where C is the nuclear molar specific heat of the cobalt ions, and R is the universal gas constant. Using the expression for CT^2/R derived by Marshall[23] for ferromagnetic media, namely,

$$CT^2/R=\tfrac{1}{3}I(I+1)(g_N\mu_N H_N/k)^2,$$

where I is the nuclear spin (for Co^{59}, $I=\frac{7}{2}$), g_N is the nuclear g factor, μ_N is the nuclear Bohr magneton, and H_N is the magnetic field at the nucleus, we computed H_N and obtained the value,

$$|H_N|=410\times10^3 \text{ oe}\pm10\times10^3 \text{ oe}. \quad (14)$$

This field is in excellent agreement with the theoretical calculations of H_N for a doubly ionized cobalt atom by Freeman and Watson.[24] They obtain the value

$$|H_N|\cong435\times10^3 \text{ oe}. \quad (15)$$

The specific heat of manganese ferrite should also contain a nuclear contribution since it too has a large nuclear magnetic moment. However, nuclear specific heat data on manganese ferrite will not be as easy to interpret, since the manganese ions enter the crystal on both A and B sites with various valencies whereas cobalt enters the crystal on the B sites as a $2+$ ion. Since ferrites have such small specific heats at low temperatures due to their large Debye temperatures and the absence of an electronic specific heat, this nuclear contribution should easily be distinguishable from the spin-wave and lattice specific heats without the necessity of going below 1°K.

We can conclude from these data that the $T^{\frac{3}{2}}$ law for the magnetic contribution to the specific heat, as predicted by spin-wave theory, is valid. However, there is a serious discrepancy in the values of the exchange parameters when measured at low and high temperature.

[24] A. J. Freeman and R. E. Watson, Phys. Rev. **123**, 2027 (1961).

ACKNOWLEDGMENTS

We would like to thank Remington Rand Univac, Division of Sperry Rand Corporation for supplying the ferrites used in this experiment and providing the chemical and x-ray analyses. In particular, we would like to thank Dr. C. Kriessman and Dr. N. Goldberg for making these and other facilities available. The many helpful discussions with Dr. H. Callen and Dr. H. Belson are gratefully acknowledged. We are indebted to the National Science Foundation for the fellowship awarded to S. R. Pollack for the year 1959–60. The assistance of Mr. Brooks Low in processing the data is sincerely appreciated.

PHYSICAL REVIEW VOLUME 125, NUMBER 4 FEBRUARY 15, 1962

Secondary Electron Emissions from Metal Surface by High-Energy Ion and Neutral Atom Bombardments

S. N. Ghosh and S. P. Khare
J. K. Institute of Applied Physics, University of Allahabad, Allahabad, India
(Received December 13, 1960, revised manuscript received July 29, 1961)

To obtain γ_e for H_2^+ ion bombardment on metal targets, an expression for the secondary electron emission coefficient by fast positive ion bombardment is obtained after adopting a method of calculation similar to that employed by Sternglass. It is shown that the experimental values of γ_e for H_2^+ ion bombardment agree with the calculated values provided it is assumed that inside the target a hydrogen molecular ion is dissociated into a proton and a hydrogen atom, each having half the energy of the molecular ion. The dissociation cross section of a hydrogen molecular ion inside the target may be given by $\sigma_d=K\sqrt{T}$, where $K=1.2$, σ_d is expressed in units of 10^{-17} cm^2, and T is in Mev.

The secondary electron emission coefficient γ_e for high-energy hydrogen atom bombardment on a metal surface is also calculated and compared with experimental data. In the calculation, a neutral beam of hydrogen atoms is treated inside the target as composed of protons and electrons in addition to hydrogen atoms. Each of these three kinds of particles are capable of producing internal secondaries.

A fair agreement between the calculated and observed values of γ_e for H^+, D^+, H_2^+, and H^0 bombardments has been obtained.

I. INTRODUCTION

It is well known that secondary electrons are emitted when metal surfaces are bombarded by positive ions. In the low-energy range (up to about 1 kev), the secondary electron emission coefficient γ_e, which is defined as the number of electrons emitted by the bombardment of one incident ion, varies directly with the ionization potential of the ion (potential ejection). Above 1 kev, the ejection depends primarily on the kinetic energy of the ion (kinetic ejection).

Secondary electron emission for potential ejection has been discussed theoretically by Oliphant and Moon,[1] Massey,[2] Shekhter,[3] Cobas and Lamb,[4] Varnerin,[5] and

[1] M. L. E. Oliphant and P. S. Moon, Proc. Roy. Soc. (London) **A127**, 388 (1930).
[2] H. S. W. Massey, Proc. Cambridge Phil. Soc. **26**, 386 (1930).
[3] S. S. Shekhter, J. Exptl. Theoret. Phys. (U.S.S.R.) **7**, 750 (1937).
[4] A. Cobas and W. E. Lamb, Jr., Phys. Rev. **65**, 327 (1944).
[5] L. J. Varnerin, Jr., Phys. Rev. **91**, 859 (1953).

Hagstrum,[6] and for kinetic ejection by Kapitza,[7] Sternglass,[8] Ross[9] and Izmailov.[10] In this paper, expressions for γ_e by high-energy positive ion and hydrogen atom bombardments have been deduced. The results are compared with the available experimental data for H^+, H_2^+, H^0, and D^+ bombardments. It is found that the values of γ_e for H_2^+ ion bombardments agree with the experimental values, provided it is assumed that hydrogen molecular ions are dissociated inside the target into protons and hydrogen atoms, each having half the energy of the molecular ion. A beam of high-energy H^0 atoms incident on a metal surface has been treated as a mixture of protons, hydrogen atoms, and electrons inside the metal.

II. EXPRESSION FOR γ_e FOR FAST POSITIVE ION BOMBARDMENT

When a metal surface is bombarded by an ion, it can interact with atoms and weakly-bound electrons of the metal leading to the production of excited electrons inside the metal (internal secondaries). A theoretical calculation of Dalgarno and Griffing[11] for the ions passing through hydrogen atoms shows that in the high-energy region ionization is the most important process. Based upon this calculation it is assumed that the internal secondaries are produced by ionization of metal atoms.[12] The number of external secondaries is then calculated after considering the escape of the internal secondaries from the metal surface.

Considering ionization cross section instead of stopping power used by Sternglass[8] and following a method similar to that employed by him, it can be shown that in the high-energy range γ_e, the secondary electron emission coefficient, is given by

$$\gamma_e = 0.5N \sum\nolimits_{nl} Q_{nl}[1/\alpha - e^{-\alpha l}/\alpha],$$

where N = number of metal atoms per cc, Q_{nl} = ionization cross section of the metal atom for the nl shell, α = absorption coefficient, and l = range of ion inside the metal; since αl is quite large, $e^{-\alpha l}$ can be neglected in comparison with unity. Hence we obtain

$$\gamma_e = (0.5N/\alpha) \sum\nolimits_{nl} Q_{nl}. \tag{1}$$

[6] H. D. Hagstrum, Phys. Rev. **96**, 336 (1954).
[7] P. Kapitza, Phil. Mag. **45**, 989 (1923).
[8] E. J. Sternglass, Phys. Rev. **108**, 1 (1957).
[9] O. V. Ross, Z. Physik, **147**, 210 (1957).
[10] S. V. Izmailov, Fiz. Tverdogo Tela, **1**, 1546 (1959).
[11] A. Dalgarno and W. G. Griffing, Proc. Roy. Soc. (London) **A232**, 423 (1955).
[12] Several observations can be cited in support of this assumption; firstly H. S. W. Massey and E. H. S. Burhop [*Electronic and Ionic Impact Phenomena* (Clarendon Press, Oxford, 1952), Chap. IX.] showed that there are many features common to the ionization of an atom and the production of secondaries by ion bombardments. Secondly, it is found from the application of the adiabatic hypothesis of Massey that the energy at which the ionization cross section is maximum is of the same order as that for which the yield of secondaries is maximum.

TABLE I. Variation of γ_e with energy and mass of the incident ion.

	H^+		D^+		H_2^+	
Energy (Mev)	γ_e for Al (cal)	γ_e for Al (obs)	γ_e for Al (cal)	γ_e for Cu (obs)	γ_e for Al (cal)	γ_e for Al (obs)
0.7	1.43	1.31	2.64	···	3.71	3.71
1.0	1.08	1.08	1.92	1.41	3.31	3.24
2.0	0.59	0.68	1.18	1.06	2.19	2.24
3.0	0.41	···	0.824	0.85	1.6	···
4.0	0.32	···	0.604	0.71	1.46	···

According to Bethe,[13]

$$Q_{nl} = \frac{2\pi Z_i \epsilon^4 c_{nl} Z_{nl}}{mv^2 |E_{nl}|} \ln\left(\frac{2mv^2}{C_{nl}}\right), \tag{2}$$

where m = mass of the electron, $Z_i\epsilon$ = charge of the ion, E_{nl} = ionization potential of the nl shell, Z_{nl} = number of electrons in the nl shell, and C_{nl} = certain mean of $E_k - E_{nl}$ having a value of the same order as E_{nl},

$$c_{nl} = (Z_{\mathrm{eff}}^2/n^2 a_0^2) \int |x_{nl,k}|^2 dk.$$

The value of the c_{nl} ranges from 0.28 for the $1s$ shell to 0.04 for the $4f$ shell of the hydrogen atom. Substituting the value of Q_{nl} in Eq. (1) and replacing v by T and mass M of the incident ion, one obtains the secondary electron emission coefficient

$$\gamma_e = \frac{0.5N}{\alpha} \frac{\pi Z_i^2 \epsilon^4 M}{mT} \sum_{nl} \frac{c_{nl}}{|E_{nl}|} \ln\left(\frac{4m}{M}\frac{T}{C_{nl}}\right). \tag{3}$$

The value of α is not known definitely. The values obtained from the experiments of Becker[14] and Partesch and Hallwachs[15] show that $1/\alpha$ is about 100 A. To determine the value of α, the calculated value of γ_e for 1-Mev (H^+—Al) emission is made to coincide with the observed value.

Assuming that the two outermost shells of Al are ionized by protons, we have

$$N \sum\nolimits_{nl} Q_{nl} = 1.86 \times 10^6.$$

Since the experimental value of γ_e for 1-Mev (H^+—Al) emission is 1.08 (Aarset *et al.*[16]), the value of α becomes 8.50×10^5, which shows that secondaries can come from a depth of about 120 A. In the above calculation, the value of c_{nl} is obtained from Bethe's table and C_{nl} is assumed to be $\frac{1}{10}$ of E_{nl}.

In Table I, the variation of γ_e calculated from formula (3) with the energy of the ions is shown for an aluminum

[13] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Clarendon Press, Oxford, 1949), 2nd ed., Chaps. IX and XI.
[14] A. Becker, Ann. Physik **2**, 249 (1929).
[15] A. Partesch and W. Hallwachs, Ann. Physik **41**, 247 (1913).
[16] B. Aarset, R. W. Cloud, and J. G. Trump, J. Appl. Phys. **25**, 1365 (1954).

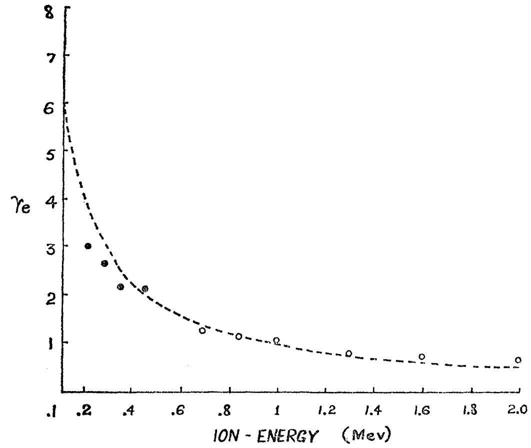

FIG. 1. Comparison of experimental values of γ_e for H^+ ion with the calculated curve as obtained from Eq. (3). (●: obtained experimentally for Al target by Hill *et al.*[17] and ○: by Araset *et al.*[16] for the same target.)

target bombarded by H^+, H_2^+, and D^+. It will also indicate the variation of γ_e with the mass of the ion. Values observed experimentally for an Al target bombarded by H^+ and H_2^+ ions by Hill *et al.*[17] and Aarset *et al.*[16] and for a Cu target bombarded by D^+ ions by Akishin[18] are also given for comparison. In Fig. 1, experimental values for H^+ ions are compared with the calculated values. For H_2^+ ion bombardment, the γ_e are calculated after considering the splitting of H_2^+ ions into protons and H atoms (see Sec. III). From Table I it follows that there is a fair agreement between the calculated and experimental values. It may be pointed out that the agreement is closer than what is apparent from the table. This is because according to Akishin the determination of γ_e for D^+ ion bombardments is correct up to $\pm 10\%$ and the error in the measurement of the incident ion energy is ± 200 kev.

It may be pointed out here that Sternglass[8] also obtained an expression for γ_e. Instead of using ionization cross sections, he utilized stopping power. Although for protons our value for γ_e agrees with that obtained by Sternglass, it may, however, be pointed out that the number of internal secondaries and the absorption coefficient obtained by us differ from those calculated by Sternglass. He assumed that the mean energy loss for the formation of a secondary is 25 ev. This value is small if we consider that the energy of an internal secondary is about this value. It may, however, be pointed out that in addition to ionization, the ion loses energy in producing excitation. According to Dalgarno and Griffing[11] the loss of energy due to excitation compared to ionization loss is about one-third at 1 Mev. Since close collisions are ineffective in producing external secondaries,[8] this ratio should be larger. Assuming the mean energy loss is 25 ev, the number of internal secondaries is about seven times greater than the value obtained by us. Furthermore, Sternglass has assumed $1/\alpha$ to be 15.5 A which is only $\frac{1}{8}$ of our value. It has been found experimentally[14,15] that for electron bombardments, its value is about 100 A. Since escape problems of secondaries produced by the bombardments of electrons and ions are the same, this value of α can be assumed also for ion bombardments. It agrees with our value but is about seven times the value used by Sternglass.

[17] A. G. Hill, W. W. Buechner, J. S. Clark, and J. B. Fisk, Phys. Rev. **55**, 463 (1939).
[18] A. I. Akishin, Zhur. Tekh. Fiz. **28**, 776 (1958).

III. SECONDARY ELECTRON EMISSION BY THE BOMBARDMENT OF HIGH-ENERGY H_2^+ IONS ON METAL

While traversing a target, high-energy H_2^+ ions may dissociate into protons and hydrogen atoms, each having half the energy of a hydrogen molecular ion. Furthermore, the hydrogen atom may be ionized, yielding another proton and an electron. In this section, γ_e has been calculated after considering the splitting of H_2^+ ions into protons and hydrogen atoms. It will be shown in the next section that for secondary electron emission, a hydrogen atom of energy T is equivalent to one proton of the same energy and an electron of energy $T/1836$.

At a depth x inside the metal, the change in the fraction of H_2^+ ions after traversing a distance dx is given by

$$df_2 = -f_2\sigma_d N dx + f_1\sigma_T N dx,$$

where σ_d and σ_T are dissociation and recombination cross sections, respectively, and

$$f_1 + f_2 = 1.$$

Since f_1 is quite small and σ_T is expected to be small in comparison with σ_d, we have

$$f_2 = e^{-N\sigma_d x}. \tag{4}$$

Assuming that the internal secondaries are produced by the ionization of metal atoms by the bombarding particles, the number of internal secondaries produced between depths x and $x+dx$ is given by

$$d\gamma_i = NQ_{H_2^+} f_2 dx + NQ_{H^+} f_1 dx + NQ_{H^0} f_1 dx, \tag{5}$$

where $Q_{H_2^+}$, Q_{H^+}, and Q_{H^0} are the ionization cross sections of metal atoms by bombardments of H_2^+, H^+, and H^0, respectively.

Since the escape probability of the internal secondaries is given by $0.5\, e^{-\alpha x}$ and $f_1 = 1 - f_2$, we obtain, after integrating Eq. (5) through the range of penetration l of bombarding of particle inside the metal,

$$\gamma_e = \frac{0.5N}{\alpha + N\sigma_d}(Q_{H_2^+} - Q_{H^+} - Q_{H^0}) + \frac{0.5N}{\alpha}(Q_{H^+} + Q_{H^0}).$$

(For the same reason as given in Sec. II, $e^{-\alpha l}$ has been neglected.) Again, since

$$\gamma_{H^+} = (0.5N/\alpha)Q_{H^+},$$

TABLE II. Variation of γ_e for H_2^+ ion bombardment with energy. (Al target.)

Energy in Mev	γ_e (calculated)	γ_e (experimental)	Percent deviation of γ_e(exp) from γ_e(cal)
0.284	5.92	6.29	+5
0.426	5.15	5.46	+5.6
0.7	3.71	3.71	0
0.85	3.62	3.4	−6.5
1.0	3.31	3.24	−2.2
1.3	2.61	2.85	+8.4
1.6	2.39	2.58	+6.9
2	2.19	2.24	+2.3

we have

$$\gamma_e=\frac{1}{1+(N/\alpha)\sigma_d}(\gamma_{H_2^+(T)}-\gamma_{H^+(T/2)}-\gamma_{H^0(T/2)})+\gamma_{H^+(T/2)}+\gamma_{H^0(T/2)},$$

where $\gamma_{H_2^+(T)}$ is the secondary electron emission coefficient for H_2^+ ions in the absence of dissociation. We finally obtain

$$\gamma_e=\frac{\gamma_{H_2^+(T)}+\{\gamma_{H^+(T/2)}+\gamma_{H^0(T/2)}\}(N/\alpha)\sigma_d}{1+(N/\alpha)\sigma_d}. \tag{6}$$

Experiments of Barnett *et al.*[19] show that for brass,

$$\gamma_{H^0}/\gamma_{H^+}=1+R,$$

where the value of R increases logarithmically with energy. In particular, its values at 200 kev and 1 Mev are 0.32 and 0.61, respectively. Since, in the high-energy range, γ_e is independent of the target material,[16,17] the above relation can be assumed for all metals. One then obtains

$$\gamma_e=\frac{\gamma_{H_2^+(T)}+\gamma_{H^+(T/2)}(2+R)(N/\alpha)\sigma_d}{1+(N/\alpha)\sigma_d}. \tag{7}$$

It is natural that in the high-energy range σ_d increases with energy. In the absence of any data the following simple relation, namely that σ_d varies directly with the velocity of the ion, has been assumed:

$$\sigma_d=K\sqrt{T}. \tag{8}$$

Expressing σ_d in units of 10^{-17} cm^2 and T in Mev, it is found that for best fit between calculated and experimental values, K should be equal to 1.2.

It can be shown that in the high-energy range, we have,

$$\gamma_{H_2^+(T)}=2\gamma_{H^+(T)}\ln\left(\frac{2m}{M}\frac{T}{C_{nl}}\right)\Big/\ln\left(\frac{4m}{M}\frac{T}{C_{nl}}\right). \tag{9}$$

[19] C. F. Barnett and H. K. Reynolds, Phys. Rev. **109**, 355 (1958).

To calculate γ_e for various energies, the values of $\gamma_{H^+(T)}$ and $\gamma_{H^+(T/2)}$ are taken from the experimental values of Aarset *et al.*[16] and Hill *et al.*[17] while the value of R is obtained from experiments of Barnett *et al.*[19] (or extrapolation from their value) and K is taken to be 1.2. The calculated values of γ_e are shown in Table II, where the experimental values are also given for comparison.

The maximum deviation between observed and calculated values of γ_e is about 8%. Considering the various assumptions involved and the simple relation which has been assumed for the dissociation of molecular hydrogen ions into protons and hydrogen atoms, this deviation is not great. The actual relation between σ_d and T may be quite complicated.

IV. SECONDARY ELECTRON EMISSION BY BOMBARDMENT OF HIGH-ENERGY HYDROGEN ATOMS

Since in the high-energy region the loss cross section σ_{01} is many times larger than the capture cross section σ_{10}, a hydrogen atom of energy T while traversing a target is ionized, yielding one proton of the same energy and an electron of energy $T/(M/m)$. Thus

$$H^0(T)\rightarrow H^+(T)+\bar{e}(T/1836). \quad (M/m=1836)$$

Hence, a neutral beam of hydrogen atoms can be treated inside the target as composed of protons and electrons in addition to hydrogen atoms. Each of these three kinds of particles are capable of producing internal secondaries.

Consider now a beam of hydrogen atoms penetrating through a metal. The fractional concentration of neutral atoms and protons at a depth x is given by[20]

$$f_0=\frac{\sigma_{10}}{\sigma_{10}+\sigma_{01}}+\frac{\sigma_{01}}{\sigma_{10}+\sigma_{01}}e^{-N(\sigma_{10}+\sigma_{01})x}, \tag{10}$$

and

$$f_1=\frac{\sigma_{01}}{\sigma_{10}+\sigma_{01}}-\frac{\sigma_{01}}{\sigma_{10}+\sigma_{01}}e^{-N(\sigma_{10}+\sigma_{01})x}. \tag{11}$$

Since each hydrogen atom produces one proton and one electron, the number of electrons is equal to f_1.

The number of internal secondaries produced between depths x and $x+dx$ is given by

$$d\gamma_i=Nf_0Q_{H^0}dx+Nf_1Q_{H^+}dx+f_1A\,dx, \tag{12}$$

where A represents the number of internal secondaries produced by electrons in traveling through unit distance. Substituting the values of f_0 and f_1 from Eqs. (10) and (11) in Eq. (12), multiplying by the escape

[20] S. K. Allison, Revs. Modern Phys. **30**, 1137 (1958).

TABLE III. Comparison of theoretical and experimental values of the ratio $\gamma_{H^0}/\gamma_{H^+}$.

Energy in kev	γ_{H^0}	$(\gamma_{H^0}/\gamma_{H^+})_{cal}$ for Al	$(\gamma_{H^0}/\gamma_{H^+})_{obs}$ for brass	Percentage deviation
200	3.70	1.20	1.32	+9.0
300	3.13	1.27	1.39	+8.7
400	2.75	1.36	1.45	+6.2
500	2.47	1.43	1.49	+4.0
600	2.24	1.50	1.52	+1.3
700	2.05	1.56	1.55	−0.7
800	1.91	1.59	1.57	−1.3
900	1.82	1.65	1.59	−3.8
1000	1.79	1.66	1.61	−3.1

probability, and then integrating, we get

$$\gamma_{H^0}=\frac{0.5N}{\alpha}Q_{H^0}\left\{\frac{\sigma_{10}}{\sigma_{10}+\sigma_{01}}+\frac{\sigma_{01}}{(\sigma_{10}+\sigma_{01})[1+(N/\alpha)(\sigma_{01}+\sigma_{10})]}\right\}+\frac{0.5}{\alpha}(NQ_{H^+}+A)\left\{\frac{\sigma_{01}}{\sigma_{01}+\sigma_{10}}-\frac{\sigma_{01}}{(\sigma_{01}+\sigma_{10})[1+(N/\alpha)(\sigma_{01}+\sigma_{10})]}\right\}. \quad (13)$$

Now

$$\gamma_{H^+}=(0.5N/\alpha)Q_{H^+},$$

and

$$\gamma_{\bar{e}}=0.5A/\alpha.$$

Hence,

$$\gamma_{H^0}=\frac{0.5N}{\alpha}Q_{H^0(T)}\left[f_{0\infty}+\frac{f_{1\infty}}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right]+[\gamma_{H^+(T)}+\gamma_{\bar{e}}(T/1836)]f_{1\infty}\times\left[1-\frac{1}{1+(N/\alpha)\sigma_{01}(1+f_{0\infty}/f_{1\infty})}\right], \quad (14)$$

where

$$f_{0\infty}=\sigma_{10}/(\sigma_{10}+\sigma_{01}) \quad \text{and} \quad f_{1\infty}=\sigma_{01}/(\sigma_{01}+\sigma_{10})$$

are the equilibrium fractions of protons and hydrogen atoms, respectively.

It was shown by Hall[21] that for metallic foils $f_{1\infty}$ is several tens times greater than $f_{0\infty}$ for energies greater than 200 kev. Hence in the energy range under consideration $f_{0\infty}$ can be neglected in comparison with $f_{1\infty}$; we then have

$$\gamma_{H^0}=\frac{0.5N}{\alpha}Q_{H^0}\frac{1}{1+(N/\alpha)\sigma_{01}}+(\gamma_{H^+(T)}+\gamma_{\bar{e}(T/1836)})\left[1-\frac{1}{1+(N/\alpha)\sigma_{01}}\right],$$

[21] T. Hall, Phys. Rev. **79**, 504 (1950).

assuming $f_{1\infty}$ to be unity, or

$$\gamma_{H^0}=\frac{[\gamma_{H^+(T)}+\gamma_{\bar{e}(T/1836)}](N/\alpha)\sigma_{01}+(0.5N/\alpha)Q_{H^0(T)}}{1+(N/\alpha)\sigma_{01}}. \quad (15)$$

To calculate γ_{H^0} at different energies, Eq. (15) is utilized. Experimental values of γ_{H^+} are taken from Hill *et al.*[17] and Aarset *et al.*,[16] while values of $\gamma_{\bar{e}}$ are taken from Brunning *et al.*[22] To calculate σ_{01} for a neutral hydrogen beam penetrating through aluminum, Bohr's relation[23] for σ_{01} is utilized. According to this relation

$$\sigma_{01}\propto Z^{\frac{2}{3}},$$

Z being the atomic number of the target. Hence we get

$$\sigma_{01(\mathrm{Al})}=\left(\frac{Z_{\mathrm{Al}}}{Z_{\mathrm{Ar}}}\right)^{\frac{2}{3}}\sigma_{01(\mathrm{Ar})}.$$

Using experimental values of $\sigma_{01(A_r)}$ given by Barnett *et al.*,[19] the values of $\sigma_{01(Al)}$ for the 200-kev to 1-Mev energy range are calculated.

In the case of hydrogen atom bombardment, the high-energy beam is rapidly changed to protons and hence the contribution to secondary electrons by bombardment of H^0 is small. Therefore, the second term in Eq. (15) can be neglected in comparison with the first term. Thus, we obtain

$$\gamma_{H^0}=\frac{[\gamma_{H^+(T)}+\gamma_{\bar{e}(T/1836)}](N/\alpha)\sigma_{01}}{1+(N/\alpha)\sigma_{01}}.$$

The calculated values of γ_{H^0} are shown in Table III. The values of $\gamma_{H^0}/\gamma_{H^+}$ are also shown and are compared with the experimental values obtained by Barnett *et al.*[19] for brass target.

The maximum deviation of the calculated and observed ratios of secondary electron emission coefficients by neutral hydrogen atoms and protons bombardments is 9%, which is not large because experimental error can be as great as 7%.[19] Furthermore, it should be noted that the experimental data for γ_{H^+} and $\gamma_{\bar{e}}$ are obtained by different investigators, who might not have performed their experiments under identical conditions. Since the positive error decreases with energy and at the most is 9%, it can be concluded that the production of the internal secondaries by neutral atoms is very small as compared with those produced by protons and electrons. It is to be noted that $\gamma_{H^0}/\gamma_{H^+}$ calculated for Al is compared with the experimental values for brass. As the agreement is quite good, it indicates that like γ_{H^+}, the coefficient γ_{H^0} is also independent of the target material in the high-energy range.

[22] H. Brunning and J. H. De Boer, Physica **5**, 17 (1938).
[23] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **18**, No. 8 (1948).