The method of subtraction used makes the observed threshold somewhat inaccurate, but it is certainly less than 40 Mev.

Results obtained with Na^{23} are shown in Fig. 5. Na^{22} may be formed by the (p, d) or the (p, pn) reaction with thresholds of 11.6 and 13.8 Mev, respectively. The observed curve seems to be in agreement with the lower value. The pronounced maxima indicates the formation of a compound nucleus, and its breadth indicates that both possible modes of decay are important. At higher energies mechanisms other than the formation of the compound nucleus become important. The general shape of the curve is in fair agreement with the one calculated[6] for the $C^{12}(p, pn)C^{11}$ reaction. However, this does not account for the decline of the cross section above 100 Mev.

The $Na^{23}(p, \alpha d)F^{18}$ and $Na^{23}(p, pn\alpha)F^{18}$ with thresholds at 20.3 and 22.5 Mev, respectively, are probably the reactions by which F^{18} is formed initially. The maxima at approximately 40 Mev indicates the formation of a compound nucleus as the principal reaction at the lower energies. In the vicinity of 50 Mev other reactions such as $(p, 3p3n)$ become energetically possible and may account for the slow decline of the cross section at higher energies.

[6] W. Hecrotte and P. Wolff, Phys. Rev. **73**, 264 (1948).

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The Origin of Bombardment-Enhanced Thermionic Emission

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Measurements on bombardment-enhanced thermionic emission from oxide cathodes show that (a) the effect is not related to normal fading and recovery of thermionic emission; (b) the emitted electrons have energies in the thermal range rather than in the secondary range. Calculations indicate that the electron bombardment releases more than enough internal secondaries to account for the effect as increased thermionic emission. A more comprehensive theory is needed for explaining why the observed effect is not even larger.

I. INTRODUCTION

A THERMIONIC emitter of (BaSr)O has its emission temporarily increased when bombarded by electrons.[1] In addition to the normal thermionic emission and to the secondary emission which normally accompanies the bombardment, there is a gradual increase of current during the first few microseconds of bombardment and a corresponding gradual decrease when the bombarding pulse is over. The persistence of the added emission after the end of the bombardment led to the belief that the emission is of thermionic rather than secondary origin. As a possible source of the bombardment-enhanced thermionic emission was suggested either a reduction of work function or an increase in the density of conduction electrons in the bombarded target. The experiments reported here deal with the energy distribution of the emitted electrons, and with the relation of the enhanced emission to the phenomenon of fading. They give further proof of the thermionic origin of the increased current, and support the view that change of electron density rather than of surface conditions is the principal cause of this current.

II. METHOD

The experiments were done with equipment similar to that described earlier. The target of activated (BaSr)O on Ni, a collector electrode and an electron gun are enclosed in a gettered and sealed-off tube. A pulsed electron beam bombards the target, with the collector negative or positive for measuring the primary or secondary current. The current of the target circuit actuates a video amplifier and is displayed on an oscilloscope. Typical results are shown in Fig. 1, which has two sets of oscillograms, (a) and (b), each of three traces, two displaced slightly from the axis which is the central trace. (The vertical strokes have been dotted in for clearness.) In the lower trace of each set the 1250-volt beam was pulsed on for 10 μsec while the collector was negative, and the trace records primary beam current. The upper trace, with the beam similarly pulsed, was made with the collector positive (with amplifier gain reduced). In Fig. 1(a) the target temperature was low and the thermionic current negligible, and the flat-topped upper trace records well-behaved secondary current. In Fig. 1(b) the thermionic current was high, but being dc it was blocked out in the coupling condensers of the circuit and does not appear in the oscillogram. The upper trace in this set shows clearly the variation of emission during and after the beam current pulse when thermionic current flows, and it is this variable emission that is under discussion.

III. EXPERIMENTS ON FADING

When temperature-limited thermionic current is drawn suddenly from an active oxide cathode there is

[1] J. B. Johnson, Phys. Rev. **73**, 1058 (1948).

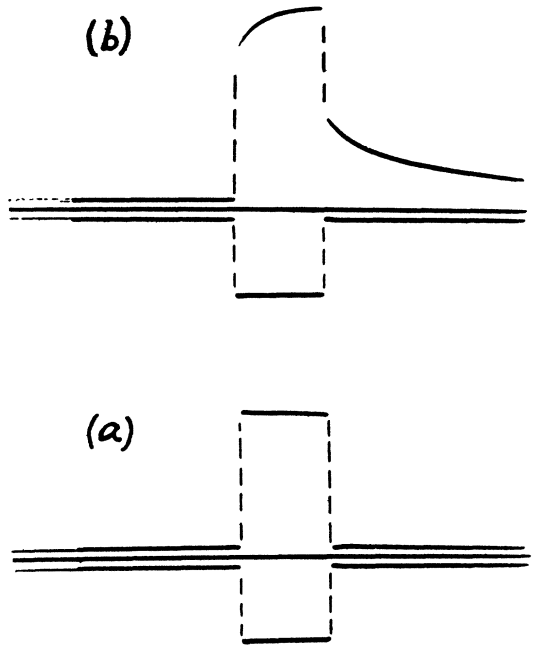

FIG. 1. Rise of enhanced emission with temperature. (a) 520°C, $I_{th}=10$ μa; (b) 670°C, $I_{th}=1500$ μa. $V_p=1250$ v, $V_c=-22$ or $+64$. Pulse 10 μsec. $i_p=31$ μa. Tube 499355. Lower trace primary current i_p, upper trace secondary current.

usually a decrease in current with time,[2] with recovery of activity when current is not drawn. This fading process is believed to be caused by a change in the surface composition of the cathode, due to material coming either electrolytically from the interior of the cathode or by evaporation from the anode.

A typical oscillogram of the fading is shown in Fig. 2. Above the line of the x-axis the current is seen to start from an ill-defined high value when the anode voltage is applied, and to have decayed by a substantial fraction within a millisecond, as indicated by the 2500-cps calibration trace below the axis. These traces were made with single sweeps. Figure 3 shows results for a different target under different conditions. The collector voltage was applied in repetitive 145-microsecond pulses

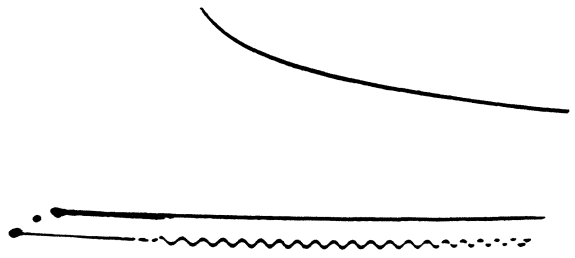

FIG. 2. Fading of thermionic emission in millisecond range. Timing trace 2500 cps. Tube LS 12.

[2] R. L. Sproull, Phys. Rev. **67**, 166 (1945); Kalaschnikov, Kubetski, and Oscher, J. Techn. Phys. USSR **16**, 1369 (1946); E. A. Coomes, J. Appl. Phys. **17**, 647 (1946); D. A. Wright, Proc. Phys. Soc. (London) **B62**, 398 (1949); G. R. Feaster, J. Appl. Phys. **20**, 415 (1949).

and fading in this time is seen. (The upper trace is electrically parallel to the axis on the 'scope.)

It seemed possible that the enhanced thermionic emission is related to this phenomenon in the following way. When the beam of primary electrons is turned on while the collector is positive, for measuring the secondary current, then the cathode has already been delivering thermionic current for a second or more and it might be in a state of reduced activity. If now bombardment by electrons could bring about a partial return of activity, there would be a growth of thermionic current when the beam is turned on and fading at the end of the bombardment.

Two types of experiments were done to see whether this might explain the observed enhanced emission. In one series the positive dc collector voltage was replaced by short positive pulses;[3] in the other were used targets with different fading rates.

In the measurements with pulsed positive collector the negative collector voltage was applied dc as usual, for measuring the primary beam current. At intervals there was superimposed on the negative bias a positive

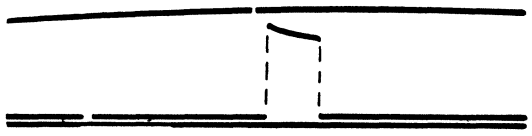

FIG. 3. Fading of thermionic current in microsecond range. 600°C, $I_{th}=430$ μa, $V_c=100$ v pulsed 145 μsec. Tube MN 74.

pulse that brought the collector voltage to about $+30$ volts for some number of microseconds. The target would then emit its full thermionic current, overloading the amplifier at the input in the direction of positive deflection. For preventing the overload the thermionic current pulse was balanced out by applying the collector pulse to an inverter circuit to give a small adjustable negative replica of the voltage pulse, which was applied directly to the input of the amplifier. This canceled the thermionic current pulse except for short spikes at the beginning and end of the pulse and for changes in the thermionic current during the pulse. Fading thus was seen even though the main component of thermionic current was canceled out by the bucking circuit. Within the collector pulse the shorter beam current pulse was applied, and then the secondary and enhanced current was seen in its proper size superimposed on the canceled-out thermionic current.

Applying this technique to targets which exhibited fading, it was found that the change in current during the 10 microsecond beam pulse was always greater than the fading of thermionic emission during even the 145-microsecond collector pulse applied as in Fig. 3. This is strong evidence that the fading and recovery process is not responsible for the changes in current on bombardment.

[3] A similar procedure was used by T. J. Jones, Nature **161**, 846 (1948). Here no enhancement was found.

This point was followed further in connection with a tube that showed no fading under any of the experimental conditions. The tube had parts made of very clean nickel that could be well outgassed. In particular, it had a dummy anode that was used during the pumping, activation, and aging. Only when the process was complete was the well-cleaned anode slid in place.

Results for this tube are shown in Fig. 4. The temperature was 640°C, the thermionic emission about 0.5 ma. The lowest oscillogram, Fig. 4(a), gives the thermionic emission during 145-microsecond pulses of collector voltage, with no evidence of fading in this time. Figure 4(b) records the primary beam current and secondary yield in a 10-μsec beam pulse, both positive and negative collector voltage being dc. The enhanced emission is evident. The amplifier gain was reduced by a factor 4 for the positive pulse, so that the secondary yield δ is about 6. The more complicated procedure for the positive pulsed collector is shown in the top oscillogram, Fig. 4(c). The axis and 10-μsec primary pulse are recorded as before. The positive collector pulse was 40 μsec long, and the flat-topped trace of this length shows the thermionic current during this pulse, without the electron beam, and with reduced gain. There is no fading. The 10-μsec positive pulse is the secondary and enhanced thermionic emission. The main thermionic current is bucked out, the spikes at the ends of the pulse representing uncompensated capacity coupling between target and collector. The rise of the positive pulse as well as the tail at the end are essentially the same for the pulsed as for the dc collector. Fading, if present at all, is certainly less in the long pulse of collector voltage than the change in current during the short bombarding pulse. If there were any significant but undetected fading, it would surely be widely different for the two operating conditions of pulsed and dc collector voltage. We conclude that the fading phenomenon is not responsible for the added emission during the electron bombardment.

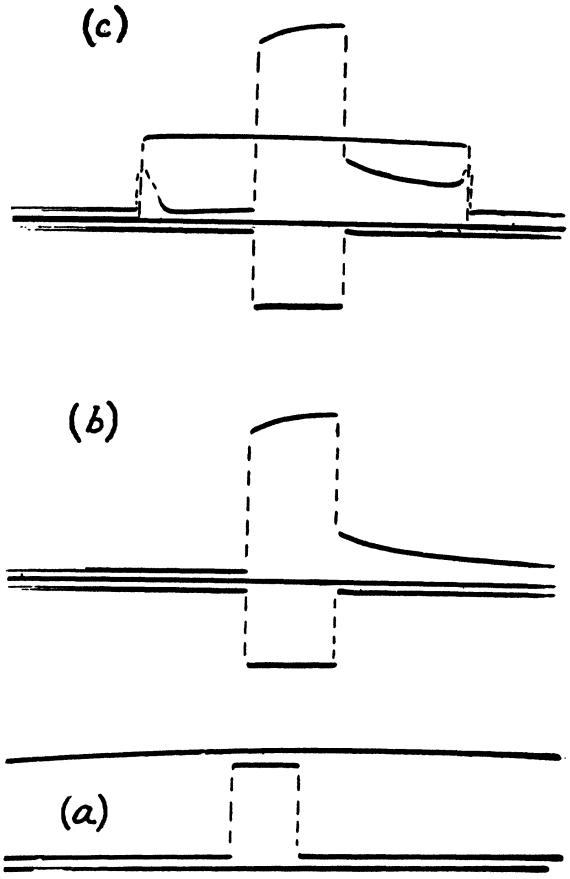

FIG. 4. Comparison of enhancement for pulsed and dc collector voltage. (a) Fading, $V_c=100$ v, pulsed 145 μsec. (b) Enhancement, $V_c=64$ v dc. (c) Enhancement, $V_c=64$ v pulsed 40 μsec. Trace 1, i_p; trace 2, i_s with I_{th} bucked out; trace 3, I_{th} alone. 640°C, $I_{th}\sim 0.5$ ma, i_p pulse 10 μsec. $V_p=1250$ v. Tube 499355.

IV. INITIAL VELOCITY DISTRIBUTION

If the positive collector voltage is not high enough to collect the full emitted current, then the variable enhanced current appears suppressed more than the normal secondary current. This selective suppression is shown in Fig. 5. Here the target was bombarded for 10 μsec during a 35-μsec collector pulse, the normal thermionic current being balanced out by the bucking pulse. The successive exposures were made with various collector voltages, -22 volts for the lowest trace, 0 for the next, and on to $+43$ volts for the highest. The first to show a rise in current during the pulse was at $+26$ volts. The shape of the curves is here evidently altered by a combination of space charge and initial velocities. Before more quantitative results are presented, the arrangement of the collector and target of this particular tube will need description.[4]

[4] See reference 1, Fig. 1, for more detailed electrode structure.

The flat coated part of the target, about 0.3 cm^2 in area, is the thermionic and secondary emitter. The central part of it, perhaps 0.03 cm^2, is bombarded by the electron beam. The collector is not plane but presents a flat internal cone to the target, with the spacing at the outside edge about 0.4 mm and greater at the center. The structure is therefore not the planar one

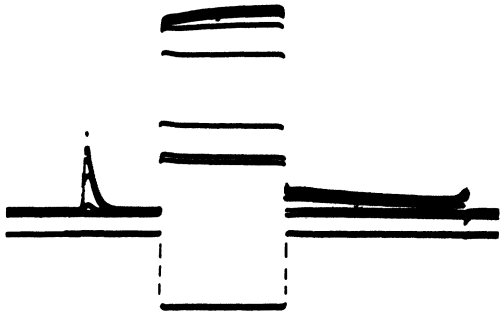

FIG. 5. Space charge limitation of secondary current. I_{th} dc, $<I_s$ pulsed. 415°C, $V_p=350$ v. V_c pulse 40 μsec; i_p pulse 10 μsec. $V_c=-22$, 0, 4.5, 9, 18, 26, 29, 33, 43 volts. Tube MN 74.

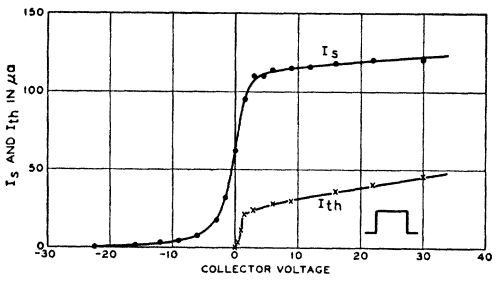

FIG. 6. Retarding potential curve without space charge. $I_{th}<I_s$, I_{th} dc, I_s pulsed. 415°C, $V_p=350$ v. Tube MN 74.

required for measurement of the normal velocity component of the emitted electrons, nor the concentric spherical called for in measuring the total velocity or energy distribution, but is in between these two. The retarding-potential curves to be presented are therefore not a proper measure of energy distribution, but they can still be used to distinguish between different groups of electrons.

Results obtained with this tube will be shown for two different temperatures. The bombarding beam of 34 μa was set at 350 volts to give a δ of about 4. The height of the response was read on the 'scope at the beginning and end of the 20-μsec pulses, for a range of negative and positive dc collector voltages. The pulse heights, measured from the bottom of the negative pulse when the collector was at -22 volts, are plotted in terms of microamperes. They are labeled I_s in Fig. 6, and in Fig. 7 I_{s1} and I_{s2} corresponding to the beginning and end of the pulse. The difference $I_{s2}-I_{s1}$ is again the enhancement under discussion. The thermionic current I_{th} was measured with a dc meter.

In the run of Fig. 6 the target temperature, 415°C, was so low that the thermionic current was less than the secondary current, and there was no appreciable space charge limitation of either. More detailed measurements on the thermionic current showed that the contact potential made the collector 0.7 volt negative with respect to the target. It saturated at about 1.5 volts, showing thereafter the gradual rise usual with oxide cathodes. At negative collector voltages the curve I_s makes a reasonable retarding-potential curve for secondary electrons, showing the presence of electrons with energy of a few volts, in contrast with the thermal energies of the thermionic electrons. The curve still rises for positive collector voltages, reaching a saturation at about 5 volts. This region of "negative energies" has often been observed in secondary emission but never clearly explained. It may be related to surface roughness or to internal fields of the target or more probably to patch fields at the collector. There was no enhancement seen in any part of this curve.

The results with the target at higher temperature, 660°C, are shown in Fig. 7. The thermionic current is now much larger than the current of the secondary pulses and is clearly limited by space charge at the lower collector voltages. For negative collector, the secondary curve is almost identical with that of Fig. 6 where the temperature was lower, so that the amount and energy distribution of the main part of the secondary current is relatively unchanged by the temperature. At high positive collector potentials the secondary pulse is again about as high as at the lower temperature of Fig. 6, but now shows the enhancement during the pulse in the region where the thermionic emission is approximately saturated. Here the enhancement amounts to about 3 percent of the thermionic current from the bombarded area. An interesting change is seen in the region from 0 to $+15$ volts. Here the pulse height is limited, over a range of almost 10 volts, to a fraction of the total secondaries. Other temperatures and thermionic currents gave the same results, the difference being only in the voltage range of the flat depressed portion of the curve. The explanation[5] seems to be that the secondaries, when they flow, add to the space charge of the thermionic current, and the new and lower potential minimum prevents the flow of an additional small fraction of the thermionic current. The effect disappears with remarkable sharpness when at some voltage, here 12 volts, the potential minimum is no longer maintained. The enhanced emission appears fully developed only at the right of the point where the potential minimum disappears, never at the left in the region of true secondaries. The significance of this is that the electrons involved in the enhanced emission have energies all in the region of thermal energies. They must be thermal rather than secondary in origin.

V. SOURCE OF THE ENHANCED THERMIONIC EMISSION

The thermionic emission generated by electron bombardment has been shown to be unrelated to the fading process, which involves a change in work function. It is too large to be explained by temperature rise of the surface due to bombardment.[1] A different way of accounting for the increased emission is to assume that the bombardment raises the density of conduction electrons available for thermionic emission near the surface of the target.[1] A rough calculation makes this hypothesis seem plausible.

In the experiment of Fig. 7 the oxide target was bombarded for 20 μsec by a 34-μa beam of 350-volt electrons. When particles bombard a semiconductor or insulator, they raise a number of electrons from filled energy bands to the conduction band, and produce an equal number of mobile positive holes in the filled bands. In comparison with other substances,[6,7] an electron-hole pair

[5] Suggested by Dr. C. Herring in discussion. A similar increase in space charge by secondary electrons emitted from the anode causes current depression in screen-grid tubes and has been observed in triodes and diodes as reported by R. K. Matheson and L. S. Nergaard at the meeting of the Division of Electron Physics of the American Physical Society on January 31, 1951 [Phys. Rev. **82**, 573 (1951)].

[6] Robert Hofstadter, Nucleonics 4, No. 4, 29 (1949).

[7] K. G. McKay, Phys. Rev. **74**, 1606 (1948); **77**, 816 (1950).

for each 10 ev of the primary particle seems reasonable for the oxide target, or here 35 per incident electron. From the shape of curves such as that of Fig. 1(b) it seems probable that the free lifetime of these carriers is not short compared with 10 μsec. Suppose half of them are left at the end of 20 μsec. The number of new conduction electrons and holes left at the end of the pulse is then $N=7.5\times10^{10}$. The distance over which the excess electron density spreads is governed principally by the ambipolar diffusion of the holes, since beyond the Debye distance electrical neutrality is maintained. It is much greater than the penetration of the primary electrons and may be estimated as follows. The Einstein relation between mobility μ and diffusion coefficient D gives for the latter $D=\mu kT/e$. The diffusion distance over which the carriers spread on the average in a time τ is given by $d=(D\tau)^{\frac{1}{2}}=(\mu\tau kT/e)^{\frac{1}{2}}$. The mobility of the holes is thought to be of the order 1 cm^2/volt sec; and using this value the diffusion distance for 20 μsec is $d=1.4\times10^{-3}$ cm, probably greater than the grain size of the oxide. The depth and the area then give a value for the volume Ω occupied by the N electrons, and the density of added electrons becomes $\Delta n=N/\Omega=1.8\times10^{15}$/cm^3. This calculated increase in density is to be justified as a reasonable source of the observed enhancement.

The total density n of conduction electrons in the oxide-target can be estimated as to order of magnitude from conductivity measurements made on very similar coatings by Hannay, MacNair, and White.[8] These authors found the conductivity remarkably reproducible, and at the temperature of our target, 940°K, obtained approximately the value $\sigma=2.0\times10^{-4}$ ohm^{-1} cm^{-1}. Combining with this the same mobility for electrons as was used previously for holes, we get a value for the density of conduction electrons, $n=\sigma/\mu e=1.25\times10^{15}$/cm^3. If this were the original density of electrons in our target and the bombardment increased it in the same ratio as observed for the emission, 3 percent, then a rise in electron density $\Delta n=3.75\times10^{13}$/cm^3 would just account for the observed enhancement. The value calculated from bombardment considerations is about 50 times greater than this. A series of similar computations for other experimental conditions gives a mean factor of about 30.

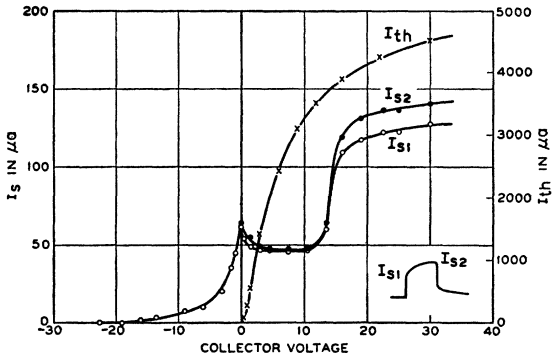

FIG. 7. Retarding potential curve with space charge. $I_{th}\gg I_s$, I_{th} dc, I_s pulsed. 660°C, $V_p=350$ v. Tube MN 74.

Considering the wide difference of approach and the very rough assignment of values to mobility and conductivity for the targets tested, this seems at first sight a reasonable accord. The difference is not trivial, however. It does not seem possible to bring the results into agreement by choosing other values of μ and σ that lie within reasonable ranges. Even adding elementary considerations of trapping and recombination of charges does not bring the results sufficiently into line. The mechanism must be more complicated than that assumed. For the present the result that the predicted enhancement is even larger than the observed value makes very plausible the hypothesis that the bombardment-enhanced thermionic emission has its origin in the increase in density of conduction electrons by the bombardment.

This work has been stimulated by frequent discussions with N. B. Hannay, C. Herring, K. G. McKay, and A. H. White, and greatly facilitated by electronic circuits designed by R. W. Hull and maintained by H. V. Matthews.

[8] Hannay, MacNair, and White, J. Appl. Phys. **20**, 669 (1949).