahlung cross section for N_2 would be to lower the temperature of N_2-Ne mixtures until the molecular nitrogen concentration dominates the N atomic concentration. Such experiments were tried. However, at the appropriate temperatures, $\sim 6700^{\circ}K$ in 20% N_2 - 80% Ne where $n_N \sim n_{N_2}$, (e) was 5×10^{-6}, and two experimental difficulties arose: (i) the experimental intensities were low, and (ii) residual ionization from impurities gave spurious results.

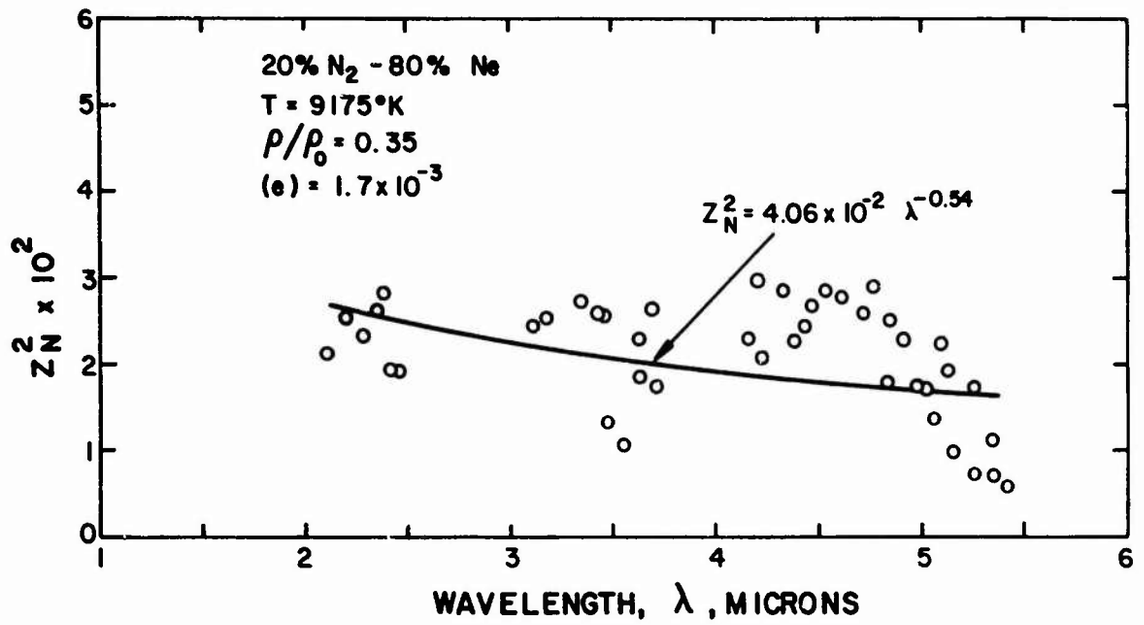


Fig. 6 Experimental values of Z_N^2 obtained from the 20% N_2-80% Ne mixture, Fig. 5. The solid curve is a two parameter function which has been fit to the data to indicate a general wavelength trend.

Instead, the following procedure was used. From Fig. 1c it can be seen that in pure N_2 at 8350°K the concentration of atomic and molecular nitrogen are about equal. This is a relatively easy experimental condition to reach, and, since (e) ~ 5×10^{-4} the difficulties (i) and (ii) mentioned for the low temperature N_2-Ne mixtures do not exist. Having determined Z_N^2 for the high temperature N_2-Ne results (Figs. 5 and 6), this result can then be combined with pure N_2 results to obtain the neutral Bremsstrahlung component for molecular nitrogen.

The absolute intensity data for N_2 as a function of wavelength are shown in Fig. 7. These data from 18 individual scans have been normalized to an average temperature of 8350°K. For these conditions the Kramers contribution to the experimental intensity is about 25%.

Using the results for Z_N^2 (λ) from Fig. 6, $Z_{N_2}^2$ (λ) has been calculated from the N_2 data of Fig. 7 and is shown in Fig. 8. An average value of $Z_{N_2}^2 = 2.1 \times 10^{-2}$ is obtained which is identical to the average value obtained for Z_N^2. Since for the N_2 conditions the concentrations of N and N_2 are about equal, the neutral Bremsstrahlung component from each species is about equal for the conditions of Fig. 7. The individual neutral free-free contributions have been indicated on Fig. 7 by the lines for N (dot-dash), N_2 (dashed) and the sum (solid).

The $Z_{N_2}^2$ data of Fig. 8 have been fit with a two parameter function, and the values of $a = 5.3 \times 10^{-2}$ and $b = -0.74$ are obtained and compared with similar values for Z_O^2 and Z_N^2 in Table II. Also shown in Table II are values of the absorption cross section Qa for N_2.

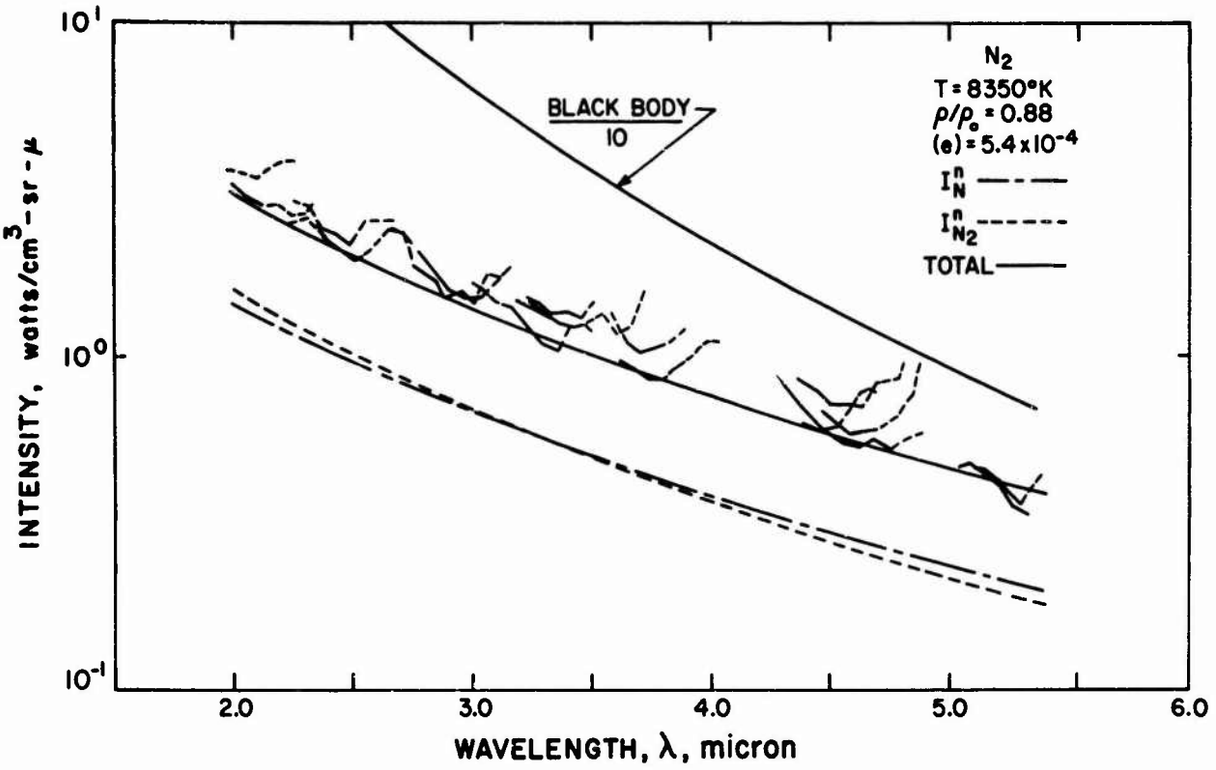


Fig. 7 Composite absolute spectral intensity for pure N_2 shock heated to 8350°K. The dashed areas of data indicate regions suspected of line radiation. The lines represent calculations of the neutral Bremsstrahlung intensity for N (dot-dash), N_2 (dash), and total including Kramers (solid).

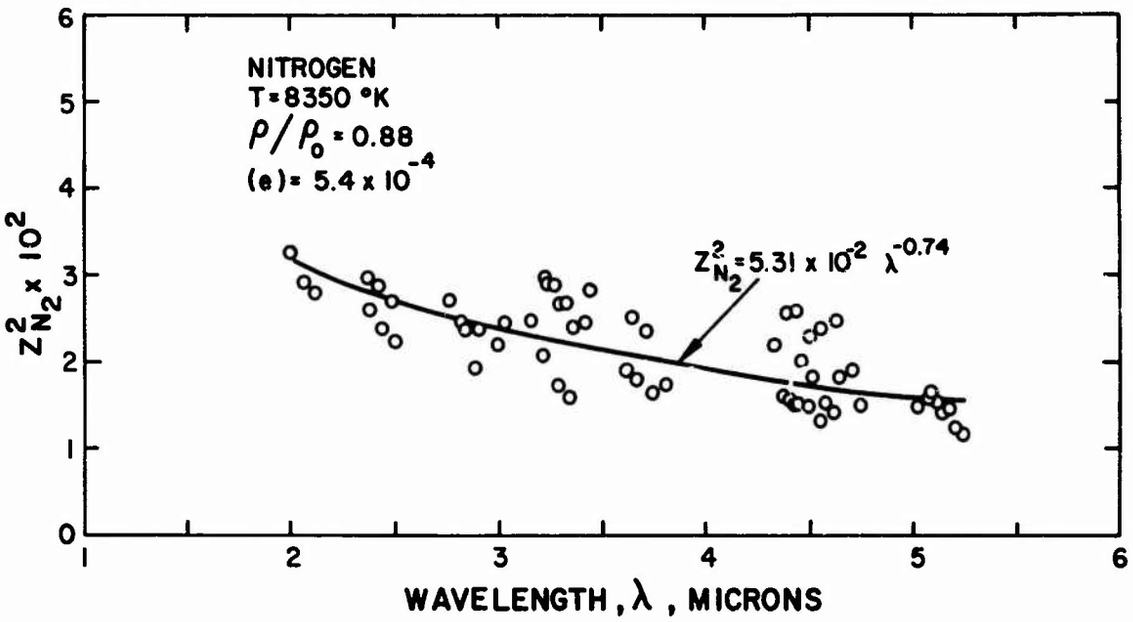


Fig. 8 Experimental values of $Z^2_{N_2}$ obtained from N_2 data of Fig. 7. The solid curve is a two parameter function which has been fit to the data to indicate a general wavelength trend.

D. Error Estimates

Since this experiment on the gas mixtures is identical to the previous study on the noble gases in terms of experimental arrangement and data analysis, the error estimates discussed in that paper apply to the present results as well and will not be repeated here. However, in the present study, there is one important additional source of error. In these gas mixtures it was necessary to subtract from the data the contribution from one component to determine the unknown contribution. Obviously such a procedure introduces cumulative errors; any systematic error in the "known" will produce an error of opposite sign in the "unknown". It is not possible to estimate the magnitude of this effect, since there are no independent, experimental values to which to compare the present results. However, the possibility of such cumulative errors is recognized, and the current values for O, N, and N_2 neutral Bremsstrahlung cross sections may have larger uncertainties than the values for Ne, Ar, and Xe which were more directly determined.

In an attempt to establish more confidence in the magnitude of the present results, two additional comparisons were tried. From Fig. 1d it can be seen that for air in the vicinity of 8000°K the concentrations of O, N, and N_2 are almost equal. Hence a comparison of air data at that temperature with a calculation of the neutral Bremsstrahlung intensity based on the present experiments will test the magnitude of the Z^2's to some extent. Such a comparison is shown in Fig. 9. The absolute intensity of air data normalized to a temperature of 7900°K is plotted against wavelength. The lines are calculations of the neutral free-free intensity for the various components - O (dotted), N (dot-dash), N_2 (dashed), and the

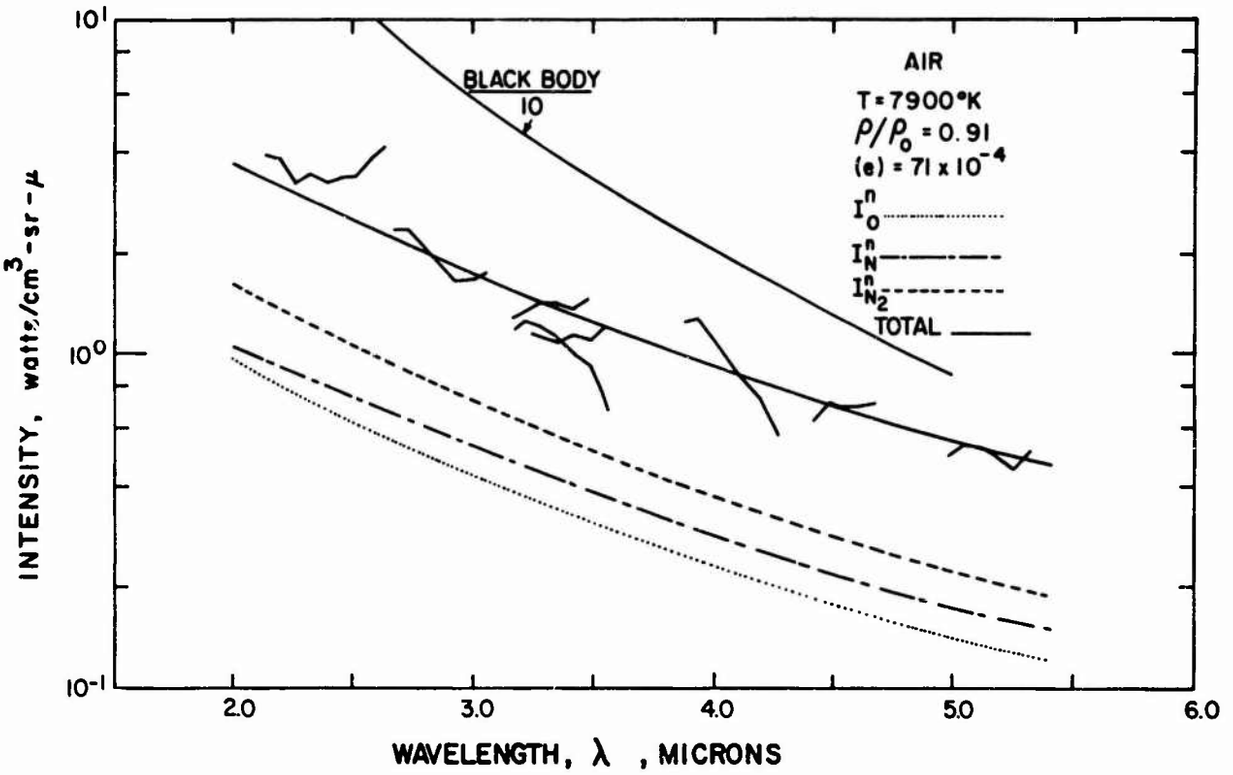


Fig. 9 Composite absolute spectral intensity for air shock heated to 7900°K. The lines represent calculations of the neutral Bremsstrahlung intensity for O (dot), N (dot-dash), N_2 (dash), and total including Kramers (solid).

total (solid). As is seen, the sum agrees closely with the data both in magnitude and wavelength dependence.

Two other comparisons were made. A limited number of experiments were run in 20% N_2 - 80% Ne at T = 8800°K and in 50% N_2 - 50% Ar at T = 9050°K. In both of these mixtures the N_2 concentration is about 25% of the total $[N + N_2]$, therefore these mixtures emphasize the Bremsstrahlung from N and the noble gas. The experimental data from these mixtures were compared with calculations of neutral Bremsstrahlung based on the values of Z^2 obtained in this study and ref. 11. These results will not be shown here, but the comparison was again excellent, both in absolute magnitude and wavelength dependence. The agreement with the N_2-Ar mixtures indicates that no significant systematic errors were introduced by the Ne carrier gas in the N_2-Ne mixture used to determine Z^2_N.

VI. DISCUSSION

The final results of this experiment are summarized in Table II. Shown for each species are the experimental conditions, average values of Z^2, the parameters of the curve fit to Z^2 (λ), and experimental values of Qa at three wavelengths - 2.0, 3.5 and 5.0 μ.

It is felt that this experimental technique of using a noble gas, particularly Ne, as a carrier gas to determine the Bremsstrahlung cross sections for the high temperature air species has been quite successful. The most serious disadvantage of this mixture technique is that any error in the determination of the Bremsstrahlung cross section for the noble gas will directly influence the value for the other neutral species. We have attempted to minimize this effect by two procedures: (i) the use of

mixtures where the carrier gas contribution is less than that of the unknown neutral species and (ii) sufficient redundancy in the measurements to establish confidence in the results. As an example of (ii), measurements were made in air and N_2-Ar mixtures, and these intensities were compared to calculated intensities based on the values of $Z^2(\lambda)$ found in the Ne mixtures and N_2. Excellent agreement was found, e.g. see Fig. 9.

Another disadvantage of the present technique is the difficulty of obtaining identical experimental conditions, particularly temperature, for all mixtures and gases. For air and N_2 the readily obtainable experimental conditions are in the vicinity of 8000°K, while for the noble gas mixtures, temperatures from 9,000 to 10,000°K are necessary to obtain sufficient ionization. A priori, one does not know the temperature dependence expected for neutral free-free cross sections. However, in a previous study[11] it was found that the temperature dependence of the neutral Bremsstrahlung for the noble gases was predicted closely by the T dependence of the Kramers-Unsold expression, i.e. $I^n \propto T^{-1/2} Z^2$. No experimental information on the temperature dependence of Bremsstrahlung for O, N and N_2 was obtained in the present study; the Kramers-Unsöld relation was used to extrapolate from one set of conditions to another. Due to the small range of temperature variation of the present experiments, this assumption should introduce no important uncertainties unless the Bremsstrahlung cross sections for air species have abnormally large temperature dependencies. The resolution of this point must await further experimental and theoretical comparison.

The absolute accuracy of the present results is difficult to establish. The general scatter in Z^2 is evident in Figs. 4, 6, and 8. The standard deviations (one σ) of the average value of Z^2 are shown in Table II and indicate that each value is known to about $\pm$ 30%. It should be pointed out that this analysis neglects the residual wavelength dependence of Z^2 which accounts for part of the deviation. The root-mean-square deviation of the two parameter curve fits are 40% for Z^2_O, 30% for Z^2_N, and 19% for $Z^2_{N_2}$.

The present results can be compared to previous values.[6] Taylor obtained $Z^2_N = 0.9 \pm 0.4 \times 10^{-2}$ and $Z^2_{N_2} = 2.2 \pm 0.3 \times 10^{-2}$ at $\lambda = 3.07\ \mu$. The values for $Z^2_{N_2}$ are in excellent agreement, while the recent value for Z^2_N appears to be somewhat higher even considering the experimental uncertainty. Taylor also concluded that the value of Z^2_O was small, $\sim 2 \times 10^{-3}$, because the air intensity of the earlier experiment could essentially be explained on the basis of the Bremsstrahlung components from N and N_2 alone. However, the determination of the individual Bremsstrahlung cross sections in the earlier experiment is considerably less direct than with the present technique. With the present values of Z^2_N and $Z^2_{N_2}$ the previous data for N_2 can be fit as well if not better than with the older values.

A more serious discrepancy between the two experiments is the fact that the present intensity for air is higher than the earlier value by almost a factor of 2 if one extrapolates the data to similar conditions. The source of this discrepancy is not known. In the more recent experiments, considerable care was exercised in the absolute calibration of the detection system. Over the course of the entire set of experiments, both noble gas

and air species studies, the detection system was stable to within 10%. This was not true of the earlier study where a different detection system was used and some long term change in the calibrations were observed. The discrepancy in absolute intensity may indicate a systematic error in one of the experiments. However, although the absolute magnitude of the values of Z^2 may be in doubt, it is believed that the relative magnitudes are well established from the present experiments.[14]

Morris and his co-workers have recently studied the continuum radiation from arc-heated N_2 between 9000 - 13,500°K.[15] Their measurements extend from 0.2 - 3.7 μ. In the infrared spectral region Morris obtains a value for $Z_N^2 = 3.5 - 5.5 \times 10^{-2}$ at T = 9000°K, i.e. about twice the value listed in Table II. However, within the estimated total scatter of both sets of experiments, ~ $\pm$ 40%, the two values are not inconsistent. Morris also observes a large continuum contribution in the visible and uv which can be attributed to N^-. The threshold energy for N^- free-bound radiation is not known, but some theoretical estimates suggest ~ 0.1 ev. If this estimate were correct, then part of the continuum infrared intensity observed by us or Morris could be due to N^- which would make the neutral Bremsstrahlung cross sections for N and N_2 smaller than obtained in the present analysis which neglects N^- radiation.

The last three columns of Table II show calculations of the neutral Bremsstrahlung radiative absorption cross section by Kivel,[4, 16] for the same experimental conditions as the data. Kivel uses a semi-empirical electron-atom interaction potential in which an approximate electron exchange force is evaluated for each individual atomic configuration. The

potential for atomic oxygen is obtained from photoabsorption cross section measurements on O^-.[17] This empirical potential is shown to be consistent with conductivity data of Lin[18] and low energy elastic scattering cross section measurements of Neynaber et al.[19] The atomic nitrogen potential is scaled from the empirical potential for O and is also shown to be consistent (to within a factor of 2) with the elastic scattering data of Neynaber et al.

If the magnitude of the theoretical Qa's are ignored for the moment, it can be seen from Table II that Kivel predicts that Qa (N)/Qa (O) ~ 3, while the experiments indicate ~ 1, with Qa (O) perhaps slightly smaller than that for N. The theoretical wavelength dependence of Qa is seen to be stronger than that observed experimentally. Finally, it can be seen that the theoretical calculations underestimate the magnitude of the Qa's by a factor of 10 to 3 with Qa (N) showing better agreement with the data than Qa (O).

For molecular nitrogen Kivel[7] calculates Qa by assuming that the neutral Bremsstrahlung cross section is proportional to the electron momentum transfer cross section[20], an approximation that is exact in the limit of zero electron energy.[21] For the momentum transfer cross section for N_2, Kivel uses the results of Frost and Phelps.[22] The calculated values of Qa (N_2) shown in Table II are about a factor of two larger than Qa (N) and moderately close to the data.

Mjolsness and Ruppel[23] have also presented recent calculations of neutral Bremsstrahlung cross sections. They use a theoretical procedure quite similar to Kivel although some differences in detail do exist.[24] To obtain their empirical interaction potentials, Mjolsness and

Ruppel fit the low energy, electron elastic scattering data of both O and N independently. Their results yield Qa's for O and N which are about equal, which is in better agreement with the present experimental observations. However, in magnitude their cross sections are about a factor of five less than the data. For N_2 Mjolsness and Ruppel also assume that Qa is proportional to the momentum transfer cross section. Their results for Qa (N_2) are slightly higher than Kivel's and therefore are in excellent agreement with the data of Table II.

It is hoped that the present experimental results and those previously reported for the noble gases will provide some additional basis for more detailed and more meaningful theoretical comparisons. Since the neutral Bremsstrahlung cross sections for a number of species have now been determined, the measurement of infrared Bremsstrahlung can provide a diagnostic technique to determine electron concentration in plasmas and high temperature gases, in a manner similar to that for Kramers' radiation which has been widely used for this purpose.

ACKNOWLEDGMENT

The advice and assistance of B. Kivel in the interpretation of the measurements and particularly in the theoretical comparison is gratefully acknowledged. C. Deradourian operated the shock tube and collected the data. R. Lynch now at the U. of California at Irvine, contributed to the experiment. Computer work and data reduction were performed by M. A. Berube and D. DiCarlo.

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)

Avco Everett Research Laboratory
2385 Revere Beach Parkway
Everett, Massachusetts

2a REPORT SECURITY CLASSIFICATION: Unclassified

2b GROUP:

3 REPORT TITLE

Experimental Determination of the Cross Section for Neutral Bremsstrahlung II. High Temperature Air Species - O, N, and N_2

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Research Report 312

5 AUTHOR(S) (Last name, first name, initial)

Taylor, Raymond L. and Caledonia, George

6 REPORT DATE	7a TOTAL NO. OF PAGES	7b NO. OF REFS
November 1968	32	24

8a CONTRACT OR GRANT NO.	9a ORIGINATOR'S REPORT NUMBER(S)
F04701-68-C-0036	Research Report 312
b. PROJECT NO.	
c	9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	SAMSO-TR-68-375

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13 ABSTRACT

The low energy cross sections for neutral Bremsstrahlung for the major species of high temperature Air-O, N, and N_2 have been measured. The experiments were performed behind reflected shocks by measuring the absolute, infrared intensity of appropriate shock heated gas mixtures. The radiation was detected with a rapid scanning infrared spectrometer covering a total spectral range of 2.0 - 5.4 μ. The data were analyzed by assuming that the observed continuum was due to free-free scattering of electrons from the neutral species in the gas studied. The neutral Bremsstrahlung cross section was determined for (1) atomic oxygen in O_2-Ne mixtures, (2) atomic nitrogen in N_2-Ne mixtures, and (3) for molecular nitrogen from data on pure N_2. Further checks on the experimental values were obtained by comparing the measured cross sections against intensity data from air and N_2-Ar and N_2-Ne mixtures. The data were analyzed for the "effective nuclear charge squared" and radiation absorption cross section of the active species. The data are compared with previous experimental measurements and with theoretical calculations.

DD FORM 1 JAN 64 1473

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14 KEY WORDS	LINK A		LINK B		LINK C	
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