Low Energy Ion–Surface Interaction—
Atomic Physics in an Ordered Atom Environment*

R. J. MacDonald and D. J. O'Connor

Department of Physics, University of Newcastle,
Newcastle, N.S.W. 2308.

Abstract

Ion–surface interactions have application within a number of areas of contemporary physics research. In particular, it is essential that an understanding of the interaction between an ion and a solid surface in a fusion reactor environment be achieved. A detailed understanding of the interaction is also essential for quantitative application of several of the modern methods of surface analysis currently available. It is unfortunate that the necessary level of understanding of the interaction of an ion (or an excited atom) in close proximity to a surface has not been achieved. This review will discuss in general the interaction of ions and atoms with surfaces, with emphasis on both the electronic aspects of the interaction, and the dependence of the interaction on the ordered environment provided by the surface. Although the interaction of atoms, ions and surfaces is not completely understood, there are several aspects of the interaction which provide information about the composition and structure of the surface. Low energy ion scattering and secondary ion mass spectrometry in particular are powerful methods of surface analysis. We consider some of our recent work related to the analysis of surfaces with these techniques, within the framework of increasing our understanding of the ion–surface interaction in general.

1. Introduction

In modern fusion reactor research programs one of the areas of special concern is the interaction between the particles which escape from the fusion plasma and the first (i.e. vacuum vessel) wall of the containment device. In many respects, this problem is similar to and an extension of the requirement in the 1950s and 1960s to understand the radiation damage processes of importance in fission reactors. There, fast recoil atoms and ions resulting from fission or from recoil from fission particles, move within the solid lattice creating damage and undesirable resultant stresses and strains. In the fusion reactor, the interaction is confined primarily to the surface of the containment vessel wall, but the interaction is still that of an ion (or atom) moving within the solid with an energy large compared with the displacement energy of the atoms of the solid. Similar interactions occur in space, where satellites encounter various energetic particles, particularly in the solar wind, and as a result are subject to damage. The description of the ion–surface interaction as a 'low energy ion– surface interaction' is of course relative. Within the context of our work this energy will be large compared with the displacement energy in the solid (~ 25 eV) or the

sublimation energy at the surface (~ 5 eV) but will be small compared with the very fast particles produced in fission and fusion reactions (of the order 10^5–10^6 eV). In this review, a low energy particle will have an energy of 10^2–10^3 eV; typical then of the energy of particles in the fusion plasma, of particles in the solar wind and of the secondary recoil atoms produced in a solid as a result of irradiation with primary fusion products.
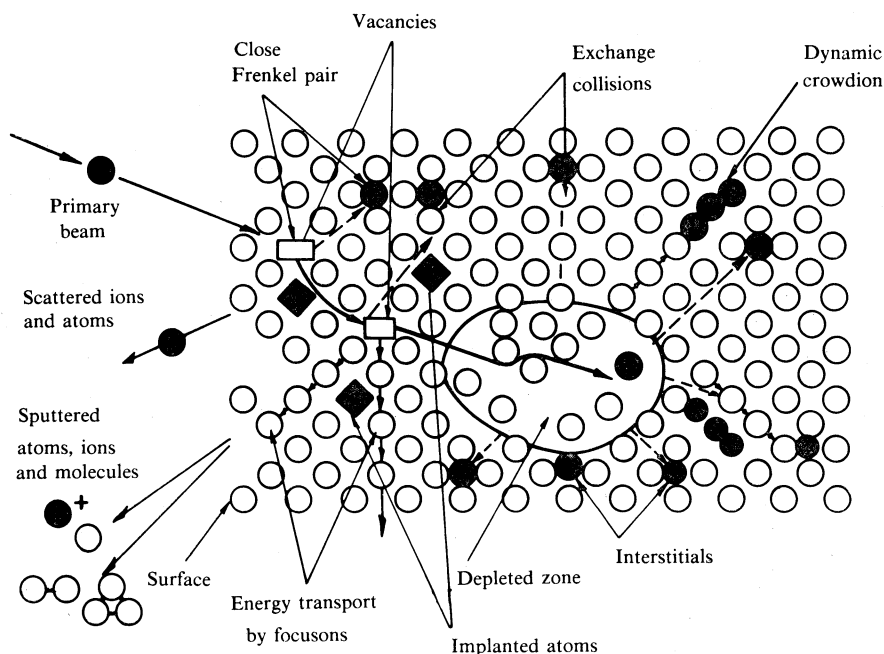
Fig. 1. Schematic representation of the interaction between an energetic incident ion and the surface and near surface region of a solid.

Ions (or atoms) in this energy range can induce damage within the solid and cause the ejection of atoms from the solid surface. However, they are also moving slow enough that their trajectories are very much influenced by the dense and usually ordered atom environment, and their electronic state is determined by a mixture of interactions with the core states of the atoms of the solid and with the broader distributed electronic states constituting the conduction bands of the solid. Local perturbation of electron energy distributions at the surface caused, for example, by adsorption of an active gas or a thin (monolayer) oxide film can drastically alter these electronic interactions. As a consequence, the low energy ion–surface interaction event is a very complex one and in this review we will attempt to provide an overview of the processes involved. We can best summarize the complexity of the interaction by reference to Fig. 1, which depicts schematically the ion–surface interaction in an ordered solid. The dimensions of the cascade introduced by a low energy ion incident on a typical metal surface are such that in general, when metals are irradiated, their grain size is of the order of, or larger than, the cascade size and the interaction with the polycrystalline target involves individual ions interacting with ordered target regions. Randomness in the target atoms will be approximated by integration of the results over the random orientation of the target grains.

In all cases within the regime of our defined low energy ion–surface interaction, the experimental observations will be the integration of individual events, each event being capable of producing displacement of atoms in the solid and consequent damage in the form initially of Frenkel pairs but probably finally in the form of defect agglomerates such as dislocation loops or voids. In addition, each incident ion can cause ejection of particles from the surface in the process of sputtering. Within the solid the incident and displaced particles may move in an average charge state determined by the degree of equilibrium between electron-capture and electron-loss cross sections for the particle moving in the electron gas. Ultimately, the particle will come to rest and in most solids will be electrically neutral. The particles which are ejected from the surface may be neutral or charged, single atoms or molecular clusters, in the ground or excited states. The final result is determined by complex electron exchange processes involving the ion (or atom) close to the surface, the core states of atoms in the solid and the distributed states of the conduction bands, and by the trajectories of the particles involved.

The processes involved in a low energy ion–surface interaction tend to be many and complex and, as a consequence, subgroups of the interaction processes have tended to develop as areas of study in their own right. This has been accentuated because the particles scattered or ejected from the surface may be charged or excited and hence are labelled producing a signal which, if it depends on either structure or composition of the surface, can be used as a means of surface analysis. Thus we have the general areas of low energy ion scattering (LEIS), secondary ion mass spectroscopy (SIMS) and sputter induced photon spectroscopy (SIPS). In our work we have aimed at an overview of the low energy ion–surface interaction and consequently we have carried out research into all of these areas. In the following discussion we will concentrate on those aspects of the interaction which are the result of the target being a solid—thus we will consider the effects of atomic and electronic structure of the solid in comparison with what one might expect from single collision events.

2. Electron Exchange Processes involving Ions (or Atoms) close to Surfaces

In 1980 we reviewed in some detail the area of LEIS (MacDonald 1980). There we considered briefly the processes which were believed to dominate the electron exchange between the ion (or atom) and the surface. Such electron exchange events are very important in all aspects of the ion–surface interaction, and therefore we should reconsider the processes involved. Up until the last few years, experiments which required interpretation in terms of the effect of electron exchange between the ion (or atom) and the surface, followed the processes suggested originally by Hagstrum (1954, 1977) to account for observed electron emission spectra produced by the interaction between very low energy (~ 10 eV) ions and surfaces. These electron ejection processes were based on the potential energy of the ion (or atom)–surface system: the kinetic energy had very little influence. The processes suggested by Hagstrum could produce ionization, neutralization or radiationless deexcitation of the ion (or atom) near the surface; they are represented schematically in Fig. 2. Hagstrum developed a time-independent perturbation theory which predicted that the probability that the particle would survive the interaction with the surface, without undergoing an exchange event, is approximately given by
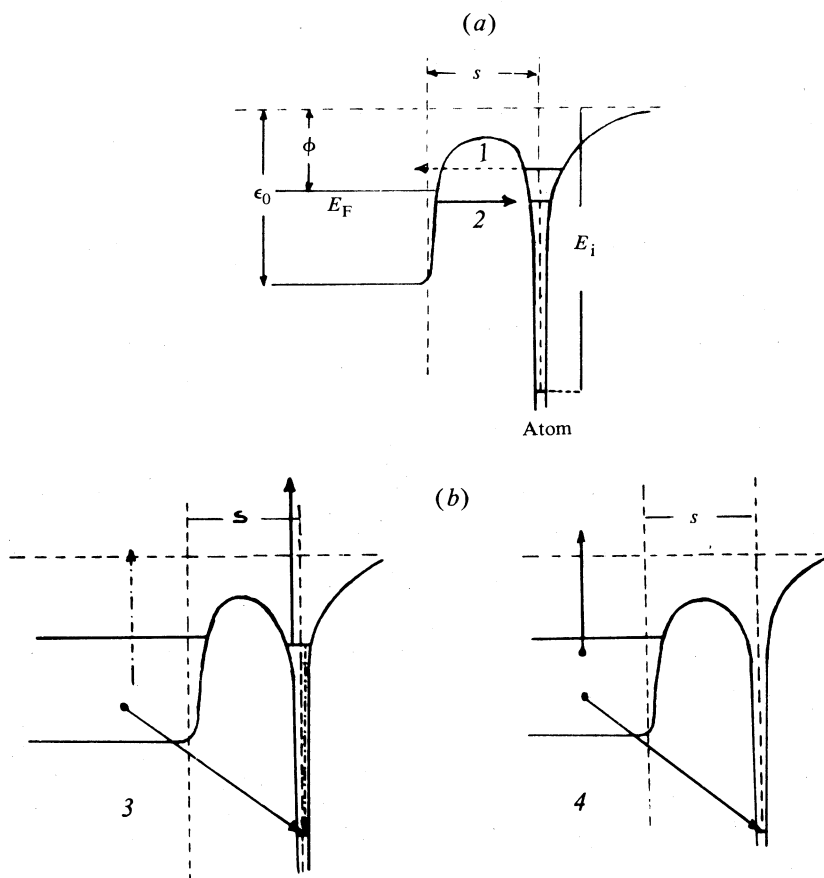
Fig. 2. Schematic representation of the exchange events possible between an atom or ion close to a surface, and electronic states of the surface region: (a) resonant ionization (1) and neutralization (2); (b) Auger deexcitation (3) and neutralization (4). [Hagstrum (1954).]

$$P = \exp(-A/av_\perp), \qquad (1)$$

where $v_\perp$ is the component of the particle velocity perpendicular to the surface, A is the transition rate at the surface and a is a distance characterizing the transition and obtained from the transition rate equation

$$R = A\exp(-as), \qquad (2)$$

where s is the distance from the surface. The result given in equation (1) was based on a number of simplifying assumptions which act to basically restrict the exchange event to large distances from the surfaces. In Hagstrum's work it was appropriate because the potential excitation occurred essentially at distances of 10 Å or so from the surface and was the *first* exchange with the surface. The subsequent trajectory of the very low energy ion (or atom) was not considered.

In subsequent work on the low energy ion–surface interaction, including the exchanges important in LEIS, SIMS and SIPS, many researchers have taken equation

(1) and Hagstrum's ideas over to the new situations, including situations in which Hagstrum's initial assumptions break down, for example in SIMS experiments where the charged particle originates from a surface site. While there is then no real physical justification for the use of equation (1), experimentally the results have been fitted to a relationship better written as

$$P = \exp(-v_c/v_\perp), \qquad (3)$$

where v_c is now simply a constant characteristic of the interaction. Agreement with equation (3) has been taken as an indication that exchange processes of the type illustrated schematically in Fig. 2 were responsible for the observed results. Woodruff (1982) has shown it is possible to integrate equation (2) along the ion trajectory, using s as the distance to atoms involved in the interaction, rather than the distance to the surface. The exchange is then essentially a multi-atom event. In this case it is more appropriate that the relative velocity of the ion with respect to the main scattering atom be used, rather than $v_\perp$. Richard et al. (1984) have reported a similar result. However, they claim that neither equation (1) nor (3) can fit their observations, but an integration of equation (2) along the true trajectory of the incident ion can fit the results very well. None of the available work, however, is able to distinguish the actual mechanism of the interaction. All the experiments involve a result which integrates over the entire trajectory, i.e. the incident path, the close encounter event leading to scattering and the exit path. While the ion and atom are widely separated, exchanges of the type illustrated in Fig. 2 are not unreasonable, but at a small distance of closest approach it seems likely that there should be a contribution from gas phase collision type processes, for example excitation and neutralization in the pseudomolecular stage of the collision. Strong evidence certainly exists for such electron exchanges in the oscillations in the neutralization cross section observed as a function of relative velocity, as was found initially for He^+ incident on Pb (Erickson and Smith 1973) and then later in a number of other scattering pairs. The oscillations in these cases are due to exchanges between the ground state of the atom of the incident ion and a core state of the target atom which is in quasi-resonance with the atom ground state.

Recently more sophisticated time-dependent perturbation calculations have been attempted (Bloss and Hone 1978; Norskov and Lundqvist 1979; Muda and Hanawa 1980; Sebastian et al. 1981; Moyer and Orvek 1982; Sroubek 1982; Lang 1983). These calculations have used the Anderson Hamiltonian formalism to calculate the occupation probability of a given state of the ion as a function of time, derived from the classical trajectory of the particle. The calculations mainly consider resonance-type exchanges, as the Auger exchange is more difficult to include in the model. It is significant that most models predict that the neutralization rate, integrated over the scattered ion trajectory, conforms to a mathematical relationship like that expressed by equation (3).

In the LEIS experiment it is obviously desirable to distinguish between the contribution to the neutralization of the incoming and outgoing trajectory and the small impact parameter collision responsible for a large part of the observed scattering angle. Experiments at Newcastle (MacDonald and Martin 1981; MacDonald and O'Connor 1983) have attempted this, using an arrangement shown schematically in Fig. 3. This allows the incident trajectory and the scattering angle to be kept constant, while the exit trajectory relative to the surface is varied. Thus the velocity component
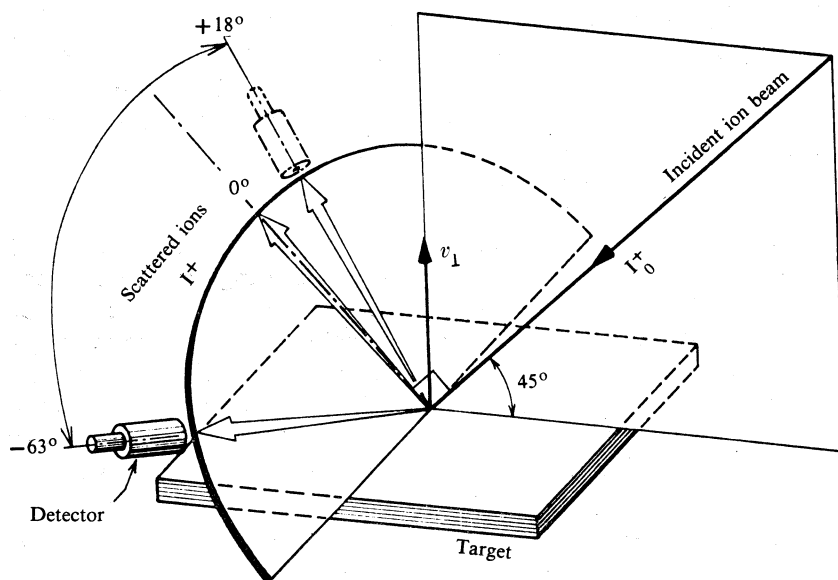
Fig. 3. Experimental arrangement used at the University of Newcastle for studies of the exit trajectory contribution to the neutralization in LEIS. [MacDonald and Martin (1981).]

normal to the surface in the outgoing trajectory is varied. The ion yield as a function of this velocity component is still observed to conform to a relationship of the form (3) (MacDonald and Martin 1981), but the characteristic velocity v_c is a function of the energy of the ion in this exit trajectory (MacDonald and O'Connor 1983). Further experiments (MacDonald et al. 1984) confirm that the neutralization observed scales as $v_\perp$, not as the relative velocity in the binary collision. The variation of the observed v_c as a function of the exit energy is shown in Fig. 4a. If we assume that the contribution to neutralization along the incoming trajectory is a similar function of the energy, the results suggest that the actual contributions to neutralization of the incoming trajectory, the outgoing trajectory and the small impact parameter collision are approximately the same. Thus gas phase type exchange processes are approximately as significant in neutralization events in the ion–surface interaction as the potential energy driven exchanges suggested by Hagstrum (see Fig. 2).

In the case of SIMS and SIPS, the Hagstrum type of exchange and the resultant probability of surviving in an ionized state (equation 1) is probably even less applicable than in the case of ion scattering. Secondary ion energy spectra, however, when compared with the sputtered atom neutral spectrum, do show a dependence mathematically similar to equation (3) (MacDonald 1974; Bayly and MacDonald 1977). The incident ion energy dependence of the yield of photons from sputtered atoms also could have a non-radiative deexcitation component which behaves in a similar way to equation (3) (White and Tolk 1971). In the case of secondary ion emission, experiments similar to those described above to measure neutralization on the outgoing trajectory have been performed (Garrett et al. 1984). These involve measurement of the energy spectrum of the secondary ions as a function of the angle of ejection to the surface, while maintaining the initial bombardment conditions constant.
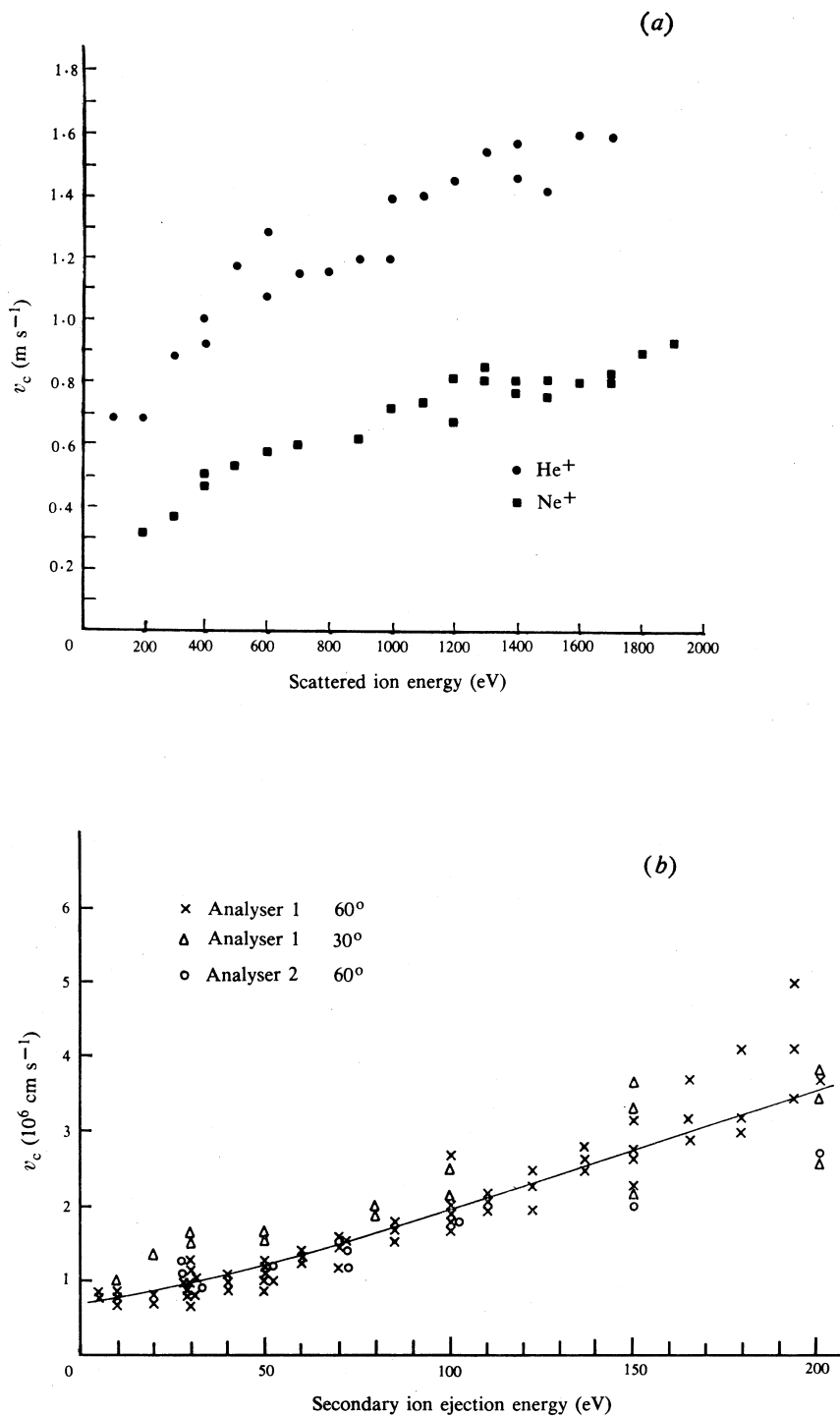
Fig. 4. Variation of v_c as a function of (*a*) the scattered ion energy (MacDonald and O'Connor 1983) and (*b*) the secondary ion ejection energy (Garrett *et al.* 1984). In (*b*) the results refer to the emission of Al$^+$ from Al as a result of bombardment with Ar$^+$.

Again the experimental results fit a relationship of the form (3), but with lower values of v_c in the secondary ion case than in the scattered ion case. The value of v_c for the secondary ions is also dependent on the energy of the ejected ion, as shown in Fig. 4b. It is not possible as yet to report on the dependence of photon emission on the angle or energy of the atom sputtered in the initial excited states.

The reported dependence of the neutralization of either scattered or sputtered ions on the exit energy of the ion indicates that the Hagstrum approach, if it were applicable to the scattered or sputtered particles, certainly requires substantial modification of the theory—this modification may simply involve the assumptions used by Hagstrum (1954) to obtain equation (1). The time-dependent perturbation approach mentioned above, with the time-dependence following from the classical trajectory, is probably the more physically realistic model but the calculations are as yet in their early stages of development. Certain predictions of these calculations have been qualitatively identified in the experimental results (MacDonald and O'Connor 1983) and it is reasonable to expect more detailed developments in the future. The problem of identifying and quantifying the neutralization event is the major unsolved problem in LEIS and in SIMS.

3. Aspects of Ion–Surface Interaction Dependent on Surface Structure

As indicated above, most of the individual ion–surface interaction events take place in an ordered atom environment. The spatially periodic arrangement of atoms about the incidence point in scattering and in sputtering experiments will modify the angular and energy distributions of the interaction products. LEIS is interpreted in the first approximation as a single elastic binary collision event involving the incident ion and a single isolated atom of the target. Several tests of the approximation over the years have indicated that it is true (within experimental error) for incident ion energies as low as 50 eV. More recent experiments (MacDonald and O'Connor 1983), particularly in our laboratory where more sophisticated scattering equipment can be used, indicate that there are inelastic loss processes involving losses only of order 10 eV at 1 keV which obviously depart from the single elastic binary collision approximation. Computer simulations indicate that the ion interacts with many atoms on each trajectory and most of the interactions have large impact parameters (Poelsema et al. 1976), but the final scattered ion energy is the result of all these interactions, with the scattering angle being mainly the result of a single collision. This is of course not surprising since the target atoms are quite closely spaced. In any one trajectory the collision times are so short compared with lattice vibration periods that the target atoms may be regarded as frozen in their positions distributed about the lattice site according to the thermal vibrational amplitude distribution. The next ion trajectory to encounter that same area of the target would of course experience a different distribution of thermal vibration amplitudes. By analysing the scattering as a function of temperature, surface Debye temperatures can be measured using LEIS (Poelsema et al. 1976).

In the earlier review of LEIS (MacDonald 1980) we demonstrated the concept of the 'single' and 'double' collision by the use of Fig. 5. The arrangement of atoms in the periodic net on the surface will obviously influence the scattered ion yield as a function of the azimuthal angle. If we consider only scattering from the first layer then the changing spacing between the atoms involved in the double collision event
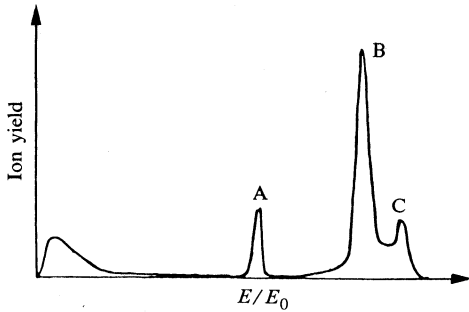
Fig. 5. Simplistic view of the single (B) and double (C) collision event, including scattering from an adsorbate (A), in LEIS experiments. [MacDonald (1980).]
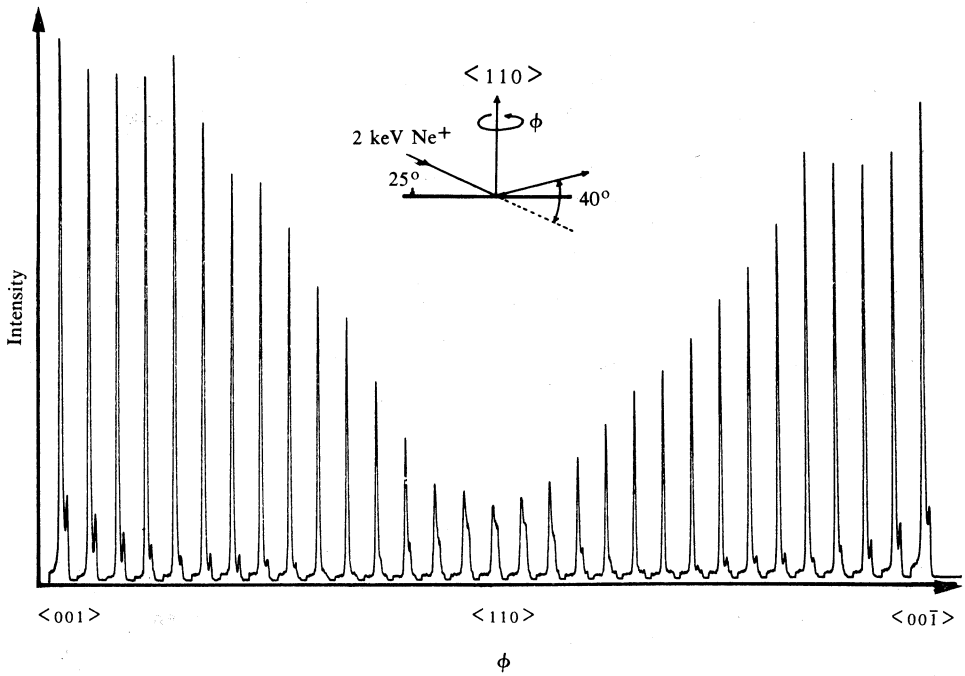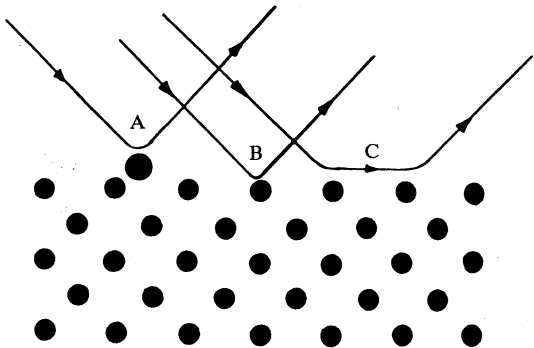
Fig. 6. Dependence of the single and double collision event contributions as a function of azimuthal angle for 2 keV Ne$^+$ incident on Ni (1 1 0).

will affect both the position of the energy peak corresponding to the double scattering and the yield of ions in that double scattering peak. The peak corresponding to double scattering occurs at a higher energy than the single scattering peak because it is the result of successive collisions each at very much smaller scattering angle than the singles cattering event. An experimental result, for Ne^+ scattered from a Ni (1 1 0) surface, showing the variation of the energy spectrum in the region of the single and double scattering peaks with change in azimuthal direction of the incident beam is shown in Fig. 6. Such results can be used to deduce arrangements of atoms on the surface of single crystal targets. The interpretation of the results is complicated, however, by the possible contributions of scattering from second layer atoms. Let
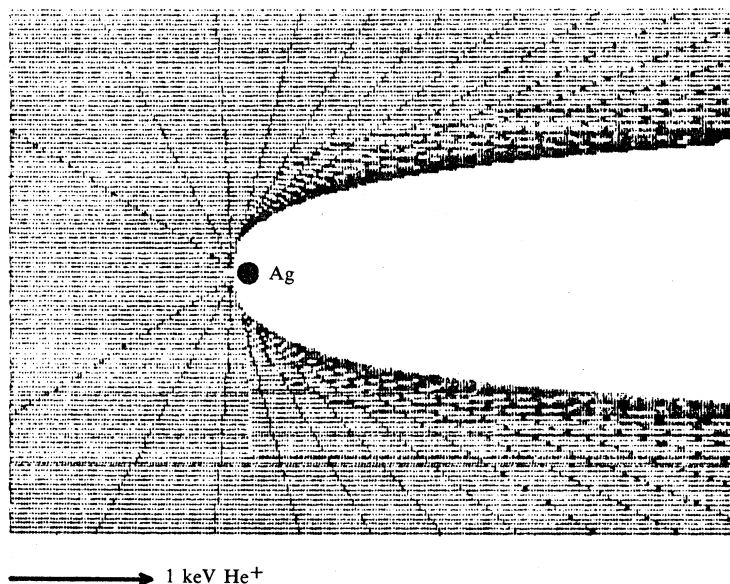

Fig. 7. Development of a shadow cone in LEIS.

us consider the situation demonstrated in Fig. 7, which shows the scattering of a uniform cross-section beam of ions incident on a single atom. In the region behind the target a shadow forms. At large impact parameter, the beam cross section remains essentially uniform after interaction with the target, because the scattering angles are so small. At small impact parameters scattering is larger, and there may be backscattering which removes those particles from the forward flux. At intermediate impact parameters, the ions are forward scattered but, in particular, in the region of the edge of the 'shadow cone' the ion flux may be increased substantially. If now we consider a group of say four atoms on the surface, with a second layer atom below the centre of that square of four atoms, it is easy to visualize a situation in which, with the correct geometry, particles from the incident beam are focused onto the second layer atom and there will be an incident geometry-dependent yield from the second layer atoms. This process is called 'wedge focusing'.

The shadow cone concept is ideal to indicate the use of LEIS for surface structure analysis. There exists a number of reports of such studies (Algra *et al.* 1980; Godfrey and Woodruff 1981; Overbury *et al.* 1981; Saitoh *et al.* 1981; Souda *et al.* 1983;

Yabuuchi *et al.* 1983) but they can be illustrated by reference to some of the work of Aono (1984). The use of the shadow for atom location studies on the surface involves monitoring the double scattering event which results from the shadow cone envelope, formed about one surface atom, interacting with a second surface atom.
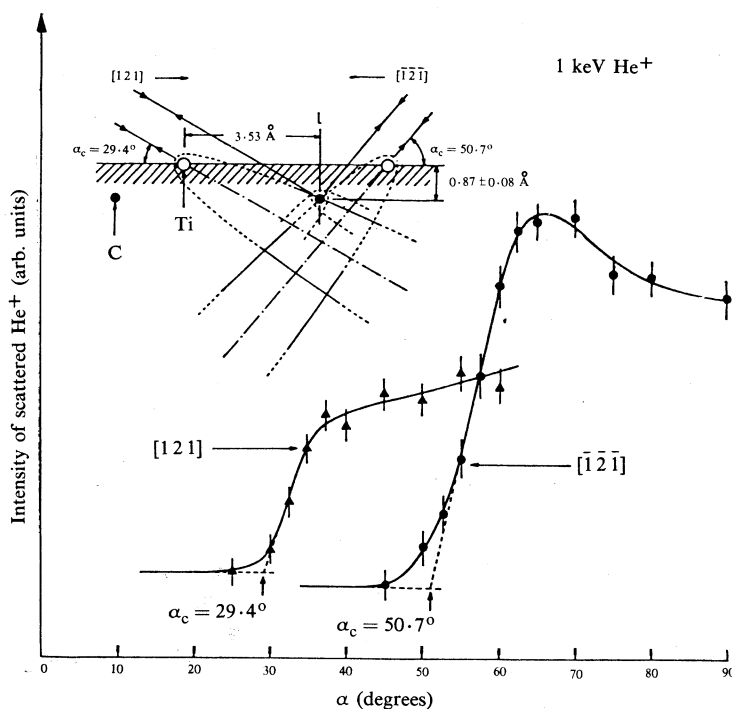

Fig. 8. Determination of the location of the C atom on a TiC surface. [Aono (1984).]

Aono (1984) has used this method to locate the carbon atom on the surface of TiC. Very large angle scattering events were used to ensure the double scattering involves ions in the shadow cone envelope; the results are given in Fig. 8. By monitoring the onset of the double scattering event, resulting from ions in the shadow cone formed around the Ti atom interacting with a carbon atom, as a function of the angle of the incident beam (and hence shadow cone axis) to the surface, the carbon atom was located with a precision of better than $0 \cdot 1$ Å.
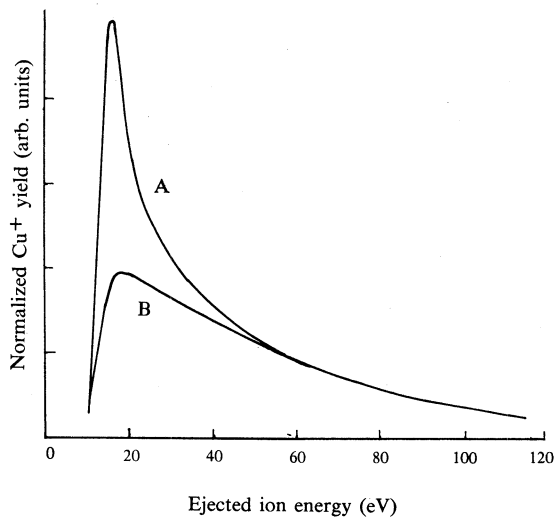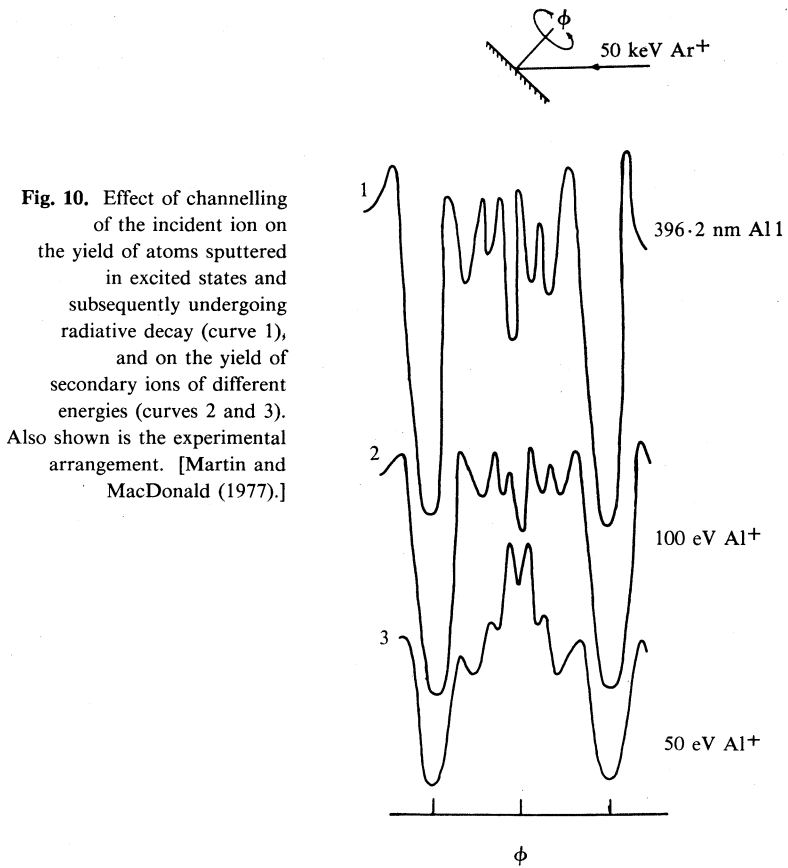
The periodic arrangement of atoms on the surface may influence the trajectory of the scattered ion over a range of more than the one or two collisions noted above. This is the process of channelling and, in the case of the low energy ion–surface interaction, we are primarily interested in the influence of so-called surface semi-channels on the scattered ion distribution. The scattering events can be understood in terms of the 'chain model' (Kivilis *et al.* 1970) and the effects are observed primarily in the angular dependence of the 'single collision' scattered ion intensity, at low scattering angles and at angles of incidence close to the surface. A typical intensity distribution showing the effect of the surface semichannels is shown in Fig. 9.
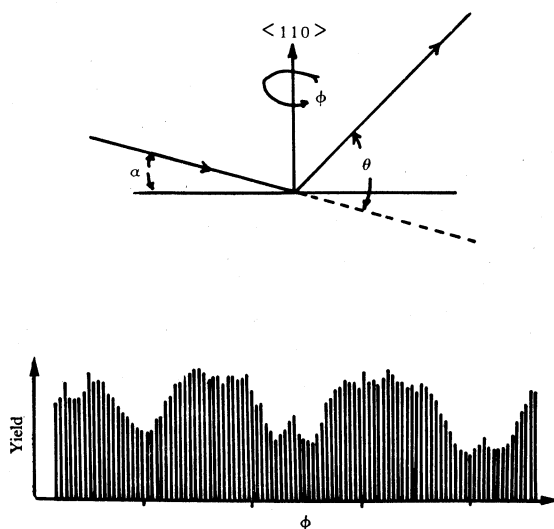
Fig. 9. Influence of surface semichannels on the LEIS from a single crystal surface. The single scattering peak on the surface is monitored as a function of the azimuthal angle of the target. The result shown is for 6 keV Ar^+ ions scattered from tungsten (1 1 0). [O'Connor (1979).]

The surface and bulk structure of the target influences the distribution of secondary ions and of atoms sputtered in excited states in a different way to the influence on LEIS. Sputtering is primarily the result of collision cascades initiated in the solid, and intersecting the surface with enough energy to overcome the surface binding and produce the sputtered atom in a neutral or ionized state, and possibly with electron excitation as well. The surface structure then influences the ion or photon yield through its influence on the propagation of the collision cascade. In cases where the ion initiating the cascade is incident along a low index (crystallographic) direction, the energy of the ion is deposited deep inside the target and there is less chance that the subsequent cascade will intersect the surface with sufficient energy per atom to induce ejection. If it does intersect the surface then the average energy of the particles in the cascade will be less than that for an ion incident in a non-channelling (random high-index) direction. As a consequence the sputter yield (i.e. atoms ejected per incident ion) is reduced when the incident ion is channelled, and so too is the yield of secondary ions and photons emitted by radiative decay of atoms sputtered in an excited state. This is demonstrated in Fig. 10 for the case of Ar^+ ions incident on an Al (1 0 0) single crystal target (Martin and MacDonald 1977). The ions were incident at 45° to the target surface and the single crystal was rotated about the normal to the surface. The yields of photons and of secondary ions of different energy are shown as a function of the angle of rotation of the target about the surface normal.

The target crystal structure can also influence the way in which the energy in the cascade propagates to the surface. Thompson (1963) was largely responsible for the development of the concept of momentum focusing first introduced by Silsbee (1957). Along low index close packed directions in the target lattice, one can easily demonstrate

50 keV Ar⁺

Fig. 10. Effect of channelling
of the incident ion on
the yield of atoms sputtered
in excited states and
subsequently undergoing
radiative decay (curve 1),
and on the yield of
secondary ions of different
energies (curves 2 and 3).
Also shown is the experimental
arrangement. [Martin and
MacDonald (1977).]

396·2 nm Al1

100 eV Al⁺

50 eV Al⁺

ϕ

Fig. 11. Effect of momentum focusing on the energy spectrum of sputtered
ions. The energy spectrum of Cu^+ ions sputtered from a Cu single crystal
and measured along the $\langle 1\,1\,0 \rangle$ direction (A) and a 'random' direction
(B) are compared by normalizing the yields at higher secondary ion
energies. [Dennis and MacDonald (1971).]

that it is possible to transport energy and momentum over relatively long distances with little attenuation, without the transfer of mass. Thus in a sputtering experiment using a single crystal target, preferential ejection of atoms along the low index directions in the target is observed (Thompson 1963). In the case of secondary ion emission, this shows up as an enhanced yield along that direction. The enhancement occurs in the lower energy part of the sputtered atom and ion energy spectrum, because one can demonstrate a high energy limit to the focusing event, above which momentum transfer along the line of atoms is defocused, or not focused. This effect is illustrated in Fig. 11 (Dennis and MacDonald 1971), which compares the energy spectrum of Cu^+ ions ejected along the Cu $\langle 1\,1\,0 \rangle$ direction from a Cu $(1\,0\,0)$ surface bombarded with Ar^+ (curve A) with that observed along a 'random' (high-index) direction (curve B). The energy spectra have been normalized at higher secondary ion energies and the enhanced yield of Cu^+ in the region below about 60 eV is obvious. A similar enhancement is responsible for the difference between the 50 and 100 eV azimuthal Al^+ scans in Fig. 10.
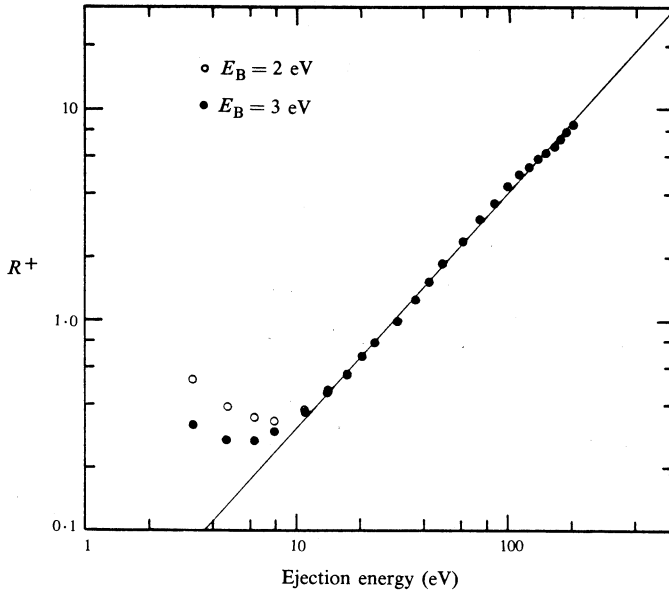

Fig. 12. Variation of the relative probability R^+, that an atom ejected by sputtering is emitted in an ionized state, as a function of the ejection energy. The result shown is for the emission of Al^+ from Al for two values of the bombarding energy. The data were fitted by the straight line $R^+(E) \propto E^{1\cdot1}$. [Garrett *et al.* (1984).]

4. Energy Dependence of the Ionization Coefficient in SIMS

Recently Garrett *et al.* (1984) have reported a measurement of the energy dependence of the ionization coefficient in the secondary ion emission of Al^+ from Al. We assume that the ion yield can be written as

$$Y^+ \, dE \, d\theta = N(E, \theta) \, \sigma(E) \, P(E) \, dE \, d\theta, \qquad (4)$$

where $N(E, \theta)$ is the energy spectrum of Al atoms sputtered at an angle θ to the surface, $\sigma(E)$ is the cross section for ionization of the sputtered atoms and $P(E)$ is the probability that the ions once formed survive the transition to the detector in an ionized state. We can use the results shown in Fig. 4b and the energy distribution of sputtered atoms given by Sigmund (1969) and Thompson (1968) in order to evaluate $\sigma(E)$. The result given in Fig. 12 shows a similarity to the dependence of the gas phase ionization coefficient on energy. This highlights our earlier remarks on ion scattering, where we indicated that the ion–surface interaction can be at least initially considered as a gas phase collision phenomenon influenced strongly by solid state effects associated with the spatial distribution of atoms and energy distribution of electrons in the solid.

5. Analysis of Surface Structure and Composition by Low Energy Ion–Surface Interaction

Many of the developments in the study of ion–surface interactions have been derived from the application of low energy ion beams to the analysis of surfaces. We have discussed above the developments in the use of LEIS for structure determination and atom location. SIMS in particular is widely used for elemental analysis of surfaces and, when combined with sectioning of the surface using sputtering, has also been widely used for depth profiling of surface constituents. Photon emission from sputtered atoms has also been used for elemental identification and for profiling but it lacks the sensitivity of SIMS. A comparison of LEIS, SIMS and SIPS for the analysis of a range of Nb/V alloys has been made (Martin *et al.* 1981), and there do exist conditions under which any of these three analytical methods will give reasonable results for the elemental composition of the surface. When using SIMS or SIPS, however, researchers involved in analysis often use an oxygen or other active gas beam or an active gas environment with an inert gas ion beam in order to obtain higher signal sensitivity. A clean surface in an ultra-high-vacuum environment when bombarded with an inert gas ion beam will give rise to a reasonably weak secondary ion or sputter induced photon signal. If an active gas ion beam is used, the secondary ion or photon signal strength often increases by up to two or three orders of magnitude. Similarly if an inert gas ion beam is used in a system established in such a way that the surface is covered with a substantial fraction of a monolayer of adsorbed gas, the signal strength increases by similar factors to those observed with the active gas beam. The mechanism responsible for this enhancement of the signal strength is not known, but while the higher signal strength will lead to lower minimum concentration detection limits, other effects intervene to affect the accuracy of the analysis. Wittmaak (1979) has noted several of these, and they are largely associated with the difficulty of knowing exactly the surface concentration of the active gas species. In Fig. 13, we show the variation of the yield of Si I photons as a function of oxygen pressure in the system, at constant beam current (Loxton 1981). The equilibrium between rate of adsorption and rate of the adsorbate sputtering as the background pressure changes establishes a varying but unknown surface coverage.

The mechanisms responsible for neutralization, for ionization and for excitation are not completely understood, certainly not to the extent of being able to predict the signal strength in a given situation. For this reason analytical methods based on low energy ion–surface interactions and intended for compositional analysis are

qualitative, unless standards suitable for comparison of signal strengths to the unknown sample are available. It is important to note, however, that even though the information available tends to be qualitative, the low energy ion beam analysis techniques are widespread and used in a wide variety of applications.
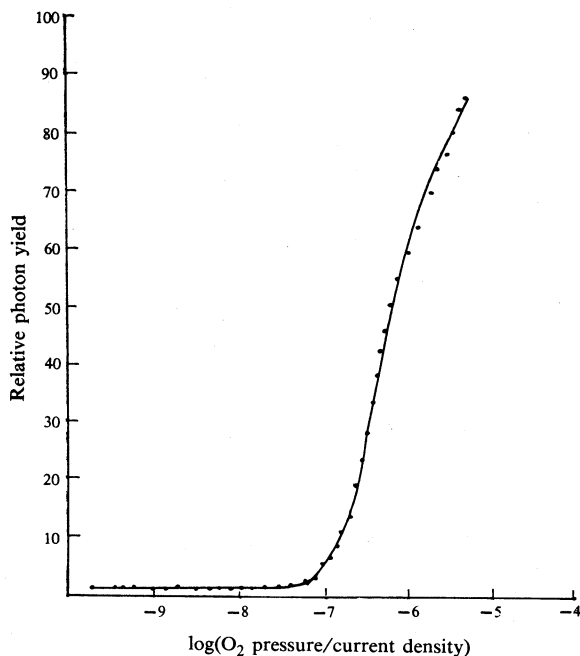

Fig. 13. Variation of $288 \cdot 2$ nm photon emission for Si 1 atoms sputtered from a surface with a varying degree of adsorbate coverage. The coverage is the result of adsorption from a varying pressure of O_2 in the chamber, in equilibrium with sputtering by a constant current density ion beam. [Loxton (1981).]

6. Conclusions

The low energy ion–surface interaction is a very complex situation involving a wide variety of atomic and electronic collisional processes. Evidence exists that many of the observations can be interpreted in terms of an extension of gas phase collisional processes modified by the ordered atomic array of target atoms and the electron energy distribution of the solid. This raises two possibilities: firstly the use of low energy ion–surface interaction for analysis of the solid state and secondly the use of the solid to produce situations experimentally desirable but difficult to achieve in the gas phase.

Acknowledgments

In this review we have cited our own work by way of example, as far as this has been possible. We wish to acknowledge the contribution to our work of others in the field, through their published work, and through personal communication. The accumulation of the equipment necessary to carry out the work has been made

possible largely through the ARGS. The results have been obtained with the help and perseverance of a number of graduate students, whose names appear on many of the published works cited.

References

Algra, A. J., Luitjens, S. B., Surmeijer, E. P. Th. M., and Boers, A. L. (1980). *Surf. Sci.* **100**, 329.
Aono, M. (1984). *Nucl. Instrum. Methods Phys. Res.* B **2**, 374.
Bayly, A. R., and MacDonald, R. J. (1977). *Radiat. Eff.* **32**, 177.
Bloss, W., and Hone, D. (1978). *Surf. Sci.* **72**, 277.
Dennis, E., and MacDonald, R. J. (1971). *Radiat. Eff.* **13**, 243.
Erickson, R. L., and Smith, D. P. (1973). *Phys. Rev. Lett.* **34**, 297.
Garrett, R. F., MacDonald, R. J., and O'Connor, D. J. (1984). *Surf. Sci.* **138**, 432.
Godfrey, D. J., and Woodruff, D. P. (1981). *Surf. Sci.* **105**, 459.
Hagstrum, H. D. (1954). *Phys. Rev.* **96**, 325.
Hagstrum, H. D. (1977). *In* 'Inelastic Ion–Surface Collisions' (Eds N. H. Tolk *et al.*), p.1 (Academic: New York).
Kivilis, V. M., Parilis, E. S., and Turaev, N. Yu. (1970). *Sov. Phys. Dokl.* **15**, 587.
Lang, N. D. (1983). *Phys. Rev.* B **27**, 2019.
Loxton, C. M. (1981). Ph.D. Thesis, Australian National University.
MacDonald, R. J. (1974). *Surf. Sci.* **43**, 653.
MacDonald, R. J. (1980). *Aust. J. Phys.* **33**, 843.
MacDonald, R. J., and Martin, P. J. (1981). *Surf. Sci.* **111**, L739.
MacDonald, R. J., and O'Connor, D. J. (1983). *Surf. Sci.* **124**, 423, 433.
MacDonald, R. J., O'Connor, D. J., and Higginbottom, P. (1984). *Nucl. Instrum. Methods Phys. Res.* B **2**, 418.
Martin, P. J., Loxton, C. M., Garrett, R. F., MacDonald, R. J., and Hofer, W. O. (1981). *Nucl. Instrum. Methods* **191**, 275.
Martin, P. J., and MacDonald, R. J. (1977). *Radiat. Eff.* **32**, 177.
Moyer, C. A., and Orvek, K. (1982). *Surf. Sci.* **114**, 295.
Muda, Y., and Hanawa, T. (1980). *Surf. Sci.* **97**, 283.
Norskov, J. K., and Lundqvist, B. I. (1979). *Phys. Rev.* B **19**, 5661.
O'Connor, D. J. (1979). Ph.D. Thesis, The Australian National University.
Overbury, S. H., Heiland, W., Zehner, D. M., Datz, S., and Thoe, R. S. (1981). *Surf. Sci.* **109**, 239.
Poelsema, B., Verhey, L. K., and Boers, A. L. (1976). *Surf. Sci.* **56**, 445.
Richard, A., Eschenbacher, H., and Dose, V. (1984). *Nucl. Instrum. Methods Phys. Res.* B **2**, 444.
Saitoh, M., Shoji, F., Oura, K., and Hanawa, T. (1981). *Surf. Sci.* **112**, 306.
Sebastian, K. L., Jyothi Blasa, V. C., and Grunley, T. B. (1981). *Surf. Sci.* **110**, L571.
Sigmund, P. (1969). *Phys. Rev.* **184**, 383.
Silsbee, R. H. (1957). *J. Appl. Phys.* **28**, 1246.
Souda, R., Aono, M., Oshima, C., Otani, S., and Ishizawa, Y. (1983). *Surf. Sci.* **124**, L236.
Sroubek, Z. (1982). *Nucl. Instrum. Methods* **194**, 533.
Thompson, M. W. (1963). *In* 'The Interaction of Radiation with Solids' (Eds R. Strumane *et al.*), p. 84 (North-Holland: Amsterdam).
Thompson, M. W. (1968). *Philos. Mag.* **18**, 377.
White, C. W., and Tolk, N. H. (1971). *Phys. Rev. Lett.* **26**, 486.
Wittmaak, K. (1979). *Surf. Sci.* **89**, 668.
Woodruff, D. P. (1982). *Surf. Sci.* **116**, L219.
Yabuuchi, Y., Shoji, F., Oura, K., and Hanawa, T. (1983). *Surf. Sci.* **131**, L412.