The Mass Attenuation Coefficients, Effective Atomic Cross Sections, Effective Atomic Numbers and Electron Densities of Some Halides

Shivalinge Gowda

***Abstract*—**The total mass attenuation coefficients μ/ρ, of some halides such as, NaCl, KCl, CuCl, NaBr, KBr, RbCl, AgCl, NaI, KI, AgBr, CsI, $HgCl_2$, CdI_2 and HgI_2 were determined at photon energies 279.2, 320.07, 514.0, 661.6, 1115.5, 1173.2 and 1332.5 keV in a well-collimated narrow beam good geometry set-up using a high resolution, hyper pure germanium detector. The mass attenuation coefficients and the effective atomic cross sections are found to be in good agreement with the XCOM values. From these mass attenuation coefficients, the effective atomic cross sections σ_a, of the compounds were determined. These effective atomic cross section σ_a data so obtained are then used to compute the effective atomic numbers Z_{eff}. For this, the interpolation of total attenuation cross-sections of photons of energy E in elements of atomic number Z was performed by using the logarithmic regression analysis of the data measured by the authors and reported earlier for the above said energies along with XCOM data for standard energies. The best-fit coefficients in the photon energy range of 250 to 350 keV, 350 to 500 keV, 500 to 700 keV, 700 to 1000 keV and 1000 to 1500 keV by a piecewise interpolation method were then used to find the Z_{eff} of the compounds with respect to the effective atomic cross section σ_a from the relation obtained by piece wise interpolation method. Using these Z_{eff} values, the electron densities N_{el} of halides were also determined. The present Z_{eff} and N_{el} values of halides are found to be in good agreement with the values calculated from XCOM data and other available published values.

***Keywords*—**Mass attenuation coefficient, atomic cross-section, effective atomic number, electron density.

I. Introduction

THE total mass attenuation coefficients or cross-sections, effective atomic numbers and electron densities are the basic quantities required in determining the penetration of X-ray and γ-photons in matter. With the extensive use of radio isotopes in medical, industrial and agricultural fields, the study on absorption of X-ray and γ-ray photons in composite materials is an interesting field of research. The knowledge of mass attenuation coefficients of X-rays and γ-photons in biological and other important materials is of significant interest for industrial, biological, agricultural and medical applications. Accurate values of photon mass attenuation coefficients or cross sections are needed to establish the regions of validity (keV to few MeV) of theory based parameterization, in addition to providing essential data in such diverse fields such as radiation dosimetry, radiation protection, nuclear medicine, nuclear diagnostics (computerized tomography), gamma ray fluorescence studies, and radiation biophysics. Accurate determination of the mass attenuation coefficients or cross sections in various composite materials is therefore essential in the development of high accuracy semi-empirical formulation [1]. Mass attenuation coefficients tend to increase with increasing atomic number at the same photon energy, so the materials with high atomic numbers (high mass attenuation coefficients) are normally chosen to shield X- and γ-radiation [2].

The scattering and absorption of X-ray and γ-ray radiations are related to the density and atomic number of an element. In composite materials, it is related to the density and the effective atomic number. A single number therefore cannot represent the atomic number uniquely across the entire energy region, as in the case of pure elements. This number for composite materials is called the "effective atomic number" (Z_{eff}) and varies with the energy [3]. Following Hine's suggestions, many attempts have been made to determine the effective atomic number (Z_{eff}) for partial and total interactions in composite materials such as Alloys [4]–[9], Dosimetric compounds [10]-[14], [17], Organic and Inorganic compounds [16], [18]-[25], Shielding materials [15]. Some empirically deduced formulae have also been reported [3], [26], [27] but their validity is limited to the experimental conditions. Tabulations of photon mass attenuation coefficients and interaction cross sections have been reported for elements and mixtures [28]. Berger and Hubbell [29] developed a computer program, XCOM, which calculates photon cross sections for partial, total interactions and attenuation coefficients for pure elements and some mixtures in the energy range of 1 keV to 100 GeV.

In this paper, we report the accurate values of total mass attenuation coefficients, effective atomic cross sections, effective atomic numbers, and the electron densities of halides at the energies 279.2, 320.07, 514.0, 661.6, 1115.5, 1173.2 and 1332.5 keV obtained by experiments. These attenuation coefficient values were used to determine the effective atomic number and hence the effective electron density of some halides as indicated earlier. We also found the elemental cross sections of the elements from the attenuation cross sections of the compounds by mixture rule [30]. The E- and Z-wise interpolation of attenuation cross sections of these elements was performed by using the logarithmic regression analysis of

Shivalinge Gowda is a Professor and Head of the department of Physics, P.E.S. College of Engineering (An Autonomous Institution affiliated to Visvewaraya Technological University, Belagavi), Mandya District - 571 401, Karnataka State, India (phone: 08232–220043-260, 09449679429; fax: 08232–222075; e-mail: sgowdapesce@yahoo.com).

the data measured by the authors and reported earlier in the energies of interest; 279.2, 320.07, 514.0, 661.6, 1115.5 and 1332.5 keV along with XCOM data for standard energies between 250 - 1500 keV. The best-fit coefficients obtained in the energy range 250 – 350 keV, 350 – 500 keV, 500 – 700 keV, 700 – 1000 keV and 1000 – 1500 keV by a piecewise interpolation method [17], [18] were then used to find the effective atomic number and electron density of halides.

II. The Method of Computation and Theoretical Basis

Commonly employed method of obtaining effective atomic number Z_{eff} of a material consisting of different elements in definite proportions is based on the determination of total attenuation cross-section for photon interaction by the transmission method. To obtain Z_{eff} of various materials or compounds, the main requirements are the total mass attenuation coefficients, total atomic cross-sections, and total electronic cross-sections.

As the materials are composed of various elements, it is assumed that the contribution of each element of the compound to total photon interaction is additive, yielding the well-known 'mixture rule' [30] that represents the total mass attenuation coefficient $(\mu/\rho)_c$ of any compound as the sum of the appropriately weighted proportions of the individual atoms. Thus,

$$\left(\frac{\mu}{\rho}\right)_c = \sum w_i \left(\frac{\mu}{\rho}\right)_i \tag{1}$$

where, $(\mu/\rho)_c$ is the photon mass attenuation coefficient for the compound, $(\mu/\rho)_i$ is the photon mass attenuation coefficient for the individual elements in the compound, and w_i is the fractional weight of the elements in that compound. The mass attenuation coefficient is proportional to the total molecular interaction cross section σ_t, through the relation

$$\sigma_t = \frac{M}{N_A}\left(\frac{\mu}{\rho}\right)_c \tag{2}$$

where, $M = \sum_i n_i A_i$ is the molecular weight of the compound, N_A is the Avogadro's number, and n_i is the total number of atoms of the constituent element, and A_i is its atomic weight.

For any compound, a quantity called the effective atomic cross section σ_a, is defined from (2). Clearly, in calculating σ_a, averaging is carried out over atoms of all the elements in the compound. Thus, we have,

$$\sigma_a = \frac{(\mu/\rho)_c}{N_A \sum_i w_i/A_i} = \frac{1}{N_A}\sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_t}{\sum_i n_i} \tag{3}$$

where, $f_i = (n_i/\sum_j n_j)$ and A_i are the fractional abundance and atomic weight respectively of the constituent element i. Here, n_i is the total number of atoms of the constituent element and $\sum_j n_j$ are the total number of atoms of all types present in the compound as per its chemical formula, and $\sum_i n_i$ is the total number of atoms in the compound. Similarly, the average electronic cross-section, σ_{el} is given by

$$\sigma_{el} = \frac{1}{N_A}\sum_i f_i \frac{A_i}{Z_i}\left(\frac{\mu}{\rho}\right)_i \tag{4}$$

The effective atomic number Z_{eff}, can now be written as

$$Z_{eff} = \frac{\sigma_a}{\sigma_{el}} \tag{5}$$

Other expressions for the effective atomic numbers are found in [25]-[27]. The effective electron number or electron density, N_{el} (number of electrons per unit mass) can be found from

$$N_{el} = \frac{(\mu/\rho)_c}{\sigma_{el}} = \frac{N_A}{M} Z_{eff} \sum_i n_i \tag{6}$$

III. Experimental Set-Up and Measurements

In the present work the mass attenuation coefficients (μ/ρ) of halides were measured by transmission method employed in a narrow beam good geometry setup [17] using HpGe detector for the energies 279.2, 320.07, 514.0, 661.6, 1115.5, 1173.2, 1332.5 keV. The mass attenuation coefficients were calculated for all halides using the relation

$$\left(\frac{\mu}{\rho}\right)_c = \left(\frac{\ln(I_o/I)}{\rho t}\right) \tag{7}$$

where, I_o = unattenuated photon intensity, I = attenuated photon intensity and ρt = mass per unit area in g/cm^2.

From the measured values of mass attenuation coefficients, the effective atomic cross section (σ_a) of halides are calculated using the relation

$$\sigma_a = \frac{(\mu/\rho)_c}{N_A \sum_i w_i/A_i} \tag{8}$$

The measured values of mass attenuation coefficients (μ/ρ) and the effective atomic cross sections (σ_a) obtained for all halides are listed in Tables I and II, respectively along with the XCOM values obtained at all photon energies of current interest. A good agreement was noticed among these values with the XCOM values of Berger and Hubbell [29] within the experimental uncertainties (2%).

IV. Computation of Effective Atomic Number and Effective Electron Density Units

The effective atomic number for each sample was determined by using the effective atomic cross sections σ_a. In this method, the effective atomic number of the sample was simply taken to be that value of the atomic number of an element whose σ_a matched with that of the sample in a given energy region. Clearly, this method requires a large pool of the elemental cross-section data over a wide range of energies.

TABLE I
Total Mass Attenuation Coefficients $\mu/\rho\,(cm^2/g)$ of Halides

Halides	En → (keV)	279.2 μ/ρ	320.07 μ/ρ	514.0 μ/ρ	661.6 μ/ρ	1115.5 μ/ρ	1173.2 μ/ρ	1332.5 μ/ρ
NaCl	Expt.	0.1075	0.1003	0.1822	0.0743	0.0579	0.0564	0.0528
	XCOM	0.1076	0.1016	0.1832	0.0744	0.0579	0.0565	0.0529
KCl	Expt.	0.1107	0.1304	0.0836	0.0749	0.0584	0.0569	0.0531
	XCOM	0.1102	0.1037	0.0843	0.0752	0.0585	0.0570	0.0534
CuCl	Expt.	0.1142	0.1059	0.0815	0.0742	0.0566	0.0552	0.0515
	XCOM	0.1144	0.1056	0.0828	0.0733	0.0566	0.0551	0.0517
NaBr	Expt.	0.1199	0.1093	0.0811	0.0714	0.0547	0.0535	0.0501
	XCOM	0.1218	0.1097	0.0821	0.0719	0.0549	0.0535	0.0501
KBr	Expt.	0.1201	0.1096	0.0818	0.0728	0.0554	0.0542	0.0507
	XCOM	0.1215	0.1099	0.0829	0.0727	0.0556	0.0542	0.0508
RbCl	Expt.	0.1225	0.1108	0.0814	0.0721	0.0550	0.0535	0.0501
	XCOM	0.1243	0.1114	0.0826	0.0721	0.0549	0.0535	0.0501
AgCl	Expt.	0.1555	0.1337	0.0871	0.0751	0.0560	0.0545	0.0513
	XCOM	0.1562	0.1336	0.0893	0.0759	0.0562	0.0546	0.0511
NaI	Expt.	0.1830	0.1483	0.0907	0.0757	0.0555	0.0535	0.0500
	XCOM	0.1839	0.1519	0.0923	0.0766	0.0550	0.0535	0.0499
KI	Expt.	0.1772	0.1452	0.0903	0.0764	0.0560	0.0540	0.0505
	XCOM	0.1777	0.1480	0.0873	0.0768	0.0555	0.0540	0.0504
AgBr	Expt.	0.1510	0.1305	0.0856	0.0730	0.0547	0.0534	0.0502
	XCOM	0.1525	0.1305	0.0873	0.0742	0.0549	0.0534	0.0499
CsI	Expt.	0.2021	0.1627	0.0951	0.0782	0.0552	0.0530	0.0495
	XCOM	0.2037	0.1651	0.0956	0.0776	0.0546	0.0530	0.0493
$HgCl_2$	Expt.	0.3616	0.2786	0.1313	0.0981	0.0614	0.0599	0.0547
	XCOM	0.3573	0.2754	0.1322	0.0987	0.0621	0.0598	0.0549
CdI_2	Expt.	0.1892	0.1531	0.0913	0.0755	0.0549	0.0532	0.0496
	XCOM	0.1905	0.1561	0.0934	0.0766	0.0546	0.0530	0.0494
HgI_2	Expt.	0.3092	0.2387	0.1176	0.0893	0.0591	0.0569	0.0527
	XCOM	0.3072	0.2386	0.1180	0.0904	0.0585	0.0565	0.0521

For this purpose, we are generating the elemental cross sections for the elements from Z = 3 to Z = 70 of all standard energies between 250 – 1500 keV from XCOM [29] along with the measured experimental cross sections in the energies 279.2, 320.07, 514.0, 661.6, 1115.5, 1173.2 and 1332.5 keV and reported earlier by using a mixture rule from the attenuation cross sections of the compounds. The elemental cross sections show a non-linear variation with respect to photon energy E and atomic number Z. Therefore, we can assume that the relation for σ could be of the type

$$\sigma = A(Z)E^{B(Z)} \tag{9}$$

where, A(Z) and B(Z) are constants with respect to energy and vary with atomic number.

TABLE II
Total Mass Attenuation Coefficients $\sigma_a\,(barn/atom)$ of Halides

Halides	En → (keV)	279.2 σ_a	320.07 σ_a	514.0 σ_a	661.6 σ_a	1115.5 σ_a	1173.2 σ_a	1332.5 σ_a
NaCl	Expt.	5.215	4.865	3.990	3.605	2.810	2.735	2.560
	XCOM	5.219	4.932	4.037	3.608	2.810	2.740	2.568
KCl	Expt.	6.855	6.400	5.175	4.635	3.615	3.520	3.290
	XCOM	6.822	6.419	5.215	4.654	3.619	3.527	3.307
CuCl	Expt.	9.385	8.705	6.699	6.100	4.650	4.535	4.230
	XCOM	9.404	8.681	6.808	6.026	4.650	4.532	4.248
NaBr	Expt.	10.243	9.335	6.925	6.100	4.675	4.570	4.280
	XCOM	10.405	9.371	7.014	6.142	4.687	4.566	4.278
KBr	Expt.	11.865	10.835	8.085	7.190	5.480	5.355	5.010
	XCOM	12.007	10.858	8.192	7.187	5.496	5.354	5.017
RbCl	Expt.	12.300	11.120	8.175	7.240	5.520	5.375	5.030
	XCOM	12.474	11.181	8.293	7.240	5.514	5.370	5.031
AgCl	Expt.	18.505	15.910	10.365	8.940	6.670	6.485	6.100
	XCOM	18.589	15.901	10.628	9.030	6.682	6.500	6.077
NaI	Expt.	22.780	18.450	11.290	9.425	6.910	6.660	6.225
	XCOM	22.890	18.906	11.549	9.538	6.847	6.655	6.207
KI	Expt.	24.420	20.015	12.450	10.525	7.715	7.445	6.955
	XCOM	24.492	20.393	12.727	10.548	7.656	7.442	6.946
AgBr	Expt.	23.540	20.350	13.345	11.375	8.535	8.320	7.820
	XCOM	23.775	20.340	13.605	11.563	8.559	8.326	7.787
CsI	Expt.	43.880	35.090	20.270	16.580	11.910	11.440	10.685
	XCOM	43.950	35.620	20.625	16.730	11.775	11.430	10.640
$HgCl_2$	Expt.	54.340	41.866	19.733	14.736	9.233	9.060	8.217
	XCOM	53.699	41.388	19.861	14.833	9.337	8.993	8.254
CdI_2	Expt.	38.350	31.027	18.517	15.297	11.137	10.763	10.063
	XCOM	38.620	31.646	18.923	15.523	11.060	10.744	10.018
HgI_2	Expt.	77.793	60.027	29.567	22.450	14.870	14.313	13.263
	XCOM	77.260	60.020	29.877	22.740	14.720	14.213	13.107

TABLE III
Best-Fit Coefficients for Halides

Energy range (keV)	Range of Atomic number (Z)	Intercept $\ln A_1$	Slope B_1	Intercept $\ln A_2$	Slope B_2
250 – 350	$13 \le Z \le 26$	-2.49783	2.46221	0.19584	-0.23327
	$26 \le Z \le 45$	-20.89143	8.14244	3.14469	-1.14469
	$45 \le Z < 70$	-31.69539	11.06852	4.30608	-1.46817
350 – 500	$13 \le Z \le 26$	-1.44452	2.03284	0.00968	-0.15777
	$26 \le Z \le 45$	-12.95977	5.53298	1.76533	-0.69196
	$45 \le Z < 70$	-30.52740	10.17734	4.14705	-1.32284
500 – 700	$13 \le Z \le 26$	0.21150	1.45406	-0.25587	-0.06491
	$26 \le Z \le 45$	-5.93435	3.31084	0.63229	-0.33355
	$45 \le Z < 70$	-26.7733	8.77672	3.52186	-1.09195
700– 1000	$13 \le Z \le 26$	1.00367	1.23622	-0.37693	-0.03160
	$26 \le Z \le 45$	-1.21198	1.88362	-0.08960	-0.11534
	$45 \le Z < 70$	-17.72649	6.20471	2.15741	-0.70345
1000 - 1500	$13 \le Z \le 26$	1.41517	1.23898	-0.43686	-0.03178
	$26 \le Z \le 45$	0.77346	1.41553	-0.37131	-0.04893
	$45 \le Z < 70$	-4.06403	2.67190	0.18249	-0.19261

Equation (9) can be further written as:

$$\ln\sigma = \ln A(Z) + B(Z)\ln E \tag{10}$$

and it represents a straight line with slope B(Z) and intercept lnA(Z).

For the presentation of results, the photon energy region of

interest was divided into five suitable regions viz., a) 250-350 keV, b) 350-500 keV, c) 500-700 keV, d) 700-1000 keV and e) 1000-1500 keV. Within each of these regions, the values of lnσ were found to vary linearly with lnE. So, a logarithmic regression analysis was performed between lnσ and lnE in all the three energy regions and the best-fit values of the slope B(Z) and the intercept lnA(Z) were determined. Further, we assume that the values of lnA(Z) and B(Z) are simple functions of atomic number and are given by the relations

$$\ln A(Z) = \ln A_1 + B_1 \ln Z \quad (11)$$

and

$$B(Z) = \ln A_2 + B_2 \ln Z \quad (12)$$

TABLE IV
EFFECTIVE ATOMIC NUMBER (Z_{EFF}) OF HALIDES

Halides	En → (keV)	279.2 Z_{eff}	320.07 Z_{eff}	514.0 Z_{eff}	661.6 Z_{eff}	1115.5 Z_{eff}	1173.2 Z_{eff}	1332.5 Z_{eff}
NaCl	Expt.	14.19	14.04	14.02	14.10	14.03	14.02	14.02
	XCOM	14.03	14.03	14.01	14.01	14.00	14.00	14.00
	[20]	14.20	14.10		14.00			
KCl	Expt.	18.00	17.95	17.73	17.98	17.98	17.98	17.97
	XCOM	18.01	18.00	18.00	18.00	18.00	18.00	18.00
	[20]	17.55	17.50		17.45			
CuCl	Expt.	23.67	23.64	22.96	23.47	23.04	23.08	23.05
	XCOM	23.38	23.29	23.11	23.07	23.03	23.03	23.03
NaBr	Expt.	25.54	25.17	23.71	23.47	23.16	23.25	23.32
	XCOM	24.58	24.20	23.47	23.30	23.13	23.12	23.12
	[20]	25.25	25.00		23.50			
KBr	Expt.	28.06	28.08	27.61	27.67	26.98	27.08	27.11
	XCOM	27.91	27.69	27.27	27.17	27.07	27.07	27.07
	[20]	28.20	28.00		27.00			
RbCl	Expt.	28.67	28.56	27.86	27.84	27.17	27.17	27.21
	XCOM	28.42	28.09	27.43	27.27	27.12	27.11	27.10
AgCl	Expt.	36.48	36.05	33.80	33.47	32.41	32.39	32.62
	XCOM	36.05	35.21	33.38	32.89	32.39	32.37	32.34
NaI	Expt.	41.23	39.69	35.23	35.06	33.50	33.20	33.25
	XCOM	39.64	38.21	34.82	33.85	32.82	32.78	32.72
	[20]	40.50	40.00		35.00			
KI	Expt.	42.96	41.85	39.24	38.60	37.12	36.85	36.91
	XCOM	41.91	40.81	38.19	37.44	36.63	36.61	36.56
	[20]	42.10	42.00		37.00			
AgBr	Expt.	42.04	42.30	41.52	41.32	40.79	40.88	41.21
	XCOM	41.93	41.75	41.34	41.22	41.10	41.09	41.08
CsI	Expt.	55.10	54.94	53.73	53.59	53.76	53.32	53.57
	XCOM	54.03	54.03	54.01	54.01	54.01	54.00	54.00
	[20]	53.75	53.70		53.65			
$HgCl_2$	Expt.	59.50	58.80	51.61	47.71	42.81	43.03	43.17
	XCOM	61.80	58.82	49.64	46.21	42.02	41.78	41.36
CdI_2	Expt.	52.51	52.40	50.98	51.09	51.09	50.96	51.13
	XCOM	51.50	51.47	51.40	51.38	51.35	51.35	51.35
HgI_2	Expt.	67.60	67.54	64.73	64.16	63.59	63.25	63.36
	XCOM	67.59	67.10	65.22	64.37	63.24	63.16	63.02

TABLE V
ELECTRON DENSITY ($N_{EL}X10^{23}$) OF HALIDES

Halides	En → (keV)	279.2 N_{el}	320.07 N_{el}	514.0 N_{el}	661.6 N_{el}	1115.5 N_{el}	1173.2 N_{el}	1332.5 N_{el}
NaCl	Expt.	2.924	2.894	2.889	2.907	2.891	2.889	2.890
	XCOM	2.893	2.891	2.887	2.887	2.886	2.886	2.886
KCl	Expt.	2.908	2.900	2.901	2.906	2.904	2.904	2.903
	XCOM	2.909	2.909	2.908	2.908	2.908	2.908	2.908
CuCl	Expt.	2.879	2.876	2.795	2.856	2.802	2.808	2.804
	XCOM	2.845	2.833	2.812	2.806	2.802	2.802	2.802
NaBr	Expt.	2.990	2.946	2.776	2.748	2.710	2.722	2.730
	XCOM	2.878	2.833	2.747	2.728	2.707	2.707	2.706
KBr	Expt.	2.840	2.842	2.794	2.800	2.730	2.740	2.743
	XCOM	2.824	2.802	2.759	2.750	2.740	2.739	2.739
RbCl	Expt.	2.855	2.845	2.775	2.773	2.706	2.706	2.710
	XCOM	2.831	2.798	2.732	2.716	2.701	2.700	2.700
AgCl	Expt.	3.065	3.029	2.840	2.813	2.723	2.721	2.741
	XCOM	3.030	2.959	2.805	2.764	2.722	2.720	2.718
NaI	Expt.	3.313	3.189	2.911	2.817	2.691	2.668	2.672
	XCOM	3.185	3.071	2.798	2.720	2.637	2.634	2.629
KI	Expt.	3.117	3.036	2.847	2.801	2.693	2.673	2.677
	XCOM	3.041	2.961	2.771	2.716	2.658	2.656	2.652
AgBr	Expt.	2.696	2.713	2.663	2.650	2.617	2.622	2.643
	XCOM	2.689	2.678	2.651	2.644	2.636	2.636	2.635
CsI	Expt.	2.547	2.541	2.490	2.511	2.492	2.471	2.485
	XCOM	2.505	2.505	2.504	2.504	2.504	2.504	2.504
$HgCl_2$	Expt.	3.959	3.912	3.401	3.167	2.915	2.929	2.872
	XCOM	4.113	3.914	3.303	3.075	2.796	2.780	2.752
CdI_2	Expt.	2.589	2.585	2.515	2.520	2.520	2.514	2.522
	XCOM	2.541	2.539	2.536	2.535	2.533	2.534	2.533
HgI_2	Expt.	2.687	2.685	2.573	2.550	2.528	2.514	2.519
	XCOM	2.688	2.668	2.593	2.559	2.514	2.511	2.506

Equations (11) and (12) represent straight lines with slopes B_1 and B_2 and corresponding intercepts $\ln A_1$ and $\ln A_2$, respectively in a selected region of elements. In each energy region, the range of elements is divided into three groups. This ensures the linearity in the selected region so that the best-fit values of $\ln A_1$, B_1, $\ln A_2$ and B_2 could be obtained for the E and Z region of interest. These values are shown in Table III. Using these best - fit values further; we obtained the formula for Z_{eff} of the form

$$Z_{eff} = \left[\frac{\sigma_a}{A_1 E^{\ln A_2}} \right]^{1/d} \quad (13)$$

where, $d = B_1 + B_2 \ln E$ and E is in keV.

In obtaining this formula, we have assumed the equivalence between Z_{eff} of the sample and the Z of the equivalent element as discussed earlier [17], [18].

Using the calculated Z_{eff} values, the effective electron density N_{el} was calculated by using the following relation

$$N_{el} = \frac{N_A}{M} Z_{eff} \Sigma_i n_i \quad (14)$$

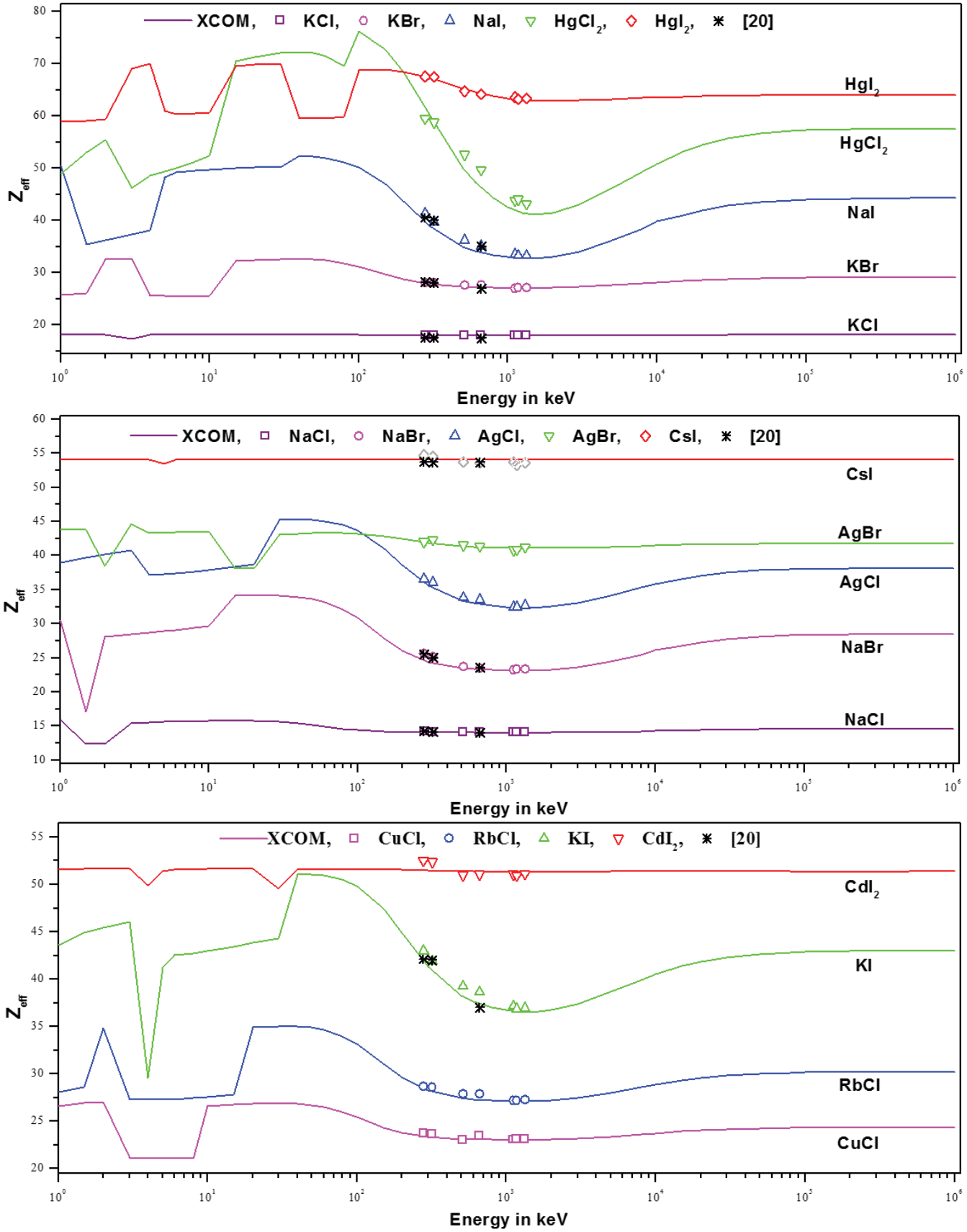

Fig. 1 Plot of Z_{eff} as a function of Photon Energy in keV

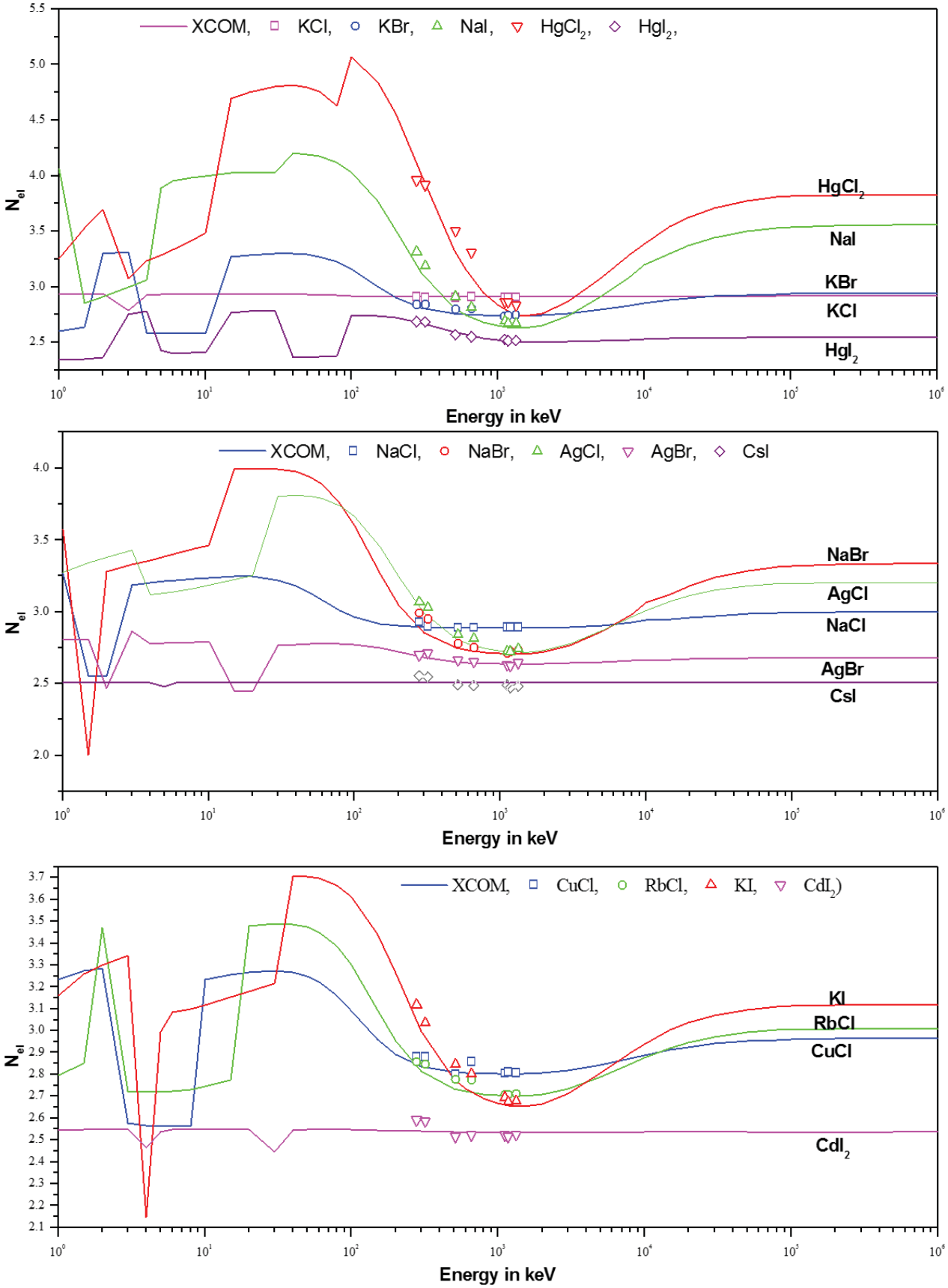

Fig. 2 Plot of N_{el} as a function of Photon Energy in keV

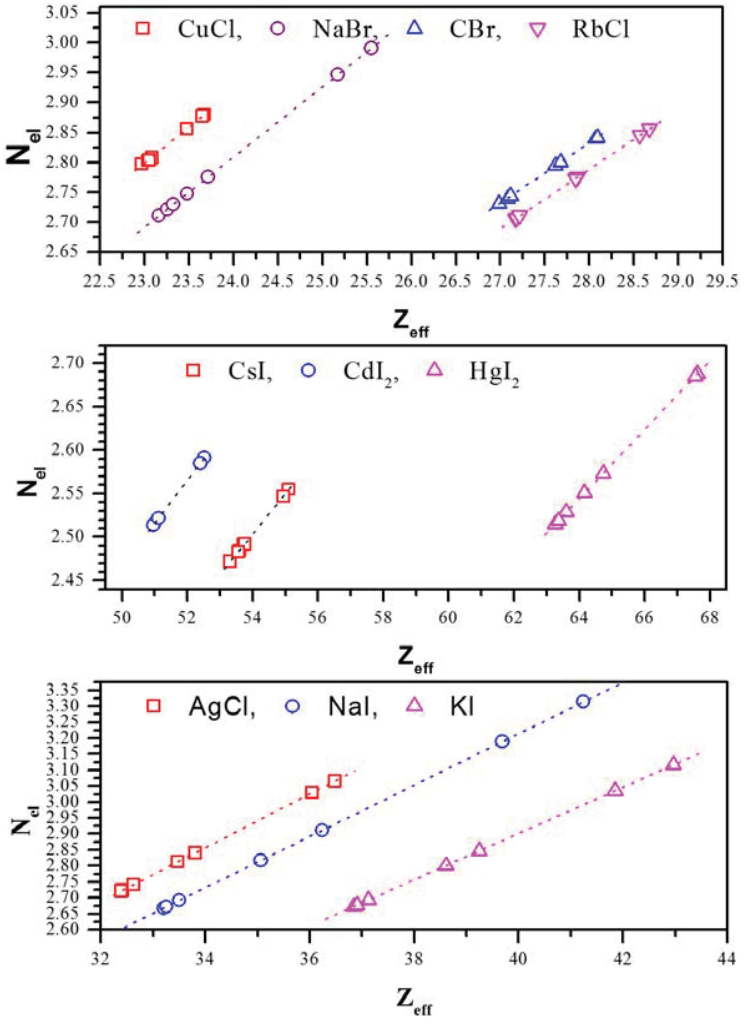

Fig. 3 Typical plot of N_{el} vs Z_{eff}

The values of Z_{eff} and N_{el} obtained using (13) and (14) are listed in Tables IV and V, respectively. These values are compared with the values calculated in an empirical formula by using XCOM values of attenuation cross sections and the other experimental values available [20]. Plots of the present values and other available measured values of Z_{eff} [20] versus energy are shown in Fig. 1, and N_{el} versus energy are also shown in Fig. 2 along with the values calculated by using XCOM data [29] for standard energies from 10^0 to 10^6 keV for all halides.

V. Results and Discussion

The measured values of mass attenuation coefficients (μ/ρ) and effective atomic cross sections (σ_a) are in good agreement with XCOM values within 2% error, whereas effective atomic numbers (Z_{eff}) and electron densities (N_{el}) are in good agreement with XCOM values within 4 % error for all halides. It is observed that the variation of Z_{eff} with energy depends on (spread) the difference between the atomic numbers of the constituent elements present in the compound. The materials, which have least spread in the atomic numbers of the constituents like NaCl, KCl, CsI and CdI_2 have almost constant values of Z_{eff} and N_{el}. In case of CuCl, NaBr, KBr, RbCl, AgCl, NaI, AgBr, and HgI_2, the spread of the constituent elements is less in the compounds, hence the variation of Z_{eff} and N_{el} with the energy is less. Whereas, in case of KI and $HgCl_2$ there is a large spread in the atomic number of the constituents hence, there is large variation of Z_{eff} and N_{el} values with energy.

The variation Z_{eff} and N_{el} with energy are shown in Fig. 1 and 2, respectively along with the measured values of available data [20]. A typical plot of N_{el} vs Z_{eff} shown in Fig. 3 for all energies show a linear relationship for all compounds.

VI. Conclusions

The effective atomic number and the electron density of halides are useful parameters in radiation detectors, dosimetric calculation of radiation dose in radiotherapy and radiation shielding. These have physical meaning and their numerical values allow many characteristics of a material to be visualized, which are used as radiation detectors in biological dosimetry of ionizing radiations. They are also useful in the field of radiation monitoring, radiographic measurements.

ACKNOWLEDGEMENT

The author is grateful to Professor Ramakrishna Gowda, Department of Studies in Physics, University of Mysore, Mysore, for providing the required facilities to carrying out this work. He also expresses his gratitude to the Principal and Management of PES College of Engineering, Mandya for their support and financial assistant.

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Dr. Shivalinge Gowda, M.Sc., Ph.D., MISTE

Dr. Shivalinge Gowda, born in Chandupura, a village in Karnataka of the Indian subcontinent on 1st June 1963. He is Bachelor of Science from the University of Mysore, Mysore, Karnataka, India (1985), Master of Science in Physics, from the University of Mysore, Mysore (1988) and Doctorate from the University of Mysore, Mysore, India (2006). His major field of study is the interaction of Photon with matter.

He was formerly a faculty in Bharathi College, Bharathinagara, Karnataka, India (Degree College under the University of Mysore Mysore). He has been a Member, Coordinator and Chairman on panels of Board of Studies and Board of Examination in PES College of Engineering, Mandya, Karnataka (An Autonomous Institution Affiliated to Visvesvaraya Technological University (VTU), Belagavi) and Other Statutory Bodies of affiliated Colleges under (VTU) Belgavi. He is presently working as Professor and Head of the Department of Physics in PES College of Engineering, Mandya, Karnataka, India (PIN-571 401).

He has published few papers on National and International Journals. He has presented and published some of the papers in national and international Conferences and Symposia. He guided nine candidates for M.Phil degree from different universities of India. His research interests are Interaction of Photons with matter (composite materials).

The author is a life member of Indian Society for Technical Education (LM 73696, 2010) and a member of The Indian Science Congress Association (L 28540, 2015). He has got best programme officer Award in National Service Scheme, University of Mysore, Mysore, Karnataka, India (1995).

Cell: +91-9449679429
Ph: +91-08232-220043
Fax: +91-08232-222075
Res: +91-8212419421
e-mail: sgowdapesce@yahoo.com