Secondary Emission by Positive Ion Bombardment

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The investigation was undertaken primarily to determine the ratio of the secondary electron current to the primary ion current, i_s/i_p, for mercury ions bombarding a mercury target. The beam constituted a source of continually renewed surface of the target material. By varying the electron accelerating potential in the ion source, the proportions of the various types of ions present in the beam were altered. Thus the influence of mercury ions having different charges upon the secondary electron yield was determined. Some work was also done with cadmium ions bombarding a cadmium target.

Singly charged mercury ions formed by electrons of up to 27 v in the ion source gave a secondary emission coefficient, γ, ranging from 1.2 percent at 4.2 kev to 4.8 percent at 9.2 kev. For electron accelerating potentials of 73 v, 110 v, and 430 v, ratios i_s/i_p were determined. At 430 v, i_s/i_p varied from 3.2 percent at 1.2 kv to 11 percent at 9.2 kv. Estimates were made of γ for Hg^{2+} and Hg^{3+} ions.

In the case of cadmium, the electron accelerating potential was maintained at 450 v. Here i_s/i_p was exceedingly high for an untreated target, varying from 35 percent at 1.5 kv to 190 percent at 7.3 kv. Renewing the surface of the cadmium target by an additional source of cadmium vapor resulted in some reduction of i_s/i_p.

INTRODUCTION

THE summary of earlier studies by Massey and Burhop[1] indicates that the secondary electron coefficient has been determined for light, slow-moving ions bombarding a variety of targets. More recently Hagstrum[2] has discussed certain discrepancies in some of the previous work. However, in contrast to light ions. there have been few attempts to use heavy, slow-moving ions. Linford[3] has bombarded many targets with high-speed mercury ions; however, no systematic study has been made hitherto with slow-moving mercury ions.

Although Bruining and deBoer[4] measured the secondary emission due to primary electrons for alkali metal surfaces on which new material was constantly condensed from the vapor phase, there appears to be little evidence in the literature of attempts to use ions and target materials of the same element.[5] This affords a means of reducing the influence of contamination of the target material. As a consequence, this investigation was undertaken with mercury ions bombarding a mercury target and with cadmium ions bombarding a cadmium target.

APPARATUS

The experimental tube is shown in Fig. 1. At A, a sample of especially pure mercury metal of instrument grade was introduced. After the tube was evacuated, the mercury served as a source of mercury vapor. The filament B, a thin tungsten spiral, was supplied with current by several storage batteries, controlled by a rheostat and indicated on an ammeter. All the electrodes were made of nickel. Electrode C, a disk of large aperture, was approximately 110 volts positive with respect to the filament B. This voltage was maintained by using a selenium rectifier and filter. By means of this arrangement, the electrons thermionically emitted by the filament were accelerated toward electrode C. The electrons, colliding with the mercury vapor in the evacuated tube, ionized some of the mercury. The ion and electron beams were separated by the presence of electrode D, a disk with a central aperture approximately 5 mm in diameter. Electrode D was made about 200 volts negative with respect to electrode C.

The main accelerating voltage was controlled by using a high-tension power supply of conventional design, filtered by a condenser of large capacity. By means of this supply, a range of voltages extending to 10 kilovolts was readily obtained. This voltage appeared across a system of two electrodes, the upper one being electrode D and the lower one, electrode E. No attempt was made to produce a sharply focused beam. However, the presence of the cup J filled with dry ice and acetone assisted the formation of an ion beam and prevented the mercury discharge from penetrating into the lower parts of the tube.

The electrodes F, G, and H and the mercury pool I constituted the collecting system. The uppermost electrode F had an aperture approximately 5 mm in diameter. Immediately below it was electrode G with an aperture roughly 12 mm in diameter. This electrode shielded the collecting cylinder H from the direct effects of the positive ion beam. The cylinder was about 2.5 cm long and 5 cm in diameter.

To maintain the voltages on the electrodes comprising the collecting system, dry cells of 22.5 and 45 volts mounted on insulating bases, were used. Relative to ground, electrode E was 45 volts positive, electrode F was at zero potential, electrode G was 45 volts negative, the collecting cylinder H was at zero potential, and the mercury pool was 22.5 volts negative. It had pre-

[1] H. S. W. Massey, and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Clarendon Press, Oxford, 1952).
[2] H. D. Hagstrum, Phys. Rev. **89**, 244 (1953).
[3] L. H. Linford, Phys. Rev. **47**, 279 (1935).
[4] H. Bruining, and J. H. deBoer, Physica **5**, 17 (1938).
[5] Y. A. Dunaer, and I. P. Flaks, Compt. rend. acad. sci. (U.R.S.S.) **91**, 43 (1953).

viously been found by using variable power supplies that a wide range of voltages could be employed without influencing the measurements. The only precaution necessary was the maintenance of the correct relative polarity between adjacent electrodes.

The following precautions were taken. The lower part of the tube was surrounded with a Faraday cage to reduce induced currents which might have been detected with the sensitive dc microammeters used for the measurement of both the target and collector currents. In order to obtain reproducible readings, it was found necessary to freeze the mercury target. Otherwise, the ion beam colliding with the mercury vapor in the vicinity of the target caused ionization which vitiated the results.

The tube was aligned so that light from the filament illuminated an area of the target. An Alnico magnet was used to neutralize the results of stray fields so that the ion beam passed through the aperture in *E*.

The vacuum system was of a simple and conventional design. The apparatus was exhausted to a pressure below 10^{-6} mm Hg by a two-stage mercury diffusion pump backed by a Cenco Presso-Vac pump. The vacuum system was provided with the usual liquid air cold traps. In addition, a large U-shaped cold trap could be maintained throughout the night by filling a large vacuum flask with dry ice and acetone. The gas pressure was read by an RCA type 1949 hot-cathode ionization gauge. The entire system had only one stopcock and this was placed on the high-pressure side of the diffusion pump.

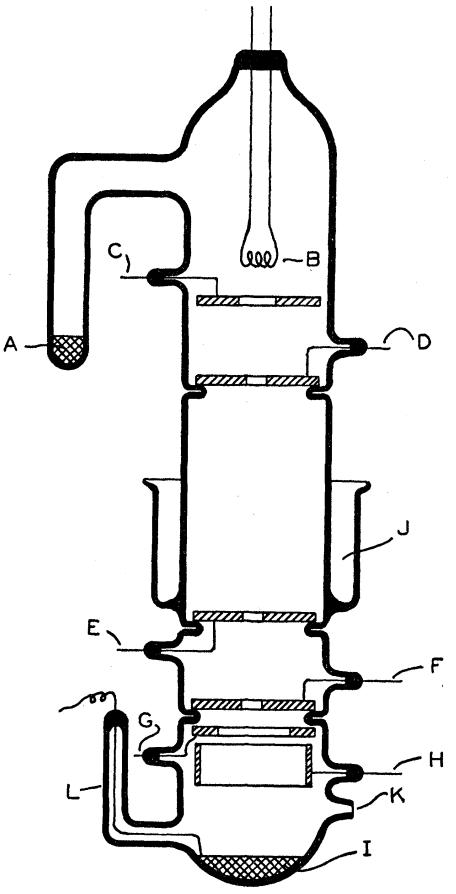

FIG. 1. Electronic tube.

MERCURY EXPERIMENT

Clean instrument mercury was put into the target receptacle I and into the reservoir *A* of the ion source. The system was evacuated to a pressure in the order of 10^{-6} mm Hg of permanent gas pressure as indicated by the ionization gauge. The filament in the ion source was then heated. This resulted in a sudden increase in the permanent gas pressure. However, within an hour the vacuum returned to about 10^{-6} mm Hg. The switches between the filament and the electrode *C* and that between *C* and *D* were then closed. The resulting electron and ion bombardment again resulted in an increase in pressure. After several hours, however, the pressure was restored. It was possible by continuous pumping over a period of several days to obtain readings with a permanent gas pressure of less than 10^{-6} mm Hg. The readings reported were obtained under these conditions.

The accelerating potential was initially set at 4 kv, and within 10 minutes or so the meters attained stable readings. Prior to this period, the readings were somewhat higher than the final values. Examination of the target revealed that a fresh clean spot of mercury, located in an essentially central position, appeared on the surface of the frozen target. From this fact, it might be inferred that the mercury ions were constantly being deposited in sufficient amount to keep the bombarded portion of the surface relatively fresh and free from adsorbed gas.

In view of the positive ion analysis of mercury by Bleakney,[6] it was decided to determine i_s/i_p for electron accelerating potentials other than 110 ev. In order to insure that the changes in the ratio constituted a real effect, it was usually customary to take alternate readings at two different electron accelerating potentials throughout the energy range. This was not done for the 27-ev case. However, each set of readings in this case was immediately followed by a set of readings of the 110-v case. Finally it is to be noted that for the two lower electron accelerating potentials, the voltage on electrode *D* was made only 30 to 90 volts negative with respect to the voltage on electrode *C*.

RESULTS AND CONCLUSIONS

Figure 2 indicates the ratios of i_s/i_p for mercury ions bombarding a mercury target. The mercury ions were produced by electrons with maximum energy of 110 ev. The trend of the curve is essentially linear with in-

[6] W. Bleakney, Phys. Rev. **35**, 139 (1930).

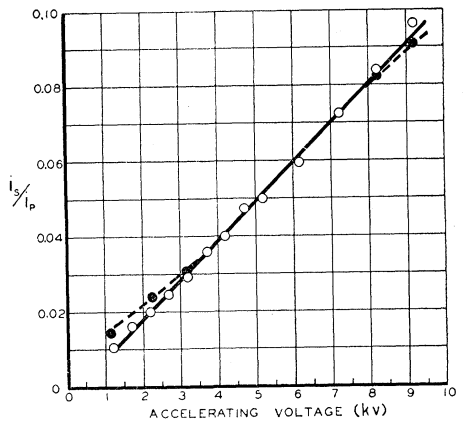

FIG. 2. Variation of secondary to primary current, i_s/i_p, with applied ion voltage for Hg ions on Hg. Solid line indicates original data. Dashed line indicates recent data with increased ion current.

creasing ion energy. A slight departure from linearity occurs at low energies. The dashed portions of the curve were obtained most recently. The ion beam was somewhat more intense and, therefore, permitted a more accurate determination of i_s/i_p at the low-energy end. The ratio varies from 1.5 percent at 1.2 kv to about 9.2 percent at 9.2 kv.

Figure 3 indicates the ratios of i_s/i_p when the electron accelerating potentials varied. Variations in the accelerating potentials cause changes in the types of mercury ions bombarding the target. Below about 30 ev the ions are singly-charged. From about 30 ev to 71 ev doubly-charged ions occur as well as singly-charged ions. At 110 ev a small percentage of triply-charged ions appear in the beam. Electron energies of 430 ev give rise to ions of four or five charges. The curves indicate the changes in the ratio for electron accelerating potentials of approximately 27, 73, 110, and 430 v, respectively. With increasing electron accelerating potential, i_s/i_p increases. Thus, at 4.2 kv, the value of i_s/i_p changes from 1.2 percent at 27 v to 5.8 percent at 430 v. At 9.2 kv, the effect is somewhat less pronounced, changing from 4.8 percent at 27 v to 11 percent at 430 v. It is to be noted, further, that at 27 v i_s/i_p is identical with γ for singly-charged mercury ions.

From the data indicated in Fig. 3, it is possible to estimate γ for Hg^{2+} and Hg^{3+} ions. The estimates, while admittedly rough, are significant in that they indicate a trend. The following consideration shows the procedure for obtaining γ for Hg^{2+} ions. A similar procedure determines γ for Hg^{3+} ions.

Let N=the number of electrons ejected by one singly-charged ion at a specified voltage, x=the number of electrons ejected by one doubly-charged ion at the same voltage, a=the fraction of singly-charged ions in the primary beam, b=the fraction of doubly-charged ions in the primary beam, and i_s/i_p=the measured ratio of the secondary electron current to the primary ion beam. Then, it follows that

$$\frac{i_s}{i_p}=\frac{aN+bx}{a+2b}.$$

From the results of Bleakney, a and b are known for each specified electron voltage. The experimental results for singly-charged ions indicated by the 27-v curve in Fig. 3 determines N. Further, i_s/i_p is given by the 73-v curve. Therefore, x can be evaluated.

The results of the analysis are shown in Table I, and the meaning of the entries can be explained as follows. Column I gives the applied voltage used for ion acceleration. For doubly-charged and triply-charged ions, the kinetic energy in kev is obtained by multiplying the applied voltage by a factor of two and three respectively. Column II gives the experimental results for Hg ions. Column III gives the calculated results for Hg^{2+} ions. A significant defect in the analysis is the fact that we have applied Bleakney's results for the efficiency of production of ions by electrons of a single energy to the electrons in the present experiment having all values up to the specified voltage. As a consequence, we somewhat underestimate the fraction of singly-charged ions. The importance of this consideration is reduced by the fact that electrons of higher energies are more effective in the production of ions and at 73 volts it is somewhat compensated by the fact that there will be a small trace of triply-charged ions and these ions have been excluded from the calculation of γ for Hg^{2+} ions. Also the fractions corresponding to 70 ev were read from Bleakney's data, tending to correct further for the above.

Column IV gives the value of γ for Hg^{3+} ions under the assumption that the composition of the beam is determined by electrons of 110 ev. However, since the range of voltages is greater in this case, there will be a more serious underestimation of the percentage of singly charged ions in the primary beam. Column V gives the values of γ for Hg^{3+} ions, if the effective electron potential is assumed to be 100 ev. While this

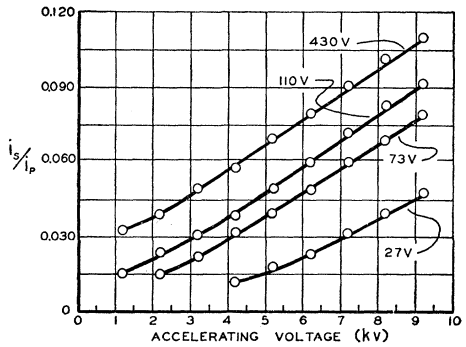

FIG. 3. Variation of secondary to primary current, i_s/i_p, with applied ion voltage for Hg ions on Hg for different electron accelerating potentials.

choice is arbitrary, it should be somewhat closer to the actual state of affairs in view of the above discussion. Further, the estimate of γ for Hg^{3+} ions is least accurate in view of the very small percentage of triply charged ions in the beam. The decrease from 1.2 to 0.96 when the energy is raised by increasing the potential difference from 8.2 to 9.2 kv is believed to represent experimental error rather than an actual decrease in the secondary emission coefficient.

According to Bleakney's results, the ionization potentials of Hg^{+}, Hg^{2+} and Hg^{3+} ions are approximately 10.4, 30, and 71 v. Columns II, III, and V show roughly that the values of γ increase with increasing ionization potential. This inference is born out by other experiments[2,7,8] in the low-energy range, and it has a theoretical interpretation since it implies that more potential energy from ions of higher charge is available to electrons of the metal for surmounting the potential barrier at the surface.

CADMIUM EXPERIMENT

Identical apparatus and similar procedures were adopted in the cadmium experiment. The sidearm A was filled with bits of cadmium metal. The target was composed of three thin cadmium disks backed by nickel for rigidity. It was found necessary to bring the filament closer to electrode C and to apply an electron accelerating potential of 450 v in order to generate ions.

In view of the high ratios in the case of cadmium, it was decided to study the nature of the surface before and after cadmium had been evaporated onto the target. Continued evaporation and pumping gradually brought the values down and these were remaining essentially constant by the fourth day. Finally, readings were also taken when mercury vapor diffused into the electronic tube from the mercury diffusion pump, after the removal of the cold trap.

TABLE I. Variations of γ with ionic charge for different applied ion voltages.

Applied ion voltage (kv)	Hg (experimental)	Hg^{2+} (corrected)	Hg^{3+} (uncorrected)	Hg^{3+} (corrected)
4.2	0.012	0.22	0.14	0.71
5.2	0.018	0.26	0.18	0.82
6.2	0.023	0.30	0.27	1.0
7.2	0.032	0.34	0.30	1.1
8.2	0.040	0.38	0.30	1.2
9.2	0.048	0.42	0.12	0.96

[7] M. L. E. Oliphant, and P. B. Moon, Proc. Roy. Soc. (London) **127**, 388 (1930).
[8] R. C. Bradley, Phys. Rev. **93**, 719 (1954).

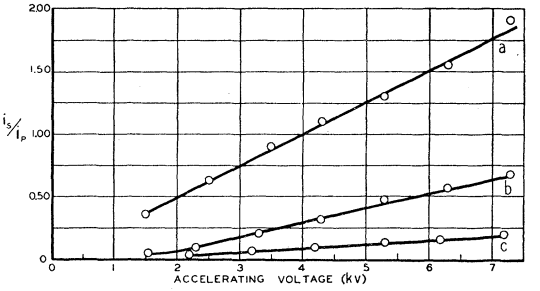

FIG. 4. Variation of secondary to primary current, i_s/i_p, with applied ion voltage for (a) untreated Cd ions on Cd, (b) Cd ions on evaporated Cd, and (c) a mixture of Hg and Cd ions on Cd with Hg present on Cd surface.

RESULTS

Figure 4 compares three different sets of data. The upper curve (a) gives the yield for an untreated cadmium target without evaporation. The yields were surprisingly high. At 1.5 kv the value of i_s/i_p is 35 percent, and at 7.3 kv it rises to 190 percent. The middle curve (b) shows the much lower ratio obtained for cadmium after evaporation. The lower curve (c) shows the further decrease in i_s/i_p when mercury diffused into the tube.

On the basis of energy and ionization potential or velocity[9] and ionization potential the results of cadmium and those of mercury should not differ to any considerable extent. It would appear that the difference must arise due to a marked difference in surface conditions.

SUMMARY OF RESULTS

The results may be summed up as follows. For a specific source of ions bombarding a specific target, the results can be understood in terms of the influence of velocity and the ionization potential of the incident ions. For ions of low energy, the ionization potential would appear to predominate in determining the secondary yield. As the energy of the ions increases, the influence of the ionization potential continues to manifest itself, although to lesser extent. The velocity factor eventually should mask the ionization potential.

In comparing two different targets, the nature of the surface of each has to be considered. Our results confirm the fact that in positive ion work, the secondary electron yields are extremely sensitive to the presence of traces of impurities adsorbed on the surface. In this work it is especially important to find a means of renewing the surface, and, thereby, of obtaining yields approaching those characteristic of the target material.

[9] W. Ploch, Z. Physik. **130**, 174 (1951).