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The paper gives a compilation of measured attenuation lengths of low-energy electrons in the energy range (40 to 2000 eV) normally employed in X-ray photoelectron spectroscopy and Auger-electron spectroscopy. An approximate formula was also derived to enable estimates to be made of attenuation lengths in materials for which no measurements had been made. [The *SCI*® indicates that this paper has been cited in over 515 publications.]

The Surface Sensitivity of Electron Spectroscopies

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During the 1960s several types of instruments became commercially available for surface characterization. The first of these was low-energy electron diffraction (LEED), in which electrons with energy in the range 20-300 eV bombarded a single-crystal surface at normal incidence and the pattern of back-diffracted electrons was observed on a fluorescent screen. The visual pattern and the changes of spot intensities with electron energy could be analyzed to deduce the structures of atoms in the outermost layers of the crystal. Next came Auger-electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS) (also referred to as electron spectroscopy for chemical analysis [ESCA]). These two techniques gave information about the chemical composition of the outermost layers of a material from measurements of the kinetic energies of Auger electrons (AES) or photoelectrons (XPS) emitted following excitation with electron or X-ray beams, respectively. The useful range of electron energies for AES and XPS was about 40-2000 eV to span most elements of the periodic table and for optimum surface sensitivity.

A key question, then and also now, concerns the actual surface sensitivity of LEED, AES, and XPS, which is directly related to the probability of inelastic electron scattering; if electrons scatter inelastically in the target material, they will not be measured in the signal of interest. A related question is the dependence of the inelastic scattering probability on electron energy and material since this information is needed for quantitative surface analyses by AES and XPS. A measure of the surface sensitivity is the electron attenuation length (AL), which is inversely related to the inelastic scattering probability. For common conditions in LEED, AES, and XPS, the AL is typically between 0.3 and 5 nm, that is, about 1 to 20 atom spacings.

My 1974 paper contained a summary of the available AL data, an analysis of the several measurement techniques, and an approximate formula for predicting ALs. The paper has been highly cited because AES and XPS have come into widespread use for surface analyses in catalysis, corrosion and wear, and semiconductor and thin-film devices. By coincidence, two other papers were published in 1974 that analyzed AL data from other perspectives, and these have been heavily cited.[1,2] All three of the 1974 papers have been largely superseded by a 1979 compilation of AL data by M.P. Seah and W.A. Dench,[3] who also developed equations to describe the data.

Early measurements of electron ALs for different materials appeared to cluster about a common curve when plotted versus kinetic energy. This curve became known as the "universal curve" and was a useful guide, even though there was no physical justification for universality. It was clear by 1974 that there was considerable scatter (up to about a factor of two) about this curve, part of the scatter being associated with substantial errors of measurement and part associated with expected material differences. A review article has recently been published that gives an assessment of measured ALs and of the available formulas.[4]

Due to the difficulties in making AL measurements with the desired accuracy, calculations have been made of a closely related quantity, the inelastic mean free path (IMFP). My NIST colleague David R. Penn recently developed an improved algorithm for calculating IMFPs that makes use of available experimental optical data.[5] About that time, Shigeo Tanuma from the Nippon Mining Company was working as a guest scientist in my laboratory. We have collaborated on an extensive series of IMFP calculations in over 30 materials.[6] Although there are approximations in the Penn algorithm, we have been able to determine more precisely how the IMFP varies with electron energy and with certain material parameters. The initial calculations[6] were for electrons with energies between 200 and 2000 eV, but recent work has extended the analysis down to 50 eV. The general formula we have derived for predicting IMFP values should also be a useful (but more approximate) guide for ALs.

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