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Energy loss of fast electrons impinging upon polymethylmethacrylate

Maurizio Dapor

European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT-FBK), Trento Institute for Fundamental Physics and Applications (TIFPA-INFN), via Sommarive 18, I-38123 Trento, Italy*

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ABSTRACT

This paper deals with the calculation of the differential inverse inelastic mean free path, the inelastic mean free path, the stopping power, the range of penetration, and the distribution function for inelastic collisions causing energy losses less than or equal to given values, for fast electrons impinging upon polymethylmethacrylate. Numerical tables are provided along with the comparison with computations of other investigators.

1. Introduction

In this paper we will deal with the energy loss of fast electrons impinging upon polymethylmethacrylate (PMMA).

The study of the interaction of electrons with polymers, and in particular with polymethylmethacrylate, has today very important applications. Line-scan of resist materials with given geometrical cross-sections deposited on silicon, and the corresponding line-width measurements, require interpretation that can be performed using Monte Carlo calculations based, in particular, on an accurate knowledge of the differential inverse inelastic mean free path [1–4]. Another important application concerns the secondary electron emission due to ion impact. Along the path of energetic protons in polymers such as PMMA and bio-molecular systems, many electrons are generated which give rise to a shower of secondary electrons: this avalanche of secondary electrons can produce damage in the material by dissociative electron attachment [5,6]. Inelastic mean free path and stopping power are average quantities very important for the study of the interaction of electrons with solid targets. For the surface spectroscopic techniques, inelastic mean free path is used to predict the depth sampled by the emerging electrons [7]. Stopping power is useful to evaluate the dose distributions of electron beams in solid targets [7].

The energy loss mechanisms of electrons in insulating materials can be roughly classified in two great categories. One concerns slow electrons, the other one fast electrons. The energy loss of slow electrons in insulating materials is ruled by electron–phonon interaction and by polaronic effects [8]. This paper is focussed on the investigation of the energy loss of fast electrons (energies higher than 100 eV) in PMMA. It can be described by the dielectric theory [9–13]. A very simple approach to the calculation of the electron energy loss function consists in the extension of the optical dielectric function, obtained from empirical data, to non-zero values of the momentum transfer q. This method was firstly proposed by Powell [14] and then developed and used by Ritchie and Howie [15], Liljequist [16], Penn [17], Ashley [7], and Tanuma, Powell, and Penn [18].

2. Theoretical framework

The energy loss function in the optical domain, *i.e.* corresponding to zero momentum transfer ($q = 0$), can be calculated by using experimental optical data. It can be well fitted by the equation [15]

$$\mathrm{Im}\left[-\frac{1}{\varepsilon(E,0)}\right] = \sum_n \frac{A_n \Gamma_n E}{(E_n^2 - E^2)^2 + (\Gamma_n E)^2}, \tag{1}$$

where E_n are the excitation energies, Γ_n the damping constants, and A_n the relative strength parameters.

The extrapolation of the energy loss function from the optical domain, *i.e.* to $q \neq 0$, can be achieved by the use of the following equation

E-mail address: dapor@fbk.eu

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$$\mathrm{Im}\left[-\frac{1}{\varepsilon(E,q)}\right] = \sum_n \frac{A_n \Gamma_n E}{(E_n^2(q)-E^2)^2 + (\Gamma_n E)^2}, \tag{2}$$

where, for the present work, the dispersion law relating the energy to the momentum transfer is calculated by [15,19]

$$E_n(q) = E_n + \frac{\hbar^2 q^2}{2m}. \tag{3}$$

Here m is the electron mass.

Once the energy loss function is known, the differential inverse inelastic mean free path can be obtained by

$$\frac{d\lambda_{\mathrm{inel}}^{-1}}{dE} = \frac{1}{\pi a_0 T}\int_{q_-}^{q_+}\frac{dq}{q}\mathrm{Im}\left[-\frac{1}{\varepsilon(E,q)}\right], \tag{4}$$

where a_0 is the Bohr radius of hydrogen,

$$q_\pm = \sqrt{2m}(\sqrt{T} \pm \sqrt{T-E}), \tag{5}$$

and T is the incident electron kinetic energy.

3. Energy loss function in the optical limit

The energy loss function of PMMA in the optical limit is presented in Fig. 1 for $h\nu < 70$ eV (experimental data by Ritsko et al. [20]) and in Fig. 2 for $h\nu > 70$ eV (experimental data by Henke et al. [21]). Solid lines, in these Figures, represent the best fit of the two sets of experimental data (see Fig. 3, where both the sets of experimental data are presented along with their best fit).

The values of the parameters obtained from the best fit of the two sets of experimental optical data can be found in Table 1.

Note that, on the one hand, for energies smaller than 70 eV, Ritsko et al. directly provided the energy loss function [20]. For energies greater than 70 eV, on the other hand, in order to calculate the energy loss function starting from the Henke et al. experimental data [21] we have followed the procedure below. The energy loss function was calculated as

$$\mathrm{Im}\left[-\frac{1}{\varepsilon(E,0)}\right] = \frac{\varepsilon_2}{\varepsilon_1^2+\varepsilon_2^2}, \tag{6}$$

where

$$\varepsilon = \varepsilon_1 + i\varepsilon_2, \tag{7}$$

$$\varepsilon_1 = \nu^2 - \kappa^2, \tag{8}$$

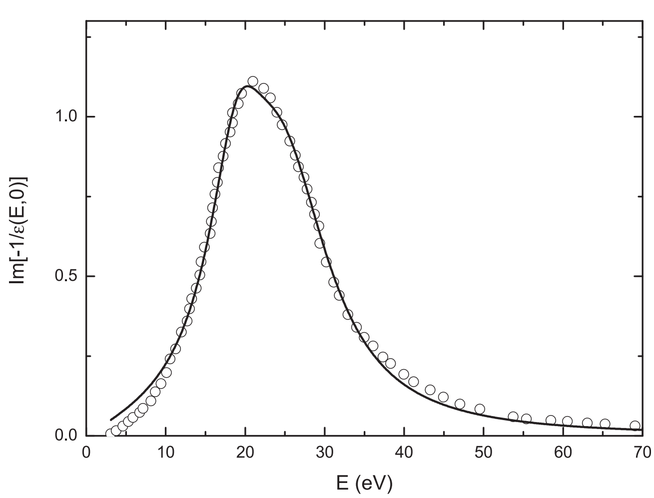

Fig. 1. Energy loss function of PMMA in the optical limit. Circles: Ritsko et al. experimental data [20]. Line: best fit (parameters can be found in Table 1).

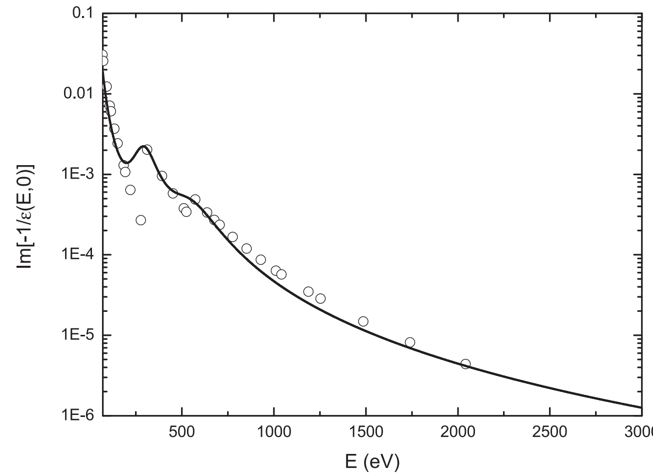

Fig. 2. Energy loss function of PMMA in the optical limit. Circles: Henke et al. experimental data [21]. Line: best fit (parameters can be found in Table 1).

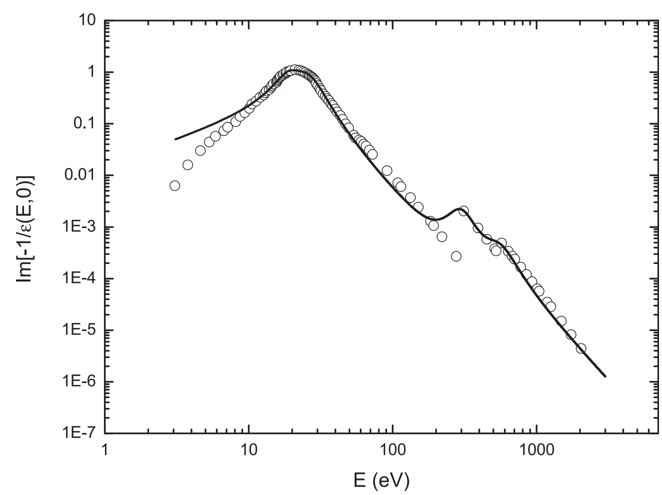

Fig. 3. Energy loss function of PMMA in the optical limit. Circles: Ritsko et al. experimental data [20] (energies smaller than 70 eV); Henke et al. experimental data [21] (energies greater than 70 eV). Line: best fit (parameters can be found in Table 1).

Table 1
Parameters used to fit the optical energy loss function of PMMA.

n	E_n (eV)	Γ_n (eV)	A_n (eV^2)
1	19.46	8.770	100.0
2	25.84	14.75	286.5
3	300.0	140.0	80.0
4	550.0	300.0	55.0

$$\varepsilon_2 = 2\nu\kappa. \tag{9}$$

In these equations, the index of refraction ν and the extinction coefficient κ can be calculated by [22]

$$\nu = 1 - \frac{e^2}{2\pi m c^2}\lambda^2 N \sum_p x_p f_{1p}, \tag{10}$$

$$\kappa = \frac{e^2}{2\pi m c^2}\lambda^2 N \sum_p x_p f_{2p}. \tag{11}$$