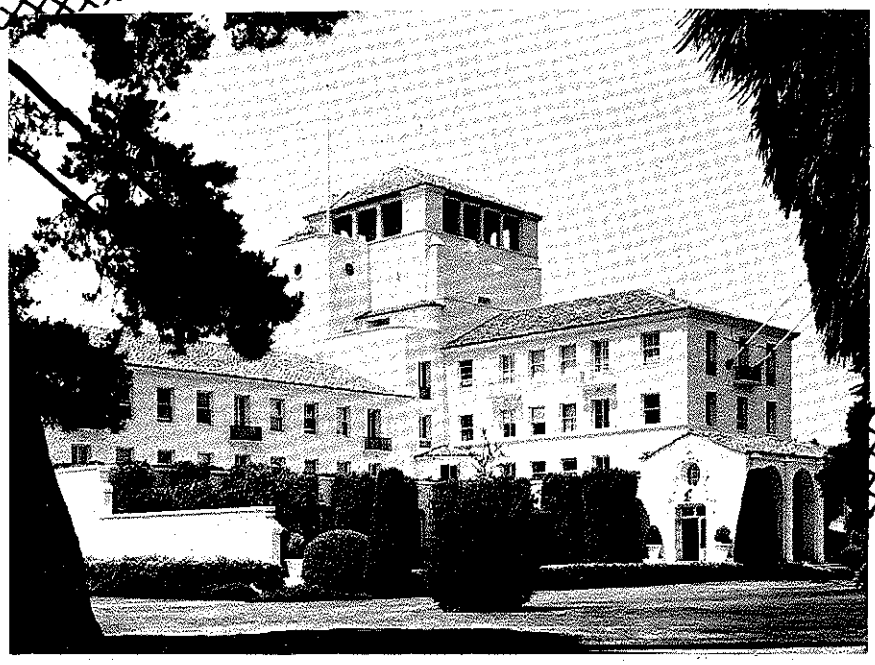
C. C. Lin

13th ANNUAL GASEOUS ELECTRONICS CONFERENCE

PROGRAM and ABSTRACTS of PAPERS



U.S. Naval Postgraduate School
Monterey, California

October 12-15, 1960

Under the sponsorship of
The American Physical Society
Division of Electron Physics,
Office of Naval Research, and
U.S. Naval Postgraduate School

THIRTEENTH ANNUAL

GASEOUS ELECTRONICS CONFERENCE

PROGRAM

and

ABSTRACTS OF CONTRIBUTED PAPERS

October 12 - 15, 1960

KING HALL
U. S. NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

JOINTLY SPONSORED BY

THE DIVISION OF ELECTRON PHYSICS,
AMERICAN PHYSICAL SOCIETY,
THE OFFICE OF NAVAL RESEARCH

and

U. S. NAVAL POSTGRADUATE SCHOOL

P R O G R A M

for the

T H I R T E E N T H A N N U A L
G A S E O U S E L E C T R O N I C S C O N F E R E N C E

October 12 - 15, 1960

Tuesday
October 11
8:00 P.M.
Advanced Registration,
Lobby of Spanagel Hall,
U. S. Naval Postgraduate School

Wednesday
October 12
8:00 A.M.
Registration,
Lobby of Spanagel Hall,
U. S. Naval Postgraduate School

ALL SESSIONS IN KING HALL

Wednesday
October 12
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Bonn University

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Lawrence Radiation Laboratory,
Livermore; General Electric,
"Irving Langmuir's Plasma".

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October 14
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Washington University

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Saturday
October 15
9:00 A. M.

Session G: OSCILLATIONS

Chairman: W. B. Kunkle,
Lawrence Radiation Laboratory

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SESSION A
Wednesday, October 12
9:30 A.M.

Chairman
G. Ecker
Bonn University

S U R F A C E S A N D C A T H O D E S

SPUTTERING OF MONOCRYSTALLINE COPPER BY ARGON ION BEAMS*

A-1

P. D. Skiff, H. K. Reynolds
University of Houston

In bombarding the (111) face of a monocrystalline Copper target with a normally incident beam of Argon ions of energy in the range of 20KV to 140KV, preferential directions of ejection of the Copper atoms were observed. An ejection pattern similar to those obtained recently at much lower ion energies was clearly evident, and showed little tendency to change at higher energies. The directions of ejection corresponded to the perpendiculars to the (110), (101), (011), (114), (141), (411) planes of the target lattice. Recent work by Koedam and Hoogendoorn[1] indicated that the (114), (141), (411) pattern disappeared at ion energies above 1500V, and Rol[2], et al reported (100), (010), and (001) ejection at 20KV. Data on the relative sputtering yields in the preferred directions, yield as a function of energy, and variation of the ejection pattern with bombarding angle will be presented.

* Supported by the United States Atomic Energy Commission and the Office of Naval Research.

1 Koedam and Hoogendoorn, Physica 26, 351, (1960).

2 P. K. Rol, et al, Proceedings of the 4th International Conference on Ionization Phenomena in Gases; Uppsala (1959).

ETCH EFFECTS FROM OBLIQUE ION BOMBARDMENT*

A-2

P. A. Harkins, G. D. Magnuson, B. B. Meckel**
Physics Section, Convair, San Diego

It has been found that metallic surfaces of Cu, Au, Al, Ta, Mo, and Ni when bombarded with 500-volt Hg^+ ions at angles of incidence other than zero, exhibit a definite surface structure or pattern. This pattern consists of hillocks or spires oriented parallel to the direction of the incoming ion beam. In Cu and Ni, steps oriented perpendicularly to the ion beam were also found. This surface pattern provides visual evidence that the sputtering process at low ion energies is a momentum transfer process. Since redeposition of sputtered atoms on the hillocks and steps could be quite large, angle of incidence yield measurements could be in error unless they are made before hillocks form. It is believed that the hillocks are formed by the more rapid removal of surrounding material, causing the hillocks to stand out in relief. It is not known what causes the reduced sputtering rate at the hillock but evidence will be presented indicating that the cause is a line imperfection in the solid.

* This work was supported by Contract No. AF 19(604)-5554.

** Now at Geophysics Corporation of America, La Jolla, California.

SPUTTERING THRESHOLD* A-3

D. E. Harrison, Jr.,** G. D. Magnuson
Physics Section, Convair, San Diego

We attempt to give a logically coherent definition of the term "sputtering threshold," and establish criteria which may determine an experimental threshold. The Silsbee chain mechanism and the experimentally obtained preferred direction of emission from single crystals are used to establish a threshold theory. Two models are required, one generally applicable when the mass ratio is less than one, and another when it is greater than one. Single crystal threshold laws are obtained, and polycrystalline laws follow for face-centered cubic crystals by averaging the single crystal forms. An approximate technique for the evaluation of surface atomic binding energies is presented so that the thresholds can be compared with experimental results. In all cases the theoretical thresholds are less than or comparable to experimental "thresholds."

* This work was supported by Contract No. AF 19(604)-5554.

** Permanent Address, University of Toledo, Toledo, Ohio.

SPECTROSCOPIC STUDIES OF SPUTTERING* A-4

G. K. Wehner and Robley V. Stuart
Mechanical Division of General Mills, Incorporated
Minneapolis, Minnesota

A sensitive spectroscopic method for measuring sputtering yields is described. Instantaneous readings for yields down to 10^{-5} atoms/ion can be obtained by measuring with a monochromator and photomultiplier the intensity of a resonance line in the emission spectrum of the target atoms which, after being sputtered, are excited in a dense, magnetically concentrated, low pressure plasma. This method does not, as most other methods do, require an accumulation of sputtered material for measurements. One can therefore clean the target surface with higher energy ions immediately before taking a reading at low energy.

Results are presented for several metals under Ne^+, Ar^+, Kr^+, Xe^+, and Hg^+ ion bombardment at energies down to 20ev. It is found that serious errors may arise at very low energies from doubly charged ions which bombard the surface with double kinetic energy. In the threshold region even a small number can become very important. As a consequence, sputtering yields at very low bombarding energy have been overestimated in the past. We find in all cases studied so far that yields are less than 10^{-5} atoms/ion at 25 ev.

* Work was sponsored by ONR and AFCRC.

HOLLOW CATHODE HIGHLY IONIZED DISCHARGE* A-5

C. Michelson**
Oak Ridge National Laboratory***

D. J. Rose
Research Laboratory of Electronics
MIT and ORNL

A highly ionized plasma can be made by the following prescription: gas flow (H_2, He, A, or N_2) 0.3 - 2 cc STP/sec through a 3 mm OD refractory hollow cathode tube (1 - 2 mm dia. axial hole) into a vacuum; any anode; 30 - 200 volts dc applied. An axial induction 100 - 1000 gauss has been used to collimate the discharge, and to aid in starting by excitation; the induction can be removed during operation. The discharge runs from the interior of the cathode. Typical operating conditions are: 50 amp, 35 volts, 0.5 cc/sec argon, external pressure 3×10^{-4} mm Hg, interior pressure where plasma forms 40mm Hg, cathode temperature 2500°C. Currents from 2 - 200 amps have been run; the configuration can be modified considerably at will. In cases where the ions sputter the cathode material or vaporize it, the cylindrical cathode interior forms into a cavity, with $p_o d \approx 1$ cm x mm Hg. Density in the exterior plasma is estimated to be about $10^{14}/cm^3$, with an average electron energy 1 - 2 ev for the consideration stated. At lower gas flow and high voltage, most of the input power is deposited at the anode, which indicates the presence of high energy electrons.

* This work was supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Scientific Research, Air Research and Development Command), and the U. S. Navy (Office of Naval Research); and in part by the National Science Foundation.

** On loan from the Tennessee Valley Authority.

*** Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

THE PARTITION OF POWER BETWEEN TUNGSTEN ELECTRODES IN D.C., LOW PRESSURE, INERT GAS AND TUNGSTEN VAPOR ARCS

A-6

Heinz G. Sell
Westinghouse Electric Corp., Lamp Div.

A.E. LaMarche
Westinghouse Electric Corp., Materials Mfg. Div.

The relative heating of a tungsten anode and cathode of equal dimensions in electrode-stabilized arcs of helium, argon, and xenon and in tungsten vapor between tungsten electrodes of a vacuum arc melting furnace has been investigated as a function of pressure at pressures lower than atmospheric. Abnormally high cathode heating, even to temperatures higher than that of the anode, occurs below a certain threshold pressure, which is lower in xenon than in argon and lowest in tungsten vapor. A study of the arc voltage dependence on electrode separation and gas pressure in a wall-stabilized neon discharge has revealed that the magnitude of abnormal heating is directly related to the anode fall and its relative position in the arc. Abnormal cathode heating is caused by an ion current which is generated by anode fall ionization as compared to normal heating which is the result of a thermally produced ion current at higher gas pressures. The relationship between abnormal cathode heating, first ionization potential of the arc medium, and ionic mean-free path is discussed. The partition of power is demonstrated by color slides.

ON A THEORETICAL TREATMENT OF GASFILLED THERMIONIC ENERGY CONVERTERS

A-7

W. Bloss
Institut fuer Gasentladungstechnik und Photoelektronik
Stuttgart, Germany

The theoretical efficiency of high vacuum thermionic energy converters with usual emitter materials is calculated. It is shown that the optimal temperature for conversion and the normal operating temperature of the emitter are nearly the same for low work function emitters.

Comparison is made with energy converters containing a low pressure noble gas filling. By partly ionizing the gas, space charge is compensated and the efficiency in comparison with high vacuum converters may be increased considerably.

RESISTANCE HEATING IN THE ARC CATHODE SPOT ZONE A-8

J. A. Rich
General Electric Research Laboratory
Schenectady, New York

For an understanding of the arc cathode spot mechanism it is essential to determine the relative importance of Joule heating within the cathode and the energy input from the arc discharge. The problem of a source of uniform current density acting over a circular area on the surface of a semi-infinite solid of conducting material is formulated and solved with the following results: (1) The Joule heat developed in the hemispherical volume directly under the cathode spot amounts to 38 per cent of the total Joule heat developed in the electrode; (2) a comparison of the energy input to the cathode spot zone due to Joule heating and the energy input due to positive ion bombardment shows that for current densities of the order of 10^6amp/cm^2 the former amounts to some 10 - 20% of the latter for high resistivity metals such as bismuth, antimony and mercury. As the current density is increased to 10^7amp/cm^2 the two energy sources become comparable for metals other than the low resistivity metals such as copper and silver; (3) the time required to bring typical electrode materials to the melting point with resistance heating only is relatively short. For $J = 10^6$amp/cm^2 and a spot radius of 2×10^{-3} cm, bismuth (271°C) requires 3.4 μsec, antimony (631°C) 35 millisec. The boiling point of mercury (357°C) is reached in 14.5 μsec.

CONTINUOUS RETROGRADE MOTION OF A MERCURY ARC A-9

Charles G. Smith
Mystic Transformer Company
Wilmington, Mass.

The anchored cathode spot racing around a clean mercury-wettable molybdenum anchor is most intense at the leading edge. It tapers off essentially exponentially to the rear. A half length of the spot along the direction of motion was in a particular case about one centimeter. These observations and their supporting background add to the phenomenological picture. Previously, the racing anchored arc has given means of separating the characteristic spot spectrum from that of the surrounding regions. Further studies of the anchored arcs have revealed characteristic curves of spot velocity versus magnetic field. Further simplifying studies will be suggested, and the more nearly complete phenomenological picture must lead to an acceptable theory or even new physics--this in spite of the large number of theories already advanced to explain the electron liberation and the retrograde motion of the cathode spot.

SESSION B
Wednesday, October 12
2:00 P. M.

Chairman
Richard Fowler
University of Oklahoma

P O S I T I V E C O L U M N

Invited Paper

THE SCOPE AND LIMITATIONS OF A FULLY ADIABATIC LAW IN COLLISION-FREE PLASMAS

B-1

O. Buneman

Cambridge University

PRESSURE CONSTRICTION' OF THE POSITIVE COLUMN* B-2

R.G. Fowler and L.W. Jones
Department of Physics
University of Oklahoma
Norman, Oklahoma

A theory of the well-known pressure constriction' was developed some years ago, (1) but very little actual experimental data existed at that time with which to compare it. An investigation has now been completed in several gases which has provided data in good agreement with this theory. Pulsed columns have been studied to remove falsifying influence of species changes owing to metastable and molecular formation.

* Supported in part by the U.S. Office of Naval Research.

(1) R.G. Fowler, Proc. Phys. Soc. Lond., 48, 130 (1955).

RECOMBINATION STABILIZED POSITIVE COLUMNS WITH POSITIVE CHARACTERISTICS IN THE RARE GASES WITH AND WITHOUT N_2

B-3

Carl Kenty
Lamp Department, General Electric Company
Nela Park, Cleveland, Ohio

Positive characteristics have been found for 1 ma hot cathode discharges in 100 mm Xe, Kr or A in 10 cm tubes. The discharges substantially fill the tube and emit a continuous spectrum. Beyond a critical current the discharge goes over into a thread-like form, of much lower voltage, emitting a line spectrum and having a negative characteristic.

The diffuse discharge operates largely by single stage ionization, the current density being so low; while the metastables are removed by molecule formation and radiation of a continuous spectrum. The constricted discharge, of about 10^4 times the current density of the diffuse form, operates by two-stage ionization via the metastable atoms.

The positive characteristic of the diffuse discharge results from the removal of the ions mainly by dissociative recombination (rather than diffusion to the walls), such removal increasing as the square of the ion concentration.

With .1% N_2 present, the gradients are reduced by a factor of five or more, indicating a high concentration of N_2 metastables (10^{13} cm^{-3}) having a lifetime of several seconds. The ionization is two stage via these metastables. The characteristic is still positive. This could result if the metastable population is substantially in a Boltzmann equilibrium with the electrons.

COMPUTATION OF FIELD- AND CONDUCTIVITY DISTRIBUTIONS ACROSS AN ELECTRODELESS RING DISCHARGE

B-4

Hans U. Eckert
Convair, Scientific Research Laboratory
San Diego, California

A previously presented method [1] for approximate, simultaneous solution of the wave equation and the electron balance equation applied to an inductive, diffusion-controlled R. F. discharge of cylindrical geometry is carried further. The radial distributions of electric and magnetic field intensities, of gas conductivity, current density, etc., are obtained in absolute terms. While the evaluations procedure is iterative in general, it is straightforward in the limits of high and low conductivity which closely cover many cases of practical significance. If the conductivity is low enough to make the skin depth larger than the tube radius, absorption of the wave is negligible and vacuum solutions apply for its intensity.
If the skin depth is small or if the product gas pressure times tube radius is large the conductivity distribution is so nearly uniform that the well-known solutions of the field equations in terms of Bessel functions may be applied. The method is illustrated by practical examples for hydrogen.

[1] Bull. Am. Phys. Soc. Ser. II, Vol. 5, p. 371, 1960.

THE STABILITY OF THE SLOW PINCH DISCHARGE* B-5

A. A. Ware**
General Atomic***
San Diego, California

The slow pinch discharges observed in Zeta, Sceptre and in other experiments exhibit a gross hydromagnetic stability which has been previously unexplained. Since the magnetic fields in these discharges are observed to have little or no magnetic shear, the stability of a discharge with constant pitch magnetic field is considered on the basis of the energy principle. Of the two types of instability which are predicted theoretically, namely 'kink' and 'interchange' instabilities, the experimental results suggest that only the interchange instability is occurring in practice. Some suggestions are put forward to explain the apparent stability against the 'kink' type instability.

* Research on controlled thermonuclear reactions is a joint program carried out by General Atomic and the Texas Atomic Energy Research Foundation.

** On leave of absence from Associated Electrical Industries Research Laboratory, Aldermaston, Berkshire, United Kingdom.

*** John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

TRAPPING AND CONFINEMENT OF A HIGH-DENSITY ELECTRON CLOUD B-6

Ralph H. Bartram, Herman O. Dressel and Gerhard E. Weibel
General Telephone & Electronics Laboratories
Incorporated
Bayside 60, New York

Experiments are described in which a cloud of electrons is trapped in a cylindrical chamber and kept in stable confinement by static electric and magnetic fields. Trapped electrons are accumulated in a controlled manner by injection of an electron stream into a potential well which is made progressively deeper during the accumulation period. A sensitive and non-destructive method has been developed for measuring the quantity of trapped charge; it consists of application of a UHF signal to the end electrodes of the trapping chamber and measurement of the impedance presented by the trapped charge as a function of frequency. This type of measurement yields the charge density as well. Pulses applied to the end electrodes are used to determine the distribution of electrons with respect to binding energy in the potential well. An electron cloud 1 cm. long and 2 mm. in diameter with a density of $5 \times 10^{10}/cm^3$ has been trapped and confined for at least 5 milliseconds. Electrons resulting from ionization of the residual gas are still present in the chamber after 10 seconds.

INSTABILITY OF A POSITIVE COLUMN IN A MAGNETIC FIELD* B-7

George A. Paulikas, T. K. Allen**and Robert V. Pyle
Lawrence Radiation Laboratory
Berkeley, California

The properties of the helical instability [1] that occurs when the longitudinal magnetic field on a positive column exceeds a critical value, B_c, have been studied in H_2, D_2, He, Ne, and A gases for several pressures, discharge tube radii, and lengths of magnet. As an example, a He discharge at a pressure of 0.22 mm Hg in a 2.75-cm-radius tube exhibits an oscillation with a frequency of 6×10^4 sec^{-1}, a wavelength of 78 cm, and an amplitude e-folding rate of roughly 2×10^4 sec^{-1} when the 200-cm-long magnetic field is slightly higher than B_c (655 gauss). These parameters, as well as values of B_c, are in good agreement with predictions of the perturbation theory of the positive column proposed by Kadomtsev and Nedospasov.[2] Measurements of B_c are also compared with the sheath instability theory of Hoh.[3]

* Work was performed under the auspices of the U.S. Atomic Energy Commission.

** Visitor from AERE, Harwell.

1 T.K. Allen, G.A. Paulikas, and R.V.Pyle, Bull. Am. Phys. Soc. II, 5, No. 2, 314 (1960).

2 B.B. Kadomtsev and A.V. Nedospasov, J. Nuclear Energy, Part C, 1960 (to be published).

3 F.C. Hoh, Phys. Rev. Letters 4, 559 (1960).

SESSION C
Thursday, October 13
9:00 A. M.

Chairman
D. E. Kerr
Johns Hopkins University

B A S I C P R O C E S S E S

OPTICAL MODEL ANALYSIS OF ELECTRON-HYDROGEN SCATTERING* C-1

B. A. Lippmann and H. M. Schey
Lawrence Radiation Laboratory
Livermore, California

Although the optical model replaces a many-body problem by an equivalent one-body problem, the correct optical model potential is usually unknown until the many-body problem has been solved. However, when target and scattering particles are well-separated, perturbation theory is applicable; the relevant part of the scattering problem then can be solved and the asymptotic form of the optical potential evaluated. In the near region, the optical potential can be approximated by imposing the symmetry conditions the exact wave function is known to obey. Applied to elastic e-H scattering, this approach is equivalent to (and therefore justifies) the heuristic procedure of Martin, Seaton, and Wallace[1], which leads to scattering lengths close to the Rosenberg, Spruch, and O'Malley[2] limits. The method can also be applied to inelastic scattering processes.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

1 Martin, Seaton, and Wallace, Proc. Phys. Soc., 72, 701 (1958).

2 Rosenberg, Spruch, and O'Malley, Phys. Rev. 119, 164 (1960).

MEASUREMENT OF THE TRANSITION PROBABILITY OF THE OI 6157A LINE IN AN OXYGEN-HYDROGEN PLASMA

C-2

J. B. Shumaker and W. L. Wiese
National Bureau of Standards

Oxygen saturated with water vapor was introduced into a wall-stabilized arc [1] operated at 50 and 100 amp. The absolute intensities of H_β and the OI 6157A line were measured with a scanning photoelectric spectrometer calibrated by means of a standard tungsten strip lamp. The electron density was determined from the line profile of H_β using Stark broadening theory. The population in the upper state of the oxygen line was then evaluated assuming local thermodynamic equilibrium and a pure oxygen plasma. The added hydrogen impurity and possible variations in its concentration with arc radius do not sensibly affect these calculations because of the practically identical ionization potentials and partition function ratios for oxygen and hydrogen and the very low relative concentration (2%) of hydrogen. The oxygen transition probability agrees well with values obtained by two other methods.[2]

1 H. Maecker, Z. Naturforsch., 11a, 32, (1956).

2 G. Juergens, Z. Physik, 138, 613 (1954).

THE COLLISIONAL DETACHMENT OF NEGATIVE IONS IN MOLECULAR OXYGEN* C-3

A. V. Phelps and J. L. Pack
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

Negative ions formed in oxygen at low E/p are observed to undergo collisional detachment at oxygen temperatures above about 400°K. The negative ions are formed in a drift tube as a result of three-body collisions between electrons and oxygen molecules.[1] As the ions drift through the tube, electrons are released in collisions of the negative ions with oxygen molecules. The electrons are separated from the ions using an "electron filter."[2] The probability of collisional detachment is calculated from measurements of the attachment probability and the ratio of the electron current produced by detachment to the electron current traversing the tube without attachment. These results are consistent with the formation of O_2^- ions in the three-body attachment process and the detachment of electrons by the inverse process, i.e., $O_2^- + O_2 \longrightarrow e + 2O_2$. The ratio of the thermal detachment frequency to the thermal attachment frequency can be used to estimate the electron affinity of molecular oxygen. Preliminary results show satisfactory agreement with the results obtained by Loeb.[2]

0.46 eV electron affinity

* Supported in part by the Air Force Research And Development Command.

1 L. M. Chanin, A. V. Phelps, and M. A. Biondi, Phys. Rev. Letters 2, 344 (1959).

2 L. B. Loeb, Basic Processes of Gaseous Electronics (University of California Press, Berkeley, California, 1955) Chap. V. especially p. 459.

MEASUREMENT OF ELECTRON TRANSFER COLLISION CROSS SECTIONS FOR NEGATIVE IONS IN GASES* C-4

T. L. Bailey and P. Mahadevan
College of Engineering, University of Florida
Gainesville, Florida

Inelastic collisions of negative ions in molecular gases are being investigated with a new collision chamber, which uses the radio frequency electron filter principle to separate quantitatively slow electrons formed by collisional detachment from slow heavy negative ions produced by electron transfer and other inelastic processes. In cases where simple electron transfer is the only process which yields heavy negative ions, measurements made with this collision chamber give separately the absolute cross sections for electron transfer and for electron detachment. Measurements made with 70-345 ev O_2^- ions in O_2 gas show that the apparent electron transfer cross sections rise with decreasing ion energy from 8.56Å^2 at 345 ev to 21.67Å^2 at 70 ev. The electron detachment cross sections drop slowly with decreasing energy from 8.04Å^2 at 345 ev to 6.69Å^2 at 70 ev. In this energy range, the sum of the detachment and exchange cross sections is in fairly good agreement with the total inelastic cross sections determined by Hasted and Smith [1] and by Muschlitz.[2]

* Supported by the Office of Naval Research.

1 J. B. Hasted and R. A. Smith, Proc. Roy. Soc. (London), A235, 349, (1956).

2 E. E. Muschlitz, Jr., Proc. of Fourth Int. Cong. on Ionization Phenomena in Gases (Uppsala), 1A52 (1960).

STUDY OF ELECTRON ATTACHMENT IN OXYGEN USING ELECTRON BEAMS* C-5

G. J. Schulz
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

Electron beam techniques have been extended to higher pressures (up to 0.5 mm Hg) in order to observe the three-body attachment processes in oxygen. A magnetically aligned electron beam traverses a collision chamber and the negative ions are collected on a cylindrical collector surrounding the collision chamber. The retarding potential difference method is used to study the effect of nearly monoenergetic electrons. The cross section for production of O^- is measured at low pressures. The pressure dependence of the O^- current is linear up to about 10^{-2} mm Hg and joins smoothly into a quadratic dependence at higher pressures, in agreement with a theory by Allis for the transition from a long mean free path to a short mean free path. At high pressures (above 10^{-1} mm Hg) and low electron energies, the production of O_2^- is observed. The O_2^- current peaks at about 0.1 ev and decreases to low values at 1 ev. The pressure dependence of the O_2^- current indicates that the O_2^- is formed in a three-body collision.

* This research was supported in part by the Advance Research Projects Agency and the Office of Naval Research.

ELECTRON LOSS PROCESSES IN NITRIC OXIDE PLASMAS AT LOW PRESSURES

C-6

R. C. Gunton and E. C. Y. Inn
Lockheed Missiles and Space Division
Palo Alto, California

Plasmas consisting of NO^+ ions, electrons and NO molecules have been produced by photoionization. Lyman alpha radiation from a pulsed hydrogen capillary light source was admitted into a small quartz cell containing nitric oxide through a lithium fluoride window transparent to the ultraviolet radiation. The Lyman alpha photon of 10.20 ev is sufficient to provide the 9.25 ev ionization energy of the molecule. Undesired radiation, which might produce dissociation, was filtered out by an intervening air path. The decay of the ionization following the light pulse was observed by placing the quartz cell in an X-band microwave cavity. From the shift in resonance frequency of the cavity, electron densities in the range 10^{10} to 10^9 cm^{-3} were observed. Measurements have been made on the rate of attachment of electrons to NO molecules. At pressures up to 16 mm of Hg attachment appears to follow a 3-body process, as observed by Bradbury[1], with a rate coefficient of 5×10^{-31} cm^6 sec^{-1} at an electron energy of about 0.1 ev. Other electron loss processes, such as ambipolar diffusion and electron-ion recombination will be discussed.

1 N. E. Bradbury, J. Chem. Phys. 2, 827 (1934).

D/u FOR ELECTRONS IN HELIUM, ARGON, AND HYDROGEN C-7

J. H Parker and R. W. Warren*
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania

The ratio of the diffusion coefficient to the mobility for electrons in helium, argon, and hydrogen has been measured at 77°K and 300°K for an E/p range of 10^{-3} to 10 volt/cm-mm Hg. The "Townsend Method" is used, in which D/u is obtained from the measured lateral spreading of electrons at a given E/p. To obtain the relationship between D/u and the lateral spreading, it is necessary to solve the mobility-diffusion equation with zero density boundary conditions at the walls of the chamber. The solution that is used in the present study, while being based on the method of images as developed by Huxley,[1] differs significantly from the solution that he obtained by this method.[1] The results of the present study are pressure independent for pressures greater than approximately 30 mm Hg and in agreement with the theoretical values of Frost and Phelps.[2] For pressures less than approximately 30 mm Hg the results are found to depend on pressure. A possible explanation of this dependence will be discussed.

* Supported by Air Research and Development Command.

1 L. G. Huxley, Phil. Mag. 7, 396 (1940).

2 L. S. Frost and A. V. Phelps, Bull. Am. Phys. Soc. Ser. II, 5, 122 and 371 (1960).

IONIC MOBILITIES IN HYDROGEN C-8

Lorne M. Chanin
Honeywell Research Center
Hopkins, Minnesota

Previously reported techniques [1] for the measurement of the mobilities of positive ions have been used to study the mobilities of positive ions in hydrogen from E/P_o = 3 to 50. Results at room temperature at low E/P_o are in good agreement with the data obtained by Lauer [2] and Mitchell [3]. As E/P_o is increased the present results merge with the data obtained by Rose [4]. Measurements have also been conducted at 195°K and 77°K. The present results which indicate an increasing mobility with decreasing temperatures lie approximately 10% below the theoretical values of Mason and Vanderslice [5] for H_2^+.

1 M. A. Biondi and L. M. Chanin, Phys. Rev. 94, 910 (1954).

2 E. J. Lauer, J. Appl. Phys. 23, 300 (1952).

3 J. H. Mitchell, quoted by A. M. Tyndall, The Mobility of Positive Ions in Gases (Cambridge University Press, 1938).

4 D. J. Rose, J. Appl. Phys. 31, 643 (1960).

5 E. A. Mason and J. T. Vanderslice, Phys. Rev. 114, 497 (1959).

MULTIPLE STATE TRANSFER OF EXCITATION IN HELIUM* C-9

Robert M. St. John, Chun C. Lin and Richard G. Fowler
Department of Physics, University of Oklahoma
Norman, Oklahoma

A theory is presented to explain the multiple state mechanism for the transfer of excitation from singlet to triplet states in helium atoms proposed by St. John and Fowler. The spin-orbit interactions of the intra- and inter-atomic type are believed to be responsible for the singlet-triplet transfer in the highly excited states. It is shown that a helium atom in an upper nP state, after colliding with a normal atom, transfers primarily into either a P or an F state. Qualitative results derived from this theory are in good agreement with the essential features of the new process. Observations have been made on light emission from certain low triplet levels of helium gas traversed by a monoenergetic electron beam. Helium pressure and electron energy were varied. A major part of the triplet excitation was formerly assigned to direct transfer from ^1P states in gross violation of the Wigner Spin Conservation rule. Transfer of excitation by a new process is proposed wherein the conflict with the Wigner rule is minimized by greatly reducing the cross sections required by data to values near the gas-kinetic value. It is assumed that many ^1P states including those with large quantum number n transfer excitation energy to neighboring triplet states having closely corresponding principal quantum numbers. The triplet states thus formed in turn populate low level triplet states by radiative transitions. It is found that states lying between n = 6 and n = 20 play the dominant role in the transfer process. The new multiple state transfer process is used in the derivation of qualitative explanations of several additional transfer phenomena.

* This work was partially supported by the Air Force Office of Scientific Research under Contract AF 49 (638)-41.

SESSION D
Thursday, October 13
2:00 P. M.

Chairman
D. W. Kerst
General Atomic
San Diego

P R O P A G A T I O N

Invited Paper

GENERAL PROPERTIES OF THE FOUR MODES OF WAVE PROPAGATION IN A PLASMA

D-1

J. L. Delcroix

University of Paris

PHASE REVERSAL OF THE ELECTRIC FIELD IN HIGH-FREQUENCY PLASMOIDS* D-2

Albert J. Hatch
Argonne National Laboratory

High-frequency plasmoids of the type first observed by Wood[1] are formed between plane parallel metal electrodes, 25 cm in diameter and 15 cm apart, by a 15-Mc/sec exciting frequency. Axial rf electric fields resulting from the applied voltage and from the plasma are detected with an rf probe technique previously described.[2] A 15-Mc/sec probe signal as observed in the absence of plasma or in the presence of a diffusion plasma ($p > 100$ microns) or a multipacting plasma ($p < 0.1$ micron) is always in phase with the applied voltage. In the pressure range from 5 to 100 microns, the magnitude of the 15-Mc/sec signal within the plasma is very nearly zero. In the high-frequency plasmoids (0.1 micron to 5 microns), however, the phase of the observed 15-Mc/sec signal is shifted by approximately 180°. The amplitude of this signal increases as the pressure is reduced toward the 0.1 micron extinction value. The apparent dc potential of the plasmoid is positive. The results appear to be explainable on the basis of the self-potential of an axially oscillating electron cloud in the plasmoid.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

1 R. W. Wood, Phys. Rev. 35, 673 (1930).

2 A. J. Hatch, Bull. Am. Phys. Soc. 3, 152 (1959).

PROPAGATION AT MICROWAVE FREQUENCIES ALONG A FLUCTUATING PLASMA COLUMN*

D-3

M. A. Allen and G. S. Kino
Microwave Laboratory, W. W. Hansen Laboratories of Physics
Stanford University, Stanford, California

Random fluctuations of plasma number density which are present as standing or traveling waves in an arc discharge plasma column affect the dispersion characteristics of a microwave signal propagating along the column. The examination on a spectrum analyzer of the signal as it propagates along the column reveals a transfer of energy into sidebands of the original frequency. This degradation of the microwave signal is shown to be due to phase modulation of the signal caused principally by the strong fluctuation which occurs in mercury-arc discharges at about 100 kc/sec. The phase modulation was examined in detail both with this internally produced modulation and an externally applied modulation of the number density. The results obtained were explained by the theory of phase modulation with the depth of modulation being independently measured by means of cavity resonator techniques.

* Supported by Air Force Research Division, Air Research and Development Command.

THE NONLINEAR INTERACTION OF AN ELECTROMAGNETIC WAVE WITH AN ANISOTROPIC PLASMA LAYER*

D-4

Romayne F. Whitmer and Eamon B. Barrett
Palo Alto Laboratories
General Telephone and Electronics Laboratories, Inc.

The theory of electromagnetic wave propagation through an anisotropic ionized layer, including the effects of the nonlinear terms in the Boltzmann transport equation, will be presented. The method of solution of the nonlinear equations involves an expansion of all of the dependent variables in a Fourier series in time. The differential equations describing the propagation phenomena are then solved, for each frequency in the series, for plane wave propagation. A solution in closed form has been obtained, under small signal conditions, for the h-th harmonic of the Fourier series. A discussion of the properties of the wave at the second harmonic frequency as a function of the dc magnetic field strength, the electron density, the electron-neutral particle collision frequency, the field strength of the incident wave, and the thickness of the plasma layer will be presented. Experimental verification of the theoretical predictions, as well as a measure of the range of validity of the "small signal" assumption, has been obtained.

* This research was supported by Air Force Contract No. AF 19(604)-4083.

ION RESONANCE IN A MULTICOMPONENT PLASMA D-5

S. J. Buchsbaum
Bell Telephone Laboratories
Murray Hill, New Jersey

Experiments will be described designed to study the phenomena associated with ion cyclotron resonance in a plasma which contains two or more ion species with different charge to mass ratios. The experiments utilize the positive column of a steady state discharge, a static magnetic field of 88 kilogauss (or less) and rf frequencies in the megacycle/sec band. The gases studied were hydrogen, helium and neon. At low electron densities ($n < \epsilon_o B^2/M$), the plasma, when forced into oscillations transverse to the magnetic field, exhibits a resonance at the cyclotron frequency of each ion. At large plasma densities, the motion of each (heavy) charged particle species is tightly coupled to the other plasma constituents through space charge fields. The result is a set of hybrid resonance frequencies, equal in number to the number of different ions in the plasma[1]. The parameters which determine the hybrid frequencies and the widths of the experimentally observed lines will be discussed.

1 S. J. Buchsbaum, Physics of Fluids, 3, 418 (1960).

MEASUREMENT OF SHIFT IN CYCLOTRON CUT-OFF D-6

Derek W. Mahaffey
Plasma Physics Laboratory
Boeing Scientific Research Laboratories
Seattle, Washington

Experiments have been carried out to test a theory of microwave propagation through a hot magnetoplasma[1]. The mode investigated was that of right hand circularly polarized microwaves propagating parallel to the direction of the steady magnetic field. The theory predicts a shift in the electron cyclotron resonance cut-off frequency, the amount of the shift depending on the ratio of electron pressure, nkT, to magnetic field pressure, $H^2/4\pi$. The experiments were conducted using a PIG Discharge placed between the pole pieces of an electromagnet, giving a field strength uniform to within 0.25% over the working volume. The discharge was pulsed through Argon gas, with a pulse duration of about 4 milliseconds. X band microwave equipment was used. The radiation and receiving antennae were in the form of crossed slots cut in straight sections of waveguide incorporated in the cathodes of the discharge tube. A shift in the cut-off frequency in the expected direction was found. The magnitude of the shift and its dependence on the parameters of the discharge are in qualitative agreement with the theory.

1 J. E. Drummond. Paper presented at 10th Annual Gaseous Electronics Conference. Bulletin of American Physical Society. Vol. 3. 86. 1958. Physical Review 112. 1460. 1958.

TRANSVERSE NORMAL MODES IN A CYLINDRICAL PLASMA D-7

W. D. Hershberger
University of California, Los Angeles

Richard L. Moore
Richard L. Moore, Consultants, Los Angeles

The reflection and absorption spectrum of a cylindrical plasma column may be elicited and observed at a fixed microwave frequency by varying the current through the column. The electric field of the incident wave is perpendicular to the axis of the column. The secondary resonances occur at values of current, and electron density, lower than that required for the principal resonance. The positions of the members of the spectrum are given by an interference-dispersion relationship given in an earlier paper.[1] The frequency ratios for the various observed modes are given equally well by the ratio X_{m1}/X_{11} where X_{m1} is the lowest value of x for which the value of the m-th order Bessel function $J_m(X_{m1})$ is zero. An interpretation of the spectrum is given in which the resonances are identified with the transverse normal modes of the plasma column and the assumptions and approximations underlying this interpretation are discussed.

1 W. D. Hershberger. Jour. Appl. Phys. 31, 417-422 (1960).

CONDUCTIVITY, ABSORPTION AND EMISSION OF MICROWAVES* D-8

Ludwig Oster
Laboratory of Marine Physics
Yale University, New Haven, Connecticut

The different methods currently used in computing the interaction of microwaves with plasmas, such as the evaluation of absorption and emission coefficients and conductivities, are compared. It is shown that they are all based on the same model assumptions and, thus, are equivalent. Power absorption and emission are then expressed in terms of temperature and density of the plasma. The resulting formulas are discussed as to their accuracy for numerical applications and their range of validity. Special consideration is given to deviations from equilibrium, both as the microwave field and the velocity distribution of the particles are concerned.

* Supported by the Office of Naval Research.

SESSION E
Friday, October 14
9:00 A. M.

Chairman
G. W. Weissler
University of Southern California

D I A G N O S T I C S

A RE-EXAMINATION OF THE MEANING OF MAGNETIC PROBE MEASUREMENTS* E-1

Richard L. Moore
Richard L. Moore, Consultants

The axial component of the magnetic field in a cylindrical plasma is shown to be proportional to the difference between two angular velocities, that of the ion gas, and that of the electron gas when the radial density is a quasi-stationary error function. By use of the functional relations between the variables, angular velocity is eliminated to obtain density as a function of the magnetic field; the initial mass per unit length, (M) and the standard deviation of the magnetic field curve, (σ) (in rationalized mks units) as follows:

$$\rho(r) = \frac{M}{2\pi\sigma^2}\left[\frac{H_z(r) - H_z(r_o)}{H_z(0) - H_z(r_o)}\right] \quad kg/m^3$$

This expression shows the internal magnetic field is frozen in and carried with the material. It gives a more consistent interpretation of density from probe measurements than present theory. It suggests that the snow-plow plasma sheath model is not consistent with experiment, but should be replaced by a bell-shaped plasma centered on the axis.

* Supported by Northrop Corporation, Norair Division, and by Rome Air Development Center, U. S. Air Force.

PROBE CURVES AND THEIR SECOND DERIVATIVES IN DOUBLE SHEATHS E-2

G. Medicus
Electronics Technology Laboratory
Wright Air Development Division
Wright-Patterson Air Force Base, Ohio

Families of probe curves and their second derivatives are automatically plotted for the probe passing through a sheath across the opening of a hollow hot cathode in Ne of about 1 mm Hg. The electron accelerating sheath is followed by a weak retarding field towards the anode. 1. At the anode side sheath edge two distinct groups of electrons are indicated, a slow group consisting of electrons having suffered inelastic collision losses, and a fast group with most of the energy acquired in the sheath retained. 2. In the middle of the sheath the slow group is absent, so that the probe curve goes linearly through space potential in accordance with theory for spherical probes. 3. At the cathode side sheath edge a slow group is indicated. In case 2 an approximate indication of space potential can be expected from the ion current which should cause a small kink in the second derivative, as long as the ion energy remains small compared to the electron energy (good energy exchange of ions with neutrals). Actually such kinks are observed.

THE INFLUENCE OF DIFFUSION LOSSES ON THE PROBE POTENTIAL IN A DENSE PLASMA

E-3

Kleber S. Masterson, Jr.*
U.S. Naval Postgraduate School
Monterey, California

G. Ecker
Institut fur theoretische Physik
Universitat Bonn

The theory of exploring probes in a plasma as originally developed by Langmuir does not apply to probes with dimensions comparable to or larger than the mean free path of the plasma carriers. On the other hand, it frequently seems necessary or desirable to use such probes for the investigation of the plasma qualities. We have calculated the relation between the measured probe potential and the true probe potential for two types of probes, with and without a magnetic field. The results for larger probe dimensions show a strong influence of the diffusion losses, which causes asymmetric distortions of the measured potential distributions. The deviations depend on the kind and the size of the probe.

* Lt., U. S. Navy.

THE STUDY OF LANGMUIR PROBES IN A CONTINUOUS ELECTRODELESS GAS DISCHARGE

E-4

Henry R. Hunczak
NASA Lewis Research Center

A preliminary investigation was conducted of the double probe[1] method of determining electron temperatures in a plasma generated by 3.75 to 10 megacycle radio frequency discharges in air and hydrogen. Electron temperatures of 6 to 11 volts were measured. Logarithmic plots of the current-voltage characteristic (Γ) indicated a Maxwellian distribution of electron velocities in a voltage range where neither probe was saturated. Electron temperatures as calculated from the slope of the logarithmic plot agreed within 6.5 per cent with those determined from an "equivalent resistance" method.[1]

1 E. O. Johnson and L. Mather, Phys. Rev. Vol. 80, No. 1 (October 1, 1950).

TJK 161

STUDIES OF DIAMAGNETISM IN GASEOUS PLASMAS WITH SPIN-RESONANCE METHODS

E-5

T. C. Marshall, R. A. Kawcyn, and L. Goldstein
University of Illinois

It has been possible to observe the occurrence of diamagnetism in active discharges by measuring shifts in spin absorption resonance frequencies of foreign substances located near the plasma. Narrow spin electronic resonances in DPPH have been used to show that the magnetization of a gaseous plasma in low pressure mercury vapor increases linearly with applied magnetic field up to about 40 gauss, where maximization occurs. Observation of the phase change in the Larmor precession of protons in a strong homogeneous field showed that the diamagnetism in a modified P. I. G. discharge in noble gases increased linearly with power input and decreased approximately as 1/H. Irradiation of the plasma with high power microwaves with frequency near the free electron gyro-frequency resulted in an increase of diamagnetism of the P. I. G. discharge. The discharge magnetic moment ranged from -10^{-3} to -0.32 erg/cm^3-gauss, depending on experimental conditions. The sensitivity of the nuclear resonance technique is one part in 10^6. It permits observation of diamagnetism to be deferred until the discharge is over. Theories of Alfven and Gordon, which attribute the diamagnetism to diffusion processes, appear to be correct, but the results are more general than these derivations would imply.

TEMPERATURE AND ENERGY BALANCE IN AN RF THERMAL PLASMA E-6

Thomas B. Reed
Lincoln Laboratory,* Massachusetts Institute of Technology
Lexington 73, Massachusetts

A new type of electrodeless thermal plasma, generated by RF is described. Temperatures have been measured as a function of radius in argon and argon-gas mixtures using the Lorentz method with inversion of the Abel integral equation. Energy losses associated with conduction, convection and radiation mechanisms have been measured.

* Operated with support from the U. S. Army, Navy, and Air Force.

LOWERING OF THE IONIZATION POTENTIAL IN AN ARGON PLASMA E-7

H. N. Olsen
Linde Company
Division of Union Carbide Corporation
Speedway Laboratories
Indianapolis, Indiana

Radial intensity distributions of the total electron continuum (free-free + free-bound) emitted from an atmospheric argon arc plasma have been measured on an absolute intensity scale at fixed wavelengths over the range 3,000 to 12,000 A.U. All radial distributions show an off-axis peak which falls at the same radius for each frequency. From earlier work [1] the measured temperature at the position of this peak was found, by the Fowler-Milne method, to be 16,000°K. From the frequency dependence of $\log \epsilon_\nu$ an experimental value of 0.85 volts has been obtained for the lowering of the ionization potential which is consistent with the observed disappearance of lines in the spectrum. This compares well with the theoretical value of 0.79 volts obtained from an iterative calculation of the plasma composition combining the Saha equation with the Ecker and Weizel [2] expression relating ΔV to the electron density, but is 50% higher than that given by the well-known Unsöld theory. Measured intensities are higher than the theoretical value given by the Krammers-Unsöld theory by a factor of about five in the red and two in the visible region of the spectrum.

1 H. N. Olsen, Physics of Fluids, 2, 614-623 (1959).

2 G. Ecker and W. Weizel, Ann. d. Phys., 17, 126-140 (1956).

SPECTROSCOPIC MEASUREMENTS OF PLASMA TEMPERATURES AND DENSITIES IN A HIGH PRESSURE CESIUM DIODE

E-8

R. Donohue, R. Majkowski, Hans Griem
General Motors Corporation
Warren, Michigan

Measurements of the electron and atom temperatures have been made in a cesium diode at 7 mm pressure. The electron temperatures (excitation temperatures) were obtained as a function of the position between cathode and anode from the relative intensities of the red (8521 A) and blue (4555.55 A) lines. The atom temperatures were derived from the Doppler broadening (which influences the line core) of both lines. The atom densities were measured from the absolute line intensities using the excitation temperatures. The electron densities were deduced from the collision (Stark) broadening which dominates in the line wings. From the atom and electron densities, the ionization (Saha) temperature was determined. All three temperatures (electron, atom and Saha) agree to within 20% (i.e. the experimental error). From the measured densities and temperatures, the total vapor pressure was computed and found to agree with the cesium vapor pressure(at cold spot) to within 20% (i.e. within experimental accuracy).

EXPERIMENTAL OBSERVATION OF STARK BROADENING OF BALMER LINES* E-9

W.S. Cooper, III, A.W. DeSilva, and J.M. Wilcox
Lawrence Radiation Laboratory
Berkeley, California

A hydrogen plasma was prepared by a high-current discharge and was allowed to decay. A pure Balmer spectrum from the plasma, merging with the continuum after nine lines, was observed. An estimate based on the Inglis-Teller method gave an ion density of about 3.5×10^{15} cm^{-3}. The line profiles of the first three members of the series, H_α, H_β, and H_γ, were measured as functions of time and were matched with theoretical line profiles calculated by Griem, Kolb, and Shen.[1] Good fits were obtained from very near the center of the lines to a point on the wings where the intensity is down by about two orders of magnitude from the value at the peak (as far as observations were extended). In the 350 μsec during which the line profiles were observed, the ion density decayed from 5.0×10^{15} cm^{-3} to 1.5×10^{15} cm^{-3}, and extrapolated back to about 6.4×10^{15} cm^{-3} at the time the discharge current was terminated, suggesting 100% ionization of the original neutral hydrogen (100μ) at that time. Temperatures were about 10^{4o}K.

* Work done under auspices of the U. S. Atomic Energy Commission.

1 H. R. Griem, A. C. Kolb, and K. Y. Shen, Phys. Rev. 116, 4 (1959); idem, NRL Report 5455, March 4, 1960.

THE UNDERWATER SPARK AS A GASEOUS DISCHARGE E-10

C.D. Maunsell
Pacific Naval Laboratory
Esquimalt, B. C.

Measurements have been made of the formative time of underwater spark breakdowns after step voltages of 1 to 15 kv are applied to a point electrode. Both fresh and sea water have been used. The breakdown in the more highly conducting sea water occurs within tens of microseconds while in fresh water hundreds of microseconds are needed. Visual observation shows the formation of a bubble on the electrode at voltages slightly below that at which breakdown occurs. These results are consistent with an hypothesis that resistive heating of the water occurs initially. After the formation of a bubble a gaseous discharge occurs if the field strength is sufficiently high. The inertia of the water causes the subsequent discharge to produce high temperatures and pressures.

SESSION F
Friday, October 14
2:00 P. M.

Chairman
R. N. Varney
Washington University

B R E A K D O W N

Invited Paper

MICROWAVE WHISTLER MODE PROPAGATION IN A DENSE LABORATORY PLASMA

F-1

Roger Gallet

National Bureau of Standards

Boulder, Colorado

ELECTRONIC COMPUTATION OF THE TEMPORAL GROWTH OF CURRENTS IN GASES, INCLUDING THE EFFECT OF SPACE CHARGE* F-2

A. L. Ward
Diamond Ordnance Fuze Laboratories
Washington 25, D. C.

The problem of the temporal growth of current in a gas between parallel plates, including the effect of space charge, has been programmed for electronic computation. The continuity equation for the electron current density, $J_-(x, t)$, is solved by using the exponential growth of $J_-(x, t)$ along an electron "world" line. The partial differential equation for the positive ion current density, $J_+(x, t)$, is solved by a difference method. The field distribution, $E(x, t)$, is determined by Poisson's equation. The initial distribution of the electron current density, $J_-(x, 0)$, and positive ion current density, $J_+(x, 0)$, across the gap, where x is the distance from the cathode, are those calculated for the static case for the given under-voltage assumed. The initial field distribution, $E(x, 0)$, is given by the sum of that calculated in the static case and a constant increment, corresponding to a step voltage applied at $t = 0$. $J_-(0, t)$ is given by the sum of the constant externally initiated current density and the contributions of both positive ion and photoelectric secondary effects. $E(0, t)$ is obtained by requiring that the total potential drop across the tube, including any parallel capacitance, and a series resistance should remain constant, or in other cases to vary with a sinusoidal time component. Results of calculations will be presented.

* Supported by the Office of Ordnance Research.

ELECTRICAL BREAKDOWN OF ARGON IN GLASS CELLS WITH EXTERNAL ELECTRODES AT 60-CYCLE ALTERNATING POTENTIAL*

F-3

J. M. El-Bakkal and L. B. Loeb
University of California, Berkeley

Breakdown in argon below 35 mm in borosilicate glass cells with external electrodes has been investigated using four different experimental techniques with varied time resolution, including steady and 60-cycle alternating potential. A fairly complete semi-quantitative description of the mechanisms at work has been achieved. Breakdown normally is of the Townsend type with a γ_p from the glass setting in above normal Townsend threshold. Near threshold breakdown is quenched by reduction of the internal field to slightly below threshold by wall charges. At high over-voltages short-lived but intense breakdowns annihilate the external field and deposit wall charges proportional to the applied potential. Very high over-voltages yield streamer-like breakdown mechanisms of ultra short rise time. Phenomena are altered by electrical properties of glass. Short duration of discharge confines breakdown to narrow channels, even at lower pressures the charges later spreading over electrode surfaces.

* Work supported in part by the Office of Naval Research.

IONIC AVALANCHES IN D_2 GAS AT VERY HIGH FIELD INTENSITIES F-4

G. W. McClure and K. D. Granzow
Sandia Corporation
Albuquerque, New Mexico

Ion avalanches initiated by D_2^+ ions in D_2 gas under the action of a very strong electric field ($E/P \simeq 4 \times 10^5$ v/cm mm Hg) are investigated by machine calculations taking into account; 1) the production of fast secondary D_2, D and D^+ through charge exchange and dissociative collisions, 2) the production of slow ions by ion-molecule collisions, and 3) the interaction of secondary ions with the gas. The avalanche developed in a distance of several times the charge-exchange mean free path is analyzed as to particle content and energy distribution. Favorable comparisons with measured energy spectra of D^+ and D_2^+ ions generated in a high voltage discharge indicate that most of the important processes have been accounted for.

THEORY OF HIGH IMPEDANCE DISCHARGE IN HYDROGEN F-5

Crawford MacCallum
Sandia Corporation
Albuquerque, New Mexico

The one-dimensional discharge in hydrogen at pressures below the Paschen minimum has been studied as a function of pressure and applied voltage for various electrode materials and electric field distributions. A generalized concept of "multiplication factor" has been developed which allows it and the asymptotic distribution of ion-electron production to be calculated numerically as solutions of an eigenvalue problem. The results have clarified the essential role played by electrons back-scattered from the anode and have supplied qualitative information about secondary electron emission by neutral molecules in the kilovolt energy range.

THE MOTION OF ELECTRONS IN A STRONG ELECTRIC FIELD* F-6

G. Ecker and K. G. Müller
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Universitat Bonn, Germany

We investigate the motion of electrons under the influence of a strong inhomogeneous electric field. The electrons start from rest and move in a monoatomic gas. It is our aim to determine the average electron velocity and the parallel and perpendicular velocity scattering as a function of the position. Elastic and inelastic collisions are taken into account. The local variation of the electric current as caused by the ionization processes is calculated. The results are applied to the cathode fall region of the glow discharge.

* Supported by the U. S. Dept. of Army through its European Research Office.

EFFECT OF LARGE STATIONARY DENSITY GRADIENTS UPON ELECTRICAL BREAKDOWN TRANSVERSE TO A HYPERSONIC STREAM OF AIR* F-7

Gary L. Marlotte
California Institute of Technology

Several new effects are introduced when a DC electrical discharge is struck across a gas moving at hypersonic speeds. The present paper results from an experimental investigation of one of these effects -- the large boundary layer density gradients that arise in hypersonic flow over electrodes. The experiments were carried out with air in the GALCIT 5-inch by 5-inch hypersonic wind tunnel with a nominal Mach number of 5.8. DC breakdown voltages were measured across a channel formed by flat-plate "Rogowski" electrodes embedded in two sharp-edged insulating flat plates. The breakdown voltages measured were considerably below the breakdown (Paschen) voltages measured in ordinary gas discharges. A theoretical treatment is given, and qualitative agreement with experiment results.

* Supported by U. S. Army Ordnance Contract No. DA-04-495-Ord-1960.

SOME ASPECTS OF THE GEIGER DISCHARGE IN HALOGEN QUENCHED COUNTERS F-8

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Eindhoven, Netherlands
Philips, Eindhoven

The propagation of the discharge was investigated for halogen counters filled with various Ne-A-Br_2 mixtures. Measurements were done for cylindrical counters with a thin wire as anode, as well as for counters with a spherical electrode geometry. It was found that the mechanism was essentially different for cylindrical counters containing 0.05% Br_2 from what was found for the conventional organic quenched counters: a. the propagation of the discharge along the anode wire takes place by long range photons b. the charge distribution along the length of the anode wire is non-uniform c. for larger cathode diameters the discharge starts along the anode but is transferred within a few microseconds to the region near the cathode surface. The behaviour of the dead time of the counter as a function of the counter voltage was measured for various counters. The results could qualitatively be explained by the above mentioned phenomena. The role of the metastable atoms and molecules and of the resonance photons was investigated by measuring the building up time for various amounts of argon and bromine mixtures. It was found that large variations of argon pressure (a factor of 10) hardly influenced the building up time. However the building up time was found to be approximately inversely proportional to the bromine pressure. This indicates that the occurrence of resonance photons governs the building up of the discharge and that the metastable atoms and molecules did not play a role with the building up of the discharge.

THE LIGHT PULSE FROM A GM COUNTER DISCHARGE* F-9

W. P. Davis, Jr. and W. C. Worthington
Dartmouth College
Hanover, N.H.

The GM counter discharge has been of considerable interest since 1928, but a detailed description of this discharge is still not possible today. It has been felt[1] that an experimental examination of the radiation emitted by the discharge might serve to clarify some of the uncertainties in the propagation mechanism, but very little work[2] has been done in this area. Light pulses from commercially available end-window GM tubes (Amperex Electronic Corp., Hicksville, N.Y.) have been observed with an RCA 5819 photomultiplier. For overvoltages of about 50 volts, these light pulses are about 1.0 μsec in length and have a distinctive shape. The emission spectrum of the GM discharge above 2800A was determined using a Hilger spectrograph. Data relating overvoltage to the behavior of the light pulse are presented as well as a possible interpretation of the shape of the light pulse. Preliminary results using GM tubes with semi-transparent cathodes will be presented.

* Supported in part by the National Science Foundation.

1 L. B. Loeb, Phys. Rev. 113, 7 (1959)

2 Locher, unpublished, see Korff, Electron and Nuclear Counters, D. Van Nostrand Co. New York (1955), pg. 176.

G. A. Condas, Bull. Am. Phys. Soc., Ser. II, 2, 375 (1957).

SESSION G
Saturday, October 15
9:00 A. M.

Chairman
W. B. Kunkle
Lawrence Radiation Laboratory

O S C I L L A T I O N S

Invited Paper

THERMAL RADIATION FROM A PLASMA WITH AND WITHOUT MAGNETIC FIELDS G-1

G. Bekefi

Massachusetts Institute of Technology

RELAXATION OSCILLATIONS IN SYNTHESIZED PLASMAS* G-2

Fred M. Johnson and Karl G. Hernqvist
RCA Laboratories
Princeton, N.J.

A theoretical and experimental study of internal relaxation oscillations in a plasma diode will be presented. An analysis is made of the steady state space charge modes in a plane parallel diode. Here ions and electrons, having a Maxwellian velocity distribution, are emitted from one electrode and are collected by the other electrode. It will be shown that there exists a set of operating conditions for such a plasma diode where no steady state solution to the space charge problem is allowed. Furthermore, the analysis indicates that an oscillatory solution exists where the potential fluctuates between a potential maximum and a potential minimum at a rate determined by the ion transit time. Experimental studies of these relaxation oscillations will be described. Tests were made with a low pressure cesium vapor type diode, having a high work function cathode, a low work function anode, and a small probe in the interelectrode space. Oscillations in the frequency range 1/2 - 1 Mc/s were observed in this diode. The nature of the oscillations as well as the conditions necessary for their occurrence are in good agreement with the theoretical analysis.

* Part of this research was sponsored by Advanced Research Project Agency, Department of Defense.

SOME MEASUREMENTS OF FLUCTUATIONS IN A PLASMA* G-3

F. W. Crawford and J. D. Lawson
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Stanford University, Stanford, California

Measurements of the fluctuations in anode voltage, tube current, and number density, have been made in a hot-cathode mercury-vapour discharge at a pressure of $\sim 1\,\mu$, under both space-charge-limited, and temperature-limited emission conditions. Substantial low-frequency fluctuations occur from zero to several hundred kc/sec with strong components at $\sim$60 and $\sim$100 kc/sec. Potential distribution curves show noise generation over the first 20 cm of the plasma column. This is poorly correlated from point to point but appears to propagate in the electron thermal velocities range. Over the remaining 50 cm of the experimental tube, the signal is well-correlated and travels at $> 10^9$ cm/sec. Despite the nonuniform noise distribution the column appears as a uniform impedance (to external signals), and an approximate expression has been derived for its Impedance/Frequency characteristic. Number density measurements made by a microwave cavity perturbation technique indicate fluctuations increasing in amplitude towards the cathode and persisting even when the discharge is temperature-limited, and other fluctuations have been substantially reduced.

* Supported by U. S. Atomic Energy Commission Contract AT(04-3)-326, P.A. 1.

THE INFLUENCE OF THE ANODE ON MOVING STRIATIONS* G-4

A. W. Cooper
U.S. Naval Postgraduate School
Monterey, California

The connection between multiple anode spots and the moving striations in the positive column of a glow discharge in argon has been investigated photoelectrically. Two spots oscillating out of phase on a cylindrical anode give rise to separate non-sinusoidal light intensity waves which travel towards the cathode. These patterns merge to form the nearly sinusoidal striation waveform in the positive column. A 50V longitudinal potential oscillation of variable frequency applied to the anode glow region controls the striation frequency over a range of 30% of its natural value. Experiments previously reported [1] have shown the critical current for disappearance of moving striations to increase with tube diameter. Thus a long discharge tube containing a center section of large diameter between narrower end sections can exhibit a normal striation pattern in the wide section while the end sections which are operated above the critical current show no oscillation. There is then no detectable mechanism connecting the striation oscillation pattern and the anode glow.

* Supported by the Office of Naval Research.

1 A. W. Cooper & N. L. Oleson
Bull. Am. Phys. Soc. 5, 5, 371, 1960.

EXPERIMENTAL TWO-BEAM EXCITATION OF ELECTRON OSCILLATIONS IN A PLASMA WITHOUT SHEATHS

G-5

M. J. Kofoid
Plasma Physics Laboratory
Boeing Scientific Research Laboratories
Seattle, Washington

Extensive experimental tests have been completed to establish the conditions under which strong standing waves of longitudinal electron oscillations can be excited in a plasma by two independent oppositely-directed electron beams, without sheaths on the beam emitting electrodes. Strong excitation was obtained when the velocity with which the electrons of each beam entered the plasma was equal to the phase velocity divided by the quantity(n + 1/4) or (n + 3/4), when n = 1,2,3,...6. It was not necessary to have equal beam velocities. A method of analysis has been worked out for finding the transit times for electrons having the above-indicated preferred entrance velocities and entering the plasma at different angles of oscillation-frequency phase. Assuming different maximum plasma oscillation electric field intensities, transit times have been computed for conditions under which strong standing waves have been excited experimentally. These calculations permit study of the electron bunching which is believed essential to the excitation of oscillations. The experiments were made with 1.0-mm diameter beams passing through 2.0 cm of plasma; standing waves were excited with one, two, or three loops at frequencies of 450 to 930 mc.

EXPERIMENTS ON DISPERSION IN PLASMA G-6

Julian Anderson
Western Development Laboratory, Philco Corp.
Palo Alto, California

The Vlasov and Landau theories of dispersion of current and field oscillators is reviewed. The existence of undamped or weakly damped poles of both field and density distributions lead to simultaneous current and field oscillations, which should be simultaneously detectable on current and field probes. An experiment is arranged to detect these oscillations and measure their dispersion. Several of the predicted oscillations are found, and a sample of their dispersion obtained. Comparisons with theory are obtained for the dispersion relations, damping decrement and frequency, velocity and wavelength cut-offs, and the initial velocity and density distributions are discussed. Evidence of a field-plasma resonance is presented, resulting in acceleration of initial distribution particles to field energies within one cycle of the plasma frequency and a spatial interval of one Debye length. The acceleration is discussed in relation to the anomalous relaxation parameters observed by Langmuir.

OSCILLATIONS IN THE ARGON SUBNORMAL GLOW DISCHARGE* G-7

D. J. Belknap, M. J. Reddan and A. L. Ward
Diamond Ordnance Fuze Laboratories
Washington 25, D. C.

In the course of measurements of static characteristics in the subnormal glow region, the transition region between the Townsend and the normal glow discharge, various oscillatory phenomena have been noted in argon at pressures of 50 mm Hg and lower. These oscillations range from nearly sinusoidal oscillations of very small amplitude to relaxation type oscillations of large amplitude. Under certain tube and circuit conditions, relaxation type oscillations occur, the frequencies of which are nearly independent of the value of the series resistance, contrary to the usual case. The frequency of these oscillations is proportional to the current and thus correlates with calculated frequencies obtained by using values of negative resistance computed on the IBM 704. Both the amplitude and frequency of these oscillations are strongly dependent upon any capacitance parallel to the tube. At very low currents, a repeating sequence of a growing oscillation which leads to a "breakdown" pulse has been observed. Pictures will be shown of various current wave-forms. Further explanation of the various phenomena will be given, and the circuit requirements for tube stability will be discussed.

* Partially supported by the Office of Ordnance Research.

A SOLUTION FOR THE TWO-ELECTRON CORRELATION FUNCTION G-8

Burton D. Fried
Space Technology Laboratories, Inc.

H. W. Wyld, Jr.
Space Technology Laboratories, Inc., and University of Illinois

Consideration of two-particle correlations provides a systematic method for correcting the Vlasov, or "collisionless" (more accurately "correlationless") kinetic equation. Existing treatments have retained the two-particle correlation function, $g(\underline{x}_1, \underline{v}_1, \underline{x}_2, \underline{v}_2, t)$, only in the limit $t \to \infty$. By studying the Laplace transform, $g_L(\omega)$, one can find how rapidly $g(t)$ actually approaches its asymptotic value. We restrict ourselves to a classical, non-relativistic electron gas, interacting via Coulomb forces in presence of a uniform background of positive charge. When the one-electron distribution function, f, is independent of position, $g_L = g_L(\underline{x}_1 - \underline{x}_2, \underline{v}_1, \underline{v}_2, \omega)$ satisfies an integral equation which can be solved in closed form for the special choice $f(\underline{v}) = (a/\pi)(a^2+v^2)^{-2}$. It is found that the "universal" poles in g_L (i.e., those not associated with particular initial conditions) consist of one at $\omega = (\underline{v}_1 - \underline{v}_2)\cdot\underline{p}/2$ (giving rise to an oscillatory term in g) and a number of (damped) poles lying on the lines $\omega = -ipa$ and $\omega = -ipa/2$, where $\underline{p}$ is the wave number conjugate to $\underline{x}_1 - \underline{x}_2$. Since for $p \ll \omega_p/a$ the "relaxation time" for g will greatly exceed ω_p^{-1}, these results indicate that the effect of g upon such phenomena as plasma oscillations may not be adequately represented by the $t \to \infty$ limit.

THE POLARIZING FIELD IN A PLASMA

G-9

O. Theimer and L. S. Taylor
New Mexico State University, Research Center

If an electromagnetic wave travels through a plasma the plasma electrons (charge -e, mass m, velocity $\underline{v}$) experience the following forces: $\underline{F}_1 = -e\underline{E}$ is the force from the radiation field $\underline{E}$. $\underline{F}_2 = 4\pi\underline{P}e/3$ is the force from the polarization charges induced on the surface of a large auxiliary sphere, centered at the test electron. The average force with which the positive ions in the sphere act on a test electron is different from zero because of the radiation induced electron motion and the resulting deviations from randomness. The electron displacement in ordinary space causes the depolarizing force $\underline{F}_3$, and the electron displacement in velocity space causes the force of dynamical friction $\underline{F}_4$. For low frequencies and weak shielding, these forces satisfy the conventional formulas $\underline{F}_3 = -4\pi\underline{P}e/3$ and $\underline{F}_4 = -m\nu_c\underline{v}$, where ν_c is the collision frequency. But both forces tend to zero at optical frequencies and are affected by shielding between opposite charges. Formulas for $\underline{F}_3$ and $\underline{F}_4$ as functions of frequency, temperature and electron density are given.

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1960

G A S E O U S E L E C T R O N I C S

C O N F E R E N C E C O M M I T T E E

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13th ANNUAL GASEOUS ELECTRONICS CONFERENCE

GENERAL INFORMATION

ADDRESS: Gaseous Electronics Conference, Department of Physics, U.S. Naval Postgraduate School, Monterey, California.

TELEPHONE: FRontier 2-7171, Extension 347. The telephone is located at the Registration Desk in the lobby of Spanagel Hall (long, five-story building).

MESSAGES: Messages for participants will be posted on Bulletin Board near the Registration Desk.

BANQUET: The cocktail party and banquet will be held on Thursday evening at 7:00 P.M. in the Bali Room of the U.S. Naval Postgraduate School. Dr. Lewi Tonks will be the afterdinner speaker, his topic being, "Irving Langmuir's Plasma." Tickets may be purchased prior to 1:00 P.M. Thursday at the Registration Desk at $4.00 per person.

PROGRAM CHANGES: Paper G-6 in the Saturday morning session has been withdrawn.

SLIDES: Persons presenting papers where slides are to be used are personally responsible for getting the slides, properly labeled and in order, to the projectionists in King Hall prior to the session in which the papers are to be presented. Slides can be reclaimed at the end of each session from a table in the lobby of King Hall.

BREAKFAST AND LUNCH: Breakfast is available in the cafeteria, located directly below the lobby of King Hall, which opens at 7:30 A.M. Lunch can be obtained after 12:45 P.M. in the cafeteria or in the Bali Room (see map on the back inside cover of the Program of Abstracts). These facilities will not be open on Saturday, 15 October. There are, of course, many outstanding restaurants on the Monterey Peninsula where excellent breakfasts and luncheons are served. Help yourself to the pamphlet "Where Shall We Eat," at the Registration Desk.

TRANSPORTATION: Special bus service will be provided for those who are staying in motels and hotels in the Monterey area. The bus will carry a placard, "GEC Conference." Your conference name tag will allow you to ride the bus without charge. The bus will bring conference participants to the session each morning and will return them to their lodgings at the end of the last session each day. It will also operate before and after the Cocktail Hour and Banquet on Thursday Evening. See the accompanying sheet labelled "Bus Schedule" for further information.

PARKING: Parking is permitted on far side of the road which runs past King Hall (see map on back inside cover of Program of Abstracts).

INTERMISSION: During each 20 minute intermission coffee will be served in the cafeteria located directly below the lobby of King Hall.

LADIES' PROGRAM: All ladies are cordially invited to participate in the Ladies' Program which is as follows:

Wednesday 12 October, 3:30 P.M.

Mrs. Allen E. Vivell, wife of the Dean has invited all ladies to a tea at the Copper Cup Room (adjacent to the Bali Room in the Administration Building). Those ladies who have not already indicated their intention to attend, please sign the appropriate sheet at the Registration Desk.

Thursday 13 October, 10:30 A.M.

Bus tour of Monterey Peninsula, including 17 Mile Drive and Carmel, through the courtesy of the Monterey Convention Bureau. Lunch ($2.50) at the Carmel Highlands Inn where a fashion show will be presented by Lanz of Carmel. All ladies who have not already indicated their intention of taking this trip, please sign at the Registration Desk. Ladies will meet at 10:20 A.M. at the Registration Desk, the bus leaving from the Postgraduate School at 10:30 A.M. and returning at 2:30 P.M.

Friday 14 October, 10:00 A.M.

Mrs. Austin R. Frey, wife of the Chairman of the Department of Physics has invited all ladies to coffee at her home in Pebble Beach. Please sign sheet at Registration Desk. Ladies will meet at 9:50 A.M. Friday morning at the Registration Desk and will be driven to Mrs. Frey's home and back to the Postgraduate School after the coffee social.

PUBLICATION OF ABSTRACTS IN THE A.P.S. BULLETIN: All abstracts will be submitted to the American Physical Society for publication unless the Secretary has received contrary instructions in writing. The abstracts will be submitted in the form that they appear in the Program of Abstracts, but the Local Committee can take no responsibility for editing or for insuring that the abstracts meet the Physical Society's length requirements. Authors who wish to make small changes or small additions to their abstracts before they are sent to the A.P.S. are requested to make these changes in a special copy of the Program at the Registration Desk. Abstracts will be sent to the A.P.S. exactly as they appear in this special corrected copy of the Program of Abstracts.

STAFF VACANCY IN THE DEPARTMENT OF PHYSICS: There is a vacancy at the rank of Assistant Professor or Associate Professor depending upon experience. The teaching load averages 10 hours, laboratory work counted at full time. Research is encouraged and expected. There are research programs currently in progress in acoustics, infra-red, gaseous electronics, nuclear physics and solid state physics. A research program is being started in plasma physics.

There is also a vacancy for a research associate to do experimental and/or theoretical work in plasma oscillation or diffusion across magnetic fields. This is a full time research position for a period of one to three years.

For further details concerning these vacancies, leave your name and local address with the Secretary of the Department of Physics, Room 100, Spanagel Hall, Extension 501, so that an appointment can be arranged sometime during the Conference.

N. L. Oleson,
Secretary,
1960 Gaseous Electronics Conference