# SPECTRAL EXCITATION BY RECOMBINATION IN THE ELECTRIC ARC

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Abstract

Recent measurements of electron velocities in arcs have made it probable that most of the light in the negative glow is emitted as a result of recombination of positive ions and electrons. Since the velocities of the positive ions are high, spectral lines emitted in this way should show Döppler broadening. This broadening was measured photometrically for a hot cathode arc in helium in which measurements of electron velocities were also made and results were obtained which can be explained by assuming all of the light in the negative glow to result from recombination of ions having a temperature about one-tenth that of the electrons.

RECENT investigations of electron densities and velocities in arcs have made it probable that spectra are emitted in the positive column of an arc principally as a result of direct excitation of atoms by electron collisions, but that in the negative glow the emission is mainly the result of recombination of positive ions and electrons. K. T. Compton suggested that, if this is the case, the lines emitted in the negative glow should show Döppler broadening corresponding to the known high velocities of the positive ions. Evidence of this broadening is presented here.

A hot cathode arc in helium was used in this investigation. The design of the arc is shown in Fig. 1. The cathode is of nickel, coated with barium oxide and heated by radiation from a tungsten spiral, and is operated at a barely visible red heat. These cathodes give a large electron emission at comparatively low temperatures and were supplied for this work by Dr. A. W. Hull of the General Electric Company, whose assistance is gratefully acknowledged. Two anodes are provided to permit striking a long arc with a positive column or a low voltage arc entirely within the bulb. The arc contains three exploring electrodes, one, two millimeters from the cathode and parallel to its upper surface, one, one centimeter from the cathode and in its axis (not shown in the figure) and one in the positive column opposite the window through which photographs of the light from the positive column were made. Currents of from a few tenths of an ampere to two amperes were put through the arc. The light intensity was very high in the negative glow as well as in the positive column, comparable to that in a small mercury arc. The negative glow, at pressures of less than a millimeter, is confined to a bright dome above the cathode and the light is sharply bounded, the remainder of the bulb being almost dark. The positive column starts sharply at the constriction and in these experiments always showed traces of striations, presumably due to the presence of hydrogen and neon as impurities, although neither of these impurities could be detected spectroscopically in exposures

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long enough to show all the helium lines. The hydrogen lines were always visible when the arc was started but disappeared after a run of from a half-hour to an hour. A charcoal tube immersed in liquid air was always connected to the arc while it was running.

Typical data obtained by the method of Langmuir and Mott-Smith[2] are given for the arc in Table I. The concentrations and electron velocities in the negative glow are the results of averages for measurements with the two electrodes near the cathode. The space potential and electron temperatures were always the same within a few tenths of a volt and the difference in

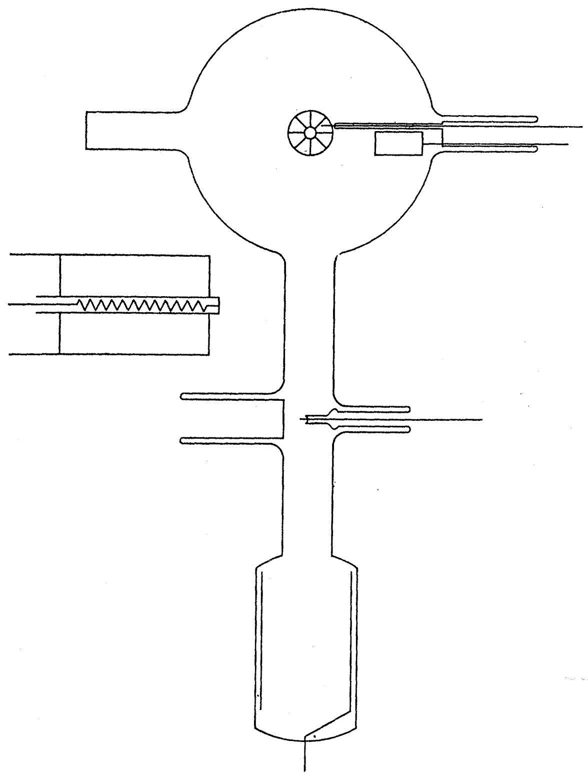

Fig. 1. Design of the arc and the cathode.

electron concentration was small and probably within the error of measurement. The difference in most probable electron velocities in the negative glow and in the positive column shows that a recombination spectrum is to be expected in the former case and an excitation spectrum in the latter, for in the negative glow only one collision of an atom with an electron in $10^8$ takes place with the energy required to excite the helium spectrum while in the positive column the electron will have sufficient energy to excite in one collision in every three. On the other hand recombination takes place almost entirely by collision of slow electrons with positive ions. The calculated ratio

[2] Langmuir and Mott-Smith, Gen. Electric Review **27**, 449, 538, 616 (1924).

of the number of collisions of this type in which the electron has less than one-tenth volt energy is about $10^4$ in the negative glow to one in the positive column. In making the measurements of line width the difference of electron concentration was exaggerated by using a smaller current during exposures in the positive column.

TABLE I. *Typical data for the arc as obtained by the method of Langmuir and Mott-Smith.*

| Potential (volts) | Current (amp.) | Pressure (mm) | Electron concentration | | Electron temperature | | Cathode fall (volts) |
|---|---|---|---|---|---|---|---|
| | | | Negative glow (Electrons per cc) | Positive column (Electrons per cc) | Negative glow (volts) | Positive column (volts) | |
| 92 | 1.6 | 1.2 | $2.5\times10^{12}$ | $4.1\times10^{11}$ | 0.74 | 3.4 | 35 |
| 93 | 1.7 | 0.9 | $1.4\times10^{12}$ | $3.8\times10^{11}$ | 0.96 | 4.9 | 36 |
| 104 | 0.36 | 0.5 | $7.0\times10^{11}$ | $9.1\times10^{10}$ | 0.52 | 5.5 | 34 |
| 39 | 2.0 | 0.4 | $3.2\times10^{12}$ | short arc | 0.88 | | |
| 55 | 1.9 | 0.25 | $1.7\times10^{12}$ | short arc | 0.88 | | |

Measurements of line width were made with a Lummer-Gehrcke plate of resolving power about 250,000. Blackening was measured in a microphotometer and the relation between intensity and blackening established by varying the time of exposure.[3] Hammer orthochromatic plates were used for the green lines, and Eastman extreme red sensitive plates for the lines 6678 and 7281. All plates were developed for four minutes at 17° in Rodinal, one part to twenty parts water. The exposure times varied from two minutes for 5016 to two hours for 7281. It was unfortunately not possible with the Lummer-Gehrcke plate available to make measurements on the orthohelium spectrum as the spectral range of the plate results in exact superposition of the "doublet" components. The lines measured were chosen for small and varying Stark effect. The data are given in Table II. Line width refers to the difference in Angstroms between the two points at which the line has one-half its maximum intensity. All but three of the measurements are averaged from two or more exposures. With the exception of one at a pressure of 0.25 millimeters of mercury all were made on the long arc. Unfortunately the correction for the instrumental width of the lines is large enough to introduce some uncertainty. The difference between the width of a line emitted in the positive column and one emitted in the negative glow is nearly independent of this correction, however. The width of the lines increases regularly with increasing wave-length, as is to be expected of a Döppler broadening. The Stark effect broadening would vary irregularly with wave-length, with 7281 as the narrowest of the lines measured. More striking evidence that the width of the lines in the negative glow is due to the high velocities of the positive ions is the regular decrease in line width with increasing pressure shown for the line 5016. Since the positive ions are dissipating energy by collision with atoms of the gas this is to be expected if they are the emitters, but on no other basis. This decrease shows that the broadening is not merely ap-

[3] That this method does not introduce appreciable errors under these conditions has been shown by the author, Phys. Rev. **30**, 774 (1927).

TABLE II. *Data on the Döppler broadening of helium lines.*

| Portion of Arc | Line | Pressure (mm) | Electron concentration (Electrons per cc) | Width | | Electron temperature* (volts) | Temperature of emitter* |
|---|---|---|---|---|---|---|---|
| | | | | observed | corrected | | |
| Negative glow | $2P-3S$, 7281A | 0.4 | $2.1\times10^{12}$ | 0.133A | 0.11A | 1.2 | 0.16V |
| Positive column | $2P-3S$, 7281 | 0.4 | $8.0\times10^{10}$ | 0.091 | 0.07 | 6.2 | 500°K |
| Negative glow | $2P-3D$, 6678 | 0.4 | $2.1\times10^{12}$ | 0.111 | 0.09 | 1.2 | 0.12V |
| Positive column | $2P-3D$, 6678 | 0.4 | $8.0\times10^{10}$ | 0.080 | 0.06 | 6.2 | 500°K |
| Negative glow | $2P-4S$, 5047 | 0.4 | $3.4\times10^{12}$ | 0.079 | 0.06 | 0.87 | 0.11V |
| Positive column | $2P-4S$, 5047 | 0.4 | $1.1\times10^{11}$ | 0.054 | 0.04 | 5.5 | 500°K |
| Negative glow | $2S-3P$, 5016 | 0.25 | $1.8\times10^{12}$ | 0.086 | 0.07 | 0.86 | 0.14V |
| | | 0.4 | $3.4\times10^{12}$ | 0.072 | 0.06 | 0.87 | 0.09V |
| | | 0.5 | $7.5\times10^{11}$ | 0.075 | 0.06 | 0.52 | 0.10V |
| | | 1.1 | $3.2\times10^{12}$ | 0.066 | 0.05 | 0.66 | 0.07V |
| Positive column | $2S-3P$, 5016 | 0.4 | $1.6\times10^{11}$ | 0.046 | 0.03 | 5.5 | 350°K |
| | | 0.5 | $9.6\times10^{10}$ | 0.050 | 0.04 | 5.5 | 400°K |

* 1 volt = 11,600°K.

parent and due to self-reversal, as the reversal would increase with increasing pressure. Any explanation based on absorption by excited atoms is, furthermore, excluded by the regularity of broadening as a function of wavelength.

When this investigation was begun it was thought from the measurements of Langmuir and Mott-Smith[2] that positive ions had energies as high as one-half the electron energies. Since then Langmuir, from consideration of what occurs in the vicinity of an exploring electrode in a gas, has come to the conclusion that the large apparent velocities of the positive ions in his measurements in mercury arcs are due to the field set up by the exploring electrode itself and not to the existence of ions of these volocities in the body of the gas. Since Dempster[4] and Harnwell[5] have shown that positive ions dissipate energy much less rapidly than we should expect on a mechanical basis it is to be expected that they will have velocities considerably higher than the velocities of the neutral atoms. The last column of Table II gives the temperature of the emitter on the assumption that the total corrected width of the line is due to Döppler broadening and that there is a Maxwellian distribution of velocities of emitters. This latter assumption is borne out by the form of the intensity curves of the lines, whose intensity drops off rapidly outside the half-width. This shows that lines are not emitted in the negative glow partly as a result of direct excitation and partly by recombination of ions having a temperature higher than that calculated from the half-width. A few measurements were made of the variation of the intensity of the light in the negative glow with varying electron concentration. The light intensity increases approximately as the square of the electron concentration, confirming the conclusion that the glow is due principally to recombination. The negative glow of a hot cathode arc thus affords a source of light of known excitation.

I wish to thank Professor K. T. Compton for many suggestions on the design of the arc as well as for the general method of attack on the problem.

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[4] Dempster, Phil. Mag. **3**, 115 (1927).
[5] Harnwell, Phys. Rev. **31**, 634 (1928).