THE MINIMUM ARCING VOLTAGE IN HELIUM.

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SYNOPSIS.

Helium Arc; Minimum Arcing Voltage.—The arc was stimulated by an intense thermionic current passed between electrodes in very pure helium. *20 volts* was found to be a well-defined minimum voltage at which the arc will strike or break, although it may be maintained on voltages as low as 8 volts after having struck.

Helium Spectrum; Voltage for Excitation of Lines and Bands.—Apparently the ordinary helium and parhelium lines and the bands are excited whenever the arc strikes. The line *4686* of the *enhanced system* was never observed below 55 volts, and was stronger above 80 volts. The lines of the *sharp subordinate series of pairs* are peculiar in that their intensity decreases, relatively to that of the rest of the spectrum, as the voltage is increased.

The results are in accord with *Bohr's theory of radiation and atomic structure.*

INTRODUCTION.

RECENT investigations of the production of radiation and ionization by electron impacts in helium[1] have shown that the minimum radiating potential of this gas is close to 20.2 volts and its minimum ionizing potential is 25.5 volts. One of the writers has shown[2] that these values apply to radiation and ionization set up by a single electron impact against a normal unexcited atom, whereas, if the electron current and gas density are relatively large, ionization may occur at any voltage above 20.2 volts. This ionization at abnormally low speed is presumably due to impacts against atoms which are in a relatively unstable condition due either to preceding impacts or to the absorption of radiation coming from neighboring atoms which have been struck. The latter of these causes is much more important than the former. Neither radiation nor ionization has ever been observed below 20 volts.

These considerations suggest that 20.2 volts should be the minimum voltage at which an arc can strike in helium and that the necessary conditions for obtaining an arc at this voltage are an intense bombarding electron current and relatively high gas pressure, so that the amount of ionization due to the comulative effect of impacts and radiation may be sufficient to cause an arc.

Rau[3] and Richardson and Bazzoni[4] have published results of experi-

[1] F. Horton and A. C. Davies, Roy. Soc. Proc. A., 95, p. 408, 1919; Franck and Knipping, Phys. Zeit., 20, p. 481, 1919.

[2] K. T. Compton, Phil. Mag. (in print)

[3] Sitz. Ber. d. Phys. Med. Ges. zu Würzburg, p. 20, 1914.

[4] Nature, 98, p. 5, 1916.

ments on arcing potentials and the arc spectrum in helium. The lowest arcing voltage found by Rau was 24.5 volts. This was in the presence of mercury vapor, whose ionization increased the current density and thus caused the helium arc to strike at a lower voltage than in pure helium. Apparently 29.5 volts is the lowest voltage at which Rau obtained the arc in pure helium. Richardson and Bazzoni, working with helium in the presence of mercury vapor, obtained the helium arc spectrum at 22.5 volts, the mercury arc spectrum appearing first at a slightly lower voltage.

The following experiments were made to determine the voltage at which the arc strikes under various conditions of gas pressure and electron current density in very pure helium. It was found that the arc could be made to strike at voltages as low as 20 volts, but never lower. Under favorable conditions, however, the arc could be maintained at much lower voltages, the lowest voltage observed being 8 volts, with a gas pressure of 5 mm. and a current of about an ampere through the gas. Observations of the spectrum were also made under various conditions.

Apparatus.

The arc was obtained between an incandescent tungsten wire cathode and a nickel disk anode, enclosed in a glass bulb. Wires of various diameters from 0.06 mm. to 0.25 mm. were used, and their lengths varied from 1 cm. to 2 cm. The distance between the electrodes varied between 1 cm. and 3 cm. in different bulbs. A large bulb of cocoanut charcoal was sealed directly to one end of the experimental tube, while to the other end was attached the glass tubing connection to the helium reservoir and pump. This connecting tube was bent into two U tubes near the bulb. The one nearest the bulb was a trap to prevent the entrance into the bulb of water or mercury vapors and the further one contained charcoal. The bulb and the charcoal tubes were baked out in an electric furnace maintained at a temperature between 300° and 350° C. for several days while the apparatus was evacuated by a diffusion pump. Liquid air was then applied to the trap and later to the two charcoal tubes before the helium gas was admitted. A mercury hand pump with a magnetically operated valve permitted the gas pressure to be adjusted to any value between 0 and 24 mm. A Hilger wave-length spectrometer was used for the examination of the spectrum. In every case observations were made at increasing filament temperatures until the wire burned out. The voltage across the arc and the current through it were regulated by series and parallel resistances connecting it to a 110 volt storage battery.

RESULTS.

From among the large number of sets of observations made only a few examples can be given in the accompanying figures. Possibly the results can be most concisely presented by discussing them under the four following cases, which are somewhat arbitrary and not always mutually exclusive.

Case I.—No arc. The current increases as ionization and radiation set in above 20 volts, but there is no discontinuous change or visible

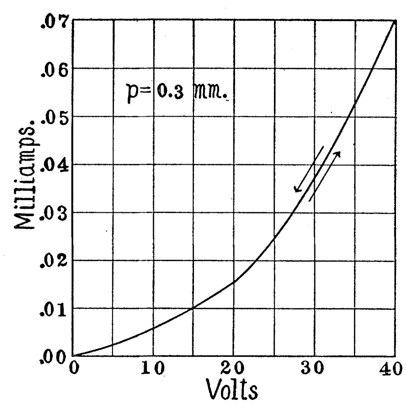

Fig. 1.

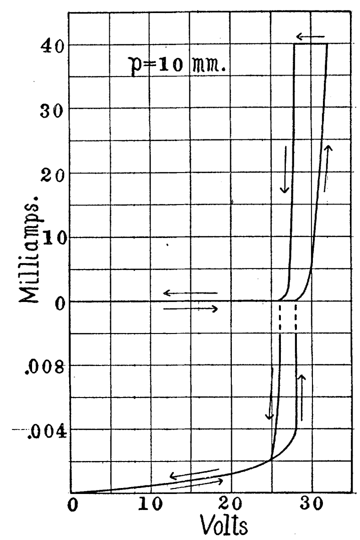

Fig. 2.

radiation. Variations of current with voltage are reversible. This case is observed at any gas pressure if the thermionic current is small and with any thermionic current if the gas pressure is small. Example: Fig. 1.

Case II.—The arc strikes at a voltage above about 29 volts and breaks at a voltage above 20 volts. There is no characteristic value for either the striking or breaking voltage, since they may be varied by varying the thermionic current or pressure. In general any change which increases one, also increases the other. The arc current always increases as the applied voltage is increased, but there is a region of irreversible changes between the striking and breaking voltages. Example: Fig. 2.

Case III.—The arc strikes at a voltage below 29 volts and breaks at 20 volts. Here it is found that, by increasing the thermionic current by raising the filament to a higher temperature, the striking voltage may be reduced as low as 20 volts, but the breaking voltage stays constant at 20 volts. Between the striking and breaking voltages the current-voltage changes are irreversible. Example: Fig. 3.

Case IV.—The arc strikes at 20 volts and breaks at 20 volts, although it may be maintained at lower voltages if the current of the arc is increased by decreasing the series resistance. But no further increase in the thermionic current will cause the arc to strike or break at voltages below 20. This seems, therefore, to be a definite minimum value for the arcing voltage — and, therefore, for the excitation of the spectrum. If, after the arc has struck, the series resistance is decreased, the current increases and the potential drop across the arc decreases. In one case the arc was thus maintained on 8 volts and in another case on 10 volts. There seems to be no lower limit for the maintenance of the arc, once it has struck, for this seems to be limited only by the size of the currents which the electrodes will carry. In every such case, as the series resistance is again increased, the voltage again rises to 20, where the arc breaks. Example: Fig. 4.

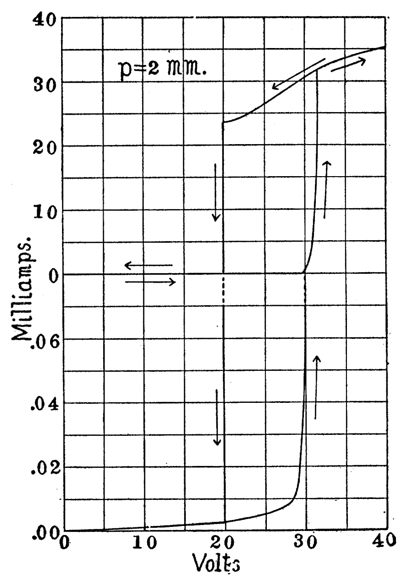

Fig. 3.

There are several interesting peculiarities of the arc which have been noticed during the experiments. Between Case III. and Case IV. there is an intermediate condition which may be considered as marking the division between them. Here the arc strikes at 20 volts, and remains at 20 volts however the current through the arc be increased by decreasing the series resistance. In this condition the resistance of the arc varies exactly inversely with the current through the arc. In one case the current between the electrodes was varied at will from 50 microamperes to 50,000 microamperes without producing any variation in the potential drop of 20 volts.

The current and voltage of the arc, with large currents, often exhibited discontinuous changes as the geometrical distribution of the arc in the tube suddenly changed. As far as we could tell, these shifts gave no indication of critical voltages in addition to that at 20 volts, since they seemed to be more or less accidental and occurred at different voltages at different pressures and with different positions and shapes of the electrodes.

It should be stated that the observed critical voltage which we have called 20 volts, in reality was sometimes as high as 20.5 volts and sometimes as low as 19 volts. These variations, however, are accounted for by the average initial velocities of emission of electrons from the filament at the temperatures used.

In securing an arc under the conditions of Case IV., the optimum gas pressure was between 4 mm. and 10 mm. Higher gas pressures would be advantageous, because of the greater probability of ionization by

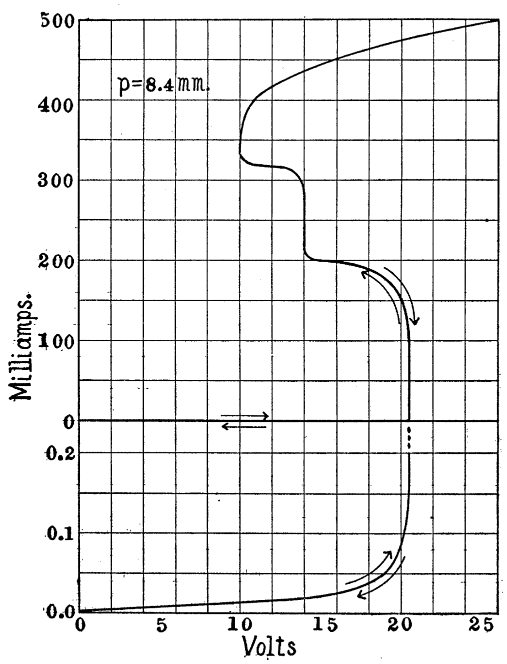

Fig. 4.

cumulative impacts, if it were not for the fact that, at such high pressures, the electrons make so many collisions in their zig-zag course that the aggregate amount of energy which they lose as a result of the momentum imparted to the atoms becomes considerable.[1] Thus, at the higher pressures, voltage greater than 20 volts must be applied in order that the electrons may acquire a velocity corresponding to 20 volts.

Spectroscopic Observations.

As far as we could tell, the entire helium spectrum, with the exception of the enhanced lines, appeared whenever the arc struck, and therefore

[1] Benade and Compton, Phys. Rev., 11, p. 184, 1918.

appeared at potential differences as low as 20 volts. This was apparently true of the band as well as of the line spectrum, although the relative faintness of the bands made it impossible to see them at voltages quite as low as 20. With the most intense arc, the lowest voltage at which the bands were observed was 26 volts, but the indications were that we missed them below this voltage because of lack of intensity rather than because they were not excited. The most prominent line of the enhanced spectrum is the first member 4686 of the series $4N[(1/3^2) - (1/m^2)]$. Rau was able to excite this line only with potential drops of 80 volts or more. At gas pressures of less than about 3 mm. and with thermionic currents not too intense, we have found that this line suddenly appears as the voltage is raised above 80 volts, but, with more intense currents and pressures between 3 mm. and 5 mm., the line may be seen at voltages as low as 55 volts. In these cases, however, the intensity of the line considerably increases if the voltage is raised above 80 volts. At still higher gas pressures, such as 10 mm., we were unable to excite this line at any voltage used.

We verified Rau's and Richardson and Bazzoni's observations that the line 4713, which is the second member of the sharp subordinate series of the system of pairs, decreased in intensity with increasing voltage, although the lines of the other series increased strongly. We observed this also in the case of the first member 7066 of the same series.

Although the band spectrum was excited at apparently the same voltage as the rest of the arc spectrum, it appeared that it was relatively most intense at high gas pressures, from 10 mm. up. At these pressures we observed the bands noted by Fowler[1] very easily, and, in addition, some fainter bands. One of these consists of two or more sections extending from about 5748 to 6044. Another seems to consist of six pairs, equally spaced, between 5719.5 and 5657. There is another set of fine lines beginning at about 4575 and extending to 4378, with evidence of the convergence of a series at the latter wave-length. We are somewhat hesitant about mentioning these, since our spectroscopic equipment was not sufficiently elaborate to permit of refined observations, and yet we are unable to attribute them to an impurity, since the gas seemed to be very pure. There was no trace of the spectra of mercury, other inert gases (with the possible exception of neon) or of hydrogen (except in the case of one bulb on which a quartz window was waxed and which could not be given adequate "baking out"). Several of the faint lines of these bands corresponded, within the limits of accuracy of our observations, with certain neon lines, but there was no trace of the three or four strongest neon lines in this region, or elsewhere in the spectrum, at pres-

[1] Roy. Soc. Proc. A, 91, p. 208, 1915.

sures at which the bands were prominent, and there was no uniformity between the neon spectrum in general and the observed spectrum.

DISCUSSION.

The results of this investigation confirm the view that ionization may occur at any voltage above the resonance potential as a result of the impact of an electron against an atom which is already partially ionized through the absorption of a quantum of resonance radiation from neighboring atoms. In other words, the presence of resonance radiation changes the condition of the atom to one of easier ionization. In the intense arcs in which the discharge was maintained far below 20 volts, it is evident that practically all the atoms were in an abnormal, easily ionizable, condition. We may picture the state of affairs as one in which an electron, returning toward its normal most stable position step by step, and radiating energy at each step, is again partially or entirely ejected towards less stable positions by absorption of radiant energy or by impact before it has an opportunity to return to the most stable position. Thus the bulb contains a large density of radiant energy of various spectral frequencies and helium atoms in all stages of ionization, or degrees of stability. The more intense the arc, the larger is the proportion of atoms whose electrons are in the outer orbits, or least stable configurations, so that the arc may be then operated on reduced voltage. The first step, however, essential to reaching this condition and the excitation of visible radiation, is the displacement of the electrons from their most stable to their next most stable configuration—a displacement requiring an amount of energy which is acquired by an electron in falling through 20 volts.

The investigations of low voltage arcs in mercury and other metallic vapors[1] are to be interpreted in a similar way. In every case the arc may be made to strike at a voltage equal to the resonance potential, and may be maintained at a lower voltage. Here, however, the voltages are low, so that the initial velocity distribution of the electrons from the filament introduces uncertainties of a relatively large magnitude as compared with those in the present case. By analogy with these metallic vapors, we should expect to find a very strong emission series in helium, with the first member (also an absorption line) at about 605 Å. and convergence at about 484 Å., corresponding to 20.2 volts and 25.5 volts.

The theories of atomic structure, which are rather uncertain with regard to the constitution and radiation of systems with more than one electron, have been quite successful in accounting for the spectra of

[1] McLennan, Phys. Soc. Lond. Proc., 31, p. 1, 1918; Hebb., PHYS. REV., 9, p. 372, 1917; 11, p. 170, 1918; 12, p. 482, 1918 and others.

atoms with a nucleus and a single electron. On Bohr's theory, the spectral series from helium atoms which have lost one electron should be given by the formulæ

$$4N\left(\frac{1}{n^2}-\frac{1}{m^2}\right),$$

whence the negative energies of the various configurations of an electron are given by $4N/n^2$, where n may have various integral values from 1 to ∞. Thus the energy required to change the electron from its most stable to its next most stable condition is $4N(1/1^2 - 1/2^2)$, or $3N$; while the energy required to completely remove it is $4N$. The minimum energy required to change the electron from the most stable condition to that condition in which it may emit the line 4686 is $4N(1/1^2 - 1/4^2)$, or $15N/4$. Thus the energy, in equivalent volts, required to remove the second electron from an atom already ionized, is 54.3 volts, while the energy required to cause such an atom to emit the 4686 line corresponds to 50.8 volts. Similarly, the minimum energy required to cause an atom, originally neutral and normal, to emit this radiation corresponds to $50.8 + 25.5 = 76.3$ volts; that required to cause an atom which has absorbed a quantum of the resonance radiation to emit this line corresponds to $76.3 - 20.2 = 56.1$ volts; that required to doubly ionize an atom at a single impact is $25.5 + 54.3 = 79.8$ volts if the atom is originally normal and is $79.8 - 20.2 = 59.6$ volts if the atom has absorbed resonance radiation.

There are thus various ways in which the 4686 radiation may be excited. Of these, the excitation by a single impact at 79.8 volts or more should predominate at low pressures and currents, while at higher pressures, with most of the atoms in the abnormal state, the excitation should be caused by 56.1 volts or possibly even by 50.8 volt impacts. These possibilities accord with our observations, in which the 4686 line was observed at voltages as low as 55 volts in a very intense arc, but with evidence of another method of excitation at 80 volts which was relatively more important at low pressures and arc intensities. The failure to observe the line at pressures above 10 mm. is evidently due to the very small chance of the electrons falling through a sufficiently large potential difference without losing their energy at an ionizing or radiating impact.

The fact that the lines of the so-called Parhelium series appear at the same voltages as those of the Helium series renders untenable Stark's conclusion that they are due to atoms which have lost more electrons than those atoms which give rise to the helium series lines.

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