Projectile dependence of ion-induced electron emission from thin carbon foils

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The total secondary-electron yield from thin carbon foils traversed by heavy ions has been measured as a function of the projectile atomic number Z_p, the initial charge state, and the incident velocity. For nearly all projectiles in the velocity region studied the number of emitted electrons per incoming projectile γ and the stopping power S have, as expected, the same velocity dependence. However, for ions with $Z_p > 29$ a slight increase of the ratio $\Lambda = \gamma/S$ with the projectile energy is observed. A systematic study of the ratio Λ as a function of the projectile atomic number Z_p indicates a $Z_p^{-0.2}$ dependence of the parameter Λ. Possible explanations for this $Z_p^{-0.2}$ dependence of the Λ parameter are given.

INTRODUCTION

It is well known that the interaction of fast ($v > 10^8$ cm/s) charged particles with a condensed medium leads to the so-called "kinetic emission of electrons."[1] This basic phenomenon is of general importance in applied physics as in plasma surface interactions, ion microscopies, the development of heavy particle detectors, and many other applications. Renewed interest was motivated by the availability of UHV techniques and surface analysis tools which allowed us to perform experiments on defined target surfaces under controlled conditions, but also by the use of new projectiles as fast ionic clusters.[2]

The kinetic emission of electrons is generally considered as a three-step process. First, the projectile transfers kinetic energy to target electrons. Next, a fraction of these electrons moves from the bulk toward the entrance surface of a massive solid or the entrance and exit surfaces in the case of thin foils, and finally a fraction of the electrons reaching the surface passes through it. Most of these electrons have energies below 20 eV and come from layers 10–20 Å below the solid surfaces.

Kinetic ejection of secondary electrons in high-energetic ion-solid collisions is strongly related to the (electronic) energy loss per unit path length, i.e., the stopping power S. Consequently, most of the theoretical approaches[3–5] consider the number γ of electrons ejected per incident projectile to be proportional to the electronic stopping power S. In order to study the validity of this proportionality, it became common practice to define a parameter Λ as the ratio between the measured secondary-electron yield and the stopping power value:

$$\Lambda = \gamma / S \ . \tag{1}$$

Some experimental studies[6–17] have been carried out to test whether the theoretically predicted proportionality between γ and the electronic stopping power really exists. Equation (1) has been confirmed experimentally for proton impact, i.e., the parameter Λ was found to be constant within a wide projectile energy range 5 keV $\leq E \leq 24$ MeV.[1,15,18,19] In this case, i.e., for protons, the parameter Λ would be expected to depend only on target properties and may be considered as a "material parameter." With heavy ions the parameter Λ has been found[15,17,20] to be independent of the projectile energy for sufficiently high projectile energies $E \geq 50$ keV/u. Furthermore, a rough overall proportionality of total electron yields from thin foils has been observed[1] for a variety of projectile nuclear charges in a wide range of projectile velocities.

In a recent work[20] we studied the secondary electron yield γ obtained with various fast projectiles impinging thin carbon foils. The projectile nuclear charge Z_p dependence of parameter Λ was determined. We found for the parameter Λ a nonequilibrium regime for $Z_p \leq 6$ ions (Λ decreasing with Z_p) and an equilibrium regime for $Z_p > 6$ ions (Λ independent of Z_p). In the present work we extend that study for heavier projecticles with $Z_p > 6$ in order to check the independence of Λ with Z_p also for these ions. It is important to mention that the independence of parameter Λ with Z_p cannot be understood for the moment in the framework of the most recent semiempirical models[21,22] describing the kinetic emission of secondary electrons from thin foils.

EXPERIMENT

The experimental work was performed at the 5-MV Tandem accelerator of the National Research Center "Demokritos" in Athens, Greece. Mass analyzed beams of Si^{q+} ($q = 4-7$), V^{q+} and Cu^{q+} ($q = 5-7$), and Ge^{q+}, As^{q+}, and Br^{q+} ($q = 5-8$) were sent through thin 20 μg/cm^2 self-supporting carbon foils. The thicknesses of

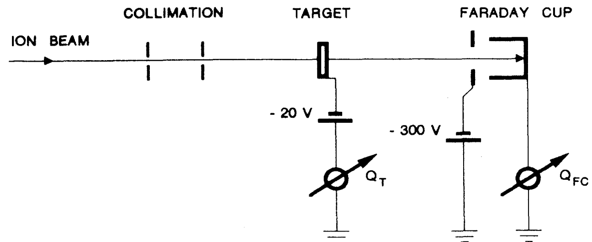

FIG. 1. Experimental setup.

the targets were large enough to ensure that charge equilibrium of the penetrating particles was attained before the ions reach the exit surface.

The experimental setup used for these measurements is fairly simple and is shown in Fig. 1. A negative voltage of 20 V was applied to the target, enough for the electron emission γ to reach a saturation value.[10] The Faraday cup was comprised of two parts: a beam-collecting cup that was grounded through the electrometer (Keithley current integrator) and a cylindrical electrode upstream of this cup which was biased -300 V with respect to the ground. This negatively biased electrode prevented (i) secondary electrons from escaping from the collecting cup and (ii) secondary electrons of the target from entering the collecting cup. Due to the very high secondary-electron yields that occur in these experiments, secondary-electron suppression in the Faraday cup is crucial for an accurate determination of high Z beam fluxes.

The number of electrons emitted per projectile ion γ is extracted by calculating the charge balance at the target[23]

$$\gamma=(Q_t/Q_{\mathrm{FC}})q_f+q_f-q_i \ , \tag{2}$$

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. The mean charge q_f of the projectiles emerging from the carbon foils was obtained from Shima *et al.*[24]

The secondary-electron coefficient γ has been measured as a function of the projectile nucleus charge, initial charge state, and velocity under standard vacuum conditions ($p \approx 1$ μTorr).

RESULTS AND DISCUSSION

The energy dependence of the coefficient γ for various incident projectiles on 20 μg/cm^2 carbon foils is presented in Figs. 2–5. For all except Si projectiles we observe an increase of the coefficient γ with the projectile energy. This can be understood from the proportionality between the electron emission yield and the stopping power. In the energy regime studied, the stopping power increases with the projectile energy. In the case of Si ions, a maximum of the secondary-electron yield is reached at an energy close to the maximum of the stopping power. The small charge state q_i dependence of γ which is generally observed (Figs. 2–5) for all projectiles is expected[15,20] because of charge exchange processes taking place in the first few monolayers of the foils, as well as distant

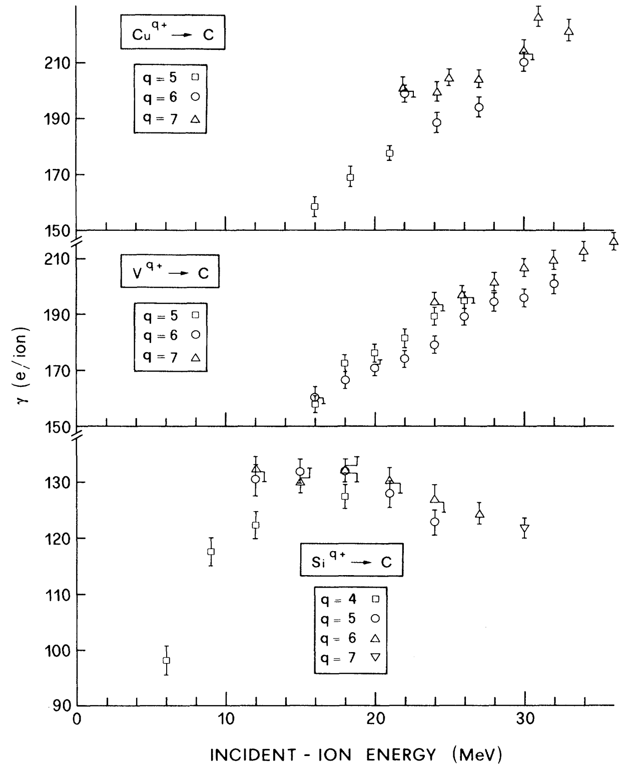

FIG. 2. Energy dependence of the total secondary-electron coefficient γ for Si, V, and Cu ions impinging on a thin carbon foil.

Coulomb excitation of electrons for unequilibrated charge state ions.

Dividing the coefficient γ by the stopping power S for each projectile energy (obtained from Ref. 25) we deduce from Eq. (1) the parameter Λ. The results are presented in Figs. 6–9 enriched with previous[15,20] data obtained with other projectiles in the same laboratory and with the

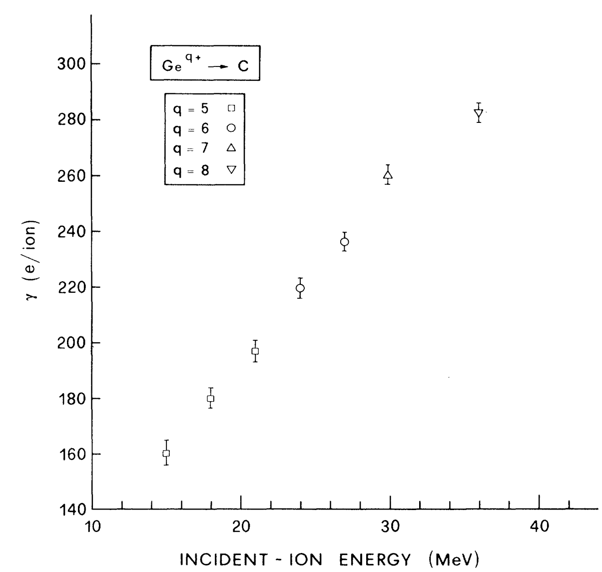

FIG. 3. Energy dependence of the total secondary-electron coefficient γ for Ge ions impinging on a thin carbon foil.

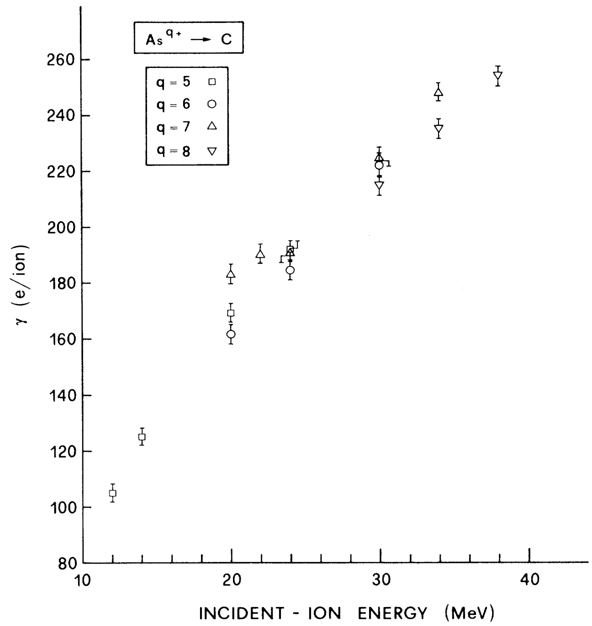

FIG. 4. Energy dependence of the total secondary-electron coefficient γ for As ions impinging on a thin carbon foil.

same experimental setup. The systematic study of the Λ parameter as a function of the incident-ion energy for different projectiles with Z_p ranging between 1 and 35 indicates that for $Z_p \leq 29$ ions the Λ parameter is independent of the projectile velocity. The independence of the Λ parameter with the projectile energy for incident-ion energies greater than 50 keV/u has also been reported previously.[15,17,20] However, for $Z_p > 29$ ions a slight increase of the parameter Λ with the projectile energy is observed. For $Z_p = 32$, 33, and 35 ions we observe a pro-

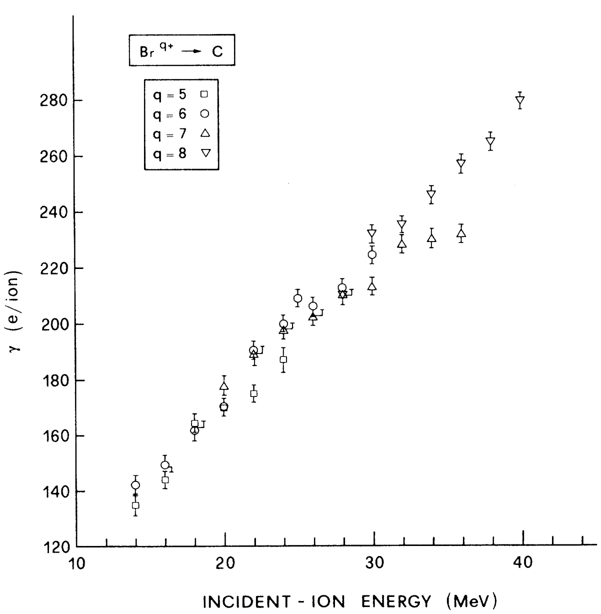

FIG. 5. Energy dependence of the total secondary-electron coefficient γ for Br ions impinging on a thin carbon foil.

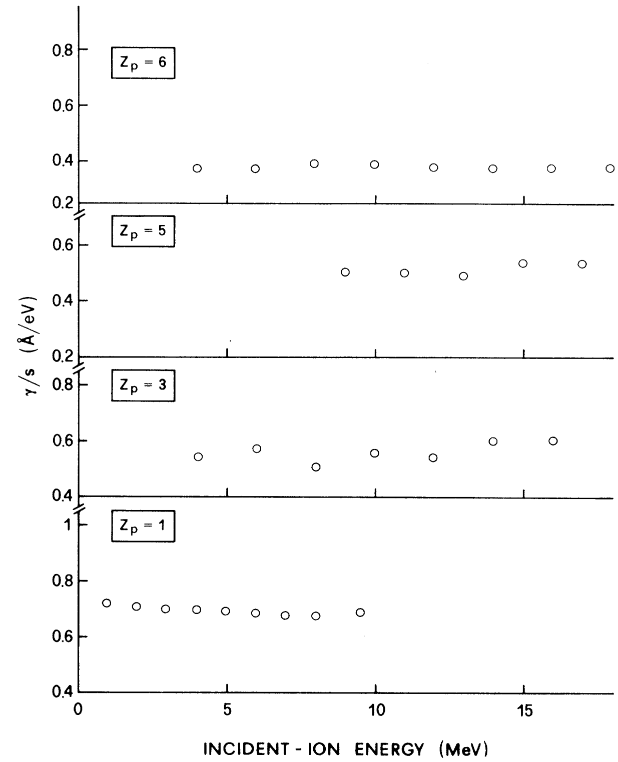

FIG. 6. Energy dependence of the ratio $\Lambda = \gamma / S$ for different projectiles ($Z_p = 1, 3, 5, 6$) impinging on a thin carbon foil.

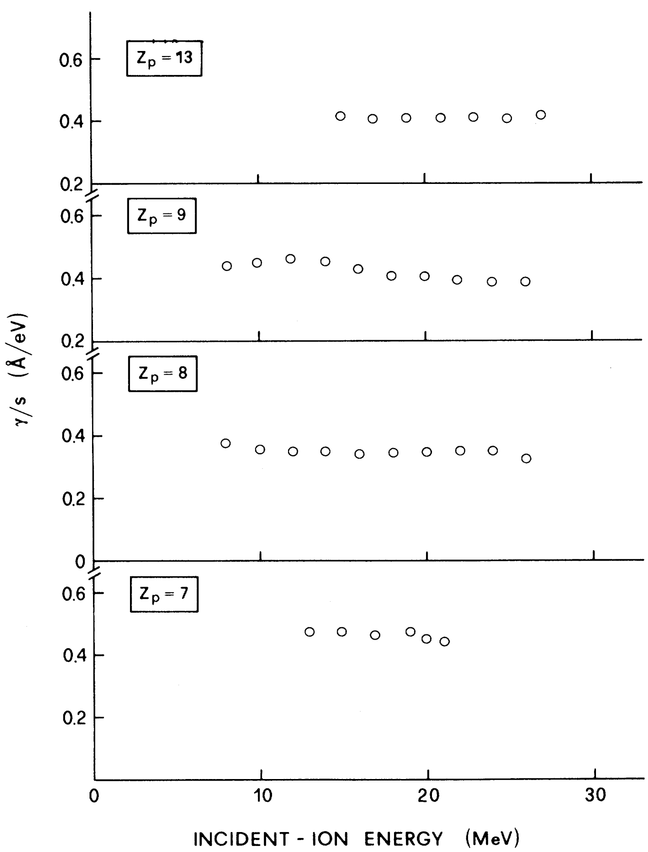

FIG. 7. Same as Fig. 6 but for $Z_p = 7$, 8, 9, and 13 projectiles.

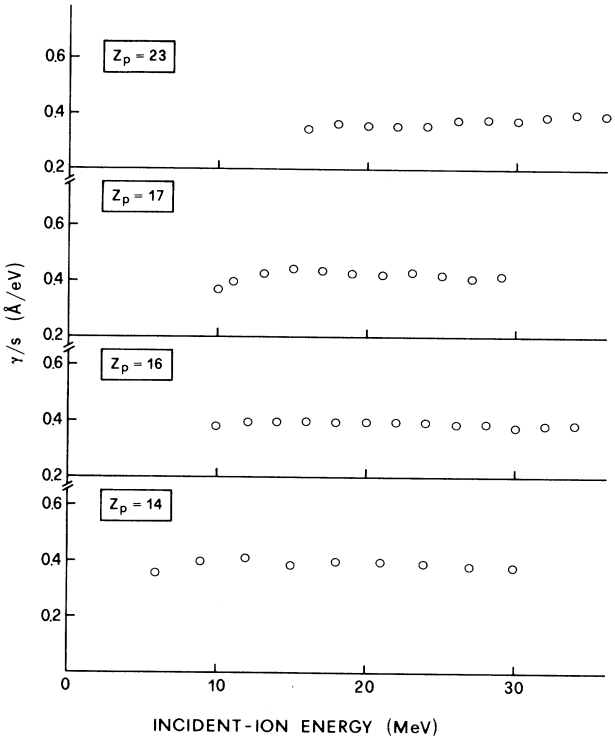

FIG. 8. Same as Fig. 6 but for $Z_p = 14$, 16, 17, and 23, projectiles.

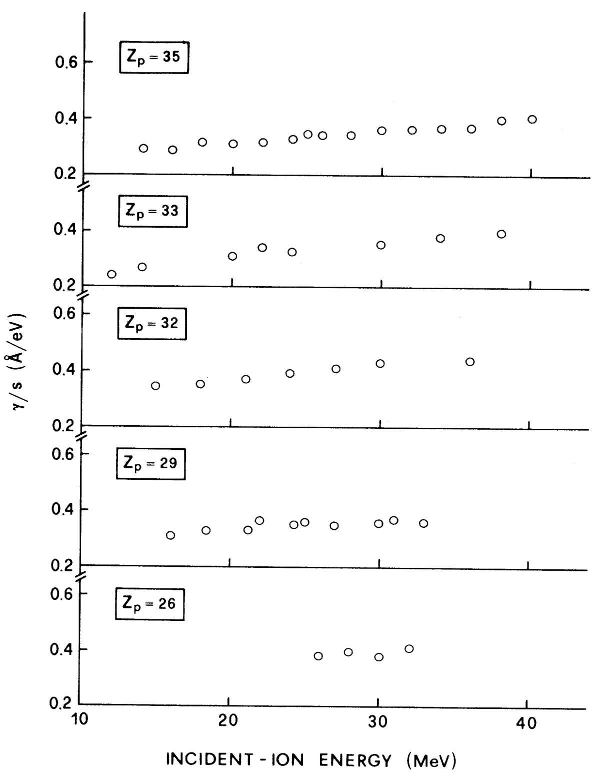

FIG. 9. Same as Fig. 6 but for $Z_p = 26$, 29, 32, 33, and 35 projectiles.

jectile energy dependence E^{α} of the Λ parameter with $\alpha = 0.35$, 0.45, and 0.35, respectively. This result must be confirmed for heavier ions.

The Λ parameter as a function of the projectile atomic number is presented in Fig. 10(a). A similar plot has first been given in our recent publication,[20] here enriched with the data of the present work. The values of Λ presented are the mean values for each projectile obtained with various incident projectile energies and initial charge states. The error bars include statistical fluctuations as well as the small incident charge state and energy (for $Z_p > 29$ ions) dependence of the total secondary-electron yield. For $Z_p \leq 6$ ions we observe a decrease of Λ with Z_p and for $Z_p > 6$ ions Λ seems to be independent of Z_p. However, neglecting the data for C and O projectiles the Λ dependence with Z_p can be reproduced (dashed lines) from Eq. (3):

$$\Lambda(Z_p) = \Lambda(Z_p = 1) Z_p^{-0.2} . \tag{3}$$

There is not any evident physical reason on the apparent anomalous behavior of C and O projectiles, so the possibility that it may result from experimental error should be discussed. In a similar experiment,[21] ion-induced electron emission measurements with carbon projectiles have been performed in the University of Frankfurt under similar vacuum conditions. The thin carbon foils used in that experiment and the carbon foils we used in our ex-

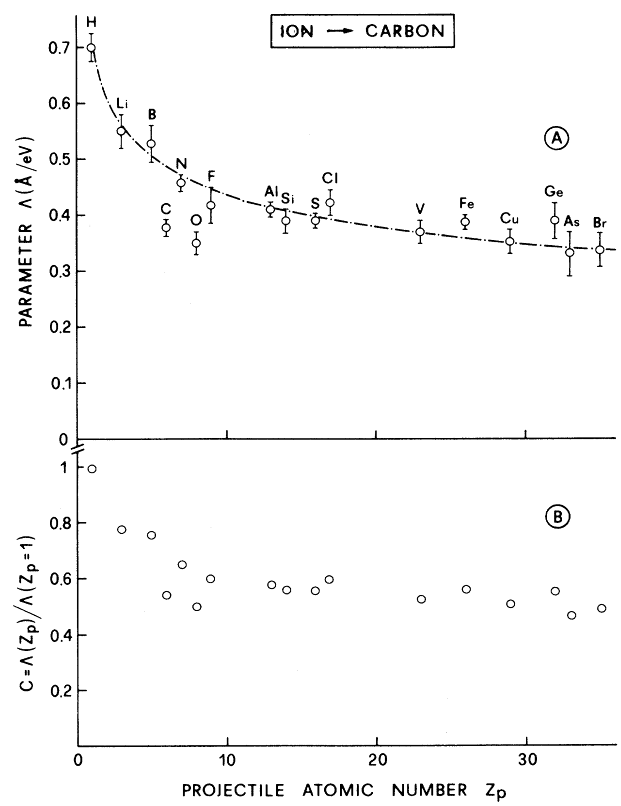

FIG. 10. Projectile atomic number Z_p of the Λ parameter and of the ratio $C = \Lambda(Z_p)/\Lambda(Z_p = 1)$. The dashed lines represent the equation $\Lambda(Z_p) = \Lambda(Z_p = 1) Z_p^{-0.2}$.

periment were produced in the same laboratory. The difference between the total secondary-electron yield obtained from the two experiments is less than 10%. For oxygen projectiles although we do not dispose different measurements of ion-induced electron emission obtained with thin carbon foils produced in the same laboratory, it is important to note that the Λ parameter in $\mu g\,cm^{-2}$/keV, presented in Fig. 10 for O projectiles, is 5.6, in very good agreement with 5.8 obtained in the University of Frankfurt[26] previously with the same projectiles and under similar vacuum conditions. The above discussion probably shows that the surprising behavior of C and O projectiles is a physical effect, which, for the moment, cannot be understood.

The factor

$$C=\Lambda(Z_p)/\Lambda(Z_p=1) \tag{4}$$

as a function of the projectile atomic number Z_p is shown in Fig. 10(b). The decrease of the C factor with Z_p can be understood in the framework of a recently proposed model by Rothard, Schou, and Groeneveld[22] which incorporates into Schou's transport theory the concept of pre-equilibrium near-surface stopping power. According to this model the C factor describes the deviation of the near-surface stopping power (connected to electron emission) to the tabulated values. The stopping powers used in expression (1) are the tabulated bulk energy-loss values and it is now well established[17,20–22] that "nonequilibrium near-surface stopping powers" both at the upstream and downstream surfaces of the foils are responsible for the production of the secondary electrons in the entrance and exit surface of the foil. The total electron yield γ, due to the small escape depth of the secondary electrons, is only sensitive to events in the first few atomic layers at the beam entrance and exit surface of the foil and consequently to the near-surface stopping power. The near-surface stopping power in comparison to the bulk energy loss can be smaller up to a factor of 1.8 in the case of heavy ions[22] in the energy regime studied in the present work. On the contrary, for fast incident protons there is indeed no difference between the near-surface stopping power and the tabulated bulk energy loss. Furthermore, a fraction r of the ion energy loss may lead to either target or projectile excitation and consequently not contribute to the production of secondary electrons. For light ($Z_p=1$) and heavy ($Z_p=6$) ions Rothard, Schou, and Groeneveld[22] found $r=20\%$ and 50%, respectively. Taking into account all of the above remarks we deduce a C factor for heavy ions of about 0.36 in good agreement with the 0.5 obtained in the present work. In the framework of the model presented in Ref. 22, the parameter C describes a variety of possible physical mechanisms that can possibly cause a projectile dependence of an effective energy loss near the entrance and exit surfaces; possibly, e.g., charge exchange, screening effects, and projectile ionization may contribute to the Z_p dependence.

In the above discussion we considered only mechanisms which are related to the production of secondary electrons. However, the secondary-electron yield γ is indeed related to the production of secondary electrons, but not exclusively. As mentioned in the Introduction the kinetic emission of electrons is a three-step process: (1) production of the secondary electrons; (2) transport of secondary electrons towards the entrance and exit surface of the foil; and (3) escape of the secondary electrons from the target surfaces. It may be possible to have a projectile dependence not only in step (1) but also in steps (2) and (3). For fast protonlike projectiles which remain fully stripped as they pass through a thin foil, the near-surface stopping power is the same as the tabulated bulk energy-loss values. For such projectiles the independence of Λ with Z_p would be expected if steps (2) and (3) of the kinetic emission process are independent of the projectile atomic number Z_p.

Borovsky and Suszcynsky[27] measured the secondary-electron yield for such fast protonlike projectiles H^+, He^{2+}, Be^{4+}, B^{5+}, C^{6+}, and O^{8+} from gold, aluminum oxide, and tantalum targets. They observed a Z_p dependence of the Λ parameter as follows: $Z_p^{-0.29}$ for gold targets, $Z_p^{-0.38}$ for Al_2O_3, and $Z_p^{-0.28}$ for tantalum targets. The principal reason for this dependence is the electric field arising from space-charge separation in the wake of the fast ion inhibiting the escape of Coulomb-scattered electrons, thereby reducing the secondary-electron yield.[27] The Z_p dependence of the Λ parameter observed by Borovsky and Suszynsky[27] is in good agreement with the $Z_p^{-0.2}$ dependence observed in the present work. However, there are two main differences between the two experiments. The first one is that in Ref. 27 the targets used were very thick (much greater than the range of any beam ion); therefore, the secondary electrons come only from a region near the entrance surface of the solid and not from both surfaces as in our experiment where thin foils were used. The second difference is that in the present experiment the projectiles inside the foils carry electrons, which, due to screening effects, will decrease the electric field in the ion wake. Consequently, the above-mentioned effect responsible for the reduction of the secondary-electron yield will not be as important as in the case of fully stripped ions.

Despite the different reasons (pre-equilibrium near-surface stopping power, projectile or target excitation, and electric field in the ion wake) mentioned above to describe the small $Z_p^{-0.2}$ dependence of the Λ parameter, the important assumption of an overall proportionality between the total secondary-electron yield γ and the electronic loss of the projectiles is demonstrated impressively in Fig. 11, which shows the total secondary-electron yield γ from carbon foils as a function of the stopping power S for 17 different projectiles with different projectile velocities and initial charge states. The values presented in Fig. 11 were obtained from the present work and enriched with previous[15,20] data obtained with other projectiles in the same laboratory and with the same experimental set-up. The correlation analysis between the coefficient γ and the stopping power S for about 250 experimental values give

$$\gamma=0.36S \tag{5}$$

with R squared (validity of the correlation) equal to 97%. In Fig. 11, Eq. (5) is represented by the straight line. The

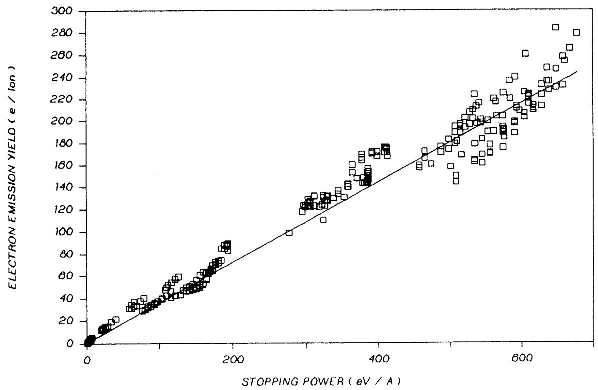

FIG. 11. Total secondary-electron yield γ from carbon foils as a function of the stopping power S for 17 different projectiles with different projectile velocities and initial charge states. The straight line represents the equation $\gamma=0.36S$.

mean value of the Λ parameter deduced from the present work is therefore $\Lambda=0.36$ Å/eV, in good agreement with the mean value $\Lambda=0.31$ Å/eV, given by Rothard and co-workers.[1,17] In Fig. 11, the deviation within a factor of 30% from the mean material parameter can be attributed to the Z_p dependence of the Λ parameter, whereas the energy dependence $\Lambda(E)=\text{const}$ is confirmed at least for $Z_p \leq 29$ ions. One must be careful in the precision attached to the mean value of the Λ parameter. In the correlation analysis we neglected any uncertainty in the stopping power S values which were simply obtained from Ref. 25. It would be desirable to simultaneously have both γ and S at the same target to reduce the uncertainty sources of Λ.

CONCLUSION

In this experimental work we measured the secondary-electron coefficient γ as a function of the projectile atomic number, charge state, and velocity. For nearly all projectiles in the velocity region studied the coefficient γ and the stopping power S have, as expected, the same velocity dependence. However, for $Z_p > 29$ ions a slight increase of the ratio $\Lambda=\gamma/S$ with the projectile energy is observed. This result must also be confirmed for heavier projectiles. The systematic study of the Λ parameter as a function of the projectile atomic number Z_p indicates a $Z_p^{-0.2}$ dependence of parameter Λ. Possible reasons for this small Z_p dependence of the Λ parameter are as follows:

(i) The reduced pre-equilibrium near-surface stopping power (in comparison to the tabulated bulk energy-loss values) responsible for the production of secondary electrons in the entrance and exit surfaces of the foil; (ii) The fraction of the ion energy loss which leads to target (or projectile) excitation and consequently does not contribute in the production of secondary electrons; (iii) The electric field in the wake of a fast ion which inhibits the escape of Coulomb-scattered electrons, thereby reducing the secondary-electron yield.

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