Heavy-ion-induced electron emission from thin carbon foils

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We have measured heavy-ion-induced ($5 \leq Z_p \leq 26$; $0.3 < E < 1.8$ MeV/u) secondary-electron emission (SEE) from thin carbon foils. For all projectiles in the velocity range studied, the SEE coefficient γ (number of emitted electrons per incoming projectile) and the stopping power S have the same velocity dependence. Similar to proton bombardment for heavy ions, we also observe a maximum of the yield of electron emission at energies very close to the stopping-power maximum. A systematic study of the ratio $\Lambda=\gamma/S$ with the projectile atomic number Z_p reveals a nonequilibrium regime for $1 < Z_p < 6$ ions (Λ decreasing with Z_p) and an equilibrium regime for $Z_p \geq 6$ ions (Λ independent of Z_p). The obtained results are discussed in the framework of an extended Sternglass-type model, taking into account nonequilibrium projectile energy losses near the exit and entrance surfaces of the carbon foils.

INTRODUCTION

The interaction between swift or heavy ions and a condensed medium can result in emission of electrons from the solid surface. This is referred to as secondary electron emission (SEE), and the total SEE yield γ is defined as the average number of electrons emitted per incoming projectile. Most of these electrons have energies below 20 eV and come from layers 10–20 Å below the solid surface. Ion-induced secondary electron emission is of interest in the fields of semiconductor physics, fusion,[1,2] the study of radiation effects in materials,[3] electron microscopy, amplification in electron multipliers, surface analysis,[4,5] and many more.

At high projectile velocities ($v > 10^8$ cm/s) the dominant production mechanism of secondary electrons is the so-called "kinetic ejection" mechanism, 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 collision" between the ion and (nearly free) valence-band electron. In almost all theoretical approaches[6–12] the kinetic emission of secondary electrons is 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 target surface, and finally a fraction of the electrons reaching the surface passes though it.

Kinetic ejection of secondary electrons in high energetic ion-solid collisions is strongly correlated to electronic stopping power of the projectile at the entrance and exit surface of the solid,[7] and the most frequently applied theoretical models[8–10] consider γ to be proportional to the electronic stopping power S. Some experimental studies[13–24] have been carried out to test whether the theoretically predicted proportionality between γ and the electronic stopping power really exists. In order to study the validity of this proportionality it is common practice to define parameter Λ as ratio between measured secondary electron yield and the stopping power value:

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

The proportionality was confirmed experimentally as a function of the projectile velocity for proton bombardment in a wide energy range 10 keV $< E <$ 10 MeV.[22,25,26] 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[22,24] to be independent of the projectile energy for sufficiently high projective energies $E > 50$ keV/u. However Λ has been found smaller for heavy ions (HI) than for light ions (H, He), i.e., $\Lambda(\mathrm{HI}) < \Lambda(\mathrm{He}) < \Lambda(\mathrm{H})$.

In this work we present a systematic study of the secondary electron yield γ obtained with various fast projectiles $5 \leq Z_p \leq 26$ impinging thin carbon foils in order to determine the projectile Z_p dependence of the parameter Λ.

EXPERIMENT

The experiments were performed at the 5-MV tandem accelerator of the National Research Center "Demokritos" in Athens. Mass-analyzed beams of B^{3+}, B^{4+}, N^{4+}, F^{3+}, F^{4+}, F^{5+}, Al^{4+}, Al^{5+}, Al^{6+}, S^{4+}, S^{5+}, S^{6+}, S^{7+}, Cl^{4+} Cl^{5+}, Cl^{6+}, Fe^{6+}, Fe^{7+} ions were sent through thin self-supporting carbon foils. The thickness of the carbon foils was 20 $\mu g/cm^2$, large enough to ensure charge equilibrium at the exit surface of the foil. A negative voltage of 20 V was applied to the target; enough for the electron emission γ to reach a saturation value.[17]

The secondary electron coefficient γ has been measured as a function of the projectile nuclear charge ($5 \leq Zp \leq 26$) and the projectile energy ($0.3 < E < 1.8$ MeV/u) under standard vacuum conditions ($p = 1$ μTorr). The experimental setup used for these measurements is fairly simple and similar to the one described in Ref. 27. The number of electrons emitted per projectile ion, γ, is extracted by calculating the charge balance at the target:[28]

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

where Q_t and $Q_{\rm FC}$ 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 were obtained from Shima *et al.*[29]

RESULTS AND DISCUSSION

Figures 1–3 present the energy dependence of the SEE coefficient, γ, for various incident projectiles on 20 μg/cm^2 carbon foils. We observe that our values are in good agreement with previous measurements[18] when data are available. Dividing for each energy, the SEE coefficient by the stopping power S (obtained from Ref. 30) we can deduce the ratio $\Lambda = \gamma / S$. We observe for all ions (Figs. 4 and 5) that the parameter Λ is independent of the projectile velocity which means that the proportionality between γ and S exists at least concerning the velocity dependence. Identical results have also been previously deduced for Li, C, and O ions in the same laboratory by Clouvas *et al.*,[22] for He, Ne, Ar, Kr, Xe by Rothard *et al.*,[24] for Cl, O by Shi *et al.*,[18] and for He, O, S, and I ions by Clerk *et al.*[31] It is worth noting that the maximum secondary electron yield for protons is reached at an energy close to the stopping power maximum depending on the target material.[32] In the present experiment, a maximum secondary electron yield was also observed for F, S, and Cl ions at energies very close to the stopping power maximum which means that also for heavy ions the yield of electron emission has a maximum at an energy close to that of the stopping power.

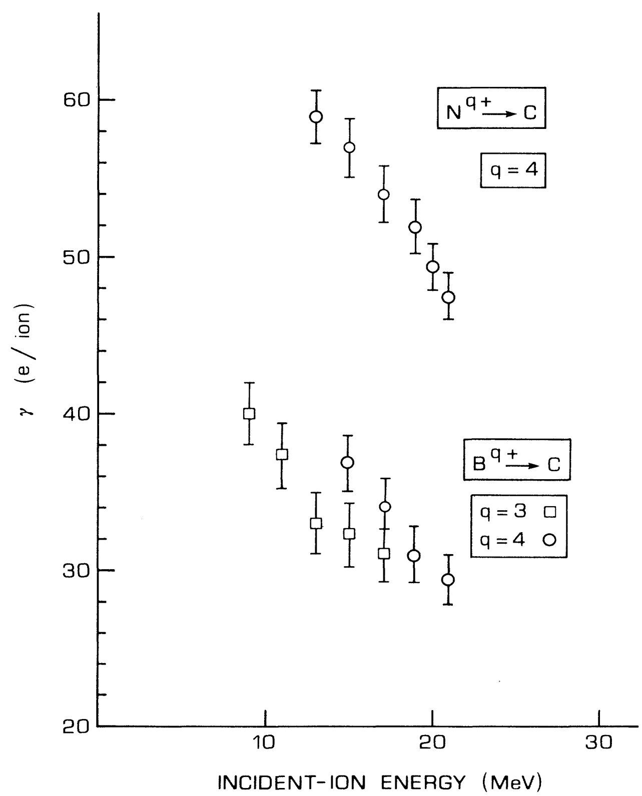

FIG. 1. Energy dependence of the total secondary electron coefficient γ for B and N ions impinging on a thin carbon foil.

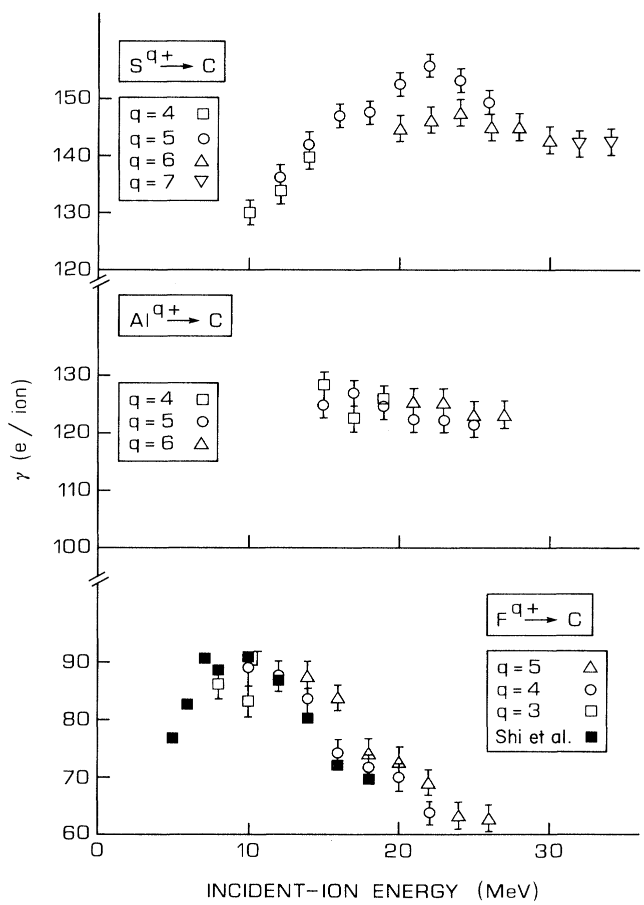

FIG. 2. Energy dependence of the total secondary electron coefficient γ for F, S, and Al ions impinging on a thin carbon foil. In the solid symbols the results obtained by Shi *et al.* (Ref. 18) are presented.

The small but significant incident charge-state dependences of γ which is generally observed (Figs. 1–3) for almost all projectiles is expected because of charge-exchange processes taking place in the first few monolayers of the foil, as well as distant Coulomb excitation of electrons for unequilibrated charge-state ions.

In Fig. 6 we present the Λ parameter as a function of the projectile atomic number. The values of Λ obtained in the same laboratory[22] with H, Li, C, and O ions are also included. 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 dependence of the total secondary electron yield.

The first remark is that the parameter Λ obtained with heavy ions (HI) is smaller to the one obtained with a proton beam. This result has also been found previously for Ne, Ar, Kr, and Xe beams[24] and can be explained in the framework of an extended Sternglass-type[7] model taking into account nonequilibrium projectile energy losses near the surfaces. The stopping powers usually used in expression (1) are the tabulated bulk energy-loss values and it is now well established[7,24] 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. Furthermore the energy loss is correlated to the nonequilibrium process of the evolution of the ionic charge state near the entrance surface[7,33,34] and to the dynamic self-screening of the projectile by bound projectile electrons.[7,35] An evolution of the "effective" projectile charge occurs at the entrance surface of the foil within some few atomic layers until the bulk effective charge value is reached, but also at the exit surface[24] where a sudden change of the projectile screening or a deexcitation of the projectile having been excited inside the foil can take place.[34] Deviations of up to a factor of 2 can occur for heavy ions between near-surface energy loss and the tabulated bulk energy loss.[24] Such reduced nonequilibrium stopping powers near the surfaces, first introduced by Koschar and coworkers,[7] can be deduced from the ratio

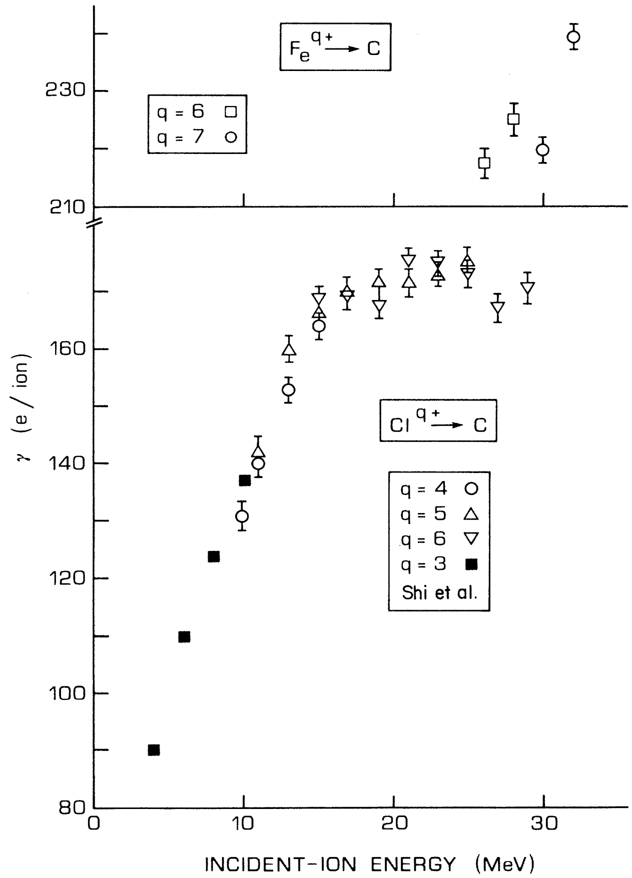

FIG. 3. Energy dependence of the total secondary electron coefficient γ for Cl and Fe ions impinging a thin carbon foil. In the solid symbols the results obtained by Shi *et al.* (Ref. 18) are presented.

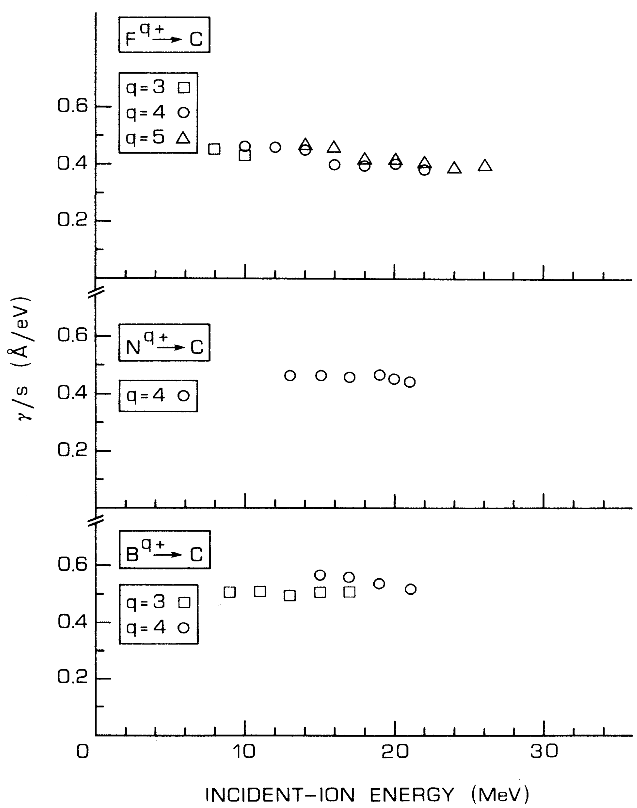

FIG. 4. Energy dependence of the ratio $\Lambda = \gamma / S$ [S is the tabulated (Ref. 30) stopping power] for B, N, and F ions impinging on a thin carbon foil.

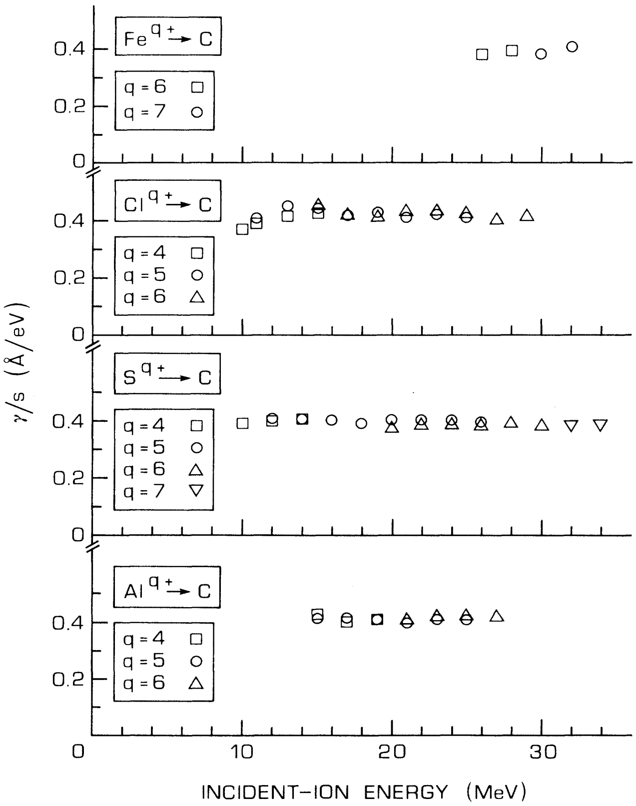

FIG. 5. Energy dependence of the ratio $\Lambda = \gamma / S$ [S is the tabulated (Ref. 30) stopping power] for Al, S, Cl, and Fe ions impinging on a thin carbon foil.

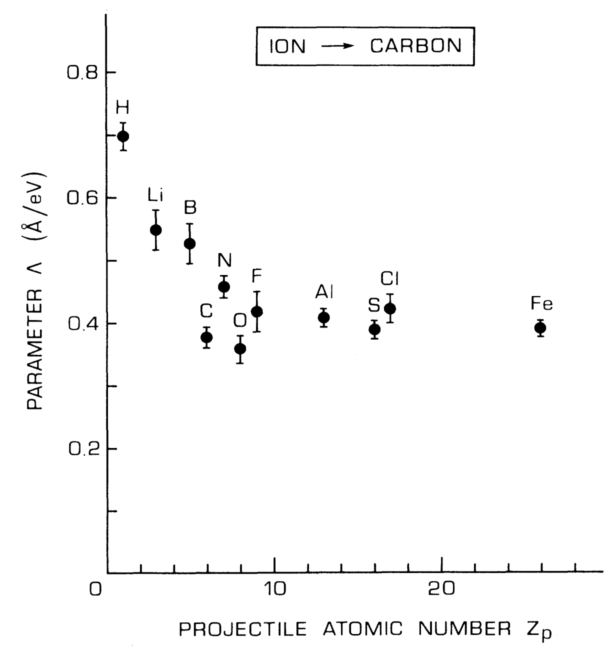

FIG. 6. Projectile atomic number Z_p dependence of the Λ parameter.

$$C = \Lambda(Zp > 1)/\Lambda(Z_p = 1) \tag{3}$$

as discussed in Ref. 24. Parameter C describes in a very general way 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, projectile ionization, or even molecular orbital excitation effects may contribute to the Z_p dependence.

We also observe in Fig. 6 that the Λ parameter first decreases with Z_p and then reaches an equilibrium value of about 0.4 Å/eV for $Z_p \geq 6$ incident ions. A correlation analysis between the coefficient γ and the stopping power S for $Z_p \geq 6$ incident ions (110 experimental values) give

$$\gamma = (0.4 \pm 0.01) S \tag{4}$$

with R squared (validity of the correlation) equal to 98% and where S is given in eV/Å. One must be very careful in the precision attached to the γ value deduced from expression (4). In the correlation analysis we neglected any uncertainty in the stopping power S values which were simply obtained from Ref. 30. It would be desirable to have simultaneous measurements of both γ and S at the same target to reduce the uncertainty sources of power Λ.

In a previous work[22] we indicated that for a given projectile velocity γ and S do not have the same Z_p dependence. We were partially right as we were in the Z_p regime where the equilibrium value of the Λ parameter was not yet reached. Now we know that for $Z_p \geq 6$ ions the Λ parameter is independent not only on the projectile velocity but on the projectile atomic number too, a new and surprising result which needs further investigation.

CONCLUSION

We have studied the SEE coefficient γ as a function of the projectile atomic number, charge state and velocity. For all projectiles in the velocity region studied, the γ coefficient and the stopping power S have the same velocity dependence. A maximum of the yield of electron emission has been also observed for heavy ions at energies very close to the stopping power maximum. The systematic study of the Λ parameter as a function of the projectile atomic number Z_p reveal a nonequilibrium regime for $1 < Z_p < 6$ ions and an equilibrium regime for $Z_p \geq 6$ ions. The obtained results can be partially understood by the semiempirical Sternglass-type model introduced by Koschar *et al.*[7] taking into account nonequilibrium projectile energy losses near the surfaces. Further work to explain the unanswered questions as the independence of parameter Λ with Z_p for $Z_p \geq 6$ is in progress.

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[1]W. O. Hofer, J. Vac. Sci. Technol. A **5**, 2213 (1987).

[2]K. Ertl and W. Behrisch, in *Physics of Plasma-Wall Interactions in Controlled Fusion,* edited by D. E. Port and R. Behrisch (Plenum, New York, 1986), p. 515.

[3]K. O. Groeneveld, Nucl. Tracks Radiat. Meas. **15**, 51 (1988).

[4]M. Burkhard, H. Rothard, J. Kemmler, K. Kroneberger, and K. O. Groeneveld, J. Phys. D **21**, 472 (1988).

[5]P. Lorenzen, H. Rothard, K. Kroneberger, J. Kemmler, M. Burkhard, and K. O. Groeneveld, Nucl. Instrum. Methods **A282**, 213 (1989).

[6]P. Sigmund and S. Tougaard, in *Inelastic Particle-Surface Collisions* (Vol. 17 of Springer Series in Chemical Physics), edited by E. Taglauer and W. Heiland (Springer, Berlin, 1981), p. 2.

[7]P. Koschar, K. Kroneberger, A. Clouvas, R. Schramm, M. Burkhard, O. Heil, J. Kemmler, H. Rothard, H. D. Betz, and K. O. Groeneveld, Phys. Rev. A **40**, 3632 (1989).

[8]E. J. Sternglass, Phys. Rev. **108**, 1 (1957).

[9]J. Schou, Phys. Rev. B **22**, 2141 (1980).

[10]J. Schou, Scanning Electron Microsc. **2**, 607 (1988).

[11]J. Devooght, A. Dubus, and J. C. Dehaes, Phys. Rev. B **36**, 5093 (1987).

[12]M. Rosler and W. Brauer, Phys. Status Solidi B **148**, 213 (1988).

[13]R. A. Baragiola, E. V. Alonso, and A. Oliva-Florio, Phys. Rev. B **19**, 121 (1979).

[14]E. V. Alonso, R. A. Baragiola, J. Ferron, M. M. Jakas, and A. Oliva-Florio, Phys. Rev. B **22**, 80 (1980).

[15]A. Koyama, T. Shikata, and H. Sakairi, Jpn. J. Appl. Phys. **20**, 65 (1981).

[16]A. Koyama, T. Shikata, H. Sakairi, and E. Yagi, Jpn. J. Appl. Phys. **21**, 586 (1982).

[17]H. J. Frischkorn, K. O. Groeneveld, D. Hofmann, P. Koschar, R. Latz, and J. Schader, Nucl. Instrum. Methods **214**, 123 (1983).

[18]C. R. Shi, H. S. Toh, D. Lo, R. P. Livi, M. H. Mendenhall, D. Z. Zhang, and T. A. Tombrello, Nucl. Instrum. Methods **B9**, 263 (1985).

[19]C. C. Dednam, S. Froeneman, D. W. Mingay, and J. van Waart, Nucl. Instrum. Methods **B24**, 366 (1987).

[20]H. Rothard, K. Kroneberger, M. Burkhard, J. Kemmler, P. Koschar, O. Heil, C. Biedermann, S. Lencinas, N. Keller, P. Lorenzen, D. Hofmann, A. Clouvas, K. O. Groeneveld, and E. Veje, Radiat. Eff. Def. Solids **109**, 281 (1989).

[21]K. Kroneberger, A. Clouvas, G. Schlussler, P. Koschar, J. Kemmler, H. Rothard, C. Biedermann, O. Heil, M. Burkhard, and K. O. Groeneveld, Nucl. Instrum. Methods **B29**, 621 (1988).

[22]A. Clouvas, H. Rothard, M. Burkhard, K. Kroneberger, C. Biedermann, J. Kemmler, K. O. Groeneveld, R. Kirsch, P. Misaelides, and A. Katsanos, Phys. Rev. B **39**, 6316 (1989).

[23]H. Rothard, K. Kroneberger, E. Veje, A. Clouvas, J. Kemmler, P. Koschar, N. Keller, S. Lencinas, P. Lorenzen, D. Hofmann, and K. O. Groeneveld, Phys. Rev. B **41**, 3959 (1990).

[24]H. Rothard, K. Kroneberger, A. Clouvas, E. Veje, P. Lorenzen, N. Keller, J. Kemmler, W. Meckbach, and K. O. Groeneveld, Phys. Rev. A **41**, 2521 (1990).

[25]D. Hasselkamp, Comments At. Mol. Phys. **21**, 241 (1988).

[26]J. E. Borovsky, D. J. McComas, and B. L. Barraclough, Nucl. Instrum. Methods **B30**, 191 (1988).

[27]H. J. Frischkorn and K. O. Groeneveld, Phys. Scr. **T6**, 89 (1983).

[28]J. Schader, B. Kolb, K. D. Sevier, and K. O. Groeneveld, Nucl. Instrum. Methods **151**, 563 (1978).

[29]K. Shima, T. Mikumo, and H. Tawara, At. Data Nucl. Data Tables **34**, 357 (1986).

[30]J. F. Ziegler, software TRIM (1987).

[31]H. G. Clerk, H. J. Gehrardt, L. Richter, and K. H. Schmid, Nucl. Instrum. Methods **113**, 325 (1973).

[32]D. Hasselkamp, Habilitationsschrift Justus-Liebig-Universitat Giessen, Germany (1985).

[33]L. B. Bridwell, N. E. B. Cowern, P. M. Read, and C. J. Sofield, Nucl. Instrum. Methods **B13**, 123 (1986) and references therein.

[34]H. D. Betz, Rev. Mod. Phys. **44**, 465 (1972).

[35]W. Brandt, in *Atomic Collisins in Solids,* edited by S. Datz *et al.* (Plenum, New York, 1975), Vol. 1, p. 261.