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AUTOIONIZATION OF Ne PROJECTILES IN COLLISIONS WITH SURFACES

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We have measured the energy distributions of Ne autoionization electrons produced in collisions of 0.5–3 keV Ne^+ ions with Al surfaces. We have found a strong broadening and a weak energy shift of the lines with increasing projectile energy. We have also identified the autoionization transitions leading to these lines.

One of the most important tools for surface chemical analysis is Auger electron spectroscopy, in which one measures the energy distribution of electrons emitted from a surface following excitation by incident X-rays, electrons or heavy particle beams. In the latter case Auger electron emission from the projectile can also occur.

This work is concerned with the Auger electrons from neon produced in the collision of Ne^+ ions with a metal surface. Several papers related to this subject have recently appeared in the literature [1–4]. Their authors gave quite different interpretations to similar experimental results. Ferrante and Pepper [1] observed Auger electrons from Ne produced during bombardment of Mg and Al surfaces with 0.4–3 keV Ne^+ ions; they attributed these electrons to excitations in asymmetric collisions between the incident Ne and the metal surface atoms.

Benazeth et al. [2] repeated the experiment at energies higher than 5 keV; the results obtained were similar to those of Ferrante and Pepper but they proposed that the Ne Auger electrons result from autoionization of Ne atoms implanted in the solid, which were excited by the incident Ne^+ in symmetric collisions. This conclusion was mainly based on their observation that the widths of the Auger lines did not depend on projectile energy, against what is expected for a moving source of electrons (Doppler effect).

In subsequent papers each group tried to reinforce its position reporting new results. Pepper and Ferrante [3] found no relation between the Ne Auger signal and the density of implanted Ne near the surface; Benazeth et al. [4]

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reported coincidences between their interpretation and experimental results, when approximate implantation parameters were taken into account in their ad hoc model.

Our work was intended to clarify this contradictory state.

We studied the Ne Auger electrons produced in the collision of 0.5–3 keV Ne^+ with an Al surface. The apparatus used in this work has been described previously [5]. The target is mounted inside an ultrahigh vacuum chamber operating at a pressure lower than 10^{-10} Torr. The Ne^+ ions were produced by an electron-bombardment-type ion gun; they were mass analyzed using a Wien filter and electrostatically deflected onto the target to separate them from possible neutral atoms in the beam. Electrons ejected in a narrow cone around a direction lying 15° from the normal to the surface (and at 133° from the beam direction), were energy analyzed with a hemispherical electrostatic analyzer with a resolution of 0.5%. The zero of the electron energy scale was determined from the observation of the elastic reflection from the target of electrons accelerated through an accurately known potential [5]. The ion current density onto the target was less than 4×10^{-9} A/mm^2.

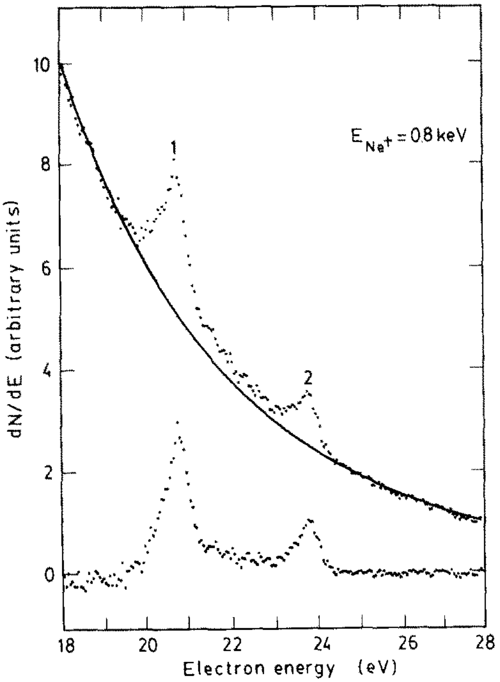


Fig. 1. Electron energy spectrum from collisions between 0.8 keV Ne^+ and Al surfaces (upper dot line). The full line is a fit to a background curve. The lower spectrum is obtained after background subtraction. The electron energy is measured from the vacuum level of the Al target with an analyzer resolution of 0.12 eV.

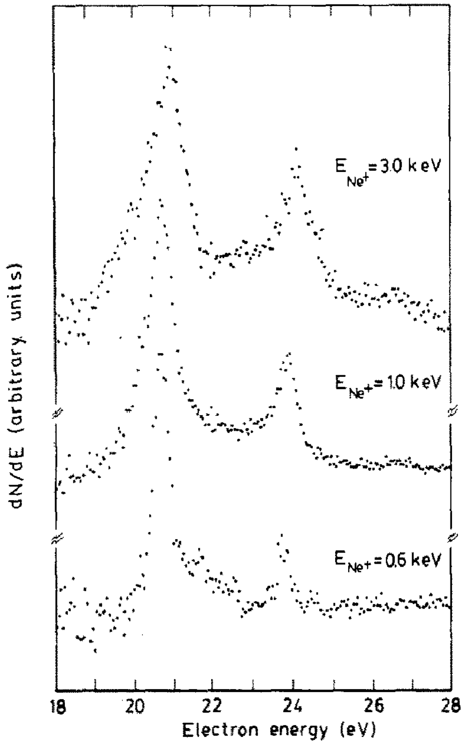
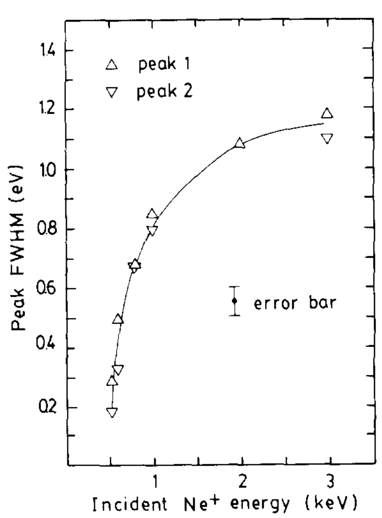


Fig. 2. Electron energy spectra (after background subtraction) from collisions of 0.6, 1.0 and 3.0 keV Ne^+ with Al surfaces.

The spectra obtained show the Auger peaks superimposed on a background curve corresponding to electrons ejected by other mechanisms. In order to study the Auger peaks, a background subtraction was needed. The background curve (see fig. 1) was determined by fitting regions of the spectra where the Auger intensity was assumed to vanish, to a function of the form $aE^{-m}+b$, where E is the electron kinetic energy and a, b and m constants to be optimized. Fig. 2 shows spectra obtained at different impact energies, after background subtraction. They show two prominent atomic like peaks which broaden and shift to high energies as the projectile energy increases.

It is important to point out that the occurrence of these peaks does not depend on bombardment time; we have verified that the peaks are already present in the first spectral scan, which is taken at a total dose as low as 10^{12} Ne/cm^2. This observation is in accordance with the result of Ferrante and Pepper in the sense that the Ne Auger signal does not depend on the density of Ne atoms implanted in the solid, at least in our energy range.

Figs. 3 and 4 show the full width at half maximum (FWHM) and the most



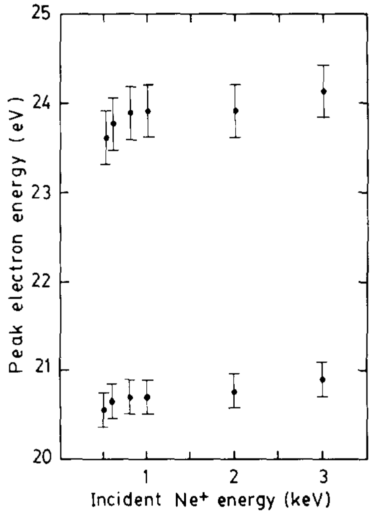


Fig. 3. Full width half maximum (FWHM) of the autoionization peaks versus projectile energy. The line is drawn to guide the eye and has no other meaning.

Fig. 4. Most probable energy of the autoionization peaks versus projectile energy.

probable energy of both peaks. The outstanding features of these figures are:
(i) The peak widths increase with projectile energy and are the same for both peaks, within the experimental error.
(ii) A threshold energy for broadening is apparent whose value is in good agreement with the threshold energy for Ne Auger electron production obtained by Ferrante and Pepper [1].
(iii) The shifts in the peak positions are small and very similar for both peaks.

Based on these findings we postulate that the Ne excitation occurs in collisions of Ne ions with Al target atoms, and that the decay occurs from a moving atom outside the surface.

We will now identify the transitions which lead to the observed peaks. The production of Ne Auger electrons in atomic collisions is well known: for heavy ion impact at high energies, they are produced mainly by excitation of a 2s electron [6]; whereas at low energies, because of quasi molecular effects, they result from the promotion of two 2p electrons [7–9]. These results suggest that the peaks observed in our experiment also correspond to the excitation of two 2p electrons (autoionizing states). In order to identify them we can make use of the results of Andersen and Olsen; they found seventeen peaks which are listed in table 1. We are then faced with the question: why do only two peaks appear in the collision with a surface? The answer comes from considering the electronic transitions which can occur if an excited atom is placed near a metal

Table 1
Autoionizing states of neon excited in atomic collisions

Label	Initial state	Excitation energy (eV)	Ionization energy (eV)	Kinetic energy (eV)	Final state
A	$2p^4(^3P)3s^2\ ^3P$	41.95	7.116	20.35	$2p^5(^2p)$
B	$2p^4(^3P)[3s3p(^3P)]^3D,\ ^3P$	44.50	4.566	22.90	$2p^5(^2p)$
C	$2p^4(^1D)3s^2\ ^1D$	45.15	7.003	23.55	$2p^5(^2p)$
D	$2p^4(^3P)[3s3p(^1P)]^3P,\ ^3D$	45.65	3.416	24.05	$2p^5(^2p)$
E	$2p^4(^3P)[3s3d]$	46.85	2.216	25.25	$2p^5(^2p)$
F	$p2^4(^3P)[3s4s(^3S)]^1P$	47.10	1.966	25.50	$2p^5(^2p)$
G	$2p^4(^1D)[3s3p(^3P)]^3F$	47.25	4.903	25.65	$2p^5(^2p)$
H	$2p^4(^1D)[3s3p(^3P)]^3P,\ ^3D$	47.55	4.603	25.95	$2p^5(^2p)$
I	$2p^4(^3P)[3s3d(^3D)]^1D,\ ^1P,\ ^1F$	47.70	1.366	26.10	$2p^5(^2p)$
J	$2p^4(^3P)[3p^2(^3P)]^3D,\ ^3P$	48.00	4.154	26.40	$2p^5(^2p)$
K	$2p^4(^3P)[3p^2(^3P)]^1D,\ ^1S,\ ^1P$	48.30	3.854	26.70	$2p^5(^2p)$
L	$2p^4(^1D)[3s3p(^1P)]^1F,\ ^1D,\ ^1P$	48.90	3.253	27.30	$2p^5(^2p)$
M	$2p^4(^1S)3s^2\ ^S$	48.90	7.008	27.30	$2p^5(^2p)$
N	$2p^4(^1D)[3s3d(^1D)]$	50.00	2.153	28.40	$2p^5(^2p)$
O	$2p^4(^1D)[3s3d(^3D)]$	50.45	1.703	28.85	$2p^5(^2p)$
P	–	51.05	–	29.45	$2p^5(^2p)$
Q	–	51.25	–	29.65	$2p^5(^2p)$
R	–	51.70	–	30.10	$2p^5(^2p)$

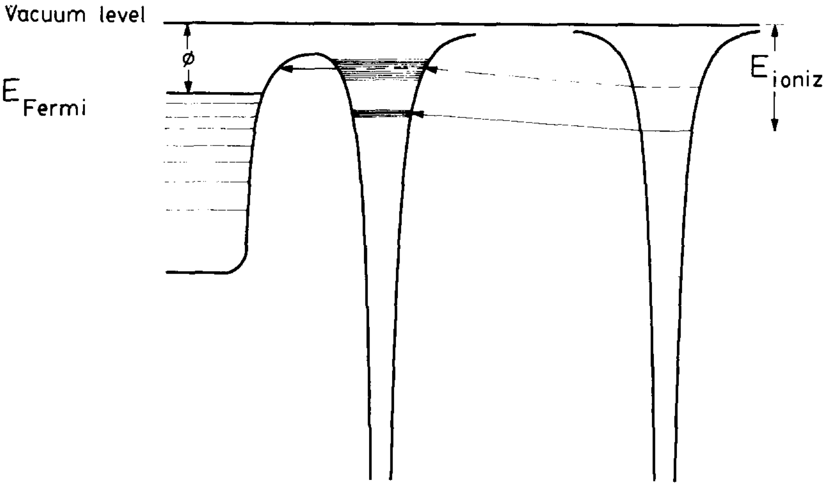


Fig. 5. This figure shows the shift and broadening of the electronic levels for an atom near a metal surface, and a resonant ionization transition from a level located opposite the empty conduction band of the metal.

surface (see fig. 5). Since resonant electronic transitions are the fastest [10] those excited states which have ionization energy smaller than the work function of the target, 4.26 eV for clean aluminum [11], will be resonant ionized. This condition reduces the possible initial states in table 1 to A, B, C, G, H and M. We have still to consider the upward shift of the electronic levels due to the interaction with the surface; this shift reduces the ionization energy and can be as large as some tenths of eV [10]. Taking into account this reduction of the ionization energy near the surface we conclude that states B, G and H can also be quenched by surface ionization, and so finally only states A, C and M can decay by autoionization.

Since the occurrence of state M is not well established [7,8], we concentrate our attention mainly on the other two states. It is seen that the kinetic energies of electrons ejected following autoionization of states A and C are in good agreement with those observed in our experiment; furthermore, if we assume that excitation cross sections for states A and C are similar (since they have the same orbital configuration: $1s^2 2s^2 2p^4 3s^2$), the intensities of the corresponding peaks should be in the ratio of their multiplicities: 9:5, which is in rough accordance with the experiment. Finally if state M occurs, its intensity should be much lower than the intensities of the former peaks, and so it is probably lost in the statistical fluctuation of the background. According to this discussion, we then assign the low and high energy peaks of fig. 2 to the peaks A and C of table 1. Following this identification we obtain that in our experiment both peaks are shifted upwards with respect to those observed in atomic collisions (fig. 4). This is just what we would expect if the Doppler effect and level shift due to the surface interaction were occurring. A detailed discussion of the shift and broadening of the lines will be published elsewhere.

In conclusion, we have measured the kinetic energies of autoionization electrons during low energy Ne^+ bombardment of an Al surface. We have found a strong broadening and a weak upward shift of the peaks as the projectile energy increases. We have also identified the transitions which lead to the observed peaks. The results favor the picture that excitation is produced in a Ne^+–Al collision and that autoionization occurs outside the solid.

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