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Secondary Electron Emission from Metal Surfaces by H^+, H^0, He^+, and He^0 Bombardments

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In this paper, secondary electron emission coefficients for metal surfaces bombarded by H^+, H^0, He^+, and He^0, and the ratios $\gamma_{H^0}/\gamma_{H^+}$ and $\gamma_{H}{}^0/\gamma_{He^+}$ have been calculated. As in a previous paper, it is assumed that internal secondaries are produced by ionization. For the energy range 20 keV–2 MeV, Bethe's formula for ionization cross section has been modified to the form $Q_B/(1+\beta/T)$, where Q_B is the ionization cross section given by Bethe's original expression, β is a constant, and T is the energy of the incident ion. For a proton beam, the capture cross section becomes appreciable for energy less than 200 keV. Hence, the beam is considered as a two-component system consisting of protons and hydrogen atoms both producing internal secondaries. Above this energy range, the beam is considered as a one-component system. Similarly, a hydrogen atomic beam has been considered as a three-component system consisting of H^+, H^0, and electrons, and a helium beam for energy greater than 80 keV as a four-component system consisting of He^0, He^+, He^{++}, and electrons. Below 80 keV, the helium beam is regarded as a mixture of He^0, He^+, and electrons which produce secondaries by ionization. The calculated secondary electron emission coefficients are compared with experimental data. The agreements are satisfactory as the percentage deviation is only about 10%.

I. INTRODUCTION

In a previous paper,[1] (henceforth referred to as Paper I), theoretical expressions for the secondary electron emission coefficient, γ_e, for metal surfaces bombarded by fast positive ions (H^+, D^+, and $H_2{}^+$) and neutral atoms (H^0) have been derived. To obtain secondary electron emission by low-energy bombardment, it may be noted that Bethe's formula[2] for ionization cross section, which has been applied in Paper I, should be modified because it holds only in the MeV region and yields higher cross sections for low energy than are observed. The importance of charge-changing collisions should also be considered in estimating secondary electron emission.

For a proton beam, the capture cross section σ_{10} is appreciable[3] at low energy and, hence, some of the protons are converted into neutral hydrogen atoms of the same energy and traveling in the same direction as the incident proton beam. Therefore, while traversing a target, a low-energy proton beam should be considered as a two-component system consisting of H^+ and H^0, each capable of producing internal secondaries. Similarly a hydrogen atomic beam should be considered as a three-component system consisting of hydrogen atoms, protons, and electrons (see Paper I).

For a beam of He^0 or He^+ for $T>80$ keV, experimental evidence[3] shows that while traversing a metal or a gaseous medium, the beam behaves as a mixture of He^0, He^+, He^{++}, and electrons, that is to say, a four-component system. Below this energy, the beam behaves as a three-component system consisting of He^0, He^+, and electrons. Each of the helium components has almost the same energy as that of the original beam. The energy of the electron is equal to $T/(M_{He}/m)$, where M_{He} is the mass of the helium atom.

In this paper, in Sec. II, γ_{H^+} is calculated for Al bombarded by protons in the energy range 25 keV–2 MeV after assuming modified values for the ionization cross section. Following a recent calculation[4] for sodium metal, the value of τ, the escape probability, has been assumed to be 0.25 instead of the value 0.5 given by Sternglass[5] which was assumed in Paper I. The calculated values are compared with the theoretical results of Izmailov[6] and also with the experimental values obtained by Cousinié *et al.*[7] and Hill *et al.*[8] for the energy ranges 5–30 keV and 78–426 keV, respectively. γ_{H^0} and $\gamma_{H^0}/\gamma_{H^+}$ are also calculated for Al in the energy range 25 keV–1 MeV. The calculated values of $\gamma_{H^0}/\gamma_{H^+}$ are compared with the experimental results of Stier *et al.*[9] and Barnett *et al.*[10] for a brass target. In Sec. III, γ_{He^+}, γ_{He^0}, and $\gamma_{He^0}/\gamma_{He^+}$ are calculated for aluminum in the energy range 40–400 keV. The calculated results of γ_{He^+} are compared with the experimental values of Bourne *et al.*[11] for Al and of Hill *et al.*[8] for Mo in the energy ranges 20–100 keV and 78–426 keV, respectively, and the theoretical values of $\gamma_{He^0}/\gamma_{He^+}$ are compared with the experimental results of Barnett *et al.*[10] for a brass target.

II. SECONDARY ELECTRON EMISSION BY PROTON AND HYDROGEN ATOM BOMBARDMENTS

The experimental results of Phillips[12] and Hall[13] for equilibrium fractions $f_{0\infty}$ and $f_{1\infty}$ for a hydrogen beam

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passing through metallic foils also show that above 200 keV, $f_{0\infty}$ is negligibly small compared to $f_{1\infty}$. Hence, above 200 keV a proton beam may be treated as an one-component system consisting of only protons, while below 200 keV it may be treated as a two-component system consisting of H^0 and H^+.

Considering Fig. 1 of Paper I, we find that compared to the experimental values, the calculated values of γ_{H^+} increase more rapidly with decrease of ionic energy. This is due to the fact that Bethe's formula is correct only in the MeV region and gives higher cross sections than observed in the low-energy region. Kaila and Saha[14] also found that Bethe's formula for stopping power gives higher values than the experimental data in the low-energy region. They introduced an empirical multiplying factor so that Bethe's formula may agree with the experimental values up to 25 keV. In a similar manner, Bethe's formula for ionization cross section is modified here and we assume

$$Q_{nl}=Q_B/(1+\beta/T)$$

where Q_{nl} is the ionization cross section of the metal atom for the nl shell, Q_B is the ionization cross section obtained from Bethe's formula, and β is a constant. Hence, we obtain from Eq. (1) of Paper I

$$\gamma_{H^+}=(0.25N/\alpha)Q_{H^+}, \tag{1}$$

where

$$Q_{H^+}=\sum Q_B/(1+\beta/T).$$

γ_{H^+} for Al at different energies ($T>200$ keV) has been calculated from this equation.

Proceeding as in Paper I for hydrogen atom bombardment, we obtain for proton bombardment, for $T<200$ keV,

$$\gamma_{H^+}=\frac{0.25N}{\alpha}Q_{H^0}\left[1-\frac{1}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]f_{0\infty}+\frac{0.25N}{\alpha}Q_{H^+}\left[f_{1\infty}+\frac{f_{0\infty}}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]. \tag{2}$$

In the above equation, the first term gives the contribution to the secondary electron emission coefficient by the bombardment of hydrogen atoms produced inside the target due to charge-changing collisions. From Eq. (2) we have

$$\gamma_{H^+}=\gamma_{H^+}'\left\{Rf_{0\infty}\left[1-\frac{1}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]+\left[f_{1\infty}+\frac{f_{0\infty}}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]\right\}, \tag{3}$$

where γ_{H^+}' = secondary electron emission coefficient when the beam is treated as a one-component system, and

$$R=Q_{H^0}/Q_{H^+}.$$

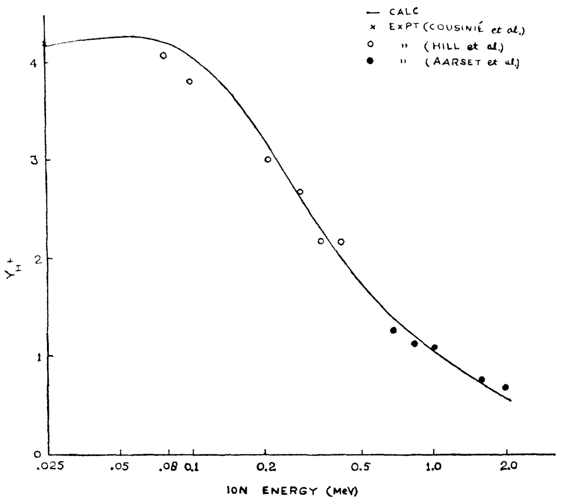

FIG. 1. Calculated variation of γ_{H^+} for aluminum with proton energy is compared with that obtained experimentally.

To calculate γ_{H^+} for Al from Eq. (3), R is obtained from the calculations of Bates and Griffing[15,16] for protons and hydrogen atoms passing through hydrogen atoms, and the same ratio is assumed for metal targets. In the absence of experimental data, $\sigma_{01}(\mathrm{Al})$ is calculated from the experimental values of $\sigma_{01}(\mathrm{Ar})$ using Bohr's[17] relation. The values of α and β as obtained by the method of least squares are as follows:

$$\beta=0.0745 \text{ MeV},$$

$$\alpha=5.28\times10^5 \text{ cm}^{-1}.$$

The calculated values of γ_{H^+} for Al obtained from Eq. (3) are shown in Fig. 1. The experimental values obtained by Cousinié *et al.*,[7] Hill *et al.*,[8] and Aarset *et al.*[18] in the energy ranges 5–30 keV, 78–426 keV, and 0.7–2 MeV are also shown for comparison.

Proceeding as in Paper I, for hydrogen atom bombardment we obtain

$$\gamma_{H^0}(T)=R\gamma_{H^+}'(T)\left[f_{0\infty}+\frac{f_{1\infty}}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]+(\gamma_{H^+}'(T)+\gamma_{\bar{e}}(T/1836))\times f_{1\infty}\left[1-\frac{1}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]. \tag{4}$$

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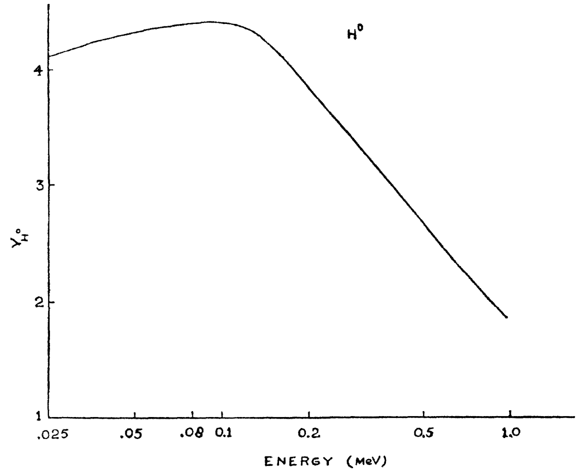

FIG. 2. Variation of γ_{H^0} for aluminum with energy of the bombarding hydrogen atom.

For $T > 200$ keV, we have $f_{0\infty}/f_{1\infty} \ll 1$ and $f_{1\infty} \simeq 1$ (see paper I); hence we obtain

$$\gamma_{\mathrm{H}^\circ}(T) = \frac{[\gamma_{\mathrm{H}^+}{}'(T) + \gamma_{\bar{e}}(T/1836)](N/\alpha)\sigma_{01} + R\gamma_{\mathrm{H}^+}{}'(T)}{1 + (N/\alpha)\sigma_{01}}. \tag{5}$$

$\gamma_{\mathrm{H}^0}(T)$ is calculated for $T < 200$ keV from Eq. (4) and for $T > 200$ keV from Eq. (5). The value of $\gamma_{\bar{e}}(T/1836)$ is obtained from the expression given by Lye and Dekker[19] after assuming $\gamma_{\bar{e}}(\max) = 1$ and $T_{\max} = 300$ eV, obtained experimentally by Bruining.[20] The calculated results are shown in Fig. 2.

The ratio $\gamma_{\mathrm{H}^0}/\gamma_{\mathrm{H}^+}$ is also estimated using the calculated values of γ_{H^0} and γ_{H^+} obtained before. The results are shown in Figs. 3 and 4. The experimental values obtained by Stier *et al.*,[9] and Barnett *et al.*[10] for brass in the energy range 20 keV–1 MeV are also given for comparison. It may be remarked that in Paper I the values of γ_{H^0} and $\gamma_{\mathrm{H}^0}/\gamma_{\mathrm{H}^+}$ are given for $T > 200$ keV. In the present paper, the same parameters are recalculated using the modified Bethe's expression for ionization and $\tau = 0.25$ instead of $\tau = 0.5$.

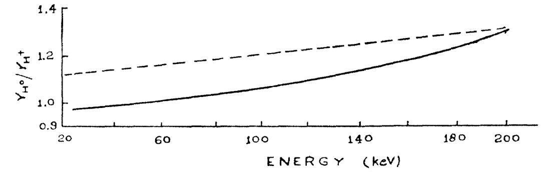

FIG. 3. Calculated variation of $\gamma_{H^0}/\gamma_{H^+}$ for aluminum with proton energy (solid curve) is compared with that obtained by Stier *et al.* (reference 9) for brass (dotted curve).

III. SECONDARY ELECTRON EMISSION BY HELIUM AND ATOM BOMBARDMENTS

Let us consider a He^0 or He$^+$ beam having energy greater than 80 keV and penetrating a metal. At a depth x, the fractions of He^0, He$^+$, and He^{++} are given by[3]

$$f_i = f_{i\infty} + [P(z,i)e^{Nxq} + N(z,i)e^{-Nxq}]e^{-\frac{1}{2}Nx\Sigma\sigma_{if}} \tag{6}$$

where

$i = 0, 1, 2 =$ charge of the helium components He^0, He$^+$, and He^{++}, respectively;

$z = 0$ or $1 =$ charge of the initial beam of helium atoms or ions;

$$q = +\tfrac{1}{2}[(g-a)^2 + 4bf]^{1/2}, \quad \sum\sigma_{if} = -(a+g),$$
$$a = -(\sigma_{10} - \sigma_{12} + \sigma_{21}), \qquad f = (\sigma_{10} - \sigma_{20}),$$
$$b = (\sigma_{01} - \sigma_{21}), \qquad g = -(\sigma_{01} + \sigma_{02} + \sigma_{20});$$

$P(z,i)$ is a function of the charge-changing cross section for a beam whose initial composition at the surface ($x = 0$) of the metal is denoted by z, and $N(z,i)$ is a coefficient for negative exponential term analogous to $P(z,i)$. The values of $P(z,i)$ and $N(z,i)$ are given by Allision[3] (Table II-1).

It is evident that if the results obtained from Eq. (6) hold, we should have

$$\tfrac{1}{2}\sum \sigma_{if} > q.$$

If the original beam consists of helium atoms, the number of electrons produced by the loss process is $f_1 + f_2$. On the other hand, for an initial beam of He$^+$ ions, the number of such electrons is only f_2.

Proceeding in the usual manner, we obtain for an initial beam of He$^+$ ions of energy T bombarding a metal target,

$$\begin{aligned}\gamma_{\mathrm{He}^+} = {} & \frac{0.25N}{\alpha}Q_{\mathrm{He}^0}\left[f_{0\infty} + \frac{P(1,0)}{1+(N/2\alpha)\sum\sigma_{if} - (N/\alpha)q} + \frac{N(1,0)}{1+(N/2\alpha)\sum\sigma_{if} + (N/\alpha)q}\right] \\ & + \frac{0.25N}{\alpha}Q_{\mathrm{He}^+}\left[f_{1\infty} + \frac{P(1,1)}{1+(N/2\alpha)\sum\sigma_{if} - (N/\alpha)q} + \frac{N(1,1)}{1+(N/2\alpha)\sum\sigma_{if} + (N/\alpha)q}\right] \\ & + \frac{0.25}{\alpha}(NQ_{\mathrm{He}^{++}} + A)\left[f_{2\infty} + \frac{P(1,2)}{1+(N/2\alpha)\sum\sigma_{if} - (N/\alpha)q} + \frac{N(1,2)}{1+(N/2\alpha)\sum\sigma_{if} + (N/\alpha)q}\right].\end{aligned} \tag{7}$$

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A similar calculation for a He^0 beam gives

$$\gamma_{He^0}=\frac{0.25N}{\alpha}Q_{He^0}\left[f_{0\infty}+\frac{P(0,0)}{1+(N/2\alpha)\sum\sigma_{if}-(N/\alpha)q}+\frac{N(0,0)}{1+(N/2\alpha)\sum\sigma_{if}+(N/\alpha)q}\right]$$
$$+\frac{0.25}{\alpha}(NQ_{He^+}+A)\left[f_{1\infty}+\frac{P(0,1)}{1+(N/2\alpha)\sum\sigma_{if}-(N/\alpha)q}+\frac{N(0,1)}{1+(N/2\alpha)\sum\sigma_{if}+(N/\alpha)q}\right]$$
$$+\frac{0.25}{\alpha}(NQ_{He^{++}}+A)\left[f_{2\infty}+\frac{P(0,2)}{1+(N/2\alpha)\sum\sigma_{if}-(N/\alpha)q}+\frac{N(0,2)}{1+(N/2\alpha)\sum\sigma_{if}+(N/\alpha)q}\right]. \quad (8)$$

To calculate the secondary electron emission coefficient for He^0 and He^+ bombardments, various charge-changing collisional cross sections and equilibrium fractions should be known. Since the equilibrium fractions of helium components for a beam of He^0 and He^+ are known experimentally for an aluminum target, γ_{He^+} and γ_{He^0} are calculated for this target. Using Bohr's relation,[17] $\sigma_{01}(Al)$ is calculated from the experimental values of σ_{01} for a helium beam passing through hydrogen gas.[3] Similarly $\sigma_{12}(Al)$ is calculated. σ_{10} and σ_{21} are obtained from the following relations:

$$\sigma_{10}/\sigma_{01}=f_{0\infty}/f_{1\infty} \quad \text{and} \quad \sigma_{21}/\sigma_{12}=f_{1\infty}/f_{2\infty}.$$

The values of $f_{i\infty}$ are obtained from the experimental data of Hall[13] and Phillips.[12] σ_{20} and σ_{02} are expected to be small for $T<400$ keV and are neglected.

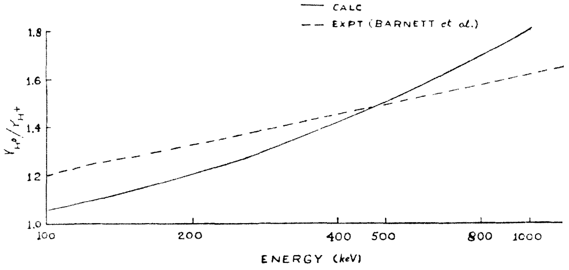

FIG. 4. Calculated variation of $\gamma_{H^0}/\gamma_{H^+}$ for aluminum with proton energy is compared with the experimental values obtained by Barnett *et al.* (reference 10) for brass.

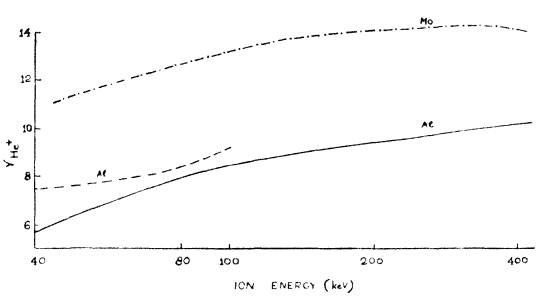

FIG. 5. Calculated variation of γ_{He^+} for aluminum with ion energy is compared with that obtained experimentally for Al and Mo targets.

As already mentioned, for energies less than 80 keV the beam behaves as a three-component system consisting of He^0, He^+, and electrons. Hence, for $T<80$ keV the expressions for γ_e for H^0 and H^+ are applicable also for a helium beam. In the absence of data for a metal target, the experimental values of σ_{if} and $f_{i\infty}$ for helium beams passing through hydrogen and argon,[3] respectively, are used to calculate the secondary electron emission coefficient. The calculated values of γ_e for an aluminum target bombarded by He^0 and He^+ in the energy range 25–400 keV are shown in Figs. 5 and 6. The experimental values obtained by Bourne *et al.*[11] for Al and those of Hill *et al.*[8] for Mo bombarded by He^+ in the energy range 20–120 keV and 43–426 keV, respectively, are also shown for comparison. In Table I, the ratio $\gamma_{He}/\gamma_{He^+}$ for an Al target is also given along with the experimental values obtained by Stier *et al.*[9] for a brass target.

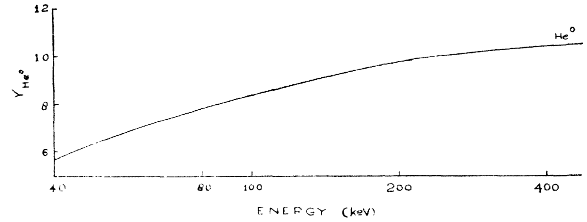

FIG. 6. Calculated variation of γ_{He^0} for aluminum with the energy of the bombarding helium atom.

IV. DISCUSSION

For a proton beam, we observe that the calculated and experimental values of γ_e agree (Fig. 1). The

TABLE I. Variation of $\gamma_{He^0}/\gamma_{He^+}$ with energy in the range 40–400 keV.

Energy (keV)	$\gamma_{He^0}/\gamma_{He^+}$ for $Al_{(cal)}$	for $brass_{(obs)}$	Percentage deviation
40	1.0	1.05	4.75
60	0.99	1.05	5.7
80	0.98	1.05	6.65
100	0.92	1.05	12.8
200	1.02	1.05	2.86
300	1.02	...	...
400	1.0	...	...

theoretical maximum occurs near 50 keV—a value expected from the trend of the experimental curves obtained by Cousinié *et al.*[7] and Hill *et al.*[8] Comparing Fig. 1 of Paper I and Fig. 1 of this paper, we find that the agreement between the experimental and calculated values is closer in the present paper, in which agreement is achieved by applying the modified Bethe formula for the ionization cross section. The percentage deviation between the experimental and calculated values is less than 10% in the whole energy range except at high energy where the deviation is 13.2%. The average deviation is of the same order as the experimental error.

The nature of the variation of γ_{H^0} with energy is the same as that for proton bombardment (Fig. 2). In the absence of experimental data for the secondary electron emission coefficient from metal surfaces by hydrogen atom bombardment for the energy range 20 keV–1 MeV, the calculated and experimental values cannot be compared. However, for the ratio $\gamma_{\mathrm{H}^0}/\gamma_{\mathrm{H}^+}$, the maximum deviation between the calculated values for Al and the experimental data for brass is 13.3%. In view of the fact that the experimental error can be as high as 7%,[9] this deviation is not large. The agreement between experimental and calculated values indicates that, like γ_{H^+} in the high-energy range, $\gamma_{\mathrm{H}^0}/\gamma_{\mathrm{H}^+}$ is also independent of the target material. Further, from Figs. 3 and 4 we find that for energies greater than 600 keV the calculated ratios are smaller than the observed ratios, while for lower energies the calculated ratios are greater than the observed ones.

The calculated variation of γ_{He^+} agrees with that obtained experimentally (Fig. 5). In the energy range 200–400 keV γ_{He^+} is practically constant, which is in conformity with the results obtained by Hill *et al.*[8] for a Mo target. Since no experimental values are available for γ_{He^0}, the calculated values cannot be compared with the experimental ones. The calculated ratio of $\gamma_{\mathrm{He}^0}/\gamma_{\mathrm{He}^+}$ in the energy range 40–400 keV is practically equal to unity, in agreement with the experimental results obtained by Stier *et al.*[9] These comparisons further indicate that, in the above energy range, γ_{He^+} is a function of target material but $\gamma_{\mathrm{He}^0}/\gamma_{\mathrm{He}^+}$ is independent of target.

Recently, Izmailov[6] developed a theory for kinetic ejection from metal surfaces by positive-ion bombardment. According to this theory, in the low-energy region γ_e is directly proportional to the ion energy. With increase of energy the slope of the curve decreases, and in the high-energy range γ_e becomes independent of T. Hence, it is evident that, from the above theory, it is difficult to explain the decrease of γ_e with the ion energy which has been experimentally observed by a large number of investigators such as Hill *et al.*[8] and Aarset *et al.*[18] (for H^+ and H_2^+ ion bombardment) and Akishin[21] (for D^+ ion bombardment).

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