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Secondary electron emission from thin foils under fast-ion bombardment

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The total secondary electron emission (SEE) coefficient γ was measured from sputter-cleaned self-supporting C, Al, Ni, Cu, Pd, Ag, Sm, Gd, Au, and Bi targets under bombardment of fast protons, as well of incident H^+, Li^{2+}, Li^{3+}, C^{3+}, C^{4+}, O^{3+}, O^{4+}, and O^{5+} ions from thin carbon foils (20 $\mu g/cm^2$) in the energy range $0.4 \le E_p \le 22$ MeV. The material paramter Λ deduced from our measurements is calculated to 0.031 ± 0.005 nm/eV for the different studied targets with $28 \le Z \le 83$. For all projectiles and velocity regions studied the SEE coefficient γ and the stopping power have the same velocity dependence. However, for a given projectile velocity, the γ coefficient and the stopping power do not have the same projectile Z_p dependence. The data are discussed in the frame of an extended Sternglass model.

INTRODUCTION

Secondary electron emission (SEE) induced by ion bombardment is one of the major consequences of the interaction of fast projectiles with solids. Research in this field started some 80 years ago and has been extensively treated in the last 30 years. Ion-induced SEE is important in such areas as the electronic properties of solid surfaces and fast timing detectors for swift heavy ions or in nuclear-fusion devices.[1] Recent reviews for ion-induced SEE have been presented by Sigmund and Tougaard,[2] Benazeth,[3] Krebs,[4] Thomas,[5] Hasselkamp,[6] Schou,[7] and Frischkorn and Groeneveld.[8]

Two mechanisms are distinguished to understand the ion-induced SEE: (1) the "potential ejection,"[9] which is the important mechanism for ion velocities below about $v < 10^7$ cm/s, and (2) the so-called "kinetic ejection" mechanism, which is important for ions with higher ($v > 10^8$ cm/s) velocities in which electrons may be accelerated as a result of the interaction of the projectile charge with the electron plasma of the solid or from direct "binary collisions" between the ion and (nearly free) valence-band electrons.

The kinematic emission is clearly related to the energy of the projectile which is communicated to target electrons (the electronic stopping power dE/dx); Sternglass[10] suggested the average number γ of electrons emitted per incoming projectile to be proportional to dE/dx. This proportionality has been tested experimentally.[11–17] There are cases where such a proportionality is verified, but others where it fails and the field is clearly open to further experimental clarification. In this work we focus our attention to two different aspects of the SEE phenomenon: (a) test of the proportionality between SEE and the electronic stopping power dE/dx for different projectiles with $1 \le Z_p \le 8$ and over a wide projectile energy range ($0.4 \le E_p \le 22$ MeV) and (b) study of the SEE as a function of the target material represented by the atomic number Z_T. Since the SEE depends dramatically on the state of the target surface this study needs ultrahigh-vacuum conditions and modern surface-cleaning techniques.

EXPERIMENT

In this work we present measurements of the SEE coefficient γ for (a) incident protons with energies 0.8 and 1.6 MeV impinging on different thin self-supporting, sputter-cleaned targets of C, Al, Ni, Cu, Pd, Ag, Sm, Gd, Au, and Bi, and (b) incident H^+, Li^{2+}, Li^{3+}, C^{3+}, C^{4+},

O^{3+}, O^{4+}, and O^{5+} on thin carbon foils. The coefficient γ was measured as function of the projectile energy in the range $0.4 \le E_p \le 22$ MeV. The experimental setup used for these measurements is fairly simple and has been described elsewhere.[8] The number of electrons emitted per projectile ion, γ, is extracted by calculating the charge balance at the target,[18]

$$\gamma = (Q_t / Q_{FC}) q_f + (q_f - q_i) , \quad (1)$$

where Q_t and Q_{FC} are the charges measured at the target and Faraday cup, respectively, q_f is the mean final charge state of the projectiles after leaving the foil exit surface, and q_i is the projectile incident charge before the foil entrance surface. The thickness of the targets was in all cases so large that charge equilibrium of the penetrating particles was attained before they exit. A negative voltage of 20 V was applied to the target; enough for the electron emission γ to reach a saturation value.[15] The experiments were performed in two institutes: at the 2.5-MV van de Graaff accelerator of the Institut für Kernphysik of the J. W. Goethe University in Frankfurt under ultrahigh-vacuum conditions ($p < 10^{-9}$ Torr) with sputter-cleaning procedures of target surfaces[19] and at the 5-MV Tandem accelerator of the National Research Center "Demokritos" in Athens under standard vacuum conditions ($p \approx 1\ \mu$ Torr).

RESULTS AND DISCUSSION

For incident H^+ projectiles the SEE coefficient γ is presented in Figs. 1 and 2 as a function of the target atomic number Z_T for two different projectile energies (0.8 and 1.6 MeV. The experiment was performed under ultrahigh-vacuum conditions and the target metal surfaces were cleaned by sputtering.[19] The absolute error of our γ values is less than 20%. We observe a nonmonotonic dependence of γ on Z_T in good agreement with the results obtained recently by Hippler *et al.*,[20] who measured the backward electron yield from 27 elemental, noncrystalline, thick solids under bombardment by H^+, $H_2{}^+$, and $H_3{}^+$ ions at 100 keV/u. They found that the yield exhibits an oscillatory dependence on the atomic number Z_T of the target material which is correlated with the periods of the periodic system. Dividing the γ coefficient for each target by the corresponding stopping power $S = dE/dx$ given by Ziegler,[21] we calculate the characteristic material parameter $\Lambda = \gamma / S$. Table I gives the material parameter Λ for the different targets as deduced from our measurements. All data from target materials with $28 \le Z \le 83$ are clustered around the mean value $\Lambda = 0.031$ nm/eV with a scatter of 16%. However, if we express the stopping power not in eV/nm but in eV $(\mu g/cm^2)^{-1}$, a nonmonotonic dependence of the material parameter Λ versus Z_T is observed (Fig. 3). Our data show that within $\pm 16\%$ the SEE is proportional to the linear stopping power and does not depend on the target material; at present we have no explanation for this new result. In a recent review,[7] Schou reported material parameters $\Lambda(\text{Al}) = 0.029$, $\Lambda(\text{Be}) = 0.028$, and $\Lambda(\text{Mg}) = 0.031$ nm/eV in very good agreement with our mean value $\Lambda = 0.031$ nm/eV obtained from eight different targets. However, our Λ values for $Z_T = 6$ and $Z_T = 13$ are up to 70% higher than the above mean value obtained for all the other materials. For Al foils a possible explanation could be that in the evaporation procedure Al is deposited as bulk Al oxide (from oxygen in the residual gas in the target production chamber) and in that case sputtering cannot produce clean metalic surfaces. A similar problem may arise with carbon foils in addition to the large uncertainty with which the density of thin carbon foils is known. We compared the γ values before and

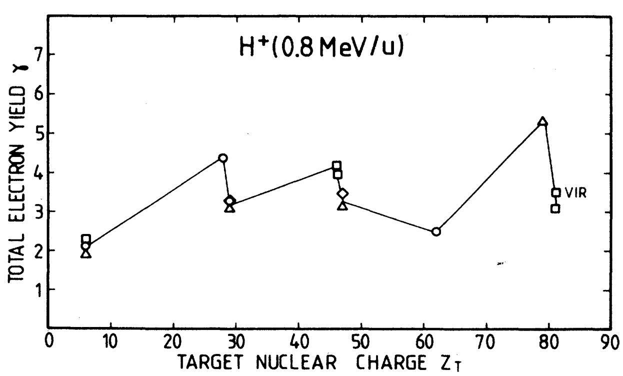

FIG. 1. The total secondary electron coefficient γ as function of the target atomic number Z_T for incident protons (0.8 MeV).

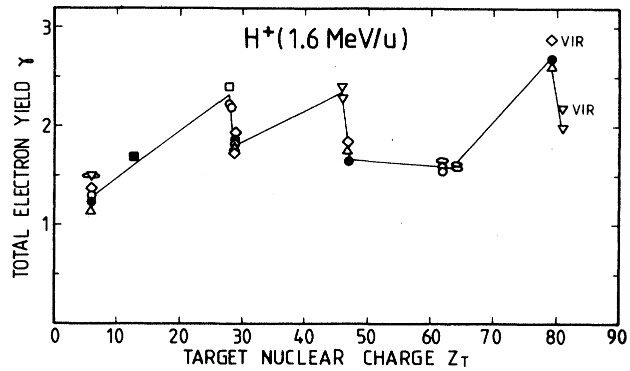

FIG. 2. The total secondary electron coefficient γ as function of the target atomic number Z_T for incident protons (1.6 MeV).

TABLE I. The Λ parameter for different materials from H^+ ($E_p = 0.8$ and 1.6 MeV) bombardment.

Target	Z_T	Material parameter Λ (nm/eV)
C	6	0.053
Al	13	0.048
Ni	28	0.030
Cu	29	0.023
Pd	46	0.028
Ag	47	0.026
Sm	62	0.037
Gd	64	0.032
Au	79	0.033
Bi	83	0.037

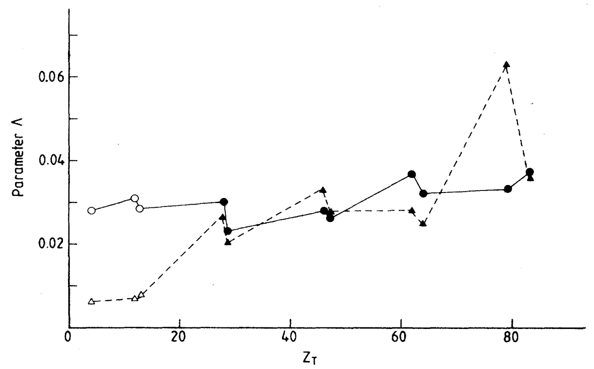

FIG. 3. The Λ parameter expressed in nm/eV (circles) and in (μg cm^{-2})/eV (triangles) as a function of the target atomic number Z_T for incident protons (0.8 and 1.6 MeV). The results presented in open symbols are obtained from Ref. 7. Straight and dashed lines are to guide the eye.

after sputter cleaning of the Au and Bi target surfaces. For both targets we observe a higher γ from the untreated solid surface than from the sputter-cleaned metalic surface. This enhanced γ is caused by adsorbates and oxides which can cover the uncleaned metalic surface.[22]

Figure 4 presents the energy dependence of γ for an incident proton beam on 20-μg/cm^2 carbon foils. This experiment has been performed under standard high-vacuum conditions ($p=1$ μTorr) and for this reason the absolute value of γ is higher (about 30%) than the one measured at the same velocity under ultrahigh-vacuum conditions. However, this difference is disregarded since we are interested here mostly in the energy dependence of the SEE coefficient and, particularly, in the linear relationship between γ and the stopping power. Dividing, for each energy, the SEE coefficient by the corresponding stopping power, we observe that the ratio $\Lambda=\gamma/S$ is independent [$\Lambda=12\pm0.4$ μg cm^{-2}/keV] of the projectile energy within the studied energy range ($0.4\leq E_p\leq 10$ MeV), as expected. Following the Sternglass model[10] the SEE coefficient γ must be proportional to the stopping power in the high-projectile-velocity regime where the electron emission results from direct collisions between atoms and electrons.

The linear relationship between the SEE coefficient γ and the stopping power S is confirmed in the case of H^+ projectiles. However, this is not the case for heavier ions where the problem has not yet been settled; for C and O projectiles Frischkorn *et al.*[23] found the expected linear relationship for projectile energies above 0.3 MeV/u. For lower energies they observed an increase of the ratio $\Lambda=\gamma/S$ with decreasing projectile energy. On the other hand, Koyama *et al.*[14] found that the ratio Λ increases with the incident energy in the energy region 4.5–8 MeV/u. Clerk *et al.*[24] measured the SEE coefficient γ for a carbon foil under bombardment with He, O, S, and I ions in the energy region 0.2–2 MeV/u. According to these measurements the dependence of γ on the energy is nearly equal to that of the electronic stopping power S for these projectiles. But, according to Oda and Lyman[25] the decrease of γ with the incident energy is gentler than that of S for He, C, O, and Ne ions in the energy region 4–8 MeV/u.

Figures 5 and 6 show the SEE coefficient γ and the ratio $\Lambda=\gamma/S$, respectively, for Li^{2+}, Li^{3+}, C^{3+}, C^{4+}, O^{3+}, O^{4+}, and O^{5+} projectiles penetrating thin carbon foils under high-vacuum conditions. The mean charge q_f of the projectiles exiting from the carbon foils and the stopping power S were obtained from Refs. 26 and 27. We observe for all ions that the ratio $\Lambda=\gamma/S$ is independent

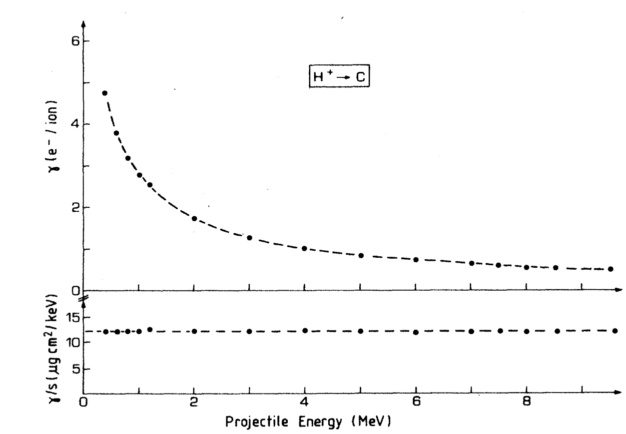

FIG. 4. Energy dependence of the total secondary electron coefficient γ for incident proton beam into carbon 20 μg/cm^2 foil. In the lower part of the figure is presented the ratio $\Lambda=\gamma/S$, where S is the corresponding stopping power.

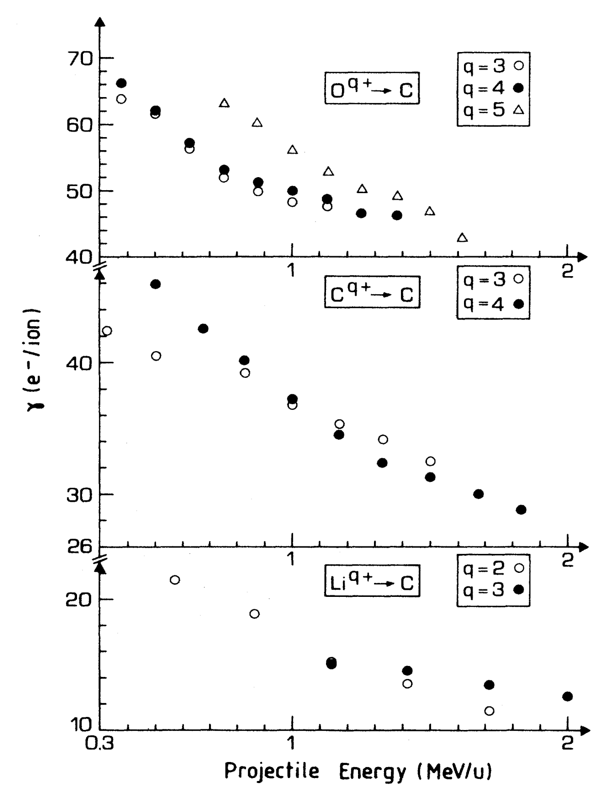

FIG. 5. Energy dependence of the total secondary electron coefficient γ for Li^{2+}, Li^{3+}, C^{3+}, C^{4+}, O^{3+}, O^{4+}, and O^{5+} projectiles impinging a thin 20-μg/cm^2 carbon foil.

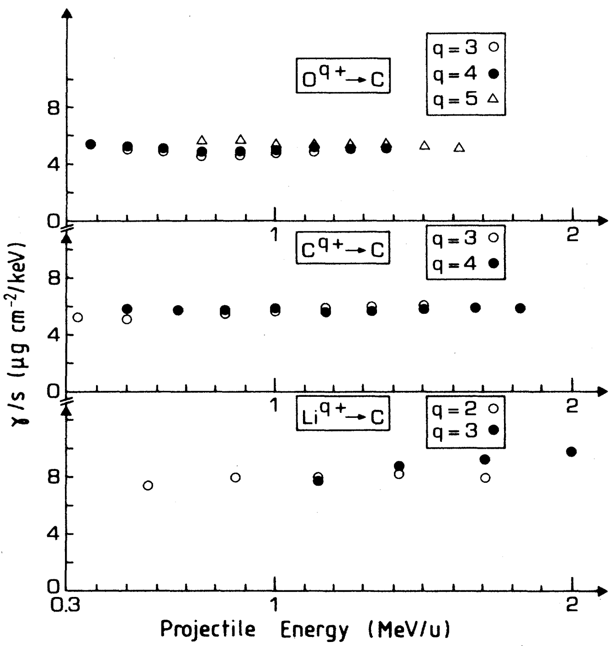

FIG. 6. Energy dependence of the ratio γ/S (S is the corresponding stopping power) for incident Li^{2+}, Li^{3+}, C^{3+}, C^{4+}, O^{8+}, O^{4+}, and O^{5+} projectiles.

(within an experimental uncertainty of $\pm 16\%$) of the projectile velocity, which indicates that the proportionality between γ and S is confirmed at least concerning the velocity dependence. One must be very careful, however, in using the simple relation $\Lambda=\gamma/S$ to check the proportionality between stopping and SEE emission for different incident projectiles (Z_p dependence). We know that γ depends also on the initial charge state q_i and, therefore, also on the different charge preequilibrium stopping powers on the entrance side of the foil. Following Koschar *et al.*[28] for thin foils a more realistic relationship between γ and Λ can be expressed by

$$\Lambda=\gamma/[aS(q_i)+bS(q_f)] \ . \qquad (2)$$

a and b are parameters related to the ratio $\gamma(f)/\gamma(b)$. The relation $\Lambda=\gamma/S$ holds in cases where $q_i=q_f$ or in experiments where we measure only the forward SEE emission. In our experiments the projectiles which nearly satisfy the $q_i \approx q_f$ condition are H^+, Li^{3+}, and nearly the C^{4+} and O^{5+} ions. The values of Λ in $\mu g\,cm^{-2}/keV$ obtained with these projectiles are 12.1, 9.2, 5.9, and 5.6, respectively, in good agreement with those previously observed, i.e., 5 and 5.8 for C and O projectiles.[23] From these results we observe that concerning the Z_p dependence there is no proportionality between secondary electron emission and stopping power; specifically, the increase of γ with the atomic number of the projectiles with the same velocity is smaller than the increase in the stopping power.

The q_i dependence of γ which is generally observed for all projectiles is expected because of charge-exchange processes taking place in the first few monolayers as well as distant Coulomb excitation of electrons for unequilibrated charge-state ions. However, the different behavior of O^{5+} in comparison with O^{3+} and O^{4+} is surprising.

CONCLUSION

In this experimental work we measured the SEE coefficient γ as a function of the projectile atomic number, charge state, and velocity, and as a function of the target material. For eight different targets with $Z_T=28-83$ the deduced material parameter Λ is found to be 0.031 ± 0.005 nm/eV. For all projectiles in the velocity region studied, the SEE coefficient γ and the stopping power S have the same velocity dependence. However, for a given projectile velocity, γ and S do not have the same Z_p dependence. The increase of γ with the atomic number of the projectiles is smaller than the increase in the stopping power. Incident charge-state dependences of γ are generally observed for all projectiles which cannot be explained easily by shell effects. Further work to explain unanswered questions is in progress. It would be desirable to have simultaneous measurements of both γ and dE/dx at the same target to reduce the uncertainty sources of Λ.

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