The Distribution of Initial Velocities of Positive Ions from Tungsten

GEORGE J. MUELLER, *Cornell University, Ithaca, New York*

(Received December 4, 1934)

The distribution of initial velocities of positive ions emitted from a hot tungsten filament in vacuum has been investigated by measuring the positive ion current from a short length (0.05 cm) of filament to a coaxial cylindrical electrode against various retarding potentials. Measurements were made for eighteen different temperatures ranging from 1300°K to 3000°K. The ion current consisted of not only tungsten ions but also those of impurities, chiefly potassium. Within experimental error, it was found that the ions were emitted with velocities distributed in accordance with Maxwell's law.

INTRODUCTION

THE distribution of the initial velocities of charged particles emitted from hot metals has been studied by a number of investigators. The pioneer experiments of O. W. Richardson and F. C. Brown[1, 2, 3] upon the initial velocity distribution of thermionic electrons were followed by the work of Schottky[4] and that of Ting,[5] Jones,[6] Potter,[7] Rössiger,[8] Congdon[9] and Germer.[10] Their experiments, especially those of Germer, show conclusively that the thermionic electrons emitted from hot metals into a high vacuum have a Maxwellian distribution of velocities.

O. W. Richardson[2] and F. C. Brown[11, 12] extended the work to include positively charged particles and examined a large number of substances. Their experiments were made at relatively low temperatures (below 1200°K) and because of the experimental technique used it was not possible to conclude with certainty that the distribution of energy was Maxwellian. In fact, Schottky[4] presented some evidence that the ions had greater energy than those found by Brown.

The ions used by Richardson and Brown in their experiments were those of impurities in the metal. Since then, Jenkins[13] and L. P. Smith[14] have discovered that at higher temperatures, ions characteristic of the metal itself were emitted. These ions have been studied by Smith,[15] H. B. Wahlin[16, 17] and L. L. Barnes.[18]

Smith[15] suggested that tungsten might slowly recrystallize in an irreversible manner at high temperatures liberating ions as a secondary effect, in which case the ions might not have a Maxwellian distribution of velocities. In view of this and the inconclusive nature of the work mentioned above, it was decided to investigate the velocity distribution of positive ions from hot tungsten.

METHOD

The experiment consists of measuring the positive ion current flowing from a hot tungsten filament to a coaxial cylindrical electrode against various retarding potentials for definite filament temperatures.

If electrons leave the filament with their velocities distributed according to Maxwell's

[1] Richardson and Brown, Phil. Mag. **16**, 353 (1908).
[2] Richardson, Phil. Mag. **16**, 890 (1908).
[3] Richardson, Phil. Mag. **18**, 681 (1909).
[4] Schottky, Ann. d. Physik **44**, 1011 (1914).
[5] Ting, Proc. Roy. Soc. **A98**, 374 (1920–21).
[6] Jones, Proc. Roy. Soc. **A102**, 734 (1923).
[7] Potter, Phil. Mag. **46**, 768 (1923).
[8] Rössiger, Zeits. f. Physik **19**, 167 (1923).
[9] Congdon, Phil. Mag. **47**, 458 (1924).
[10] Germer, Phys. Rev. **25**, 795 (1925).
[11] Brown, Phil. Mag. **17**, 355 (1909).
[12] Brown, Phil. Mag. **18**, 649 (1909).
[13] Jenkins, Phil. Mag. **47**, 1025 (1924).
[14] Smith, Phys. Rev. **33**, 279 (1929).
[15] Smith, Phys. Rev. **35**, 381 (1930).
[16] Wahlin, Phys. Rev. **34**, 164 (1929).
[17] Wahlin, Phys. Rev. **37**, 467 (1931).
[18] Barnes, Phys. Rev. **42**, 487 (1932).

law, Schottky[4] has shown that for an infinitely long cylindrical arrangement of this kind, the relation between the current i reaching the collector and the retarding potential V is,

$$i=i_0\frac{2}{\pi^{\frac{1}{2}}}\left[(Ve/kT)^{\frac{1}{2}}\epsilon^{-Ve/kT}+\int_{(Ve/kT)^{\frac{1}{2}}}^{\infty}\epsilon^{-x^2}dx\right], \quad (1)$$

where i_0 is the saturation current, e the charge on the electron, k the Boltzmann constant and T the temperature of the filament in degrees Kelvin. The sign of V is chosen positive for retarding voltages applied between collector and filament. This expression will also hold in the case of positive ions, where e is now the charge on the ion, and the sign of V is again chosen positive for retarding voltages. In the calculation of Eq. (1), it has been assumed that the diameter of the filament is small as compared with the diameter of the collector, and that the current is not limited by space charge. C. Davisson[19] has discussed the limiting conditions due to space charge.

The relation between $\log_{10}(i_0/i)$ and Ve/kT is approximately linear except in those cases where $(Ve/kT)<6$. Thus, it is convenient to plot the $\log_{10} i$ *vs.* V from Eq. (1) corresponding to the temperatures used and see if the experimental points fall on the resulting curves.

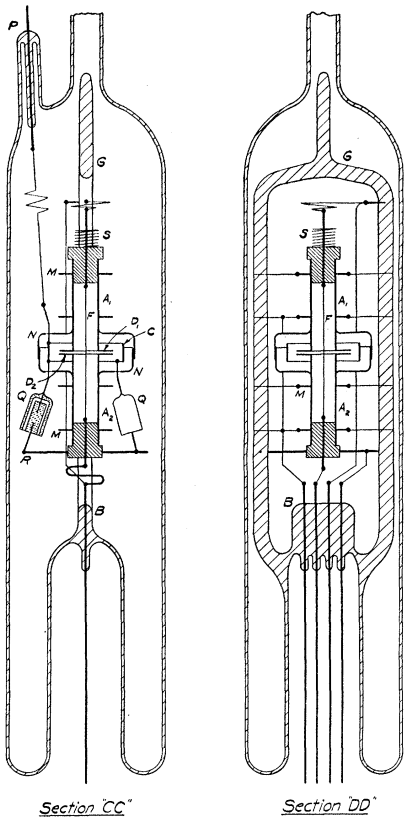

FIG. 1. Construction of the experimental tube (section *CC* is taken at right angles to *DD*).

THE EXPERIMENTAL TUBE

The disturbing effect of electrons from the filament had to be eliminated. With the simple arrangement of a straight filament surrounded by a collecting cylinder, the measured current includes, in addition to the positive ions reaching the collector against the retarding potential V, the thermionic electrons from the filament and photoelectrons from various metal parts of the tube due to light from the filament. Of these, the thermionic electrons greatly exceed in number the positive ions. To prevent thermionic electrons from ever reaching the collector, an arrangement of concentric cylinders and applied potentials was used. As shown in Fig. 1, the filament F coincides with the axis of nickel cylinders A_1 and A_2 carrying flanges D_1 and D_2 separated 0.05 cm. This serves to expose a short length of filament δ to the collecting cylinder C.

During the experiments, cylinder A was made sufficiently negative (about twelve volts) with respect to the filament to produce saturation of the ion current and at the same time prevent thermionic electrons from reaching C. The retarding potential V was applied between the collector C and the filament F. Thus, although the ions are first accelerated and finally retarded, they effectively experience a retarding potential V.

It was established that no photoelectrons from the flanges reached the collector, for with an increase in V no reversal of the collector current was detected.

With this arrangement of cylindrical electrodes, the fields are essentially radial and consequently Eq. (1) would hold if the filament F were a unipotential surface. However, the

[19] Davisson, Phys. Rev. **25**, 808 (1925).

exposed length of filament was chosen so small that its effect was negligible as was shown by a mathematical analysis.

Cross sections of the assembled experimental tube are shown in Fig. 1. The filament is of tungsten 1.74×10^{-2} cm (7 mil) in diameter and 5.7 cm long. It is supported vertically by lavite plugs and held taut along the axis of the nickel cylinder A of diameter 0.792 cm and length 7.6 cm by a molybdenum spring S. The two flanges of outside diameter 2.38 cm were silver soldered to cylinders A_1 and A_2. The outside cylinder C, 2.86 cm in diameter and 0.79 cm long, was supported by three quartz insulators Q from a ring of tungsten wire R embedded in the glass framework G. All cylinders were made of 10 mil nickel sheet, butt jointed and silver soldered. In addition, cylinders A_1 and A_2 were reinforced with 15 mil nickel rings M. The shield N, consisted of two cups spun from sheet nickel, connected to and supported by cylinder A, completely surrounded cylinder C. The supports and electrical connection to C passed through holes cut in N. The electrical lead from C then passed through a special seal P. Leads to cylinder A, tungsten ring R, and the filament left the tube through the large press-seal B.

All metal parts were heated in an atmosphere of hydrogen, before being placed in the tube, to free them of oxides and other contaminations. The tube was then assembled and remained on the vacuum system during the entire experiment. Proper heat treatment was given the metal parts with an induction furnace, and the tube was baked out at 475°C for six hours before any measurements were made. The gas pressure was always less than 10^{-6} mm of mercury as shown by a McLeod gauge and an ionization gauge. The filament was not flashed, since the ions emitted at low temperatures (1300°K) were to be measured. The procedure was to bring the filament up to some desired temperature and age it at that temperature until the positive ion current reached a steady value, after which observations were made for various retarding potentials.

The Current Measuring System

The current measuring system attached to the collecting cylinder is shown in Fig. 2. It consists

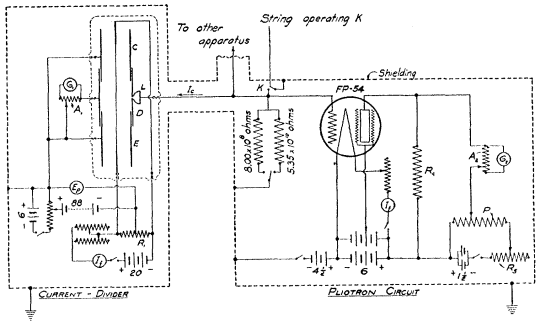

FIG. 2. The current measuring system.

essentially of a current-dividing tube as described by L. P. Smith[20] and a FP-54 Pliotron with its necessary controls. The current-divider was designed to deliver a small negative current I_1 which when balanced against the positive ion current I_2 from the experimental tube was indicated by a zero reading of the galvanometer in the plate lead of the Pliotron tube. The Pliotron with its associated circuit was also used to calibrate the current-dividing tube.

The maximum stable sensitivity of the Pliotron circuit was 60,000 mm per volt, allowing ion currents in the range 10^{-16} to 10^{-10} ampere to be measured. The entire measuring system, with the exception of the filament battery and the control rheostats of the current-dividing tube, was completely shielded. A brass box containing the FP-54 tube was made air tight and arranged in a manner such that dry air could be passed through the chamber to prevent electrical leakage.

The Essential Circuit

A diagram of the essential circuit is given in Fig. 3. The tube filaments were heated by large capacity storage batteries, V_1 and V_3. The current flowing through the experimental filament was accurately determined by measuring the drop across a standard 0.1 ohm with a Wolff potentiometer. The position of the slider on the potentiometer R_2 was accurately adjusted so that a reversal of the filament current produced no effect on the positive ion current. V_4 and V_5, two twelve volt storage batteries, supplied the necessary accelerating and retarding

[20] Smith, Rev. Sci. Inst. **2**, 237 (1931).

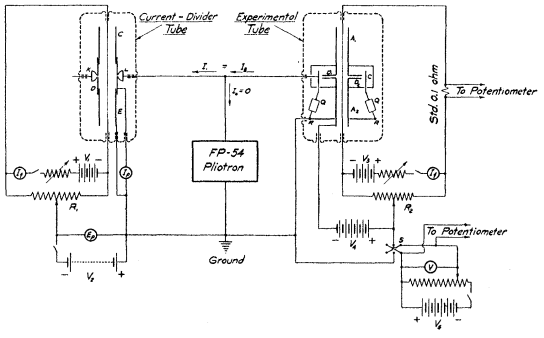

FIG. 3. The essential circuit.

potentials. The tungsten ring R, supporting the quartz insulators Q, was grounded to eliminate leakage across the insulators.

Both the current-dividing tube and the experimental tube were placed in a large metal box in which was placed a quantity of calcium chloride to reduce electrical leakage due to moisture. Guard rings were placed on all the special glass leads from the tubes. Leakage over the inner surfaces was eliminated by proper spacing in the design of the tubes.

PROCEDURE

The positive ion current to cylinder C, for a given retarding potential and filament temperature, was balanced by an electron current of known magnitude thus insuring that the potential of C remained constant. This was accomplished by increasing the temperature of the filament in the current-divider until the flow of electrons to its Faraday collector just neutralized the positive charge on electrode C of the experimental tube as indicated by a zero reading of the galvanometer in the Pliotron circuit. With this null method a flow of positive ion current of 10^{-16} ampere could be detected. This balance, after some practice, could be attained with little effort. Such a method was found very reliable since the calibration of the current-dividing tube did not change over a period of two months.

The temperature of the filament in the experimental tube was determined from the diameter and the heating current, using the temperature characteristics of tungsten given by H. A. Jones and I. Langmuir.[21] The heating current was checked at the start and at the end of each set of measurements.

EXPERIMENTAL RESULTS

Some of the various sets of measurements are shown graphically in Figs. 4 and 5. The curves show the theoretical values of $\log_{10} i$ as calculated from Eq. (1) with the use of observed

[21] Jones and Langmuir, Gen. Elec. Rev. p. 310, June, 1927.

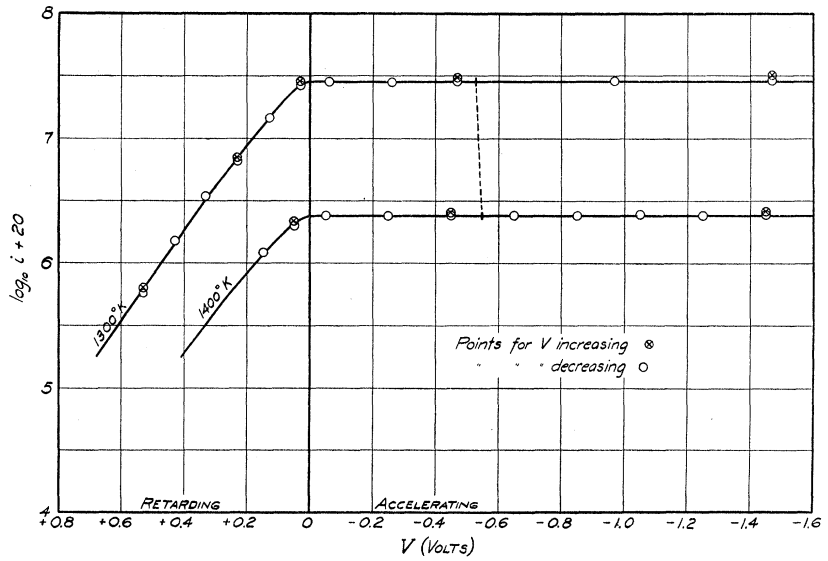

FIG. 4. Current-voltage data for low temperatures.

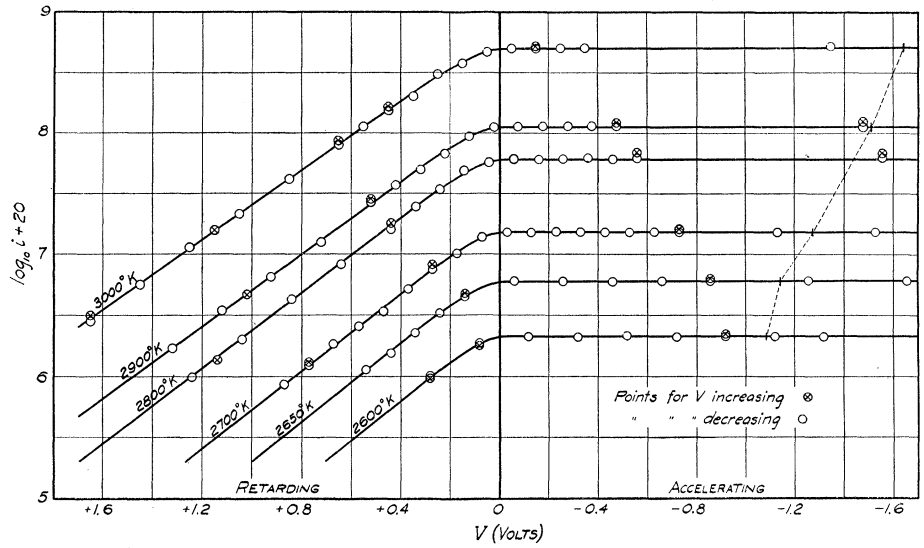

FIG. 5. Current-voltage data for high temperatures.

values of saturation current and temperature. The points indicate the observed values of $\log_{10} i$ after making a correction for the contact difference of potential between the collector and the filament. This correction may be illustrated by the data for $T=1300°K$. The observed points gave a curve which broke sharply at $V=-0.53$ and $\log_{10} i=7.45-20$. This value was taken for $\log_{10} i_0$ and the contact potential of the filament relative to the cylinder as + 0.53 volt. Such a correction was necessary for each set of observations since the contact difference of potential increased with temperature. The magnitude of V at the intersections of the dashed line and the various curves gives the contact potential differences.

In taking points, the curves were traced twice, once for increasing values of retarding potential and then immediately for decreasing values of retarding potential ending at -12 volts. Germer experienced some difficulty in obtaining values of $\log_{10} i_0$ and of contact differences of potential at the higher temperatures due to space charge effects. No such difficulty was encountered in the present investigation since the current density was extremely low. Not all of the results are shown in the figures, but only representative sets of data. The first ions detected were those emitted at 1300°K. Mass-spectrograph studies of tungsten filaments made in this laboratory and elsewhere have shown that these low temperature ions are due chiefly to potassium found as an impurity in the tungsten. This emission disappeared above 1500°K. The next ions detectable were those given off at 2300°K. These were, very likely, a mixture of the ions of tungsten as well as those of impurities. It would, of course, be desirable to study the ions of tungsten alone, but present mass-spectrograph

TABLE I. *Summary of data.*

Order	Filament	Heating current (amp.)	T (°K)	$\log_{10} i_0+20$	Contact diff. of potential (volts)
7	2	1.00	1300	7.45	+0.53
8	2	1.15	1400	6.38	0.55
9	2	1.32	1500	6.29	0.58
1	1	3.00	2300	6.33	0.79
2	1	3.11	2350	6.40	0.83
3	1	3.25	2400	6.47	0.89
4	1	3.36	2450	7.51	0.96
5	1	3.47	2500	7.69	1.02
6	1	3.60	2550	7.85	1.06
10	2	3.70	2600	6.33	1.08
11	2	3.82	2650	6.78	1.14
12	2	3.95	2700	7.18	1.27
13	2	4.10	2750	7.60	1.39
14	2	4.23	2800	7.78	1.44
15	2	4.35	2850	7.90	1.48
16	2	4.50	2900	8.05	1.52
17	2	4.62	2950	8.17	1.55
18	2	4.75	3000	8.69	1.65

studies made in this laboratory by A. Fogelsanger have apparently disclosed that no known method of aging or flashing of a tungsten filament is successful in eliminating the ions of impurities.

A summary of the data is given in Table I to show the range of the measurements. The first column indicates the order in which sets of observations were made. After the observations at 2550°K were made, a nickel tab holding one end of the filament, parted. The filament was replaced, the tube assembled, baked out, and the observations were continued.

Conclusion

This investigation shows conclusively that the number of ions with given initial velocity components from tungsten at high temperatures into a high vacuum, irrespective of their nature, are in accord with Maxwell's law.

The above results do not substantiate the statement made by Schottky regarding ions of high energy, nor do they support the hypothesis that ions are emitted as a result of an irreversible process.

Acknowledgment

The author wishes to express his appreciation to Professor Lloyd P. Smith for suggesting this problem and for his constant help during the course of the work. Grateful acknowledgment is made to the Faculty of the Department of Physics for the facilities and apparatus provided. He wishes also to thank Mr. Banta for the construction of the glass apparatus.