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Experimental Determination of Electron Interaction Parameters of Medically Significant Polymers

S. Ramesh Babu[1], N.M.Badiger[2]

[1]Department of Medical Physics, Karnataka Institute of Medical Sciences, Hubli, Karnataka, India-580025
[2]Department of Physics, Karnatak University, Dharwad, India-580003

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Corresponding author
Dr. S. Ramesh Babu
KIMS, Hubli-25.

ABSTRACT

Relativistic electron interaction parameters of medically significant polymers have been determined by measuring their mass stopping power in transmission geometry. Using Cs^{137} and Bi^{207} IC electrons in a narrow beam good geometry set-up, the incident and transmitted electrons were recorded with Si(Li) detector coupled to an 8K MCA. Experimentally determined effective atomic number for electron interactions have been compared with that computed by direct method for both electron and photon interactions. The stopping cross section and effective electron density values are determined from mass stopping power and effective atomic number. Validity of these interaction parameters over a wide range of relativistic energy up to 10 MeV is discussed.

KEYWORDS: Interaction parameter; Mass stopping power; Effective atomic number; Effective electron density; Polymers

I. INTRODUCTION

Polymer is a macromolecule made up of many repeated subunits of organic elements called monomers. The larger molecular weight of polymers, provide them with unique physical properties like toughness, visco elasticity, tolerability, functional properties, environmental stability, light weight, and durability. Further due to their tissue compatibility they find significant application in medical field. In view of the broad medical applications of both the polymers as well as radiations, we have determined the radiation interaction indices called electron interaction parameters of ten important polymers which are widely used in medical field.

Interaction parameters quantify the interaction process of the specified energy and type of radiation with matter. Mass Stopping Power (MSP) being the easily measurable interaction parameter, it is used to derive other interaction parameters like Stopping Cross Section (SCS), effective atomic number (Z_{eff}) and effective electron density (N_e). *SCS* is the energy loss of the radiation per atom of the sample and has several applications in research fields like radiobiology, medical physics and electron transport modeling etc. N_e is the number of electrons per gram which can produce the specified interaction process between the given radiation and the material. It is often used in radio diagnosis to decide the contrast and in nuclear medicine to estimate the emitted radiation. Z_{eff} gives how radiation interacts with different types of material in the selected energy region. It is also used to characterize the radiological properties of dosimetric materials. Hence the study of Z_{eff} of multi-elemental system for photon interaction (PI), electron interaction (EI), proton interaction and alpha interaction has been a subject of experimental as well as theoretical interest.

Many authors have determined Z_{eff} and N_e of various biological samples, chemical compounds and polymers for photon interactions both experimentally as well as theoretically using Win-XCOM [1]. Details of such studies can be found in our earlier paper [2]. By using the MSP of electrons, protons and heavy ions from ICRU reports [3,4] or NIST-ESTAR [5] database, several investigators have determined Z_{eff} of various substances and have shown that the Z_{eff} is not constant, but varies with type and energy of the incident radiation.

White [6] analyzed the photon and electron interaction with the matter and showed that Z_{eff} depends on type of radiation also. Taylor et al.,[7,8] have calculated Z_{eff} for Radiative, Collisional and total electron interaction processes in dosimetric materials to study the variation of Z_{eff} with the type of interactions over a wide range of energy. Parthasarathy et al.,[9], Kurudirek et al., [10] and Guru Prasad et al.,[11] have computed Z_{eff} of several medically significant materials for photon, electron, proton and alpha.

However, to the best knowledge of the authors, there is no experimental determination of Z_{eff} for electron interaction in polymers. Due to wide applications of many polymers as well as different type of radiations in the

medical field, we have experimentally determined all the interaction parameters of medically significant polymers at the representative relativistic energies of electrons and compared the same with that of photons of same energies.

II. MATERIALS AND METHODS

A. Semi Empirical Formula between MSP & Z_{eff}

Atomic number is an important parameter contributing to all basic properties of an element. Such similar quantity called effective atomic number, Z_{eff} is introduced for composite materials namely compounds, mixtures and alloys. As Hine [12] pointed out the effective atomic number of a composite material varies with the type of radiation and energy of the radiation with which it interacts. A summary of different ways of defining and determining the effective atomic number of composite materials for different radiations can be found in our earlier work [2]. In our earlier paper [2] we have also established a relation between the *MSP* and atomic number of organic elements (H, C, N and O) as

$$MSP\ (MeV\text{-}cm^2/gm) = A_0 + A_1\, e^{-(BZ)} \quad (1)$$

This formula is arrived by plotting the ESTAR [5] *MSP* value of organic elements against their atomic number as shown in Fig.1 for 614 keV, 942 keV & 1016 keV electrons. We have included ^{4}He data also to get smooth curve fitting with the fitting parameters A_0, A_1 & B as shown in Table-1.

Table-I: Fitting parameters for the incident energies of 614 and 942 keV

Einc (keV)	A_0 (MeV-cm^2/gm)	A_1 (MeV-cm^2/gm)	B
614	1.7387	37.3668	2.7926
942	1.6532	33.3150	2.7263

The correctness of fitting is verified by calculating the percentage deviation, PD of *MSP* obtained using equation (1) from that downloaded from ESTAR [5] as given in Table-2.

Table-II: PD between the *MSP* values determined using ESTAR [5] & eq.(1)

Elements		H	C	N	O
Atomic Number		1	6	7	8
Atomic Weight		1.010	12.010	14.010	16.000
614 keV	ESTAR value	4.028	1.722	1.755	1.728
	Fitted Value	4.028	1.739	1.739	1.739
	PD	0.004	-0.970	0.929	-0.619
942 keV	ESTAR value	3.834	1.634	1.686	1.663
	Fitted Value	3.834	1.653	1.653	1.653
	PD	-0.001	-1.175	1.945	0.589
1016 keV	ESTAR value	3.817	1.625	1.682	1.659
	Fitted Value	3.817	1.649	1.649	1.649
	PD	-0.001	-1.477	1.962	0.603

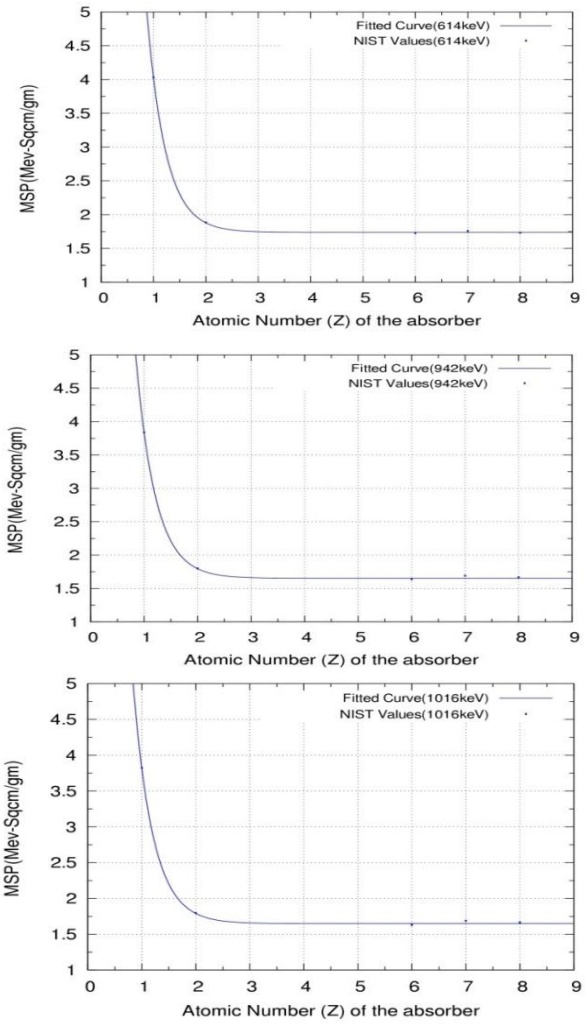

Fig.1. ESTAR [5] MSP versus Z of organic elements for 614 keV, 942 keV and 1016 keV

Using the measured *MSP* of the polymers and by knowing the constants A_0, A_1 and B, we have determined the Z_{eff} for electron interaction of these polymers. SCS and N_e are calculated from MSP and Z_{eff} as given below.

$$SCS = MSP/N \quad and \quad (2)$$

$$N_e = \mathrm{N}\ Z_{eff} \quad where \quad (3)$$

$$\mathrm{N} = \text{No. of atoms/ gm} = N_A / A_{eff} \quad (4)$$

If the sample contains n_i number of ith element of atomic weight Ai then, the effective atomic weight of the sample is given as $A_{eff} = \sum_i ni\ Ai\ / \sum_i ni$ (5)

B. Source of Electrons

We have used ^{207}Bi radioactive source, which emits IC electrons of energies 481.7, 555.4, 975.4 and 1049.4 keV. This radioactive source is electroplated on platinum foil and encapsulated in stainless steel of 1.52 cm outer diameter and covered with 18.8 mg/cm^2 thick beryllium foil. After correcting for the attenuation of IC electrons in beryllium foil and air column between source and detector, their effective energies are 443.9, 518.8, 941.7 and 1015.5 keV respectively. All these four electrons are used to calibrate the MCA at a time under the same environmental conditions.

We have also used ^{137}Cs radioactive source which emits 624.2 keV, K-shell internal conversion electrons. This source is covered with thin mylar foil of thickness 1.2 mg/cm^2 to avoid the source spilling and contamination. After correcting for this source coverings and air attenuation between the source and the detector, the effective energy of the IC electrons becomes 614 keV.

C. Experimental Arrangement

The experimental arrangement to measure the MSP of polymer using internal conversion electrons is shown in Fig.2. The details of the experimental technique have been presented in our earlier paper [13]. The incident and transmitted IC electrons through the polymeric foils are detected with selection grade NE – Si (Li) detector coupled to charge sensitive pre-amplifier of charge sensitivity 15 mV/MeV and then to delay line amplifier and to 8K multichannel analyzer.

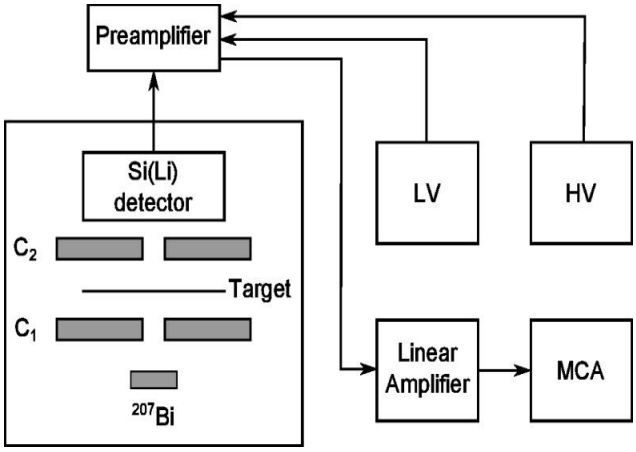

Fig.2. Block diagram of the experimental arrangement used to measure the MSP

In order to prevent the scattered electrons from entering into the detector, two collimators C_1 and C_2 are used; one collimator C_1 near the source and the other collimator C_2 near the detector. These two collimators are made up of aluminum. As the detector is light sensitive, the whole assembly has been placed in a light-tight box. The target such as the polymer of reagent grade is placed between the C_1 and C_2 and then transmitted spectrum of internal conversion is recorded. By knowing the incident spectrum of internal conversion without polymer and the transmitted spectrum through polymer, the Z_{eff} values of the polymers have been determined.

D. Experimental Procedure:

The stability of Si (Li) detector spectrometer was checked by recording the 942 keV and 1016 keV internal conversion electrons before and after the experiment. It was observed that there was no shift in channel number during the experiment. First we recorded the incident spectrum of ^{207}Bi without keeping the polymer in between the collimators C_1 and C_2. Such a spectrum is shown in Fig.3. From this figure, we notice that four peaks are observed due to 444, 519, 942 and 1016 IC electrons. To obtain the channel numbers corresponding to these peaks, they are fitted to exponentially modified Gaussian (EMG) as shown in Fig.-3. By plotting these channel numbers corresponding to the peaks against their energies, we obtained the calibration curve and is shown in the inset of Fig.3. The slope of this curve, 0.2968 ± 0.0003 keV per channel is the calibration constant.

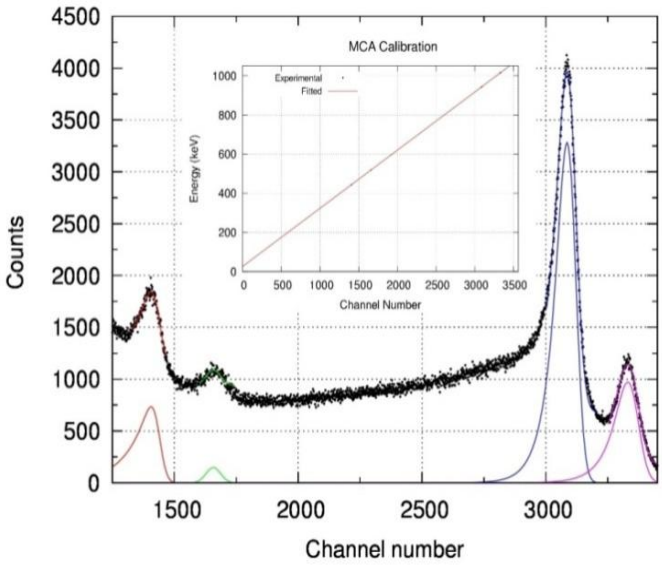

Fig.3: EMG fitted, incident ^{207}Bi spectrum along with the calibration graph

The 614 keV IC electrons from ^{137}Cs radioactive source is used as the incident spectrum. After checking the uniformity of thickness of the polymeric foils, they are placed between the collimator C_1 and C_2 without disturbing the setup to acquire the transmitted spectra. The spectra of 614 keV electrons transmitted through various polymers along with the EMG fitting are shown in Fig.4.

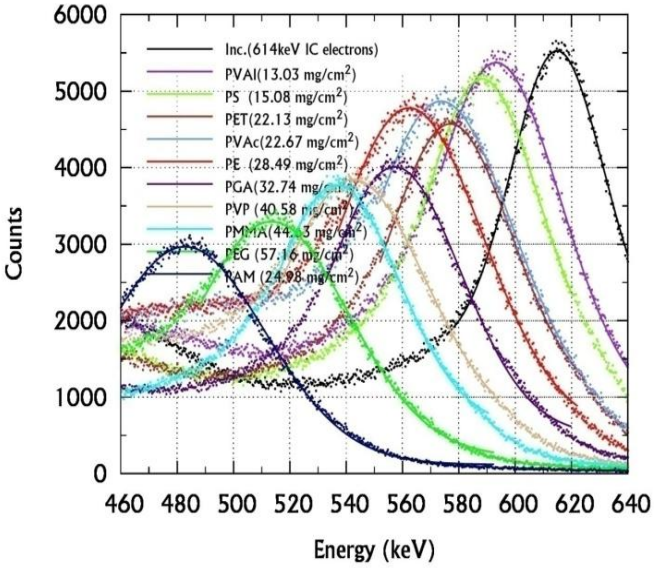

Fig.4: Spectra of 614 keV IC electrons transmitted through various polymers

The thickness of each polymer was determined by measuring their mass with a sensitive balance and area with travelling microscope. By knowing the peak energy of the incident beam and transmitted beam and thickness of the polymer, the energy loss and hence the MSP were determined. By substituting these *MSP* values in equation- 1 and by knowing the constants A_0, A_1 and B, the Z_{eff} for 614 keV electrons were determined. The effective electron density and the scattering cross section were obtained using the equations - 2, 3, 4 and 5.

This procedure was repeated with the ^{207}Bi IC source for each polymer to determine their *MSP*, Z_{eff}, N_e and *SCS* for 942 keV and 1016 keV electron interactions. The EMG fitted incident and transmitted spectra at 942 keV and 1016 keV for various polymers are shown in Fig.5 and Fig.6 respectively.

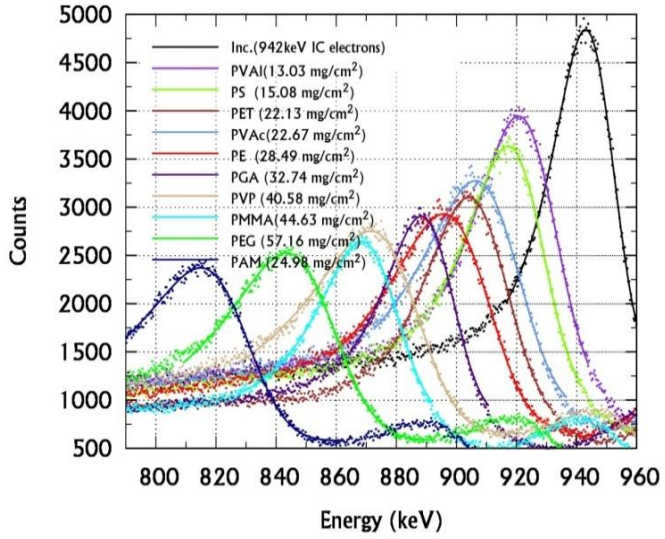

Fig.5: Spectra of 942 keV IC electrons transmitted through various polymers

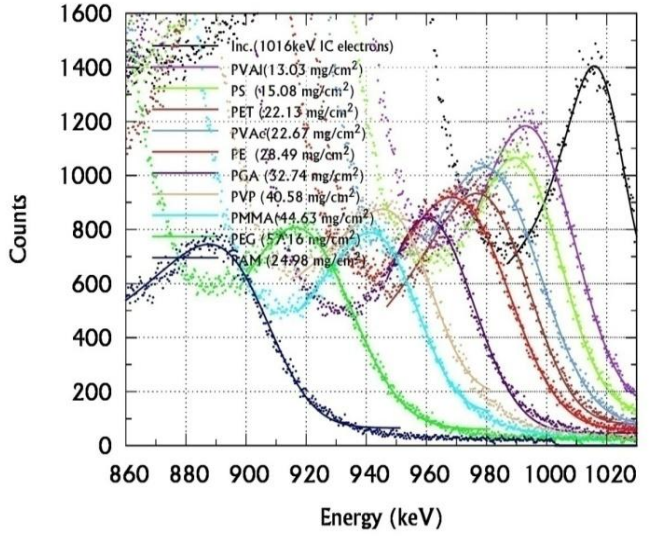

Fig.6: Spectra of 1016 keV IC electrons transmitted through various polymers

III. RESULTS AND DISCUSSION

In the present experiment, we have used 614 keV electrons from Cs^{137} and the 942 keV and 1016 keV electrons from Bi^{207} radioactive source. In Table-3, 4 and 5 we present the experimentally measured energy loss, *MSP*, Z_{eff} for electron and photon interactions, (Z_{eff}/A_{eff}), N, N_e and *SCS* of selected polymers for 614 keV, 942 keV and 1016 keV. The statistical error in the measured value is less than 1% as area under the peak is more than 10000. We have also compared our measured Z_{eff} for electron interactions with theoretical values calculated by direct method for both EI and PI.

From table- 3, 4 and 5, we notice that our measured values for 614 keV, 942 keV and 1016 keV IC electrons closely agree with the theoretical values for all selected polymers. Further we notice that measured Z_{eff} values for EI are found to be smaller than Z_{eff} values for PI by about 7% for all selected polymers at measured energy region establishing the dependence of Z_{eff} on the type of radiation. It can also be observed that Z_{eff}/A_{eff} is a constant and A_{eff}, N, N_e,*SCS* all varies linearly with the Z_{eff} for electron interaction in the current energy range of measurement.

Our energy range of measurements lies in the minimum ionization point (mip) region around which the variation in MSP and hence other interaction parameters are insignificant over a wide range of energies. Analysis of ESTAR [5] data shows a maximum of ±4% variation in MSP over the energy range between 500-750 keV and 750-2500 keV. As this statement holds good for all elements of Z = 1 to 98, MSP and SCS measured at 614 keV and 942 keV of this work can be used over the energy range 500-750 keV and 750-2500 keV within an accuracy of ±4%. As established by Prasad et al.,[11], Z_{eff} is constant over a wide range of energy around 1- 10MeV for EI and hence the Z_{eff} and N_e determined for 942 keV electrons in this work can be used at any energy of 1-10 MeV electron interactions.

IV. CONCLUSIONS

We have measured the energy loss and *MSP* of 614 keV, 942 keV and 1016 keV IC electrons in various polymers of medical interest. We have devised an empirical formula with energy dependent fitting constants to relate the *MSP* and Z_{eff} of organic materials using ESTAR [5] *MSP* values. This formula is used to obtain Z_{eff} from measured *MSP*. This Z_{eff} determined using the measured *MSP*, agrees well with the theoretical values calculated using direct method. In the given energy range of measurement Z_{eff} is more for PI than the EI by a factor of around 7%. We have also calculated the derived quantities of Z_{eff} namely Z_{eff}/A_{eff}, N_e and *SCS* for electron interactions at 614 keV, 942 keV and 1016 keV. All these quantities show linear variation with Z_{eff} for electron interaction. As these energies are in mip region, electron interaction parameters determined in this work can be used for any relativistic electrons of energies up to 2.5 MeV, within an accuracy of ±4%.

V. CONFLICT OF INTEREST

The authors declare no conflict of interest.

Table-III: Electron interaction parameters of medically significant polymers at 614keV

Polymer Sample	Thickness mg/cm^2	MPE keV	Energy Loss keV	*MSP* MeV-cm^2/gm	Z_{eff} for EI Experiment	Z_{eff} for EI Theory	Z_{eff} for PI Theory	A_{eff}	Z_{eff} / A_{eff}	N=N_A/ A_{eff} 10^{23} mol/gm	*SCS*=*MSP*/N 10^{23}MeV-cm^2	N_e= Z_{eff} *N 10^{23}e-/ gm
Inc	7.360	614.399	0.000	-	-	-	-	-	-	-	-	-
PAM	74.94	483.953	130.444	1.741	3.533	3.576	3.798	7.109	0.497	0.847	2.055	2.993
PE	28.49	563.852	50.545	1.774	2.493	2.488	2.665	4.677	0.533	1.288	1.378	3.210
PEG	57.16	514.702	99.695	1.744	3.164	3.168	3.398	6.208	0.510	0.970	1.798	3.069
PET	22.13	575.902	38.495	1.739	3.854	4.329	4.543	8.735	0.441	0.689	2.523	2.657
PGA	32.74	557.411	56.986	1.741	3.550	3.673	3.907	7.326	0.485	0.822	2.118	2.918
PMMA	44.63	536.694	77.702	1.741	3.467	3.373	3.598	6.675	0.519	0.902	1.930	3.128
PS	15.08	588.130	26.267	1.742	3.362	3.293	3.498	6.510	0.516	0.925	1.883	3.110
PVAc	22.67	574.952	39.445	1.740	3.690	3.601	3.831	7.175	0.514	0.839	2.073	3.097
PVAl	13.03	591.691	22.705	1.743	3.289	3.203	3.426	6.294	0.523	0.957	1.821	3.147
PVP	40.58	543.699	70.698	1.742	3.323	3.314	3.527	6.539	0.508	0.921	1.892	3.061

Table-IV: Electron interaction parameters of medically significant polymers at 942keV

Polymer Sample	Thickness mg/cm^2	MPE keV	Energy Loss keV	*MSP* MeV-cm^2/gm	Z_{eff} for EI Experiment	Z_{eff} for EI Theory	Z_{eff} for PI Theory	A_{eff}	Z_{eff} / A_{eff}	N=N_A/ A_{eff} 10^{23} mol/gm	*SCS*=*MSP*/N 10^{23}MeV-cm^2	N_e= Z_{eff} *N 10^{23}e-/ gm
Inc	7.360	942.414	0.000	-	-	-	-	-	-	-	-	-
PAM	74.94	818.387	124.033	1.655	3.586	3.581	3.798	7.109	0.504	0.847	1.954	3.037
PE	28.49	894.220	48.200	1.692	2.479	2.485	2.665	4.677	0.530	1.288	1.314	3.193
PEG	57.16	847.563	94.857	1.660	3.144	3.176	3.398	6.208	0.507	0.970	1.711	3.050
PET	22.13	905.825	36.595	1.654	4.107	4.334	4.544	8.735	0.470	0.689	2.399	2.831
PGA	32.74	888.224	54.196	1.655	3.541	3.681	3.907	7.326	0.483	0.822	2.014	2.911
PMMA	44.63	868.487	73.933	1.657	3.374	3.377	3.598	6.675	0.505	0.902	1.836	3.044
PS	15.08	917.429	24.991	1.657	3.311	3.289	3.498	6.510	0.509	0.925	1.791	3.063
PVAc	22.67	904.905	37.516	1.655	3.635	3.606	3.831	7.175	0.507	0.839	1.972	3.051
PVAl	13.03	920.813	21.607	1.658	3.226	3.208	3.427	6.294	0.512	0.957	1.733	3.086
PVP	40.58	875.165	67.255	1.657	3.299	3.315	3.527	6.539	0.504	0.921	1.800	3.038

Table-V: Electron interaction parameters of medically significant polymers at 1016keV

Polymer Sample	Thickness mg/cm^2	MPE keV	Energy Loss keV	*MSP* MeV-cm^2/gm	Z_{eff} for EI Experiment	Z_{eff} for EI Theory	Z_{eff} for PI Theory	A_{eff}	Z_{eff} / A_{eff}	N=N_A/ A_{eff} 10^{23} mol/gm	*SCC*=*MSP*/N 10^{23}MeV-cm^2	N_e= Z_{eff} *N 10^{23}e-/ gm
Inc	7.360	1015.593	0.000	-	-	-	-	-	-	-	-	-
PAM	74.94	892.053	123.706	1.651	3.609	3.582	3.798	7.109	0.508	0.847	1.949	3.057
PE	28.49	967.707	48.052	1.687	2.483	2.483	2.665	4.677	0.531	1.288	1.310	3.198
PEG	57.16	921.169	94.590	1.655	3.166	3.177	3.398	6.208	0.510	0.970	1.706	3.071
PET	22.13	979.253	36.506	1.650	3.978	4.334	4.544	8.735	0.455	0.689	2.393	2.742
PGA	32.74	961.712	54.047	1.651	3.595	3.682	3.907	7.326	0.491	0.822	2.008	2.955

PMMA	44.63	942.034	73.725	1.652	3.419	3.378	3.598	6.675	0.512	0.902	1.831	3.084
PS	15.08	990.828	24.931	1.653	3.280	3.288	3.498	6.510	0.504	0.925	1.787	3.034
PVAc	22.67	978.333	37.426	1.651	3.571	3.607	3.831	7.175	0.498	0.839	1.967	2.997
PVAl	13.03	994.212	21.548	1.654	3.245	3.209	3.427	6.294	0.516	0.957	1.728	3.104
PVP	40.58	948.683	67.077	1.653	3.308	3.315	3.527	6.539	0.506	0.921	1.795	3.047

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