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DIFFERENTIAL ELECTRON FLUX AS DETERMINED BY AURORAL OBSERVATIONS OF THE N_2 POSITIVE AND N_2^+ SYSTEMS

BY

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Abstract

The relative emission rates of the auroral N_2 positive and N_2^+ systems can be used as measures of the differential electron flux distribution function, due to the remarkable differences in electron excitation functions. Observations of aurora over the years have suggested that the four major systems are excited mainly by electrons. In the present work, calculations of relative emission rates using recently measured electron cross-sections are entirely consistent with the ground based and rocket-borne measurements. However the electron distribution function, with an analytic form $\Phi \propto E^n$, corresponding to the auroral observations gave a spectral index $n \approx -1.4$, in serious disagreement with recent high resolution electron spectrometer measurements in the low energy region ($n \approx -3$). The application of an index $n = -3$ would require a large increase in Φ at some energy $E > 100$ eV in order to account for the N_2^+ system emission rates. We suggest that a distribution of this kind could not be plausibly explained, given the auroral characteristics.

Differential Electron Flux as Determined by Auroral Observations of the N_2 Positive and N_2^+ Systems

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I. Introduction

Measurements of the auroral differential electron flux (Φ) in the low energy region (Heikkila and Matthews, 1964, Ulwick, 1968, and Feldman et al, 1971) suggest an energy (E) dependence of the form $\Phi \alpha E^n$. The estimated values of n have been less than -2.0, and the latest high resolution observations according to Feldman et al, indicate a value of n = -3, independent of auroral altitude. This latest value appears to be in good agreement with the theoretical calculations by Rees et al (1969), although the experimental measurements do not contain the theoretically predicted fine structure.

We discuss in this article whether the direct measurements of flux distribution are consistent with the observed optical aurora. The electron excitation functions of the $N_2$1P (first positive) and $N_2$2P (second positive) systems are sharply peaked in the low energy region (10-15 eV), as compared to those of the N_2^+1N (first negative) and N_2^+M (Meinel) systems, which have broad maxima in the region of 100 eV. The electron excitation rates of the N_2 positive systems relative to the N_2^+ systems are thus quite sensitive to the electron energy distribution in the 10-100 eV region. The four systems are allowed transitions, and it is generally agreed that the excited state populations in aurorae are, in effect, determined directly by electron excitation and radiative decay. There is some evidence suggesting other processes (cf. Hunten, 1958, Chamberlain, 1961, Broadfoot and Hunten, 1964, Shemansky and Vallance Jones, 1968) but the effects are small enough to be neglected for the purposes of the present discussion.

The following discussion of both ground based and rocket auroral measurements shows that the emission rates are consistent with the measured electron excitation cross-sections. However, the average relative emission rates correspond to a differential electron flux with a spectral index of $n \simeq -1.4$, suggesting a significantly larger proportion of energetic electrons than the distribution obtained from the direct observations of the low energy electron spectrum. The optical auroral observations along with physical considerations appear to place rather well defined limits on the electron energy distribution. The energy distribution obtained from the direct electron spectrometer measurements and the theoretical calculations predict relative emission rates of the N_2 positive and N_2^+ systems an order of magnitude different from those observed in the average aurora. The discrepancies are thus rather serious. If one attempts to explain the optical observations, using an $n = -3$ flux distribution for electrons in the 10 eV - 100 eV region, a large increase in the differential flux must be postulated at some energy $E > 100$ eV in order to account for the N_2^+ system emission rates. Given the characteristics of the average aurora, we suggest that a flux distribution of this kind extending from at least 200 km down to the lowest auroral altitudes, cannot be explained in a plausible manner.

II. Theory and Nomenclature

The volume emission rate of a band is written

$$I_{v'v''} = N_{v'}A_{v'v''} \quad (1)$$

where the symbols have their usual meaning. If there is no radiationless deactivation we may also write

$$I_{v'v''} = g_{v'}A_{v'v''}/A_{v'} \quad (2)$$

where $g_{v'}$ is the population rate.

$$I = \sum_{v'} \sum_{v''} I_{v'v''} = \sum_{v'} \sum_{v''} g_{v'}A_{v'v''}/A_{v'} = g \quad (3)$$

is the total volume emission rate.

For excitation by electrons the population rate ($g_{v'}$) is given by

$$g_{v'} = [N_2X] \int Q_{v'} \Phi \, dE \quad (4)$$

where $[N_2X]$ is the ground state population density and $Q_{v'}$ is the excitation cross-section to level v'. The values of $g_{v'}$ as observed in the aurora along with physical considerations place a constraint on the possible shape functions of the differential electron flux (Φ).

III. Relative Emission rates of N_2 and N_2^+ Systems

The relative emission rates, which are almost certainly equal to the population rates at normal auroral altitudes, can be obtained from Eq. 4 using measured excitation cross-sections, if one provides an electron distribution function.

The relative g_v values have been calculated using a distribution function $\Phi \propto E^n$. The predicted relative emission rates are given in the Figure as a function of the spectral index (n). It is clear that the emission rates of the N_2 positive systems relative to the N_2^+ systems are quite sensitive to the value of the spectral index. Note that the relative rates of the two positive systems and the two N_2^+ systems considered separately show very little variation. The $N_2$1PG emission rates used in the production of the graphs include the cascade contribution from the $N_2$2PG. The excitation functions used in the calculation are due to Shemansky and Broadfoot (1971a) for the N_2 positive systems at low energies, extended to higher energies through the measurements of Aarts et al (1969) and Brinkmann and Trajmar (1970). The measured thresholds of the cross-sections according to Shemansky and Broadfoot correspond to the spectroscopic energies of the excited levels above the ground state. Table 1 gives the peak values of the cross-sections along with the corresponding energies. The values given in the Table for the N_2^+1N system are based on the measurements by Borst and Zipf (1970), and those for the N_2^+M system are due to Shemansky and Broadfoot (1971a). Transition probabilities used in the calculation were obtained from the tables given by Shemansky and Broadfoot (1971b).

A measure of the spectral index (n) corresponding to the auroral emission rates can be obtained by plotting the various observations on the appropriate curves given in the Figure. A number of independent auroral observations are available in the literature, and the average values have been plotted as circled points. All of the points fall in the $n = -1.2 - -1.6$ region.

A number of details concerning the auroral measurements should be kept in mind in the following discussion. The relative emission rates of the N_2 positive and N_2^+ systems in the aurora vary on a short time scale, generally over a factor of about 2. According to ground based observations of $N_2$1P and N_2^+M emissions (Shemansky and Vallance Jones, 1968) the fluctuations are greater at high altitudes; on rare occasions the N_2^+M system was too weak to be measured relative to the $N_2$1PG, indicating a variation of an order of magnitude - the reverse situation of very weak $N_2$1PG relative to the N_2^+M system, was never observed. This tendency toward dominance of the $N_2$1PG at high altitudes appears to be a general characteristic of virtually all auroral types. Observations from the ground by Omholt (1957), Shemansky and Vallance Jones (1968) and the recent rocket measurements which are compiled here, all suggest a gradual decrease of the average emission rate of the $N_2$1PG with decreasing altitude, relative to either the N_2^+1N or N_2^+M systems. The vertical marks on the curves given in the Figure indicate the range of observed values which were averaged to produce the plotted points. Thus the observations suggest that the spectral index appropriate to an average auroral emission at high altitude in the 170-200 km region would be $n \approx -1.7$, and a type-B red aurora at 80 km, say, would typically correspond to $n = -1.0$.

The plotted average ratio (I2PG/I1N) was obtained from the measurements by Petrie and Small (1952) and Hunten (1955). The two sets of measurements are in very good agreement and fall in the region of $n = -1.3$ in the Figure. The average value due to Hunten is based on the average relative emission rates of the $N_2^+1N_{0,0}$ and $N_2 2PG_{0,2}$ bands. The value due to Petrie and Small is based on the emission rates of virtually all of the bands observable from the ground. The average ratios (I1PG/IM) are due to estimates by Chamberlain (1961) and Shemansky and Vallance Jones (1968). The value due to Chamberlain ($n \approx -1.3$) is derived from a compilation of a number of earlier measurements. The value due to Shemansky and Vallance Jones ($n \approx -1.6$) is based on the average ratio ($I1PG_{4,1}/IM_{3,0}$). All of the average ratios ($I1PG_{5,2}/I1N_{0,0}$) are due to rocket-borne photometric observations on NASA flights 4.163, 4.217 and 4.309. All of these observations although more transient in nature, fall in the same region of spectral index, $n = -1.2 - -1.4$. We do not include the measurements of flight 4.162 due to the unusual, spectacular variations that are not at all representative of normal aurora (cf. Donahue et al,1968). The measurements obtained on flight 4.217 were obtained at only two points in the low altitude region due to contamination by moonlight in the $N_2$1PG photometer. The results of this flight are included here for the purpose of comparison with low energy electron spectrometer measurements (Feldman et al,1971) in the same experimental package.

Thus all of the auroral measurements are consistent with the measured electron excitation cross-sections in that the observed average relative emission rates can be reproduced with a single electron flux distribution function.

The relative intensities of the long and short wavelength ends of the auroral spectrum have always been rather uncertain, for a number of reasons. Photographic spectra were difficult to analyze due to the limited dynamic range and the necessity of comparing features with widely differing differential brightness to brightness ratios. Photoelectric scanning spectrometers were limited in sensitivity and only one set of auroral measurements simultaneously enclosing the N_2^+1N and $N_2 1P$ systems has been published (Hunten, 1955). Extinction of the short wavelength emissions in the lower atmosphere added to the difficulties. As a result, estimates of the auroral $N_2 1P$ and N_2^+M brightnesses have been indirect for the most part, and uncertain to the tune of factors of 2 or 3. However we now have the rocket-borne photometer measurements of the $N_2 1PG_{5,2}$, $N_2 1PG_{4,1}$, and $N_2^+1N_{0,0}$ bands. The positions of the measured points on the I2PG/IN, I1PG/IM, and $I1PG_{5,2}/I1N_{0,0}$ curves of the Figure clearly conform to the relative emission rates (I1PG/I2PG) predicted from the measured electron excitation cross-sections. Thus we now appear to have a good measure of the $N_2 1PG$ and N_2^+M emission rates in average aurorae. The earlier estimates by Chamberlain (1961) and Shemansky and Vallance Jones (1968) thus appear to be a factor of about 3 too large. The predicted relative population rates of the $C^3\pi_u$, $B^3\pi_g$, $A^3\Sigma_u^+$, $A^2\pi_u$, $B^2\Sigma_u^+$ states in average aurorae ($n = -1.37$) are given in Table 2. The total population rates correspond to the auroral brightness (kR) in an IBCI aurora, for the corresponding transitions. The predicted relative rates for the N_2V-K ($A^3\Sigma_u^+ - X^1\Sigma_g^+$) system in the $v' = 0,1$ levels are about an order of magnitude greater than the ground based measurements (cf. Broadfoot and Hunten, 1964) due to the high radiationless deactivation rate of the $A^3\Sigma_u^+$ state; the measured relative rate $IV\text{-}K_0/I2PG_{0,0} \approx 4.8$ at 200 km (Sharp, 1971), where the radiationless deactivation rate is much slower, is in good agreement with the predicted value from Table 2, $IV\text{-}K_0/I2PG_{0,0} = 5.9$.

IV. Discussion

It is clear that the functional relationship of g_v and Φ is not unique in that a number of different electron distribution functions could produce the same set of relative g_v values for the four systems. However the average auroral relative emission rates dictate that the excitation of the N_2 positive systems must be due mostly to electrons with energies $E < 100$ eV; the electron excitation cross-sections of the N_2 positive systems are far too low above 100 eV and decrease too rapidly (cf. Brinkmann and Trajmar, 1970) with increasing energy in comparison with the N_2^+ systems, to account for the observed auroral relative emission rates. Thus the N_2 positive systems require a relatively large low energy differential electron flux due to the sharply peaked cross-sections at 11 eV and 15 eV in order to produce emission rates comparable to the N_2^+ systems, in the average auroral ratio. The question then is whether the flux of low energy electrons is also largely responsible for the N_2^+ emission in the average aurora.

In the above calculations we assumed that the differential electron flux $\Phi \alpha E^n$ for $E > 7.4$ eV. This shape function conforms with the observed electron spectra, and with the envelope of the calculated spectra (cf. Stolarski, 1968, Rees et al, 1969). However the value of the spectral index determined here ($n \stackrel{\sim}{\sim} -1.3$) from the optical measurements is significantly smaller in magnitude than either the recent electron spectrometer measurements of flight 4.217 (Feldman et al 1971) or the theoretical calculations ($n \stackrel{\sim}{\sim} -3$); the measured ratio ($I1PG_{5,2}/I1N_{0,0}$) on flight 4.217 is an order of magnitude lower than one would expect with a differential electron flux having an index of

$n = -3$ (cf. Figure). Errors in the measurement of the electron excitation cross-sections of this magnitude are out of the question, especially in view of the results presented in the Figure. If we apply a spectral index of $n = -3$ extending from $E = 7.4$ eV to $E \gtrsim 100$ eV as the Feldman et al estimate indicates, it would be necessary to introduce a large increase in Φ at some higher energy region $E > 100$ eV to account for the N_2^+ emission rate. A distribution in Φ of this nature would be very difficult to explain in physical terms at normal auroral altitudes. As the plotted point for flight 4.217 suggests, there is no indication that the particular aurora contained characteristics deviating significantly from an average aurora. We must then explain how a deep well in the electron spectrum could exist in the energy region $100 \text{ eV} < E < 1 \text{ keV}$, say, in normal aurorae, extending from the region of 200 km down to the lowest auroral altitude. At normal auroral altitudes the low energy secondary electrons must be produced locally (cf. Chamberlain, 1961), by the precipitating primary electrons. The proposed distribution in Φ thus could not be explained without the introduction of a variable accelerating electric field, since, on the scale of energies we refer to here, the differential production rate of secondary electrons and the loss rates to thermal electrons and neutral particles are all monotonic increasing functions with decreasing energy (cf. Rees et al, 1969). The net effect is the production of a monotonic increasing Φ with decreasing energy, with the imposition of some small scale structure due to energy loss to the neutral particles. Note that the structural feature at $E \gtrsim 15$ eV in the Rees et al calculation would be much less pronounced and possibly not measurable in the noise of the measured spectrum, if one applied the more recent experimental excitation functions of the N_2 systems .

If an electric field is introduced to explain the proposed distribution in Φ, the uniform distribution of N_2 and N_2^+ relative emission rates in the 100 km - 200 km region observed in the rocket flights into normal aurorae could not be reasonably explained. On the contrary one would expect highly variable relative emission rates such as those measured on NASA flight 4.162 (Donahue, et al 1968).

In summary, we suggest that the relative emission rates of the N_2 and N_2^+ systems cannot be explained in a plausible manner with respect to the measured differential electron flux. The peculiar electron distribution function one must postulate for energies $E > 100$ eV to explain the optical aurora, given the measured distribution for $E < 100$ eV, could not be maintained over the 100 km region of altitude as dictated by the auroral characteristics. In our opinion serious consideration should be given to the possibility that difficulties in the direct measurement of the electron spectrum may contribute to the discrepancy. It is noteworthy that the uncorrected electron energy spectrum measured directly on flight 4.163 (Parkinson et al, 1970) yields a spectral index, $n = -1.35$, remarkably close to the present average value obtained from the relative emission rates. The theoretical computations of Φ, which display an envelope distribution $\Phi \alpha E^n$, also do not correspond to the optical observations. The structural features in the Rees et al computation, if one applies the more recent excitation functions, have little effect on the calculated relative emission rates, and the theoretical estimates would correspond roughly to $\Phi \alpha E^{-3}$ in the energy region of interest. The measured auroral relative emission rates of the N_2 positive and N_2^+ systems correspond to those predicted from the measured electron excitation cross-sections for a differential electron flux distribution $\Phi \alpha E^n$ for $n = -1.2 - -1.4$.

The recent rocket borne experiments appear to have finally provided a reasonably accurate measure of the emission rates of the long wavelength auroral features relative to the short wavelength emissions. Table 2 shows the predicted relative population rates of the states involved in the above discussion (n = -1.37), for an average aurora. An estimate of the population rates of the $N_2A^3\Sigma_u^+$ state is included. Both the gound based and rocket borne optical measurements indicate a gradual average increase in the $N_2$1PG emission rate, relative to either of the N_2^+ systems, with increasing altitude. According to the rocket observations this trend continues at least up to the region of 200 km. This apparent softening of the electron spectrum at the higher auroral altitudes suggests that the primary electron flux may contain a rather broad spectrum of energies, extending to relatively low energies.

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TABLE CAPTIONS

Table I. Measured Peak Electron Cross-Sections (Q_v) of N_2 and N_2^+ States for Excitation from $N_2 X^1\Sigma_g^+$

a. E_{TH} - threshold energy.

E_P - energy at peak cross-section.

b. From Shemansky and Broadfoot (1971a).

c. Rough estimate by Shemansky and Broadfoot (1971a) from energy loss measurements by Williams and Doering (1969), Brinkmann and Trajmar (1970), relative to $B^3\pi_g$.

d. From Borst and Zipf (1970) measurements of $N_2^+ 1N_{0,0}$ band.

Table II. Predicted Relative Population Rates (g_v) of N_2 and N_2^+ States in Average Aurora.

a. Includes cascade contributions from $N_2$2PG.

b. Includes cascade contribution from $N_2$2PG and $N_2$1PG.

c. Total relative rates represent Brightness in kR in IBCI aurora for the appropriate transitions, provided the populations are controlled entirely by radiative deactivation.

Table I

Measured Peak Electron Cross-Sections (Q_v) of N_2 and N_2^+ States for Excitation from $N_2 X^1\Sigma_g^+$

v	E_{TH}/E_p (a) eV	$C^3\pi_u$ (b) $x10^{-17} cm^2$	E_{TH}/E_p eV	$B^3\pi_g$ (b) $x10^{-17} cm^2$	E_{TH}/E_p eV	$A^3\Sigma_u^+$ (c) $x10^{-17} cm^2$	E_{TH}/E_p eV	$A^2\Sigma_u$ (b) $x10^{-17} cm^2$	E_{TH}/E_p eV	$B^2\Sigma_u^+$ (d) $x10^{-17} cm^2$
0	11.0/14.7	2.1	7.4/10.2	0.73	6.2/9.1	0.017	16.7/100	3.0	18.8/100	2.48
1	11.3/15.0	1.15	7.6/10.4	1.8	6.3/9.2	0.094	16.9/100	3.8	19.0/100	0.262
2	11.5/15.2	0.42	7.8/10.6	2.3	6.5/9.4	0.27	17.2/100	2.8	19.3/100	0.0028
3	11.7/15.4	0.12	8.0/10.8	2.3	6.7/9.6	0.54	17.4/100	1.5		
4			8.2/11.0	1.8	6.8/9.7	0.88	17.6/100	0.70		
5			8.4/11.2	1.3	7.0/9.9	1.21	17.8/100	0.29		
6			8.6/11.4	0.78	7.2/10.1	1.47				
7			8.8/11.6	0.46	7.3/10.2	1.65				
8			8.9/11.8	0.26	7.5/10.4	1.70				
9			9.1/12.0	0.14	7.6/10.5	1.65				
10			9.3/12.2	0.070	7.8/10.7	1.53				
11			9.5/12.4	0.036	7.9/10.8	1.36				
12			9.6/12.5	0.018	8.1/11.0	1.17				
13					8.2/11.1	0.98				
ΣQ_v		3.8		12.0		18.0		12.0		2.76

(a) E_{TH} - threshold energy, E_p - energy at peak cross-section.

(b) From Shemansky and Broadfoot (1971a)

(c) Rough estimate by Shemansky and Broadfoot (1971a) from energy loss measurements by Williams and Doering (1969), Brinkmann and Trajmar (1970), relative to $B^3\pi_g$.

(d) From Borst and Zipf (1970) measurements of $N_2^+ 1N_{0,0}$ band.

TABLE II

Predicted Relative Population Rates (g_v) of N_2 and N_2^+ States in Average Aurora

v	$C^3\pi_u$	$B^3\pi_g$ (a)	$A^3\Sigma_u^+$ (b)	$A^2\pi_u$	$B^3\Sigma_u^+$	
0	0.52	0.73	1.50	1.90	1.42	$C^3\pi_u$ - $B^3\pi_g$ - $N_2$2PG
1	0.28	0.98	1.45	2.40	0.150	$B^3\pi_g$ - $A^3\Sigma_u^+$ - $N_2$1PG
2	0.10	1.15	1.20	1.77	0.0016	$A^3\Sigma_u^+$ - $X^1\Sigma_g^+$ - N_2V-K
3	0.029	1.07	1.00	0.95		$A^2\pi_u$ - $X^2\Sigma_g^+$ - N_2^+M
4		0.83	0.92	0.44		$B^2\Sigma_u^+$ - $X^2\Sigma_g^+$ - N_2^+1N
5		0.57	0.92	0.19		
6		0.35	0.93			
7		0.21	0.93			
8		0.11	0.92			
9		0.060	0.87			
10		0.030	0.80			
11		0.015	0.70			
12		0.007	0.59			
13			0.50			
Σg_v (c)	0.93	6.1	15.2	7.6	1.58	

(a) includes cascade contribution from $N_2$2PG.

(b) includes cascade contribution from $N_2$2PG and $N_2$1PG

(c) Total relative rates represent brightness in kR in IBCI aurora for the appropriate transitions, provided the populations are controlled entirely by radiative deactivation.

Figure Caption

Relative Emission Rates of N_2 and N_2^+ Systems as a Function of Electron Energy Distribution*.

(1) Hunten (1955)

(2) Petrie and Small (1952).

(3) Chamberlain (1961)

(4) Shemansky and Vallance Jones (1968).

(5) NASA Flight 4.163

(6) NASA Flight 4.217

(7) NASA Flight 4.309

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*Differential electron flux $\Phi \alpha E^n$.

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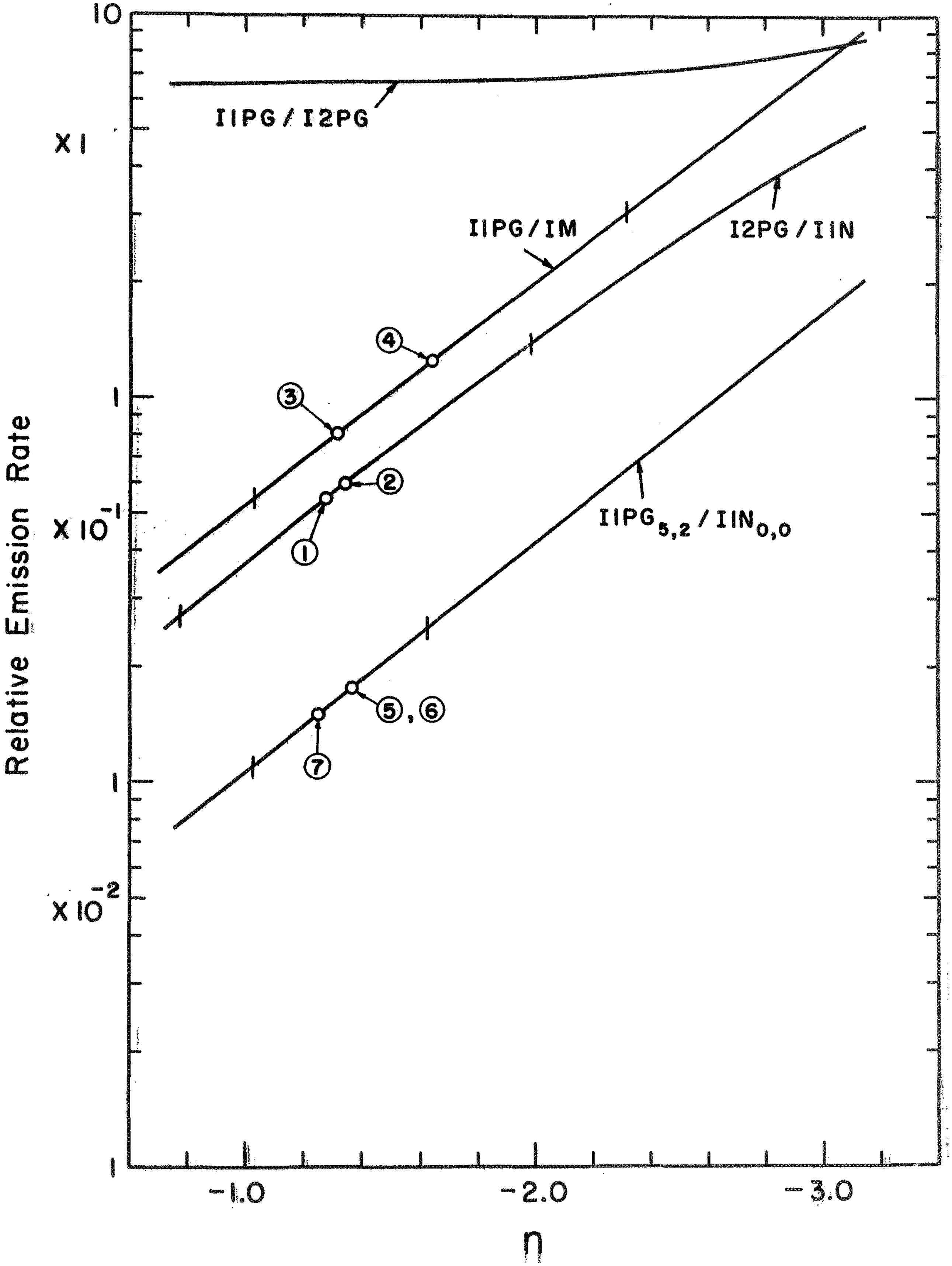
10
X1
1
X10⁻¹
1
X10⁻²
1
Relative Emission Rate
I1PG/I2PG
I1PG/I1M
I2PG/I1N
I1PG5,2/I1N0,0
①
②
③
④
⑤, ⑥
⑦
-1.0
-2.0
-3.0
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