Kinetic Secondary Electron Ejection from Molybdenum by Cesium Ions*

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Secondary electron emission yields have been measured for cesium ions on clean molybdenum as a function of ion kinetic energy for two angles of incidence. For the two incidence angles measured 0 and 40°, the energy threshold was the same, approximately 2 keV. From this threshold there was a quadratic rise in the values of γ_i (the number of secondary electrons per incident ion) with an increase in energy up to 5.5 keV. From then on, the values of γ_i were a linear function of ion energy up to 15 keV, where they were 0.55 and 0.69 for the 0 and 40° angles of incidence, respectively. The values of γ_i for the 40° angle of incidence were always greater than those for normal incidence by the factor of sec 40°, i.e., 1.3. The targets were atomically cleaned by flashing at 2000°C. All measurements were taken with ambient pressures less than 5×10^{-8} Torr.

BECAUSE of the common use of cesium in the study of plasmas and as a propellant in ion propulsion, there has been an increased interest in the collision phenomena of cesium ions with solids, particularly metals. These phenomena are sputtering, ion reflection, neutralization, and secondary electron emission. In this paper the results of a study of kinetic electron emission for cesium ions with energies of 1 to 15 keV are reported.

The energy necessary for the ejection of electrons from a metal by the impact of an ion can have its source in either the potential or the kinetic energy of the incident ion. For the potential energy of the ion to contribute to the production of secondary electrons, called potential ejection, the ionization potential of the ion must be at least twice the work function of the metal. This process has been studied extensively both experimentally and analytically, mainly by Hagstrum.[1–4] The features of the process are: (1) It is a direct ion-conduction electron interaction; and (2) the electron yields are essentially not dependent on the ion kinetic energy, but rather on the difference between the ionization potential of the ion and the work function of the metal. When the kinetic energy of the ion is used in the creation of secondary electrons and the yields are energy-dependent, the process is called kinetic ejection. Not as much effort has been spent studying this phenomenon. Experimentally (Waters,[5] Petrov,[6] and Brunnee)[7] the data are not conclusive; theoretically (Von Roos[8] and Parilis and Kishinevskii[9]) the data are incomplete, giving only qualitative information. The features of the kinetic ejection process are: (1) it is an ion-lattice atom interaction; (2) it exhibits a threshold energy E_t for the creation of secondary electrons; and (3) the electron yield increases linearly for the most part with an increase in ion energy above E_t. The threshold energy is directly related to the mass of the ion; the greater the mass the higher the E_t. Consequently, the greater the ion mass, the lower the electron yield. According to Parilis and Kishinevskii,[9] the threshold point is not an energy threshold but an ion velocity threshold.

If ions with sufficiently high ionization potentials (such as the noble gas ions) are given kinetic energy in excess of 1 or 2 keV, the electron yield can be from the combination of the two processes. Since the work function of molybdenum, 4.2 eV, is greater than the ionization potential of cesium, 3.98 eV, the electron yields measured in this experiment are from the kinetic ejection phenomenon only.

The presently available data on the number of secondary electrons per incident ion γ_i for cesium on polycrystalline refractory metals vary from investigator to investigator. Each one is self-consistent and produces self-reproducible measurements but shows little or no agreement with any other. Waters[5] measured γ_i for 0.15 to 1.5 keV cesium on tungsten and found that in this entire energy range the probability of secondary emission always existed even though it was vanishingly small for the low energies. Petrov[8] studied cesium on molybdenum in the same energy range. His yields were considerably higher, but he did measure an energy threshold of approximately 0.2 keV. Brunnee[7] made extensive measurements of γ_i and related phenomena for alkali ions on molybdenum in the energy range of 0.4 to 4 keV, essentially finding a higher threshold energy of ~1.5 keV and therefore lower electron yields for cesium on molybdenum. Previous work by the author[10] on kinetic ejection for cesium ions up to 20 keV on tungsten gave an extrapolated value of 2.5 keV for E_t; otherwise the results agree well with those of Brunnee in the energy range common to both measurements.

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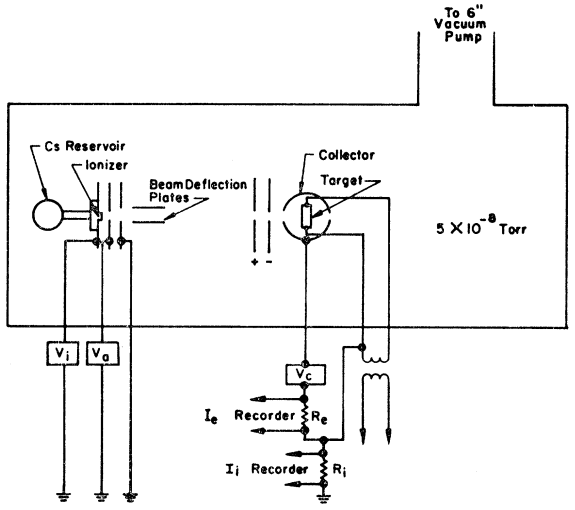

FIG. 1. Schematic diagram of apparatus.

It is permissible to compare the results of measurements of γ_i for cesium on different refractory metal surfaces such as molybdenum and tungsten, since it has been found experimentally[6,11] that the target material has little influence on electron yields in kinetic ejection.

Secondary electron yields are very sensitive to the adsorption of ambient gases on the target surface. This has been demonstrated by Hagstrum[2] in potential ejection, and by Waters[5] and Arifov[11] in kinetic ejection. In the study of kinetic ejection using alkali ions, there is the added problem that the neutralized ions on the target surface can drastically affect the data. These problems have led to ingenious and sometimes complicated methods of measurement, prolonged and exhaustive target cleaning procedures, and the use of ultra-high vacuum equipment.

A schematic representation of the apparatus used in this experiment, with the secondary emission detector, beam deflection plates, and ion source within a vacuum chamber is shown in Fig. 1.

The secondary emission detector consists of a target made of 0.002-in. thick pure molybdenum filament and a cylindrical collector with slits in front and rear. The latter allows higher pumping speed around the target. The size of the active area of the target, determined by the collimation of the ion beam, is 0.5 by 1 cm. The nickel rods holding the filament position the target at different angles of incidence for the ions. The target can be flashed by direct resistance heating. Biased slits are situated in front of the collector. They collimate the beam, prevent the escape of secondary electrons that are ejected towards the front opening, and extract electrons that may be in the beam. The edges of the slits are chamfered, and the slits become progressively larger from the first slit to the collector in order to prevent the production of extraneous electrons by the ion beam. An electrostatic shield (not shown in Fig. 1) made of copper screen and connected to the negative, slitted gate surrounds the collector, to shield it from stray electrons and ions. The values of the incident ion and secondary electron currents are obtained by measuring the voltage drops across precision resistors. These are read out on a two-channel chart recorder. The collector potential is provided by a 0 to 300 V dc voltage supply in conjunction with a polarity switch.

The cesium ions are produced by a surface ionization ion source using a back side-fed porous tungsten ionizer operating at 1000 to 1200°C. This source can generate up to 5 mA of cesium ion current with a maximum current density at the target of approximately 1 to 2 mA/cm^2. The magnitude of the ion current is controlled by electrical heaters on the cesium reservoir. The reservoir is also equipped with cooling coils for further control of the temperature, especially during bake out. The cesium is greater than 99.5% pure with the major impurity being rubidium.

The fraction of neutral cesium atoms for the currents used in this experiment was less than 0.01. This represents a neutral cesium incidence rate corresponding to monolayer adsorption times of greater than 5 h. All measurements were taken with low ion-current densities of 1 to 10 μA/cm^2. The singly charged cesium ions, accelerated by the three-electrode structure, are monoenergetic except for their thermal velocity distribution. The ions are accelerated and slightly focused by the accelerating and decelerating electrodes situated directly in front of the ionizer.

Two pairs of electrostatic deflection plates are in turn situated in front of the electrodes. They position the ion beam directly on the target and also deflect it away when the target is being cleaned.

The vacuum chamber is a 1-ft. diam stainless-steel cylinder 3 ft. in length. It is pumped by a liquid-nitrogen trapped silicon-oil diffusion pump. The chamber can be baked to 300°C with either an oven or strap heaters for the outgassing phase of the pump down. Copper gaskets are used on all flanges. A liquid-nitrogen liner within the chamber is used to freeze out all condensibles. It is baked out by passing hot gas through it. The pressure is measured with a Bayard–Alpert-type ionization manometer. The system is capable of pressures lower than 1×10^{-9} Torr if proper care and techniques are used.

The bake out and pump down of the vacuum system is a two-step process. Initially the chamber, cold trap, and baffling are baked out at 250–300°C for approximately 12 h with only the fore pump in operation. Next, the cold trap and baffling are cooled with liquid nitrogen and the diffusion pump is started. An addi-

[11] U. A. Arifov and R. Rakhimov, Transactions of the Ninth All Union Conference on Cathode Electronics, Moscow, 1959 (unpublished).

tional 12 h is required to reach the desired pressure with the target, ionizer, and chamber hot. During this second stage of the pump down to the low 10^{-8} Torr range, the molybdenum filament is heated continuously at about 1500°C (with occasional flashes to 2000°C), and the ionizer is baked at approximately 1350°C. Up until the time of measurement, the cesium reservoir is cooled by passing cold gases through the cooling coils. This prevents the cesium from evaporating and escaping into the vacuum system.

The procedure used in measuring γ_i is a modification of Petrov's dc ion-pulse method. The cesium ion beam is deflected off the detector while the target is being flash-cleaned for 10 sec at 2000°C. During this time the collector is held at a negative potential so that it may collect any positive ions evaporated from the surface. Three to four seconds after flashing, when the target has cooled to below thermionic emission temperatures, the collector potential is switched to a +60 V and the chart recorder is started. Two seconds later the ion beam is pulsed onto the target. The primary ion current and secondary electron currents are recorded continuously. If desired, the beam can be deflected off the target to insure that the zeros of the ion and electron currents have not shifted. This procedure is carried out for each data point as the ion energy and angle of incidence are changed.

The flashing temperature of the target was chosen because of the results of Hagstrum[4] with his extensive work on producing atomically clean surfaces. The use of higher temperatures did not accomplish anything except to shorten the life of the filament. The temperature was measured with an optical pyrometer.

The collector potential of a +60 V was chosen somewhat arbitrarily after measurements showed that the value of γ_i did not vary with a change in collector potential from 20 to 80 V.

The instant that the beam strikes the target, the values of the incident ion and secondary electron currents, I_i and I_e, rise from their zero values to their initial values. These zero-value currents are due to insulation leakage caused by a cesium film which builds up on them as measurements are taken. The ratio of these initial value increments was taken to be γ_i for clean molybdenum. There is little observed variation in I_i with time, but I_e immediately begins to increase steadily until a saturation value is reached (see Fig. 2). Not only is the initial γ_i for a clean surface reproducible, but so is the final γ_i for a cesiated surface if sufficient time is allowed.

The values of γ_i for an equilibrium cesiated surface are not given here. The percentage coverage of cesium on the molybdenum surface for these γ_i's is not known, and therefore the data were judged to be inconclusive. A calculation of an approximate value for the coverage was attempted by multiplying the incident ion current by the time needed for a saturation value of γ_i to be

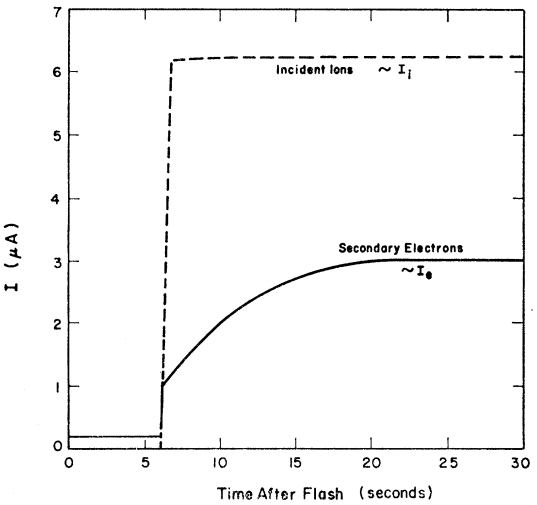

FIG. 2. Typical primary ion and secondary electron currents as functions of time. 6 keV Cs^+ on Mo.

reached to obtain the number of ions impacting on the target, and then correlating this with the number of cesium atoms per unit area for monolayer coverage, the assumption being that all ions adhered to the surface. Any other assumption was improbable because it was not possible to estimate nor measure the sputtered neutral cesium. The results were not consistent. Low ion-energy values gave coverages close to a monolayer for the equilibrium condition. However, higher kinetic-energy ion values for coverages were greater than a monolayer. This is a strong indication that the higher energy incident ions sputter cesium adatoms from the molybdenum surface. Another argument supporting this is that although γ_i for clean surfaces is a linearly increasing function of ion energy, for cesiated surfaces it increases at a declining rate. This may be explained by the supposition that the equilibrium surface coverage decreases with an increase in energy because of the higher sputtering rates of the higher energy ions.

In conjunction with this the author believes that many of the secondary electrons come from the adsorbed cesium rather than directly from the target, even though the work function of the surface is reduced drastically by cesium coverage. The work function of cesium alone is very low, 1.9 eV, and because of the equality of the masses of the impacting particles there can be a maximum transfer of energy to the cesium on the surface.

Since all measurements were taken with a total background pressure less than 5×10^{-8} Torr, it is believed that the 5- to 8-sec delay from the cessation of the target heating current to the time when the ion beam is pulsed onto the target does not allow time for the ambient adsorable gases to appreciably adsorb on the target surface. Approximate monolayer adsorption times can be obtained by extrapolating values

measured[12] for pressures close to those used in this experiment. This gives times of about 2.5 to 3 min. A quick measurement showed that the adsorption time for the target filament in the low 10^{-8} Torr range was greater than 100 sec. This gives a maximum value for surface coverage of less than 8%. The author is of the opinion that this is the worst condition and that the average value is approximately 4%. More accurate adsorption times were not attempted because it would have required modification of the detector and manometer. The accepted values were considered sufficiently accurate.

The results of these measurements are shown in Fig. 3. In agreement with other measurements, a threshold energy for the production of secondary electrons was measured although it was a little higher than previous values, approximately 1.8–2.0 keV. This E_t was the same for both 0 and 40° angle of incidence. From E_t the γ_i's rose quadratically with an increase in energy up to 5.5 keV where they became linear functions of energy with $\partial\gamma_i/\partial E$'s of 0.046 and 0.061 electrons per ion per keV for 0 and 40° angles of incidence, respectively. Ion energies below 1.8 keV produced no secondary electrons. The method of measurement and the equipment used would be capable of measuring a γ_i accurately down to about 0.005.

Figure 4 presents the data obtained here for normal incidence in comparison with other measurements. The threshold energy agrees well with the measurements of Brunnee[7] and the theories of Von Roos[8] and Parilis and Kishinevskii.[9] The quadratic rise of γ_i followed by a linear increase is also in agreement with Von Roos[8] and Brunnee.[7] Although Brunnee did not take measurements with sufficiently energetic cesium ions to get to the linear portion of the data, he did so with sodium and potassium ions and these show the same general relationship. The measurement of γ_i for two angles of incidence cannot sufficiently determine the relationship of γ_i with the angle of incidence θ, but it did show agreement with the predicted equation, $\gamma_\theta=\gamma_0 \sec\theta$. The values of γ_i for the 40° angle were 30% greater than for normal incidence throughout the entire energy range.

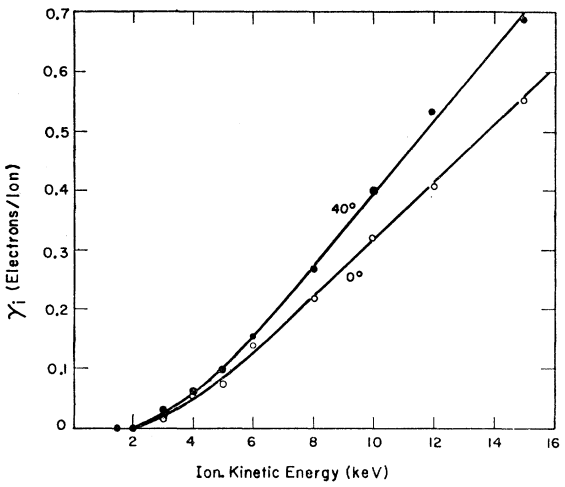

FIG. 3. Secondary electron yields as a function of cesium ion energy for 0 and 40° angles of incidence.

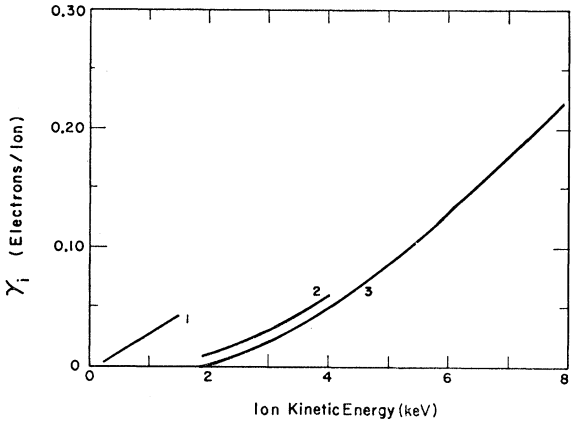

FIG. 4. Comparison of measured values of γ_i for Cs^+ on Mo as a function of ion energy. 1-*N*. Petrov; 2-*C*. Brunnee; 3-present data.

Because of the very low threshold energy of 0.2 keV and the higher electron yields, the author considers that the data of Petrov are not for a clean surface. The relatively high pressure, 10^{-6} Torr, which he uses, does not permit him the 2 to 3 sec he uses in making a measurement.

It is hoped that further measurement of γ_i and related phenomena can be made for cesium ions on a variety of surfaces, in particular on a cesium surface, for a better understanding of these ion impact interactions.

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[12] P. Mahadevan, J. Layton, and D. Medved, Phys. Rev. **129**, 79 (1963).