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SHOT EFFECT OF THE EMISSION FROM OXIDE CATHODES

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Abstract

Experimental procedure in the study of fluctuations in the space current of a thermionic emitter is outlined. A new method of measuring *shot-circuit impedance* is introduced. Conditions under which the observed fluctuations may be applied to determine the electronic charge are pointed out. A method is described whereby the frequency of oscillating circuits used in this investigation may be determined and controlled. An investigation has been made of the fluctuations associated with the emission from barium-strontium oxide cathodes, particularly in the space charge region. The presence of positive ions in the emission from oxide coatings has been experimentally verified. These positive ions moving in an electron space charge cause abnormally high shot-fluctuations in an aperiodic circuit at high amplifier frequencies. The characteristic fluctuations associated with the emission from oxide cathodes have been reproduced in a vacuum tube of special design in which positive ions from an independent Kunsman potassium ion emitter interact with electron space charge about a metal emitter. This is taken as evidence that the same process goes on in the emission from barium-strontium oxide cathodes. Some results obtained in a study of the shot effect of films evaporating from a tungsten wire are included.

THE shot effect has been successfully used in the determination of electronic and ionic charge by an entirely independent method. The emitters used for electronic currents in these determinations have been pure metals such as tungsten or thoriated tungsten. Williams and Huxford,[1] in the determination of the positive ion charge, used a Kunsman potassium ion emitter. This work was done at shot-amplifier frequencies in the region of 100,000 cycles per second. It was found that even at these frequencies, abnormal fluctuation voltages occur in the case of certain oxide electron emitters. It was to discover the underlying mechanism of these fluctuations that this investigation was carried out. A brief description of the apparatus and experimental procedure follows.

THE SHOT CIRCUIT AND AMPLIFIER

An experimental arrangement for studying the shot effect of thermionic currents is shown in Fig. 1. The vacuum tube S, consisting of a collector plate and an emitter is mounted in a shielding compartmen . The emitter is heated by a storage battery located outside this compartment. The accelerating potential is applied to the collector plate through a wire-wound resistor R. It can be seen from the diagram of Fig. 1 that the positive end of the high potential battery is grounded to the shield. The negative terminal

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[1] N. H. Williams and W. S. Huxford, Phys. Rev. **33**, 773 (1929).

is connected to the filament leads, which are carefully insulated from direct current grounds, but are kept at ground potential for high frequency currents by the use of a one microfarad condenser having very low leakage current.

If the emitter is heated by means of the storage battery, and a positive potential is applied to the collector plate through the resistor R, electrons will flow from the emitter to the collector. The value of the electron space current is given by the direct current milliameter A. If the electron stream were perfectly continuous, only a direct difference of potential would exist between A and B equal to $I_0 R$. But since the arrival of electrons at the plate is a discontinuous process, voltage fluctuations will occur across the resistance AB. These fluctuations will be called the "shot voltage" between A and B. The space current and the space charge conditions in the tube can be controlled by variation of the emitter heating current and the accelerating potential across the tube.

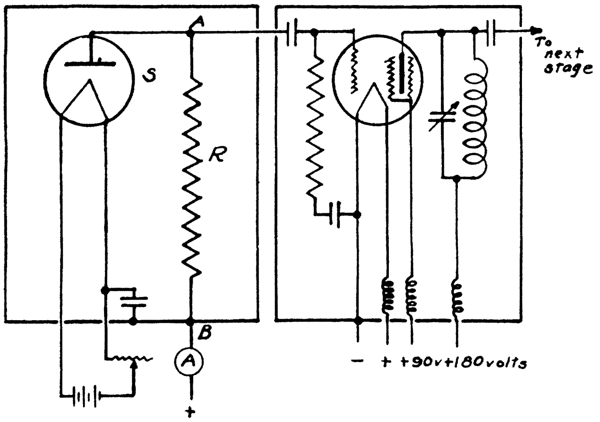

Fig. 1. Aperiodic shot effect.

The shot voltage developed across AB is impressed on the grid-filament circuit of a tuned-plate five-stage amplifier employing screen-grid tubes. Thus a narrow band of frequencies from the total "shot voltage" is selected and amplified. Coupled loosely to the tuned-plate circuit of the last amplifier tube is a coil of a few turns of wire. Voltages induced in this coil by alternating currents in the plate circuit cause current to flow through a 990 ohm vacuum thermal junction connected aross it. The magnitude of the thermoelectromotive force is directly proportional to the heating of the junction and hence to the square of the current in the circuit or to the square of the voltage across it. In this manner a direct current galvanometer across the thermoelement is used to detect high frequency voltages.

It is evident that an amplifier correctly designed, and operated under suitable conditions will show a linear relation between the input and output voltages. Since both the input voltage and output current, which is proportional to the output voltage, are measured by the thermo-junctions in circuits to be described later, the fidelity of the amplifier may be determined by a plot of input against output galvanometer deflections. This must give a straight line relation for all normal voltages applied to the amplifier.

General Experimental Procedure

In an experimental determination of the value of the electronic charge, the following method is employed:

The amplifier and shot-tube emitters are heated for about thirty minutes before actual observations begin. In this way the amplifier reaches a stable condition which can be maintained indefinitely. The plate circuit of the shot tube is then closed, giving a definite space current through the tube which is measured by ammeter A of Fig. 1. The shot voltage across the resistance AB is applied to the grid-filament circuit of the screen-grid amplifier, giving a deflection on the output galvanometer, G_0, which is proportional to the mean square voltage across AB. The shot circuit is then disconnected and a sine voltage is applied to the amplifier at its resonant frequency. This sine voltage is then varied until the deflection obtained with a definite space current in the shot circuit is reproduced. The magnitude of this sine voltage is the quantity V of the equation

$$\epsilon = V^2/2A\,i_0Z^2$$

as derived by Williams and Vincent.[2] Thus a measurable sine voltage at the resonant frequency of the amplifier is substituted for the actual voltage existing across AB due to the shot effect. Under ordinary conditions, this voltage is of the order of 25 micro-volts. Its value is obtained from the inductive drop along an inductance potentiometer.

In order to obtain the value of the charge of the electron from the equation of the shot effect, the quantities A and Z must be determined. A is the amplifier resonance area and is a constant for any series of measurements. The impedance Z of the shot circuit, measured between A and B, is a function of the space charge in the shot tube. The method of determining Z is discussed in the following section. Substitution of the quantities, i_0, V^2, A, Z^2 in the shot equation gives the charge of the electron. The space current and the accelerating voltage in the shot tube are varied, and conditions under which the true value of the electronic charge is given by the shot effect equation can be studied. Obviously, this method of investigation will show any abnormalities in the shot-effect characteristics of a given vacuum tube.

When thermionic currents of 300 microamperes or less are used in the shot tube, the deflection of the amplifier output galvanometer is small. Then the duplication of this deflection using only the inductance potentiometer results in large inaccuracies, since the I of $I\omega Ld$ is small. In order to minimize this error, the current is attenuated to a small fraction of its original value and this fraction is passed through the inductance potentiometer. The complete circuit used for the duplication of output galvanometer deflections due to the shot effect of the thermionic current in the tube S is shown in

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[2] N. H. Williams and H. B. Vincent, Phys. Rev. **28**, 1250 (1926).

Fig. 2. With the use of the attenuator, high frequency voltages of the order of 10 microvolts can be measured with a probable error of one percent.

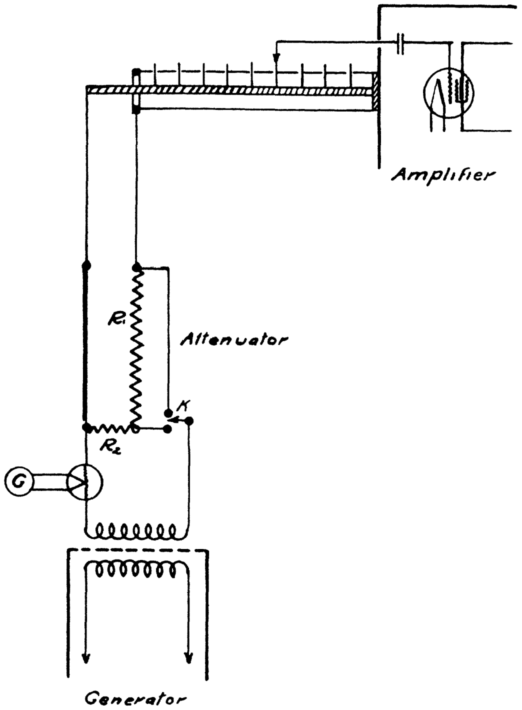

Fig. 2. Inductance potentiometer and attenuator.

MEASUREMENT OF IMPEDANCE OF THE SHOT CIRCUIT

The impedance of the shot circuit involved in the equation

$$\epsilon = V^2/2A i_0 Z^2$$

is that between the points A and B (Fig. 3) across which the voltage due to the fluctuations from the long time mean value of the space current is developed.

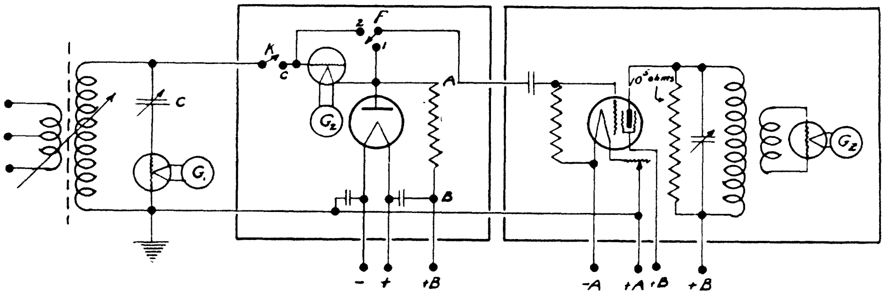

Fig. 3. Measurement of shot circuit impedance.

A process of measuring the impedance which is more direct than that of Williams and Huxford[3] and experimentally very simple has been developed. It was found that a coil and thermojunction system G_z, Fig. 3, coupled to the tuned plate circuit of the *first* screen-grid amplifier tube gives practically a linear response to the square of the high frequency voltage applied to the grid-filament circuit of the amplifier, if the tuned plate circuit is shunted by a resistance of the order of 100,000 ohms. In this way, the impedance of the plate circuit to the high frequency current, and the voltage amplification are lowered. We see that as the external impedance is made lower, say by shunting the tuned circuit with a high resistance, the voltage across it due to a given voltage applied to the grid filament circuit will decrease. The response of the first amplifier tube to various voltage inputs to the grid filament circuit is shown in curves I and II of Fig. 4.

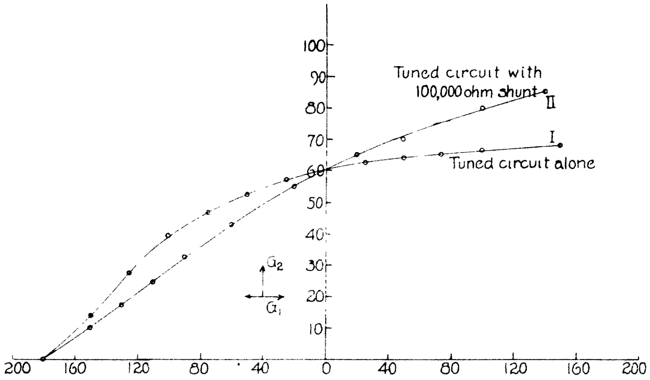

Fig. 4. Response of first amplifier tube as a high frequency voltmeter.

If any voltage at the resonant frequency of the amplifier is applied to the circuit at *CB*, Fig. 3, a current I_2 will flow through it. Also a deflection proportional to the square of the voltage between *A* and *B* will be observed on the galvanometer of G_z. The thermojunction measuring the current I_2 into the shot circuit is then shorted by key *F*, thus eliminating the voltage drop along it. The deflection previously obtained on the galvanometer of the system coupled to the plate circuit of the first amplifier tube is now duplicated by varying the current through the standard condenser, *C*. As the amplifier tube responds to the mean square voltage between *A* and *B* regardless of phase, it is evident that the voltage giving the same output deflection without the thermojunction G_2 in the circuit is now exactly the same as previously existed between *A* and *B*. The impedance of the circuit is then given directly by E'/I_2 where E' is the voltage applied directly between *A* and *B* for the observed deflection on G_z, and I_2 is the current read by the thermojunction system G_2. We have then, for the impedance of the shot circuit between the points *A* and *B*,

$$Z = I_1'/I_2C\omega.$$

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[3] N. H. Williams and W. S. Huxford, Phys. Rev. **33**, 773–778, (1929).

Typical impedance characteristics of vacuum tubes, investigated under conditions of constant current at various voltages between the anode and cathode are shown in Fig. 5.

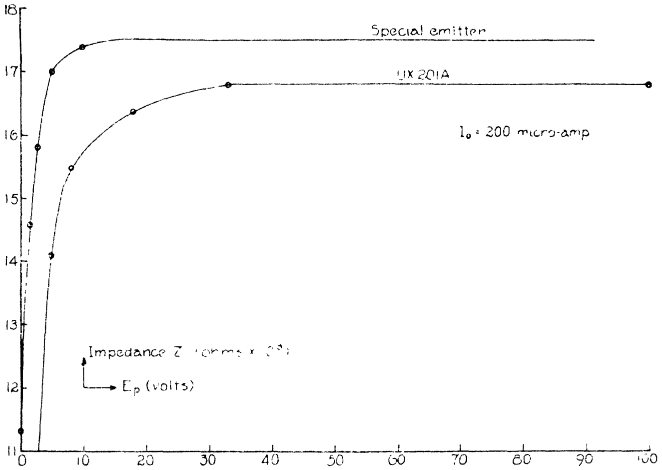

Fig. 5. Typical impedance characteristics of vacuum tubes.

FREQUENCY DETERMINATION AND CONTROL

We see that

$$\epsilon = V^2/2Ai_0Z^2$$

the shot effect equation, can be written in the form

$$\epsilon = \frac{I^2\omega^4L^2C^2}{2Ai_0I_1^2/I_2^2}\,.$$

This follows from the fact that v, the high frequency voltage applied to the input circuit of the amplifier at its resonant frequency to give the same output deflections as the shot effect associated with a definite space current, is obtained from the inductance potentiometer and is given by

$$V = I\omega L.$$

Also the impedance Z is given by E/I_2 or as outlined in a previous section,

$$Z = I_1/I_2C\omega.$$

It is evident that oscillator frequency, entering the expression in the fourth power must be accurately determined and completely controlled.

Methods have been used whereby the frequency of the generator can be determined and held constant to one part in 100,000. A self-maintained tuning fork whose frequency may be varied from 800 to 1000 cycles per second is used as a primary standard of audio frequency. This is calibrated by a synchronous-motor clock which operates continuously when the fork is in operation. The audio frequency is introduced in the input circuit of a distortion amplifier. By the use of several stages of amplification, harmonics of the audio frequency as high as 150 times the fundamental can be obtained. These are easily identified by a precision wave-meter and tuned circuits together with a heterodyne oscillator. By adjusting the frequency of the fork so as to obtain a zero beat of a harmonic with the fundamental frequency of a crystal-controlled or Hartley oscillator, the latter can be easily calibrated to an accuracy well within the needs of the procedure.

A crystal-controlled oscillator having a frequency of 117,034 cycles per second was calibrated by the procedure outlined and used as a high frequency standard. This was coupled to the Hartley oscillator used for the calibrating shot voltage and impedance measurements by means of pick-up coils and the amplified beat note was kept at one or two cycles per second. An audio frequency amplifier and dynamic loud speaker allowed the coupling between the crystal and the Hartley oscillator to be made so loose that there was no possibility of reaction of the circuits. The standard oscillator and audio amplifier were operated during actual observations so that any change in the frequency of the Hartley oscillator due to change of plate and filament voltage could immediately be noted and corrected.

In the determination of the resonance curve of the high frequency shot amplifier, the ratio of the amplification of a given voltage input at various frequencies to that at resonant frequency is measured. A convenient method of obtaining known frequencies in the pass band of the amplifier is that of selecting frequencies of the distortion amplifier in a suitable range. The Hartley oscillator is then adjusted to zero beat with these frequencies, whose separation is given immediately by the fundamental frequency of the tuning fork. Thus the resonance curve can be determined without the use of a wave-meter and with much greater precision and speed.

MEASUREMENT OF THE ELECTRONIC CHARGE FROM THE THERMIONIC EMISSION OF A METAL

Measurement of the shot effect of thermionic currents from a pure metal offers few complications and yields, under proper conditions, the accepted value of the electronic charge. The shot tubes used consist of a cylindrical collector plate of nickel, and a co-axial tungsten or thoriated tungsten emitter. The pressure in selected tubes is probably of the order of 10^{-6}mm of mercury. These tubes have been well outgassed and flashed with a getter. No evidence of ionization of the residual gas with the voltages employed has been found.

The shot effect associated with various anode currents from 100 to 6000 microamperes was studied. In all cases investigated, it may be said that the apparent charge of the electron, as given by the equation $\epsilon = V^2/2Ai_0Z^2$, agrees within the limits of experimental error with the values obtained by previous investigators, if the electron current leaving the cathode is temperature limited. That is, conditions in the experimental tube are such that all of the electrons leaving the emitter with a random distribution in time arrive at the collector in the same manner. Experimentally this condition can be realized if the accelerating voltage across the tube is high and the space current is low. When an increase of the accelerating voltage causes no further increase in the space current, the electron stream is purely temperature-limited. Substitution of observed quantities under these conditions in the shot effect equation will give the accepted value of the electronic charge.

The space current for any given emitter temperature will be a function of the accelerating voltage up to the saturation region. When voltages higher than the saturation voltage are applied, little or no increase in the space current is observed. Thus a possible method of studying the shot effect associated with thermionic emission is that of holding the emitter at a constant temperature, and varying the voltage across the tube.

It is essential to distinguish very carefully between the value of "ϵ" obtained by the substitution of measured quantities in the equation of Williams and Vincent when the fundamental assumptions of Schottky's small-shot theory are fulfilled and values obtained when they obviously are not. Thus *only* at high accelerating potentials and low space currents, giving no first order space charge interaction of electrons, are we justified in using the equation as a measure of the electronic charge. At low voltages and high space-currents the equation merely gives values which are proportional to the voltage fluctuations occurring in the shot tube and circuit.

When the voltage between the emitter and the collector is low, the current is no longer temperature-limited and the space-charge density near the emitter may become very large. An electron emitted from the cathode is acted upon by a repulsive force due to the electrons in the space charge sheath. The redistribution in time due to such interaction is to make the fluctuations smaller than those existing with the same current at higher voltages. This we call space-charge depression. Under these conditions the deflections of the output galvanometer may become very small. An extensive investigation of space-charge depression of shot fluctuations is now in progress in this laboratory. Another effect, the fluctuation of the space charge itself, has been studied in the case of the electron emission from barium-strontium oxide coated cathodes. The shot effect of this emission has been investigated and the cause of certain abnormal defects has been determined.

SHOT EFFECT OF THE EMISSION FROM BARIUM-STRONTIUM OXIDE CATHODES

During the summer of 1928, Williams and Huxford investigated the shot effect of electron currents from barium-strontium oxide emitters. The tube used contained a cylindrical quartz sleeve wound with platinum wire and then coated with a layer of barium-strontium carbonate mixture. The sleeve was surrounded by a co-axial cylinder as anode. Current passed through the platinum wire heats the emitter. The tube used had a geometry identical with the Kunsman emitter of positive ions described by Huxford.[4] It was hoped that the results obtained with the Kunsman emitter of positive ions

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[4] W. S. Huxford, Dissertation, University of Michigan, 1928.

and an emitter of electrons such as barium-strontium oxide would allow calculation of the influence of the mass of the carrier on the space charge.

This tube was sealed onto a high vacuum system and baked and outgassed with the induction furnace until the vacuum could be maintained at 10^{-6}mm of mercury. With the vacuum system in operation the shot effect characteristics of the two were studied. The ordinary shot effect curves for an electron emitter were expected. Actually it was found that the shot effect behaved very abnormally under certain conditions of space charge. The shot-effect characteristics are graphically shown in Fig. 6. Four complete shot-characteristic curves were taken with this tube. The tube was on the pumps continually and the emitter was being heated except for a very short time between curves II and III when the system was brought to atmospheric pressure for adjustment. We notice the characteristic space-charge depression at very low accelerating voltages on the tube. As the voltage on the tube is increased, v^2 increases very rapidly, reaches a maximum, and falls rapidly with a further increase of accelerating potential. From then on, with further increase of accelerating potential the behavior is similar to that in a metallic emitter. At high accelerating voltages, the value of v^2 is such as to give values of the electronic charge which agree with the accepted value within the limits of experimental error. Thus, since there is no possibility of gas ionization, and the abnormally high fluctuations disappear with high accelerating potentials, when space charge is obliterated, it appears that there exists an agency which operates on the space charge in such a manner that large, mean-square fluctuations are produced. It should be noted that there is a very good correlation between the length of time that the emitter has been heated, or activated, and the magnitude of the space-charge peak. In the following sections the cause of these fluctuations will be discussed and experimentally verified by an independent method.

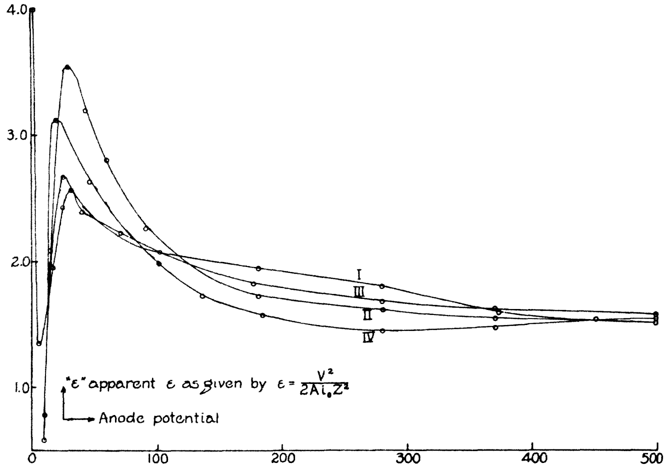

Fig. 6. Shot effect of electrons from barium oxide. $I_0=200$ microamps.

In order to obtain more data on the shot effect with oxide coated emitters, commercial tubes of the UY-227 type were studied. These are the familiar indirectly heated barium-strontium oxide cathode type, designed for alternating current operation. During the process of activation the barium and strontium carbonates break down into the oxides, with the evolution of carbon dioxide. Thus the gas content of a tube of the 227 type is higher in general than that of a tube employing a pure metal emitter. In every case, the shot-fluctuation voltages at high accelerating potentials are from three to four times normal value. The deflection of the high frequency amplifier output galvanometer, which is proportional to v^2, is not steady but may fluctuate from its mean position by as much as 25 percent. This is a good indication of the presence of gas in the tube.

If an evacuating system is sealed on to any of the commercial tubes studied, and the tube is well outgassed and held on the vacuum system at a pressure of 10^{-6}mm of mercury, a curve of "ϵ" against the accelerating voltage using a constant space current is found which has all of the essential characteristics of the oxide emitter described by Williams and Huxford. Thus we can conclude that even a small amount of gas in a shot tube will introduce fluctuations over and above the normal fluctuations in purely thermionic emission. This action of the gas is probably due to the positive ions and electrons obtained by ionization. In order to correlate the effects in the space charge region, all tubes subsequently studied were investigated under a high vacuum.

ACTIVATION OF THE EMITTER AND SHOT EFFECT IN THE SPACE CHARGE REGION

Commercial tubes whose emitters were unactivated were fitted with a five-millimeter-diameter evacuating tube and were sealed on to the evacuating system to obtain a high pumping speed. The pressure was brought down to 10^{-5}mm of mercury and the tube was then baked for 2 or 3 hours with an electric furnace at a temperature of 350–400°C, with the emitter operated at half-voltage. Large quantities of gas were evolved in the process. Toward the end of the treatment, the emitter was operated at normal temperature. The metal parts of the tube were then outgassed with an induction furnace. The emission from the cathode was measured by applying a low voltage between the cathode and the collector plate. By overheating the emitter for a short time and then bringing it back to its normal operating temperature, it was found that the emission materially improves. An application of the induction furnace in the early stages of activation causes the emission to decrease temporarily.

A detailed study shows that a very good correlation exists between the shot effect associated with the emission from an oxide cathode and the degree of activation of the cathode. The shot effect characteristics were determined under conditions of constant anode current for various anode voltages at successive stages in the activation of the emitter. They are represented in the curves of Fig. 7. In the case of curve I, we see the beginning of a small peak in the space charge region. The high values of v^2 at higher voltages are obviously due to gas ionization as is shown by the sharp upward trend beyond 120 volts. A comparison of the curves shows that the magnitude of the peak in the space-charge region increases with the length of time the emitter has been heated. Curve III shows complete stability even at high voltages. A study of the activation curves of the emitter shows an increase in the reverse current as the emitter becomes more activated. This indicates that positive ion emission increases. These results show that the fundamental cause of the abnormal fluctuations in the space charge region is the activity of positive ions emitted from the oxide cathode into the space charge region.

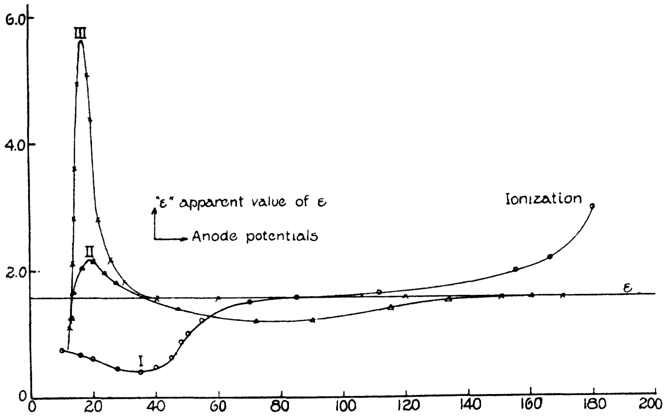

Fig. 7. Shot effect of electrons from barium oxide. $I_0 = 200$ microamps.

A study of the activation of oxide emitters shows that the electron emission increases with the length of time the cathode has been heated. If the cathode is overheated, the electron emission rapidly improves to a maximum value and then slowly decreases. An oxide emitter may be completely activated merely by a prolonged heat treatment, gas-ion bombardment not being at all necessary to the process. At the time of the decrease of electron emission, measurable amounts of reverse current may be detected between the emitter and the plate if a negative potential is applied to the latter. By a high overheat it is possible to get 10 microamperes or more of reverse current. A more critical investigation shows that the reverse current does not consist entirely of positive ions in all cases. For one commercial tube, only 10 percent of the total reverse current was found to consist of positive ions. The remainder is due to photo-emission of electrons from the plate and grid elements by the radiation from the cathode. This has been verified by illuminating the elements with light from an external source, keeping the barium-strontium emitter cold. The magnitude of the current thus obtained is of the same order as with the cathode hot. If the plate and grid are negative with respect to the oxide emitter and they are photo-active, we are unable to distinguish between positive ions going to them from the oxide and photoelectrons going in the opposite direction. The photoactivity of the grid and plate is very probably due to the evaporation of barium or barium oxide from the cathode and a recondensation on these elements so as to give a surface with a low photoelectric work function.

The problem of identifying positive ions in the emission from barium-strontium cathodes was solved by the use of the familiar magnetron method of Hull.[5] He has shown that in the case of co-axial cylindrical emitter and collector and a uniform magnetic field applied along the axis of the system, the magnetic field required to prevent electrons or ions emitted by the inner cylinder from reaching the outer collector is given by

$$H = \left(\frac{8m}{e}\right)^{1/2} \frac{V^{1/2}}{R}$$

where m is the mass of the electron or ion, e is the charge of the electron or ion, V is the accelerating potential between the cylinders and R is the radius of the outer collecting cylinder. This assumes that the ratio of the radius of the inner cylinder to that of the outer cylinder is small. We see immediately that for a given voltage, the magnetic field required to prevent a barium or strontium ion from reaching the plate will be about 500 times that required for an electron. For

$$\frac{H_p}{H_e} = \left(\frac{m_p}{m_e}\right)^{1/2}.$$

A special tube containing a unipotential oxide-coated emitter and a nearly co-axial collecting cylinder of molybdenum was constructed. The radius of the collector was large compared to that of the emitter. The plate was therefore located so far from the emitter that recondensation and consequent photo-activity was very small. A solenoid consisting of several thousand turns of copper wire, layer wound, was so constructed that the special tube could be placed in the core with the collector and emitter axes parallel to the magnetic field produced by passing a direct current through the solenoid. Thus the above equation for the motion of the electrons or positive ions under the influence of the electric and magnetic field applies in all detail.

A potential of 22 volts positive with respect to the emitter was applied to the collector. A reflecting galvanometer of sensitivity 10^{-8} amperes was used to measure the space current. When the magnetic field was applied, the current dropped to 20 percent of its original value. It did not drop to a smaller value probably due to a lack of complete symmetry in the arrangement of the emitter and collector. This is the behavior to be expected with electrons. More elaborate experiments might serve to detect the presence of negative oxygen ions in the emission. The potentials were then reversed and the emitter heated until the same space current was again obtained. Application

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[5] A. W. Hull, Phys. Rev. **18**, 31 (1921).

of a magnetic field now caused less than 0.5 percent decrease in the space current. This can be taken as conclusive evidence that heavy ions are emitted from oxide emitters. Evidence from photoelectric long wave limits points to these ions being barium or strontium. Absolute determination of the magnetic field would allow the mass of the ions to be determined. However, a mass spectograph analysis would perhaps be easier to carry out and would yield information about the relative proportions of the various ions present.

A report by Glass[6] on the variation in emission of oxide filaments assumes that all of the reverse current is composed of positive ions. Obviously he has neglected the possibility of photo-emission from the grid and plate. This in commercial tubes is of the same order as the emission of positive thermions.

SHOT EFFECT AT CONSTANT EMITTER TEMPERATURE

In order to obtain the preceding shot-effect curves with constant space current for a range of accelerating voltages it is necessary to vary the temperature of the emitter over a rather wide range. This raises a question as to whether the abnormal fluctuations may not be due to a property of the emitting surface at a certain temperature. To test this point, characteristics of the shot effect were obtained under conditions of constant emitter temperature. The power input to the cathode was held constant at a convenient value, and the fluctuations as observed by the output galvanometer of the high frequency amplifier were studied as a function of the space current as the accelerating potential was varied. The space-current characteristic and the fluctuations observed are plotted against accelerating voltage in Fig. 8. We notice first the typical lack of saturation of the oxide emitter. Here again we have the familiar space-charge depression of fluctuations at very low voltages, then a space-charge peak at higher accelerating field, and finally a portion where the fluctuations are directly proportional to the space current. This is shown by the space current and fluctuation curves becoming parallel. Absolute values of Z and V^2 under these bonditions will yield the true value of the electronic charge. Thus it is evident that the peak is not due to changes in the structure of the emitter with temperature, but is a function of space charge. A series of curves taken with various power inputs to the cathode shows that the peak moves toward higher voltages with increased emission.

At a critical value of space charge, a positive ion emitted from the cathode travels in the direction of the potential minimum. By virtue of its large mass and consequent low mobility, it can release a large number of electrons from space charge. Langmuir[7] has shown that a single ion can release several hundred electrons from space charge. The random emission of positive ions from the cathode and their passage through the space charge region causes large fluctuations in the space charge, producing an abnormally high V^2 across the shot circuit. It is natural to suppose that the magnitude of

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[6] Myron S. Glass, Phys. Rev. **28**, 521 (1926).

[7] Irving Langmuir, Phys. Rev. **33**, 954 (1929)

the peak will be a function of the amplifier frequency. Peaks have been found at audio frequencies with oxide coated commercial tubes in this laboratory by Mr. Thatcher. The frequency characteristics of the phenomenon are now under investigation. It is to be observed that when space charge is obliterated by the use of high accelerating potentials, the mechanism of the fluctuation no longer exists. Positive ions emitted from the cathode are unable to travel in the tube because of the adverse field, and there are no space charge electrons to be released. Therefore, under these conditions, the true value of

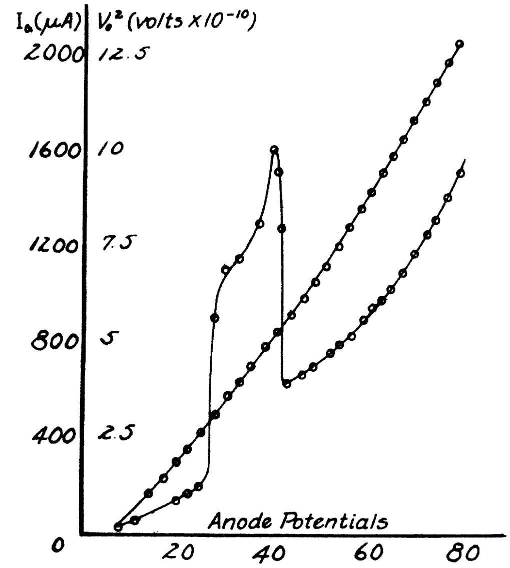

Fig. 8. Shot effect with barium oxide emitter at constant temperature. $I_f = 1.71$ amp., $E_f = 2.66$ volts.

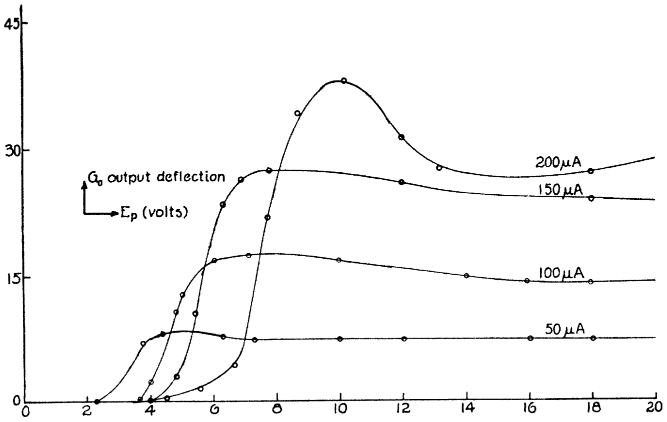

Fig. 9. Position of space charge shot effect peak for various I_0 values. Barium oxide emitter.

the electronic charge is obtained. As the space current becomes smaller and smaller we would expect the magnitude of the space charge peak to decrease. A series of four curves given in Fig. 9 taken with four constant space currents at various accelerating voltages shows the dependence on current. The results are of the same nature as Johnson reports with the flicker effect at low frequencies. If the space current is low enough, normal fluctuations are obtained.

An Experimental Verification of the Space Charge Effect

Since the abnormal behavior of the fluctuation voltage is due only to positive ions in the presence of an electron space charge, an attempt was made to reproduce artificially the conditions believed to exist with an oxide emitter. A vacuum tube containing two independent emitters mounted very close together and surrounded by a cylindrical collector plate was constructed. The first emitter is a pure tungsten wire which emits only electrons when heated. The second is a Kunsman oxide emitter. This, at a temperature of about 900°C, gives off positive potassium ions and a small number of electrons. The ratio of the positive ion to the electron emission is about 1000 to 1 at 900°C. If the shot effect of each emitter is studied separately, the results obtained are normal. That is, at low voltages, the fluctuation voltage is very low due to the effect of space charge on the random distribution in time of the emitted ions or electrons. However, if the two emitters are operated simultaneously, positive ions emitted by the Kunsman emitter, will, at low voltages across the tube, travel into the electron space charge region. Space-charge density can be controlled by the temperature of the tungsten emitter, and by the voltage between the emitters and the anode. A typical curve for this tube operated under conditions simulating those believed to exist in an oxide-emitter tube is given in Fig. 10. A curve for the tungsten emitter alone is also included. The

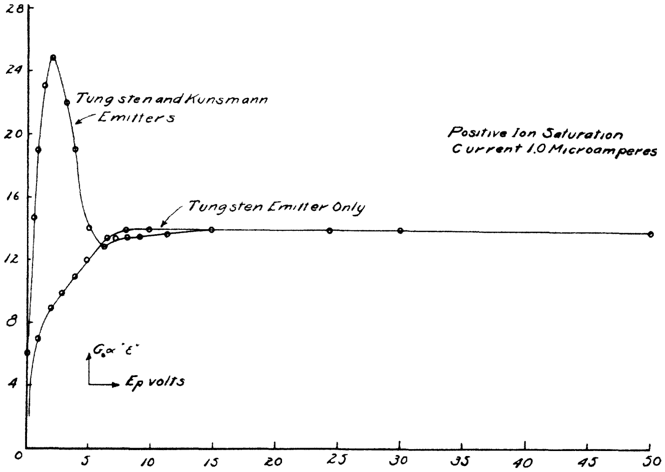

Fig. 10. Shot effect for special tube. $I_0 = 150$ microamps.

space current in the tube using first only the tungsten emitter, and then the combination of tungsten and Kunsman emitters, was held constant at 150 microamperes. The general characteristics of the shot effect are those obtained with the oxide coated emitter. It is interesting to note that as soon as space charge is removed, the peak disappears.

Thus it has been shown that the abnormally high shot voltage observed in the space charge region when an oxide emitter is used can be duplicated by the interaction of positive ions from an independent emitter with an electronic space charge. The thermions from a Kunsman[8] emitter have been identified by the mass spectograph as positive potassium ions. The abnormally high shot effect observed disappears when the source of positive ions has been cut off, and also disappears at high accelerating potentials. Therefore, we have conclusive evidence that the abnormal shot effect is due to positive ions moving through space charge.

SHOT EFFECT OF EVAPORATING SURFACE FILMS

During the study of the shot effect, a special tube containing a barium oxide and a tungsten emitter mounted close to one another was used. This tube was very highly evacuated and thoroughly outgassed, and then sealed off. The oxide emitter was thoroughly activated during the process of evacuation. No trace of residual gas was detected with the voltages applied to the tube. The tungsten emitter alone gave normal shot effect. If, however, the barium oxide emitter was operated for a short time with the tungsten cold, and then the tungsten emitter was suddenly brought to full brilliancy, the shot-output galvanometer gave a deflection of the order of 3000 mm. This decreased exponentially with the time to the normal value of 30 mm corresponding to the shot effect associated with the space current used. On the basis of Becker's[9] work with oxide emitters, it is probable that some barium of the surface layer of the activated emitter evaporates from the oxide emitter and condenses on the tungsten emitter. On bringing this tungsten emitter to its operating temperatures suddenly, the barium evaporates in the form of barium ions which interact with the space charge in the usual manner. No such surge was noticed with a high accelerating voltage across the tube. The same phenomenon was noticed with the Kunsman tungsten emitter tube.

Absolutely no surge is noticed on bringing the tungsten emitter to full brilliancy after it has been thoroughly cleaned of this layer by operating at a high temperature for three or four minutes. The decay of the surge due to a layer formed by evaporation of either barium or barium oxide onto the tungsten emitter can be controlled by varying the operating temperature. It appears that the process of this film leaving the surface is quite the same as occurs in the deactivation of a thoriated tungsten emitter. No evidence of such a surge was found using a thoriated tungsten emitter brought suddenly to a temperature where the thorium leaves the tungsten and leaves it deactivated. This can probably be interpreted to mean that thorium leaves a thoriated tungsten emitter in a neutral state and not as an ion.

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[8] N. A. Barton, C. P. Harnwell, C. H. Kunsman, Phys. Rev. **27**, 739–746 (1926).

[9] Joseph A. Becker, Phys. Rev. **34**, 1323 (1929).