Applied Radiation and Isotopes 70 (2012) 296–300

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Stopping power and mean free path for low-energy electrons in ten scintillators over energy range of 20–20,000 eV

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ARTICLE INFO

Article history:
Received 10 July 2011
Accepted 13 August 2011
Available online 22 August 2011

Keywords:
Stopping power
Inelastic mean free path
Scintillator
Dielectric theory

ABSTRACT

Systematic calculations of the stopping powers (SP) and inelastic mean free paths (IMFP) for 20–20,000 eV electrons in a group of 10 important scintillators have been carried out. The calculations are based on the dielectric model including the Born–Ochkur exchange correction and the optical energy loss functions (OELFs) are empirically evaluated because of the lack of available experimental optical data for the scintillators under consideration. The evaluated OELFs are examined by both the *f*-sum rule and the calculation of mean ionization potential. The SP and IMFP data presented here are the first results for the 10 scintillators over the energy range of 20–20,000 eV, and are of key importance for the investigation of liquid scintillation counting.

1. Introduction

Stopping power (SP) and inelastic mean free path (IMFP) are two characteristic quantities to describe the inelastic interactions of energetic electrons with matter. The SP represents the mean energy loss per unit distance traveled by an energetic electron and the IMFP indicates the average distance traveled by an energetic electron between energy-loss events. These two quantities are of essential importance in many fields of research, such as microdosimetry, electron beam lithography, electron probe microanalysis, and liquid scintillation counting. For example in microdosimetry the calculation of energy deposition of energetic electrons passing through biological tissues is required for understanding radiation effects, and the SPs need to be provided for this calculation. Furthermore, in the Monte Carlo investigation of electron beam lithography the SP and IMFP are required for simulating track structure of energetic electrons and for calculating spatial distribution of energy deposition.

The scintillators are a group of important materials used in liquid scintillation counting (Rodríguez-Barquero and Los Arcos, 2010). In liquid scintillation counting, the calculations of the counting efficiency usually require the detailed knowledge of SPs for electrons in energy range below several hundreds of keV (Malonda and Carles, 1999; Carles et al., 2004). The Bethe's theory (Inokuti, 1971), as well known, may give a good evaluation of SPs for electrons with energies higher than 10 keV, but this theory is, in general, invalid at lower energies. Therefore, it is a subject of great interest to evaluate SPs for low-energy electrons in scintillators. For toluene, and a scintillator with a simple composition constitution García et al. (2004) have presented a calculation of its SPs and IMFPs for electrons, based on a semi-empirical method with the combination of the calculated inelastic electron scattering cross-sections and experimental energy loss spectra, and Tan et al. (2009) have also evaluated its SPs and IMFPs for electrons, using the dielectric model.

In this work the SPs and IMFPs for electrons in a group of 10 important scintillators at energies below 20 keV are systematically calculated. These 10 scintillators are Optiphase HiSafe 2 (HS2), Optiphase HiSafe 3 (HS3), Insta-Gel Plus (IGP), Ultima Gold (UG), Ultima Gold AB (UG-AB), Ultima Gold XR (UG-XR), Ultima Gold LLT (UG-LLT), Ultima Gold MV (UG-MV), Ultima Gold F (UG-F), and Hionic-Fluor (HF). The calculations are based on the dielectric model developed previously and including the Born–Ochkur exchange correction. Because there are no available experimental optical data for these 10 scintillators their optical energy loss functions, which are required for the SP and IMFP calculations, are evaluated by means of the approach proposed in previous work (Tan et al., 2004). The aim of this work is to provide the SPs and IMFPs for low-energy electrons in these 10 scintillators because of the importance of these data in liquid scintillation counting, and the data presented here are the first results for these scintillators over the energy range of 20–20,000 eV.

2. Calculation method

The dielectric response theory is commonly used to describe the inelastic interaction between low-energy electrons and matter. In the

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doi:10.1016/j.apradiso.2011.08.012

framework of the dielectric response theory, many attempts (Ashely et al., 1978; Ashley and Williams, 1980; Penn, 1987; Tanuma et al., 1993, 2008; Dingfelder et al., 1998; Akkerman and Akkerman, 1999; Tan et al., 2004; Emfietzoglou and Nikjoo, 2005, 2007) have been made for calculating the SPs and IMFPs for low-energy electrons penetrating into matters.

Incorporating the Penn statistical approximation (Penn, 1987) into the dielectric response theory and taking into account the exchange effect between the incident electron and target electrons by using the Born–Ochkur correction method (Fernández-Varea et al., 1993), the resultant SP (dE/dS) and IMFP (λ) for low-energy electrons can be expressed as (Tan et al., 2004, 2006)

$$-\frac{dE}{dS}=\frac{1}{2\pi a_0 E}\int_0^{E/2}(\hbar\omega)\mathrm{Im}[-1/\varepsilon(\omega)]v(\alpha)d(\hbar\omega) \quad (1)$$

$$\lambda^{-1}=\frac{1}{2\pi a_0 E}\int_0^{E/2}\mathrm{Im}[-1/\varepsilon(\omega)]w(\alpha)d(\hbar\omega) \quad (2)$$

where E is the kinetic energy of the incident electron, a_0 is the Bohr radius, $\hbar\omega$ is the energy loss, $\mathrm{Im}[-1/\varepsilon(\omega)]$ is the optical energy loss function (OELF), and $v(\alpha)$ and $w(\alpha)$, respectively, are

$$v(\alpha)=\frac{2s}{(1+\alpha)(1+\alpha+s)}+\ln\left\{\frac{(1-\alpha^2)(1+\alpha)}{(1-\alpha-s)(1+\alpha+s)^2}\right\} \quad (3)$$

$$w(\alpha)=\frac{3\alpha^2+3\alpha+1}{(1+\alpha)^2}\ln\frac{1+\alpha-s}{1+\alpha}+\ln\frac{1-\alpha}{1-\alpha-s}+\frac{2\alpha^2+\alpha}{(1+\alpha)^2}\ln\frac{1+\alpha}{1+\alpha+s}+\frac{2\alpha s}{(1+\alpha)^2(1+\alpha+s)} \quad (4)$$

with $\alpha=\hbar\omega/E$ and $s=\sqrt{1-2\alpha}$.

It is clear from Eqs. (1) and (2) that the calculations of SP and IMFP require deriving the OELF. Usually, OELF can be numerically obtained from experimental optical data, i.e., the refractive index and extinction coefficients. However for the ten scintillators under consideration there are no available experimental optical data, and thus their OELFs will be evaluated with the use of the approach proposed in previous work (Tan et al., 2004). In this approach a free parameter is used for making the obtained OELF satisfy the *f*-sum rule expected by dielectric response theory. The *f*-sum rule can be described as an effective number Z_{eff} of electrons per atom or molecule through the following formula:

$$Z_{\mathrm{eff}}=\frac{2}{\pi\hbar^2\Omega_{\mathrm{P}}^2}\int_0^{(\hbar\omega)_{\max}}(\hbar\omega)\mathrm{Im}\left[-1/\varepsilon(\omega)\right]d(\hbar\omega) \quad (5)$$

where $\Omega_{\mathrm{P}}=(4\pi ne^2/m)^{1/2}$ with n as the density of atoms or molecules and m the mass of electron. According to the dielectric response theory Z_{eff} is expected to become Z, total number of electrons per atom or molecule, when $(\hbar\omega)_{\max}\rightarrow\infty$.

3. Results and discussion

In the present work, the considered 10 scintillators, HS2, HS3, IGP, UG, UG-AB, UG-XR, UG-LLT, UG-MV, UG-F, and HF, and their composition constitutions as well as mass densities are presented in Table 1.

As shown above, OELF is required in the calculations of SP and IMFP. The *f*-sum rule due to dielectric response theory is a test for the accuracy of the obtained OELFs. For the 10 scintillators considered in the present work the OELFs evaluated using the approach of Tan et al. (2004) satisfy the *f*-sum rule. Fig. 1 presents the examples of evaluations of Z_{eff} as a function of $\hbar\omega$ for UG, UG-AB, and HF. According to Table 1 the respective total numbers of electrons for these 3 scintillator stoichiometric units are

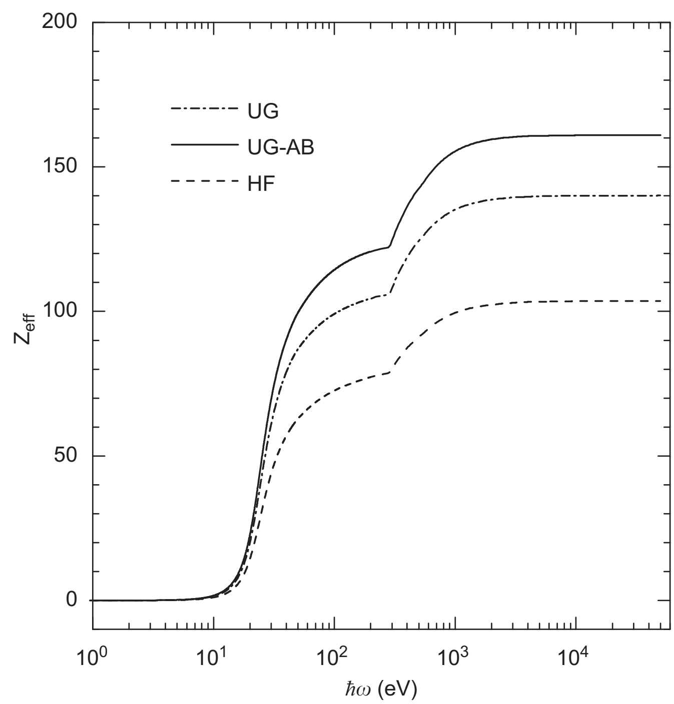

Fig. 1. Effective number, Z_{eff}, of electrons per stoichiometric unit as a function of photon energy loss $\hbar\omega$ for UG, UG-AB, and HF.

Table 1
Composition, densities, and $\bar{I}$ values for the 10 scintillators.

Scintillator	Composition								ρ (g/cm^3)	$\bar{I}$(eV)	
	C	H	N	O	P	S	Na	B		Calculated	NIST
HS2[a]	17.81	25.37	0.03	1.59	0.02	0.07	0.08	0.02	0.9931	63.6	65.6
HS3[a]	19.91	29.79	0.06	2.23	0.04				0.9970	62.9	64.8
IGP[a]	19.93	31.29	0.03	2.79					0.9535	63.0	64.7
UG[a]	16.77	24.92	0.09	1.48	0.11	0.01	0.02		0.9845	63.1	65.0
UG-AB[b]	18.66	28.25	0.02	2.53	0.01				0.9800	63.1	65.0
UG-XR[b]	18.18	29.57	0.04	2.83	0.09	0.03	0.03		0.9900	63.7	65.5
UG-LLT[b]	18.63	28.17	0.02	2.54					0.9830	63.2	65.1
UG-MV[b]	17.01	26.23	0.04	1.67	0.09	0.02	0.02		0.9600	62.8	64.6
UG-F[b]	15.99	19.77	0.02	0.01					0.9600	61.6	63.4
HF[b]	10.83	18.74	0.05	1.97	0.18	0.04	0.04		0.9650	65.1	67.1

[a] From Rodríguez-Barquero and Los Arcos, (2010) density is taken and composition is calculated based on the weight proportion.
[b] From Perkin Elmer (http://www.nucleide.org/ICRM_LSC_WG/2010_LSC_cocktails_elementary_composition.pdf) density is taken and composition is calculated based on the weight proportion.