

Scattering in Electron Spectrometers, Diagnosis and Avoidance, I: Concentric Hemispherical Analysers

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ABSTRACT

The unwanted scattering of electrons in electron spectrometers leads to (i) a loss of sensitivity, (ii) distortion of the spectral background and (iii) problems in calibrating spectrometer intensity/energy transmission functions. Here we develop three methods to analyse the extent of the contribution and how to reduce it to an insignificant level. The three diagnostic methods involve the measurement of either (a) the region of the $M_{4,5}VV$ Auger electron peaks from Ag in AES, (b) the reflection of an electron beam from a biased sample, or (c) the $3d_{5/2}$ photoelectron peak from Ag irradiated with $MgK\alpha$ X-rays. In this work, Part I, analyses are made for concentric hemispherical analysers. In Part II cylindrical mirror analysers are studied. In this Part, it appears that in our spectrometers, a modified VG Scientific ESCALAB II with (a) the original analyser and (b) a 210 analyser, the major scattering contributions arise from high energy electrons which strike the outer hemisphere giving rise to a spectrum of secondary electrons. These cause the scattered electron contribution to vary approximately as $E_p^{-2.43}$, where E_p is the pass energy, to increase approximately in proportion to the spectrometer input slit area for AES studies, to fall approximately inversely with an increase in the lens magnification from 1 to 3 and, in the constant ΔE mode, to increase with the analysed electron energy. Thus, for each lens magnification, there exists a range of slits and pass energies for which the scattering may be maintained at less than 1%. In the constant ΔE mode, pass energies of 50 eV or more are generally safe whereas, in the constant $\Delta E/E$ mode, retardation ratios of 4 or less are required.

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1 INTRODUCTION

In all optical imaging systems an important problem is that of unwanted radiation reaching the detector and so reducing the contrast and quality of the image as well as causing systematic errors in measurements of intensity. In light optics the unwanted radiation is reduced by coating the internal surfaces of non-optical components by optical blacks and by the use of appropriately placed apertures in the system. In electron spectroscopy, electron optical focusing similarly occurs for one of two reasons: (i) to form an image of the surface and (ii) to obtain spectral analysis. In this paper we shall consider the appearance of unwanted scattering in electron spectra although the basic concepts are equally applicable to the loss of contrast in spatial imaging.

Since the earliest designs of practical electron spectrometers, the above problem has been known and systems of electron blacks have been developed^(1,2) to reduce the unwanted scattered electrons. Manufacturers of commercial instruments take considerable care to develop coatings for electrode surfaces and appropriate electron optics to minimise the number of unwanted scattered electrons present. If these electrons appear in the spectra they lead to (i), extra unwanted noise which reduces sensitivity and (ii), spectral background shape distortion making analysis of the data more difficult. A third problem which has appeared more recently concerns the calibration of electron spectrometers used in Auger electron spectroscopy (AES) or X-ray photoelectron spectroscopy (XPS) for their intensity/energy transmission functions⁽³⁻⁵⁾. For a detailed calibration over the whole energy range, the spectral background from reference samples must be measured. This can only be done accurately if the unwanted scattered electron intensity can be reduced to below 1% of the true spectral intensity. Controlling the unwanted scattered electrons is, therefore, very important. To illustrate the problem, Figure 1 shows examples of XPS spectra in which there is both little scattering in the spectrometer and also where there is a moderate scattering enhancement of the background.

Of course, few users of an AES or XPS instrument are going to take their spectrometer to pieces to re-coat the inner surfaces with more efficient electron blacks. However, there are ways of reducing the electron scattering already available within the suite of operating conditions which allow us to understand the sources of scattered electrons and how to reduce them to an acceptable limit. This understanding will, in turn, assist the manufacturers to make better instruments without greatly adding to the cost. To the author's knowledge little systematic work has ever been published on internal scattering in electron optical systems.

The work described in this paper formed part of the background study for the *metrology spectrometer* used to establish basic reference spectra⁽³⁻⁵⁾. This spectrometer is essentially a VG Scientific ESCALAB II but the overall concept presented here and the broad description of the behaviour of the unwanted scattered electrons is appropriate to all spherical sector electron spectrometers.

2 THE APPARATUS

A schematic of the *metrology spectrometer* with the standard ESCALAB II analyser is shown in Figure 2. Electrons may be analysed either from a point source on the sample, as in AES, or from a large area of the sample, as in XPS. Electrons emitted from the sample move in all directions in a field-free space. Those entering the $\pm 6^\circ$ lens aperture experience an accelerating and focusing field of an electro-static lens whose magnification may be set at 3, 1 or $\frac{1}{3}$ to image electrons of a given energy at the entrance to the spherical sectors. At this point there is a choice of entrance slits to the sectors which cover a range of slit width or aperture sizes. Many of these are detailed in Table 1⁽³⁾. The slits are intended to provide energy resolutions in the sectors ranging from 0.25% to 2% whereas the apertures are intended for selected area XPS measurements^(6,7).

Electrons of the given energy are retarded to a lower energy just before the entrance slit so that they are focused through the spherical sectors at the pass energy, E_p , to reach the output slit and so to the detector. For the standard analyser in the ESCALAB II the detector is a single channel electron multiplier used in the pulse counting mode. The general trajectories of electrons are shown in Figure 2 for the lens used at a magnification of 3.

In the second analyser tested, a VG 210 analyser with 5 channel electron multipliers the arrangement is very similar except that alpha plates are inserted between the hemispheres to improve the energy resolution, and a meshed hole is placed in the outer hemisphere along the line of the lens axis.

In the next section we consider possible sources of stray electrons and hence the methods for altering their intensity and how to eliminate them.

3 SOURCES OF STRAY ELECTRONS

(a) Possible sources

The first source to consider arises from electrons and X-rays from the sample liberating further electrons from the inner surface of the earthed central element of the transport lens. These currents will be relatively weak for AES using electron beams of less than 10 keV and may, in general, be ignored. With other lens designs, particularly involving retarding elements these currents may become significant.

The second source comes from electrons of higher energy than those to be analysed which are focused beyond the entrance slits and strike the outer hemisphere at S as shown in Figure 3. Electrons with an energy close to the pass energy strike to the right of S to an extent dependent on their energy above the pass energy. At 10% excess energy they strike within 10 mm of S , at twice the pass energy within 5 mm of S and at higher energies effectively at S . Some of the secondary electrons subsequently emitted from this region have the correct energy and angle of emission to pass the exit slit and be detected. These electrons give rise to the spurious background in Figure 1(b). Note that electrons do not have a line of sight from S to the detector.

The third source of electrons is similar to the second but arises from electrons of lower energy than those to be analysed and which thus strike the inner hemisphere, liberating secondary electrons. This source will be very much weaker than the second source. A fourth source may come from electrons with energy close to those being analysed and which therefore strike the edges of the output slit and liberate electrons there. These scattered electrons affect the tails of spectral peaks and may be seen in some spectrometers as small satellite peaks close to intense narrow peaks. Here they were well below 0.1% and so will be ignored.

It is clear from the above comments that the main source of scattered electrons are those emitted from the region near S . We calculate the intensity of these electrons below.

(b) Scattered electron intensities

The flux of electrons emitted from the sample is simply $I_0 n(E)$ when I_0 is the primary electron beam flux in AES and XPS and $n(E)$ is the sample electron emission spectrum. We shall consider first AES with the flux $I_0 n(E)$ emitted from some point on the sample. The intensity transmitted by the lens is $I(E)$ which, if the lens is correctly set, will peak close to the energy of analysis, E_A , and fall rapidly as E departs from E_A . The lens acts as a crude energy pre-filter. If the lens were without aberration and the input slit were a small aperture at earth potential the filter would be very narrow, however if the input slit is large the filter

is much broader. Figure 4 shows the trajectories of electrons of successively higher energies E_B and E_C than E_A and how, above E_B , some are stopped by the slit. It is straightforward to note that, without aberration, the energy width of the filter that passes 100% of the electron intensity, $E_B - E_A$, is simply proportional to the slit area. Also, in the regime where the cone of high energy electrons more than fills the slit, the fractional solid angle of those that can be transmitted also depends on the slit area. Thus, the total number of unwanted electrons depends approximately on the input slit area. In AES, the number of true electrons does not depend on this area whereas in XPS with unmonochromated sources it does. Thus, in AES the relative effects of the scattered electrons should increase with the slit area whereas in XPS there should be no such dependence.

In the above we have assumed that the input slit is at earth potential. In reality it is at the pass energy of the spectrometer. In this case the energy width of the lens pre-filter not only depends on the slit width but also, from Figure 4, on the reciprocal of the cone solid angle of electrons from the lens being passed by the slits so as to be able to strike the outer hemisphere. In this analyser the cone solid angle at the lens output is approximately proportional to $(E_p/E)^{0.5}$ for (E_p/E) values greater than 0.23 and proportional to (E_p/E) for (E_p/E) values less than 0.23⁽³⁾. Thus, the lens term $l(E)$ may be re-expressed $Ak_M(E, E_A, E_p)$ where A is the entrance slit area in AES and is a constant for XPS, and $k_M(E, E_A, E_p)$ depends on the lens magnification, M , the electron energy, E , the pass energy, E_p , and other lens terms. Thus, an intensity $I_o n(E) Ak_M(E, E_A, E_p)$ strikes the outer hemisphere at an energy of approximately $E - E_A + \frac{1}{2}E_p$ where E_A is the analysed energy. The secondary electrons emitted from the outer hemisphere with an energy E_s have a spectrum $n_s(E_s)$ and those of an energy qE_p , where q is a constant in the range 1.2 to 1.6, can pass around the spheres and be detected with the true electrons. The intensity of the scattered electrons is thus proportional to

$$I_o \int_{E_A}^{E_o} n(E) A k_M(E, E_A, E_p) n_s(E, E_A, qE_p) dE$$

with many other constants omitted, whereas the intensity of the true spectrum is proportional to $I_o n(E_A)$. Thus, the relative intensity of the scattered electrons, B_s , to the true electrons, B_o , is approximately:

$$\frac{B_s}{B_o} \propto \frac{A \int_{E_A}^{E_o} n(E) k_M(E, E_A, E_p) n_s(E, E_A, qE_p) dE}{n(E_A)} \quad (1)$$

In the above the upper limit of the integral, E_o , is the maximum energy of electrons in the spectrum of $n(E)$. If $n(E)$ is only slowly varying and if $k_M(E)$ rapidly falls at higher and lower energies than E_A , the above relation becomes:

$$\frac{B_s}{B_o} \propto \frac{A n(E_A) \int_{E_A}^{E_o} k_M(E, E_A, E_p) n_s(E, E_A, qE_p) dE}{n(E_A)} \quad (2)$$

The integral of $k_M(E, E_A, E_p) dE$ may be replaced by $K_M E_A (E_A/E_p)^n$, where $n = 0.5$ for $E_p > 0.023 E_A$ and $n = 1.0$ for $E_p < 0.023 E_A$, since the width of the crude energy filter

formed by the lens is proportional to $E_A(E_A/E_p)^n$. K_M is a lens constant depending on the magnification M so that finally:

$$\frac{B_s}{B_o} \propto A n_s(E_A, qE_p) K_M E_A(E_A/E_p)^n \quad (3)$$

In this analysis we have ignored the effects of changes in the precise position of the electrons striking the outer hemisphere and the changes of $n_s(E_s)$ in both shape and intensity as E increases in the integrals of Eqs. (1) and (2). We therefore rewrite Eq. (3) as follows where x, y and z are unknown powers whose values may be associated roughly with Eq. (3):

$$\frac{B_s}{B_o} \propto A E_A^x M^y E_p^z \quad (4)$$

In the sections that follow we study this relation.

4 MEASUREMENTS OF SCATTERING

a) The effect of spectrometer pass energy, E_p

The dependence of B_s/B_o on E_p may be derived from the data published earlier in Figure 7 of reference (3). There we measure the intensity of the peak, P , and the background B for the silver Auger electron peaks formed by a 5 keV electron beam at 30° to the surface normal, as shown in the inset to Figure 5. Note that the peaks themselves are not used as the changing spectrometer conditions alter the energy resolution and hence the peak heights. It is actually the peak area we need and this is proportional to the background associated with the peak, as shown by P in the inset to Figure 5. From the earlier plot of P/B we may calculate B_s/B_o as follows:

$$\frac{B_s}{B_o} = \left(\frac{P/B \text{ for } E_p = 200}{P/B \text{ for } E_p} \right) - 1 \quad (5)$$

Thus, in Figure 5 we plot B_s/B_o as a function of E_p on log axes. It is known from work in AES⁽⁸⁻¹¹⁾ that the low energy part of the secondary electron emission spectrum from solid surfaces follows a power law giving a linear result on log axes such as that seen in Figure 5. On log axes the multiplier q in Eq. (3) merely shifts the data on the abscissa but does not affect the shape of the plotted function unless it too depends on E_p . The gradient of this plot is - 2.43. Now, it is known that the inner surfaces of the hemispheres of this analyser are coated with a form of carbon and, furthermore, measurements of standard spectra in AES show that, over the energy range up to 50 eV, the power dependence of the emitted spectrum from carbon is around - 2.0⁽¹²⁾. Thus, from Eq. (3), B_s/B_o should depend on $E_p^{-2.5}$. This is very close to the result shown in Figure 5. At energies above 50 eV the power dependence may alter but the scattering is too weak to make sensible measurements here.

Figure 5 thus shows that the higher pass energies sample, progressively, the least intense part of the scattered electron spectrum, $n_s(E_s)$. For a scattering contribution to the background of less than 1%, pass energies above 28 eV are required when using the conditions of Figure 5, ie the lens at a magnification of 1 and the 5 mm input aperture. We see below how changes in the lens magnification and aperture size affect this result.

Before leaving this section it should be noted that not all spectrometers are coated internally with carbon. Other materials may be used which give a spectral power dependence which

is, in general, weaker. Thus, they may have a lower scattering than the result shown in Figure 5 at 2 eV pass energy but higher at 20 eV or vice versa.

b) The effect of aperture size, A , lens magnification, M , and electron energy, E_A

The background scattering in Figure 5 may be described by the relation:

$$\frac{B_s}{B_o} = s E_p^{-2.43} \quad (6)$$

where the constant s , for the silver Auger electron peak shown, is 32 for the lens set at $M = 1$ with the 5 mm input aperture. From Eq. (4) it is known that s is a function of A , M and E_A .

Figure 6 shows some further plots for silver and also for a similar measure at 875 eV for the copper $L_{3M_{4,5}}M_{4,5}$ peak indicating that the E_p dependence in Figure 5 is general. Two of the data sets in Figure 6 are for copper and two for silver with one of each for the lens at a magnification of 1 and one each at a magnification of 3. These data, together with those reported earlier⁽³⁾, give a measure of the effect of the lens magnification M , the aperture area A and the energy E_A on the parameter s . The precise effects of A and M for the silver peaks are shown in Figure 7. Note that, for $E_p > 10$ eV, the scattering falls rather faster than our $E_p^{-2.43}$ dependence discussed above. The shape of these curves is discussed later. Eq. (6) and Figure 7 may be taken to describe the *upper limit* for the scattering.

From Figure 7 the dependence of s on A is validated reasonably well and it is clear that, if for the silver data we write:

$$\frac{B_s}{B_o} = A E_p^{-2.43} E_A K_{M,Ag} \quad (7)$$

then $K_{1,Ag} = 0.0094$ and $K_{3,Ag} = 0.0024$ for a 5 keV beam incident at 30° .

For copper the results also show $K_{1,Cu} = 0.0094$ and $K_{3,Cu} = 0.0024$. The solid lines in Figures 6 and 7, for $E_p \leq 10$ eV, are drawn for Eq. (7) with these values. Thus, it is clear that the general form of Eq. (7) is correct and that, for the lens configuration shown in Figure 2, K_M is approximately inversely related to M .

Less extensive measurements have been made using the 210 analyser. For the Ag sample data have been recorded for the equivalent of the 6, 3 and 1.5 mm entrance slits for a 5 keV electron beam at 30° incidence to the surface normal. Equation (7) retains validity but now K_{1Ag} is reduced to 0.0032. This represents an improvement of a factor of 3 on the standard spectrometer.

c) Spectral measurements of scattering

In order to ensure that all scattering effects may be removed from spectra, we measure the spectrum of scattered electrons arising from monoenergetic electrons entering the spectrometer. One way of doing this would be to use an electron gun mounted on the sample holder and to direct a beam into the spectrometer. We do not choose this approach since (i) the beam will not fill the analyser optics in the same way as electrons scattered from the sample, and (ii) it will not lead to a generally applicable method. Instead we reflect electrons from the sample as shown in Figure 8. By using 900 eV electrons from the electron gun and by applying a bias of more than - 900 V to the sample holder, monoenergetic 900 eV electrons may be projected into the spectrometer. By moving the electron beam to the right

and left of the optimal point, it is clear that the reflected electrons are projected to the left and right of the lens axis. Thus, by rastering an appropriate area of the sample one may be sure of fully filling the entrance aperture of the transport lens.

Figure 9 shows a typical widescan measure of the scattered electrons reaching the detector as a function of the spectrometer energy in the constant ΔE mode at 20 eV pass energy. Inset is shown the intensity of the monoenergetic electrons causing the scattering. In this measurement a 6 mm entrance slit and a lens magnification of 1 are used. If the lens is switched off the scattering does not cease below 670 eV but extends fairly evenly down to zero energy exactly as one would expect from the discussion given earlier (the spectrometer output, overall, falls by a large factor as well, of course).

Measurements as a function of pass energy in the range 100 down to 5 eV show the spectral shape of the scattered contribution to be fairly independent of E_p . Only the relative intensity of the unscattered and scattered electrons changes. The ratio of these two intensities, I_s/I_o , is shown in Figure 10 for the above condition. The solid line, represents the same dependence as used for Ag and Cu in Figure 6 showing that this appears to be a reasonably accurate description even for this case where there is no real sample present. These measurements may be made with much greater sensitivity than those using the Ag or Cu samples and enable us to show that the scattering continues to decline as E_p increases to 100 eV.

Now that Eq. (7) is reasonably well validated it is worth returning to the XPS results shown in Figure 1. The large hump in the central energy range for the spectrum at 5 eV pass energy is clearly a result of analyser scattering. Just above the $M_{4,5}NN$ Auger peaks at 350 eV the background rises as the lens pre-filter function, $k_M(E)$, increases proportionally with the energy. This occurs between 350 and 550 eV. At higher energies the filter function has run off the plateau leading to the 3d peaks and, from Eq. (1), the fall in the spectral intensity, $n(E)$, above 900 eV leads to smaller scattering contributions. Thus, as the energy rises to 900 eV the intensity of higher energy electrons within the range of the pre-filter function steadily falls. The characteristic hump shaped contribution of analyser scattering in Figure 1 is thus a direct result of the combination of a low pass energy, a lens whose filter function increases with energy and the true spectral shape. If the true spectrum is represented by peaks at 900 eV and 1200 eV with a flat spectrum of losses extending to zero eV, as shown by the dotted line in Figure 11(a), the scattering spectrum may be calculated directly if $k_M(E)$ and the proportionality constant of Eq. (3) are known. The solid curve in Figure 11(a) is for a Gaussian $k_M(E)$ with a standard deviation of $0.45 E_A$ and serves to illustrate the energy dependence of the unwanted scattering contribution. The relative contributions of the scattered and true electrons are obviously dependent on all of the parameters discussed earlier. Figure 11(b) illustrates, for the same example, the effect for an analyser with no input lens, ie $k_M(E)$ is a constant. Results of the magnitudes shown in Figures 11(a) and (b) would only be expected for extremely low pass energies but errors at the 10% level can occur at 10 eV pass energy. Note that if the true intensity were constant from zero to high energies the scattered contribution would rise continuously across this spectral range.

So far all our measurements of scattering have been made with electron beams. The results using a broad area unmonochromated X-ray source should behave as in Eq. (7) except, as discussed earlier, for the dependence on A . The measurements here are not as easy as those with an electron beam as the count rates are low for the low pass energies. To ensure that the worst situation is covered we measure the height of the Ag $3p_{1/2}$ peak, shown in Figure 1(a), above its background. This peak is close to the energy of maximum scattering as shown in Figure 1(b). The peak is broadened by lifetime effects to a full width at half maximum height of 3 eV so that the further broadening arising from the spectrometer at pass energies below 25 eV may be ignored. Measurements for this peak, using $MgK\alpha$ radiation for the 210 analyser, are shown in Figure 12. We see exactly the same effects as previously. The data in Figure 12 show the average result for data using the 6 mm, 3 mm and $1\frac{1}{2}$ mm

input slits with the error bars encompassing the full range of the three measurements. results are clearly unaffected by the slit size, as predicted earlier.

It is worth making a small point here about sensitivity and signal-to-noise ratios for peaks. The peak in Figure 12 could be measured at the same energy resolution using 6 mm input slits at 5 eV pass energy or 3 mm slits at 10 eV. The signal-to-noise ratio at 10 eV may be given by⁽¹³⁾:

$$(S/N)_{10} = \frac{P}{(P + 2B)^{1/2}} \quad (8)$$

where P and B are the counts per channel. From Figure 12, $B_s = 0.37 B_0$ and $B_0 = 1.88 P$ so

$$(S/N)_{10} = \left(\frac{P}{6.15} \right)^{1/2}$$

Now the lower pass energies and larger slits are usually used as the spectrometer is then more efficient. Let us assume that this condition gives k times the count rate of the 10 eV, 3 mm slit condition. Thus, the signal-to-noise ratio for the 5 eV condition is given by

$$(S/N)_5 = \frac{kP}{(kP + 2kB)^{1/2}} \quad (10)$$

where, from Figure 12, now $B_s = 2 B_0$. Thus:

$$(S/N)_5 = \left(\frac{kP}{12.28} \right)^{1/2} \quad (11)$$

ie k would have to exceed 2 for there to be any benefit. Even so, the changing background under the peak may cause other problems. For AES or XPS using a monochromator the improvement on using the narrower slit is greater and the k factor is smaller so that it is always better to use the narrower slits and higher pass energies rather than let the pass energy fall into the range in which scattering is significant.

Table 2 summarises the set of operating conditions for the constant ΔE mode which may be used in this instrument, with the standard analyser, for AES excited with a 5 keV electron beam which give less than 1% scattering contribution to the spectral intensities up to 800 eV and less than 2.5% up to 2000 eV. This Table is deduced from the above data and the slit areas defined by the data in Table 1. The energies for the 210 analyser are a factor of 1.3 to 1.6 lower. Clearly the 100 eV pass energy setting is safe for all operating conditions for both AES and, since the sample will fill most of the larger apertures in the $M = 1$ condition where the situation is worst, also for XPS. The 50 eV setting may also be used with many options but at 20 eV problems may occur. The 10 and 5 eV settings should be avoided if spectral backgrounds are important in the measurement. The data for XPS are not as extensive but the $M = 1$ condition shown in Figure 12 is the most severe. Here, for pass energies above 30 eV the scattering is insignificant.

For the constant $\Delta E/E$ mode the results are somewhat different from the above in that the problems occur at low electron energies where the pass energy is also low. Figure 13 shows the example illustrated in Figures 11(a) and (b) but for a high retardation ratio, $R(= E/E_p)$, in the constant $\Delta E/E$ mode. As the retardation ratio is reduced the fraction of scattered electrons reduces but the major problems still occur at low energies. Curve (a) represents the predictions analogous to those in Figure 11(a), where the same input lens is used, and curve (b) the result with no lens. For the constant $\Delta E/E$ mode the analogous constraints to those

shown in Table 2 are given in Table 3. This gives the maximum values for the retardation ratios to give less than 1% scattering contribution for energies down to 100 eV and 2.5% contribution down to 40 eV.

The above results do not carry over to cylindrical mirror analysers in any detail. The problems there can be rather more severe and can occur throughout the energy range. This is discussed in Part II⁽¹⁴⁾.

5 CONCLUSIONS

Scattering of electrons in spectrometers can reduce spectral sensitivity and distort the background shape. This latter effect gives rise to problems in calibrating spectrometer transmission functions. The scattering in hemispherical sector analysers with accelerating lenses occurs mainly at the outermost hemisphere and its contribution in the spectra, described in Eq. (4) and for AES in Eq. (7), may be reduced dramatically by using higher pass energies. Improvements in AES also occur by reducing the entrance aperture area and increasing the lens magnification. In the *metrology spectrometer* the spectral scattering contribution may thus be reduced to below 1%. To assist in the diagnosis three methods have been devised (a) using a 5 keV beam incident at 30° to a silver sample to study the spectral shape near the $M_{4,5}VV$ peaks, (b) using an unmonochromated $MgK\alpha$ X-ray source to study the $Ag\ 3p_{1/2}$ peak and background intensities, and (c) in which the sample is negatively biased to reflect electrons from an electron gun directly into the spectrometer. This provides a spectral delta function with no electrons at higher or lower energy than that of the beam. Electrons appearing at these energies, due to scattering in the spectrometer, are thus easily measured. Spectrometers may be improved by replacing the region at S in Figure 3 by a mesh covered hole to reduce the number of scattered electrons. In this way the scattered flux is reduced here by a factor of 3 so that, for instance, pass energies may be reduced by a factor of 1.3 to 1.6 from those given in Table 2. In general, problems in the constant ΔE mode used for XPS occur increasingly as the pass energy falls below 20 eV and, in the constant $\Delta E/E$ mode used for AES as R exceeds $E/20$. These results are expected to be typical for all spherical sector analysers with accelerating input lenses. Spectrometers without lenses will generally perform less well.

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TABLE 1

Slits available for the standard analyser with the NPL VG ESCALAB II

Identifier	Entrance slit (mm)	Exit slit (mm)
A1	$\frac{1}{2}^a$	6 x 15
A2	1 ^a	6 x 15
A3	3 ^a	6 x 15
A4	5 ^a	6 x 15
B1	10 ^a	6 x 15
C1	6 x 15	6 x 15
C2	3 x 15	3 x 15
C3	1.5 x 15	1.5 x 15
C4	0.75 x 15	0.75 x 15

^a Aperture

TABLE 2

Conditions of operation of the *metrology spectrometer* in the constant ΔE mode to reduce the scattered electrons in AES, generated with a 5 keV beam, to less than 1% of the spectral intensity for energies below 800 eV and less than 2½% for energies below 2000 eV. The table gives the minimum value of the pass energy, E_p , for various slits and lens magnifications for the standard ESCALAB II spectrometer. The values for the 210 analyser are approximately a factor of 1.3 to 1.6 lower.

Identifier	Minimum value of pass energy, eV	
	M=1	M=3
A2	15	10
A3	25	20
A4	35	25
B1	45	35
C1	50	35
C2	40	30
C3	35	25
C4	30	20

TABLE 3

Conditions of operation of the *metrology spectrometer* in the constant $\Delta E/E$ mode to reduce scattered electrons in AES, generated with a 5 keV beam, to less than 1% of the spectral intensity at 100 eV or 2.5% at 40 eV. The table gives the maximum value of the retardation ratio, (E_A/E_p) , for various slits and lens magnifications with the standard ESCALAB II analyser. The values for the 210 analyser are approximately a factor of 1.3 to 1.6 higher.

Identifier	Maximum value of	Retardation Ratio
	M=1	M=3
A2	18	28
A3	8	12
A4	6	8
B1	4	6
C1	4	6
C2	5	7
C3	6	8
C4	7	9

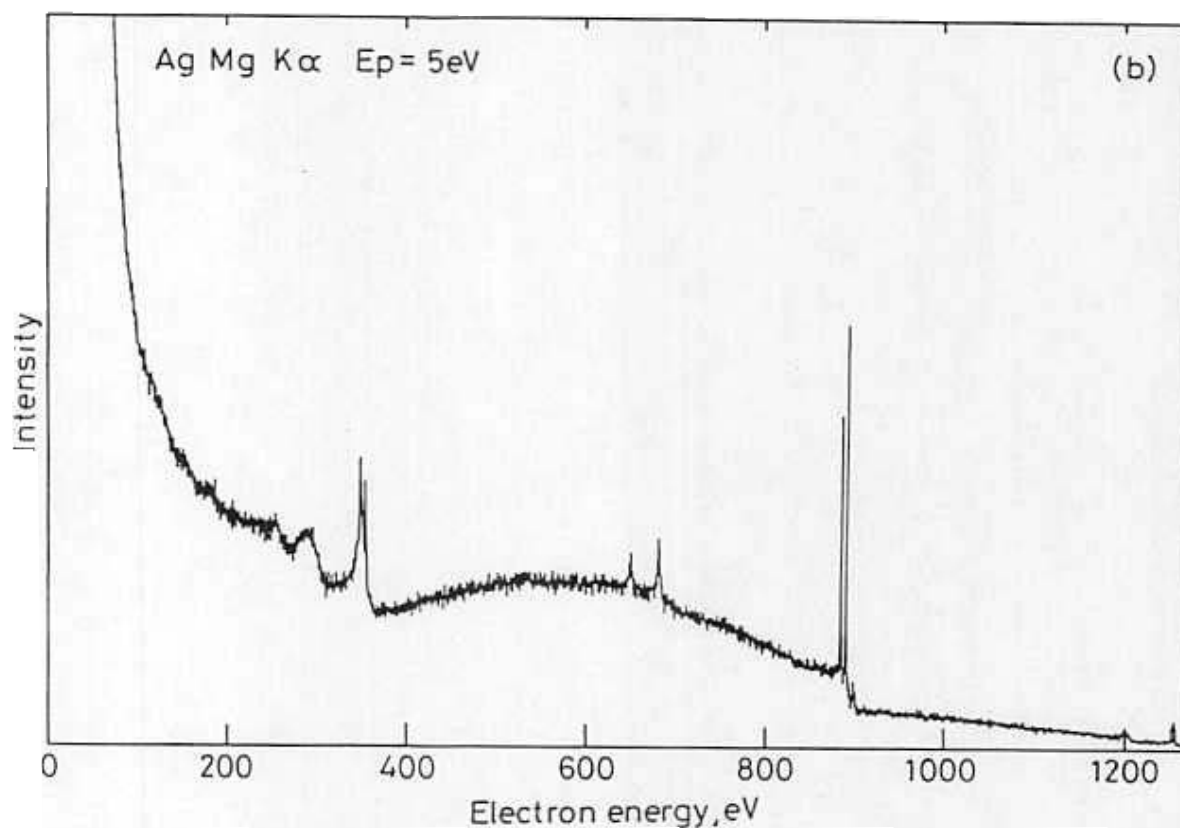
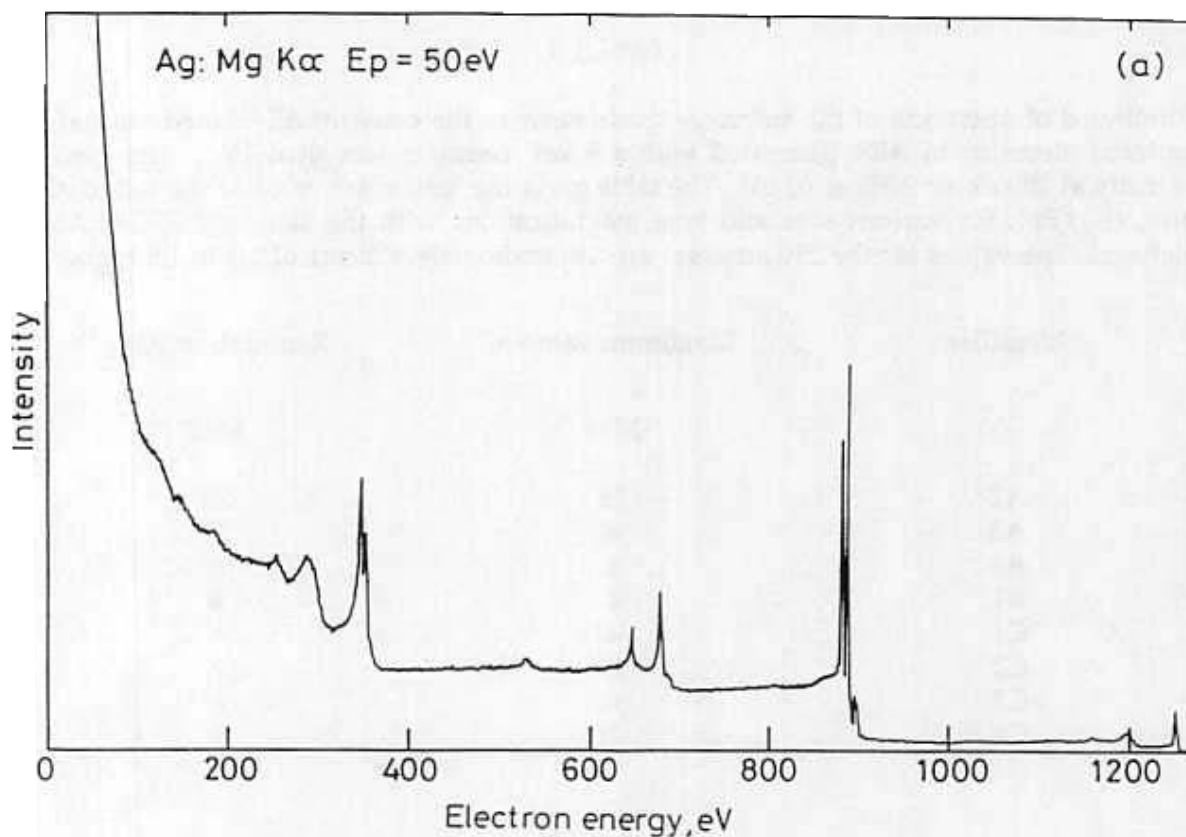


Fig 1 XPS spectra of silver using the constant ΔE mode with the 6 mm input slit, a lens magnification of 3 and pass energies of (a) 50 eV, and (b) 5 eV. These conditions are chosen to illustrate low and high analyser scattering effects, respectively.

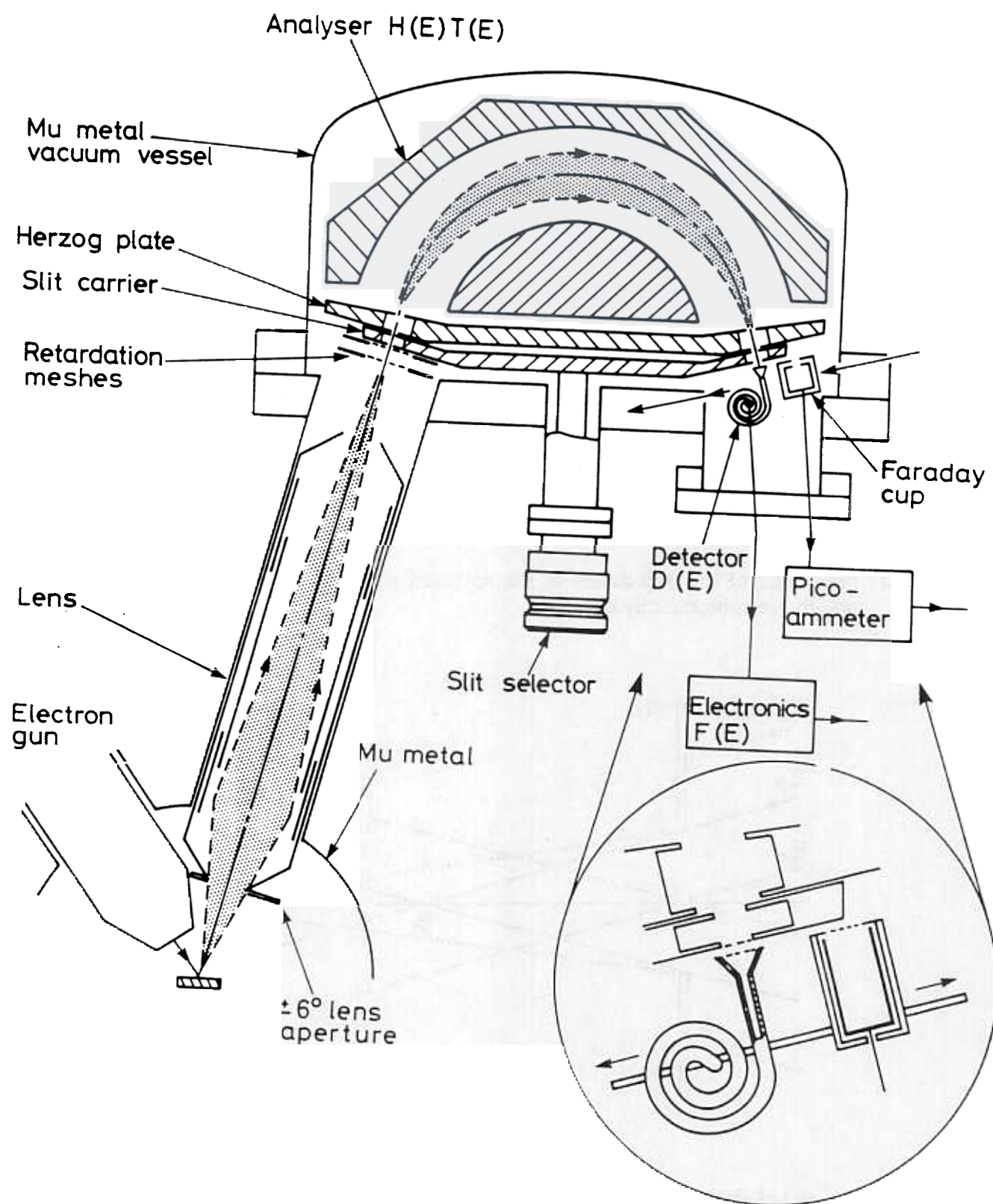


Fig 2 Schematic of the *metrology spectrometer*, a modified VG Scientific ESCALAB II with the standard analyser, after Seah and Smith⁽³⁾.

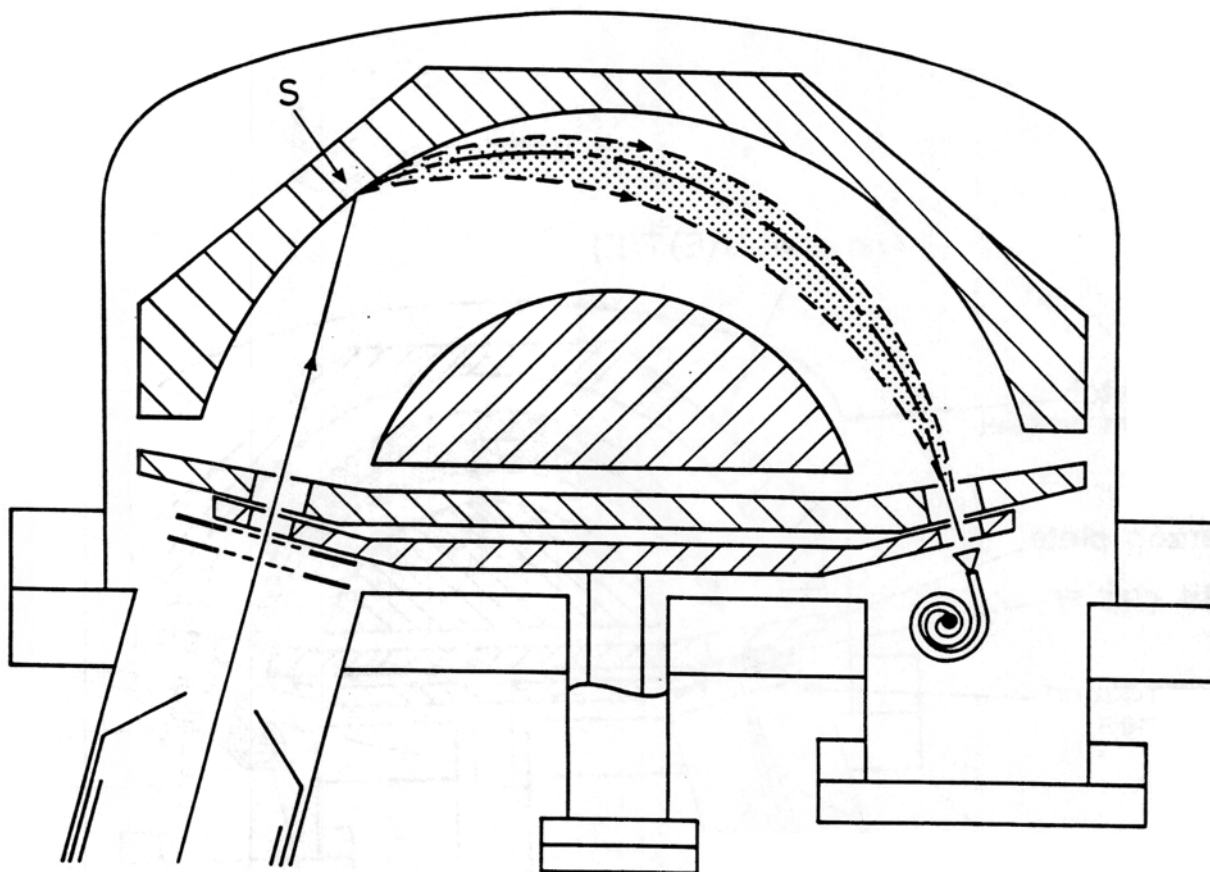


Fig 3 Schematic of the trajectories of the scattered electrons from the outer hemisphere which are subsequently detected.

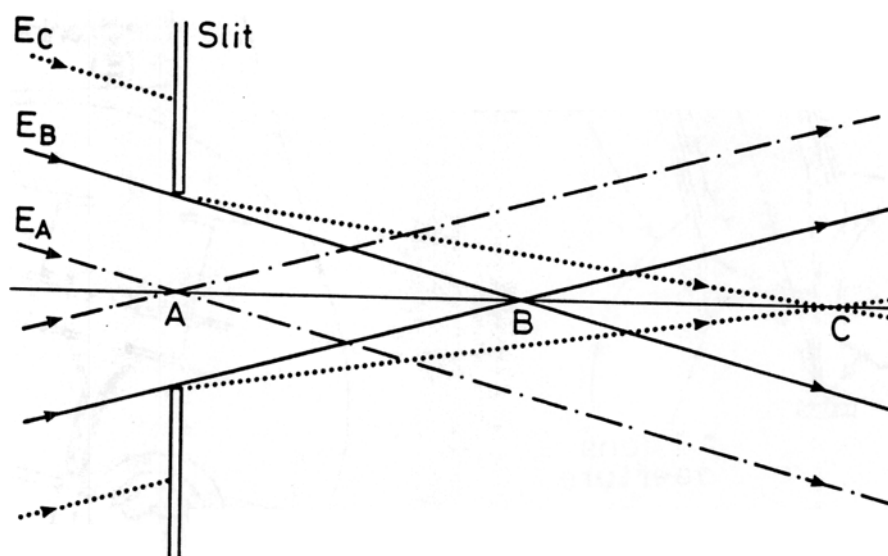
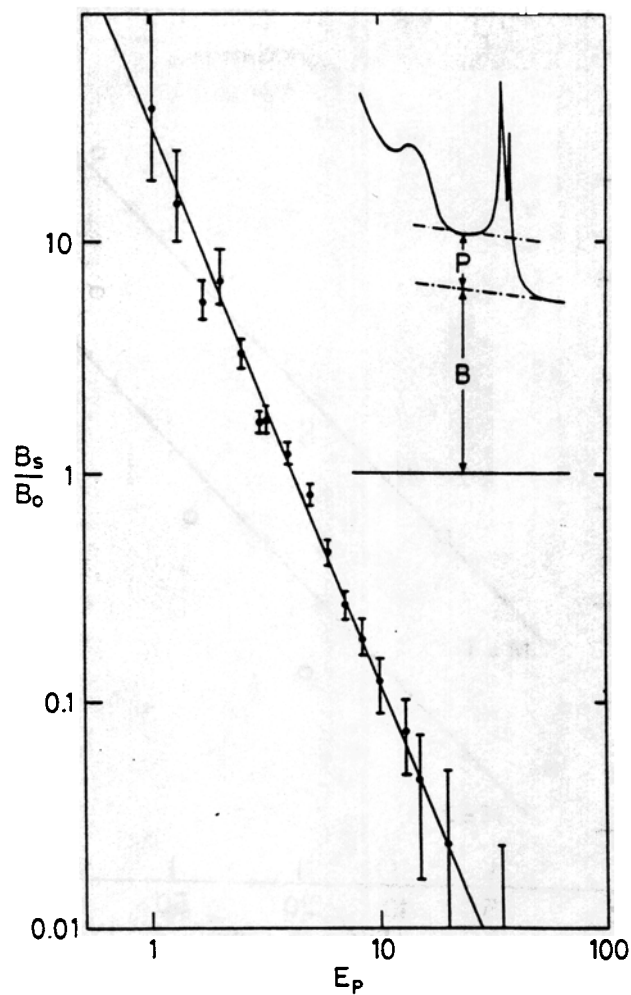
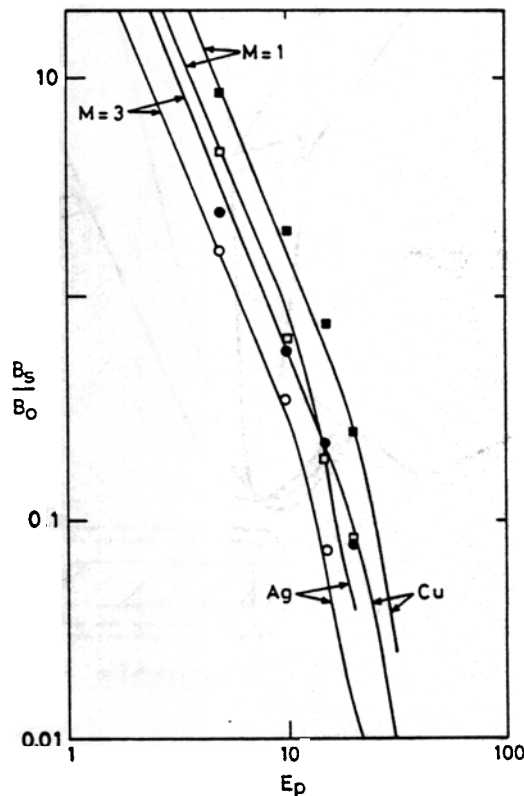


Fig 4 Schematic of electron trajectories forming a point focus from the lens at successively higher energies, E_A , E_B and E_C where the lens is set to focus those of energy E_A at A in the plane of the entrance slit to the electron spectrometer. As shown in Figs 2 and 3, the slit arrangement in the *metrology spectrometer* is actually much more complex than this simple illustration. Electrons with energies in the range E_A to E_B are transmitted with undiminished intensity.



The ratio of the scattered intensity to the true background intensity at 320 eV in silver AES spectra as a function of the spectrometer pass energy, E_p . The electron beam is set at 5 keV with 30° angle of incidence and the spectrometer is operated with the 5 mm diameter input aperture and a lens magnification of 1. The data points are those originally reported elsewhere⁽³⁾ in a different format.



Plots of the scattering contribution to the spectral backgrounds produced using a 5 keV electron beam at 30° to the surface normal for silver at 320 eV and copper at 875 eV, as a function of E_p , for the 6 mm input slit and lens magnifications of 1 and 3. The solid lines for E_p values below 10 eV are for Eq (7) with $K_1 = 0.0094$ and $K_3 = 0.0024$.

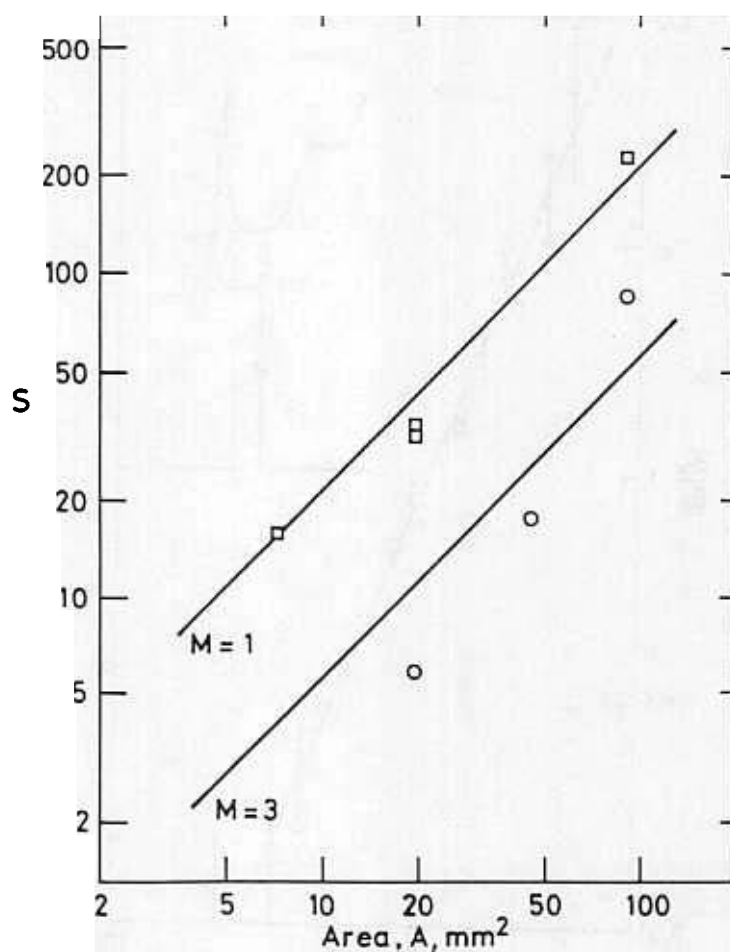


Fig 7 Plots of the scattering parameter s versus the entrance slit area A for the spectral background produced using a 5 keV electron beam for silver at 320 eV with lens magnifications of 1 and 3. The solid lines are for Eq (7) with $K_1 = 0.0094$ and $K_3 = 0.0024$.

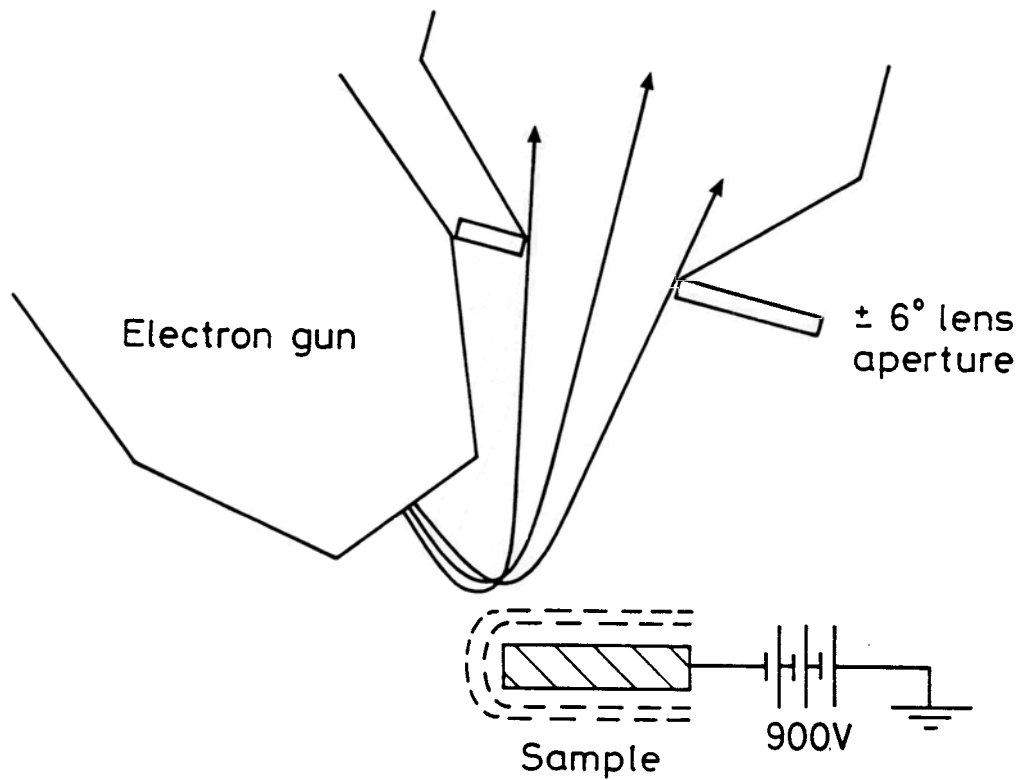


Fig 8 Schematic electron trajectories for a 900 eV electron beam rastered over the end of a sample biased by - 900 V.

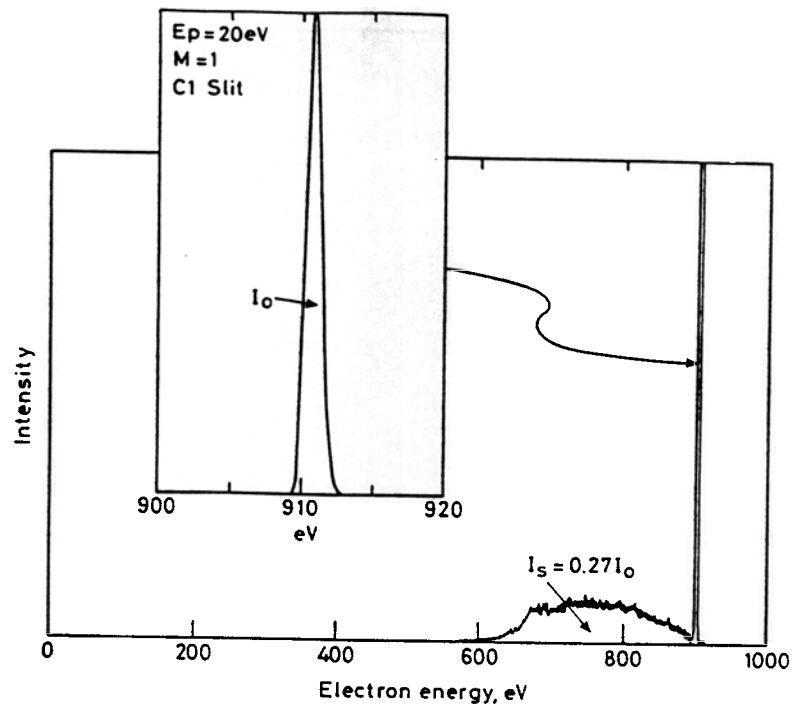


Fig 9 The intensity of scattered electrons as a function of the measured energy with, inset, the intensity of the monoenergetic electrons reflected into the spectrometer and producing the scattered electrons. In this measurement the spectrometer is scanned in the constant ΔE mode with a pass energy of 20 eV, a 6 mm input slit and a lens magnification of 1.

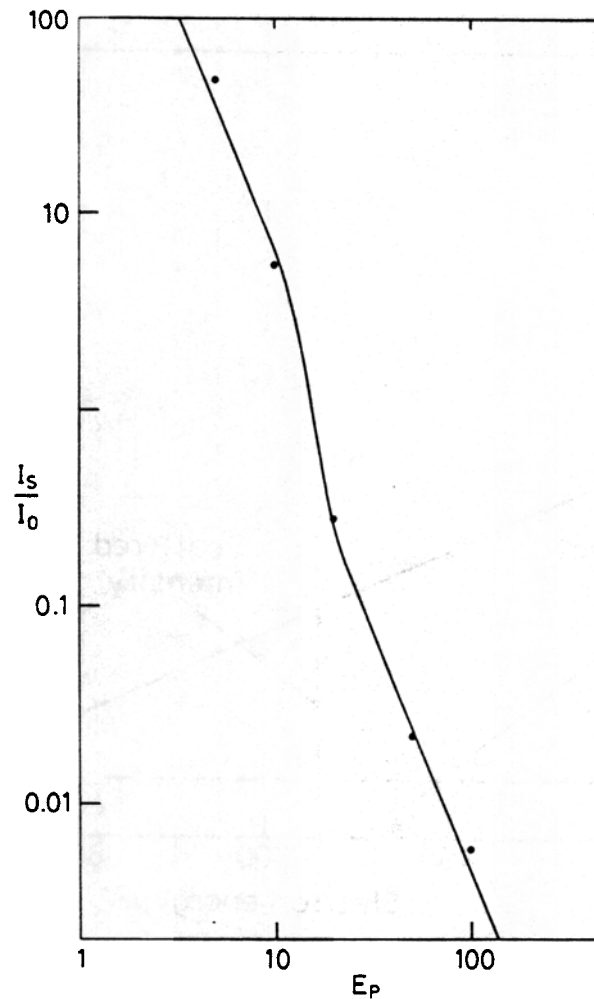


Fig 10 The intensity ratio for the scattered and unscattered electrons as measured using the reflected electron beam at 900 eV with the sample biased to - 900 eV. In this example the 6 mm input slit is used and the measurements are made with the lens at a magnification of unity. The solid line for low pass energies is for Eq (7) with $K_1 = 0.0216$ and at high pass energies $K_1 = 0.0040$.

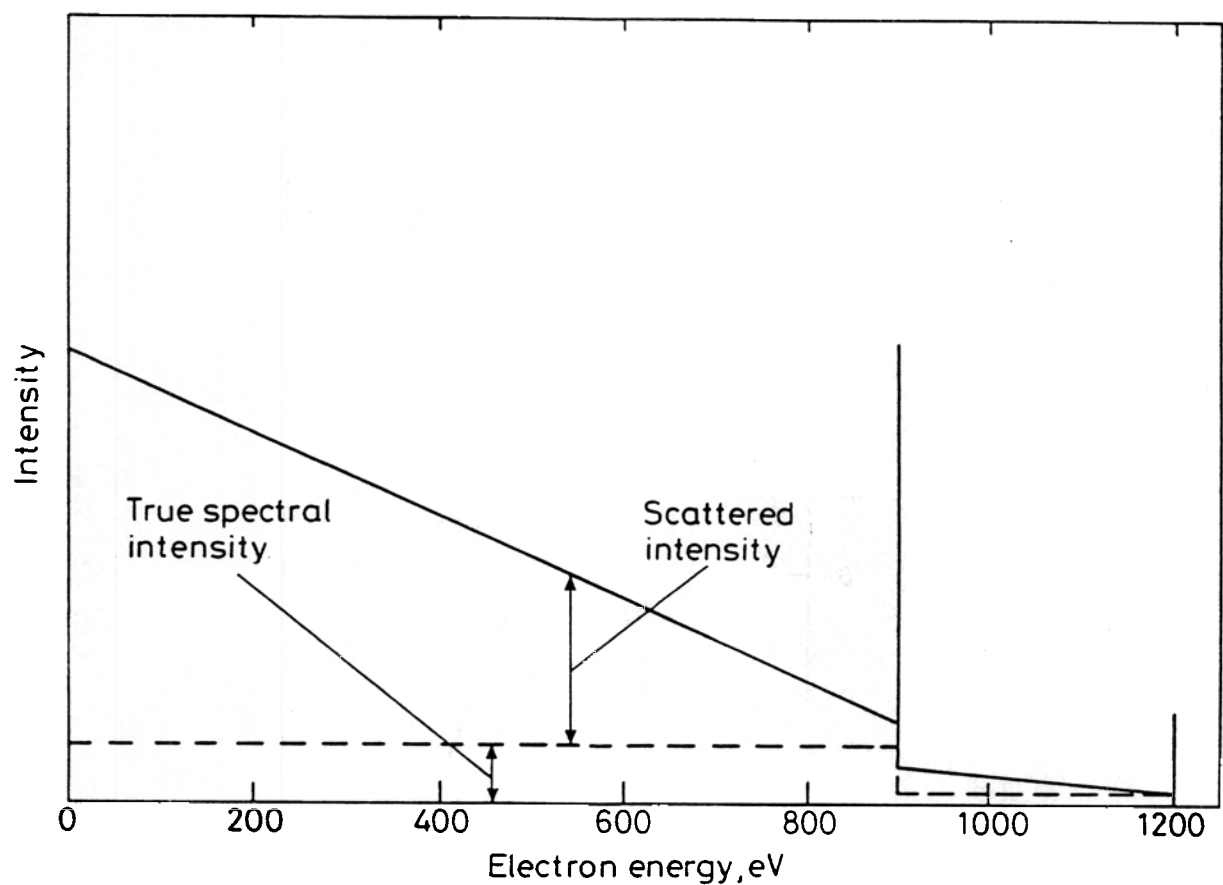
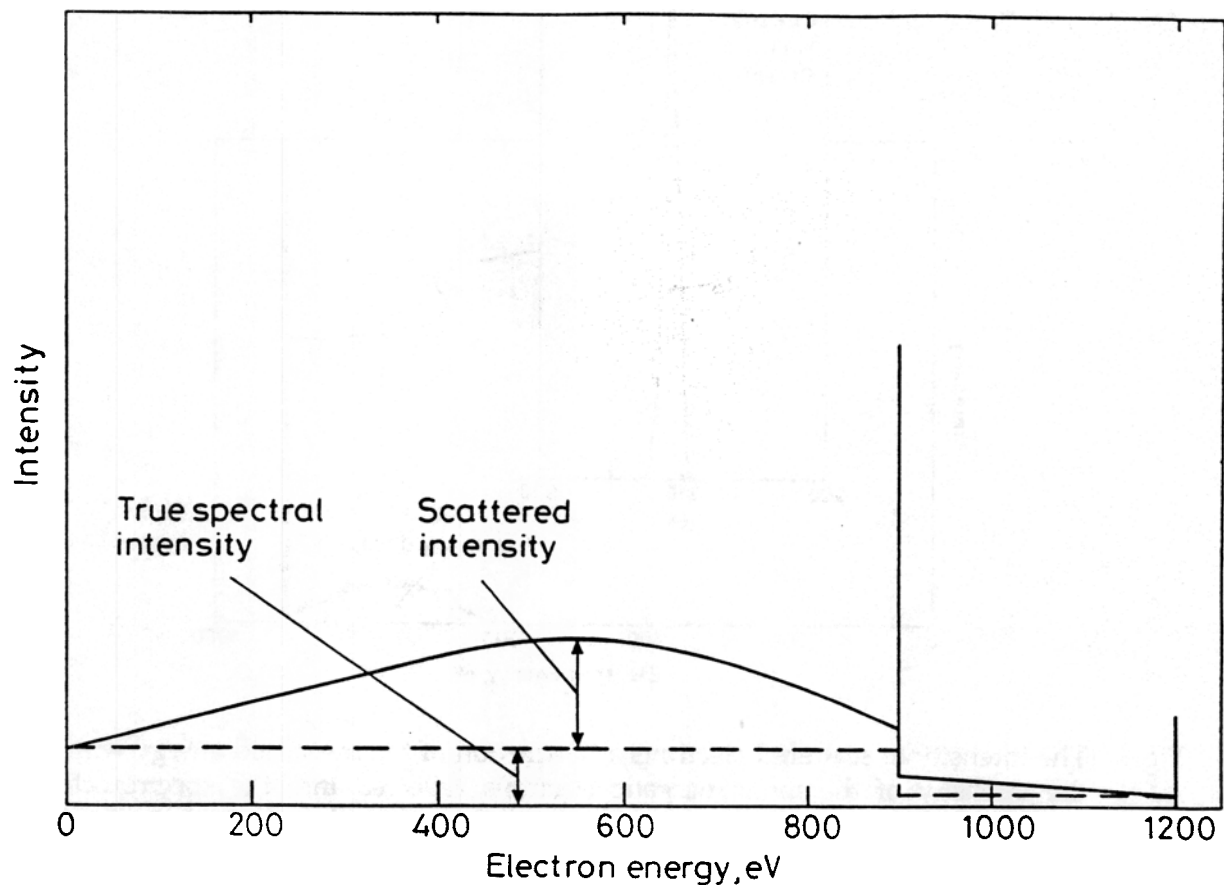


Fig 11 The predicted scattered intensity superimposed on a true intensity represented by a flat background from 900 to 1200 eV and a background of five times that intensity from 0 to 900 eV. The spectra are for the constant ΔE mode and represent simple XPS spectra. Figure 11(a) represents the result with an input lens with a Gaussian transmission function with a standard deviation of $0.45 E_A$. Figure 11(b) is the result for a spectrometer with no input lens.

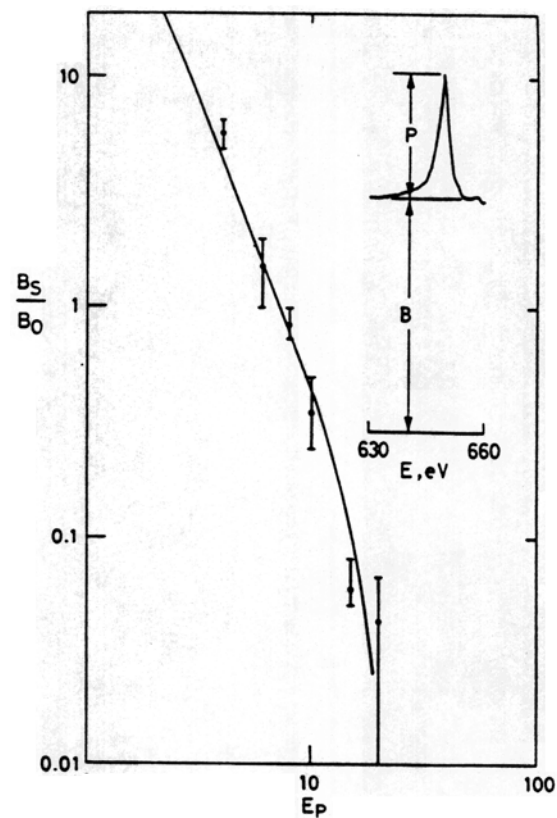


Fig 12 The ratio of the scattered intensity to the true background intensity at 650 eV in silver XPS spectra using Mg K α X-rays. The 210 analyser is operated with the 6 mm entrance slit and a lens magnification of 1. The inset shows the 3p_{1/2} peak at 100 eV pass energy. The line drawn has the same shape as those in Fig 6 for silver and for low pass energies follows Eq (7) with $AK_{1,Ag} = 0.182$.

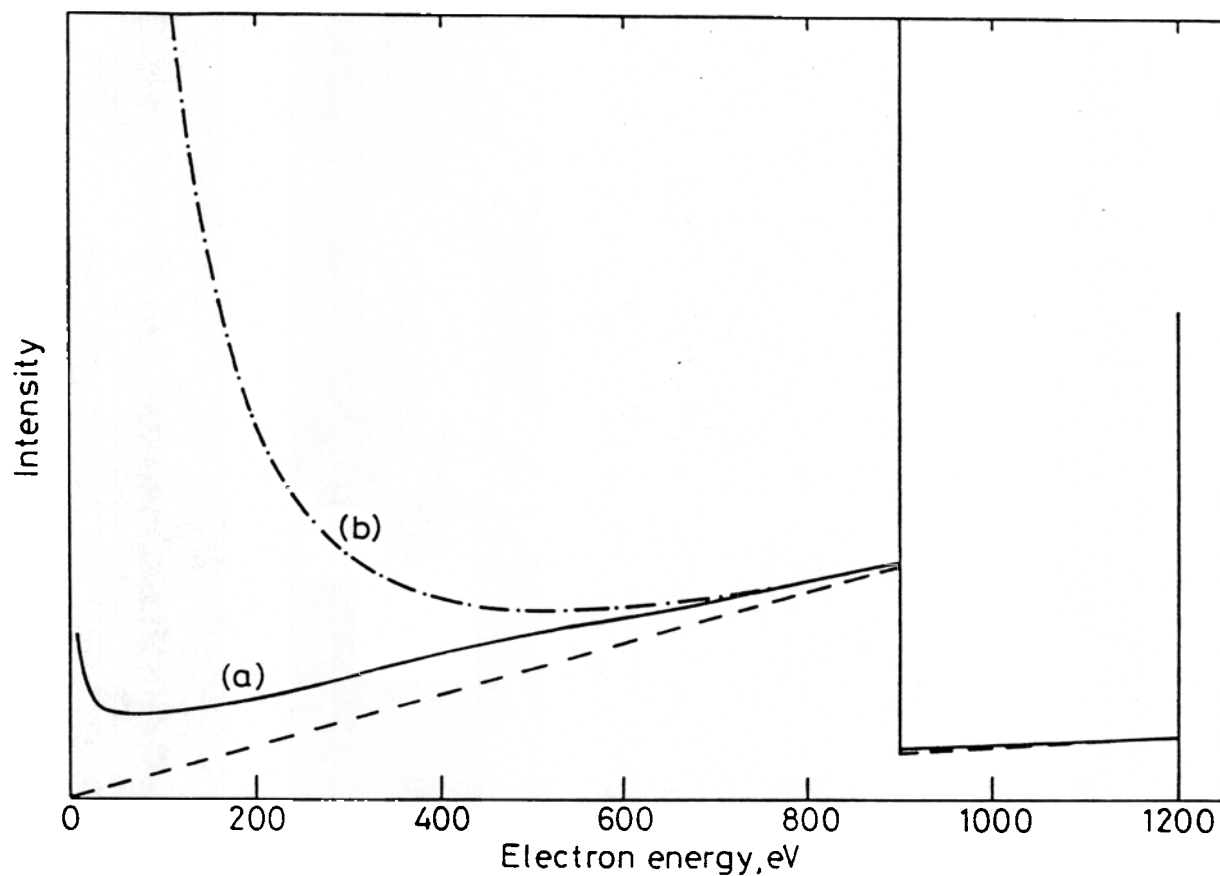


Fig 13 As for Fig 11 but using the constant $\Delta E/E$ mode. Curve (a) is the result with a lens and (b) with no lens.