Excitation of Electrons from an Al Surface by Grazing-Angle-Incident Fast Heavy Ions

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Measurements were made, at various emission angles, of energy spectra of electrons from Al induced by grazing-angle-incident ions of N^{6+}, Ar^{12+}, and Xe^{27+} with equal velocities corresponding to 0.98 MeV/amu. A new line which could not be explained by any of the hitherto identified mechanisms was observed at an energy obviously larger than that of an electron with a velocity equal to the projectile. The projectile and emission-angle dependences of the line are consistent with the dynamic-image-potential acceleration mechanism.

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When a fast charged particle penetrates a solid medium, it emerges accompanied by electrons which move at the same velocity as the ion; these electrons captured in the continuum states of the projectile are called convoy electrons (CE). The charged projectile emerging near the surface induces a dynamic image potential (DIP) due to polarization of surface electrons.[1,2] The force due to the DIP may accelerate the CE. Burgdörfer calculated the DIP-induced energy increase of CE which were emitted normal to the surface.[3] However, hitherto no evidence of DIP acceleration has been obtained for such normal-emitted CE.

If the particle is incident or emerges almost parallel to the surface, the interaction time between the surface and the projectile is very long, and the interaction time between the CE and the DIP should also be long; acceleration of CE may be significant and observable. de Ferrariis and Baragiola measured the energy spectra of electrons ejected from an Al surface due to grazing-angle-incident H^+ ions.[4] A broad peak was observed but no description was given for the influence of the DIP of the CE spectra. Hasegawa, Kimura, and Mannami measured energy spectra of electrons emitted from a SnTe single-crystal surface following the impact of grazing-angle-incident H^+ and He^+ ions.[5] For H^+ ions, the most probable energy of the peak was not larger than $E_l = \frac{1}{2} m v_l^2$, where m is the mass of an electron and v_l is the velocity of the projectile. However, for He^+ ions, the peak energy was larger than E_l, and DIP acceleration was evoked to explain this energy increase. Winter, Strohmeier, and Burgdörfor measured the energy spectra of electrons emitted from a Si(111) surface, for grazing-incident-angle H^+ ions, and also observed significantly broadened cusp-shaped lines. They attributed this broadening to a deviation from the Coulombic final-state interaction near the surface due to the DIP.[6] Recently, Hasegawa *et al.* measured the incident-energy dependence of the peak energy for the He^+-SnTe system.[7] They calculated the peak energy based on the DIP acceleration model, and obtained results qualitatively consistent with the experiments.

In the present work, we report energy spectra of electrons emitted from Al following grazing-incident-angle irradiation by heavy ions. Each spectrum shows a new structure which is dependent on the emission angle and the species of projectile, and is clearly different from any structure due to Auger electrons, convoy electrons, loss electrons, or those excited by binary collisions. The most probable energy of the structure is larger than E_l by 60–250 eV, for emission angles smaller than 10°–20° relative to the incident beam direction, and the energy difference from E_l is approximately proportional to the equilibrium charge of the projectiles. These results provide new evidence for the DIP acceleration of CE.

Equal-velocity ions of N^{6+}, Ar^{12+}, and Xe^{27+} with energies of 0.98 MeV/amu ($E_l = 532$ eV) were provided by the linear accelerator of the Institute of Physical and Chemical Research. The ionic charges are nearly equal to the equilibrium ones at the present incident energies. It is considered, therefore, that their charge states are changed insignificantly by interactions with the surface, and thereby the experimental results may be explained. Charge separation was achieved by use of a bending magnet, and the target-chamber vacuum was kept below 2×10^{-10} Torr during measurements. Al was evaporated *in situ* onto an optically flat Si substrate of 10 mm width

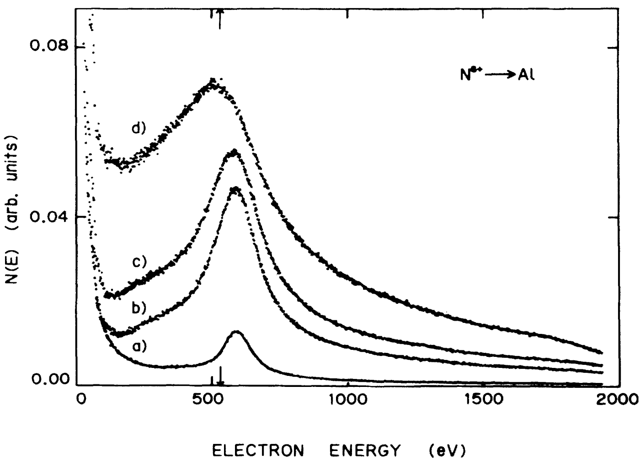

FIG. 1. Energy spectra of electrons emitted from an Al surface induced by N^{6+} ions of 0.98 MeV/amu incident at 1° with respect to the surface. Detection angles, with respect to the incident beam direction, are curve *a*, 3°; *b*, 6°; *c*, 8°; and *d*, 15°.

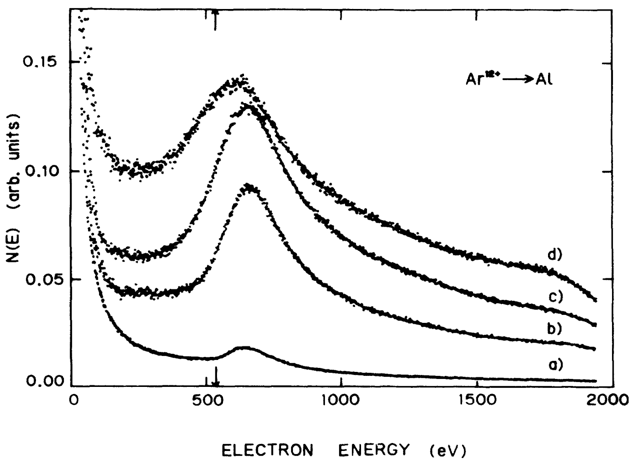

FIG. 2. Same as in Fig. 1, but for projectiles of Ar^{12+} ions isotatic with the N^{6+} ions.

and 20 mm length, in a vacuum of better than 10^{-8} Torr. Surface structures created by the evaporation seemed to decrease the most probable energy of excited electrons, and, therefore, the data adopted here were only from targets whose surface structures were not observable by scanning electron microscopy. Surface contamination was checked by Auger electron spectroscopy, and not detected. The electron energy was analyzed by using a parallel-plate analyzer with angular resolution of ±0.6° and energy resolution of 1%. A lowering of the energy and angular resolution caused by an extended electron source at grazing-angle incidence of the projectiles originates mainly from an increase in the range of inlet angles of the electrons to be analyzed. However, the inlet-angle range was restricted to within ±1° by analyzer slits, and the lowering of the energy resolution was only ±0.1%, which was negligible. Electron emission angles were, therefore, determined within an accuracy of ±1°, while projectile incident angles were regulated to within ±0.2°. Energy calibration of the electron analyzer was done by using electrons of known energy from an electron gun. That of the accelerator was carried out by using beam-foil-induced convoy electrons; their energies as measured by the electron analyzer indicated a value of 532 eV, which was equal to that expected from the projectile energies.

Figure 1 shows the energy spectra of electrons induced by N^{6+} ions incident at an angle of 1° with respect to the target surface and emitted at various angles with respect to the incident beam direction: curve *a*, 3°; *b*, 6°; *c*, 8°; and *d*, 15°. The ordinate is proportional to the number of electrons induced by a projectile into the unit energy interval $N(E)$. The arrow shows E_I, the energy of electrons isotatic with the projectile. Figures 2 and 3 show similar spectra for Ar^{12+} and Xe^{27+} ions at the same grazing-incident angle, and electron emission angles as in Fig. 1. It is well known that the energies of electrons produced in atomic collisions are representative of the respective excitation mechanisms.[8] Each spectrum obtained here shows a large peak of low-energy secondary electrons. Binary peaks are clearly seen for Xe^{27+} ions due to their large cross sections at energies higher than 1500 eV. The peak with the most probable energy of 500–800 eV cannot be explained by any of the hitherto identified mechanisms. It is not due to target Auger electrons, since there are no Auger-electron peaks in this energy range for either Al or Si, and any energy shift due to the Doppler effect is negligibly small at the present incident energy.[9] The peak is also not due to projectile Auger electrons. From kinematic considerations, if it were due to projectile Auger electrons, another peak should be observed in the energy range of 300–400 eV with an intensity similar to this peak.[10] Furthermore,

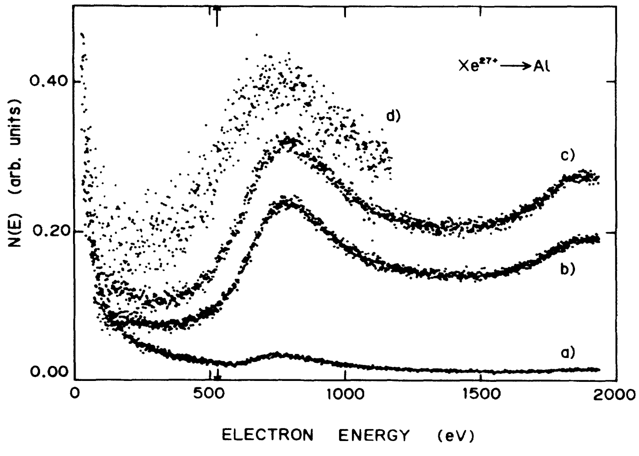

FIG. 3. Same as in Fig. 1, but for projectiles of Xe^{27+} ions isotatic with the N^{6+} ions.

the peak intensity increases steeply as the direction of electron emission deviates from the incident beam; such Auger electrons. This peak cannot, of course, result from the usual CE because of the energy increase observed.

The following results are obtained from the figures. (I) The energy difference between the highest E_e and E_I is 60 eV for N^{6+}, 120 eV for Ar^{12+}, or 250 eV for Xe^{27+}, and is approximately proportional to the projectile charge q. (II) The peak width increases with increasing q. The values of FWHM at the emission angle of 6° are about 200 eV for N^{6+}, 300 eV for Ar^{12+}, and 400 eV for Xe^{27+}. (III) The emission angle at which E_e is largest increases with projectile charge. (IV) The peak intensity increases steeply with increasing emission angle from 3° to 6°.

These results can be explained in terms of the DIP acceleration of CE. CE may be mainly produced by projectiles emerging from the surface, because the outgoing part of the projectile trajectory plays an important role in the CE excitation.[6] These CE should be accelerated by the DIP. The potential is retarded from the projectile by a distance of about $0.1V_I/\omega_s$, where ω_s is the surface-plasmon frequency.[11] This retardation causes the acceleration of CE. The potential also repels CE from the surface towards vacuum, and makes them deviate from the projectile trajectory. When $\mathbf{v}_a$ is the velocity increase due to the potential, its value is proportional to q, because the height of the potential is proportional to q. Its direction with respect to the outgoing part of the ion trajectory, θ_a, is independent of the projectile species; based on classical mechanics, it depends approximately only on the initial phase-space coordinates of the CE. The velocity of the accelerated electrons is given by the vector sum of $\mathbf{v}_a$ and $\mathbf{v}_I$. The energy increase is given by

$$E_e - E_I = mv_I v_a \cos\theta_a + mv_a^2/2 \simeq v_I \Delta P \cos\theta_a \,, \tag{1}$$

where ΔP $(=mv_a)$ is the impulse due to this potential. The direction of the accelerated electrons with respect to the emerging ion velocity, θ_e, is given by

$$\tan\theta_e = v_a \sin\theta_a/(v_I + v_a \cos\theta_a) \,. \tag{2}$$

The energy increase is expected to be proportional to projectile charge q, as seen from Eq. (1), because the impulse ΔP is proportional to q. This is supported by the experimental results (I). The linewidth should increase with increasing q, because line broadening is a result of the energy variation for different trajectories of electrons, which are emitted at the same angle θ_e, and because the energy difference will increase with q. This is also consistent with the results (II). Result III is explained by means of Eq. (2); θ_e increases with v_a which is proportional to q for constant θ_a. Finally, result IV can be explained: Equation (2) means that θ_e cannot be smaller than some value, because θ_a is not small, as well as v_a, due to the DIP repelling electrons from the surface. Consequently, it results that electrons are almost all emitted at angles higher than 3°. The charge dependence of these experimental results is not due to either energy straggling or angular divergence of the emerging projectiles; the observed energy and angular distribution of unaccelerated CE produced by emerging projectiles is narrow compared with that of the accelerated electrons, and, therefore, that of the emerging projectiles should be also narrow.[12] Thus the DIP acceleration model is qualitatively in good agreement with the present experimental results.

Quantitatively, based on the DIP acceleration model, Iitaka *et al.* carried out a numerical calculation of the energy and angular distribution of accelerated CE.[13] They calculated, using a Monte Carlo method, trajectories for a large number of CE which were induced by a projectile moving parallel to the surface and accelerated by the DIP approximated by a simple dipole poential, as used by Winter, Strohmeier, and Burgdörfer.[6] The calculated energy increases were almost equal to the present experimental values. Therefore, it is concluded that when a projectile is incident at a grazing angle to a surface, CE are accelerated by the DIP.

In summary, energy spectra of electrons emitted from Al were measured for grazing-angle-incident heavy ions. For emission angles smaller than 10° with respect to the target surface, a prominent and comparatively sharp peak was observed at an energy larger than that of electrons isotatic with the projectile. This peak cannot be explained by any of the hitherto identified excitation mechanisms. The present experimental results are consistent with the dynamic-image-potential acceleration mechanism.

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