TABLE I. Experimental slopes from Figs. 2 and 3 and corresponding values of α.

Reflection	μt	Slope	α
220	21.71	-2.48×10^{-3}	0.99_9
220	29.08	$-3.39_5\times10^{-3}$	1.02_7
400	20.92	$-4.65_6\times10^{-3}$	1.02_7
400	30.95	-6.85×10^{-3}	1.01_8

It can be seen from the table that a single value of $\alpha=1.01\pm0.015$ will fit the measurements for the four crystals. This is in contradiction to the results in (I) which were subject to error due to thermal gradients in

the specimens perpendicular to the diffracting planes. These results now substantially agree with Okkerse's and indicate that Debye-Waller factor for germanium diffracting in the symmetric Laue case is very close to e^{-M}. This, coupled with the same experimental temperature dependence for symmetric Bragg reflection,[5] suggests that in general the Debye-Waller factor for perfect crystals is e^{-M}. This should not, however, be taken as proof of its general validity without further experiments and the development of a sound theoretical treatment of thermal vibrations in an absorbing perfect crystal.

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[5] B. W. Batterman, Phys. Rev. 127, 686 (1962).

Kinetic Secondary Electron Ejection from Tungsten by Cesium Ions*

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Initial measurements of the number of electrons ejected per incident ion, γ_i, have been made for medium-energy (1–21 keV) cesium ions at normal incidence on a clean polycrystalline tungsten surface. The residual gas pressure was $\leq5\times10^{-9}$ Torr. The tungsten surface was cleaned by prolonged bakeouts and by flashing before each measurement. A dc ion-beam pulse method of measurement was used to prevent cesium coverage of the tungsten surface. In the energy range of 3–21 keV γ_i is a linear function of the ion kinetic energy with $\partial\gamma_i/\partial E\simeq0.04$ electron per ion per keV. At 3 and 21 keV γ_i is 0.02 and 0.74, respectively. If the data are extrapolated to $\gamma_i=0$, a threshold energy of 2.5 keV is obtained. Below this energy the measured values of γ_i were equal to zero within the accuracy of the measurement. The change of γ_i with cesium adsorption on the tungsten was also recorded.

U SE of cesium as propellant in ion propulsion has increased the interest in the interaction of medium-energy cesium ions with solids. One of the interactions in which there has been a basic as well as a practical interest is that of the kinetic ejection of electrons from metals due to the bombardment of cesium ions. In the energy range of interest, 1–20 keV, there is little published data. Waters,[1] measured secondary electron yields for low-energy (150–1500 eV) cesium and lithium ions on tungsten. Arifov et al.,[2] and Petrov[3] have published data for alkali ions up to 10 keV impinging on various metals. In the energy range of 1–4 keV Brunnee[4] has measured γ_i for the alkali ions on molybdenum.

No close agreement exists among published values. This paper presents the measured yields of secondary electron emission from clean polycrystalline tungsten by normally incident cesium ions of energies of 1–21 keV.

Since the ionization energy of cesium, 3.87 eV, is less than the work function of clean tungsten, about 4.5 eV, the electron yields presented are due to the kinetic ejection process only and not to the Auger or potential-ejection[5] process. The apparatus used is shown in Fig. 1.

The vacuum chamber is a stainless-steel cylinder, 3 ft in length with a diameter of 1 ft. It is pumped by a liquid-nitrogen trapped, 6-in. silicon oil diffusion pump. The chamber can be baked to 300°C with either an oven or strap heaters. Copper gaskets are used for all flanges. Within the tank a liquid-nitrogen liner is used to freeze out all condensibles. It can be baked out by passing hot gas through it. Pressure is measured with a Bayard-Alpert type ionization gauge. The system is capable of pressures lower than 1×10^{-9} Torr if proper care and technique are used.

The cesium ions are produced by a surface-ionization ion source using a porous tungsten ionizer operating at 1000–1200°C.[6] This source can generate up to 5 mA of cesium ion current with a maximum current density at the target of approximately 1–2 mA/cm². The fraction of neutral cesium atoms for the currents used in this

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[1] P. M. Waters, Phys. Rev. 111, 1053 (1958).

[2] U. A. Arifov and R. R. Rakhimov, Transactions of the Ninth All Union Conference on Cathode Electronics, Moscow, 1959 (unpublished), p. 666.

[3] N. N. Petrov, Fiz. Tverd. Tela 2, 949 (1960) [English transl.: Soviet Phys.—Solid State 2, 865 (1960)].

[4] C. Brunnee, Z. Physik 147, 161 (1957).

[5] H. Hagstrum, Phys. Rev. 96, 336 (1954).

[6] G. Kuskevics and B. Thompson, AIAA J. 2, 284 (1964).

experiment was less than 0.01. This represents neutral cesium incidence rates corresponding to monolayer adsorption times of greater than five hours. All measurements were taken with low ion-current densities of approximately 10 μA/cm^2. The singly charged cesium ions, accelerated by the three electrode structures are monoenergetic except for their thermal velocity distribution.

The secondary electron emission detector consists of the target made of 0.003-in.-thick tungsten filament, and a cylinder collector with slits in front and rear. The latter allows higher pumping speed around the filament. 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 toward the front slit, and extract electrons that may be in the ion beam. The edges of the slits are chamfered and the width of the slits becomes progressively larger from the first slit to the collector. The values of the incident ion and secondary electron currents are obtained by measuring the voltage drop across precision resistors. These are read out on a Westronic two-channel chart recorder. The collector potential is provided by a dc voltage supply in conjunction with a polarity switch.

During the bakeout and pump down of the vacuum system to the 10^{-9} Torr range (approximately 24 h) the tungsten filament is heated continuously at about 1600°K. The procedure used in measuring is a modification of Petrov's dc pulse method.[3] With the ion beam deflected off of the detector the target is flashed for 15 sec at approximately 2300°K with the collector at a negative potential so that it collects any positive ions evaporated from the surface. Three to four seconds after flashing when the target has cooled below thermionic emission temperatures, the collector potential is changed to a +45 V and the chart recorder is started.
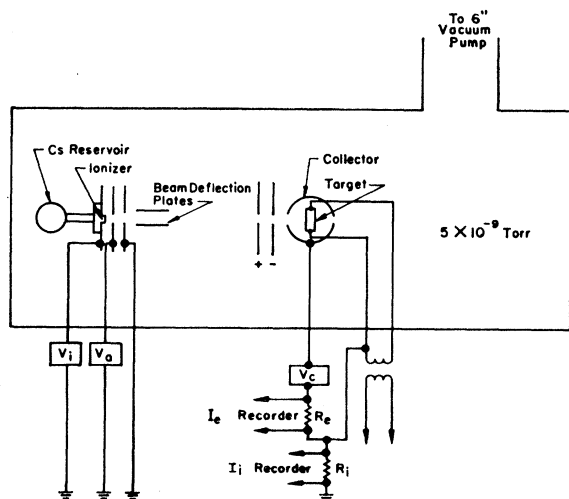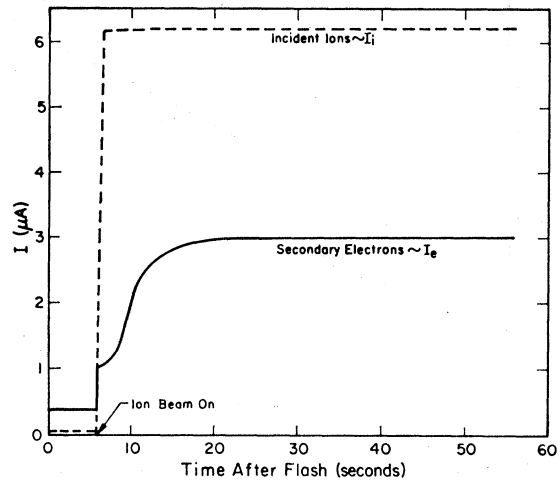

FIG. 2. Typical primary and secondary currents as functions of time. 6 keV Cs$^+$ on W.

About 2 sec later the cesium-ion beam is pulsed onto the target. The primary ion and secondary electron currents are recorded continuously. If desired, the ion beam can periodically be deflected off of the target to insure the zeros of the ion and electron currents have not shifted.

The instant the beam strikes the target the values of I_i and I_e rise from their zero values to their initial values. These incident ion and secondary electron zero-value currents are due to insulator 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 tungsten. There is little observed variation of I_i with time but I_e immediately begins to increase steadily until a saturation value is obtained (see Fig. 2). Not only is the initial γ_i for clean tungsten reproducible but so is the final γ_i for cesiated tungsten if enough time is allowed. Since all measurements were taken with background pressures $\leq 5 \times 10^{-9}$ Torr the authors believe that the 5–10 sec delay from the end of the flash to the time of the initial measurement does not allow time for ambient gases to appreciably adsorb on the target. Exact monolayer adsorption times have been measured for these pressures[7] and they are of the order of 10 min. A quick check showed the adsorption time to be greater than 5 min for conditions under which these data were taken. This gives a value of surface coverage by ambient gases less than 3%.

The results of these measurements are shown in Fig. 3. In agreement with previous measurements a linear increase in γ_i was obtained for an increase in incident ion energy, $\partial \gamma_i / \partial E \simeq 0.04$ electron/ion per keV. But contrarily, a higher kinetic ejection threshold energy for cesium on tungsten was obtained. This threshold, 2.5

FIG. 1. Schematic diagram of apparatus.

[7] P. Mahadevan, J. Layton, and D. Medved, Phys. Rev. 129, 79 (1963).
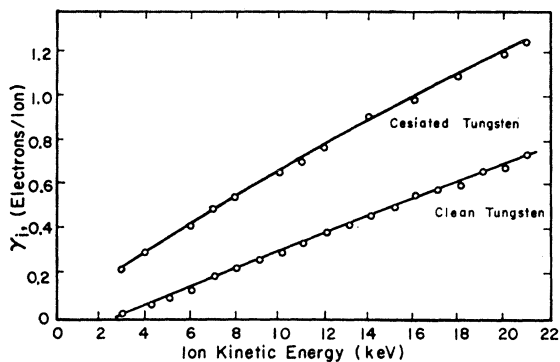
FIG. 3. Secondary electron yields as a function of cesium-ion energy for clean and cesiated tungsten.

FIG. 4. Comparison of measured values of γ_i as functions of cesium-ion energy. 1—Waters, Cs on W; 2—Petrov, Cs on Mo; 3—Brunnee, Cs on Mo; 4—present data.

keV is arrived at by extrapolating the data down to a $\gamma_i = 0$. Also, γ_i was zero within the accuracy of the measurement below this energy for what the authors believe to be clean tungsten. The equipment and method of detection used would be capable of detecting a γ_i down to about 0.005. For cesiated tungsten, nonzero values of γ_i were observed for energies down to 1 keV.

In Fig. 4 the data presented in this paper are shown in comparison with other measurements. Because of the measurement of a threshold energy for γ_i for cesium on tungsten and because of the lower values of γ_i obtained, the authors believe the previous measurements of Waters and Petrov are in error. This error is probably due to cesium or adsorbed gas coverage on the target. In the energy range common to both measurements, the values of Brunnee agree very well with those presented here. There is a difference in the $\partial\gamma_i/\partial E$'s and also in the threshold energy. This could be due in part to the differ-
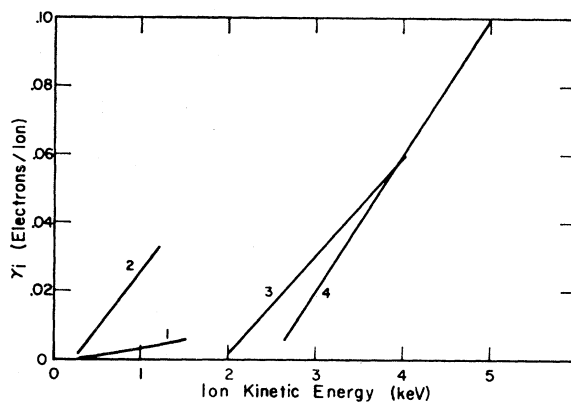
ence in properties of tungsten and molybdenum. The threshold energy of 2.5 keV corresponds to a cesium-ion velocity of approximately 0.6×10^7 cm/sec. This is in excellent agreement with the theoretical value of the velocity threshold for kinetic ejection of electrons calculated by Parilis and Kishinevskii.[8]

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[8] E. S. Parilis and L. Kishinevskii, Fiz. Tverd. Tela 3, 1219 (1960) [English transl.: Soviet Phys.—Solid State 3, 885 (1960)]