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SECONDARY ELECTRON EMISSION DUE TO
POSITIVE ION BOMBARDMENT

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SECONDARY ELECTRON EMISSION DUE
TO POSITIVE ION BOMBARDMENT*

by

John Wallace Murdock
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ABSTRACT

Stray electrons were produced in the Ames Laboratory linear accelerator by the ion beam striking the target and various other parts of the accelerator. This experiment was done to determine if the stray electrons from parts of the accelerator other than the target could be reduced by using construction materials other than brass. Measurements of the number of electrons produced from several materials, however, indicated that there is no particular advantage in using other materials in place of brass.

The ratio of electrons produced per proton bombarding a copper target varied from 1.15 to 1.57 with a high at 1.64 as the ion beam energy was varied from 23 kilovolts to 130 kilovolts. In this same beam energy, the range varied more for diatomic and triatomic hydrogen. The ratio for triatomic hydrogen increased from 1.48 to 3.59.

Measurements showed that most of the electrons produced at the target had an energy less than thirty electron volts. The curves for the integral electron energy distribution were similar to the curves for diode vacuum tubes. The energy measurement methods were similar to those used to produce the space charge limited curve of a diode; thus, it was assumed that the electrons bombarded from the target produced a space charge at the target similar to the space charge formed at the cathode of a diode.

*This report is based on a Master's thesis by John W. Murdock submitted June, 1955 to Iowa State College, Ames, Iowa. This work was done under contract with the Atomic Energy Commission.

INTRODUCTION

The experimental work described in this report resulted from radiation problems arising in early experiments with the Ames Laboratory Kevatron, a positive ion accelerator. The positive ion beam ejected electrons from the target and from certain metallic surfaces of the Kevatron. These electrons, conventionally referred to as secondary electrons*, were accelerated to the positive ion source. They produced x-rays at the ion source of sufficient intensity to cause a radiation hazard. It was found that the electrons ejected from the target could be returned to it by a properly positioned negatively charged guard ring as illustrated in Fig. 1. The number of electrons ejected from other surfaces was reduced by improved ion beam focusing and by a different design of certain parts of the Kevatron along the beam path. There was also a possibility that different materials might be used for certain accelerator parts that would not emit as many electrons per ion as brass, which is the material normally used. Measurements were made in this experiment to determine the secondary electron properties of various materials when bombarded by positive ions.

The results of these measurements were intended to be a guide in the selection of materials for accelerator design; however, if any materials were found to have a high secondary electron ratio**, they might be useful in the construction of electron multipliers for particle detection. In this connection it would be desirable to find some material for which the secondary electron ratio was a sensitive function of the particle energy, thus offering a means of measurement of the primary particle energy. Also, the data might assist theorists by supplementing the limited amount of data now available on secondary electron emission due to positive ion bombardment.

*Normally the term "secondary electrons" is used to describe electrons that are emitted from the surface of a material when it is bombarded by other electrons. The term is expanded in this report to include those electrons that are emitted from the surface when it is bombarded by positive ions.

**Secondary electron ratio is defined in this report as the ratio of the number of electrons emitted from the surface of a material to the number of positive ions striking the material. It is represented by the Greek letter δ .

LITERATURE REVIEW

One of the earliest papers on electron emission due to positive ions appeared in 1930. M. L. E. Oliphant (1) worked with ions of energies from eighty to one thousand volts. Best results were obtained from a molybdenum target. Cold and heated targets were used. Smooth and reproducible results were obtained with the heated target. The secondary electron ratio was found to range from about 20% to about 70% for the heated target and approximately 35% to 125% for the cold target, the percentage increasing as the ion energy increased. When the electron emission percentage was plotted as a function of energy of the bombarding helium ions, a sharp increase in emission was observed at a velocity of about 2×10^7 centimeters per second.

Oliphant also examined the energy spectrum of the emitted electrons. He used two methods to determine the spectrum--the retarding potential method and the magnetic analysis method. The retarding potential method was used in the experiment described in this report. It is described in the section entitled THE INVESTIGATION.

After the target had been heated for some time and after the helium was purified, the velocity distribution curve of the emitted electrons changed considerably and several maxima appeared in the energy range from zero to twenty-five volts. The position of these maxima differed only slightly for nickel, molybdenum, and tungsten. M. L. E. Oliphant and P. B. Moon (2) discussed possible theories to explain the results of Oliphant's work.

In 1936, Healea and Chafee (3) measured the emission of electrons from a hot nickel target when it was bombarded by hydrogen ions. The target was heated to 900°C or above for six weeks before consistent results were obtained. Ion accelerating potentials up to about 1600 volts were used. The secondary electron ratio which was expressed as a percentage increased linearly through this range, being about 22% at 1600 volts. No secondary electron velocity distribution curve was made because of the instability of the measurements. The retarding potential method was used to measure the secondary electron percentage. They found that they had to correct all of their measured percentages by a small amount because of undesired currents resulting from scattered ions.

In 1939, Monica Healea (4) reported that the curve for secondary electron yield due to bombardment by deuterium had a bend near the top of the voltage range (around 1500 volts). She suggested that this leveling off of the curve might be a mass dependence.

In 1935, Leo H. Linford (5) studied secondary electron emission due to mercury ions in the range of 0.7 to 2.35 Mev. He was careful to keep stray electrons away from the target, to align the collector by a fluorescent screen, to keep slow electrons from leaving the collector by use of a 45-volt suppressor ring, and to prevent leakage from collector and associated circuits. He reported current between the chamber walls and the target due to the following combinations:

1. Current originating at target
 - (a) Secondary electrons
 - (b) Photoelectrons
2. Current originating at the chamber walls
 - (a) Photoelectrons.

Linford also used the retarding potential method of measurement of secondary electrons. An accurate measurement of the energy distribution of any component was said to be impossible since the photoelectrons gave rise to other slow electrons. Seven to twenty electrons per ion were emitted from the target when it was bombarded with mercury in range of 0.7 to 2.35 Mev.

In 1939, Hill, et al, (6), did experiments similar to the one reported in this report. The initial yield of secondary electrons was found to be high at any bombarding ion energy. Two hours of high vacuum followed by thirty-minute bombardments at 400 kolovolts yielded consistent results. Protons, molecular hydrogen and helium ions were used as primary particles. Molybdenum, copper, aluminum, and lead were used as target materials. The number of secondary electrons appeared to be independent of the target material used. No maximum yield of δ was observed for protons; however, a maximum yield was observed for molecular hydrogen around 100 Kev. Secondary electrons due to helium ions reached a maximum around 300 Kev. A measurement of the energy spectrum of the secondary electrons was attempted by the retarding field method but little was accomplished.

James S. Allen, (7) also in 1939, measured the secondary electron yield from metals bombarded with protons. He used beryllium, carbon, copper, nickel, and platinum as target materials. While A. G. Hill, et al., reported a decrease in secondary emission of copper with an increase in ion energy, Allen reports an increase in secondary emission. Allen's data were taken for a well outgassed target. The following table shows the difference in their reports:

TABLE 1

Comparison of δ for protons bombarding copper as measured by different investigators.

Investigator	Secondary electron ratio for proton energies from 78 to 213 kolovolts										
	78	83	96	107	108	120	121	130	142	166	212 213
1. A. G. Hill, <u>et al.</u>	3.8			3.61					3.41		2.90
2. James S. Allen						1.8				1.8	2.1

Timoshenko (8) concluded that secondary electrons were due primarily to gas layers on the surface of the targets. The data presented by various persons and the inconsistency of the results among them indicate that the surface condition is important in secondary emission, even if not as important as Timoshenko reported it to be.

THE INVESTIGATION

I. Target Selection and Preparation

The elements, copper, molybdenum, and gold, were selected as target materials to determine if a relation between secondary electron yield and atomic number would be suggested. The element carbon was also used but the sample was of unknown purity. The metal targets were mechanically polished until they had a mirror finish. Then they were cleaned with organic solvents.

Brass, acetylene carbon on brass, stainless steel, and silver-magnesium metal were also used as targets. These materials were not polished or cleaned but were used in the same condition that would exist in normal accelerator construction.

The copper, molybdenum, and gold targets were heated by electrical coils during the experiment. A dark spot formed on the target in the area where the ion beam struck unless the target was heated continually. The exact temperature of the target was not known but the heat was controlled so that measurements were stable during the recording of data. When the target was not heated, measurements were slightly erratic with values usually increasing with time. Data are given in Table 8 showing the change of δ with time as the target was heated and cooled. The target was considered sufficiently outgassed when the chamber pressure did not increase as the target was heated.

II. Secondary Electron Equipment.

The secondary electron equipment, illustrated in Fig. 1, was attached to a brass tube leading from a magnetic analyzer. The analyzer was adjusted so that the component of the Kevatron beam that was selected to strike the target would consist of singly charged monatomic, diatomic, or triatomic hydrogen ions. It was necessary to prevent electrons from flowing either into or out of the tube from the target chamber. A negatively charged guard ring located between the tube and the target chamber accomplished this electron isolation. Teflon o-rings were used to electrically insulate the parts of the equipment so that leakage currents would not interfere with the secondary electron measurement.

Lavite, a ceramic material, was used to support the target and its heating elements. The elements were placed on the opposite side of the target from where the ion beam struck. The Lavite outgassed in a short time after the heating element was turned on. A pressure of about 10^{-6} mm Hg was maintained while measurements were being made.

III. Measurement Techniques.

The secondary electron ratio, δ , has been defined as the ratio of the number of electrons emitted from the target to the number of positive ions striking the target. The

Fig. 1. Sketch of equipment used to measure the secondary electron ratio.

measurements of the secondary electron ratio were made by a method similar to that described by Oliphant in the paper discussed in the section LITERATURE REVIEW. For an ion beam at a desired energy, the magnetic analyzer was adjusted until a particular component of the beam was focused on the target. The collector was made 90 volts positive with respect to the target, so that all emitted electrons were collected. The guard ring was negative with respect to the analyzer and with respect to the target. This prevented electrons that were formed in the analyzer from flowing to the collector and also isolated the electrons emitted from the target from the analyzer. With the collector at a 90-volt positive potential, the target current consisted of the ion beam current, the secondary electron current, and the ionization current formed from the collision of ions in the beam with residual gas atoms in the target chamber.

A bridge circuit was used to measure δ , the secondary electron ratio. The ionization current formed in the target chamber increased the measured value of δ . This increased value of δ was determined as follows, where the term δ' was used to distinguish this ratio from the true value of δ :

- i_p positive ion current,
- i_s secondary electron current from target,
- i_1 ionization current from gas atoms formed in target chamber,
- R_1 fixed resistance in bridge circuit,
- R_2 variable resistance in bridge circuit,
- G galvanometer.

Fig. 2 Bridge circuit for determining δ' .

When the bridge circuit was balanced so that the galvanometer read zero with the collector at 90 volts positive the following equation was written:

$$i_p R_2 = (i_s + i_1) R_1.$$

This equation was solved for the ratio $\frac{R_2}{R_1}$ which gave a

numerical value to the ratio of the currents as shown in the following equation:

$$\frac{i_s + i_1}{i_p} = \frac{(R_2)}{R_1} = \delta'.$$

The subscript 2 was used to refer to the value of $\frac{R_2}{R_1}$ measured under the conditions given in Fig. 2. The equation for δ was solved for the secondary electron ratio, δ , as follows:

$$\frac{i_s}{i_p} = \delta \left(\frac{R_2}{R_1} \right) - \frac{i_1}{i_p}. \quad (1)$$

The numerical value of $\frac{i_1}{i_p}$ was found by changing the bridge circuit as shown in Fig. 3 and making the following calculations:

i_p positive ion current,

$i_s = 0$ because collector was sufficiently negative to repel all secondary electrons.

Fig. 3 Bridge circuit for measuring i_1/i_p .

When the value of R_2 was adjusted so that the bridge was balanced

$$(i_p - i_1)R_2 = i_1R_1.$$

This equation was solved to give

$$\frac{i_1}{i_p} = \frac{(R_2/R_1)_3}{(R_2/R_1)_3 + 1}.$$

Here the subscript 3 referred to the circuit conditions that existed in Fig. 3. When this value of $\frac{i_1}{i_p}$ was substituted in equation (1) the following equation was obtained:

$$\frac{i_s}{i_p} = \delta = \left(\frac{R_2}{R_1}\right)_2 - \frac{(R_2/R_1)_3}{(R_2/R_1)_3 + 1} \quad (2)$$

The second term $\frac{(R_2/R_1)_3}{(R_2/R_1)_3 + 1}$ in equation (2) was

sufficiently small in many cases so that equation (1) was used in some graphs instead of the corrected value. The term, δ' , was used when this correction was not made. The secondary electron ratio as determined by equation (2) was measured for a range of accelerator voltages. The accelerator voltages were chosen at points where the ion beam was most stable. For this reason the accelerator voltages in several graphs and tables did not increase by equal steps. There was sufficient overlapping of data, however, that comparisons were made of δ' for different materials.

The integral secondary electron energy distribution was measured for the targets gold, copper, and molybdenum. The collector voltage was varied from a sufficiently positive potential to collect all secondary electrons to a negative potential that rejected all secondary electrons. The sign of the second term of equation (2) was changed when the collector voltage became negative. This change of sign was necessary because the ionization current reversed under this new condition. Equation (2) became

$$\frac{i_s}{i_p} = \delta = \left(\frac{R_2}{R_1}\right)_2 + \frac{(R_2/R_1)_3}{(R_2/R_1)_3 + 1} \quad (3)$$

The bridge circuit of Fig. 2 did not balance when the collector reached a sufficiently negative potential. The bridge circuit of Fig. 3 was then used to complete the measurements. A different equation was needed from the one for $\frac{i_1}{i_p}$ because the collector was not negative enough to stop all the secondary electrons. This new equation was derived from the conditions in Fig. 3 except $i_s \neq 0$.

When the bridge was balanced

$$(i_p + i_s - i_1)R_2 = (i_1 - i_s)R_1.$$

When this equation was solved the value of δ was

$$\frac{i_s}{i_p} = \frac{i_1}{i_p} - \frac{(R_2/R_1)}{(R_2/R_1) + 1}.$$

The previously determined value of i_1/i_p was substituted in this equation to obtain

$$\frac{i_s}{i_p} = \frac{(R_2/R_1)_3}{(R_2/R_1)_3 + 1} - \frac{(R_2/R_1)}{(R_2/R_1) + 1}.$$

The ratio R_2/R_1 was the value measured when $i_s \neq 0$ in the circuit illustrated in Fig. 3.

EXPERIMENTAL RESULTS

The experimental results were summarized in the following table and graphs. The corrected value of δ was used in most cases. The secondary electron ratio was listed in Table 2 for copper, molybdenum, and gold. It was not possible to adjust the accelerator voltage to the same voltage for each experiment; therefore, the data were collected for the three metals at different accelerator voltage. The results of the experiment on these metals were grouped in Table 2 for comparison. These data were illustrated graphically in Fig. 4 and in Fig. 5.

There were only three readings taken for carbon. There was no current detected for i_1 so that the measurements listed in Table 3 were direct bridge circuit measurements. The secondary electron ratio was high for carbon compared to the ratio for most of the materials. Measurements at given voltages for several materials were listed in Table 4 for comparison. The molybdenum, copper, and gold targets were polished. The measurements of δ were less for them than the other materials. Stainless steel had relatively few secondary electrons compared with other unpolished targets with the exception of brass.

Data were summarized in Tables 5, 6, and 7 for the integral secondary electron distribution. Distribution data were taken for the polished molybdenum and copper and for carbon. The measured value of δ was taken for carbon because there was no ion current detected for it. The corrected value of δ for molybdenum and copper was computed. These data were illustrated graphically in Fig. 6 and in Fig. 7.

TABLE 2

Secondary electron ratio versus accelerator voltage for ions bombarding different materials.

Accelerator voltage (kilovolts)	for						
	H ₁ ⁺	Copper H ₂ ⁺	H ₃ ⁺	H ₁ ⁺	Gold H ₂ ⁺	H ₃ ⁺	Molybdenum H ₁ ⁺
23.3	1.15	1.52	1.48				1.00
26.1							1.40
34.6							1.54
43.1	1.42	2.03	2.13				
45.7				1.95			
46.5							1.64
49.8				1.99	3.23	4.15	
55.1							1.72
57.3	1.55	2.32	2.51				
63.5				2.00			
64.0	1.58						
65.1							1.74
70.6							1.80
74.3	1.62	2.57	2.92				
74.4				2.02			
81.4							1.88
83.2	1.64	2.68	3.07				
85.7				2.00			
96.1	1.58	2.67	2.79				
99.9							1.80
100.3				2.00			
104.1				1.96	3.67	4.60	
108.1	1.60	2.82	3.31				
110.7							1.72
117.4				1.96			
121.1	1.62	2.96	3.51				
129.7	1.57	2.96	3.59				
131.7				1.97			
136.1							1.76
137.0							1.74

Fig. 4 Secondary electron ratio versus accelerator voltage for ions bombarding copper target.

Fig. 5 Secondary electron ratio versus accelerator voltage for ions bombarding gold, molybdenum, and copper.

TABLE 3

Secondary electron ratio versus accelerator voltage for ions bombarding carbon.

Accelerator voltage (kilovolts)	H_1^+	H_2^+	H_3^+
62.2	3.95	5.70	6.41
72.7	4.00	5.72	6.59
87.8	4.36	6.61	8.42

TABLE 4

Comparison of δ' of various materials with ion energies from 126 to 131 kilovolts.

Target material	H_1^+	H_2^+	H_3^+
Mo	1.8		
Cu	1.7	3.1	3.77
Au	2.0	4.0	
Brass 1 ^a	3.6	6.8	9.3
Brass 2 ^b	2.9	5.5	7.3
AgMg ₃	4.8	6.3	8.8
Steel (stainless)	2.3	5.0	6.2
Carbon	3.9	6.6	8.2

^aBrass 1 Surface covered with carbon from acetylene flame.

^bBrass 2 Stock brass with no special surface cleaning.

TABLE 5

Integral secondary electron energy distribution for 48 kilovolt protons bombarding a copper target.

Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)
118.4	1.53	33.6	1.30	15.3	0.41	-4.6	0.09
101.4	1.53	32.1	1.22	12.3	0.30	-6.1	0.07
84.4	1.53	30.5	1.13	10.7	0.27	-7.7	0.07
67.5	1.52	29.0	1.04	9.2	0.24	-9.2	0.05
58.2	1.52	27.4	0.95	7.7	0.21	-10.7	0.04
52.0	1.52	25.9	0.85	6.1	0.17		
44.3	1.51	24.4	0.70	4.6	0.14	-12.3	0.03
42.8	1.49	22.8	0.71	3.1	0.11	-13.8	0.03
39.7	1.40	21.3	0.62	1.5	0.09	-15.3	0.02
38.2	1.43	19.8	0.56	0.0	0.07	-16.7	0.01
36.6	1.39	18.2	0.50	-1.5	0.13	-18.2	0.01
35.1	1.35	16.7	0.45	-3.1	0.11	-19.8	0.00

TABLE 6

Integral secondary electron energy distribution for 137 kilovolt protons bombarding molybdenum target.

Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)	Collector voltage (volts)	Ratio (δ)
118.4	1.75	42.8	1.72	22.8	0.78	3.1	0.13
101.4	1.75	41.3	1.70	21.3	0.68	0.0	0.12
84.4	1.75	39.7	1.69	19.8	0.60	-3.1	0.14
67.5	1.75	38.2	1.67	18.2	0.54	-6.1	0.10
65.8	1.75	36.7	1.64	16.7	0.48	-9.2	0.07
58.2	1.74	35.1	1.61	15.3	0.41	-10.7	0.07
56.6	1.74	33.6	1.55	13.8	0.37	-12.3	0.05
55.1	1.74	32.1	1.45	12.3	0.32	-15.3	0.04
53.6	1.74	30.5	1.34	10.7	0.29	-16.7	0.02
52.0	1.74	29.0	1.22	9.2	0.25	-19.8	0.01
50.5	1.74	27.4	1.09	7.7	0.21	-22.8	0.01
48.9	1.73	26.0	0.97	6.1	0.18	-24.4	0.00
45.8	1.72	24.4	0.88	4.6	0.15	-33.6	0.00

TABLE 7

Integral secondary electron energy distribution for protons
bombarding a carbon target.

Collector voltage (volts)	Ratio (δ)
118.4	3.97
101.4	4.02
84.4	4.02
67.5	4.01
61.2	3.75
58.2	2.96
55.1	2.47
52.0	1.96
50.5	1.77
41.3	0.69
33.6	0.42
24.4	0.25
16.7	0.17
7.7	0.11
0.0	0.08
-7.7	0.05
-16.7	0.03
-24.4	0.02
-33.6	0.01
-41.3	0.00
-118.4	0.00

Fig. 6 Integral secondary electron energy distribution for protons bombarding molybdenum and copper.

Fig. 7 Integral secondary electron energy distribution for protons bombarding carbon.

The secondary electron ratio changed with the temperature of the target and the length of time the beam was on the target. This variation was greater on the materials that had not been polished. Measurements were made for a brass target and were recorded in Table 8.

TABLE 8

Dependence of δ' on target temperature.

Accelerator voltage (kilovolts)	Time (minutes)	H ₂ ⁺	Heater	Beam current (microamps)
124	0.0	4.53	on	6.5
124	1.5	4.45	on	6.5
124	6.5	4.38	on	6.5
124	9.5	4.37	on	6.5
124	10.0	4.37	off	6.5
124	11.0	4.35	off	6.5
124	12.25	4.37	off	6.5
124	12.75	4.38	off	6.5
124	13.25	4.39	off	6.5
124	14.0	4.41	off	6.5
124	15.5	4.44	off	6.5
124	16.25	4.46	off	6.5
124	17.75	4.50	off	6.5
124	19.0	4.53	off	6.5
124	20.0	4.56	off	6.5
124	25.5	4.68	off	6.5
124	30.0	4.77	off	6.5
124	31.0	4.79	off	6.5
124	31.5	4.80	off	6.5
124	33.0	4.82	on	6.5
124	33.5	4.82	on	6.5
124	36.5	4.81	on	6.5
124	37.75	4.79	on	6.5
124	38.25	4.77	on	6.5
124	39.0	4.75	on	6.5
124	39.5	4.74	on	6.5

The data in Table 8 were illustrated graphically in Fig. 8. The variation probably was due to gas layers that formed on the cooler targets rather than on the temperature of the target. Because of a power failure this phase of the experiment was not continued for sufficient time to determine whether the value 4.53 could be reached again.

DISCUSSION

The data in this paper indicated that there was a large dependence of δ on target surface conditions. The data compared in Table 1 illustrated the lowering of δ as the target surface was more thoroughly cleaned. It was not determined, however, that an ideally clean surface would not emit electrons. However, the data in Table 8 illustrated further how target conditions influence the secondary ratio. The increase of δ with an unheated target probably represented the influence of contamination of the surface due to absorption of gas and oils by the target at room temperature.

Initial experiments were made on brass not specially cleaned. Reproducible or stable results were difficult to obtain. Better reproducibility of results and of stability during measurements was found when the brass was cleaned by mechanical polishing and washed in organic solvents. A gold target was tried next because the target surface would not oxidize between the time it was cleaned and the time it was bombarded. The desired stability was not obtained with a gold target.

The data were grouped into the following categories:

- (1) Secondary electron ratio versus accelerator voltage for ions bombarding copper, gold, and molybdenum.
- (2) Comparison of δ for various materials.
- (3) Integral electron energy distribution for molybdenum, copper, and carbon.
- (4) Dependence of δ on target temperature.

Fig. 8 Dependence of secondary electron ratio on target temperature.

This research was undertaken to determine the factors and materials that would be most desirable to reduce secondary electrons in positive ion accelerators. The energy distribution of δ and the dependence of δ on accelerator voltage were also measured because the equipment could readily be used for these measurements. The dependence of δ on the temperature for brass was measured to demonstrate the effect of surface contamination under fixed target chamber conditions.

The integral energy distribution curves (Fig. 6 and 7) for copper, molybdenum, and carbon were quite similar to each other. Also the similarity of the curves to the saturation curve for a regular diode was quite apparent. The target chamber was essentially a diode but in this case the electrons were produced by bombarding particles rather than thermionically. Normally the plate current of a diode falls to zero at approximately zero plate voltage but the collector current was detectable in this experiment until the collector voltage was twenty-five to thirty volts negative. The electrons reaching the negative collector must therefore have received excess energy from the proton beam. Neglecting the work function of the target on the emission of electrons, the maximum energy of the secondary electrons was around twenty to thirty volts. The integral curves for the secondary electron energy distribution for protons bombarding molybdenum and copper were drawn smooth through the zero point. The bump in the data plotted at the zero point for these curves was interpreted as follows. The curves to the left of zero gave a measure of the secondary electron ratio of electrons that had an energy greater than or equal to the stopping potential (abscissa) times the electronic charge. This was an integral curve and therefore decreased monotonically as the voltage was made more negative. The bump indicated that there were more electrons that had an energy greater than several electron volts than electrons that had an energy greater than zero. This was impossible. The positive ions measured in the ratio $\frac{i_i}{i_p}$ flowed to the collector when it was negative.

When there was no potential difference between the target and the collector there was no ion current, i. e. many of the ions recombined and on the average as many of one sign as the other drifted to the target or collector. When the collector was positive the positive ions would drift to the target. This change of direction of the ion current accounted for the bump in the data. It was observed that the integral curve for protons bombarding carbon had no bump at zero collector potential. There was also no measurable ionization current for this part of the experiment.

The curves in Fig. 4 indicated that δ was dependent on the bombarding particle mass since the curves for H_1 , H_2 , and H_3 were different. The dependence, however, was probably due to the velocity of the bombarding particles, because the energy acquired by an interacting electron by the Bohr formula is

$$\frac{p^2}{2m} = \frac{2z^2e^4}{mv^2b^2}$$

where

v = velocity of ion

b = impact parameter

$\frac{p^2}{2m}$ = energy acquired by the electron

ze = charge of bombarding particle

m = mass of electron.

The mass of the bombarding particle did not enter into the above equation. Those electrons that acquired sufficient energy by the effect described in this formula to escape the surface of the target contributed the secondary electron current.

Several things can happen at the surface of the target to make it difficult to derive a general relationship between specific ion beam and secondary electron yield. First, the surface condition of the target which was not subject to a quantitative measure was an important factor in secondary electron yield. In addition to this, the diatomic and triatomic particles probably divided as they came into the potential field of the target. This gave a variety of combinations that could have produced secondary electrons. For instance, the triatomic ion could possibly break into two particles of masses one and two, where either part keeps the electrons or divides them. The triatomic particle could have separated into three particles, each with unit mass, with one or none carrying the electrons. It was found that a certain small number of protons sometimes carried two electrons and thus entered the target with a negative charge. The equipment was not designed to measure the results due to these separate effects.

The primary purpose of this experiment was to compare the secondary electron ratio for various materials. It was necessary to open the target chamber each time the target material was changed. It was difficult to reproduce the same pressure, target temperature, and accelerator voltage for each target. The pressure was reduced to about 10^{-6} mm Hg for each target and held at this pressure until stable results were obtained. The comparison of the δ 's for the different materials was made in the range of 126 to 131 kilovolts. The data listing the dependence of δ on accelerator voltage showed that no large changes due to accelerator voltages are to be expected over this five-kilovolt interval. Data were given for monatomic, diatomic, and triatomic hydrogen. The data were taken for various surface conditions which definitely influence δ . The metals, molybdenum and copper, were polished until they had a mirror finish. This was done in order to obtain more consistent data for the integral energy distribution curves. Although data were presented on unpolished copper and molybdenum, preliminary measurements taken on unpolished targets of these metals were considerably higher than for the polished target. The secondary electron ratio for brass was among the lower values of the materials not specially cleaned.

Thus, if an ion beam is to pass through an iris or similar opening where some of the ions will strike the edges of the construction material, the use of brass stock will not cause a significant increase of stray electrons in the system. Although δ for brass is not significantly higher than the ratio for other materials, other considerations may preclude its use.

Measurements were made in one case to illustrate the effect of target temperature on δ . The variation in δ was greater for materials not polished than for materials that were polished. No attempt was made to obtain extensive quantitative data because it was difficult to operate the linear accelerator for long periods of time at uniform conditions. The electrical power was interrupted at thirty-nine and one-half minutes which stopped the run listed in Table 8. The data in Table 8 were presented, however, because the dependence of δ on target conditions was well illustrated. When the target material was polished to a mirror finish, the variation in δ was slight and disappeared after the beam had been focused on the target for a few minutes if the target were heated.

The secondary electron yield was not highly dependent on the ion beam energy. Protons, ranging in energy from 23 kilovolts to 121 kilovolts, bombarding copper caused δ to change from 1.15 to 1.62. The ratio increased for protons on copper, molybdenum, and gold until the proton energy reached about 80 kilovolts. Then the ratio remained essentially constant up to 140 kilovolts. A slight decrease was noted at these higher voltages but accelerator limitations did not permit measurements at higher voltages to determine if this decrease would continue.

Fig. 4 (Secondary electron ratio versus accelerator voltage for ions bombarding copper) illustrated this leveling off with increased energy and indicated the possible velocity relationship. Data are graphed for monatomic, diatomic, and triatomic hydrogen over the same accelerating voltage range. The secondary electron ratio due to protons, which would acquire the greatest velocity of the three particles at a given voltage, reached a maximum and began to decrease. The ratio due to diatomic hydrogen appeared to have almost reached its maximum. The secondary electron ratio for the triatomic hydrogen which would have the smallest velocity at a given accelerator voltage was still increasing at 140 kilovolts.

The yield for a diatomic ion of energy, $2E$, was less than twice the yield for a proton of energy E . This was an indication that the simple picture of a diatomic hydrogen ion breaking up into two protons at the target, each of one half the original energy, and an electron did not apply here. This agrees qualitatively with the findings of Allen (6).

Multiplication of current due to secondary electrons served to enhance weak lines from the magnetic analyzer. A multiplication of proton current by a factor of four could be obtained with a carbon target. This multiplication was used to determine if any of the protons picked up two electrons, after being accelerated. The field of the magnetic analyzer was reversed and then the strength of the field increased until a line was found. This line was found for the same magnetic field strength as the normal proton beam, but represented a beam of negative charge. The line was very feeble and could be measured only with a carbon target which emitted approximately four electrons per ion bombarding the target.

There were several uncertainties in the experiment. The accelerator voltage, the collector voltage, and the bridge circuit contributed normal experimental errors. The accelerator voltage error was estimated to be five percent. The resistance boxes used in the bridge circuit were accurate to 1%. The bridge circuit galvanometer sensitivity was on the order of 10^{-8} amperes per millimeter deflection.

It was possible at a given instant and at a given accelerator voltage to detect a unit change in the ratio of the resistance boxes in the third decimal place. It was not normally possible, however, to duplicate the reading at a later time closer than a unit in the second decimal place. For this reason most of the data were recorded to the second decimal place.

Several systematic errors added to the uncertainties. The following phenomena were probably occurring in the target chamber to some extent:

- (1) The ions in the beam were combining or separating as they approached the target. This effect could have reduced the homogeneity of the beam in both charge and mass.
- (2) A certain percentage of the ion beam was probably scattered from the target. The scattered ions could have produced secondary electrons from parts of the target chamber other than the target.
- (3) Secondary electrons were probably produced at the collector by the original secondary electrons as they were collected. This would change the currents being measured.
- (4) Oxides or gas layers probably formed on the target surface. Because the production of secondary electrons is basically a surface phenomenon, these oxides or gas layers could have changed the results significantly.
- (5) Photoelectrons could have been produced if the beam produced light or if the beam spot on the target heated sufficiently to produce light. These electrons would have changed the current readings also.

It was not possible to determine the percentages error caused by these systematic errors. They were estimated by comparing this work to that of James Allen (7).

The measurements taken in this experiment compared favorably to those taken by Allen but were considerably lower than those taken by Hill, et al. (6). The conditions in Allen's experiment were more like the conditions reported in this report. In the case of protons bombarding copper at 120 kilovolts the data reported in this report differed from those of Allen by 1%. The systematic errors probably would have been a little different in Allen's experiment from this experiment because of different designs and conditions. It might be reasonable to assume then that except for a major factor not yet known that these systematic errors contributed an error of an order of magnitude of one or two percent.

Future work on secondary electron ratio experiments might be concentrated on some of the following points:

- (1) Increase the vacuum in the target chamber to 10^{-8} mm Hg,
- (2) More accurate beam energy measurements,
- (3) Use more sensitive equipment for current measurements,
- (4) Use a target which has been plated on a base right in the system,
- (5) Perform a magnetic analysis of the electron energy distribution,
- (6) Analyze the effects of polyatomic ions,
- (7) Redesign the target chamber to reduce possible systematic errors.

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