PHYSICAL REVIEW B VOLUME 22, NUMBER 1 1 JULY 1980

Z_1 dependence of ion-induced electron emission from aluminum

E. V. Alonso, R. A. Baragiola, J. Ferrón, M. M. Jakas, and A. Oliva-Florio*
Centro Atómico Bariloche† *and Instituto Balseiro,*†‡
8400 San Carlos de Bariloche, Argentina
(Received 29 October 1979)

We have measured the electron emission yields γ of clean aluminum under bombardment with H^+, H_2^+, D^+, D_2^+, He^+, B^+, C^+, N^+, N_2^+, O^+, O_2^+, F^+, Ne^+, S^+, Cl^+, Ar^+, Kr^+, and Xe^+ in the energy range 1.2–50 keV. The clean surfaces were prepared by *in situ* evaporation of high-purity Al under ultra-high-vacuum conditions. It is found that kinetic electron emission yields γ_k, obtained after subtracting from the measured γ a contribution due to potential emission, are roughly proportional to the electronic stopping powers, for projectiles lighter than Al. For heavier projectiles there is a sizable contribution to electron emission from collisions involving rapidly recoiling target atoms, which increases with the mass of the projectile, and which dominates the threshold and near-threshold behavior of kinetic emission. The results, together with recently reported data on Auger electron emission from ion-bombarded Al show that the mechanism proposed by Parilis and Kishinevskii of inner-shell excitation and subsequent Auger decay is negligible for light ions and probably small for heavy ions on Al and in our energy range. We thus conclude that kinetic electron emission under bombardment by low-energy ions results mainly from the escape of excited valence electrons.

I. INTRODUCTION

Electron emission (EE) from solids under ion bombardment can proceed via two distinct mechanisms.[1–7] In potential EE (PEE) electrons can be liberated from the solid by the energy released upon neutralization of the incident ion. This process can occur if the ground-state recombination energy of the ion, E_i, exceeds twice the work function of the target ϕ, and being exothermic, it has no kinetic threshold. The number of electrons released per incident ion through PEE, γ_p, can be predicted fairly accurately[7,8] at low impact velocities using a model developed by Kishinevskii.[9] PEE yields are known[6,10] to be fairly constant at velocities lower than 5×10^7 cm/sec and are expected to fall rapidly at higher velocities.[11]

Ions with velocities exceeding a certain threshold, in the range $0.4-2.5 \times 10^7$ cm/sec, can eject electrons by the kinetic EE (KEE) mechanism. Here, the energy required to release electrons from the target is provided by the kinetic energy of the projectile.

In a recent paper[12] (to be referred to as I) we have reported total ion-electron emission yields γ for 2–50-keV H^+, H_2^+, and He^+ in a variety of clean metal targets. It was shown there that KEE for light-ion bombardment can be understood on the basis of a model of direct binary collisions between the light ions and the valence electrons of the target. We have also shown that inner-shell ionization plays a negligible role for low-energy light-ion impact.

Here, we present measurements of electron yields of clean aluminum for different incident ions in the 1.2–50-keV energy range. A good insight into the role of inner-shell Auger processes can be obtained in this case since detailed studies of the excitation of Al $2p$ electrons for light and heavy ions in our energy range have been published recently.[13]

The use of heavy ions also offers the opportunity to test whether the proportionality between electron yields and electronic stopping powers, observed in I for H^+ impact, is of a general nature.

The interest in studies of the dependence of electron yields with Z_1, the atomic number of the projectile, lies also in the possibility of isolating target-dependent quantities related to electron transport and escape through the surface barrier, which should enter as a common factor.

We should mention that several detailed studies of the $\gamma(Z_1)$ dependence have been performed in the past,[14–25] but they all relate to targets which were not clean and therefore, although of possible great technical importance, they do not allow the test of physical models, since electron yields are known to be strongly dependent on the state of the surface which was not well defined in those experiments.

II. EXPERIMENTAL

We will recall here only the main aspects of the apparatus and the experimental technique since a detailed description has been given in I. The ion beams were produced in a conventional accelerator equipped with a radio-frequency (rf) ion source and a magnetic mass analyzer, and which was connected to the UHV target chamber *via* two stages of differential pumping.

The target formed part of a shielded Faraday cup equipped with an electron suppressor electrode. The electrons emitted from the target were collected into a positively biased electrode. Clean polycrystalline samples were prepared by fast *in situ* evaporation of high-purity aluminum (purity better than 99.999%) at pressures in the 10^{-9}-Torr range, and deposition o to a polished stainless steel substrate. Clean sample were also prepared using the standard technique c sputter cleaning with energetic argon ions and we found to give the same EE yields as freshly evaporated surfaces to within our 2% statistical uncertainties. This indicates that trapped Ar and bombardment induced surface topography had no effect on the yields which could be discerned in our experiments. A similar finding was previously reported by Hagstrum[26,27] in the low-energy, PEE region.

The cleanliness of the target could be conveniently monitored by the yield measurements which are known to depend markedly on the degree of gas adsorption. Special care was taken to use very small bombardment doses ($<10^{13}$ ions/cm^2) when using chemically reactive ions, to keep the targets from contaminating to any noticeable extent.

The total experimental errors in the yields amounted to ±4% which include systematic errors arising from the emission of secondary ions from the target (backscattered and sputtered) and from the presence of neutral projectiles in the incident beam.[12] The measurements of the beam energy were accurate to within ±(0.1% +30 eV).

Two more sources of uncertainties can be identified in this work. One is the presence of an unknown fraction of excited metastable ions in the beam, which gives a larger PEE yield than ground state ions.[28,29] This effect is nonexistent for H^+, negligible for He^+,[30] and possibly also for Ne^+.[28,29] For the other ions the uncertainties are expected to be important at our low-energy end in cases where PEE is comparable with KEE. Nevertheless, the results were found to be insensitive to ion source operating conditions which could be expected to result in variation of the population of ion beam particles in excited states.

The other source of uncertainty is the contamination of the atomic ion beam (Y^+) with doubly charged diatomic molecular ions (Y_2^{2+}) which cannot be separated in the magnetic analyzer due to their identical mass to charge ratios. This effect could be important only for N^+ and O^+ since only in cases of using beams of these ions the accelerator produced substantial beams of the respective homonuclear molecular ions N_2^{2+} and O_2^{2+}. The existence of this uncertainty does not allow us to study the molecular effect in EE for these ions, as has been done for hydrogen ions.[31]

III. RESULTS

The experimental results are shown in Figs. 1–5. Figures 1–4 also show the results of other workers

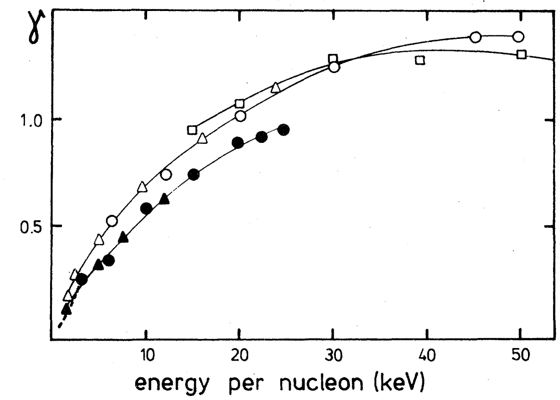

FIG. 1. EE yields per atom vs the energy of the projectile. ○-H^+, ▽-D^+, ●-H_2^+, ▼-D_2^+, this work; – – –-H_2^+ from Ref. 32. □-H^+ from Ref. 33, data for 60° incidence normalized to 0° by dividing by $2=\cos^{-1}(60°)$.

who made efforts to produce and keep their surfaces reasonably clean. The results of Losch[32] for H_2^+ are in good agreement with ours. This author treated his samples in an Ar discharge and conducted measurements at 10^{-8} Torr. Since at these pressures gas adsorption occurs rapidly Losch measured γ as a function of time and extrapolated the results to zero time. The Toulouse group[33] measured yields on surfaces cleaned by sputtering with 40-keV Ar^+ ions and kept in an UHV (10^{-9} Torr) environment. The measurements were done at $\theta=60°$ where θ is the angle between the direction of the ion beam and the normal to the surface. To compare these results with our data we have assumed the law[5] $\gamma=\gamma_0 \sec\theta$ to be valid and have divided their data by $\sec 60°=2$, and found a very good agreement for H^+ and Ar^+ bombardment.

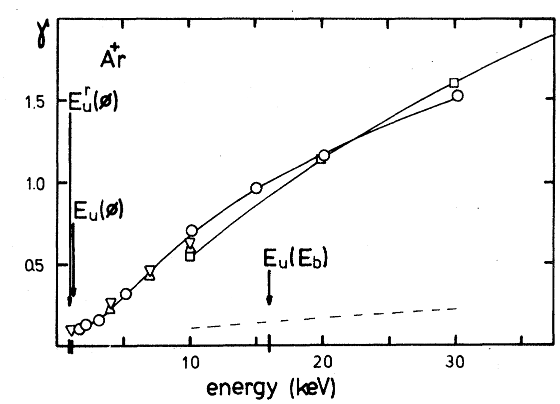

FIG. 2. EE yields for Ar^+ ions vs energy. ○-this work, Δ-Ref. 34, ▽-Ref. 35, □-Ref. 33, data for 60° incidence normalized to 0° by dividing by $2=\cos^{-1}(60°)$. The dashed curve is an estimate of the recoil contribution to EE. See text for the meaning of $E_u(\phi)$, $E_u^r(\phi)$, and $E_u(E_b)$.

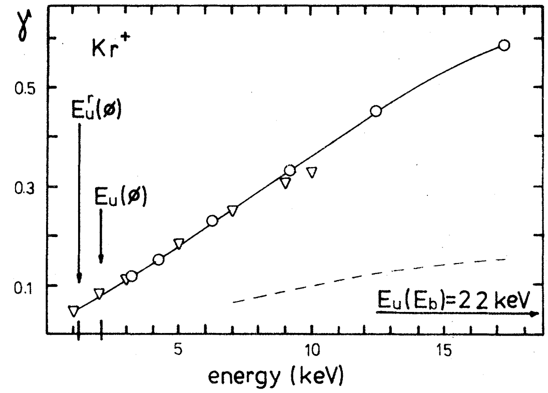

FIG. 3. EE yields for Kr^+ ions vs energy. ○-this work, ▽-Ref. 35. The dashed curve is an estimate of the recoil contribution to EE. See text for the meaning of $E_u(\phi)$, $E_u^r(\phi)$, and $E_u(E_b)$.

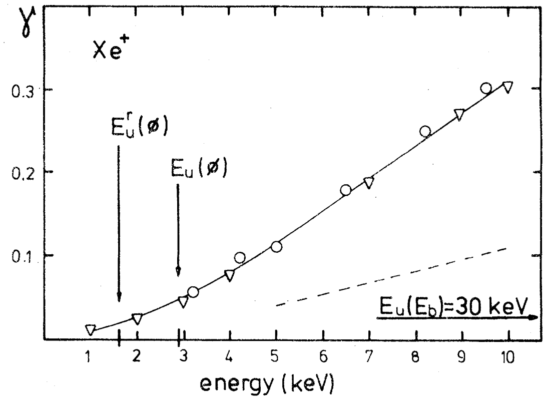

FIG. 4. EE yields for Xe^+ ions vs energy. ○-this work, ▽-Ref. 35. The dashed curve is an estimate of the recoil contribution to EE. See text for the meaning of $E_u(\phi)$, $E_u^r(\phi)$, and $E_u(E_b)$.

The results of Magnuson and Carlston[34] for 1–10-keV Ar^+ on polycrystalline Al and those of Carlston *et al.*[35] for Ar^+, Kr^+, and Xe^+ on Al(111) single crystal surfaces are in excellent accord with ours. These workers performed their experiments at 10^{-8} Torr and used high beam current densities ($>10\ \mu A/cm^2$), thus keeping their surfaces clean by sputtering. The comparison of our results with those of Carlston *et al.* for Al(111) is meaningful since these workers found that highly packed (111) surfaces of fcc metals give yields which are nearly identical to those of polycrystalline surfaces.

Figure 5 shows the dependence of the yields with velocity v, for all the ions studied. The general trend is for γ to be proportional to velocity for the lighter ions and to be larger the heavier the projectile. A notable exception is the behavior shown by F^+ and Ne^+ ions. This particular behavior has previously been observed by Hagstrum[27] and by Gaworzewski *et al.*[36] for Ne^+ on silicon crystals, and is not understood at present.

IV. DISCUSSION

A. Inner-shell ionization (comparison with the theory of Parilis and Kishinevskii)

This theory[37] disregards the direct excitation into vacuum of valence electrons from the target and the

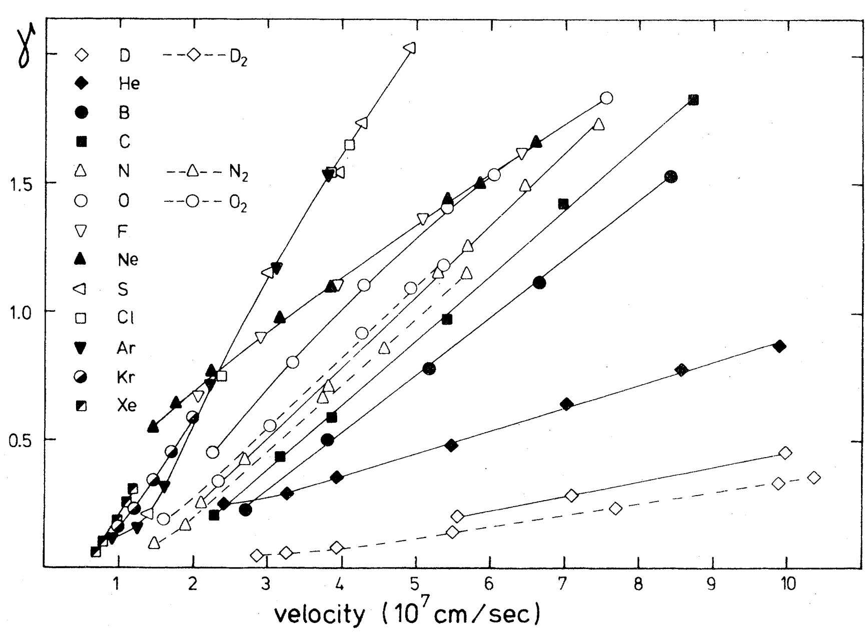

FIG. 5. EE yields for different ions on Al vs the velocity of the projectiles.

projectile and considers KEE to result from a two-step process. In the first, and as a result of a violent collision, a core electron of the target is excited just over the Fermi level; the second step is the filling of the core hole through an Auger process involving valence band electrons. The cross section for inner-shell excitation is taken as $\sigma = S(E_b)/J$ where $S(E_b)$ is the inelastic stopping power for collisions in which the transferred energy is at least equal to E_b, which is the binding energy of the core electron with respect to the Fermi level, and J is the mean energy spent by the projectile in producing electron-hole pairs in the target. Parilis and Kishinevskii (PK) calculate $S(E_b)$ with a modified version of Firsov's friction model for energy loss in atomic collisions[38] which uses a Thomas-Fermi description of the atoms. This stopping power which corresponds to both inner- *and* outer-shell excitation of the projectile *and* the target is incorrectly taken by PK to represent only the stopping due to inner-shell excitation of the target.

One of the consequences of the PK theory is the existence of a threshold velocity for KEE which is the projectile velocity at which the maximum inelastic energy transfer equals E_b. At velocities sufficiently large so that the projectiles lose only a small fraction of their energy over the mean electron escape depth L, PK obtain for the kinetic EE yield:

$$\gamma_k^{PK} = \sigma N L W \ , \tag{1}$$

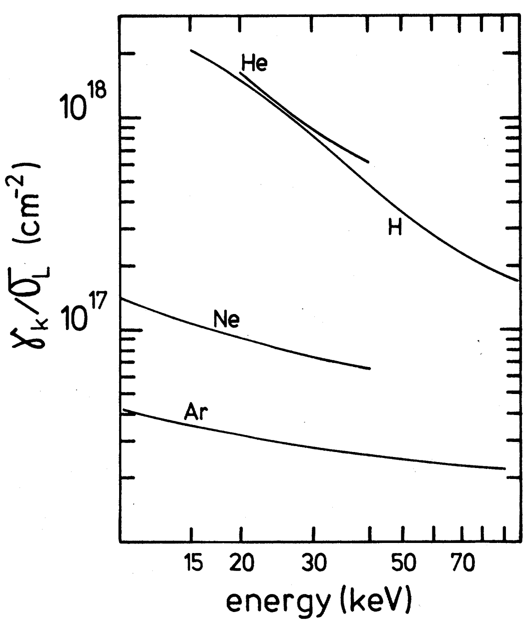

FIG. 6. Ratios between KEE yields γ_k and cross sections σ for Al $2p$ inner-shell excitation vs the energy of the projectiles. KEE yields were obtained by subtracting PEE yields given in Ref. 9 from our measurements. The curves are derived from smooth fits to our data and to cross-section data (Ref. 13).

where N is the target atom density and W is the probability that the Auger process results in EE. W is taken empirically from work on potential EE as $W = 0.016\ (E_b - \phi)$ where ϕ is the work function of the target.

One can test the PK theory by evaluating Eq. (1) and comparing the result with experiment but the uncertainties in the values of J, L, and W do not allow us to make a good judgement on the underlying model. A more meaningful test of the model can be obtained by plotting $\gamma(E)/\sigma(E)$ which according to Eq. (1) should be independent of the projectile energy E and on the nature of the projectile. This has been done in Fig. 6 where we have used $\gamma_k = \gamma - \gamma_p$ with γ as measured in this work and γ_p calculated from Kishinevskii's formula,[9] and the results of Benazeth *et al.*[13] for Al L-shell excitation cross sections.[39] It is clear from Fig. 6 that γ/σ depends strongly not only on energy but also on the type of projectile. This is sufficient to rule out inner-shell excitation from being the only excitation mechanism in KEE. What remains unknown is the relative importance of this mechanism in the total yield; Fig. 6 just tells us that its role will be insignificant for the lighter ions on Al in our energy range.

B. Excitation of valence-band electrons

It was shown above that the neglect of the excitation of valence electrons leads to results in disagreement with experiment. Let us first consider the simple picture in which these electrons are treated as free and in which the perturbation set up by the heavy projectiles in the electron gas is small. In I it was shown that the maximum energy that can be transferred in the binary interactions is:

$$T_m = 2mv(v + v_F) \ , \tag{2}$$

where m is the mass of the electron, v the velocity of the ion, and v_F the Fermi velocity. A threshold velocity v_u for KEE is obtained when $T_m = \phi$, and is given by:

$$v_u = \tfrac{1}{2} v_F [(1 + 2\phi/m v_F^2)^{1/2} - 1] \ . \tag{3}$$

For aluminum ($v_F = 1.97 \times 10^8$ cm/sec, $\phi = 4.26$ eV) we obtain $v_u = 1.75 \times 10^7$ cm/sec.

The fact that valence electrons are not really free but can exchange momentum with the lattice during excitation will cause T_m to be larger than given in Eq. (2) and correspondingly v_u will be smaller than given by Eq. (3). Nevertheless it was shown in I that the extrapolations of the yields of H^+ to very low velocities are not inconsistent with the prediction of this simple model for v_u (the extrapolated threshold velocity for He^+ ions is much lower than v_u due to a substantial potential contribution caused by the high ionization potential of He).

The energy transfer mechanism described for light ions is inefficient due to the large difference between ion and electron masses in the binary screened Coulomb interaction. The situation is different in the case of heavy projectiles which carry many electrons into the collision. In this case electron-electron interactions produce excitations more efficiently as the electron clouds are compressed during the collision. This excitation mechanism, often referred to as electron promotion or Pauli excitation is well known to occur in inelastic processes involving atoms in the gas phase.[40] Then, for heavy ions, the maximum energy transfer and the threshold velocity will be higher and lower than given in Eqs. (2) and (3), respectively.

It is worth noting here that the picture of a weakly perturbed, nearly free valence electron gas will tend to lose its meaning in the case of heavy ions moving slowly in solids since the localized dynamic perturbation which is produced in the system is very strong. The situation will resemble more the case of atomic collisions in gases except for transitions which occur at large internuclear distances.

In analogy with the model proposed in I, we will assume that for projectile energies E such that the maximum inelastic energy transfer $T_m >> \phi$, the number of electrons excited by the projectile above the vacuum level and in the depth interval x, $x+dx$, is:

$$n(x)dx = \frac{S_e(E)}{J}dx \quad , \tag{4}$$

where $S_e = -dE/dx$ is the electronic stopping power and J is the average energy spent by the ion in exciting one electron to final states above the vacuum level.

In this simple model, the electron cascade and attenuation is described by an exponential factor $\exp(-x/L)$ where L takes into account both elastic and inelastic mean free paths and is averaged over electron energies in the cascade and paths to the surface. The average electron escape probability through the surface barrier will be called P and it is dictated by the angular and energy distribution of the electrons reaching the surface and by the height of the surface barrier. Thus, in the path-length approximation:

$$\gamma = -\frac{P}{J}\int_0^\infty -S_e(E)\exp(-x/L)dx \quad . \tag{5}$$

Now, our first condition, $T_m >> \phi$ is valid for initial energies $E_0 >> E_u$ $[T_m(E_u)=\phi]$ since T_m is roughly proportional to $\sqrt{E}$.[37,38] Therefore, and since L is of the order of a few nm,[41] we can expect the energy of the projectile and therefore S_e, not to vary much over distances of this order in such an energy range. We can then take $S_e(E)$ outside the integral and obtain:

$$\gamma = \frac{PL}{J}S_e(E_0) \quad . \tag{6}$$

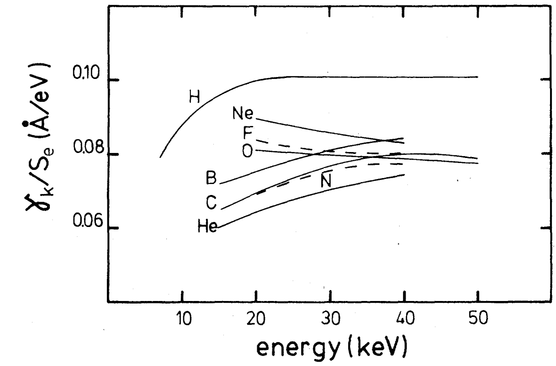

FIG. 7. Ratios between KEE yields γ_k and electronic stopping powers S_e vs ion energy. The curves are derived from smooth fits to KEE data and to stopping power data (Ref. 42).

We have already noted in I for H^+ impact on different metals that for not too low ion velocities v_0, γ/S_e was roughly independent of v_0 which implies that the spatial and energetic distribution in the cascade (which determines PL/J) does not depend much on ion velocity.

Figure 7 shows the ratios γ/S_e from our measurements of γ and those of Ormrod *et al.*[42] for S_e. These workers obtained the stopping powers from measurements of energy loss of ions passing through thin (300–400 Å) Al foils and with equipment of small (~1.15°) angular acceptance. The values of S_e so derived represent, therefore, a lower bound to the total electronic stopping, since the most violent collisions are excluded. To obtain the kinetic contribution to EE we have subtracted from the data potential EE yields γ_p obtained using the formula of Kishinevskii[9] which was recently shown[7,8] to be fairly accurate for a variety of ion-target combinations. Corrections for potential EE are important only in the cases of He^+, F^+, and Ne^+.

We can observe in Fig. 7 that all values of $(\gamma-\gamma_p)/S_e$ fall in a narrow band to within 30%. This spread can be partly attributed to experimental uncertainties and partly to a variation of J with Z_1, analogous to that observed in ion-pair formation in gases.[43] The trend of γ/S_e to decrease at low energies is due to the existence of a threshold energy for KEE below which $\gamma=0$ while S_e has a finite value. For F^+ and Ne^+ projectiles the situation is different with γ/S_e increasing as the energy decreases; this is related to the particular behavior of γ for these projectiles as shown in Fig. 5.

C. Thresholds and recoil effects

The data obtained in this work do not allow us to determine thresholds for KEE with any certainty. Some of the data can, however, be extrapolated with confidence and provide, at least, higher limits for threshold energies. Using the modified Firsov theory[37] we have calculated threshold energies for Ar^+, Kr^+, and Xe^+ impact and have indicated the values in Figs. 2–4. $E_u(E_b)$ is the threshold obtained with the PK theory which assumes that L-shell excitation is responsible for KEE and that therefore the minimum energy transfer required for KEE is E_b, the binding energy of the Al L-shell electrons with respect to the Fermi level. The figures show that these thresholds are clearly too high. The situation is improved if we calculate $E_u(\phi)$ which occurs when the maximum energy transfer equals the work function of the target.

There exists also the possibility that fast recoil atoms from the target produce EE even when the projectile energy is lower than $E_u(\phi)$. This effect, which can be expected to be more important the heavier the projectile, will determine the existence of a new threshold energy $E_u^r(\phi)$. Following this idea we have calculated the threshold energy $E_u'(\phi)$ for Al projectiles and then calculated the minimum projectile energy $E_u^r(\phi)$ to produce an energy transfer $E_u'(\phi)$ to the recoil. These values have also been plotted in Figs. 2–4; it can be observed that a better agreement with experimental data is obtained, particularly for Xe^+ ions.

In the case of light ion impact, the threshold velocity of 1.75×10^7 cm/sec given in I for direct binary interactions with valence electrons, is consistent with the data for projectiles H^+ to N^+ if due account is taken of potential EE, particularly in the case of He^+ ions.

The broken lines in Figs. 2–4 represent an estimate of the contribution of the recoiling target atoms to the KEE yields and were evaluated using two Monte Carlo calculations[44] which followed the histories of projectiles and recoil atoms in the target. In both cases, the effect of elastic collisions on the trajectories was calculated using the Moliere approximation to the Thomas-Fermi interatomic potential, and the modified Firsov theory[37] was used to calculate inelastic energy transfers larger than ϕ as a function of depth. Assuming that the same values of P, J, and L apply for both projectile and recoil induced EE, we finally obtained the percentage contribution of recoiling atoms to the KEE yield. The calculations were limited to energies not too close to the energy threshold since J may vary in a strongly and as yet unknown manner in this energy region. The results show that, as expected, the contribution of recoiling atoms to KEE is more important the larger the mass of the projectile.

D. Z_1 dependence

We have pointed out before that $\gamma(Z_1)$ can be directly related to $S_e(Z_1)$. We will now make a fuller discussion by comparing the observed $\gamma(Z_1)$ dependence with predictions of theories of KEE and electronic stopping.

In the PK theory, which is based in the Firsov model of energy loss:

$$\gamma=f(v)F_1(Z_1,Z_2) \quad ,$$

where

$$f_1(Z_1,Z_2)=\left|\frac{Z_1+Z_2}{Z_1^{1/2}+Z_2^{1/2}}\right|^2 \quad \text{for } \frac{1}{4}<\frac{Z_1}{Z_2}<4 \quad ,$$

and where $f(v)$ is a function of ion velocity but not of Z_1. In a subsequent paper Kishinevskii and Parilis (KP)[45] extended the same theory to be able to deal approximately with light ions (which were not well treated in the Thomas-Fermi model used by Firsov) and obtained a new factor:

$$f_2(Z_1,Z_2)=\frac{(Z_1^{1/2}+Z_2^{1/2})}{(Z_1^{1/6}+Z_2^{1/6})^3} \quad .$$

Two semiempirical relations exist, besides the Firsov theory, for the Z_1, Z_2 dependence of the electronic stopping at low velocities. Lindhard and Scharff[46] proposed, using dimensional arguments

$$S_e \propto Z_1^{7/6}Z_2N/(Z_1^{2/3}+Z_2^{2/3})^{3/2} \quad ,$$

where N is the number density of the target atoms.

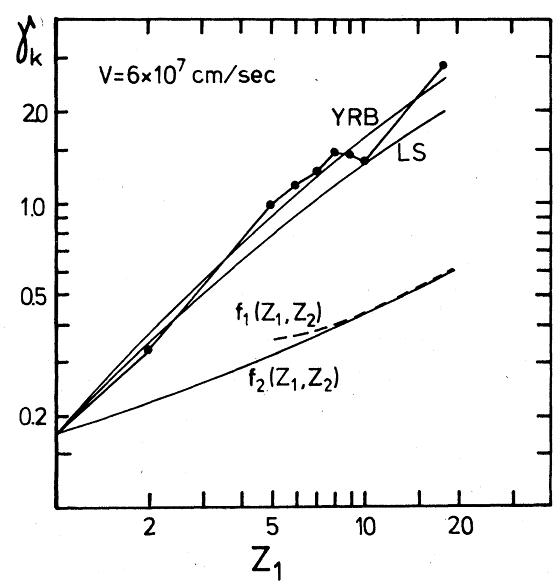

FIG. 8. KEE yields γ_k vs Z_1, the atomic number of the projectiles for a fixed value of initial impact velocity, $v=6\times10^7$ cm/sec. ●-this work, except for Ar^+ ($Z=18$) which is taken from Ref. 33. Theoretical or empirical estimates are: $f_1(Z_1,Z_2)$ from Ref. 37 with $Z_2=13$, $f_2(Z_1,Z_2)$ from Ref. 45 with $Z_2=13$, Lindhard and Scharff (LS) from Ref. 46, Yarlagadda, Robinson, and Brandt (YRB) from Ref. 47. Curves $f_2(Z_1,Z_2)$, LS, and YRB are normalized to coincide with our proton data. $f_1(Z_1,Z_2)$ is normalized to $f_2(Z_1,Z_2)$ at $Z_1=13$.

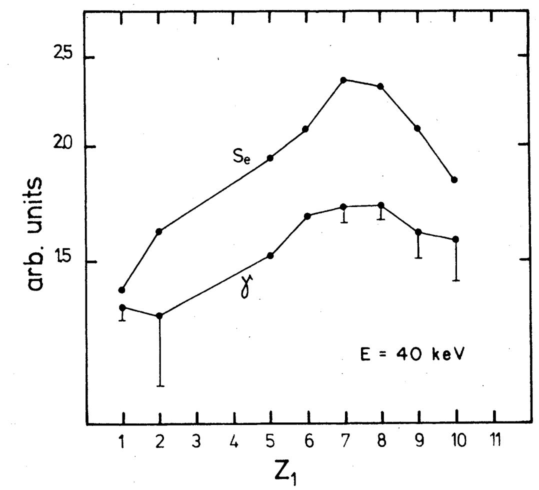

FIG. 9. EE yields γ and electronic stopping powers S_e vs Z_1, the atomic number of the projectile for a fixed value of incident energy, $E_0=40$ keV. γ-this work, S_e from Ref. 42. The bars gives the magnitude of the PEE yields $\gamma_p(0)$ in the low velocity limit as given in Ref. 9. γ_p (40 keV) are expected to be substantially smaller than $\gamma_p(0)$ for H^+ and He^+ ions.

Yarlagadda *et al.*[47] in a more empirical approach proposed:

$$S_e \propto Z_1^2[1-\exp(-0.95Z_1^{-2/3})]^2 \ .$$

A comparison between these theories and KEE yields $(\gamma-\gamma_p)$ is made in Fig. 8 for a projectile velocity of 6×10^7cm/sec. Good agreement is found between the Z_1 dependence of KEE and the models of Lindhard and Scharf and Yarlagadda *et al.* for electronic stopping while the KEE theories of PK and KP give a very different Z_1 dependence.

Besides the general trend apparent in Fig. 8 one can also observe a small superimposed structure. This structure is more conspicuous when γ vs Z_1 is plotted at a fixed projectile energy rather than velocity. Figure 9 shows S_e and γ vs Z_1 at 40 keV. Also indicated in the figure are the magnitudes of potential EE yields calculated with Kishinevskii's formula; at these energies, however, we can expect a reduction in the values of γ_p especially for light ions, due to their large velocity.[48]

It can be observed in Fig. 9 that the maxima of $\gamma(Z_1)$ and $S_e(Z_1)$ occur at approximately the same position but that the relative magnitude of the structure is larger in stopping than in KEE and that there are differences in the relative behavior of H^+ and He^+. The larger relative structure in $S_e(Z_1)$ is possibly related to the larger average impact parameters involved in S_e determinations using a small angle transmission experiment. This idea is supported by the facts that S_e measurements under channeling conditions (which heavily discriminate against small impact parameters) show very large Z_1 oscillations[49–51] and that measurements of energy loss straggling (which gives more weight to small impact parameter collisions) show practically no structure.[52]

V. CONCLUSIONS

Our measurements of electron emission yields from clean aluminum induced by ion bombardment have allowed us to evaluate the importance of Parilis and Kishinevskii's mechanism of inner-shell excitation and subsequent Auger decay in KEE. It was found that this mechanism does not account for the main part of the observations and furthermore that its role is negligible for light ions in the keV energy range; on the contrary, the excitation of valence electrons seems to predominate at these low energies.

We have also evaluated the role of recoiling target atoms finding that in the case of heavy ion bombardment they account for the energy threshold in KEE. In the case of projectiles of mass smaller or comparable to the mass of the target, the contribution of recoils is small and the KEE yields were found to be roughly proportional to the electronic stopping power at energies not too close to threshold. The proportionality factor was found not to depend much on the type of projectile providing evidence for a more general relationship between electronic stopping and KEE yields.

ACKNOWLEDGMENTS

This work was partially supported by the International Atomic Energy Agency under Contract No. 1928/RB and by the Multinational Program in Physics of the Organization of American States.

*Mayor, Fuerza Aérea Argentina.
†Comisión Nacional de Energía Atómica.
‡Universidad Nacional de Cuyo.

[1] M. Kaminsky, *Atomic and Ionic Phenomena on Metal Surfaces* (Springer, Berlin, 1965).
[2] D. B. Medved and I. S. Strasser, Adv. Electron. Electron Phys. 21, 101 (1965).
[3] I. A. Abroyan, M. A. Eremeev, and N. N. Petrov, Usp. Fiz. Nauk. 92, 105 (1967) [Sov. Phys. Usp. 10, 332 (1967)].
[4] K. H. Krebs, Fortschr. Phys. 16, 419 (1968).
[5] G. Carter and J. S. Colligon, *Ion Bombardment of Solids* (Heinemann, London, 1968).
[6] U. A. Arifov, *Interaction of Atomic Particles with a Solid Surface* (Consultants Bureau, New York, 1969).
[7] R. A. Baragiola, E. V. Alonso, J. Ferrón, and A. Oliva-

Florio, Surf. Sci. 90, 240 (1979).
[8]H. Oeschner, Phys. Rev. B 17, 1052 (1978).
[9]L. M. Kishinevskii, Radiat. Eff. 19, 23 (1973).
[10]M. Perdrix, S. Paletto, R. Goutte, and C. Guillaud, Phys. Lett. A 28, 534 (1969).
[11]H. Hagstrum, Phys. Rev. 96, 336 (1954).
[12]R. A. Baragiola, E. V. Alonso, and A. Oliva-Florio, Phys. Rev. B 19, 121 (1979).
[13]C. Benazeth, N. Benazeth, and L. Viel, Surf. Sci. 78, 625 (1978).
[14]D. Herold, Z. Angew. Phys. 20, 113 (1965).
[15]M. van Gorkon and R. E. Glick, Intern. J. Mass Spectrom. Ion Phys. 4, 203 (1970).
[16]F R. Cawthron, Aust. J. Phys. 24, 859 (1971).
[17]R. . Lao, R. Sander, and R. F. Pottie, Int. J. Mass Spectrom. Ion Phys. 10, 309 (1972/73).
[18]R. F. Pottie, D. L. Cocke, and K. A. Gingerich, Int. J. Mass Spectrom. Ion Phys. 11, 41 (1973).
[19]U. Fehn, Int. J. Mass Spectrom. Ion Phys. 15, 391 (1974).
[20]U. Fehn, Int. J. Mass Spectrom. Ion Phys. 21, 1 (1976).
[21]G. Staudenmaier, W. O. Hofer, and H. Liebl, Int. J. Mass Spectrom. Ion Phys. 21, 103 (1976).
[22]S. Rogaschewski and H. Düsterhöft, Phys. Status Solidi B 75, K173 (1976).
[23]R. J. Beuhler and L. Friedman, Int. J. Mass Spectrom. Ion Phys. 23, 81 (1977).
[24]R. J. Beuhler and L. Friedman, J. Appl. Phys. 48, 3928 (1977).
[25]M. A. Rudat and G. H. Morrison, Int. J. Mass Spectrom. Ion Phys. 27, 249 (1978).
[26]H. D. Hagstrum, Phys. Chem. Solids 14, 33 (1960).
[27]H. D. Hagstrum, Phys. Rev. 119, 940 (1960).
[28]H. D. Hagstrum, Phys. Rev. 104, 309 (1956).
[29]H. D. Hagstrum, J. Appl. Phys. 31, 897 (1960).
[30]R. A. Baragiola and E. R. Salvatelli, Phys. Rev. A 12, 806 (1975).
[31]R. A. Baragiola, E. V. Alonso, O. Auciello, J. Ferrón, G. Lantschner, and A. Oliva-Florio, Phys. Lett. A 67, 211 (1978).
[32]W. H. P. Losch, Phys. Status Solidi A 2, 123 (1970).
[33]N. Benazeth (private communication).
[34]G. D. Magnuson and C. E. Carlston, Phys. Rev. 129, 2403 (1963).
[35]C. E. Carlston, G. D. Magnuson, P. Mahadevan, and D. E. Harrison, Phys. Rev. 139, A729 (1965).
[36]P. Gaworzewski, K. H. Krebs, and M. Mai, Int. J. Mass Spectrom. Ion Phys. 10, 425 (1972/73).
[37]E. S. Parilis and L. M. Kishinevskii, Sov. Phys. Solid State 3, 885 (1960).
[38]O. B. Firsov, Sov. Phys. JETP 36, 1076 (1959).
[39]In Ref. 13, Al $2p$ Auger electrons were assumed to be produced in projectile-Al collisions. Whether this is true or whether Al-Al collisions are more important only affects the interpretation of the meaning of σ given by these authors, but not the conclusions which are drawn here.
[40]J. S. Briggs, Rep. Prog. Phys. 39, 217 (1976).
[41]T. F. Gesell and E. T. Arakawa, Phys. Rev. Lett. 26, 377 (1971).
[42]J. H. Ormrod, J. R. MacDonald, and H. E. Duckworth, Can. J. Phys. 43, 275 (1965).
[43]J. R. MacDonald and G. Sidenius, Phys. Lett. A 28, 543 (1969).
[44]E. V. Alonso, Ph.D. thesis (Universidad Nacional de Cuyo, 1978) (unpublished); The Monte Carlo simulation is a modified version of the TRIM program written by J. Biersack (unpublished).
[45]L. M. Kishinevskii and E. S. Parilis, Bull. Acad. Sci. USSR, Phys. Ser. 26, 1432 (1962).
[46]J. Lindhard and M. Scharff, Phys. Rev. 124, 128 (1961).
[47]B. S. Yarlagadda, J. E. Robinson, and W. Brandt, Phys. Rev. B 17, 3473 (1978).
[48]H. D. Hagstrum, in *Electron and Ion Spectroscopy of Solids*, edited by L. Fiermans, J. Vennik, and W. Dekeyser (Plenum, New York, 1978).
[49]L. Eriksson, J. A. Davies, and P. Jespersgaard, Phys. Rev. 161, 219 (1967).
[50]F. H. Eisen, Can. J. Phys. 46, 561 (1968).
[51]J. Bøttiger and F. Bason, Radiat. Eff. 2, 105 (1970).
[52]I. Hoffmann, E. Jäger, and U. Müller-Jahreis, Radiat. Eff. 31, 57 (1976).