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Experimental Determination of Relativistic Electron Interaction Parameters of Standard Inorganic Salts of d-block Elements

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Abstract: **Electron interaction parameters of 16 standard inorganic salts of d-block elements are determined by measuring their mass stopping power by recording the spectrum of electrons incident on and transmitted by them. ^{137}Cs and ^{207}Bi internal conversion sources are used as the source of 614 keV and 942 keV internal conversion electrons and Si (Li) detector coupled to an 8K multichannel analyzer as the spectrometer to record these spectra. The effective atomic number of these salts for 614 keV and 942 keV electron interactions are determined by substituting their measured mass stopping power in the semi empirical relation between the mass stopping power and atomic number. This semi empirical formula is arrived at by plotting and fitting the measured mass stopping power of Al, Cu, Ag, Sn, Au and Pb against their atomic number. The experimental results are compared with the theoretical values of effective atomic number for electron and photon interaction for organic and inorganic samples. It is observed that effective atomic number of inorganic salts is the same for both electron and photon interactions in the energy range of current study. Stopping cross section is derived from mass stopping power and effective electron density from the effective atomic number and their dependence on effective atomic number are studied.**

Keywords: **Internal conversion electron, Interaction parameters, Mass stopping power, Effective atomic number, Effective electron density.**

I. INTRODUCTION

Electron interaction with matter is of high importance among other radiation interaction with matter. It is mainly because, all type of radiation interactions results in release of electrons which interacts with the matter to cause physical, chemical and biological damages. Hence the measurement of interaction parameters of electrons like Mass Stopping Power (MSP), Energy Loss Straggling (ELS), Stopping Cross Section (SCS), Effective atomic Number (Z_{eff}) and Effective electron density (N_e) became a necessary ingredient for many parts of basic science, medical applications and technological applications.

As mentioned in our earlier paper [1], many authors have determined photon interaction parameters for various biological samples, chemical compounds and polymers. Singh et al., [2] has measured the interaction parameters of 123 keV-1132 keV photons with different compounds. They found that the variation in mass attenuation coefficient is mainly due to the variations in the energy and hence in photon interaction processes rather than the variation in properties of matter. Icelli et al., [3] has measured the interaction parameter of 15.74–40.93 keV photons with some boron compounds and trommel sieve waste using mixture rule and compared their results with the theory. Niranjan et al., [4] has estimated the interaction parameters of 1keV -105 MeV photons with oxides of lanthanides using the mass attenuation coefficient from WinXCom and mass energy absorption coefficient from Hubbell and Seltzer. Yüksel and Kurudirek [5] have measured the

interaction parameters of 59.54keV photons in 21 different compounds, using a narrow beam good geometry set-up and compared their results with the theory.

Several investigators [6-10] have studied the charged particle interaction parameters in many organic materials using the mass stopping power downloaded from ESTAR web database [11] as detailed in our earlier paper. Recently the MSP and ELS of ions in different oxides such as ZnO, Al_2O_3, HfO_2, ZrO_2, TiO_2 and Ta_2O_5 have been measured [12, 13]. The ELS of alpha particles in varying thickness of Al, Ti and Ni metallic foils have also been measured to test the existing theory [14]. The energy losses of Li and C ions in aluminium foils have been studied to understand collisional energy loss and charge exchange straggling [15].

However, the experimental study of interaction parameters of medium energy electrons in biological and non-biological absorbers is very rare. There is only theoretical estimation of electron interaction parameters in biological and non-biological absorbers. In our earlier paper [16] we have measured MSP of inorganic elements and derived a semi empirical relation between the MSP and Z for Z =10-82. In the present research work, we have experimentally determined the electron interaction parameters for relativistic electrons of energies 614 and 942 keV in inorganic salts of d block elements using their measured MSP in the above semi empirical relation. To the best of our knowledge, this is the first attempt to understand experimentally the interaction of relativistic electrons in inorganic materials.

Inorganic salts dissociate to release ions which are used for many important functions of the body like neural transmission, pH regulation etc. As, d-block elements are in between s-block and p-block elements in their position and properties, they are the best representative of entire periodic table. Depending on their non-metallic part, they can be broadly classified into oxides, nitrides, sulphides and halides. As the MSP-Z relation is different for Z < 10 and for Z >10, we dropped down the oxides and nitrides containing nitrogen and oxygen of Z<10. We by measuring the MSP determined all the interaction parameters of sulphides and halides of commonly used d-block elements for 614keV and 942 keV electron interactions.

II. THEORY

Interaction parameters are the parameters providing essential information about the interactions. The five important interaction parameters of electron interaction are:

1. Mass Stopping Power, the energy loss per unit thickness of the sample. It can be determined accurately by measuring the absorber thickness, the incident and transmitted spectra. As MSP is easily measurable, it is often used to derive all other interaction parameters.

2. Energy Loss Straggling is the fluctuation of the energy loss around its mean value. It can be determined from the FWHM of the incident and transmitted spectra. As it demands high degree of target thickness uniformity and accurate spectral fitting it is used mainly in very large scale integration modelling and programs to create analytic functions of ion implantation distributions.

3. Stopping Cross Section is the energy lost per atom of the sample. SCS has several applications in research fields like radiobiology, medical physics and electron transport modelling etc. SCS is derived from MSP as below:

$SCS = MSP/N$ Where (1)

$\mathrm{N} = \text{Atomic density} = \text{Number of atoms per gram} = N_A / A_{eff}$ (2)

If the sample contains n_i number of i^{th} element of atomic weight Ai then,

Effective atomic weight of the sample $= A_{eff} = \sum_i ni\, Ai \,/ \sum_i ni$ (3)

4. Effective atomic number, Z_{eff} is a weighted arithmetic mean of the atomic number of the constituent atoms with the weighing factor accounting for the type of radiation, material and interaction. Hence it is widely used in radiation studies, particularly to characterize the interaction processes in composite materials. It can be determined accurately from the knowledge of MSP of the sample and MSP-Z relation of pure elements in the energy range of interest. It can also be determined with fairly good accuracy by adopting the following formula of direct method used for photon interactions [17].

$$Z_{eff,ei} = \frac{\sum_i Fi\ Ai(MSP)i}{\sum_i Fi\ Ai(MSP)i/Zi} \quad (4)$$

Where $(MSP)_i$, A_i and F_i are the MSP, mass number and molar fraction of the element "i" in the sample.

5. Effective electron density, N_e is the number of electrons per gram corresponding to the Z_{eff} of the sample. It is used in radio diagnosis to decide the contrast and in nuclear medicine to estimate the emitted radiation. N_e is derived from effective atomic number as below.

$$N_e = \mathrm{N}\ Z_{eff} \quad (5)$$

The energy absorption in any composite material can be obtained using well established formulae, if their interaction parameters namely Z_{eff} and effective electron density are known. In our earlier paper [16] we have established that the variation of MSP of pure elements, against their atomic number can be represented by a first order exponential decay as

$$MSP\ (MeV - cm^2/gm) = A_0 + A_1 e^{-BZ} \quad (6)$$

Where Z >10 and A_0, A_1 & B are the energy dependent fitting parameters as shown in table-I. The correctness of this formula is verified [16] by calculating and comparing the MSP of all elements with the ESTAR [11] and Batra et al., [18] values for Z=10 to 82. The curve fitting process is as shown in figure-1, where we have measured and used the MSP of Al, Cu, Ag, Sn, Au and Pb to obtain the fitting parameters A_0, A_1 and B.

TABLE I: Fitting parameters for the incident energies of 614 & 942 keV

Einc (keV)	A_0 (MeV-cm^2/gm)	A_1 (MeV-cm^2/gm)	B
614	1.0551	0.7168	0.0285
942	0.8754	0.7168	0.0148

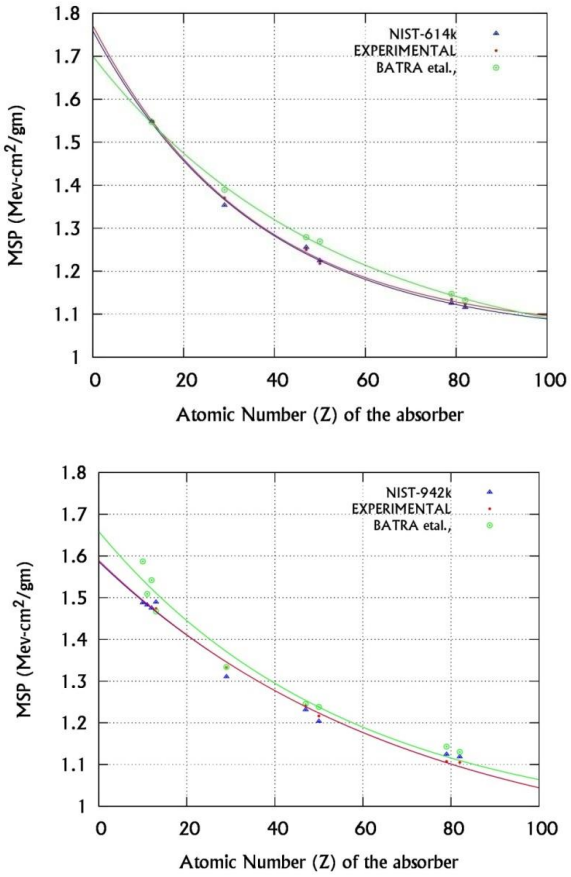

Fig.1- MSP vs Z of pure elements for 614 keV and 942 keV electron interactions.

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III. EXPERIMENTAL ARRANGEMENT

The experimental arrangement to measure the MSP of the relativistic electrons is as detailed in our earlier paper [19]. In nutshell, figure-2 is the schematic representation of the experimental setup with two collimators C_1 & C_2 between which the sample is to be placed. Here the labels LV, HV and MCA represent the Low voltage unit, High Voltage Unit and Multi Channel Analyzer respectively.

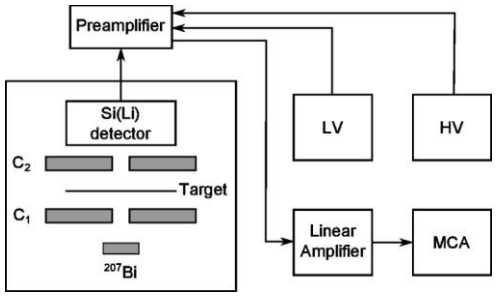


Fig.2- Experimental arrangement for measurement of the MSP

We have used ^{207}Bi and ^{137}Cs IC source as the source of relativistic electrons. ^{207}Bi IC source used in this experiment is electroplated on a platinum foil and encapsulated in stainless steel of 1.52 cm outer diameter with 18.8 mg/cm^2 thick beryllium window to prevent the source spilling and contamination. It emits 481.7, 555.4, 975.7 and 1049.4 keV IC electrons. After correcting for the attenuation by the beryllium window of the source and the air column between the source and detector, their effective energies will be 444, 519, 942 and 1016 keV respectively.

^{137}Cs radioactive source 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 coverings & air attenuation between the source and the detector, the effective energy of the IC electrons becomes 614 keV.

The selection-grade NE Si (Li) detector used in this experiment has 0.2 cm depletion area and 15 cm^2 active areas. Detector output is connected to an 8K MCA through a charge sensitive ORTEC preamplifier of charge sensitivity 15mV/MeV (Si eq.) and a delay line amplifier. The entire assembly is placed in a light tight box as in figure 2.

The absorbers are the inorganic salts of reagent grade. The samples are prepared by sandwiching a measured quantity of the finely powdered inorganic salt between two thin polythene films of negligible attenuation. The sample thickness is found using travelling microscope and a sensitive balance. Thickness uniformity of the sample is verified from the sharpness of the transmitted spectra.

IV. PROCEDURE

After checking for the stability of the spectrum over time, the ^{207} Bi spectrum with four peaks due to 444, 519, 942 and 1016 keV IC electrons is acquired without any material between the source and detector. All these four peaks are fitted to four EMG to get the channel number corresponding to peaks as in Fig.3. A plot of these corresponding to the peaks against their energies called the calibration graph of the spectrometer is shown as inset in figure-3. The calibration factor of the spectrometer is found to be (0.2996 ± 0.0009) keV/channel.

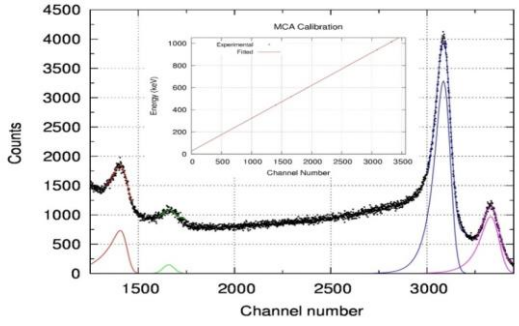
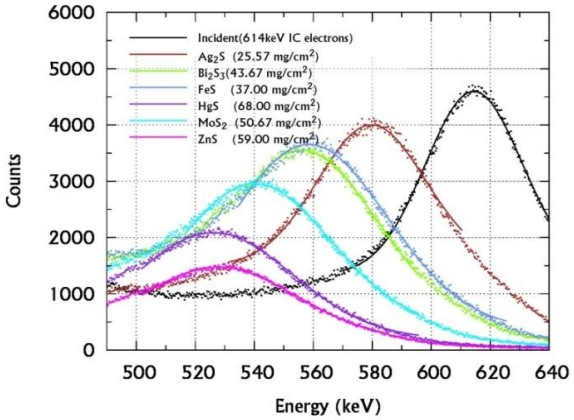
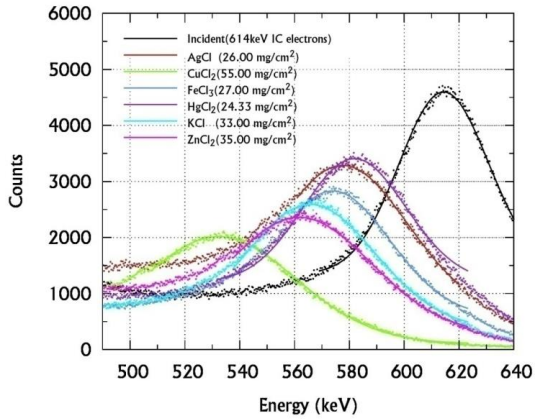


Fig.3- EMG fitted, incident ^{207}Bi spectrum along with the calibration graph.

The incident and transmitted spectra of ^{137}Cs are acquired without and with the sample between the collimator C_1 and C_2. Such spectra of different sulphides, chlorides, bromide-iodides are shown in figures 4 (a), (b) & (c)



(a)



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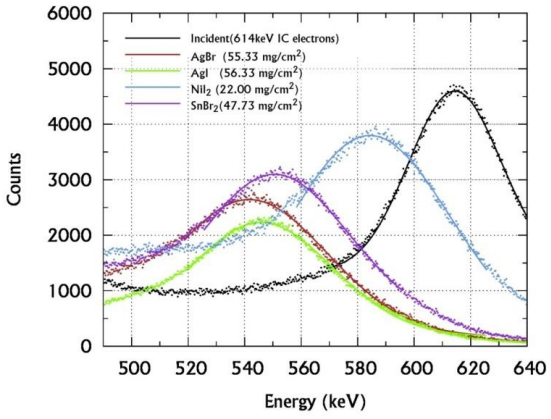

(c)

Fig.4-Spectra of 614 keV electrons transmitted through various (a) Sulphides (b) Chlorides (c) Bromides & Iodides

From these spectra the Most Probable Energy (MPE) and hence the energy loss are obtained and used to evaluate their MSP of the sample. Thus evaluated MSP are substituted in the empirical relation (6) to determine the Z_{eff} of sulphides and halides for 614keV electron interactions and presented in the table II. The SCS and N_e are computed from using the equations (1), (2), (3) and (5) and presented in the table III.

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Table II. *MSP* and Z_{eff} of various inorganic salts for 614 keV electron and photon interactions

Sample	Thickness mg/cm^2	MPE keV	Energy Loss keV	*MSP* MeV-cm^2/gm	Z_{eff} for *EI*		Z_{eff} for *PI*
					Experiment	Theory	Theory
Incident		614.400			….	….	
AgBr	55.33	543.743	-70.657	1.277	41.192	40.851	41.253
$SnBr_2$	47.73	552.935	-61.465	1.288	39.530	39.865	40.382
NiI_2	22.03	586.747	-27.653	1.255	44.818	44.599	45.602
AgI	56.33	545.225	-69.175	1.228	49.946	50.025	50.090
KCl	33.03	565.291	-49.109	1.487	17.806	17.993	18.001
$FeCl_3$	26.97	574.774	-39.626	1.469	19.265	19.122	19.279
$CuCl_2$	55.00	534.543	-79.857	1.452	20.766	20.765	21.072
$ZnCl_2$	35.00	563.680	-50.720	1.449	21.015	21.078	21.421
AgCl	26.13	579.078	-35.322	1.352	30.992	31.112	33.025
$HgCl_2$	24.63	582.028	-32.372	1.314	35.733	36.049	47.186
FeS	37.03	560.590	-53.810	1.453	20.660	20.855	21.046
ZnS	59.03	529.969	-84.431	1.430	22.737	22.754	23.110
MoS_2	50.93	542.233	-72.167	1.417	24.008	24.198	25.235
Ag_2S	25.73	580.618	-33.782	1.313	35.922	35.974	37.595
Bi_2S_3	44.47	557.586	-56.814	1.278	41.102	40.921	53.872
HgS	68.97	528.135	-86.265	1.251	45.612	46.028	57.482

Table III- Z_{eff}/A_{eff}, N_e and *SCS* of different inorganic salts for 614 keV electron interactions

Sample	Z_{eff}	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)
AgBr	41.1918	93.886	0.439	0.064	19.909	2.642
$SnBr_2$	39.5300	92.839	0.426	0.065	19.853	2.564
NiI_2	44.8184	104.167	0.430	0.058	21.712	2.591
AgI	49.9462	117.386	0.425	0.051	23.937	2.562
KCl	17.8063	37.274	0.478	0.162	9.203	2.877
$FeCl_3$	19.2648	40.549	0.475	0.149	9.893	2.861
$CuCl_2$	20.7660	44.815	0.463	0.134	10.805	2.790
$ZnCl_2$	21.0154	45.427	0.463	0.133	10.931	2.786
AgCl	30.9917	71.659	0.432	0.084	16.085	2.604
$HgCl_2$	35.7327	90.497	0.395	0.067	19.751	2.378
FeS	20.6600	43.953	0.470	0.137	10.606	2.831
ZnS	22.7372	48.720	0.467	0.124	11.571	2.810
MoS_2	24.0082	53.357	0.450	0.113	12.555	2.710
Ag_2S	35.9216	82.599	0.435	0.073	18.008	2.619
Bi_2S_3	41.1020	102.828	0.400	0.059	21.815	2.407
HgS	45.6117	116.325	0.392	0.052	24.160	2.361

This study is repeated with ^{207}Bi source to obtain all the above mentioned interaction parameters for the 942 keV electrons in sulphides, chlorides, bromides and iodides samples as presented in Tables-IV and V. Figures 5(a),(b) and (c) presents the EMG fitted spectra of 942 keV IC electrons incident on and transmitted through various sulphides, chlorides, bromides and iodides salts of d-block elements.

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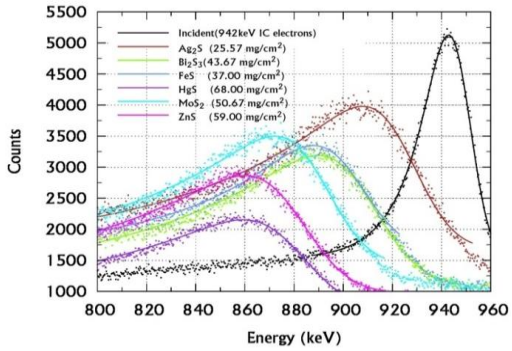
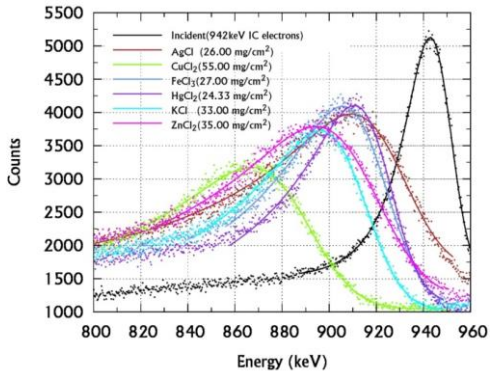


(a)



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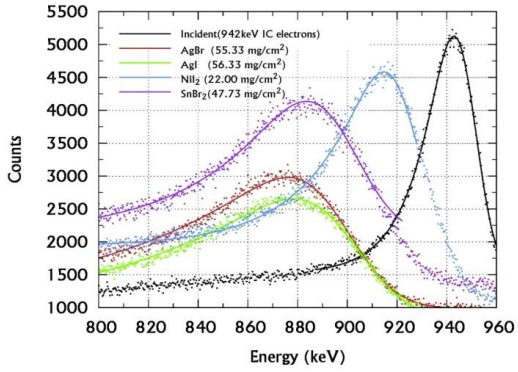

(c)

Fig.6 - Spectra of 942 keV electrons transmitted through various (a) Sulphides (b) Chlorides (c) Bromides & Iodides

Table IV- *MSP* and Z_{eff} of various inorganic salts for 942 keV electron and photon interactions

Sample	Thickness mg/cm^2	MPE keV	Energy Loss keV	*MSP* MeV-cm^2/gm	Z_{eff} for *EI* Experiment	Theory	Z_{eff} for *PI* Theory
Incident		942.42			….	….	
AgBr	55.33	875.759	-66.661	1.205	40.634	40.855	41.253
$SnBr_2$	47.73	884.663	-57.757	1.210	39.880	39.875	40.382
NiI_2	22.03	916.420	-26.000	1.180	44.248	44.701	45.602
AgI	56.33	878.133	-64.287	1.141	50.388	50.033	50.090
KCl	33.03	896.535	-45.885	1.389	18.218	17.993	18.001
$FeCl_3$	26.97	905.142	-37.278	1.382	18.949	19.119	19.279
$CuCl_2$	55.00	867.300	-75.120	1.366	20.692	20.762	21.072
$ZnCl_2$	35.00	894.754	-47.666	1.362	21.117	21.080	21.421
AgCl	26.13	909.149	-33.271	1.273	31.448	31.202	33.025

$HgCl_2$	24.63	911.968	-30.452	1.236	36.247	36.480	47.186
FeS	37.03	891.934	-50.486	1.363	20.955	20.871	21.046
ZnS	59.03	862.700	-79.720	1.351	22.363	22.784	23.110
MoS_2	50.93	874.572	-67.848	1.332	24.414	24.299	25.235
Ag_2S	25.73	910.633	-31.787	1.235	36.378	36.115	37.595
Bi_2S_3	44.47	889.115	-53.305	1.199	41.516	41.580	53.872
HgS	68.97	861.809	-80.611	1.169	45.994	46.668	57.482

Table V- Z_{eff} /A_{eff}, N_e and SCS of different inorganic salts for 942 keV electron interactions

Sample	Z_{eff}	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)
AgBr	40.6340	93.886	0.433	0.064	18.783	2.606
$SnBr_2$	39.8802	92.839	0.430	0.065	18.655	2.587
NiI_2	44.2479	104.167	0.425	0.058	20.415	2.558
AgI	50.3880	117.386	0.429	0.051	22.246	2.585
KCl	18.2180	37.274	0.489	0.162	8.598	2.943
$FeCl_3$	18.9487	40.549	0.467	0.149	9.307	2.814
$CuCl_2$	20.6923	44.815	0.462	0.134	10.164	2.781
$ZnCl_2$	21.1172	45.427	0.465	0.133	10.273	2.799
AgCl	31.4484	71.659	0.439	0.084	15.151	2.643
$HgCl_2$	36.2475	90.497	0.401	0.067	18.580	2.412
FeS	20.9553	43.953	0.477	0.137	9.951	2.871
ZnS	22.3626	48.720	0.459	0.124	10.926	2.764
MoS_2	24.4138	53.357	0.458	0.113	11.803	2.755
Ag_2S	36.3785	82.599	0.440	0.073	16.945	2.652
Bi_2S_3	41.5159	102.828	0.404	0.059	20.468	2.431
HgS	45.9940	116.325	0.395	0.052	22.577	2.381

V. RESULTS AND DISCUSSION

The choice of Bi^{207} IC source follows the fact that, it emits wide ranges of IC electrons, all of which can be used simultaneously for the MCA calibration under the same environmental conditions to enhance the accuracy of the calibration. The data acquisition time is so chosen that the total count under each spectral peak is greater than 10,000 and hence the counting error is less than 1%.

In Table II and IV, we present the experimentally measured energy loss, *MSP*, Z_{eff} for electron interaction and photon interaction of different inorganic salts of d block elements for 614 keV and 942 keV. We have also compared our measured Z_{eff} for electron interactions with theoretical values calculated by direct method for both electron and photon interactions of the same energies. We notice that our measured values of Z_{eff} for 614 keV and 942 keV IC electrons agree with the theoretical values within ±1% for all inorganic salts under investigations. It is observed further that in all cases except the mercuric salts $Z_{eff,ei}$ and $Z_{eff,pi}$ too agrees within ±2%. This is against the variation of ±7 % observed with organic compounds. This questions the variation of Z_{eff} with type of radiation especially for the materials of atomic number greater than 10. Further experimental studies of more inorganic salts in this regard may confirm this conclusion.

Table-III and V presents the derived interaction parameters for the relativistic electron interactions with the common inorganic salts of d-block elements. All these interaction parameters MSP, SCS, A_{eff} and N_e are found to vary linearly with their $Z_{eff.}$ The ratio Z_{eff}/A_{eff} and hence N_e have a constant value of nearly 0.5 and $3x10^{23}$ electron /gm in all stable compounds as was the case in stable elements.

VI. CONCLUSIONS

We have measured the electron interaction parameters of representative d-block elements by measuring their MSP for 614 keV and 942 keV IC electrons. The effective atomic number is determined using the semi empirical formula devised by us to relate the *MSP* and Z_{eff} of elements of Z > 10 [16]. Thus determined Z_{eff} are compared with the theoretical Z_{eff} values of electron and photon interactions computed using direct method. A good agreement within ±1-2% between the experimental $Z_{eff,ei}$ and theoretical $Z_{eff,ei}$ as well as $Z_{eff,pi}$ is observed. This agreement between $Z_{eff,ei}$ and $Z_{eff,pi}$ doubts the variation of Z_{eff} with the type of radiation especially for materials of Z > 10. This result needs to be confirmed by further experimental investigations with more number of inorganic salts. We have also determined the derived interaction parameters 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.

Our energy range of measurements lies in the minimum ionization point 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 well 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.,(10), Z_{eff} is constant over a wide range of energy around 1- 10 MeV for electron interactions 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.

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