THE ELECTRON ENERGY DISTRIBUTION IN THE CROOKES DARK SPACE OF A GLOW DISCHARGE

by

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If a sufficient potential is applied between the electrodes of a gas filled tube, a visible discharge will result. As the pressure decreases the appearance of the discharge changes. At a pressure of 0.1 millimeter of mercury the discharge consists of a series of light and dark sections. Starting from the cathode these sections are: the cathode glow, cathode (or Crookes) dark space, negative glow, Faraday dark space, and a positive column that may or may not have striations filling the remainder of the tube. The type of gas in the tube determines the appearance of the positive column.

Early experimenters (7, pp. 528-530) discovered that if the anode were moved toward the cathode with the discharge operating at a constant pressure and current the appearance of the discharge remained unchanged with each striation disappearing as the anode passed through the position for that striation. The discharge operated until the anode reached the leading edge of the negative glow. If an aluminum cathode is used, any electrode distance less than the distance to the leading edge of the negative glow will not sustain a discharge. If copper or brass electrodes are used, the discharge becomes a rapid flicker at this position. Closer distances will decrease the amount of flickering until the discharge dies out completely. Since the discharge does remain stable until the leading
edge of the negative glow is reached, it is concluded that the fundamental processes of the discharge occur in the Crookes dark space.

Several theories have been advanced concerning the Crookes dark space. The one most commonly accepted was developed by H. A. Wilson (10, pp.227-237). He suggested that electrons accelerating from the cathode toward the anode will collide with gas molecules and ionize them. These ion pairs are in a strong electric field and will separate, the positive ions accelerating toward the cathode and the electrons accelerating toward the anode. The positive ions will gain energy through their fall to the cathode and will release this energy upon bombarding the cathode. This bombardment will release more electrons to traverse the dark space producing more positive ions to complete the cycle.

Compton and Morse (3, pp.227-237) made quantitative calculations using Wilson's theory and concluded approximately 50 ion pairs are produced in the dark space by each primary electron leaving the cathode. For equilibrium this would indicate 50 positive ions are needed to eject an electron at the cathode.

Calculating the efficiency of ionization, P. T. Smith (6, pp. 1293-1302) found the maximum efficiency of ionization at an electron energy of 100 to 300 electron volts. Higher energy electrons ionize less efficiently with the ionizing ability being inversely proportional to the electron energy. Using this information, J. J. Thomson (9, pp.293-316) developed a theory for helium at 1 millimeter
of mercury pressure and concluded three ion pairs are produced by each primary electron while crossing the dark space. M. L. E. Oliphant (5, pp.373-387) also found three positive ions necessary to eject an electron when the cathode fall of potential was 200 volts. Extrapolating his data to a cathode fall of 1700 volts, it is assumed one positive ion will eject two electrons at the cathode.

J. J. Thomson (8, pp.1-33) attempted to measure the energies of the electrons after passing through the dark space. A brass tube served as anode and a beam of electrons was allowed to pass through the tube. This beam was then bent by a magnetic field and fell on a fluorescent screen. If a distribution of electron energies had been present, the pattern on the screen would have shown a line of spots; a spot for electrons with no energy loss, a spot for electrons that have lost energy in one collision, etc. Thomson obtained a single spot with a very faint tail. This spot indicated no energy loss by collision. The same result has been verified by Brewer and Westhaver (1, pp.779-782).

Since low energy electrons will not cause a screen to fluoresce and the resolving power of the apparatus may not show adequate distinction between two adjacent electron energies, it was suggested the electron energies could be measured by placing a collector behind the anode and applying retarding potentials to the collector. This retarding potential is used to control the number of electrons reaching the collector. If all of the primary electron energies correspond to the potential drop across the tube, no ion pairs could be formed. If the primary electrons have lost energy, the electron
current measured at the anode should show a decrease at high retarding potentials. If low retarding potentials are used, the energies of the slow electrons and the approximate location of ionization could be determined. A graph of electron current at the collector measured at various retarding potentials should show the extent of ion formation.
APPARATUS

The apparatus was constructed with two identical electrodes and ion collectors. With the discharge operating, one collector would receive the electron current and the other would receive the positive ion current. If one collector should fail to operate at high retarding potentials the voltage across the tube could be reversed and the other collector used with retarding potentials.

The tube was constructed of 51 millimeter Pyrex tube 22 centimeters long. End seals were made of 50 mil tungsten wire beaded in uranium glass. The uranium glass was joined to Pyrex tubing, and this tubing was flaired to seal to the 51 mm tubing. A side arm of 10 mm Pyrex tubing was joined to the main tube, and other side arms were joined to the first for the vacuum gauge and outlets to the vacuum pump and the controlled leak. Vacuum stopcocks were placed in the latter two outlets to maintain the vacuum while the tube was idle. The vacuum gauge used was a thermocouple gauge type 501 developed by the Vacuum Engineering Division of the National Research Corporation of Cambridge, Massachusetts. This gauge was sealed to the 10 mm side arm with Pyramid sealing wax.

The electrodes were disks 44 mm in diameter cut from 1 mm copper sheeting. A slit 1.5 mm in width and 23 mm long was filed in the center of each disk. A 40 mil nickel wire was silver soldered to each disk for electrical contact and electrode support. The ion collectors were constructed of tantalum foil cut and bent into
rectangular boxes 28 mm long, 12 mm wide and 10 mm deep. An opening 1.8 mm wide was left in the lid to allow electrons to pass into the collector. A 40 mil nickel wire was spotwelded to one side of the collectors before the assembly was completed to provide electrical contact with the collector after assembly. A layer of Sauereisen Insa-Lute Cement No. 1 paste (Sauereisen Cements Company, Pittsburgh) was spread on the back of the copper disks. The collectors were placed in position as shown in Figure 1, and the cement was allowed to dry. The two nickel leads were spotwelded to the endseal wires and all exposed metal between the copper disks and the glass in the endseals was painted liberally with cement. After the cement dried, the endseals were placed in an oven and baked at approximately 175 degrees Fahrenheit to insure drying the cement. Then the temperature was raised to 500 degrees Fahrenheit for an instant and slowly lowered. This baking process changed the cement from a conducting medium to a good insulator. Both electrodes were tested with the full tube potential to detect any leak current. Both appeared to be adequately insulated. The baking process formed a layer of copper oxide on the electrodes so they were polished with emery cloth before the tube was assembled.

The endseal assemblies were placed at each end of the glass tube so that the copper disks were centered in the tube at a distance of 38 mm apart. The pyrex tube was assembled and annealed.

Two five thousand volt power supplies equipped with variacs supplied potentials of zero to 1700 volts. One was used to maintain
A. Brass Electrodes
B. Ion Collectors
C. Nickel Wires

Insulation

Fig. 1. Electrode Assembly
the discharge and the other to supply the retarding potentials. A third power supply with a range of 0 to 400 volts was used for retarding potentials at both the high and low range of potentials. This supply provided more accurate control and adjustment. The power supplies used for retarding potentials were placed in series with ten 10,000 ohm resistors to produce a voltage divider with greater sensitivity than the power supply and variac combination. With retarding potentials of zero to 400 volts the positive terminal of the small supply was connected to the anode and the negative terminal to the collector. All other readings were taken with the negative terminal of power supplies connected to ground.

The meters used to record data were: 1, a Simpson meter, model 260, used to measure the retarding potentials; 2, a Simpson milliammeter, 0 to 1 milliamps, used to measure the total tube current; 3, a Simpson microammeter, 0 to 50 microamps, used to measure the positive ion current; 4, a Weston microammeter, 0 to 30 microamps, used to measure the electron current.

The vacuum pump was a Cenco-Megavac constructed by the Central Scientific Company of Chicago. A pinch clamp placed on rubber vacuum hose between the pump and the experimental tube permitted excellent control of the pumping speed.

The controlled leak was assembled with a short piece of rubber vacuum hose with a 20 mil nickel wire in the center. A pinch clamp over this hose also permitted fine adjustment. For operation the rate of leakage remained constant and pressure was controlled by changing the pumping rate.
Other apparatus consisted of resistors to shunt the meters and switches to facilitate operation.

During the first data run it was discovered that ionized air molecules bombarding copper will cause atoms of copper to be ejected from the cathode and be deposited on the walls of the tube. Since this was undesirable from possible field alteration, the tube was cut apart and cleaned. One electrode was arbitrarily chosen for the cathode and was plated with aluminum by evaporating aluminum from a heated filament. The tube was again cleaned and assembled.
PROCEDURE

After the tube was completed, it was connected to the vacuum pump with a length of vacuum tubing. Electrical components were arranged as illustrated in Figure 2. The pressure was lowered to a millimeter of mercury, and a potential of 1700 volts was placed on the anode. The discharge at this pressure has a uniform positive column. The voltage was kept constant, and the pressure reduced until the leading edge of the negative glow was almost at the anode. Reducing the pressure further would cause the discharge to stop.

The pressure was slowly reduced, and one of the ammeters was read at the instant the discharge stopped. The pressure was increased until the discharge started again, and the process was repeated with another ammeter. This process was continued until all three ammeters and the voltmeter were read.

After this set of readings was completed, a low retarding potential was placed on the electron collector. Another set of readings was taken, and the retarding potential was increased. This process continued until the range of retarding potentials from 0 to 1700 volts had been explored, and the data was reproducible to within 5 percent.
Fig. 2. Location of Meters

A₁ Total Tube Current
A₂ Positive Ion Current
A₃ Electron Current
V Retarding Potential
RESULTS

A summary of all data is shown in Figure 3. Data from the end ranges of 0 to 400 volts and 1300 to 1700 volts retarding potentials were taken in detail with the 400 volt power supply and voltage divider. No two curves gave exactly identical values, but the slopes of all curves were the same at various potentials. The curves chosen represent the most accurate data taken in these ranges. Data runs over the full range of retarding potentials were made with the large power supply and indicated the general shape of the center portion of the curve. Since none of the recorded data actually fell on the center portion of the curve, this area is not shown with a solid line. Actual curves indicated the slope and the curve was matched with accurate data at 400 and 1300 volts retarding potentials.

Three areas of this curve are of special interest. The range near 1700 volts retarding potential is reproduced in Figure 4. The curve is smooth with an increasing slope as the retarding potential increases until 1680 volts is reached. Here the curve shows a rapid decrease in electron current. This indicates primary electrons that have lost energy through one ionization collision and cannot reach the collector. The ionization potentials for oxygen and nitrogen are 13.61 and 14.54 volts respectively (4, p.124). If two collisions were made the curve should break at 27 volts or higher from ground potential. Since the curve does reach a maximum at 20 volts from ground potential, it is concluded that the primary electrons produce
Electron Collector Current (microamperes) versus Retarding Potential (volts)

Fig. 3.
Electron Collector Current (microamperes) 
versus Retarding Potential (volts)

Fig. 4.
only one ionizing collision. This is consistent with results obtained by Brewer and Westhaver when they concluded the resolving power would not distinguish between electrons making no collisions and electrons making one collision (1, pp. 782).

The second and third regions of the curve that are of importance are reproduced in Figure 5. Two sections of this curve are linear. The line from 0 to 15 volts retarding potential results from collisions made in the edge of the negative glow. If the pressure is slowly increased and the amount of negative glow increased, the curve is still linear from 0 to 15 volts, but the slope is much steeper. The current shown here is the minimum current that will maintain a discharge.

The line from 20 to 140 volts retarding potential is the third region of interest. This indicates electrons are produced by collision outside the negative glow. If a linear potential drop is assumed, these collisions occur after the primary electrons have traveled over nine tenths of the distance to the anode. At the pressures used the calculated mean free path of the electrons is approximately equal to the distance between electrodes. Since this is the average electron path, it can be assumed that not all primary electrons will produce positive ions by collision.

One data run produced a change of total tube current with an increase in time. To locate the cause of this effect both the leak rate and the pumping rate were increased. Immediately the total tube current dropped to its original value. It was concluded that the
Electron Collector Current (microamperes) versus Retarding Potential (volts)

Fig. 5.
controlled leak was permitting a non-uniform diffusion of the gases in the atmosphere. It was suggested data be taken with a discharge in a hydrogen atmosphere. The tube was flushed with hydrogen several times and a discharge obtained. The combination of protons bombarding aluminum caused sputtering of the aluminum from the cathode. This destroyed the usefulness of the tube, so further data could not be taken without rebuilding the tube. The area of the cathode that contributed to the discharge was measured from the sputtered area. Using the area of the slit, area of the cathode, positive ion collector current, and total tube current, the ratio of positive ions produced per primary electron was calculated. For this experiment this ratio is 0.39. Only about one third of the primary electrons are making ionizing collisions. For equilibrium the average positive ion bombarding the cathode must produce 2.6 electrons. This is in excellent agreement with Oliphant's extrapolated data.

If the current in Figure 3 is the sum of several independent currents at the slit to the electron collector, it should be possible to isolate these currents. Figure 6 shows a plot of the three currents that may be present and a comparison between the sum of these currents and the actual curve of Figure 3. The electron current should be maximum when no electrons are excluded by retarding potentials. After the low energy electrons are excluded, this current should remain constant until the retarding potential is high enough to repel electrons that have made one collision. At this potential the current should drop and the electrons making no
Fig. 6. Electron Currents (microamperes) Versus Retarding Potential (volts)
collisions would give a constant current until the retarding potential is equal to the tube potential. This curve is drawn using one third of the primary electrons making collisions.

The secondary electron current plot is reproduced from graphs published for tantalum surfaces by H. Bruining (2, p.36). These graphs are for bombardment by electrons only.

For the positive ion curve, more positive ions are accelerated into the collector as the potential is increased. A linear increase in current is the simplest rate that could be assumed. This rate is usually obtained by probe studies in an ion plasma.

The sum of these three currents agrees very well with the actual current in the center portion of the graph. Deviation at low retarding potentials can be expected since the electric field penetrating the collector at the slit may be too small to cause appreciable currents. Deviation at high retarding potentials may result from poor extrapolation of the secondary emission curve when the primary electrons have a low energy. This agreement is very good considering the assumption of a linear positive ion current increase. Also, secondary emission of electrons from the collector could result from positive ion bombardment.

To summarize, only three energy ranges exist for electrons in the Crookes dark space. First; most of the primary electrons travel through the dark space without producing any ionization and have the energy corresponding to their fall through the dark space. Second; about one third of the electrons make one collision with the gas
molecules in the tube and have an energy equivalent to the potential drop across the tube minus the energy used to ionize the gas molecules. Third; slow electrons produced by the collision fall a short distance to the anode and have the energy of the potential drop between the point of collision and the anode. Also, the amount of ionization actually occurring in the Crookes dark space is practically negligible in maintaining the discharge.
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