Auger Spectroscopy and Surface Analysis*

S. M. Thurgate

School of Physical Sciences, Engineering and Technology,
Murdoch University, Murdoch, WA 6150, Australia.

Abstract

In 1925 Pierre Auger reported on his observations of low energy electrons associated with core-ionised atoms in cloud chamber experiments. He was able to correctly identify the mechanism for their production, and such electrons are now known as *Auger electrons.* Typically Auger electrons have energies in the range 10 eV to 2 keV. The short distance that such low energy electrons travel in solids ensures that Auger electrons come from the surface layers. The data generated by the AES technique are complex. There are at least three electrons involved in the process, and there are many possible configurations for the atom. These possibilities led to spectra that are not readily interpreted in detail. Theory lags behind experiment in this area. In principle, it should be possible to find information about the chemical environment of atoms from Auger spectra. While there are clear changes in spectral lineshapes, there is no simple way to go from the spectra to an understanding of the chemical bonding of the atom.

There are a number of experiments currently underway which aim to improve our understanding of the Auger process. Synchrotron experiments with tunable energy x-rays are providing new insight. Experiments that use positrons to excite Auger emission have also produced further recent understanding. Coincidence experiments between photoelectrons and Auger electrons have also made recent advances. Auger photoelectron coincidence spectroscopy reduces the complexity of Auger spectra by only counting those electrons that occur as a consequence of selected ionisations. The effect is to reduce the complexity of the spectra, and to isolate processes that are often clouded by the simultaneous occurrence of other effects.

1. Introduction

Pierre Auger (1925) reported his observation of low energy electrons associated with the relaxation of atoms that had been ionised. He was analysing data collected in cloud chamber experiments. He correctly identified the mechanism that produced these electrons, and such electrons are now known as Auger electrons.

Despite the early identification of Auger electrons in nuclear physics, Auger electron spectroscopy had to wait for the development of modern surface analysis in the 1960s for it to become widely used as a key technique in surface characterisation (Duke 1994). It is now an essential technique for the identification of surface species. It has a very high sensitivity, excellent spatial resolution and small data acquisition times. However, the data from the technique are often difficult to

* Refereed paper based on a plenary lecture given at the 12th Australian Institute of Physics Congress, held at the University of Tasmania, Hobart, in July 1996.
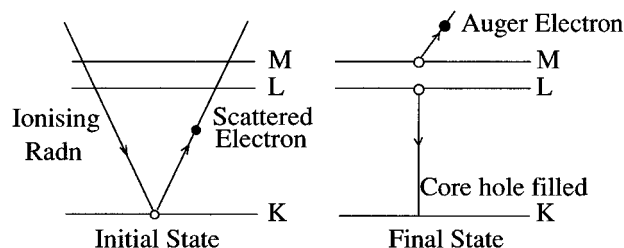
Fig. 1.   The Auger process is generally thought of in two stages, the formation of the initial state as the atom is ionised and the creation of the final state with the emission of the Auger electron. Auger lines are named after the sequence of holes created, using the x-ray convention to name the shells that the holes form in. Hence, the process shown is a KLM Auger process.

interpret beyond a superficial estimation of the ratio of atoms present on the surface (Weightman 1995).

The complexity of the data arises from the nature of the atomic processes that generate Auger electrons. In the simplest case, an Auger electron is emitted when an electron from an outer shell occupies an inner shell hole. The process is in direct competition with x-ray emission. For lighter elements, Auger emission is more likely than x-ray emission. The process is shown in Fig. 1.

Auger emission from solid surfaces was first reported by Howarth (1935). The advent of clean vacuum systems in the 1960s led to increased interest in the possibility of Auger spectroscopy as a tool for elemental surface determinations. In 1968 Harris (1968) gave details on how to use energy modulation techniques with continuous detection schemes to differentiate the output from electron spectrometers. This technique could be used with LEED optics or cylindrical mirror analysers. The consequences were that Auger spectra could be rapidly acquired and displayed in differential form, where the background was small compared with the signal. Since that time, Auger spectroscopy has been widely used as a technique for finding the elemental composition of surfaces. The advantage it has over competing techniques, such as XPS, is that it has high elemental sensitivity. It is the technique of choice for deciding if a surface is clean. As an electron beam can be used to stimulate Auger electron emission, it also has high spatial resolution, and can be made part of an electron microscopy system. However, the reason why Auger electron spectroscopy is not even more widely used is due to the complexity of interpreting the chemical information from the lineshape. It was recognised early that Auger lines would contain information about the local density of states. This information is often clouded by a wide range of secondary processes and collective effects.

Auger photoelectron coincidence experiments can be used to simplify Auger spectra. Currently such experiments are being used to find out more about the detail of the Auger process, to determine which are the more important secondary processes. The ambition is that we will be able to use this type of experiment to build better models of the Auger process and so be able to use Auger spectroscopy more effectively.

2. The Auger Process

The simplest case of Auger emission is from an isolated atom. An Auger electron is emitted when an inner shell electron is removed, forming a core hole, and the vacant orbital is filled by an electron from an outer shell in a non-radiative transition. The process is generally divided into two steps, the formation of the initial state, the core hole-state, followed by the decay via Auger emission to the final state. Part of the complexity of Auger spectroscopy comes from the large number of configurations for both the initial state and the final state. High resolution electron spectroscopy of the Auger emission from isolated atoms shows many fine structure peaks (Weightman 1995) due to different atomic terms arising from the different initial state and final state configurations.

As well as the straightforward Auger process, there are a variety of complicating secondary processes that can occur. These include initial state shake-up/off events. In such processes the ionising radiation causes the emission of more than one electron. The additional electron is said to be shaken from the atom in a monopole transition (Weightman 1984). Thus the initial state can have more than one hole. In such cases, the Auger electron will have less energy due to the additional Coulomb interaction with the ion core (Sawatzky 1988). Similarly, the Auger decay itself may result in more than one electron being emitted. A second electron can be shaken from the atom during the formation of the final state. In this case, the energy of the transition is shared between the Auger electron and the shake electron. Such a process is known as a final state shake-up/off event.

A further complication that can arise is due to the processes known as Auger cascades. In these an electron from a deep level within the atom is removed in the ionisation event, an electron from a higher levels fills this in an Auger decay, creating another hole. This hole can also be filled in an Auger process, with emission of a second Auger electron. Clearly, if the initial hole was deep enough and the atom complex enough, this process could go on. If the initial and second holes in an Auger process are in the same level (i.e. have the same principal quantum number) then the Auger process is known as a Coster–Kronig process. Auger cascades often involve Coster–Kronig processes and can occur in a range of materials. Such processes can have important consequences in the shape of Auger lines.

Auger spectra from surfaces are complicated by a number of solid state effects. Perhaps the most interesting of these is the observation that Auger lines are sometimes very similar to their isolated atom counterparts, while at other times they reflect the band structure of the solid. These effects were understood by Sawatsky (1977) and, independently, by Cini (1977). The idea that Auger lines could reflect the band structure of the solid had been proposed by Lander (1953). For an Auger process that involved the emission from the valence band, then the lineshape should reflect the density of states (DOS). The reason why is quite clear. If an inner shell hole is being filled by an electron from the valence band, then the electron can come from any part of that band. If both the Auger electron and the electron that filled the inner shell hole were both from the valence band, then the Auger line should appear as the self fold of the filled DOS. However, this is not always the case. Sawatsky and Cini were able to show that the interaction energy of the two holes left in the final state play a

significant role. If this interaction energy U_{eff} is greater than twice the width of the valence band, then the holes are unable to delocalise into the bands, and the resulting Auger line is largely the same as the lines from isolated atoms. Otherwise, the line can reflect the DOS.

An alternative way to understand this picture is to see that when the core hole is formed, there is an increased central potential for that atom. In some cases this will pull orbitals that are in the bands clear of the bands, so the resultant Auger line will have all the attributes of an atomic process. If the levels are not pulled clear of the band, then the band-like nature of the transitions will be seen in the spectra. It is also possible for materials to demonstrate mixed behaviour, showing both atom-like and band-like parts in their spectra. If a transition is band-like, then the Auger lineshape will reflect the DOS, though the actual shape of the Auger line will also be influenced by the variation in transition probability across the band. This, in general, will not be constant.

When an electron is emitted from the surface region it must traverse some thickness of material to escape the solid. As it does this it can lose energy through a variety of so-called extrinsic processes. The outgoing electron can interact with the electron gas producing electron–hole pairs, or exciting plasmons, or it can ionise other atoms. These processes result in a background being associated with each Auger line. This inelastic background can be subsequently removed with a variety of procedures. The most complete of these uses an estimation of the electron energy loss function. This is used to numerically remove the extrinsic contribution to the lineshape.

If the source of ionisation is an electron beam then the Auger spectra will be superimposed on a background of low energy electrons that come from the backscattering of the incident beam. This background is generally rapidly decreasing at low energies, and increases towards the primary beam energy. Auger peaks may be as low as a few per cent of background at some energies. This has led to the widespread practice of presenting Auger spectra in differential format, as the background is strongly suppressed.

Hence, clearly, the Auger lineshape is very complex. When compared with the other major technique used for surface analysis, x-ray photoelectron spectroscopy, AES suffers in that local information about the chemical environment is not readily accessible. Changes in binding energy give a first order indication of the oxidation state of a particular ion. The Auger process is certainly also dependent on the oxidation state of the ion, but there are many processes that can obscure the effect making clear identification difficult. Changing the oxidation state may well change U_{eff}, giving rise to substantial changes in lineshape or, in cases where the transition is atom-like, a change in oxidation state may well generate different atomic terms, with little relationship to the emission from the ion in another state. Similarly, changing the oxidation state can dramatically change the probability of shake-up/off processes. Hence, Auger spectroscopy has been little used as a technique for determining the chemical state of surface atoms. Clearly though, the information about the local environment of the atom is contained in the Auger lineshape, and a more complete understanding of the processes involved may well led to AES being routinely used for analysis of chemical information.

3. APECS

Auger photoelectron coincidence spectroscopy (APECS) is the name of the technique whereby an Auger electron is counted only when the photoelectron which gave rise to that Auger electron is also collected. In this way, the origins of various peaks in the Auger spectra can be determined. The essential idea of APECS is that it allows us to transfer our understanding of the photoelectron spectra to the Auger spectra. While photoelectron spectroscopy is by no means a simple process, it is much better understood than Auger spectroscopy. Hence we are able to associate features in the Auger spectra with those in the XPS spectra, which is better understood.

The first demonstration of APECS was made by Haak and Sawatsky (Haak *et al*. 1978). They were able to confirm that the satellite on the low energy side of the main peak in the $L_3M_{4,5}M_{4,5}$ spectra of Cu was indeed due to a spectator hole created by a preceding $L_2L_3M_{4,5}$ Coster–Kronig process, in an Auger cascade, as explained previously. The process is shown in Fig. 2. This explanation of the satellite was proposed by Roberts *et al*. (1975) some years before.
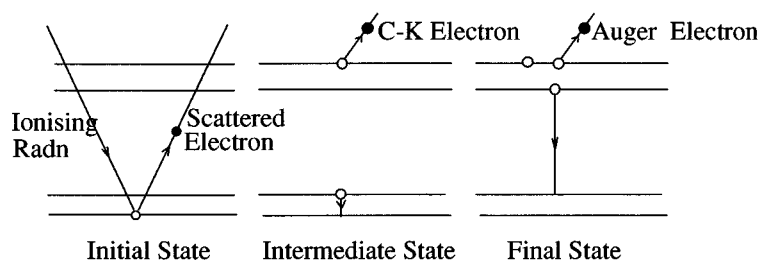

Fig. 2. An Auger cascade is a process where the initial ionisation occurs at a deep level. If this is filled in an Auger process by an electron from a level with the same principal quantum number, then the process is known as a Coster–Kronig transition. The hole created by such a cascade can remain local and affect the energy of the consequent Auger transition. In copper, this process generates a satellite some $4\cdot5$ eV beneath the main L_3VV Auger line.

A second APECS experiment was constructed by Jensen *et al*. (1989) using the VUV storage ring at the Brookhaven synchrotron. They used the pulse structure of the UV light to generate very good timing resolution. In their initial experiments, they investigated the possibility of using APECS to get resolutions better than the natural width of the photoemission lines. This idea had been proposed by Haak (1983) in his PhD thesis which used the fact that energy conservation implied that the sum of the kinetic energy of the photoelectron and the Auger electron was constant. The Auger line in Cu has sharp, well defined atomic terms. By selecting one of these, and measuring in coincidence with it, they were able to reduce the width of the photoelectron line.

In 1990 an APECS experiment was constructed at Murdoch University (Thurgate *et al*. 1990). It used purpose built analysers designed to have very good time resolution. In most other ways it was the same as the experiment of Haak and Sawatsky. The group at Murdoch has used it to look at a number of materials

in the 3d and 4d transition series of the periodic table, and have been able to identify a number of complicating effects in Auger spectroscopy. This apparatus has been used to study a number of intrinsic processes that move intensity away from the mainline emission.

4. Apparatus

Any APECS experiment requires at least two electron analysers, one for the Auger electron and one for the photoelectron. The principal problem that the system must overcome is to distinguish between the true coincidences and those that are due simply to random coincidences between electrons in the background (Thurgate 1996). Such accidental coincidence counts are uniformly distributed in time, while the true counts occur with a fixed time separating the counts in each analyser. The system must have very good timing resolution in order to differentiate between the true coincidence counts and the accidentals. The better the resolution, the better the ratio of true counts to accidental counts.

There have been two approaches to the problem of building electron spectrometers with good timing resolution. The first type is one where the electron spectrometers themselves have good timing resolution. This is the approach used by Sawatzky (1988) and by Thurgate *et al*. (1990). The second approach is to use the pulse structure from the output of a synchrotron. This is the technique used by Jensen *et al*. (1989). In the case where a conventional x-ray source is used, then the spectrometers must have good timing resolution. It was shown by Volkel and Sandner (1983) that the principal source of loss of timing information comes from the variety of flight paths through the electron spectrometer that have different pathlengths. In most conventional spectrometers, electrons that are incident on the spectrometer are slowed by an input lens system before they are passed through the electrostatic deflecting system, which separates them in energy. The fact that the electrons have been slowed down means that slight changes in the length of the flight paths can generate relatively large changes in flight times.

The electron analysers used in the Murdoch experiment have been constructed so that the length of the flight paths are roughly constant for those electrons that fall within the entry cone of the analysers. This is done following the procedures set out in the work of Volkel and Sandner (1983). They proposed that for a 127° cylindircal deflecting analyser (CDA), a multichannel plate placed at the exit slit at the appropriate angle could act to compensate the variation in pathlengths, producing a so-called 'flight time corrected' analyser. The analysers used in the Murdoch experiment are shown in Fig. 3. The total time spread through both analysers and through all the electronics is 1·6 ns. This is still perhaps the best that has been achieved anywhere.

The electronics and arrangement of the system is typical of such coincidence systems and is shown in Fig. 4. True coincidence events add to a peak in the time to amplitude converter (TAC) spectrum. Random events generate a flat background. The signal-to-noise is determined by the number of counts in the peak, and the number of counts in the background. One interesting consequence of this style of experiment is that as the signal depends on the photon current, while the background depends on the square of this current, the signal-to-noise decreases with increasing photon current (Thurgate 1996). In the limit, the additional information generated by increasing the photon current is
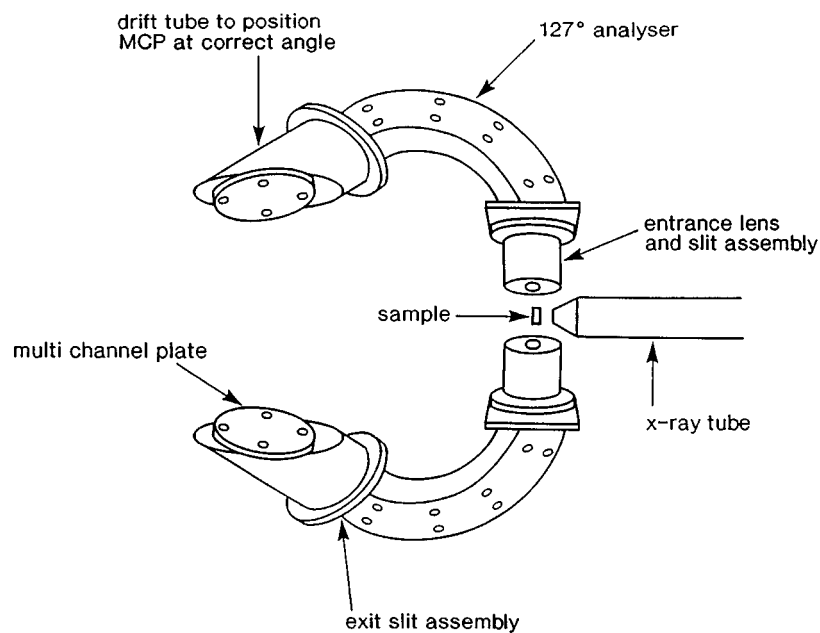
Fig. 3. Experimental arrangment for the APECS experiment at Murdoch. The electron analysers are positioned at right angles to each other and to the x-ray tube.
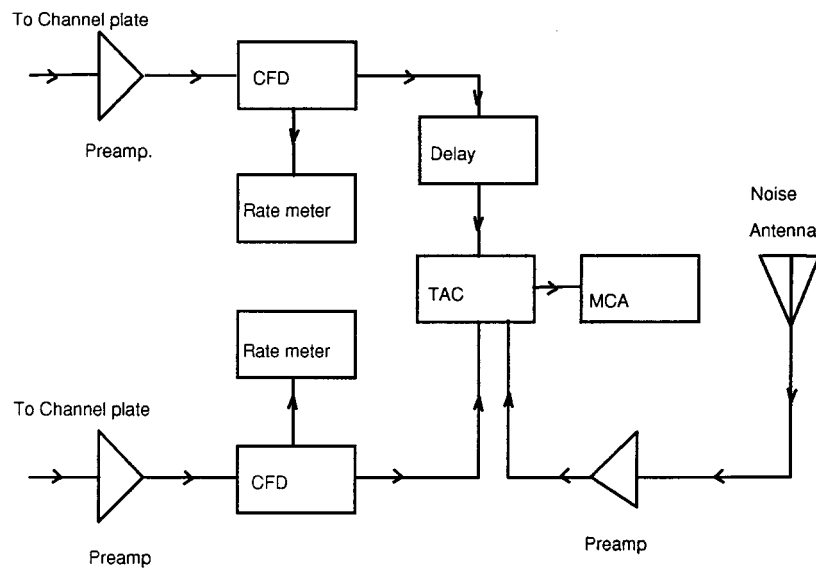

Fig. 4. Electronics of a typical APECS experiment. The time to amplitude converter (TAC) measures the time between start and stop pulses. If the pulses are correlated in time, then a peak will appear in the pulse-height spectrum.

obscured by the additional noise generated by it. Most estimates however put most experiments some distance from this limit.

A typical APECS experiment therefore involves preparing a target, running a program that slowly scans one analyser through a region of interest while it collects TAC spectra for each energy setting. At the end of the day, data are taken from the machine, the sample is cleaned and the data added to the cumulative spectra. The average time to collect data from the Murdoch experiment has been 30 days. Currently the machine is being re-built with analysers which have a wider acceptance angle. It is anticipated that significant progress will be made in reducing data acquistion times.

5. APECS Data from the 3d Metals

The complexity of Auger lines is dramatically evident in the spectra from the 3d transition series. In these materials, the 3d band is progressively filled in with increasing atomic number. The Fermi level lies in the band and so there is a high density of both filled and unfilled states near the Fermi level. This makes it possible for electrons to be excited into the continuum through a variety of processes. This has a number of consequences (Lund *et al.* 1996). The 3d transition metals include nine elements, from Ca to Cu. As the 3d band is filled in across the transition series, there are a number of trends that are important to the Auger spectra. These include (i) decreasing valence bandwidth, (ii) movement of the Fermi level to the top of the band, and (iii) increasing separation of the $2p_{1/2}$ and $2p_{3/2}$ levels across the series.

APECS has done much to illustrate the significance of many of the possible processes. At Murdoch we have collected data from Fe, Co, Ni, Cu and Ga. We have also investigated the effect of alloying Ni and Fe. The Auger lines we have examined are the $L_{2,3}VV$ lines. These APECS data have revealed that a number of processes are significant to the Auger lineshape. These include (i) Coster–Kronig preceded processes, (ii) initial state shake-up/off, and (iii) final state shake-up/off.

6. Coster–Kronig Preceded Processes

The ability of APECS to separate out the component of the L_3VV line which is due to the Coster–Kronig preceded process was first demonstrated by Haak *et al.* (1978), as indicated above. We have collected data in coincidence with the $2p_{1/2}$ on Fe, Co, Ni and Ga as shown in Fig. 5. The Auger lineshapes in coincidence with the $2p_{3/2}$ are shown in Fig. 6. In all but Ga, there is intensity in the L_3VV line which was initiated by a hole in the $2p_{1/2}$. What is interesting is that the Auger decay has now taken place in the presence of an additional hole in the 3d level. The effect that this hole has depends on a number of factors. The most significant of these is the relative width of the valence band. As discussed previously, if the band is sufficiently narrow, then the conventional, two-hole final state Auger process will produce an atom-like Auger line. However, in the case where a Coster–Kronig process has preceded the Auger decay, there is an additional positive charge that must be taken into account. If the band is narrow, then the decay may well produce Auger emission that is characteristic of the singly charged ion rather than the neutral atom. Haak was able to explain the main features of the Cu data in such terms. In our data we have seen examples
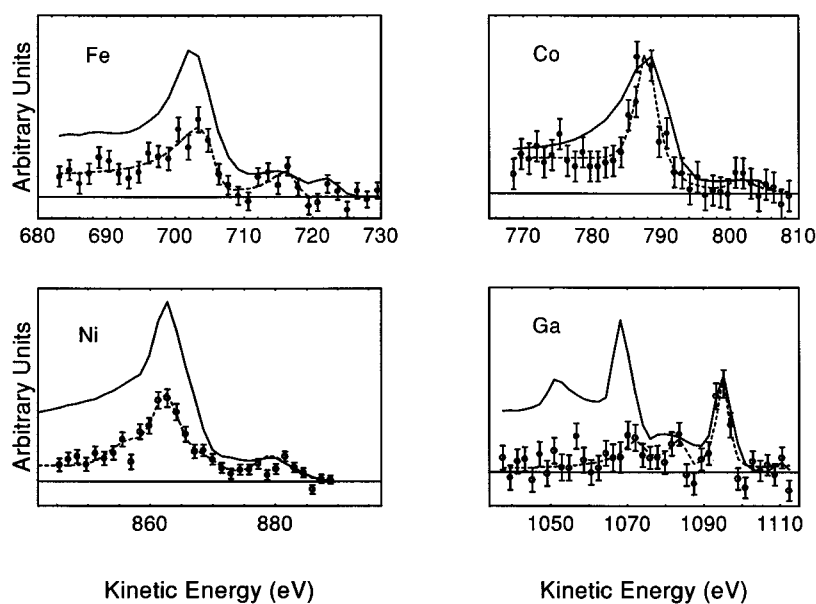
Fig. 5. APECS spectra from three 3d metals and Ga. The $L_{2,3}VV$ region is shown as collected in coincidence with the $2p_{1/2}$ photoelectron line.
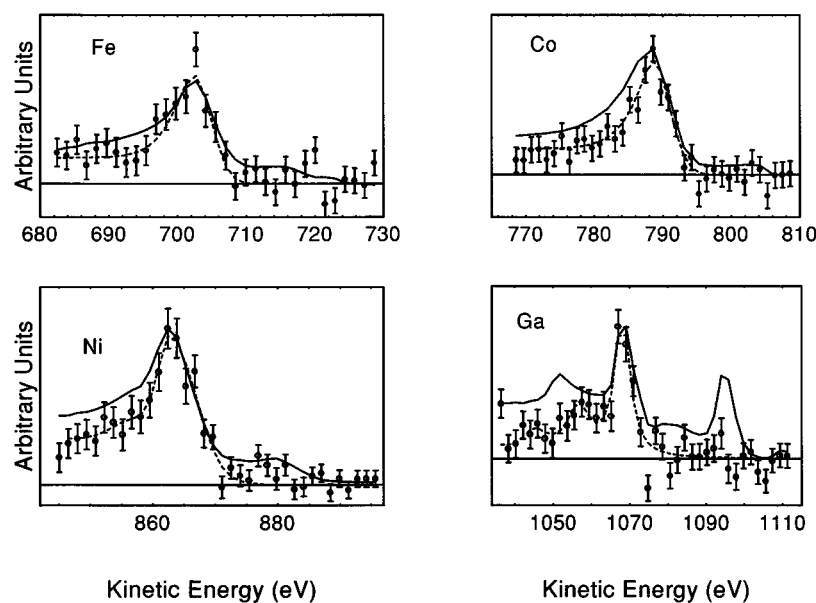

Fig. 6. APECS spectra from three 3d metals and Ga. The $L_{2,3}VV$ region is shown as collected in coincidence with the $2p_{3/2}$ photoelectron line.

of the other behaviour. Iron produces a band-like Auger signal. The data in Fig. 5 show that even in the presence of the additional hole, the Fe line has the same width. We conclude from this that the screening of the valence band hole is enough so that the Auger emission is largely unaffected. Cobalt is thought to be band-like. However, as can be seen in Fig. 5, the emission into the L_3VV

in coincidence with the $2p_{1/2}$ is substaintially narrower than the regular, singles emission. This is consistent with an increase in the hole–hole interaction in the final state, due to the incomplete screening of the hole created by the initial Coster–Kronig event. Nickel has both a band-like and an atom-like part to its Auger line. The band-like part of the line is missing, however, in coincidence with the $2p_{1/2}$. The explanation of this is that the additional electrostatic interaction pulls the levels clear from the band, so that then there is no part of the line which reflects the band. In the case of gallium, there is no part of the L_3VV which is in coincidence with the $2p_{1/2}$. This is simply because the 3d band is complete and has moved further away from the valence band. The energy separation of the $2p_{1/2}$ and $2p_{3/2}$ is no longer enough to overcome this difference, so the Coster–Kronig process no longer generates intensity in the L_3VV from the $2p_{1/2}$ ionisation.
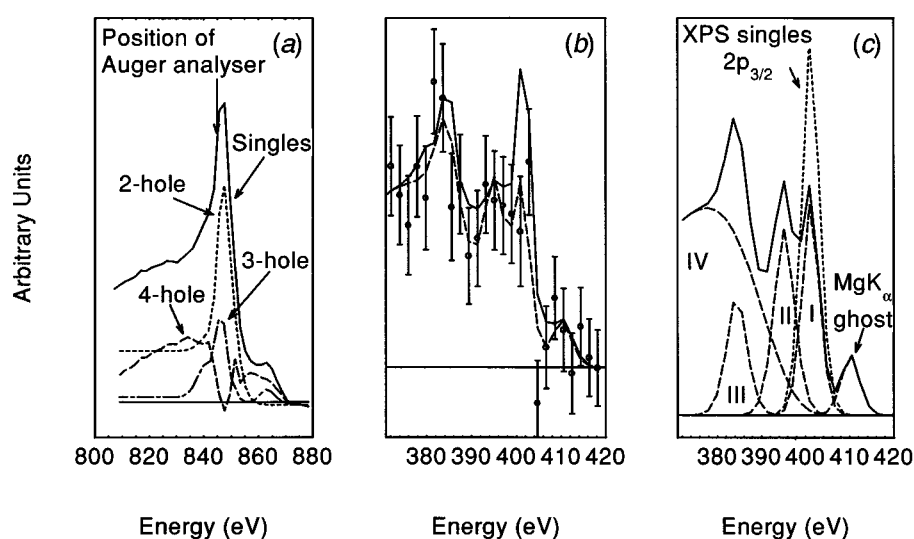

Fig. 7. APECS spectra of Ni in $Ni_{80}Fe_{20}$. Panel (a) shows the APECS separation of the two-, three- and four-hole components of the Auger line. Panel (b) shows the 2p photoelectron region collected in coincidence with the three-hole part of the Auger line. Hence it contains intensity from those regions that produce the three-hole final state. Panel (c) shows a best fit decomposition of the data into a peak at the $2p_{3/2}$ position (contribution due to overlap of the Auger analyser with the two-hole final state), a peak at the shake-up energy (three-hole component due to process an initial state shake-up) and a peak at $2p_{1/2}$ energy (Coster–Kronig preceded process). Note that there is substantial generation of the three-hole final state from shake-off, as indicated by the increasing background below the $2p_{1/2}$ peak.

7. Initial State Shake-up/off Processes

An initial state shake-up/off event is one where an electron in an outer shell, or the valence band, is knocked out at the same time as the initial state is formed by the creation of a core-hole. This shake electron shares the energy of the ionising radiation. If the radiation was a photon, then the energy of the outgoing photoelectron and the shake electron must share the energy of the photon. If the shake electron ends up in a well-defined state above the Fermi

level, then the photoelectron will also have a well-defined energy and appears as a well-defined satellite at a lower energy than the mainline. Such an event is known as a shake-up rather than a shake-off. If the shake electron ends up in the continuum of states in the vacuum, then the event is a shake-off and results in a less well-defined increase in intensity below the mainline. Nickel shows a well-defined shake-up satellite some $6 \cdot 0$ eV below the mainline. Haak (1983) measured the Auger emission appearing in coincidence with this satellite. He was able to show that the resulting three-hole satellite was similar to the emission in coincidence with the $2p_{1/2}$ and appeared at the same energy. At Murdoch we have performed the reverse of this experiment and, with one analyser set at the energy of the three-hole final state in the Auger line, we have swept through the 2p lines with the other analyser (Lund and Thurgate 1996). In this way we have been able to identify all those initial state processes that result in creation of the three-hole final state in the one experiment. Interestingly, initial state shake-off plays an equally important role in creating the three-hole final state in some materials. This can be seen in Fig. 7, which shows data from this experiment.

There are no reasons why we should expect to see only three-hole final states generated by processes in the initial state. Four-hole processes have also been predicted. Martensonn *et al.* (1984) predicted three-hole and four-hole final state configurations resulting from the following processes in the initial state:

Description	Three-hole process		
Coster–Kronig	$L_1L_3M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}$
Coster–Kronig	$L_2L_3M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}$
Initial state shake	$L_3M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}$

Description	Four-hole processes				
Coster–Kronig chain	$L_1L_2M_{4,5}$	$\rightarrow$	$L_3M_{4,5}M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}M_{4,5}$
Initial state shake	$L_1M_{4,5}$	$\rightarrow$	$L_3M_{4,5}M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}M_{4,5}$
and Coster–Kronig	$L_2M_{4,5}$	$\rightarrow$	$L_3M_{4,5}M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}M_{4,5}$
Double initial state shake	$L_3M_{4,5}M_{4,5}$	$\rightarrow$	$M_{4,5}M_{4,5}M_{4,5}M_{4,5}$		

The effect of these processes is to generate intensity in the low energy tail of the Auger line. This intensity is due to intrinsic processes, so it should be included in any estimation of the quantity of any element present. If one is trying to ascertain the quantity of any one component, then it is important to know when the true secondary background starts and the Auger emission ends. These multi-hole final state satellites make it difficult to distinguish that point.

We have estimated the size of the initial state shake by adding together the $2p_{1/2}$ and $2p_{3/2}$ coincidence spectra, and then finding the difference between this and the regular Auger singles spectra. To first order, this difference should look like the size of the initial state shake-off. The background on the low energy side of the summed coincidence spectra is that signal which has remained in coincidence with the photoelectron; hence, it must be due either to inelastic scattering as the electron leaves the solid or to final state shake processes, as explained below. We have good knowledge of the effect of inelastic scattering, and we can make a good estimate of it. On the other hand, if the photoelectron

shares its energy with a shake-up/off electron, then it would have moved away from the energy of the analyser, and so such initial state shake events will not be recorded in coincidence. Hence, the difference is due primarily to initial state shake events. There are other effects that we have ignored in reaching this conclusion. The largest of these is the contribution from any Auger cascade that was initiated by a 2s ionisation. However, this is known to be small (Haak 1983).
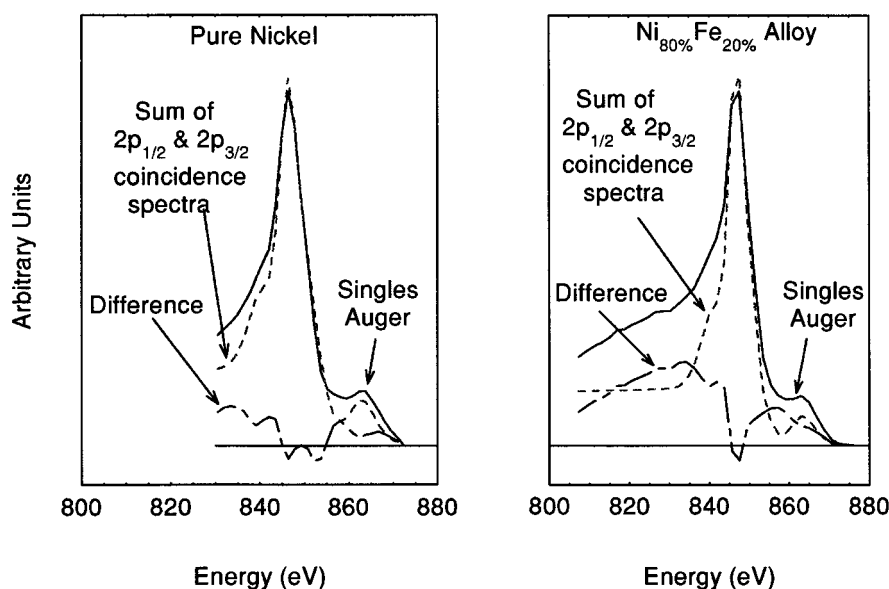

Fig. 8. Summed coincidence spectra are shown as dashed curves, while the regular singles spectra are shown as solid curves. Note the difference in the height of the low energy tail of the summed coincidence spectra. This is due to a change in the probability of the initial state shake-up/off as the alloy ratio changes. The singles spectra are identical near the Auger line.

8. Final State Shake-up/off

Complex multi-hole final state configurations can also be induced by the decay into the final state. The energy of the outgoing Auger electron can be shared with another electron, shaken from the valence band. Such an event will create an additional hole in the valence band, giving rise to satellites in the tail of the Auger line. As outlined in the previous section, we are able to distinguish these final state effects from initial state effects by using the fact that final state shake events remain in coincidence with the photoelectron. Thus, the low energy tail of the Auger line that remains in coincidence with either the $2p_{1/2}$ or the $2p_{3/2}$ photoelectrons, following removal of the extrinsic inelastic component, is due to final state shake effects.

We have found that the final state and initial state shake events tend to complement each other, at least in the case of Ni/Fe alloys. We investigated the initial state shake features in the low energy tails of the L_3VV spectra of Ni in Ni/Fe alloys. We measured the appropriate spectra of $Ni_{50}Fe_{50}$, $Ni_{70}Fe_{30}$, $Ni_{80}Fe_{20}$ and pure Ni. The spectra are shown in Fig. 8. We conclude from these

measurements that when the initial state shake event is more probable, the final state shake is less probable. This can be seen clearly by the fact that the low energy tail in the $Ni_{50}Fe_{50}$ peak is suppressed compared to that of pure Ni. The explanation of this is that if an initial state shake event has occurred, then there are fewer electrons available for the final state shake. It is known that the initial state shake event is more probable, as the shake-up satellite in Ni is brighter in the alloy than in the pure material.

9. Conclusion

The Auger process is of undoubted importance in surface analysis. It maybe that its role can be enhanced, but to do so requires a deeper understanding of the process. Currently we are aware of the complexity, though we have often have no real handle on the magnitude of the competing effects. APECS is playing a role in helping to overcome this by breaking down complex spectra into their component parts. In the future, we hope that the data which are coming from these types of experiments will be used to generate comprehensive packages for the analysis of Auger data that will generate a full description of the surface under investigation.

Acknowledgments

References

Auger, P. (1925). *J. Phys. Radium* **6**, 205.

Cini, M. (1977). *Solid State Commun.* **24**, 681.

Duke, C. B. (1994). 'Surface Science: The First Thirty Years' (North Holland: Amsterdam).

Haak, H. W. (1983). Auger photoelectron coincidence spectroscopy: A study of correlation effects in solids. PhD Thesis, University of Groningen.

Haak, H. W., Sawatzky, G. A., and Thomas, T. D. (1978). *Phys. Rev. Lett.* **41**, 1825.

Harris, L. A. (1968). *J. Appl. Phys.* **39**, 1419.

Howarth, L. J. (1935). *Phys. Rev.* **48**, 88.

Jensen, E., Bartynski, R. A., Hulbert, S. L., Johnson, E. D., and Garrett, R. (1989). *Phys. Rev. Lett.* **62**, 71.

Lander, J. J. (1953). *Phys. Rev.* **91**, 1382.

Lund, C. P., and Thurgate, S. M. (1996). *J. Elect. Spectrosc. Related Phenom.* **77**, 283.

Lund, C. P., Thurgate, S. M., and Wedding, A. B. (1996). *Phys. Rev.* B, in press.

Martensson, N., Nyholm, R., and Johansson, B. (1984). *Phys. Rev.* B **30**, 2245.

Roberts, E. D., Weightman, P., and Johnson, C. E. (1975). *J. Phys.* C **8**, L301.

Sawatzky, G. A. (1977). *Phys. Rev. Lett* **39**, 504.

Sawatzky, G. A. (1988). *Treatise on Materials Sci. Technol.* **30**, 167.

Thurgate, S. M. (1996). *J. Elect. Spectrosc. Related Phenom.* **81**, 1.

Thurgate, S. M., Todd, B., Lohmann, B., and Stelbovics, A. (1990). *Rev. Sci. Instrum.* **61**, 3733.

Volkel, M., and Sandner, W. (1983). *J. Phys.* E **16**, 456.

Weightman, P. (1984). *In* 'Electronic Properties of Surfaces' (Ed. M. Prutton), pp. 135–92 (Adam Hilger: London).

Weightman, P. (1995). *Microscopy Microanal. Microstructure* **6**, 263.