BOMBARDMENT OF METAL SURFACES BY SLOW-MOVING ELECTRONS.

BY H. E. FARNSWORTH.

SYNOPSIS.

Secondary Electrons Produced by Electronic Bombardment of Nickel.—The main features of the apparatus used are: an equi-potential nitrate-coated Pt cathode heated by radiation from a tungsten spiral filament; a series of insulated diaphragms to limit the beam of primary rays and for use in determining their velocity; and a long Faraday cylinder in front of which the nickel target could be alternately interposed and withdrawn. By baking out the tube and using liquid air traps an extremely low vacuum corresponding to less than 10^{-7} mm. was attained. The secondary current was determined from the difference between the current to the Faraday cylinder and that to the interposed target. (1) *Ratio of the secondary (emergent) to the primary (incident) electron current* was found to be independent of the roughness of the surface, but to vary with the treatment. After heating the target red-hot by high frequency induction for some minutes, a limiting curve was reached which probably represents the characteristics of *nickel itself, free from surface contamination.* In this case the secondary electrons begin when the primary velocity is as low as 0.2 volt; the ratio to primary current then increases rapidly with primary velocity to about 4 volts, remains constant to about 9 volts, then again increases reaching a value of unity for a primary velocity corresponding to about 260 volts. *The effect of exposure to air or hydrogen* is to increase very considerably the secondary current and to round out the flat part of the curve between 4 and 9 volts. (2) *Velocity distribution curves of the secondary electrons* indicate that for primary electrons of less than 9 volts velocity, most of the secondary electrons have velocities nearly equal to the primary velocity, while for primary velocities above 9 volts, the percentage of secondary electrons having small velocities increases with the primary velocity, although a small proportion have velocities nearly equal to the primary velocity up to at least 110 volts.

Reflection and Emission of Electrons from a Nickel Surface Bombarded with Electrons of Velocity 0 to 260 Volts.—It is suggested by the above results, that reflection occurs for all the primary velocities investigated, and that emission or ionization begins at about 9 volts and increases with the primary velocity.

Contact difference of potential between a gas-free nickel surface and an ordinary baked nickel surface was found to be 0.8 volt.

Method of making a gas-tight glass joint for high vacuum work by soldering with Wood's metal, the platinized and copper-coated surfaces of a ground joint, is described.

INTRODUCTION.

STUDIES of the secondary electrons produced by electronic bombardment of metal surfaces have previously been made by various experimenters. However, the fact that most of the results were obtained previous to the development of modern high-vacuum technique combined with the failure of the small amount of recent work to agree with these older results, leaves the important questions of this problem still unanswered. It is well known that the number of secondary electrons depends upon the velocity of the incident or primary beam, that more electrons leave the surface than strike it if the primary velocity is great enough, but the following characteristics of various metals are still not definitely determined: (1) the magnitude of the secondary electron current as a function of the primary velocity; (2) the velocity distribution of the secondary electrons for any given primary velocity.

Some of the earlier experiments carried out by Gehrts,[1] von Baeyer,[2] and Campbell [3] indicate that the above characteristics are the same for all metals tried, platinum, copper, nickel, aluminum, lead and cobalt. Secondary electrons were found when using a primary velocity as low as one volt. The number of secondary electrons increased with increase of the primary velocity up to about 5 volts. With further increase of primary velocity to about 11 volts, the secondary current decreased. Beyond 11 volts it increased rapidly to a maximum at about 200 volts and then decreased gradually and continuously. Above about 30 volts primary velocity more electrons were found to leave the surface than strike it. Most of the secondary electrons apparently had velocities less than 10 volts while none were found with velocities greater than 30 volts even when the primary velocity considerably exceeded 30 volts.

A. W. Hull,[4] working more recently with copper, obtained a slight minimum in his secondary electron curve, but it comes at 5 volts instead of at 11 volts, with a slight maximum at 2.6 volts. He found the ratio of the secondary electron current to the primary, for any given primary velocity, to be much smaller than that of the previous experimenters, being only about 40 per cent. at 50 volts primary velocity. I. G. Barber,[5] also working recently with copper, concluded that there were no secondary electrons when the primary velocity was less than about 10 volts. F. Horton and Miss A. C. Davies[6] found secondary electrons from platinum when the primary velocity was as low as 3 volts. They found no secondary electrons with velocities greater than 10 volts when using a primary velocity of 70 volts. They did not heat the platinum above 300° C. Davisson and Kunsman,[7] working with nickel, found some secondary electrons with velocities nearly equal to that of the primary beam. They

[1] Gehrts, Ann. d. Phys., *36*, p. 995, 1911.

[2] O. von Baeyer, Phys. Zeitschr., *10*, p. 176, 1909; Deutsch. Phys. Gesell., Verh., *10*, 24, p. 953, 1908; Ber. d. D. Phys. Ges., *10*, p. 96 and p. 953, 1910.

[3] N. R. Campbell, Phil. Mag., *22*, p. 276, 1911; *24*, p. 527, 1912; *25*, p. 803, 1913; *28*, p. 286. 1914; *29*, p. 369, 1915.

[4] A. W. Hull, Phys. Rev., *7*, p. 1, 1916.

[5] I. G. Barber, Phys. Rev., *17*, p. 322, 1921.

[6] F. Horton and Miss A. C. Davies, Royal Soc. Proc., *97A*, p. 23, 1920.

[7] Davisson and Kunsman, Science, *54*, p. 522, 1921.

did not investigate the number of secondary electrons as a function of the primary velocity.

The object of the present investigation is to obtain the characteristics of various metals which have been freed from gas under the best vacuum conditions available, and to see how these characteristics vary with the metal and the roughness of the surface. Up to the present only nickel has been studied in detail.

APPARATUS.

An apparatus suitable for the carrying out of this investigation must be so constructed that the following conditions may be realized: (1) a primary electron stream of uniform velocity and cross-section; (2) an accurate means of measuring the total primary current; (3) an accurate means of measuring the secondary electron current; (4) means of measuring velocities of both primary and secondary electrons.

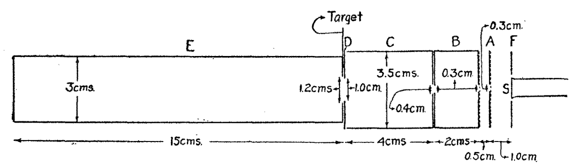

Fig. 1.

The final form of apparatus used is shown in cross-section in Fig. 1. Condition (1) is satisfied by accelerating the primary electrons to the diaphragm, *A*, from an equipotential source, *S*. Some of these electrons shoot through the hole in *A*, through *B* and *C* into *E*. The primary beam is thus limited in cross-section by the various sharp-edged diaphragms along the path. *F* is a focusing plate concentric with *S*. The electron stream is kept from scattering by means of a magnetic field in the direction of the stream. Condition (2) is realized by the use of the long cylinder, *E*, which is practically a perfect absorber for the electrons that once get into it. (3) By means of a magnetic control[1] a nickel target can be moved over the hole in the end of *E*, into the path of the electron stream. The secondary electrons which leave the target are received by the cylinder *C*. The insulated diaphragm *D* makes it possible to determine whether the presence of the target causes any scattering of the primary beam. (4) The velocity distribution of the primary electrons can be obtained by putting a variable retarding potential on *D* and *E* and measuring the total current as a function of the potential in the usual way. Similarly, the velocity distribution of the secondary

[1] The magnetic control was placed to the left of the cylinder, *E*, as far away from the source as possible, to avoid changing the state of magnetization of that part of the apparatus which limits the electron stream.

electrons may be obtained by varying the potential of *C* and *D*. The apparatus was constructed entirely of nickel, glass and quartz except for the nitrate-coated platinum source of electrons. A quartz tube, supports the platinum source which is coated with barium, strontium, and calcium nitrates to increase the emission of electrons. The heat for the source is furnished by an electric current which passes through a plane tungsten spiral, placed inside the quartz tube and very close to but not in contact with the platinum foil. With this arrangement the source is always an equipotential one which permits an accurate measurement of its potential. A larger primary current was obtained when fine nickel gauze was placed over the openings in *A* and *B*, as indicated in Fig. 1 by the dotted lines. This is probably because there is less distortion of the field at the openings when the gauze is used. The cylinders *B*, *C*, and *E* were lined with fine nickel gauze so as to decrease any possible multiple reflection of electrons. The whole apparatus was cleaned with distilled ether after assembling to remove any grease that might be present. The apparatus was enclosed in a glass tube which, after being evacuated, was heated by an electric furnace to 400° C. for several hours with the pumps working continuously. Liquid air was kept on the condensing trap continually during the time that the tube was connected to the vacuum line, so that oil and mercury vapors were never allowed to enter the tube. The pumps were kept going during the observations so that the results were obtained under extremely good vacuum conditions. A pressure of 10^{-6} mm. Hg could be observed on the McLeod gauge used and while the observations were taken the mercury stuck to the top of the gauge, a negative pressure of 2 cm. of Hg being necessary to release it, so that the gas pressure in the tube must have been much less than 10^{-7} mm. Hg. Observations as well as calculation show that ionization of the residual gas at this pressure is negligible since practically no current to *C* and *D*, Fig. 1, was observed when primary electrons were driven into *E*.

In order to facilitate adjustment and to prevent the waste of time necessitated by cutting open the tube containing the apparatus, a ground glass joint, having the same diameter as the tube (2 inches), was sealed on one end. To make the joint air tight and to avoid the presence of wax vapor, the joint was copper plated and soldered together with Wood's metal. The glass was first platinized by painting on a solution of platinum chloride and dextrine, then heated in an electric furnace until the platinum was reduced to the metallic form. Four or five separate coats and heatings were necessary to make the platinum sufficiently conducting so that a uniform deposit of electrolytic copper could be obtained. At first difficulty was experienced in obtaining a deposit of copper which did not let air through between the copper and platinum. This was finally overcome by taking special precautions in the cleanliness of the solution of copper sulphate used, and by the addition of a small amount of glucose to the solution, which produced a finer grained deposit. The copper was deposited on the two parts of the joint so that when they were fitted together the copper plating completely covered the outside of the joint. Wood's metal was used to solder the two parts together because of its low melting point. With zinc chloride it required very little heating to coat the surface of the copper with the alloy. The vapor pressure of Wood's metal is not exactly known, but it should cause no trouble in the tube since two inches of tight-fitting ground-glass joint intervene to make the rate of diffusion extremely small. The ground joint was placed near one end of the tube and far enough from the metal parts so that it was possible to bake out the apparatus without heating up the joint. The inner seal which was attached to the removable part of the ground joint supported the wires carrying the heating current and the quartz tube, and also two small glass tubes, one of which held the focusing plate, F, and the other the diaphragm, A.

Method of Procedure.

Since the magnitude of the primary current was found to vary with the velocity of the primary electrons, the ratio of the secondary current to the primary current was measured as a function of the primary velocity. The secondary current was obtained by taking the difference between the total primary current to E when open, and the current to the target when it was over the hole in the end of E. Direct measurement of the secondary electron current to the cylinder, C, gave the same result as the above method. B, C, D, and E were all grounded during this measurement so that the number and energy of the secondary electrons were not affected by an external field. In order to obtain larger primary currents for the small velocities a retarding field was placed between A and B, so that the primary electrons were first accelerated to A, retarded to B, and then passed on into E with a velocity measured by the difference between the accelerating and retarding potentials. The procedure was then to measure the primary and secondary electron current for various primary velocities, obtained by varying the potential of S.

To determine the velocity distribution of the primary electrons, *i.e.*, to find out what fraction of the total number had a velocity corresponding to the net accelerating voltage, a varying retarding potential was put on E and D, with E open, the potential of the two being the same. This potential was varied in steps from zero up to the accelerating voltage, and the corresponding currents to the cylinder, E, measured. By trial, it was found that no electrons hit D. The velocity distribution of the secondary electrons for any given primary velocity was obtained by measuring the current to the target as the potential of B, C, and D (all being the same) was varied in steps from zero up to the voltage corresponding to the primary velocity. B was kept at the same potential as C and D, for it was found that the primary stream was scattered if there was an appreciable potential gradient between B and C. This procedure is based on the assumption, which seems to be a reasonable one, that the velocity of impact of the primary electrons is given by the potential drop from the target to the source, independent of the potentials of B, C, and D. Changes in the potential of B, C, and D produce changes in the magnitude of the primary electron stream, but these are taken account of, since the total current to E, as well as the current to the target, was measured each time that the potential of B, C, and D was changed. The ratio of the secondary electron current to the total current received by E as a function of the retarding potential on B, C, and D then gave a measure of the velocity distribution of the secondary electrons, since the secondary electrons which leave the target must have a velocity greater than that corresponding to the retarding field which tends to keep them on the target.[1]

Results.

As shown by the curves of Fig. 2, the ratio of the secondary to the primary current as a function of the velocity was obtained for the following: (1) a polished nickel target; (2) a nickel target which had been cleaned with fine emery paper; (3) nickel target etched with acid; (4) nickel target covered with fine nickel gauze; (5) a copper target; (6) a polished nickel target after prolonged heat treatment at bright red heat. The first five curves were obtained with targets which had received the same heat treatment as the rest of the apparatus, *i.e.*, baked at 400° C. for several hours. The results show that the number of secondary electrons is independent of the roughness of the surface, but that covering

[1] The above method assumes, of course, that the retarding potential on the cylinder, C, is a measure of the total velocity, and not of components perpendicular to the surface of the cylinder. This would only be true if a small target was placed at the center of a hollow spherical conductor large compared to the size of the target. However, the error introduced by an apparatus having the dimensions of Fig. 1 should not be serious. In any case, it would be constant and such as to make the value obtained for the velocity smaller than the true value, so the fact that large values were obtained for at least some of the secondary electrons would not be altered.

the surface with fine nickel gauze considerably reduces the number of secondary electrons. The secondary electron current from a copper target seems to be greater than that from a nickel target. However, since the above observations were taken before sufficient heating to eliminate the effects of occluded gas, no final conclusion can be drawn as to the difference in the secondary electron current from copper and nickel.[1]

Prolonged heating of the nickel target at bright red heat was accomplished by high-frequency induction. The target could be moved up into a bulge in the tube so that only the target was heated to red

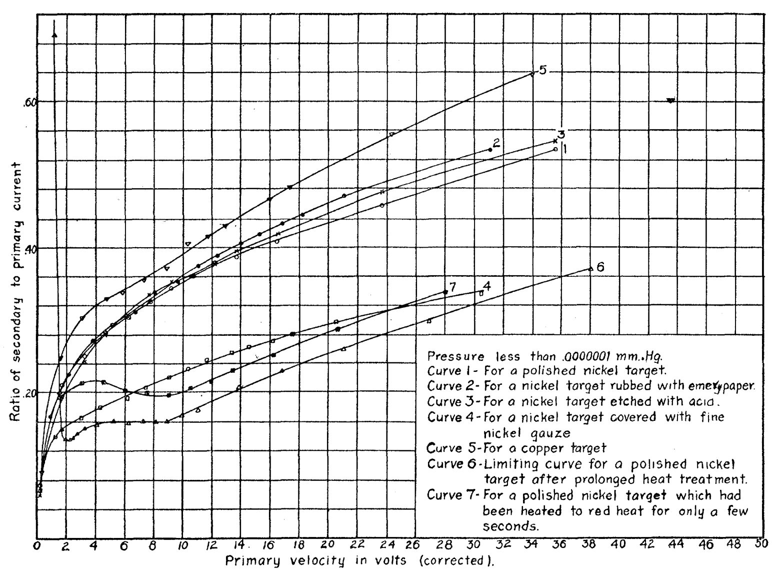

Fig. 2.

heat when the tube was surrounded by a few turns of wire which carried the high-frequency current. The appearance of the target was unchanged by the heat treatment, although a considerable amount of nickel was evaporated onto the walls of the glass tube opposite the target. Since the pumps were kept going during this heat treatment the gas pressure remained small at all times (less than .00001 mm. Hg), and when the heating had been continued until the limiting curve was obtained the gas pressure even during the heating was so low that the mercury stuck to the top of the McLeod gauge.

[1] It is interesting to note that a curve of the same form as curve 1 was obtained with a preliminary form of apparatus, in which the nickel target was moved along the axis of the tube, similar to the arrangement used by A. W. Hull.

As shown by curve 6, the prolonged heat treatment reduces the secondary electron current considerably and changes the general shape of the curve. Curve 7 was obtained after the target had been heated to bright red heat for only a few seconds (about 10). Further heating gradually changed and lowered the curve from the form 7 to the form 6. Curve 6 seems to be the limiting value since additional heating produced no further change. To make sure that the change produced was due to elimination of gas and not to a change in the structure of the metal, the apparatus was exposed to air and then evacuated and baked at 400° C., after which the original curve 1 was obtained. Curve 6 was then repeated after prolonged heating. Exposing the apparatus to hydrogen at a pressure of 2 cm. Hg for several days increased the second-

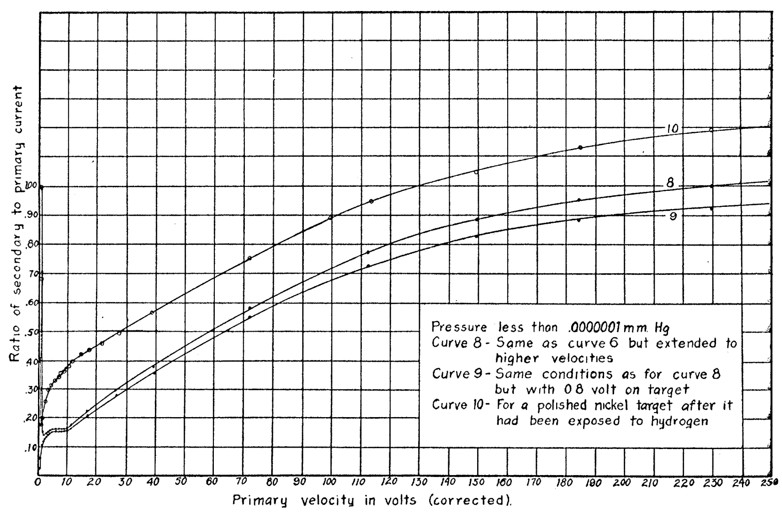

Fig. 3.

ary electron current as shown by curve 10, Fig. 3, but again heating the target at bright red heat reduced this current to the same limiting values which it reached after heating subsequent to the exposure to air, so that it seems safe to conclude that the final curve is one which represents the true characteristics of the metal.

As already seen from curve 7, an enormous change in the curve was produced by only a few seconds heating of the target at bright red heat, and practically the whole change produced by the continued heating at this temperature was found to take place during the first few minutes. The curve obtained after 30 min. of this heating was only slightly higher than that obtained after one hour of heating. Further heating produced no noticeable change in the curve, *i.e.*, the limiting form was reached after about one hour of heating at bright red heat. Only about 20 min. of this heating seemed to be necessary to obtain the limiting curve subsequent to the exposure of the apparatus to hydrogen under the conditions previously stated. The heating at red heat was not effected continuously, but at about one-minute intervals for periods of one minute, so as to prevent overheating of the glass tube. No results for a copper target after continued heating have been obtained as yet, due to experimental difficulties.

After the target had been heated to red heat it assumed a negative potential of about 0.8 volt with respect to the surroundings, thus producing the sharp rise at the low-velocity end of the curves obtained after heating. By neutralizing this negative potential with a positive potential of 0.8 volt, curve 9 was obtained. It will be noticed that this curve lies below curve 8, the difference between the two curves increasing with the primary velocity. This, however, is easily explained if we consider that before the contact potential is neutralized the secondary electrons are pulled off the target by a potential difference of 0.8 volt which causes more electrons to leave the target than would if no field existed. This difference would naturally increase with increase in the number of secondary electrons. Curve 9 can then be considered as representing the true secondary electron characteristics of nickel produced in an equipotential region. The curve obtained after allowing the apparatus to stand over night, during which time the pressure remained less than .00001 mm., was found to be somewhat higher than the limiting form, *i.e.*, the secondary electron current had increased slightly. The contact potential of the target had also slightly decreased. This result is probably due to absorption of gas and to gas diffusing out from the interior of the target.

A typical set of data, taken after prolonged heat treatment, is shown in Table I. Column 1 shows the retarding potentials used between A and B, Fig. 1. These retarding potentials gave the best velocity distribution of the primary electrons, although no difference could be noticed in the curve obtained with a constant retarding potential of 20 volts. Column 2 contains the primary velocity in volts (uncorrected). The total current was measured before and after the current to the target was observed and the average taken as indicated in Column 3. Column 5 contains the current to the diaphragm, D, when the cylinder E was open and when it was closed by the target. As stated in the description of apparatus, these observations show whether the presence of the target causes any scattering of the primary beam which would result in an

TABLE I.

1	2	3			4	5 (5, a)	(5, b)	6	7
		Total Current.				Current to D.			
Retarding Potential between A and B.	Velocity in Volts (Uncorrected).	First.	Last.	Average.	Current to Polished Target.	With Target over Hole in E.	With E Open.	Col. 3–Col. 4.	Ratio of Secondary to Primary Current.
3.0	1.0	62.0	62.0	62.0	0.0	0.0	0.0	62.0	1.000
3.0	1.5	162.5	161.5	162.0	1.0	0.0	0.0	161.0	0.994
3.0	1.8	187.5	187.5	187.5	11.5	0.0	0.0	176.0	0.938
3.0	2.0	215.0	222.0	218.5	71.0	0.0	0.0	147.5	0.675
3.0	2.3	234.0	237.0	235.5	193.0	0.0	0.0	42.5	0.181
3.0	2.5	227.0	229.0	228.0	194.0	0.0	0.0	34.0	0.149
3.0	2.7	208.5	208.0	208.2	180.0	0.0	0.0	28.2	0.135
3.0	3.0	218.0	217.0	217.5	188.0	0.0	0.0	29.5	0.136
3.0	3.2	233.0	235.0	234.0	202.0	0.0	0.0	32.0	0.137
3.0	3.5	231.0	233.0	232.0	198.5	0.0	0.0	33.5	0.144
3.0	4.0	232.0	234.0	233.0	197.8	0.5	0.0	35.2	0.151
4.5	5.0	216.0	217.0	216.5	183.8	1.2	0.2	32.7	0.151
6.0	6.0	238.0	238.0	238.0	200.0	1.5	0.3	38.0	0.160
6.0	7.0	225.3	228.0	226.6	191.0	2.0	0.3	35.6	0.157
7.5	8.0	237.0	239.0	238.0	200.0	2.0	0.2	38.0	0.160
7.5	9.0	247.0	247.0	247.0	208.0	2.6	0.2	39.0	0.158
9.0	10.0	235.0	234.0	234.5	197.0	3.0	1.0	37.5	0.160
10.5	11.0	236.0	238.0	237.0	197.0	3.2	1.0	40.0	0.169
10.5	12.0	239.0	235.0	237.0	196.0	5.0	1.2	41.0	0.173
10.5	14.8	222.8	222.2	222.5	176.5	5.8	1.2	46.0	0.206
10.5	17.7	241.0	240.6	240.8	186.0	5.8	1.2	54.8	0.228
20.0	22.0	243.0	242.0	242.5	180.0	6.0	1.0	62.5	0.258
20.0	27.2	219.0	218.0	218.5	153.5	6.5	0.7	65.0	0.298
20.0	40.0	235.5	235.5	235.5	147.0	7.5	0.8	88.5	0.376
20.0	72.5	236.0	236.0	236.0	100.0	14.5	0.5	136.0	0.576
20.0	113.0	239.0	243.0	241.0	56.0	19.8	0.7	185.0	0.768
20.0	150.0	248.0	243.0	245.5	29.5	22.5	1.0	216.0	0.880
20.0	185.0	226.0	226.0	226.0	12.0	27.8	2.0	214.0	0.947
20.0	230.0	212.0	213.0	212.5	1.0	27.0	1.5	211.5	0.995
20.0	260.0	233.0	228.0	230.5	−5.0	33.0	2.8	235.5	1.020

apparent secondary electron current. The observations show that practically no primary electrons hit D, but nearly all went through the hole into E, when E was open. The current to D was somewhat larger when the target was over the hole in E. It was, however, much too small to account for the apparent secondary electron current by a scattering of the primary beam. From Column 5a, Table I., we see that there was no current to D until a primary velocity of 4 volts (uncorrected) was reached, after which the ratio of this current to the total secondary current (obtained by taking the ratio of the corresponding values of Column 5*a* and Column 6) increased to about 0.12 at 15 volts primary velocity and then remained more or less constant until 150 volts primary velocity was reached, after which it again increased to about .14 at 260 volts. The magnitude of this current is easily explained if we consider that, of the secondary electrons which leave the target in random directions,[1] a small percentage will be intercepted by *D*, for, although *D* was as close as practicable to the target (something less than one mm.), it subtended an angle sufficient to account for the current which it received.[2] Column 7 was obtained, as previously explained, by dividing the difference between the total current and the current to the target by the total current. Since only the ratio of the currents was desired no attention was paid to their absolute magnitudes. The currents for velocities of the order of a volt and less were easily measured with a D'Arsonval galvanometer of sensibility 10^{-10} amps. per mm. of deflection and much larger currents were obtained for the higher velocities.

The velocity distributions of the primary electrons, obtained as previously explained, are shown in Figs. 4 to 6. The dotted curves in

[1] John T. Tate, PHYS. REV., *17*, p. 394, 1921. C. Davisson and C. H. Kunsman, Science, *54*, p. 522, 1921.

[2] In this case we should expect that the ratio of the current to *D* to the total secondary current would remain constant, independent of the magnitude of the secondary current. The increase of this ratio for the lower primary velocities may be due to the effect of the magnetic field, causing the bulk of the secondary electrons, having sufficiently low velocities, to leave the target in the direction of the field, *i.e.*, along the axis of the tube and thus preventing them from striking *D*. Then, only those secondary electrons which have a velocity sufficient to overcome the effect of the magnetic field would be able to reach *D*. The ratio of this number to the secondary current would obviously increase with the primary velocity until the bulk of the secondary electrons had a velocity great enough to be unaffected by the magnetic field (see velocity distribution curves of secondary electrons below). The increase of current to *D* which begins at the higher velocities may be the result of reflection of the secondary electrons from the inner surface of the cylinder, *C*, back to *D*. Although this reflection is decreased by the presence of gauze on the surface, as previously seen, the velocity distribution curves of secondary electrons, shown below, indicate that there are some high-velocity secondary electrons leaving the target which might produce an appreciable effect due to their reflection from the cylinder *C* back to the diaphragm *D*. Some of these reflected secondary electrons would also strike the target and thus introduce an error since it has been assumed, for the results obtained, that the only electrons hitting the target are primary electrons. This effect, however, would not be noticeable until comparatively large values of the primary velocity had been reached. A rough calculation shows that, for a primary velocity of 30 volts, less than 0.3 per cent. of the incident electrons on the target are secondary electrons from the cylinder *C*. At 100 volts it amounts to less than 1.0 per cent. This error would cause the observed secondary electron curve to lie below the correct curve. In this calculation it was assumed that, due to the effect of the magnetic field, all of the secondary electrons from the target left in directions so as to hit the opposite end of the cylinder *C*, instead of leaving in random directions, and a similar assumption was made for those leaving the end of the cylinder *C*.

Fig. 4 were obtained by plotting the slopes of the original curves as ordinates. The ordinate at any point is then proportional to the number of electrons having a velocity corresponding to the retarding potential.

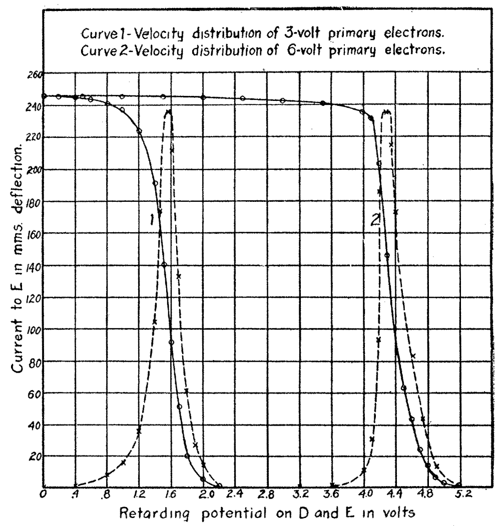

Fig. 4.

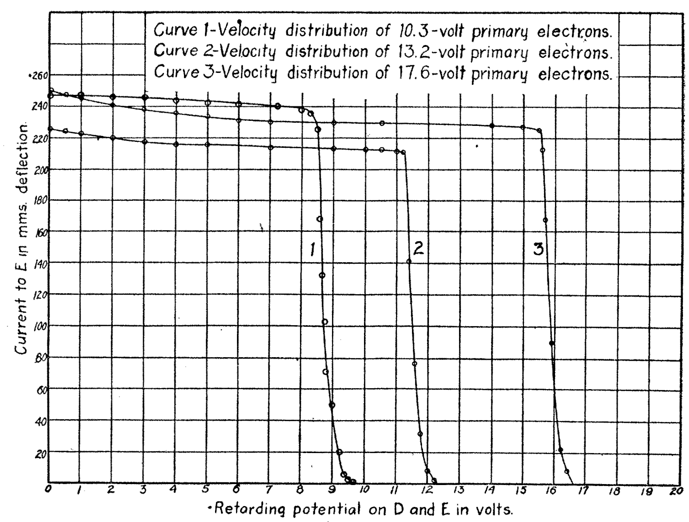

Fig. 5.

It will be noticed that, although the velocity distribution is probably as good as could be expected, the bulk of the electrons have velocities somewhat lower than that corresponding to the net accelerating voltage applied. This must be due to a contact potential between the platinum source and the nickel. Because of this difference the velocities as given in Column 2 of Table I. must be corrected. This correction, which varies slightly with the primary velocity, was made before the curves were plotted so that the abscissa of the curves in Figs. 2 and 3 are the corrected velocities. Since the velocity distribution curves show that

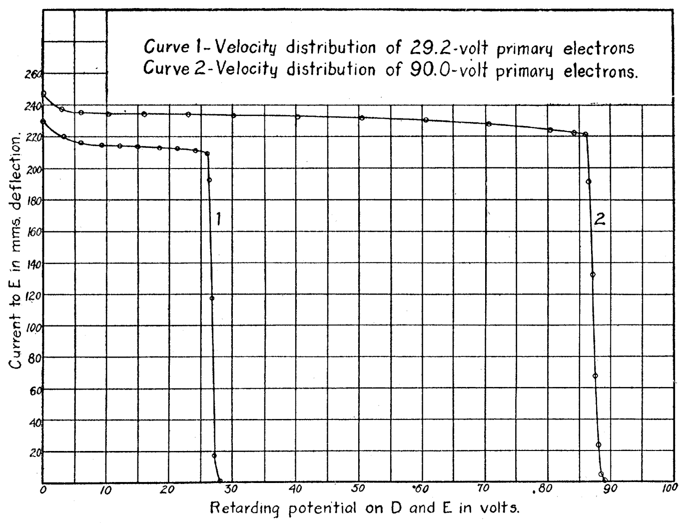

Fig. 6.

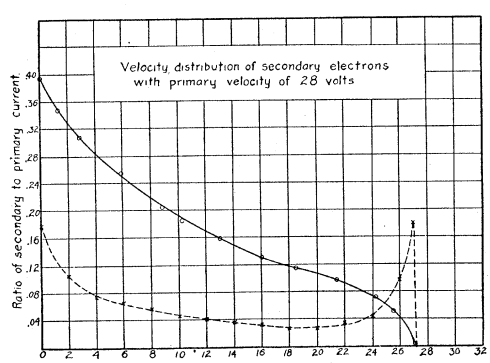

Fig. 7.

the velocities vary over a range of about one volt, the mean value was taken as the correct one. It was found that the velocity distribution of the primary beam depended to a slight extent on the potential of the focus plate, F, the best distribution being obtained with the potential of F the same as that of the source, S. For this reason S and F were kept at the same potential during all the observations although there were other potentials of F which gave larger primary currents.

The velocity distributions of the secondary electrons, obtained as explained under "procedure," are shown in Figs. 7 to 9. The dotted curves were obtained by plotting the slopes of the other curves as ordi-

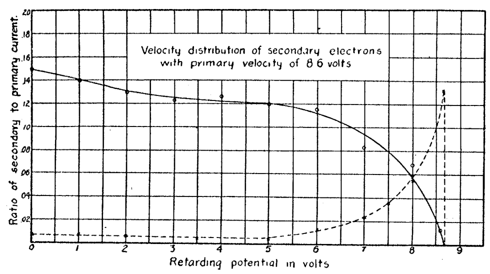

Fig. 8.

nates. These curves indicate that, when the primary velocity is below about 9 volts, a large percentage of the secondary electrons have velocities nearly equal to the primary velocity and a very small percentage have velocities less than one volt. For higher primary velocities the distribu-

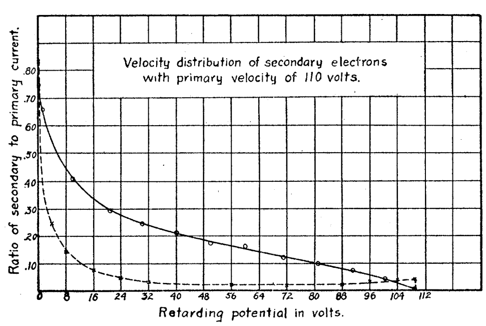

Fig. 9.

tion changes, there being many secondary electrons having low velocities. The percentage of secondary electrons having velocities less than 5 volts, say, increases as the primary velocity increases. There are, however, a few per cent. having velocities nearly equal to that of the primary electrons when the primary velocity is as great as 110 volts. As stated in the introduction, Gehrts and von Baeyer found no secondary electrons with velocities greater than 30 volts. The present results, however, agree qualitatively with those of Davisson and Kunsman, who found some secondary electrons with velocities nearly equal to that of the primary stream.

Discussion of Results.

In the preceding discussion the use of the words "reflection" and "emission" has purposely been avoided, since there has been some difference of opinion as to whether actual reflection of the primary electrons occurs or whether all of the secondary electrons are produced by ionization at the metal surface. It is certain that emission occurs at high velocities where more electrons leave the surface than strike it, but the question is obviously, whether reflection occurs at all, and if so, at what velocity of impact emission begins. Gehrts and von Baeyer concluded from the nature of their results (see introduction) that reflection occurred only below 11 volts, and that at this velocity an emission began which increased rapidly with the primary velocity. They were, however, unable to interpret the maximum in the secondary electron curve at 5 volts. They considered that their explanation would have seemed more plausible if the number of secondary electrons had decreased steadily with the primary voltage up to 11 volts and then increased, instead of showing a maximum at about 5 volts. The phenomena could then have been considered as due to reflection which was large for small primary velocities but which decreased with increasing velocity to 11 volts, where an emission began and increased rapidly with further increase in primary velocity. The results of the present investigation show that the maximum which they observed at 5 volts was probably due to the effects of absorbed gas, since it disappears with continued heating. Since I. G. Barber obtained no secondary electrons below about 10 volts' primary velocity he concluded that there is no such thing as reflection of electrons and that emission begins at about 10 volts.

The following features of the present investigation show that a new factor enters into the production of secondary electrons from nickel at about 9 volts: (1) the sudden change in slope of the secondary electron curve (Figs. 2 and 3) at about 9 volts; (2) the difference between the velocity distribution of secondary electrons when the primary velocity is 8.6 volts or less, and that when the primary velocity is considerably greater than this. These results lead one to the interpretation that reflection of electrons from nickel occurs for all the primary velocities investigated, the reflection increasing between 0 and 4 volts' primary velocity and then remaining constant to 9 volts, where emission begins and increases with increase of primary velocity to at least 260 volts. That there are some high-velocity electrons present, when the primary velocity is as great as 110 volts, indicates that reflection continues after emission begins, so that above 9 volts there is both reflection and emission. According to this idea the reflected electrons may be considered to have velocities nearly equal to the primary velocity, *i.e.*, reflection involves a change in direction without much loss in energy, while the emitted electrons have a much smaller velocity.

The above interpretation is further substantiated by a phenomenon which was observed when obtaining the velocity distribution of the primary electrons. It will be noticed, from the velocity distribution curves of the primary electrons, that when the primary velocity was less than 9 volts, all of the primary electrons had velocities nearly equal to that corresponding to the applied voltage. For larger primary velocities, however, there are some low velocity electrons present, as indicated by the rise of the left end of the curves. Also, the number present appears to increase with the primary velocity. This can be explained, with the previous interpretation, as being due to emission of electrons from the edges of the diaphragms which limit the primary beam. Thus, since below 9 volts no emission occurs, there are no low-velocity electrons present in the primary beam.

The accuracy in determining the ionization potential depends, of course, on the velocity distribution of the primary beam. Since the velocity varies over a range of about one volt, the mean velocity was taken as the correct one, as previously mentioned. If, however, the electrons with the highest velocity are sufficient in number to produce an appreciable effect, an error will be introduced equal to the difference between this higher velocity and the mean value. Hence the value obtained may be subject to a small correction.

Since the number of secondary electrons obtained at the low velocities was much greater before the continued heating than after, one must conclude that the reflection of electrons from the atoms of gas on a metal surface is greater than from the metal freed from gas. Since the ionization potential of hydrogen is about 11 volts, the increased secondary current below this velocity, as shown in curve 10, Fig. 3, is probably due to reflection from hydrogen atoms in the surface rather than ionization of them. The fact that curve 10 lies above the limiting curve for all velocities up to 260 volts also shows that more electrons are knocked out of the hydrogen atoms than from the nickel atoms. This is also true for air.

The method used is particularly well adapted to the extension of the investigation to other metals. Targets of the various metals can be inserted and the characteristics of each studied under the same conditions by moving them successively into the path of the primary electron stream. There is no reason to believe that the secondary electron characteristics should be the same for all metals, and a knowledge of their characteristics in this respect should be of value in connection with the electron theory of metals.

Summary and Conclusion.

1. The secondary electron characteristics of nickel, for low primary velocities, have been investigated in detail. The results are independent of the particular target used and also of the roughness of the surface.

2. Heating the nickel target to bright red heat in vacuo changed the shape of the secondary electron curve (Figs. 2 and 3) and decreased the magnitude of the secondary electron current. Exposing the surface to hydrogen again increased the secondary electron current. The same limiting form of curve was obtained after prolonged heating of the target at bright red heat independently of whether it had previously been exposed to air or hydrogen.

3. A sudden change in slope of the secondary electron curve occurs at about 9 volts' primary velocity, which, together with a difference in the velocity distribution of the secondary electrons for primary velocities below and above 9 volts, suggests that emission or ionization at the surface begins at this voltage and increases with primary velocity, and that between 0 and 9 volts only reflection occurs. The presence of secondary electrons with velocities nearly equal to that of the primary beam for the higher velocities suggests that reflection continues after emission begins.

This problem was suggested by Professor Max Mason and was carried out under the direction of Professor C. E. Mendenhall. The author wishes to express his indebtedness to these gentlemen for many valuable suggestions and criticisms throughout the progress of the work.

The University of Wisconsin,
May, 1922.