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Secondary electron interactions in materials with environmental and radiological interest

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Abstract Important environmental and radiological applications require energy deposition models including the interactions between the secondary electrons and the atoms or molecules of the medium. In this work we propose a method to obtain reliable cross-section data to be used in these models by combining total and ionisation cross-section measurements with simple calculations of the differential and integral elastic cross sections. The energy loss spectra obtained in this experiment have been also used to derive the stopping power of the considered materials for electrons. Some examples of results for atomic (Xe) and molecular (CF_4) targets are presented and discussed in this paper.

Key words electron scattering • energy deposition • electron stopping powers

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Introduction

Important environmental and radiological applications require detailed energy deposition models in which the effect of the secondary electron must be included. These electrons, through successive collisions, are the final responsible of the radiation damage to the atoms or molecules of the medium. However, the introduction of these effects in the models take some difficulties. Firstly electron scattering cross sections, both differential and integral, should be required for a large number of possible processes over a wide energy range. In principle, from the high energy of the primary particle, typically in the keV range, up to the final steps of the energy degradation process. Secondly, because there is a large number of atomic and molecular targets involved in the systems of interest and they can be found in gaseous or condensed phases.

At really high incident electron energies (above 10 keV), the first Born approximation [6] gives a reasonable description of the electron scattering cross sections from these targets. There is also abundant cross-section data at low energy in the literature [7, 8, 10, 11]. However, in the intermediate–high energy region (from 100 to 10,000 eV) experimental data are scarce and the model potential approximations [1], which are customarily used to describe the electron interactions in this energy range, require some improvements. In this work, we propose a method to obtain reliable cross-section data at intermediate and high energy by combining total and ionisation cross-section measurements with simple calculations of the differential and integral elastic cross sections. As an example, electron scattering cross-section data for some atomic (Xe) and molecular (CF_4) targets, which are relevant in the above mentioned applications are given and the coherence of the present results is discussed.

Simple dosimetric models are based on the stopping power of the electrons passing the target through of interest. For this reason these parameters are also given for CF_4 in the energy range considered here.

Measurements

Experimental set-up

The experimental set-up used to measure the total electron scattering and ionisation cross sections is shown in Fig. 1. The electron gun consists of a thorium–tungsten filament, electrostatic focusing lenses and a combination of magnet and electrostatic deflecting system, providing typical currents of 10^{-7} A in a 1 mm diameter electron beam with an energy spread of about 0.1 eV. The gun can be also operated in a pulsed mode by means of a pulse generator connected to the deflecting system. The gas cell was limited by two 1 mm diameter apertures separated by the length L, which can be changed from 50 to 100 mm according to the experimental requirements. The gas pressure in the cell was measured by an absolute capacitance manometer MKS Baratron 127-A. The ion collection system was formed by two parallel plates fixed inside the chamber. One of them, provided with a guard electrode, measured the total ion current in a continuous beam operation mode and the other had a 5 mm diameter aperture to extract the ions in pulsed operation mode. The extracted ions were accelerated through a 300 mm length drift tube and finally detected by a two stage microchannel plate system to analyse their charge and mass by means of a time of flight technique. A new electrostatic deflecting system select the angle of analyse at the exit of the collision chamber. The energy analyser is a combination of a retarding lens and a hemispherical electrostatic spectrometer. Using 1 mm slit apertures, the energy resolution of the spectrometer was of 0.5% with respect to the transmitted energy, which was selected by the retarding lens. The free distance D between the chamber and the analyser defines the angular resolution of the detector and was varied from 10 to 250 mm according to the experimental requirements. The transmitted electrons were finally detected by a two stage microchannel plate electron multiplier connected with a counting electronic system controlled by a computer. The electron gun and energy analyser regions were differentially pumped by two turbo pumps, reaching an ultimate pressure below 10^{-7} Torr.

Procedure

Energy loss spectra were recorded by sweeping the entrance potential of the analyser by means of a computer controlled ramp synchronised with the counting electronic system. A typical result for 2000-eV electrons colliding with Xe is shown in Fig. 2. The energy loss spectrum can be considered as a probability distribution function for the intensity of the scattered electron $I(E_l)$, in a given direction, *vs*. the energy loss E_l. We can, therefore, define a mean excitation energy (I_0) as:

$$I_0 = \frac{\int_0^{E_0} E_l I(E_l)\mathrm{d}E_l}{\int_0^{E_0} I(E_l)\mathrm{d}E_l}, \tag{1}$$

where E_0 is the electron incident energy.

The total cross sections (σ_T) have been obtained by measuring the attenuation of the electron beam as a function of the gas pressure in the collision chamber. A detailed description of this procedure and error analysis can be found in previous papers [3]. These parameters define the mean free path (λ) of electrons in the chamber as:

$$\lambda = \frac{1}{\sigma_T N}, \tag{2}$$

where N is the molecular density of the target.

The "apparent" ionisation cross sections were derived from the simultaneous measurement of the electron current and the ion current produced in a well determined length

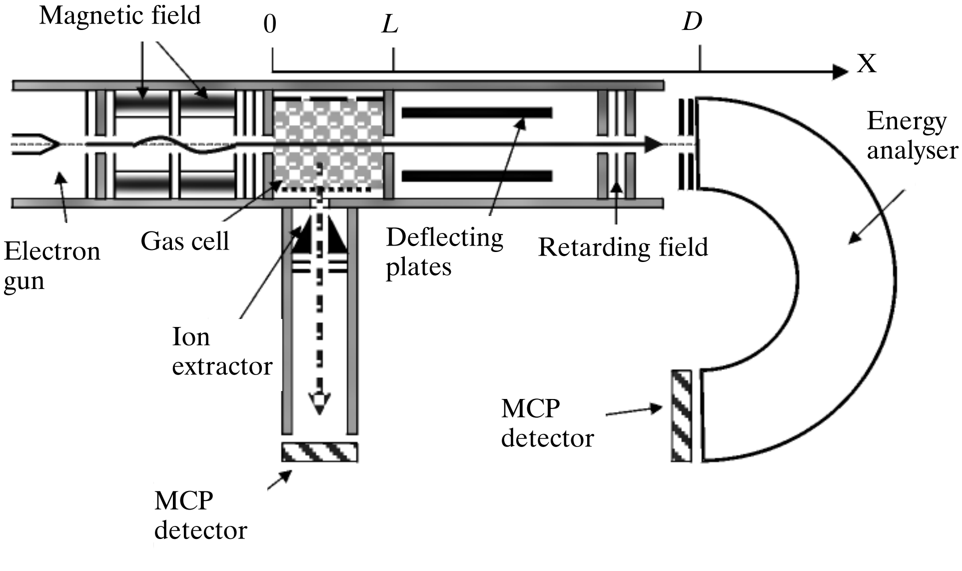

Fig. 1. Experimental set-up used to obtain electron energy loss spectra, total electron scattering cross sections and ionisation cross sections.

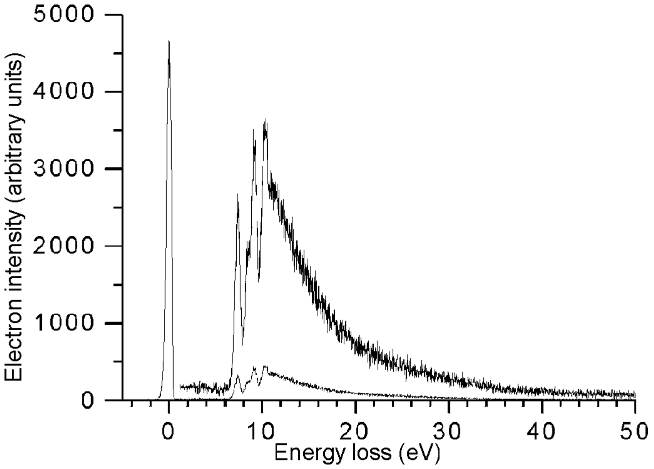

Fig. 2. Energy loss spectrum for 2000 eV incident electrons and 10 mTorr of Xe in the collision chamber.

of the electron beam path, for a given target pressure. To minimize the attenuation of electron beam along the ion collection region, measurements were performed at a gas pressure below 1 mTorr. Nevertheless, since we had previously measured the total cross sections, this beam attenuation effect could be corrected in this experiment. The ion extraction potential was selected (between 50 and 100 eV) to reach the ion current saturation, ensuring that the ion collection length agrees with the size of the collecting electrode. A magnetic field compensates the deflection of the electron beam due to the ion extraction electrostatic field. During the ion current measurement the energy analyser was used as a simple faraday cup which gives the net electron current reaching the analyser by means of an electrometer. Operating the system in pulsed mode, the charge of the collected ions could be analysed by means of a time of flight technique, and then the total ionisation cross sections were derived from the "apparent" ionisation cross sections.

As mentioned above, in this study the differential ($d\sigma_{el}/d\Omega$) and integral (σ_{el}) elastic cross sections have been calculated by means of a scattering potential method.

Finally, the integral inelastic cross sections (σ_{inel}) can be obtained by subtracting the elastic part from the total scattering cross sections.

By regarding the matter as an homogeneous assembly of N individual atoms or molecules per volume unit, the stopping power for electrons ($-dE/dx$) can be expressed as a function of the cross section (σ_n) to excite the n level (discrete or continuous) of the target and the excitation energy (E_n) as:

$$-\frac{dE}{dx} = N\sum_n E_n\sigma_n = NI_0\sigma_{inel}, \tag{3}$$

where I_0 is the mean excitation energy defined in eq. (1).

Calculations

The scattering potential method used to calculate differential and integral electron scattering cross sections from atoms has been described previously [4]. This method has been also applied for molecular targets by assuming that the incident electron energy is high enough to validate the independent atom model [2].

Simulations

The simplest simulations of the energy deposited for electrons in matter are based on continuous models using the stopping power. Although this is a rough representation, these models can be improved by using the result derived from eq. (3) for energies below 10 keV, where reliable data are not available in the literature.

However, the environmental and radiological applications concerned in this study require a more detailed description and single interactions suffered by the electrons in the energy degradation process must be taken into consideration.

We propose here a discrete event program in which the mean free path, defined by the total cross section, decides when a collision event takes place. Then the probability distribution of the integral elastic and inelastic cross section decides on the type of event. If it is elastic, there are not energy loss, but the probability distribution of the differential elastic cross sections decides on the direction of the scattered electron, starting a new step governed again by the mean free path. On the contrary, if the event is inelastic there is an energy loss in the collision which is given by the probability function derived from the energy loss spectrum. In addition, the differential probability distribution draws the direction of the scattered electron which enters in a new step with less energy.

The program proposed for the simulations is based on the Geant 4 code [5] developed at CERN, but with important modifications in order to consider individual electron scattering events according to the scheme described above.

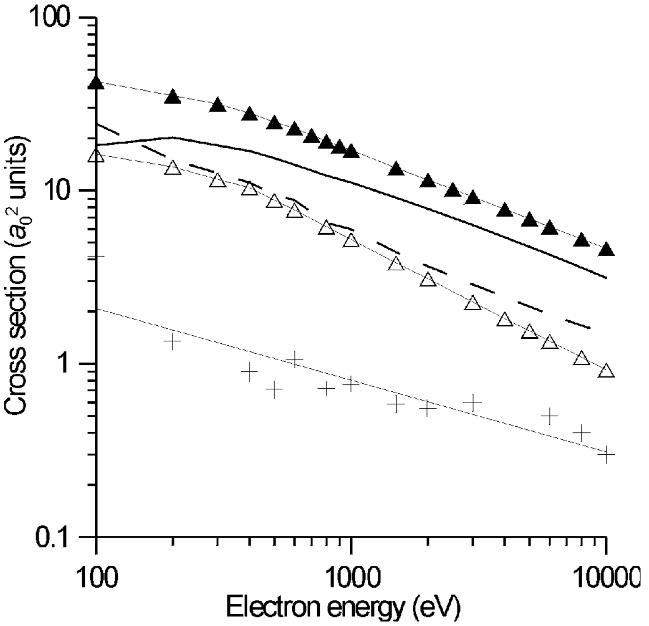

Fig. 3. Integral cross section for electron scattering by Xe. ▲, total electron scattering cross sections. —, integral elastic cross sections. ---, integral inelastic cross sections. △, ionisation cross sections. +, excitation cross sections.

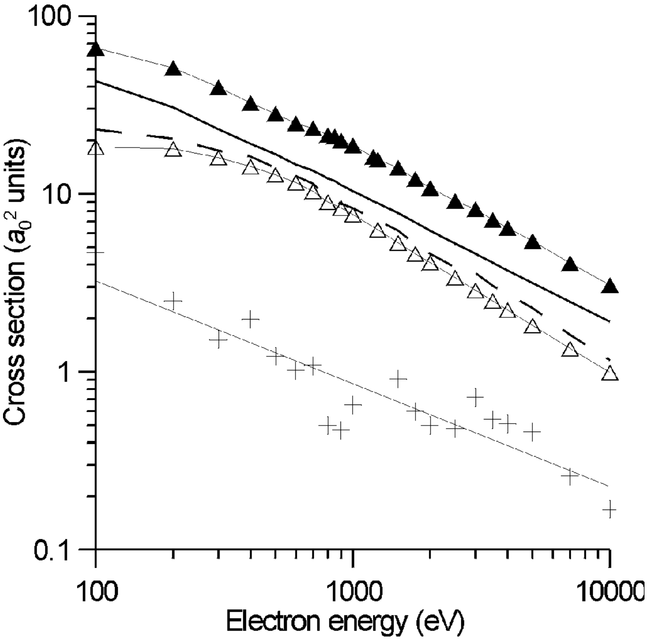

Fig. 4. Integral cross section for electron scattering by CF_4. ▲, total electron scattering cross sections. —, integral elastic cross sections. ---, integral inelastic cross sections. △, ionisation cross sections. +, electronic excitation plus neutral dissociation cross sections.

Results

In this section, we present some examples of results for representative targets of interest in the above applications. More complete set of cross section data useful for energy deposition models will be given in the next paper.

The integral electron scattering cross sections for Xe are shown in Fig. 3 at incident energies from 100 to 10,000 eV. Total electron scattering and ionisation cross sections have been measured by the method described above and the experimental errors are of 3 and 7%, respectively. The integral elastic cross sections have been calculated by the above method and the estimated errors are about 10%. By subtracting these values from the total cross section the integral inelastic cross section can be obtained with uncertainties within 12%. Finally, excitation cross section values, within 20%, can be derived from these data.

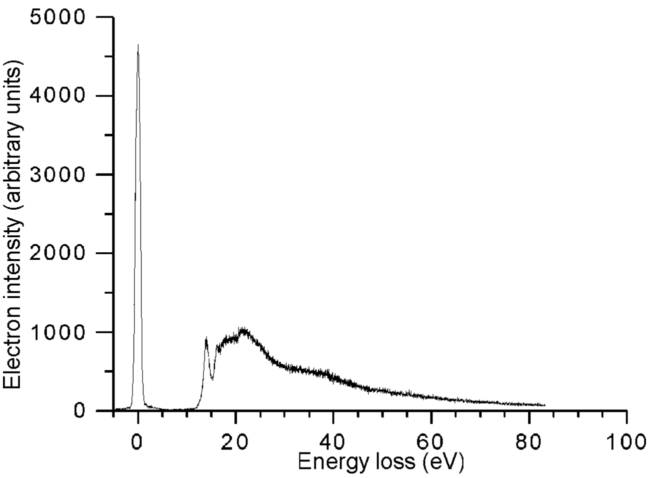

Fig. 5. Energy loss spectrum for 2000 eV incident electrons and 10 mTorr of CF_4 in the collision chamber.

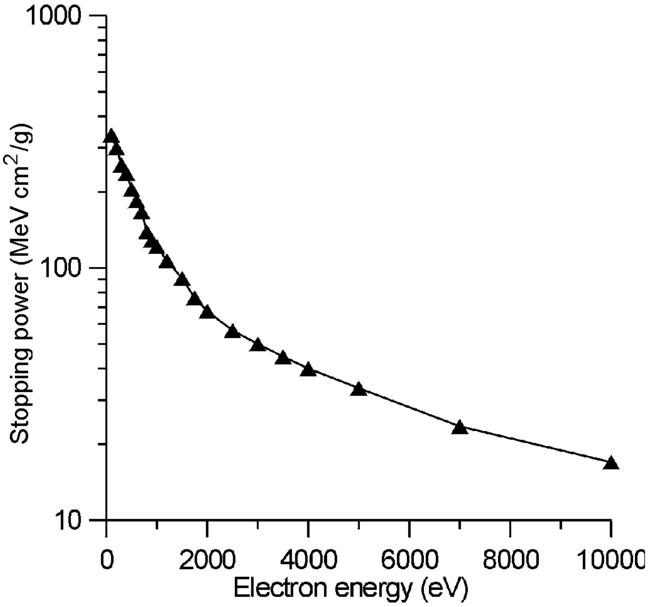

Fig. 6. Stopping power of CF_4 for electrons.

As a representative molecular target we present the results of CF_4 which has been the subject of a recent study [9]. Total electron scattering, ionisation, integral elastic and integral inelastic cross sections are given in Fig. 4. In this case, electronic excitation cross sections include neutral dissociation processes which cannot be distinguish by the present method. Figure 5 shows an energy loss spectrum for electrons in CF_4 that can be used to calculate the mean excitation energy as defined in eq. (1).

Finally, the stopping power of CF_4 for electrons have been derived by computing data required in equation (3). The corresponding results are shown in Fig. 6.

Conclusions

In this work, we propose a method to obtain reliable cross section data at intermediate and high-electron energy that can be very useful for energy deposition models in which the role of the secondary electrons is included. The proposed scheme can be considered as a first approximation that should be improved by taking into account more processes, as (e,2e) interactions, and by extending the simulation to lower energies, where new competitive processes should be considered (electron attachment, vibrational and rotational excitation, etc.).

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