Radiative Processes in Thermionically Controlled Discharges in Helium

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Recent measurements have been made of the intensity of radiation from the low voltage arc in helium as a function of gas density, tube current and tube potential. The experimental results indicate that the radiation is the result of a primary electron process. This process has been generally assumed to be direct excitation. Such an explanation is not fully in accord with the phenomena observed. The possibility of an unrecognized process is suggested.

INTRODUCTION

IN an attempt to lay a foundation for study of the abundance curves of quantitative spectrochemical analysis, O. S. Duffendack and O. G. Koppius[1] investigated the variation of intensity with abundance in gas mixtures. Over the range in densities investigated, the curves were found to be of the saturation type. This saturation was interpreted as the complete utilization of available primary electrons in inelastic impacts, direct excitation being regarded as the source of the radiation.

The initial purpose of the present research was to extend this knowledge to more complex cases involving primary electrons of sufficient energy to undergo multiple collisions. For this purpose intensity *versus* helium abundance curves were plotted for a number of electron velocities. It was immediately apparent that the simple excitation theory was not capable of satisfactory extension either to variable electron velocity or large abundances. The projected research then developed a twofold objective: first, to obtain exact information about the dependence of the discharge intensity upon its controlling variables, and second, to propose a more satisfactory mechanism to account for the observed results. Accordingly a precise investigation was made of the density-intensity and current-intensity relations in the discharge over wide ranges of gas density and current. Many attempts were made to formulate corrections of the simple excitation theory which would explain the observed data, but no progress has been made toward an adequate approximation.

PART I

Apparatus

Many experimental tubes were employed during the course of the investigations. In their basic features the tubes were all quite similar. A cylindrical cathode 4 mm in diameter and 50 mm long, coated with a mixture of barium and strontium oxides was surrounded by a concentric anode cylinder 16 mm in diameter. The system was then placed with its axis perpendicular to a plane quartz viewing window, through which the entire discharge could be observed with a spectrograph.

Tube elements were made of nickel; leads were tungsten sealed to glass, and the one piece construction of the tubes was completed, in the case of the principal experimental tubes, with quartz windows sealed on by means of graded seals. The tubes were then connected to a mercury diffusion pump via a barium getter tube, sodium trap, and liquid air traps. It was possible to isolate the system from the pumps by stopcocks.

The various tube elements were thoroughly outgassed by means of an induction furnace or direct electrical heating. The barium getter served to remove any belated traces of carbon dioxide released by the oxide coating. The sodium getter and liquid air prevented mercury vapour from diffusing into the tube from the MacLeod gauges. Hydrocarbon vapors from the greased stopcocks were controlled by the liquid air. The effectiveness of these precautions was attested by the fact that only slight traces of the extremely sensitive carbon monoxide bands in the ultraviolet were observed in an intense three-day exposure of the discharge in helium.

Oxide-coated equipotential cathodes were used to restrict the range of velocities of the emitted electrons. No tests were made of the actual distributions involved, but it was assumed that deviations are small on the average, since previous investigators have demonstrated the homogeneity of the electron beams obtained in this manner.

Helium was chosen as the medium of the research,

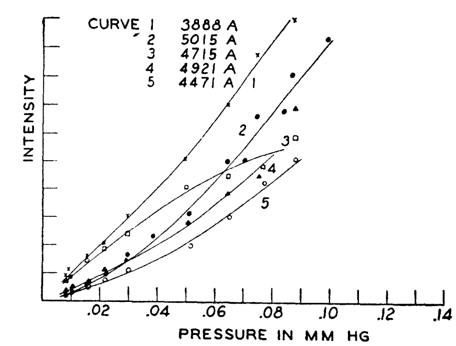

FIG. 1. Abundance curves for five characteristic transitions in the low pressure region. Tube potential 70 volt: tube current 50 milliamperes.

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[1] O. S. Duffendack and O. G. Koppius, Phys. Rev. 55, 1199 (1939).

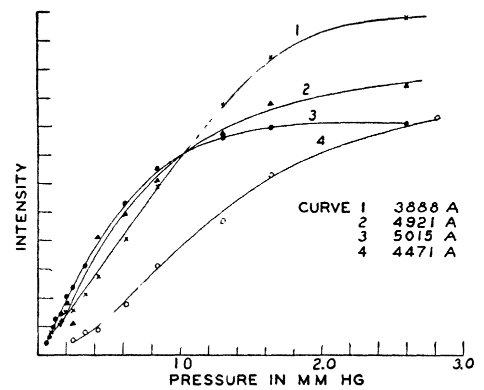

FIG. 2. Abundance curves for four characteristic transitions in the middle pressure region. Tube potential 70 volts; tube current 50 milliamperes.

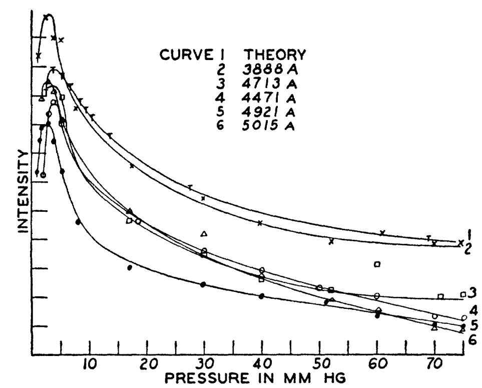

FIG. 3. Abundance curves for five characteristic transitions in the high pressure region. Tube potential 50 volts; tube current 30 milliamperes.

because of the simplicity of its spectrum, its chemical inertness, and the ease of manipulation in vacuum technique.

Since the relative intensities of the spectral lines were measured by a method of photographic spectrophotometry, methods of plate calibration and standard intensities became a critical factor in the investigations. The choice of helium for a gas made the spectral lines available for use fall in a rather undesirable sensitivity region of the photographic emulsion. In the visible and near ultraviolet, the change in plate contrast with wave-length renders the use of an internal calibration unreliable over large ranges of intensity variation, if the wave-length separation of the line pairs is appreciable. For this reason a modification of the ordinary procedure was adopted. Studies of the glow discharge in helium have shown that this discharge remains sensibly constant in intensity if the tube is properly prepared and the discharge circuit carefully controlled. Such a lamp, diaphragmed to the requirements of a point source, was placed on an optical bench so that its alignment and distance from the spectrograph slit could be accurately and quickly set, and a succession of calibration exposures was taken at graded distances, using the same exposure time that was used on the experimental spectra. By use of the inverse square law it was then possible to obtain a calibration at every desired helium wave-length, calibrated in light of exactly that wave-length. The intensity ratios of the experimental wave-lengths could thus be measured in units of the intensity of the identical wave-lengths emitted by this particular glow discharge tube.

A medium dispersion Hilger quartz spectrograph provided ample resolution for this work, and was used because of its speed and convenience. The spectrograph was fitted with a fixed slit to avoid the uncertainties inherent in a movable slit.

Eastman 103-B and Wratten Process Panchromatic plates were used, and photometry was carried out on a direct reading modified Moll-type microphotometer. The precision of this instrument was such that galvanometer deflections could be reproduced within 2 percent over a period of several hours.

The electrical circuits involved were extremely simple. It was chiefly necessary to have plate and filament supplies which did not vary appreciably during the interval required for the longest exposure, This was accomplished by using storage batteries in a balanced charge-discharge circuit. Such an arrangement was stable enough to reduce fluctuations in the plate voltage to less than 1 percent.

Quantitative Experimental Results

The dependence of the intensity of the spectral lines upon tube current was investigated at both high and low gas densities holding tube potential constant. The relationship was found to be linear within the experimental error between the extremes of 1.4×10^{14} and 2.5×10^{16} atoms per cubic centimeter.*** This relationship was observed for all types of transitions, and over a current range from one to one hundred milliamperes. This is in accordance with and further extended by the work of Lees[2] who reports a linear de-

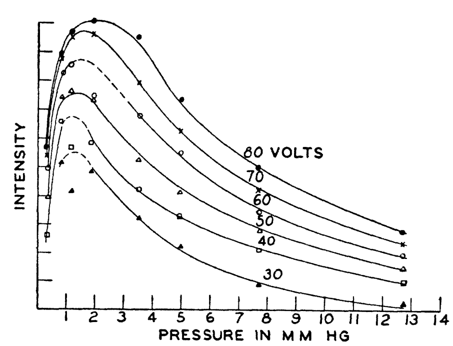

FIG. 4. A family of abundance curves at various tube potentials for the 5015A line of helium; 10 milliamperes tube current.

*** The range of these measurements has been extended recently to 10^{18} atoms per cubic centimeter in a series of experiments which will be reported later. No essential deviations from linearity have been observed.

[2] J. H. Lees, Proc. Roy. Soc. **137**, 173 (1932).

pendence existing as low as 0.2 milliampere for all transitions.

Spectral intensities as a function of gas density in particles per unit volume were investigated over a wide range of density extending from 2×10^{13} to 1×10^{18} molecules per cubic centimeter holding tube current and potential constant, for several representatives of each of five different line series in helium. These are given in Figs. 1, 2, and 3, plotted in different scales to bring out different regions of significance. Only one representative of each series is given, for it was found that all members of a given series have essentially the same form. Intensities are arbitrary for each line, being expressed in terms of the intensity of the same line in the standard lamp.

Particular attention should be paid to the form of these curves in the region of low densities, and in the region of high densities. At low densities the decrease of intensity is frequently in accord with a higher power of the density than the first power. This has been observed in every case and under comparable circumstances by Lees.

It was at first thought that the rapidly decreasing intensity of the discharge at high densities might result from occulatation of the part of the discharge in the vicinity of the rear of the 50-mm long cathode by the front end of the cathode. A lens was therefore introduced between the spectrograph slit and discharge tube in such a position that the image of the rear of the cathode as seen from the collimator lens of the spectrograph appeared slightly larger than the image of the front end. The light from the rear of the cathode should then have been 90 percent recorded even in the case of discharge layers extremely close to the cathode surface. This, combined with an improved technique of photometry, produced only a slight reduction in the rate of decay from saturation as can be seen by comparing Figs. 3 and 4.

All of the density curves have essentially the same form, rate of decay, and location of the maximum. One outstanding exception is found in the 2^3P-3^3D transition which had a broader maximum and slower rate of decay than the others. The maximum was located at about 15 mm Hg pressure, about five times the value found for other transitions. Since this transition is the yellow line at 5875A, the anomaly leads to a pronounced color change in the discharge between high and low pressures, the high pressure discharge being yellow, while the low pressure discharge is blue green.

Intensity as a function of density at different tube potentials holding current constant is given as a family of curves for the 2^1S-3^1P transition (5015A) of helium in Fig. 4. These measurements are somewhat inferior to those of the curves of Figs. 1–3, since they were made earlier using a step diaphragm calibration and an internal standard calibration line. This resulted in undue emphasis of the departure from linearity at low densities and the decay from saturation at high densities.

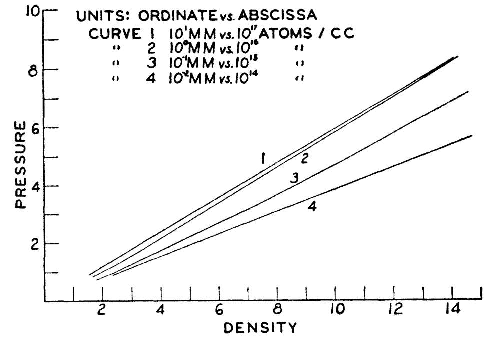

FIG. 5. Density (in atoms per cc) *versus* gas pressure in millimeters. For use with Figs. 1–4. The densities have been computed by the use of gas temperatures measured under operating conditions.

TABLE I. Gas temperatures °K.

Pressure (mm Hg)	Radius (cm) 0.00 (cathode)	0.15	0.29	0.44	0.58 (anode)
4.74	586	546	540	493	480
1.84	533	518	492	466	446
1.05	516	493	462	448	433
0.39	457	437	421	408	397
0.17	441	422	395	381	369
0.044	416	400	378	366	359
0.014	470	449	417	396	383
0.005	468	447	415	394	381

Figure 5 is a conversion curve to give gas densities from the experimentally observed pressures. Extensive measurements were made of gas temperatures in the discharge to obtain the data for Fig. 5. The temperatures were measured by means of a fine wire platinum-platinum rhodium thermocouple mounted as a probe which could be passed at will through a hole in the anode. Data were taken on the temperature with discharge on and off over the entire range of gas pressures used, and at several positions between anode and cathode.

The actual significance of such temperature measurements in gases at low pressure is uncertain. It was assumed, however that the results were an approximation to the true gas temperature. Other than the use of a very fine thermocouple wire, no precautions were taken against loss of energy by conduction, so that the temperatures must be regarded as minimum values.

At first the probe was used naked, but in a later series of experiments a small shield was placed over the tip, thermally insulated from it, to reduce the effect of radiation on the couple. Measurements were made on the gas temperature as a function of position of the probe and gas pressure maintaining the plate current constant at 40 ma and the plate voltage at 70 volts. These data are given in Table I.

The data in Table I include the effect of radiation on the thermocouple. This accounts for the rise in apparent

TABLE II. Curve fitted cross sections for hypothetical collisions of the second kind.

	q_2	Probability
5015A	1.2×10^{-15} cm^2	0.5
3964A	2×10^{-15} cm^2	0.5
4921A	6×10^{-16} cm^2	0.14
3888A	4×10^{-16} cm^2	0.16
5875A	2×10^{-19} cm^2	0.00006
4471A	2.5×10^{-16} cm^2	0.12

temperatures at the lower pressures. The temperature due to radiation alone was estimated by adjusting the color temperature of the cathode in vacuum to the same as that observed with gas in the tube. This showed the equilibrium temperature for the couple, under radiation only, to vary from 343°K at the anode to 392°K at the cathode for pressures greater than 0.050 mm Hg, and from 405°K at the anode to 508°K at cathode for the space charge limited case (less than 10^{-6} mm Hg).

It may be concluded from this that the temperature of the gas does not vary extravagantly from cathode to anode. In the observation of the pressure curves, measurements were made on the temperatures of the discharge at a point halfway from cathode to anode, using the shielded probe. These temperatures were used to compute the gas densities. They varied from 363°K at 0.011 mm Hg to 563°K at 10.4 mm Hg.

Interpretation of the Results

Conventional approaches to the analysis of the experimental data had been planned before the experiments were performed, along the lines indicated by Koppius.[1] Basic to this approach was the assumption that the radiation observed is the result of direct excitation by electron impact. Implied also are assumptions regarding the mechanism of the low voltage arc. These are, briefly, that the thermionically emitting cathode is surrounded by a thin single or double sheath, the thickness of which depends on tube potential and gas density, with practically the entire anode-cathode potential difference being concentrated in the region of this sheath.[1] The rest of the discharge space is filled with a plasma in which weak long range fields are experienced by the charged particles. The plasma serves as a reservoir of positive ions from which the positive ion space charge of the sheath is maintained. Electrons accelerated by the strong cathode fall of potential in the sheath produce ionization and excitation in the plasma while moving as in a field free space. Difficulty was encountered early when an attempt was made to discuss the experimental results on the basis of this assumption. The theory developed by Koppius calls for exponential saturation curves of the form

$$I=I_0(1-e^{-QDL})$$

where I is the intensity of the radiation at the gas density D, I_0 is the intensity at full utilization of the primary electrons, Q is the total cross section for inelastic impacts, and L is a discharge-space parameter. Such an equation obviously does not describe the observed behavior of the density-intensity curves at either end of the density scale.

Any departure from a saturation curve of this form implies either that there is a deficiency in the production of excited systems, or that there is a process of destruction of these systems other than the radiative process. A number of possible processes have been considered, all of which have seemed unsuitable to account for this behavior: (1) Collisions of the second kind between excited atoms and either plasma electrons or normal atoms; (2) extinction of excited atoms by diffusion to the electrodes and walls; (3) a reduction in the actual number of primary electrons because total (electron plus positive ion) current was maintained constant under experimental conditions while the positive ion current must increase with increasing gas density; (4) loss of primary electron energy by electron-electron impacts in the plasma.

Considering each of these processes, diffusion losses must be so rare as to be negligible in the extreme, while collisions of the second kind are of uncertain importance. The loss of excited systems of a particular state j between plane electrodes one of which emits primary electrons will be governed under the assumptions cited by Koppius by the differential equation

$$\frac{\theta}{D}\frac{d^2C}{dx^2}-\sum_k A_{jk}C-q_2DCv-q_2'C_eCv_e=-\frac{i}{e}q_jDe^{-QDx}. \quad (1)$$

In this equation C=excited atom concentration, D=normal atom concentration, θ=diffusion coefficient at unit concentration, A_{jk}=Einstein transition probability from state j to state k, q_2=cross section for normal atom-excited atom collisions of the second kind, q_2'=cross section for excited atom—plasma electron

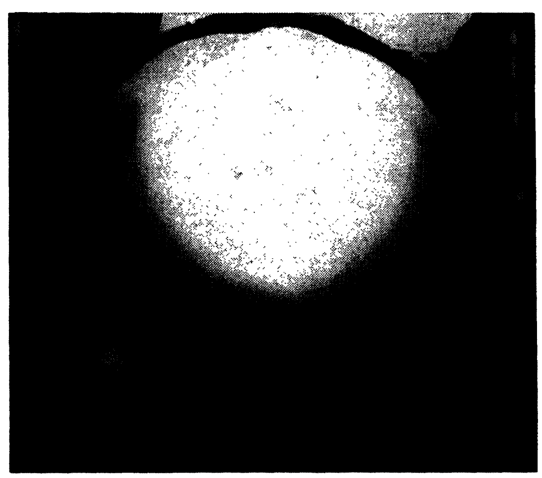

FIG. 6. Radiation produced in helium by an electron beam projected into space. 60 volts accelerating potential; 0.1 mm pressure.

collisions of the second kind, C_e = plasma electron concentration, v_e = plasma electron velocity, v = average speed of gas molecules, i = primary electron current, e = electron charge, q_j = cross section for excitation of state j, Q = total collision cross section for inelastic impacts.

The relative importance of the diffusion term can be determined by an investigation of the number of atoms lost at the boundaries relative to those emitting radiation freely in space. This is found to vary asymptotically as the fraction $(DQ^2\theta/A_j)^{\frac{1}{2}}$, where $A_j = \sum_k A_{jk}$. Evaluation using $\theta = 1.4\times10^{19}$ cm/sec., $Q = 8\times10^{-17}$ cm^2 (after Normand), $A_j = 10^7$ sec.$^{-1}$, and $D = 2.5\times10^{17}$ atoms per cc (this value being that at which the decay in intensity is half), fixes the proportion between these losses at about $1:10^6$, a wholly negligible amount.

Collisions of the second kind between excited atoms and plasma electrons, will only be important if the second and fourth terms of Eq. (1) are of the same order of magnitude. Assuming that the concentration of ions does not exceed 1 percent that of neutral atoms and that there is an average electron energy of about 1 volt, q_2' must be of the order of 10^{-15} cm^2, if all collisions are inelastic. Although this is rather large it is not prohibitive, and a second argument is more certain. Such a process is jointly proportional in frequency to two quantities (C_e and C) which each vary linearly with current. Its effect upon the tube intensity should thus be quadratic in current. Since, however, the tube intensity was found to vary linearly with tube current, the presence of such a process is unlikely.

The loss of excited atoms by collisions of the second kind with normal atoms is much more likely to be important. The solution of Eq. (1) for this process would be

$$I = \frac{I_0(1 - e^{-QDL})}{1 + (q_2 v D/A_j)} \tag{2}$$

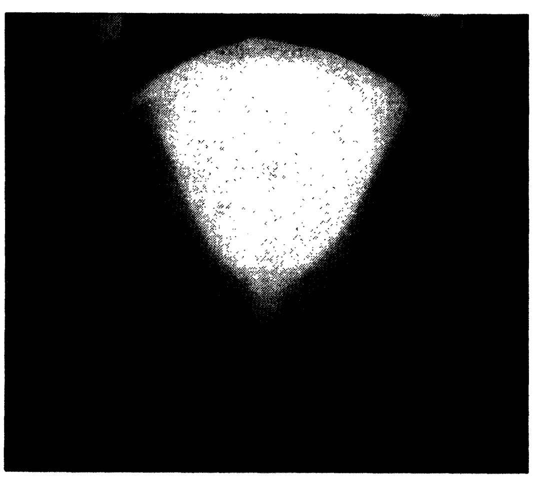

FIG. 7. Radiation produced in helium by an electron beam projected between metal plates, in comparison with Fig. 6, the influence of the electrodes on the contour of the discharge can be seen. 0.04 mm pressure; 60 volts accelerating potential.

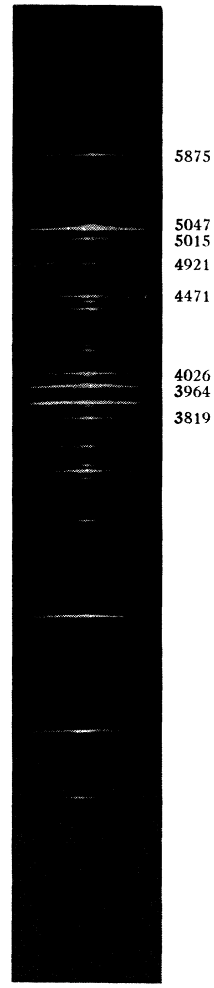

FIG. 8. Spectrogram of the glow around an electron beam projected between metallic electrodes. 100 volts accelerating potential; 0.06 mm pressure.

where I_0 is the saturation intensity neglecting losses. This equation can be made to give an excellent fit to the observed data, and the cross section q_2 which would be needed can be evaluated. In Table II values of this cross section for several observed transitions are given. Given also is an estimate of the ratio between this cross section and a theoretical cross section calculated from radii of the normal and excited atoms. This might be interpreted as the probability of the process. Seemingly satisfactory as the general agreement is, the process demands that an overly large proportion of the collisions result in a complete transfer of the excitation energy to kinetic energy. In addition, certain other data which will be described in Part II of this paper seem capable of common explanation, which this does not afford. It is extremely probable, however, that this process is in some measure active in the discharge. It is impossible to decide for or against this process on a basis of these experiments.

Of the processes affecting the number of primary electrons available, the reduction of the actual number of primary electrons available for impact when total tube current is held constant, cannot be evaluated without a solution of the second order, second degree, inhomogeneous differential equation governing the behavior of free ions. If recombination could be neglected, the primary electron current would be

$$i_e = i_T/(1+2q_i/Q)$$

in terms of the tube current i_T. This represents a maximum of the reduction to be expected from this cause, and would amount to about $\frac{1}{2}$. It is certainly not adequate to explain the observed decay of intensity.

The second process, impacts between the primary electrons and the plasma electrons, is a matter for uncertainty. Diverse opinions have been expressed on the importance of this process. A wave mechanical treatment of the problem of the energy losses of low speed electrons traveling through an electron gas has not been found. Such classical computations as have been attempted seem to place the process very close to the border of significance. Further attention must be given to this possibility, even though any large losses from such a process would be expected to affect the tube current—intensity relation in a fashion other than linearly.

During the period in which the experiments described above were done, the observations from another set of experiments suggested an alternative explanation to the authors. These experiments will be described in Part II of this paper.

Diffusion processes might be invoked to account for the decay in tube intensity with density if the lifetime of the system radiating were sufficiently long to permit migration. Serious consideration of the free ion as such a possible system is precluded by the necessary quadratic dependence of random recombination losses upon ion concentration, which must lead to non-linear dependence of intensity on tube current at all densities.

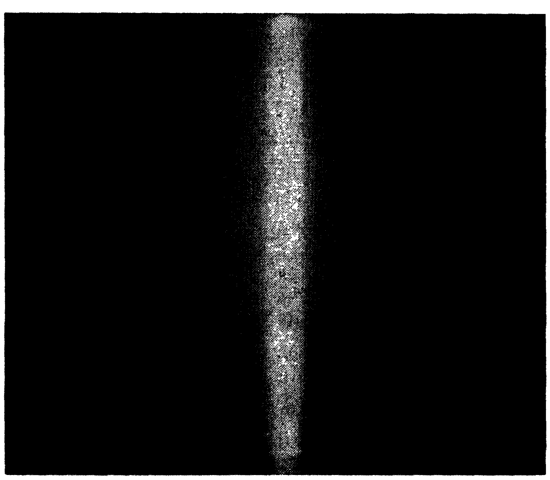

FIG. 9. Photograph, using green filter, of the 5875A glow about a beam passing between metallic plates. The accelerating potential on the beam has been increased to 100 volts.

To explain the observed effects as a diffusion process, and at the same time to satisfy the observed current-intensity relation requires the loss of excited systems to be a linear function of the concentration of the systems. Thus it is proposed that there may exist a process, as yet unrecognized explicitly, which fulfills these conditions.

Specifically it is suggested that in dense plasma regions the local fields are intense enough that the problem of recombination cannot be treated as the statistical extension of the problem of the incidence of a plane wave upon a center of force. The plasma electrons may not be free agents, but may bear established relationships with respect to the plasma as a whole as do the electrons in a metal. It is well established that in their diffusion, ions and electrons assist each other to migrate. During this process their mutual relations may be such as to promote recombination at a rate independent of the electron concentration. This process is essentially the one proposed by Franck,[3] and described as initial recombination. There have been others as well who proposed linear laws of recombination.[4]

In Fig. 3 a plot is made of the function which is obtained from the differential equation arising from a linear law of recombination. The constants used in the computation of this curve were the best which could be arrived at from the available data. The total inelastic collision cross section was estimated at 8×10^{-17} cm^2 by subtracting the theoretical elastic cross sections given by Mott and Massey[5] from the total collision cross sections of Normand.[6] The diffusion coefficient at unit density was calculated to be 2.0×10^{20} cm^{-1} sec.$^{-1}$ from the expression given by Schottky[7] for the ambipolar diffusion coefficient, using the kinetic theory value of the molecular diffusion coefficient, the gas temperature as measured in the discharge tube, and electron temperatures of the order of magnitude reported by Koppius. The linear recombination coefficient was chosen as 3×10^5 sec.$^{-1}$ for reasons which will be cited later. The curve obtained does not decay quite as rapidly as the experimental curves, but has the same general shape and the maximum is in the same general vicinity. While the introduction of a recombination hypothesis may itself be gratuitous, it should be noted that the other possibility (collisions of the second kind) could be active here also to reduce the population of the excited states and cause a greater rate of decay than was predicted by recombination alone.

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[3] J. Franck, J. Franklin Inst. **205**, 473 (1928).
[4] H. W. Webb and D. Sinclair, Phys. Rev. **37**, 182 (1931); W. R. Harper, Phil. Mag. **29**, 434 (1940); P. J. Nolan, Proc. Royal Irish Acad. **46A**, 77 (1940); F. L. Mohler and C. Boeckner, Bur. Stand. J. Research **2**, 489 (1929).
[5] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Clarendon Press, Oxford, 1933), p. 178.
[6] C. E. Normand, Phys. Rev. **35**, 1217 (1930).
[7] W. Schottky, Physik Zeits. **25**, 342 (1924).

PART II

Introduction

In one of the early experiments described in Part I it was observed that a beam of electrons emerging from a hole in the anode possessed a geometrically sharp core, but was surrounded by a nebulous cloud of glow which spread in all directions. This beam was assumed to be well collimated because of the large ratio between the electron energy supplied by the tube potential and the thermal agitation energy for electrons leaving the cathode surface, but this effusion of glow has been observed by others[8] even with beams carefully collimated by successive pinholes. While there are certainly other origins possible for this effused glow, the phenomenon would be a necessary attribute of such a diffusion process as was proposed in Part I, and hence was given further study.

Apparatus

Tubes were constructed in which a beam of electrons could be admitted to a spacious region visible through a large quartz window. In one style of tube the beam was flanked on both sides by a pair of electrodes 4 cm apart by means of which a field could be applied to the region containing the beam. A discharge was maintained between a cylindrical cathode and anode as in the previous experiments. The anode cylinder was attached to a plane metal shield cut to fill the aperture between the tube housing the discharge and the tube for viewing the beam. A 4 mm diameter hole was made through cylinder and shield on their line of tangency. An intense discharge of about 100 milliamperes was maintained in the main discharge, and on a basis of the relative areas of the hole in the anode cylinder through which the beam passed, and the anode as a whole, the current in the beam must have been about 1 milliampere.

Experimental Results

The sharp delineation of the path of the primary electrons was one of the striking features of the experiment. The beam remained coherent to the end of its range, broadening slightly because of the curvature of the cathode surface from which the electrons were emitted, and because of the mutual repulsions of the electrons.

The glow was distributed with cylindrical symmetry about the beam in tubes which contained no auxiliary electrodes. Introduction of electrodes into the view space caused a diminution of the glow in the vicinity of the electrodes from that which was present without them. Figures 6 and 7 illustrate this, presenting the discharge under similar conditions in tubes without and with electrodes.

Spectra were made of the glow by imaging the primary beam upon the slit of the spectrograph, the beam crossing the middle of the slit at right angles. Such a spectrogram is given in Fig. 8. It will be seen that the composition of the radiation from the glow differs little with that from the central beam.

No measurements were actually made of the proportion of radiation between beam and glow, desirable as these would be. Estimates of the proportion visually, and from the spectrogram of Fig. 8, indicate at least equivalence. Estimates from such a photograph as Fig. 7 would be less, but will be misleading because of the unknown contrasts of the film and prints. Future measurements of this quantity are contemplated.

Application of cross-fields to the glow show that it is affected markedly. Figures 9 and 10 show contrasting photographs of the glow with and without fields. The region surrounding the negative electrode is cleared completely of radiating systems, if the potentials applied are not excessive. There is a slight increase in radiation from the anode side of the beam. At high potentials (greater than 150 volts in the present case) the situation was complicated by the appearance of the negative glow discharge around the field cathode. As noted in a paper by Gurney and Morse[9] potentials applied to a region in which a plasma is being maintained do not produce the fields which would be expected in vacuum. The field is largely concentrated in sheaths around the electrodes, leaving the plasma almost field free. Estimates of the field in the plasma made from the deflection of the electron beam indicate that the beam moved in a cross-field of not more than 1.5 volt per cm, even though the potential difference between the electrodes was 300 volts at a separation of only 4 cm.

The effects described were present without alteration of any feature except the extension of the glow, for values of density from 5×10^{14} atoms per cc to 5×10^{16} atoms per cc, at which latter point the range of the

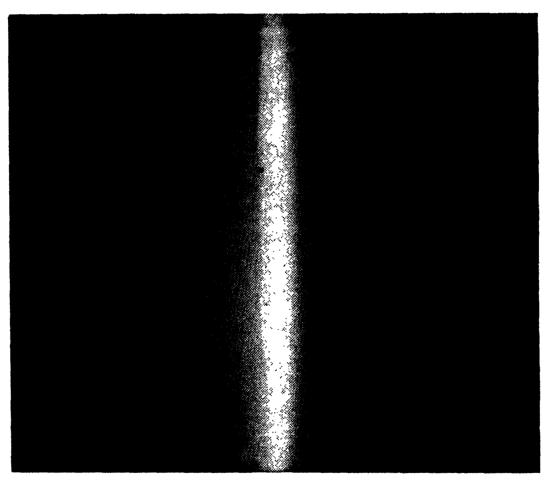

FIG. 10. Same condition as Fig. 9, except for 300 volts potential applied between deflector plates. Notice assymmetry of beam.

[8] L. R. Maxwell, J. Franklin Inst. **214**, 533 (1932); see also reference 2.

[9] R. W. Gurney and P. M. Morse, Phys. Rev. **33**, 789 (1929).

electrons in the beam had become so short that the entire beam remained inside the anode cylinder.

Interpretation

A number of processes could account for the effused glow independently of the decay of intensity with increasing density. The process which has been advocated by those previously describing the effect[8] is diffusion of radiation from the central beam, with absorption and reradiation by the neutral or metastable atoms. Such a process could not show the sensitiveness to electric fields noted in the present experiments.

The sharp delineation of the central beam indicates the existence of two distinct processes. It is probable that the beam itself is outlined in radiation arising from direct excitation, since the lifetime of the excited systems would not permit them to move more than 0.01 mm before radiating. If the effusion of the glow involved a reprocessing of the radiation emitted by excited atoms in the beam, the beam would not be sharply defined. Another possibility, namely, exciting collisions by electrons scattered elastically at wide angles, should produce an increasing disintegration of the beam with range which was not observed.

No measurements have yet been made specifically on the intensity of the glow as a function of tube current, but assuming that the glow process must have been present in the intensity measurements of Part I in about the same proportion as here, it very likely depends linearly upon tube current. The indications being that the glow originates in a first order process, in which the radiating systems are created directly by the primary electrons or by action of a single intermediary, second order processes (involving two intermediaries) seem rather doubtful explanations. This includes such processes as excitation of metastable atoms by slow plasma electrons or collisions of the second kind with other metastable atoms.

Of the two processes which could have explained the decay of the density—intensity curves, only the diffusion process is certainly adequate. The impacts of primary electrons on ultimate electrons might produce enough fast ultimate electrons to cause the observed diffuse excitation, but since the concentration of ultimate electrons will be proportional to the primary current, and the number of these which experience accelerating collisions will again be proportional to the primary current, a quadratic dependence is suggested. Since the argument again hinges on the current dependence of the glow intensity, a more direct investigation of this point is needed.

The extension of the diffuse glow is of the order of magnitude of 2–5 cm. The velocity of neutral helium atoms under the experimental conditions was about 10^5 cm/sec. Assuming an increase of a factor of 10 in this velocity because of the ambipolar nature of the diffusion, the mean lifetime of the supposed systems which diffuse would be of the order of 2×10^{-6} sec. This is of the same order of magnitude as the previous estimate from fitting of data to the density-intensity curves.

The field sensitivity of the glow and the apparent boundary effects are being investigated further by other workers and a report is expected soon on their results.

PART III

Time Lag in Emission of Radiation

It is possible to measure the lifetime of an excited system of modulating the discharge at variable frequency. Frey[9] has impressed oscillatory potentials up to 10^7 cycles per second on glow discharge tubes. Measurement may be made either of the phase lag between current and intensity or the frequency at which the modulation ripple is no longer reproduced in the radiation from the tube.

A tube of the general construction described in Part I was operated as the plate load of a type 6L6 vacuum tube driven by an external oscillator. Radiation from the tube was imaged on a type 929 near-ultraviolet sensitive vacuum photo-tube. The output of the phototube, suitably amplified, was applied to an oscilloscope. No change in the ratio between the amplitudes of the potential difference applied to the tube and the output of the photo-cell was detected up to 10^4 cycles per sec. Beyond this a decrease could be observed, but a simultaneous decrease occurred in the amplifier gain, which made the results of no value beyond this point.

Interpretation

Before the modulation experiments were performed, any process, which had a sufficiently long lifetime for diffusion to act before radiation, was viewed as a possible explanation of these effects. Establishing the fact that the mean lifetime of the supposed diffusable systems is less than 10^{-4} sec. disposed of processes of random recombination between electrons and ions, which Mohler[10] and Kenty[11] have shown to last for about 10^{-3} sec.

On the other hand Frey has shown that in the glow discharge tube in air, operated at high frequencies, the radiation did not persist for times of much more than 10^{-7} sec. The experiments would conclusively invalidate any proposal for the existence of a longer lifetime process, were it not for the extremely small diameter of the discharge tube used (1 mm) and the low pressure of the discharge. Under these circumstances, transitions from a process of 100 times the duration of excitation might contribute as little as 1 percent to the total tube radiation, systems being lost principally by diffusion.

Recently Rayleigh[12] has called attention to the long duration of the emission of radiation from a beam of

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[9] A. R. Frey, Phys. Rev. **49**, 305 (1936).
[10] F. W. Mohler, Bur. Stand. J. Research **19**, 447 (1937).
[11] C. Kenty, Phys. Rev. **32**, 624 (1928).
[12] R. J. Strutt (Rayleigh), Proc. Roy. Soc. **183**, 20 (1944).

excited hydrogen gas driven out of an electrodeless discharge into a side tube by the sudden pressures generated during the discharge. He found a lifetime for this radiation of the order of 10^{-5} sec. Zanstra[13] has offered electronic recombination as the explanation of these phenomena. It may be therefore that in these experiments Rayleigh has observed a process similar to the one proposed by the authors. There are, however, certain difficulties with this view, notably that the intensity of the exploded beam is continuously variable from the original intensity of the discharge tube at one end to extinction at the other. Direct excitation should be visible in the form of a discontinuity in intensity at the mouth of the side tube. Further investigation of Rayleigh's phenomenon is currently in progress.

CONCLUSION

The simplest explanation which can be given of the foregoing set of experiments is that a process exists for the production of radiation which is slow enough to permit diffusion during the lifetime of the systems from which the radiation originates. Estimates of the order of magnitude of the lifetime are of the order of 10^{-5} to 10^{-6} sec. This hypothesis is not in discord with any known experimental facts, and may account for some theoretical difficulties such as the discrepancy between experimental and theoretical cross sections for excitation of the triplet states in helium, which are in disagreement by a factor of about 10^6.

The indications are that the process is one in which the active systems are charged electrically, suggesting that they are ions. Conventional recombination of ions moving at random cannot be accorded with the facts, and a new type of recombination is proposed as a concomittant of the orderly processes now known as ambipolar diffusion. It is suggested that it is impossible to neglect the perturbing fields of the entire ion cloud in the theory of the recombination process, and perhaps even in the production of ionization.

[13] H. Zanstra, Proc. Roy. Soc. 186, 237 (1946).

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Radiation Accompanying Meson Creation

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Electromagnetic radiation is expected to accompany the creation of charged mesons in nucleon-nucleon collisions. The amount and character of this radiation is calculated for mesons of spin 0, $\frac{1}{2}\hbar$, and $\hbar$, in each case with normal magnetic moment. The ratio of radiated energy to initial meson energy increases logarithmically for high meson energy in the first two cases, and is of the order of 1 percent for the highest energies of interest in cosmic radiation. For vector (spin $\hbar$) mesons, this ratio is $(11\alpha/4860\pi)(E/mc^2)^4$ in the relativistic region, where α is the fine-structure constant, and m and E are the rest mass and the initial energy of the meson in the coordinate system in which the center of mass of the colliding nucleons is at rest. This is so large at high energies that the assumption that π-mesons have spin $\hbar$ would, with a plausible theory of the multiplicity of meson production, account for the observation of soft radiation in conjunction with energetic nuclear events.

I. INTRODUCTION

THERE appears to be good evidence that a substantial part of the soft component of cosmic radiation originates in events that are identical with or closely related to those collisions of primary cosmic rays with air nuclei that give rise to the hard component.[1] A possible mechanism for the production of both components in nuclear collisions assumes that charged and neutral mesons are strongly coupled to nucleons, and that the neutral mesons decay quickly into electron-positron pairs or gamma-rays.[2] At the present stage of nuclear force theory, however, there is little reason to assume the existence of such neutral mesons, and the decay process is based on the further assumption that negative protons exist at least in intermediate states.[3,4] It seems of interest, therefore, to consider in some detail the electromagnetic radiation that, according to currently accepted theory, is a necessary by-product of the creation of any charged particle.[4a]

[1] B. Rossi, Rev. Mod. Phys. 20, 537 (1948), interprets the data and gives a bibliography of experimental results; see especially Sections 15 and 18.

[2] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. 73, 127 (1948).

[3] R. J. Finkelstein, Phys. Rev. 72, 415 (1947).

[4] High energy gamma-rays recently observed by Moyer, York, and Bjorklund [Phys. Rev. 75, 1470 (1949)] cannot be accounted for by the results of the present paper. If not explained in some other way (bremsstrahlung), they may eventually provide evidence for the existence of unstable neutral mesons.

[4a] S. Hayakawa and S. Tomonaga, Prog. Theor. Phys. 2, 161 (1947), have considered the radiation produced by the decelera-

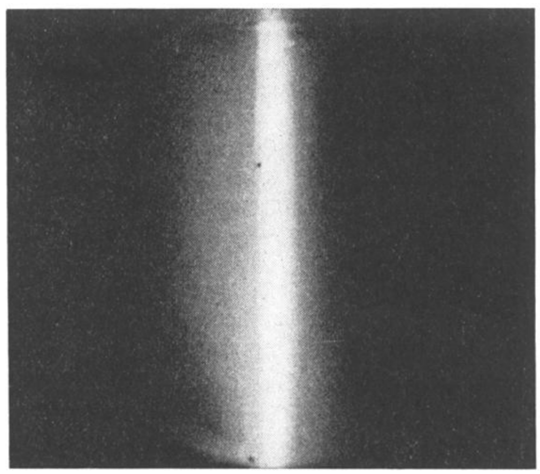

Fig. 10. Same condition as Fig. 9, except for 300 volts potential applied between deflector plates. Notice assymmetry of beam.

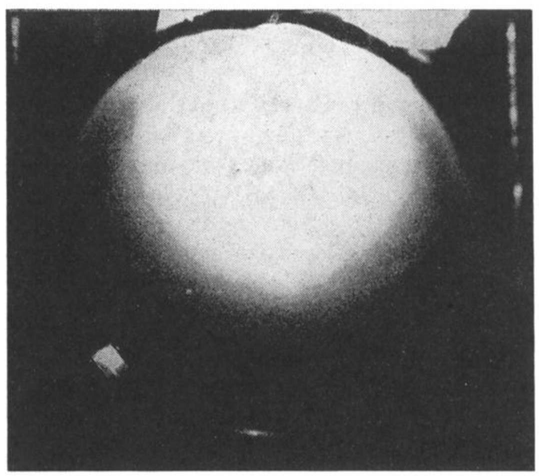

FIG. 6. Radiation produced in helium by an electron beam projected into space. 60 volts accelerating potential; 0.1 mm pressure.

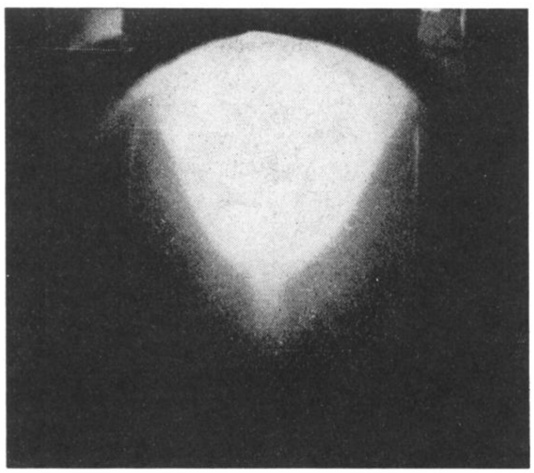

FIG. 7. Radiation produced in helium by an electron beam projected between metal plates, in comparison with Fig. 6, the influence of the electrodes on the contour of the discharge can be seen. 0.04 mm pressure; 60 volts accelerating potential.

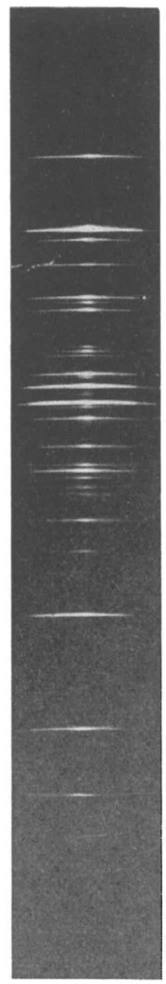

FIG. 8. Spectrogram of the glow around an electron beam projected between metallic electrodes. 100 volts accelerating potential; 0.06 mm pressure.

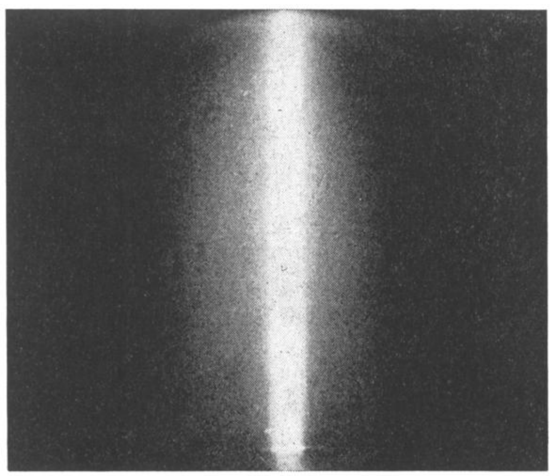

FIG. 9. Photograph, using green filter, of the 5875A glow about a beam passing between metallic plates. The accelerating potential on the beam has been increased to 100 volts.